Heavy Ion Physics with the ATLAS Detector

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for the ATLAS Collaboration

Outline:

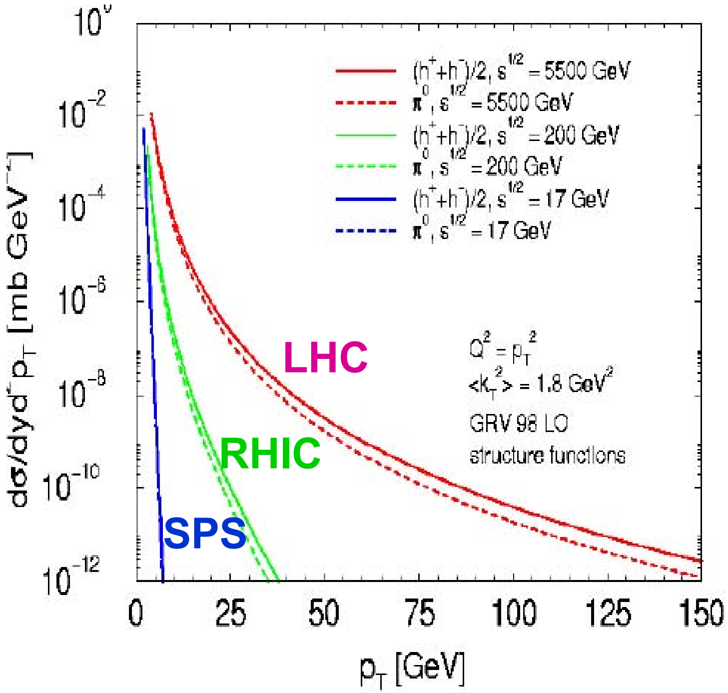
- Capabilities
- On going studies
- Summary

Heavy Ion Physics at LHC

$\sqrt{s_{NN}}$: **RHIC** 200 GeV → **LHC** 5,500 GeV

Initial state: Color Glass Condensate? → Fully saturated (CGC)

System created: strongly-coupled QGP → hotter, denser, longer lived, weakly-coupled?

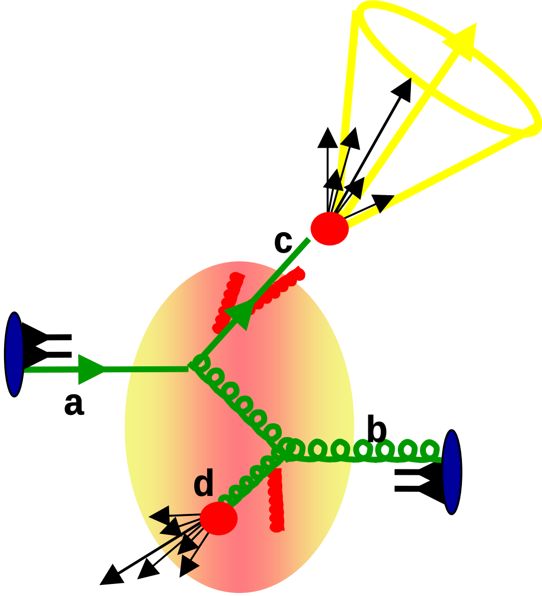


- Enormous increase of high-p_T processes
- Plenty of heavy quarks (b,c)
- Weakly interacting probes available (Z^0, $W^\pm$)

High-p_T Results

Jet quenching observed in Au+Au collisions at RHIC:

→Direct evidence that high energy density matter interacts strongly with high p_T partons!



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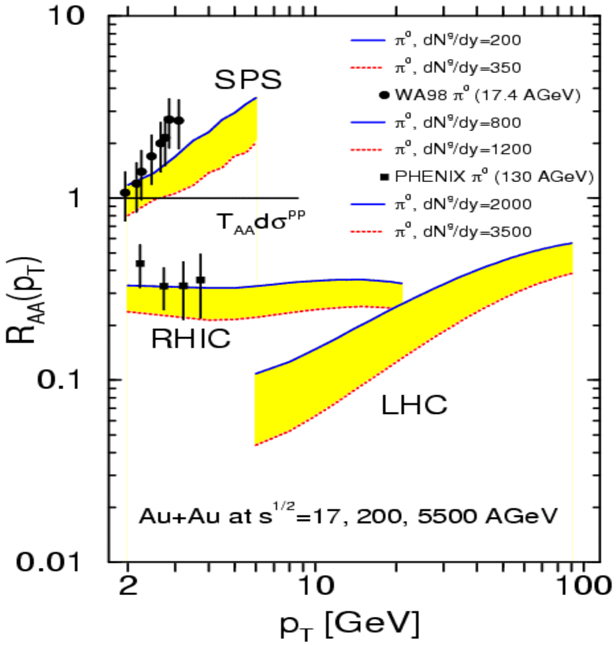
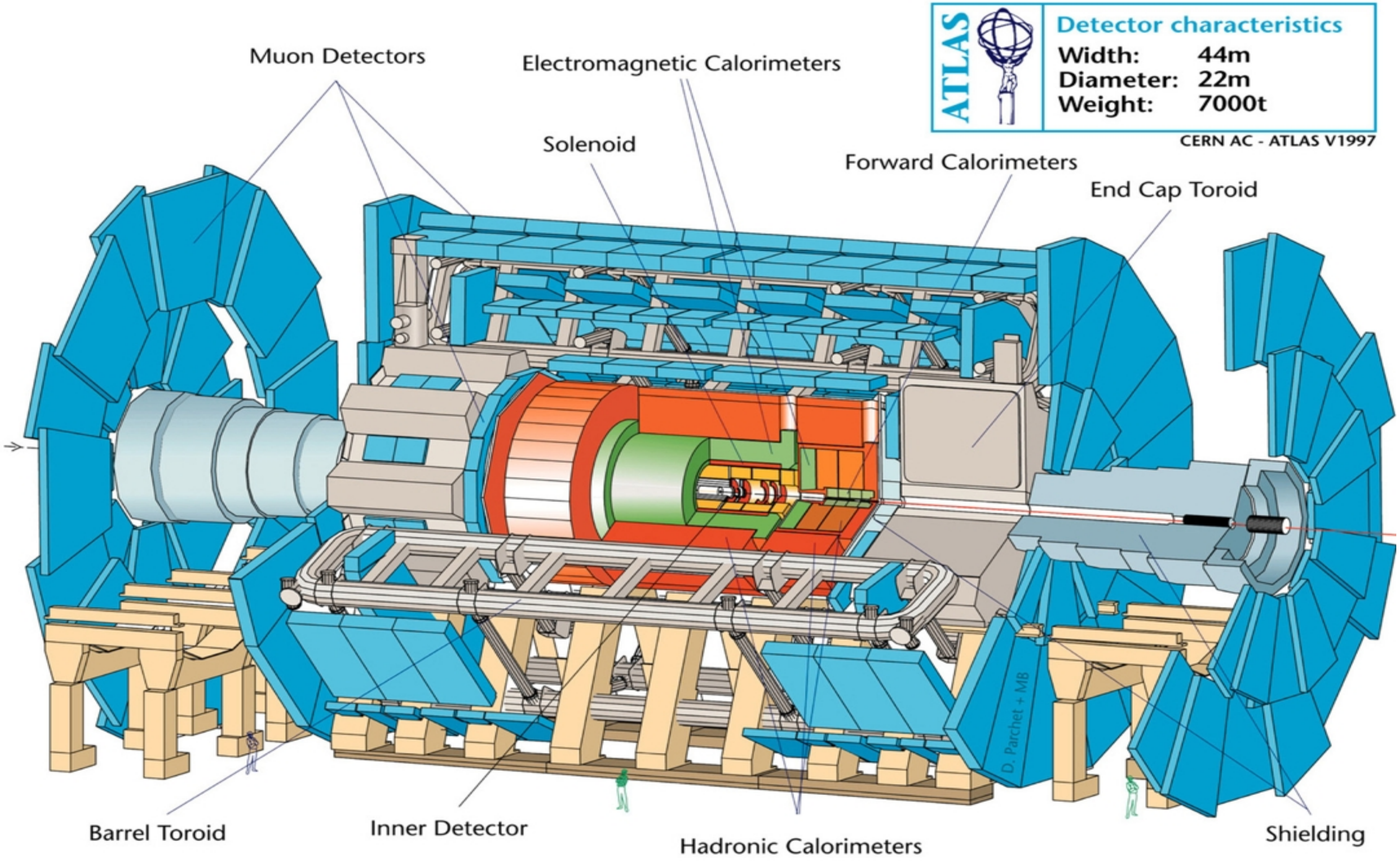
Jet quenching at SPS, RHIC, LHC



Hard processes: excellent probes of the hot QCD matter!

ATLAS: A Detector for High-p_T Studies



ATLAS as a Heavy Ion Detector

1. Excellent Calorimetry

- Hermetic coverage up to $|\eta| < 4.9$
- Fine granularity (longitudinal and transversal segmentation

High p_T probes (jets, jet shapes, jet correlations, π^0)

2. Large Acceptance Muon Spectrometer

- Coverage up to $|\eta| < 2.7$

Muons from Υ, J/ψ, Z^0 decays

3. Inner Detector (Si Pixels and SCT)

- Large coverage up to $|\eta| < 2.5$
- High granularity pixel and strip detectors

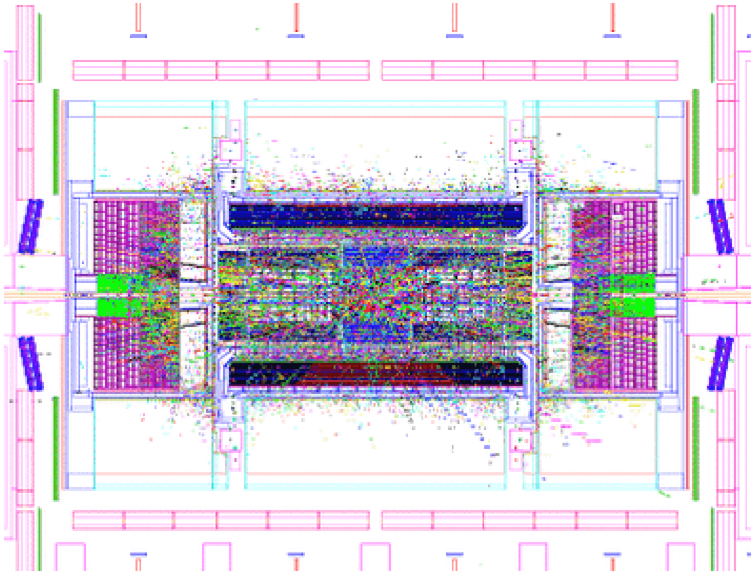
Tracking particles with $p_T \geq 0.5$ GeV/c

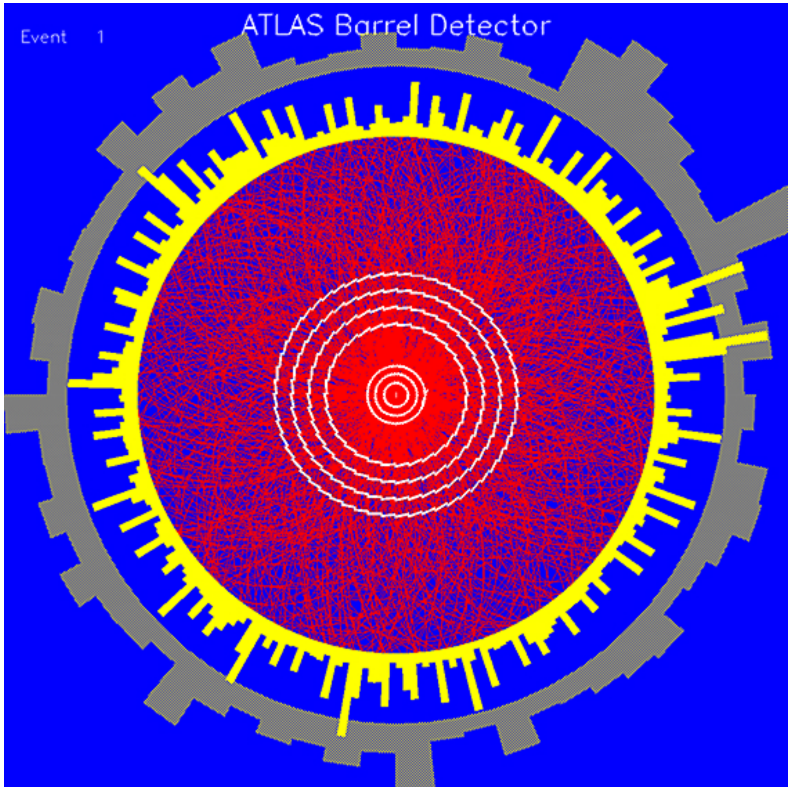
2.+ 3. Heavy quarks(b), quarkonia production (J/ψ ,Υ)

1.& 3. Global event characterization ($dN_{ch}/d\eta$, $dE_T/d\eta$, flow);
Jet quenching/unquenching

One Central Pb+Pb Event in ATLAS

HIJING + GEANT3 simulations - b < 1fm





Detector occupancies:

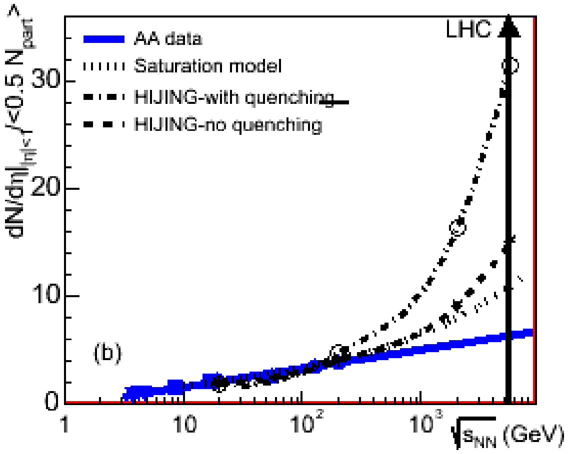
Pixels < 2%
SCT < 20%
Muon chambers:
0.3 – 0.9 hits/chamber
(<< pp at 10^{34} cm^{-2} s^{-1})

$|\eta| \leq 0.5$

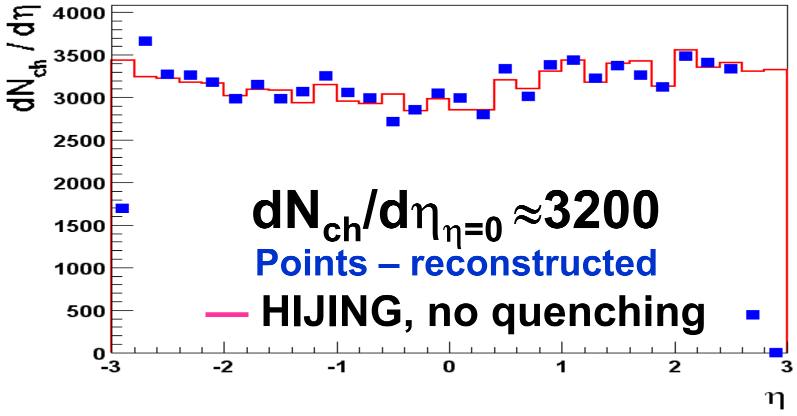
Global Event Characterization

Day-one measurements: N_{ch}, $dN_{ch}/d\eta$, ΣE_T, $dE_T/d\eta$, b

- **Constrain model prediction**

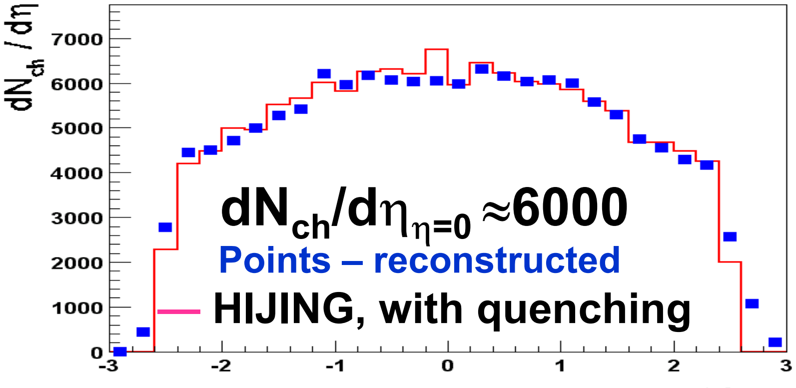


Single Pb+Pb event, b =0-1fm



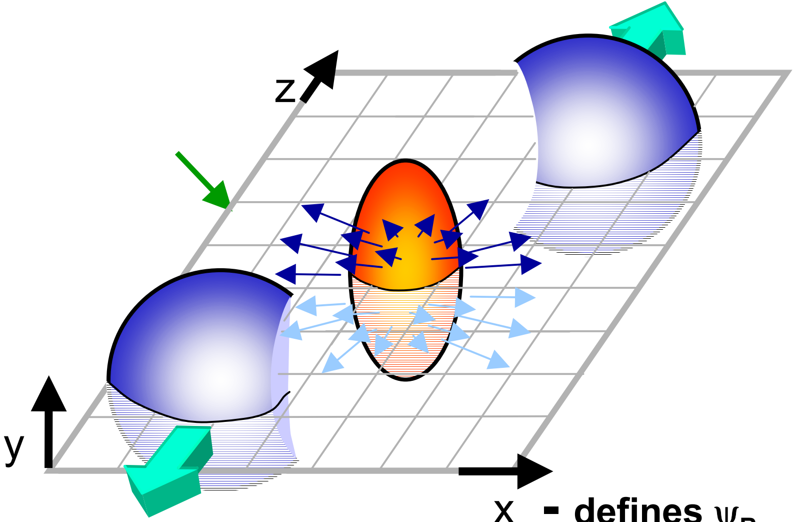
- **Indispensable for all physics analyses**
- **Obtained using small sets of simple measurements:**

position of hits or hit clusters in ID
position and energy in Calorimeters



Reconstruction errors ~5%

Collective Flow Effects in AA Collisions

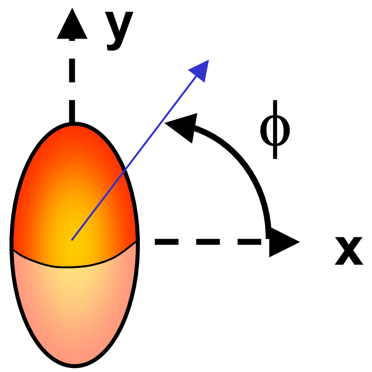


x **- defines $\psi_{R,}$**
(direction of the impact parameter)

Elliptic Flow: v_2

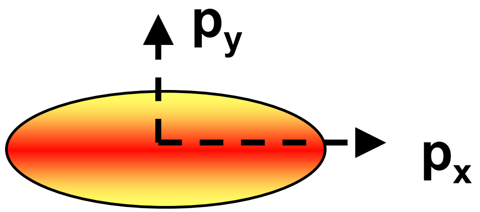
$$v_2 = \langle \cos 2(\phi - \psi_R) \rangle \equiv \left\langle \left(\frac{p_x}{p_T}\right)^2 - \left(\frac{p_y}{p_T}\right)^2 \right\rangle$$

Initial spatial deformation



Rescatterings
(pressure gradients)

Final momentum asymmetry

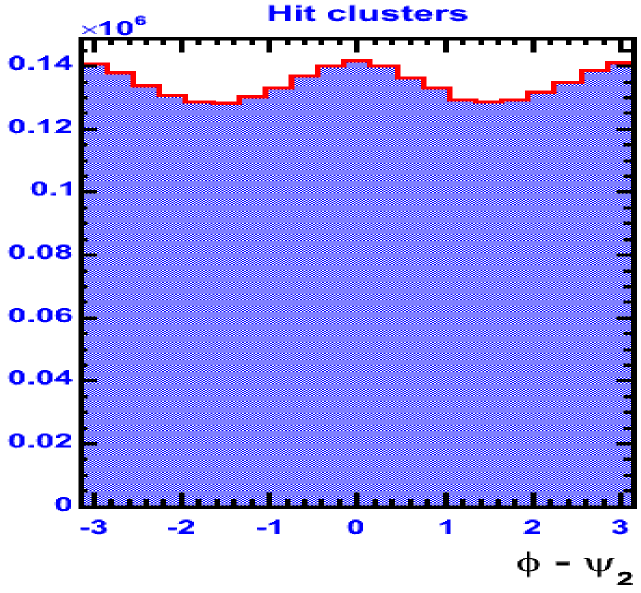


RHIC v_2 measurements → a perfect fluid nature of the system!

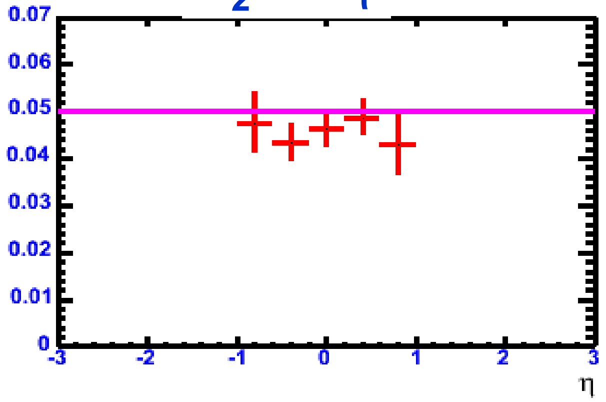
Elliptic Flow Reconstruction in ATLAS

Hijing simulations with v_2 = 0.05; const(N_{ch}, η, y, p_T)

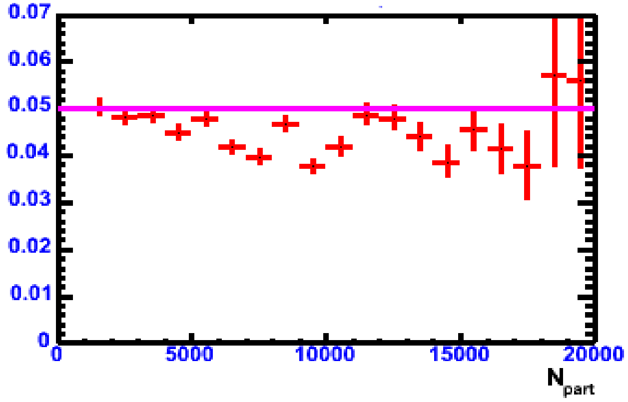
v_2 signal measured using azimuthal angles of Hit Clusters in Pixel barrel; reaction plane estimated from the energy depositions in FCAL.



v_2 vs η



v_2 vs N_{ch}



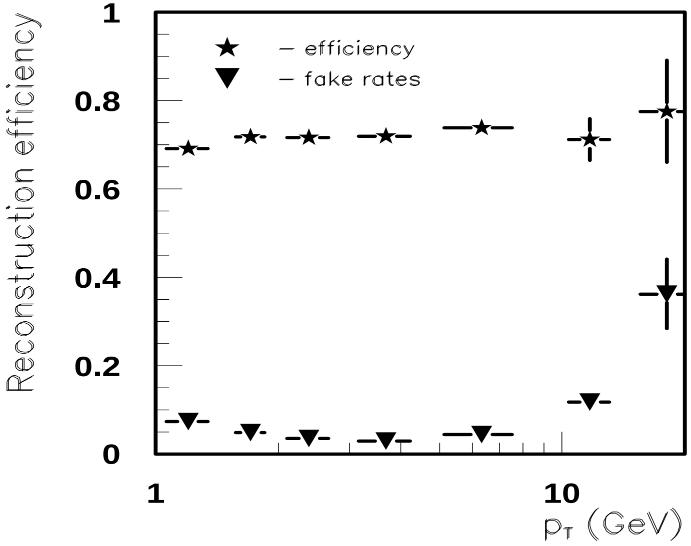
Remaining difference (~10%) is due to non - flow correlations and will be accounted for by MC corrections.

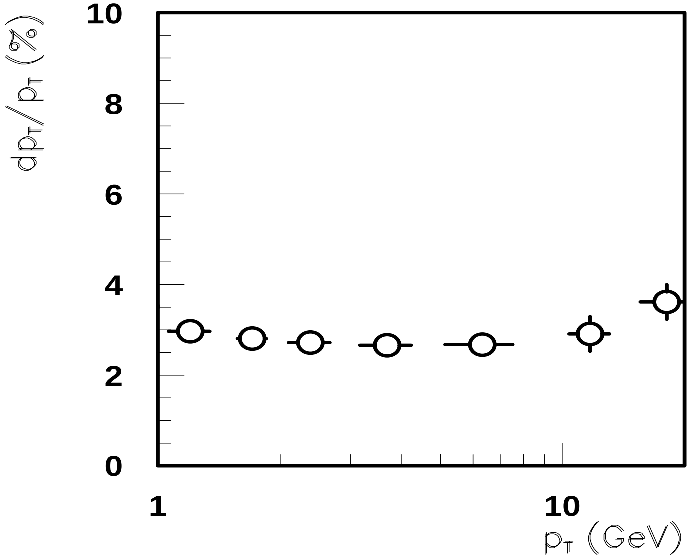
Track Reconstruction

Standard ATLAS reconstruction for pp is used, not yet optimized for PbPb.

- **Pixel and SCT detectors, not TRT**
- **p_T threshold of 0.5 GeV**
- **Uses 10 hits out of 11(13) available in the barrel (end-caps)**

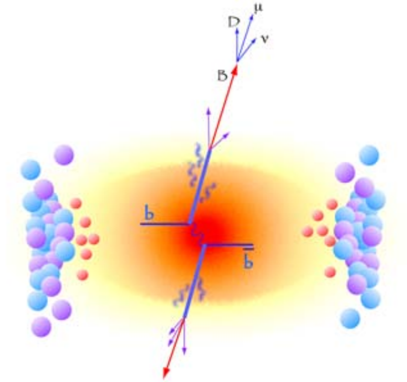
For p_T: 1 - 10 GeV/c:
efficiency ~ 70 %
fake rate ~ 5%
Momentum resolution ~ 3%
(2% - barrel, 4-5% end-caps)





Heavy Quark Production

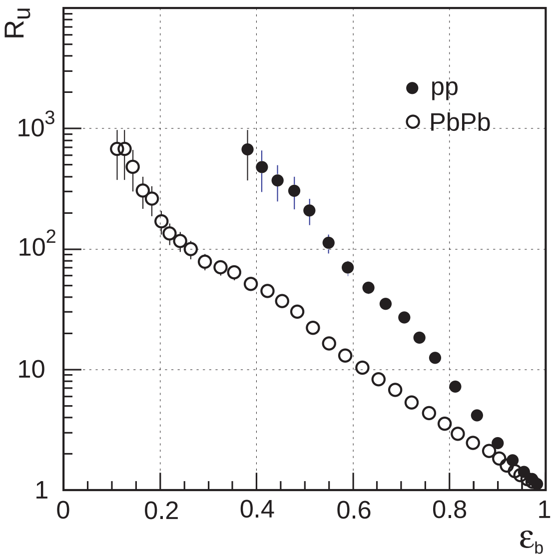
Motivation: **Heavy quarks may radiate less energy in the dense medium (dead-cone effect) than light quarks.**



b-tagging capabilities offer additional tool to understand quenching.

To evaluate b - tagging performance:

- **$pp \rightarrow WH \rightarrow l\nu b\bar{b}$ events overlayed on HIJING background have been used.**
- **A displaced vertex in the Inner Detector has been searched for.**



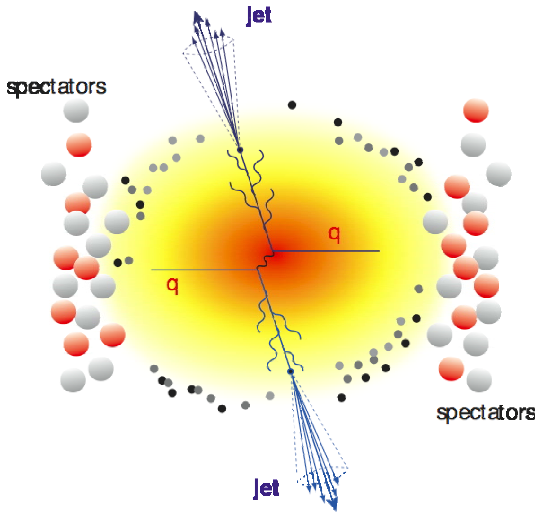
Rejection factor against u- jets ~ 100 for b-tagging efficiency of 25%

Should be improved by optimized algorithms and with soft muon tagging in the Muon Spec.

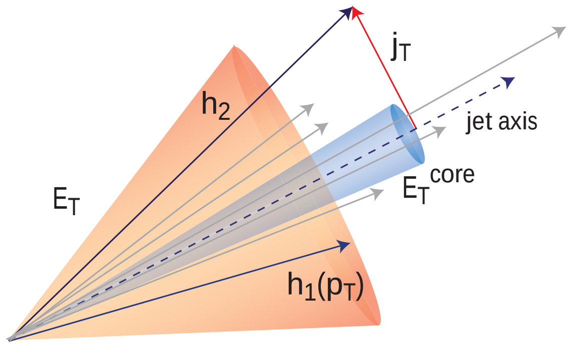
Jet Studies

Goal is to determine medium properties.

Jet quenching



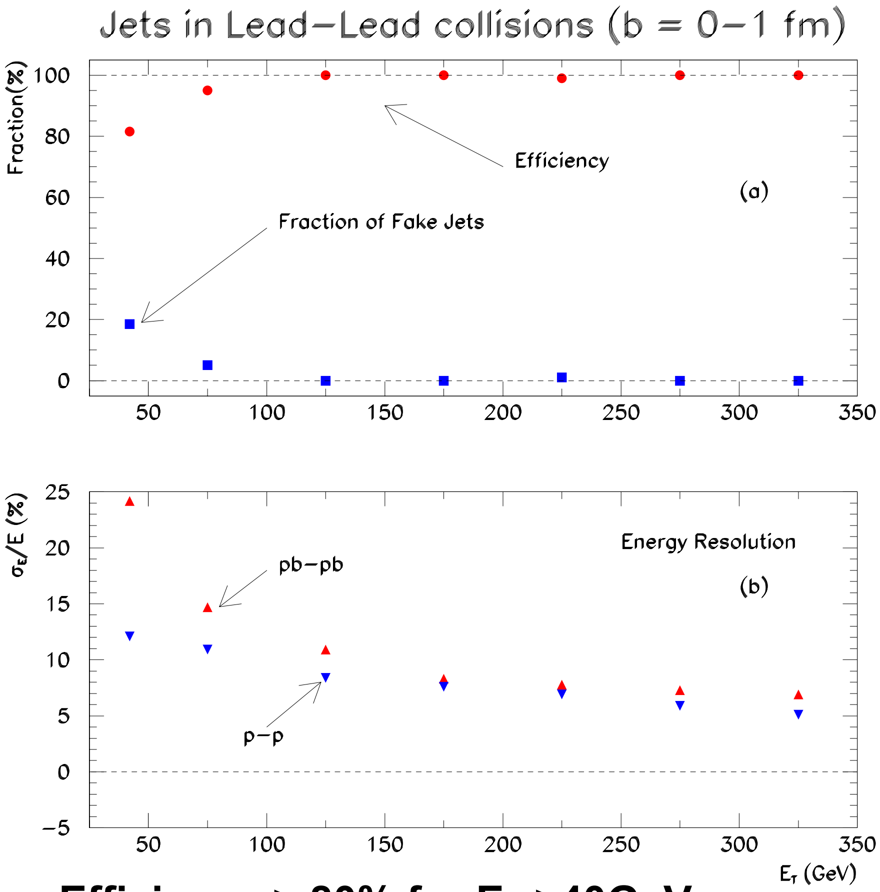
Modifications of the jet fragmentation function



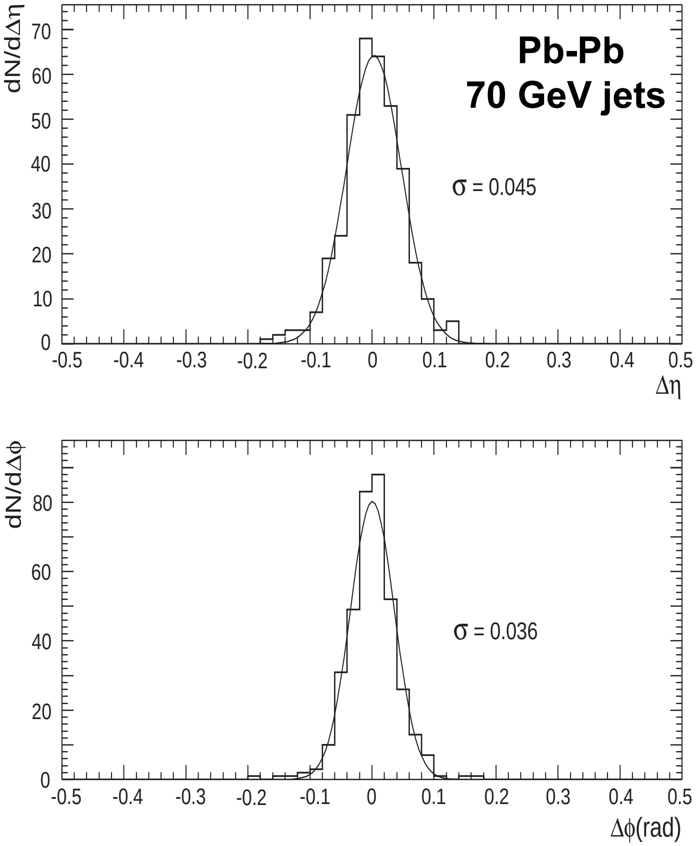
- Jet inclusive cross-sections
- Fragmentation function using tracks
- Core E_T and jet profile using calorimeters
- Neutral leading hadrons using EM calorimeters

Jet Reconstruction

- Sliding window algorithm, $\Delta\eta \times \Delta\phi = 0.4 \times 0.4$, after subtracting the pedestal (the average pedestal is 50 ±11 GeV)



- **Efficiency > 80% for E_T >40GeV**



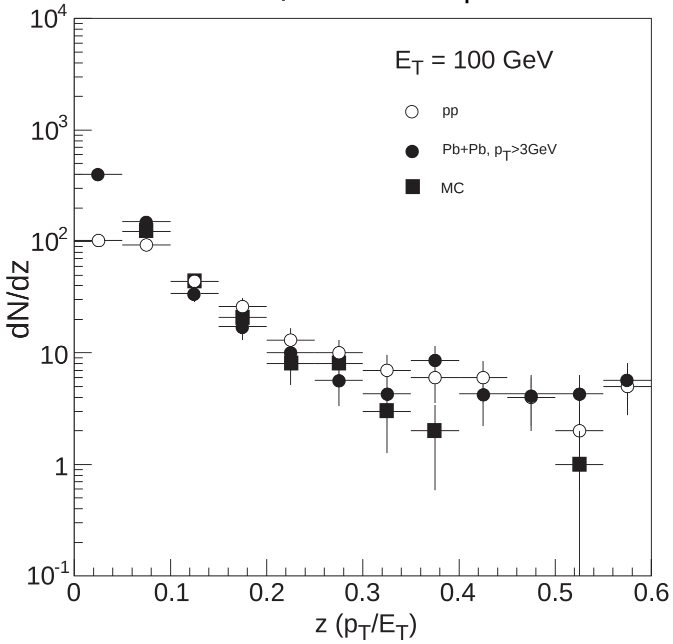
Angular resolution is about a factor of 2 worst than in pp

Jet Studies with Tracks

Fragmentation function

- Jets with E_T = 100 GeV
- Cone radius of 0.4
- Tracks with p_T > 3 GeV

$$z = p_T^{track} / E_T^{jet}$$

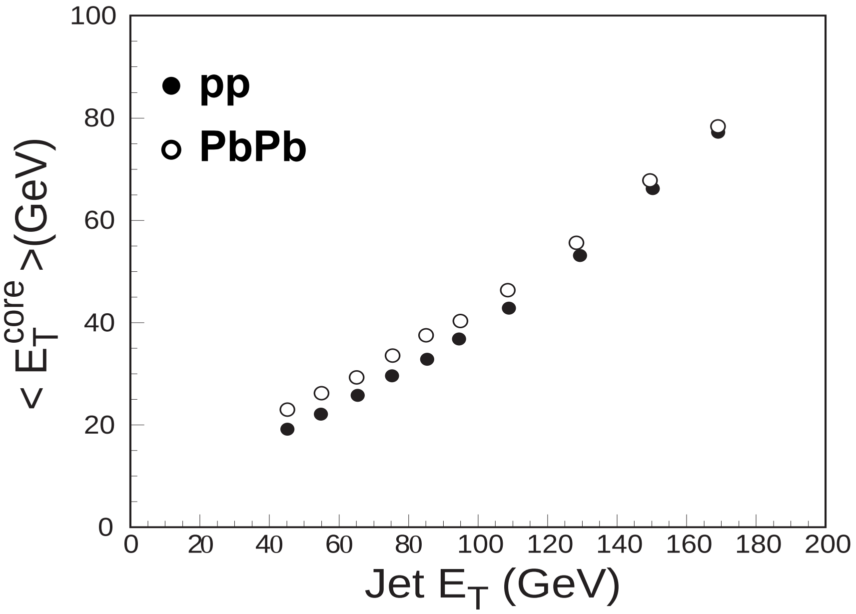


PbPb ≈ HIJING-unquenched ≈ pp

E_T^{core} Measurements

Energy deposited in a narrow cone:
R < 0.11 (HADCal), R < 0.07 (EMCal)

$\langle E_T^{core} \rangle$ sensitive to ~10% change in E_T^{jet}



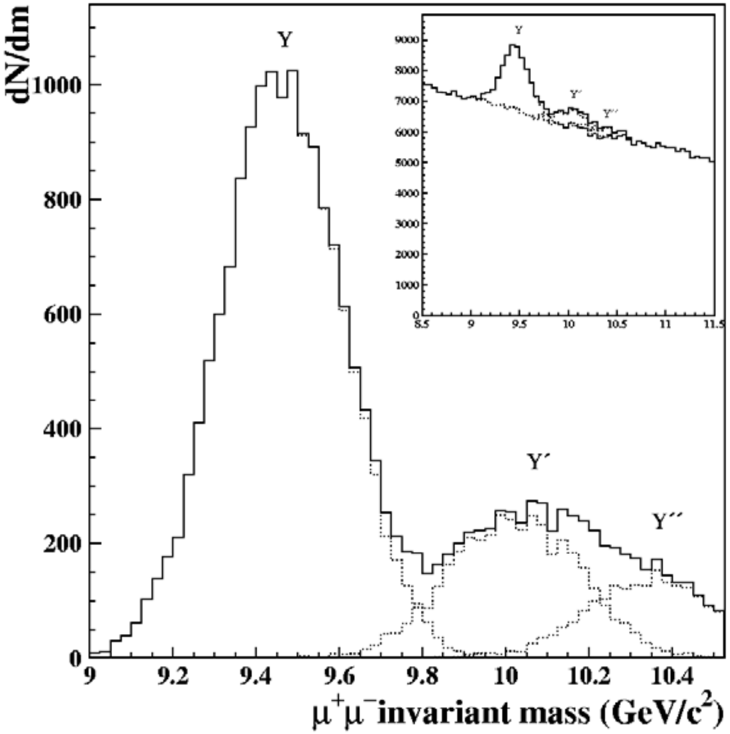
The background has not been subtracted:
$\langle E_T^{core} \rangle^{PbPb} > \langle E_T^{core} \rangle^{pp}$

Promising, but a lot of additional work is needed!

Quarkonia Reconstruction via $\mu^+\mu^-$ Decay

Measurements of quarkonia suppression allow to study the modifications of the heavy-quark screening potential.

$\Upsilon \to \mu^+\mu^-$ $|\eta| < 2$, $p_T^\mu > 3$GeV/c

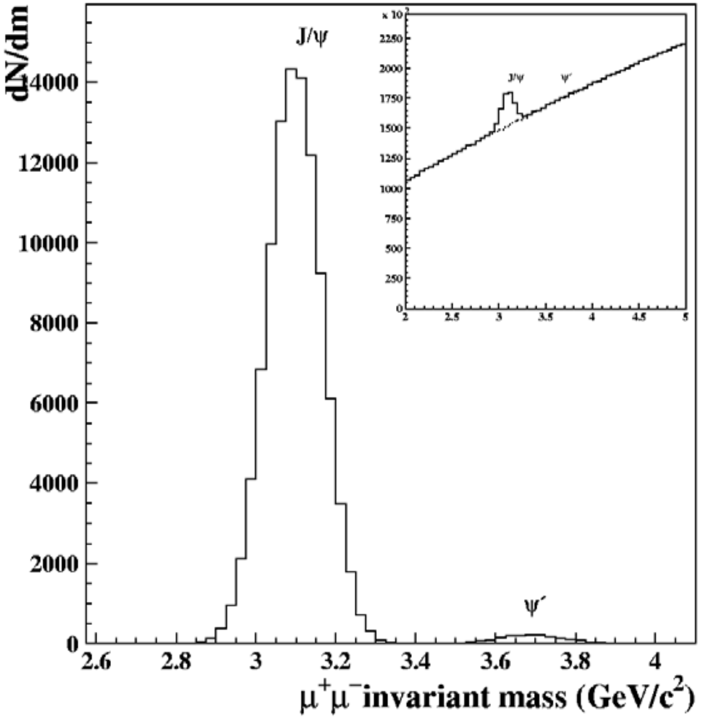


$\sigma(M)$ = 145 MeV/c²

Acc.+eff. =12.5%

15K Υ/month of 10^6s at L=4×10^{26} cm^{-2} s^{-1}

$J/\psi \to \mu^+\mu$ $|\eta| < 2.5$, $p_T^\mu > 1.5$ GeV



$\sigma(M)$ = 68 MeV/c²

Acc.+eff. = 0.53% (0.055% for $p_T^\mu > 3$GeV)

100K(11K) **J/ψ - 10^6s at L=4×10^{26} cm^{-2} s^{-1}**

Trigger and DAQ

Interaction rate of 8 kHz for $L = 10^{27}$ cm^{-2} s^{-1}

Event size ~ 5 MB for central PbPb (a conservative estimate)

Data rate to storage the same as in pp: ~300 Hz × MB

$\Rightarrow$Output rate (after HLT) ~ 50 Hz for central events

- Unbiased interaction trigger (LVL1) – use forward calorimeters (FCAL)

- Triggering on the total E_T in FCAL with a Trigger Tower threshold of 0.5 GeV selects 95% of the inelastic cross-section.

- Triggering on events with $b < 10$ fm - use full ATLAS Calorimetry

- High Level Triggers (ATLAS T/DAQ) - jet trigger, di-muon trigger,...

Jet rate ~ 40 Hz for E_T threshold = 50 GeV
~ 0.1 Hz for E_T threshold = 100 GeV

On Going Studies

→ **Physics Performance Report** → **Day 1 Readiness**

***Tracking**: Use of TRT with higher signal threshold (lower occupancy)
→ improves tracking capability and $\mu\mu$ mass resolution;
optimization of tracking algorithms

***Jets**: Improving efficiency at low E_T; Background reduction; Jet fitting algorithm; Energy calibration; γ+j, Z^0+j

***Minimum-bias pp, AA, pA**

***Ultra-Peripheral Nuclear Collisions:** High energy $\gamma\gamma$,γN; PDF(CGC)

***Triggering**: low-p_T muons, jets, e/γ, global E_T; use of MBTC, LUCID, ZDC

***Hardware**: ZDC design and integration

***Software**: Integration of HI algorithms with the ATLAS Athena framework

Summary

The ATLAS Experiment has a very good potential for a comprehensive study of heavy-ion collisions:

✓*High-p_T phenomena;*
✓*Heavy quark and quarkonia production;*
✓*Collective effects;*
✓*Global event characterization.*

This can be achieved thanks to the properties of the ATLAS detector:

- ***high granularity and large coverage of the calorimeter system,***
- ***acceptance of the external muon spectrometer,***
- ***coverage and tracking capabilities of the inner detector.***

ATLAS Collaboration “LoI for Heavy Ion Physics with the ATLAS Detector”, CERN-LHCC-2004-009/I-013.
H. Takai et al., “Heavy Ion Physics with the ATLAS Detector”, J. Phys. G: 30, s1105 (2004).
H. Takai et al., “Heavy Ion Physics with the ATLAS Detector”, Eur.Phys.J.C34:S307-S315,2004.
L. Rosselet et al., „Heavy-ion physics with the ATLAS Detector”, Czech.J.Phys.55:B343-B350,2005.
A. Olszewski et al.., ”Heavy Ion Physics with the ATLAS Detector”, Proc. of Sci. HEP2005, p.144 (2006).

ATLAS Heavy Ion Working Group

S.Aronson, K. Assamagan, M. Baker, B. Cole, R.Debbe, A.Denisov, M.Dobbs, J. Dolejsi, N.Grau, H. Gordon, F. Gianotti, I. Gavrilenko, V. Kostyukin, S. Lebedev, M. Leltchouk, M. Levin, F. Marroquim, A. Moraes, J. Nagle, P. Nevski, A.Olszewski, V. Pozdnyakov, M. Rosati, L. Rosselet, M. Spousta, P. Steinberg, H. Takai, S. Tapprogge, S. Timoshenko, B. Toczek, A. Trzupek, M.A.B.Vale, Yu. Vertogradova, F. Videbaek, S. White, B. Wosiek, K. Woźniak

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Back-up slides

Detector Occupancies

b = 0 – 1fm

Si detectors:

Pixels < 2%
SCT < 20%

TRT:

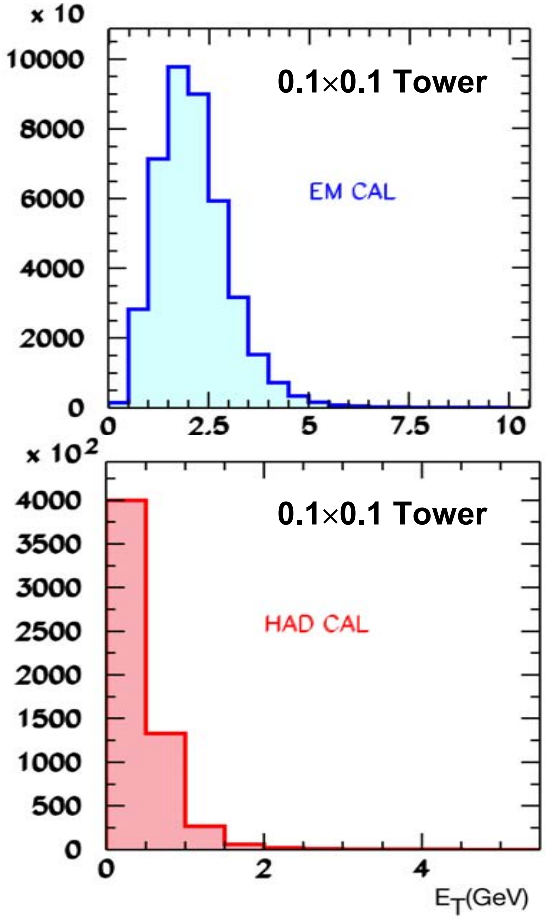
too high occupancy,
not used for these studies

(limited usage for AA
collisions is under investigation)

Muon Chambers:

0.3 – 0.9 hits/chamber
(<< pp at 10^{34} cm^{-2} s^{-1})

Calorimeters ($|\eta| < 3.2$)



Average E_T (uncalibrated):

~ 2 GeV/Tower

~ .3 GeV/Tower

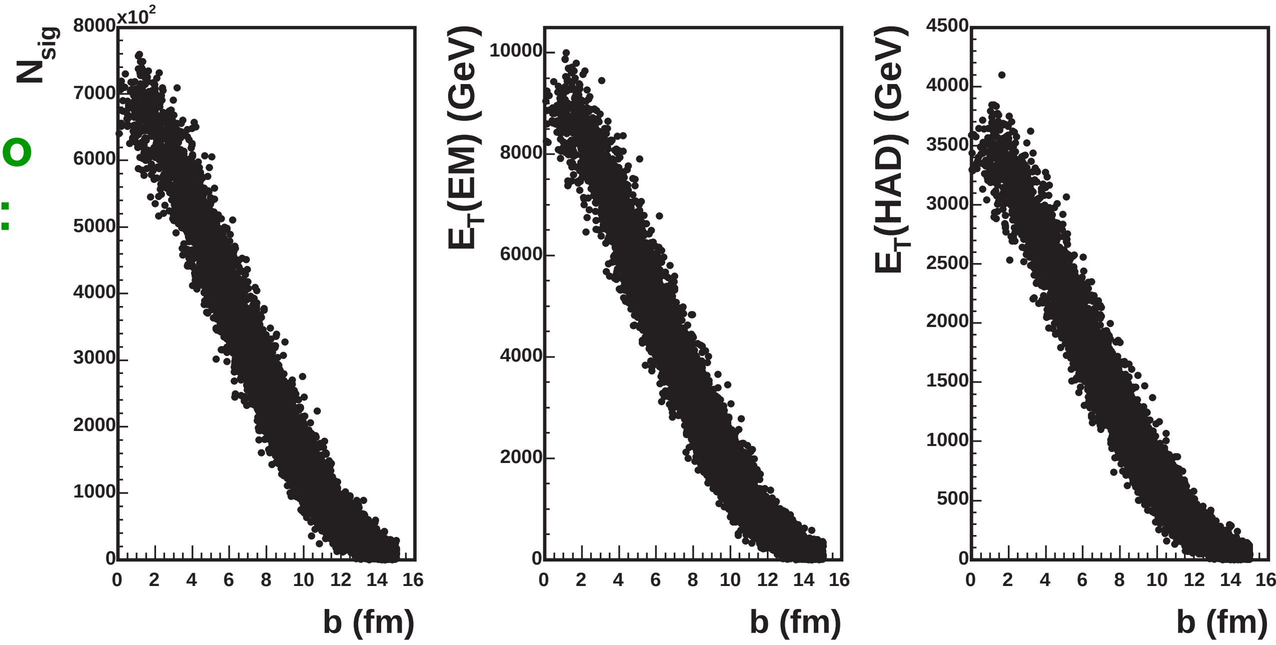
Collision Centrality

Use 3 detector systems to obtain impact parameter:

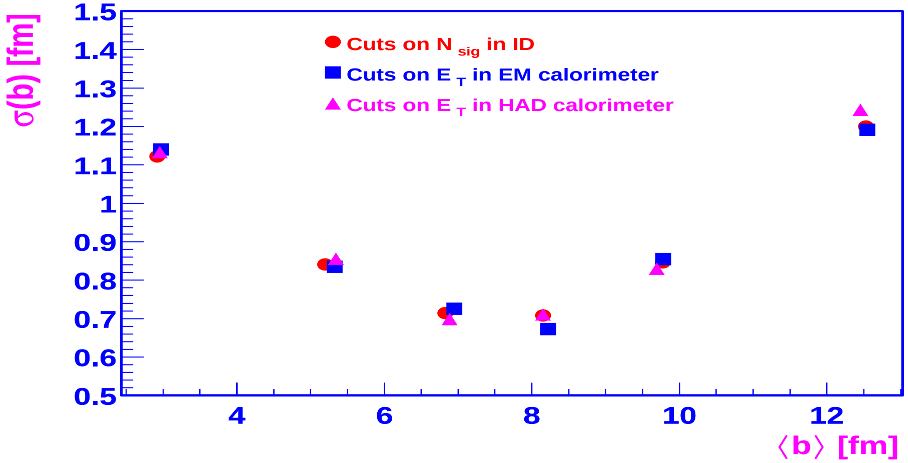
Pixel&SCT,

EM-Cal

HAD-Cal



Resolution of the estimated impact parameter ~1fm for all three systems.



Jet Rates

For a 10^6s run with Pb+Pb at $L=4\times10^{26}$ cm^{-2} s^{-1}
we expect in $|\eta| < 2.5$:

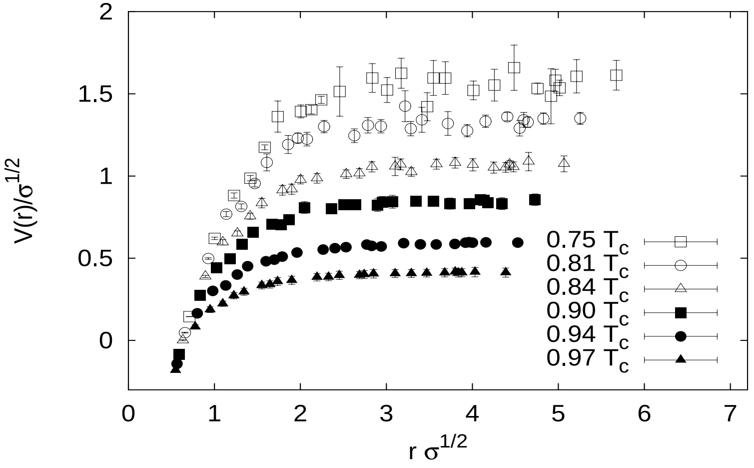
E_T threshold	N_{jets}
50 GeV	3.0×10^7
100 GeV	1.5×10^6
150 GeV	1.9×10^5
200 GeV	4.4×10^4

And also: ~10^6 γ + jet events with $E_T > 50$ GeV
~500 $Z^0(\mu\mu)$ + jets with $E_T > 40$ GeV

Quarkonia Suppression

Color screening prevents various ψ, Υ, χ states to be formed when $T \rightarrow T_c$ for the phase transition to QGP

(color screening length < size of resonance)



QGP thermometer

Upsilon family	**Υ(1s)**	**Υ(2s)**	**Υ(3s)**
Binding energies (GeV)	**1.1**	**0.54**	**0.2**
Dissociation at the temperature	**~2.5T_c**	**~0.9T_c**	**~0.7T_c**

Important to separate Υ(1s) and Υ(2s)!

Quarkonia Reconstruction via $\mu^+\mu^-$ Decay

Measurements of quarkonia suppression allow to study the modifications of the heavy-quark screening potential: ~thermometer for the plasma

Reconstruction of low momentum muons:

- method A: **use tracks fully traversing the μ-spectrometer and associate them with ID tracks through a global fit.**
- method B: **select ID tracks whose extrapolation coincide with a track segment in the μ-spectrometer**

Better p measurement and purity of A over B
Lower p threshold (larger acceptance) of B over A

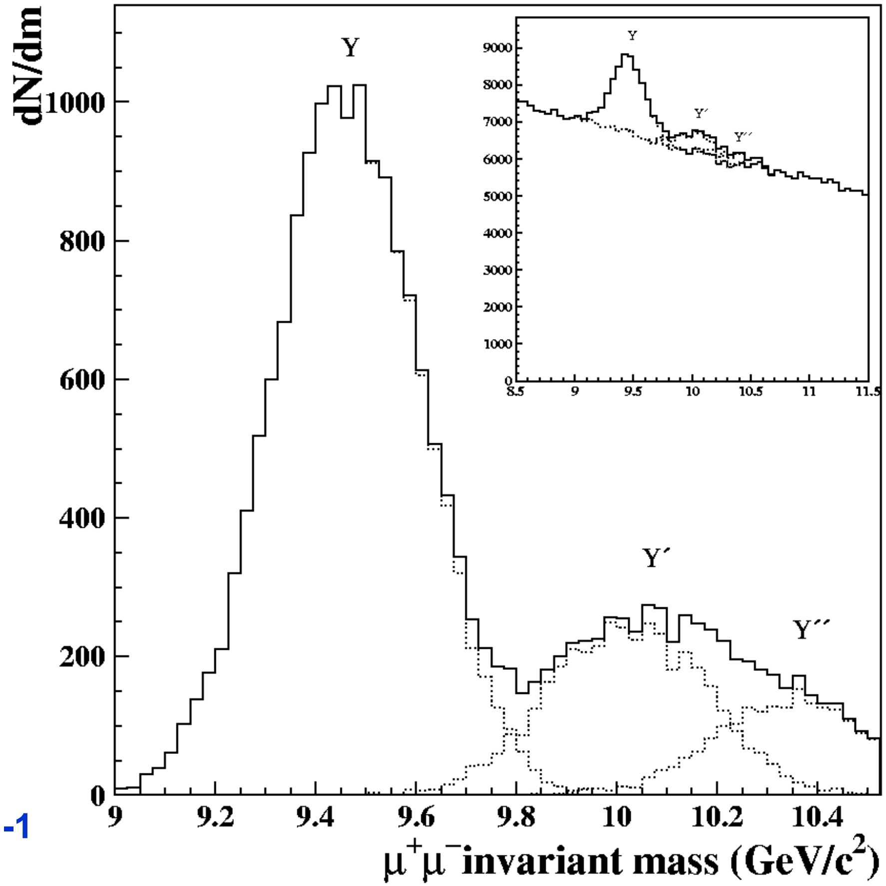
Reconstruction of Q→ $\mu^+\mu^-$:

- **Global Fit:** both muons reconstructed with method A
- **Global+Tag:** one muon from method A, one from B

$\Upsilon \rightarrow \mu^+\mu^-$ Reconstruction

Global Fit Global+Tag	p_T^μ >3 GeV		
	$\lvert\eta\rvert < 1$	$\lvert\eta\rvert < 2$	$\lvert\eta\rvert < 2.5$
Acceptance + efficiency	2.6% 4.7%	8.1% 12.5%	12.0% 17.5%
Resolution	123 MeV	145 MeV	159 MeV
S/B	0.4 0.3	0.3 0.2	0.3 0.2
$S/\sqrt{S+B}$	31 37	45 46	55 55
Rate/month		10,000 15,000	

$\lvert\eta\rvert$ <2

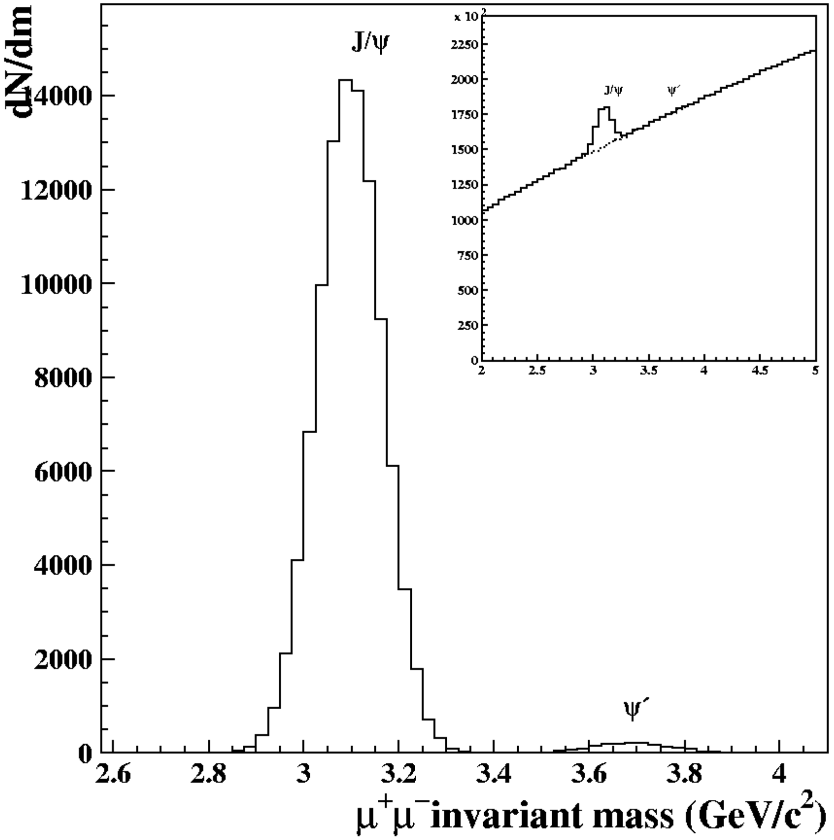


For $\lvert\eta\rvert$ < 2 (12.5% acc+eff) we expect 15K Υ/month of 10^6s at L=4×10^{26} cm^{-2} s^{-1}

$J/\psi \rightarrow \mu^+\mu^-$ Reconstruction

Global Fit Global+Tag	$\lvert\eta\rvert < 2.5$	
	$p_T^\mu > 3$ GeV	$p_T^\mu > 1.5$ GeV
Acceptance + efficiency	0.039% 0.055%	0.151% 0.530%
Resolution	68 MeV	68 MeV
S/B	0.5 0.4	0.2 0.15
$S/\sqrt{S+B}$	52 56	72 113
Rate/month	8,000 11,000	30,000 104,000

$\lvert\eta\rvert < 2.5$, $p_T^\mu > 1.5$ GeV



We expect 8K to 100K $J/\psi \rightarrow \mu^+\mu^-$ per month of 10^6s at $L = 4\times10^{26}$ cm^{-2} s^{-1}

If a trigger is possible forward with a muon $p_T > 1.5$ GeV, we gain a factor 4 in statistics…A solution might be to reduce the toroidal field for HI runs

Trigger and DAQ

- Triggering on events with b < 10 fm - use full ATLAS Calorimetry
- High Level Triggers (ATLAS T/DAQ) - jet trigger, di-muon trigger,...

Jet rate ~ 40 Hz for E_T threshold = 50 GeV
~ 0.1 Hz for E_T threshold = 100 GeV

Selection signatures

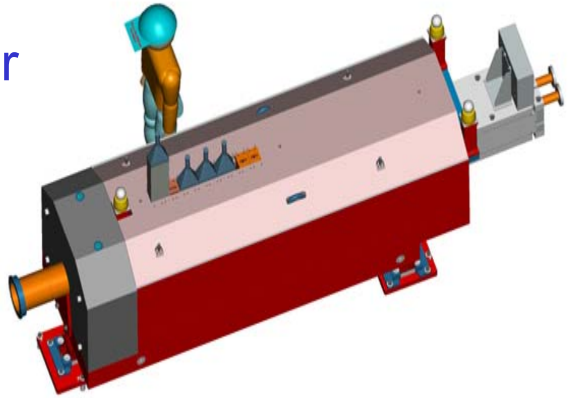
LVL1 signature	HLT signature	Physics coverage
random	random	Zero-bias sample
INT(FCAL)	int(FCAL)	Centrality/interaction
EM	e	$Z \to ee$
EM	γ	Photon production
2EM	2e	$Z \to ee$
MU	μ	$Z \to \mu\mu$, $\Upsilon \to \mu\mu$
2MU	2μ	$Z \to \mu\mu$, $\Upsilon \to \mu\mu$
nJ	nj	Jet production

Ultra-Peripheral Nuclear Collisions

High-energy γ-γ and γ-nucleon collisions

- Measurements of hadron structure at high energies (above HERA)
- Di-jet and heavy quark production
- Tagging of UPC requires a Zero Degree Calorimeter

Ongoing work on ZDC design and integration with the accelerator instrumentation:



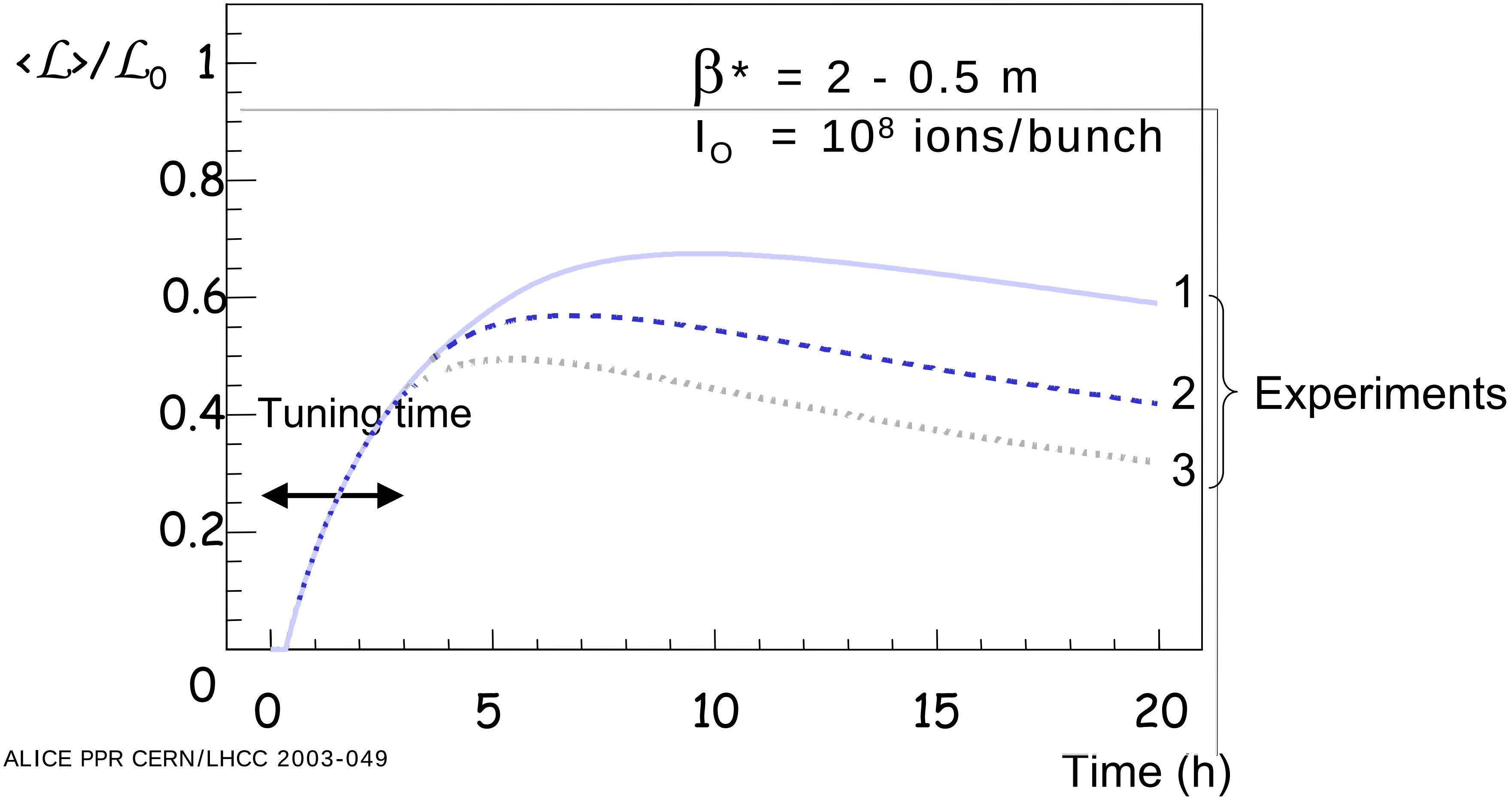
Proton-Nucleus Collisions

- **Link between pp and AA physics**
- **Study of the nuclear modification of the gluon distribution at low x.**
- **Study of the jet fragmentation function modification**
- **Full detector capabilities (including TRT) will be available.**

  L~10^{30} translates to about 1MHz interaction rate (compare to 40 MHz in pp)

Luminosity Issues

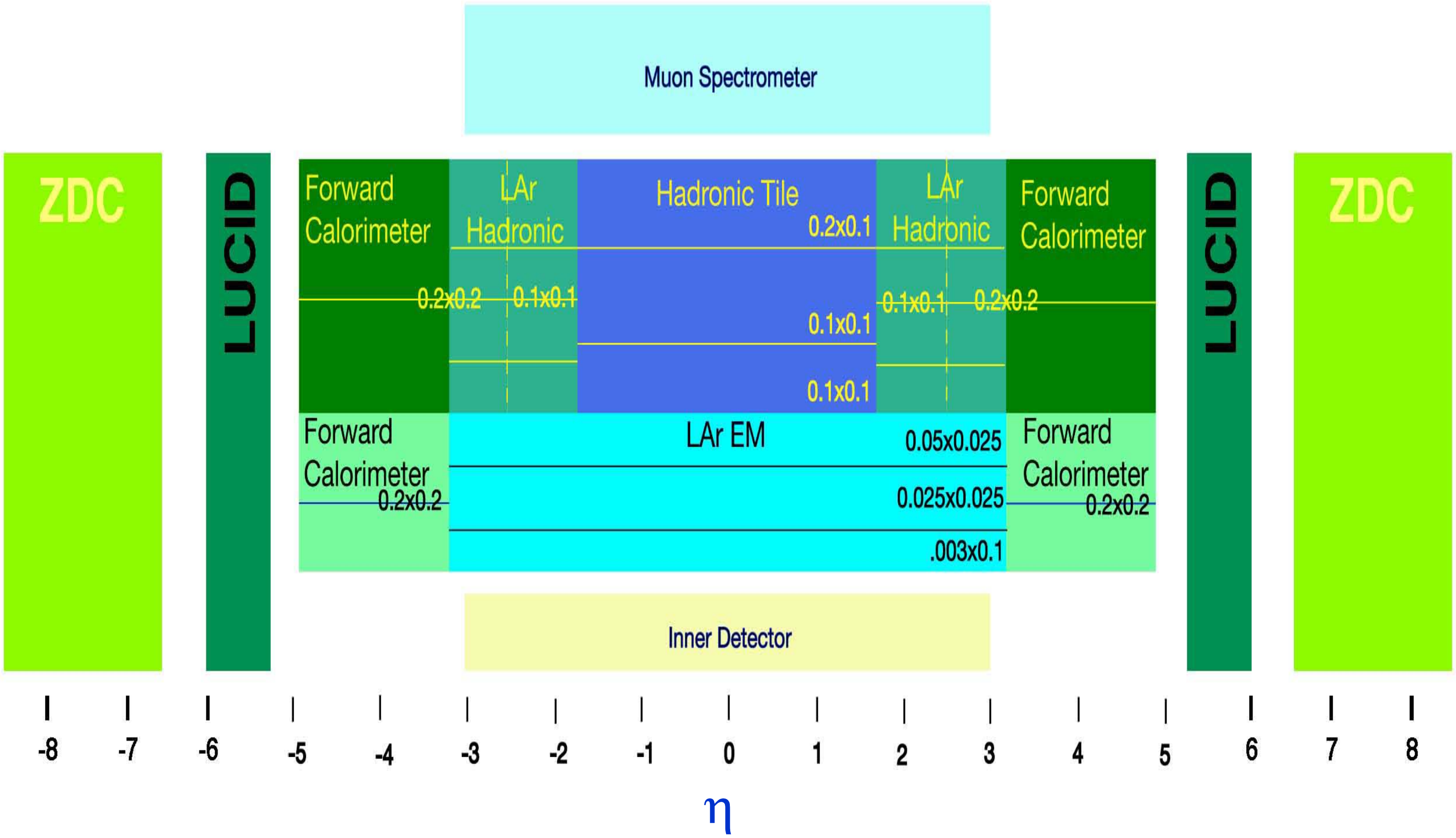
Yves Schutz, QM’2004



ALICE PPR CERN/LHCC 2003-049

20% reduction for 3 experiments as opposed to 2 experiments

ATLAS Calorimeters & Forward Det.



Muon Spectrometer

ZDC

LUCID

Forward Calorimeter

0.2x0.2

LAr Hadronic

0.1x0.1

Hadronic Tile

0.2x0.1

0.1x0.1

0.1x0.1

LAr Hadronic

0.1x0.1

0.2x0.2

Forward Calorimeter

LUCID

ZDC

Forward Calorimeter

0.2x0.2

LAr EM

0.05x0.025

0.025x0.025

.003x0.1

Forward Calorimeter

0.2x0.2

Inner Detector

-8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8

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