
METODOLOGIE SPERIMENTALI IN FISICA E ASTROFISICA DELLE PARTICELLE

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Aprile-Maggio 2015

1a parte

Programma

■ 1a parte

- ❑ Alcune proprietà fondamentali dei muoni (e dei neutrini) rilevanti (o meno) per un uso applicato.
- ❑ Utilizzo di muoni cosmici per radiografie e tomografia nel campo della sicurezza, dell'archeologia, della geofisica e del controllo ambientale.

■ 2a parte

- ❑ Reattori pilotati da acceleratori, un nuovo approccio alla produzione di energia col nucleare e alla soluzione del problema delle scorie.

Alcuni spin-offs della HighEnergyPhysics

- Hadron therapy for otherwise untreatable tumors
- Positron-Emission-Tomography (PET)
- Medical Imaging
- Free Electron Laser
- The World Wide Web
- Grid-Computing
- NeuroBayes - Neuronal Bayesian statistics for economy
- ...
- Superconducting magnets, high vacuum, low temperatures (on a large scale)
- Training, international collaboration (science brings nations together)
- non è un caso → pag. seguenti

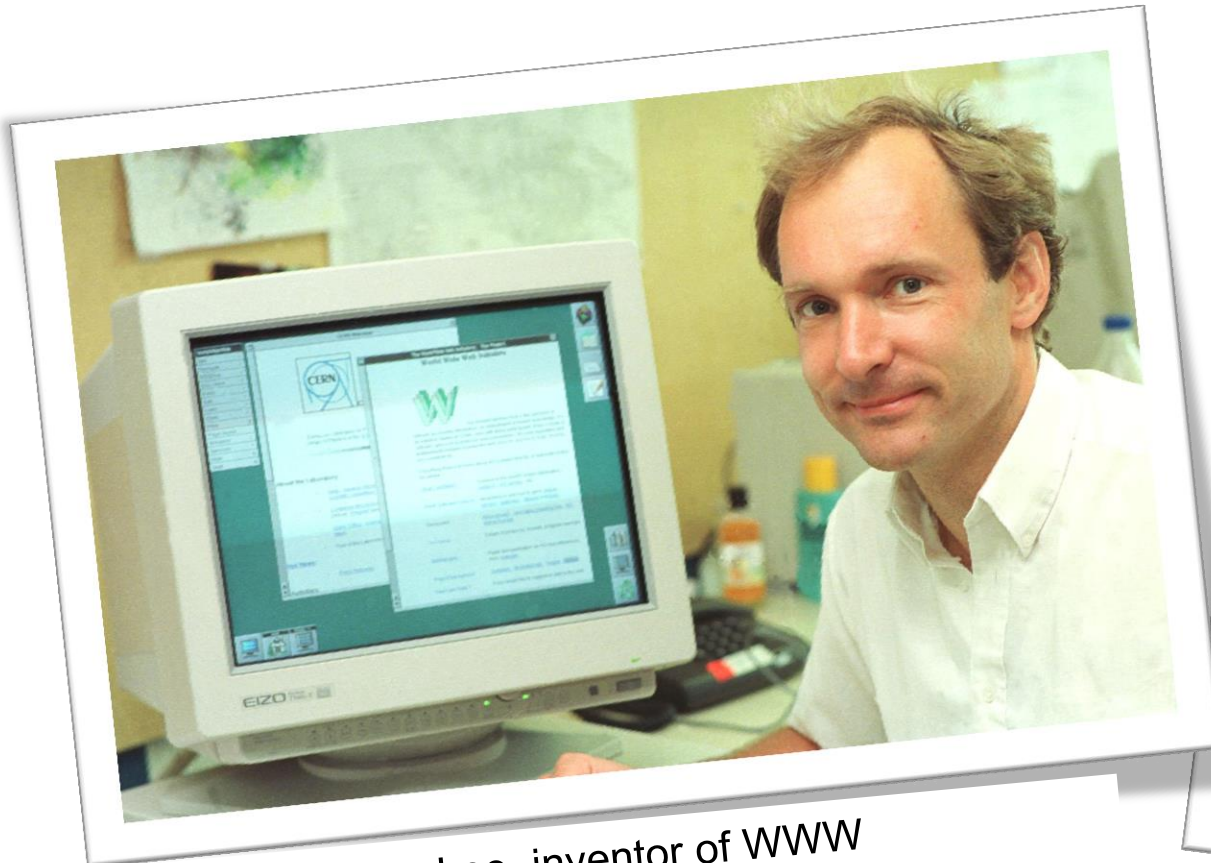
Applications: e.g. the World Wide Web!

Tim: a physicist from Oxford, working at CERN on accelerator (PS, LEP) controls in the 1980s

Network + Hypertext:
developed in 1989 with the
LHC project in mind

Software released freely
by CERN in 1993

Free for everybody ever
since



Sir Tim Berners-Lee, inventor of WWW



The European strategy for particle physics

Particle physics stands on the threshold of a new and exciting era of discovery. The next generation of experiments will explore new domains and probe the deep structure of space-time. They will measure the properties of the elementary constituents of matter and their interactions with unprecedented accuracy, and they will uncover new phenomena such as the Higgs boson(*) or new forms of matter. Longstanding puzzles such as the origin of mass, the matter-antimatter asymmetry of the Universe and the mysterious dark matter and energy that permeate the cosmos will soon benefit from the insights that new measurements will bring. Together, the results will have a profound impact on the way we see our Universe; ...

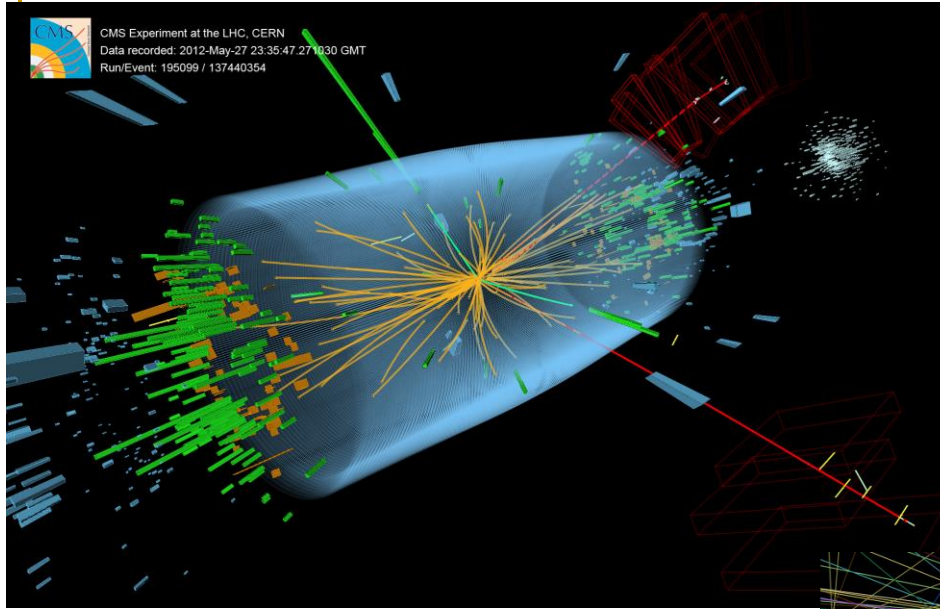
CERN Council, Lisbon, 14 July 2006

(*) done, 4 July 2012, CERN Seminars, varie pubblicazioni successive

2012- ... a success of the LHC

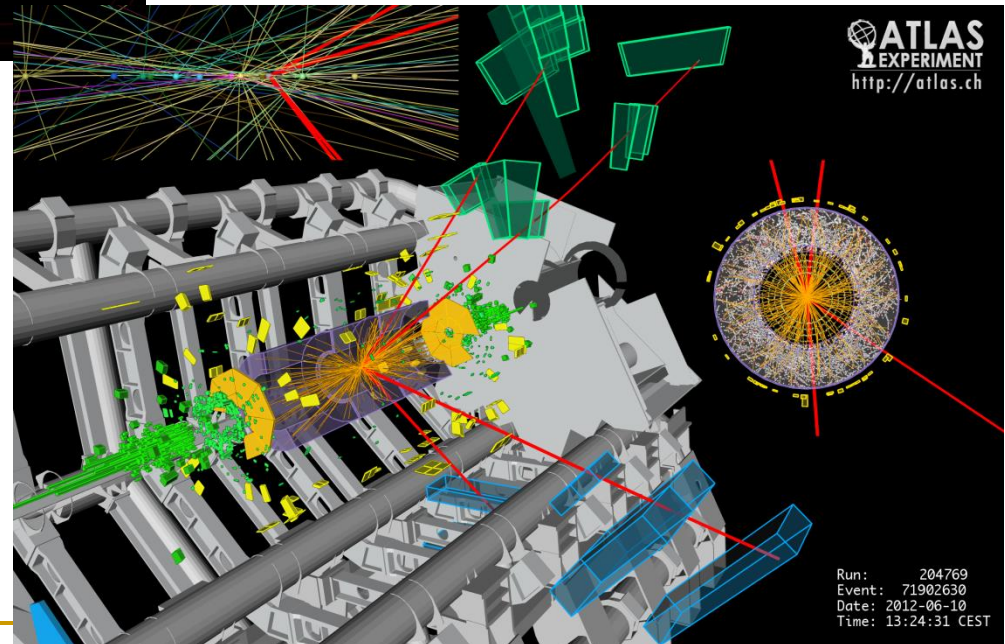
- 2012 discovery of a Brout-Englert-Higgs-like boson by ATLAS and CMS using 7 and 8 TeV pp data (announced on 4 July 2012)
- 8 October 2013 NP awarded to Francois Englert and Peter Higgs for their 1964 papers on the BEH mechanism
- Spring 2015 LHC resumes at 13 TeV and ... you may follow it any time on Twitter

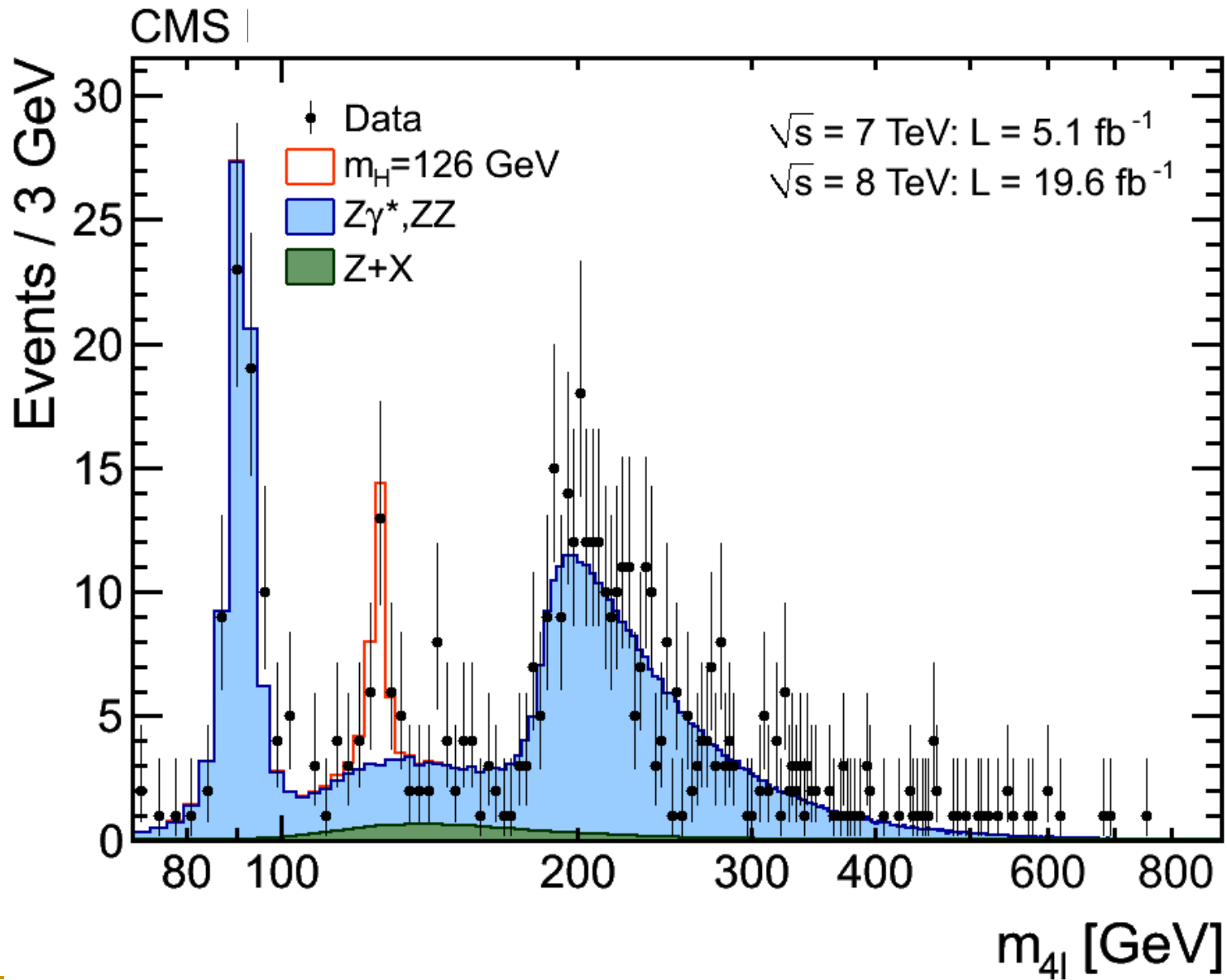




Higgs candidate:
 $H \rightarrow ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-$

Higgs candidate:
 $H \rightarrow ZZ \rightarrow e^+e^-\mu^+\mu^-$





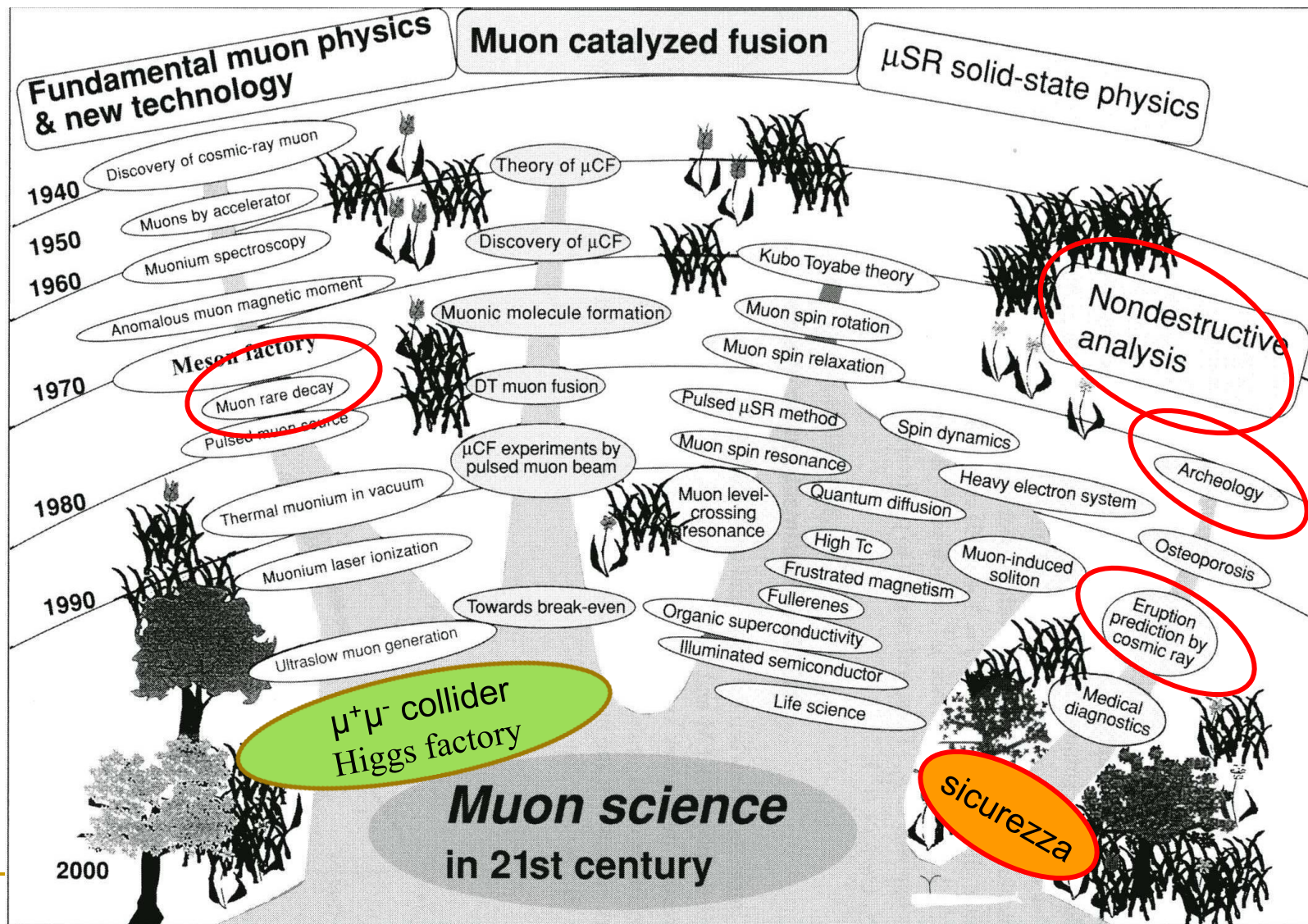
Eu Strategy: Complementary Issues, Outreach & Technology Transfer

- Fundamental physics impacts both scientific and philosophical thinking, influencing the way we perceive the universe and our role in it. It is an integral part of particle physics research to share the wonders of our discoveries with the public and the youth in particular. Outreach should be implemented with adequate resources from the start of any major project; ...
- Technology developed for nuclear and particle physics research has made and is making a lasting impact on society in areas such as material sciences and biology (e.g. synchrotron radiation facilities), communication and information technology (e.g. the web and grid computing), health (e.g. the PET scanner and hadron therapy facilities); ...
- The technical advances necessary for particle physics both benefit from, and stimulate, the technological competences available in European industry; ...

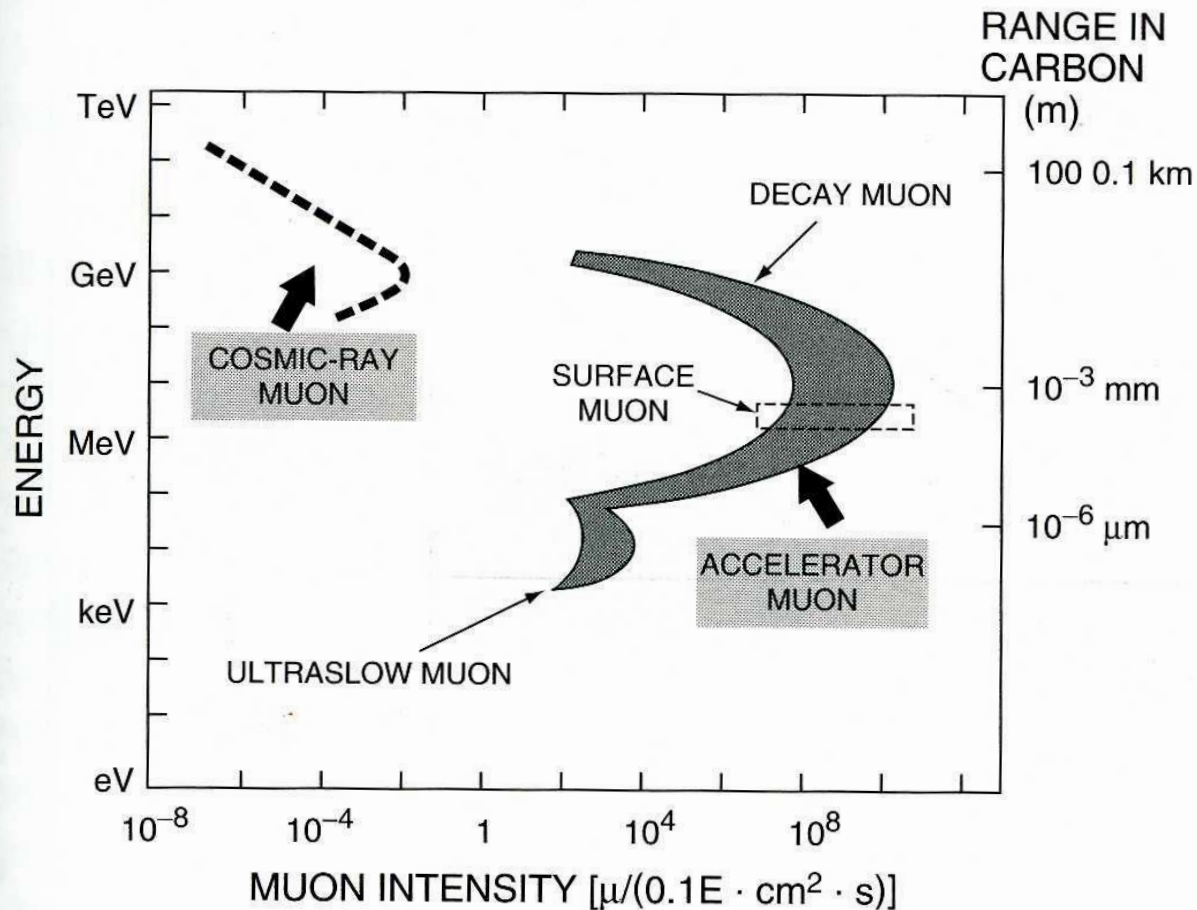
Fisica fondamentale ed applicata con i μ

- dal 1937-38 (Anderson&Neddermeyer, scoperta del μ) in poi, progressi in quattro direzioni:
 - fisica fondamentale e nuova tecnologia
 - fusione catalizzata da muoni
 - muonSR e fisica dello stato solido
 - analisi non distruttiva (muografia)
- S.H. Neddermeyer and C.D. Anderson, Note on the Nature of Cosmic-Ray Particles, Phys. Rev. **51** (1937) 884; Nature of Cosmic-Ray Particles, Rev. Mod. Phys. **11** (1939) 191.

Che cosa si può fare con i muoni



E, range e intensità delle sorgenti di μ



Muon Science

Inner Structure of Geophysical Substance

*μ SR Condensed Matter
Biomedical Application
Muon Catalyzed Fusion,
etc.*

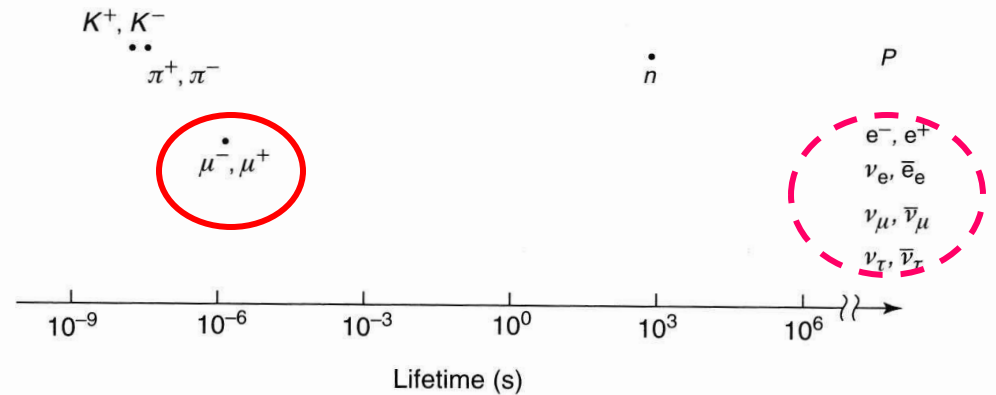
Surface Science

Muoni (e neutrini) in una frase

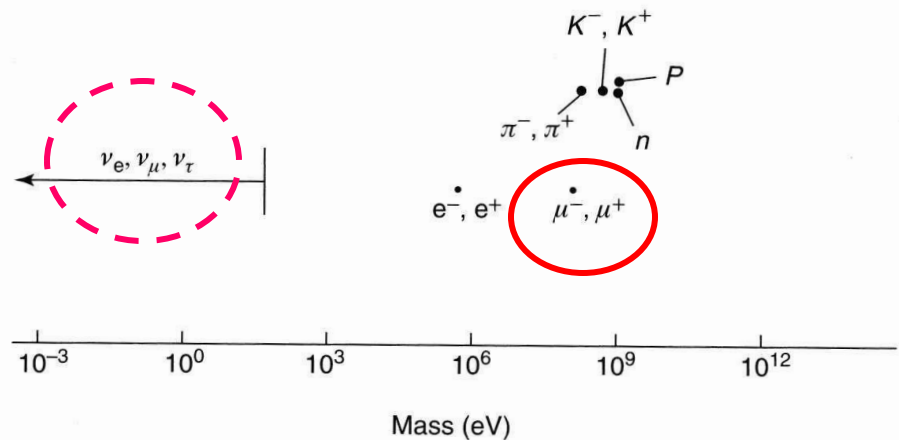
- I muoni sono particelle instabili con due tipi di cariche elettriche (μ^+ , μ^-) che hanno spin $\frac{1}{2}$, una massa intermedia fra quella del p e quella dell'e ($\frac{1}{9} m_p$, $207 m_e$), una vita media di $\sim 2.2 \mu\text{s}$ e non hanno interazioni forti.
- I neutrini non hanno carica elettrica, hanno spin $\frac{1}{2}$, massa molto piccola ($\ll m_e$), ma non nulla (oscillano fra un sapore e l'altro, LFV), interagiscono molto poco ed in molti esperimenti ad alta energia appaiono come energia mancante.

Vite medie e masse di varie particelle elementari

- Il muone ha la seconda più lunga vita media dopo il n fra le particelle instabili (i neutrini sono stabili) ed ha la seconda più piccola massa fra tutte le particelle elementari dopo l' e (e i neutrini)



(a)



(b)

Qualche proprietà dei μ (e ν)

■ μ^\pm

- $m = (105.6583668 \pm 0.0000038) \text{ MeV}$
- $\tau = (2.1969803 \pm 0.0000022) 10^{-6} \text{ s}$
- interazioni: e.m. e debole
 - un e^\pm pesante (“E questo chi lo ha ordinato?”, I.I. Rabi), diverso da e^\pm rispetto alla perdita di energia
 - energia critica (Radiaz. = Ioniz.) ϵ_μ – diverse centinaia di GeV, dipende da Z → **particella penetrante**

■ $\nu_{e,\mu,\tau}$ (anche anti)

- $m < 1\text{-}2 \text{ eV}$, interazione debole → **molto penetrante**
- $\sigma_\nu \sim 0.68 10^{-38} E_\nu(\text{GeV}) \text{ cm}^2$ [CC, ν_μ ; 0.33 $\text{anti}\nu_\mu$]

Misure di precisione con acceleratori

- vita media del μ^+
- cenno alla ricerca dei decadimenti rari del μ
e.g. $\mu^+ \rightarrow e^+ \gamma$

τ_μ : input per il MS

correzioni di QED e QCD

$$1/\tau_\mu = G_F^2 m_\mu^5 (1 + \Delta q) / (192 \pi^3)$$



Enrico Fermi

fine structure constant

$$\alpha = 1/137.035\,999\,76\,(50)(0.004\text{ ppm})$$

PDG2014: $\alpha = 1/137.035999074(44)$

Fermi constant

$$G_F = 1.16639(2) \times 10^{-5} \text{ GeV}^{-2} \text{ (17 ppm)}$$

MuLan2013: $G_F = 1.1663787(6) 10^{-5} \text{ GeV}^{-2}$

Z-boson mass

$$M_Z = 91.1876(21) \text{ GeV}/c^2 \text{ (23 ppm)}$$

vita media
del μ^+

(nelle box stato al 2007; oggi 2014-15: α 0.32 ppb; G_F 0.5 ppm; M_Z invariato)

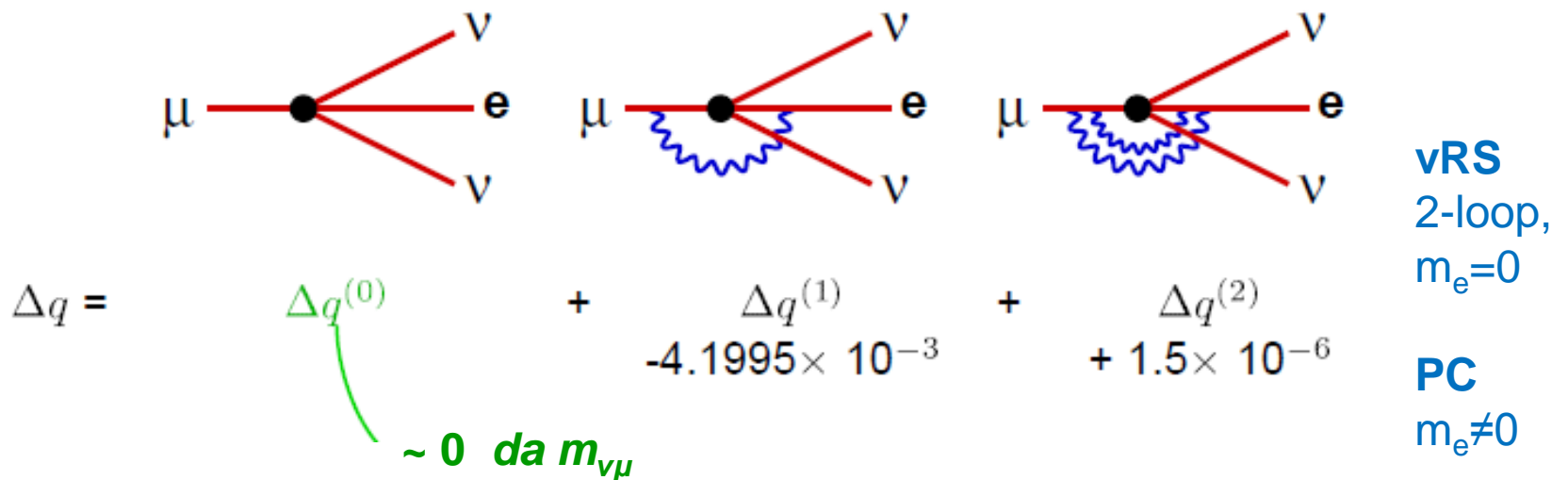
Dalla vita media del muone a G_F

$$\frac{1}{\tau_\mu} = \Gamma_\mu = \frac{G_F^2 m_\mu^5}{192 \pi^3} (1 + \Delta q)$$

0.13 ppm

T. van Ritbergen and R.G. Stuart, Phys. Rev. Lett. 82, 488 (1999)
 A.Pak and A. Czarnecki, Phys. Rev. Lett. 100, 241807 (2008)

Incertezza
teorica (G_F)
0.3 ppm
0.14 ppm



Stato sperimentale della vita media del μ^+

| | | | | |
|------|-----------------------------------|---------------|---------------------|-------------|
| 2011 | Webber <i>et al.</i> | ± 2.2 ps | 10^{12} ← N_μ | |
| 2008 | Barczyk <i>et al.</i> | ± 35 ps | 10^{10} | |
| 2007 | Chitwood <i>et al.</i> | ± 24 ps | : | |
| 1984 | Bardin <i>et al.</i> | ± 66 ps | : | |
| 1984 | Giovanetti <i>et al.</i> | ± 60 ps | 10^9 | |
| 1974 | Balandin <i>et al.</i> | ± 80 ps | : | |
| 1973 | Duclos <i>et al.</i> | ± 300 ps | 10^8 | |
| 1972 | Williams & Williams <i>et al.</i> | ± 800 ps | : | (μ^-) |
| 1963 | Meyer <i>et al.</i> | ± 2000 ps | 10^6 | |
| 1962 | Lundy | ± 4000 ps | : | |
| 1936 | Anderson and Neddermeyer | discovery | 1 | |

I due esperimenti recenti per la misura di $\tau_{\mu}(\mu^+)$

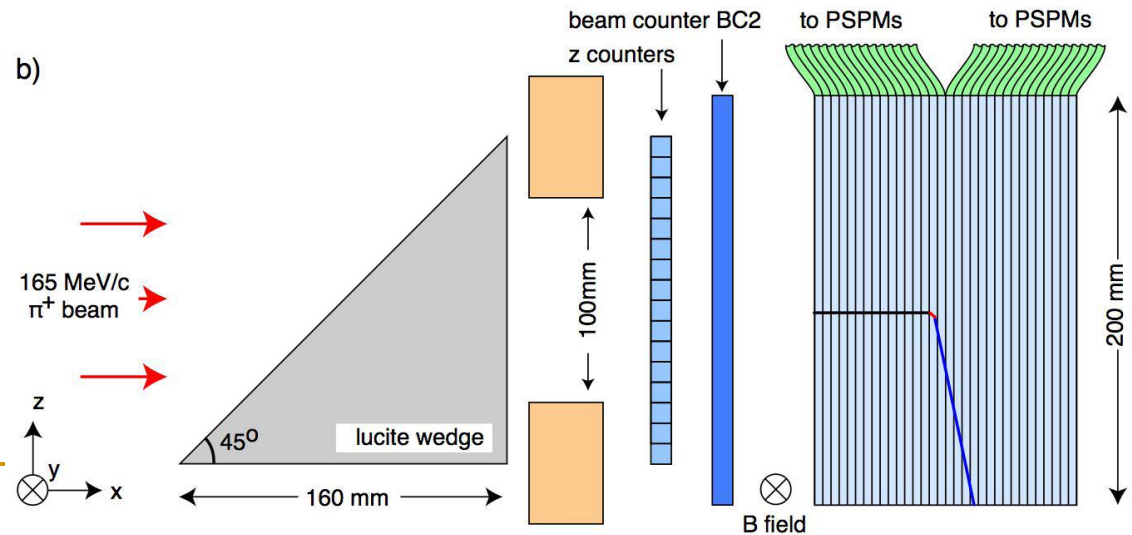
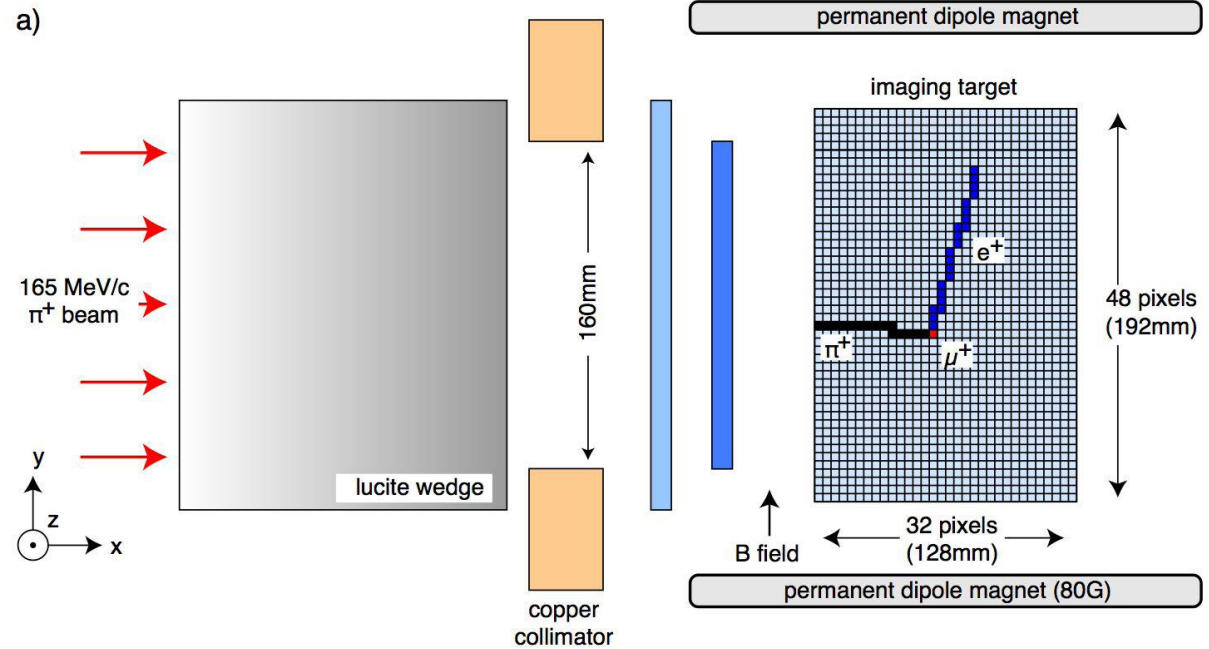
- FAST (obiettivo: 2 ppm; realizzato: 16 ppm)
- MuLan (obiettivo: 1 ppm; realizzato: 1 ppm)

Misure recenti di vita media del muone+

- Esperimento FAST (Fibre Active Scintillator Target) al PSI di Villigen/Zurigo
- obiettivo una misura di τ_{μ^+} con 2 ppm di incertezza (G_F con 1 ppm)
- $\pi^+ \rightarrow \mu^+ + \nu_{\mu}$ (DC, $p = 165 \text{ MeV}/c$) seguito da $\mu^+ \rightarrow e^+ + \bar{\nu}_{\mu} + \nu_e$ a riposo
- i π si fermano nel bersaglio (attivo, 32x48 pixel, barrette scintillatore plastico 4x4x200 mm³) dopo aver perso tutta l'energia
- lettura delle barrette con fibre WLS e Hamamatsu H6568-10 PositionSensitivePMT

FAST

- l'assorbitore a cuneo distribuisce i punti di arresto dei π^+ uniformemente
- si registrano i tempi di decadimento della catena $\pi \rightarrow \mu \rightarrow e$ usando CAEN V767 multihit TDC (da $-8 \mu\text{s}$ a $+22 \mu\text{s}$ rispetto al π -stop)
- trigger LV2 ($\pi \rightarrow \mu$ decay), 30 kHz, in totale $\sim 10^{10}$ eventi



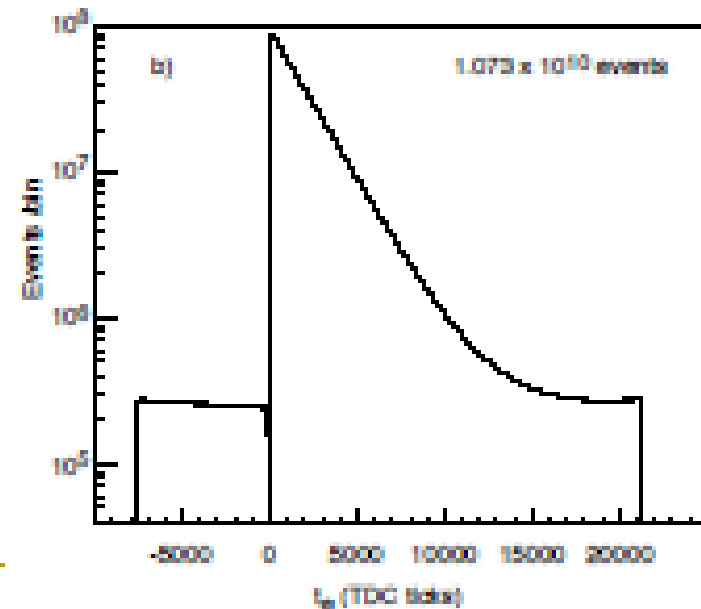
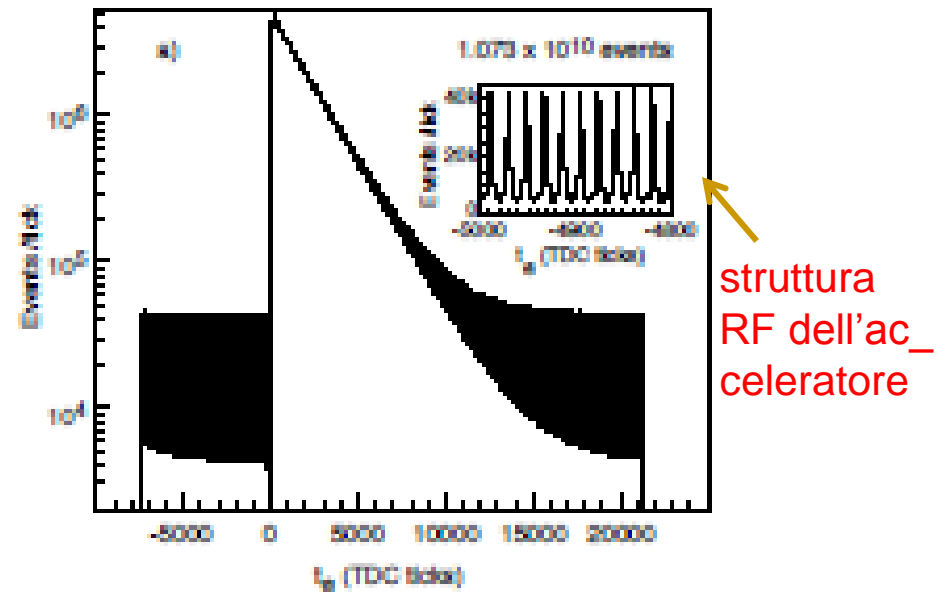
Il rivelatore



- bersaglio:
1536 pixel,
ciascuno
letto con 2
fibre WLS

FAST/2

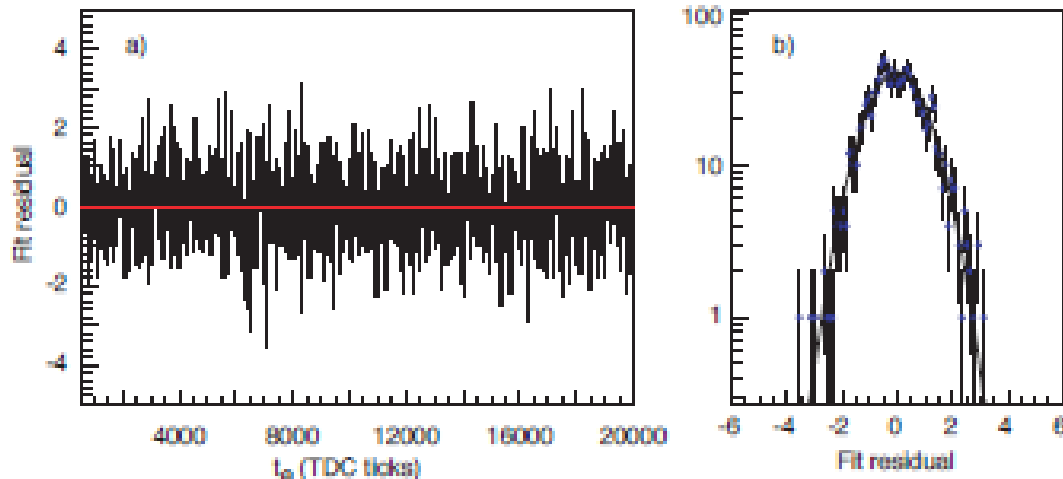
- per la misura finale LV2 deve operare ad 1 MHz, ~7 TB/g di dati → l'analisi è fatta online accumulando 1200 istogrammi separati di vita media (informazioni per la misura e lo studio dei sistematici)
- trasferimento dati dai 4 crates VME a 20 MB/s a 4 PCs per il DAQ, poi ad una farm di PCs per l'analisi attraverso un Gigabit ethernet switch
- scala dei tempi: Rb atomic clock 30 MHz (~ 0.5 ppm)



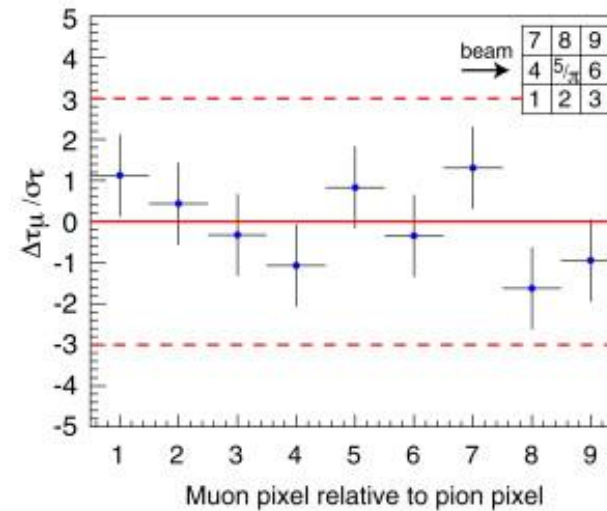
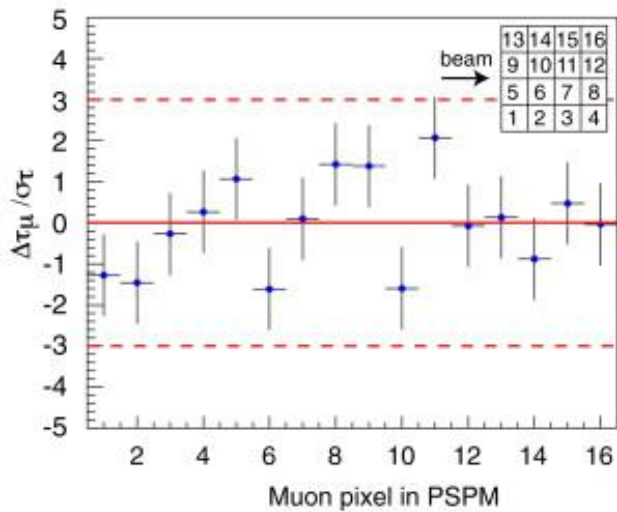
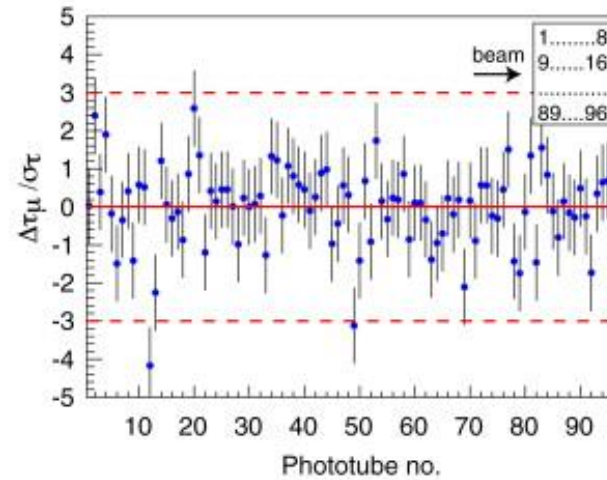
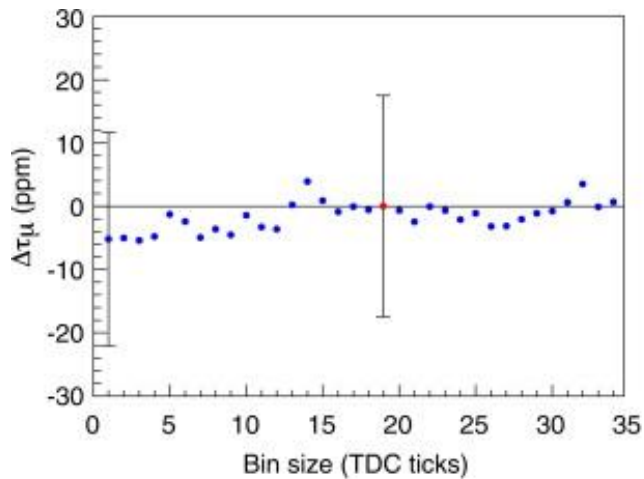
a) bin ~1.04 ns; b) bin integrato su 19 ns (periodo acceleratore)

FAST/3

- fit $N(t_e) = f_{\text{TDC}}(t_e) (Ae^{-t_e/\tau_\mu} + Be^{t_e/\tau_\mu} + C)$
 f_{TDC} – non linearità del TDC
A segnale di decadimento del μ
B fondo correlato crescente
C fondo scorrelato
- $\tau_{\mu^+} = [2.197083 (32) (15)] \mu\text{s}$ (stat) (sist)



FAST/4 - sistematici

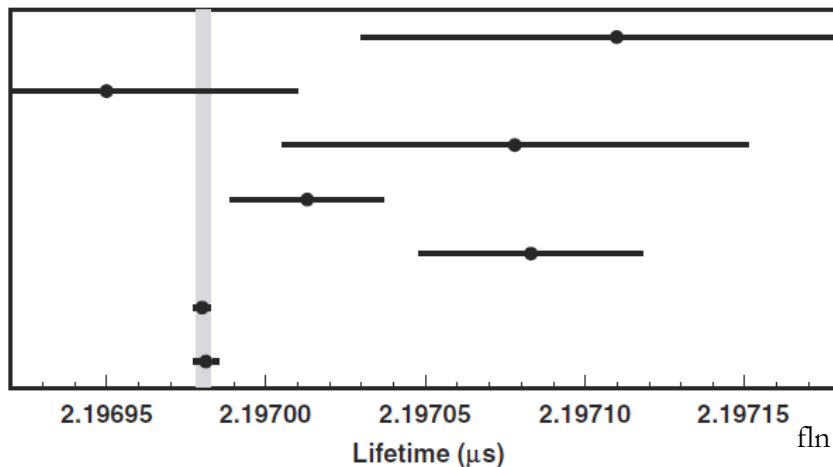
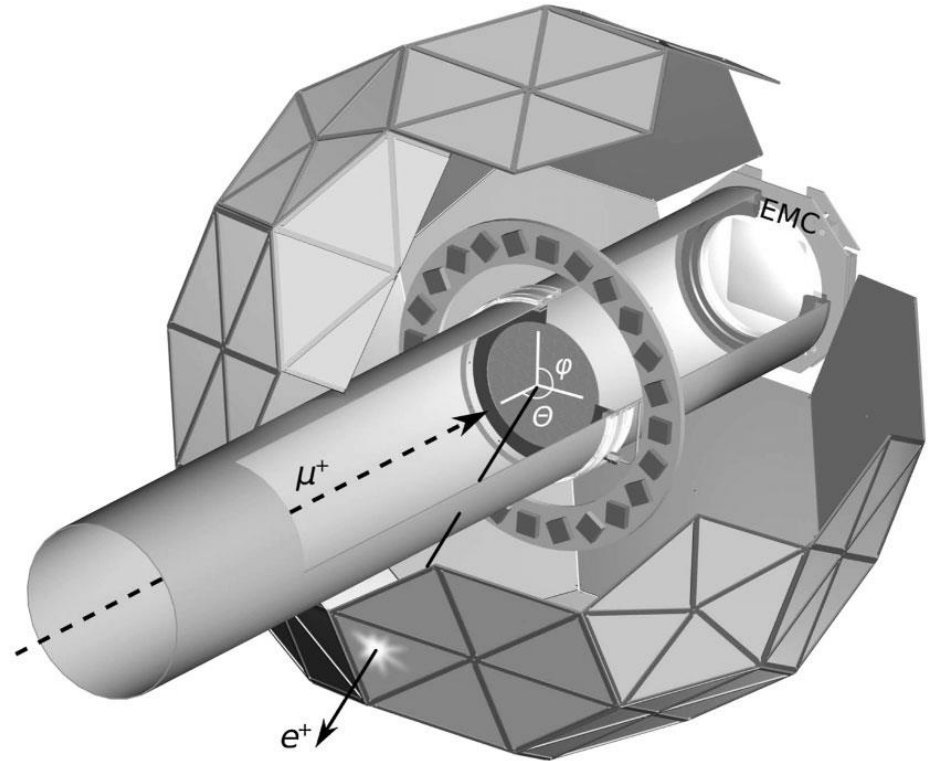


MuLan

- si fermano i mu in un fascio pulsato al PSI e si misura il t di decadimento (bersagli di AK-3 ferromagnetico, 0.4 T, run6, e SiO₂ con B=0.013 T, run7)

- tile scintillatori x2 triangolari

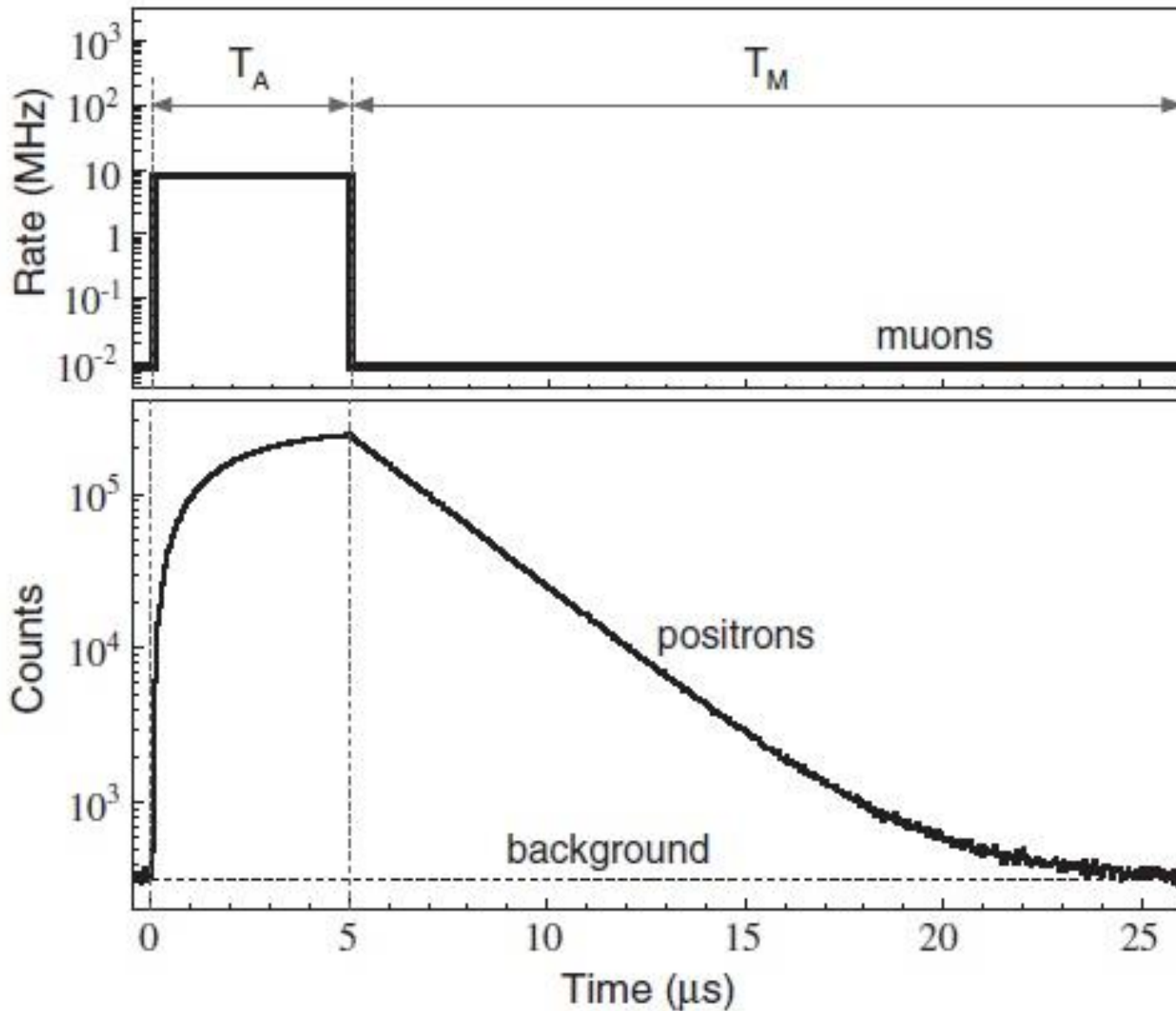
- $1.6 \cdot 10^{12}$ mu a 10^7 mu/s



fln apr-mag 2015

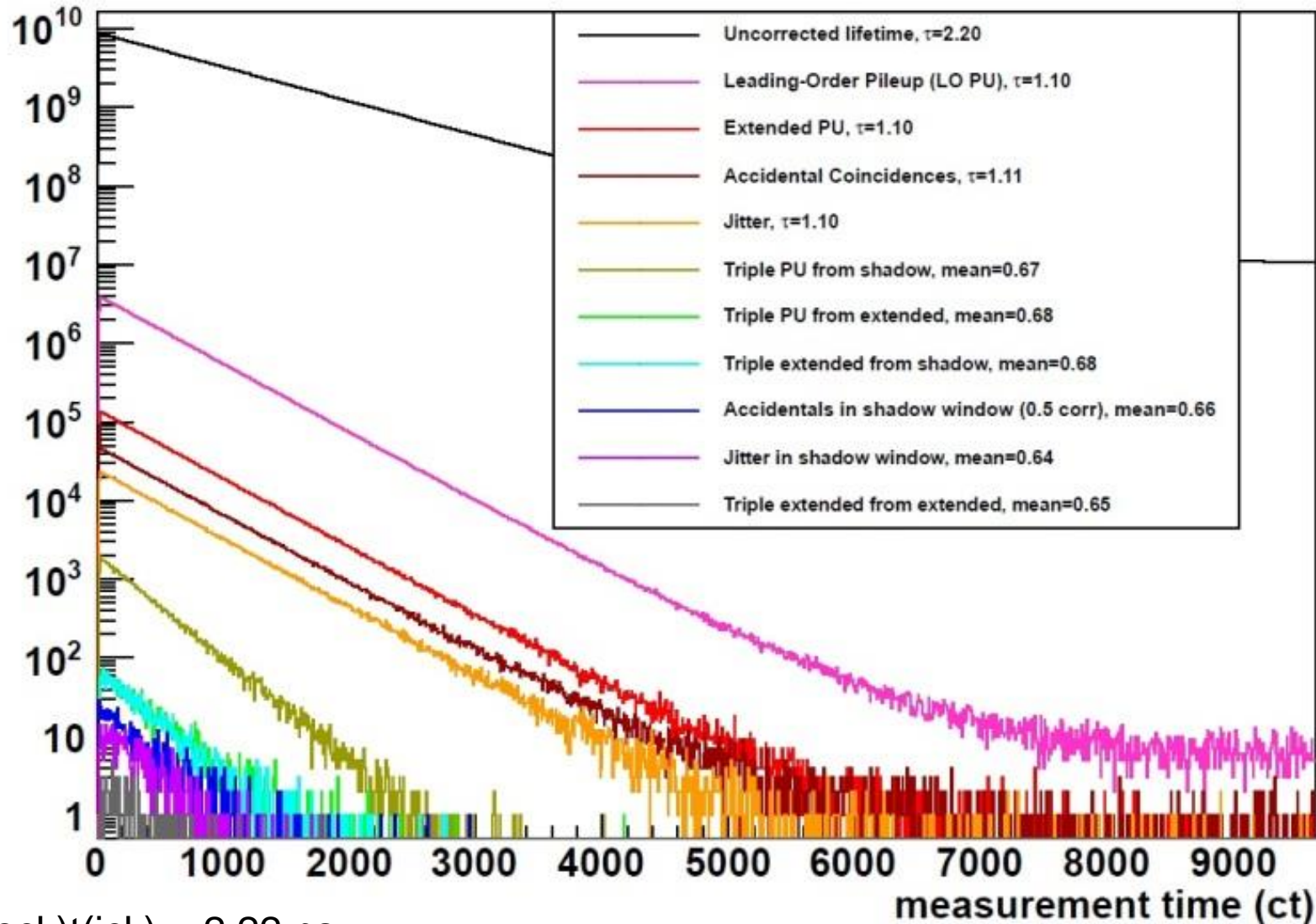
- set-up il piu` possibile simmetrico (per evitare effetti dovuti alla polarizzazione)
- sfasamento dell'insieme di μ nel bersaglio

MuLan/2 – principio della misura



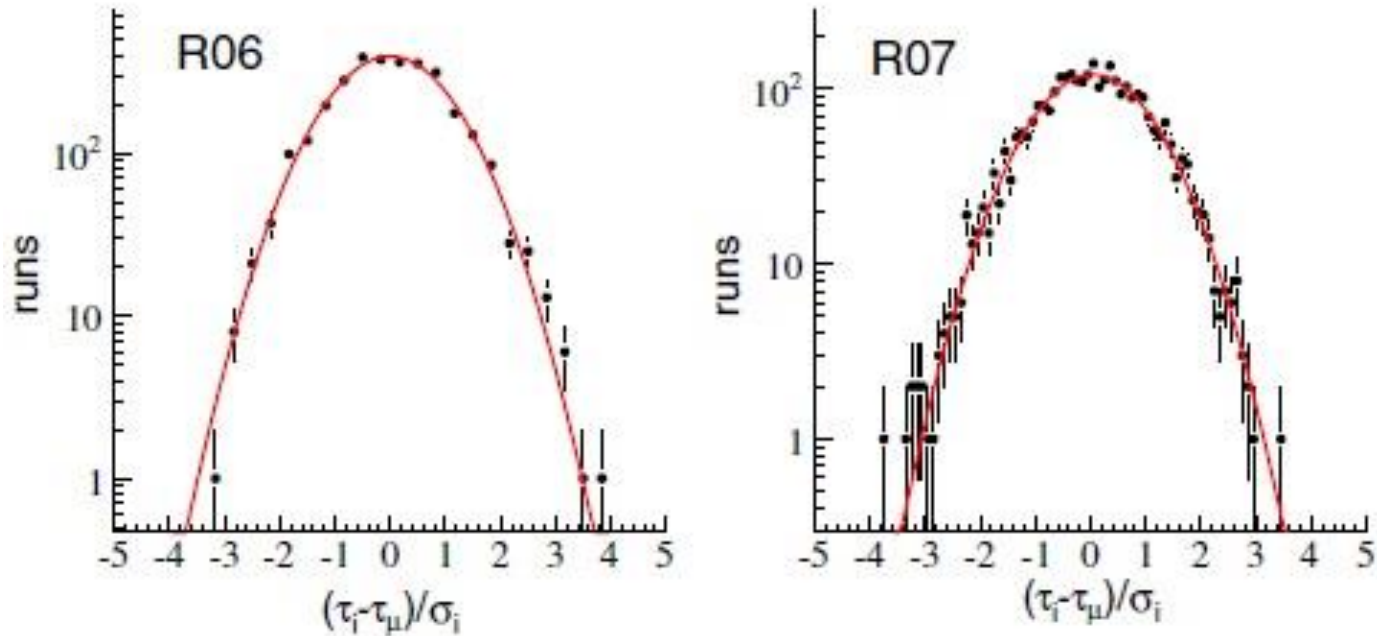
MuLan correzioni per il pileup

A(rtif)D(ead)T(ime) = 6 ct



$1c(\text{lock})t(\text{ick}) = 2.22 \text{ ns}$

MuLan consistenza delle misure



The distribution of the normalized deviations of the fitted lifetimes from the individual runs from the final result. The data points are the run-by-run results and the solid curve is a least squares fit to a Gaussian distribution. The left panel is the AK-3 data set and the right panel is the quartz data set.

Bibliografia – misure recenti di τ_{μ^+}

- MuLan Collaboration: D.M. Webber et al. Phys. Rev. Lett. **106** (2011) 041803; V. Tishchenko et al., Phys. Rev. **D87** (2013) 052003. The mean life of μ^+ was measured to a precision of 1 ppm using a low-energy, pulsed muon beam stopped in a ferromagnetic target, which was surrounded by a scintillator detector array. The result, $\tau_{\mu^+} = 2.1969803(22) \mu\text{s}$, is **much more precise** (1 ppm) **than the previous world average**. The new value determines the Fermi constant $G_F = 1.1663787(6) \times 10^{-5} \text{ GeV}^{-2}$ (0.5 ppm). Additionally, the precision measurement of the positive muon lifetime is used to determine the nucleon pseudoscalar coupling g_P .
- FAST Collaboration: A. Barczyk et al., Phys. Lett. **B663** (2008) 172-180. An initial measurement of the μ^+ lifetime to a precision of 16 parts per million (ppm) was performed with the FAST detector at the Paul Scherrer Institute. The result is $2.197083(32)(15) \mu\text{s}$, where the first error is statistical and the second is systematic. The muon lifetime determines the Fermi constant, $G_F = 1.166352(9) \times 10^{-5} \text{ GeV}^{-2}$ (8 ppm).

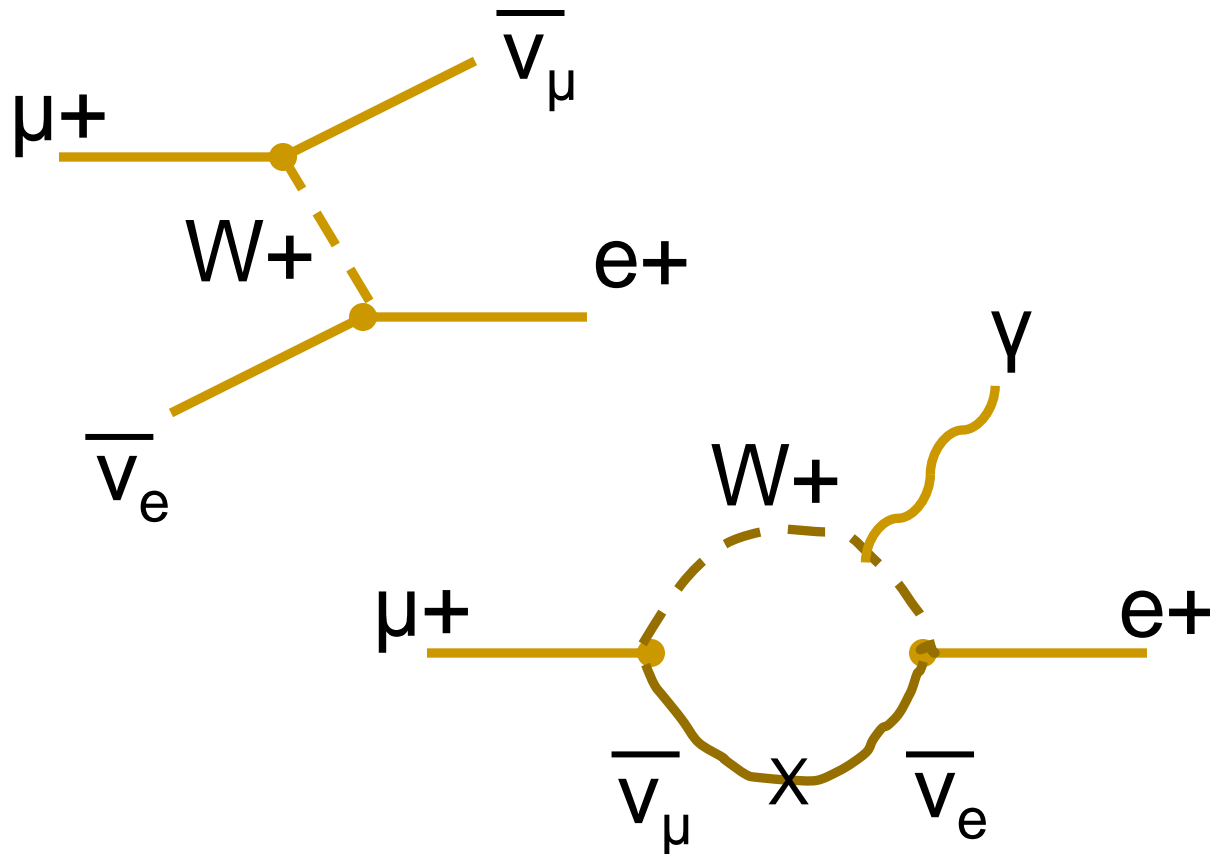
Decadimenti rari del μ

- Il μ potrebbe essere la chiave del mistero del flavour, osservando la ChargedLFV in alcuni decadimenti rari del μ in e senza neutrini, oppure nella conversione di μ in altri leptoni carichi, visto che LFV è già osservata con i ν che oscillano fra i vari sapori

Decadimenti rari del μ ($\mu^+ \rightarrow e^+ \gamma$, LFV)

- SM: introducendo masse e mixing dei neutrini il processo è permesso, ma $BR \sim (\delta m_\nu / M_W)^4 \leq 10^{-51}$ – troppo piccolo per una misura (cfr con $b \rightarrow s \gamma$, $BR \sim 10^{-4}$, grazie alla grande massa del top)
- BSM: SUSY, GUT & teorie con extra dimensioni predicono BR nell'intervallo 10^{-12} - 10^{-14} , misurabile
 - Barbieri, Hall, Strumia NPB 445 (1995) 219
 - Hisano, Noumura, Yanagida PLB 437 (1998) 351
 - Raidal et al. Eur.Phys.J. C57 (2008) 13

Michel decay vs $\mu^+ \rightarrow e + \gamma$ in SM



Decadimenti rari del μ (LFV): limiti sperimentali

| Canale | UL(90%CL) | Anno | Esp./Lab. |
|--|----------------------|------|----------------|
| $\mu^+ \rightarrow e + \gamma$ | $1.2 \cdot 10^{-11}$ | 2002 | MEGA/LAMPF |
| | $5.7 \cdot 10^{-13}$ | 2013 | MEG/PSI |
| $\mu^+ \rightarrow e + e + e^-$ | $1.0 \cdot 10^{-12}$ | 1988 | SINDRUM I/PSI |
| $\mu + e^- \leftrightarrow \mu^- + e^+$ | $8.3 \cdot 10^{-11}$ | 1999 | MACS/PSI |
| $\mu^- \text{-Ti} \rightarrow e^- \text{-Ti}$ | $6.1 \cdot 10^{-13}$ | 1998 | SINDRUM II/PSI |
| $\mu^- \text{-Ti} \rightarrow e + \text{Ca}^*$ | $3.6 \cdot 10^{-11}$ | 1998 | “ |
| $\mu^- \text{-Pb} \rightarrow e^- \text{-Pb}$ | $4.6 \cdot 10^{-11}$ | 1998 | “ |
| $\mu^- \text{-Au} \rightarrow e^- \text{-Au}$ | $7 \cdot 10^{-13}$ | 2006 | “ |

Conversione muonio-antimuonio (1999)

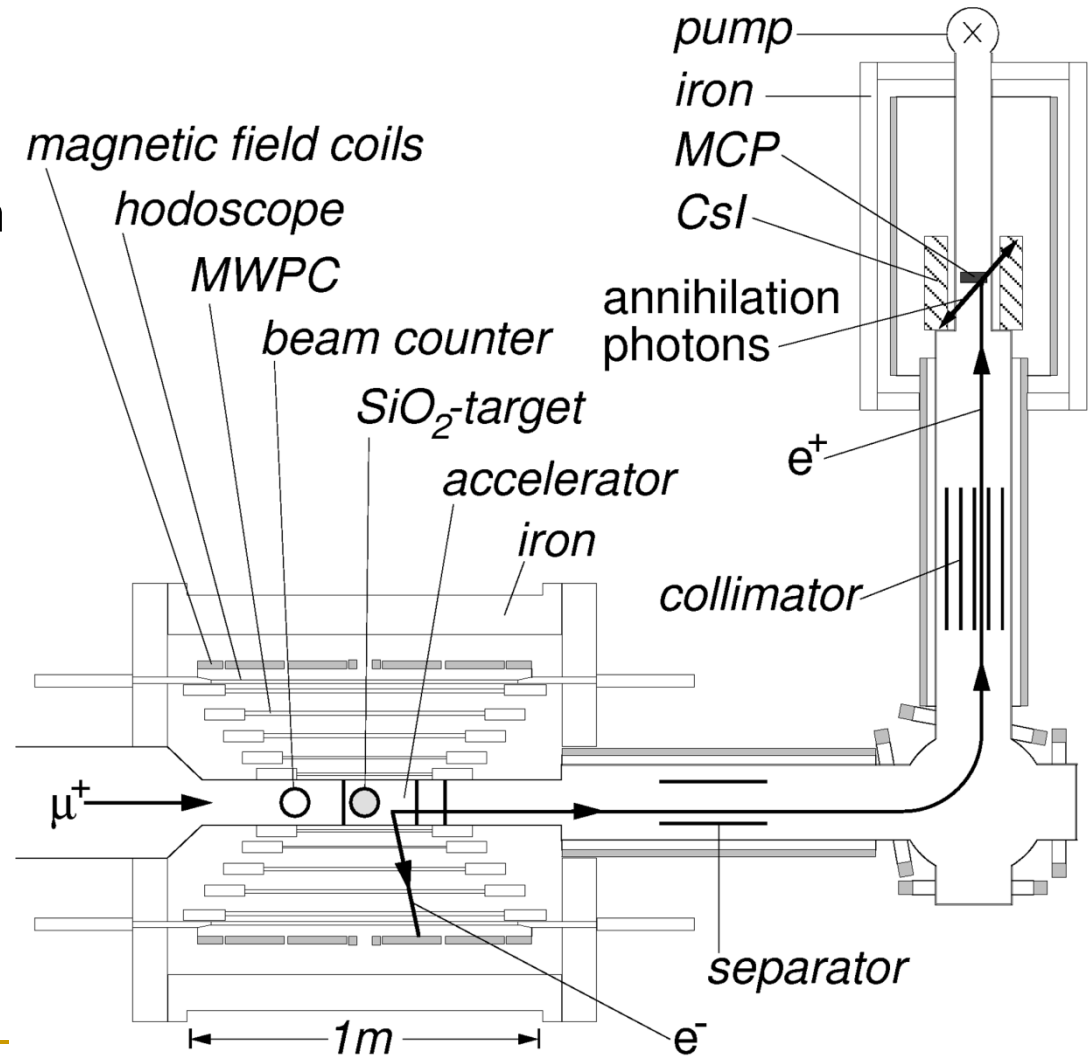
The MACS apparatus at PSI searching for M-antiM conversion. The signature requests the energetic e^- from the μ^- decay of M in a magnetic spectrometer in coincidence with the atomic shell e^+ , which is accelerated and magnetically guided onto a microchannel plate (MCP), and at least one annihilation photon in a CsI calorimeter.

26 MeV/c μ ; $8 \cdot 10^6 \mu/s$

1730 h run; $6.6 \cdot 10^{10} M$

beam scintillator 280 μm

expect. bckgd ~ 2 evts



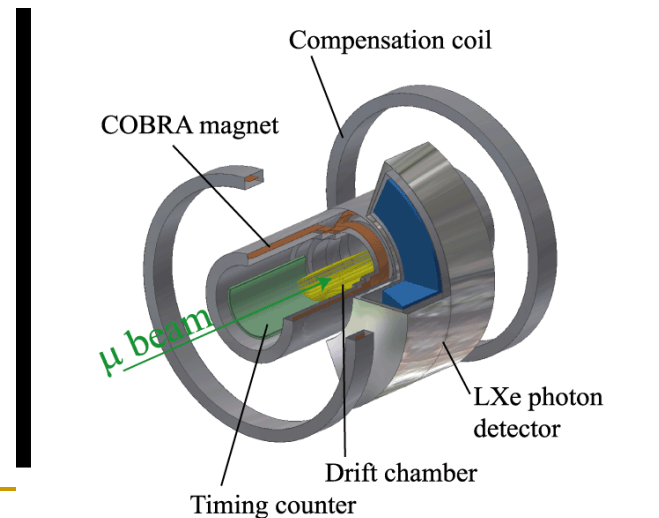
$\mu^+ \rightarrow e + \gamma$, considerazioni sperimentali

- μ^+ a riposo, decadimento a due corpi, segnature
 - γ ed e^+ collineari
 - $E_\gamma = E_{e^+} = m_\mu/2 = 52.8 \text{ MeV}$
 - $t_\gamma = t_{e^+}$
 - tracciamento preciso
 - calorimetria superba ($\Delta E=1.2\%$, $\Delta t=65\text{ps}$, $\Delta x \approx 4\text{mm}$; protot.)
 - ottimo timing
- fondi
 - Radiat. Michel Decay $\mu^+ \rightarrow e + \nu_e \bar{\nu}_\mu \gamma$ con $\nu_e \bar{\nu}_\mu$ poco energ.
 - accidentali fra un MD normale e un RMD (limite sperimentale)

Ricerca di decadimenti rari del muone: $\mu^+ \rightarrow e^+ \gamma$ (esperimento MEG)

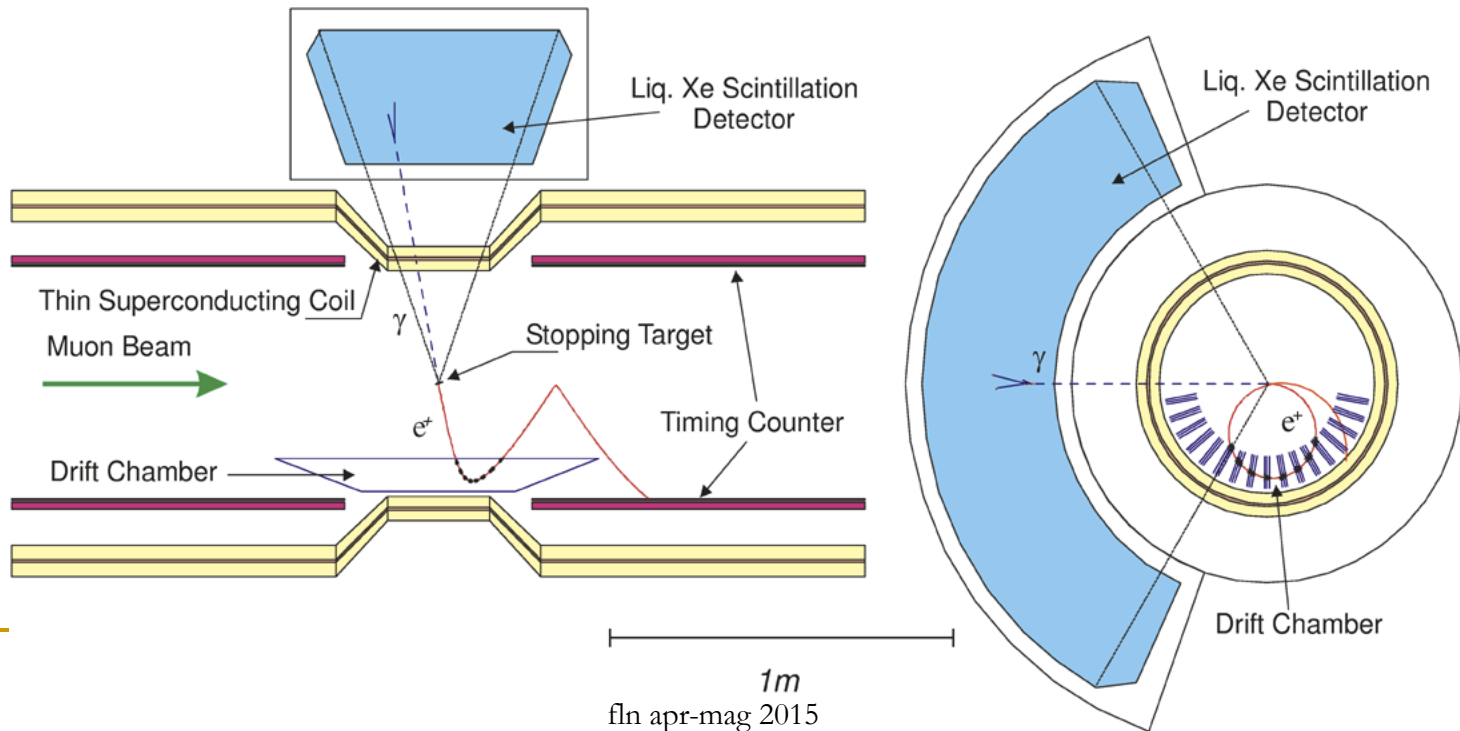


- Fascio di μ al PSI, $\pi E5$
- Calorimetro a LXe per il fotone (900 lt, $\lambda=178$ nm)
- Camera a drift per l' e^+ (1%)
- Magnete superconduttore, cavo di NbTi/Cu
- stop rate 3×10^7 Hz, totale 3.6×10^{14} μ (2009-11), = (2012-13)
- obiettivo $BR < 2 \times 10^{-13}$



MEG set-up

- The magnetic field is shaped such that positrons are quickly swept out of the tracking region thus minimizing the load on the detectors. The cylindrical 0.9 m³ single-cell LXe detector is viewed from all sides by 846 UV-sensitive PMTs immersed in the LXe allowing the reconstruction of photon energy, time, conversion point and direction and the efficient rejection of pile-up signals

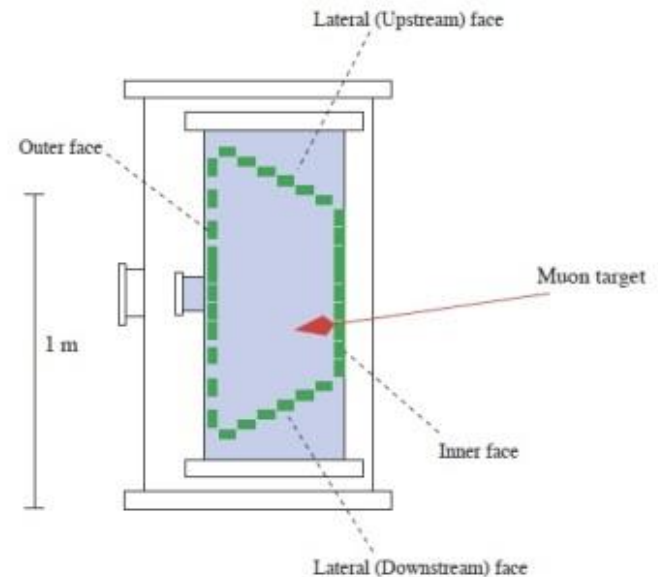
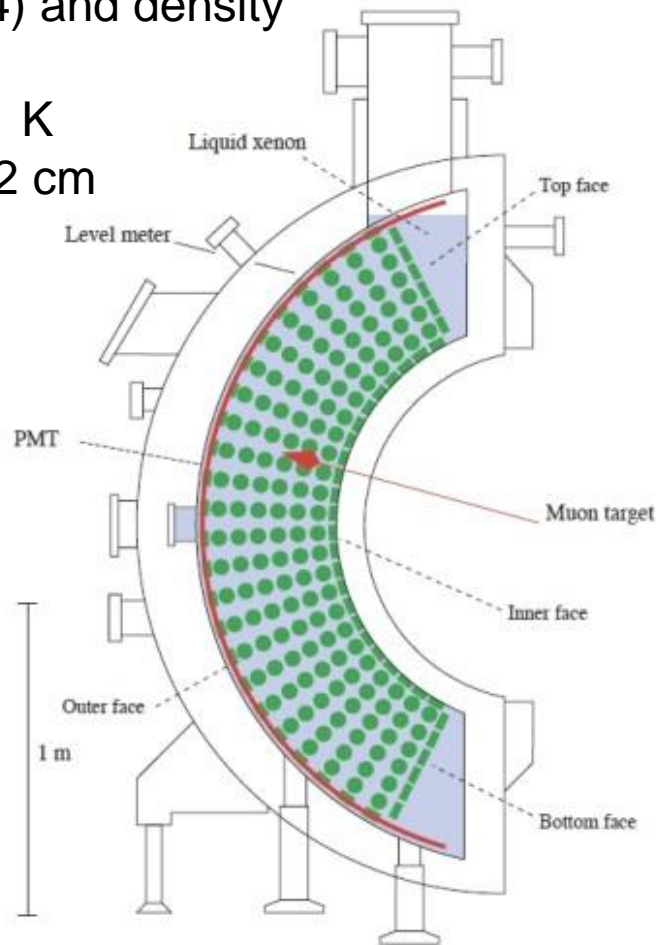


Liquid Xe calorimeter

no radioactive isotopes
high Z (54) and density
2.953 kg/l
b.p. 165.1 K
 $X_0 = 2.872$ cm

costo: LXe 800 \$/kg = 260 \$/l
-> 230 k\$ (prezzo del 2007)
900 l -> 2.66 t

very good scintillator: 46 ph/keV
 $\lambda = 175$ nm



Liquid Xe calorimeter

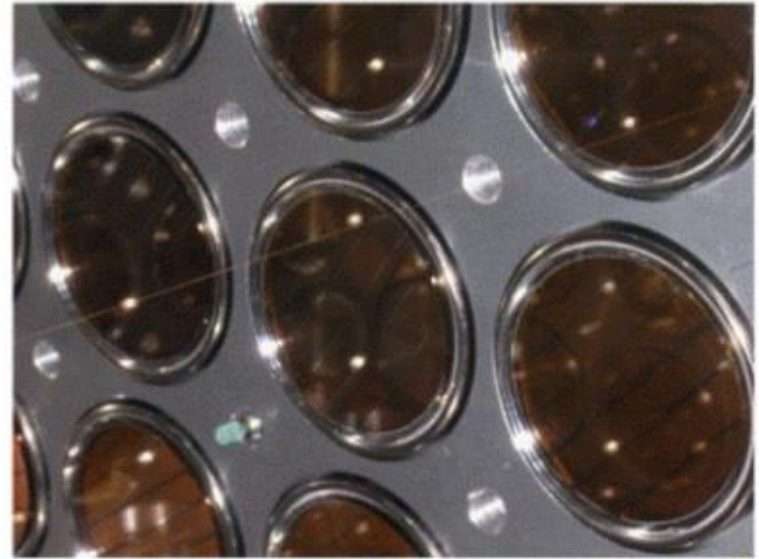
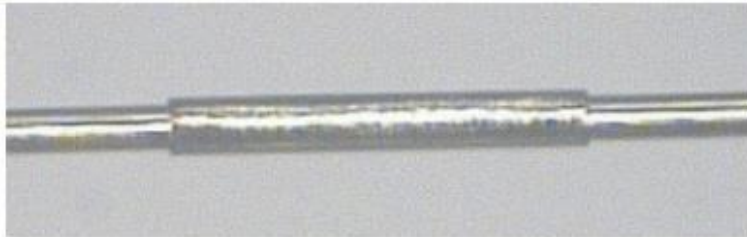
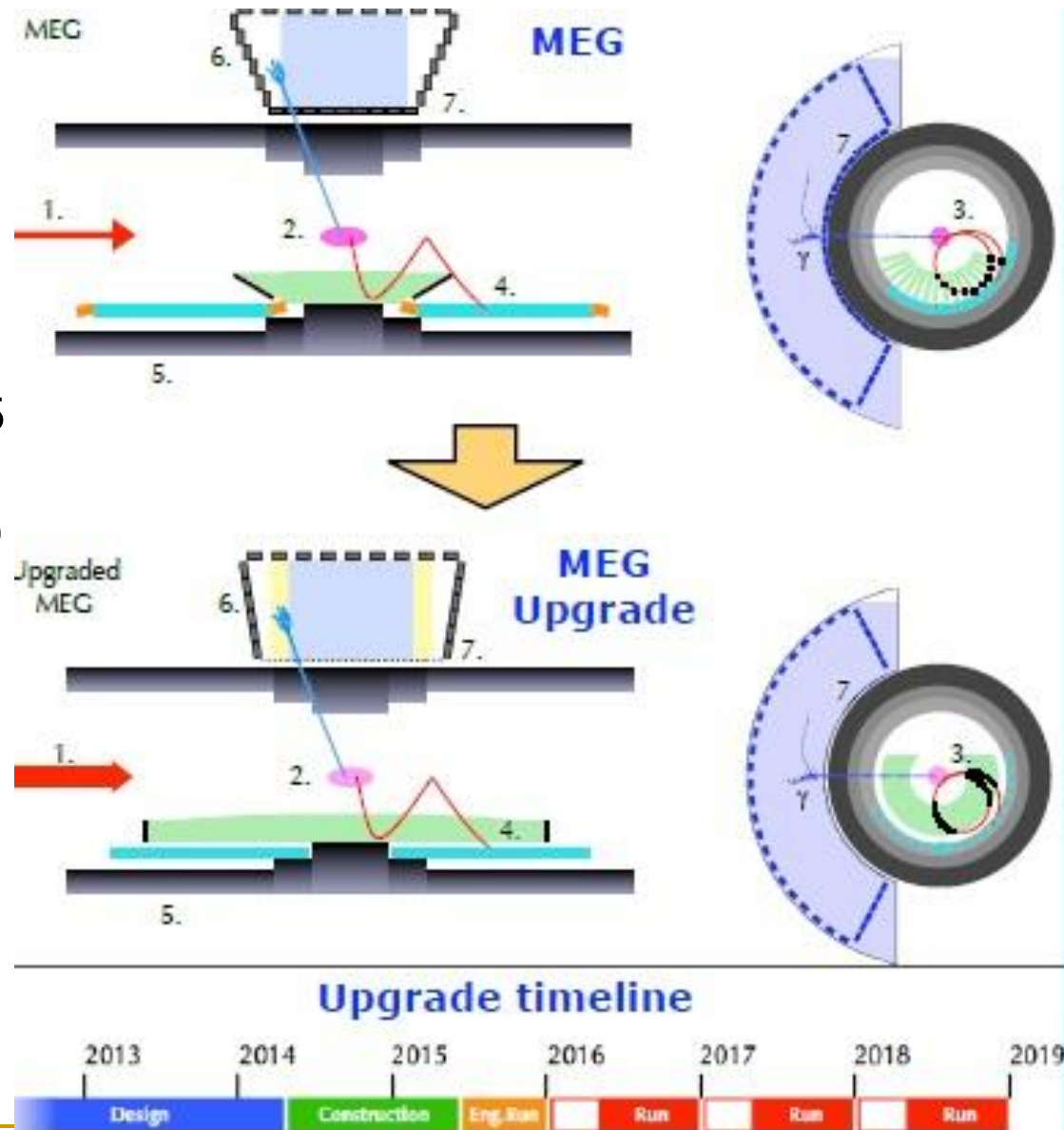


Figure 5. ^{241}Am alpha source deposited on 100- μm gold-plated tungsten wire (left) and source wire fixed on photomultiplier holder in second prototype (right).

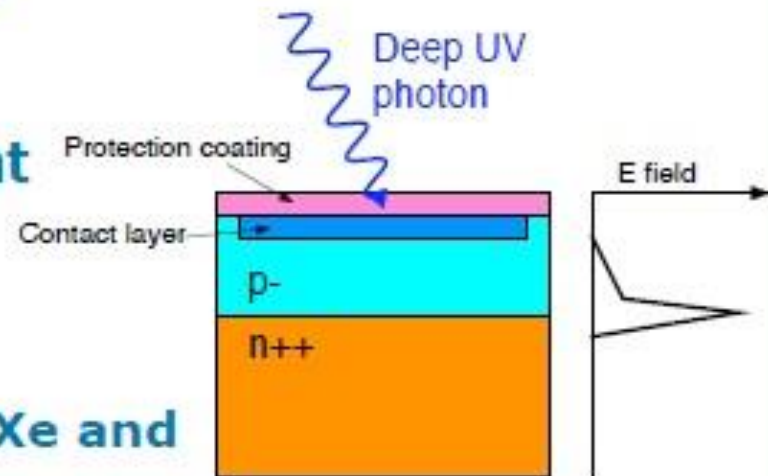
MEG upgrade

- con i dati 2012-13 il fondo diviene dominante
- nuovo obiettivo (2019) BR $\sim 5 \cdot 10^{-14}$
- più alta intensità del fascio (1)
- bersaglio attivo, sottili fibre scintillanti, 250 μm , lette da SiPM (2)
- DC con configurazione a fili con angolo stereo (3,4)
- nuovi contatori di timing pixellati, ad alta risoluzione, letti da SiPM (5)
- LXe letto con UV-SiPM (6,7)



UV-enhanced MPPC

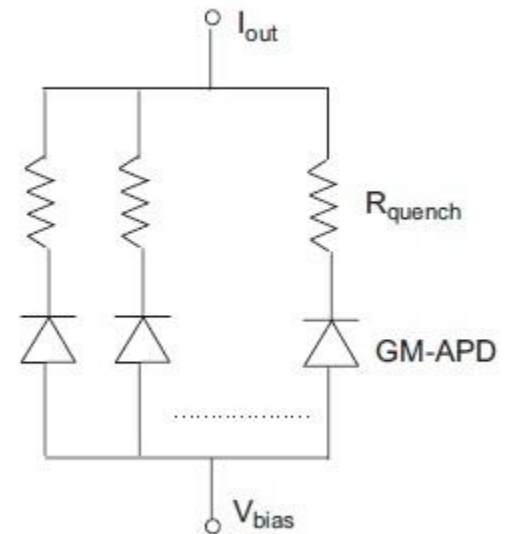
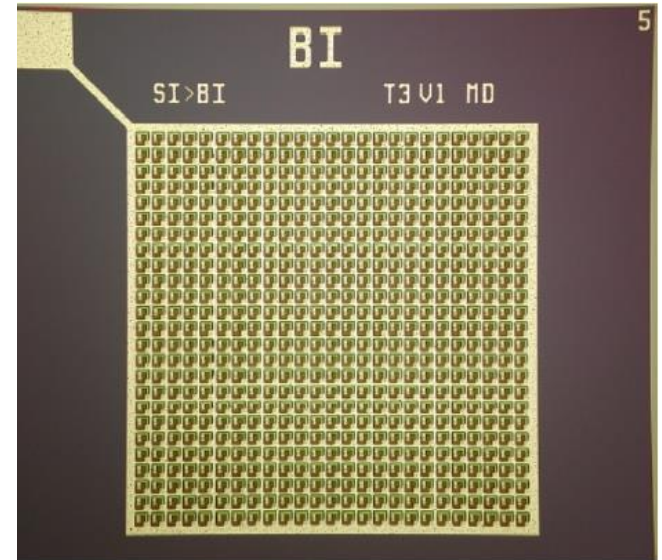
- Commercial SiPM is NOT sensitive to LXe scintillation light in VUV range ($\sim 175\text{nm}$).
- UV-enhanced MPPC is under development in collaboration with Hamamatsu Photonics.
- Requirements
 - Photon detection efficiency (PDE) ($> 10\%$)
 - Large sensitive area ($\sim 12 \times 12\text{mm}^2$)
 - Single photon counting capability
 - Fast signal (fall time $< 50\text{ns}$)
- Improving sensitivity to VUV light
 - Remove protection coating
 - Thinner contact layer
 - Optimize optical matching bw/ LXe and Si (refractive index, AR coating)



SiliconPM

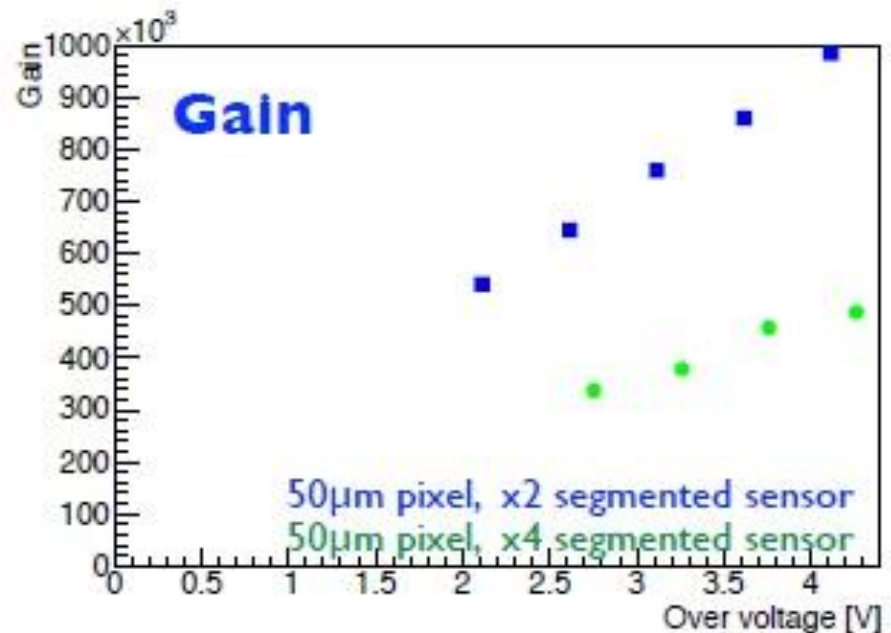
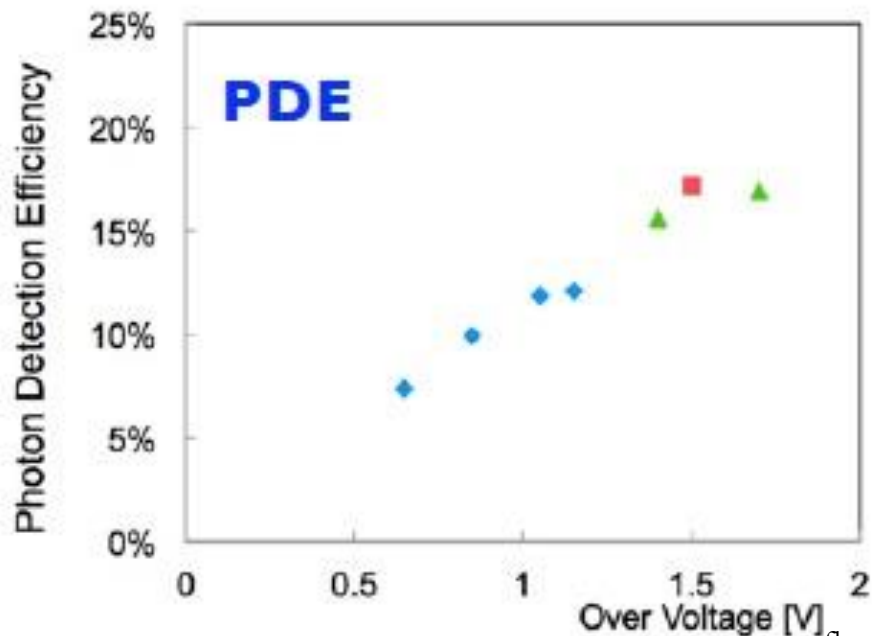
diodi a valanga (APD) in modalità Geiger, sviluppati in Russia fine anni 90 – in Italia, FBK-INFN e STM - Giappone, Hamamatsu (MPCC)

- $A \sim 1 \times 1, 2 \times 2, 3 \times 3 \text{ mm}^2$
pixel min 20×20 max $100 \times 100 \mu\text{m}^2$
- Elevata PDE ($> \text{PMT}$), limitata dalla geom. pixel (spazi morti)
- Elevato guadagno $10^5 - 10^6$
- Risoluzione singolo ph.el.
- Buona risoluzione temporale
- Bassa HT $\sim 30 - 80 \text{ V}$
- Insensibili a B fino a 4 T
- Spesso usati per leggere fibre (1 mm diam.)
- Rumore termico statistico (dark current) prop. $A \rightarrow$ raffreddare, ma compare afterpulsing
- Danno da radiazioni: sensibili ai p, meno sensibili ai γ



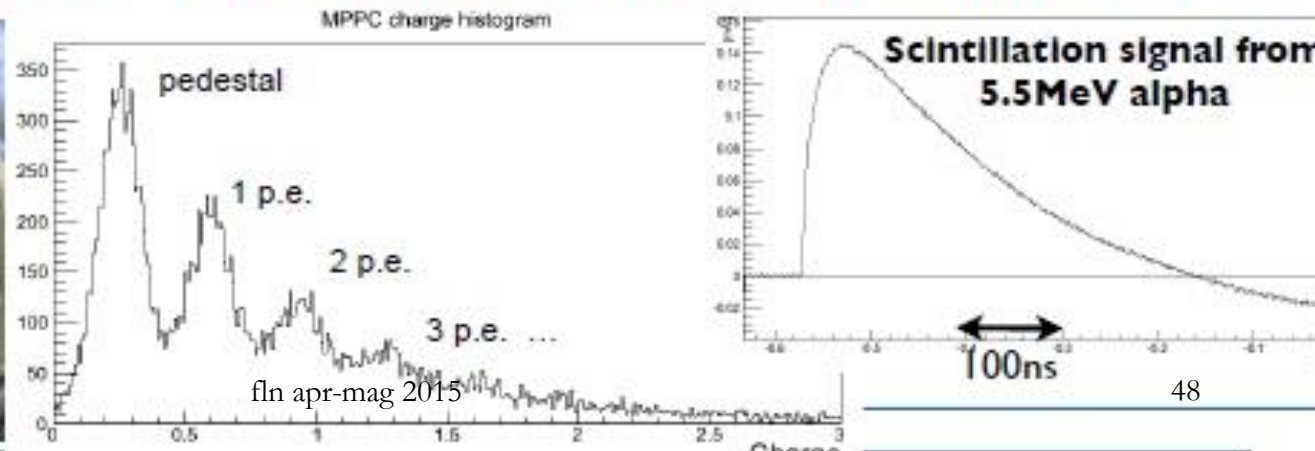
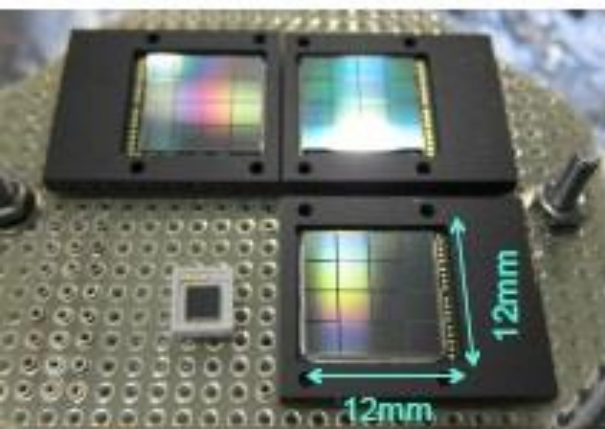
UV-MPPC Performance

- ✓ Development of UV-MPPC is in good shape.
- ✓ LXe scintillation light is successfully detected by prototypes of UV-enhanced MPPC.
- ✓ Best prototypes already show **PDE~15%** and **gain>5×10⁵**, which more or less fulfill our requirement.



UV-MPPC Performance

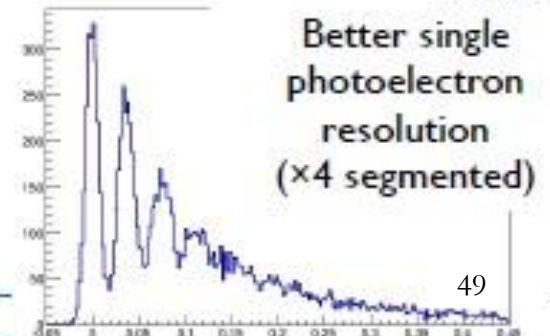
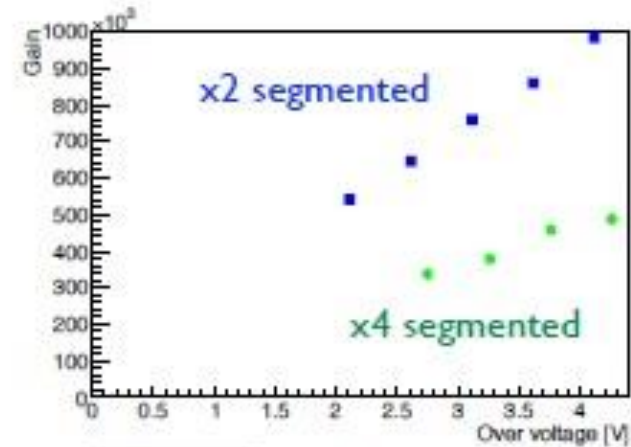
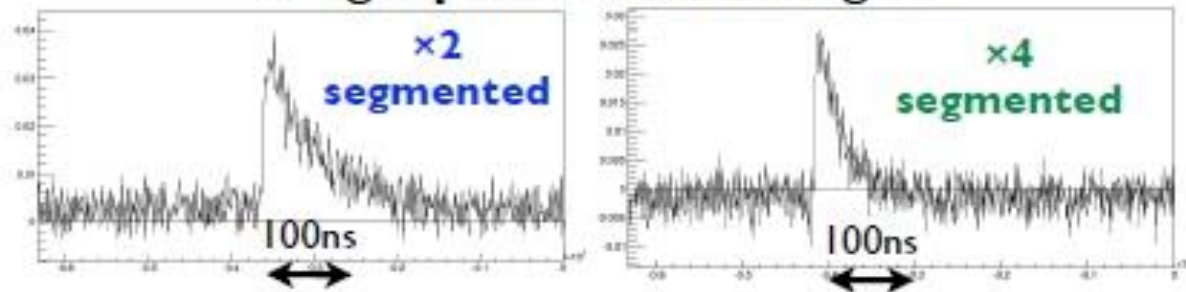
- ✓ Full size prototype successfully tested in LXe.
 - ✓ Active area: $12 \times 12 \text{mm}^2$ ($\leftrightarrow \leq 3 \times 3 \text{mm}^2$ for commercial MPPC)
 - ✓ $50 \mu\text{m}$ pixel pitch, 57600 pixels.
- ✓ Single photoelectron peak is clearly resolved.
- ✓ Dark count rate is quite low ($\sim 750 \text{Hz}$) at LXe temp.
- ✓ World's largest VUV-sensitive SiPM with single photon counting capability!
- ✓ Long signal tail ($\sim 200 \text{ns}$) due to large sensor capacitance would be an issue (\rightarrow pileup in high rate environment).



Sensor Capacitance Issue

- ☑ Tested the scheme using 4×MPPCs (6×6mm² each)
- ☑ **x4 segmented**: all 4 MPPCs connected in series
- ☑ **x2 segmented**: Two sets of two MPPCs connected in parallel are connected in series.
- ☑ **Signal fall time reduced down to 30-50ns!**
- ☑ **Still reasonably high gain (>5×10⁵)**

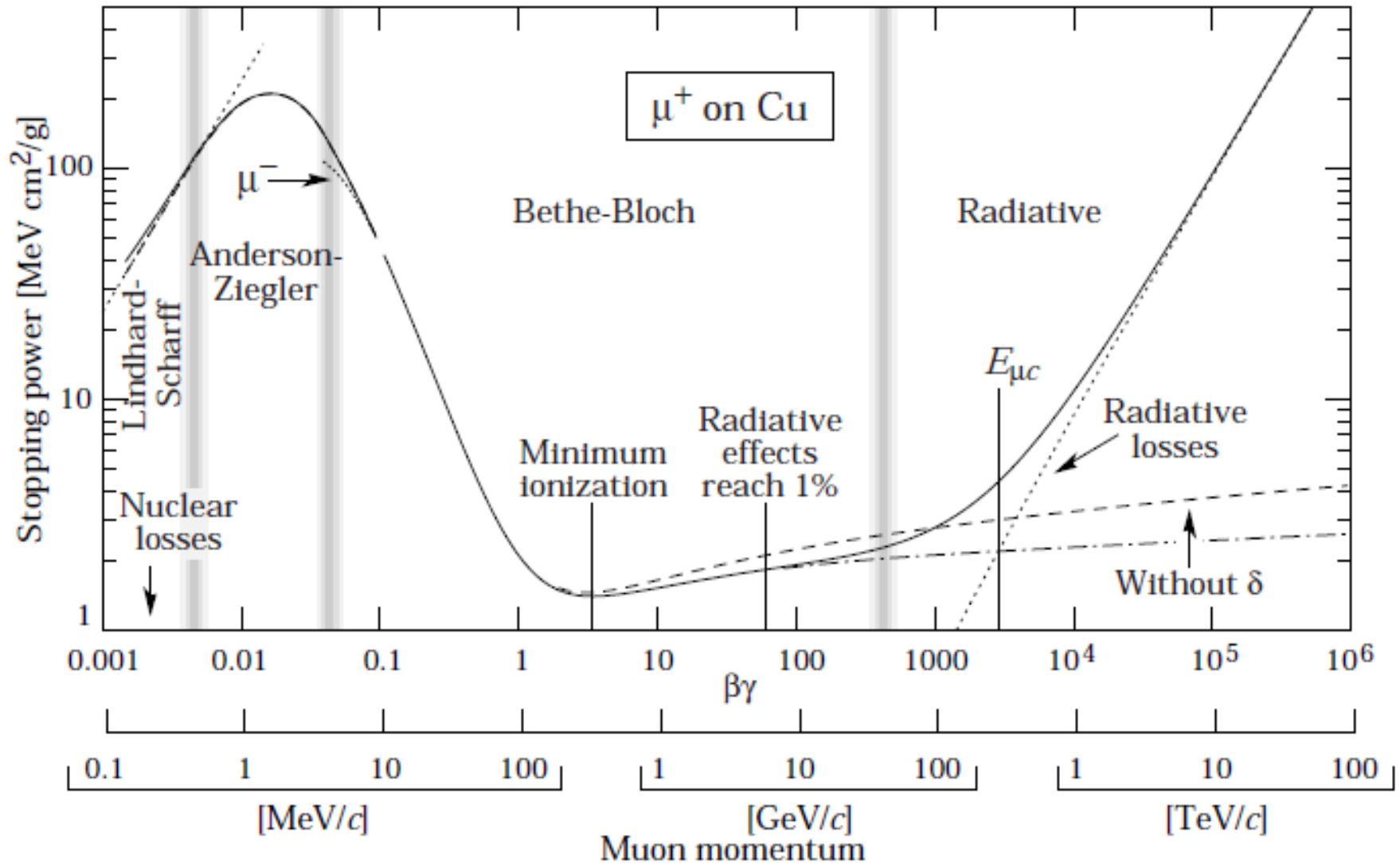
Single photoelectron signal



| | Non-segmented | x2 segmented | x4 segmented |
|-----------|---------------|--------------|--------------|
| Fall time | 200ns | 45ns | 25ns |

Perdita di energia e range dei μ in vari materiali, scattering multiplo

Perdita di energia dE/dx vs impulso del μ



-dE/dx di particelle pesanti in vari materiali

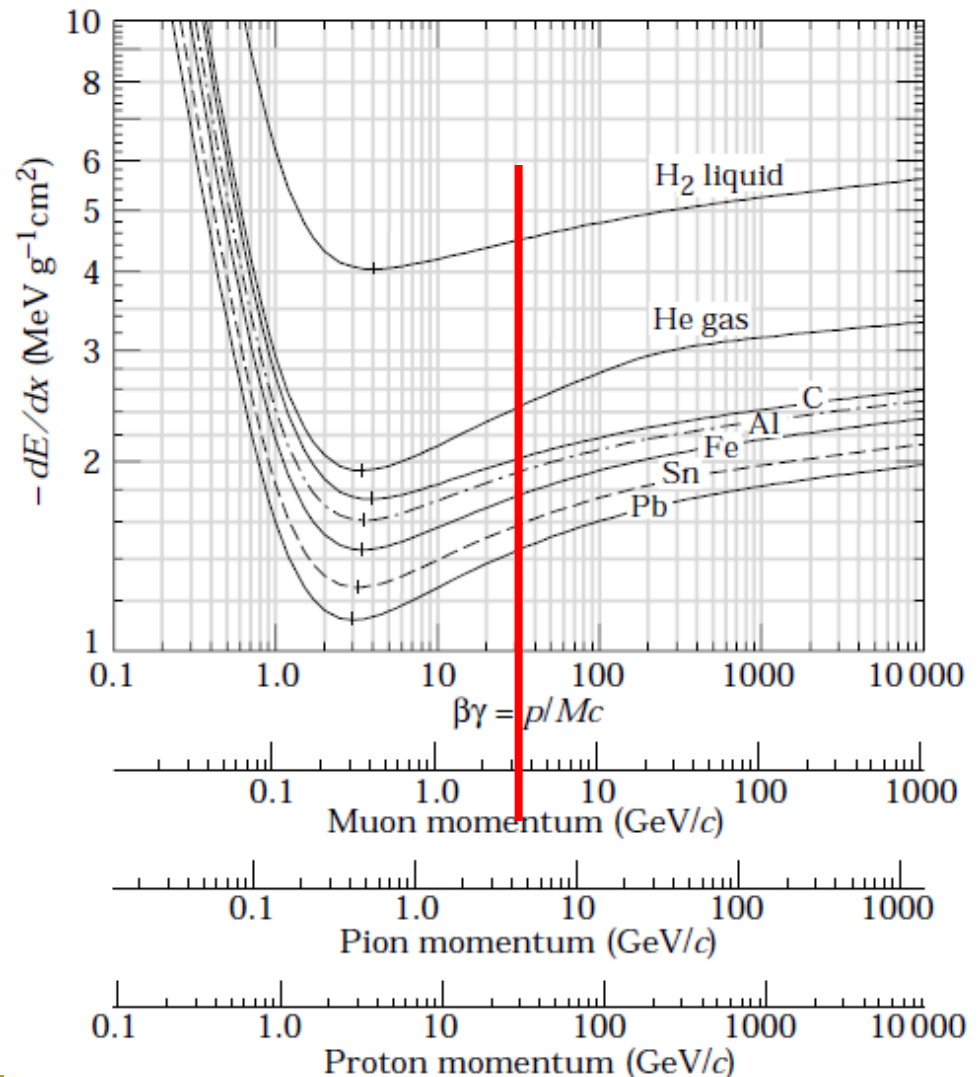
$$-dE/dx = K Z/A 1/\beta^2 \cdot$$

$$\cdot \left[\frac{1}{2} \ln(2m_e c^2 \beta^2 \gamma^2 T_{\max}/I^2) - \beta^2 - \delta(\beta\gamma)/2 \right]$$

per $0.1 \leq \beta\gamma \leq 1000$ e Z intermedio e` valida a qualche %

Non sono inclusi effetti radiativi, rilevanti per μ in Fe per $E \geq 100$ GeV, in roccia per $E \geq 600-700$ GeV ($A = 22$, $Z = 11$, $\rho = 2.65$ g/cm²)

$\langle E_\mu \rangle \sim 3-4$ GeV, muoni cosmici sulla superficie della terra \rightarrow
 $dE/dx > dE/dx_{\min}$



Perdita di energia/3

- parametrizzazione per i μ

$$dE/dx = a + bE_\mu$$

con a e b funzioni del materiale e (deboli, ~logaritmiche) di E_μ , rispettivamente ionizzazione e radiazione \rightarrow energia critica $\epsilon_\mu = a(\epsilon_\mu)/b(\epsilon_\mu)$ eg circa 650-750 GeV nella roccia

Muon range R and energy loss parameters calculated for standard rock

| E_μ (GeV) | R (km.w.e) | a (MeV g ⁻¹ cm ²) | b (10 ⁻⁶ g ⁻¹ cm ²) | ϵ_μ /GeV |
|------------------|-----------------|---|--|---------------------|
| 10 | 0.05 | 2.15 | 1.91 | |
| 100 | 0.41 | 2.40 | 3.12 | 769 |
| 1000 | 2.42 | 2.58 | 4.01 | 643 |
| 10,000 | 6.30 | 2.76 | 4.40 | |

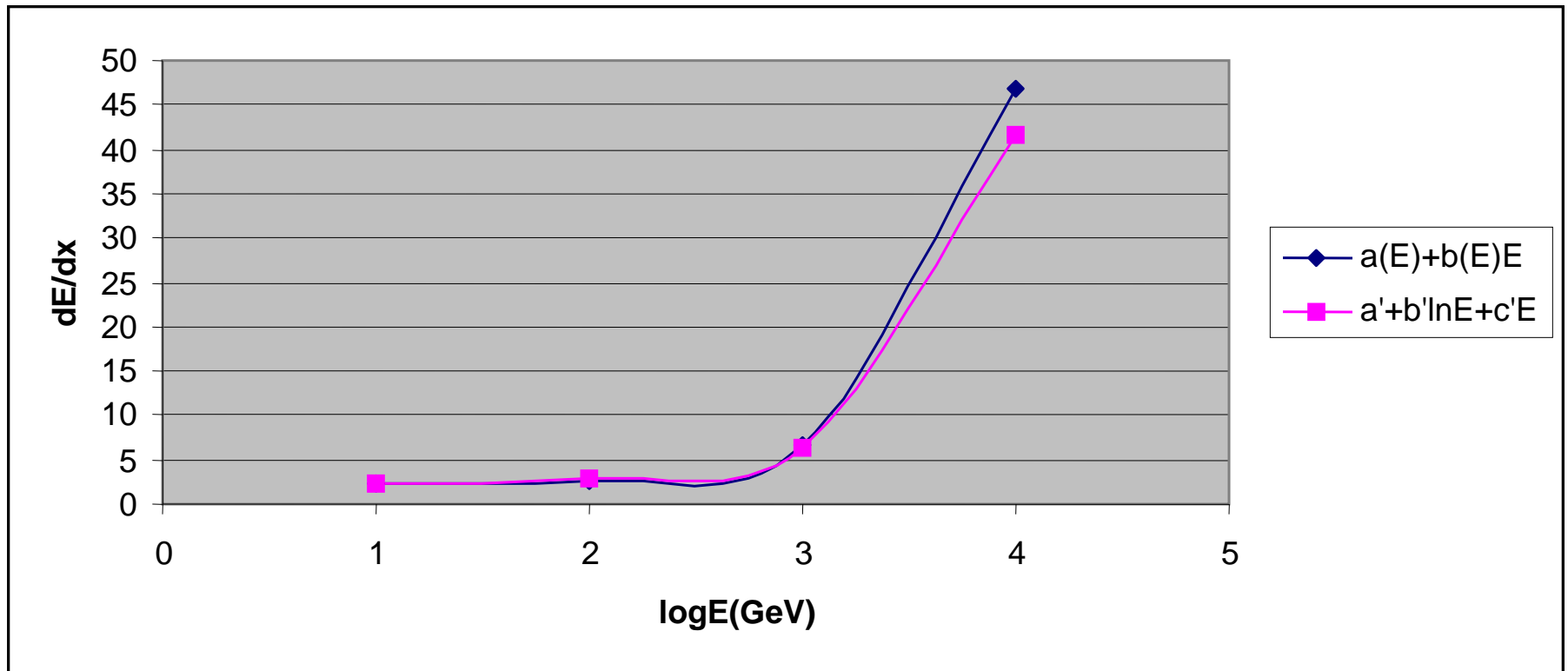
Range is given in km-water-equivalent. = 10⁶ kg m⁻² = 10⁵ g cm⁻²

altra par.: $dE/dx = (1.888 + 0.0777 \ln(E_\mu / m_\mu) + 3.9E_\mu) 10^{-6} \text{ TeV cm}^2/\text{g}$ (*)

ionizzazione
bremms

Perdita di energia/4

confronto fra le parametrizzazioni, μ in roccia, dE/dx in MeV cm²/g



integrando la formula (*) per la perdita di energia si ottiene il range

$$X = 2.5 \cdot 10^5 \ln(1.56E_\mu + 1) \text{ g/cm}^2$$

- ossia per 1 TeV, $X = 2.35 \cdot 10^5 \text{ g/cm}^2 = 0.9 \text{ km di roccia}$ ($\rho = 2.65 \text{ g/cm}^3$)

Range di particelle cariche pesanti

Grosso modo, al minimo:

Fe $\rho = 8 \text{ g/cm}^3$

$$-dE/dx|_{\min} = 1.45 \text{ MeV}/(\text{g cm}^{-2})$$

1 m Fe $\Rightarrow 800 \text{ g/cm}^2 \cdot 1.45 = 1160 \text{ MeV}$

roccia/cemento $\rho = 2.65 \text{ g/cm}^3$

$$-dE/dx|_{\min} = 1.69 \text{ MeV}/(\text{g cm}^{-2})$$

1 m r/c $\Rightarrow 265 \text{ g/cm}^2 \cdot 1.69 = 450 \text{ MeV}$

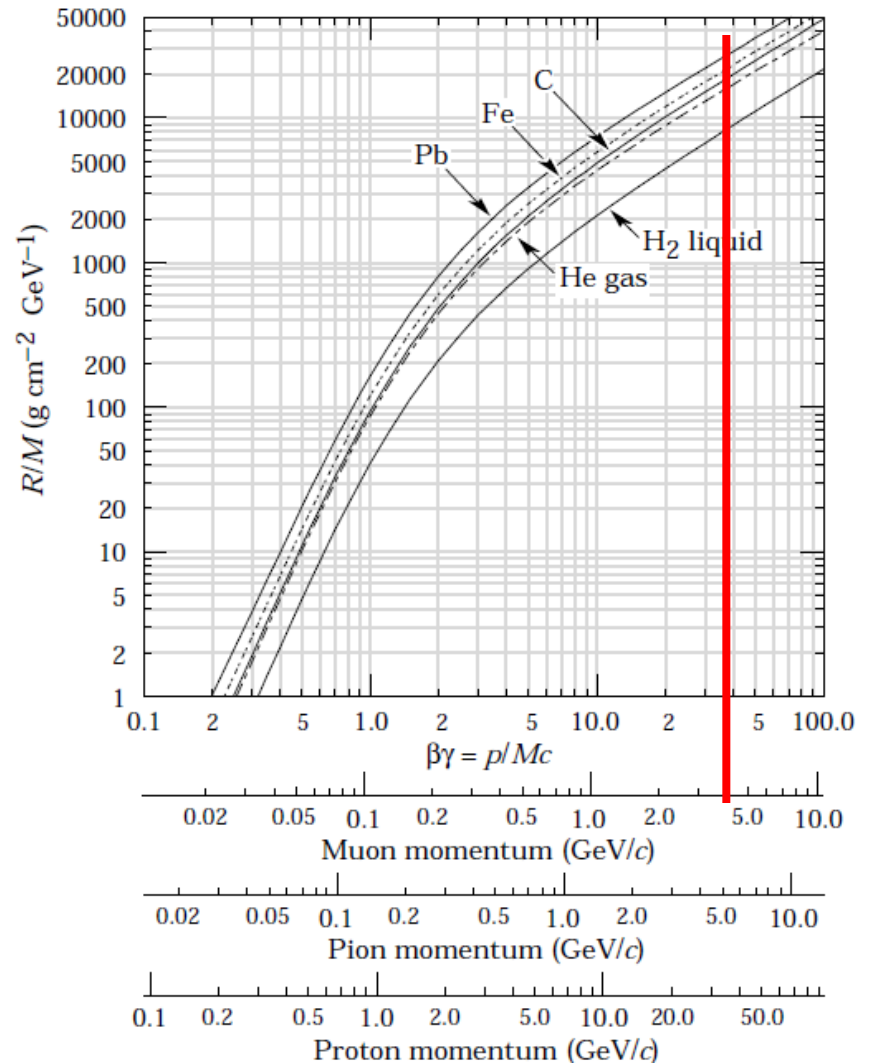
per $\langle E_\mu \rangle \sim 4 \text{ GeV}$, i μ penetrano

$\sim 2400 \text{ g cm}^{-2}$ di Fe = 3 m

$\sim 2100 \text{ g cm}^{-2}$ di r/c = 8 m

in realtà bisogna integrare lo stopping

$$\text{power } R = \int_0^{E_\mu} dE_\mu / \langle dE/dx \rangle$$



la perdita di E nell'atm, 1 kg/cm^2 , è circa 2 GeV per μ di 6 GeV

Scattering multiplo coulombiano

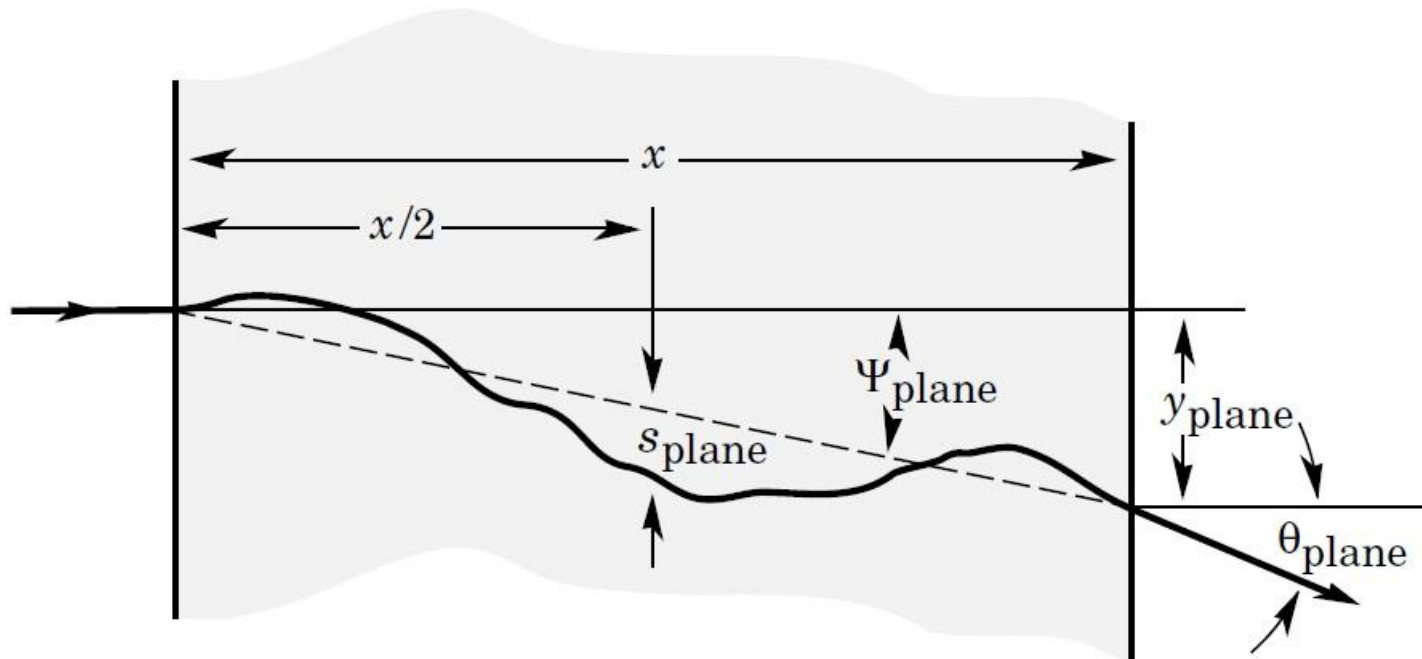
- per angoli piccoli si ha lo scattering à la Rutherford, $\sim 1/\theta^4$, e, tenuto conto dello screening degli e^- e dell'estensione finita del nucleo, si ottiene per l'angolo quadratico medio (nello spazio) per unità di spessore attraversato (a parte termini correttivi, $\sim \log$) – la distribuzione è gaussiana (solo in 1a approx) + code

$$\frac{d\langle\vartheta^2\rangle_{av}}{dx} = \vartheta_s^2 = \left(\frac{E_s}{\beta cp}\right)^2 \frac{1}{X_0} \quad \text{con } E_s = (4\pi/\alpha)^{1/2} m_e c^2 = 21.2 \text{ MeV}$$

$$\langle\theta^2\rangle_{av} = x\theta_s^2 = (E_s/\beta cp)^2 x/X_0 \quad x \text{ piccolo, niente perd. di ener.}$$

$$\begin{aligned} \langle\theta^2\rangle_{av} &= (E_s/c)^2 1/X_0 \int_{p_1}^{p_2} p^2 1/[\beta^2(-dp/dx)] dp/p^2 \\ &= (E_s/c)^2 1/X_0 1/(p_1 p_2) (p_2 - p_1)/[\beta^2(-dp/dx)] \\ &= E_s^2/(c^2 p_1 p_2) x/X_0 \quad \text{includendo la perdita di energia} \end{aligned}$$

Scattering multiplo coulombiano/2



distrib. angol.: $dN \sim 1/(2\pi x \theta_s^2) \exp(-\theta^2/(2x\theta_s^2)) d\Omega$

$$\langle \theta^2 \rangle = \langle \theta_y^2 \rangle + \langle \theta_z^2 \rangle = 2\langle \theta_y^2 \rangle$$

$$\langle \psi_{\text{plane}}^{\text{rms}} \rangle = 1/\sqrt{3} \langle \theta_{\text{plane}}^{\text{rms}} \rangle$$

$$\langle y_{\text{plane}}^{\text{rms}} \rangle = 1/\sqrt{3} x \langle \theta_{\text{plane}}^{\text{rms}} \rangle$$

$$\langle s_{\text{plane}}^{\text{rms}} \rangle = 1/(4\sqrt{3}) x \langle \theta_{\text{plane}}^{\text{rms}} \rangle$$

y, z: indipendenti,
stesse distribuzioni

Scattering multiplo coulombiano/3

- consideriamo l'angolo proiettato sui piani xy (e xz), si ha $\theta^2 = \theta_y^2 + \theta_z^2 = 2\theta_y^2$; si può mostrare che la probabilità di avere un angolo fra θ_y e $\theta_y + d\theta_y$ ed uno spostamento fra y e $y + dy$ è data da

$$P(x,y,\theta_y) = 2\sqrt{3}/\pi \ 1/(\theta_s^2 x) \exp[-4/(\theta_s^2 x) \cdot (\theta_y^2 - 3y\theta_y/x + 3y^2/x^2)]$$

e le distribuzioni integrate sono

$$Q(x,\theta_y) = \int_{-\infty}^{+\infty} dy \ P(x,y,\theta_y) = 1/\sqrt{\pi} \ 1/(\theta_s x^{1/2}) \exp(-\theta_y^2/(\theta_s^2 x))$$

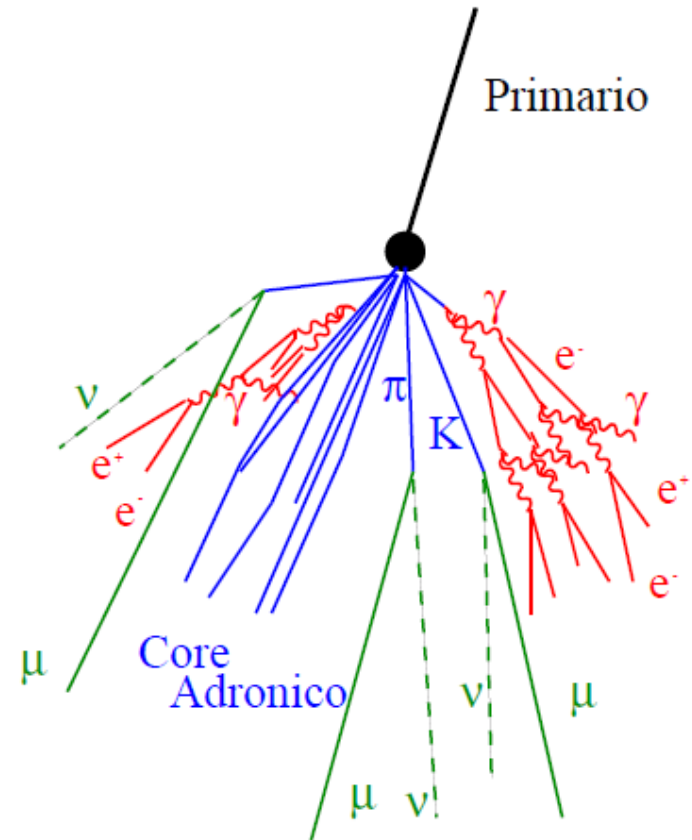
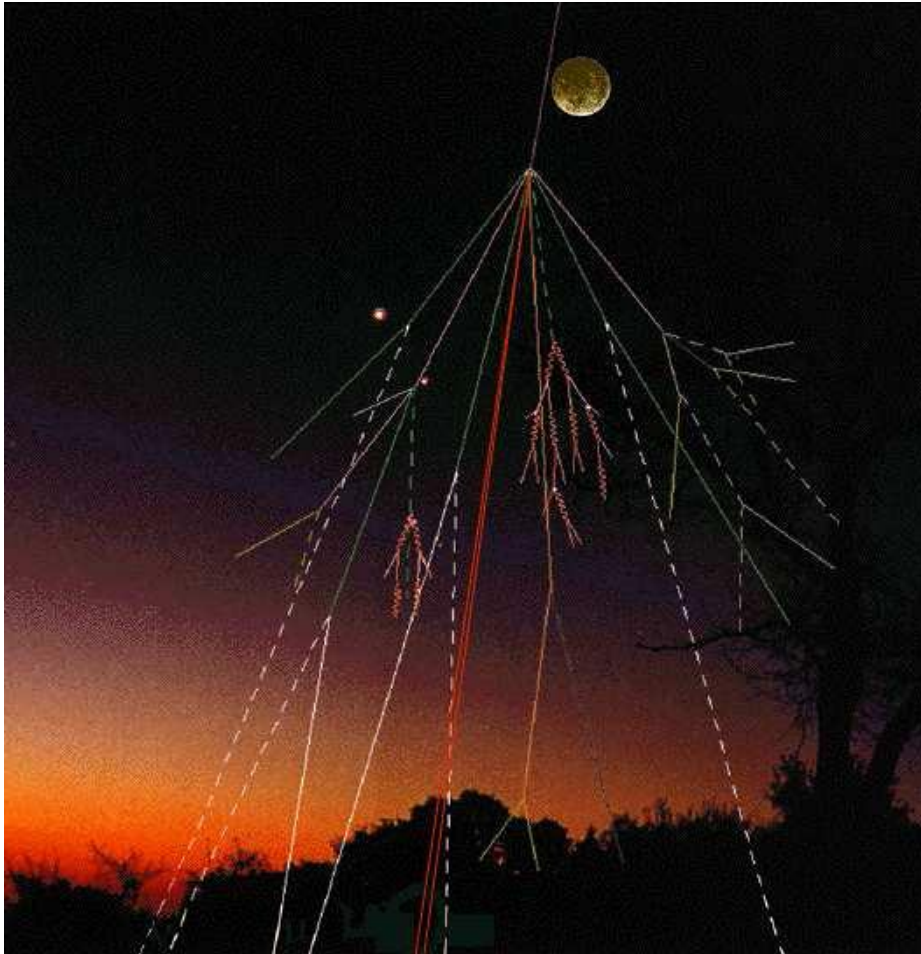
$$S(x,y) = \int_{-\infty}^{+\infty} d\theta_y \ P(x,y,\theta_y) = \sqrt{3}/\pi \ 1/(\theta_s x^{3/2}) \exp(-3y^2/(\theta_s^2 x^3))$$

$$\langle \theta_y^2 \rangle_{av} = 1/2 \ \theta_s^2 \ x$$

$$\langle y^2 \rangle_{av} = 1/2 \ \theta_s^2 x^3/3 = \langle \theta_y^2 \rangle_{av} \ x^2/3$$

(il termine in θ_y integrato dà 0 perché $\langle \theta_y \rangle = 0$)

Un impiego particolare di particelle subnucleari: tomografia con μ (e ν) cosmici



Un fascio gratuito di particelle: i μ dei Raggi Cosmici

- disponibili ovunque sulla terra
- 😊 ■ disponibili sempre 24/7
- non implicano una produzione addizionale di radiazioni

ma

- ☹ ■ intensità, spettro di energia, distribuzione angolare non sono aggiustabili, dipendono da dove ci si trova

Muons (and Neutrinos) are the Main Component of Cosmic Rays at the Earth's Surface and Below

- Primary cosmic rays interact in upper atmosphere

- Mainly high energy protons
- Showers of π 's/K's created
- Decay within 10's - 1000's meters or collide with nuclei in air

$$\langle h \rangle \sim 16 \text{ km}$$

$$\lambda_{\text{int}} \sim 90 \text{ g/cm}^2$$

$$c\tau_{\pi} = 7.8 \text{ m}$$

$$c\tau_K = 3.7 \text{ m}$$

- Muons are produced in decays of π /K

- Do *not* have nuclear interactions
- Lifetime much longer than π /K and dilated by relativity

$$c\tau_{\mu} = 660 \text{ m}$$

$$(E_{\mu} = 4 \text{ GeV}) \gamma c\tau_{\mu} = 25 \text{ km}$$

- Approximate muon rate at Earth's surface (**horizontal**)

$$\sim 1 \text{ cm}^{-2}\text{min}^{-1}$$

Spettro dei mu cosmici in superficie

Intensità verticale della
componente dura al liv. mare

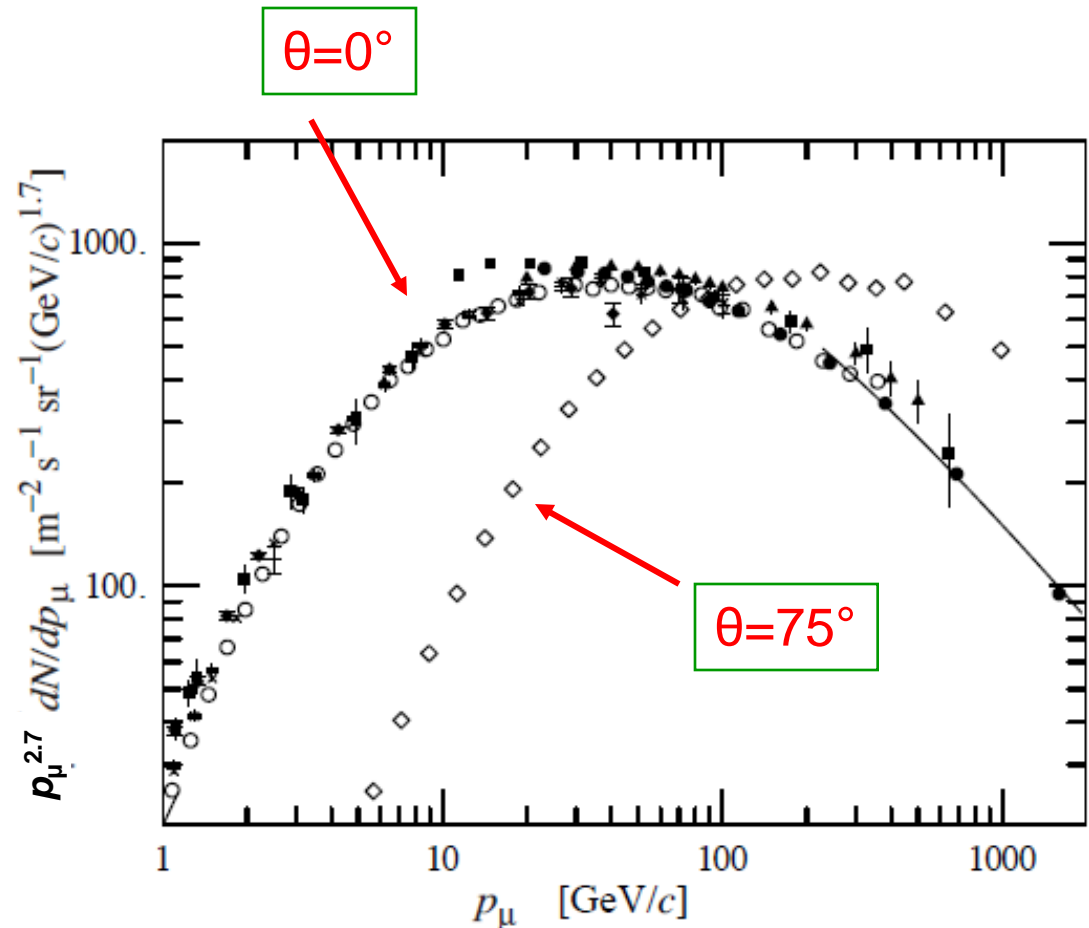
$$I_v = 80 \text{ m}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

Al liv.mare $\langle E_\mu \rangle \sim 4 \text{ GeV}$

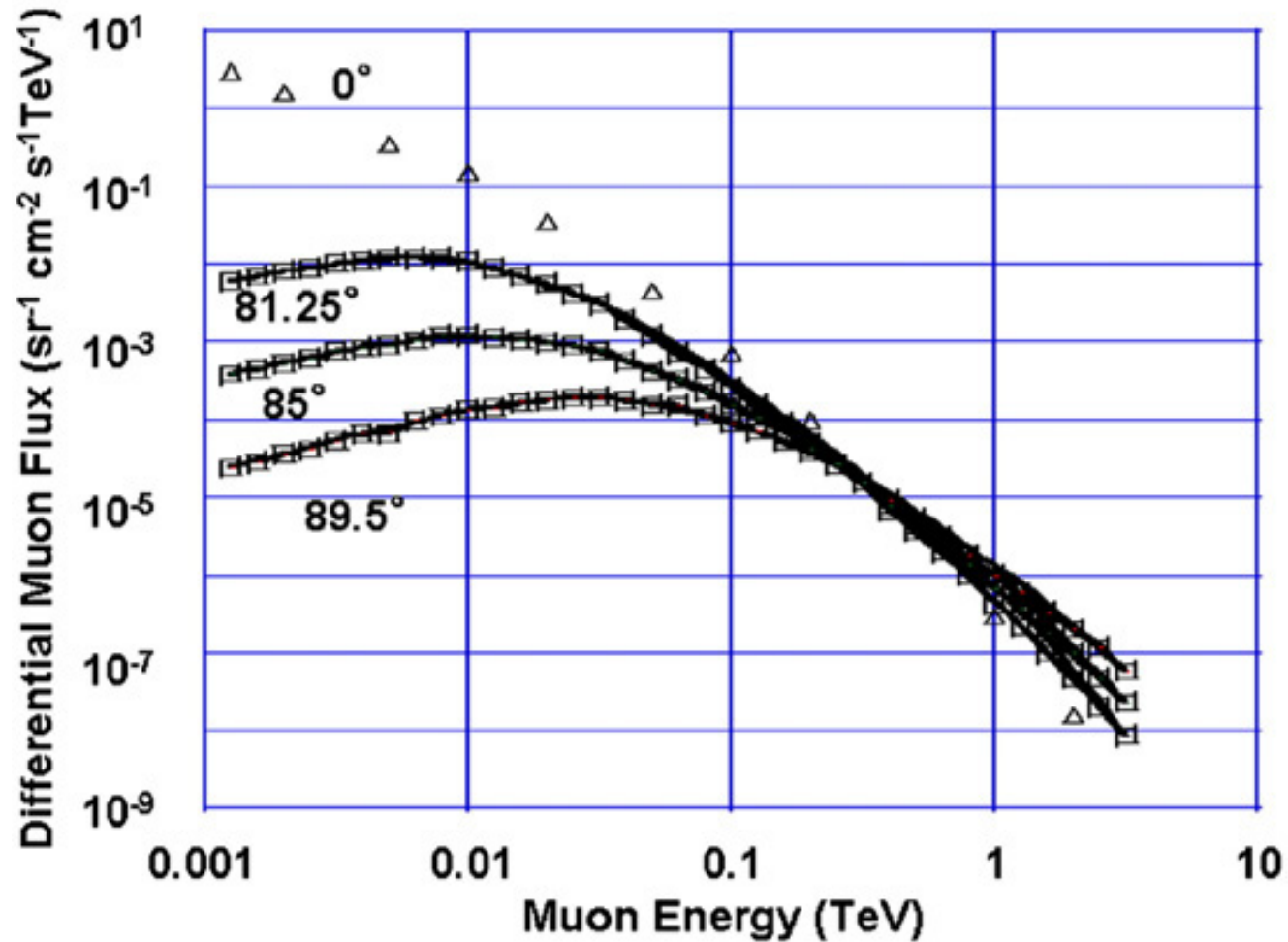
Lo spettro è piatto sotto
1 GeV diventa gradualmente
più ripido a 10-100 GeV
poichè lo spettro dei primari
 $\sim E^{-2.7}$ e asintoticamente
diventa 1 potenza più ripido
(molto oltre 1 TeV)

La distribuzione angolare va
come $\cos^2\theta$ per E_μ bassa e
cambia in $1/(1+aE_\mu\cos\theta)$ per $E_\mu \gg \epsilon_\pi = 115 \text{ GeV}$
e $\theta < 70^\circ$ con θ zenith (rispetto alla verticale)

[a 115 GeV la probabilità di interagire dei π uguaglia quella di decadere]



Spettro dei mu cosmici/2; angoli grandi

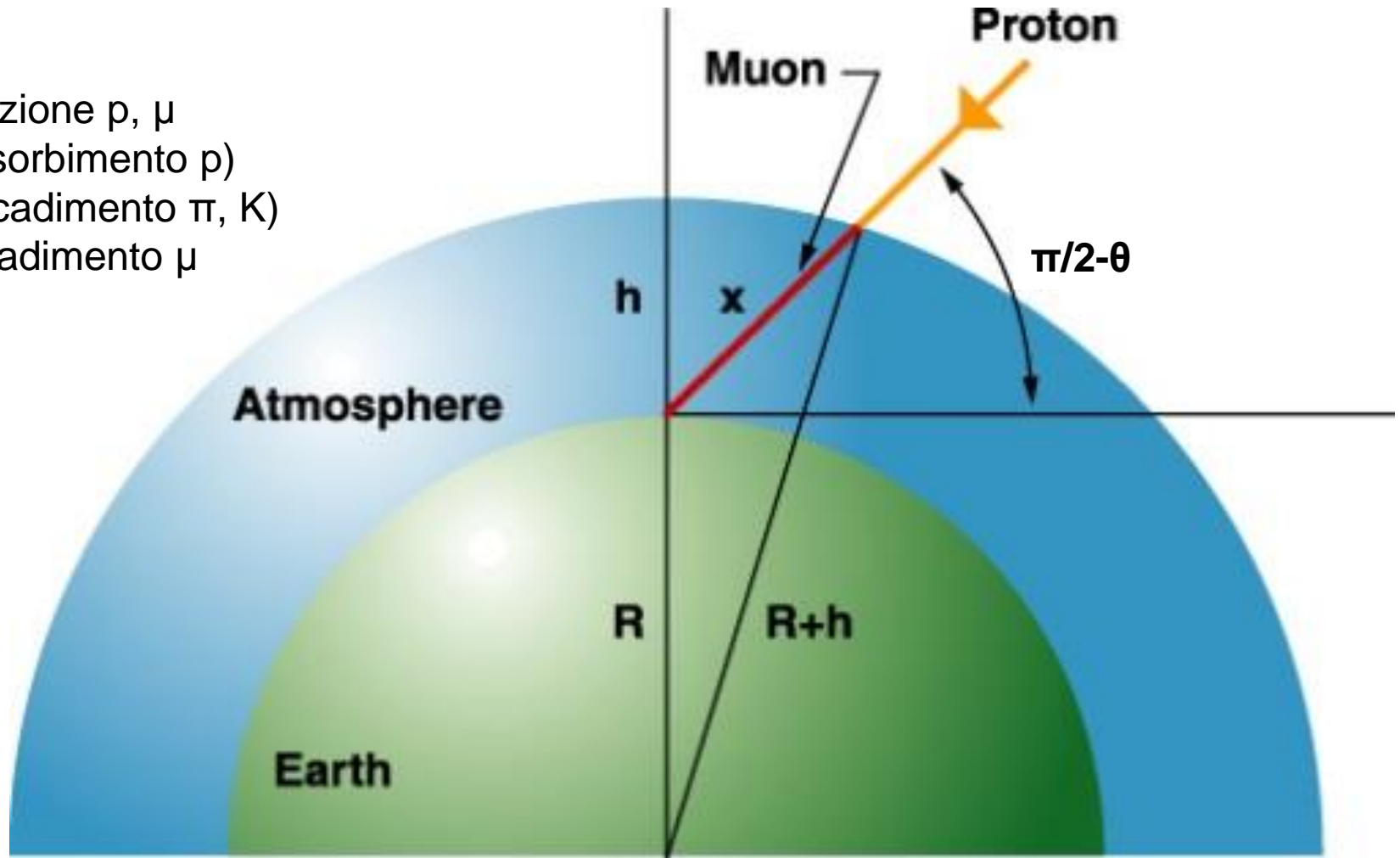


1 cm⁻²TeV⁻¹ = 10 m⁻²GeV⁻¹
cfr pagina precedente

DEIS, Allkofer et al. 1981

Modello per i muoni cosmici

direzione p, μ
(assorbimento p)
(decadimento π, K)
decadimento μ



$$(R+h)^2 = R^2 + x^2 - 2Rx \cos(\pi-\theta)$$

Intensità dei cosmici

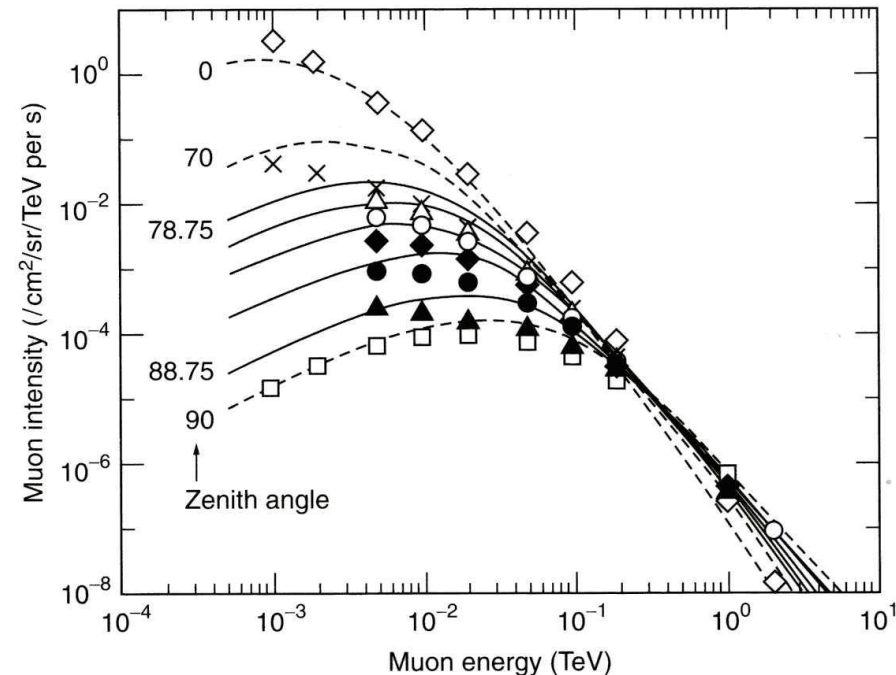
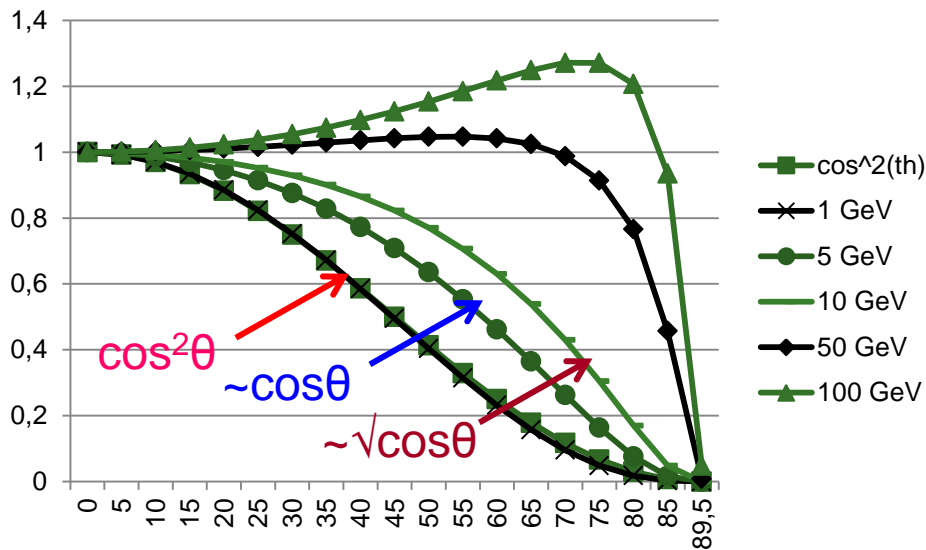
$$I(E, \theta) = \frac{dN(E', \theta)}{dE'} = 1.2 \times 10^{-6} E'^{-2.7} (\text{TeV}) \times$$

$$\times \left[\frac{0.9}{1 + \frac{E' \cos \theta}{E_\pi}} + \frac{0.1}{1 + \frac{E' \cos \theta}{E_K}} \right] \dots (\text{s}^{-1}/\text{cm}^2/\text{sr}/\text{TeV})$$

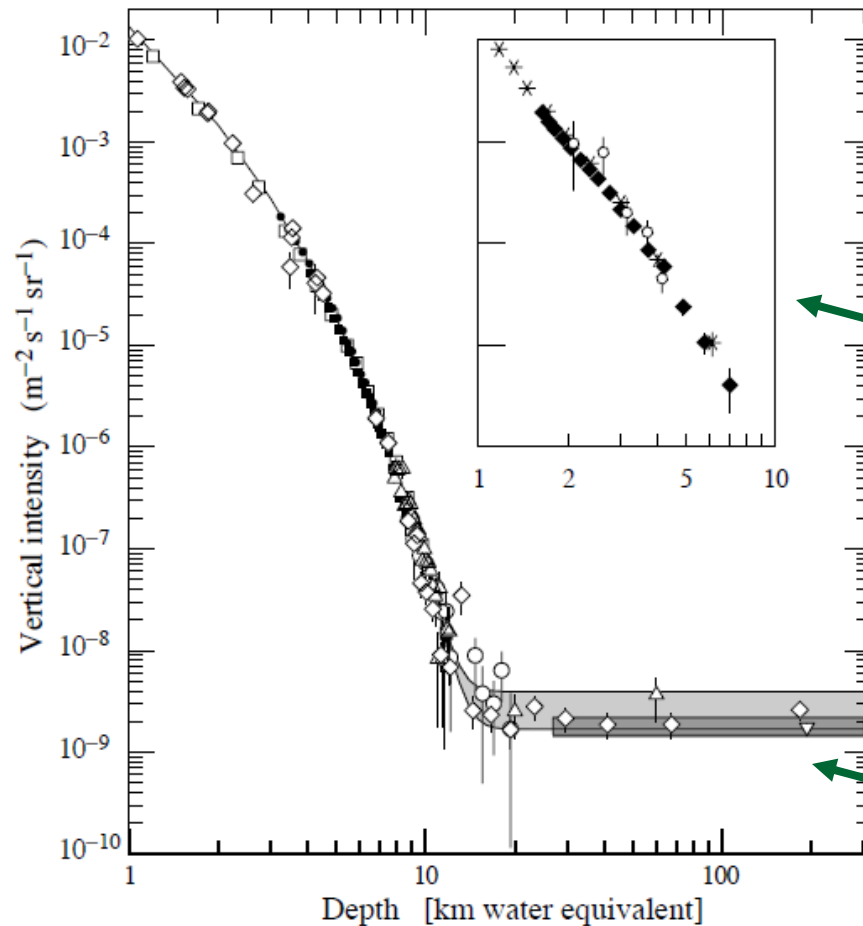
- $E_\pi = 0.092 \text{ TeV}, \quad E_K = 0.54 \text{ TeV}$
- $E' = E + \Delta E_{\text{air}}/\cos \theta \quad (L_0 = 1.013 \text{ kg/cm}^2, \Delta E_{\text{air}} = 0.0026 \text{ TeV})$
- $L/L_0 = [(R^2 \cos^2 \theta + 2RL_0 + L_0^2)^{1/2} - L_0 \cos \theta]/b \quad (\theta \sim 90^\circ, L \sim 25L_0)$
 R – raggio terra, L_0 – spessore atmosfera
 (i μ orizzontali hanno + tempo x decadere \rightarrow spettro + duro)
- $L_d = 6200 E(\text{TeV}) \text{ km} \quad \text{decadimento}$
- $N_\mu(E_c, \theta) = \int_{E_c}^\infty I(E, \theta) dE \quad N \text{ con } E > E_c$

Intensità dei raggi cosmici a grande angolo

- la parametrizzazione (Adair&Kasha, 1976) è indistinguibile da $\cos^2\theta$ a bassa E , va come $\cos\theta$ a ~ 5 GeV ed è molto più piatta ad alta E (a sx, curve vs θ normalizzate a 1 a $\theta = 0^\circ$; a dx curve assolute vs E_μ a 0° e grande angolo)



Intensità verticale dei μ cosmici vs lo spessore di roccia



1 km.w.e. = 10^5 g cm^{-2}
di roccia standard
~ 400 m

misure in acqua e ghiaccio
– minore perdita di E
→ minore pendenza

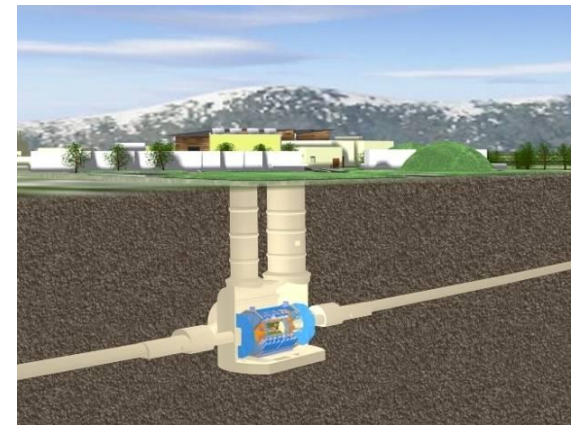
interazioni CC di ν_μ
 $E_\mu > 2 \text{ GeV}$ – linea
superiore, μ orizzontali,
linea inferiore μ verticali
verso l'alto

Muoni nelle caverne di LHC

- a ~100 m sotto la superficie del suolo (profondità delle caverne degli esperimenti ATLAS e CMS a LHC), l'intensità dei μ cosmici è ridotta di un fattore 100 rispetto alla superficie della terra
- i μ cosmici sono stati usati per la calibrazione dei rivelatori quando si stava aspettando l'acceleratore (e sono tuttora usati, per es. adesso durante il LS1 e dopo)
- si possono ottenere radiografie dei volumi (dei vuoti) vicino alle caverne
- misure di cosmici a ~60-100-170 m di profondità sono state fatte precedentemente all'epoca di LEP da L3, DELPHI e ALEPH

10 ms of cosmics

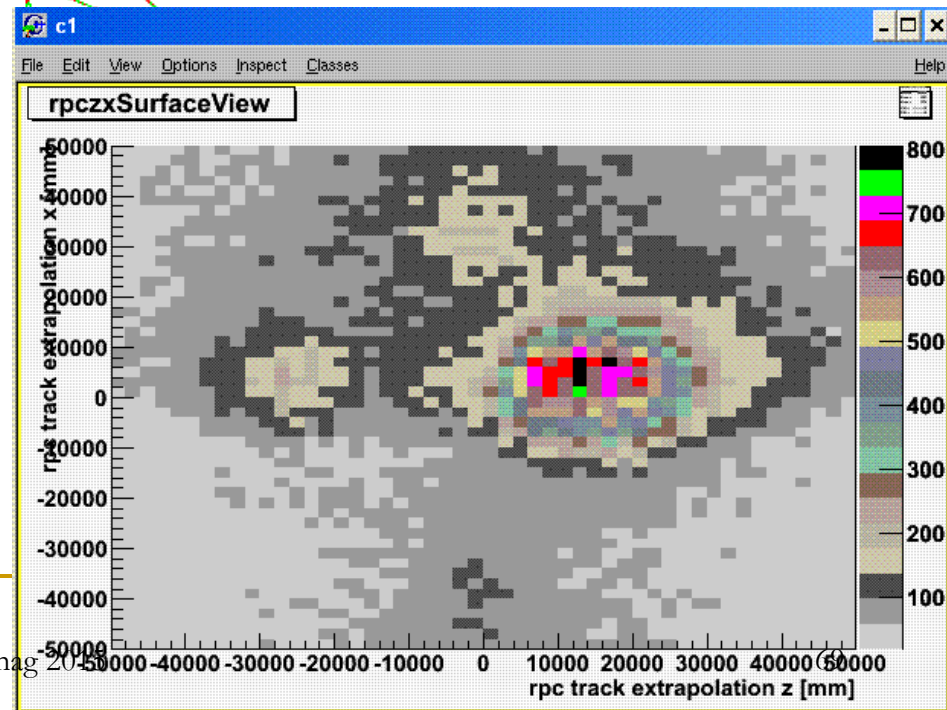
Simulated cosmics flux
in the ATLAS cavern



Cosmics data:

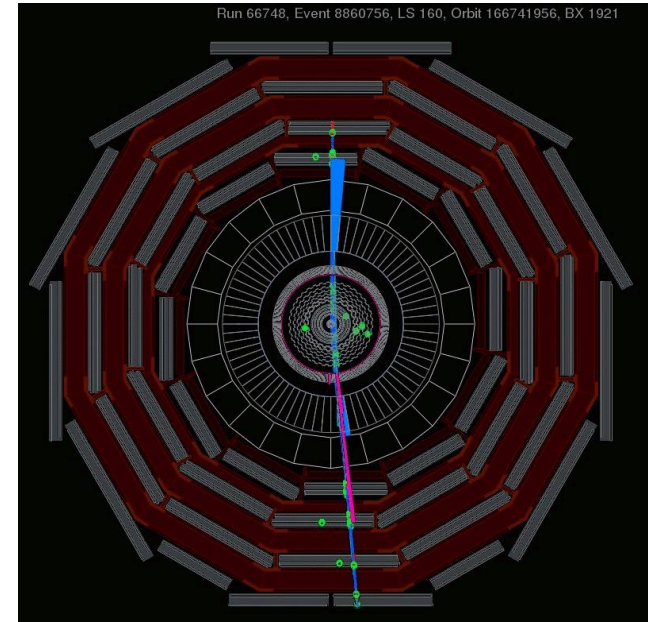
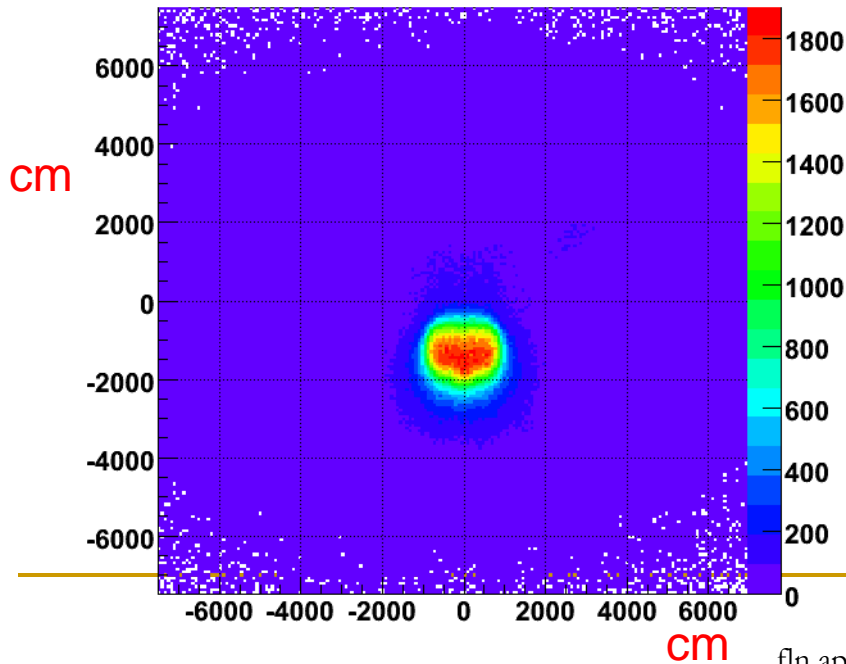
Muon impact points extrapolated
to surface as measured by
Muon Trigger chambers (RPC)

Rate ~100 m below ground:
~ O(100 Hz)



μ cosmici: CMS ott08 pre-LHC

- a circa 100 m di profondità, $\sim 230\text{Hz}$ sul barrel di CMS
- CosmicRaysAtFour Tesla (CRAFT)
- $B = 3.8\text{ T}$
- dal centro
 - pixels
 - strips
 - ECAL
 - HCAL
 - criostato
 - DT/RPC



Cosmici (DT) estrapolati alla superficie (coord. CMS)
Si vede il pozzo per l'accesso!

Radiografia con particelle

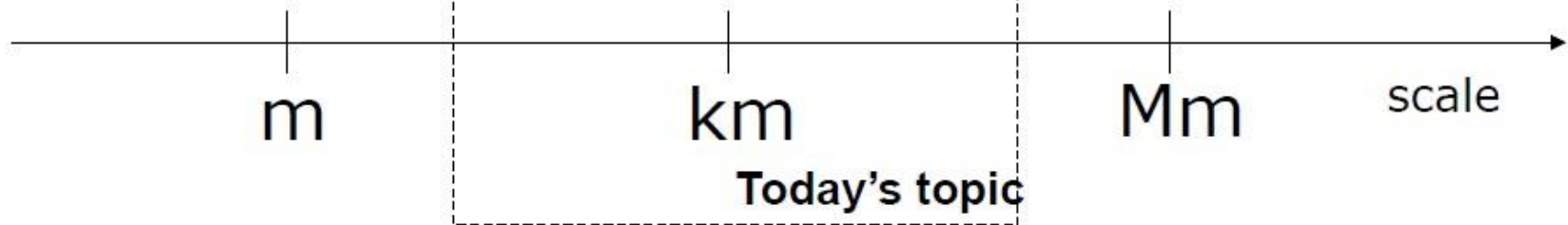
photography



muography



neutrinography



Due tipi di misure con muoni cosmici

1. **Misure di assorbimento/trasmissione dei μ cosmici**, come si fa coi raggi X, se E_μ è appropriata e se gli spessori sono grandi
 - In questo caso la diffusione/scattering è un problema \rightarrow ad es. per ridurlo si può indurire lo spettro circondando il rivelatore con blocchi di Fe, oppure misurare e/o limitare E_μ
 - Questa misura è possibile anche con neutrini, se l'assorbitore è sufficientemente grande (R_T) e l'energia elevata
2. **Misura delle traiettorie dei μ entranti ed uscenti dal materiale, scattering**, ricostruzione del punto di intersezione – l'angolo di scattering aumenta con Z e con lo spessore – se E_μ è appropriata e se gli spessori sono relativamente piccoli

Storia – applicazioni dell'assorbimento di μ

- E. P. George, Misura dello spessore di materiale/roccia sopra un tunnel, 1955
- L.W. Alvarez, Piramidi di Giza, 1970
- K. Nagamine, H. Tanaka et al., Radiografie di vulcani, 1995 →
- H. Tanaka, Radiografie di strutture di cemento rinforzato (MC), 2008
- W.B. Gilboy et al., R. di impianti industriali, 2007
- A. Menchaca-Rocha et al., R. di piramidi azteche, 2004 →
- R.F. Schwitters et al., R. di piramidi Maya, 2006 →
- P. Strolin et al., R. di vulcani (MU-RAY, INFN), 2008 →
- C. Carloganu et al., Puy de Dome, 2010 →
- D. Bryman, Muon geotomography at the Myra Falls mine in Canada, Advanced Applied Physics Solutions, 2011-12 →

Attività recente

- Ad es. una intera sessione a GeoSciences, Vienna, Apr. 2011 (EGU General Assembly)
 - Paris-Lyon-Rennes-Grenoble, Muon tomography and Volcanic Risks in the Lesser Antilles, 2010 →
 - Paris-Lyon-St Ursanne, Muon tomography: study of the geological layers above the Mont Terri (Jura) underground rock laboratory, 2009 → (per individuare un deposito di scorie r.)
 - Catania-Paris-Lyon, Geophysical imaging using CR muons: the Etna volcano, 2010 →
 - L'Aquila-Nagasaki-Tokyo-Napoli, Imaging the lava dome structure with CR muons at Unzen, Dic 2010 →
 - ...
- Muon and Neutrino Radiography Conf.: MNR12, 13, 14 Tokyo

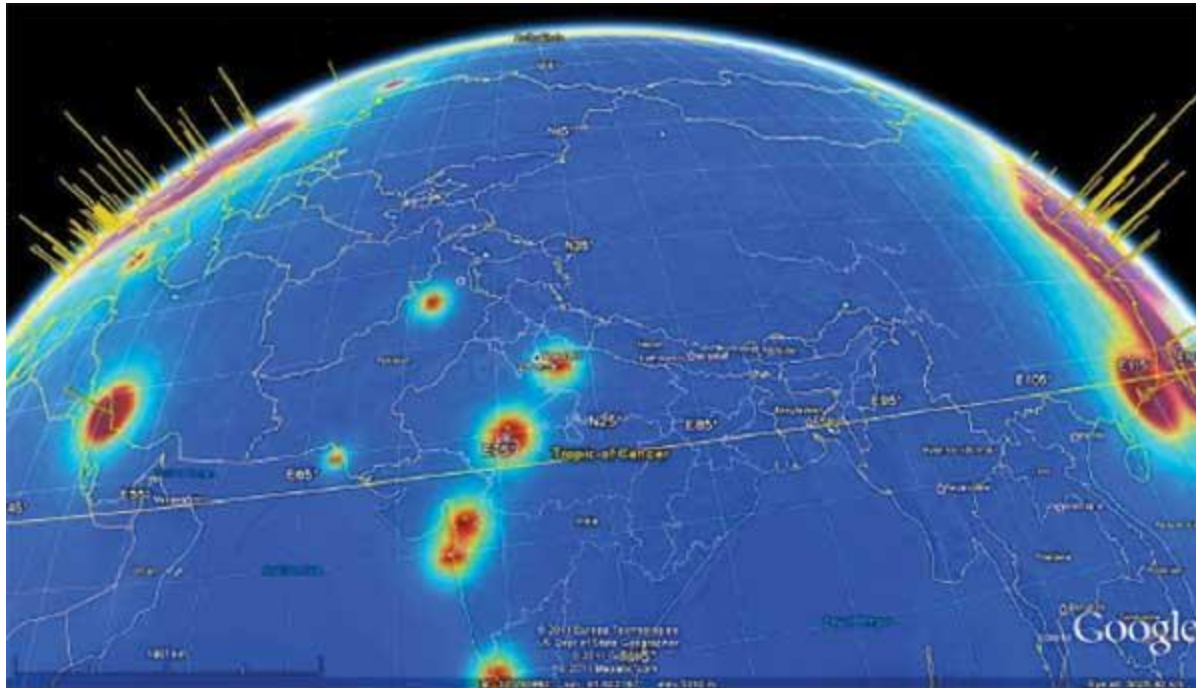
Special issue of GI (Geoscientific Instrum.)

- Muon radiography for exploration of Mars geology, S. Kedar et al., Geosci. Instrum. Method. Data Syst., 2, 157-164, 2013
- A novel technique to detect special nuclear material using cosmic rays (Resistive plate chambers for tomography and radiography), C. Thomay et al., Geosci. Instrum. Method. Data Syst., 1, 235-238, 2012
- CCC (Close Cathode Chamber) - based muon telescope for examination of natural caves, L. Oláh et al., Geosci. Instrum. Method. Data Syst., 1, 229-234, 2012

Storia – applicazioni dell'assorbimento di ν

- A. Placci e E. Zavattini, Radiografia della terra, proposta, 1973 (fascio di ν da FNAL o dal SPS del CERN)
- ...
- International Workshop on High Energy Earth Science: Muon and Neutrino Radiography – Tokyo, Japan, June 26-27 2008 (e.g. constraints on the Earth's dynamics sampling density anomalies with Neutrino Radiography using IceCube; IceCube, Evidence for high-energy extraterrestrial neutrinos, Science 342 (2013) 1242856)
- MNR12, MNR13 e MNR14, già citate
- $\lambda_{\text{int}} \sim R_T$ a 25 TeV, la terra diventa opaca ai ν

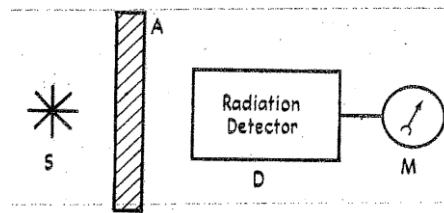
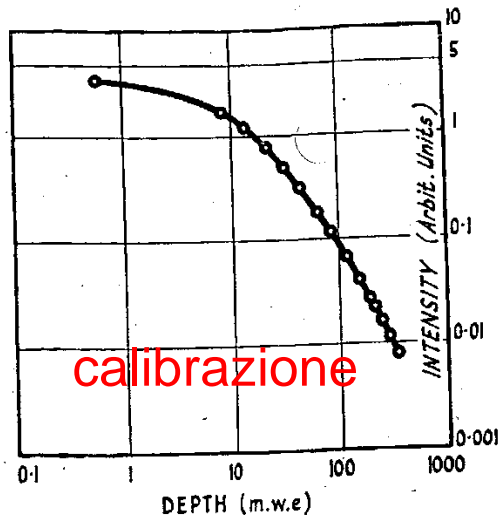
WATCHMAN – uso applicato di antineutrini (da reattore)



Emissione globale di antineutrini da reattore

Misura dello s. di roccia sopra un tunnel nel New South Wales(*)

- Guthega-Munyang tunnel (Snowy Mountains, NSW, Australia)
- profilo del terreno molto vario, difficile da misurare
- misura per confronto fra le intensità dei mu cosmici all'ingresso del tunnel (all'aperto) e dentro al tunnel



- telescopio di 100 contatori Geiger (+ 4" Pb)
- $R = 0.0128 \rightarrow 163 \pm 8 \text{ m.w.e.} = 16.3 \pm 0.8 \text{ kg/cm}^2$
- un foraggio particolare nella stessa zona dà per es. uno spessore di $17.5 \pm 0.6 \text{ kg/cm}^2$, consistente

(*) E.P. George, Commonwealth Engineer, July 1 (1955) p. 455

Altre misure di spessore di montagne/roccia

- Measurements on the cosmic radiation intensity in the Mont Blanc tunnel, fra 40 e 4100 mwe
C. Castagnoli et al., *Il Nuovo Cimento* **35** (1965) 969
- Montagne nell'Utah, fra 2000 e 8000 mwe
H.E. Bergeson et al., *Phys. Rev. Lett.* **19** (1967) 1487; **21** (1968) 1182
- Kolar Gold Fields (*), vicino a Bangalore, India, profonda fino a 3200 m
C.V. Archar et al., *Proc. Phys. Soc. (London)* **86** (1965) 1305
-



(*) nel 1965 vi è stata rivelata la prima interazione sotterranea di neutrini

Alvarez et al.

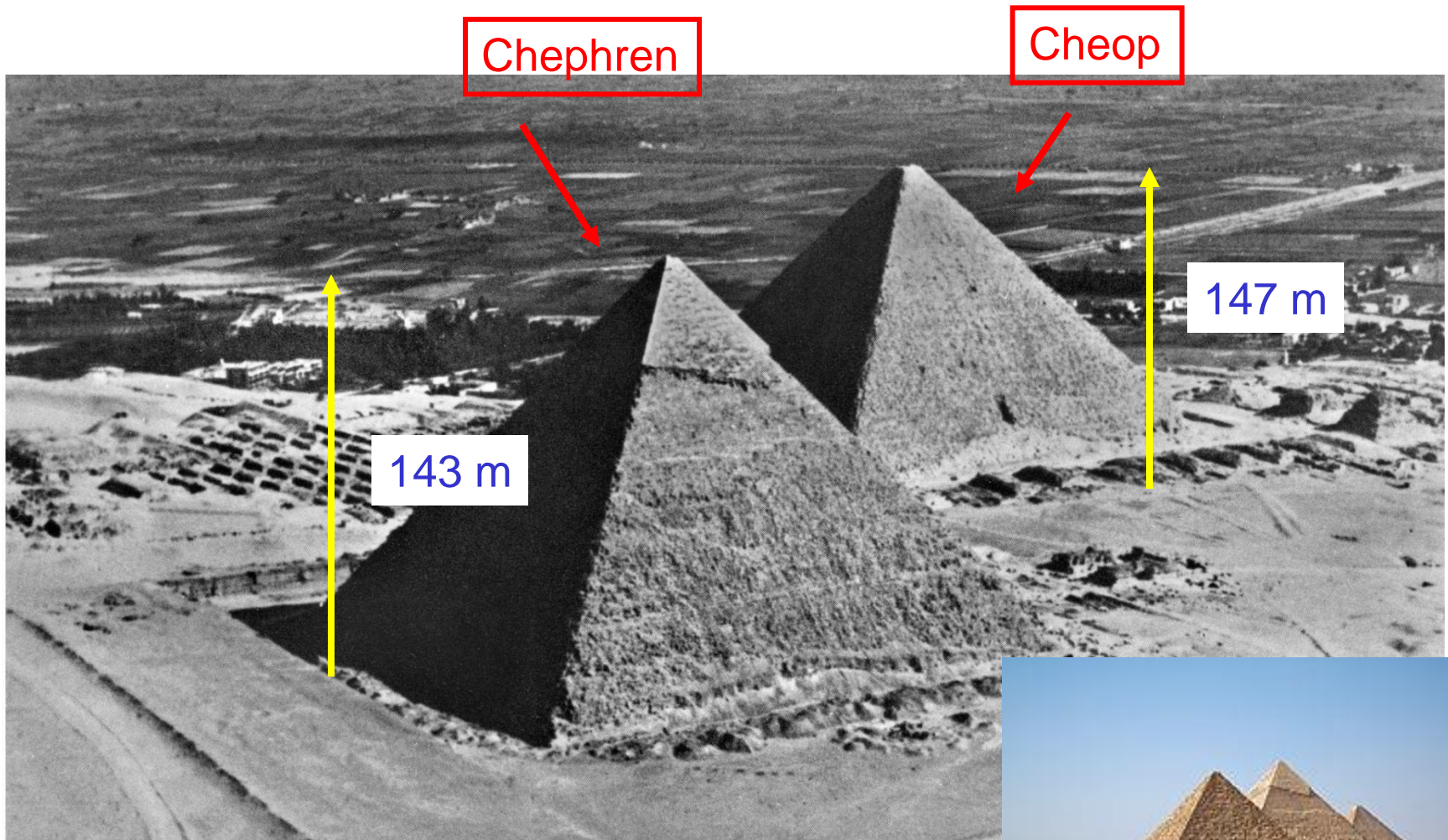
- Luis Alvarez(*) used muon tomography in 1960's to study the 2nd Pyramid of Chephren
- Spark chambers surrounded by Fe blocks were used to track muons from Belzoni Chamber
- System worked well—could see structures of caps
- Main discovery: No other chambers exist

(it could look like the story with the Higgs, at least until two years ago, now it looks more like SUSY)

- (*) L.W. Alvarez, *et al*, *Search for Hidden Chambers in the Pyramids Using Cosmic Rays*, *Science* **167** (1970) 832-839



Gizah, le due grandi piramidi



L'apparato di Alvarez et al.

(sx) apparato e racks nella Belzoni Chamber (dx) particolari (scintillatori per il trigger, PM, camere a fili magnetostrittive per il tracciamento, Fe)

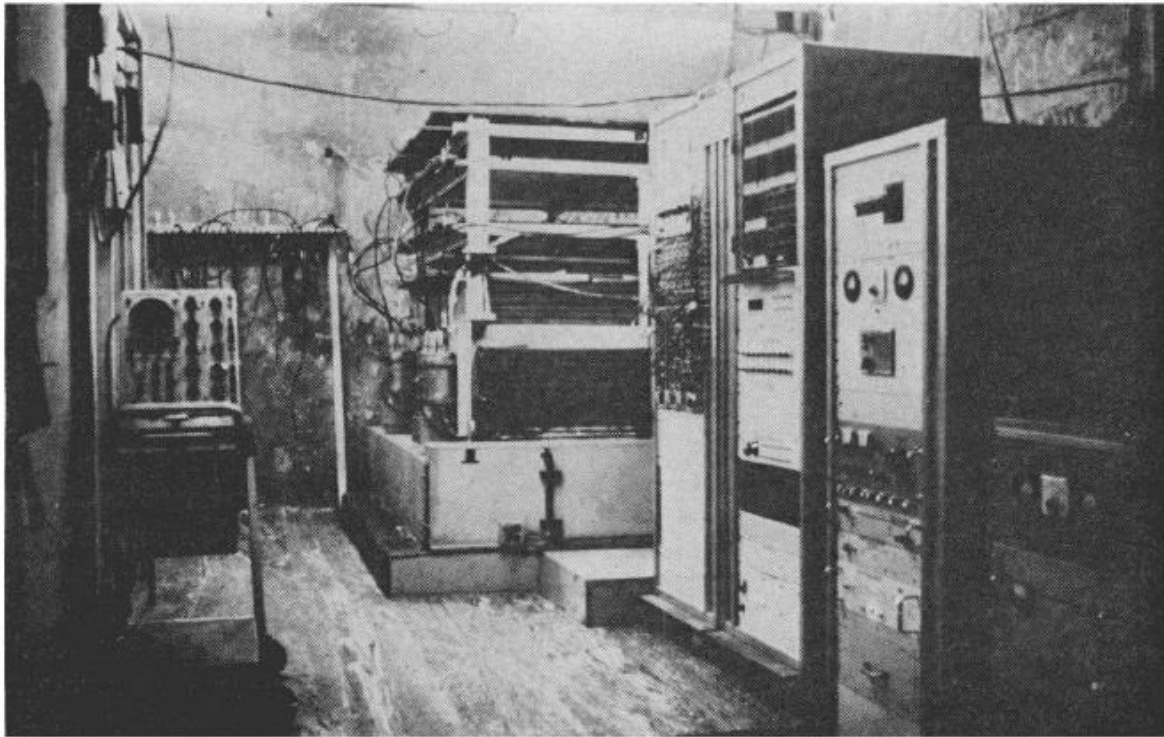
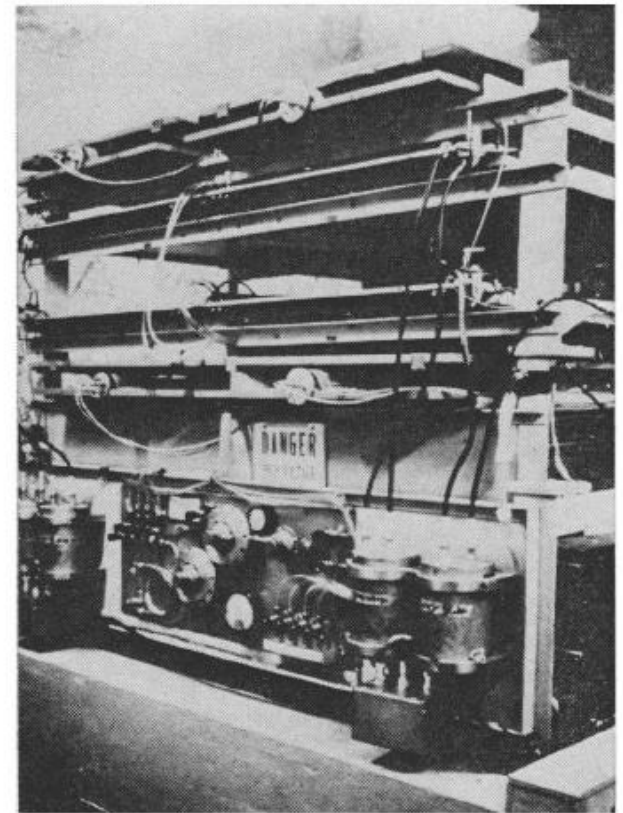
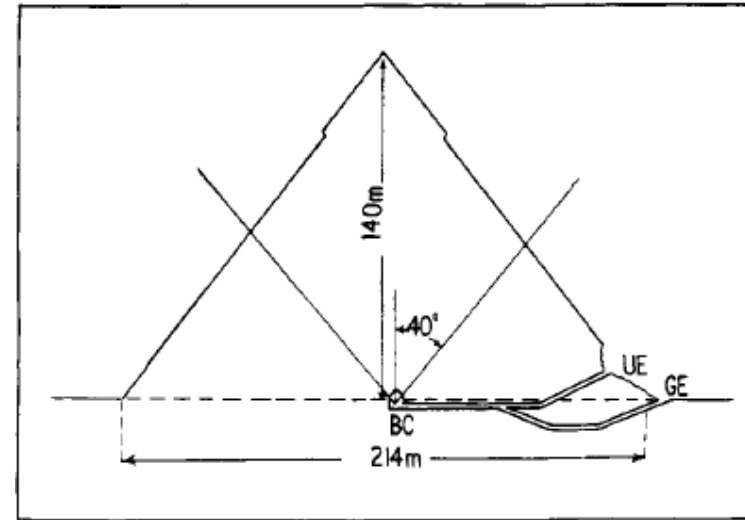
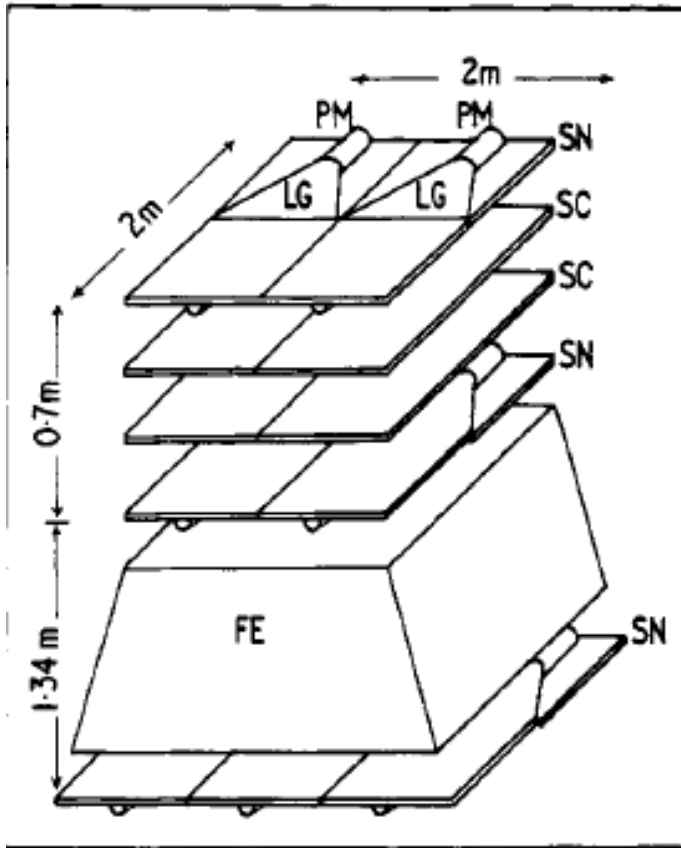


Fig. 6 (left). The equipment in place in the Belzoni Chamber under the pyramid.
Fig. 7 (right). The detection apparatus containing the spark chambers.



Piramide di Chephren

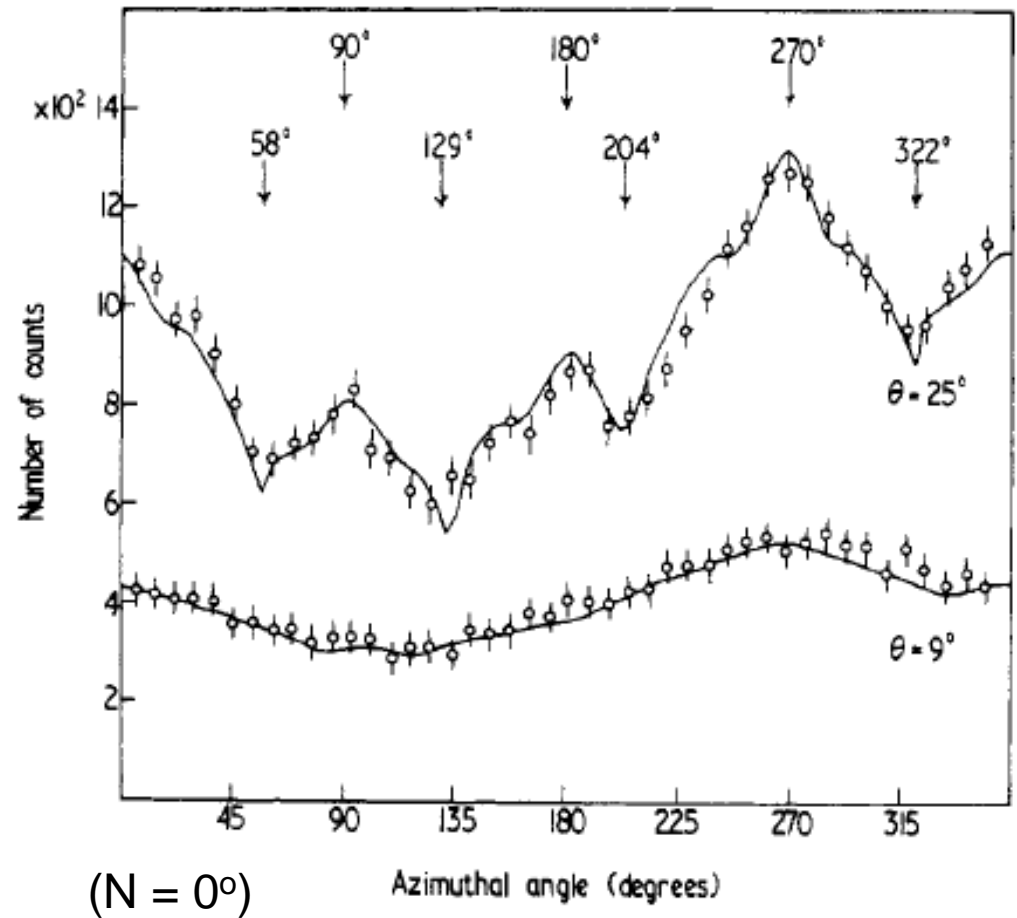
Alvarez, El Bedewi ...1969



- 14 scint. plast. (SN) 1x1 m²
- 4 camere a scintilla a fili magnetostrittivi (SC) 1x2 m² $\Delta\theta \sim 0.2^\circ$ (3.5 mrad)
- Fe spesso 1.2 m, $E_\mu > 1.4$ GeV
- 500 m cavi, IBM 1130

Piramide di Chephren/2

- 4 mesi, 2 M mu
- $E_{\mu} = 50-70 \text{ GeV}$
- 80-110 m roccia
- θ fra 0° e 40° ,
 φ fra 0° e 360°
- ottimo accordo fra dati e valori calcolati (in assenza di camere nascoste) – minimi = spigoli della piramide



Alvarez et al., analisi dei dati

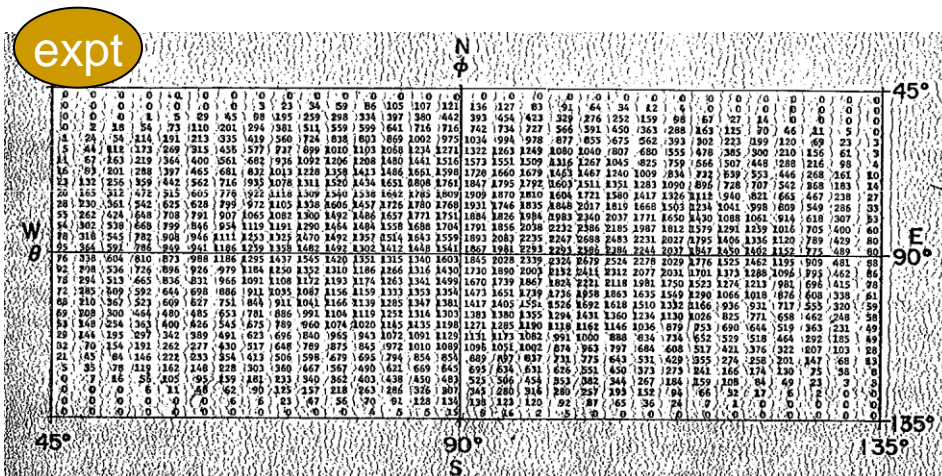


Fig. 8. An array containing the numbers of events (uncorrected) observed during several months of operation in each 3- by 3-degree bin.

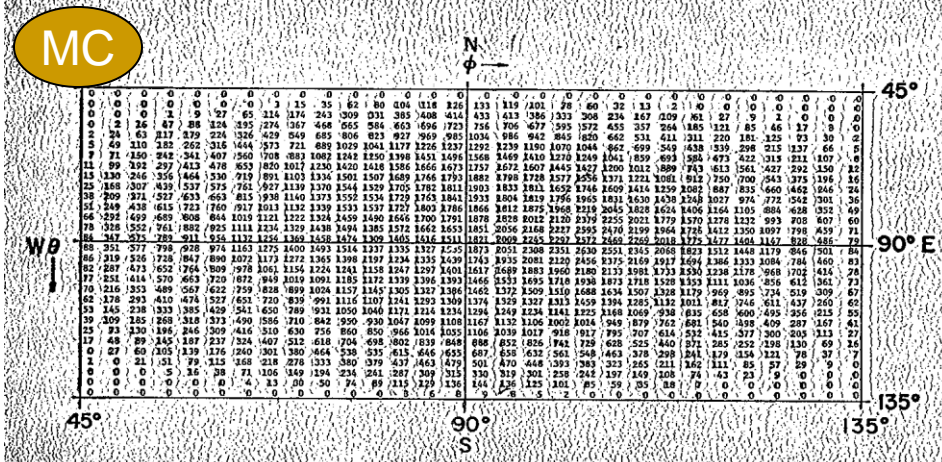


Fig. 9. An array containing the predicted number of events in each 3- by 3-degree bin for the best fit to the data.

→ nessuna camera

- si considerano solo bin con $N_{th} > 30$ (Monte Carlo), fit complessivo con χ^2 , risultati espressi in n.o di st.dev.
- 750 punti, χ^2 iniziale era circa 3000, sceso a 1400 dopo le correzioni

risultati, in σ , più 'camera nascosta'

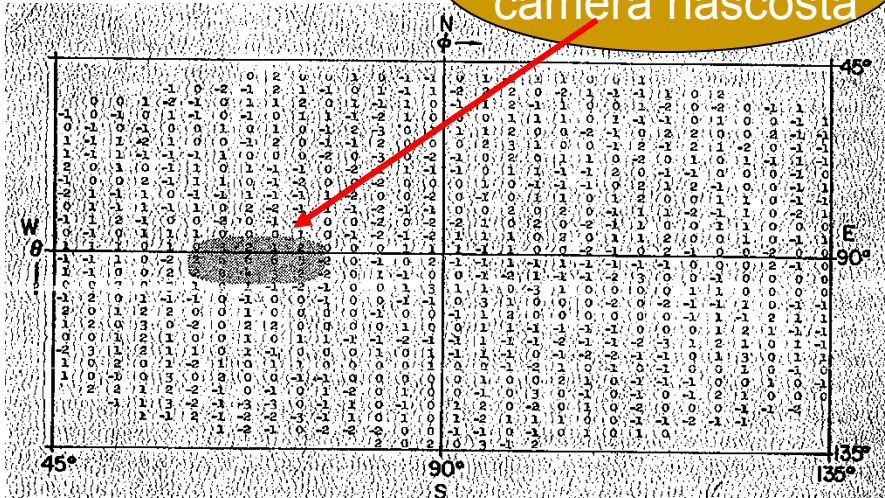


Fig. 11. The display of Fig. 10 as it would have appeared had there been a "King's Chamber" in the pyramid 40 meters above the apparatus. The group of numbers larger than 3 at the center-left (shaded area) indicates the chamber's position.

Analisi dei dati/2

- ci sono 750 punti utili, il χ^2 atteso è circa 750, quello dei fit iniziali era circa 3000 ed è sceso a circa 1400 una volta inclusa la fotogrammetria della UAR (stereographically determined contours of the pyramid)
- se le deviazioni sono puramente statistiche ci si aspetta che 87% dei bin abbiano +1,-1,0; 12% +-2; 1% +-3. C'è una possibilità su tre di trovare un bin con +-4, una su 200 di trovare +-5 ed una su 3×10^4 di trovare +-6: nessun bin mostra +-4 che è la minima evidenza di un effetto
- è stato possibile anche osservare il cappello in limestone/calcare in cima alla seconda piramide (i cappelli delle altre piramidi sono stati rimossi nel Medio Evo)

Progetti per studiare piramidi in America Latina/Messico/Belize

- Piramide del sole pre-azteca a Teotihuacan vicino a Città del Messico – A. Menchaca-Rocha et al./Univ. of Mexico: risultati preliminari a ICRC11 e 13
- Piramidi Maya a La Milpa nel Belize – R. Schwitters et al./Univ. of Texas: qualche seminario sui progressi, installazione nel 2013(?)

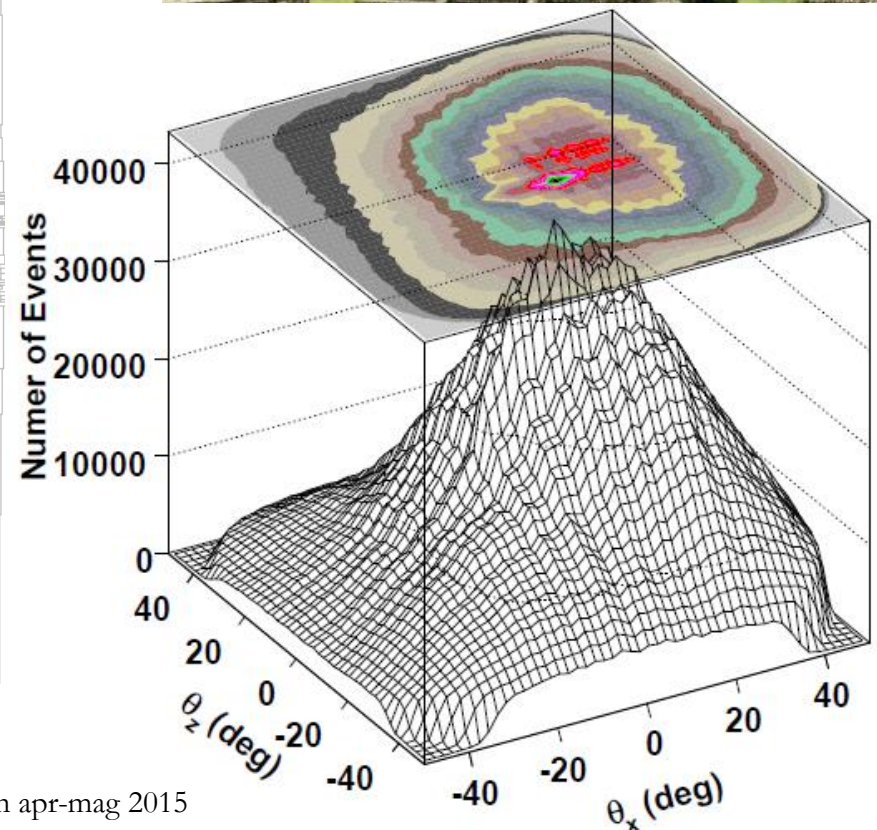
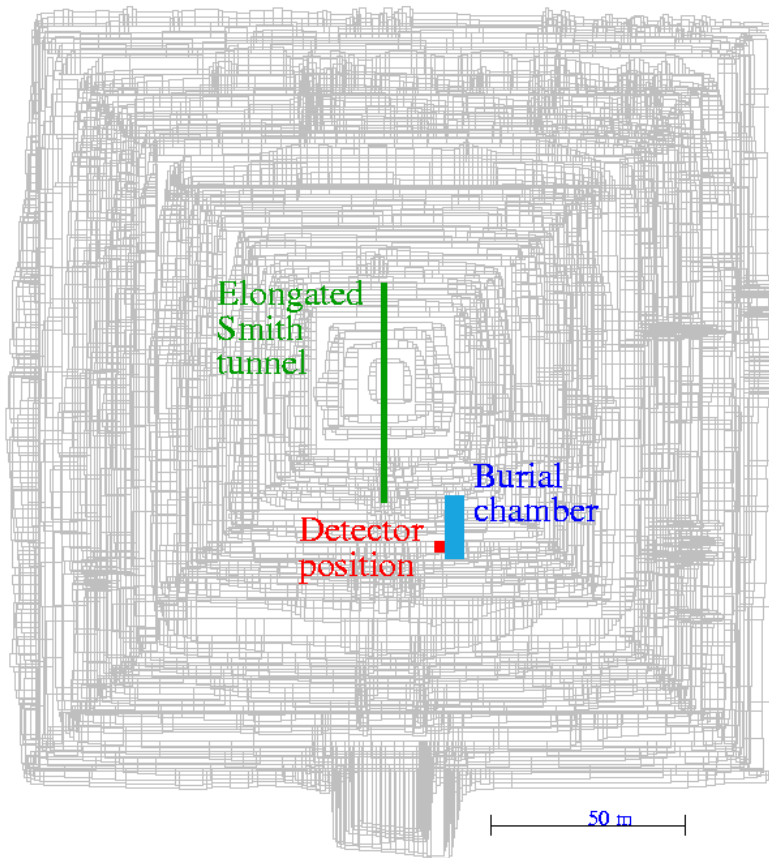


I siti



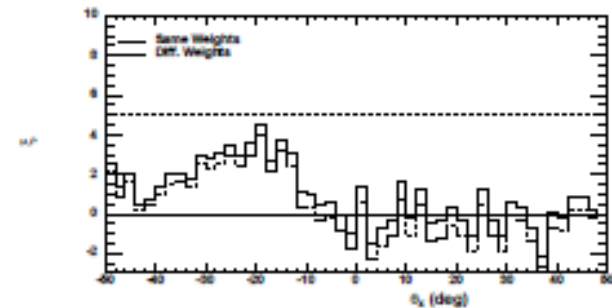
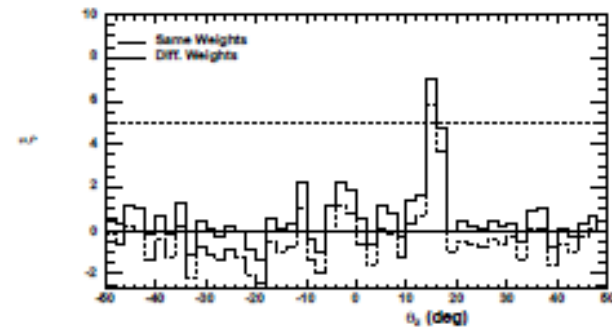
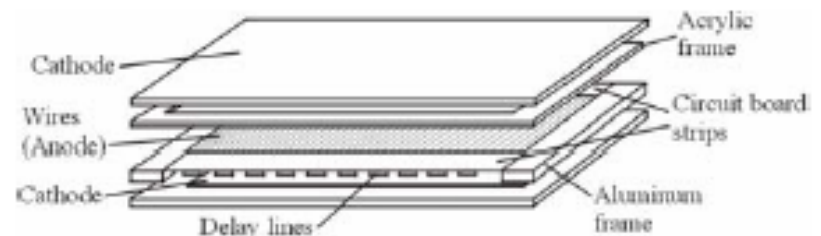
La piramide del sole a Teotihuacán (A. Menchaca-Rocha et al.)

- Camere a fili dentro la piramide
(simulazioni di una struttura)



Teotihuacan/Univ. of Mexico

- la situazione è molto simile a quella della misura di Alvarez et al., c'è un tunnel 8 m sotto la base della piramide che finisce vicino all'asse di simmetria
- rivelatore simulato: due piani di scint. $1 \times 1 \text{ m}^2$, trigger; sei MWPC per tracciare il mu (fili ogni 5 mm, $25 \mu\text{m}$ diametro)
- GEANT4, $\sigma_R \sim 0.02 \text{ L}$ (L spessore traversato, max 80m)
- cavità simulata $60 \times 3 \times 2 \text{ m}^3$
 $5 \times 10^7 \mu/\text{simul.}$, $0^\circ - 50^\circ$
- inizio presa dati 2010-11



Il rivelatore dell'Univ. of Mexico

- 4 piani di scintillatori plastici (2+2) per il trigger, $1 \times 1 \text{ m}^2$, letti da barrette di WLS $1 \text{ m} \times 1 \text{ cm} \times 1 \text{ cm}$ (eff. $> 95\%$)

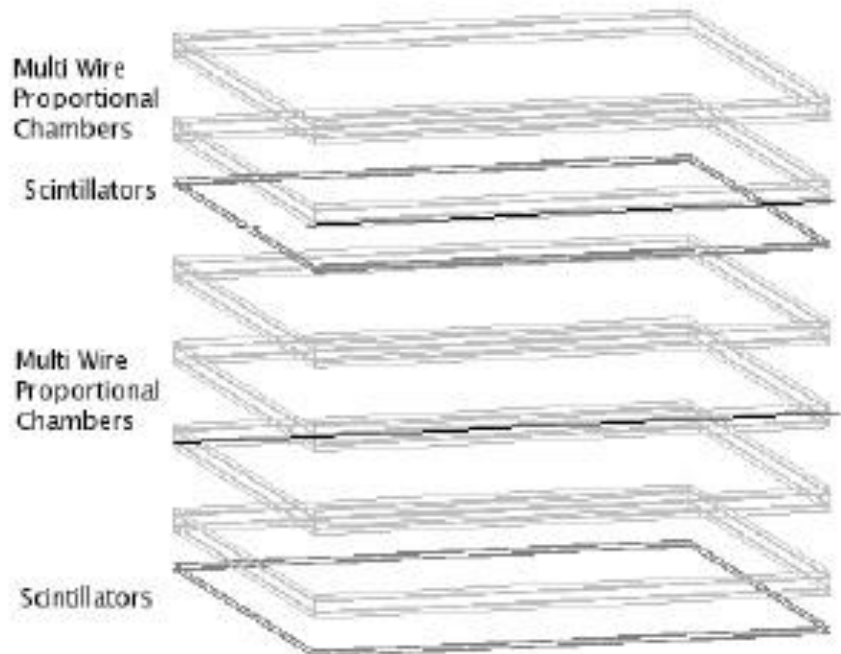
- 6 piani di MWPC, 200 fili, 5mm di distanza, anodi letti con linee di ritardo; 5 GS/s waveform digitizers usati

come Constant Fraction Discriminators

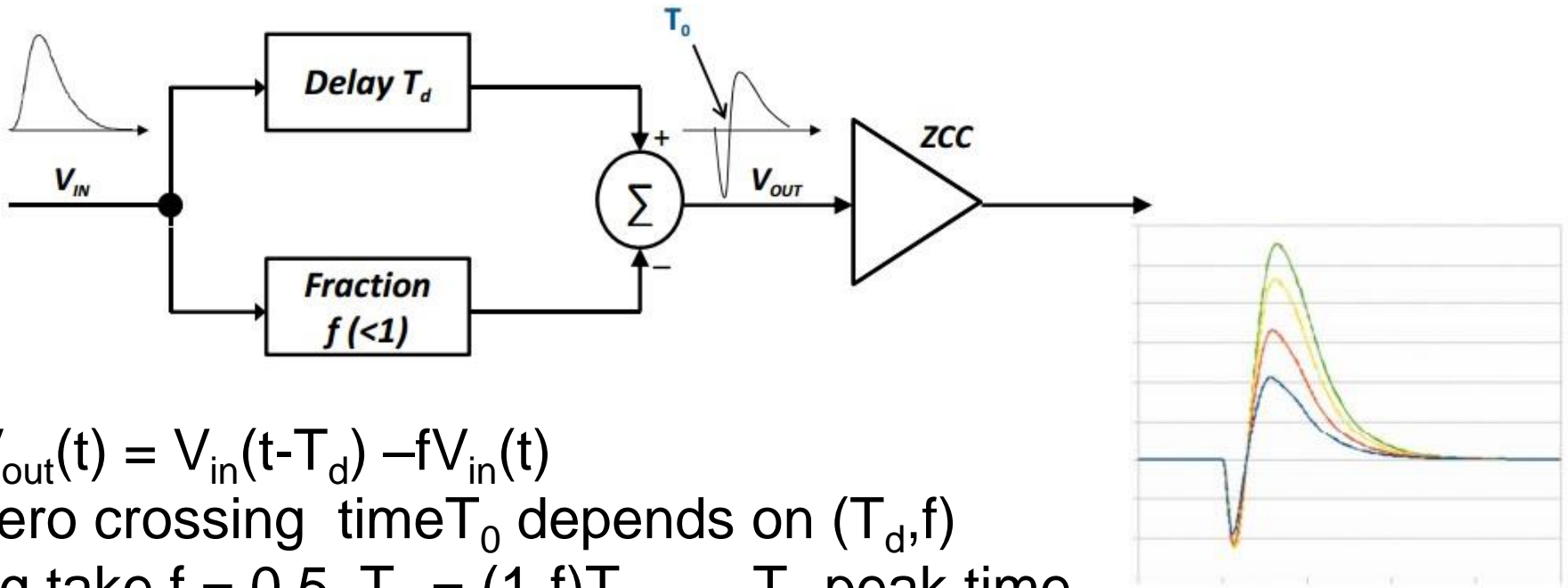
(t_{rise} variabile da 10 a 50 ns); pitch 4ns corrisponde a 5 mm e permette di separare i fili, risoluzione in $t \sim 0.7 \div 1.2 \text{ ns}$

- $E_{\mu} \geq 200 \text{ MeV}$ (cin.), $p = 290 \text{ MeV}/c$ (?)

- trigger rate = $(2.7 \pm 0.05) \text{ Hz}$ (MC: 2.62 Hz)



Constant fraction discriminator or Zero crossing



$$V_{out}(t) = V_{in}(t-T_d) - fV_{in}(t)$$

zero crossing time T_0 depends on (T_d, f)

eg take $f = 0.5$, $T_d = (1-f)T_p$ - T_p peak time

the -ve pulse is max at T_p and there is max cancellation with the delayed +ve pulse at $T_0 = T_p$, if then $T_d = 0.5T_p \rightarrow V_{out} = 0$ (see with triangular pulses for simplicity)

the time jitter is greatly reduced wrt fixed threshold discrim.:

eg 0.01-1 V input, $T_p = 75$ ns, $\Delta T_0 = 0.14$ ns (max-min)

UM, risultati preliminari

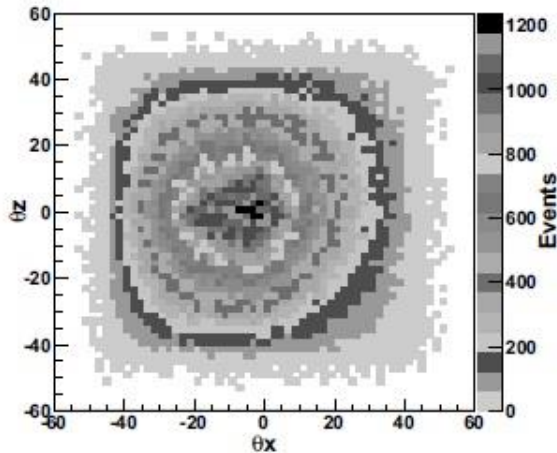


Figure 4: 2D-plot of projection angles from Monte Carlo Simulation.

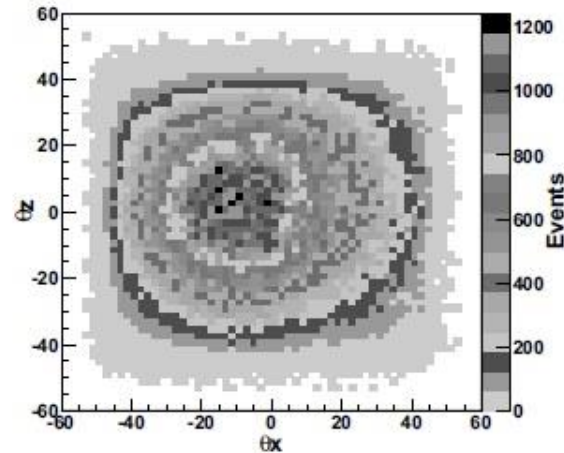


Figure 5: Experimental projection angles 2D-plot.

- le discrepanze dati-MC possono essere dovute sia alla simulazione (il rivelatore non è al centro della piramide, mentre la foto dell'esterno è centrata), sia agli errori nella stima dell'efficienza di rivelazione vs E e posizione (per mancanza di un acceleratore adatto in Messico
- problemi tecnici: network, rete elettrica, composizione/qualità del gas premiscelato (90% Ar, 10% CO₂): efficienza ridotta del 50%

UM, risultati preliminari/2

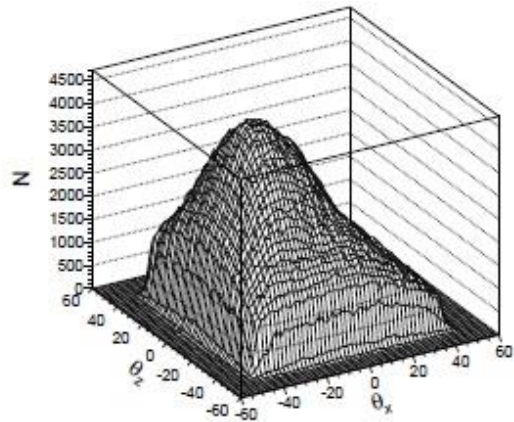


Fig. 3: Angular distribution of simulated events corrected by the detector acceptance in the detector cave. The distribution is normalized to the one in Fig. 5.

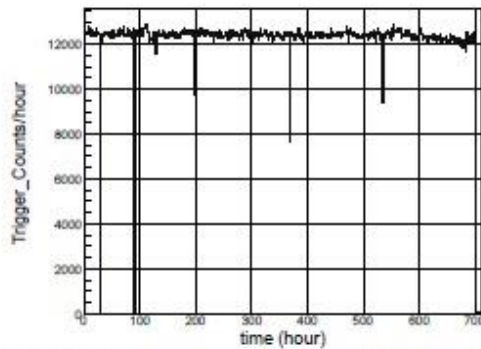


Fig. 4: Trigger count rate for a one-month time period. The vertical lines in the plot are due to the interruptions in data collection time.

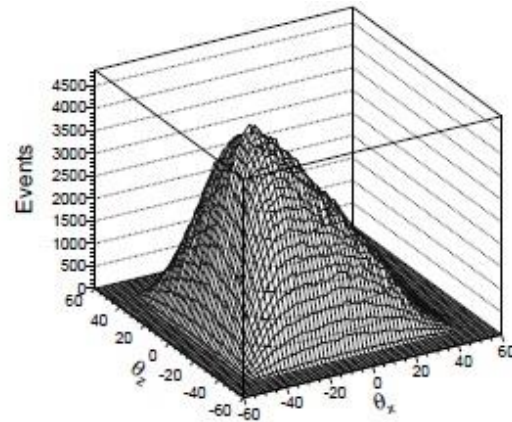


Fig. 5: Angular distribution of detected events, see the text.

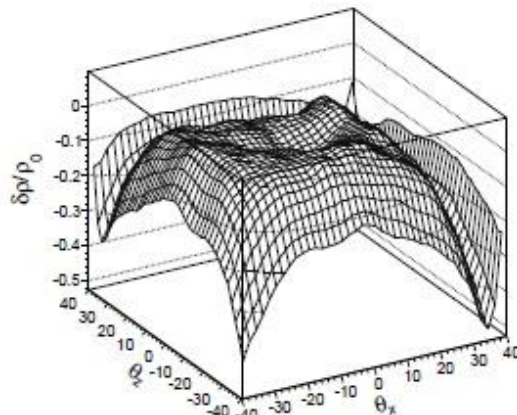


Fig. 6: Preliminary data of relative density distribution inside the pyramid volume.

presentati
a ICRC13

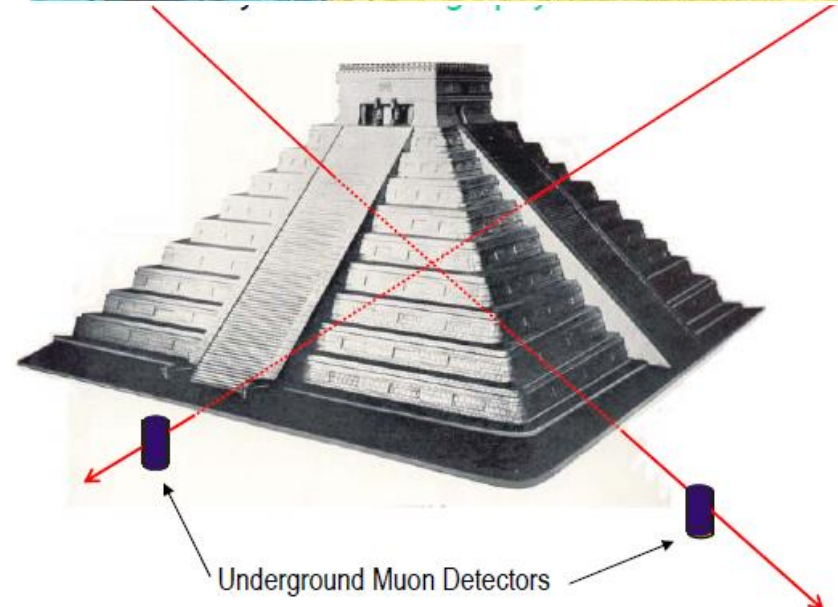
due anni di
presa dati

buona
stabilità su
un mese

problemi ai
bordi del
campo di
vista

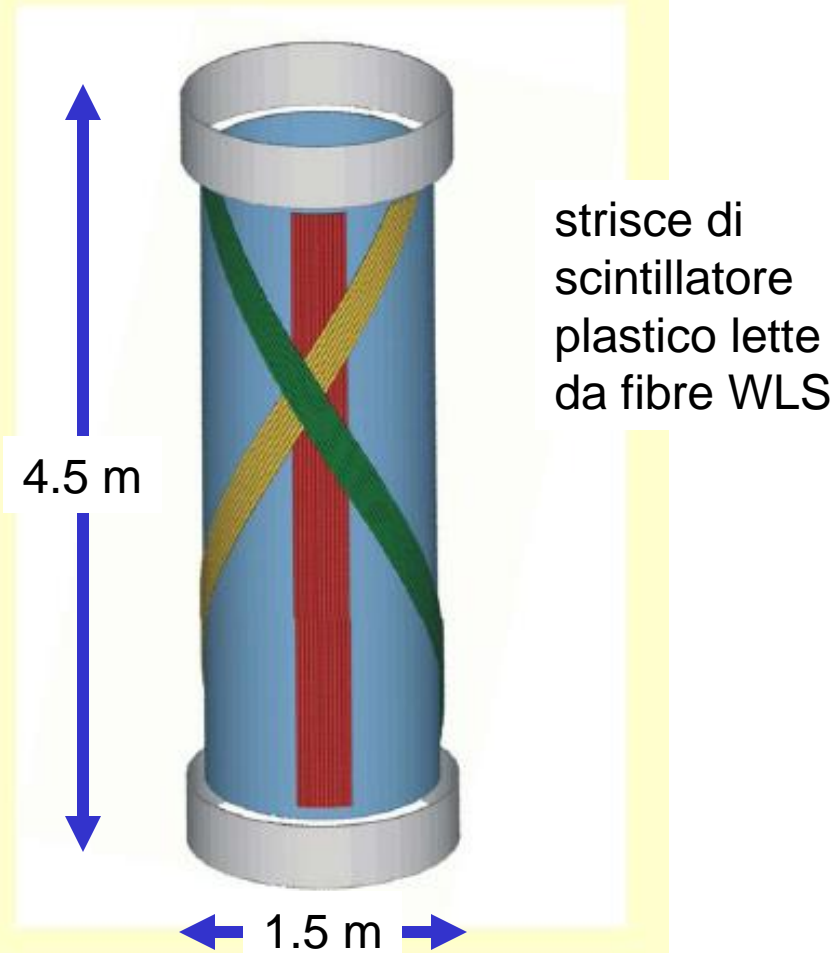
Applicazione dei metodi di HEP alle piramidi dei Maya

- Qual'è la struttura interna? (questa volta non vi sono tunnel di accesso) → rivelatori 'esterni'
- Radiografia o tomografia: si può misurare la distribuzione spaziale del materiale all'interno della piramide usando i μ cosmici con uno o più rivelatori sotterranei
- Univ. of Texas et al. – inizio presa dati 2013 (??) – in ogni caso le riunioni del gruppo "Maya Muons" dell'UT sono programmate tutti i venerdì alle 15 fino al 2016!



Rivelatori

- Cylindrical structure
 - 1.5 m diameter
 - 4.5 m long
- Muon tracking
 - 3 stereo layers
- (MINOS) - WLS-scintillator technology
 - PMT readout
- Threshold energy selection
 - Use inner volume as a Cherenkov radiator
 - PMT readout
- Other systems
 - Electronics
 - Mechanical
 - Power/communications



Costruzione del rivelatore



Il sistema di tracciamento



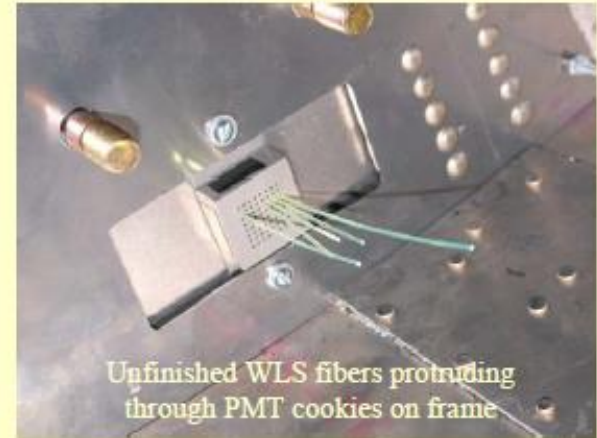
“MINOS” scintillatore

30 mm wide
10 mm thick

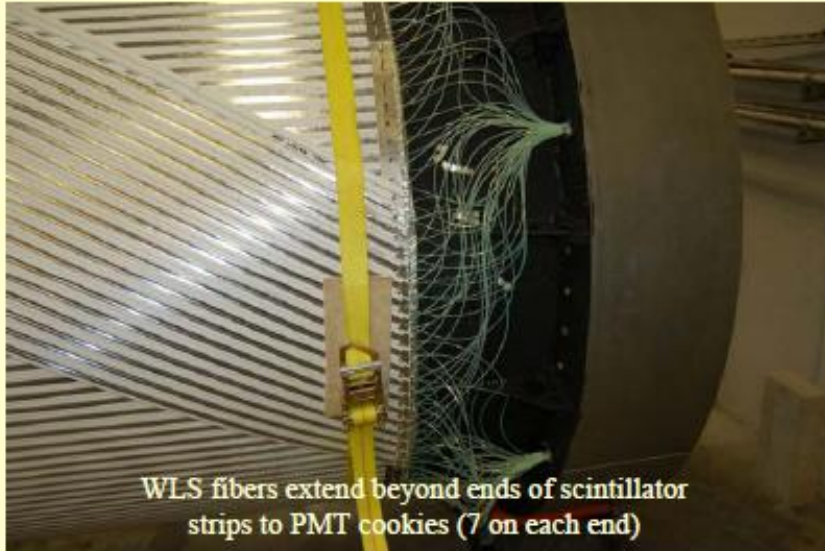
WLS fiber readout

2 helical layers
1 axial layer (center)

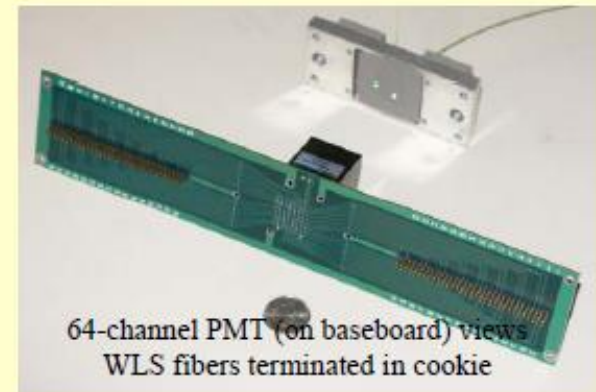
441 total strips



Unfinished WLS fibers protruding
through PMT cookies on frame



WLS fibers extend beyond ends of scintillator
strips to PMT cookies (7 on each end)



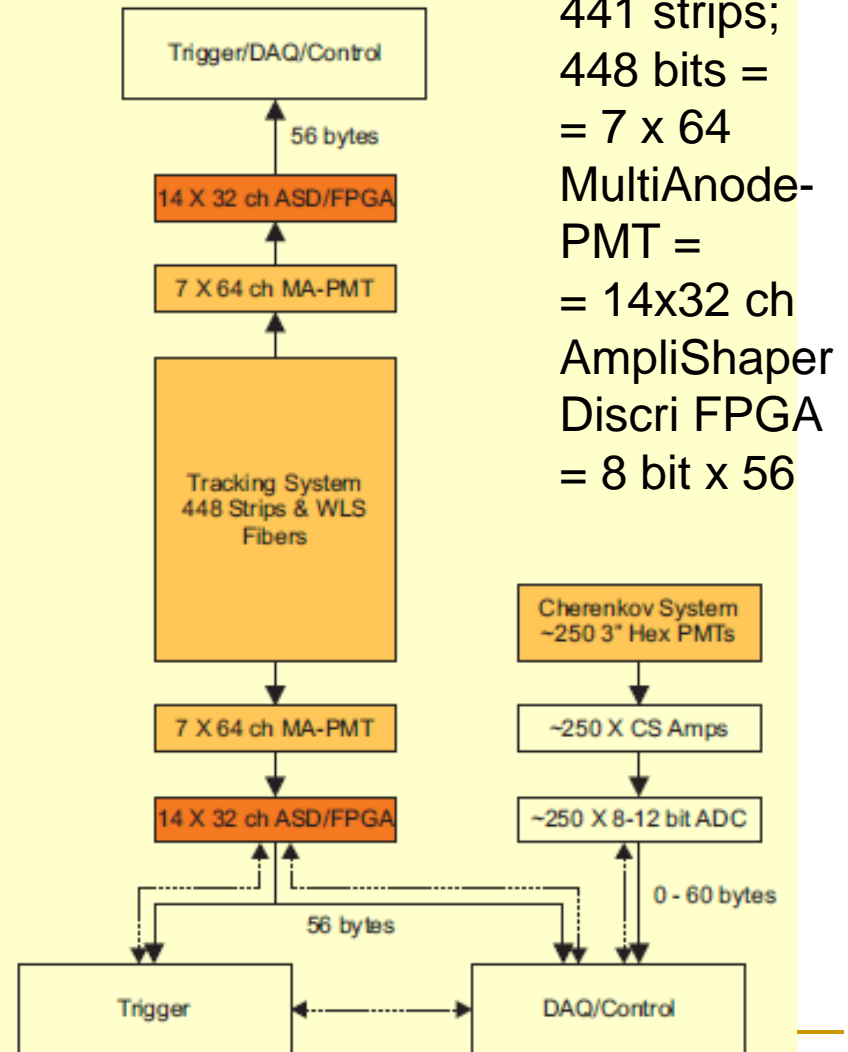
64-channel PMT (on baseboard) views
WLS fibers terminated in cookie

Installazione delle striscie



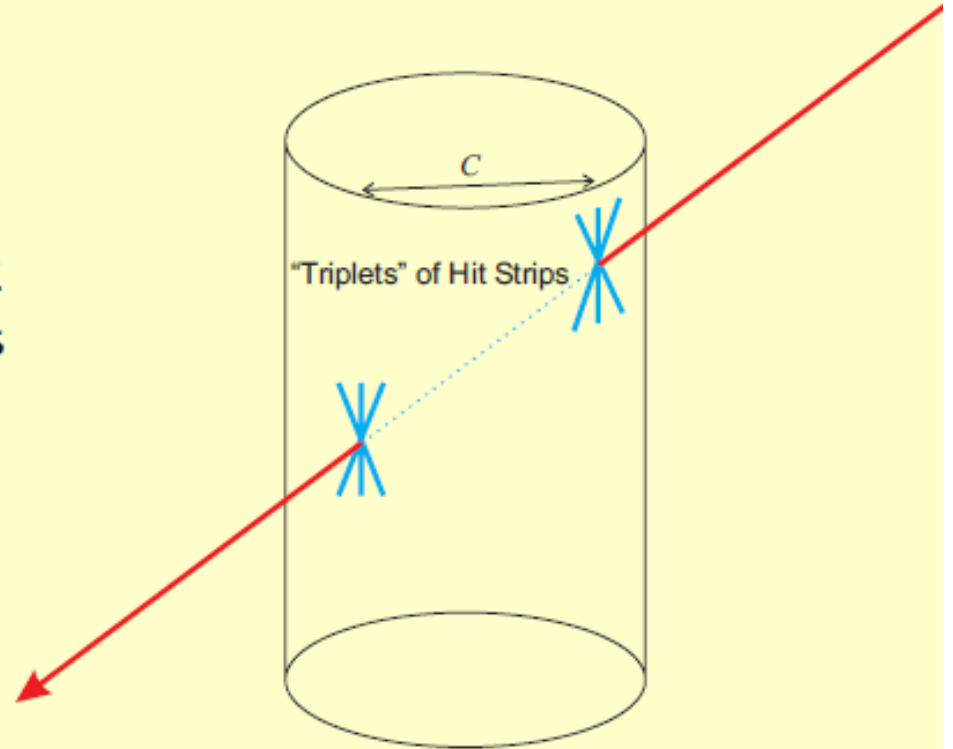
Elettronica (le fibre sono lette ai due estremi)

- Data from detector
 - Tracking: 2X448 “hit” bits
 - Cherenkov: Analog out
- Trigger
 - Based on tracking information only
 - Programmable logic
- DAQ
 - All tracking bits
 - Cherenkov hits *above* pedestal
- Control
 - Trigger/DAQ control
 - Monitor all detector systems

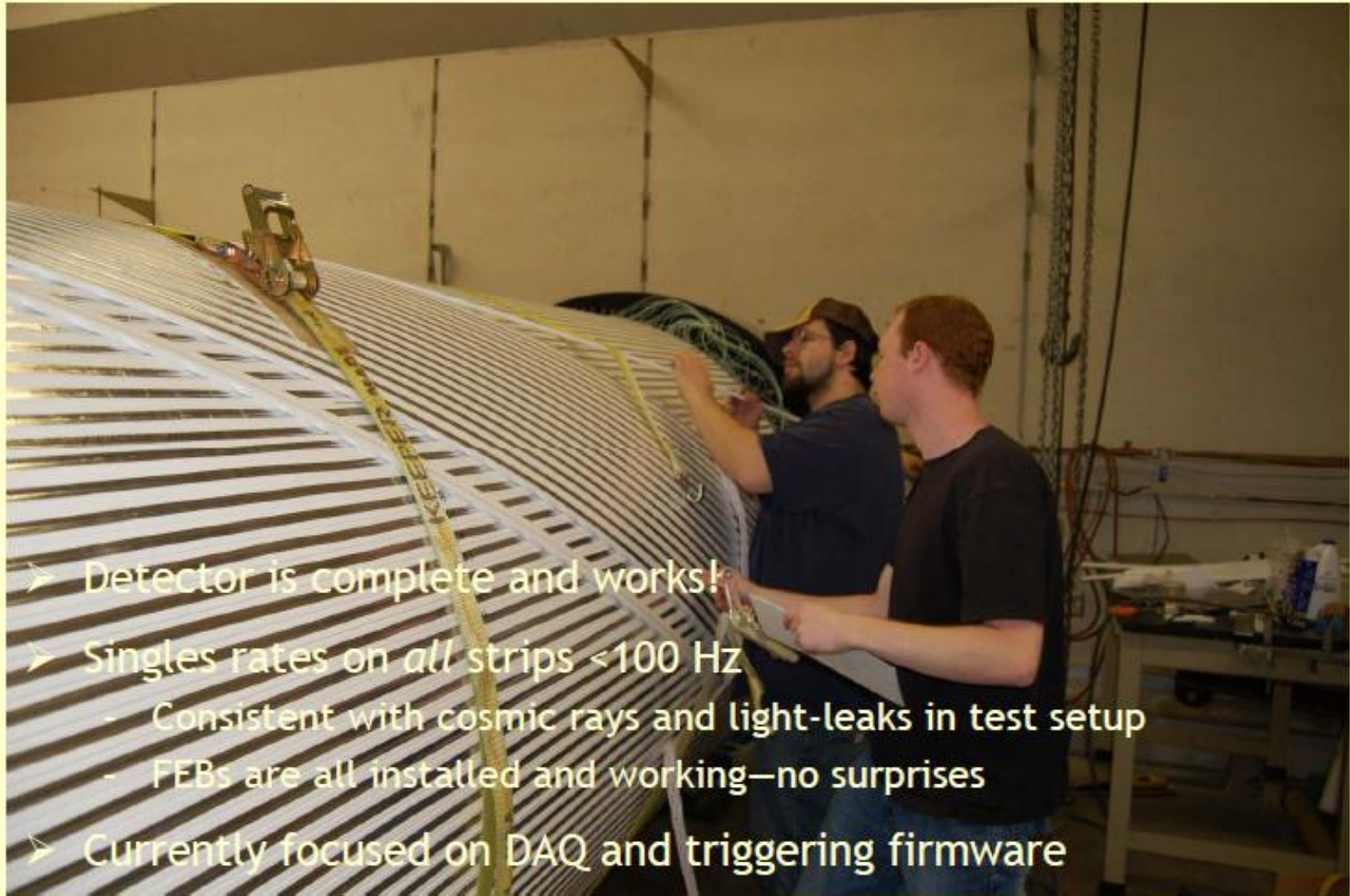


Trigger

- Use only tracking information
- Require:
 - ≥ 2 Hit “Triplets”
 - Chord $c > c_{\min}$
 - Direction ?
- Flexible definition of Triplet
 - Coincidence gate: 25–50 ns
 - Number/pattern of hits to balance:
 - Noise - singles rates
 - Inefficiencies
- Typical rates:
 - True events ~ 100 Hz
 - CR singles:
 - ~ 4 KHz full detector
 - ~ 25 Hz per strip

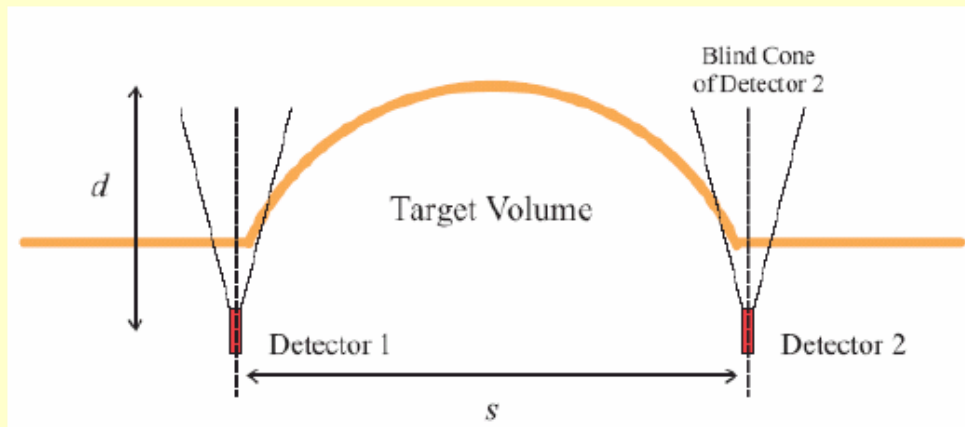
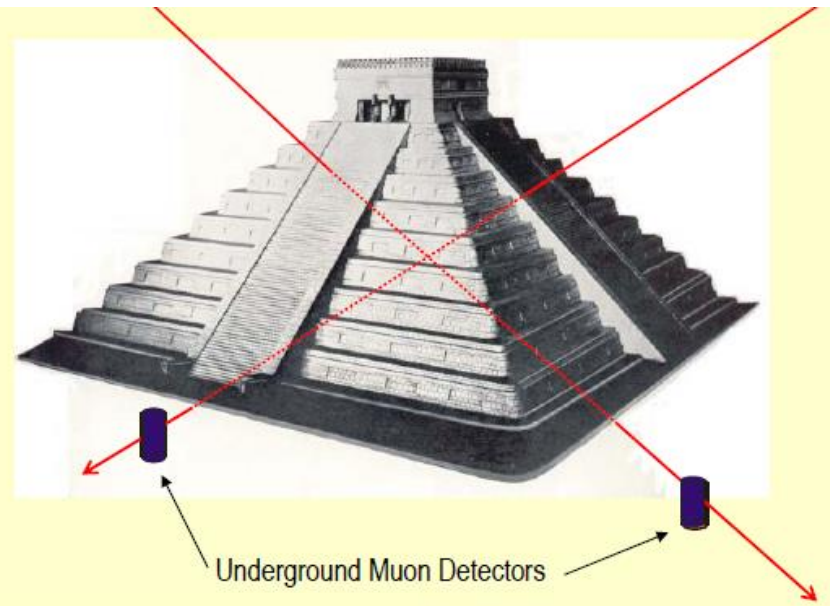


Un rivelatore completo



- Detector is complete and works!
- Singles rates on *all* strips < 100 Hz
 - Consistent with cosmic rays and light-leaks in test setup
 - FEBs are all installed and working—no surprises
- Currently focused on DAQ and triggering firmware

Rivelatori/ posizionamento



- Use 2 or more detectors
 - Compensates for “blind cone” inherent in cylindrical detectors
 - Improved stereo sampling of target volume
 - Symmetry of cylindrical detectors good for measuring “average” image
- Minimizes excavation

Interazioni dei μ nella piramide

- Energy loss: predominately by ionization

$$\frac{dE}{dx} \approx 2.3 \text{ MeV/gm/cm}^2 \approx 0.6 \text{ GeV/m in rock}$$

~ 25 GeV

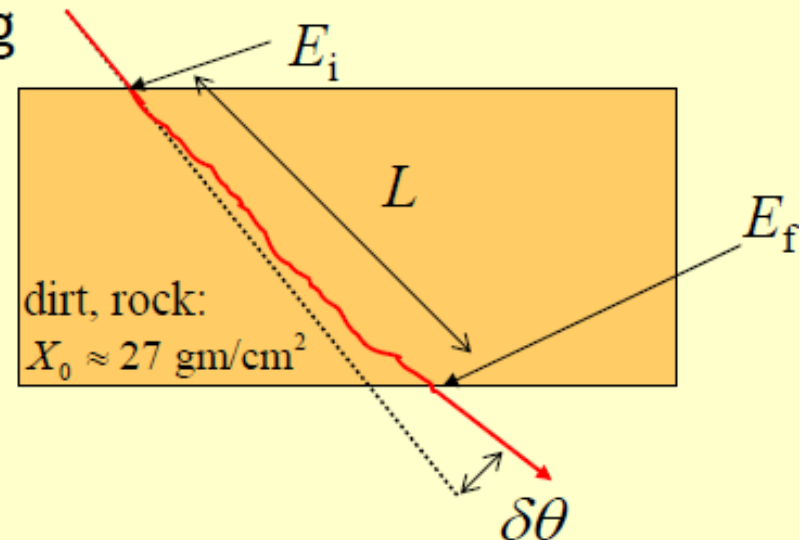
- Multiple-Coulomb Scattering

$$\delta\theta \approx \frac{13.6 \text{ MeV}}{\sqrt{E_i E_f}} \sqrt{\frac{L}{X_0}} \quad (*)$$

L è grande

$$E_i - E_f \approx L \frac{dE}{dx}$$

10 cm



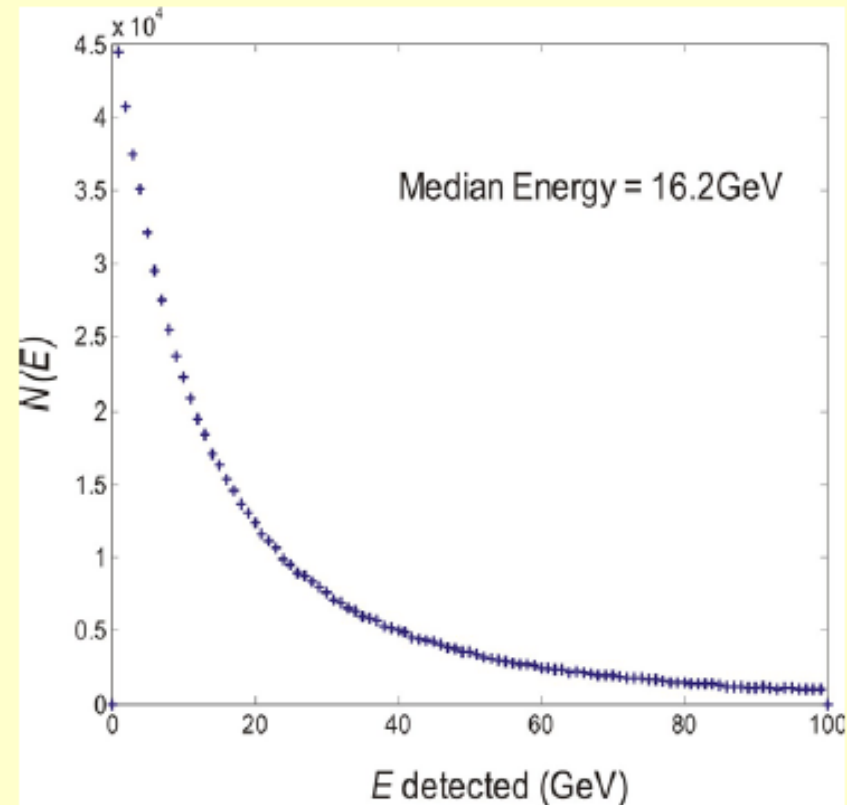
(*) parametrizzazione di Lynch e Dahl, 1991, trascurando un termine corret. fln apr-mag 2015

I μ nel rivelatore

- Typical detected energy spectrum shown:
- Coulomb scattering large for tracks near end of range; nearly *independent* of scattering material and initial muon energy

$$\delta\theta \approx \frac{0.055}{\sqrt{E_f(\text{GeV})}} \text{ for } E_f \ll E_i \quad (*)$$

- May need to “harden” the spectrum to reduce blurring (Alvarez used iron absorber)



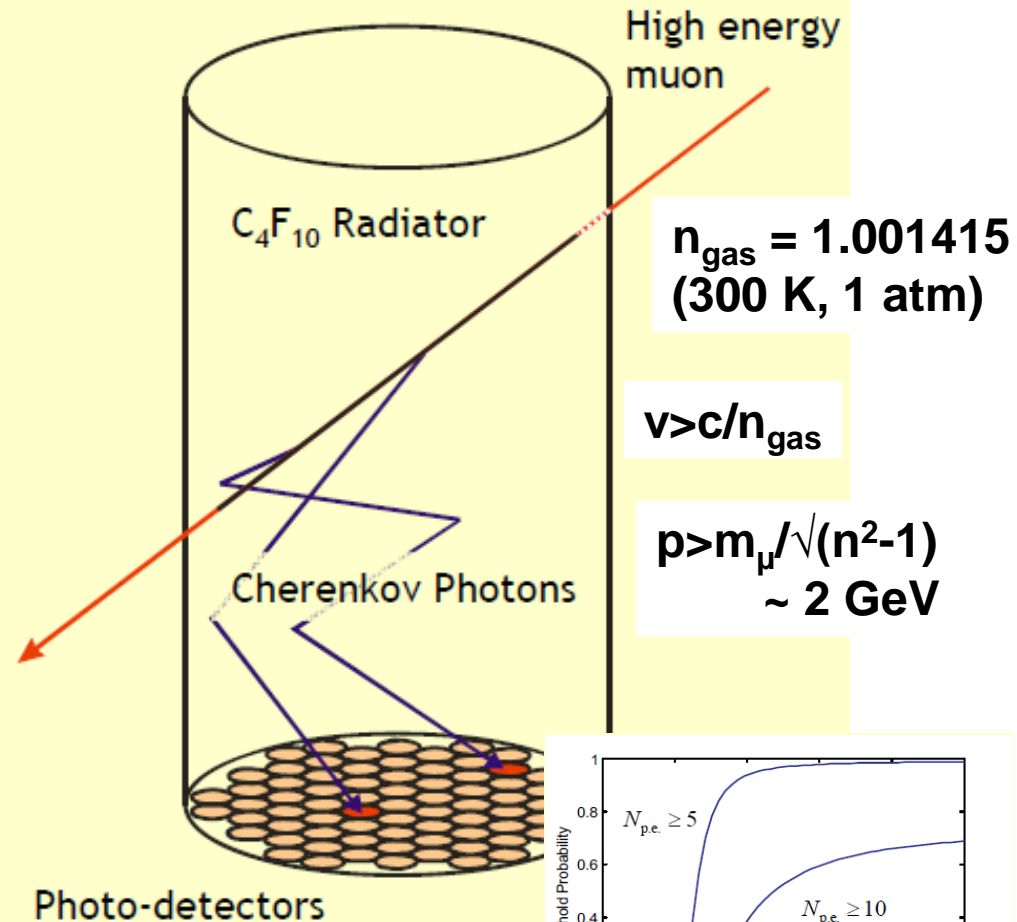
per $E_f \ll E_i$, $L = (E_i - E_f)/(dE/dx)$, sostituendo i parametri per la roccia si ha (*)

Conteggi, tempi di esposizione

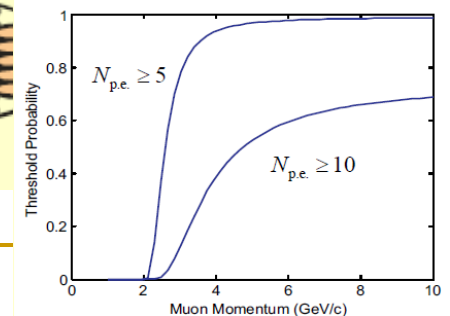
- Caso estremo
 - 1 m³ vuoto a 50 m dal rivelatore
 - $\Delta\Omega = (1/50)^2$
 - Area attiva 3 m²
 - 100 eventi/giorno per bin di $\Delta\Omega$ e per rivelatore
 - scan a 1σ richiede 10 gg (contrasto $\sim 1.5 \times 1/50$) – 1000 ev, 3% di errore
 - scan a 3σ richiede 3 mesi - 9000 ev, $\sim 1\%$
- con un secondo rivelatore le stime migliorano più di un fattore 2: il vuoto può essere più vicino

Discriminazione dei μ di bassa E (hardware \rightarrow software): il Cherenkov (a soglia)

- Fill central cylindrical volume of detector with Cherenkov radiator gas: C_4F_{10}
 - Muon threshold ~ 2 GeV
 - $\beta = 1$ p.e. yield: ~ 35 /meter of radiator
 - C_4F_{10} is a freon used for fire suppression
- Make inner surface of cylinder optically reflecting
- Place array of photon detectors on *bottom* of cylinder

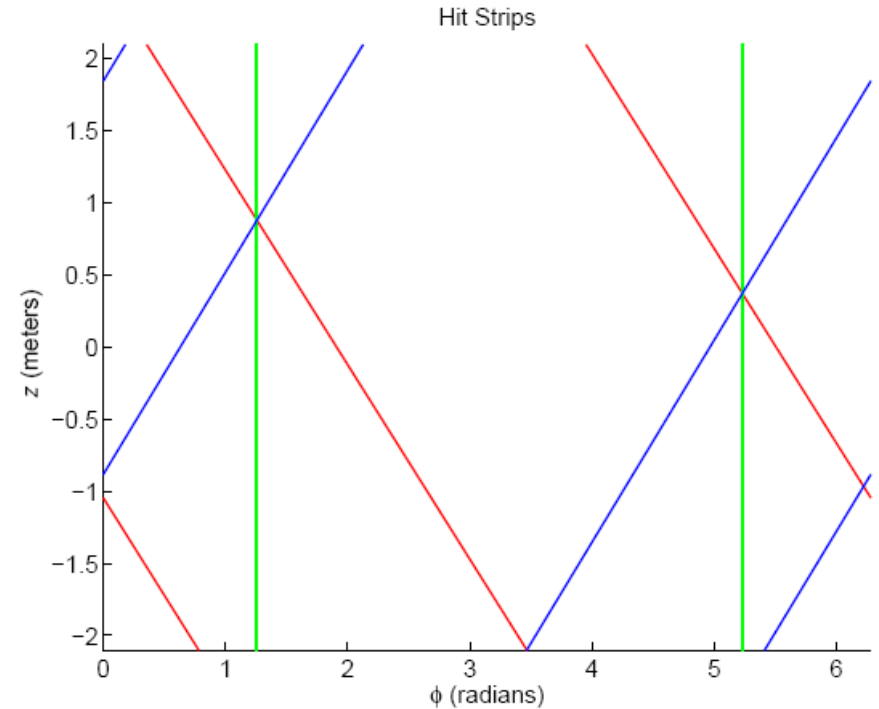
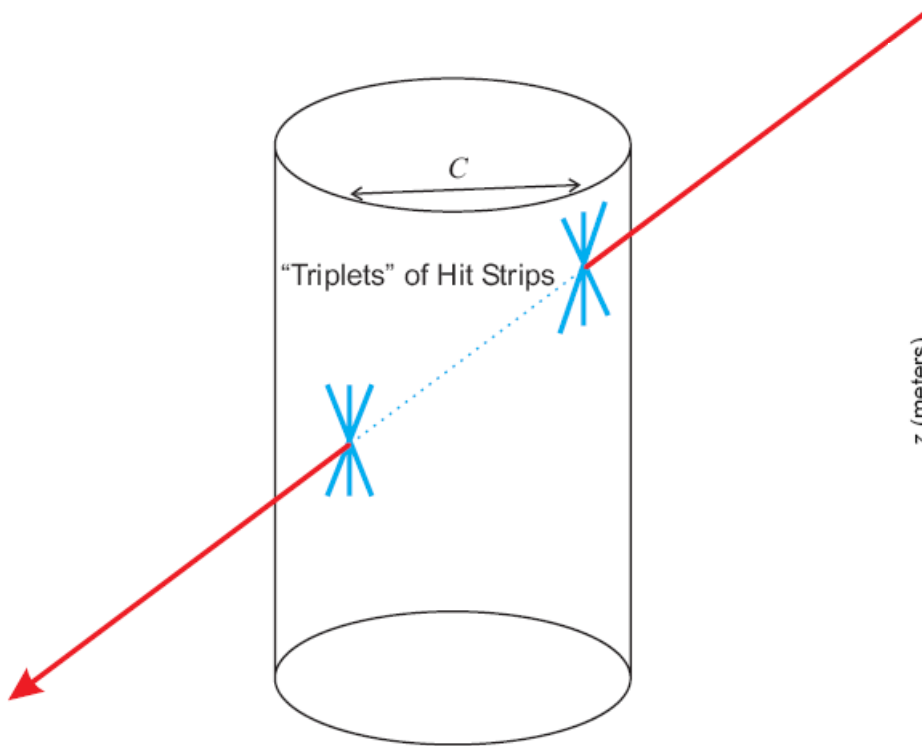


- la soglia può essere richiesta e/o variata durante l'analisi



Ricostruzione

- i colori diversi indicano gli strati di strisce di scintillatore
- i tempi non sono ancora usati



The offline software is capable of rejecting spurious events with relative ease. The software constructs look-up tables for strip addresses from the three layers that overlap and ranks the quality of the overlap by a χ^2 parameter. A track is thus formed by connecting the coordinates of the entry and exit triplets with the lowest χ^2 parameter.

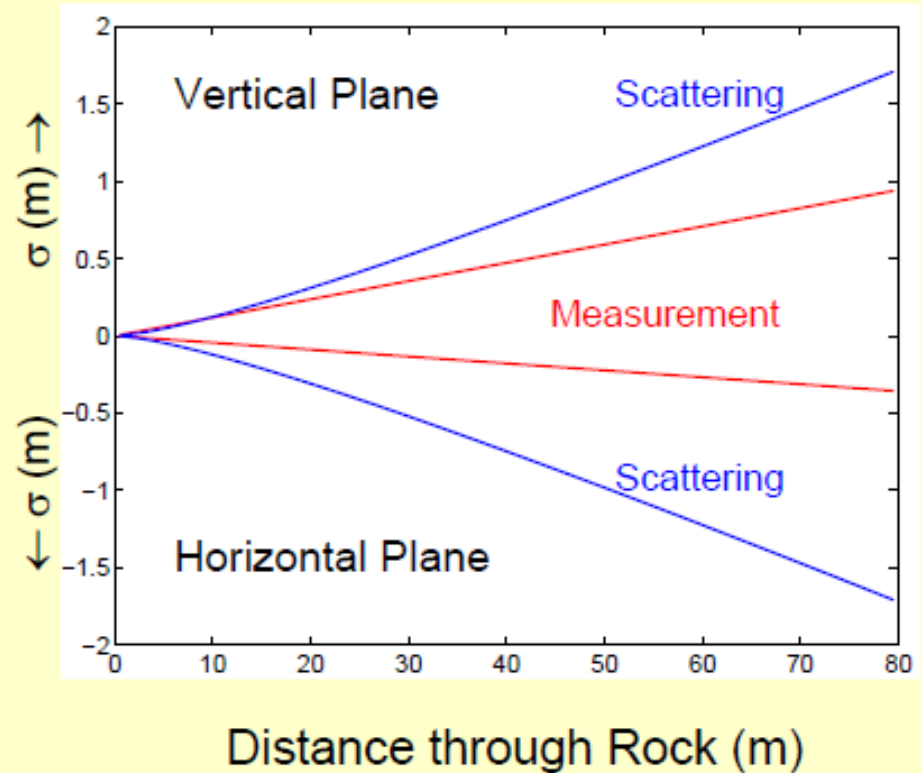
Risoluzione

$$\begin{aligned} \langle \sigma_{\varphi} \rangle &= 5.0 \text{ mrad} \\ \langle \sigma_{\cot\theta} \rangle &= 0.013 \\ \langle \sigma_z \rangle &= 8.9 \text{ mm} \end{aligned}$$

↔ 3.8 mm

$\Theta = 60^\circ$

- Measurement errors
 - Determined by strip width and stereo angle
 - $\sigma < 1\text{m}$ in both planes
- Multiple-scattering
 - Will dominate tracking errors for $R > 40\text{ m}$
 - Higher Cherenkov threshold can mitigate
 - GEANT simulations in progress



Analisi dati

- Discrete detector tracking elements lead to artifacts in reconstructed images
 - 55,360 allowed triplets $\Rightarrow \sim 10^9$ unique reconstructed tracks
 - Not a problem for change-detection
 - A big problem for viewing static images
 - Will be solved by computing appropriate track weights
- 3D reconstruction?
 - Stereo permits a “focus” that can resolve range
 - Multiple detectors planned to better survey volumes of interest
 - They can use help in developing 3D codes!

Cylindrical Projection
Top DAQ

cylproject3d_yx

Entries 1.688191e+07

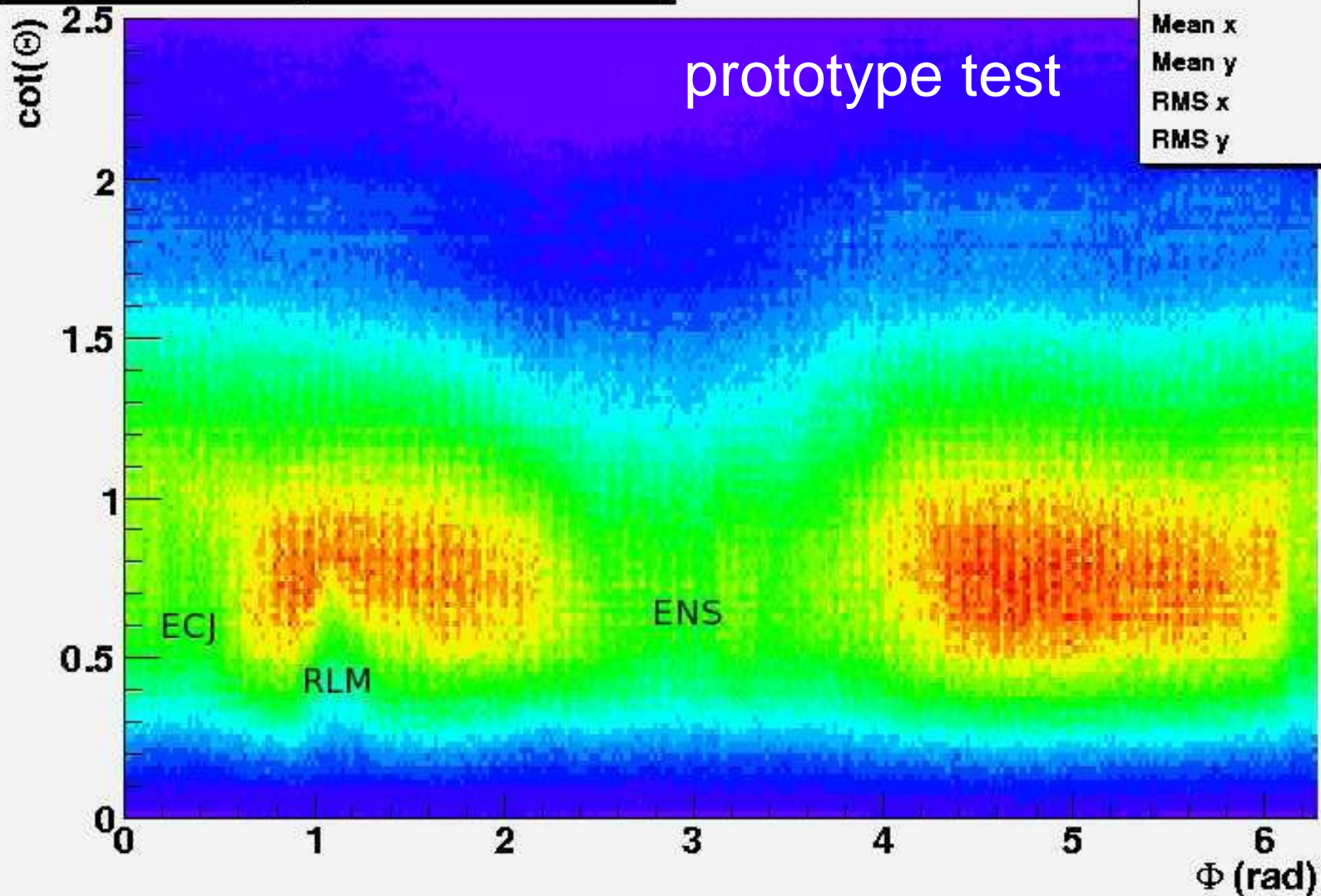
Mean x 3.22

Mean y 0.9728

RMS x 1.866

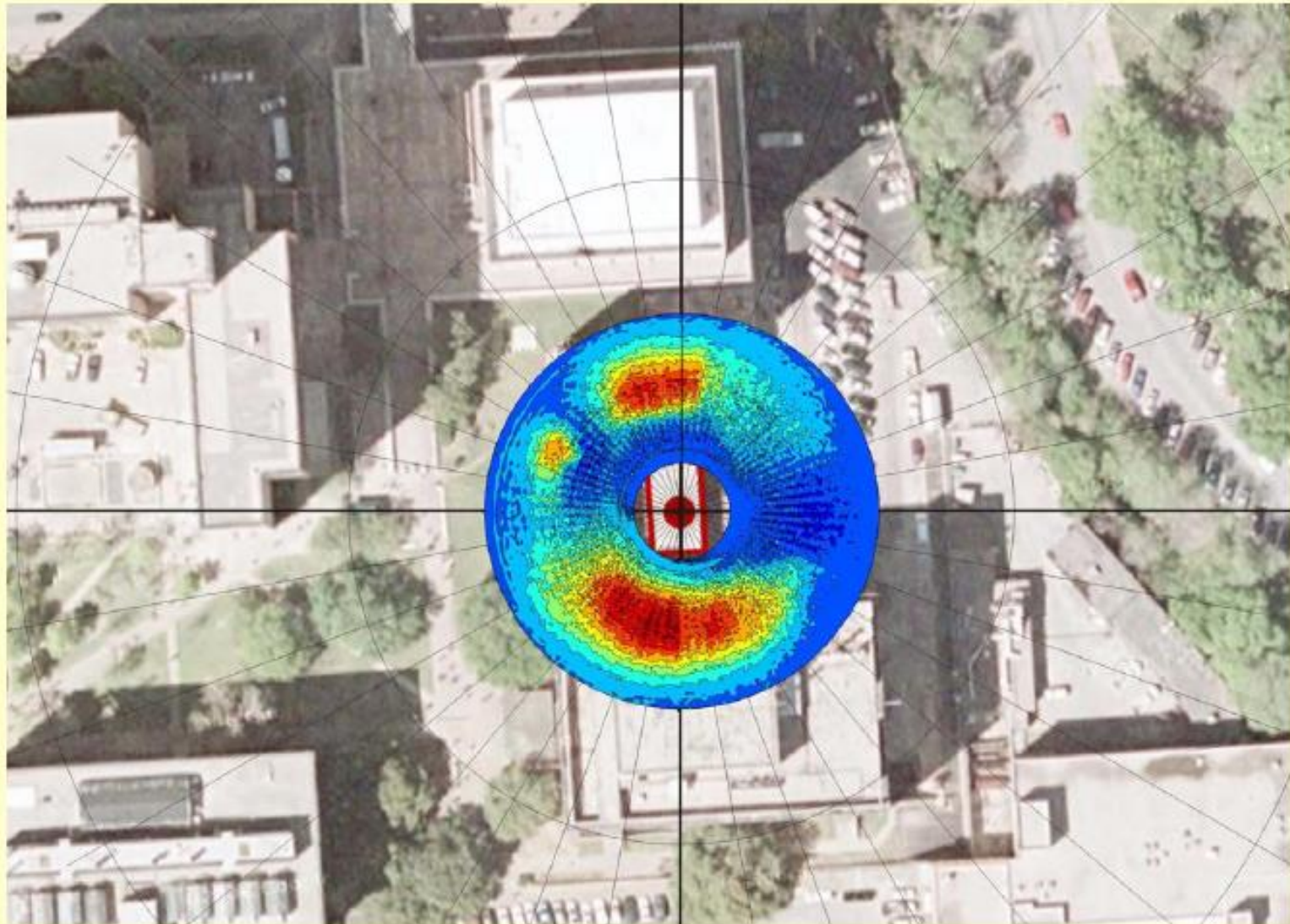
RMS y 0.4946

prototype test



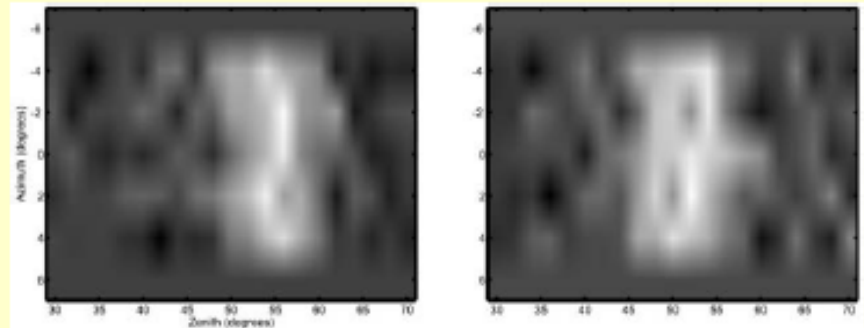
ECJ, RLM, ENS – edifici del campus nelle vicinanze del rivelatore/prototipo

Net Muon "Deficit" in θ versus ϕ

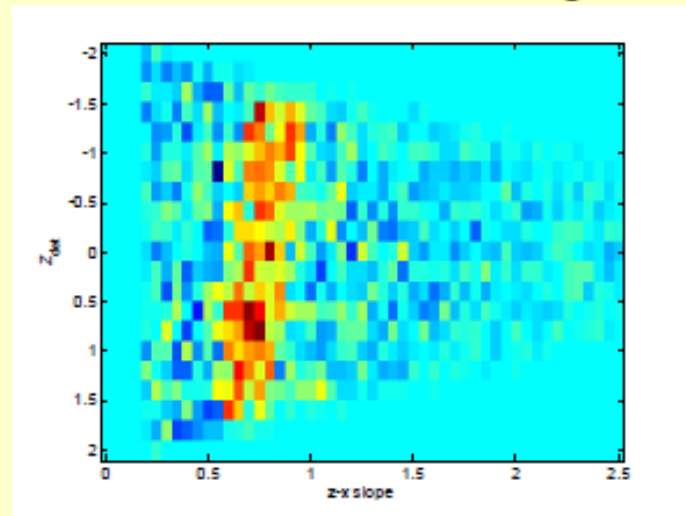


Imaging

- Have begun studies of imaging with a single detector
 - Stereo pairs of spherical projections
 - Radon transformations
- Collaboration expected with UT CS experts
- Extensive sets of tools available:
 - MATLAB
 - LabVIEW



Simulated tunnel 20m distant
in one week of running



Conclusioni sui Maya

- Muon tomography is feasible
 - Proven in Alvarez experiment
 - New technologies enable simplified detector design
 - WLS/scintillator tracking well-developed/good match
 - Cherenkov threshold detector is indicated
 - New approach to problem of low-energy multiple-scattering
 - Well-understood physics/technology
 - Simplifies system design
- Excellent project for engaging students
- Other applications are possible
- Maybe they can help to learn more about the Maya!

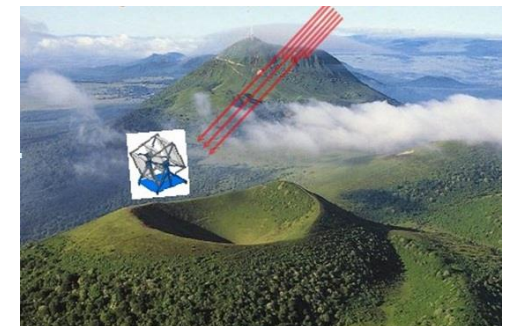
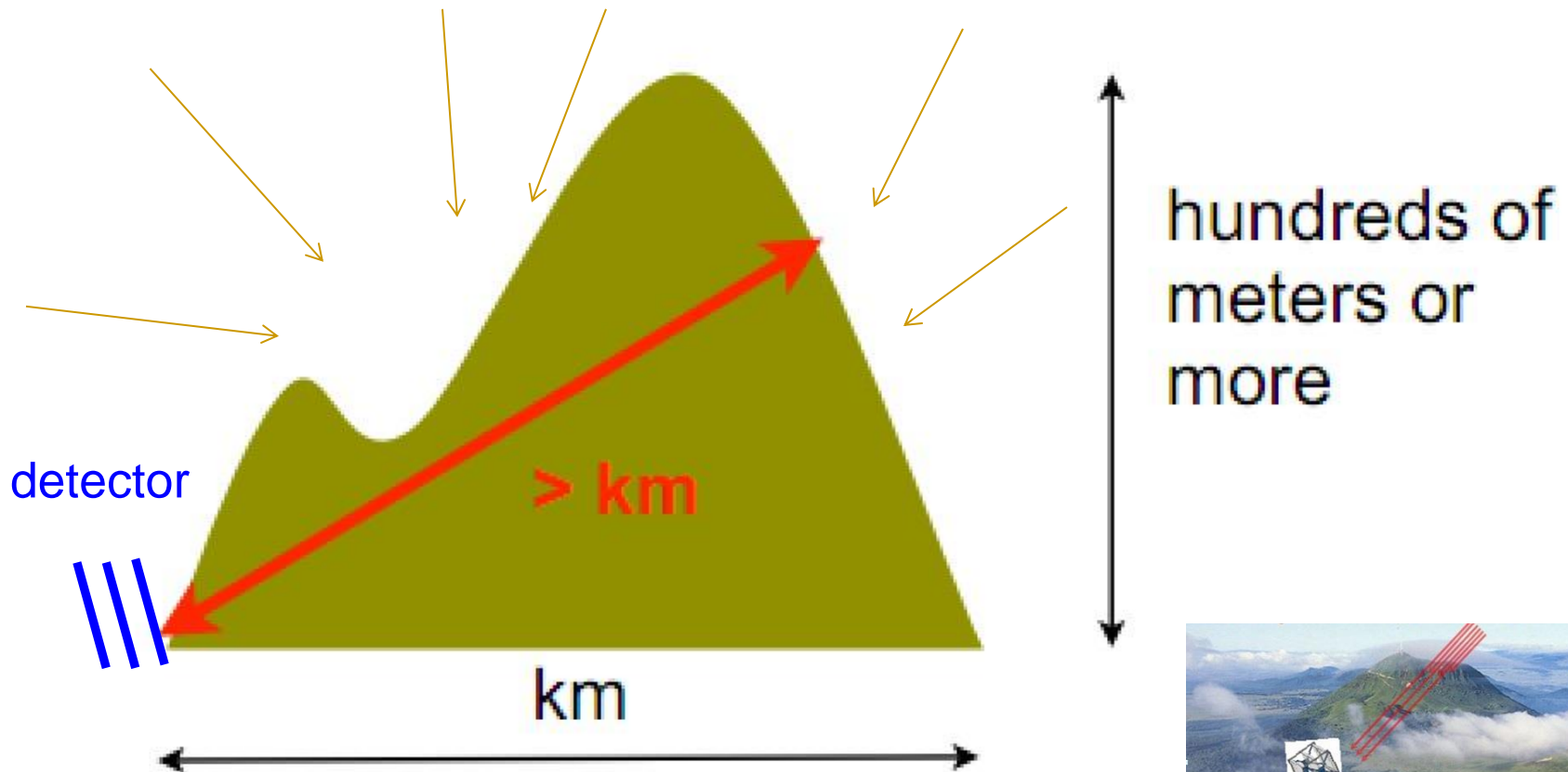
"If you see a spot with more muons, it means there's a space there."

— ROY SCHWITTERS,
UNIVERSITY OF TEXAS
AT AUSTIN

Altre applicazioni della misura di assorbimento dei μ

- Muon Tomography is good for monitoring large underground volumes ($\sim 100 \text{ m}^3$), provided:
 - You are interested in structures of scale 1 m – 10 m
 - You can afford to wait for weeks to months to acquire the data
 - The volume of interest is between your detector and the sky
- Geological studies of aquifers
- Monitoring of geology surrounding underground sites: e.g. underground nuclear waste storage, mining site
- Bank vaults?!

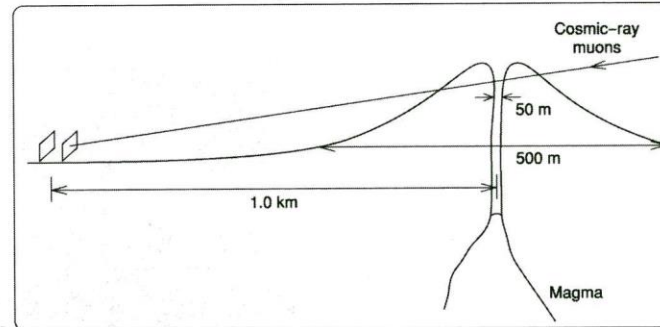
Uso dell'assorbimento dei μ per lo studio di strutture geofisiche



μ cosmici e strutture a scala geofisica

- Muoni quasi orizzontali: spettro di E più duro di quello verticale (montagne \rightarrow rivelatori \sim verticali)
- Rate a cielo aperto: $\sim 10 \mu/(\text{m}^2 \text{ sr s})$ a 70° , $\sim 10^{-1}$ a 90°
- Rate decresce vs spessore attraversato, $E > E_c$: per 500 m di roccia, $E_c > 0.42 \text{ TeV}$, il flusso è $3 \cdot 10^{-2} \mu/(\text{m}^2 \text{ sr s})$ per $\theta > 70^\circ$
- Si misura il rate cfr con cielo aperto
- Tempi di misura tipici: $80 \text{ k}\mu/(\text{m}^2 \text{ sr})$ in un mese ($E_c > 0.42 \text{ TeV}$)

Obiettivi delle misure su vulcani



- Immagini statiche, o su tempi lunghi per verificare gli effetti di eruzioni
- Monitoraggio di possibili cambiamenti a tempi più brevi eg risalita del magma

Prime radiografie di vulcani

Method of probing inner-structure of geophysical substance with the horizontal cosmic-ray muons and possible application to volcanic eruption prediction

K. Nagamine ^{a,b,*}, M. Iwasaki ^a, K. Shimomura ^a, K. Ishida ^b

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^b Muon Science Laboratory, The Institute of Physical and Chemical Research (RIKEN), Wako, Saitama, Japan

Received 4 July 1994; revised form received 12 September 1994

Abstract

One potential use of cosmic-ray muons arriving nearly horizontally along the earth is a probe of the inner-structure of a gigantic geophysical substance, such as a volcanic mountain. A simple detection system comprising a plastic scintillator **nodoscope** which is expandable to a larger scale was developed. The first successful measurement of the inner-structure of Mt. Tsukuba is described. The future perspective of the application of the present method towards the prediction of volcanic eruption is discussed.

NIM A356 (1995) 585

Mt. Tsukuba, 877m



High resolution imaging in the inhomogeneous crust with cosmic-ray muon radiography: The density structure below the volcanic crater floor of Mt. Asama, Japan

Hiroyuki K.M. Tanaka ^{a,b,c,*}, Toshiyuki Nakano ^d, Satoru Takahashi ^d, Jyunya Yoshida ^d, Minoru Takeo ^a, Jun Oikawa ^a, Takao Ohminato ^a, Yosuke Aoki ^a, Etsuro Koyama ^a, Hiroshi Tsuji ^a, Kimio Niwa ^d

^a Earthquake Research Institute (ERI), University of Tokyo, 1-1-1 Yayoi, Bunkyo, Tokyo 113-0032, Japan

^b Atomic Physics Laboratory, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

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^d Physics Department, Nagoya University, Furo-cho, Chikusa, Nagoya, Aichi 464-8602, Japan

risultati pubblicati in:

**Earth and Planetary
Science Letters**

263 (2007) 104-113

Una storia di eruzioni

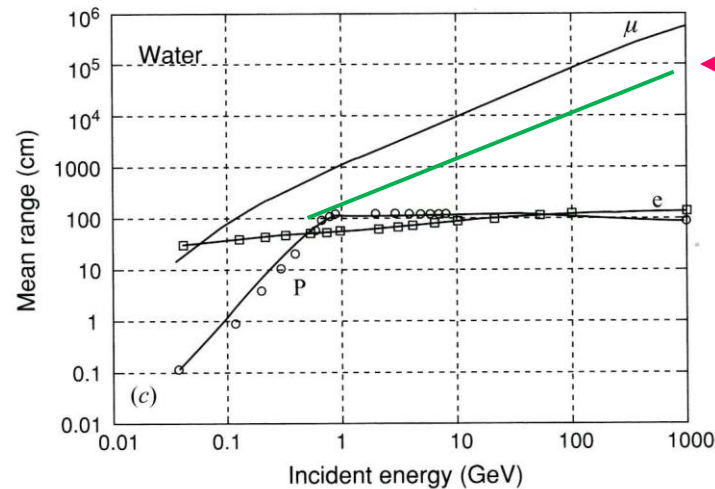
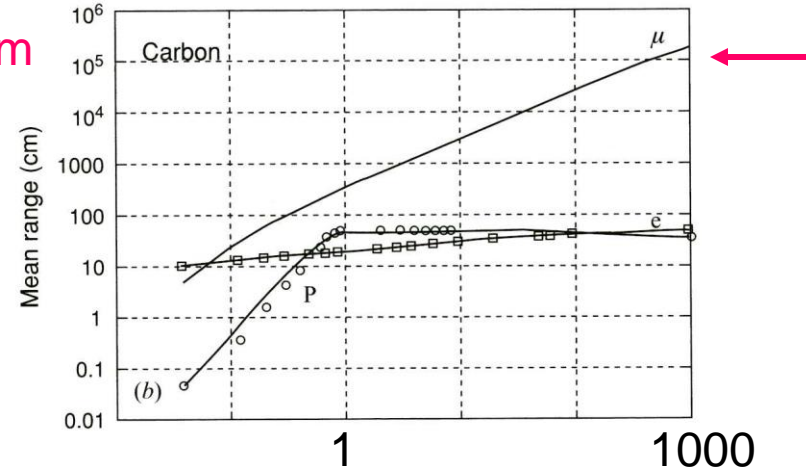
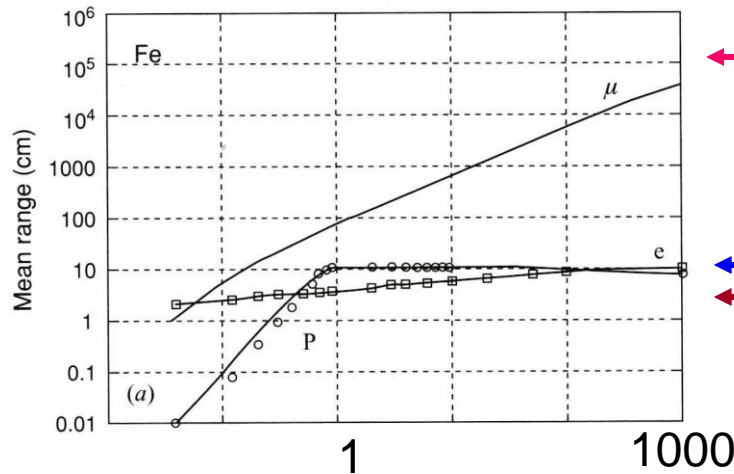
- The eruptions of Mount Asama (2568 m, 145 km north-west of Tokyo) mark the span of Japan's recorded history, including: **2009 (2 Feb.)**, **2008**, **2004**, 2003, **1995**, 1990, **1983**, **1982**, 1973, 1965, 1961, 1958-59, 1953-55, 1952, 1952, 1950-51, 1949, 1947, 1946, 1944-45, 1938, 1937, 1935, 1934, 1934, 1933, 1931-32, 1930, 1929, 1929, 1928, 1927, 1926, 1925, 1924, 1924, 1923, 1922, 1921, 1919, 1918?, 1917, 1916, 1915, 1914, 1913, 1912, 1911, 1910, 1907, 1907, 1906, 1905?, 1904, 1903, 1902, 1901, 1899, 1894, 1893, 1892, 1891, 1890, 1889, 1879, 1878, 1877, 1876, 1875, 1874, 1873, 1872, 1871, 1870, 1869, 1868, 1867, 1866, 1865, 1864, 1863, 1862, 1861, 1860, 1859, 1858, 1857, 1856, 1855, 1855, 1854, 1853, 1852, 1851, 1650?, 1649, 1648, 1648, 1647, 1645, 1644, 1609, 1605, 1604, 1600, 1598, 1597, 1596, 1596, 1595?, 1591, 1590, 1532, 1528, 1527, 1518, 1427?, 1281, **1108**, 887, 685



Penetrazione dei muoni attraverso grossi spessori

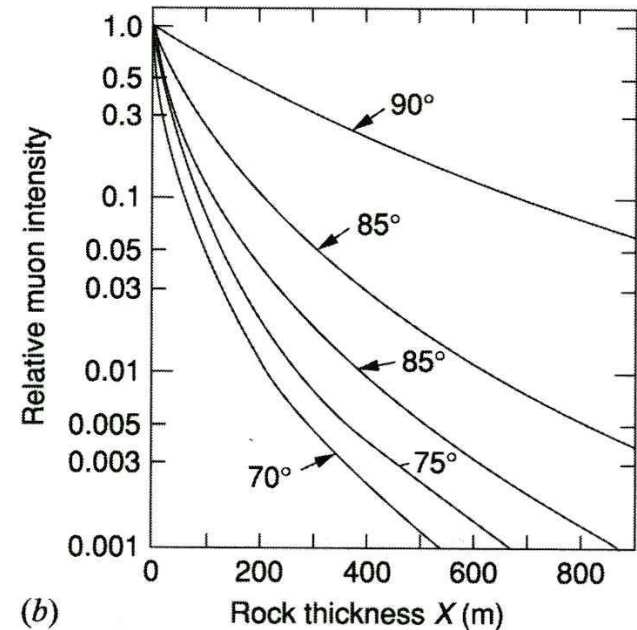
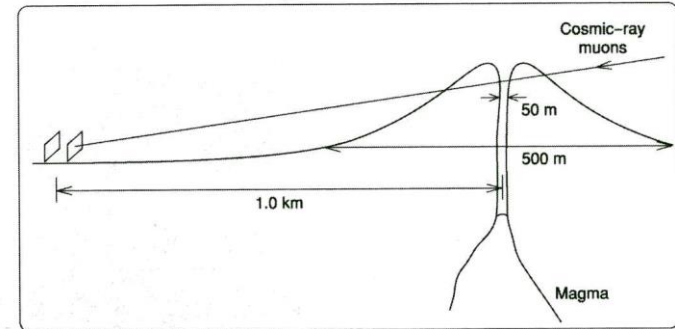
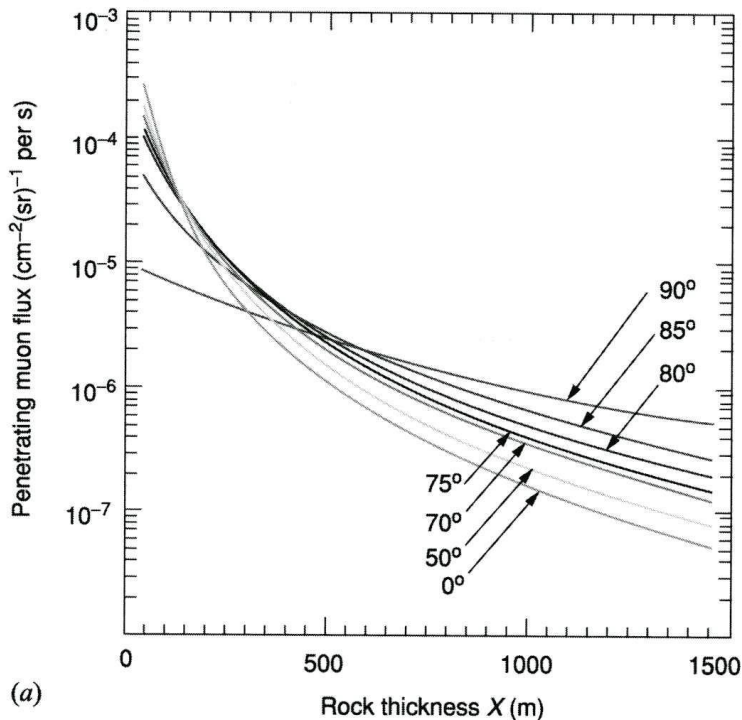
- Condizioni necessarie per usare mu quasi-orizzontali come sonda
 - dipendenza angolare e dall'energia
 - range nella roccia ($\rho = 2.5-2.65 \text{ g/cm}^3$)
 $dE/dX = [1.888 + 0.077 \ln(E/m) + 3.9E] \times 10^{-6} \text{ TeVcm}^2/\text{g}$
($E = 1 \text{ TeV}$) $X = 2.5 \times 10^3 [\ln(1.56E(\text{TeV})) + 1] \text{ hg/cm}^2$
 - intensità attraverso una roccia di spessore $X \rightarrow$ relazione unica fra X e intensità dei mu penetranti $N_\mu(E_c(X), \theta)$; noto X si trova E_c e $N_\mu(E_c, \theta)$; viceversa la misura di $N_\mu(\theta)$ determina unicamente X

Range medio di μ in vari materiali



spessore di materiale
che attenua il 50%
delle particelle incidenti
p ed e sciamano, in Fe
 $\lambda \sim 10$ cm, $X_0 \sim 2$ cm

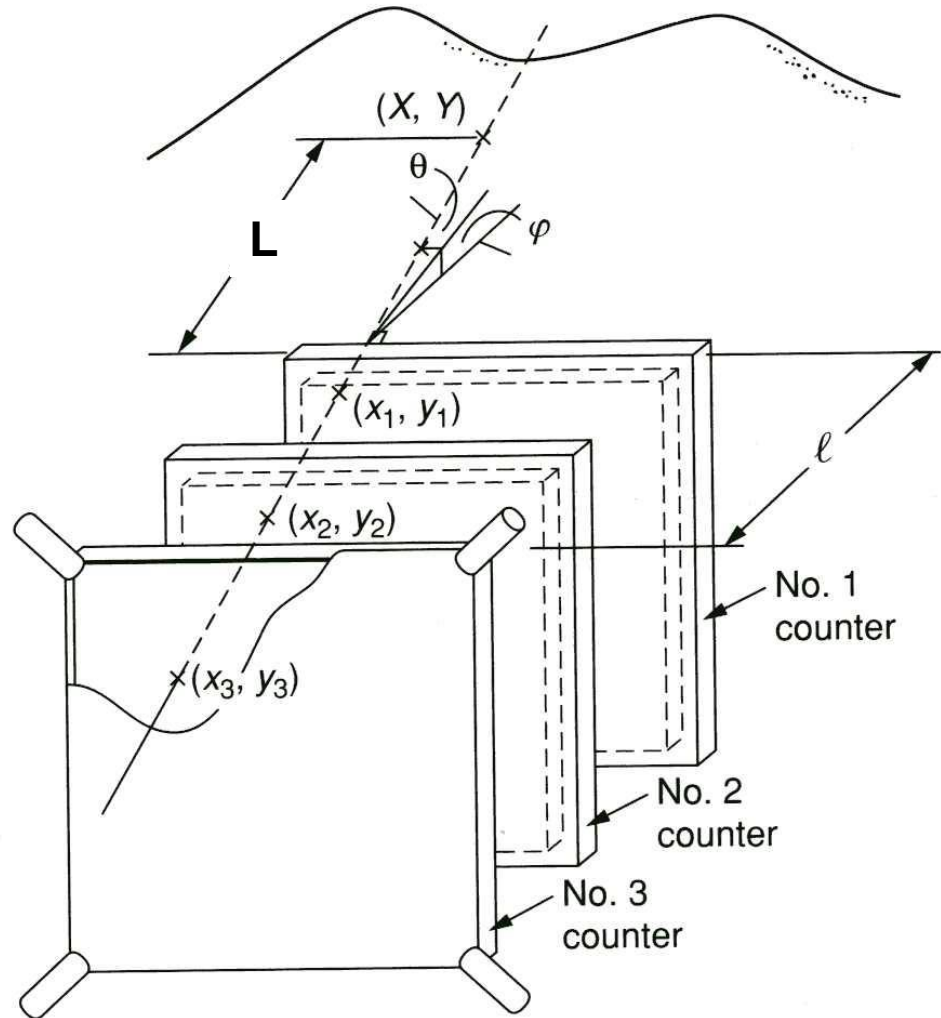
Flusso integrato dei cosmici vs θ



- es: montagna circolare di diametro 500 m, cavità di 50 m (variazione di 10% in X), $\theta = 90^\circ$, E_c passa da 0.416 a 0.364 TeV e N_μ passa da 1.61×10^{-6} a 1.87×10^{-6} ($\text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1}$) ossia cambia del 16%

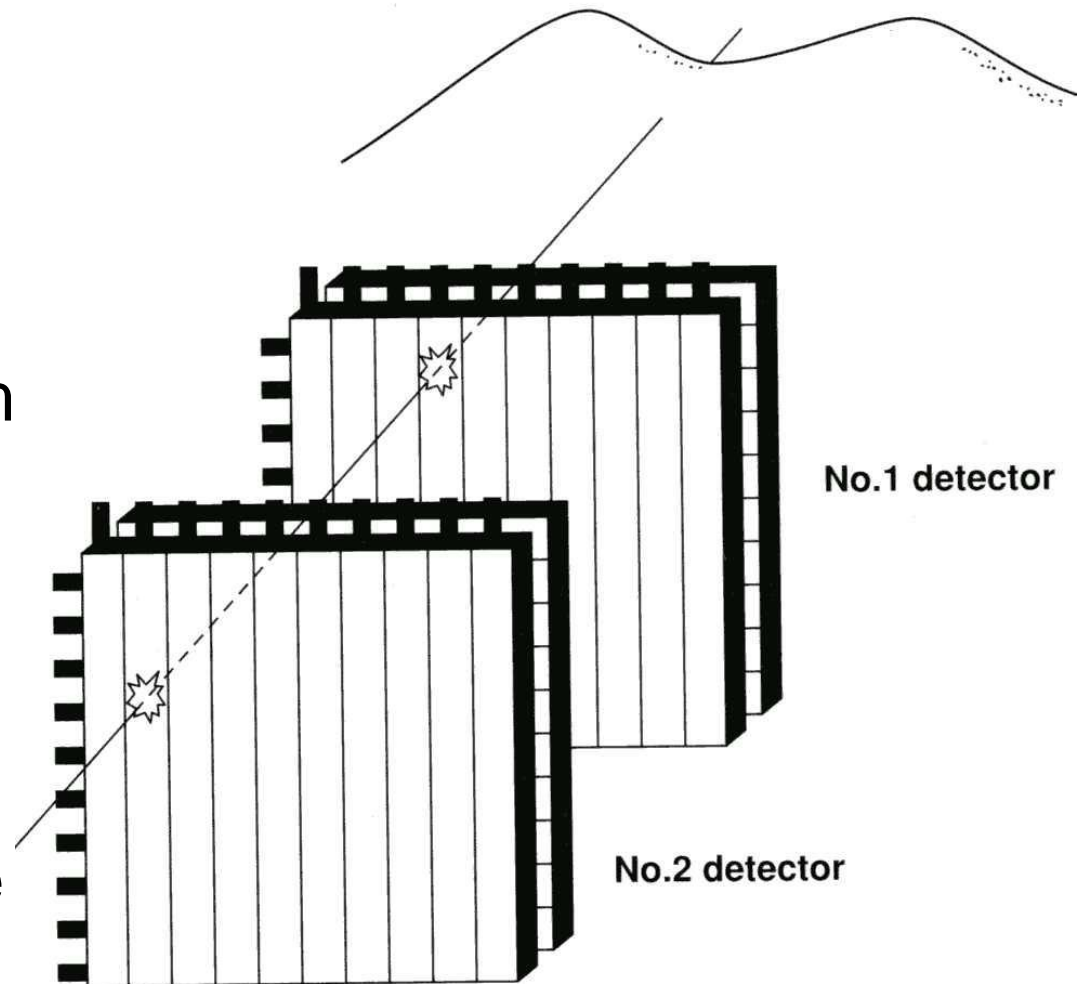
Mt. Tsukuba

- scintillatori plastici
~1m²
- punto d'impatto
determinato dalle
differenze del
tempo di arrivo
della luce nei PM,
 $\Delta x = \Delta y = 2.5$ cm
- $\Delta X = (L/l)\Delta x = 33$ m
 $\Delta Y = (L/l)\Delta y$
- $l = 1.5$ m $\rightarrow \Delta t =$
10 ns \rightarrow F/B
- $\Delta\theta = 33$ mrad



Mt. Asama

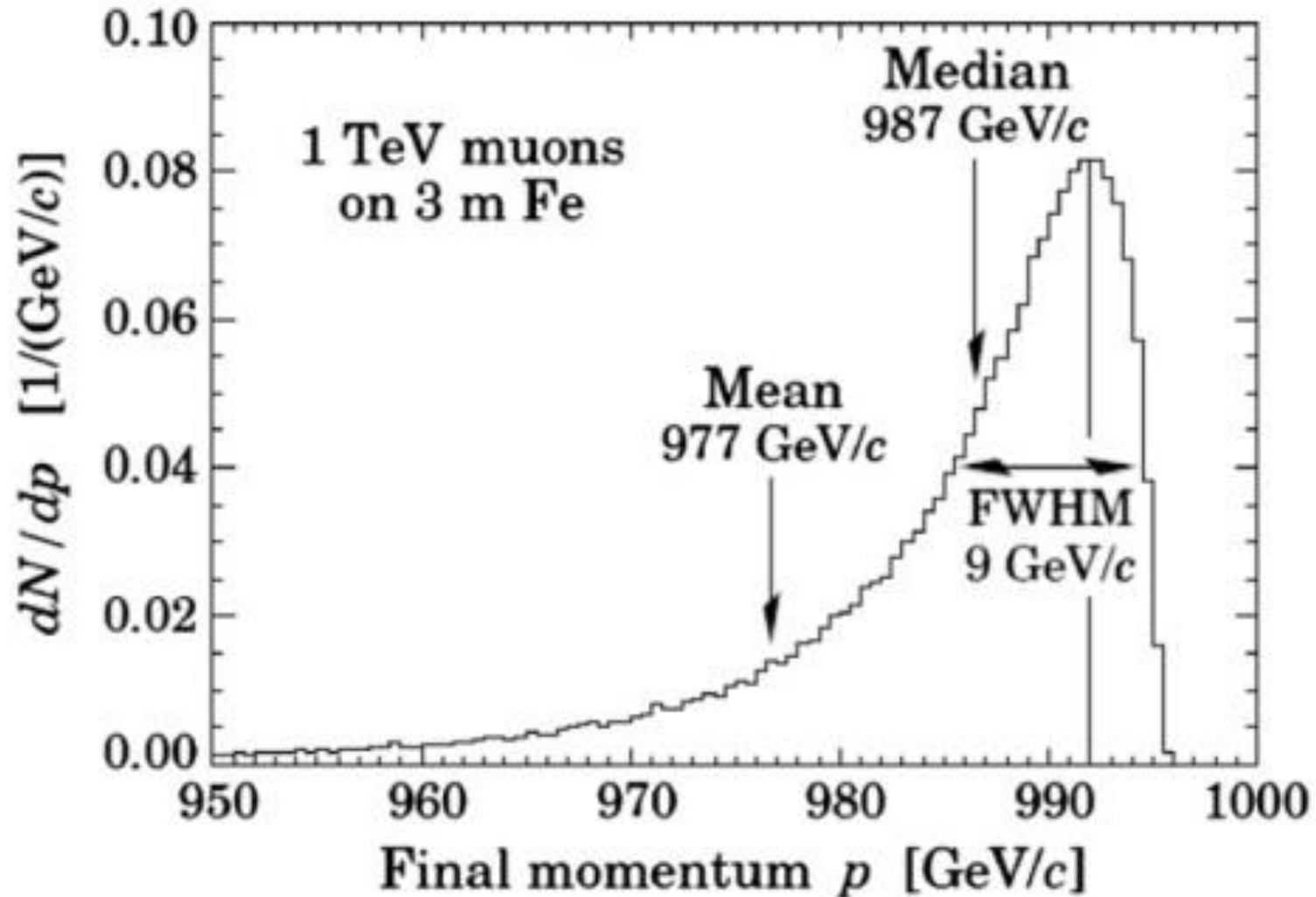
- scintillatori plastici segmentati ($10 \times 100 \times 3 \text{ cm}^3$), $L = 2.75 \text{ km}$, $l = 2 \text{ m}$
- $\Delta\theta = 66 \text{ mrad}$
- piani di scintillatori intervallati da piastre di Fe per eliminare la componente soffice dei RC



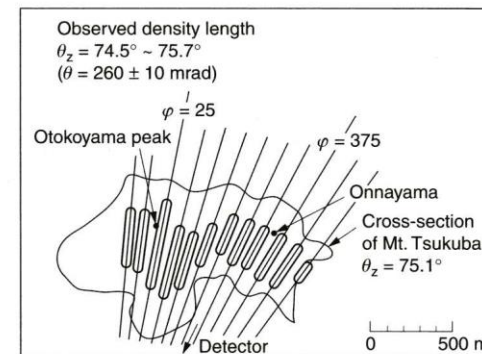
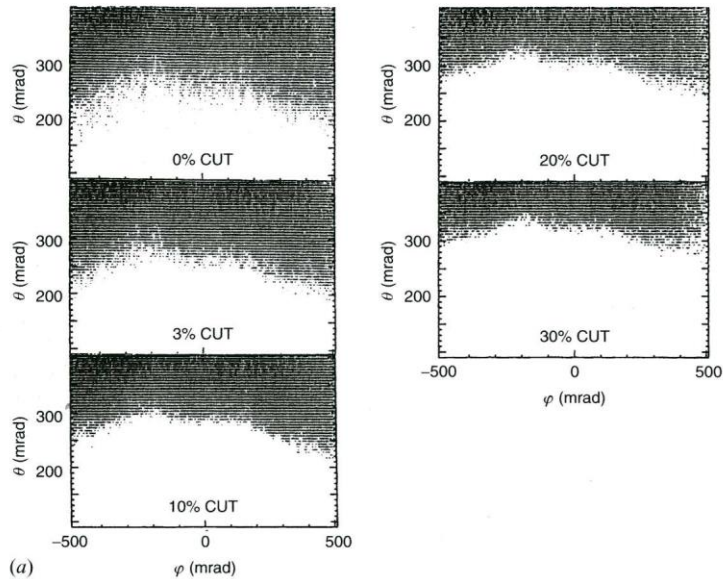
Multiple scattering e range straggling

- m.s.: calcoli di MC usando la teoria di Molière danno per $\theta > 70^\circ$ una dispersione angolare sotto i 5 mrad (= 5 m/1 km) per una montagna spessa 500 m
- straggling: è importante per mu di alta E per via del bremsstrahlung, tenendo conto dello spettro di E, l'incertezza sullo spessore attraversato può essere mantenuta sotto l'1% per un attraversamento di 500 m

Simulazione di μ ad alta energia



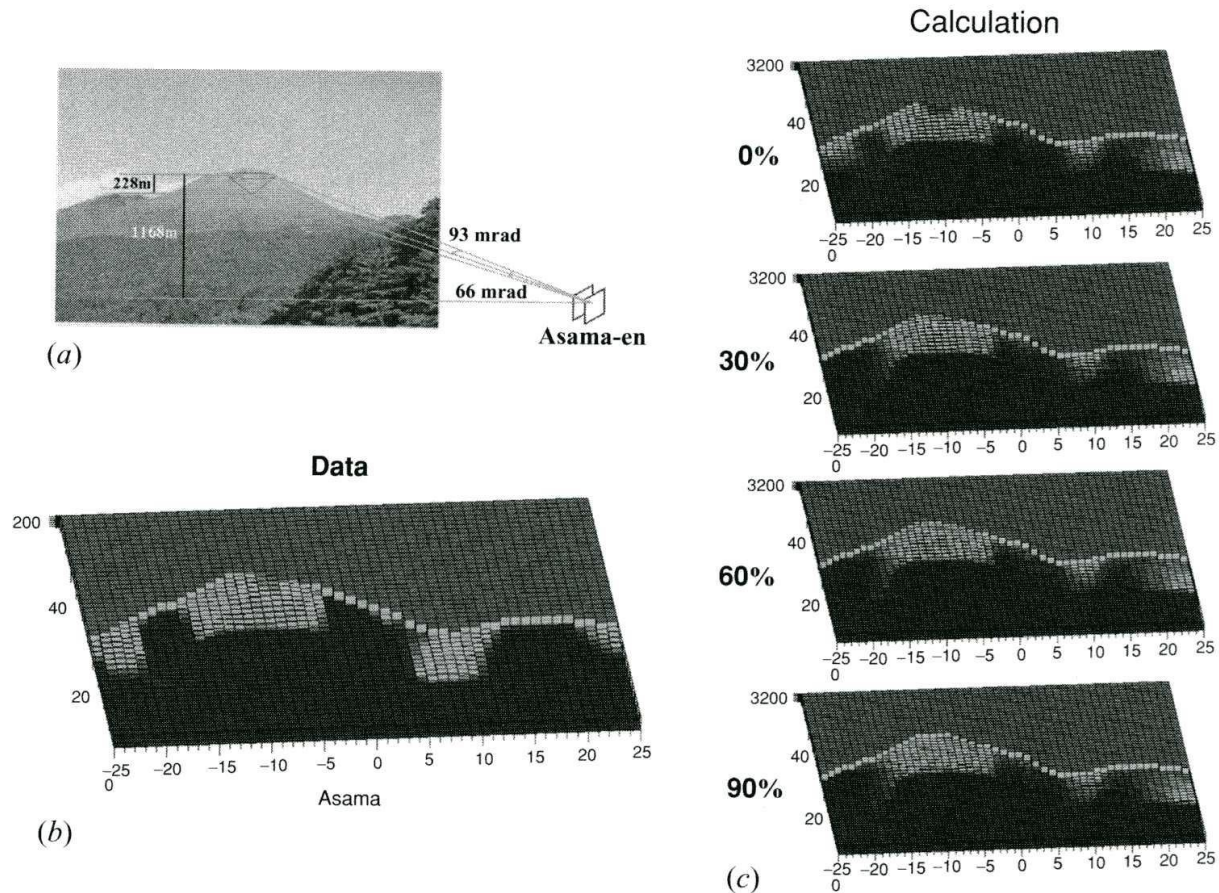
Mt. Tsukuba



- 33 giorni, rivelatore analogico, 2 km, discriminando sul valore più basso del rate (per ciascun punto dell'istogramma)

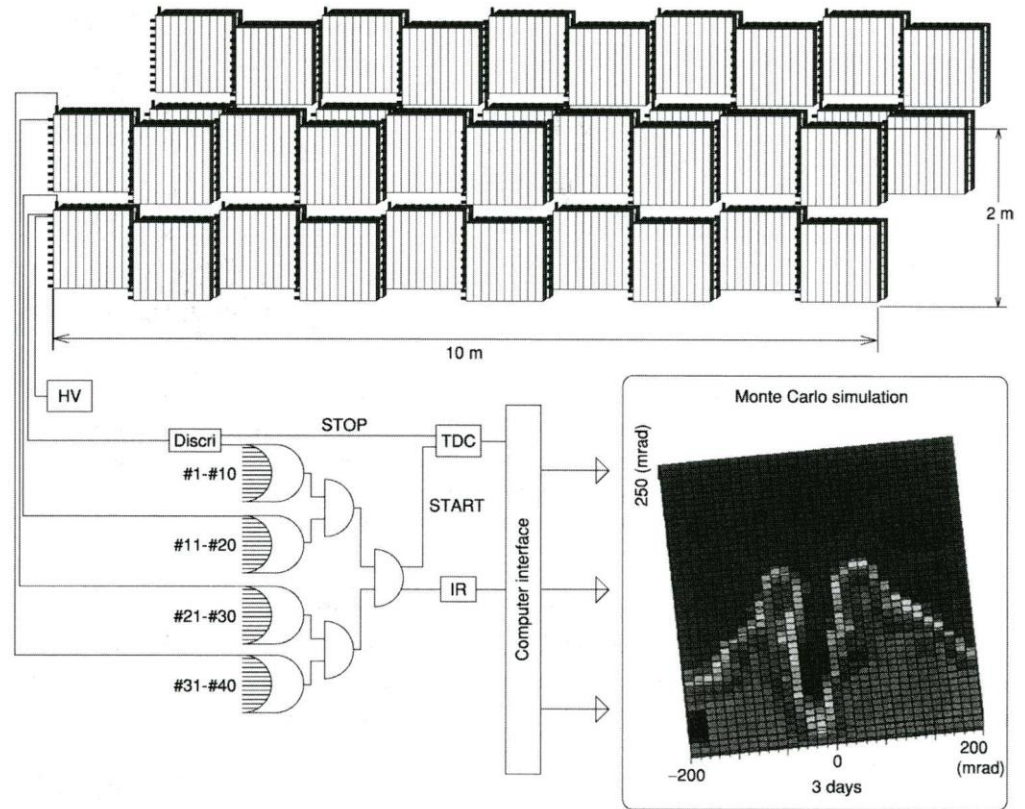
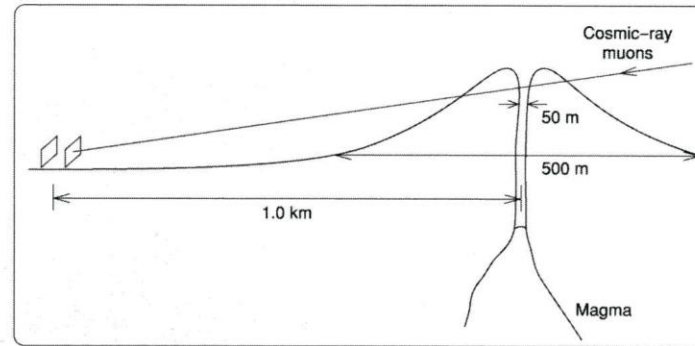
Mt. Asama

- contatori segmentati, 90 giorni, 2.75 km

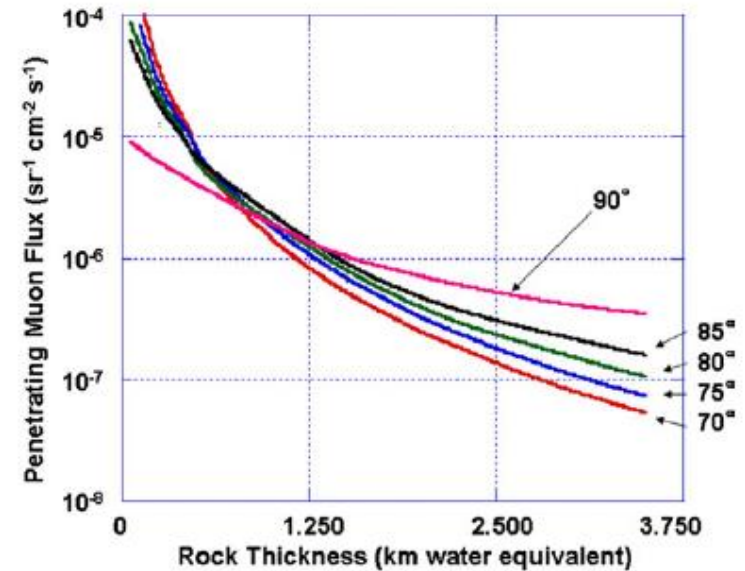
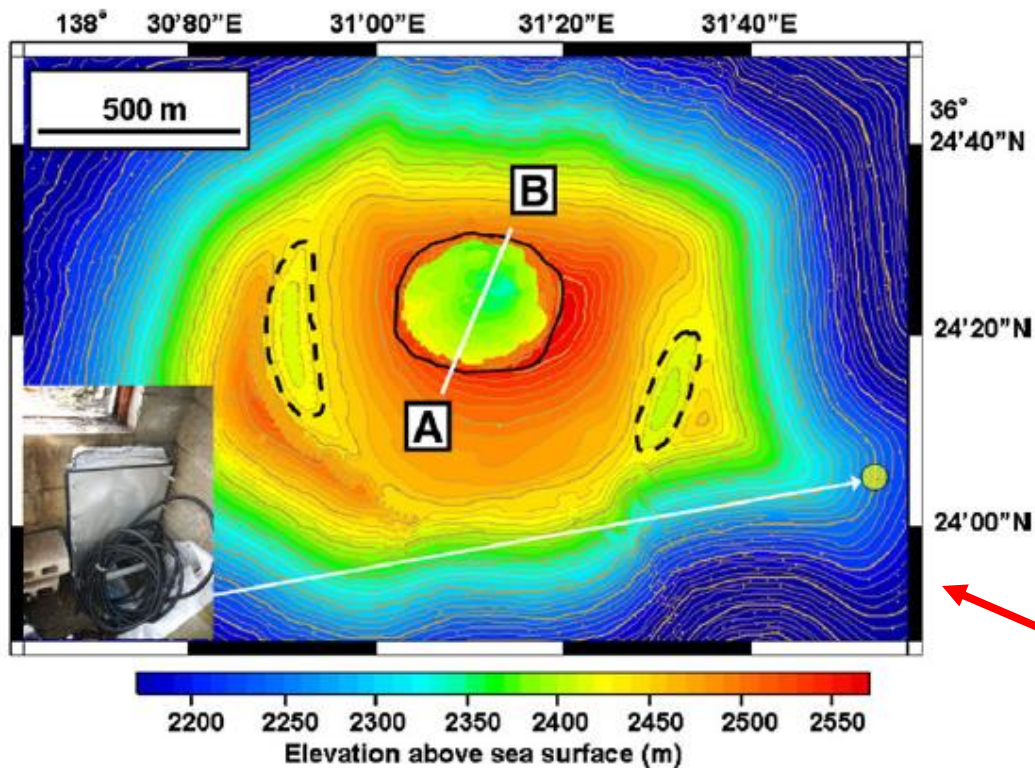


(*) calcolo in funzione della % di magma nel cratere, vs dati $\rightarrow < 30\%$

Possibile rivelatore per la predizione di eruzioni



Rivelatore con emulsioni



mappa del Mt. Asama con vecchi crateri parzialmente ricoperti - - - o nuovi ----- e posizione del rivelatore

- emulsion cloud chamber, passivo (niente HV, LV): sandwich di piastre di Fe e fogli di emulsioni nucleari, superficie 4000 cm^2 (40 cm length \times 50 cm width \times 10 cm thickness \times 2 sets) – la misura delle emulsioni è ormai automatica (e veloce)

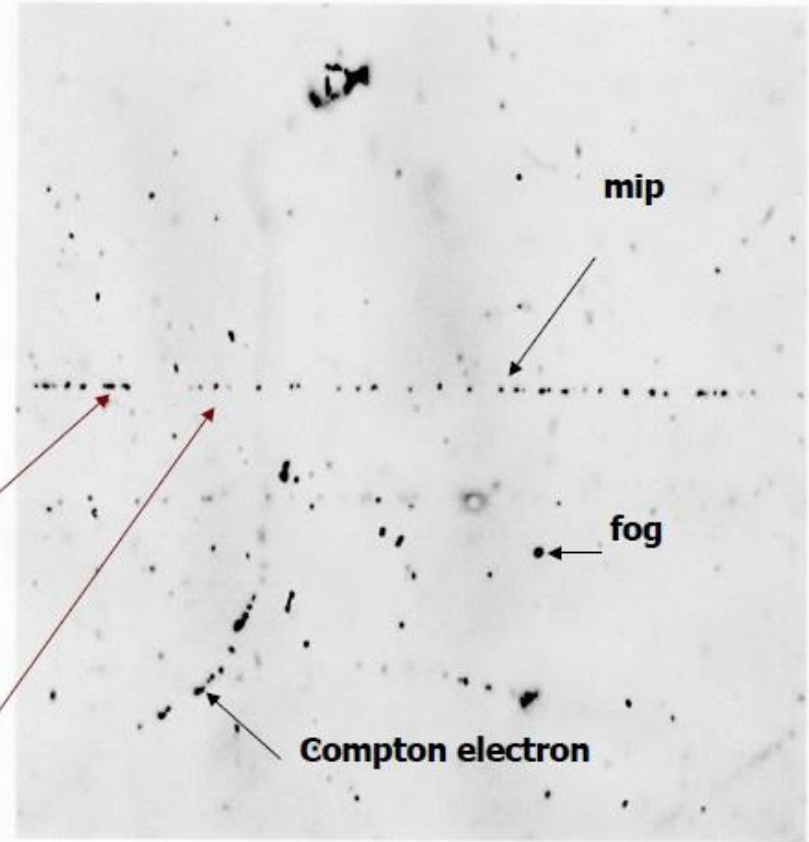
Nuclear emulsion films

Made of AgBr crystals poured
in an organic gelatine.

Passage of charged particles
can be recorded with accuracy
better than 1micrometer

charged particles crossing emulsions
ionize AgBr crystals. *Fixing* and
development turn ionization points
into black grains

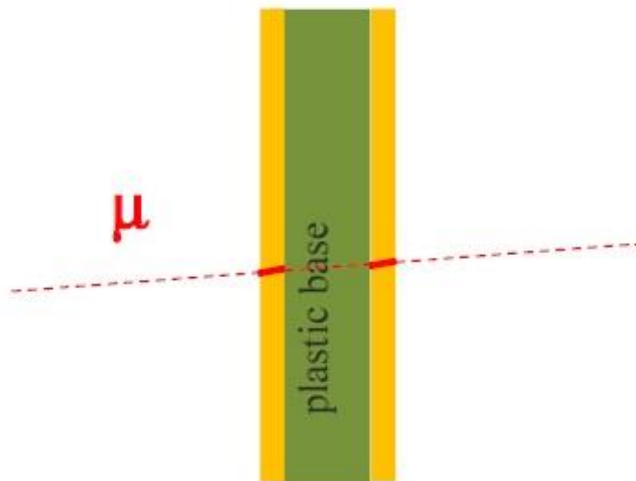
A track is defined as a sequence of
aligned black grains



About 35grains/100microns
on OPERA-like emulsions

(optimized for detection of m.i.p. particles)

Emulsion films as tracking detectors

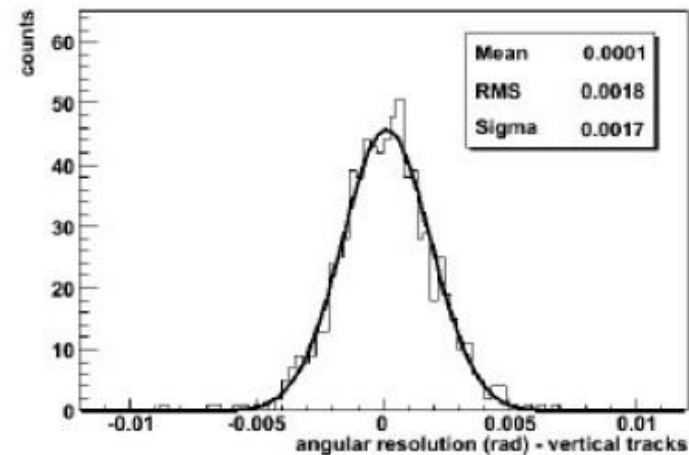


emulsion film
300 μm
(thickness of each
emulsion layer: 45 μ)

Micrometric position resolution

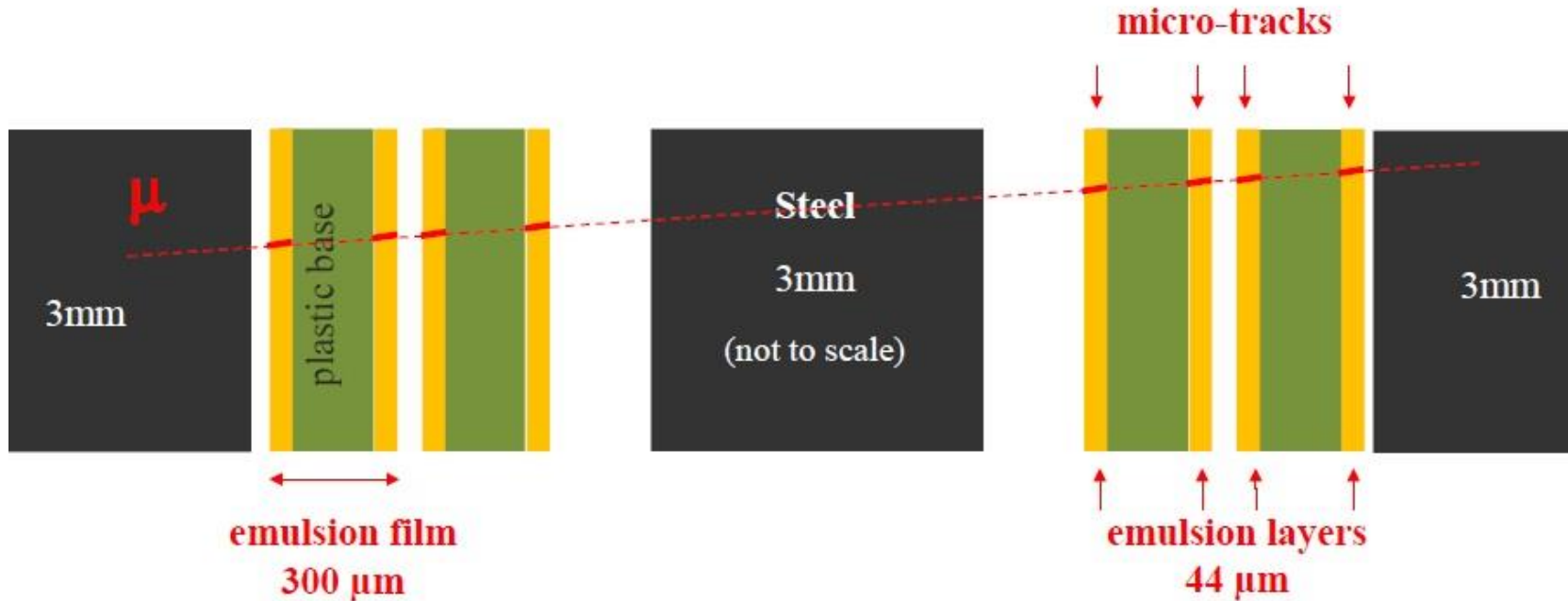
Films exposed orthogonal
to the beam

Angular resolution:
from $\cong 2$ to a few mrad
depending on track angle



Track angular resolution (mrad)

Emulsion telescope



4 emulsion films / 8 emulsion layers / 8 micro-tracks

→ Few mrad resolution

→ Redundant tracking for background rejection

→ Low momentum particle rejection by multiple scattering analysis

Nuclear emulsion muon telescope

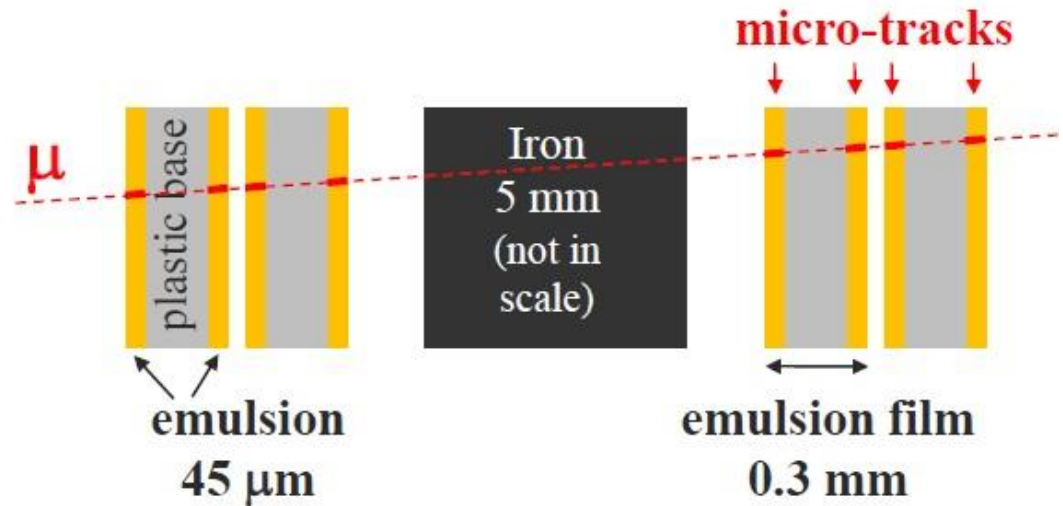
Longitudinal structure

4 emulsion films

1 iron plate

Very compact

Precise and redundant tracking
(1 micro-track / em. film)



- telescopio da 0.4 m² usato al Mt Asama
- adesso telescopio da 1 m² prende dati alla cupola di lava di Unzen
- l'inverno 2012-13 1 m² a Stromboli (risultati non ancora completamente disponibili)

Issues in emulsion film analysis

Detector surface issue:

Detection surface limited by scanning power:
present limits: $\cong 0.02 \text{ m}^2/\text{day}/\text{microscope}$ (ESS system) (*)

New generation microscope (10 times faster) under development

Timing issue:

Emulsion integrate ionizing radiation *anytime* from production to development, *no timing information* available:

- dedicated analysis to *separate “transportation background”* from exposure signal
- need for *shielding* from radioactive background to *keep emulsion films “clean”*

(*) European Scanning System, in Japan $\approx 0.075 \text{ m}^2/\text{day}/\text{microscope}$

High speed automated emulsion scanning

Two approaches

EU: ESS (European Scanning System)



- Scanning speed/system: 20cm²/h
- Customized commercial optics and mechanics
- Asynchronous DAQ software

Japan: SUTS (Super Ultra Track Selector)



- Scanning speed/system: 75cm²/h
- High speed CCD camera (3 kHz), Piezo-controlled objective lens
- FPGA Hard-coded algorithms

Issues in emulsion film analysis/2

Temperature issue:

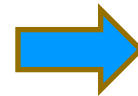
Ionizing radiation creates a *latent image* in emulsion films, fixed and developed by chemical treatment.

Latent image rapidly fades away before development at temperature above $\cong 20^\circ$



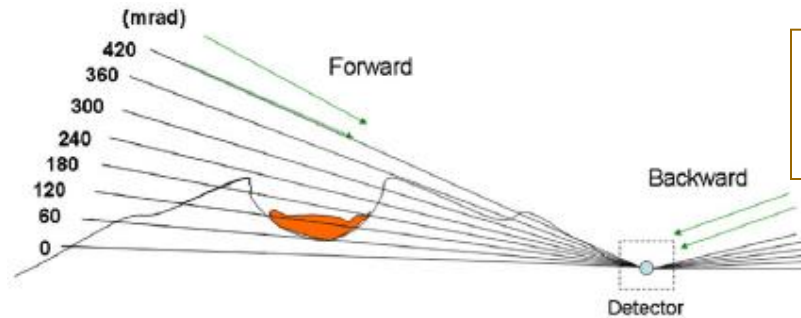
e.g.

Thermic insulation at Stromboli site.



Emulsion exposure done
in autumn-winter

Risultati

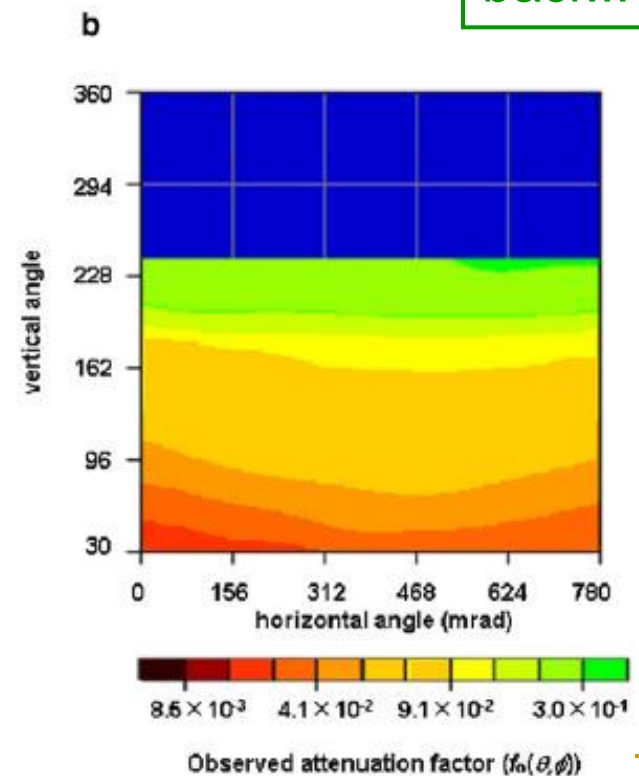
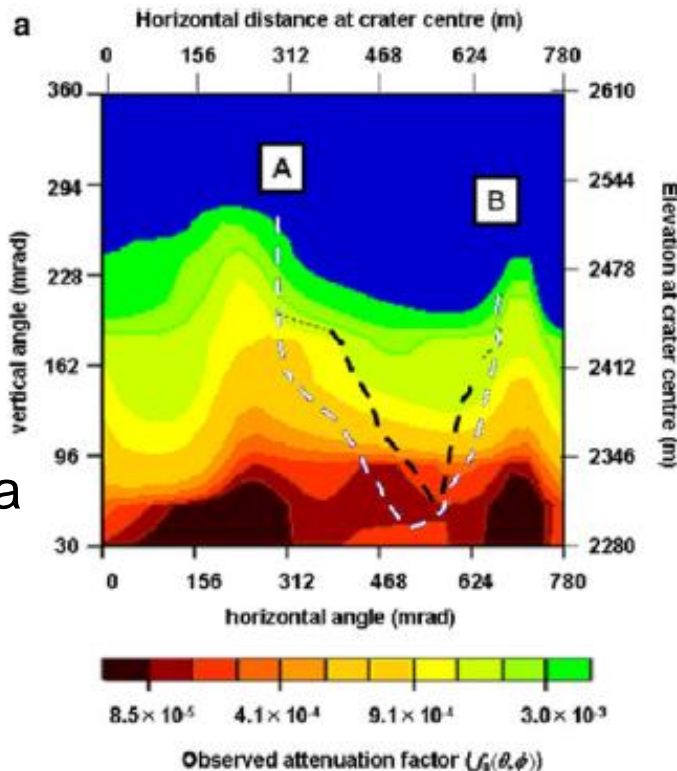


sezione trasversa
del Mt Asama

forward

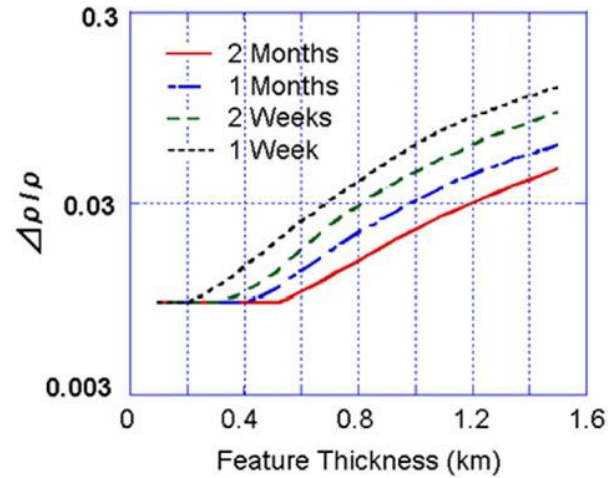
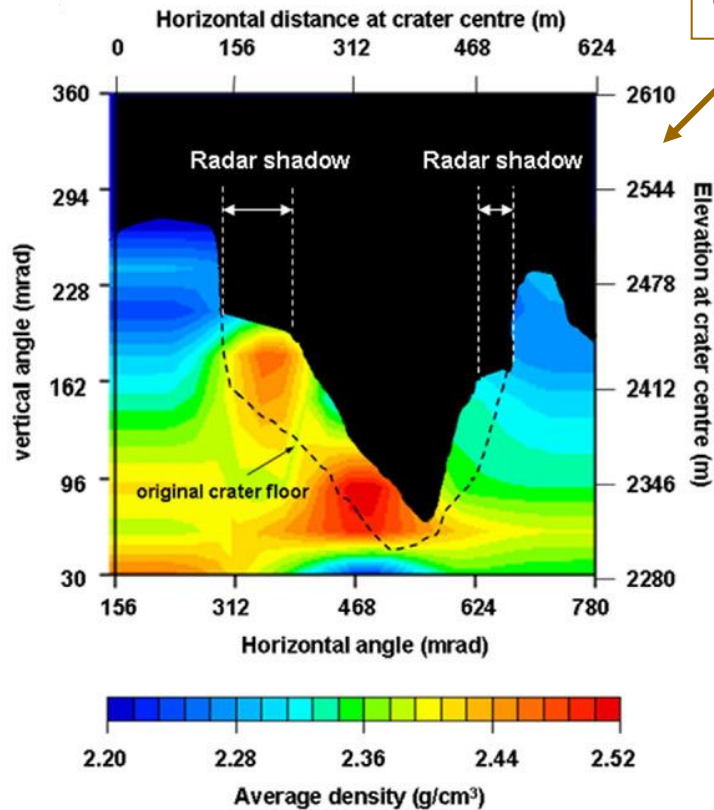
backward

L'attenuazione dipende da:
- lunghezza attraversata
- densità media lungo il percorso



Mt. Asama con varie risoluzioni

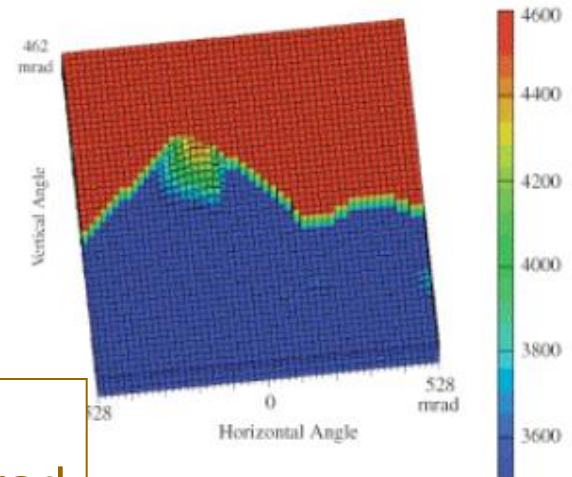
$\langle \rho \rangle$ ricostruita



emulsioni, risoluzione < 10 mrad

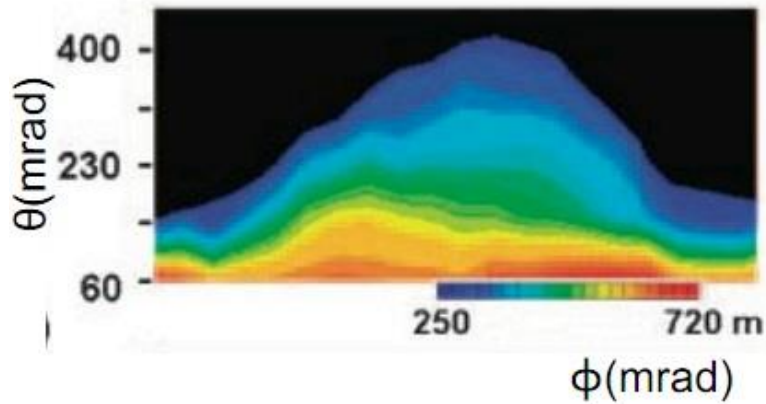
(effetti del ms < 5 mrad)

scintillatori,
risoluzione = 66 mrad

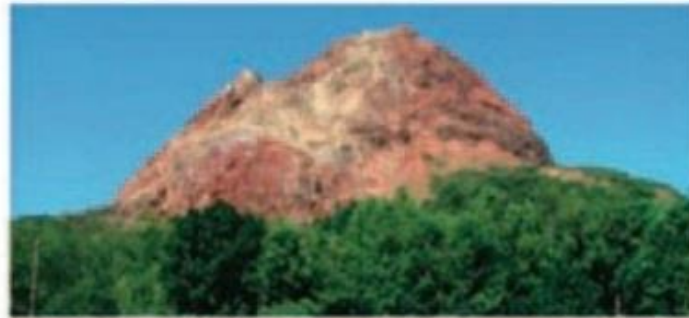


Radiografia di una cupola vulcanica (Usu)

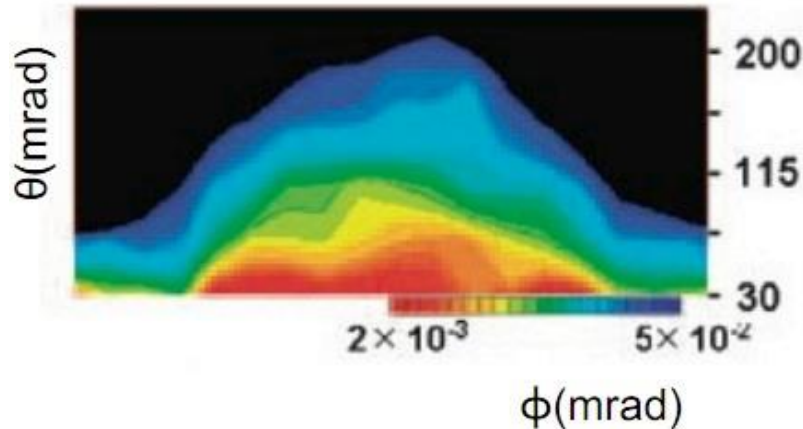
rock range



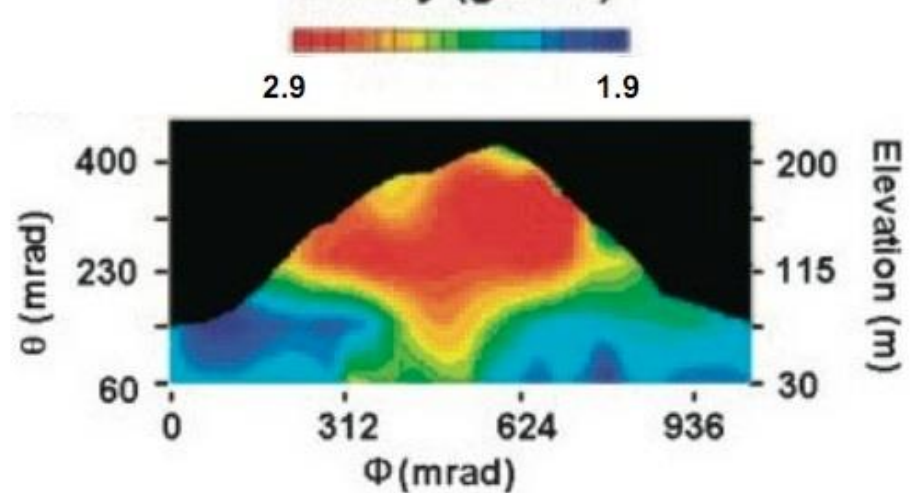
Tanaka et al, Proc Jpn Acad, Ser B 84 (2008)



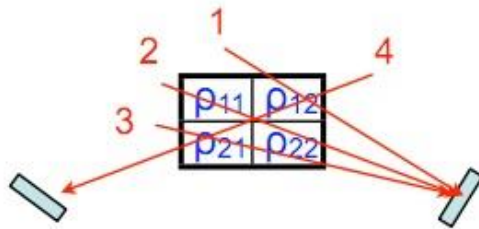
Muon intensity



Density (g/cm³)



Tomografia computerizzata per vulcani



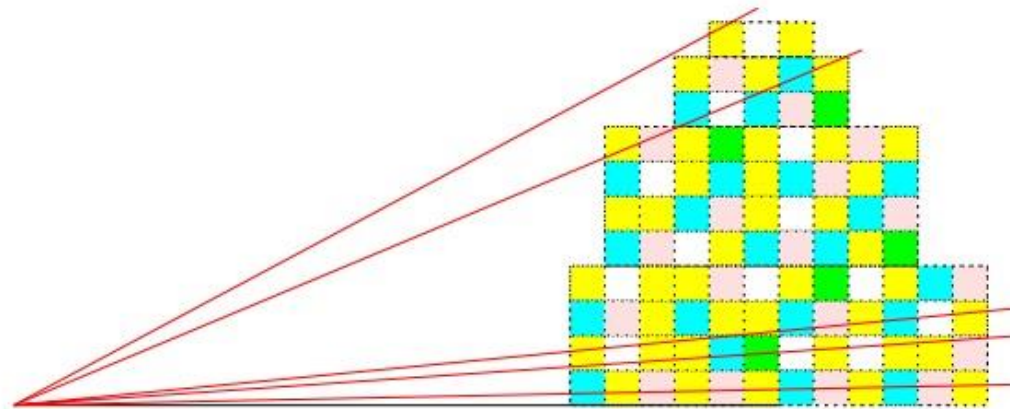
$$\rho_1 = 0 * \rho_{11} + 1 * \rho_{12} + 0 * \rho_{21} + 0 * \rho_{22}$$

$$\rho_2 = 1 * \rho_{11} + 0 * \rho_{12} + 0 * \rho_{21} + 1 * \rho_{22}$$

$$\rho_3 = 0 * \rho_{11} + 0 * \rho_{12} + 1 * \rho_{21} + 1 * \rho_{22}$$

$$\rho_4 = 0 * \rho_{11} + 1 * \rho_{12} + 1 * \rho_{21} + 0 * \rho_{22}$$

Mt. Asama ~ 1000 voxel (100x100x100 m³ ciascuno)



Un primo tentativo

Three-dimensional computational axial tomography scan of a volcano with cosmic ray muon radiography

Hiroyuki K. M. Tanaka,¹ Hideaki Taira,² Tomihisa Uchida,³ Manobu Tanaka,³ Minoru Takeo,¹ Takao Ohminato,¹ Yosuke Aoki,¹ Ryuichi Nishitama,¹ Daigo Shoji,¹ and Hiroshi Tsuiji¹

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 115, B12332, doi:10.1029/2010JB007677, 2010

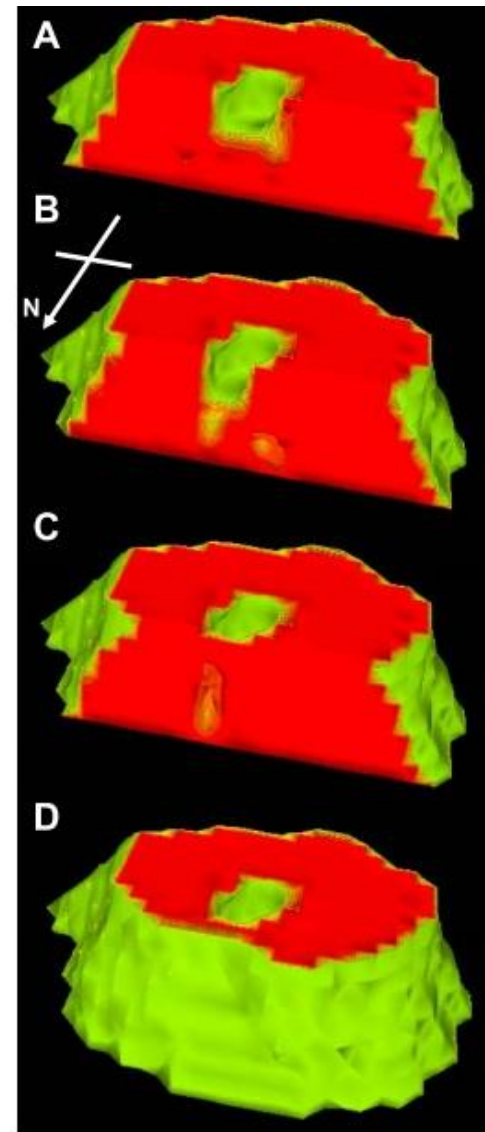
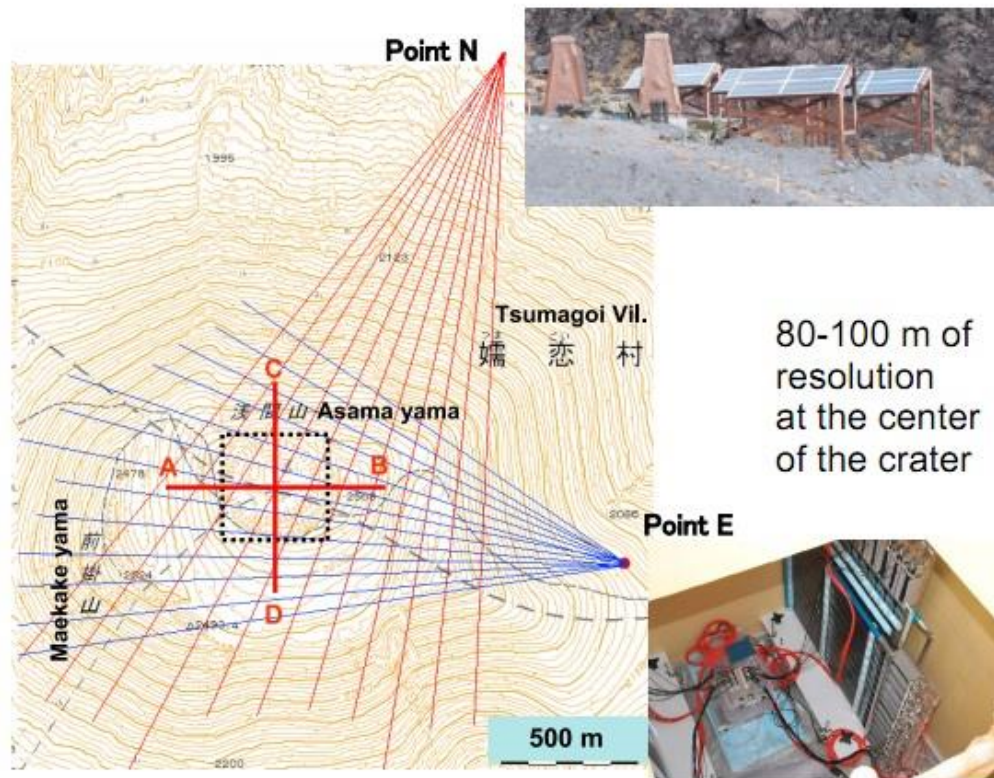


Figure 2. Map of Asama volcano showing the location of the Mu-CAT system. The dotted box show the area where the value of W_m is reduced. Red lines show the location of the density distribution as shown in Figure 4.

- Altezza 930 m s.l.m., attività vulcanica ordinaria a 750 m
- Attività "stromboliana": esplosioni intermittenti dovute ad accumulo di gas, condotto essenzialmente aperto
- Rara e modesta attività effusiva
- Il segnale dovuto all'attività esplosiva e il tremore vulcanico hanno origine a piccola profondità, a circa 200 m al di sotto dell'area craterica.



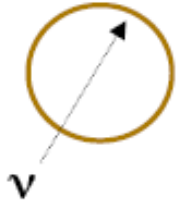
(*) recentemente 'cambiato' in MURAVES (MIUR)

Grande interesse per radiografia

Linee guida del progetto MU-RAY

- Fattibilità dimostrata da osservazioni in Giappone
- Obiettivo di MU-RAY: radiografia ad alta risoluzione in 3D con accesso a zone profonde: (importanti passi in avanti)
- Coll. Internazionale, Vesuvio come progetto pilota
- Sviluppare telescopio adattabile ad altri vulcani (Stromboli, ... Antille ... Giappone ...) e con capacità di "zoom"
- Uso di scintillatori con tecnologie collaudate
- **In parallelo:**
 - Progetto e realizzazione dei (3) telescopi MU-RAY
 - Prime misure sul campo con telescopio giapponese: area 1m^2 , basse accettanza e risoluzione angolari

Full simulation



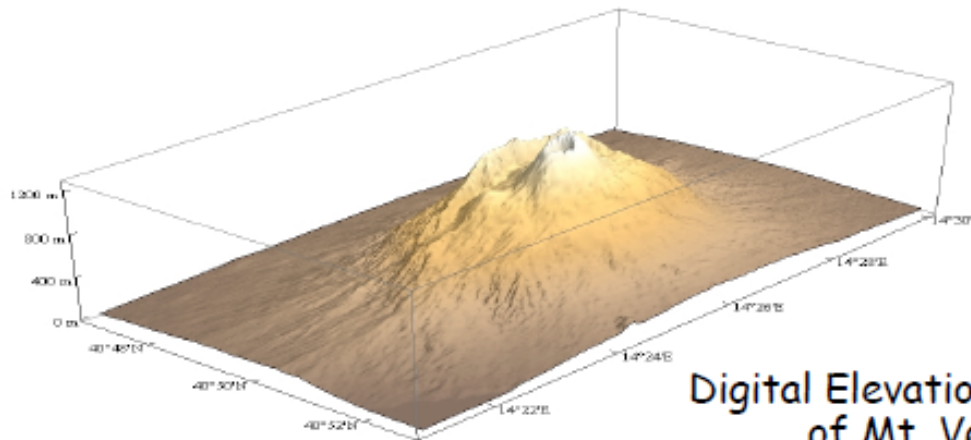
Similarity with
Earth radiography by neutrinos

$\nu \leftrightarrow \mu$

Earth \leftrightarrow volcano



Methods and codes have been developed:
first applied to Earth radiography (Miele and coll.),
now being applied to Mt. Vesuvius

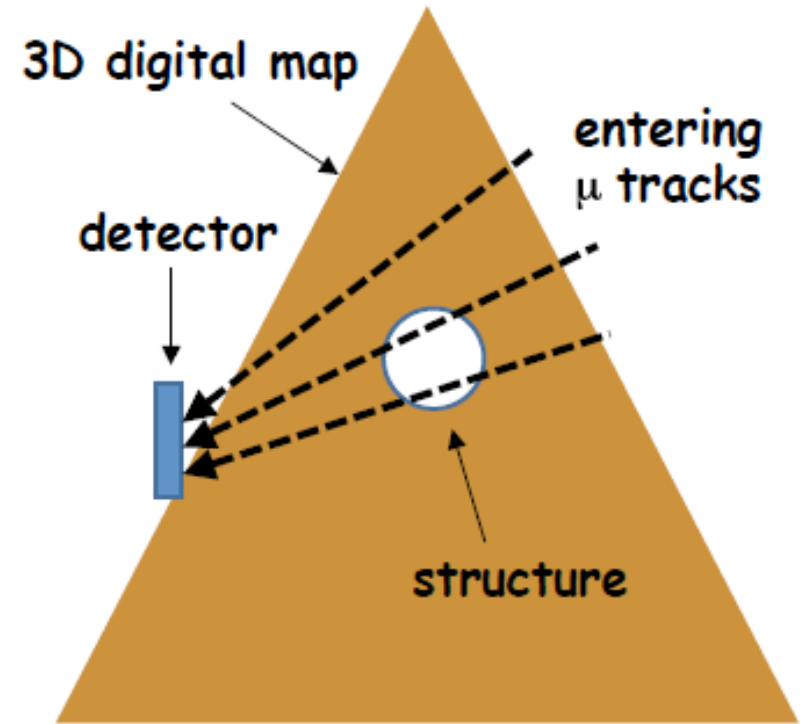


Digital Elevation Map (DEM)
of Mt. Vesuvius

Sul Vesuvio esiste
un osservatorio
dell'INGV

Step 1: generate atmospheric muons

- 3D Digital Elevation Map
- Tracks intercepting the detector generated and projected backward
- Along their directions, muons generated according to the known spectrum (from PDG)



Input to full simulation of μ reaching the detector through Vesuvius

Step 2: full simulation of μ reaching the detector through Mt. Vesuvius

- Simulation of the geometry and μ tracking done with GEANT4 (Geometry ANd Tracking tool)
- "Experimental apparatus" defined as Vesuvius + detector
- The longitudinal dimension of the apparatus is the length of rock intercepted by the track (from the previous step)
- The experimental apparatus can consist of zones with different densities, allowing to simulate structures inside Vesuvius
- The rock initial density will be taken to be 2.2 g/cm^3

Strisce di scintillatore con lettura WLS (MINOS/OPERA)

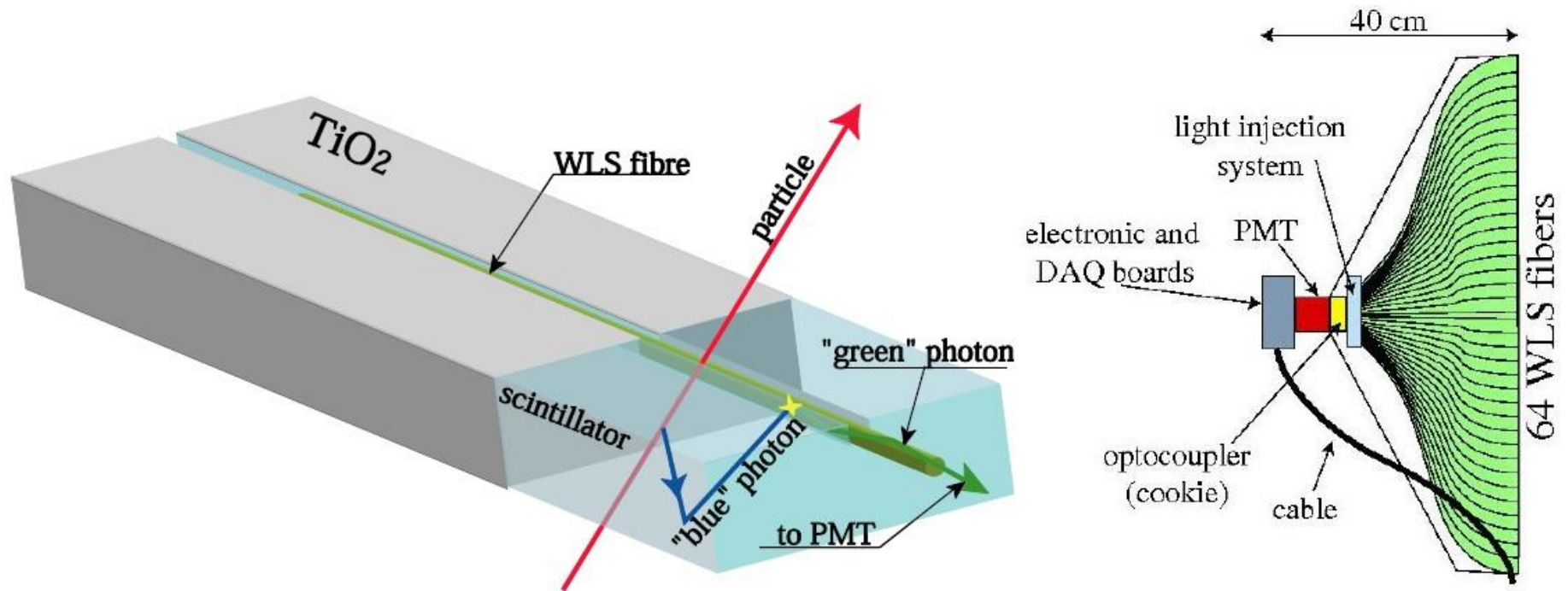
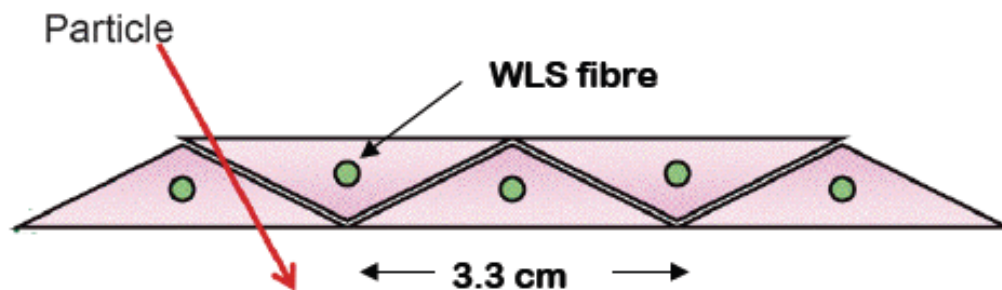
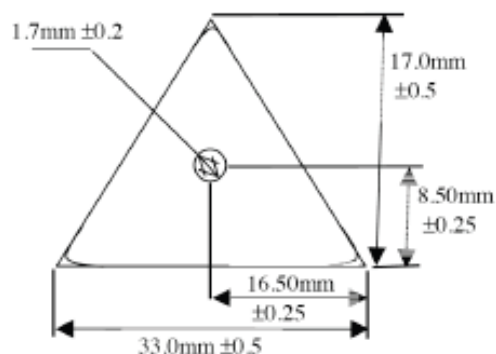


Fig. 15. The plastic scintillator strips (left figure) of the OPERA neutrino experiment and their readout by optical wavelength shifting fibres and multianode PMT (right figure).

The MINERvA Inner Detector scintillators



→ lettura con SiPM

- The triangular shape offers advantages:
 - No gaps between strips
 - Continuous position determination by weighted average of the signals from two strips: no pixel effects
 - Good spatial resolution ($\sim 3\text{ mm}$)
 - **10 mrad** angular resolution with "short" lever arm ($\sim 0.5\text{ m}$)
- Wave Length Shifting Fibre in a hole created in extrusion
- Strips with co-extruded coating: easier to assemble

Stromboli



- **“Strombolian” activity**
 - essentially open conduit
 - intermittent eruptions due to increase in gas pressure
 - rare effusive activity
- **Summit at 926 m a.s.l.**
- **Crater at ~ 750 m a.s.l.**

L'obiettivo finale (Stromboli)

▪ **Scientific interest**

- Open conduit
- Stromboli well studied using other techniques
- Combine information by different techniques

▪ **Large rock thickness**

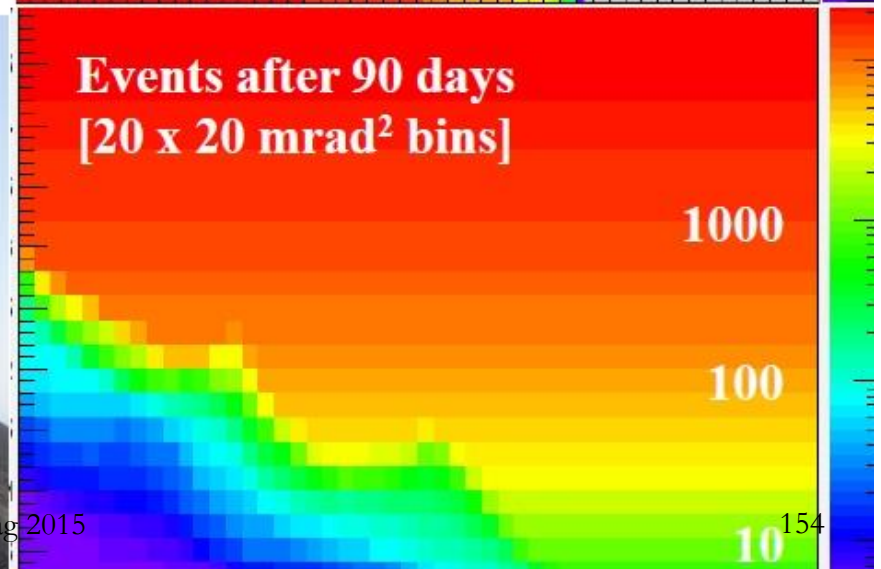
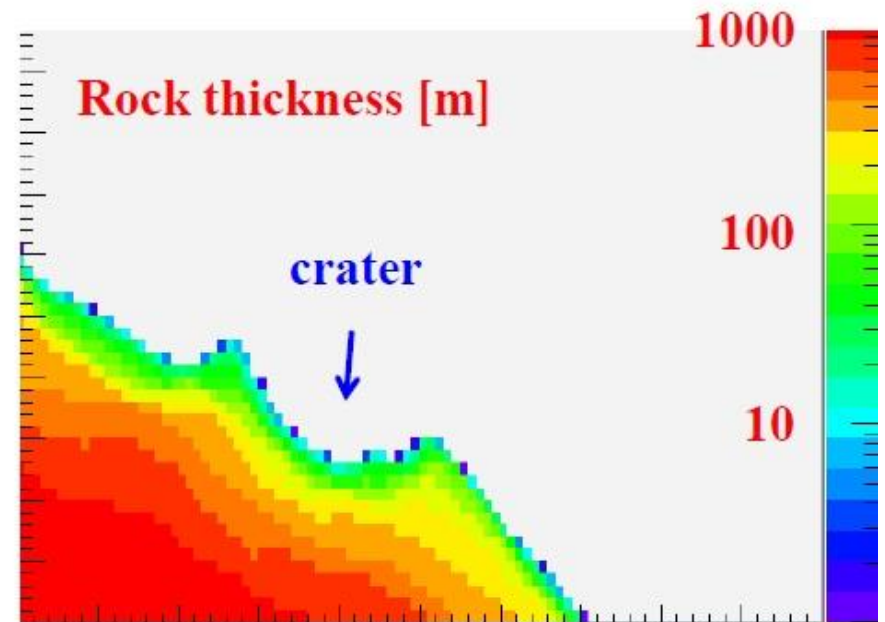
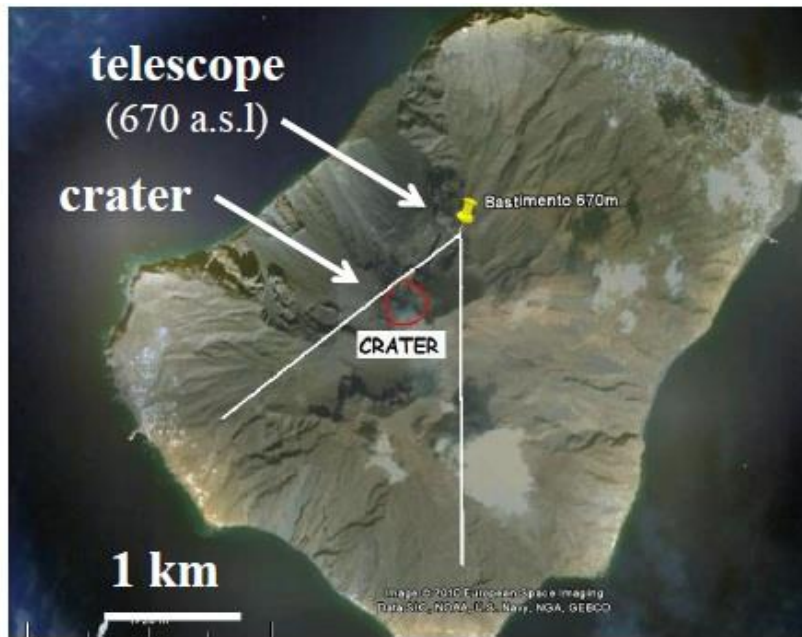
- similar problems as for Mt. Vesuvius
- harsher environment e.g. non c'è una base INGV
- MU-RAY telescope in some future?

▪ **Top part of the conduit (crater region)**

Investigated using nuclear emulsion

(same Italian-Japanese team as for Unzen lava dome)

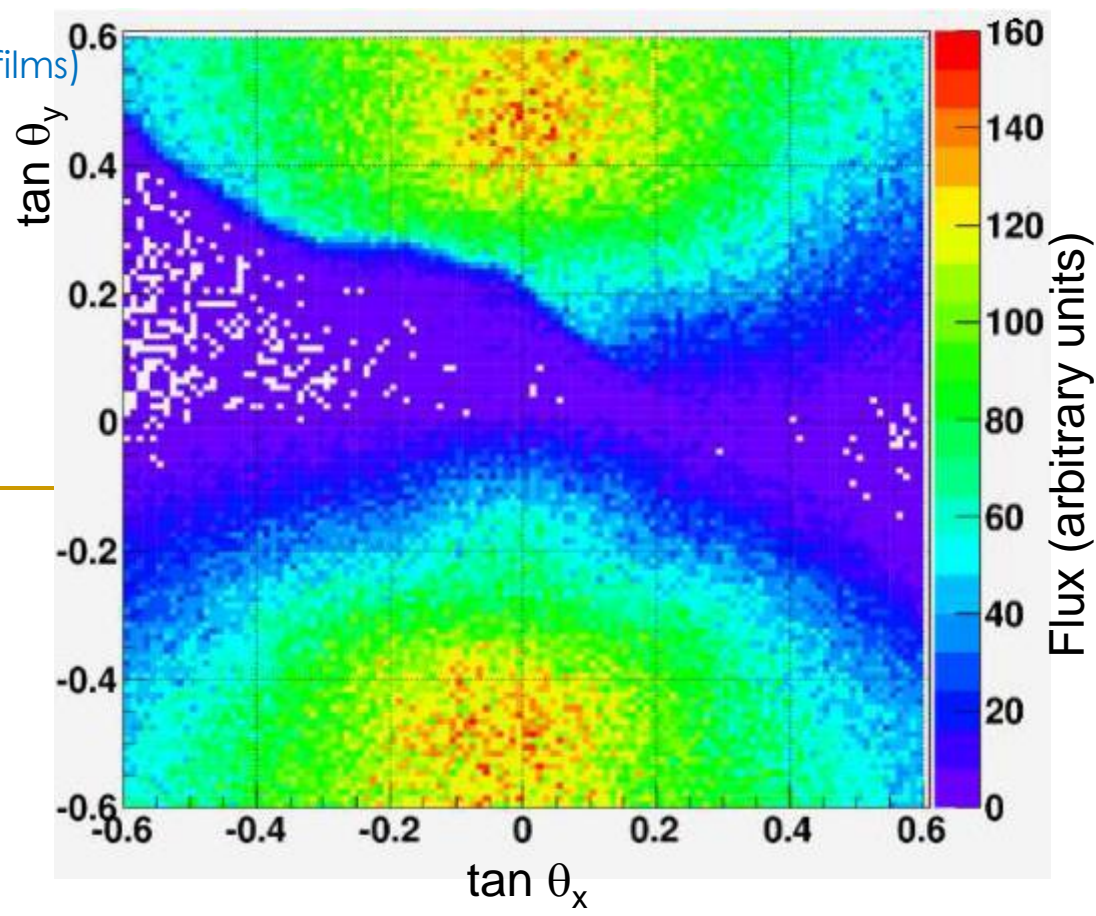
Expected at Stromboli (emulsions)



Muon detectors made of nuclear emulsion

Stack tracks at Stromboli (3 out of 4 films)

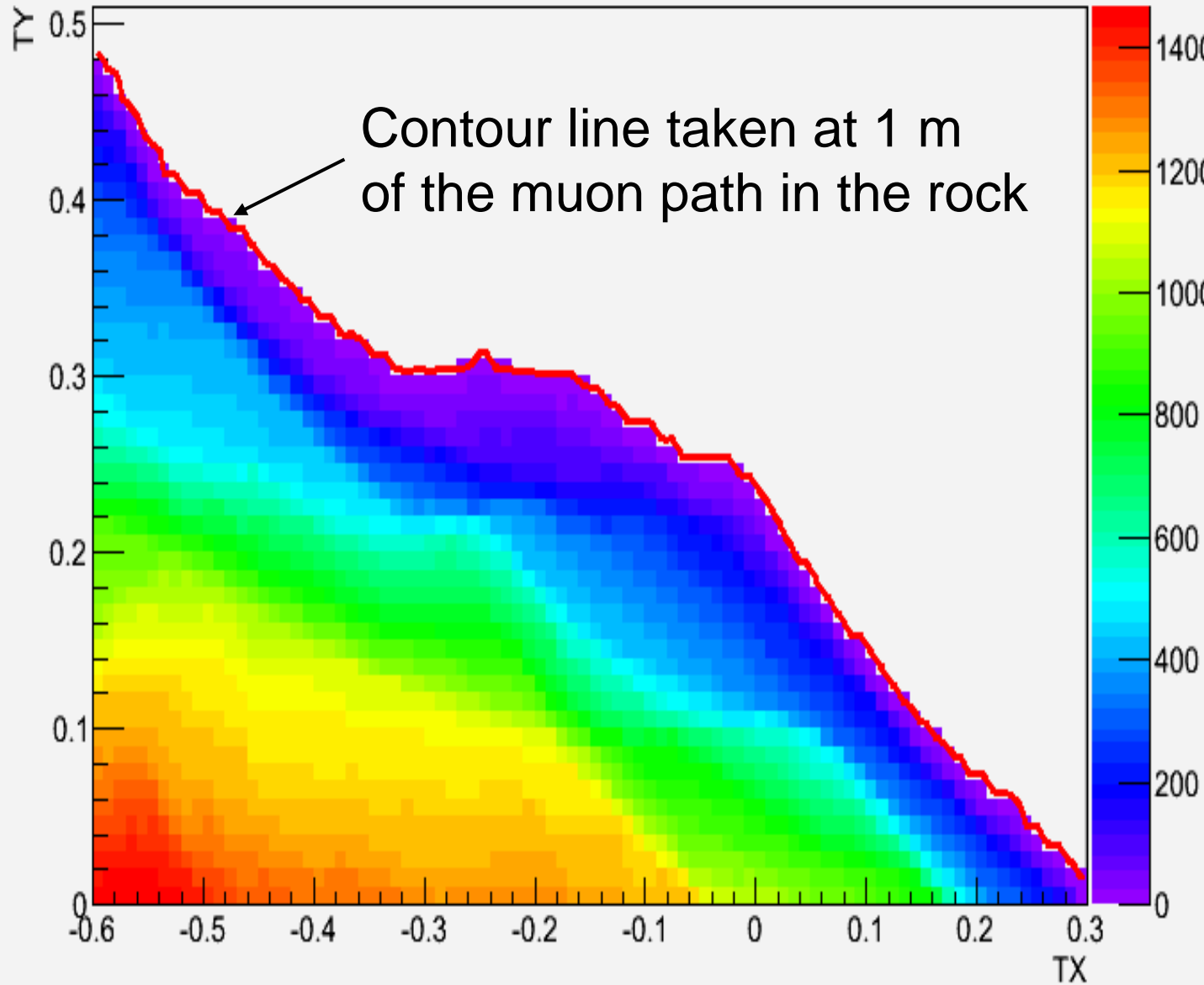
Volcano profile and track counts from emulsion (Stromboli)



Rock thickness

From DEM and detector position

h_mc_thickness
Entries 7381



Contour line taken at 1 m
of the muon path in the rock

Rock thickness
on the path of
muons
travelling to
the detector

DEM+MC
viewer are
used. Detector
is positioned on
the DEM using
the coordinates
taken from high
precision GPS
measurements

(back to Vesuvius)

Marigliano

Nola

Cognoli di S Anastasia
(1086)

Punta del Nasone
(1132)

Cognoli di Ottaviano
(1112)

Mt. Somma and its caldera

Canalone
dell'Arena

Valle del Gigante
(885)

Sommità
del cono
(1281)

Valle
dell'Inferno
(830)

Atrio del Cavallo
(831)

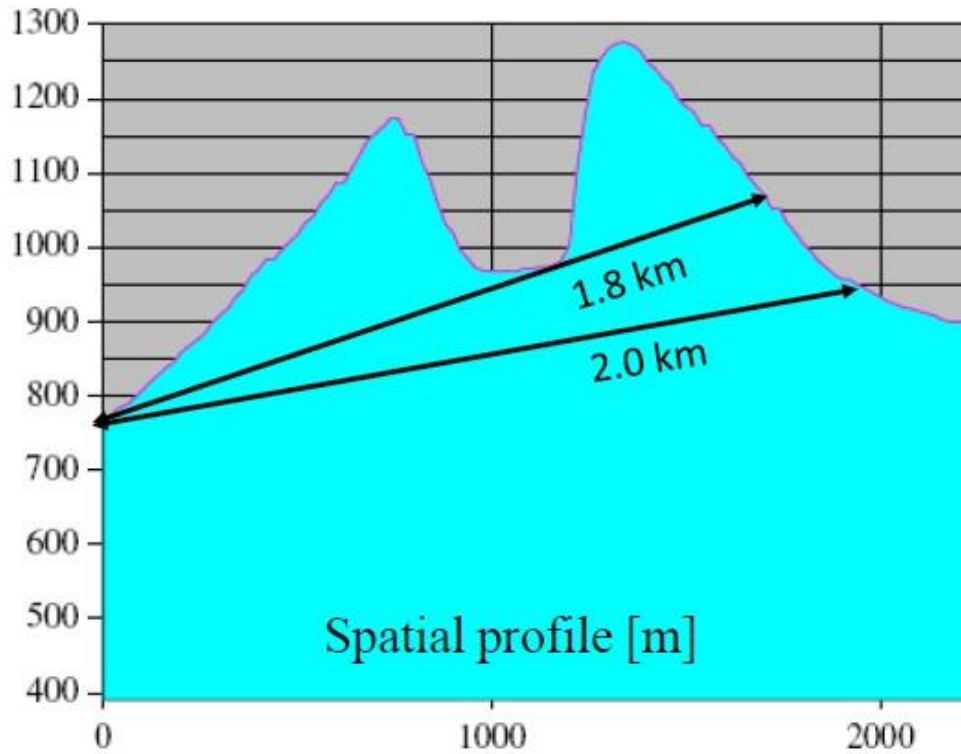
Stazione Superiore
(1158)

Fondo del Cono
(951)

La Capannuccia
(1170)

“Gran Cono” of Mt. Vesuvius with its 300 m deep caldera

Il problema del Vesuvio



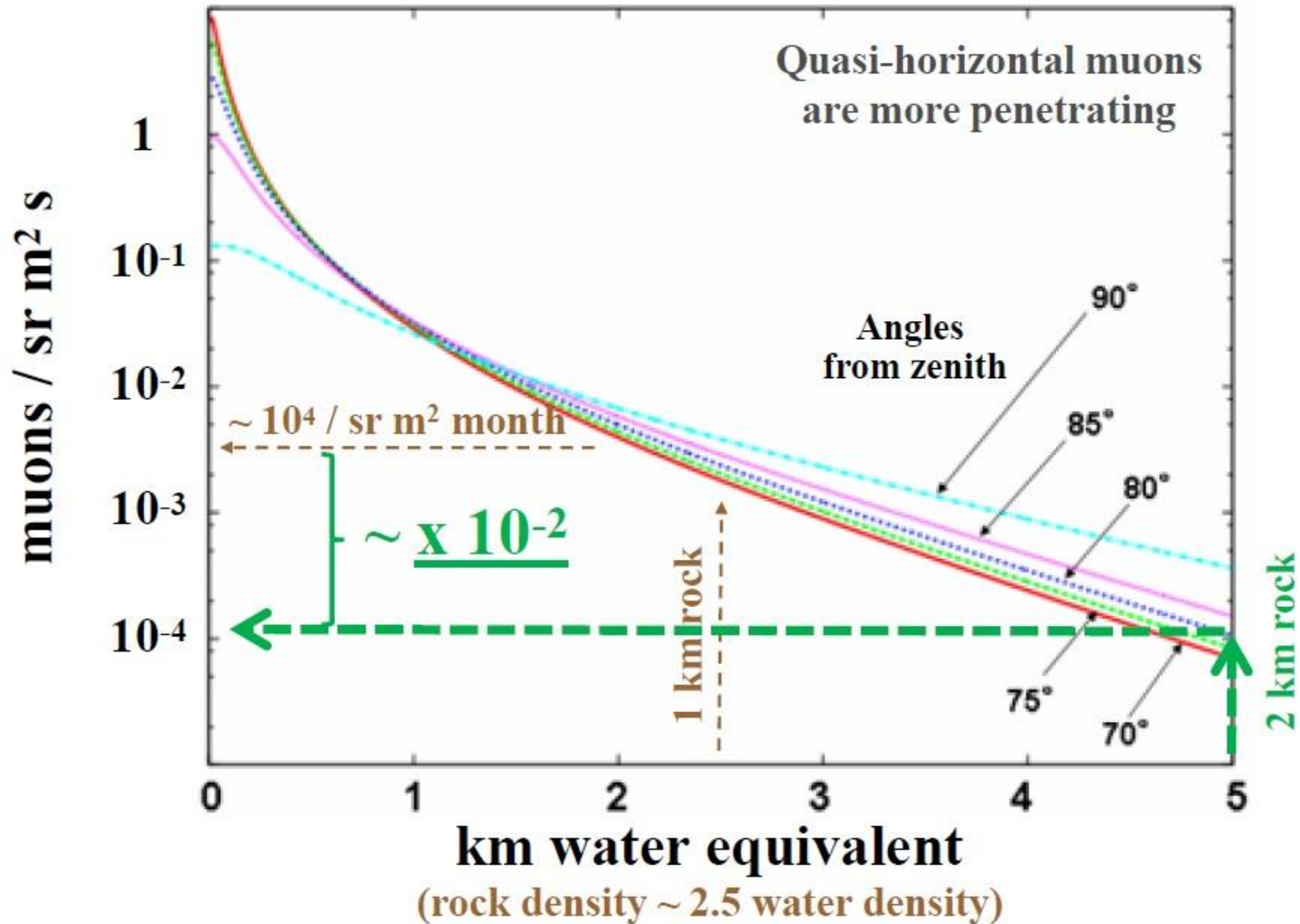
~ 2 km rock from a telescope at 750 m a.s.l.



need to Improve sensitivity

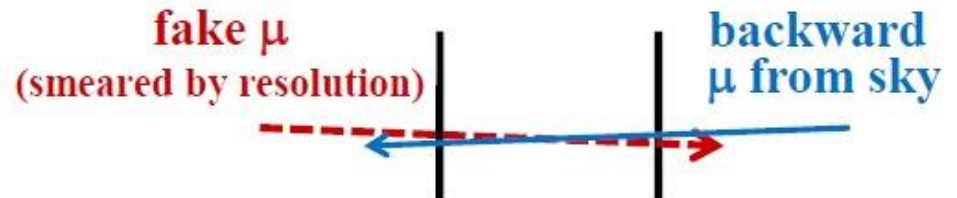
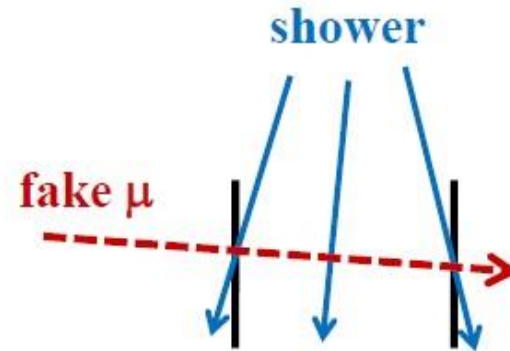
with respect to previous radiographies (< 1 km rock)

Perdita di sensibilita`



Recupero di sensibilità

- area rivelatore: 1 m² → 10 m²
- presa dati: da ~mese a ~anno
- fondi (sono proporz. più grandi)
 - tracking
 - tof
 - ph, molteplicità



..... ?

Telescopio giapponese (dal 2009 prende dati sul Vesuvio a 750 m s.l.m.)

- Two x-y measuring stations
- 1 m² area
- 8 cm wide plastic scintillator strips
- Hardware filling of a counter coincidence matrix (no info on single events)
- Hardware multiplicity cut (1 hit/plane) to reject fake muons from showers
- No forward-backward discrimination

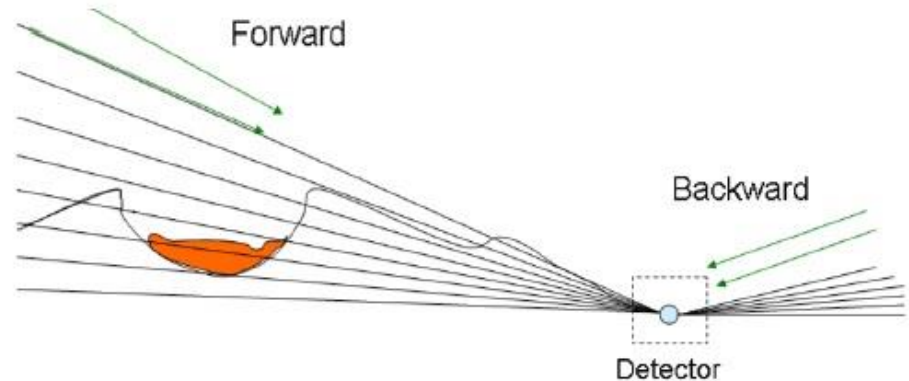


- **Practice with experimental methods (e.g. muon flux normalization)**
- **Support to MU-RAY choices:**
 - tools for background rejection
 - better resolution
- **Infrastructure ready for prototype MU-RAY telescope**

Metodi per la normalizzazione del flusso

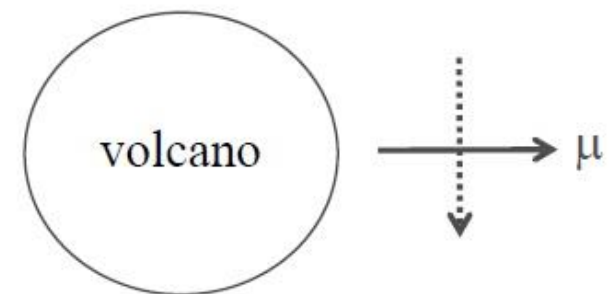
“Backward” method

- Muons from sky on opposite side
- In parallel with data taking
- Used in previous radiographies



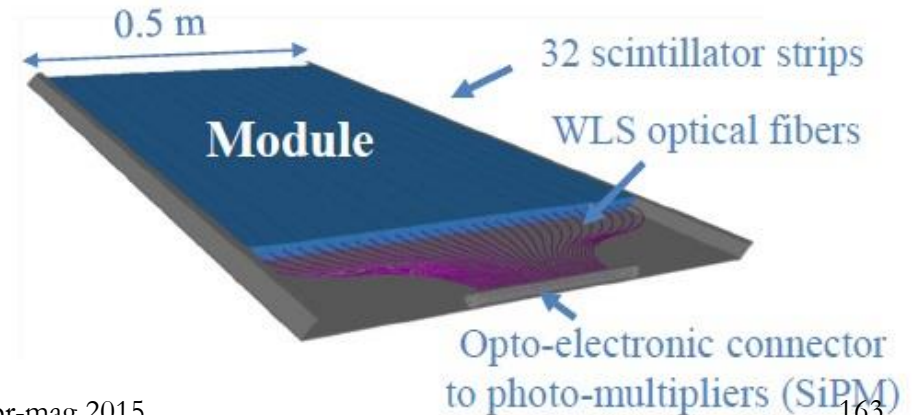
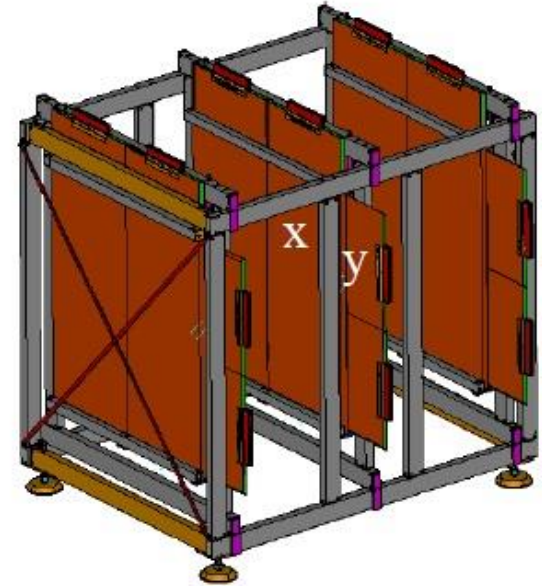
“90°” method

- Muons from sky at 90°
- Special (short) runs with rotated telescope
- Same angles, same counter coincidences
- Successfully tried at Mt. Vesuvius

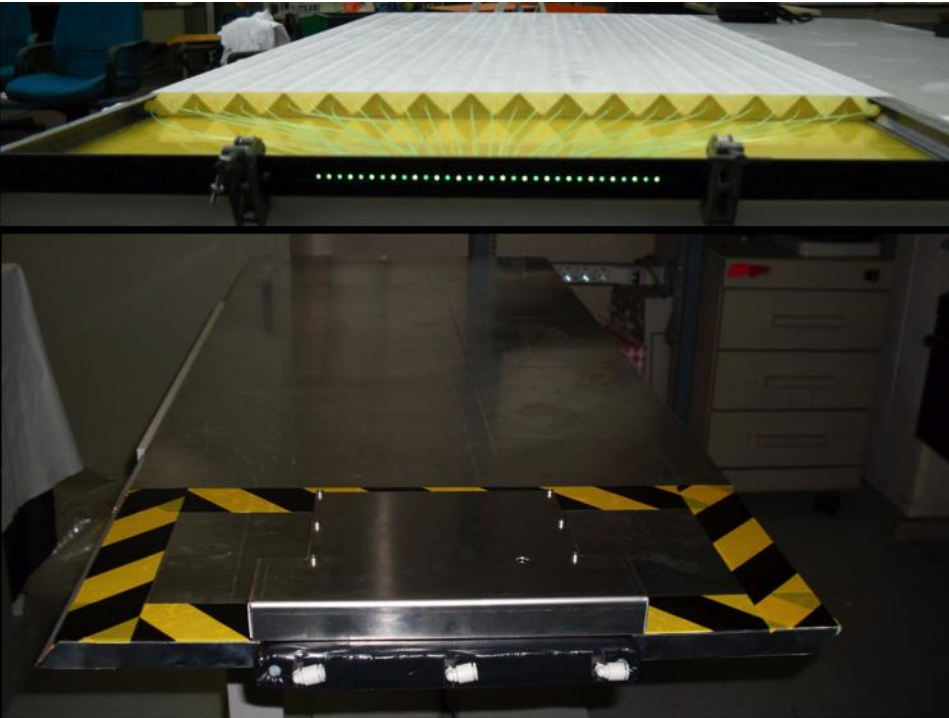


Il telescopio di MuRay

- Basic technique: strips of plastic scintillators
- **Precise and redundant tracking**
 - 3 x-y measuring stations
 - ~ 5 mm space resolution
 - ~ 10 mrad **angular resolution**
- 1-4 m² area for one telescope (1 m² for prototype)
- Modular construction
- **Event-by-event information** for offline analysis
 - time of flight
for muon direction discrimination
 - pulse height
from each scintillator strip
 - hit multiplicities



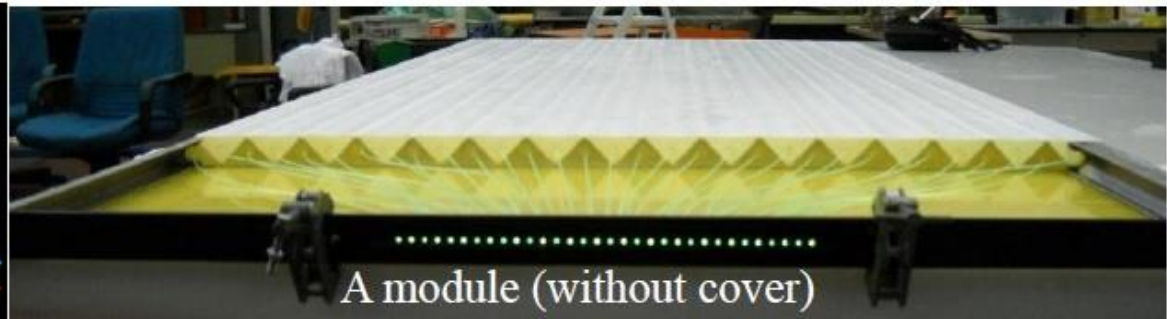
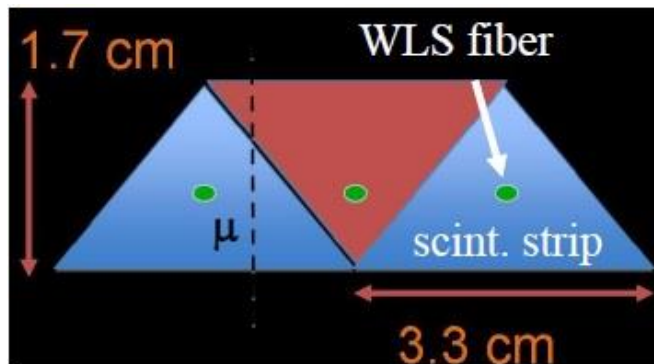
Il telescopio di MuRay/2



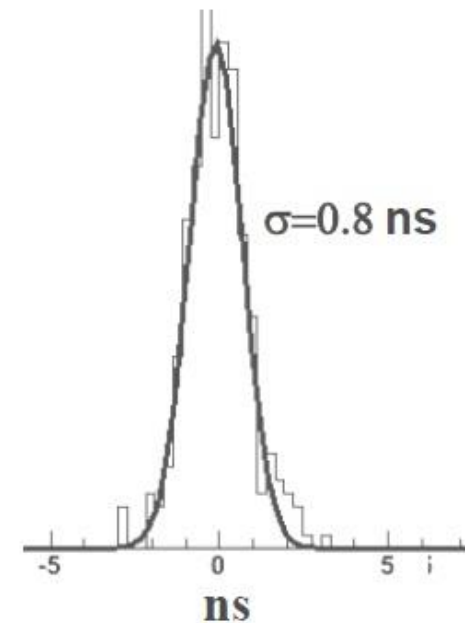
- in basso il modulo chiuso con FE board e scambiatore di calore ad acqua

- 12 moduli che formano 3 piani x-y assemblati nel supporto di Al

Scintillatore e fibre WLS

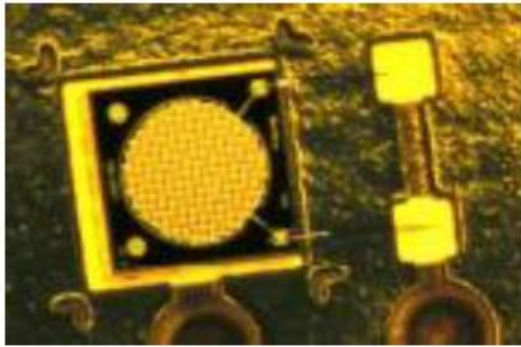


- Strips with triangular section (NICADD-Fermilab)
- ~ 5 mm **space resolution**
by interpolating signals in adjacent strips
- Co-extruded hole for Wave Length Shifting (WLS) optical fibers
- **Fast re-emitting fibers** (Bicron BCF 92)
for time of flight measurement within ~ 1 ns
- Fibers convey light to an opto-electronic connector
- 32 strips glued together to form a “module”



Time resolution

Silicon Photomultipliers (SiPMs)



A naked SiPM wire bonded
($\Phi = 1.4$ mm, ~ 300 diodes)

NEW TECHNOLOGY

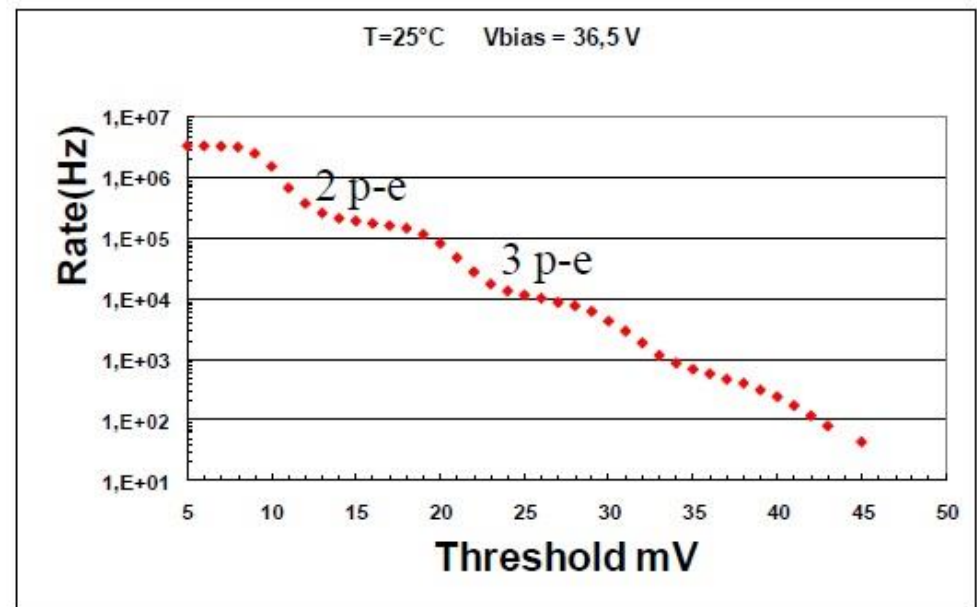
MU-RAY: “naked” SiPMs

by FBK-IRST (Trento, Italy)
developed in a joint venture with INFN

- **Matrix of diodes in Geiger mode** (inverse polarization)
Analog sum of the signals
 - **amplification** $\sim 10^6$ (depending on V_{bias} and temperature)
 - **proportionality**
 - **photo-electron counting** (useful for gain monitoring and control)
- Photo-detection efficiency = quantum x geometric x Geiger $\sim 50\%$
- Solid state device: **no HV and very low power consumption** (tens of μW)
 - applications where electricity supply is not available
(muon radiography of volcanoes, physics in space, ...)

Rumore dei SiPM

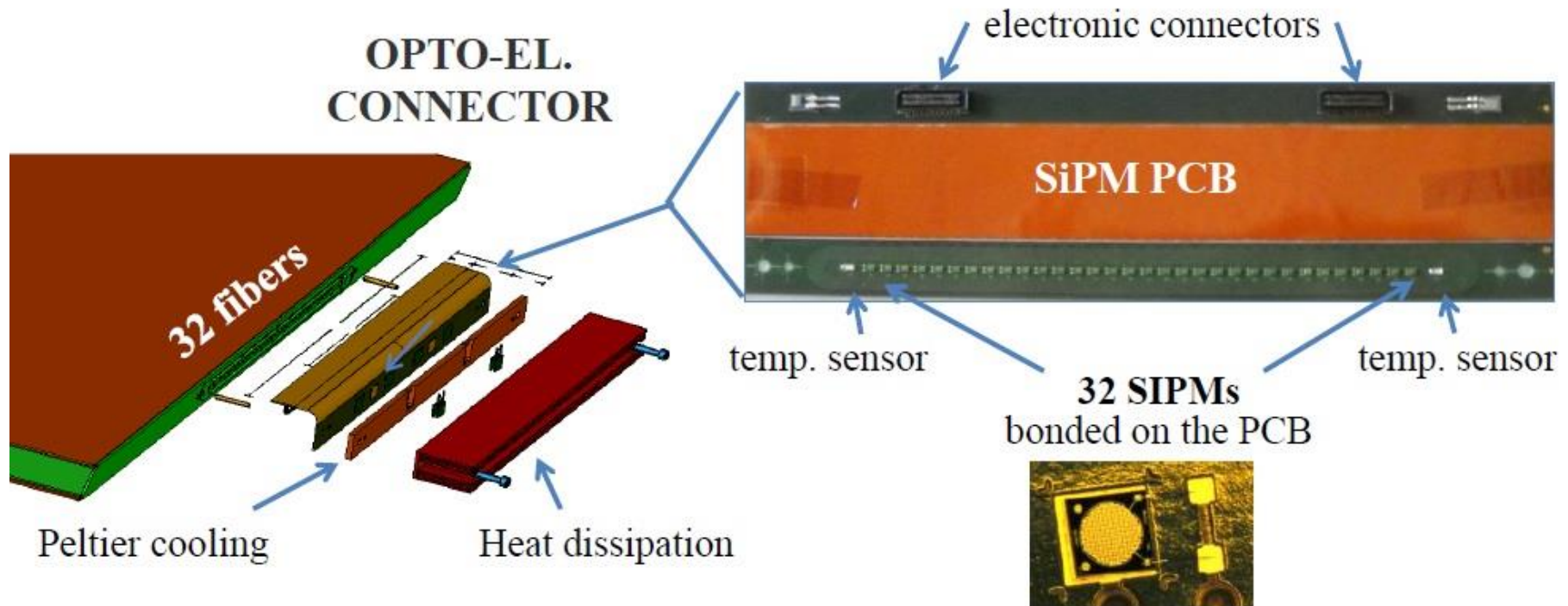
- cresce con la temperatura
 - mantenere T costante $<25^{\circ}\text{C}$
- decresce come $\sim 10^{-1}/\text{pe}$
 - soglia su Npe
 - coincidenze multiple
- (purtroppo quelli della FBK sviluppati per MURAY erano inaspettatamente rumorosi!)



Dark noise rate (FBK-IRST)

SiPM PCB e connettore optoelettronico

- ❑ Naked SiPMs wire bonded on a custom designed **Printed Circuit Board (PCB)** thermally isolated from the environment : cool only the SiPMs (Peltier)
- ❑ PCB mounted on the **opto-electronic connector** : fibers and corresponding SiPMs are relatively positioned within $<100 \mu\text{m}$



L'elettronica di front-end



Based on the
Application-Specific Integrated Circuit (ASIC)

SPIROC -> EASYROC

(developed by the Omega group at LAL-Orsay)

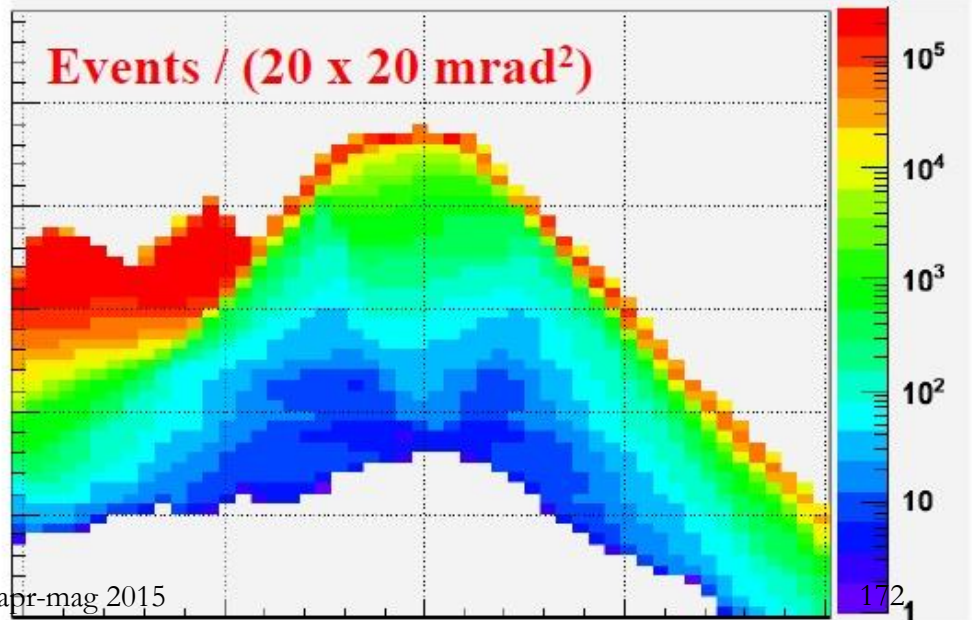
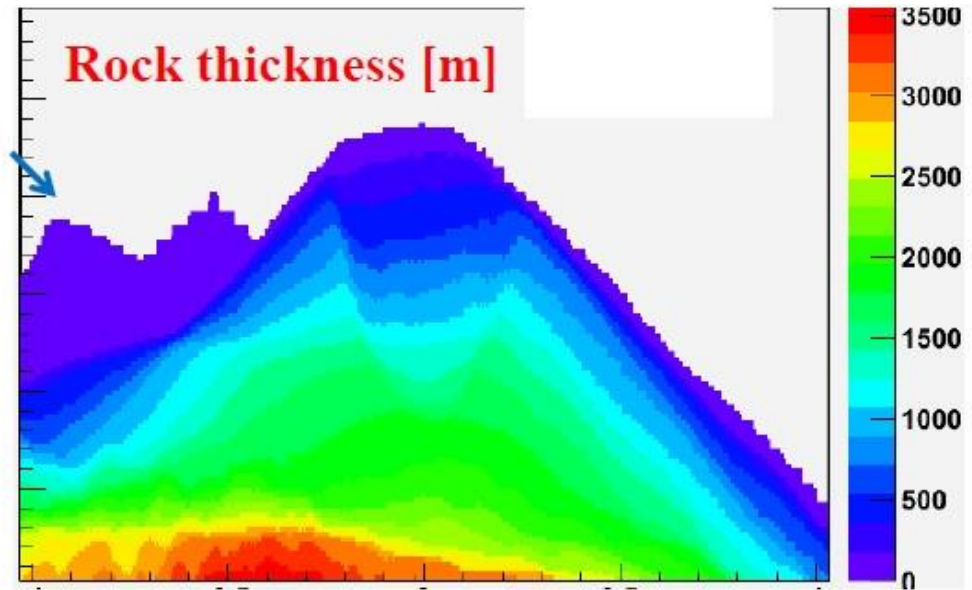
SPIROC1 (designed for collider experiments) **at present**

- Up to 36 channels (SiPMs) management
- Independent V_{bias} fine setting for gain control of each SiPM
- Independent threshold setting for each channel
- Variable gain for signal amplification
- Fast amplifier for time measurement
- Power consumption 20 μW /channel
- Multiplexed analog output
- External trigger

SPIROC-light (designed for experiments in space) **in the future**

Simulazione del Vesuvio (prototipo 1 m², 1 anno, senza fondo)

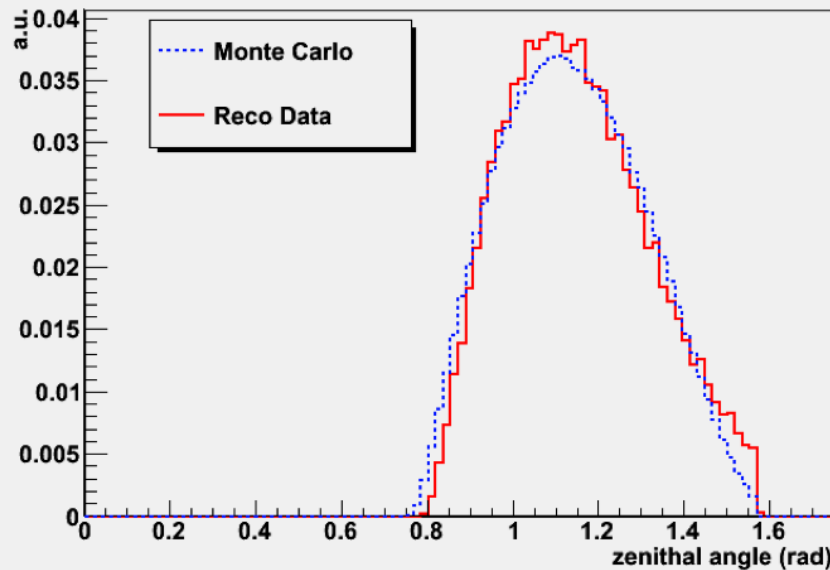
Mt. Somma



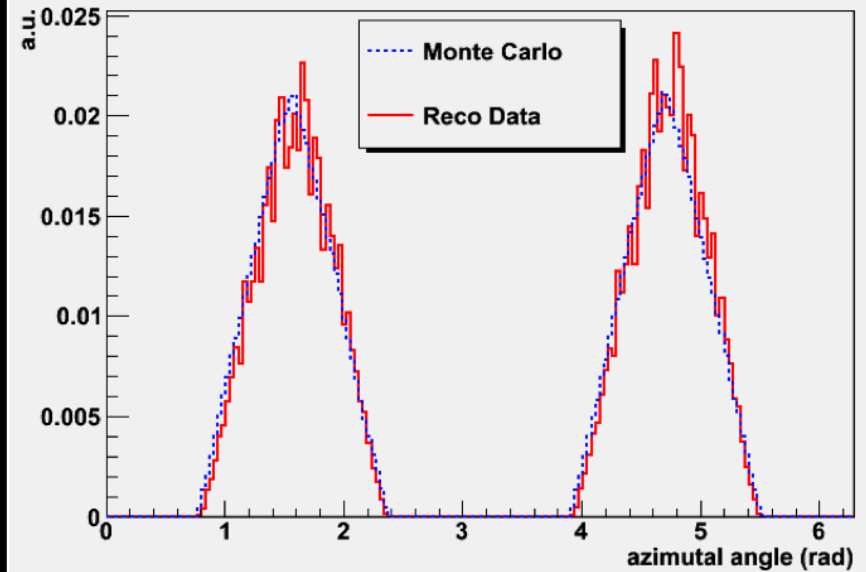
Forthcoming first step in the
“Mt. Vesuvius challenge”

Dati a cielo aperto vs MC

Comparison Monte Carlo - Reco Data

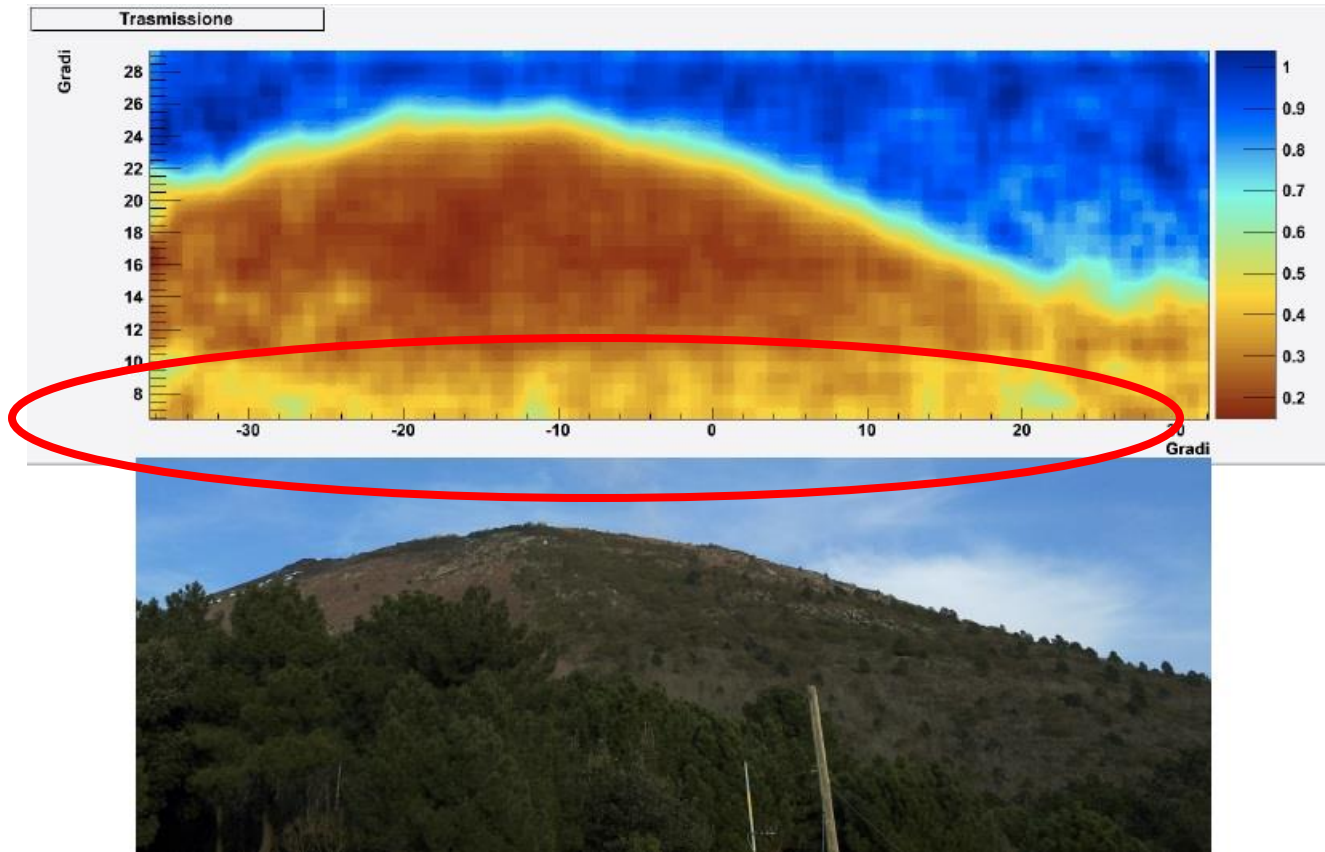


Comparison Monte Carlo - Reco Data



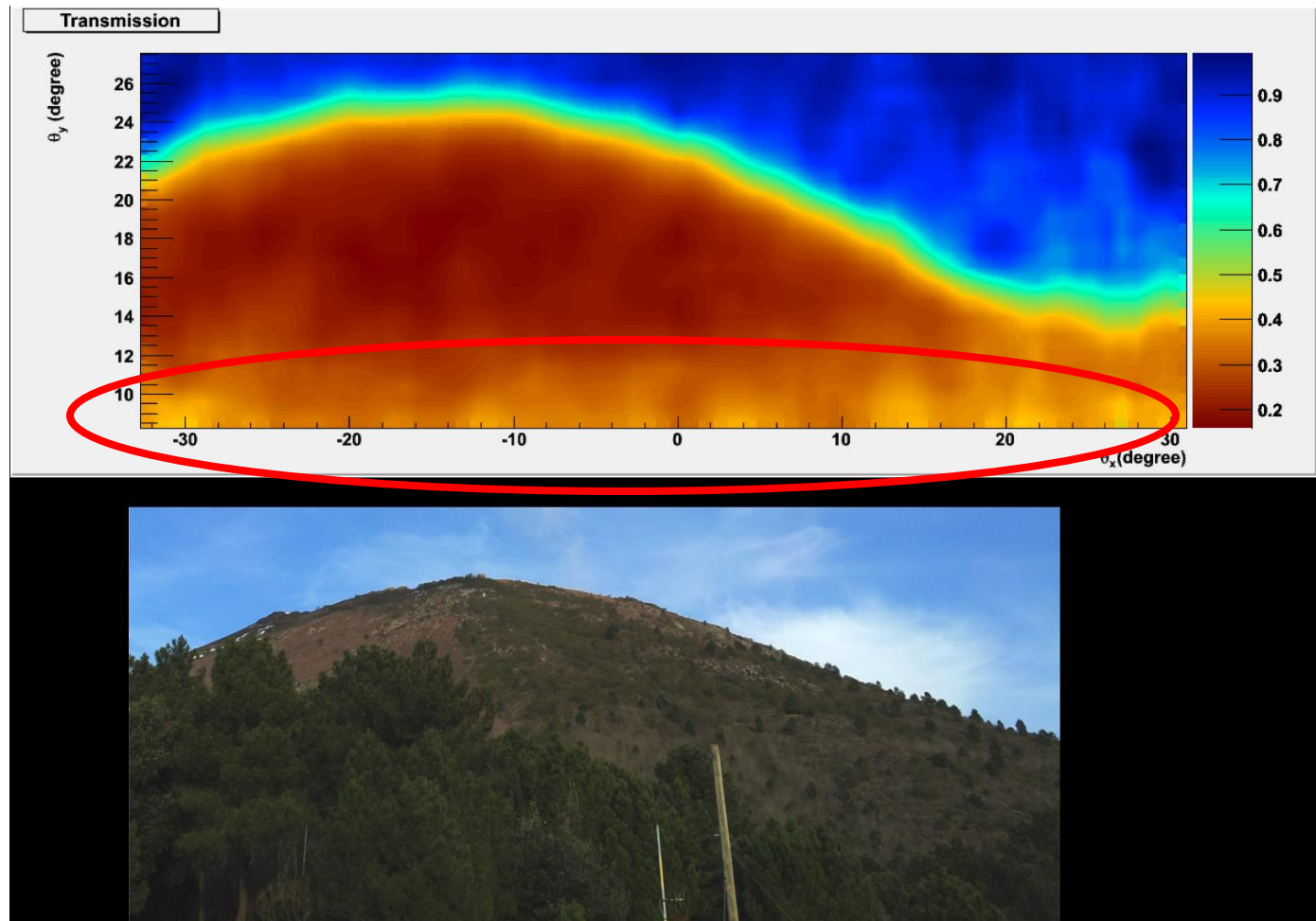
- una settimana di presa dati; buon accordo: un po' di fondo per i mu orizzontali ($>80^\circ$), forse mu dal verso sbagliato (la misura del tof non era attiva)

Primi dati del Vesuvio: una settimana di presa dati (1a versione)

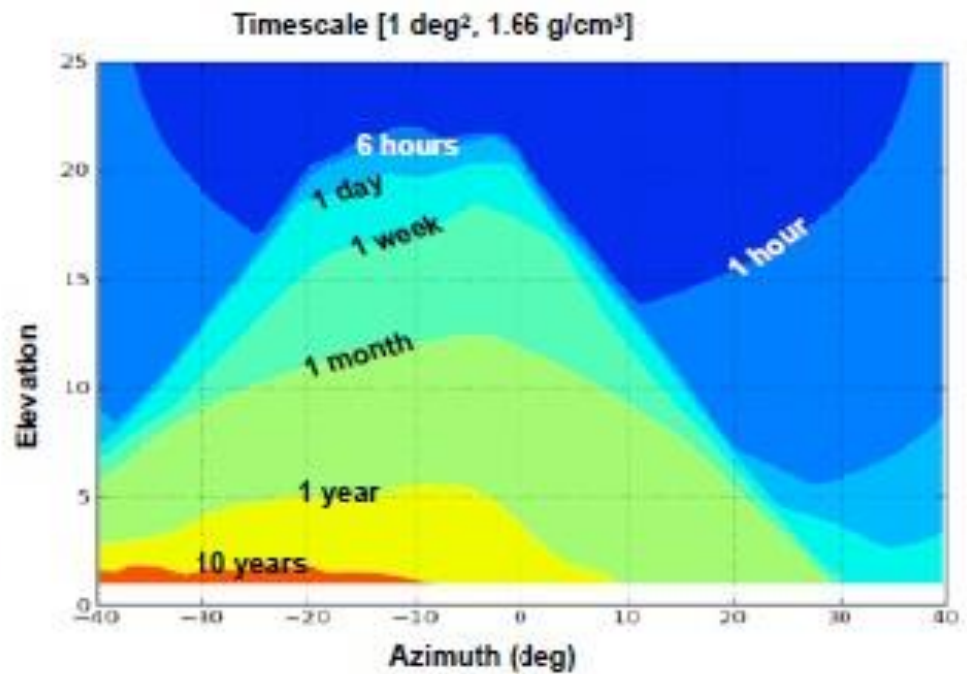
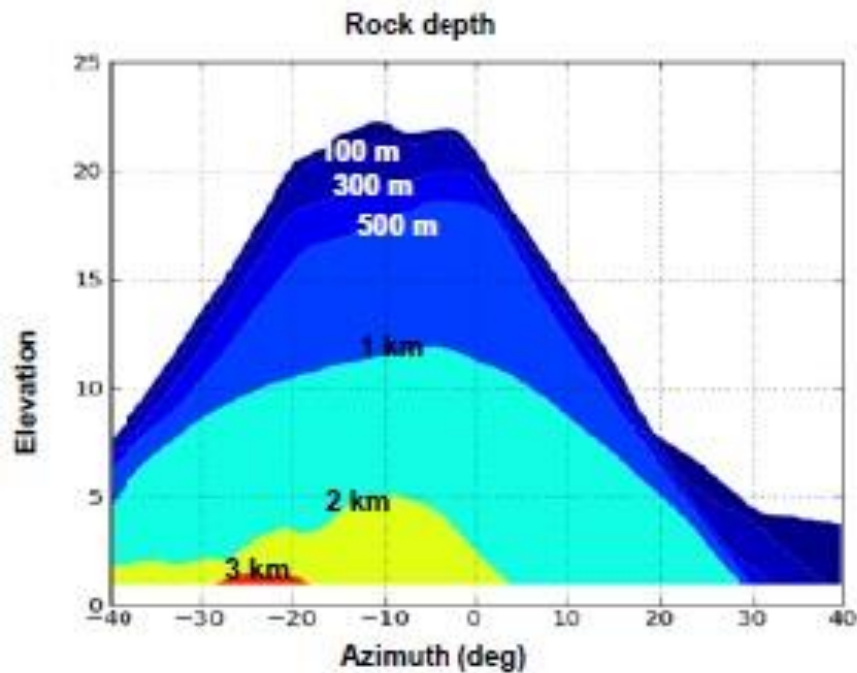


Primi dati del Vesuvio: una settimana di presa dati (2a versione)

lab. INGV
attrezzato, ma
problemi di
alimentazione
per il
raffreddamento,
run corti e
continue
calibrazioni,
inefficiente
continuare più a
lungo



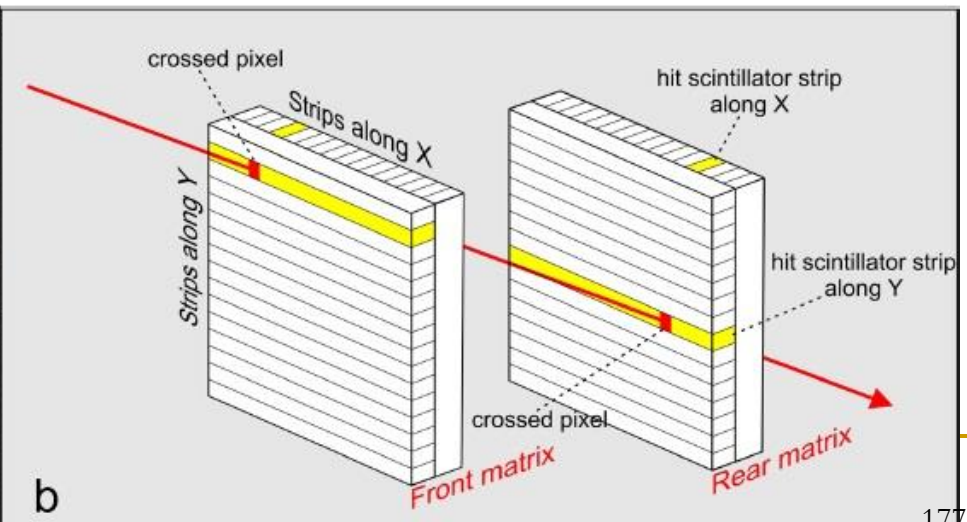
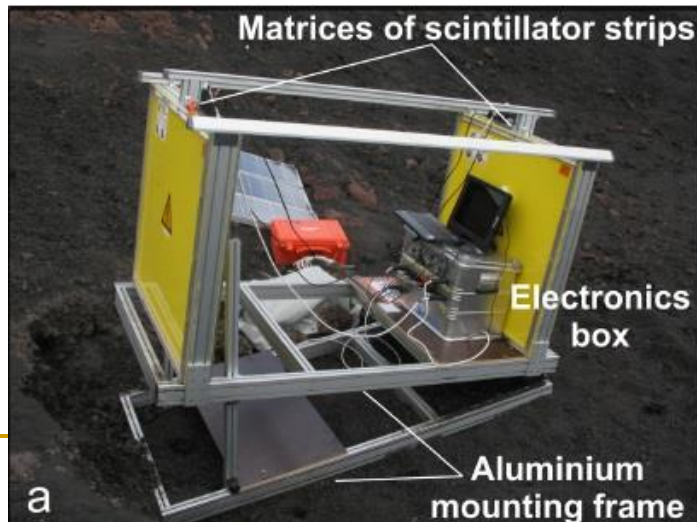
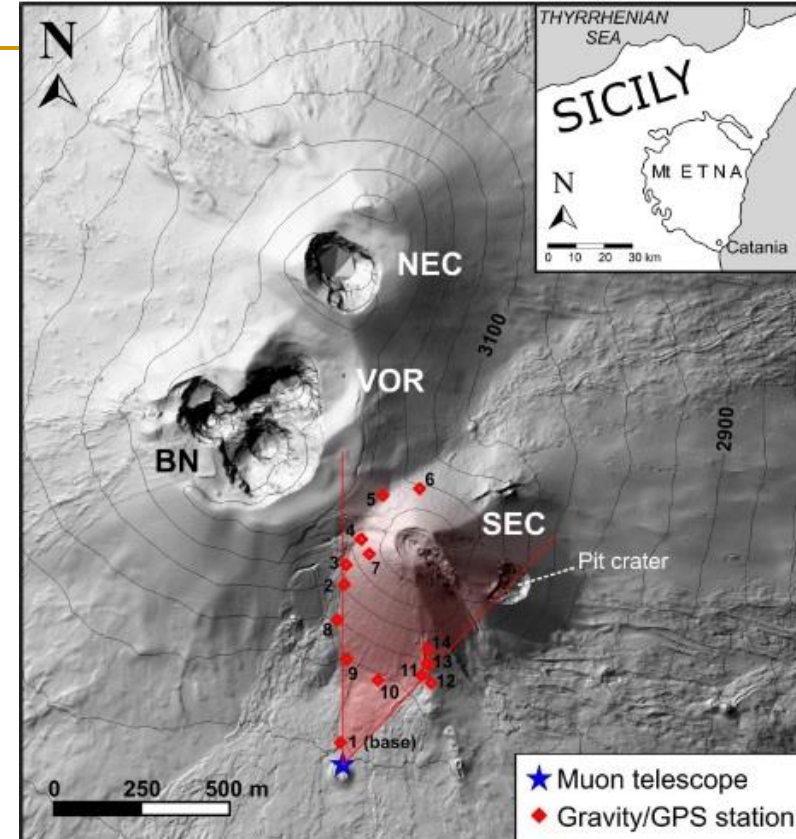
Tipici tempi di misura in funzione dello spessore di roccia



Computation for a uniform target with $\rho=1.66\text{g/cm}^3$ and a 0.67 m^2 ideal detector

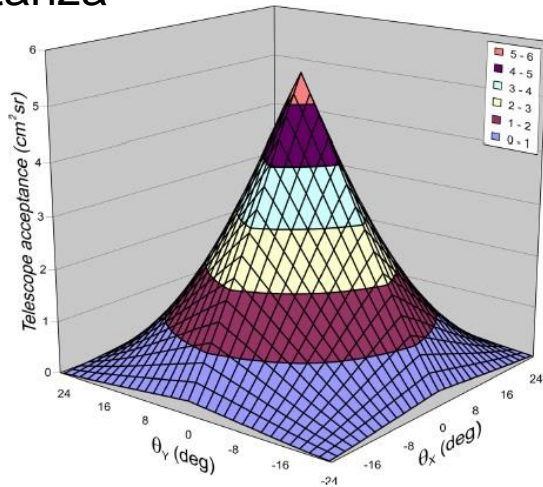
L'Etna (estate 2010)

- scintillatori plastici (5 cm) 16x16 per piano (256 pixel), lettura con fibre WLS e MAPMT, distanza fra i piani 170 cm, a circa 170 cm, ossia una risoluzione di 20 m a circa 650 m (30 mrad) dal vulcano

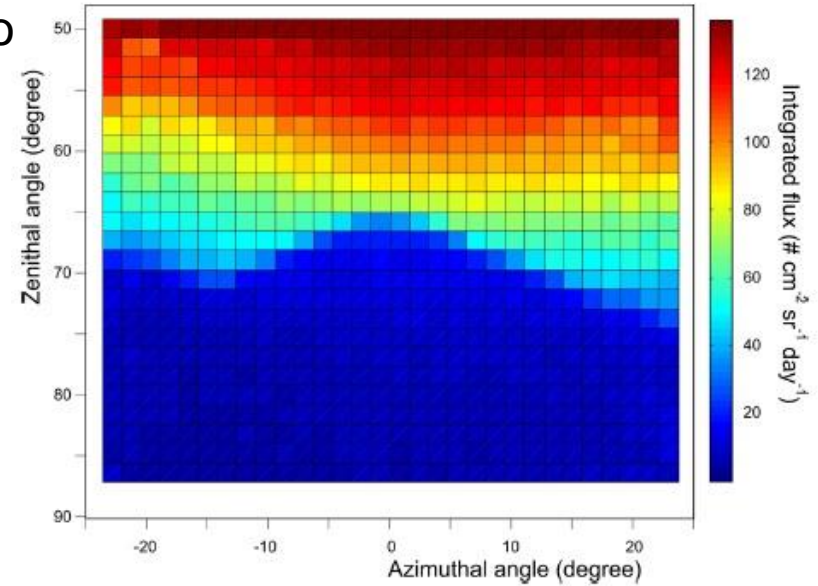


L'Etna/2

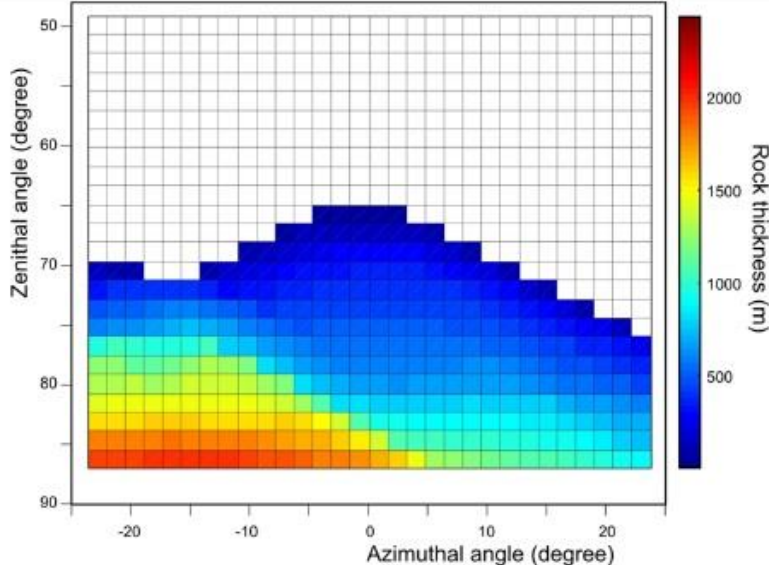
accettanza



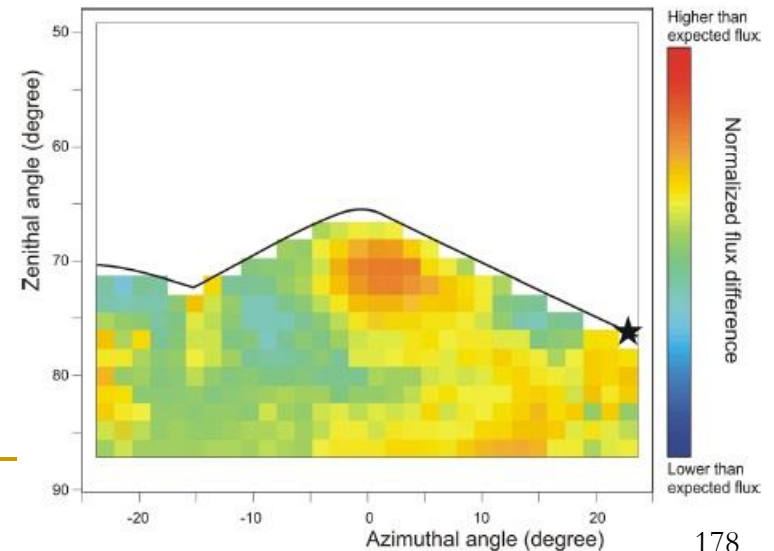
flusso integrato
su 30 giorni



lo spessore di roccia



flusso normalizzato ad un modello
omogeneo, * indica un cratere laterale



Vari (altri) tipi di rivelatori

Scintillators

DIAPHANE



position res: 35 mm
angular res(@1m) : 35 mrad
time resolution : 1 ns
surface: 0.64 m²

Micromegas

T2DM2



position res: 0.22 mm
angular res(@10 cm) : 2 mrad
time resolution : 25 ns

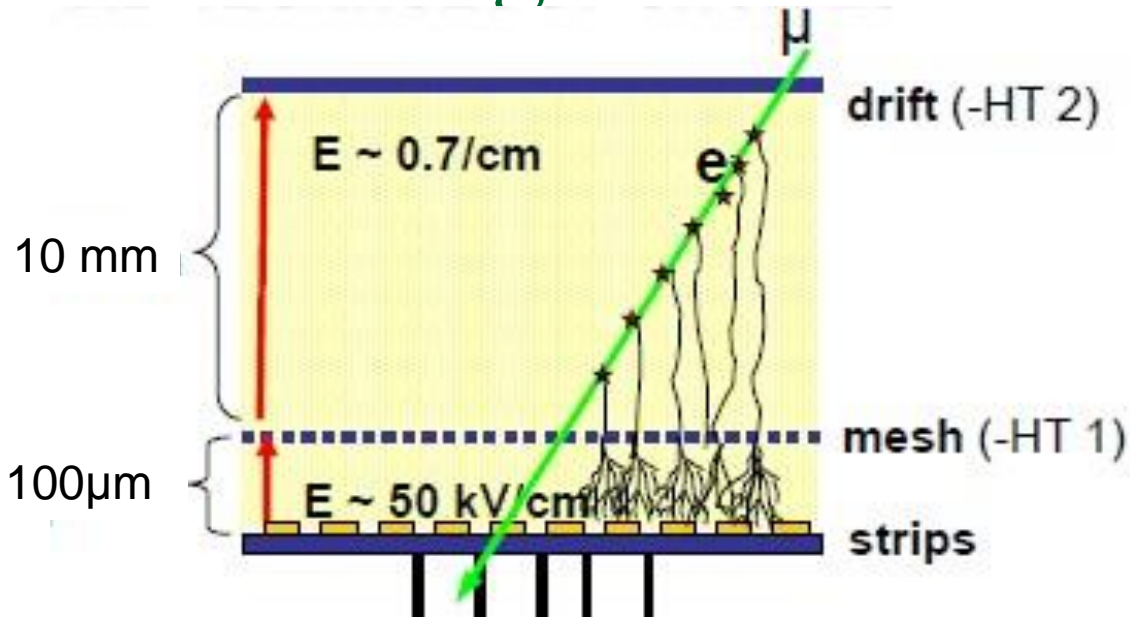
GRPCs

TOMUVOL



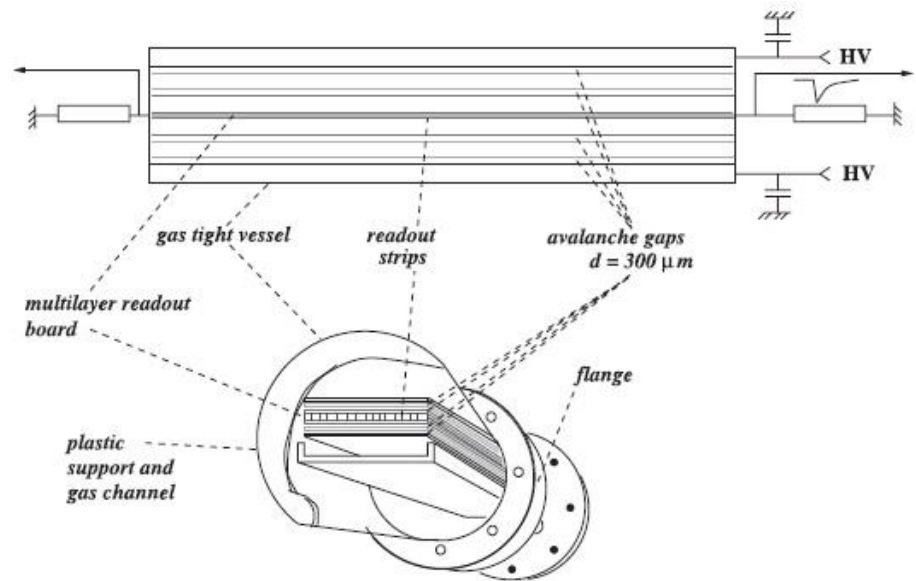
position res: 4 mm
angular res(@1m) : 4 mrad
time resolution : 200 ns
surface: 1 m²

Micromegas e GRPC



Micromegas
 HV ~ 1-1.5 kV
 p = 1 atm
 Ar, CF₄, C₄H₁₀ (88/10/2)

Glass RPC
 HV ~ 6-7 kV
 p = 1 atm
 C₂F₄H₂; SF₆, C₄H₁₀ (85/10/5)



Bibliografia

- N. Lesparre et al., Geophysical muon imaging: feasibility and limits, *Geophys. J. Int.* (2010) **183**, 1348
- International Workshop on "Muon and Neutrino Radiography 2012"
<https://indico.in2p3.fr/contributionListDisplay.py?confId=6275>
- International Workshop on "Muon and Neutrino Radiography 2013", <http://www.eri.u-tokyo.ac.jp/ht/MNR13/>
- G. Saracino, presentazione alla commissione V dell'INFN, maggio 2013
- F. Ambrosino et al., The MU-RAY project: detector technology and first data from Mt. Vesuvius, 2014 *JINST* **9** C02029

2. Diffusione dei μ : applicazioni

- LANL L. Schultz, K. Borozdin et al., Rivelazione di materiali ad alto Z con DC/DT (sicurezza), 2003, 2004 →
- Pd-LNL-Bs-Ge P. Checchia et al., Rivelazione di materiali ad alto Z con le DT di CMS, 2004 →
- Tsinghua Univ., ITEP Protvino, DT di ATLAS
- FloridaInstTechnology M. Holmann et al., Rivelazione di muoni con GEM GasElectronMultipliers, (2006)2007 →
- Altri: US commerciale (Decision Science), in coll. con LANL, UK, Canada

Bibliografia iniziale essenziale

■ LANL

- ❑ K. Borozdin, et al., Nature 422 (2003) 277.
- ❑ L.J. Schultz et al., Nucl. Instrum. Meth. A 519 (2004) 687–694.
- ❑ L.J. Schultz et al., IEEE Trans. on Image Proc. 16 (2007) 1985.

■ Pd-LNL-Bs-Ge

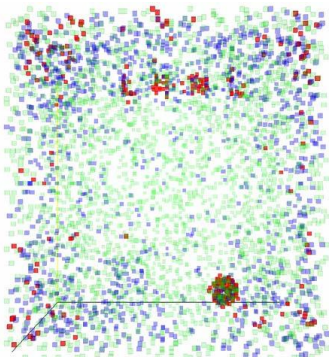
- ❑ S. Pesente et al., First results on material identification and imaging with a large-volume muon tomography prototype, Nucl. Instr. Meth. A604 (2009) 738
- ❑ <http://muradio.pd.infn.it> e bibliografia citata

I primi a occuparsi del problema

Original idea from Los Alamos (2003):
Muon Tomography with Drift Tubes

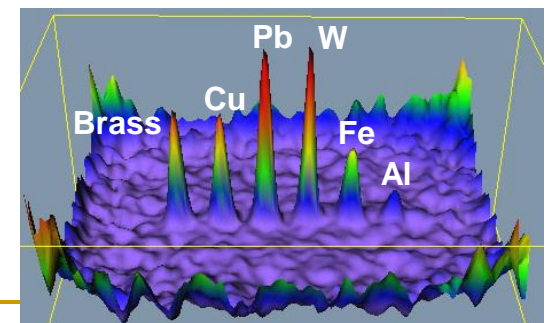


INFN Padova, Pavia & Genova: Muon Tomography
with spare CMS Muon Barrel Chambers (Drift Tubes)



J.A. Green et al., "Optimizing the Tracking Efficiency for Cosmic Ray Muon Tomography", LA-UR-06-8497, IEEE NSS 2006

E. Conti et al., IPRD08 Siena, October 2008



Efforts also by Tsinghua U., IHEP Protvino
— (ATLAS chambers), Decision Science (U.S. commercial) collaborates with LANL

fln apr-mag 2015

Qual'è il problema?

may

- Terrorist **smuggle highly enriched uranium (HEU)** or plutonium across borders and destroy a city by detonating a nuclear bomb, or

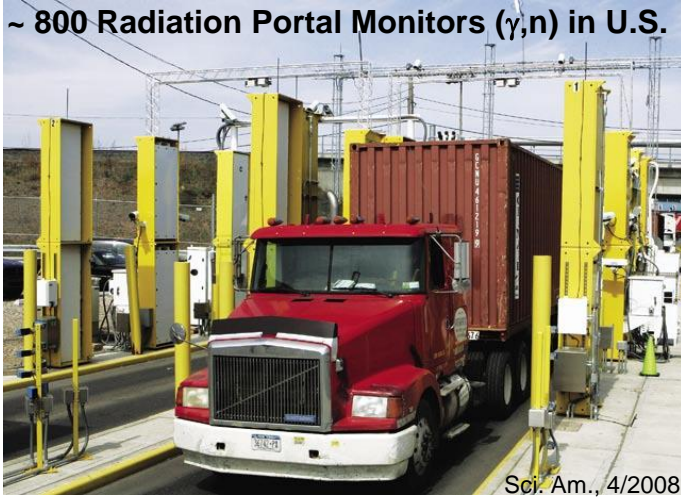
- Terrorists **smuggle highly radioactive material** into a city and disperse it with a conventional explosion (“dirty bomb”) making portions of the city uninhabitable.



T.B. Cochran and M.G. McKinzie, Scientific American, April 2008

Problema con il contrabbando nucleare

~ 800 Radiation Portal Monitors (γ, n) in U.S.



Sci. Am., 4/2008

- In 2002, reporters managed to smuggle a cylinder of **depleted uranium (DU)** shielded in lead in a suitcase from Vienna to Istanbul via train and in a **cargo container through radiation monitors into NY harbor**. Cargo was even flagged for extra screening, but DU undetected.
- In 2003, took route Jakarta – LA, same result...



6.8 kg DU



HEU can be **hidden** from conventional radiation monitoring because it **is easy to shield emanating radiation** within regular cargo

NATIONAL SECURITY

DETECTING NUCLEAR SMUGGLING

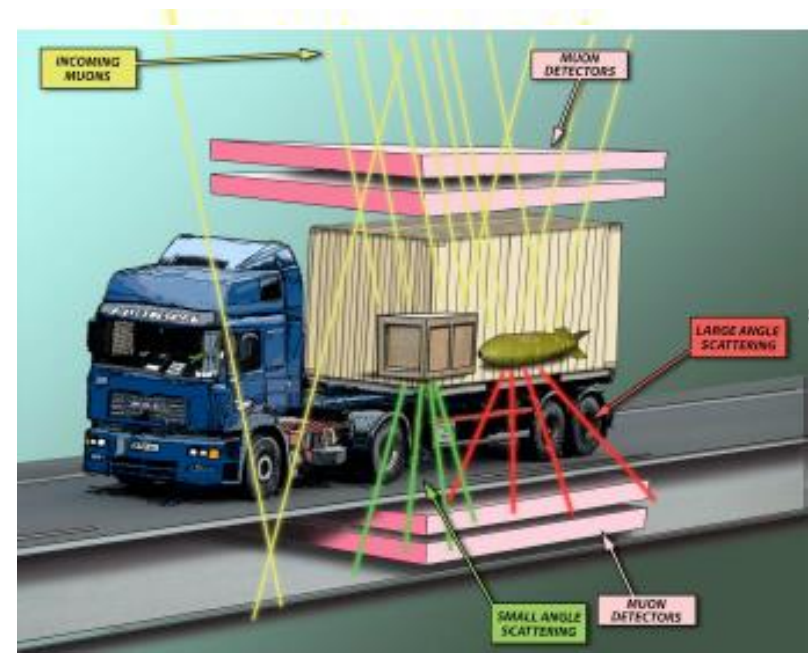
! Radiation monitors at U.S. ports cannot reliably detect highly enriched uranium, which onshore terrorists could assemble into a nuclear bomb !

By Thomas B. Cochran and Matthew G. McKinzie

Scientific American, April 2008

Los Alamos Muon Detector Could Thwart Nuclear Smugglers

Existing radiographic methods are inefficient for detecting shielded nuclear materials and present radiation hazards to inspectors and vehicle passengers. Muon radiography uses the natural scattering of muons - produced by the decay of cosmic rays showering down on Earth - as a radiographic probe. In fact, efforts to shield nuclear materials with lead or similar heavy metals make a smuggled object easier to detect with muons.



Vantaggi

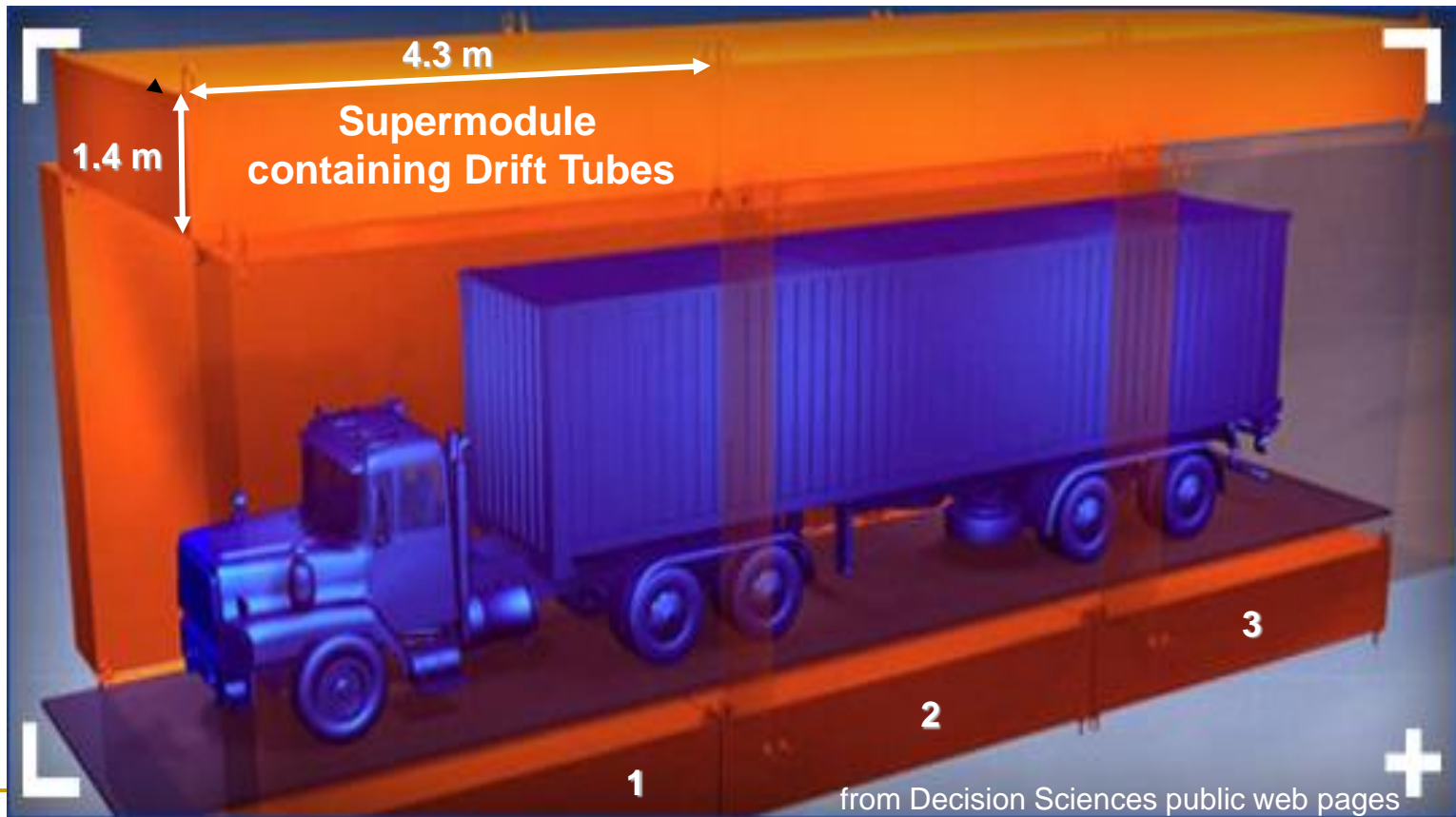
- Un vantaggio delle radiografie con μ è la loro abilità a discriminare fra materiali usati tipicamente per la schermatura e materiali meno densi. Con un'energia media di 3 GeV, gran parte dei μ possono penetrare circa 180 cm di Pb (circa 240 cm di Fe).
- 2° vantaggio: i μ cosmici arrivano da tutte le direzioni permettendo di ottenere un imaging tomografico in 3D
- I raggi γ sono molto meno penetranti, producono soltanto immagini bidimensionali confuse, che necessitano interpretazioni addizionali e richiedono materiali pericolosi come il ^{60}Co .

Svantaggi → vantaggio

- Uno svantaggio dei sistemi di rivelazione tipo quelli in uso negli aeroporti è la necessità che gli operatori interpretino immagini e dati. L'automazione insita nell'algoritmo di Los Alamos (vedi più avanti) rende più semplice il lavoro degli ispettori poiché non converte i dati da circa un milione di coordinate del rivelatore in immagini. Invece, usando tecniche di machine learning, l'algoritmo è allenato con esempi noti finché non può decidere autonomamente se siano presenti una bomba, materiali nucleari o schermatura (con una frazione di falsi positivi e falsi negativi $< 3\%$).
- Un prototipo di rivelatore può radiografare grossi oggetti metallici (eg camion, container) in 60s → 20s [con qualche miglioramento nel software]

Una possibile realizzazione commerciale

Design by Decision Sciences Corp. in cooperation
with Los Alamos National Lab



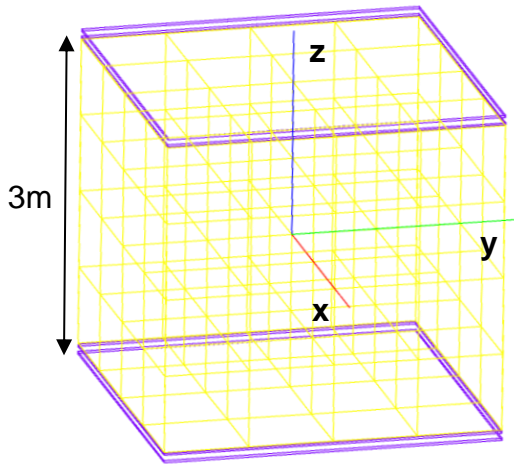
Una possibile realizzazione su larga scala



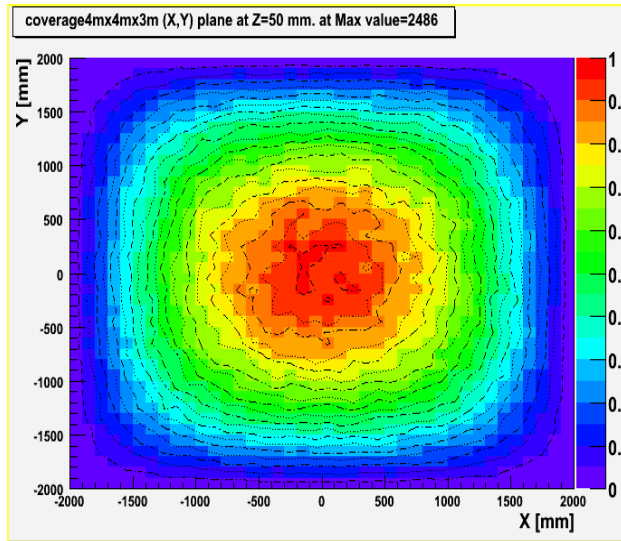
Possibili geometrie

MT station type

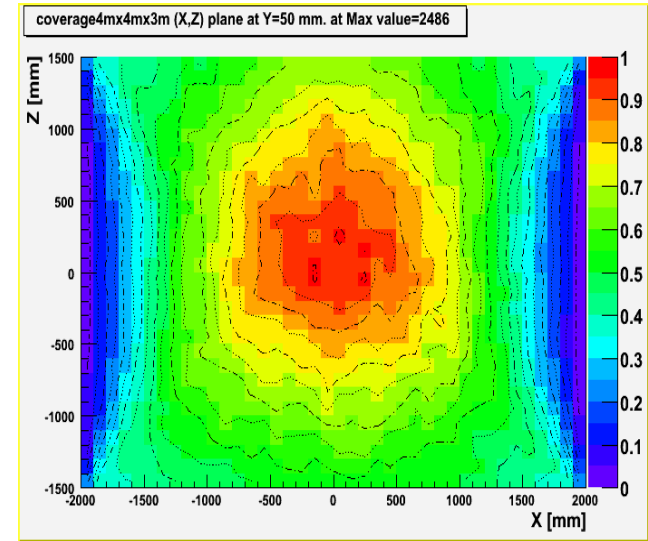
Top & bottom detectors only



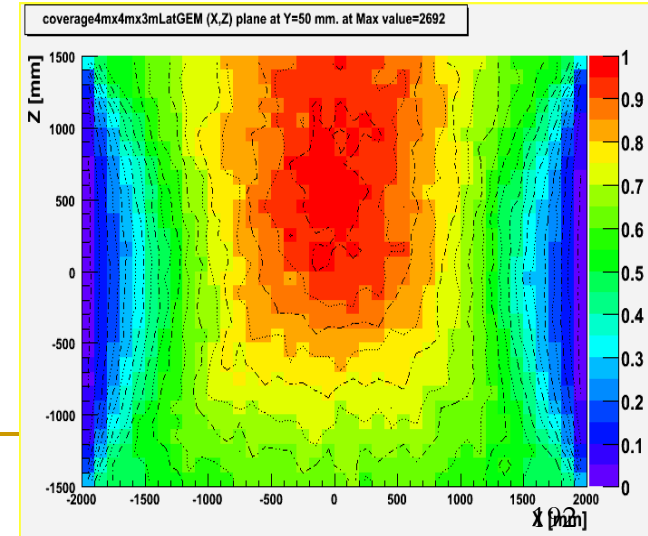
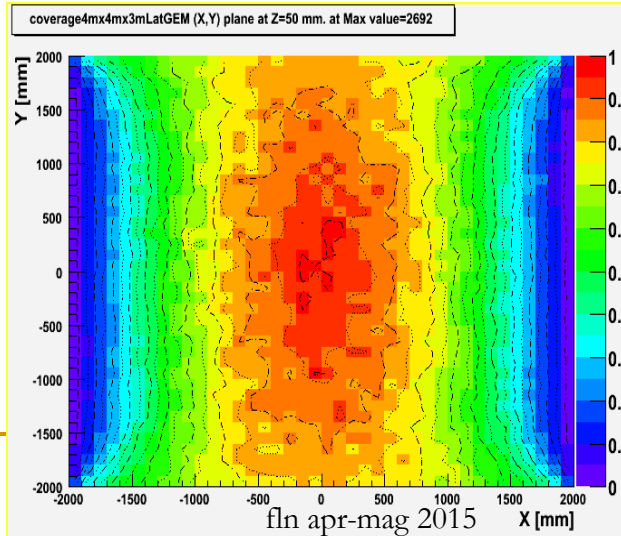
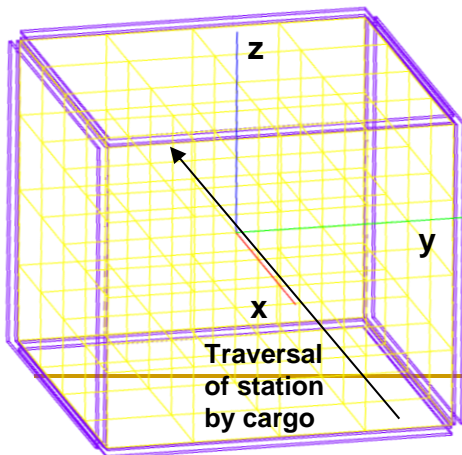
Top View (x-y plane)



Side View (x-z plane)

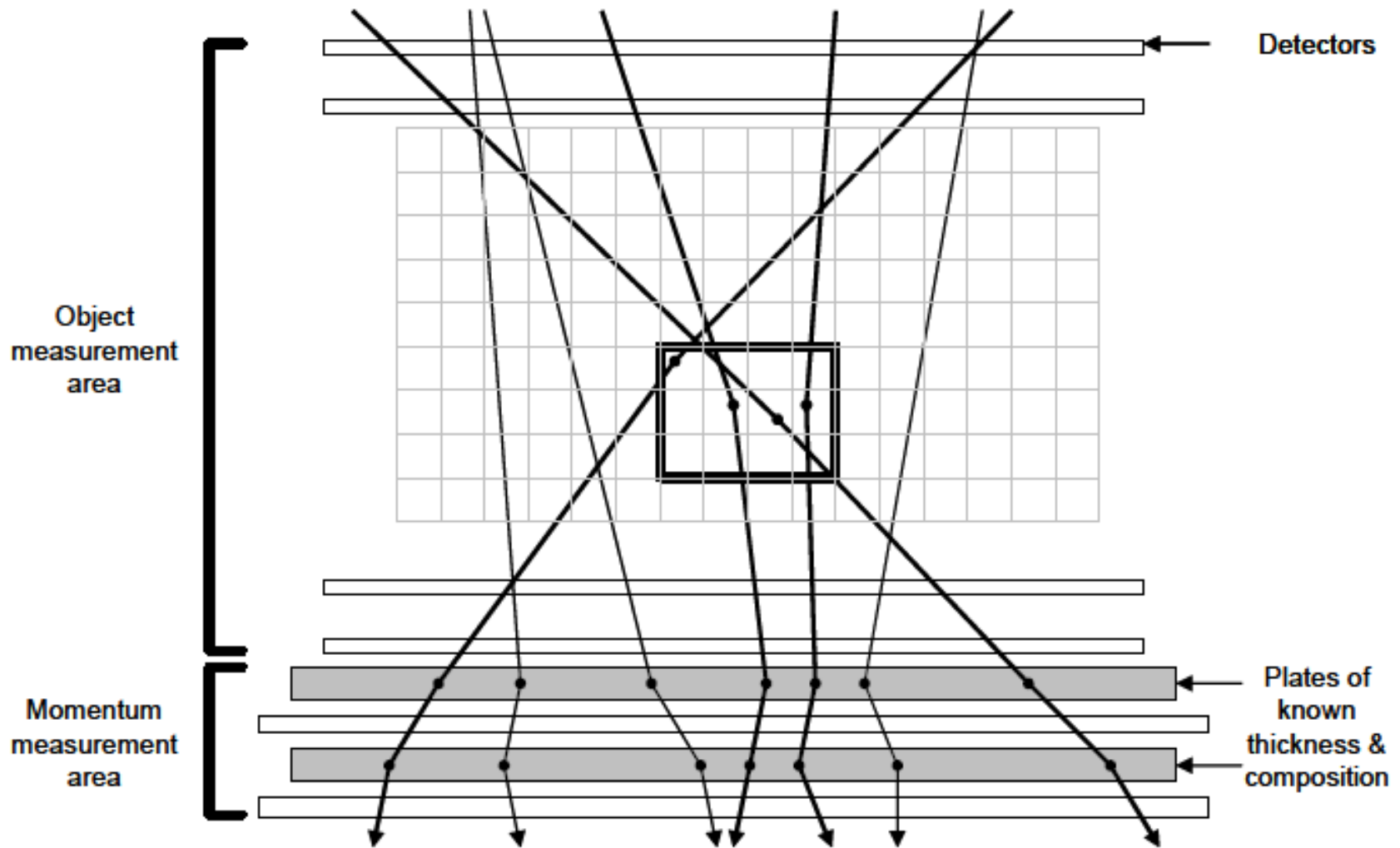


Top, bottom & side detectors



fln apr-mag 2015

Schema di principio (LANL & Pd)



Scattering multiplo in uno spessore L

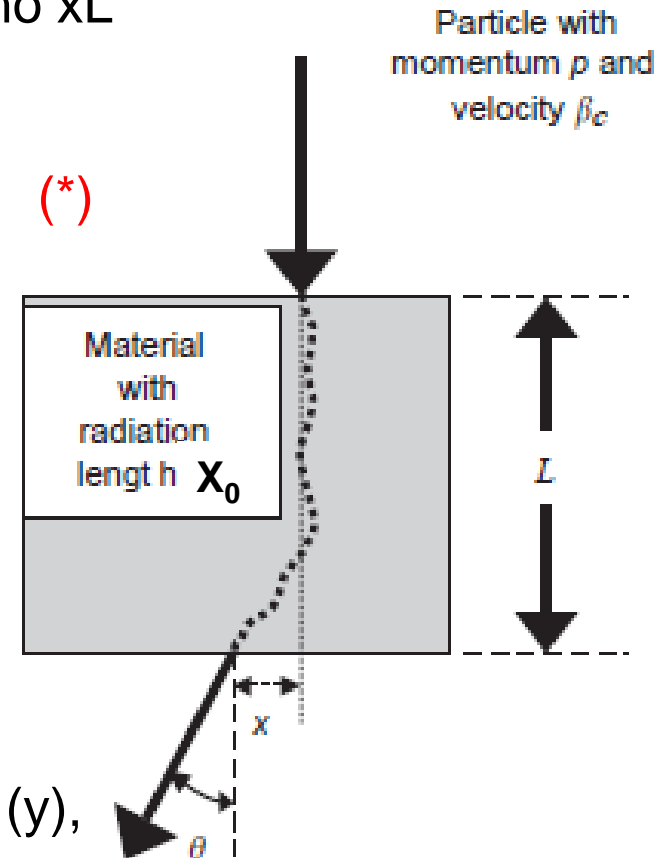
$$\frac{dN}{d\theta} = \frac{1}{\sigma_\theta \sqrt{2\pi}} \exp\left(-\frac{\theta^2}{2\sigma_\theta^2}\right) \quad \text{in un piano } xL$$

$$\sigma_\theta = \frac{13.6 \text{ MeV}}{\beta c p} \sqrt{\frac{L}{X_0}} \left[1 + 0.038 \ln\left(\frac{L}{X_0}\right) \right] \quad (*)$$

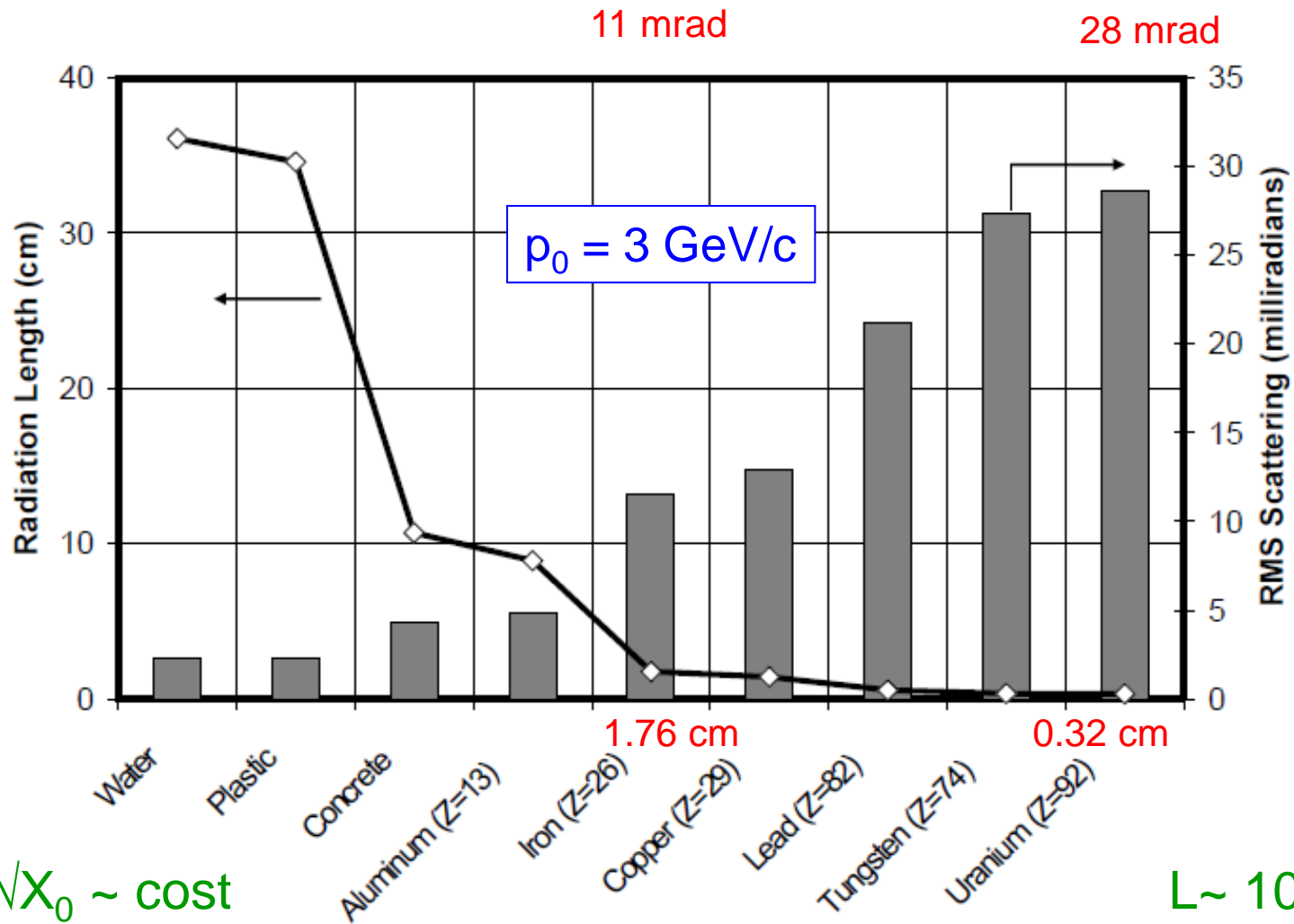
$$\sigma_x = \frac{L}{\sqrt{3}} \sigma_\theta$$

$$\rho_{x\theta} = \sqrt{3} / 2$$

- La distribuzione angolare è \approx gaussiana (al 98% + lunghe code)
- X_0 - lunghezza di radiazione (Z)
- nel piano \perp a xL : distribuzione indipendente (y), stessi valori
- per $\beta=1$, (*) valida entro 11%, $\forall Z, L \in (0.001, 100) X_0$
(Lynch & Dahl, 1991)



Scattering multiplo – diversi materiali



$$\theta_{\text{RMS}} \sqrt{X_0} \sim \text{cost}$$

$L \sim 10 \text{ cm}$

Identificazione del materiale via μ scattering

- μ : $\beta c = 1$; dimentichiamo il \ln

$$\sigma_{\theta} \approx \frac{13.6 \text{ MeV}}{p} \sqrt{\frac{L}{X_0}}$$

- fissiamo un impulso, eg $p_0 = 3 \text{ GeV}/c$; def: scattering quad. medio di μ nominali per unità di spessore – scattering strength

$$\lambda_{\text{mat}} = \left(\frac{13.6}{p_0} \right)^2 \frac{1}{X_{0,\text{mat}}} (\cong \sigma_{\theta_0,\text{mat}}^2) \quad \text{mrad}^2/\text{cm} \quad \begin{array}{l} \text{Fe} \sim 12 \text{ mrad}^2/\text{cm} \\ \text{U} \sim 65 \quad \quad \quad \text{“} \end{array}$$

$$\hat{\lambda} = \frac{1}{N} \sum_{i=1}^N \left(\frac{p_i^2}{p_0^2} \frac{\theta_{xi}^2 + \theta_{yi}^2}{2L_i} \right)$$

N muoni, due viste, impulso p_i , spessore attraversato L_i

Errori

$$\frac{\Delta\lambda}{\lambda} \cong \frac{\Delta N}{N} = \sqrt{\frac{1}{N}} \quad \text{eg } 10 \text{ cm}^3; 100 \text{ } \mu\text{/min}; 10\%/\text{min}$$

- tenendo ora conto dell'errore sulla stima di p_i , $\Delta p/p = \varepsilon_p$

$$\hat{\lambda} = \frac{1}{N(1 + \varepsilon_p^2)} \sum_{i=1}^N \left(\frac{p_i^2}{p_0^2} \frac{\theta_{xi}^2 + \theta_{yi}^2}{2L_i} \right)$$

- lo scattering in uno spessore noto permette 2 (x,y) stime di p : date $M(>4)$ misure si ha

$$\frac{\Delta\lambda}{\lambda} \cong \sqrt{\frac{1}{N}} \sqrt{\frac{M-1}{M-4}}$$

- in effetti (MC): l'incertezza con $M=4$ è circa doppia rispetto a $M=6$ → con due spessori, $\Delta\lambda/\lambda$ diventa $3.2 \cdot \sqrt{N}/N$

Identificazione di materiali di Z diverso

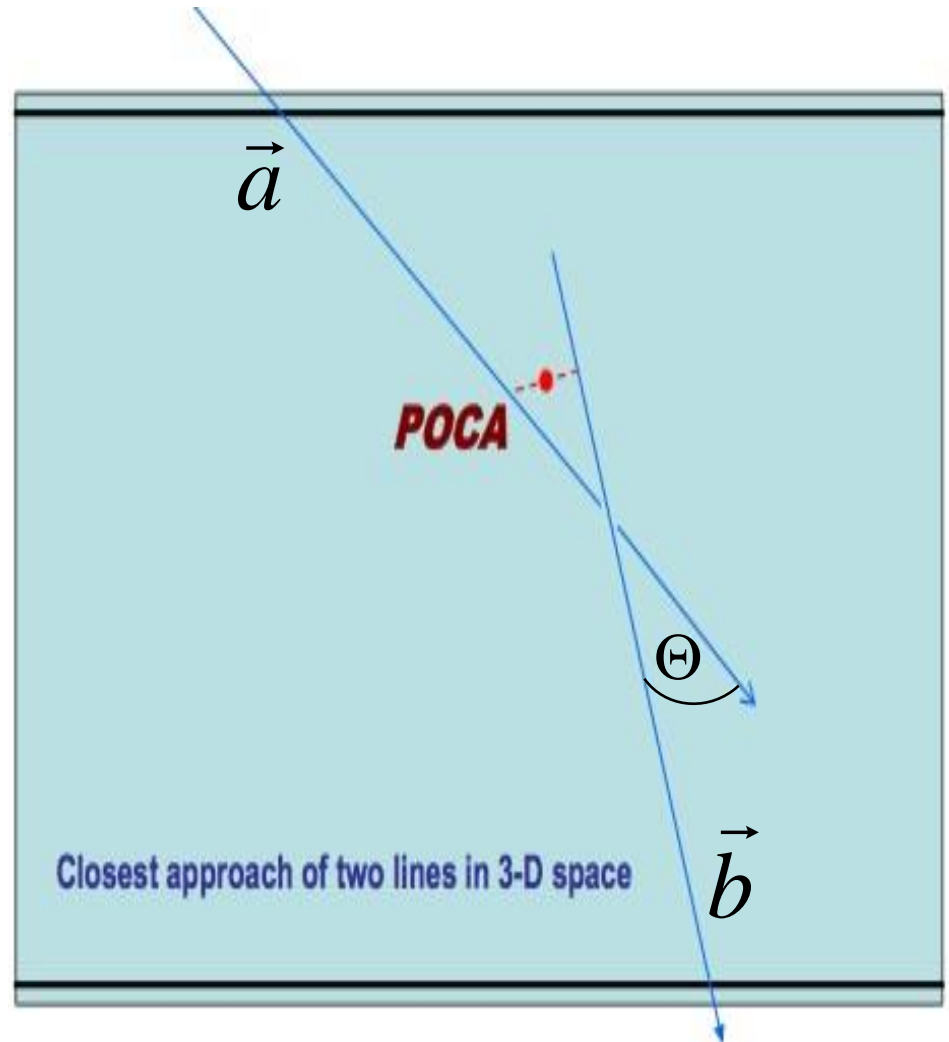
- grosso modo: tre blocchi, 10 cm^3 (cemento, Fe, U); 100μ in 1 min; tre spessori per la misura di p ($3\Delta\lambda/\lambda \sim 50\%$)
- $\lambda_{\text{cemento}} = 1.6 \text{ mrad}^2/\text{cm}$
intervallo di confidenza con 3σ [0.8,2.3]
- $\lambda_{\text{Fe}} = 11.7 \text{ mrad}^2/\text{cm}$
i.c. [5.9,16.5]
- $\lambda_{\text{U}} = 65 \text{ mrad}^2/\text{cm}$
i.c. [33,98]
- chiaramente separabili in 1 min

con due spessori: i tempi aumentano: per una separazione min ci vogliono 2 min

Ricostruzione

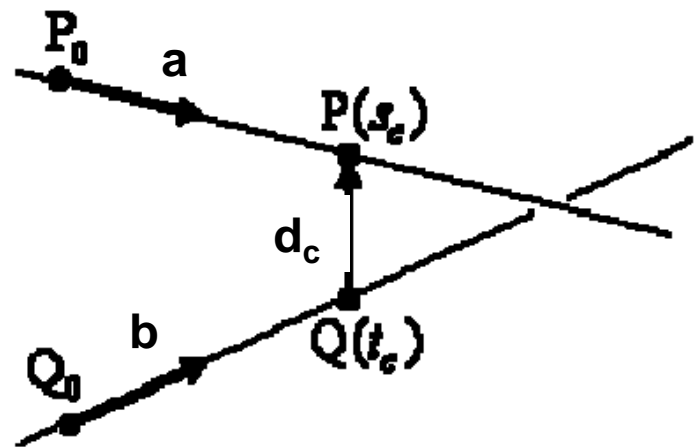
- Algoritmo di ricostruzione semplice usando il **Point of Closest Approach** (PoCA) delle tracce incidenti e uscenti in 3-D
- Si assume una **singola diffusione**
- Veloce $O(N_\mu)$, memoria $O(1)$
- Angolo di scattering:

$$\theta = \cos^{-1} \left(\frac{\vec{a} \cdot \vec{b}}{|\vec{a}| |\vec{b}|} \right)$$

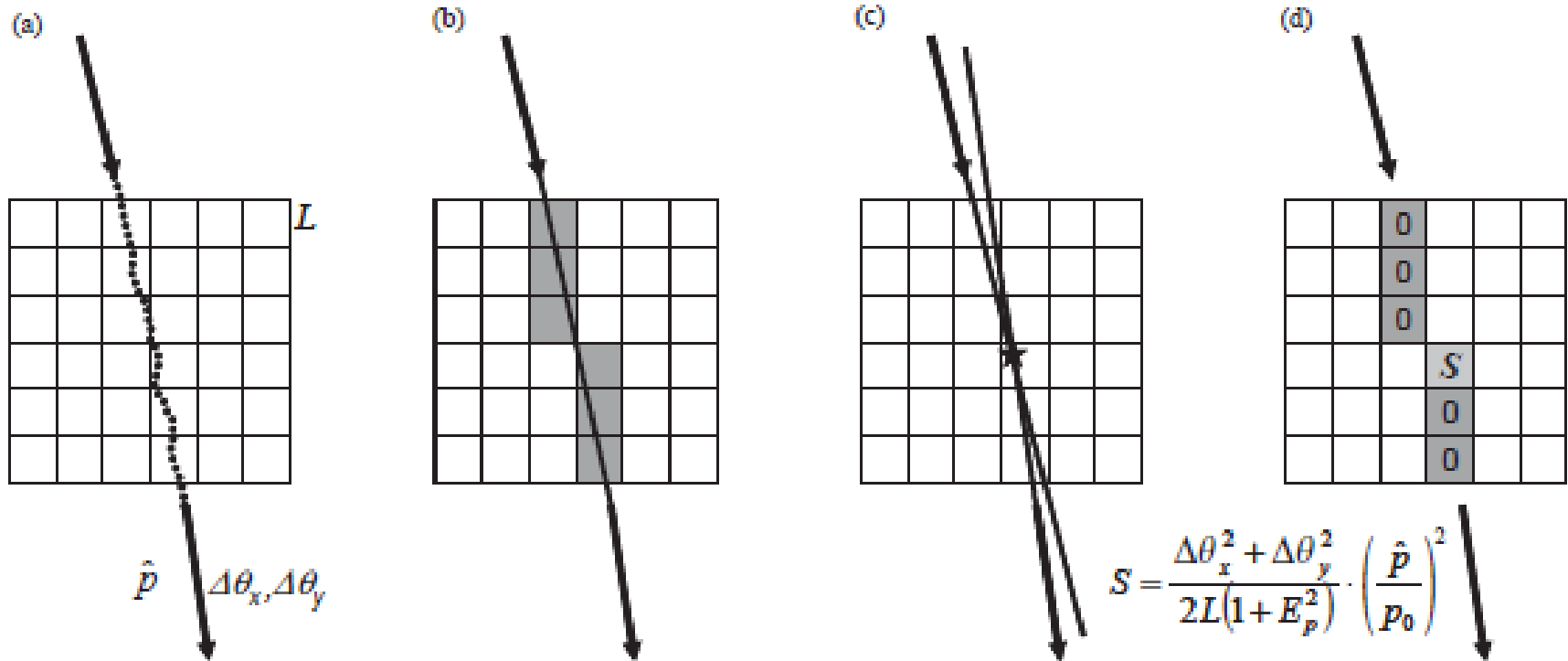


Minima distanza

- date due linee $P(s) = P_0 + s(P_1 - P_0) = P_0 + sa$, $Q(t) = Q_0 + t(Q_1 - Q_0) = Q_0 + tb$, il vettore che unisce due punti è $\mathbf{d}(s,t) = P(s) - Q(t)$ e la minima distanza si ottiene per $|\mathbf{d}(s_c, t_c)| = \min$ per cui $\mathbf{d} \perp \mathbf{a}, \mathbf{b}$ ossia $\mathbf{d} \cdot \mathbf{a} = 0$ e $\mathbf{d} \cdot \mathbf{b} = 0$
- si ottengono 2 eq. da cui si ricava [$\mathbf{a} \cdot \mathbf{a} = A$, $\mathbf{a} \cdot \mathbf{b} = X$, $\mathbf{b} \cdot \mathbf{b} = B$, $\mathbf{a} \cdot \mathbf{d}_0 = A_0$, $\mathbf{b} \cdot \mathbf{d}_0 = B_0$, $\mathbf{d}_0 = P_0 - Q_0$]
 - $s_c = (B_0 X - A_0 B) / (AB - XX)$
 - $t_c = (B_0 A - A_0 X) / (AB - XX)$
- $PoCA = [P(s_c) + Q(t_c)] / 2$



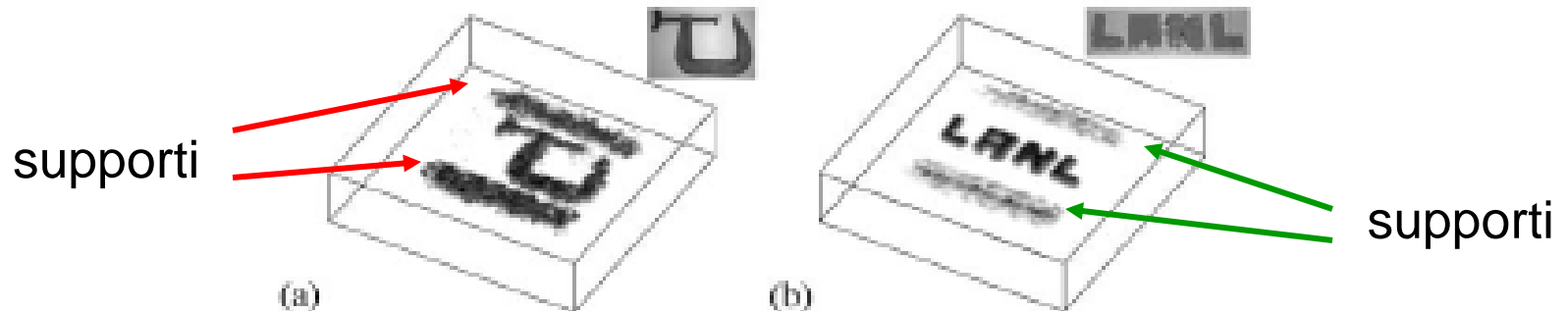
3D: Point of Closest Approach (PoCA)



- a) stima di p (o meno)
- b) voxel attraversati (linea retta, scattering \sim mrad)
- c) PoCA (assumendo un singolo urto)
- d) il segnale (λ) è attribuito a quell'unico voxel

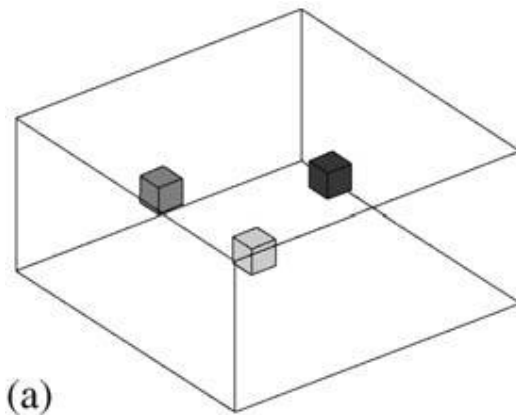
Prova sperimentale

- due gruppi di camere a drift, poste sopra e sotto gli oggetti, **a) un morsetto di Fe** **b) LANL con blocchetti di Pb da 1"**; 400 μm FWHM, 2 mrad FWHM; angolo solido limitato, p non misurato; 100k μ , ossia ~ alcune ore; usando PoCA

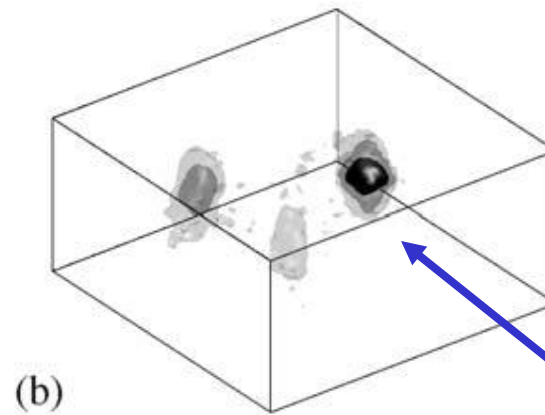


Simulazione MC (e validazione con blocchetto di W)

- tre cubetti 5x5x5 cm³, C (basso Z), Fe (medio Z), W (Z grande); rispettivamente definiti come $0.25 \leq \lambda < 3$, $3 \leq \lambda < 20$, $\lambda \geq 20$; 100k μ ; ricostruzione PoCA;



lo scenario



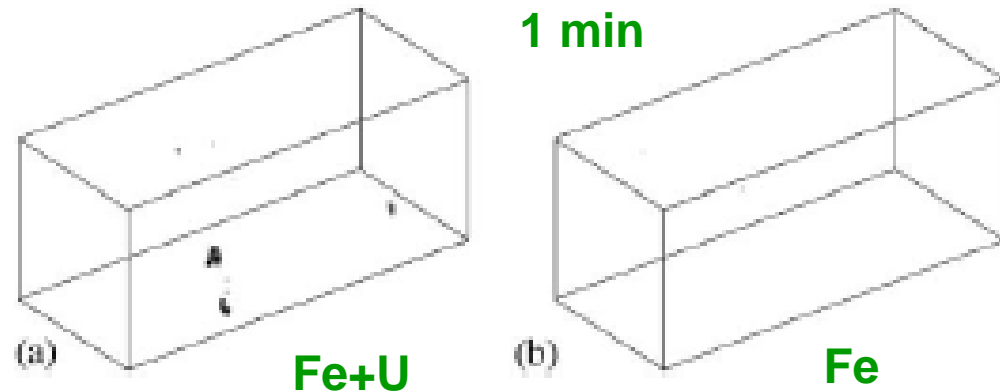
la ricostruzione simulata

alone:
artefatti
dovuti agli
spigoli

Algoritmo di identificazione di alto Z e simulazione di un container

- Si eliminano
 - le tracce con $\theta < \theta_{\text{cut}}$
 - $\text{DistanceCA} > d_{\text{cut}}$
- Si normalizza il segnale (λ) al numero di μ che lo hanno attraversato
- Si evidenziano le regioni con $\lambda > \lambda_{\text{tresh}}$

Scena simulata: container di $6 \times 2.4 \times 2.4 \text{ m}^3$, pareti di 3 mm Fe, con 12 t di Fe distribuite uniformemente, tre mattoni di U $9 \times 9 \times 12 \text{ cm}^3$ nascosti nel Fe (a) Fe+U (b) solo Fe, t. misura $\sim 1 \text{ min}$



Legnaro-Pd-Bs-Ge

CMS Muon Barrel Chambers

➤ Requirements:

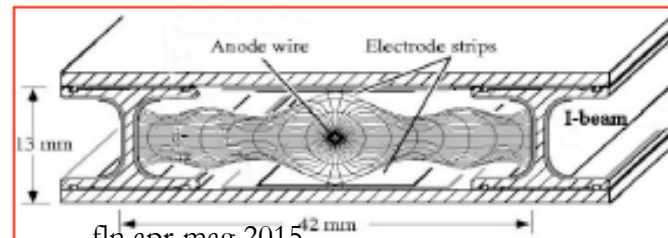
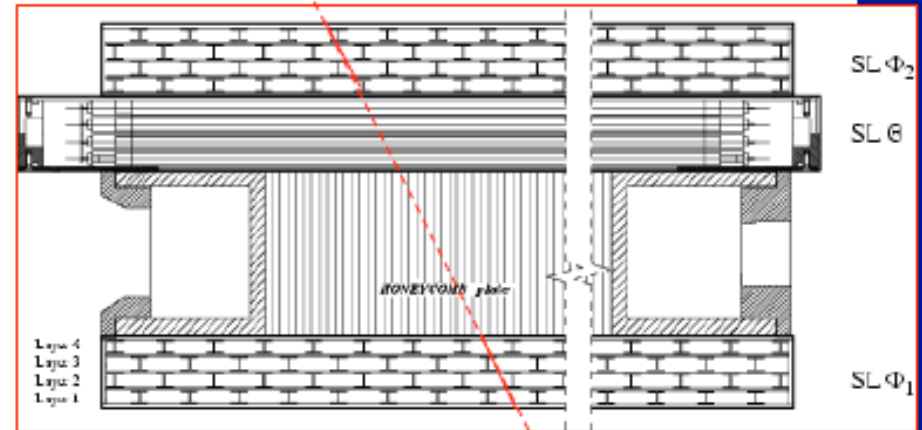
- large area tracking device
- angular resolution ≤ 10 mrad

➤ CMS muon barrel drift chambers:

- 3m x 2.4m ≈ 7 m² active area
- position resolution ≈ 200 μ m
- angular resolution (for $p = 200 \div 300$ GeV/c muons):
 - ≈ 1 mrad in PHI view (2 SuperLayers, with lever)
 - ≈ 10 mrad in THETA view (1 SL, no lever)
- at low momentum (90% cosmic-ray flux has $p \leq 10$ GeV/c) resolution is worse because of multiple scattering on the materials of the chamber itself (about 40mm of Al).

$p_0 = 3$ GeV/c
 ~ 2.5 mrad
 ~ 10 mrad

➤ self-triggered

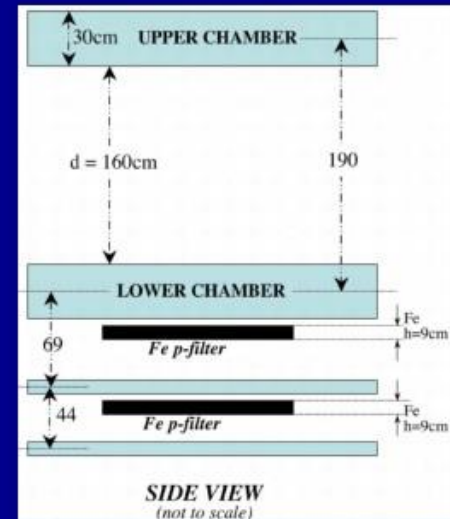


Drift cell

EXPERIMENTAL SETUP

At the INFN National Laboratory of Legnaro (Padova, Italy) an apparatus for the study of muon radiography has been assembled using two spare Muon Chambers Detectors, produced for CMS (CERN experiment at LHC)

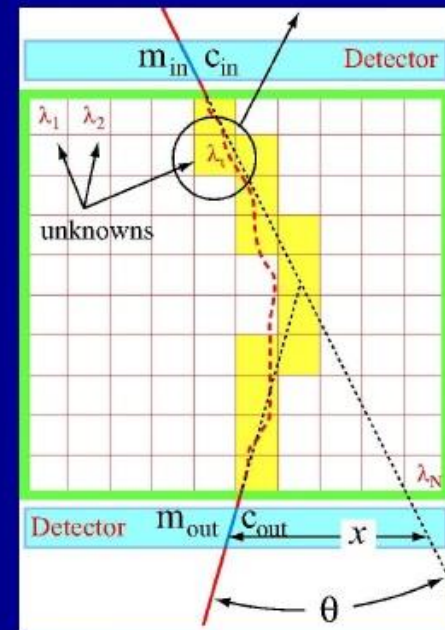
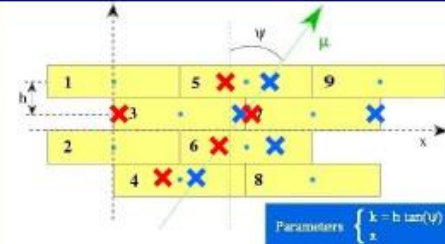
- Two Drift Chambers $2.5 \times 3.0 \text{ m}^2$
- Gap between chambers: 160 cm (vol. $\approx 11.5 \text{ m}^3$)
- 2 extra SLs to measure p ;
- Fe p-filter
- Trigger: upper chamber (events “pointing” from upper to lower chamber)
- Acquisition rate: 350 Hz



DATA ANALYSIS

- **Pattern recognition software** identifies hits of the same track (selects the best straight line fits) and solves left right ambiguity inherent to any drift chamber;
- **Track reconstruction algorithm:** track trajectory is computed with a fit algorithm, position and slope of the track is calculated;
- **Event selection:**
 - > Single track in both views;
 - > 6-8 hits in phi SL, 4 hits in theta SL;**=> Good tracks after selections: 65% for each chamber**
- **Image reconstruction:** Rigorous data treatment requires a maximum likelihood approach together with iterative techniques similar to those applied in the advanced processing of medical imaging data (PET, SPECT). The results presented in this contribution are obtained using
 - a 3D projector-backprojector pair (proback) where only angular deviations are modeled.
 - a 3D tomographic reconstruction incorporating the angular deviation and the effects of lateral shift, called "x displacement".

(Ref. L.J. Schultz, IEEE TRANSACTIONS ON IMAGE PROCESSING, VOL. 16, NO. 8, AUGUST 2007)

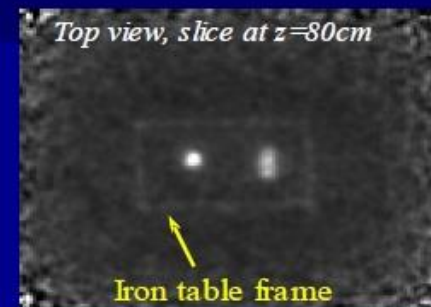
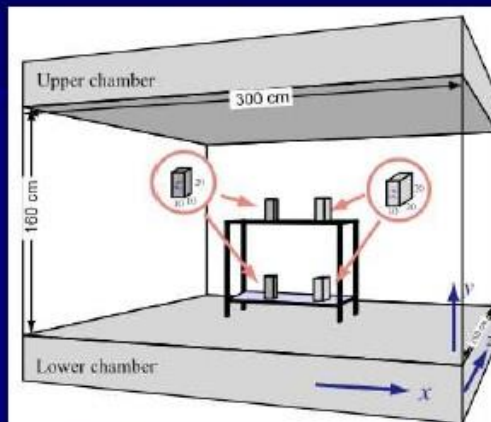


IMAGING CAPABILITY OF THE SYSTEM

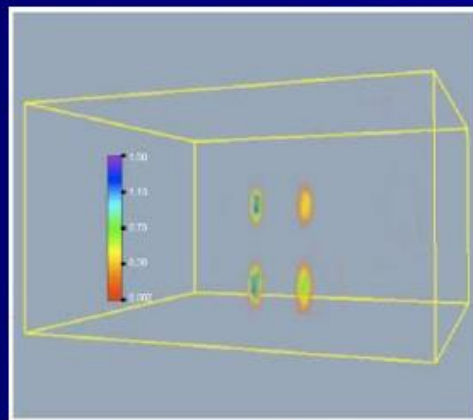
INFN made of Pb blocks



2 Pb bricks (left) + 2 Fe bricks (right) at different height



$T_{acq} \sim 8$ min with optimized detectors



- Position of the blocks reconstructed correctly
- Reconstructed scattering density for Pb larger than for Fe.
- Poor spatial resolution along the vertical direction (only the scattering angle ($\Delta\Phi$) used!)

Results published in NIM A, 604 (2009) 738-746

Legnaro, il container



Altra tecniche: GEM e scintillatori

- Al posto delle DriftChambers di LANL e LNL, il gruppo del FloridaInstTech vuole utilizzare grandi Gas Electron Multipliers, con una geometria a priori notevolmente più compatta ed una migliore accettazione
- Il gruppo di Catania vuole utilizzare scintillatori plastici (3m x 1cm x 1cm, letti con fibre WLS e SiPM) per coprire una superficie di 6m x 3m con 8 piani di rivelatori (4 misure x-y): qui i piani devono essere distanziati (1m) quindi il rivelatore è potenzialmente meno compatto delle altre soluzioni

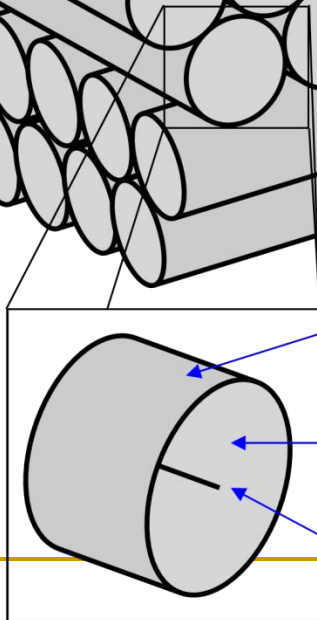
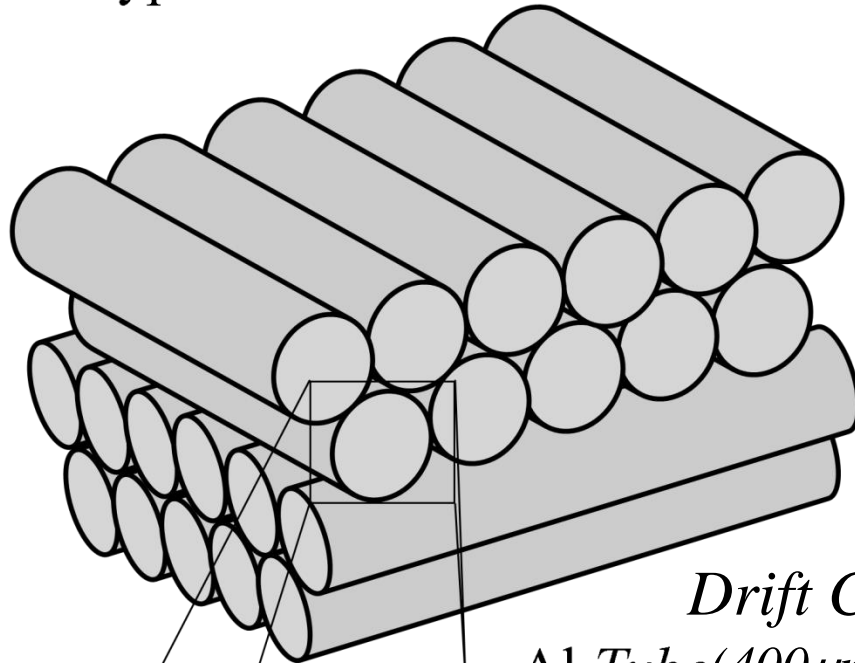
Confronto fra le geometrie

Drift Tube Detector

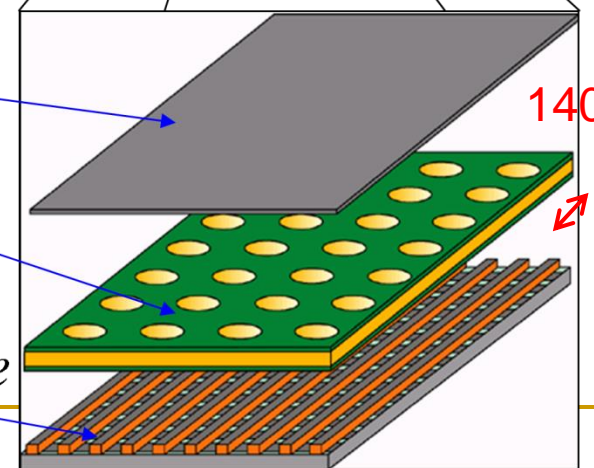
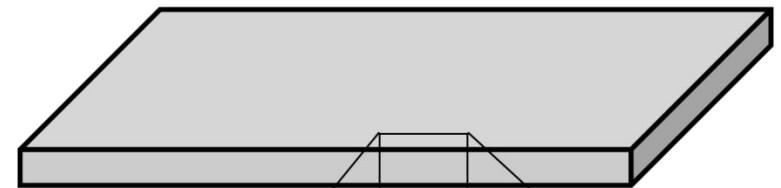
Typical Tube Diameter = 5cm

GEM Detector

Typical Thickness = 1cm

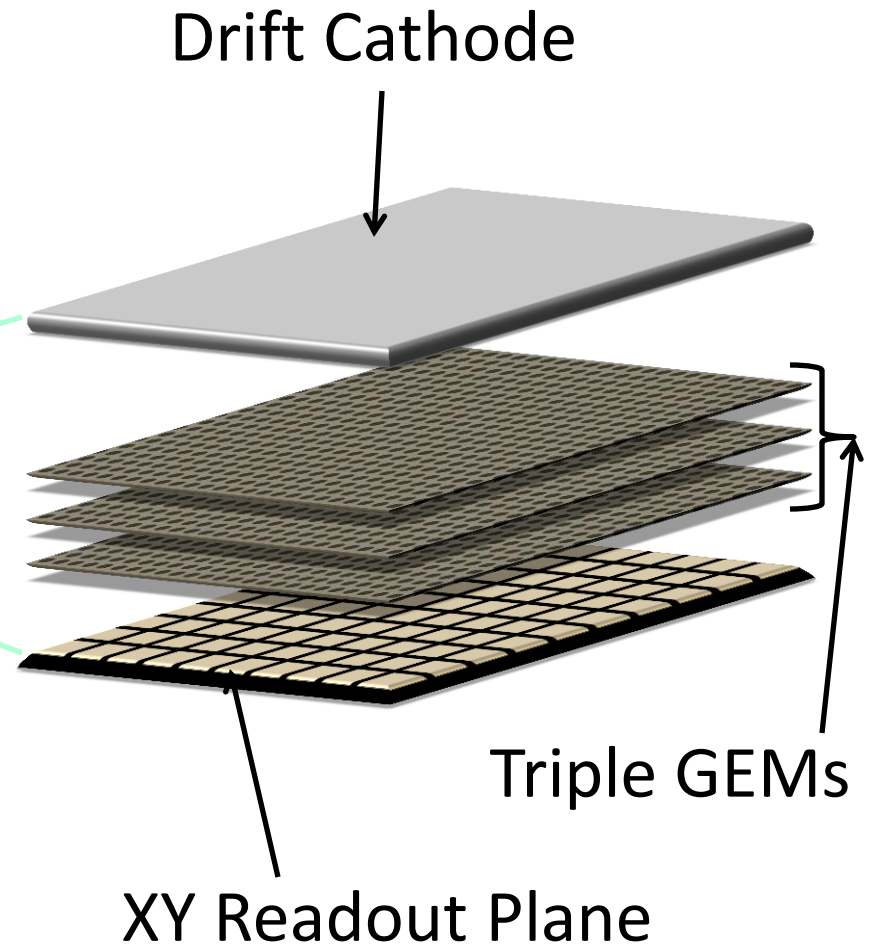
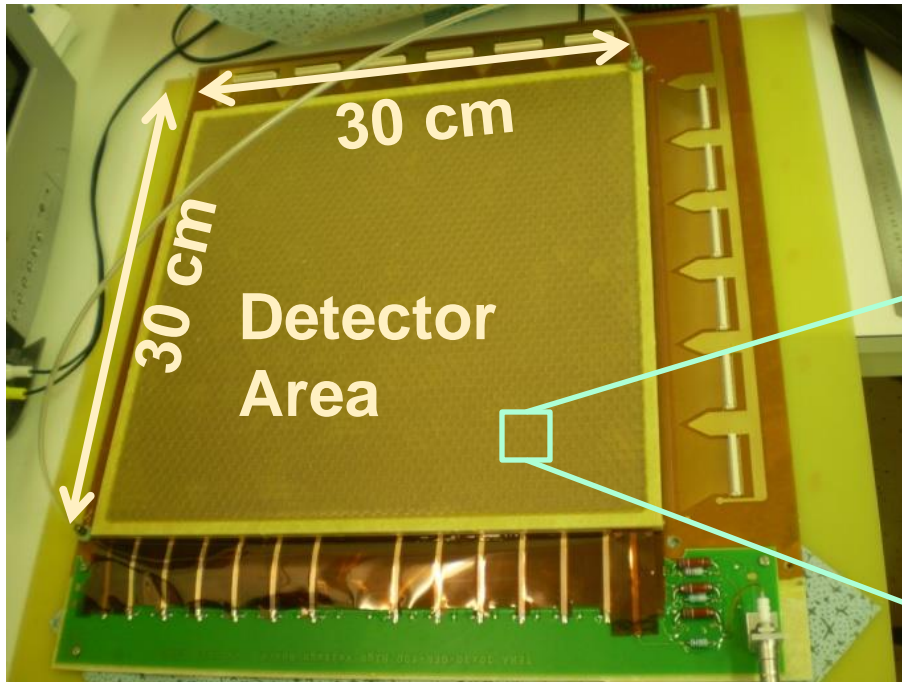


Drift Cathode
Al Tube (400 μm wall)
3 GEM Foils
Ar / CO₂
x-y Readout Plane
Readout Wire



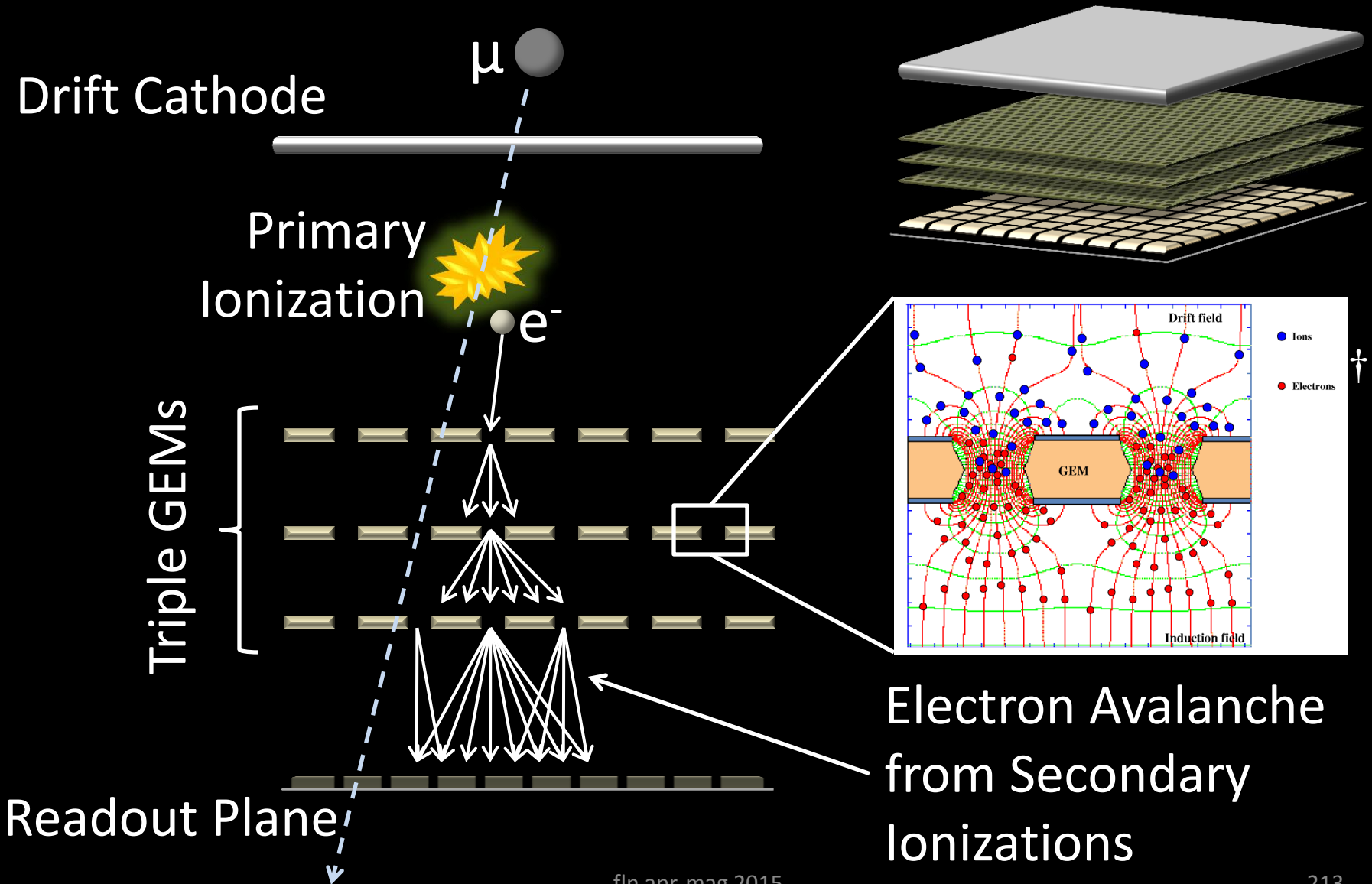
140 μm

Micropattern Gas Electron Multiplier (GEM) Detector

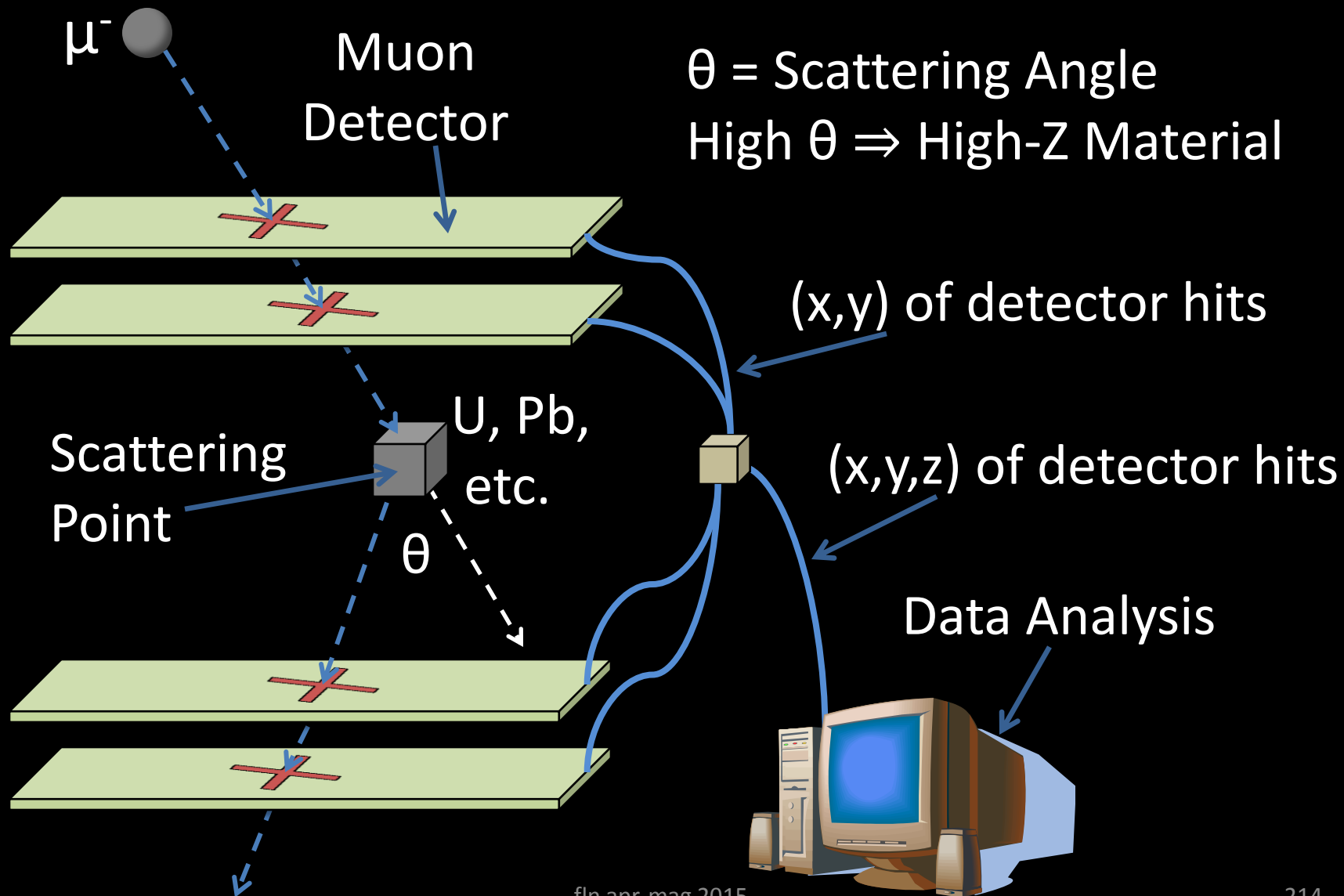


- Cost and space efficient.
- High resolution.

GEM Detector Operation



Muon Tomography Concept



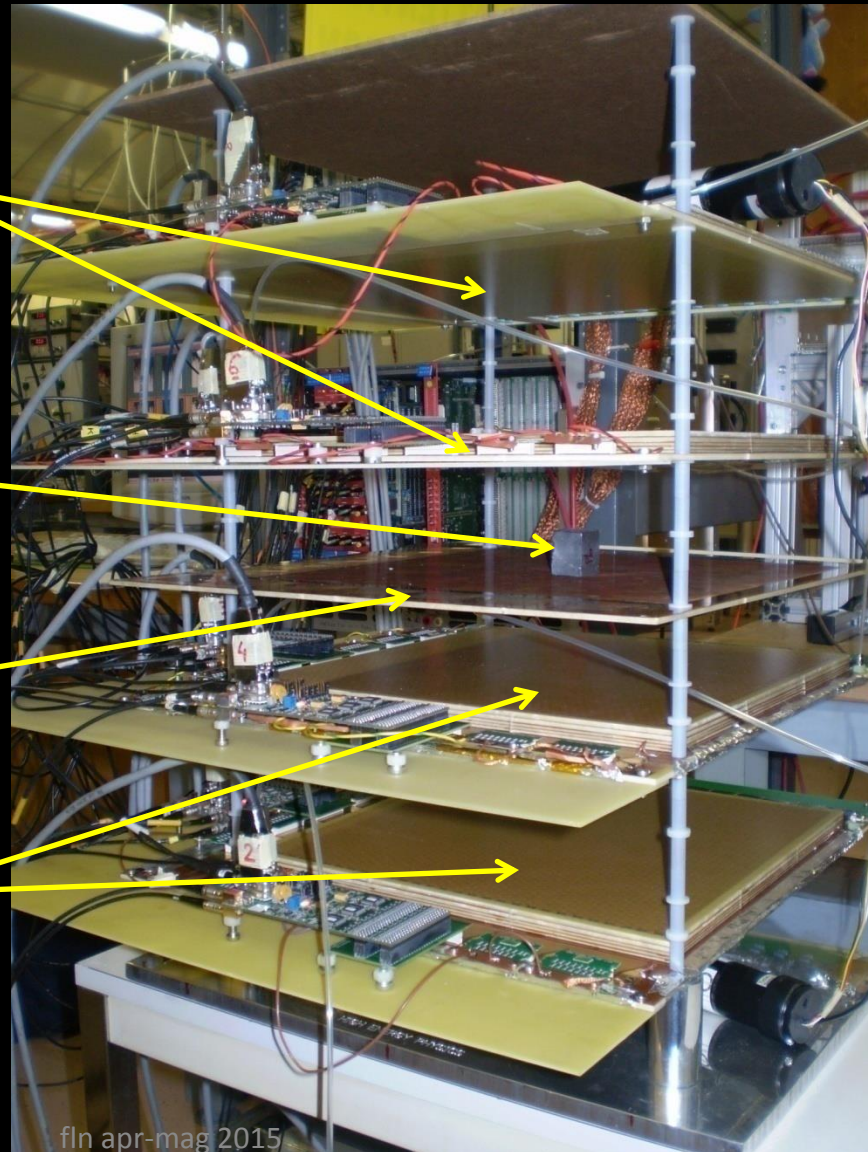
Prototype Muon Tomography System

30x30 cm²
GEM Detectors
(Only 5x5 cm² Used)

3x3x2 cm³
Pb Block

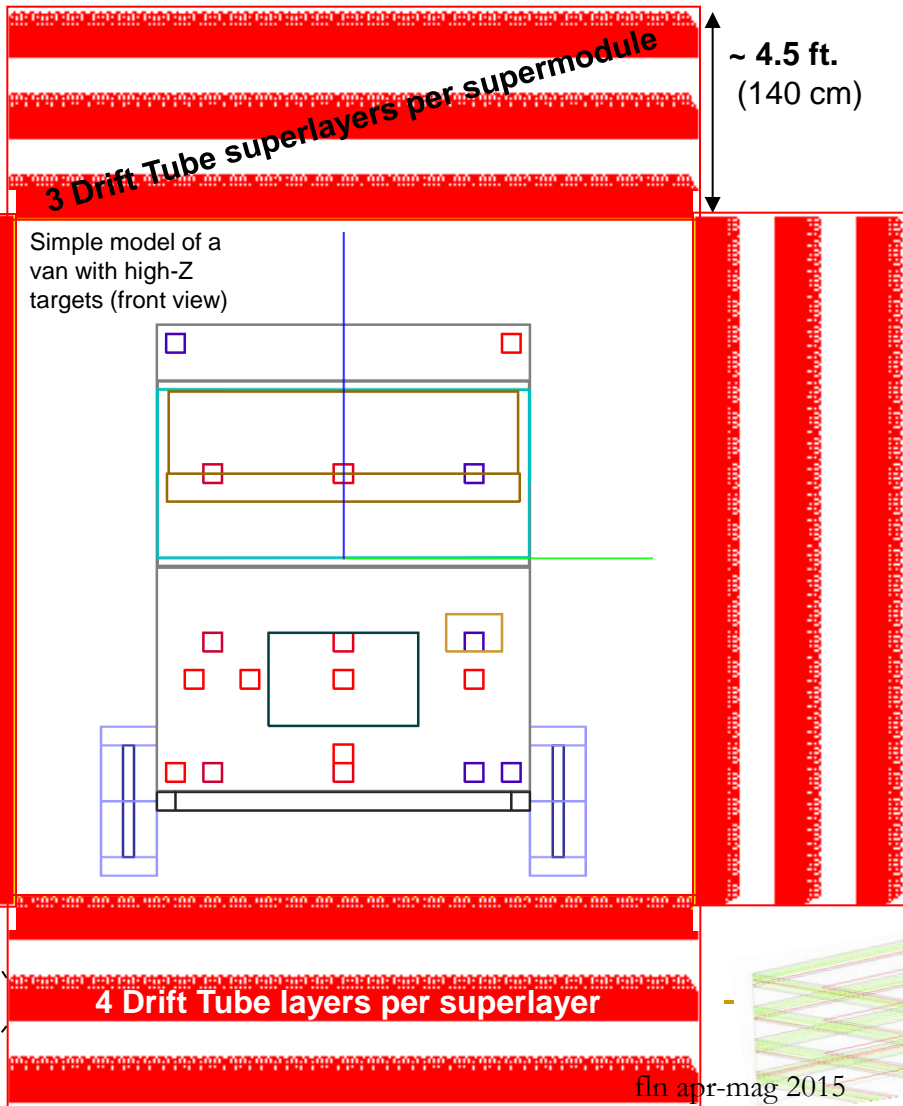
Target Support

GEM Detectors

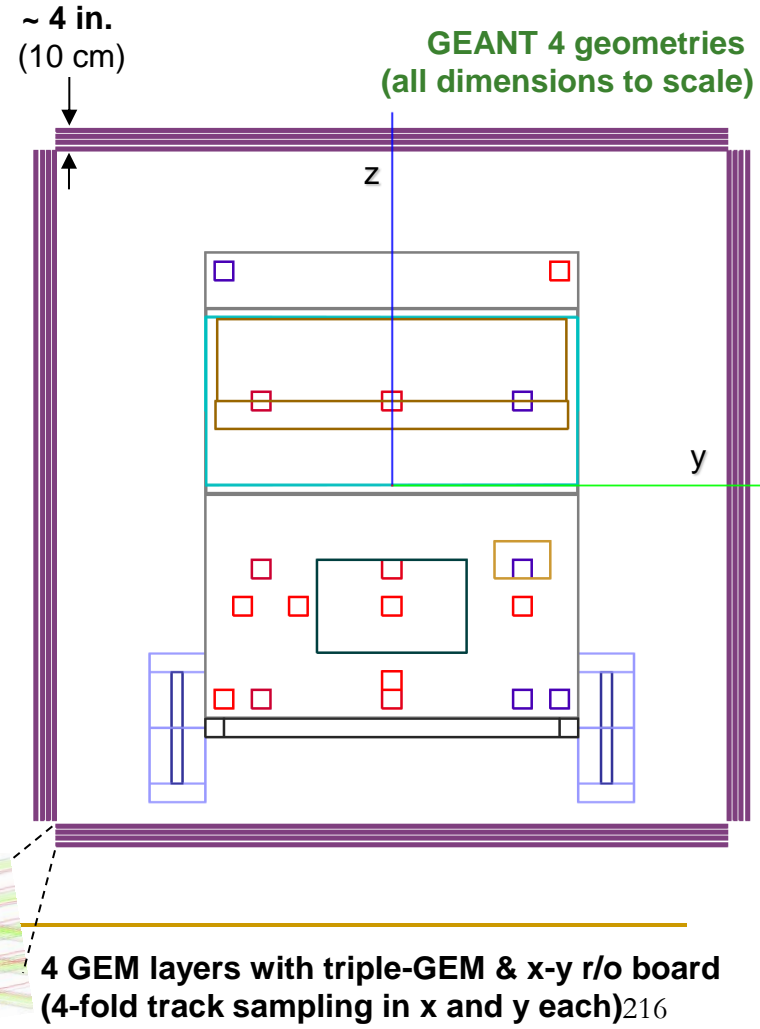


Geometria delle stazioni di misura

DS/LANL: Drift Tube Station



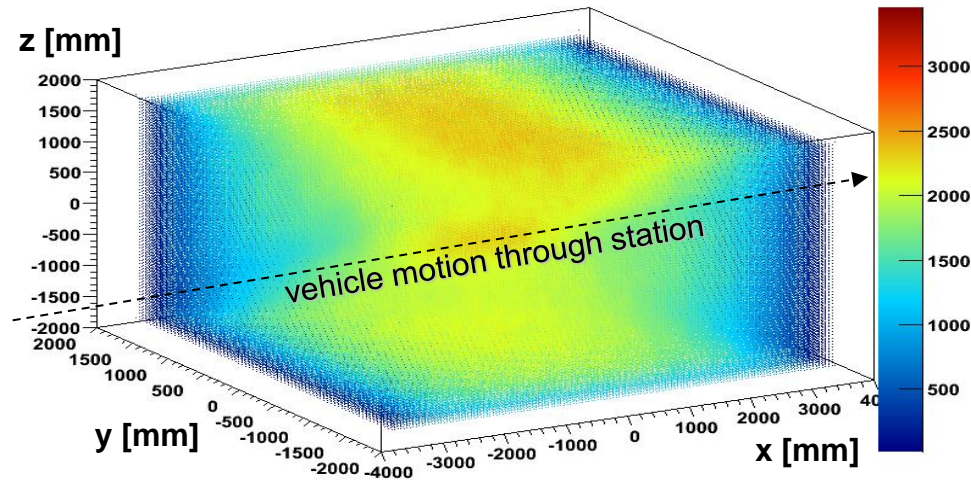
FIT: Compact GEM station (same detector area as DTs)



Confronto delle accettanze

DT station

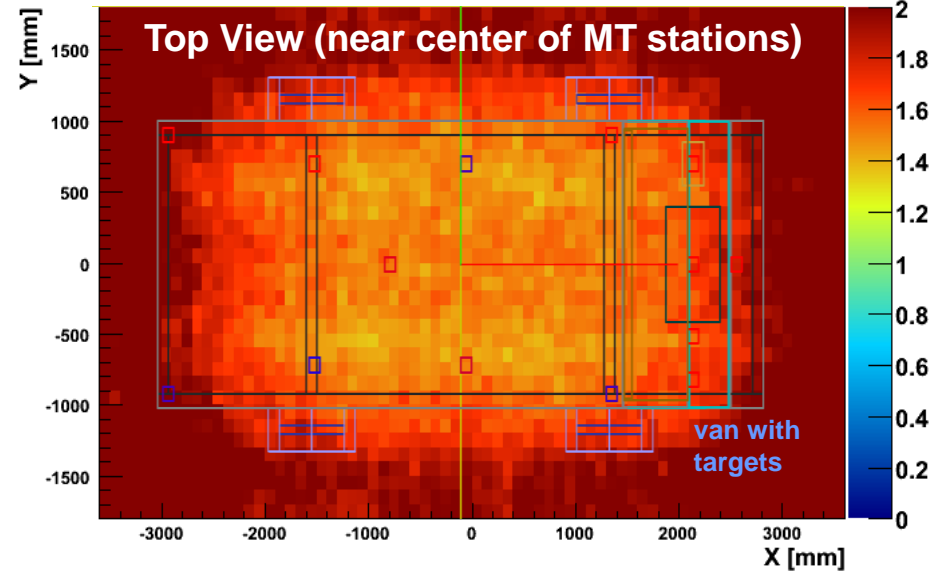
No. muons in 10cm×10cm×10cm voxel in 10min



GEM MT station provides
50-100% better muon acceptance
of the interrogated vehicle

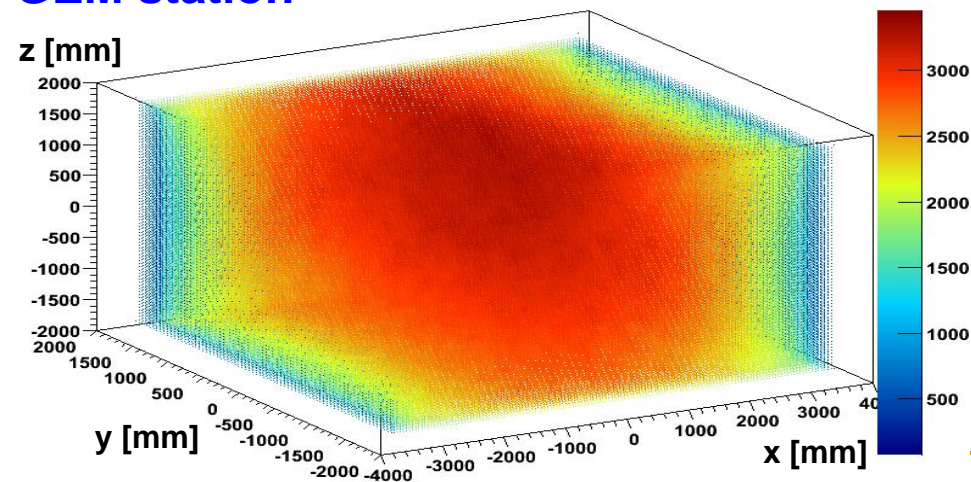
Acceptance Ratio

$\frac{\text{GEM accept.}}{\text{DT accept.}}$



GEM station

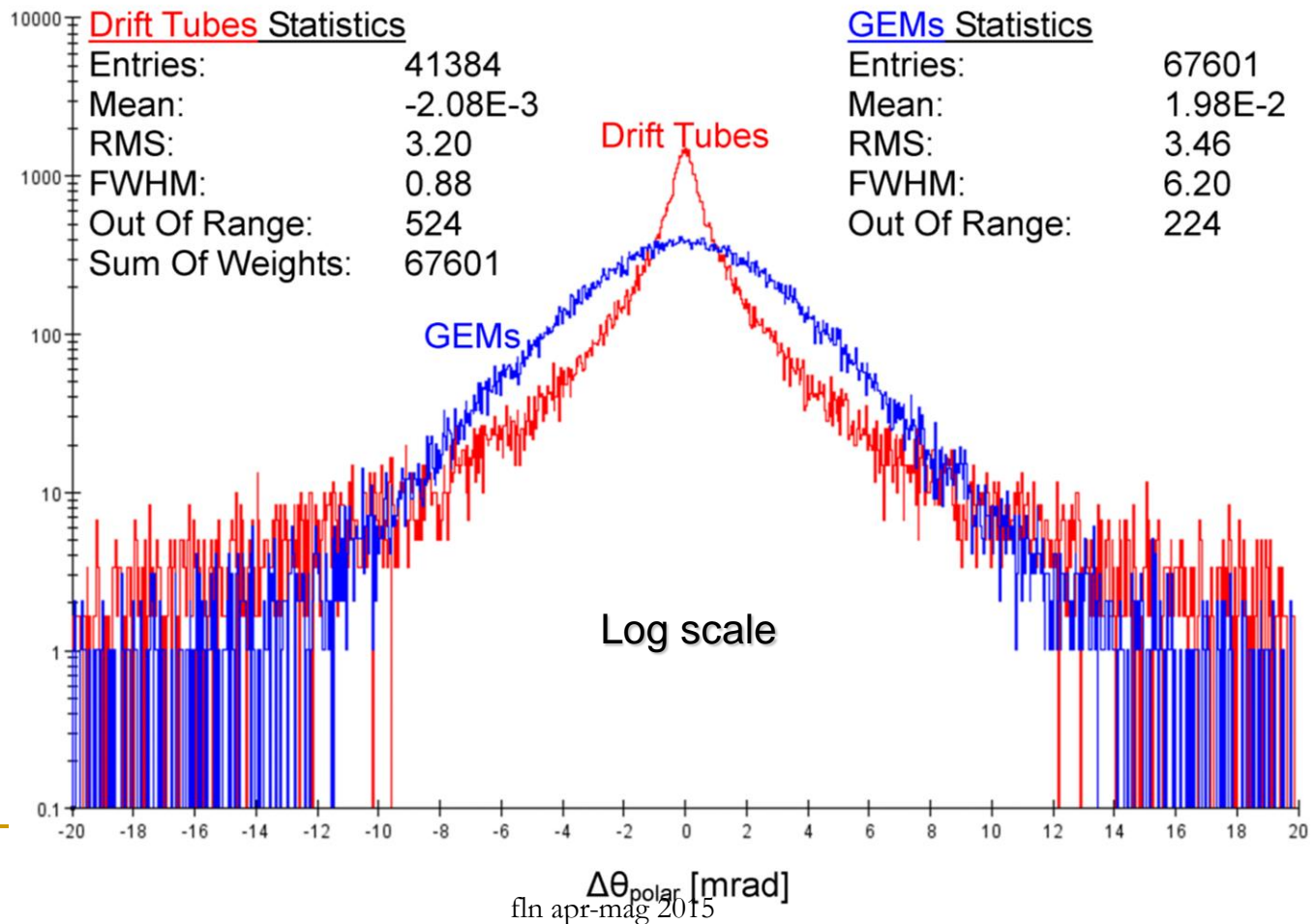
No. muons in 10cm×10cm×10cm voxel in 10min



- Require ≥ 3 hits in DT or GEM station to accept muon
- Reduced DT acceptance is mainly due to “holes” in solid angle coverage in the corners of the DT station

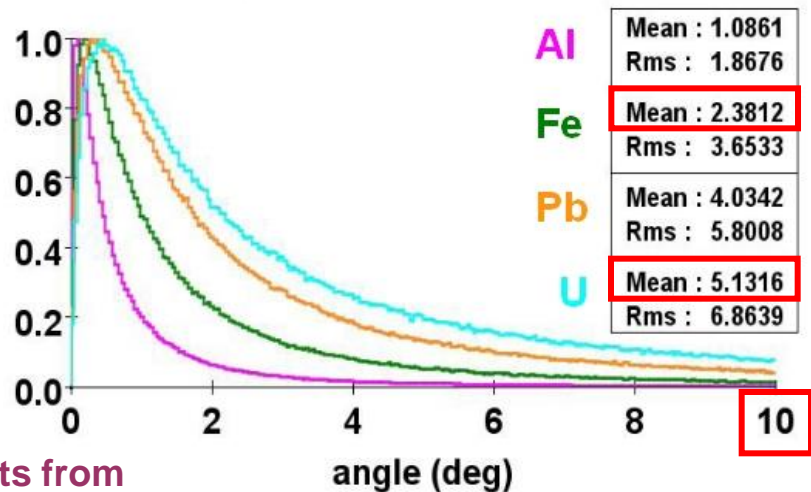
Confronto fra le risoluzioni

quasi la stessa r.m.s., $\text{FWHM}_{\text{DT}} \ll \text{FWHM}_{\text{GEM}}$

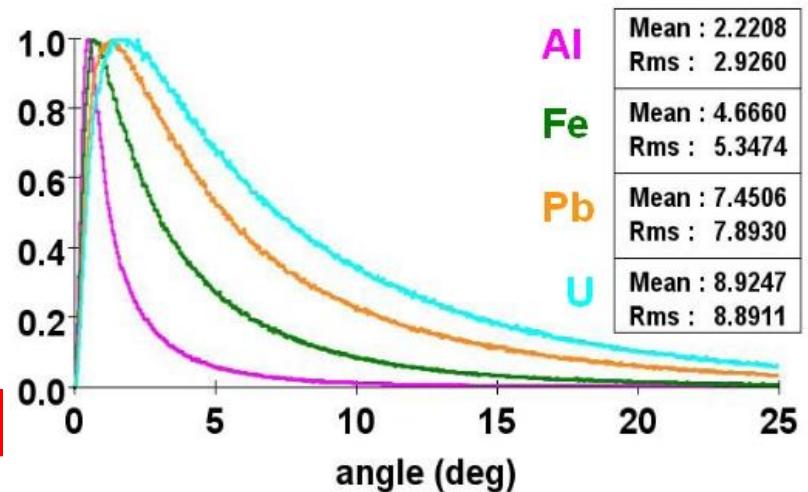


Distribuzioni dell'angolo di scattering

perfect resolution

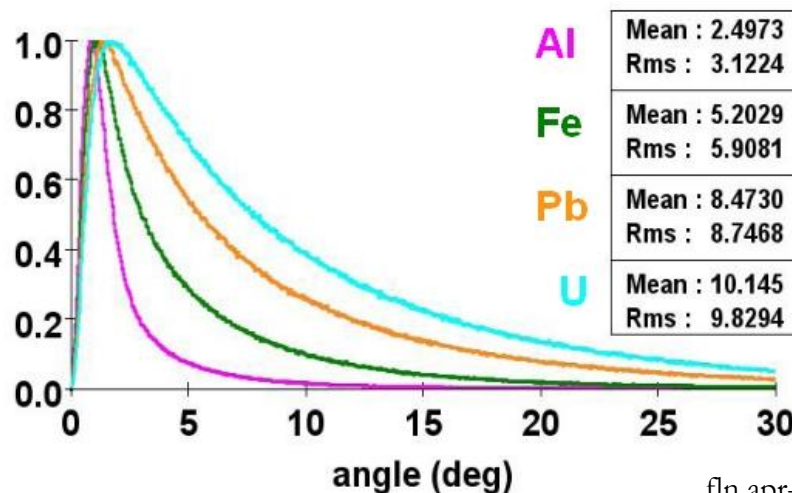


50 micron resolution

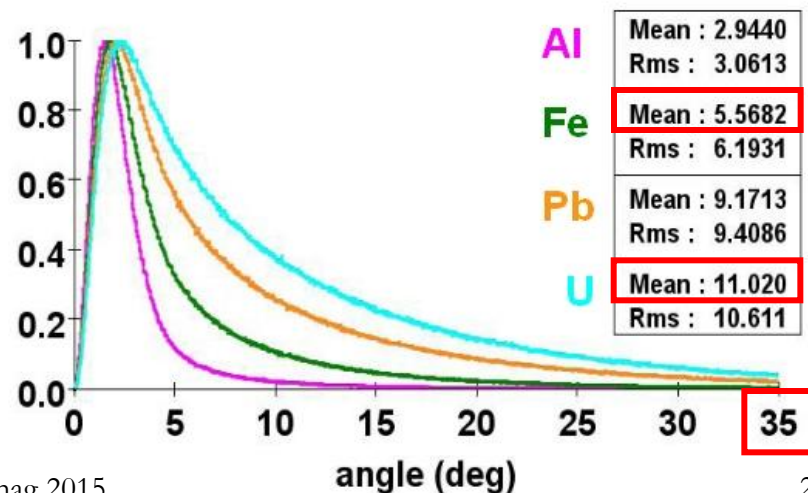


Results from
high-statistics
MC samples

100 micron resolution



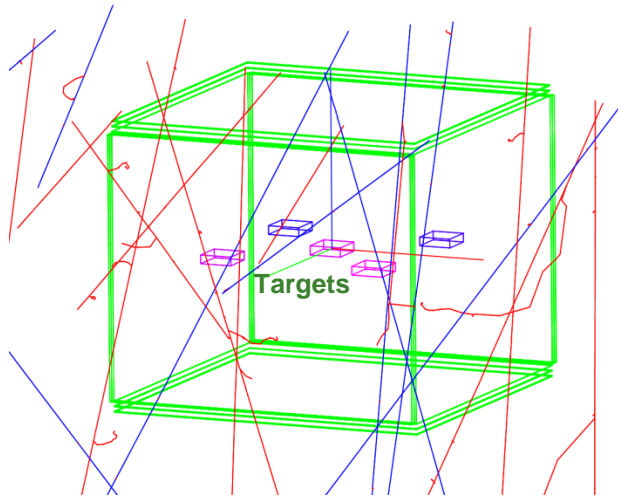
200 micron resolution



Statistica semplice per separare Z: angoli medi di scattering

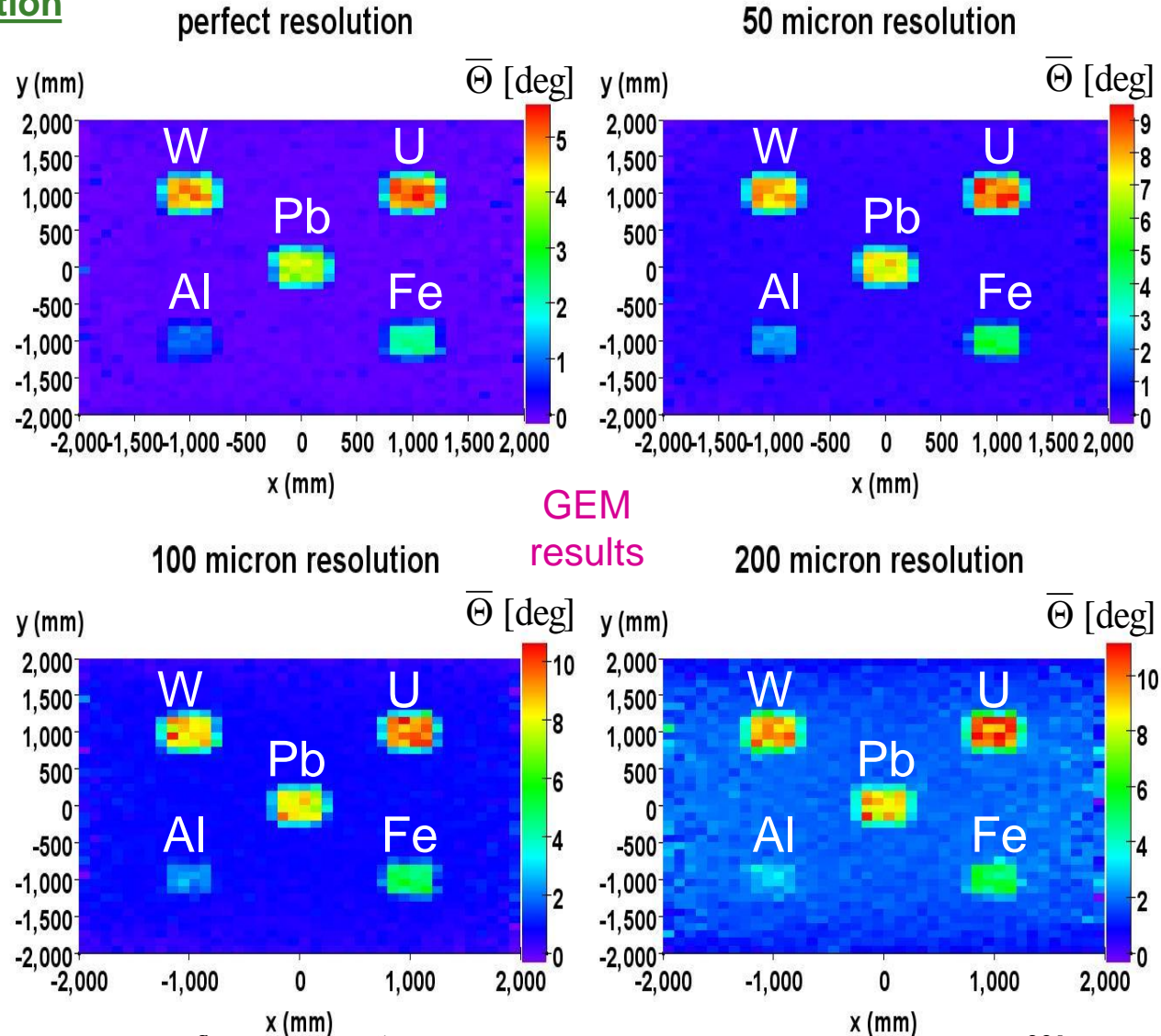
Simple MC Scenario for GEM station

- Top, bottom & side detectors
- 40cm x 40cm x 10cm targets
- 5 materials (low-Z to high-Z)
- Divide volume into 1-liter voxels
- **10 min exposure**



Results:

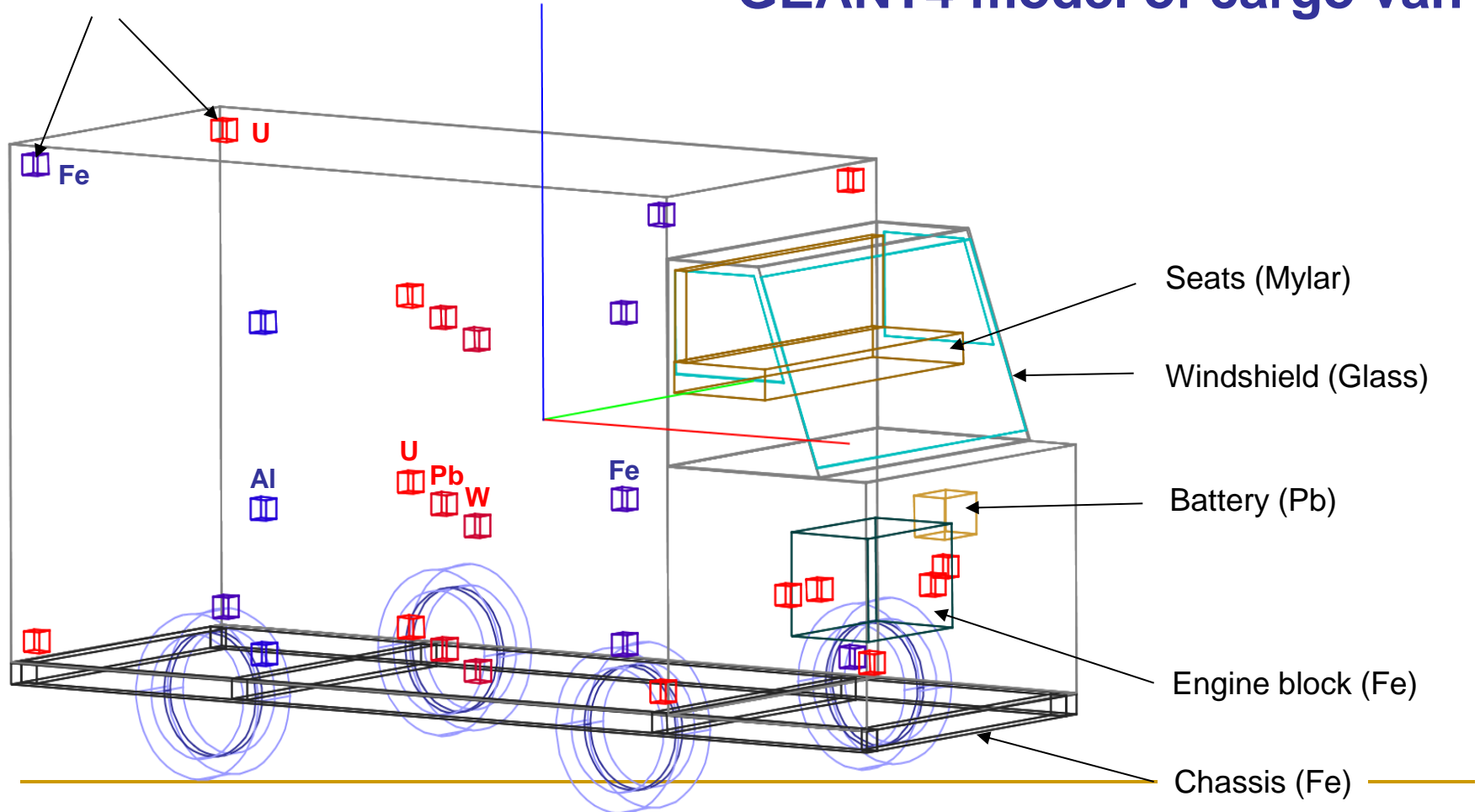
- Scattering angles 20-100 mrad;
>> angular resolution (few mrad)
- Good Z discrimination
- Targets well imaged
- Detector resolution matters



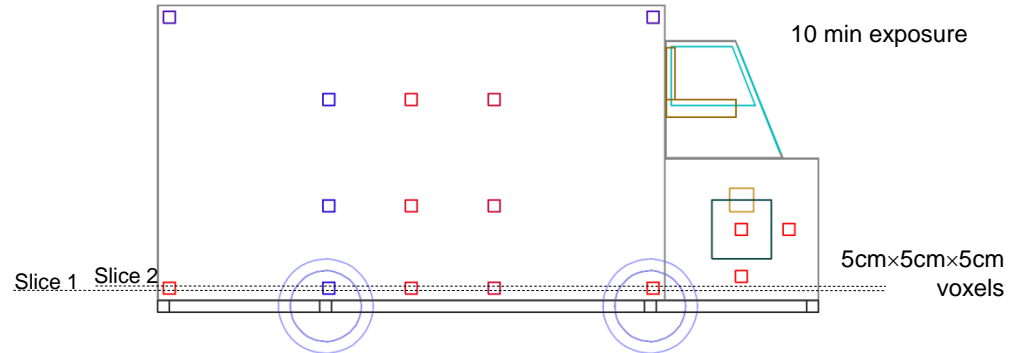
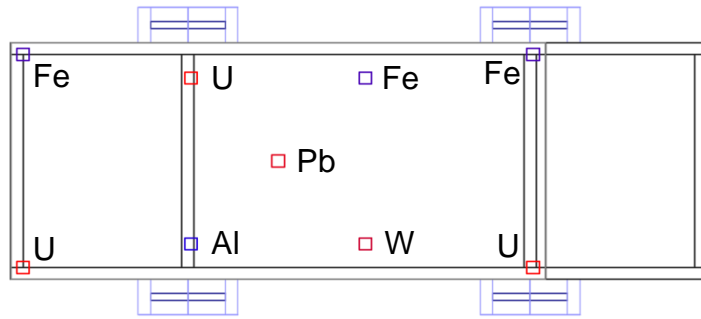
Scenario avanzato: camion

Target cubes (1 liter)

GEANT4 model of cargo van

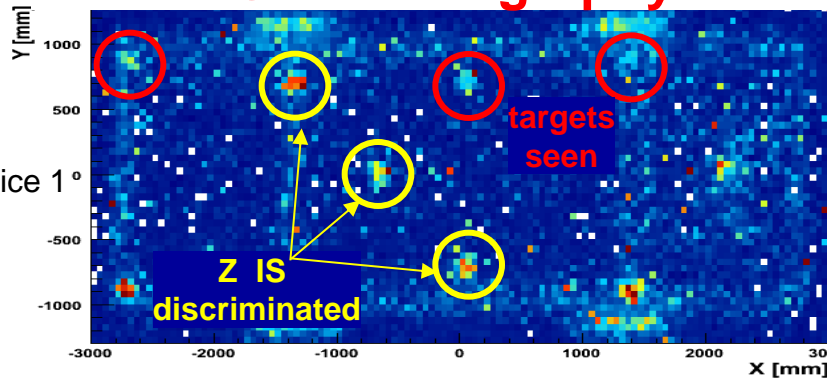


Rivelazione dei blocchetti



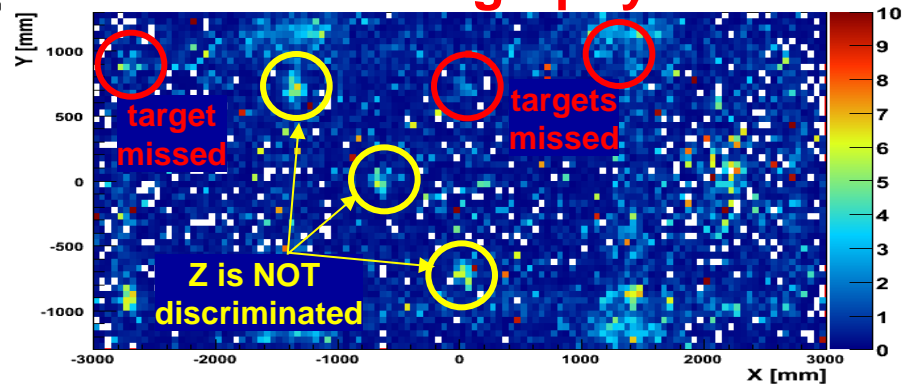
GEM tomography

$\langle \theta_{\text{scatt}} \rangle [^\circ]$

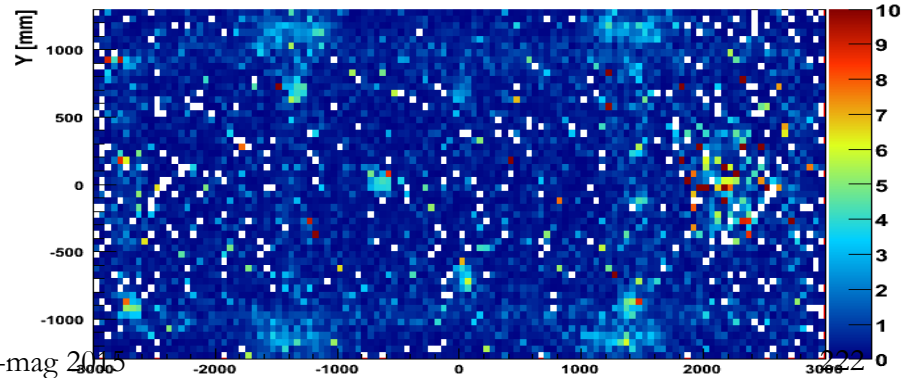
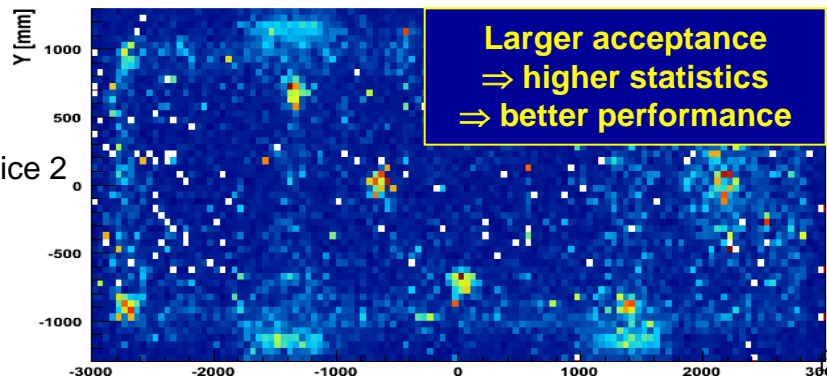


DT tomography

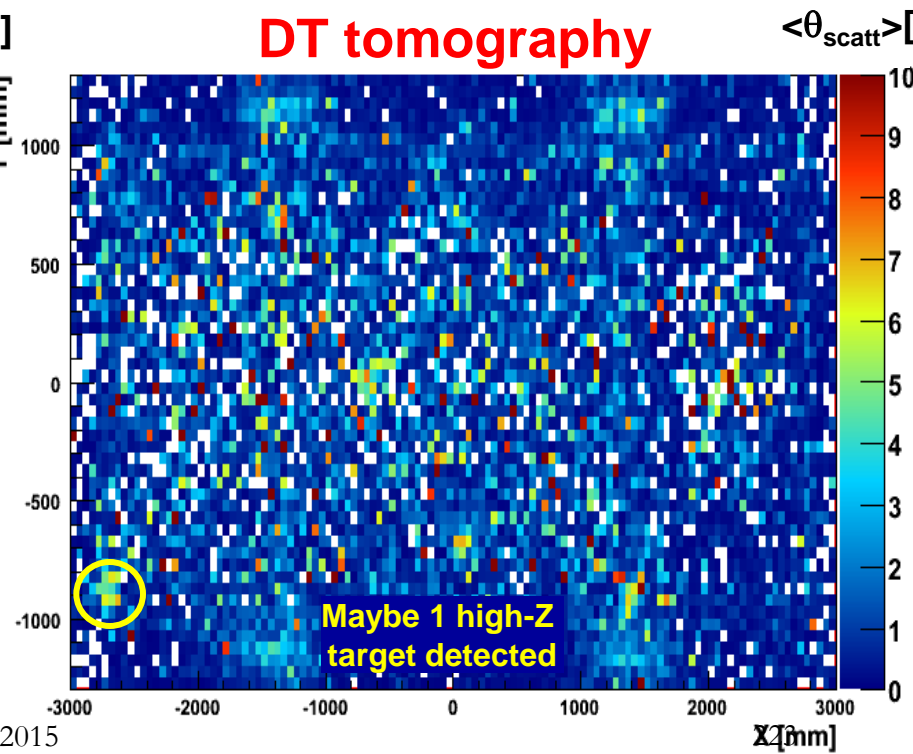
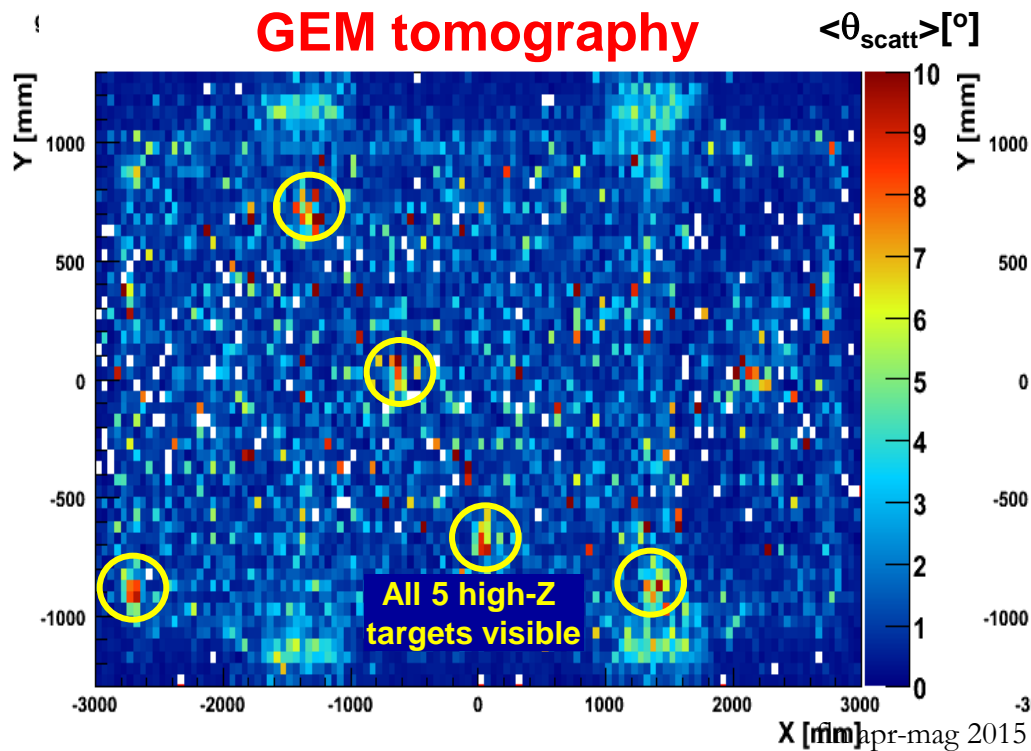
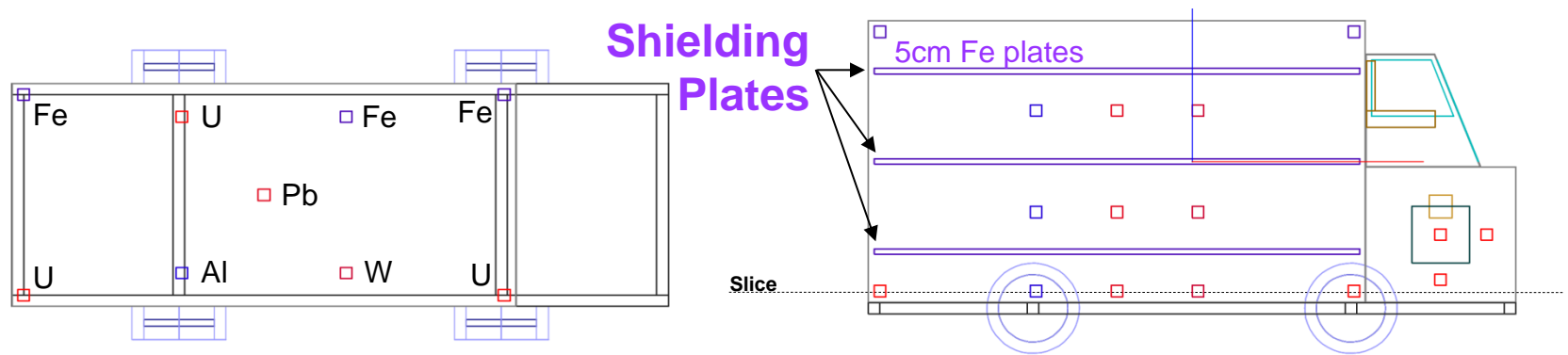
$\langle \theta_{\text{scatt}} \rangle [^\circ]$



Larger acceptance
 \Rightarrow higher statistics
 \Rightarrow better performance



Risultati con schermatura aggiuntiva

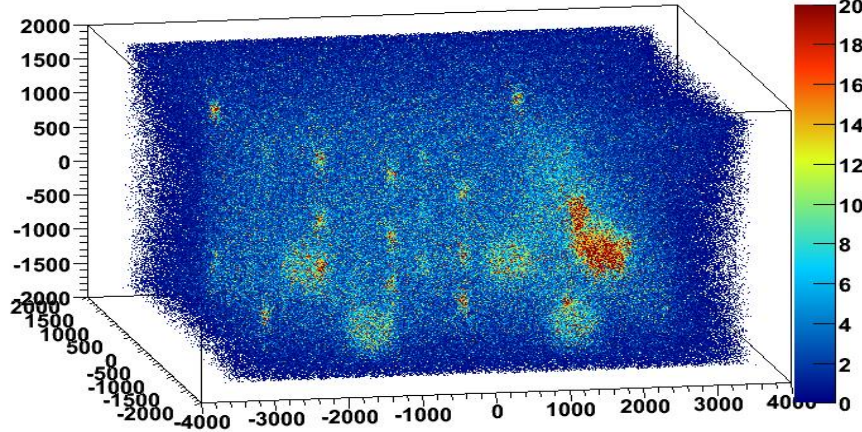


Ricostruzione in 3D del camion

Mean Angle (w/o momentum)

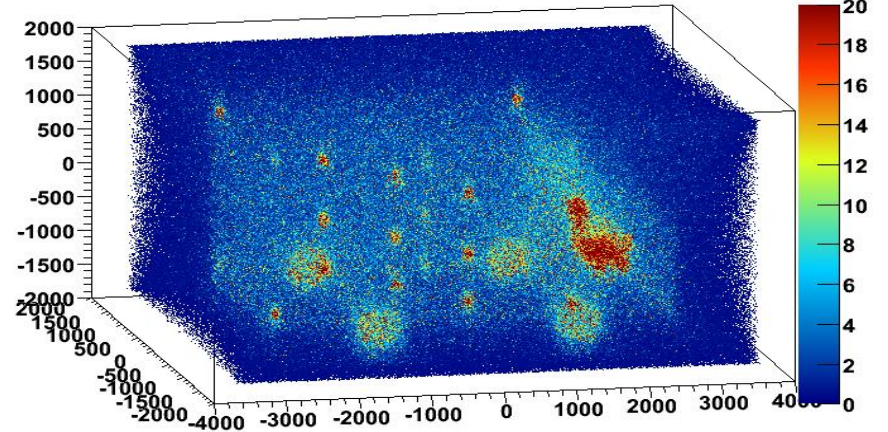
Drift Tubes

zpoça:ypoça:xpoça:vpoça



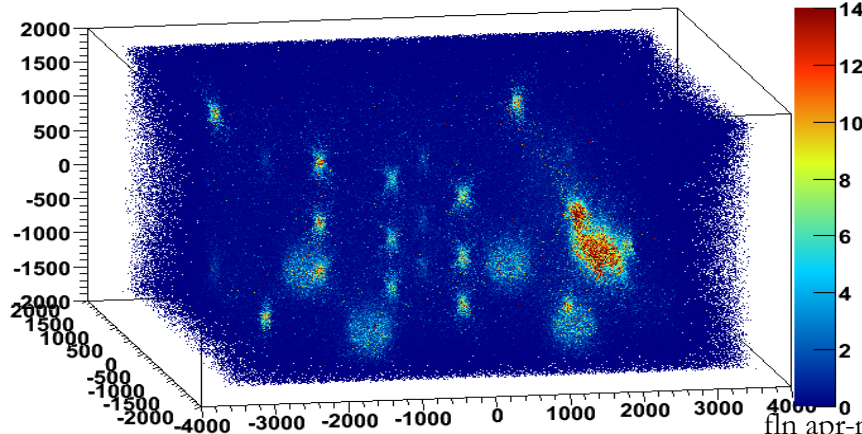
GEMs

zpoça:ypoça:xpoça:vpoça

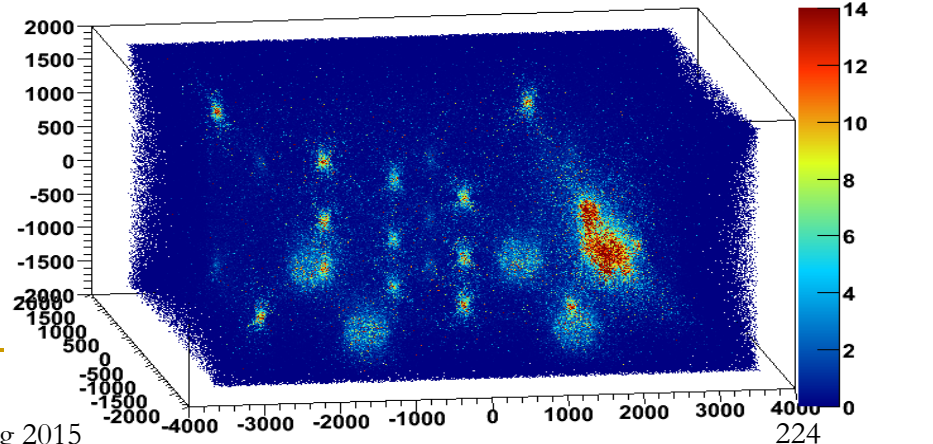


10 min. exposures Scattering Density (w/ momentum)

zpoça:ypoça:xpoça:vpoça



zpoça:ypoça:xpoça:vpoça

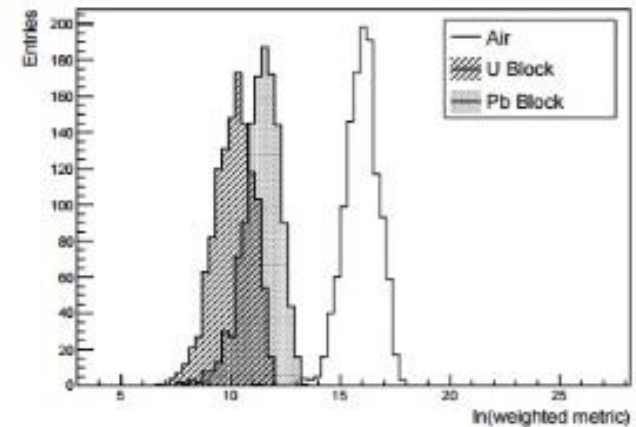


Riconoscimento (senza immagine): binned clustering algorithm (C. Thomay et al. JINST 8)

- 6 piani di RPC [7x4 m², distanti 65 cm, $\Delta x,y < 500 \mu\text{m}$] (3x, 3y) sopra e sotto il volume da indagare
- ricostruzione in 2 passi, 3x-3y poi 6x-6y con vertice in comune (7-p $v_{x,y,z}$, 4 angoli)
- MC, si assume p_{vero} , dopo ricostr. e tagli in χ^2 , in 1 min 100-150 kevts
- $p_{\text{norm}} = 1 \text{ GeV}/c$ [sotto(sopra) θ pesato -(+)]
- $m_{ij} = \|\mathbf{v}_i - \mathbf{v}_j\|$ distanza metrica dei vertici in un sottovolume (eg lato 25 cm per un oggetto 10x10x10 cm³ da individuare)

bca (cont.)

- $m^*_{ij} = m_{ij}/[(\theta_i p_{r,i})(\theta_j p_{r,j})]$ con $p_r = p/p_{\text{norm}}$
- scenario con blocchi 10x10x10 cm³, 1 min, taglio sull'angolo di scattering, griglia multipla (per contenere sempre il blocco), n tracce = 50, 10 s su PC
- L'algoritmo ritorna la più piccola mediana di tutti i sotto-volumi di tutte le griglie da usare come discriminante (soglia)



Algorithm(*n* tracks)

For each sub-volume in each grid:

- Sort tracks by descending normalized scatter angle. Consider only the *n* highest-ranked tracks.
- For each combination of considered tracks:

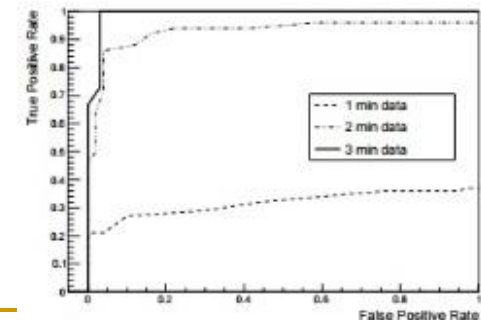
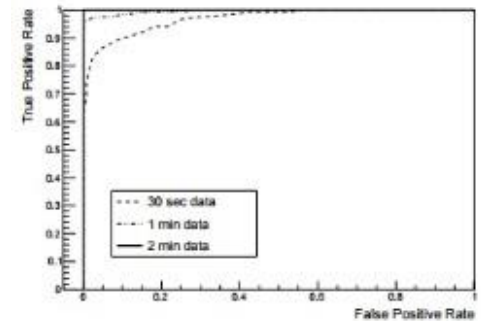
- Calculate \bar{R}_v .
- Fill histogram with $\ln(\bar{R}_v)$.

- Calculate median of distribution.
- If median is lowest so far, assign as temporary discriminator.

Output overall lowest median as final discriminator.

bca: ROC analysis

- grafici Receiver Operating Characteristics (ROC) sono usati per analizzare la qualità di un classific. – dati un classificatore (Y,N) ed un'istanza (p,n), ci sono 4 possibilità [pY, nY, pN, nN]
- W 9x9x9 cm³ (dati con un prototipo)
- blocco U in Fe distribuito (simulaz.)
- scenari distribuiti e blocchi piccoli richiedono più tempo (sono più difficili da selezionare)



Miglioramento della ricostruzione con p noto

$$\theta_{\text{scattering}} \propto \sim \mathbf{p}^{-1}$$

- Reconstruct scattering density λ of material:

$$\lambda = \frac{(\theta_{\text{scattering}})^2}{2L(1 + E_p^2)} \left(\frac{p}{p_0} \right)^2$$

L = path length of muon within target (set to 1, a priori unknown)
 E_p = momentum error (set to 0 for now)
 p = momentum of cosmic ray muons
 p_0 = average momentum of cosmic ray muons (3 GeV)

- Use average λ value in i^{th} voxel as statistic:

$$\langle \lambda \rangle_i = \frac{\sum_j \lambda_{ij}}{N_i}$$

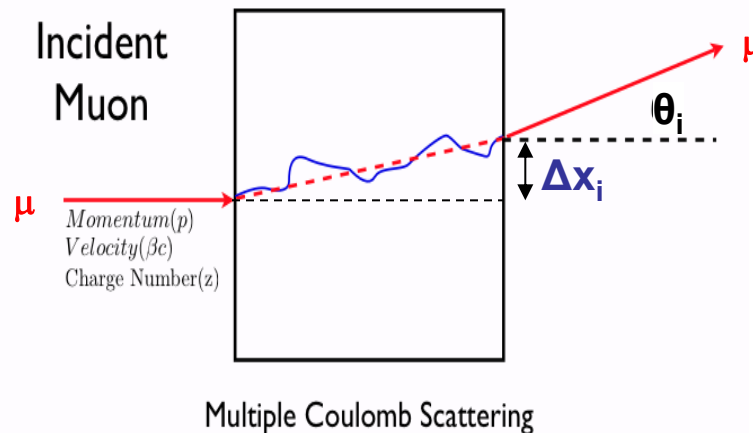
λ_{ij} = λ -value for j^{th} muon scattered in i^{th} voxel (based on PoCA)
 N_i = number of muons scattered in i^{th} voxel

Caveat: As currently designed, neither detector type (DT, GEM) actually provides a momentum measurement; this would require additional instrumentation

Algoritmo avanzato di ricostruzione

Maximum Likelihood-EM Method:

- **Input:** Use lateral shift Δx_i in multiple scattering in addition to information from scattering angle θ_i for each muon track



- **Procedure:**
 - Maximize log-likelihood for assignment of scattering densities to all voxels given all observed muon tracks
 - **Analytical derivation leads to iterative formula for incrementally updating λ_k values in each iteration**
- **Output:** Scattering density λ_i for each voxel of the probed volume

Scattering attraverso uno spessore

Modello fisico usa θ_x , Δx (da adattare ai dati raccolti \rightarrow Fit)

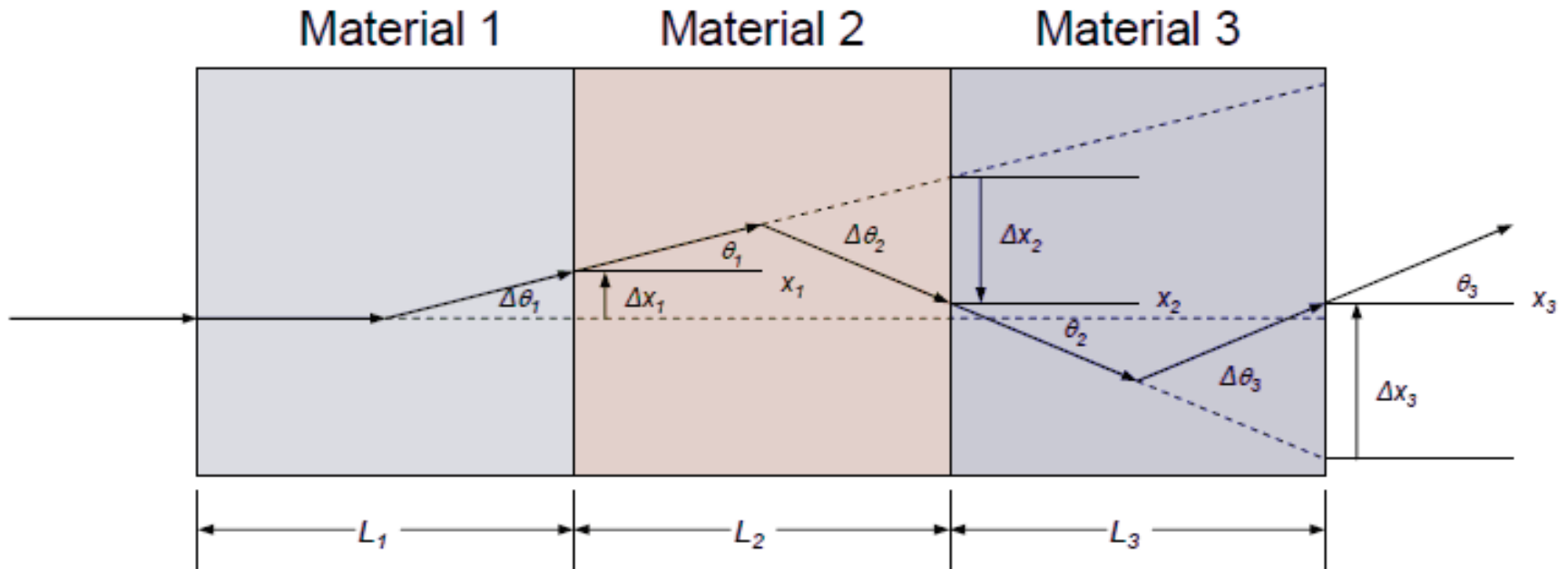
$$\left. \begin{aligned} \sigma_\theta &\approx \frac{13.6}{p} \sqrt{\frac{L}{X_0}} \\ \lambda(X_0) &= \left(\frac{13.6}{p_0}\right)^2 \frac{1}{X_0} \end{aligned} \right\} \begin{aligned} \sigma_\theta^2 &= \lambda L p_r^2 \\ \sigma_{\Delta x}^2 &= \frac{L^2}{3} \sigma_\theta^2 = \frac{L^3}{3} \lambda p_r^2 \\ \sigma_{\theta \Delta x} &= \frac{L}{2} \sigma_\theta^2 = \frac{L^2}{2} \lambda p_r^2 \end{aligned} \quad p_r = p_0/p$$

Matrice di covarianza (Gaussiana bidimensionale), il coefficiente di correlazione fra θ e Δx è $\sqrt{3/2}$

$$\Sigma = \lambda \begin{bmatrix} L & \frac{L^2}{2} \\ \frac{L^2}{2} & \frac{L^3}{3} \end{bmatrix} p_r^2 = \lambda A p_r^2$$

Analogamente per θ_y , Δy .
Le distribuzioni nelle due coordinate spaziali sono identiche e scorrelate

Scattering multiplo attraverso strati successivi



assume $\Delta x_i \ll L_i$

$$x_3 = x_2 + L_3 \cdot \tan(\theta_2) + \Delta x_3 \quad \theta_3 = \theta_2 + \Delta\theta_3$$

$$x_2 = x_1 + L_2 \cdot \tan(\theta_1) + \Delta x_2 \quad \theta_2 = \theta_1 + \Delta\theta_2$$

$$x_1 = \Delta x_1 \quad \theta_1 = \Delta\theta_1$$

$$\theta_3 = \Delta\theta_1 + \Delta\theta_2 + \Delta\theta_3$$

$$x_3 = \Delta x_1 + L_2 \cdot \tan(\theta_1) + \Delta x_2 + L_3 \cdot \tan(\theta_2) + \Delta x_3$$

$$x_3 = \Delta x_1 + L_2 \cdot \tan(\Delta\theta_1) + \Delta x_2 + L_3 \cdot \tan(\Delta\theta_1 + \Delta\theta_2) + \Delta x_3$$

assume small angles

$$x_3 = \Delta x_1 + \Delta x_2 + \Delta x_3 + \Delta\theta_1(L_2 + L_3) + \Delta\theta_2(L_3)$$

NB $\Delta\theta_j$ e Δx_j non sono osservabili, sono i dati nascosti (H_{ij}), usati in seguito nell'algoritmo EM

Dopo N strati

$$\Delta\theta = \sum_{j=1}^N \Delta\theta_j$$

$$\Delta x = \sum_{j=1}^N (\Delta x_j + T_j \Delta\theta_j) \quad (*) T_j = \sum_{k=j+1}^N L_k; j < N; T_N = 0$$

$$\Sigma = \begin{bmatrix} \sum_{j=1}^N L_j \lambda_j & \sum_{j=1}^N \left(\frac{L_j^2}{2} + L_j T_j \right) \lambda_j \\ \sum_{j=1}^N \left(\frac{L_j^2}{2} + L_j T_j \right) \lambda_j & \sum_{j=1}^N \left(\frac{L_j^3}{3} + L_j^2 T_j + L_j T_j^2 \right) \lambda_j \end{bmatrix} p_r^2 = \sum_{j=1}^N \begin{bmatrix} W_{1j} & W_{2j} \\ W_{2j} & W_{3j} \end{bmatrix} \lambda_j p_r^2$$

- la forma rimane la stessa se gli strati diventano pixel, solo che j è l'indice dei pixel e T_j sono calcolati secondo la (*), come somma dei pixel a valle del pixel j , secondo la traiettoria del μ ; inoltre ci sarà un indice per l' i -esimo μ , che ho soppresso, $i = 1, M$
- $L_{(i)j}$ è il percorso 3D di μ_i nel pixel j (=0 se il μ non ci passa)

Likelihood

- si misura θ_{in} e θ_{out} , x_{in} e x_{out} per ciascun μ (x_{proj} è la proiezione del raggio incidente in uscita)

- $\Delta\theta_i = \theta_{out,i} - \theta_{in,i}$

- $\Delta x_i = (x_{out,i} - x_{proj,i}) / \cos[(\theta_{in} + \theta_{out})/2]$

- vettore dei dati per l'i-esimo μ

- probabilità di avere \mathbf{d}_i data Σ_i (ossia i λ_j)

$$\mathbf{d}_i = \begin{bmatrix} \Delta\theta_i \\ \Delta x_i \end{bmatrix}$$

$$P(\mathbf{d}_i | \Sigma_i) = \frac{1}{2\pi |\Sigma_i|^{1/2}} \exp\left(-\frac{1}{2} \mathbf{d}_i^T \Sigma_i^{-1} \mathbf{d}_i\right)$$

$$P(\mathbf{d}, \lambda) = \prod_{i=1, M} P(\mathbf{d}_i | \Sigma_i)$$

- si tratta di trovare una stima per i λ_j che massimizza la likelihood o il suo logaritmo

Likelihood \rightarrow ME

- La funzione costo, $\sim -\log(\text{likelihood})$, da minimizzare è

$$F(\hat{\lambda}) = \frac{1}{M} \sum_{i=1}^M [\log |\hat{\Sigma}_i| + d_i^T \hat{\Sigma}_i^{-1} d_i]$$

La soluzione non può essere ottenuta in forma chiusa, si possono utilizzare metodi iterativi, e.g. Newton-Raphson, sviluppo in serie di Taylor, ma ci vogliono le derivate prime e seconde.

- EM: si introduce una funzione $Q(\lambda, \lambda^{(n)})$ che denota l'aspettazione condizionata della log likelihood completa, dei dati sia osservati che nascosti, d_i e H_{ij} , fissati i valori dei dati osservati, usando il fit corrente per i parametri.

EM

- In effetti basta quella dei dati nascosti (i d_i sono funzione univoca degli H_{ij})

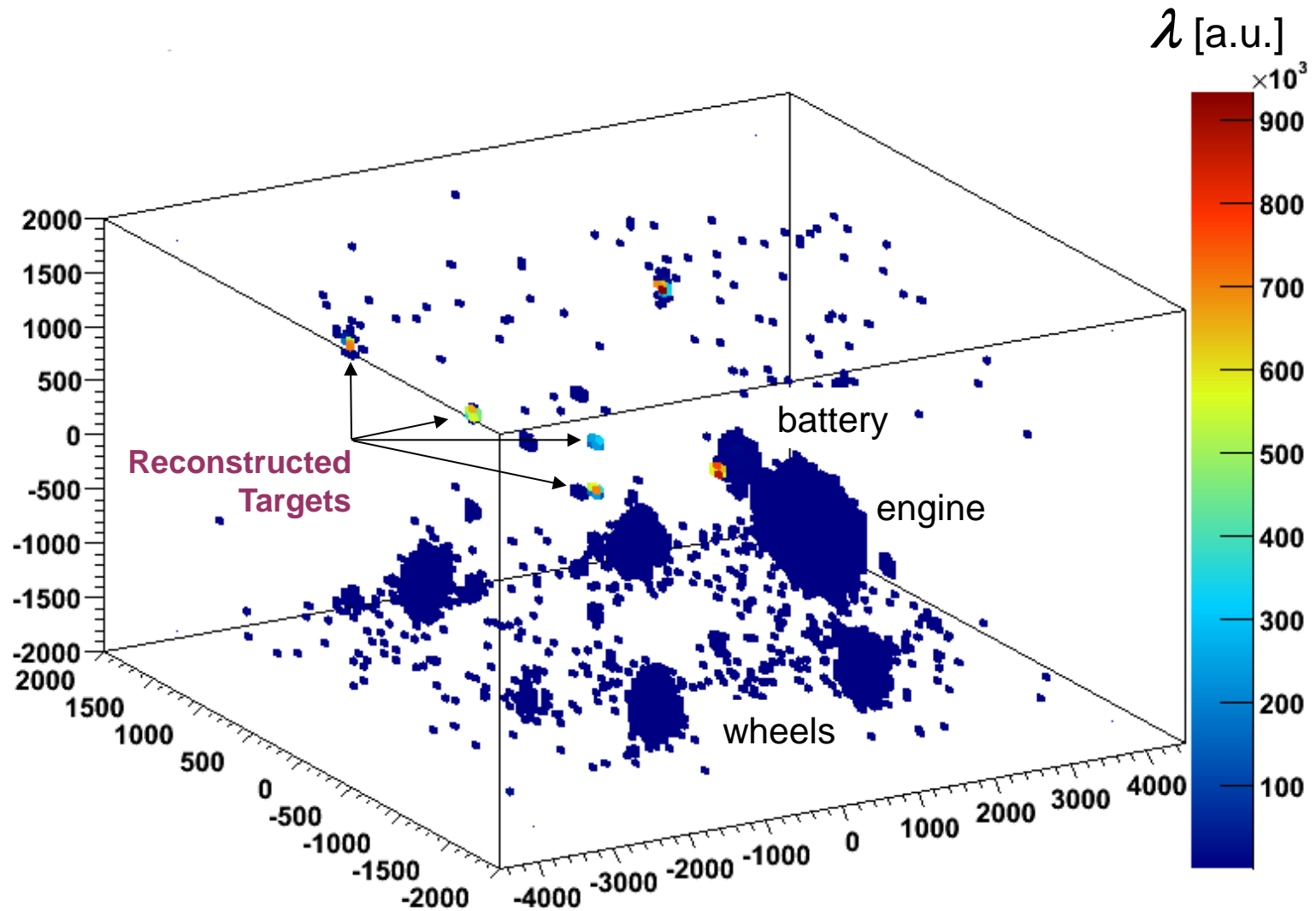
$$Q(\lambda; \lambda^{(n)}) = E_{H|d, \lambda^{(n)}} [P(H | \lambda)]$$

- E-step: stima della distribuzione condizionale dei dati nascosti (il modello statistico è lo stesso del singolo strato)
- M-step: massimizzazione della Q; uguagliando a 0 le derivate rispetto a λ_j , dopo numerosi passaggi, si ottiene una formula iterativa per λ_j (si usa la mediana perché m.s. è gaussiano solo al 98%)

$$\lambda_j^{n+1} = \lambda_j^n + (\lambda_j^n)^2 \text{Mediana} \left(\sum_{i: L_{ij} \neq 0} C_{ij}^n \right)$$

$$C_{ij} = [d_i^T \Sigma_i^{-1} W_{ij} \Sigma_i^{-1} d_i - \text{Traccia}(\Sigma_i^{-1} W_{ij})] p_{r,i}^2$$

Risultati per il camion con ML-EM



Ricostruzione
statistica con
expectation-
maximization
della maximum
likelihood
(EM-ML)



Fig. 13. Illustration of major objects in a simulated passenger van.

media

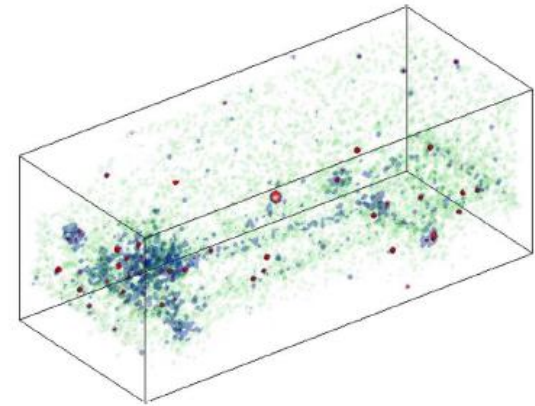
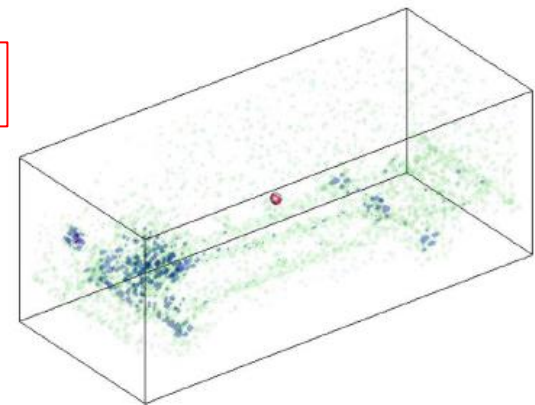


Fig. 14. Reconstruction of 1 min of simulated muon exposure of the passenger van via the *mean* method.

mediana



Gli ultimi sviluppi (Decision Sciences Int. Corp.)

- container scanner passed on 15 April 2015 final milestone at Freeport Container Port in the Bahamas (operating since August 2012)
- contract for 2.1 M\$ awarded from US Defense Dept. for scanning portable electronics
- contract awarded by Toshiba in August 2014 for a detector to look inside Fukushima Daiichi unit 1 (another muon detector is being built by KEK for unit 2)

Installation of the first muon detector at unit 1, Fukushima Dai Ichi (Image – TEPCO)



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Fine della 1a parte