(191)

[redacted]

Cours/Lecture Series

1987-1988 ACADEMIC TRAINING PROGRAMME

LECTURER : W. GEIST / LBL Berkeley & CERN-EP

TITLE : Heavy ion collisions at high energy

DATE : 21, 22, & 23 October

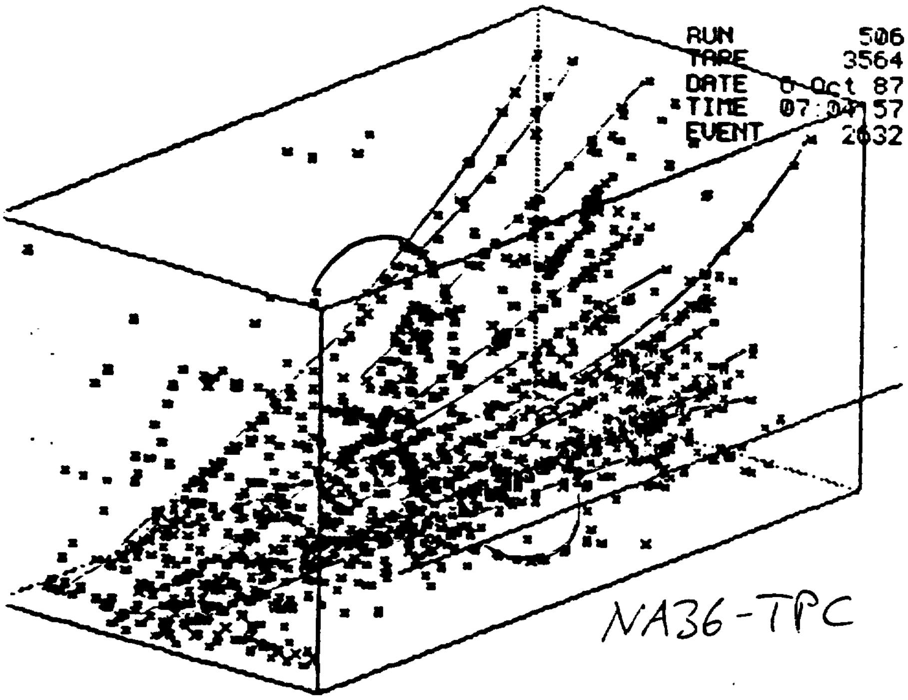
TIME : 11.00 to 12.00 hrs

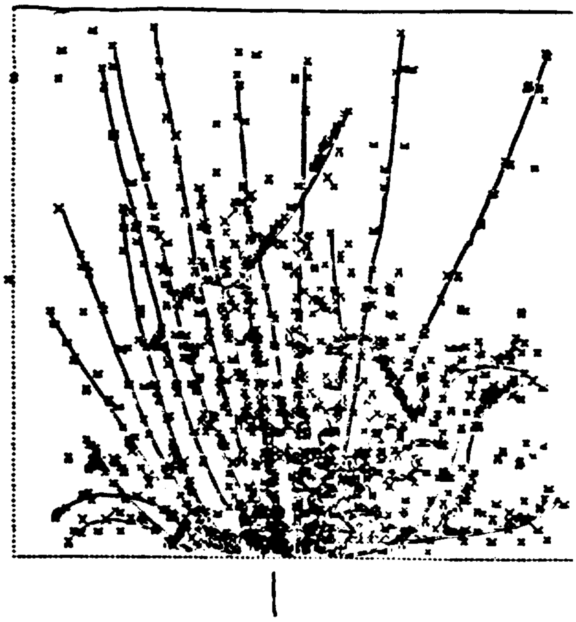
PLACE : Auditorium

ABSTRACT

An elementary introduction to the phenomenology of ultra relativistic heavy ion collisions will be given. It is focussed on the expected features of the quark-gluon-plasma in terms of thermodynamical behaviour, hydrodynamic expansion and of its detectable signatures. Selected data obtained with high energy light projectiles (p,α) and lower energy heavy ions will serve as a reference for the subsequent review of current experiments on high energy collisions. Finally, a look at future experiments at CERN and with RHIC will be attempted.

SIS/H/346





NA36-TPC

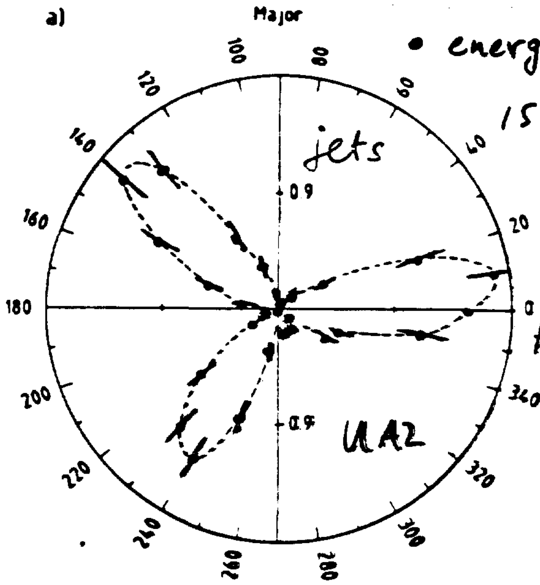
Heavy Ion Collisions at High Energy

NA 35

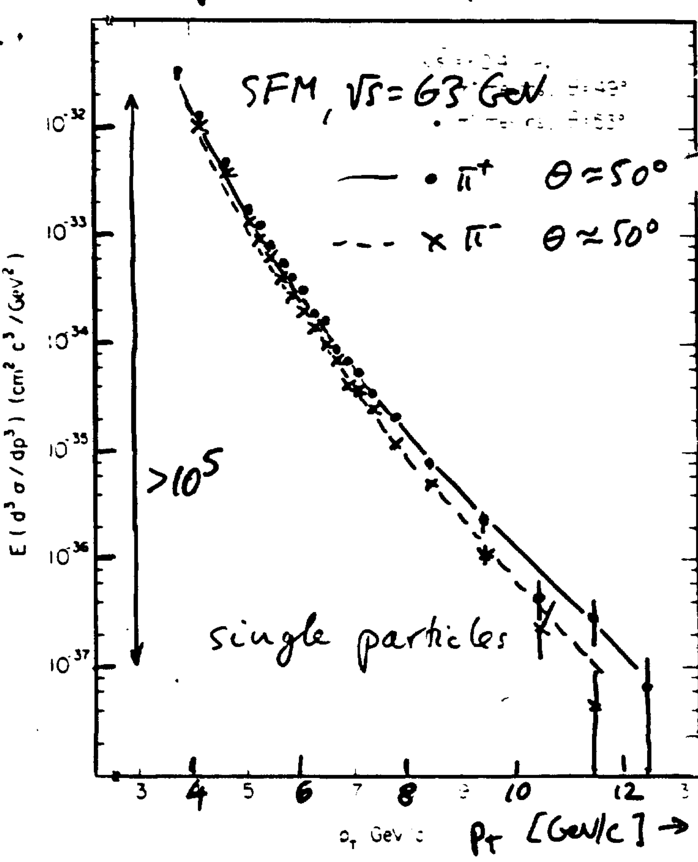
0. Introduction

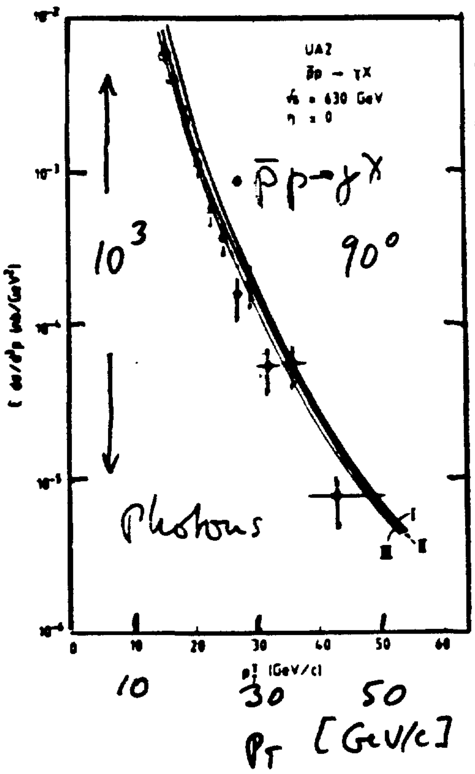
Why does one need a new type of strong interaction experiments?
After all, QCD is in good shape:

Ansari, Z. Phys. C 36, 175



Dreijard, NP B208, 1





UA2 PL 176B, 239

- QCD successful, where α_s small
- limitations due to hadronization
- confinement: true vacuum such that colored objects do not move more than ≈1 fm
- New approach to vacuum/confinement: create region of free q & gl by phase transition in A'A coll.

- Is there a chance for a phase transition in A'A?

free atoms, mol. $\boxed{\text{gas}}$ ← e.g. steam

↓ energy ← $T \approx 10^4 - 10^8\,°K$ / 1eV–10keV

free A^+, e^- $\boxed{\text{el. m. plasma}}$ ← sun

↓ ← $T \approx 2.3 \cdot 10^{12}\,°K$ / 200 MeV

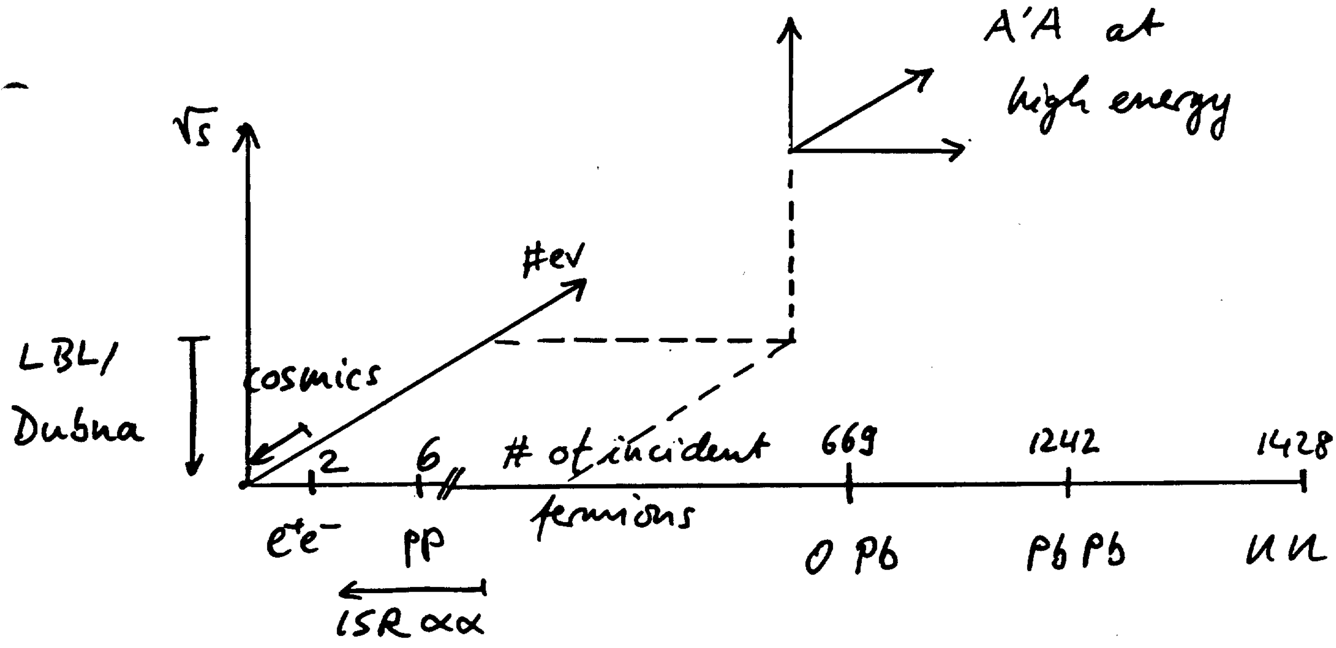
– free q, gl? $\boxed{\text{QGP}}$ ← early universe ← A'A at high energy

↑

QCD thermodynamics?

- A'A at high energy:

–



Problem & motivation: <u>little overlap</u> with previous experiments

Contents

0) Introduction

A) Conventional features of A'A Collisions

- Cross sections, nuclear effects
- Inclusive distributions for meson & baryons
- Collective effects
- El. magn. processes

B) Phenomenology of QGP

- Phase transitions & thermodynamics
- Space-time history:
  Kinetic theory / hydrodynamics

C) Search for QGP

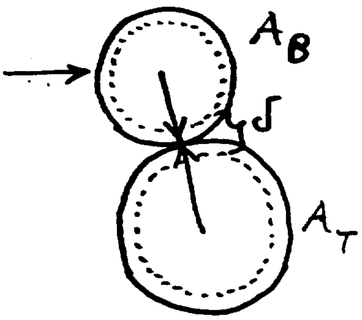
- Current experiments
- Theory & practice of signatures
- Look into future

A, Conventional Features of pA and A'A Collisions

1.) Cross sections

mean free path $\lambda_N \approx 1.7$ fm : radii : ^{12}C : 2.7 fm, ^{208}Pb : 7 fm

$\Rightarrow$ nucleus = black disc



$$\sigma_T = \pi R^2 = \pi r_0^2 (A_B^{1/3} + A_T^{1/3} - \delta)^2$$

$r_0 \approx 1.2$ fm $\qquad \delta \approx 1.3$

Exptl. problem:

$$\sigma_T = \underset{\uparrow \text{ small}}{\sigma(\text{el., coh.+incoh.})} + \underbrace{\sigma(\text{nucl. breakup}) + \sigma(\text{prod.})}_{\sigma_{in}} + \underset{\downarrow (\text{A.II.})}{\sigma(\text{el.m.})}$$

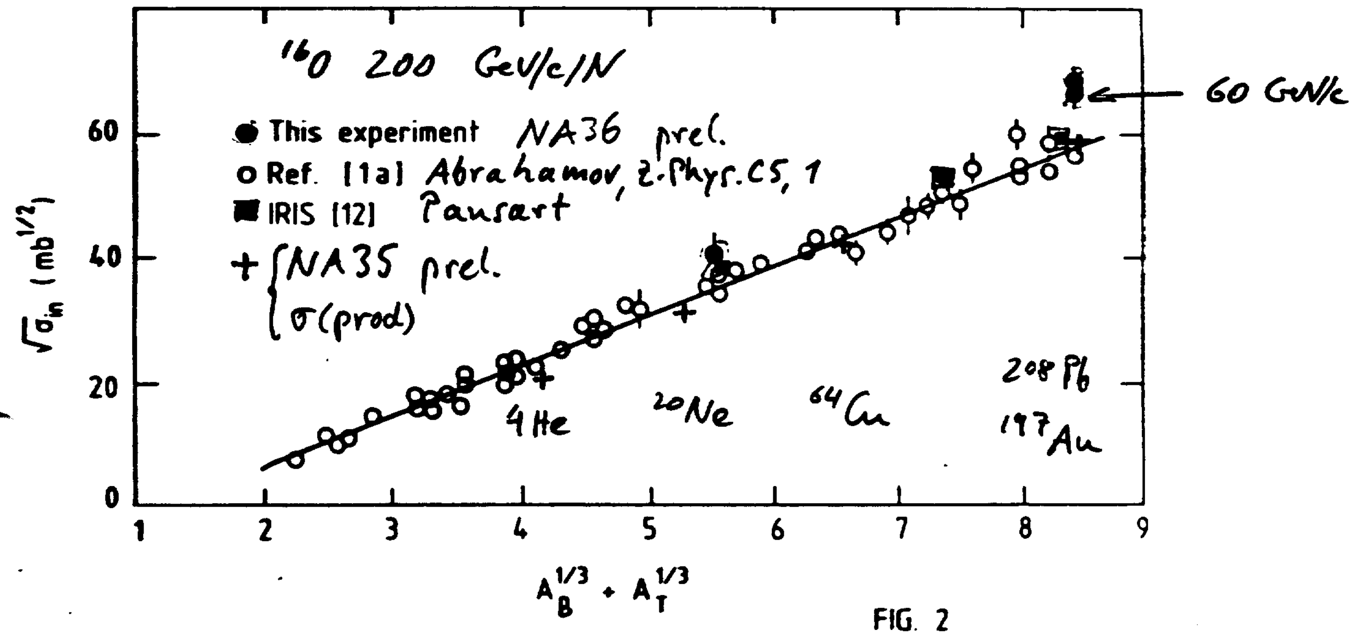


FIG. 2

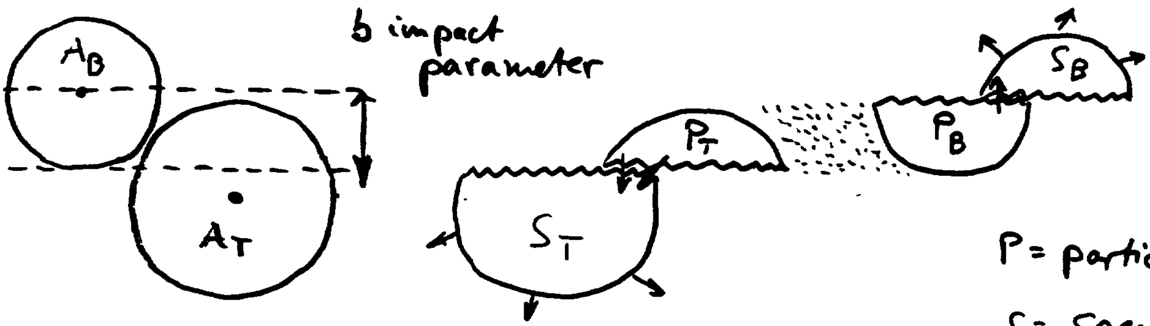
eg.: $\sigma_{in}(^{16}O\,^{208}Pb) \approx 3.6 \div 4.2$ b $\qquad \sigma_{in}(pp) \approx 34$ mb (PDG)

$\approx$ indep. of $\sqrt{s}$

$\sigma_{in}(^{16}O\ Em) \approx 1015$ mb between $p_{Lab} = 2.1 \rightarrow 200$ GeV/c

[EMU03: Badawy, priv. comm., Ardito CERN-EP/87-162, Friedlander, PR C27, 1489]

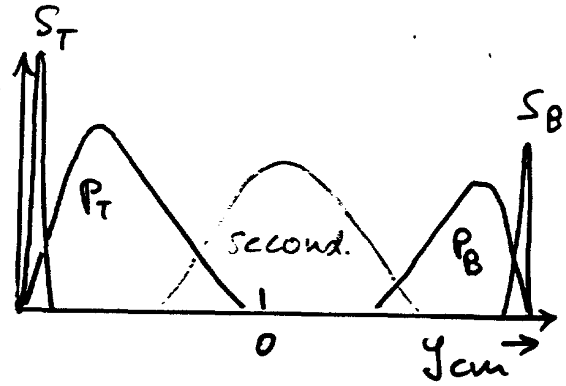
2. Event Structure and Geometry



P = participants

S = spectators

$y = \text{arcth } v$



- Simple picture: Abrasion-Ablation:
  assuming straight line trajectories
  i.e <u>Glauber</u> framework $\hat{=}$ geom. optics

- # spectators given by $\vec{b}$ measure violence of collision
  b very small : central coll.

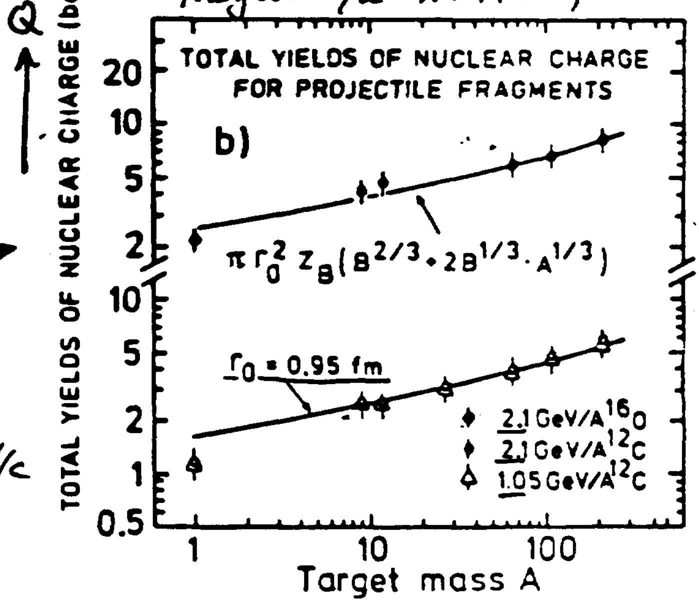
- Check of idea:

Nagamiya NPA 335,517

$\overline{Z}(P)/Z_B = A_T^{4/3}/(A_B^{1/3}+A_T^{1/3})^2$

Q = charge yield of spect.

$Q = (Z - \overline{Z}) \cdot \pi r_0^2 (A_B^{1/3}+A_T^{1/3})^2 \rightarrow$



but: $r_0 < 1.2$ fm

Reason? Glauber for > 2 GeV/c only

3. Nuclear Fragmentation

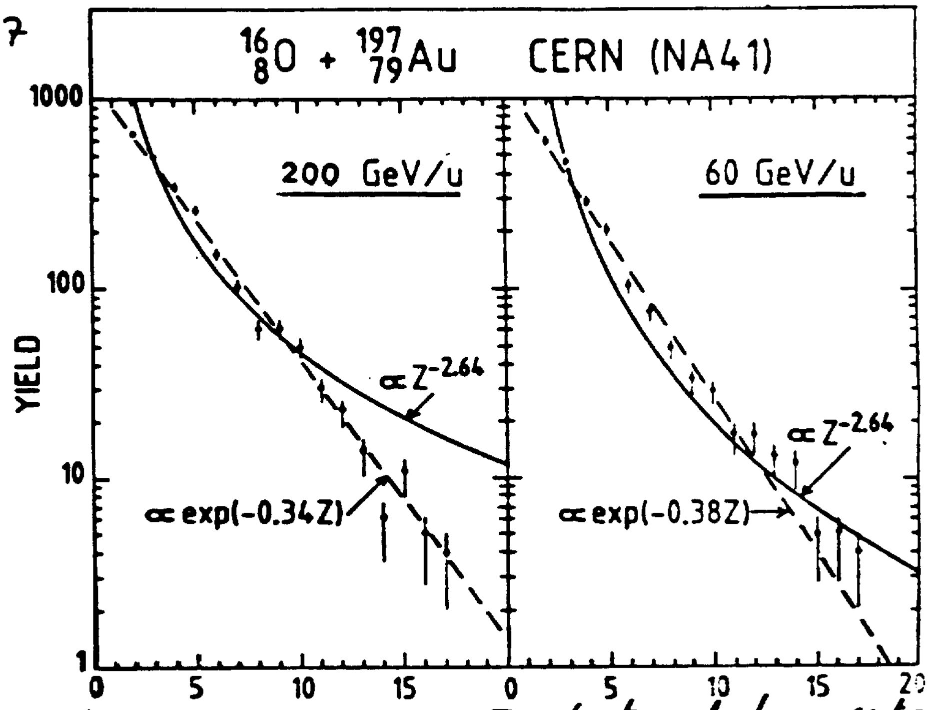
[Hüfner, Phys. Rep. 125, 129]

(consequences for design of expt.)

lower $\sqrt{s}$ and p beams:
- $dN/dA \sim A^{-\tau}$, $\tau \approx 2.6$
- geom. approach : no $\sqrt{s}$ dependence
- $E_{excit} \lesssim 1$ GeV $\Rightarrow$ no complete break-up

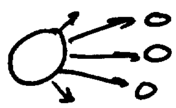
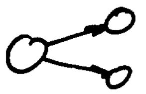
Berthier, PL 193B, 417

target fragmentation



Z of target fragments

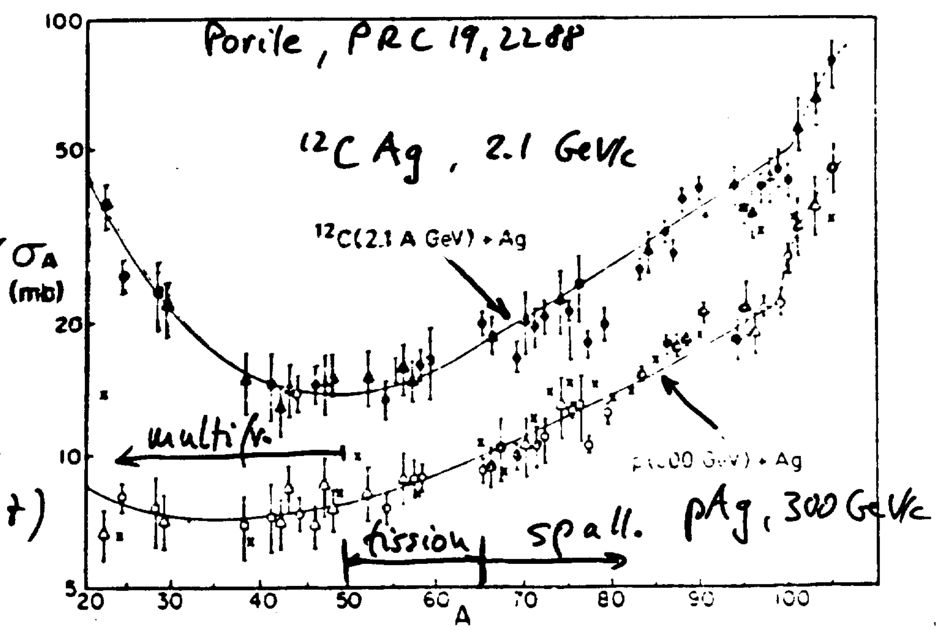
Type of mechanism:

- $A \approx 10-50$  Multi-fragment.
- $A \approx 50 - \frac{2}{3} A_T$  fission
- $A > \frac{2}{3} A_T$ spallation

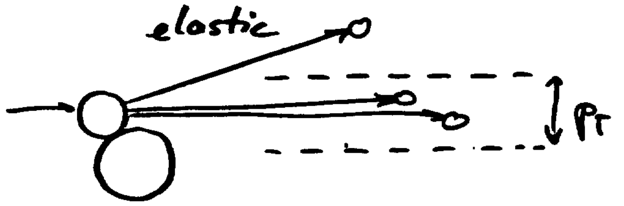
Note: for $E_{lab} \underline{> 3 \text{ GeV}}$

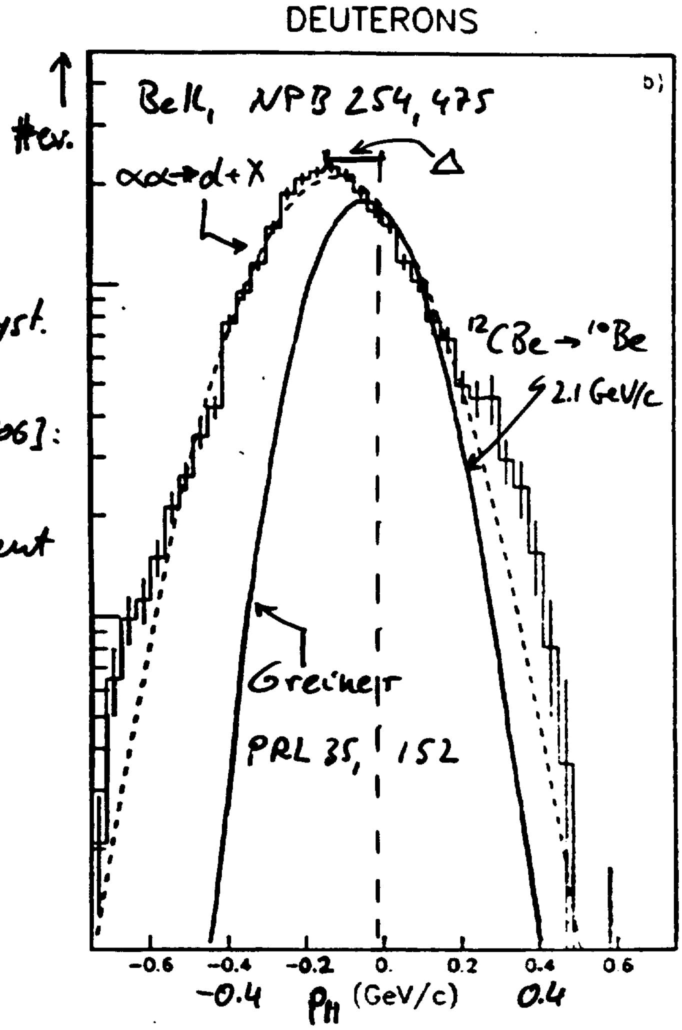
yield indep. of $\sqrt{s}$

(for p Au at least, Kaufmann, PRC 22, 167)



4. Fermimotion of Fragments





- boost into projectile rest syst.

expectation [Goldhaber, PL53B, 306]:

$$\sigma_{\parallel} = \frac{p_F}{\sqrt{5}} \sqrt{\frac{A_F(A - A_F)}{A-1}} \quad , F: \text{fragment}$$

p_F = Fermimomentum

$= (3\pi^2 n)^{1/3}$, n = nuclear density

[Landau-Lifshitz V]

- Δ: probably due to binding [Gugelot, PRC 30, 654]
- Measured widths consistent with p_F

Note:

- $\frac{dN}{dA}(\sqrt{s})$ & $\frac{dN}{d\vec{p}}(A) \approx$ known for fragments in average collisions
- simulation possible for expt. design & analyses (e.g. MC Fai, NPA 404, 551)
- From $\sigma_{\parallel}$: fragments are expected at polar angles $\theta_{Lab} = (0 \pm 0.3)^{\circ}$, $p_{Lab} \gtrsim 60$ GeV/c

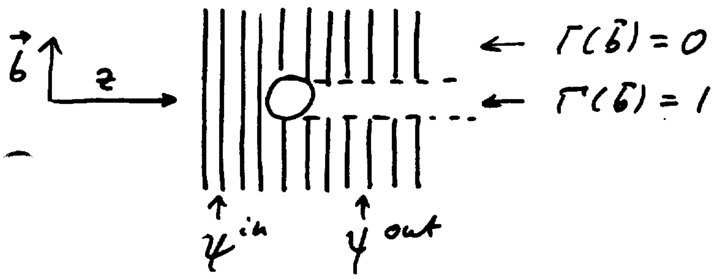
I. Particle Production: Theoretical Ideas

a) Geometrical optics: straight light rays

High energy elastic scattering: strong maximum at small angles

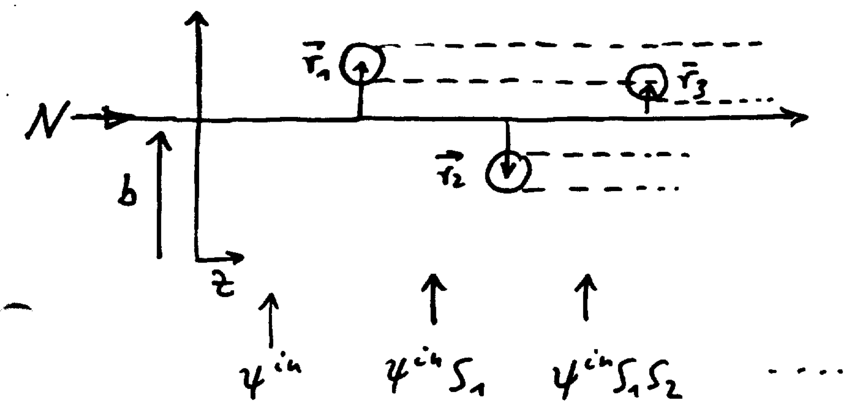
$\Rightarrow$ Glauber theory: [Franco, PR 142, 1195]

$$\psi^{out}(\vec{z}) = \psi^{in}(z)\, S(\vec{b}) = \psi^{in}(z)\,(1-\Gamma(\vec{b})),\ \vec{b} \perp z$$



Γ = profile function

- multiple scattering in nucleus A



$$S_A(\vec{b}) = \int \prod_i S_i(\vec{b} \pm \vec{r}_i)\, \rho_A(\vec{r}_1 \cdots \vec{r}_i)\, d\vec{r}_1 \cdots d\vec{r}_i$$

$\leftarrow$ A wave function

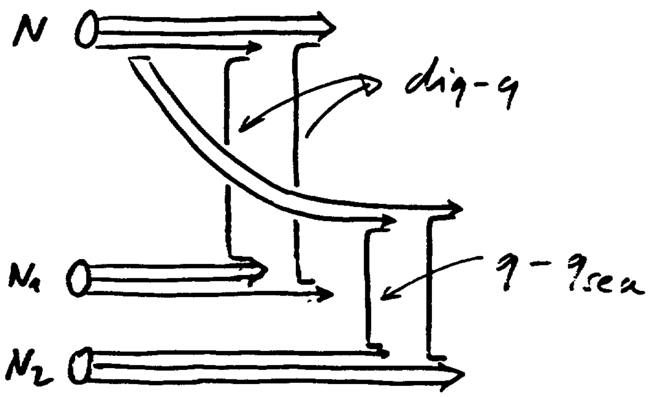
scattering amplitude $F(\Delta\vec{q}) \sim \int d^2b\,[1 - S_A(\vec{b})]\,\exp(i\,\vec{b}\cdot\Delta\vec{q})$

$\uparrow$ momentum transfer

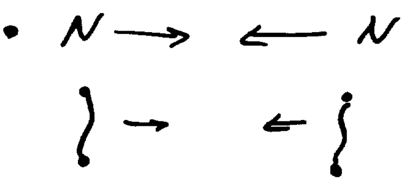
- From $F(\Delta\vec{q})$ one can calculate probabilities for multiple interactions in A'A collisions
- Probabilities of this type are needed in production models for A'A collisions

b) <u>Dual Parton Model</u> (Capella, PL 81B, 68)

- In A'A collisions strings can be formed between diq − q and q − q.
- Structure functions are needed for all partons
- Strings hadronize ; $q-\bar{q}$ strings fit e^+e^- data
- The number of strings is determined via Glauber weights.

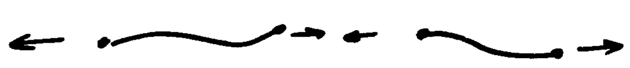


c) <u>Lund-Fritiof</u> (Andersson, NP B281, 289)



the collision leads to a momentum transfer

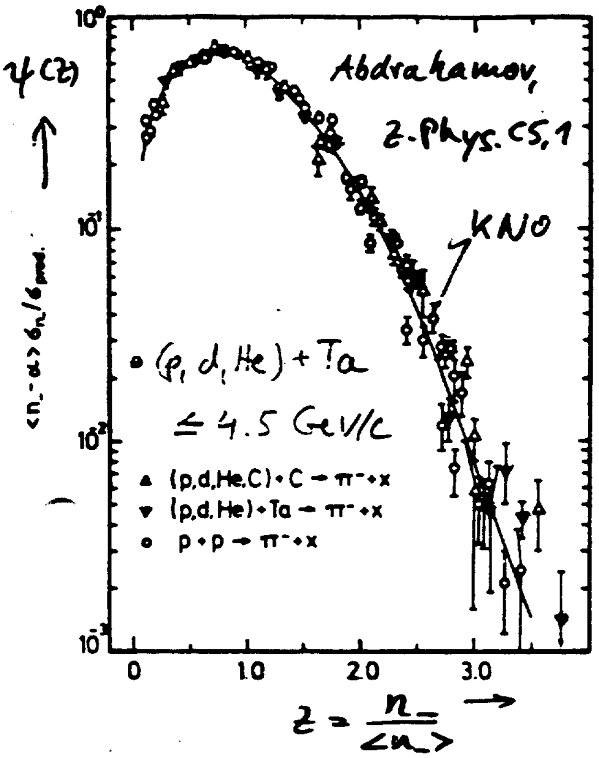
↓



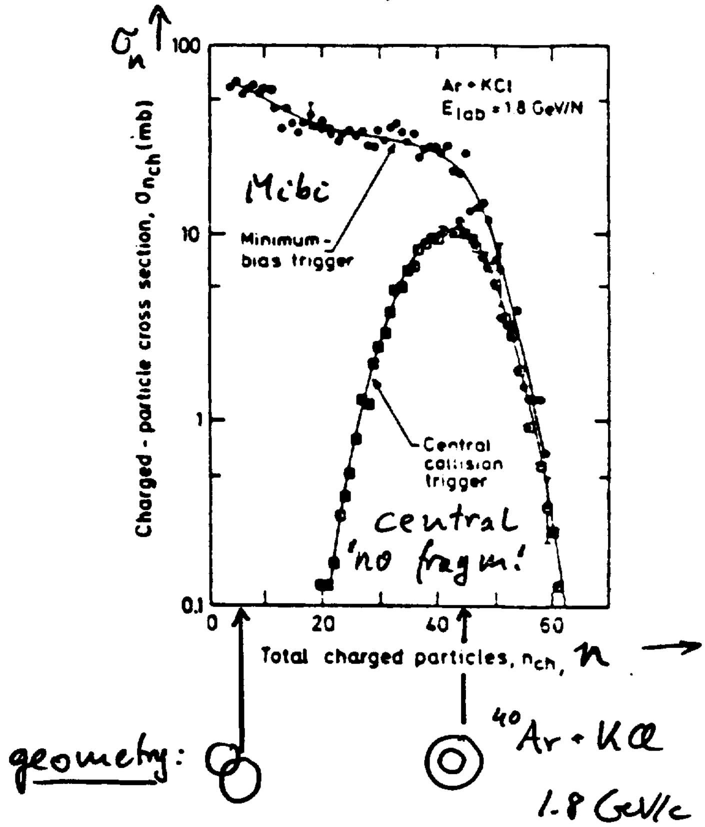
- shape of momentum transfer chosen
- strings break into hadrons
- A'A: multiple scattering probabilities are generated based on straight line trajectories

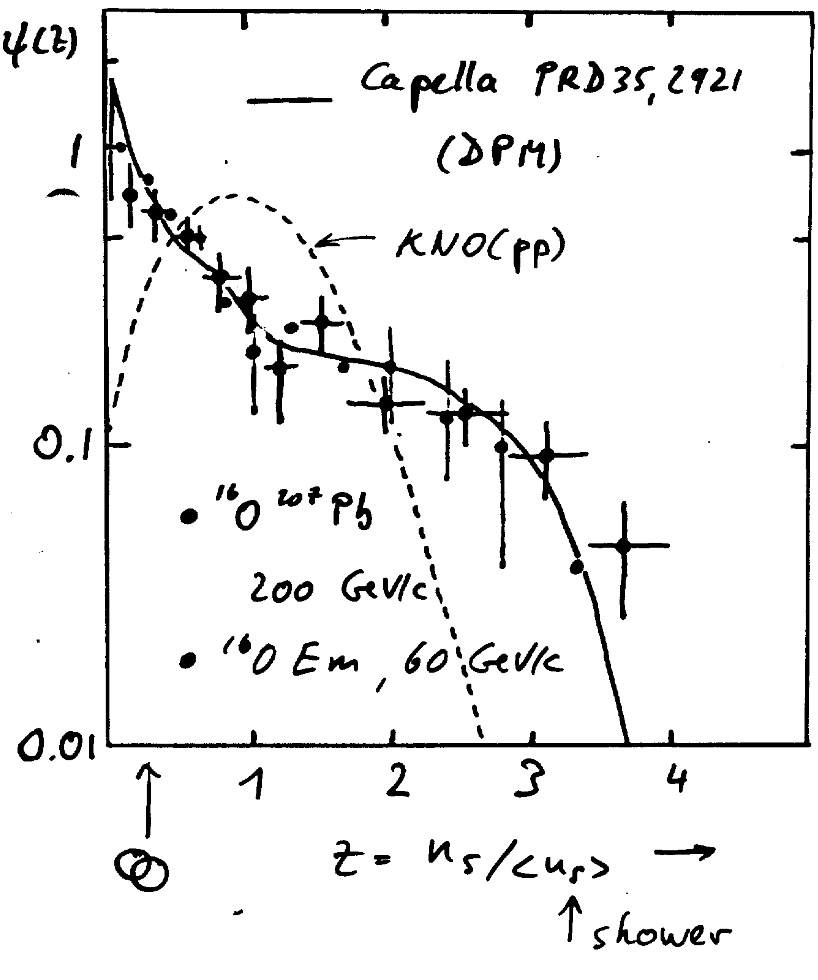
6. Multiplicity Distributions

$$\psi(z) = \langle n\rangle\, \sigma_n / \sigma_{in}$$



Sandoval, PRL 45, 874





- O Em at 60 GeV/c:

  EMU03: Badawy, priv. comm.

  $\langle n_s \rangle = 27.8 \pm 0.3$

- O Pb at 200 GeV/c

  EMU05: Takahashi PANIC XI, '87

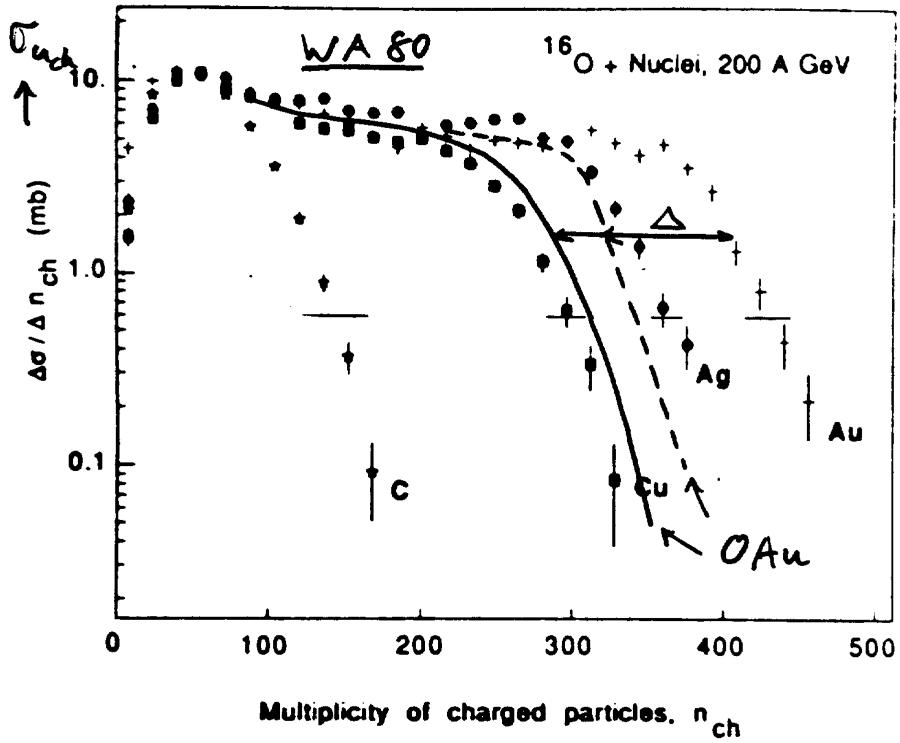
  $\langle n_s \rangle = 88$

- Capella, Z. Phys. C 10, 249:

  $\langle n_{ch} \rangle \approx 88$

- All data ≈ consistent DPM fits

4π detector:



prelim. Gutbrod, priv. comm.

MC for ^{16}OAu/Pb:

—— DPM

- - - Attila

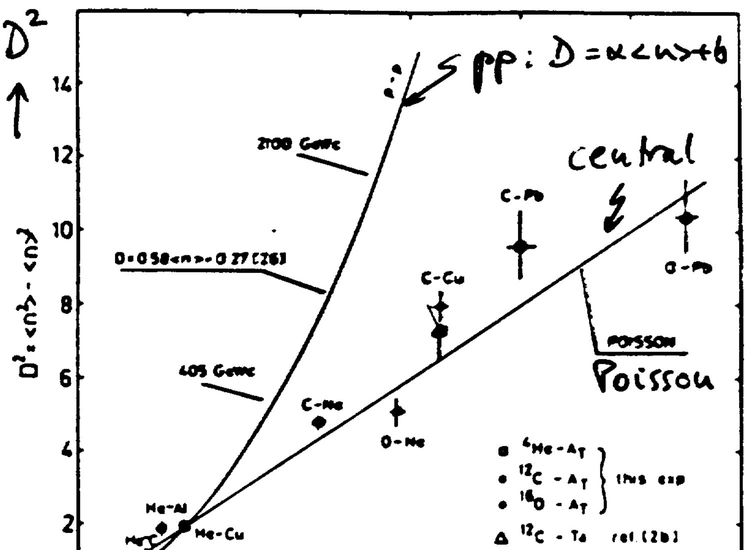
[Gyulassy CERN-TH 4794/87]

- $\Delta \approx 80-120$ • WA80 ≈ NA35 in same $\Delta\Omega$

$\Rightarrow$ 80-120 extra charged particles in target region?

- n_{ch} (plateau/10) $\sim A_T^{1/3}$: diameter of target

Aksinenko NPA 348, 518



<u>Poisson</u> for central collisions:

$$\langle n\rangle_A \approx \langle w\rangle \langle n\rangle_{pp}$$

$$\Rightarrow D_A^2 = \langle w\rangle D_{pp}^2 + \langle n\rangle_{pp} D_w^2$$

$$\frac{D_A^2}{\langle n\rangle_A} = \frac{D_{pp}^2}{\langle n\rangle_{pp}} + \frac{D_w^2}{\langle w\rangle}$$

w = # of indep NN collisions

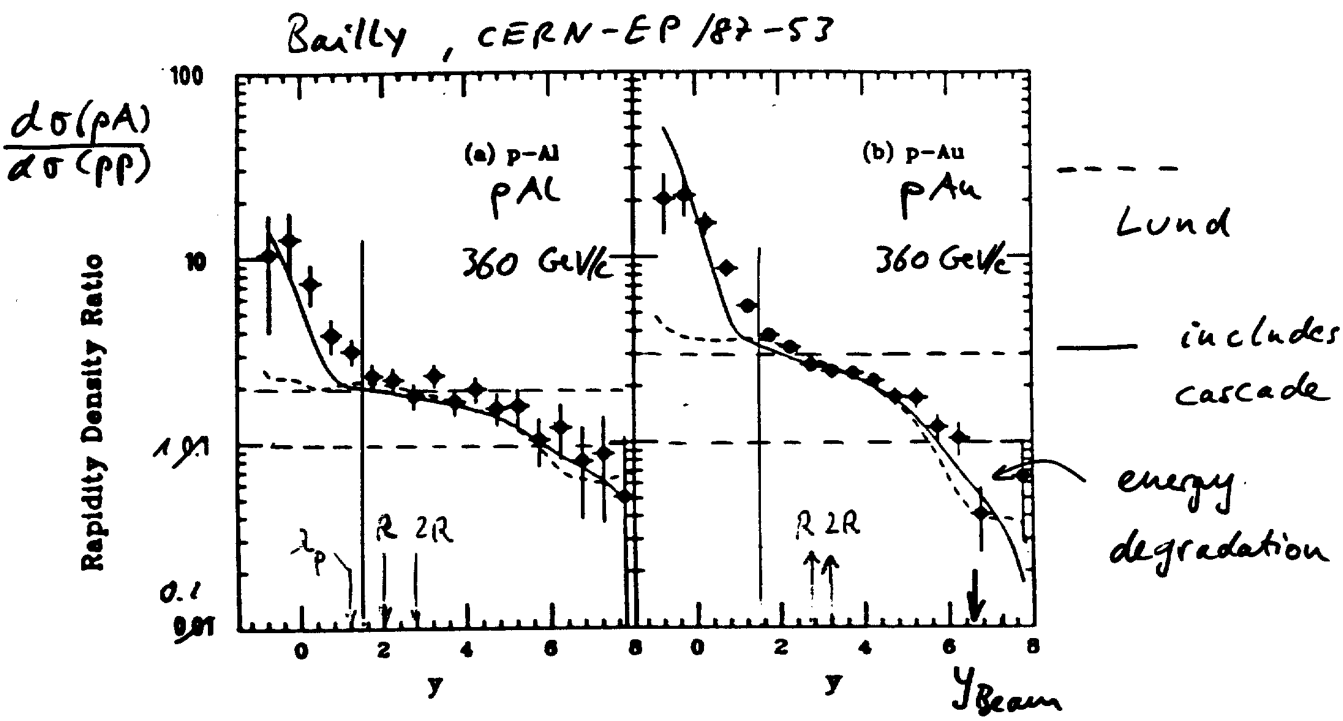
central coll. $D_w^2 \rightsquigarrow 0$

$$\underline{D_A^2 = \left(\frac{D^2}{\langle n\rangle}\right)_{pp} \langle n\rangle_A}$$

f) Inclusive Rapidity Distributions

e) Formation time in pA collisions

Bailly, CERN-EP/87-53



- $y \lesssim 1.8$ strong increase of multiplicity: cascading

formation time $\tau_0 \rightsquigarrow \gamma\tau_0 = \tau_0 \cosh y = \beta\ell \approx \ell$

$$\ell \le \lambda_p \Rightarrow y_c = \cosh^{-1}(\lambda_p/\tau_0), \quad \tau_0 \approx 1\,fm$$

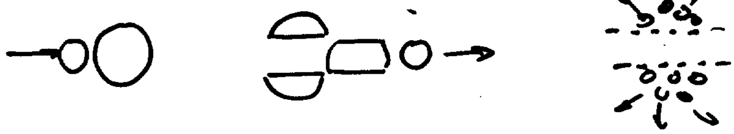
$$y_c \approx 1.12$$

Exptl. results consistent with parton picture:

- $y < y_c$: partons hadronize ⇒ cascading inside nucleus
- $y > y_c$: multiple parton collisions in nucleus

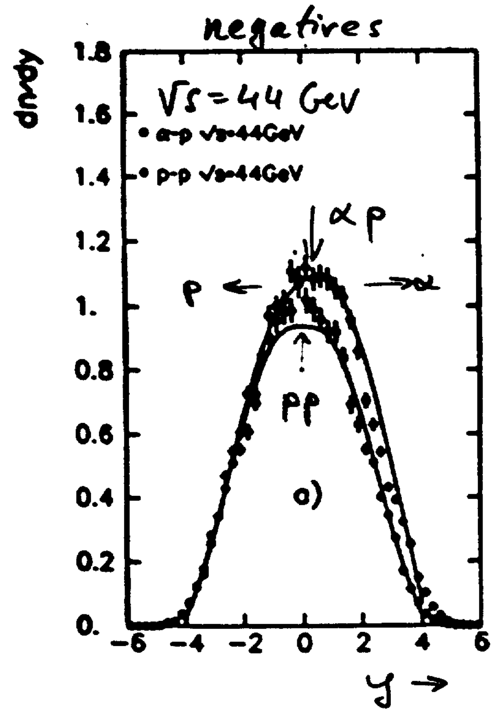
Should have experiment with particle ident. in target region

Note: ion-ion collisions:



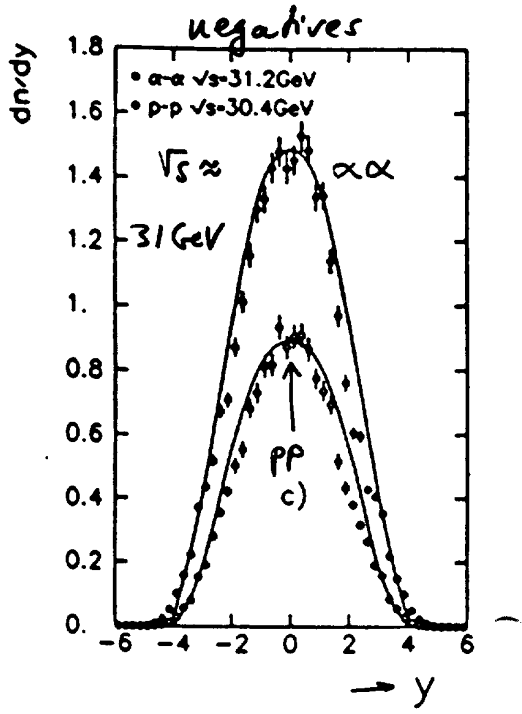
less cascading in dilute matter?

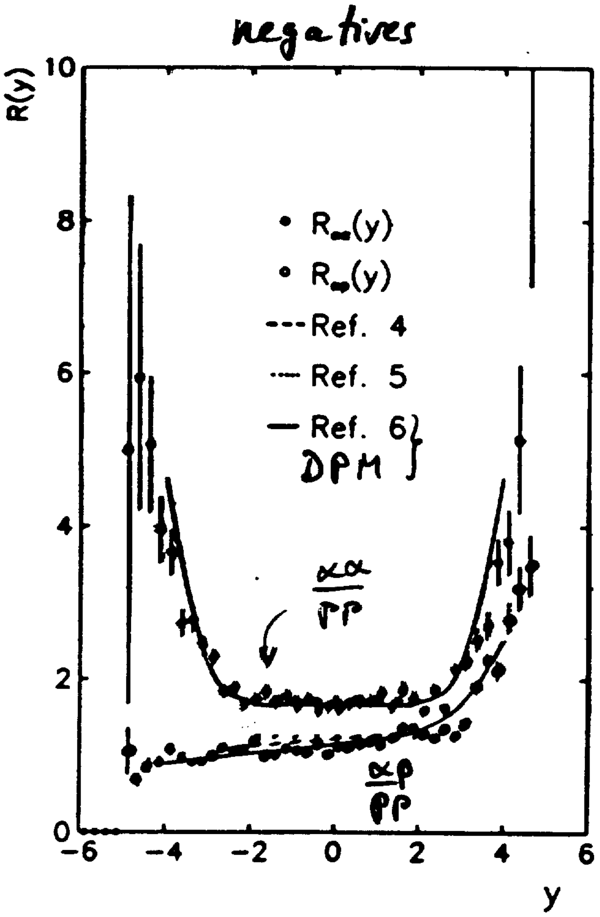
b) Isospin effects



Bell,
Z Phys C27, 191

— DPM





$$R_{\alpha\alpha}(y) \sim \frac{\sigma(p\to\pi^-) + \sigma(n\to\pi^-)}{\sigma(p\to\pi^-)}$$

$$= 1 + \frac{\sigma(n\to\pi^-)}{\sigma(p\to\pi^-)}$$

$$= 1 + \frac{\sigma(p\to\pi^+)}{\sigma(p\to\pi^-)}$$ isospin

↑ increases with x, y
due to valence quarks

- $|y| \leq 2.5$ or $x_F \leq 0.4$:
  no evidence for valence quarks

Note:

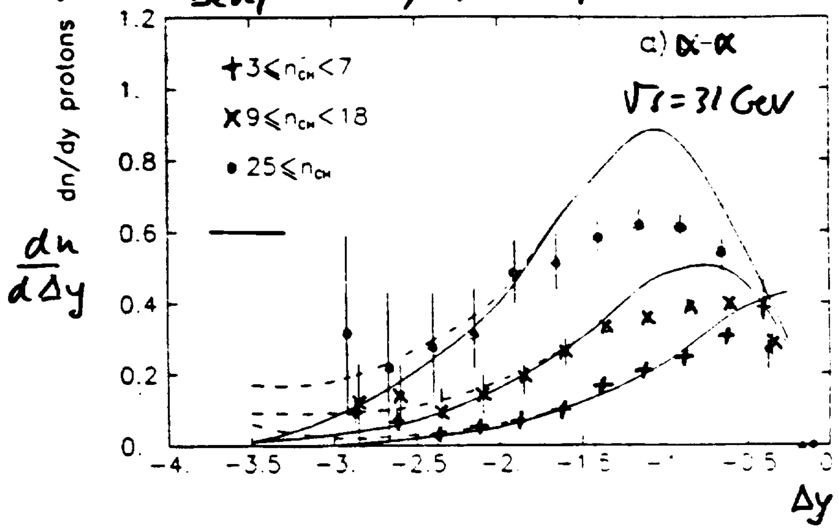
A =	Al	Cu	Ag	Au	Pb
Z/A =	0.48	0.46	0.43	0.4	0.4

c) Stopping of baryons

$\alpha\alpha$ at SFM/ISR : proton identification on statistical basis

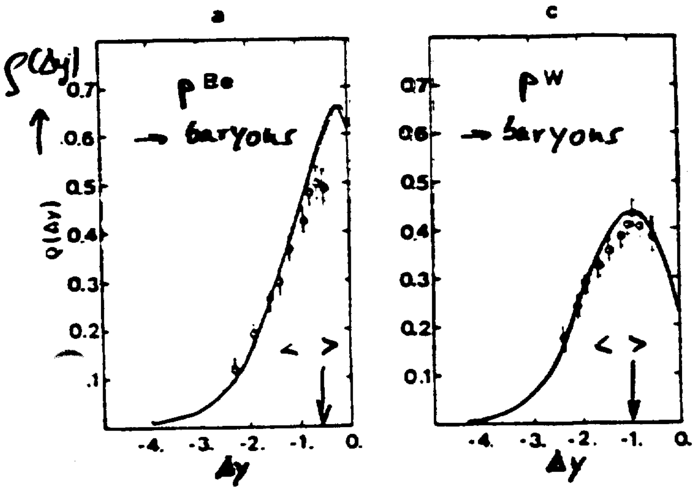
$\rho(+) - \rho(-) \approx \rho(p - \bar{p})$

Bell, Z. Phys A 325, 7

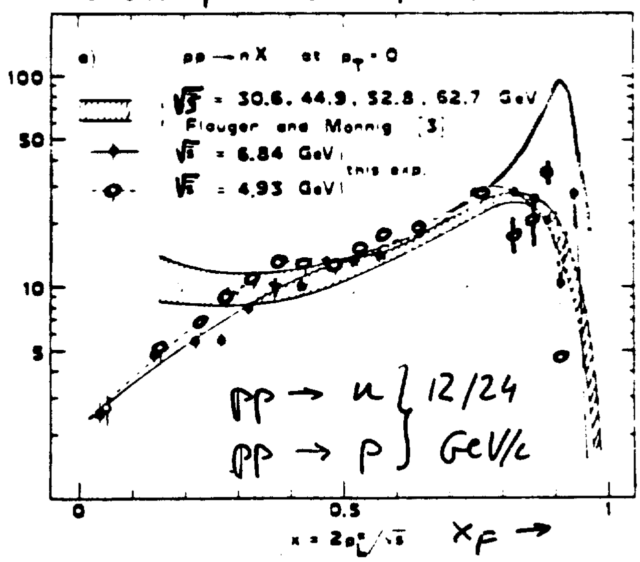


- $n_{ch} \approx \langle n_{ch} \rangle$
  $\langle \Delta y (pp) \rangle \approx \langle \Delta y (\alpha\alpha) \rangle$
- $n_{ch} \gtrsim 1.5 \langle n_{ch} \rangle$
  $\langle \Delta y (\alpha\alpha) \rangle \approx 1.45$

Jezabek, PL B175, 206



Blobel, NP B135, 379



↑ covers all p_T / **assumptions** for neutrons

neutrons loose more energy : **no diffraction** in pp

- $\langle \Delta y \rangle$ smaller than earlier results : more work

Motivation:

One can choose $\sqrt{s}$ such that $y_{Beam} = \Delta y$

$\Rightarrow$ baryons **come to rest** in cms ($p_{lab} \approx 3 \div 25$ GeV/c)

8. Inclusive Transverse Momentum Distributions

Cronin

PRD 11, 3105

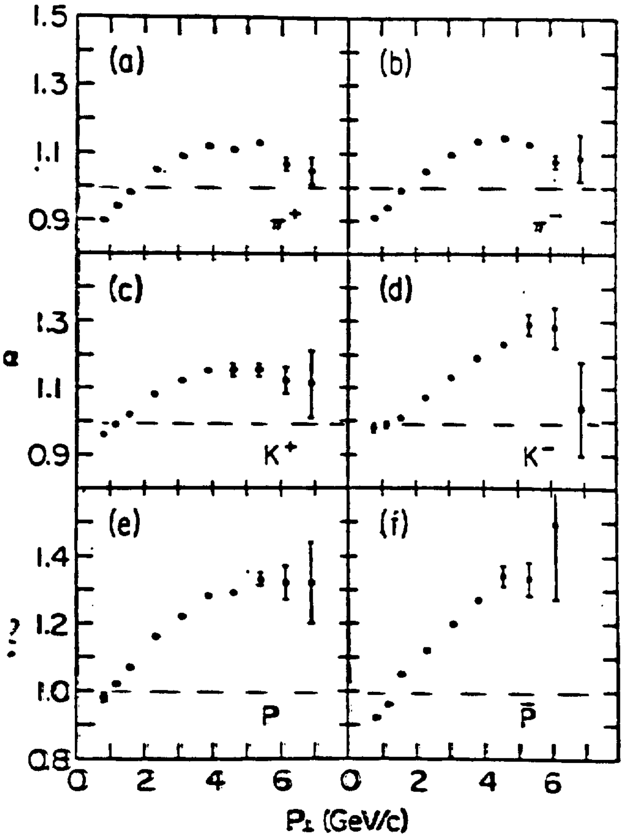
$\sigma(pA) \sim A^{\alpha(p_T)}$

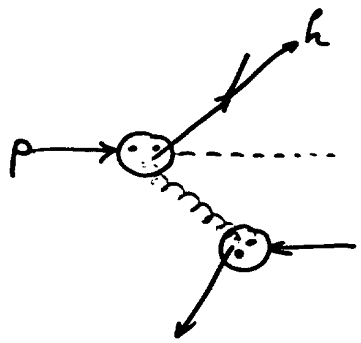
naively: $\alpha = 1$

$\alpha > 1$??

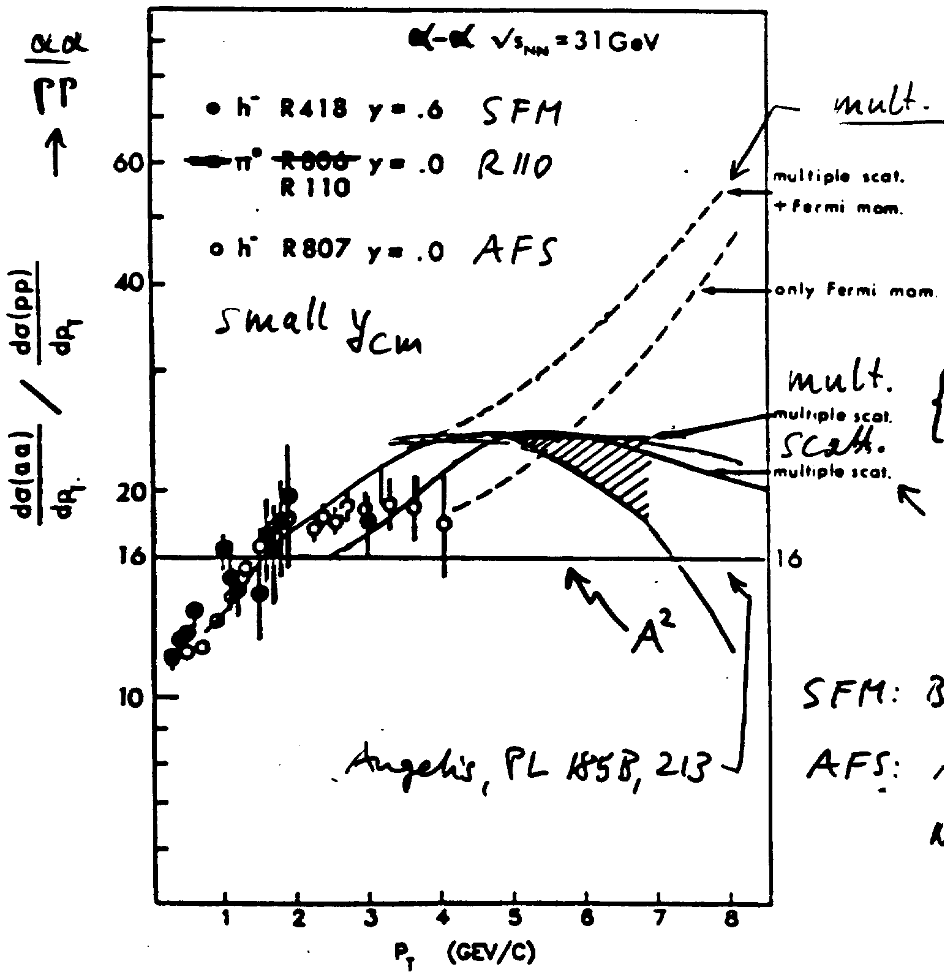
mult. scatt.?

Fermi motion?





pointlike scatt. (q, g)



mult. & Fermi

Staszel

Z. Phys. C 19, 7

mult. scatt.

Sukhatme
PR 25, 1978

Lev

Z. Phys C 21, 155

Angelis, PL 185B, 213

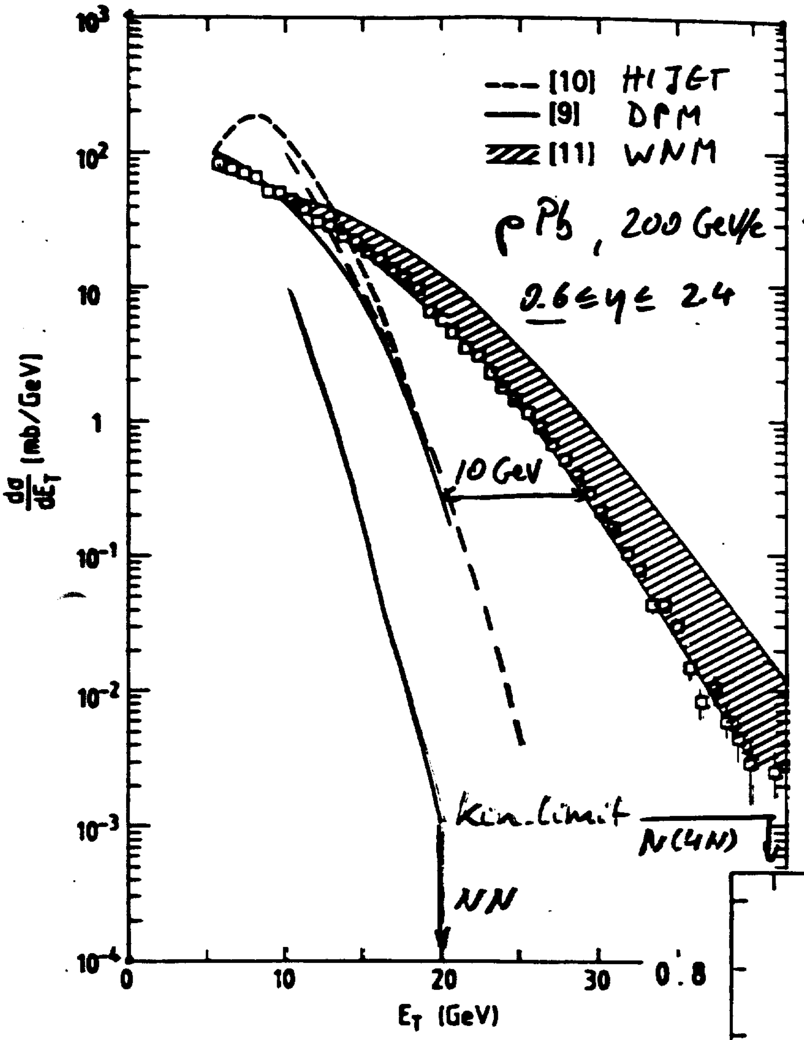
SFM: Bell, PL 114B, 271

AFS: Akesson

NP B 209, 309

9, Multiparticle systems with large E_T

a) p Pb



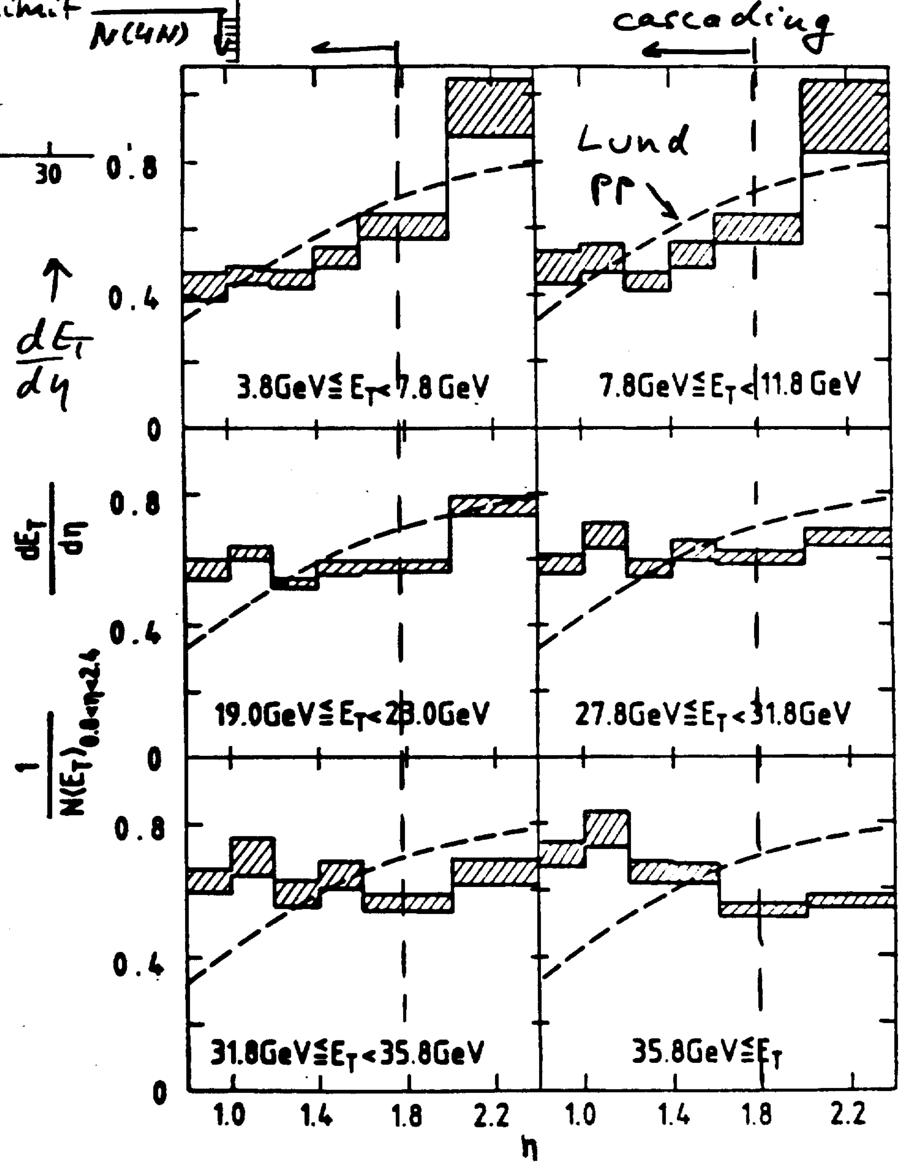
← Åkesson, CERN-EP/87-170

Gomez, PRD 35, 2736:

pPb at 800 GeV/c, $\sqrt{s} = 39$ GeV

$$\left.\begin{array}{l} — \; |\eta_{cm}| < 0.55 \\ --- \; |\eta_{cm}| < 0.85 \end{array}\right\} \text{slope} \hat{=} \text{MC}$$

- <u>not</u> outside kin. limits
- $\alpha \approx 1.75$!



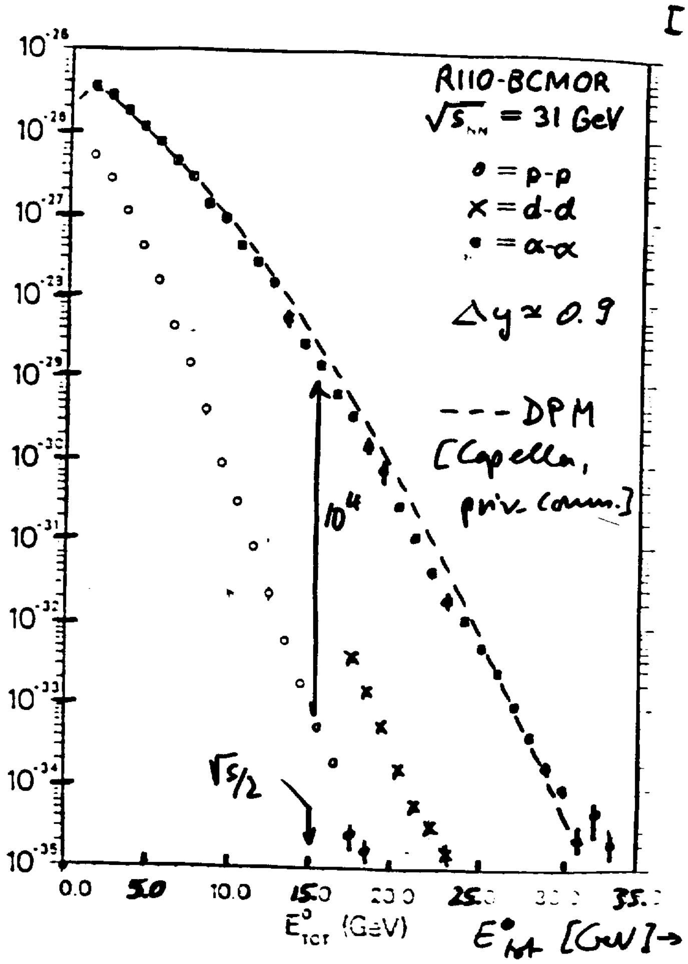
Conclusion:

- very large E_T due to cascading?
- Why does WNM fit the data?

b) $\alpha\alpha$

Angelis PL 141B, 140
PL 168B, 158

Measured total neutral energy E^0_{TOT}



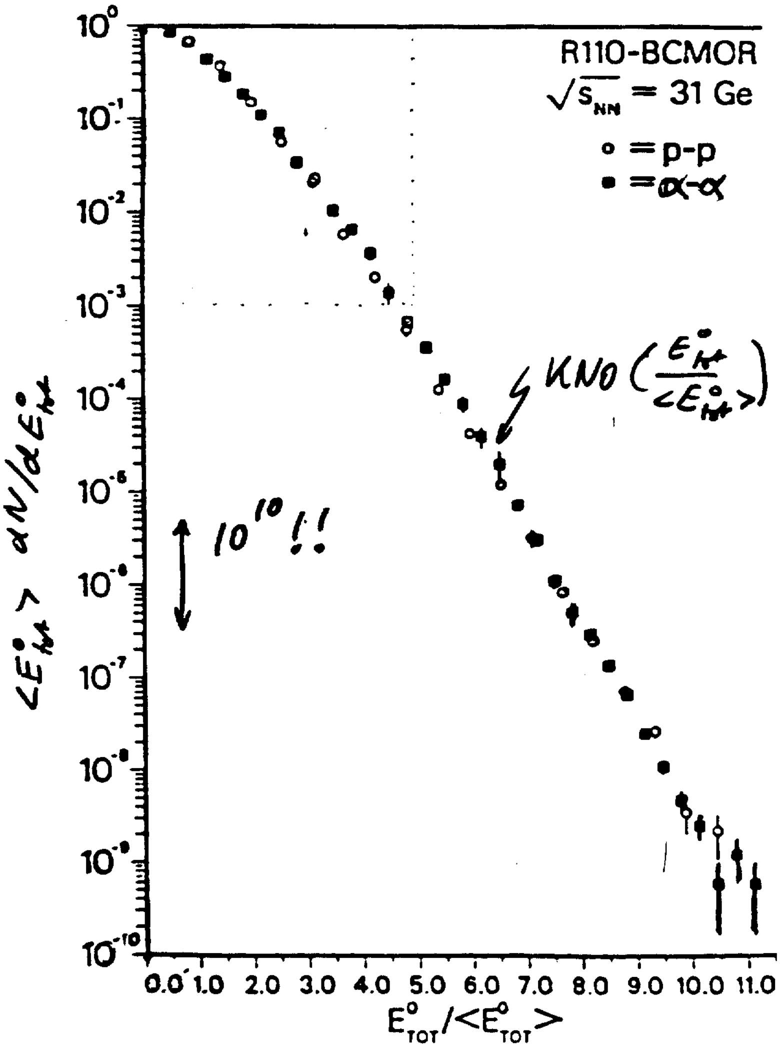
pp data:

$$\frac{1}{\sigma}\frac{d\sigma}{dE} \sim \frac{\alpha}{\Gamma(p)}(\alpha E)^{p-1} e^{-\alpha E} \quad (*)$$

⇒ expect for n indep. coll.:

$$\frac{\alpha}{\Gamma(np)}(\alpha E)^{np-1} e^{-\alpha E}$$

i.e. $p \to np$



← found:

good fit to (*)

with same p, $\alpha \to \alpha \frac{\langle E_{tot}\rangle_{pp}}{\langle E_{tot}\rangle_{\alpha\alpha}}$

if indep. coll.:

$F = f \otimes f \otimes f \otimes$

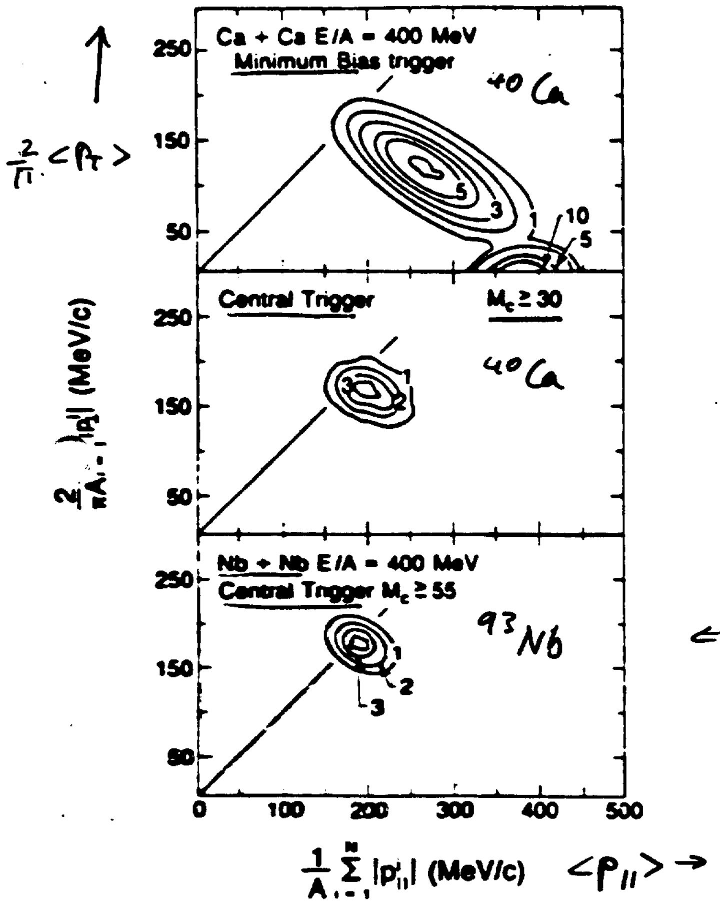
and $F \neq f$

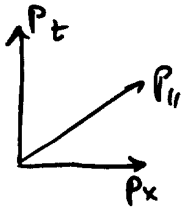
Here one has found same shapes for F and f

⇒ correlations

10. Isotropic Events and Collective Flow

Gustafsson PL 142 B, 141 (Ströbele PRC 27, 1349)





isotropy $\Rightarrow$

$$1 = \frac{\langle p_x \rangle}{\langle p_{\parallel} \rangle} = \frac{2}{\pi} \frac{\langle p_T \rangle}{\langle p_{\parallel} \rangle}$$

$\leftarrow$ isotropic central coll. events

Conclusion: $A > 40$

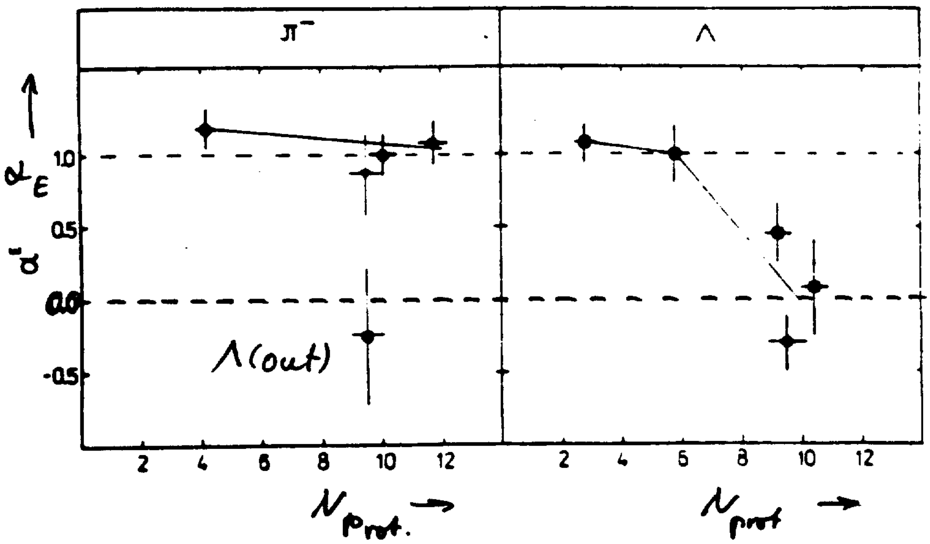
Coll. of He $\to$ Ne at 4.5 GeV/c : Gadzdicki, Z. Phys. C31, 549

α_E measures isotropy

$\alpha_E = 1$: like pp

$\alpha_E = 0$: isotropic

- if Λ outside NN kin. limits
  $\Rightarrow$ Λ and π isotropic



Λ_{out} : $\sim 10^{-3}\, \sigma_{central} \sim 10^{-4}\, \sigma_{in}$

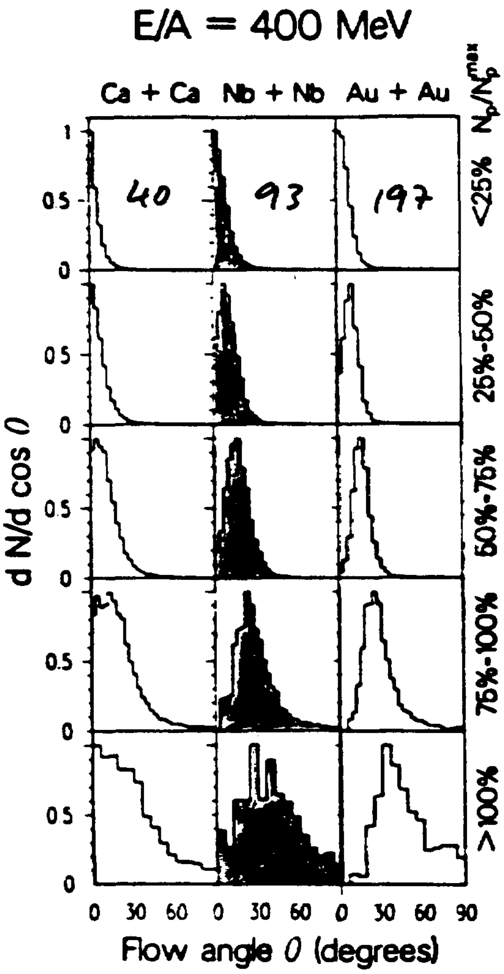
' fully stopped and thermalized hot source ' stopping of nuclei → compression

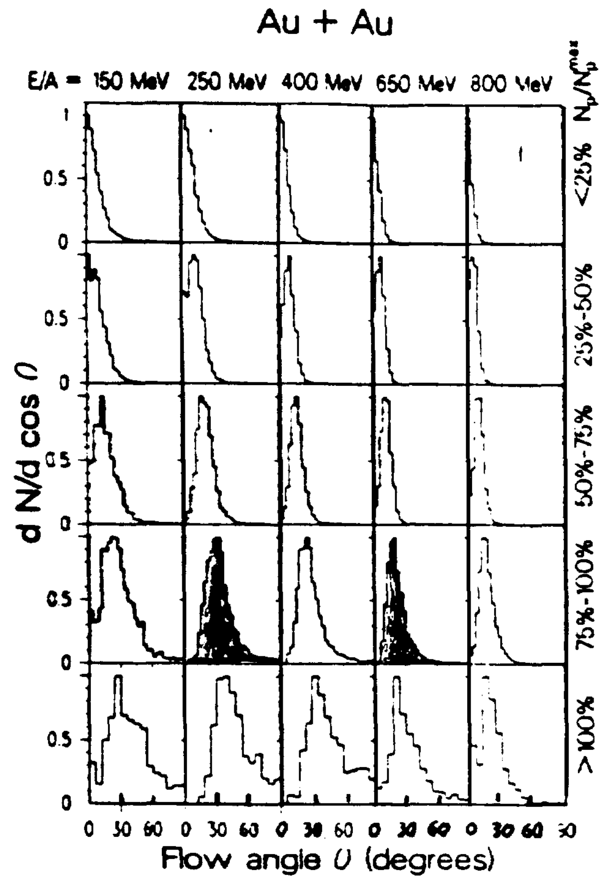
→ collective flow after expansion?

(Gustafsson PRL 52, 1590)

Ritter, NPA 447, 3c

A =



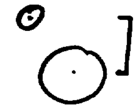


$\langle\theta\rangle$ decreases for $E/A \gtrsim 400$ MeV

finite flow angle should give a handle
on compressional effects in nuclear matter

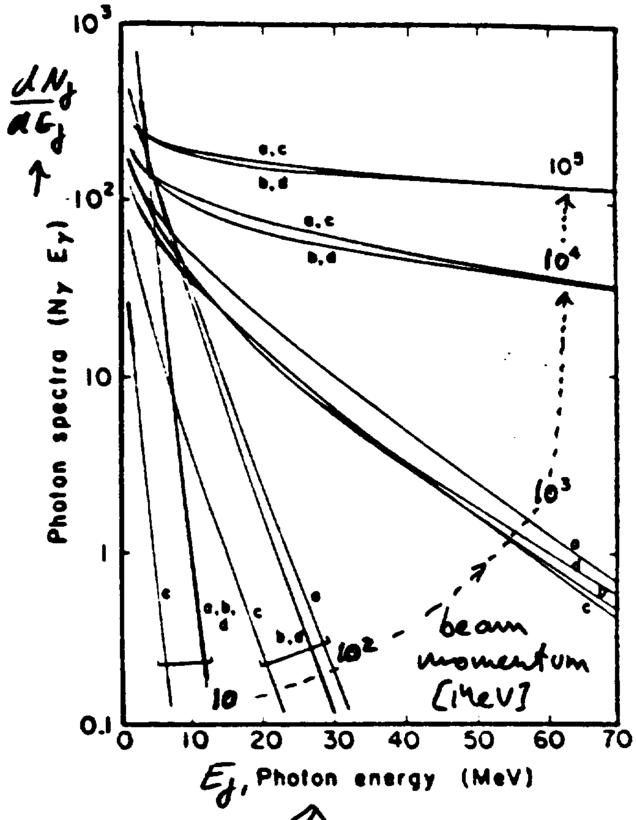
(see section B tomorrow)

11. Electromagnetic Dissociation

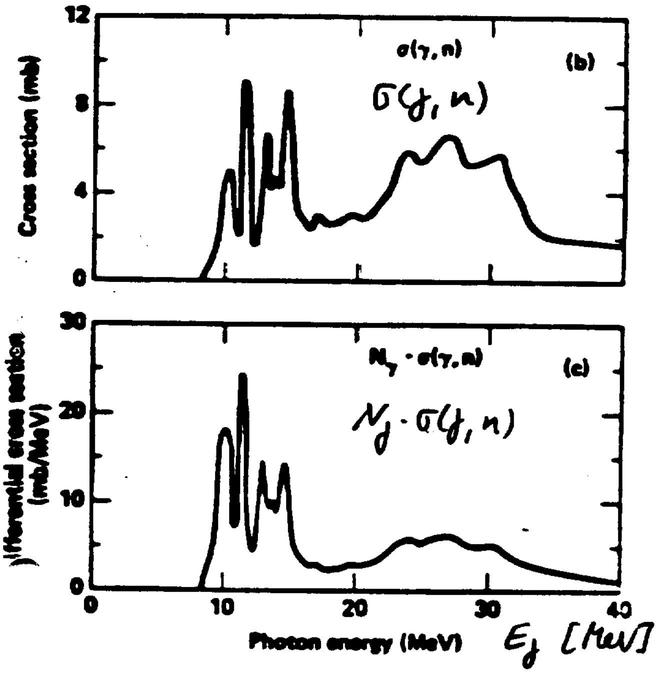


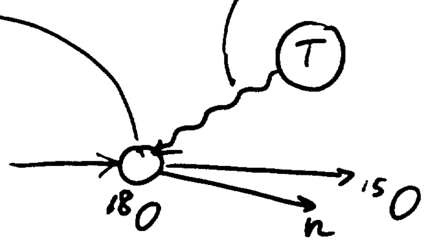
$\rightarrow$] $b > R_1 + R_2$

- no nuclear interaction
- but $Z_1^2 \cdot Z_2^2$ large!



Olsen, PR C24, 1529



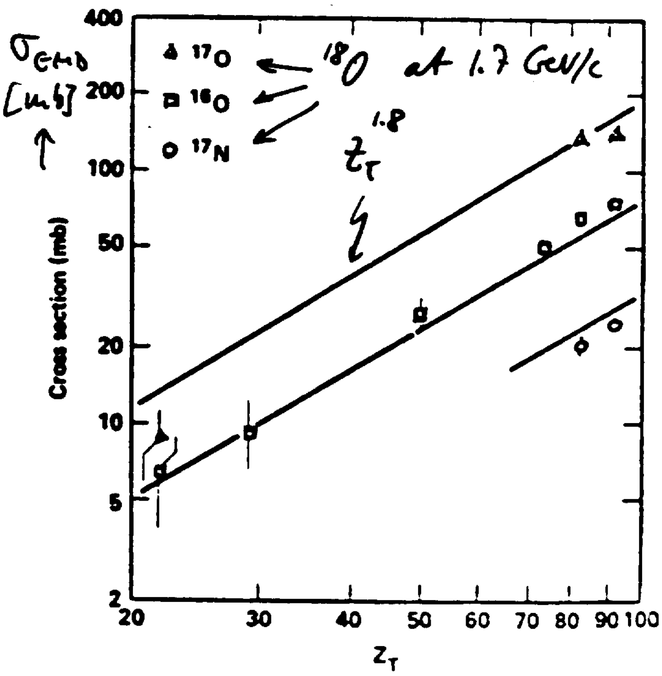


[Jackson, Classical Electrodyn.]

Weizsäcker-Williams:

$$\sigma_{EMD} \sim \int \frac{dN_\gamma}{dE_\gamma} \sigma(\gamma, n)\, dE_\gamma$$

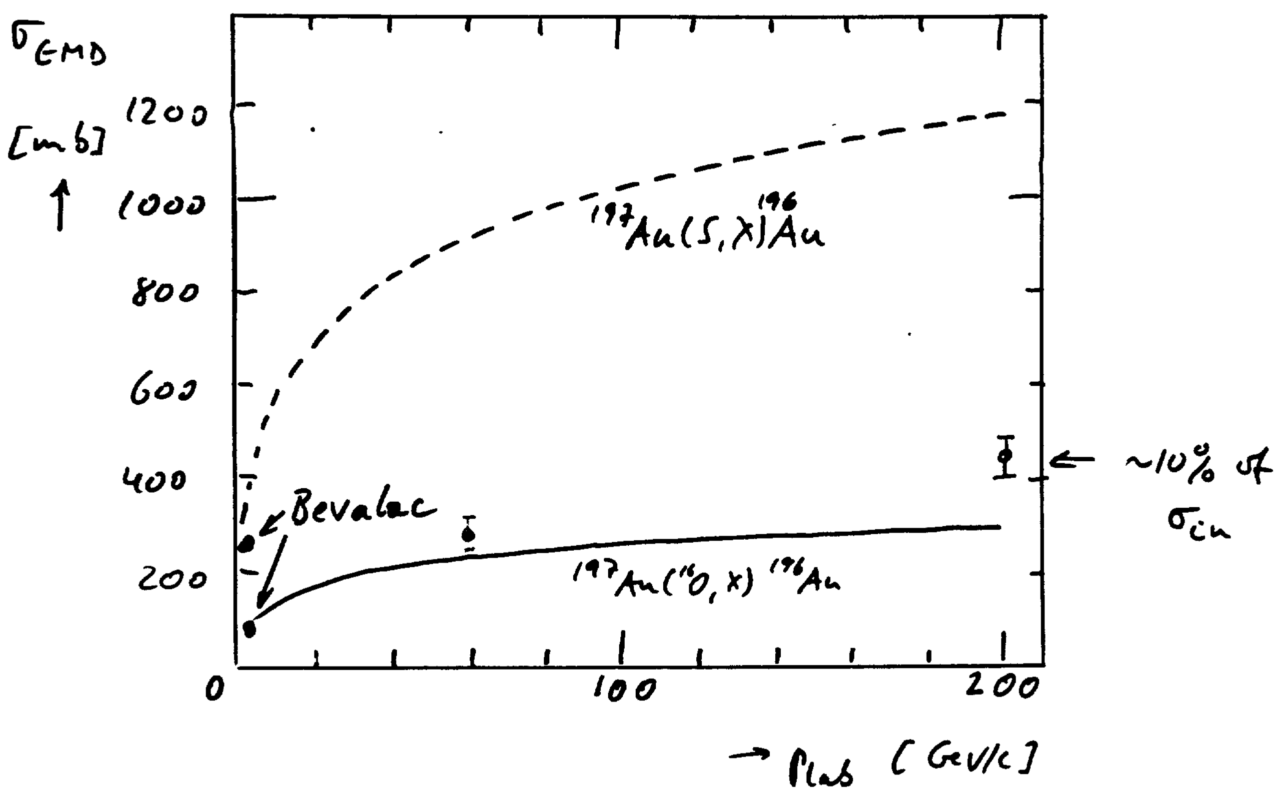
$$\sim Z_T^{1.8}$$



Remember:

- $\sigma(^{16}O\,Au) \approx 4$ b at 200 GeV/c
- expect strong p_{lab} dependence

NA40 prelim., J. Hill priv. comm.

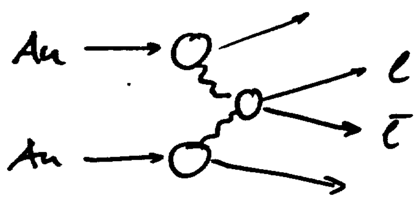


- consequence: Au Au at 100 × 100 GeV/c:

  σ_{emd} (Au Au) ≈ $\underline{30 \div 60 \text{ b}}$ >> $\underline{\sigma_{in} \sim 9.4 \text{ b}}$

  limits beam lifetime and/or luminosity

- If these cross sections are large, what about



ℓ = e, μ, τ, ... c, b ??

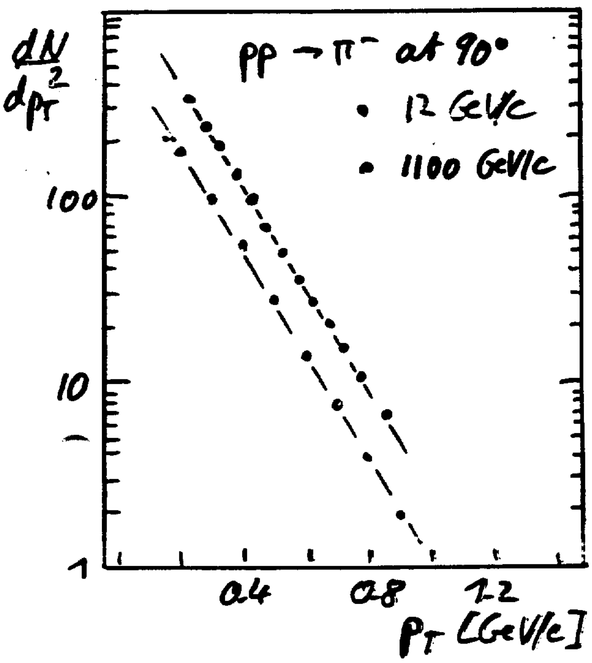
γγ physics with ion beams !?

(theoretical predictions soon)

B. Theoretical Concepts & QCD Plasma

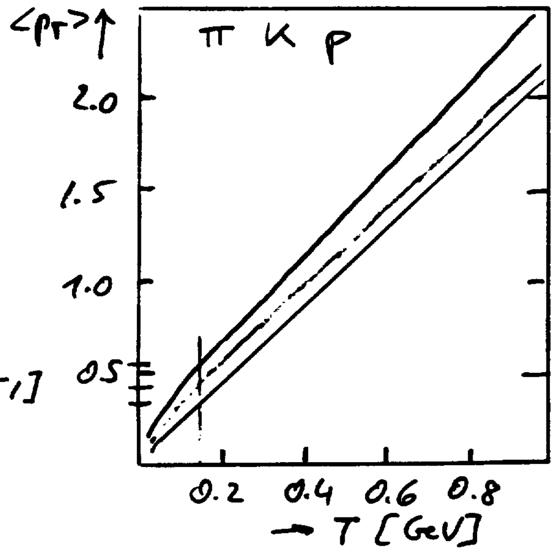
I. Phase Transitions

1. Experimental hints

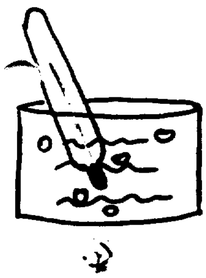


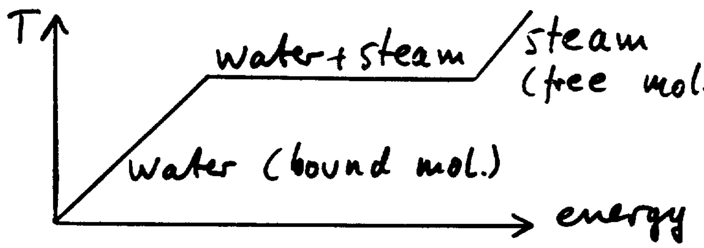
- $\frac{dN}{dp_T^2} \sim e^{-a E_T}$ $E_T = \sqrt{m^2 + p_T^2}$
- Boltzmann: $\frac{dN}{dv^2} \sim e^{-E/kT}$

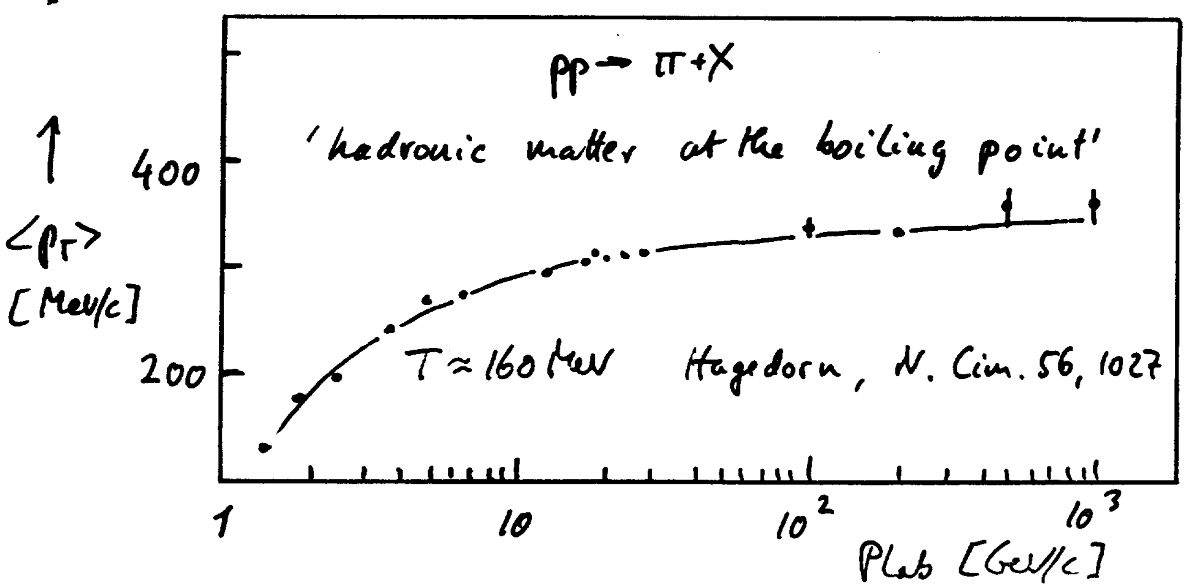
$\Rightarrow$ thermodyn.: $\underline{\langle p_T \rangle \leftrightarrow T}$



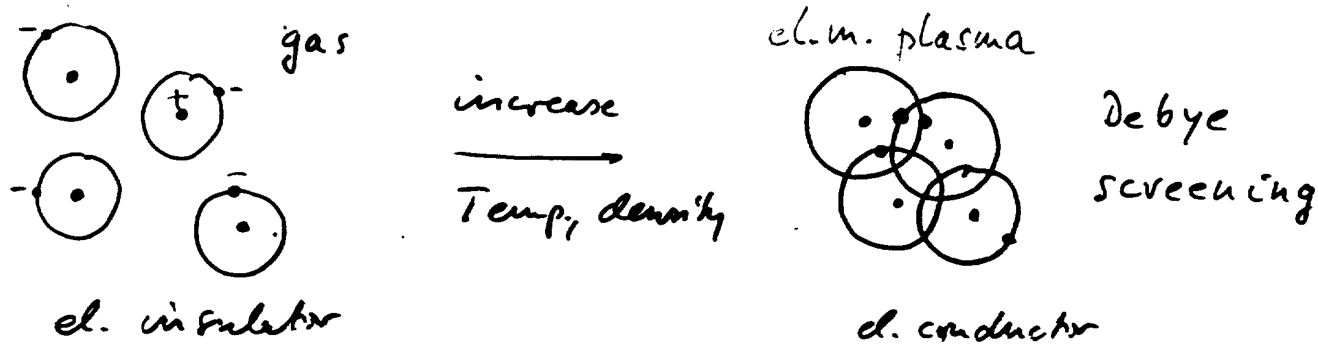
- complete formula
  [Ruuskanen, Act. Phys. Pol B18, 551]



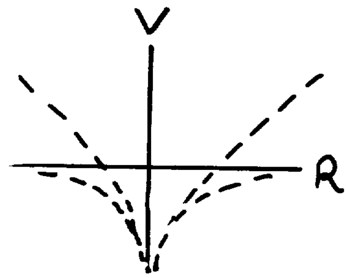




2. Intuition



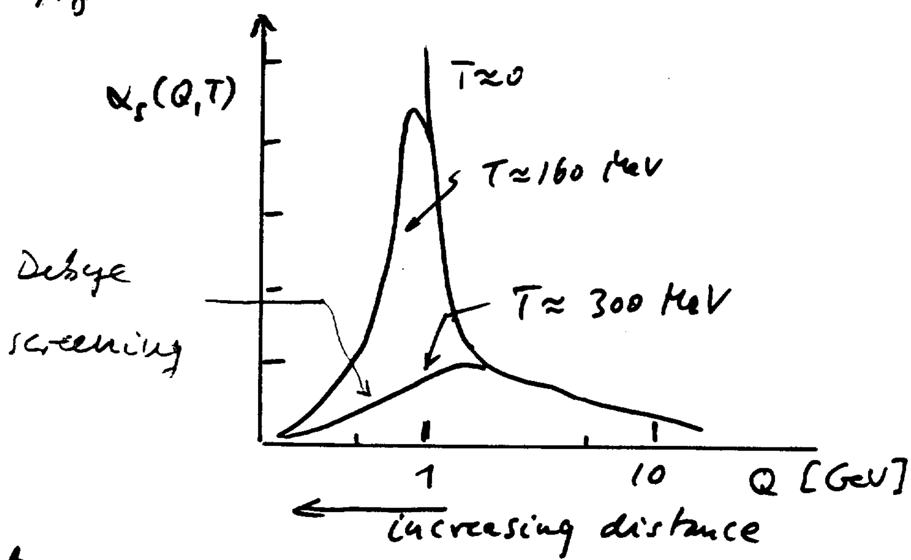
$V_{el} \sim -\frac{\alpha}{r}$



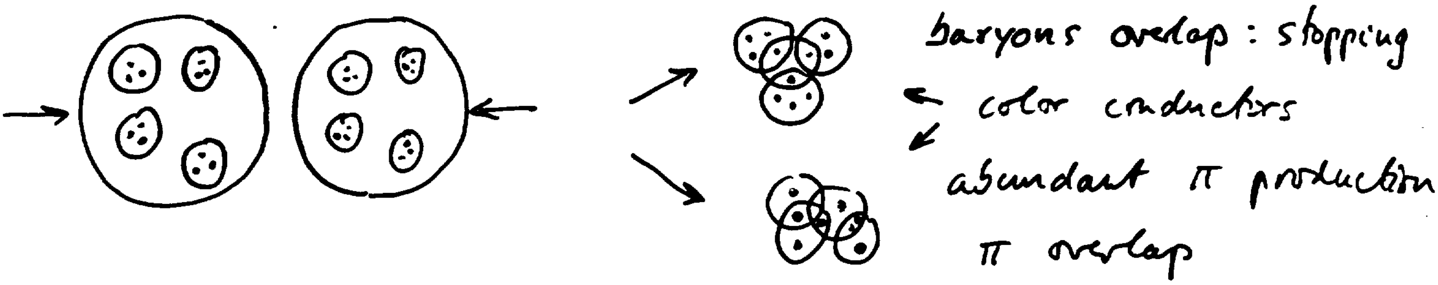
$V_{QCD} \sim -\frac{\alpha}{r} + \sigma r$

$V_{el} \approx V_{QCD}$ at very small R $\Rightarrow$ also Debye screening?

$V_{Debye} \sim \frac{\alpha}{r} e^{-r/r_0}$



color insulator



Ions better than N:
- more effective screening
- better equilibration
- more space

3. Thermodynamics in a Nutshell

- $N_q \approx 240$ ($^{16}O\,^{64}Cu$), $N_q \approx 1400$ (UU)
- no heat bath: thermodynamics justified?

- 1st law of thermodyn.: (Heat = energy, energy conservation)

$$dE = T\,dS - P\,dV + \mu\,dN$$

E = energy, T = temperature, P = pressure
V = volume, N = # particles
S = entropy: measures # of states accessible to system
μ = chem. potential: governs flow of particles between systems

equiv.: $dS = \frac{1}{T}dE + \frac{1}{T}P\,dV - \frac{1}{T}\mu\,dN$

- equilibr. 2 phases: $\delta(S_1+S_2) + \alpha\,\delta(E_1+E_2) + \beta\,\delta(V_1+V_2) + \gamma\,\delta(N_1+N_2) = 0$

$$\Rightarrow \underbrace{T_1 = T_2}_{\text{thermal}} \qquad \underbrace{\mu_1 = \mu_2}_{\text{chemical}} \qquad \underbrace{P_1 = P_2}_{\text{mechan.}} \qquad \text{(Gibbs) equilibr.}$$

2 variables independent: i.e. for $P_1 = P_2 \Rightarrow T_c = T_c(\mu_c)$

↑ phase diagrams

- Generally: $P = P(T, V, \mu)$ equation of state EOS
(remember ideal gas: $p \sim \frac{RT}{V}$)

- Equiv.: $\underline{\Omega} = E - TS - \mu N = \underline{-PV} \rightsquigarrow$ minimum
($\hat{=}$ F free energy for $\mu = 0$)

$\Rightarrow$
- system goes into state of P_{max}
- If Ω known $\Rightarrow$ EOS known (see below)

- Statistical Mechanics

$$\underline{\Omega = -T \ln Z} \qquad Z = \text{grand partition function}$$

- classical $\quad Z = \sum_i \exp(-\frac{1}{T}(E_i - \mu N_i))$
  sum over occupied states i

- QCD: $\quad Z$ = integral over field (q, gl) configurations
  $\Rightarrow$ LQCD

- From Z one gets:

energy density $\quad \varepsilon = \frac{E}{V} = \frac{T^2}{V} \frac{\partial \ln Z}{\partial T} + \mu N$

particle density $\quad n = \frac{N}{V} = \frac{T}{V} \frac{\partial \ln Z}{\partial \mu}$

entropy density $\quad s = \frac{S}{V} = \frac{1}{V} \frac{\partial (T \ln Z)}{\partial T}$

pressure $\quad P = \frac{\partial (T \ln Z)}{\partial V}$

$\Rightarrow$ one can calculate EOS etc. from Z,
e.g. properties of phase transitions ..

Landau - Lifshitz V

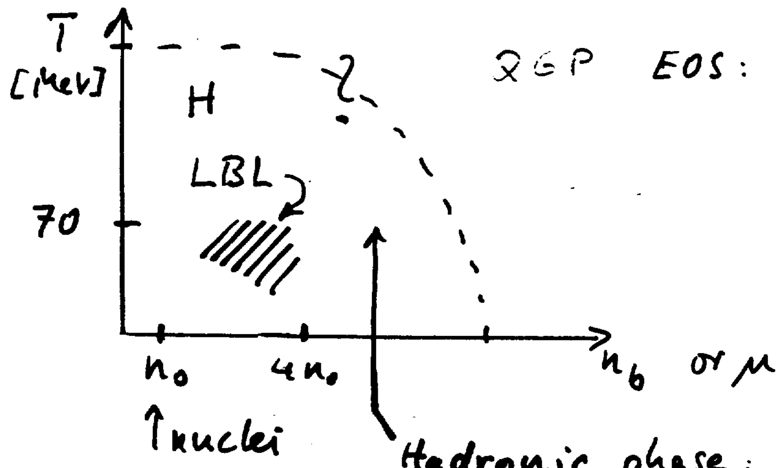
Kittel : Thermal Physics

Landsberg: Thermodyn. and Stat. Mechanics

Cleymans Phys. Rev. 130, 217

QGP EOS: $\varepsilon_Q = \varepsilon_Q(T, V, \mu)$

$P_Q = P_Q(T, V, \mu)$



Hadronic phase: $\varepsilon_H(T, V, \mu)$

$P_H(T, V, \mu)$

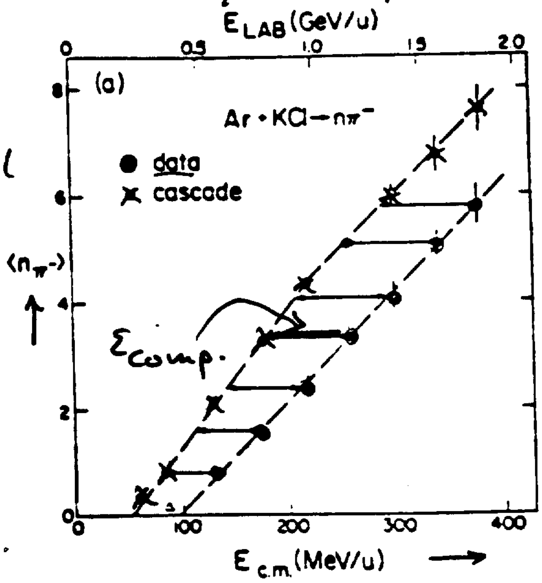
Gibbs: e.g. $P_H(T_c) = P_Q(T_c)$ need EOS for H, Q!

a) EOS extracted from data: [e.g. Stock, Phys. Rep. 135, 259]

at fixed $\sqrt{s}$, $\langle n_\pi \rangle$ smaller than <u>predicted</u>

$\Rightarrow$ evidence for compressional energy?

Harris, PL 135B, 377



//// $\varepsilon_H = \varepsilon_0 + \varepsilon_{comp} + \varepsilon_{therm.}$

Note: compression should cause flow (sect. A.10)

b) EOS of ideal hadron gas:

<u>no</u> N, for $\frac{m_\pi}{T} \to 0$: $\varepsilon_H = \varepsilon_\pi(\text{free } \pi) = 3_Q \frac{\pi^2}{30} T^4$ Stefan-Boltzm.

$P_H = \underline{\frac{1}{3}} \varepsilon_\pi$ (remember pressure of black-body radiation) assumptions: $\alpha_s = 0$, $m = 0$, $\mu = 0$

$$\Rightarrow \quad n = \frac{1}{(2\pi)^3} \int d\vec{p} \left[\exp\left(\tfrac{1}{T}(E-\mu)\right) \pm 1\right]^{-1}$$, n = parton density

$$E = p \;\&\; \mu = 0$$

$$n = \frac{4\pi}{(2\pi)^3} \int p^2 dp \left[\exp\left(\tfrac{1}{T} p\right) \pm 1\right]^{-1}$$

($+$: Fermi, $-$: Bose)

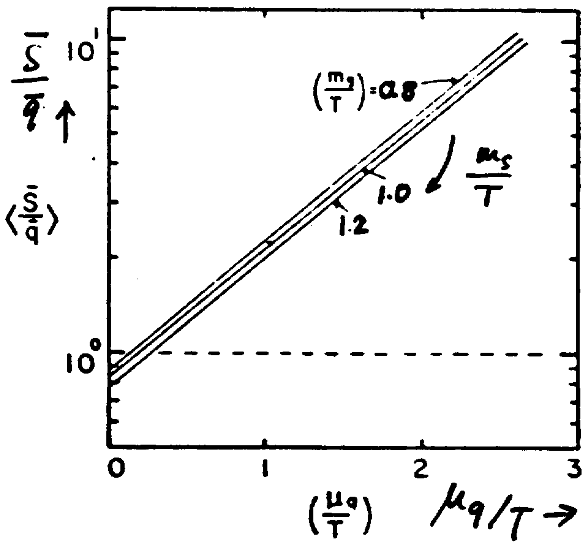
$$\left.\begin{matrix}\text{Landau-}\\\text{Lifshitz V}\end{matrix}\right\} = \frac{4\pi}{(2\pi)^3} T^3 \cdot \begin{cases} (1-2^{-2})\,\Gamma(3)\zeta(3) = \frac{3.6}{4\pi^2} T^3 = n_q \\ \Gamma(3)\zeta(3) = \frac{2.4}{2\pi^2} T^3 = n_g \end{cases} \text{ per dof}$$

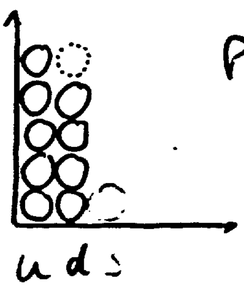
strangeness: $m_s \neq 0$

$$n_{\bar{s}} = n_s = \frac{1}{2\pi^2} m_s^2 T K_2\left(\frac{m_s}{T}\right)$$

Koch, Phys. Rep. 142, 167

- $\frac{\bar{s}}{\bar{q}} \nearrow$ for $T \nearrow$ or $m_s \searrow$
- $\mu \neq 0$: $\frac{\bar{s}}{\bar{q}} \nearrow$ for $\mu \nearrow$





Pauliprinciple

$$\varepsilon = \frac{1}{(2\pi)^3} \int p^3 dp [\quad J' = \frac{4\pi}{(2\pi)^3} T^4 \begin{cases} (2^3-1)\pi^4 B_2 & \text{Fermi} \\ \frac{(2\pi)^4}{8} B_2 & \text{Bose} \end{cases} \quad (B_2 = 1/30)$$

$$\Rightarrow \text{per dof} \quad \varepsilon_q = \frac{7}{8}\frac{\pi^2}{30} T^4 \qquad \varepsilon_g = \frac{\pi^2}{30} T^4$$

total $\underline{\mathcal{E}_Q = \frac{\pi^2}{30}(g_g + \frac{7}{8} g_q) T^4 = \frac{\pi^2}{30} a T^4}$ (black body)

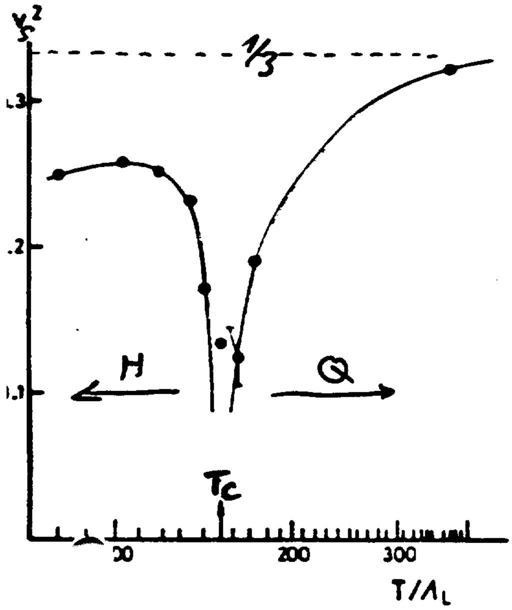
dof: $g_g = 2_s \times 8_c$ $\quad g_q = 2_s \times 3_c \times 2.5_F$ lots of gluons

From above: $\bar{E}$/parton $= \frac{\varepsilon}{n}$ $\quad (\mu = 0)$

gl: $\frac{\varepsilon}{n} = 2.71\,T$ $\quad \underline{\bar{p}_T} = \frac{\pi}{4}\bar{E} = \underline{2.13\,T}$

quarks: $\frac{\varepsilon}{n} = 3.16\,T$ $\quad \underline{\bar{p}_T} = \underline{2.48\,T}$!

also: entropy/parton $= \frac{s}{n}$



$s = \frac{1}{v_s^2}\frac{\partial\varepsilon}{\partial T} = \frac{1}{3}\frac{\partial\varepsilon}{\partial T}$ (v_s = speed of sound)

$\Rightarrow$ gluons: $\underline{\frac{s}{n} = c_g = 3.61}$

quarks: $\underline{\frac{s}{n} = c_q = 4.21}$

← Redlich, PRD 37, 3747

Numerical examples:

$\mathcal{E}_N = 0.5$ GeV/fm^3 $\quad \mathcal{E}_Q(\mu = 0) \approx 12 \cdot T^4$ GeV/fm^3 factor

$\mathcal{E}_A = 0.17$ GeV/fm^3 $\quad \mathcal{E}_\pi \approx T^4$ GeV/fm^3 10

Absolute prediction: $T_c = (200 \pm 40)$ MeV $(T^4!)$
$\qquad\qquad\qquad\qquad\uparrow$ LQCD

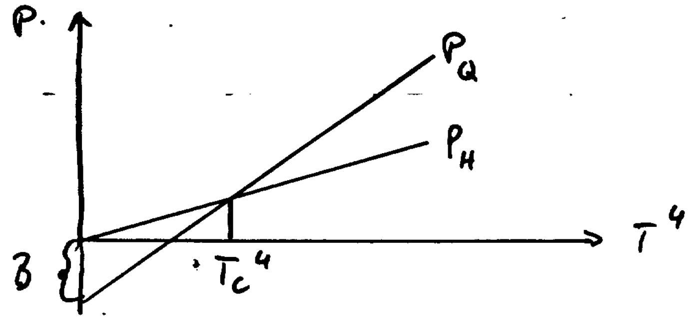
(for $\mu \neq 0$, see Cleymans, Phys. Rep. 130, 217)

d) Phase diagrams

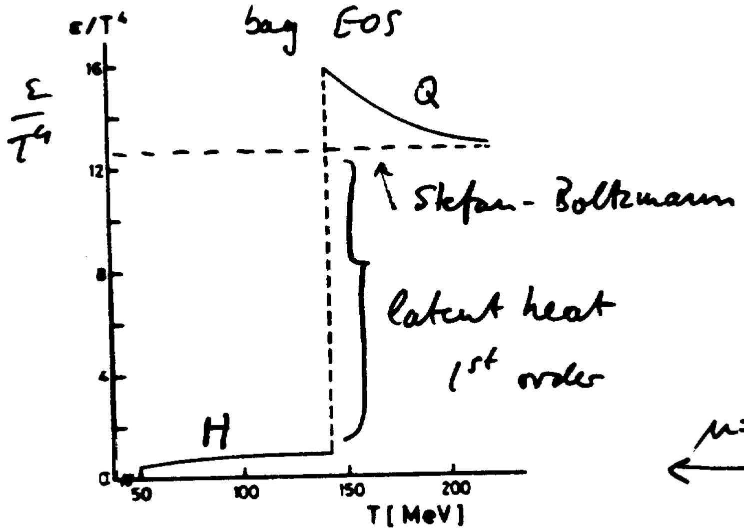
bag EOS : $\varepsilon_Q \rightsquigarrow \varepsilon_Q + B$ $\qquad$ B = bag constant

$$P = \frac{1}{3}(\varepsilon_Q - 4B) \qquad P_H = P_Q \Rightarrow \frac{\pi^2}{120}(g_Q - 3)\,\underline{T_c^4} = \underline{B}$$

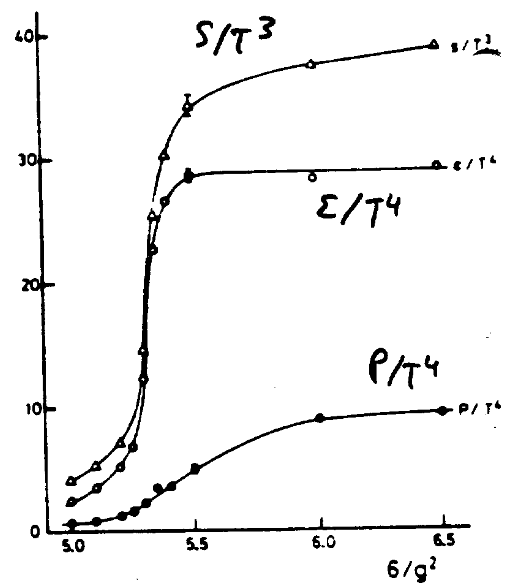
g_Q: # dof QGP $\qquad$ 3: π



Zedlich PRD 33, 3747



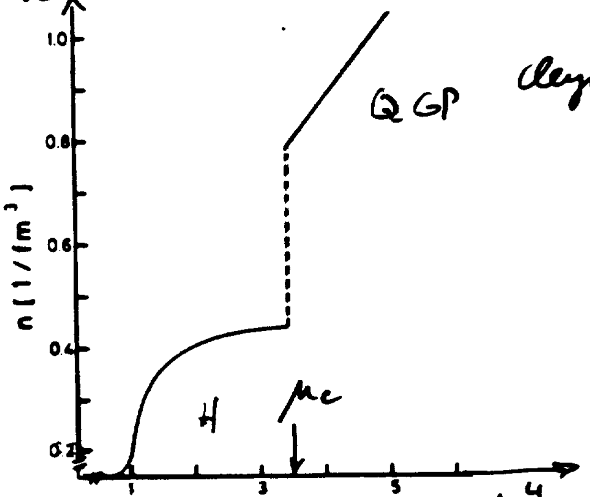
$\mu = 0$

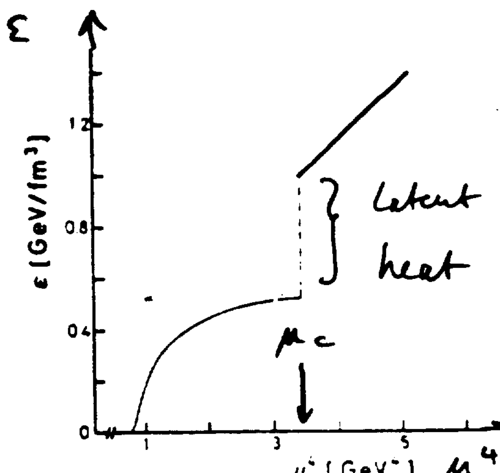


$\mu \neq 0$

$T = 0$

Cleymans, Z.Phys C 33, 151



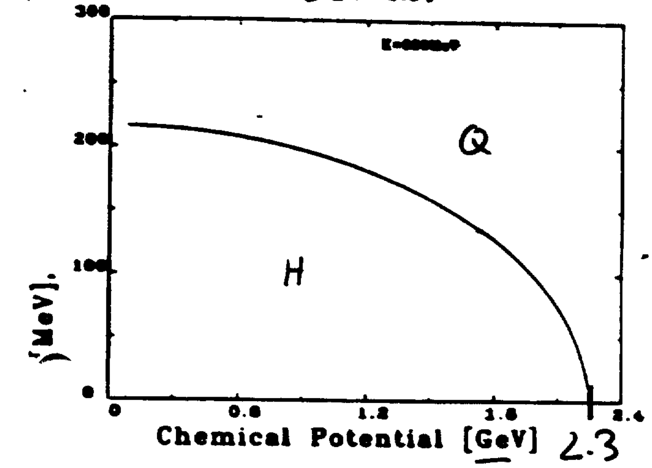


Evidently, predictions depend on EOS assumed

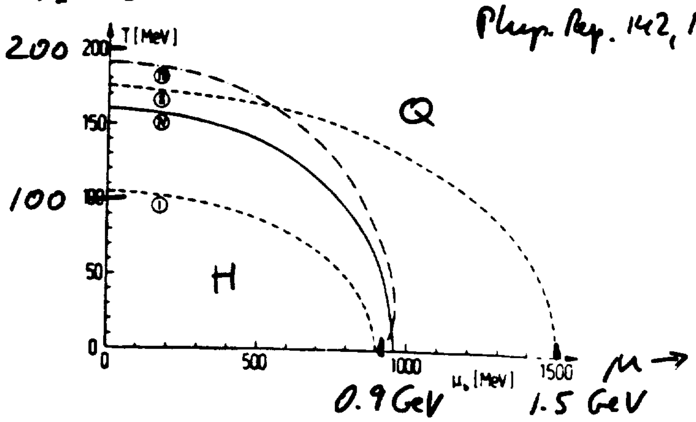
⇒ important work at <u>Bevalac</u> and <u>LQCD</u>

↓ empirical EOS

Csernai



bag EOS, Koch, Phys. Rep. 142, 167



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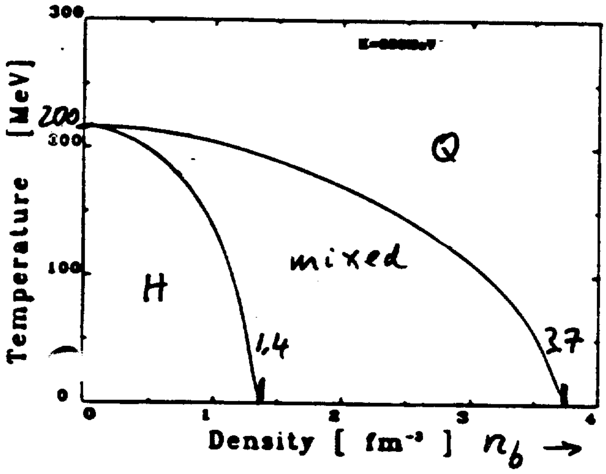
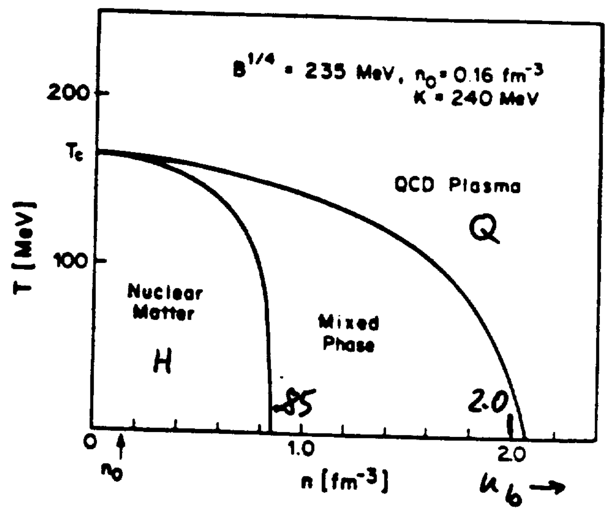
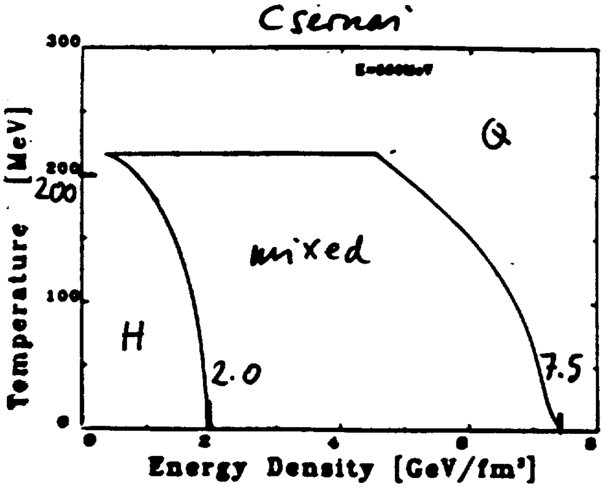




Csernai



Conclusion from these examples

<u>Depending on EOS:</u>

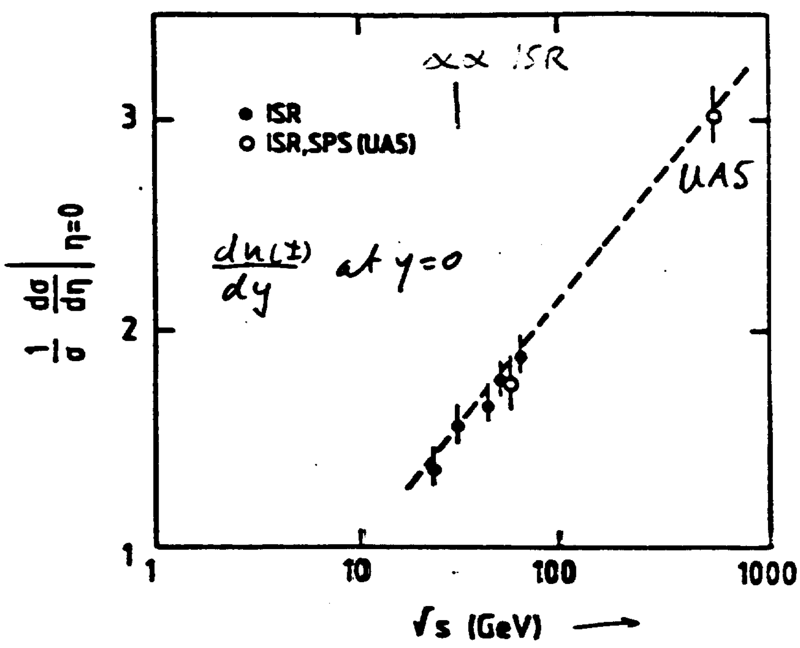
$T_c \approx (160 \div 220)\,\mathrm{MeV}$

$\varepsilon_Q(T=0) \approx 2 \div 7.5\ \mathrm{GeV/fm^3}$

5. How to produce QGP? a) high T: π production ...

$$\varepsilon^{\pi}_{exp} = \frac{\Delta E}{\Delta y}\,\Delta y\,\frac{1}{V} \quad \text{with } V = \tau_0\,\Delta y\,A_\perp \;\&\; \tau_0 = 1\,\text{fm} \quad \left[\begin{matrix}\text{Bjorken}\\ \text{PRD 27, 140}\end{matrix}\right]$$

$$\varepsilon^{\pi}_{exp} = \langle m_T\rangle \frac{dN}{dy}\frac{1}{\tau_0 A_\perp} \;:\; pp\ \sqrt{s} = 50\ \text{GeV/c} : \varepsilon^{\pi}_{exp} = 0.75\ \text{GeV/fm}^3$$



Remember: $\varepsilon_Q > 2$ GeV/fm^3

for A'A: $\frac{dN}{dy} = A\left(\frac{dN}{dy}\right)_{pp}$ (cosmics)

$\Rightarrow \varepsilon^{\pi}_{exp} \sim A^1/A^{2/3} \Rightarrow$ cons!

$\varepsilon_{exp} = \varepsilon_Q$ isentropic process

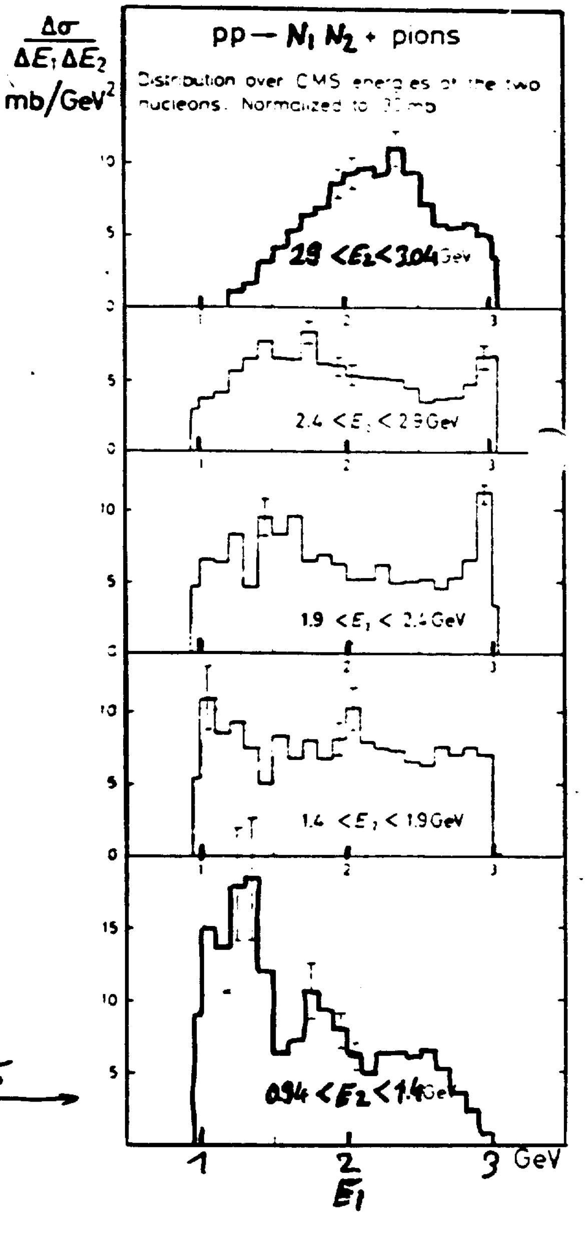
b) Stopping: $\mu \neq 0$

$$\varepsilon = 2\varepsilon_0\,\gamma\cdot\gamma$$

LT into cms   Lorentz contraction

$\varepsilon > \varepsilon_Q \Rightarrow p_{lab} \gtrsim 10$ GeV/c (BNL)

pp 19 GeV/c, Bøggild NP B91, 365 →



c) [illegible] in fragmentation region

Anishetty PR D 22, 2793

d) Various Comments

a) Order of phase transition (Landau-Lifshitz V)
- latent heat corresponds to 1^{st} order phase transition
- 1^{st} order: coexistence of 2 phases possible
  also supercooling / superheating
- 2^{nd} order phase transition
  no latent heat, no phase coexistence

b) chiral phase transition
above: $m_q = 0$ assumed

e^- in conductor: solid: $\underline{m_e \neq m_{vac}}$
due to boundary conditions [Kittel, Solid State Physics]
$\underline{m_q \neq 0}$ maybe because of <u>confinement</u>?

if $m_q \neq 0 \Rightarrow$ Lagr. includes $m \langle \psi \bar{\psi} \rangle$
<u>not</u> invariant for $\psi \to \gamma_5 \psi$

<u>LQCD</u>: (Satz, Z. Phys. C31, 167)
chiral phase trans. at deconfinement!

c) $\alpha_s = 0$ assumed throughout

$\alpha_s \neq 0 \rightarrow \varepsilon_{QGP} \rightsquigarrow 0.6\, \varepsilon_{QGP}(\alpha_s = 0)$

reduce effective #dof

lower T_c !?

e.g. [Rafelski, Phys. Rep. 88, 331]

II. Space-Time History of A'A Collisions

1. Introduction

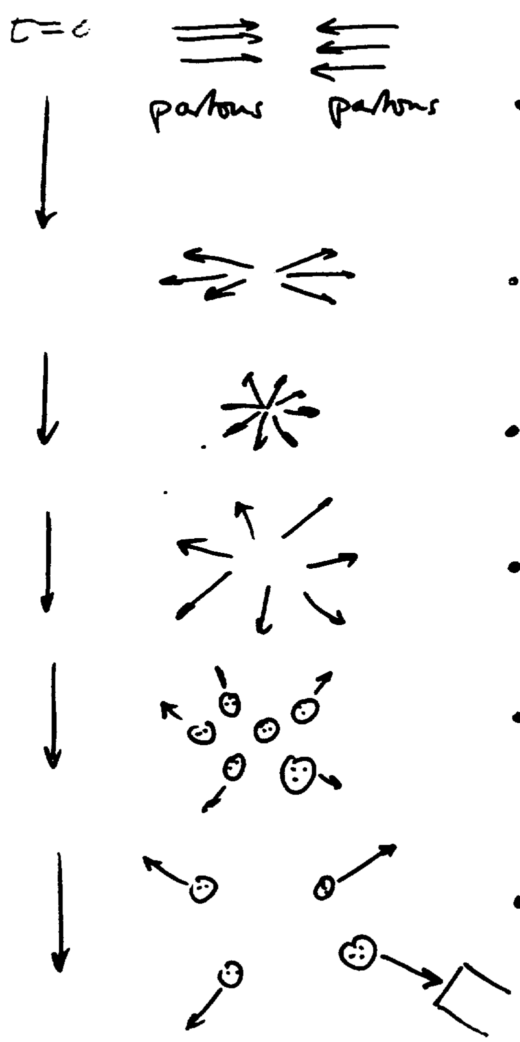
- Typical A'A coll at SPS: no symmetry
- central collisions: cylindrical sym.
- now $A' = A$: symmetric
- $\sqrt{s}$ very high & $\mu = 0$, i.e. $y_{cm} \approx 0$

  $\Rightarrow$ will be discussed in the following

- SPS: probably $\mu \neq 0$

  but: simple scenario $\sqrt{s} \to \infty$, $\mu = 0$

  useful to develop intuition



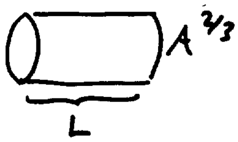
occasionally 

- formation of on shell partons ('initial conditions')
- towards therm. equilibr. (kinetic theory)
- thermal QGP (EOS)
- expansion (hydrodynamics)
- hadronization and expansion of hadron gas } { confinement, kinetics & hydrody. of hadrons
- freeze out & detection

1. Formation of plasma

Dimensional arguments: (Blaizot, Act. Phys. Pol. B18, 659)

- No of partons $\sim A$
- Volume comoving



only variable k_T of partons: $L \sim \frac{1}{k_T}$

- $\lambda_{parton} < L$ to equilibrate

$\lambda \sim \frac{1}{\sigma n}$ assume (QCD): $\sigma \sim \frac{1}{\hat{s}} \sim \frac{1}{k_T^2}$

and $n = \frac{A}{V} \sim A^{1/3} \cdot k_T$

from $\lambda_{part} < L \Rightarrow \underline{k_T \sim A^{1/6}}$ for partons 'creating' QGP

- Consequences

- $\underline{\varepsilon} = \frac{E}{V} \sim \frac{A\, k_T}{V} \sim \underline{A^{2/3}}$ ($A^{1/3}$ in sect. I.5)
- $\underline{\lambda} \sim \underline{\tau}$ (formation) $\sim k_T^{-1} \sim \underline{A^{-1/6}}$
- $\underline{\lambda / R_A} \sim A^{-1/6} / A^{1/3} \sim \underline{\frac{1}{\sqrt{A}}}$ (measure of multiple scattering)

i.e if A small $\Rightarrow$ no equilibration

$\Rightarrow$ use ions

see also: Blaizot, NP B289, 847. Kerman, PRL 56, 219

Hwa, PRL 56, 696

2.) Approach to Equilibration: Kinetic Theory

a) Collisions of partons may yield equilibrium

$f(\vec{x},\vec{p},t)$ = phase space density

Boltzmann eqn. for gases:

$$\otimes \quad \frac{df}{dt} = \frac{\partial f}{\partial t} + \dot{\vec{x}}\,\nabla_x f + \dot{\vec{p}}\,\nabla_p f = -\left(\frac{\partial f}{\partial t}\right)_{coll} \quad , \dot{\vec{p}} = -\nabla U = \vec{F}$$

at equilibrium: $\frac{df}{dt} = 0$

near equilibrium: $\frac{df}{dt} = -\frac{f-\bar{f}}{\tau_c}$, $\bar{f}$: equilibr.

← relaxation approx.

- In principle $\otimes$ holds here as well for df_i/dt , $i = u,\bar{u},d,\bar{d},s,\bar{s},g$

  $\Rightarrow \left(\frac{\partial f}{\partial t}\right)_{coll}$ includes creation & annihilation of q and gluons

- It has to be modified, however: color is exchanged

  $\Rightarrow$ color is dynamic variable $\Rightarrow$ term: $\nabla_Q f \cdot \dot{Q}$,

  also quantum mechanical framework

b) • Simple example: $s\bar{s}$ production by $gg \to s\bar{s}$, $q\bar{q} \to s\bar{s}$

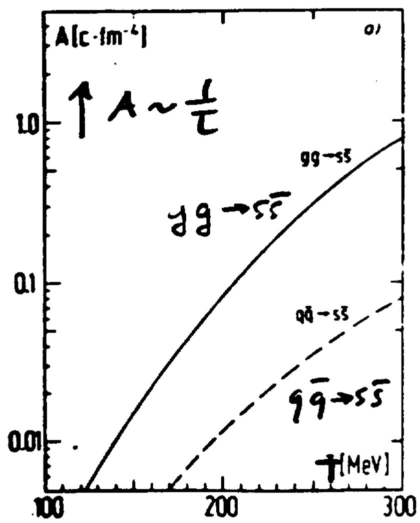
with $\nabla f_s = 0$ and $\rho_s = \int f_s \, d\vec{p}$

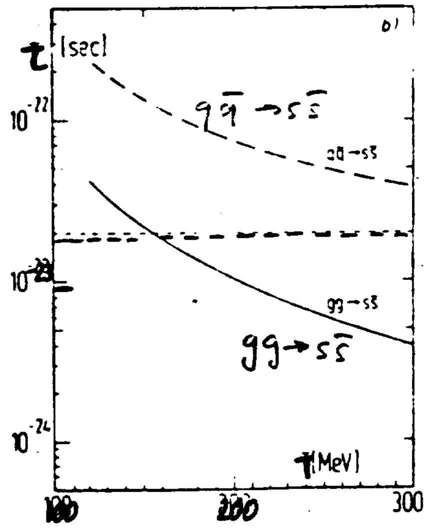
Koch, Phys. Rep. 142

$$\Rightarrow \frac{d\rho_s}{dt} = \frac{\bar{\rho}_s}{\tau_c}\left[1 - \rho_s/\bar{\rho}_s\right]$$

Conclusion:

- gg dominates $\underline{s\bar{s}}$ production (16 dof)
- $\underline{s\bar{s}}$ produced $\underline{\text{fast}}$





c) Transition to hydrodynamics of fluids

Start from $\frac{df}{dt} = \frac{\partial f}{\partial t} + \dot{x}\frac{\partial f}{\partial x} = -\frac{\partial f}{\partial t}\Big|_{coll}$, i.e. $\vec{F}=0$

this term is source of dissipative effects giving transport coefficients: heat conductivity, viscosities

One can show that: [Molitoris, Progr. Part & Nucl. Phys. 15]

i) $\int \frac{df}{dt} d\vec{p} = 0 = \frac{\partial \varrho}{\partial t} + \mathrm{div}(\varrho \vec{u})$ $\quad \varrho = \int f dp$, $\vec{u} = \overline{\vec{v}}$

continuity eqn. $\quad$ fluid element $\quad$ particles in fluid

ii) $\int \frac{df}{dt} \vec{v} d\vec{p} = 0 = \frac{\partial \varrho\vec{u}}{\partial t} + \nabla(\varrho\vec{u}\cdot\vec{u}) + \nabla P$

Euler equation $\quad$ stress tensor

iii) $\int \frac{df}{dt} \vec{v}^{\,2} d\vec{p} = 0 = \frac{\partial \varepsilon}{\partial t} + \nabla(\varepsilon\cdot\vec{u}) + \nabla(\vec{u}P)$

energy conservation

- Hence: by integration (loss of information) one arrives at <u>hydrodynamic equations</u> for <u>viscous fluids</u> (stress tensor P includes transport coeff.)
- For viscous fluids <u>Euler equation</u> $\hat{=}$ <u>Navier–Stokes eqn.</u>
- From kinetic theory transport coefficients can be <u>calculated</u> to be <u>used</u> in hydrodynamics.
- Kinetic theory may suggest that the QCD plasma does <u>not</u> consist of free gl. & q!

  e.g. [Heinz, NP A 461, 49c]

Dissipative phenomena: Danielewicz, PRD 31, 53, Hosoya, NPB250, 666

3. Hydrodynamics

a) Assume: relativistic case, no viscous (dissipative effects)

To remember: $\underline{\frac{\partial \varepsilon}{\partial t}} + \underline{\nabla(\varepsilon \vec{u}) + \nabla(u \cdot P)} = 0$ (previous page energy conser.)

<u>Relativistic</u> hydrodyn. starts from an energy-momentum tensor $T^{\mu\nu} = (\varepsilon + P)\, u_\mu u^\nu - g^{\mu\nu} P$

$$u^\mu = \gamma(1, \vec{v})$$

$$\frac{1}{\tau} x^\mu = u^\mu$$

<u>energy momentum</u> conservation

$$\partial_\mu T^{\mu\nu} = 0 \quad \Rightarrow \quad u_\nu \partial_\mu T^{\mu\nu} = 0$$

$$\Rightarrow \quad \underline{u^\nu \partial_\nu \varepsilon} + \underline{(\varepsilon + P)\, \partial_\nu u^\nu} = 0 \qquad \text{(see above!)}$$

Now: from $\varepsilon + P = Ts + \mu n \;\rightarrow\; d\varepsilon = T ds + \mu dn$

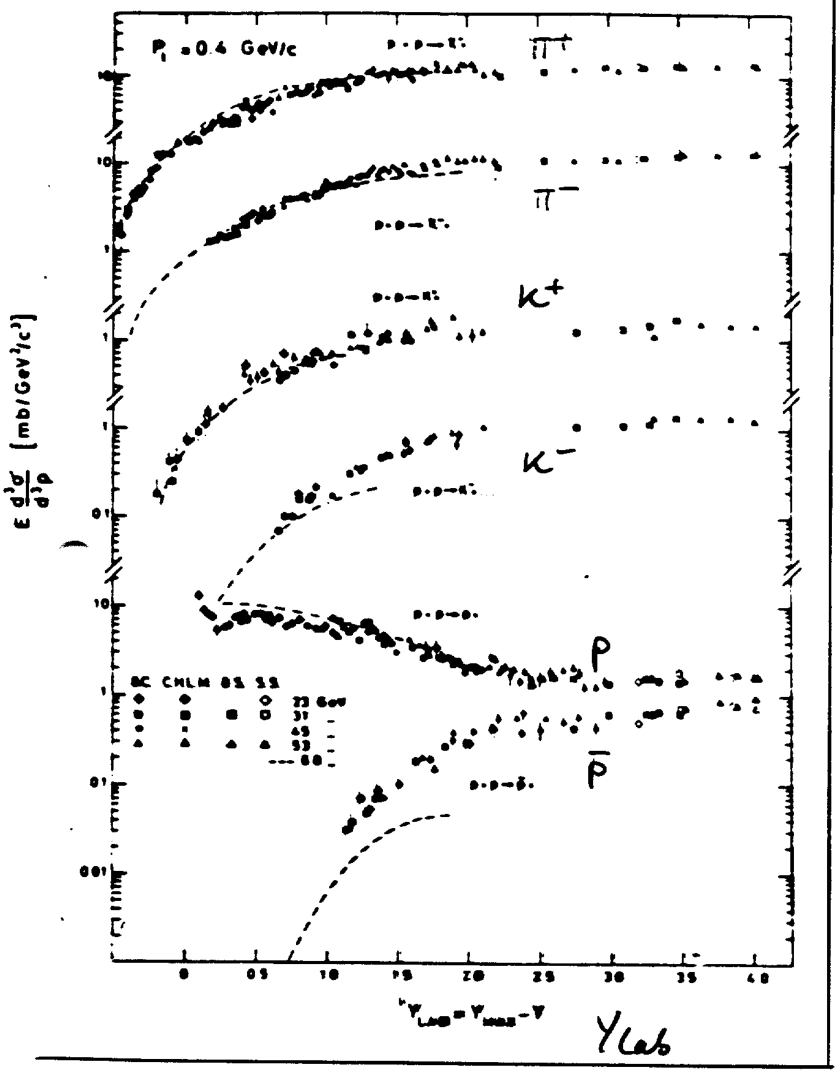
one has $u^\nu T \partial_\nu s + u^\nu \mu \partial_\nu n + (Ts + \mu n)\partial_\nu u^\nu = 0$

or $T\, \partial_\nu (u^\nu s) + \mu \underbrace{\partial_\nu (n u^\nu)}_{\text{particle conservation: } = 0} = 0$

$\Rightarrow \quad \partial_\nu (u^\nu s) = 0$ entropy conservation

e.g. [Landau-Lifshitz VI, Cleymans, Phys. Rep. 130, 217]

2) *Scaling Hydrodynamics:* (Bjorken, PRD27, 140)



$\frac{dn}{dy} \approx$ const.

$\Rightarrow$ invariance under Lorentz boost along $z \parallel$ beam

$\Rightarrow$ physics quantities depend on the <u>only</u> <u>Lorentz</u> scalar τ,
$\tau = \sqrt{t^2 - z^2}$,

- <u>longitudinal</u> flow $v = \frac{z}{t}$
- from previous page one finds with $u^\nu \partial_\nu = \partial/\partial\tau$, $\partial_\nu u^\nu = \frac{1}{\tau}$

$$\frac{\partial \varepsilon}{\partial \tau} = -\frac{\varepsilon + P}{\tau}$$

or with $Ts = \varepsilon + P$ ($\mu = 0$) $\Rightarrow \frac{\partial s}{\partial \tau} = -\frac{s}{\tau} \Rightarrow$ <u>$s \cdot \tau = \text{const}$</u>: isentropic

$s \sim \frac{1}{\tau}$ 1-dim. expansion

Consequences:

- $dN(\text{partons}) = \int dV\, n = \int dy\, \tau\, d^2x_\perp \frac{s}{c}$ (remember $c = \frac{s}{n}$)

$\Rightarrow$ <u>$\frac{dN}{dy} = \frac{1}{c} A_\perp \tau_0 s_0 = \frac{1}{c} A_\perp \tau_f s_f$</u> f = final

One can relate observed particle density to initial entropy density s_0 (or $\varepsilon_0 \frac{4}{3} = s_0 T_0$)

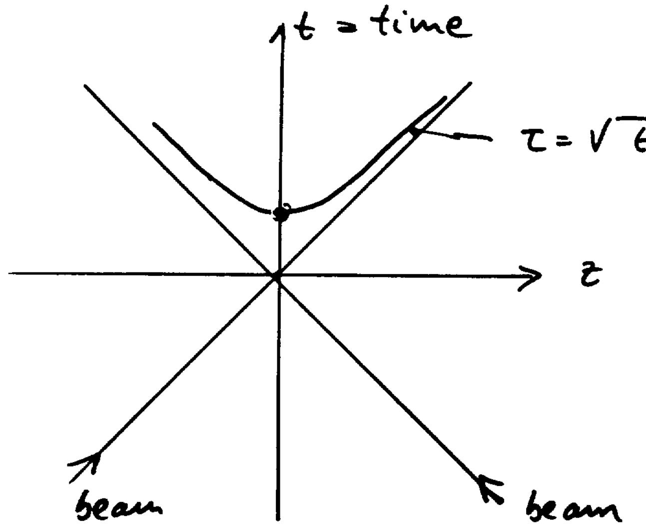
- $\underline{\frac{dN}{dy}} = \frac{1}{c} A_\perp \tau_0 s_0 \qquad s \sim \frac{\partial \varepsilon}{\partial T} \sim T^3$

  $\sim \frac{1}{c} A_\perp \tau_0 T_0^3$

  $\sim A^{2/3} A^{-1/6} (A^{1/6})^3 = \underline{A^1}$ (cosmics!)

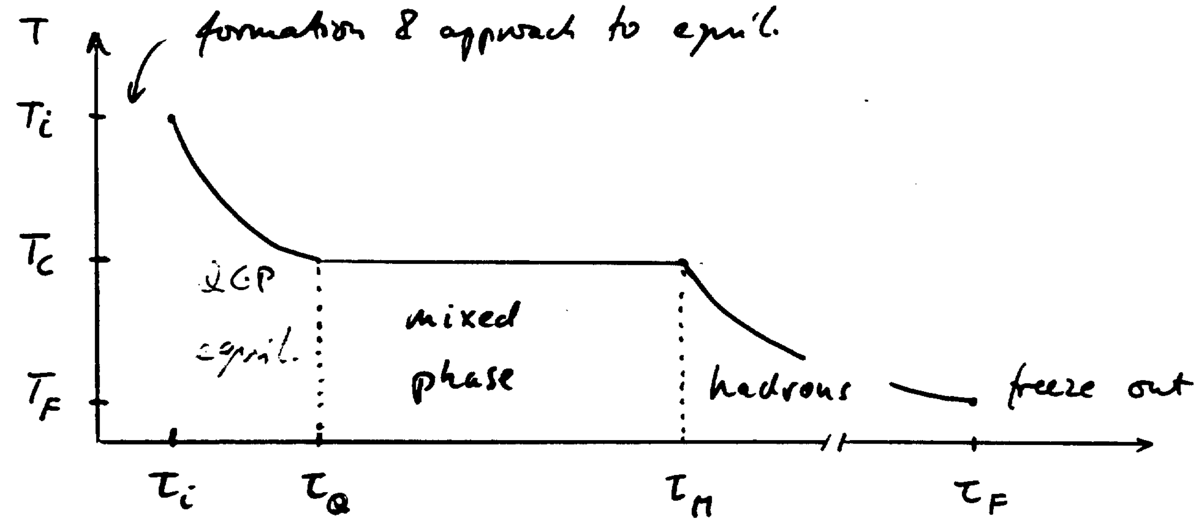
- $\tau T^3 \sim \tau s = \text{const}$ with $\tau \sim A^{-1/6} \Rightarrow \underline{T \sim A^{1/6}}$

  $\Rightarrow$ use ions

- 

  $\tau = \sqrt{t^2 - z^2} = \text{const}$

  physics depends only on τ
  $\Rightarrow$ slow particles ($v = z/t$) are created first
  (inside-outside cascade)

- 

$s \cdot \tau \sim \tau T^3 = \text{const} \Rightarrow \underline{\tau_Q} = \tau_i \left(\frac{T_i}{T_c}\right)^3 \sim A^{-1/6} \cdot (A^{1/6})^3 = \underline{A^{1/3}}$

$\tau_M = \tau_Q \frac{s_Q}{s_H} \qquad \tau_F = \tau_M \left(\frac{T_c}{T_F}\right)^3$

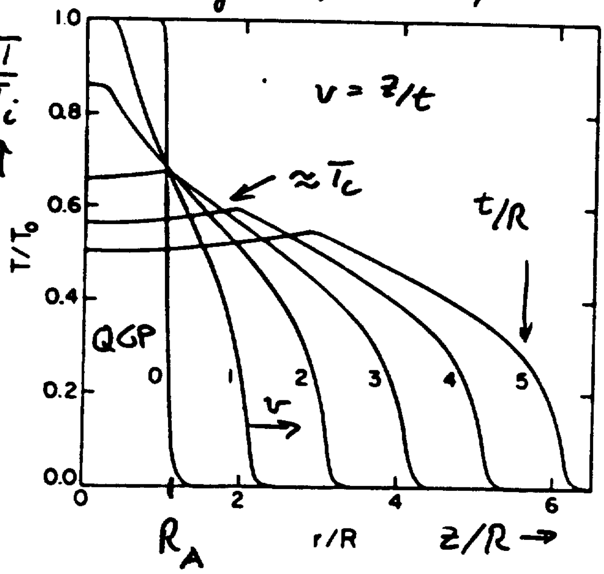
$\tau_i : \tau_Q : \tau_M : \tau_F \approx 1\,\text{fm} : \underline{8} : 80 : 240$

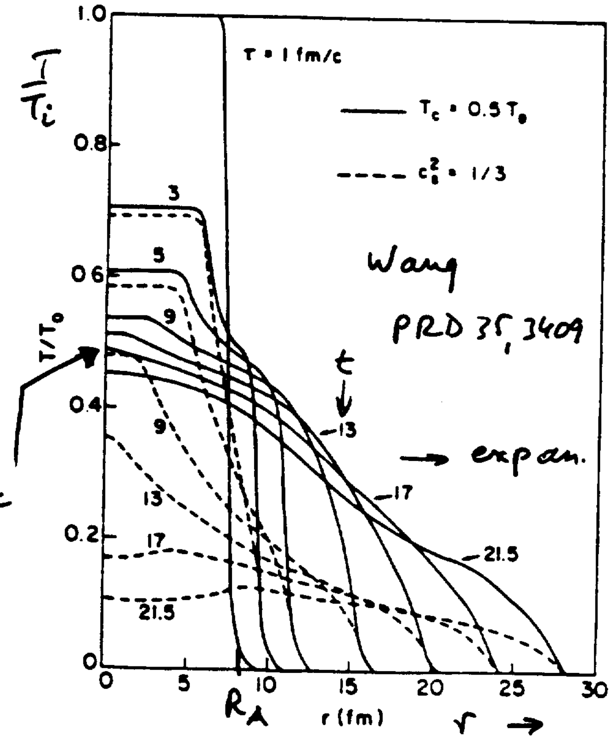
c) Transverse expansion

long. & radial exp.

scaling hydr., long. flow

Baym NPA 407, 541

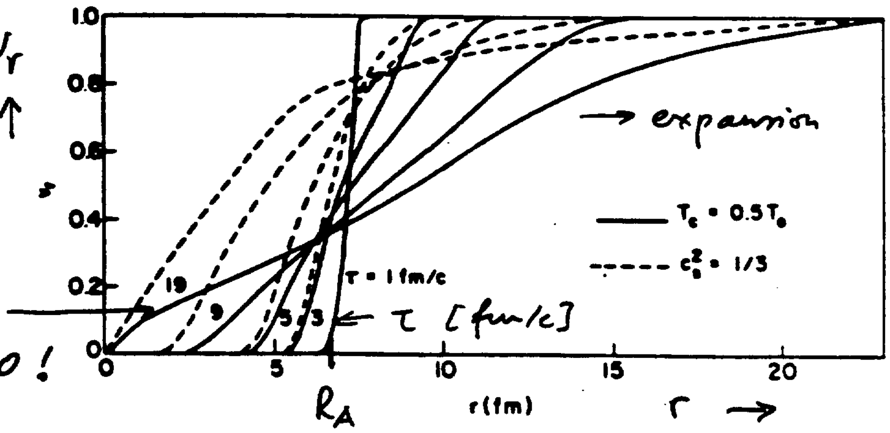




very similar: cooling governed by long. expansion

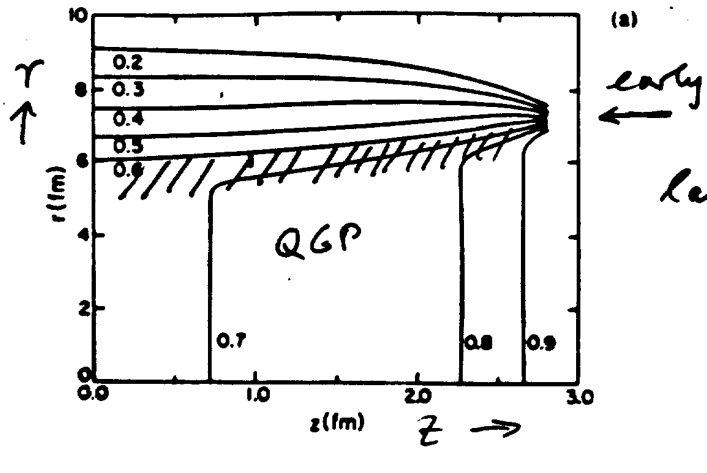
radial velocity v_r ↑

arrives late at r=0!



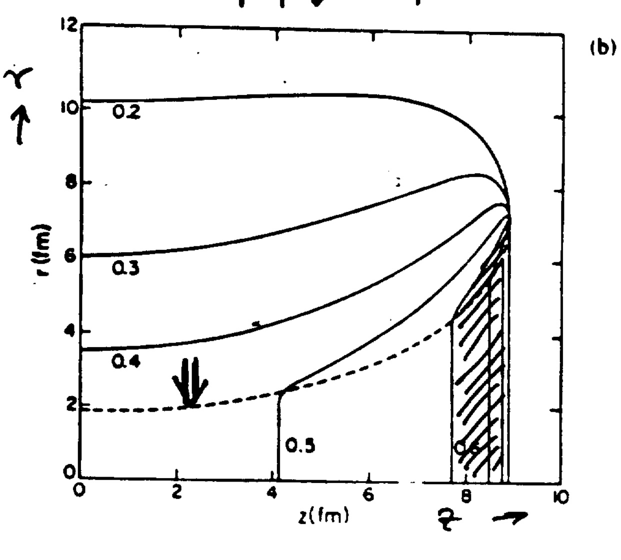
Baym NPA 407, 541

lines of T/T_i = const.

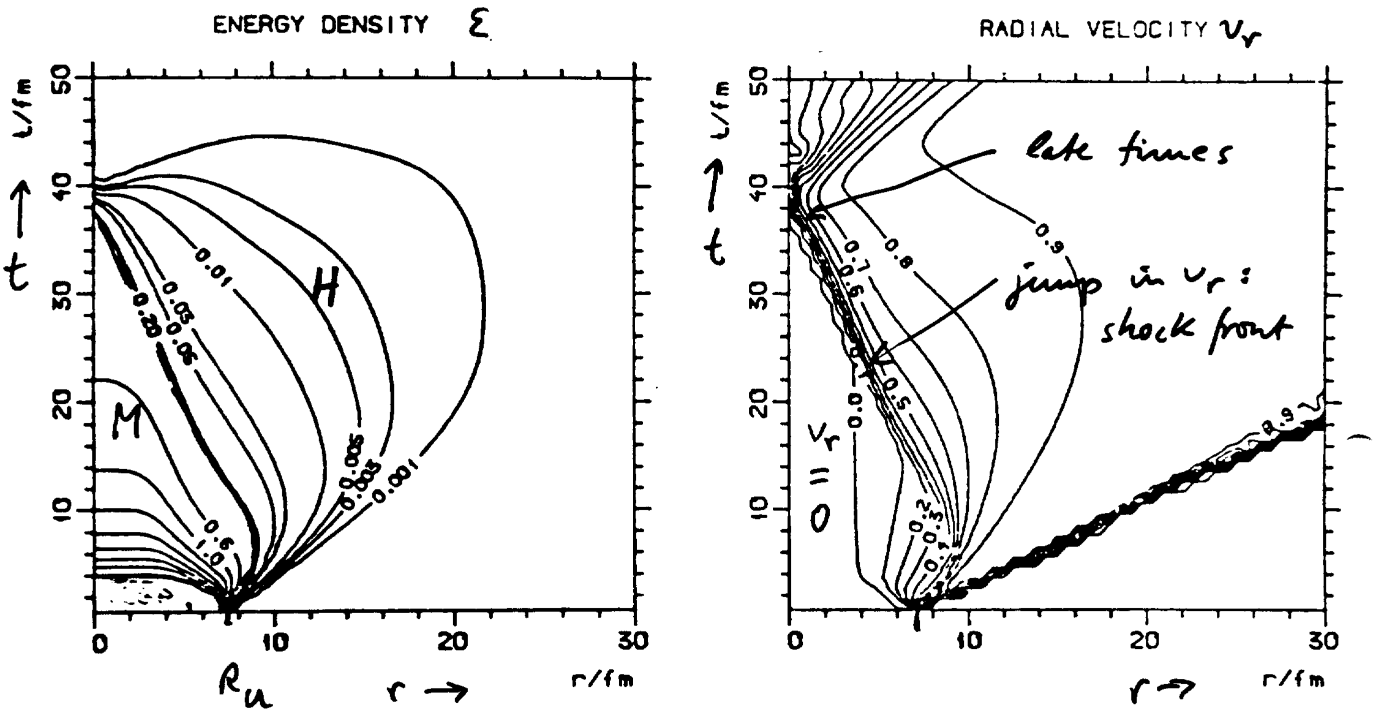


late →

radial exp. ↑, ⇓ rarefaction wave

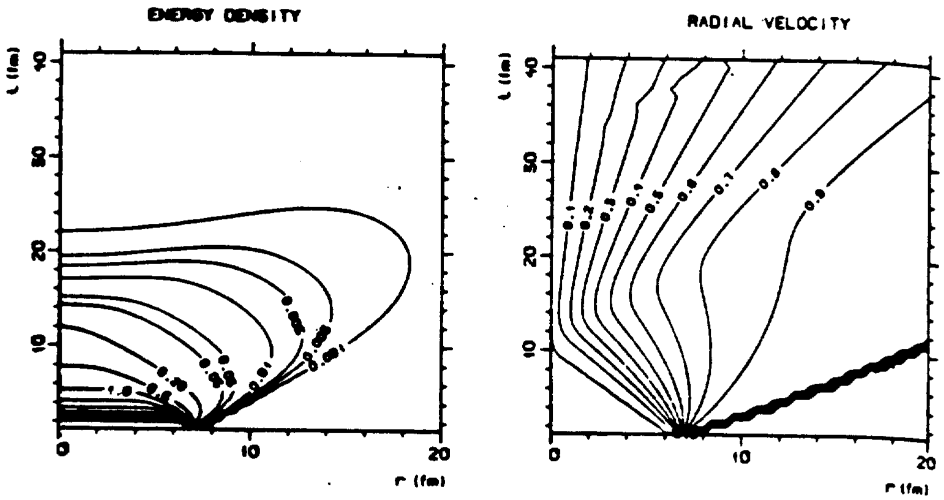


Kataja, PRD 34, 2755



Since shock front arrives late at $r \approx 0$, there is no plasma any more $\Rightarrow$ does not affect strongly previous arguments (T_i, τ_i)

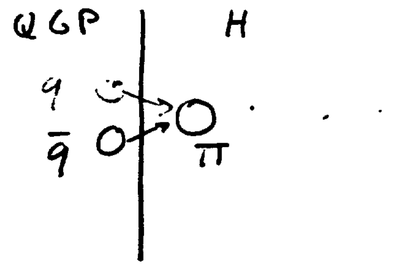
<u>no</u> phase transition:



[shocks: Landau-Lifshitz VI]

more on hydrodyn.: von Gersdorff PRD, 34, 794, Baym: NP A407, 541

2) Recombination



Problem: $S = sV \simeq$ const

but $c = \frac{s}{n} = 4.2$

$\frac{s}{n} = 4.2$

$\frac{s}{n} = 3.6$

$\underbrace{\quad}_{\#\text{dof } 6}$ $\underbrace{\quad}_{\#\text{dof } 3}$

$\Rightarrow$ entropy not conserved

2 ways out: a) increase V b) fragmentation

consequence of recomb. for $\mu \neq 0$:

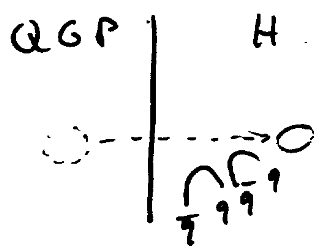
it is easier for a quark to find other quark q than to find $\bar{q}$

$\Rightarrow$ easier to produce e.g. $K^+ = \bar{s}u$ than $K^- = s\bar{u}$?

easier to produce $\Lambda = suu$ than $\bar{\Lambda} = \bar{s}\bar{u}\bar{u}$?

therefore, s quarks might be accumulated in QGP $\Rightarrow$ strange matter?

3) Fragmentation



new $q\bar{q}$ pairs i.e. entropy created

Note: this changes flavor composition in H

[see also: van Hove Z.Phys. C 27, 135]

→ Kinetic theory for chemical equilibration in Hadron Phase (Koch, Phys. Rep. 142)

$$\underbrace{\pi\, K\, N\, Y\, \Xi\, \Omega}_{\text{at hadronization}} \longrightarrow \underbrace{\pi\, K\, N\, Y\, \Xi\, \Omega}_{\text{at freeze out}}$$

For rate equations one needs

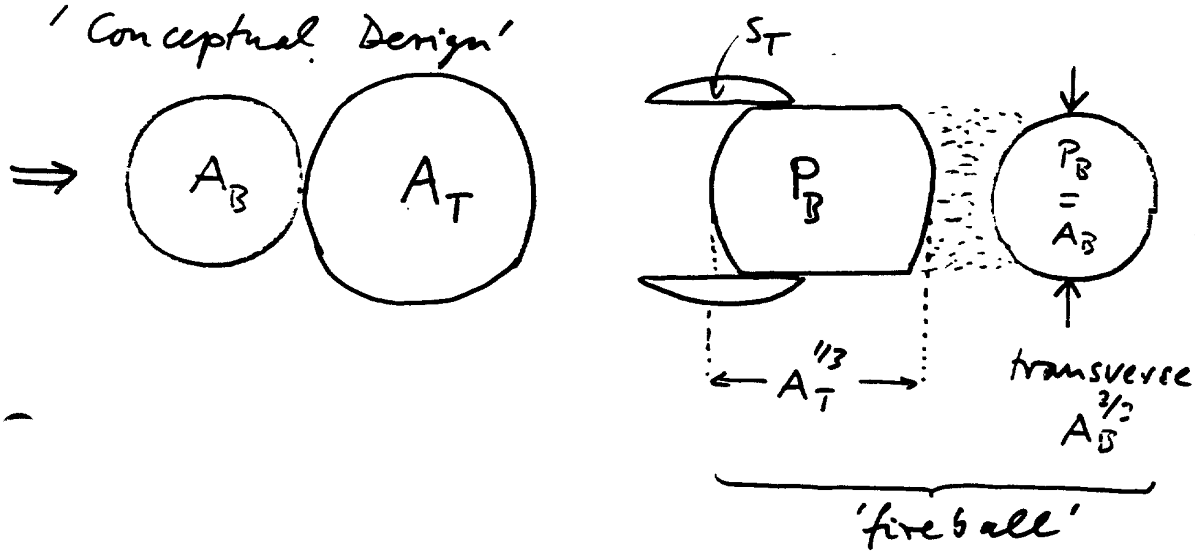
$$\sigma\left(\begin{matrix}\pi\\K\\N\\Y\\\Xi\\\Omega\end{matrix} + \begin{matrix}\pi\\K\\N\\Y\\\Xi\\\Omega\end{matrix} \rightarrow \begin{matrix}\pi\\K\\N\\Y\\\Xi\\\Omega\end{matrix} + X\right)$$

including resonances!

... search for the QGP

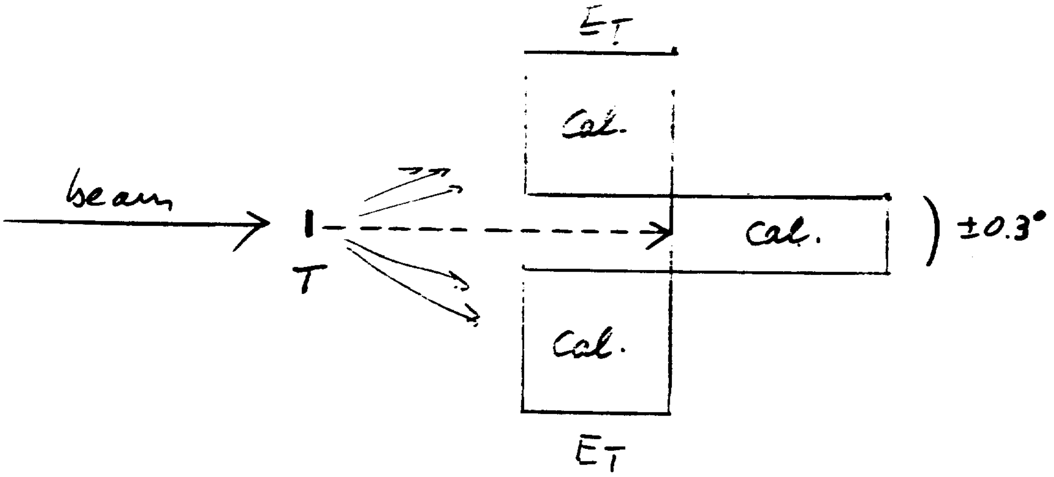
... Experiments

'Conceptual Design'



central coll.: *no* beam spect.

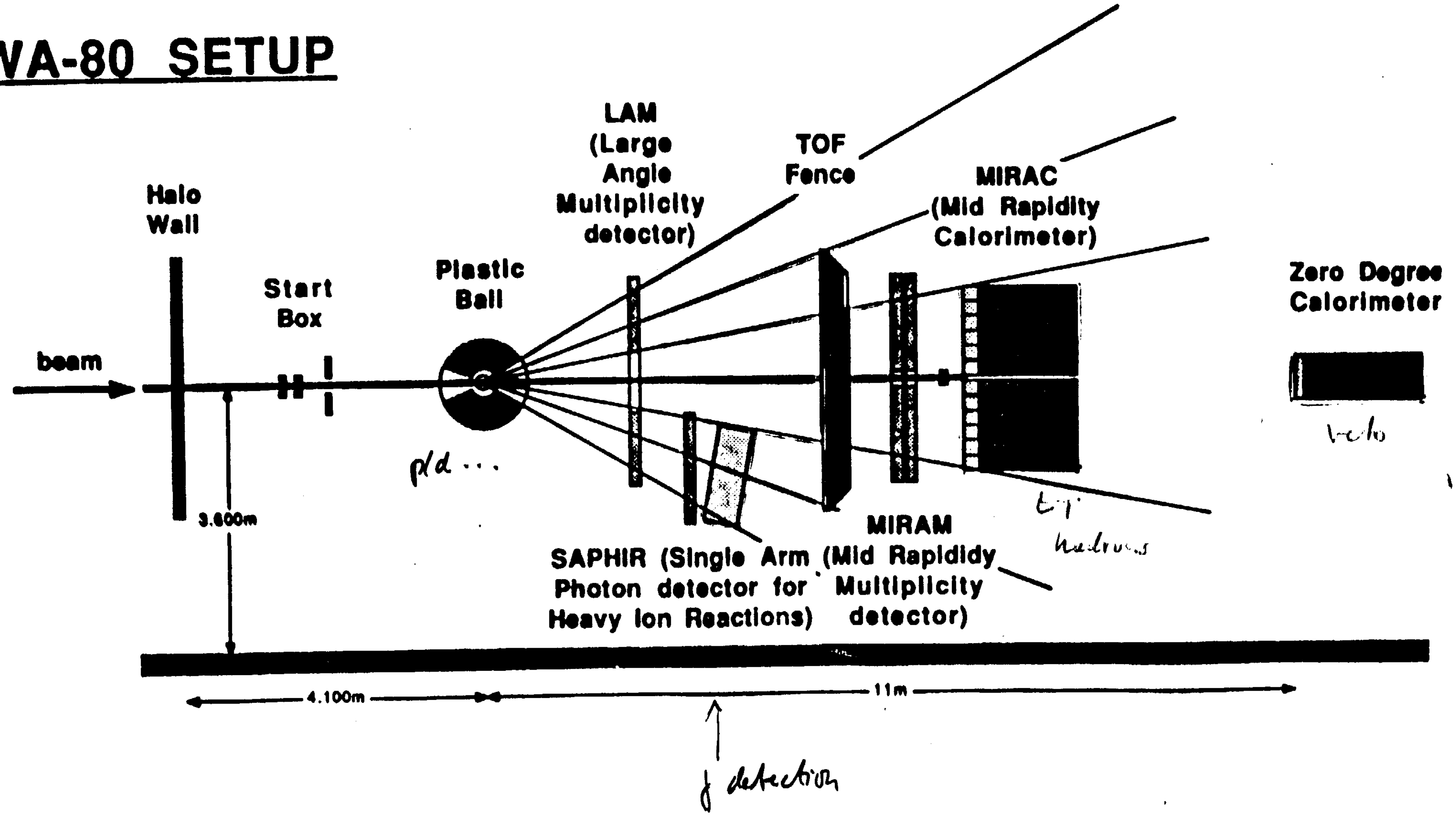
Consequence: Common features of (nearly) *all* expts.:



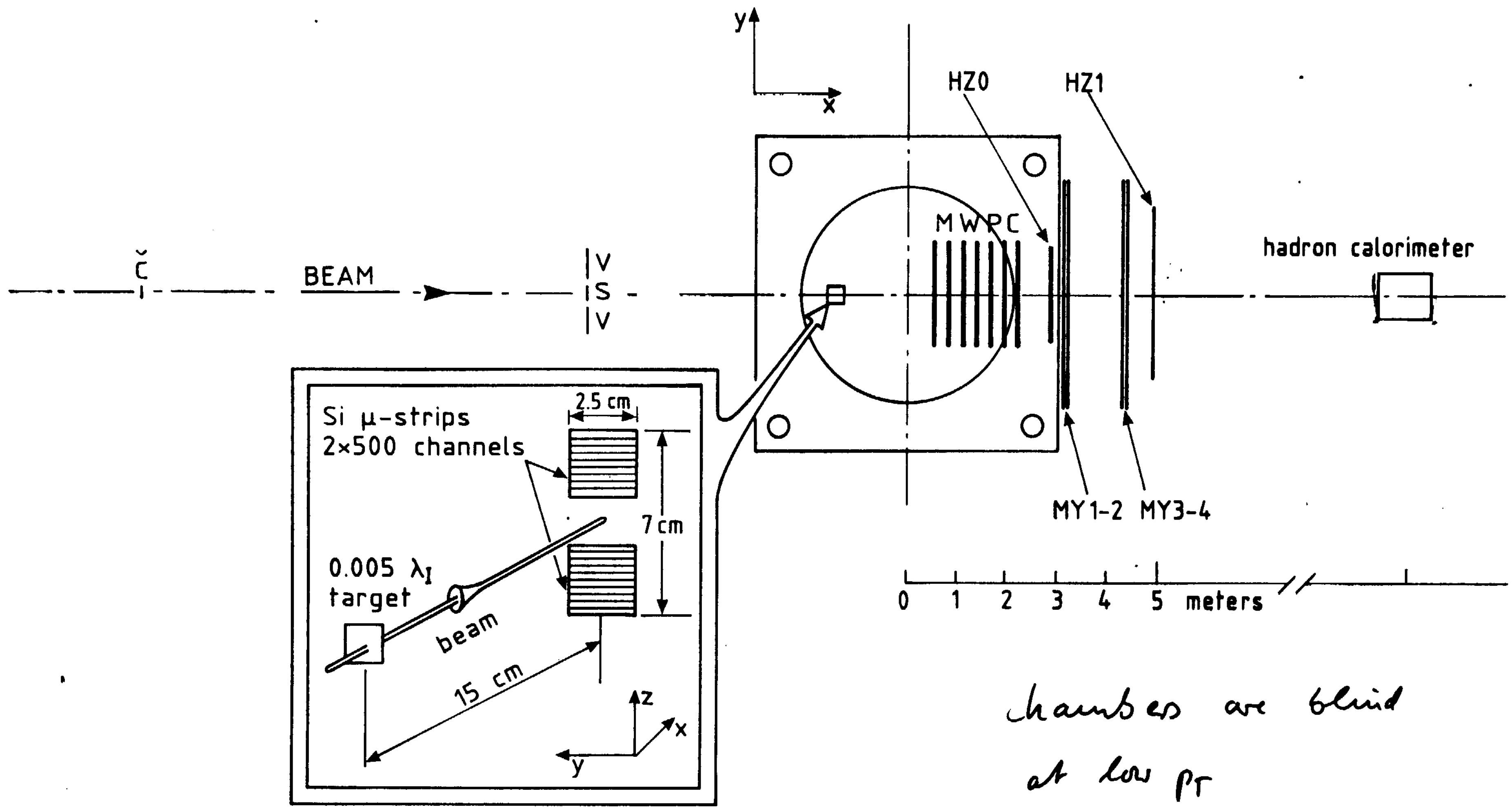
central coll. '*no*' spect.

GSI - LBL - LUND - Marburg - Münster - Oak Ridge - Warsaw

WA-80 SETUP



WA 85 (...)



chambers are blind
at low p_T

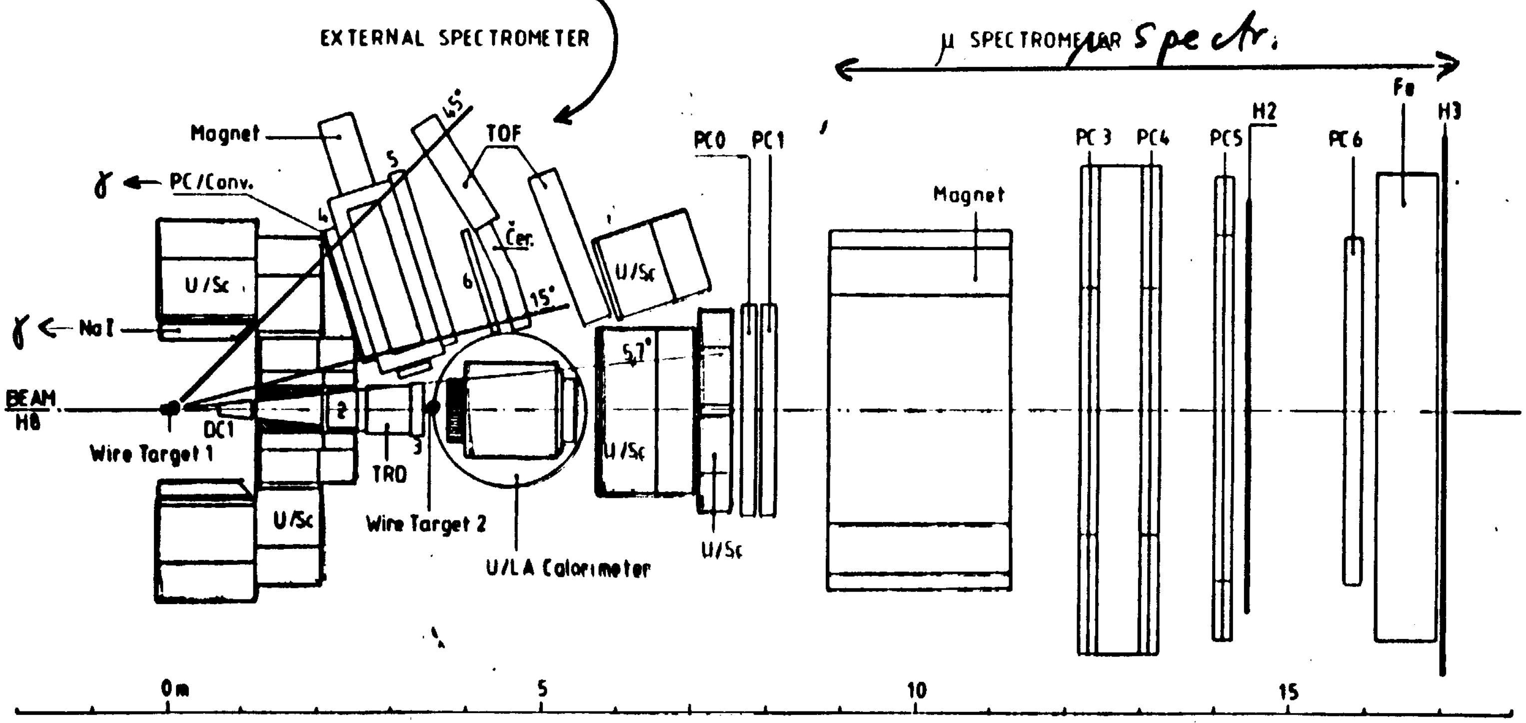
III 1 b

Expt. NA34

III 1 c

NA 34/2: BNL - CERN - Heidelberg - London - Los Alamos - Lund - Montreal
Moscow - Novosibirsk - Pittsburgh - Rutherford - Saclay
- Syracuse - Tel Aviv

slit: K/π/p/d/α



4π calor:

main signatures: K/π / single γ / μμ

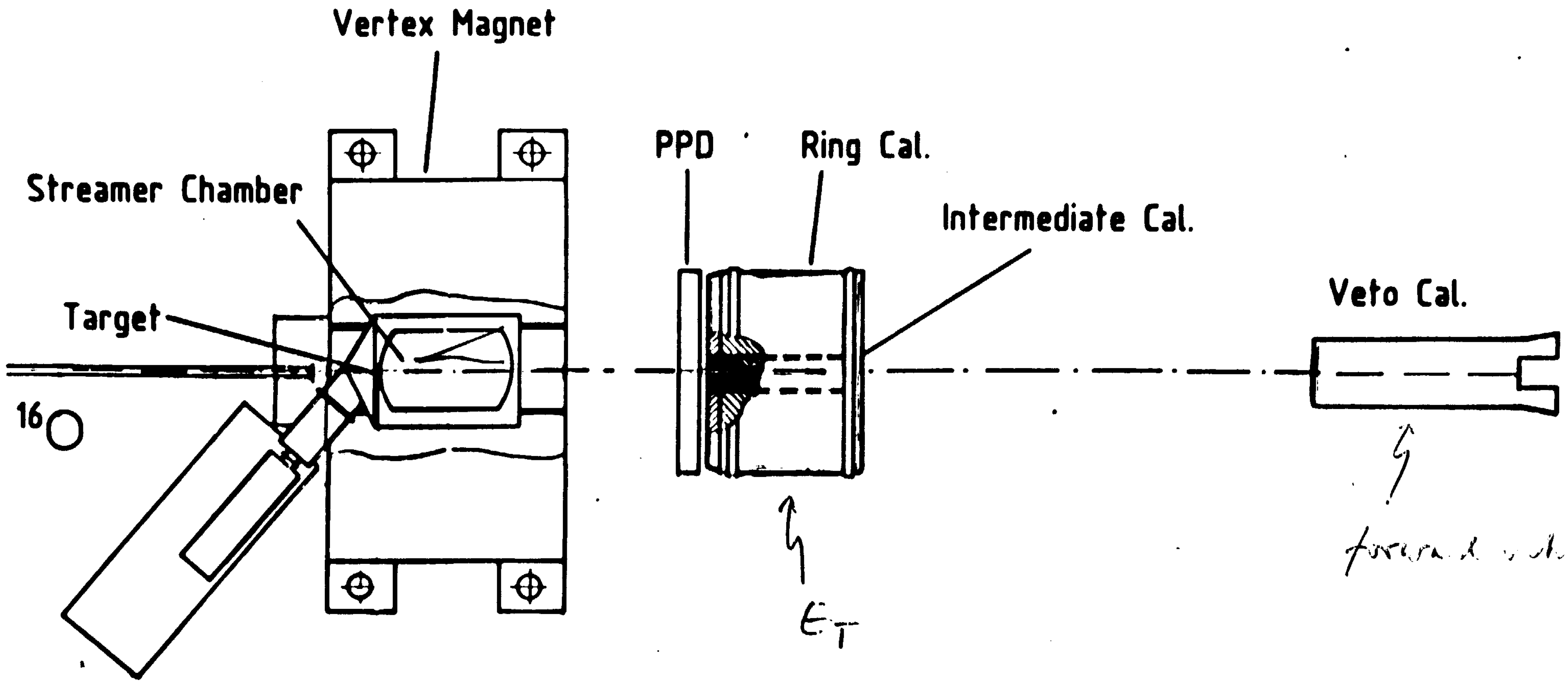
Experiment NA34: Lepton production

≈ all components exist due to NA 34/1

NA35

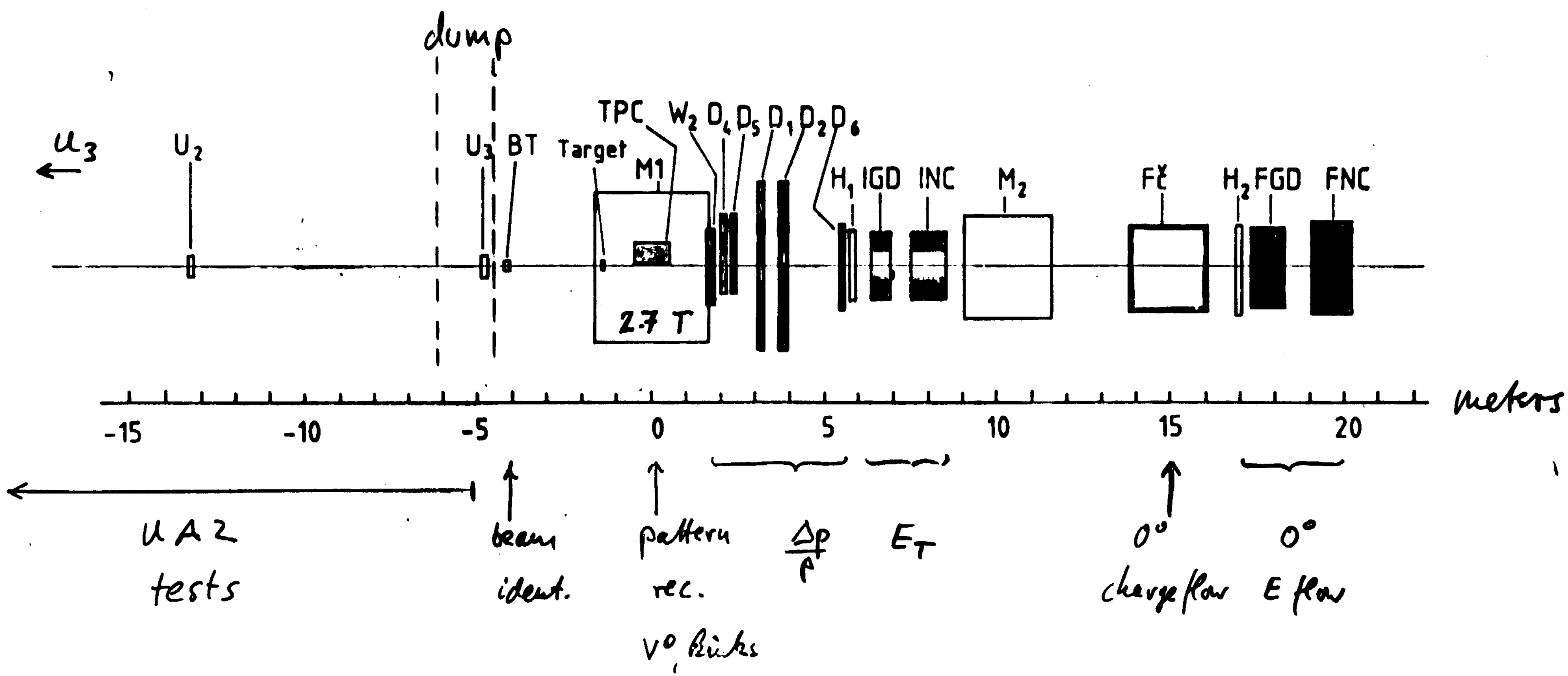
Athens - Cracow - GSI - Frankfurt - Heidelberg - LBL - Marburg - Texas - Warsaw - Zagreb

III 1 d



Experiment NA35: Study of Relativistic Nucleus-nucleus Collisions

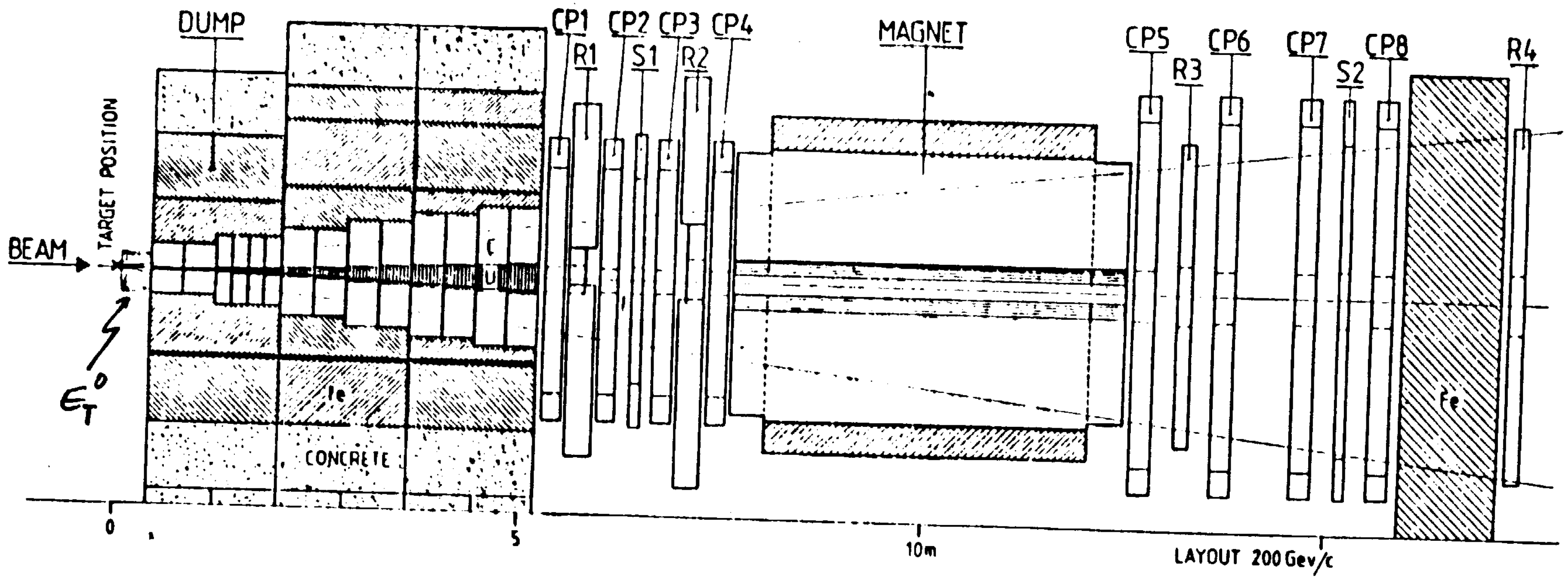
Side view of NA36 set-up (compressed EHS)



N 138

Bergen - CERN - Clermont-Ferrand - Ecole Polytechnique
Lisbon - Lyon - Neuchâtel - Orsay - Strasbourg - Valencia

using NA10 μ-pair spectrom.



high rate, high mass $\mu\mu$ $\gtrsim J/\psi$

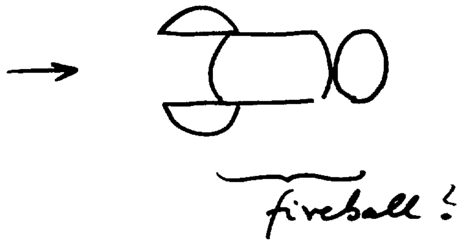
Expt. NA10

III 1 f

I. Experimental Results

1) 'Systematics'

a)• Do central collisions occur?



b)• Is there evidence for an isotropic fireball?

c)• Characteristics of E_T production: geometry and energy density?

Warning: nearly all results unpublished ⇒ preliminary

WA80

^{16}O ^{12}C

geom. probab. for central collision small

a)

Energy flow at $(0 \pm 0.3)^\circ$

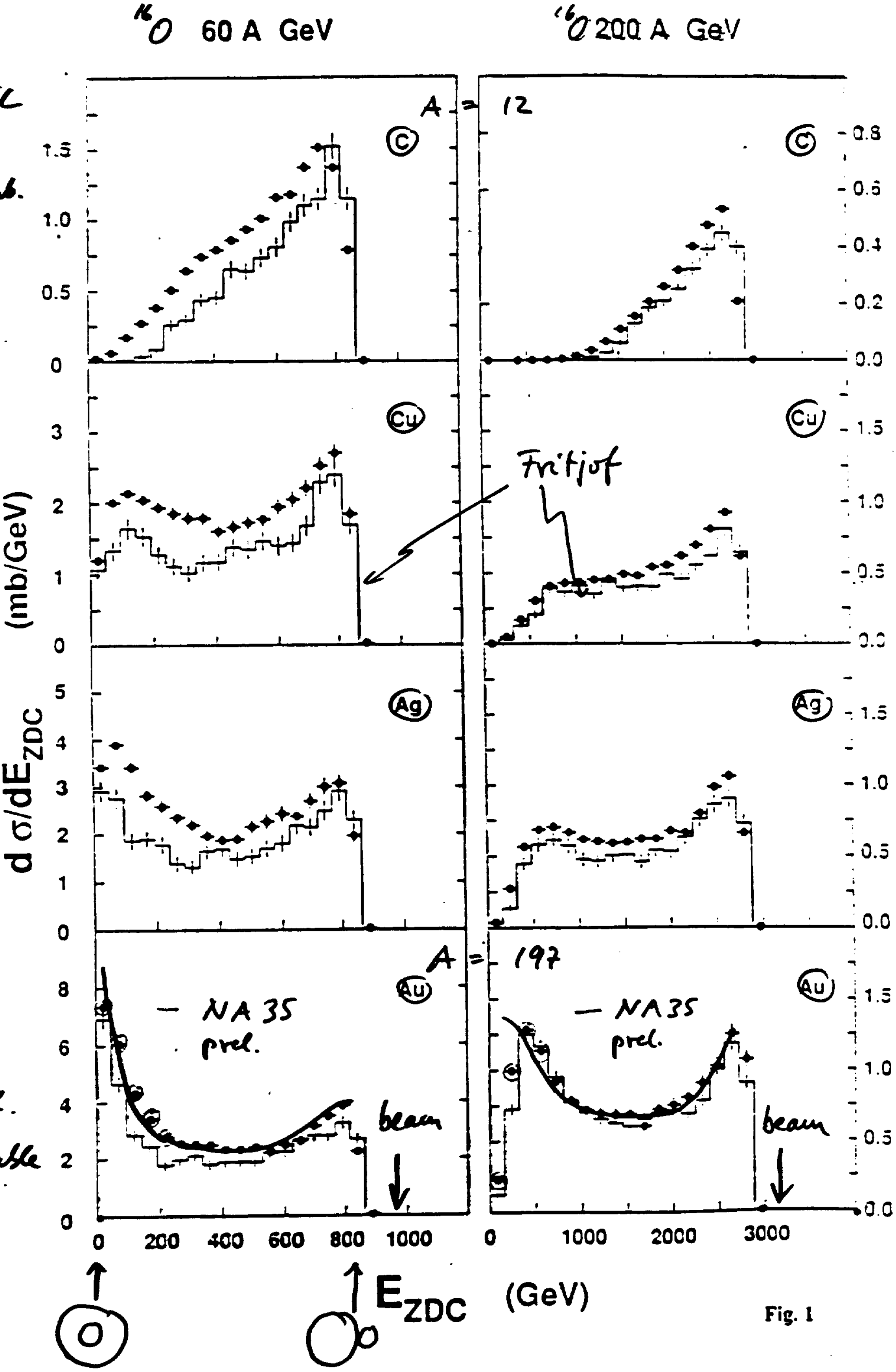


Fig. 1

^{16}O Au

central coll. rather probable

60 GeV/c: very often projectile stopped in target Au

200 GeV/c: there are events where projectile is stopped in Au!

Note: prev. lectures: stopping expected at $p_{lab} \times 3 \to 25$ GeV/c

b) (Pseudo-)Rapidity distributions for central events

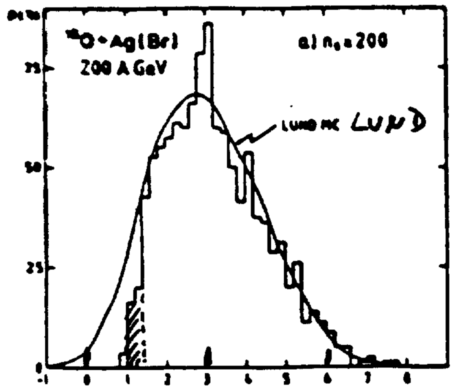
Holynski, HEA-55-87-04 (KLM)

EMU01

0 Ag(Br)

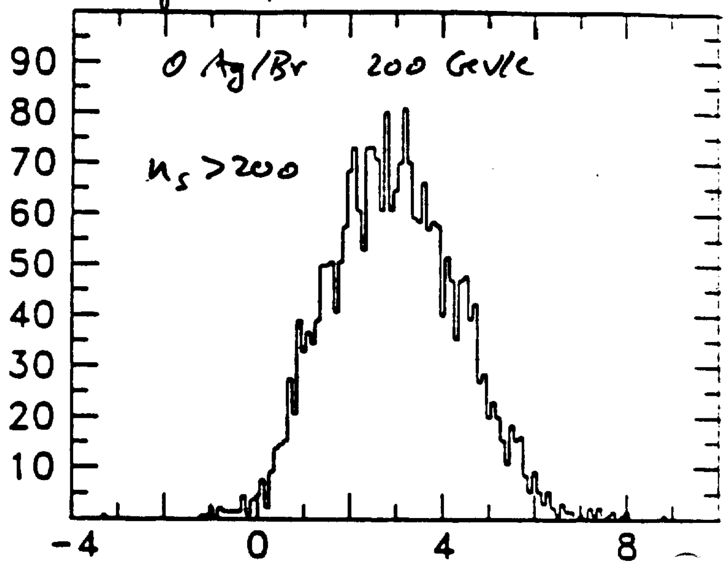
200 GeV/c

$n_s \geq 200$



0 3 7 6 η →

[Adamovich, LUND LUIP 8704]



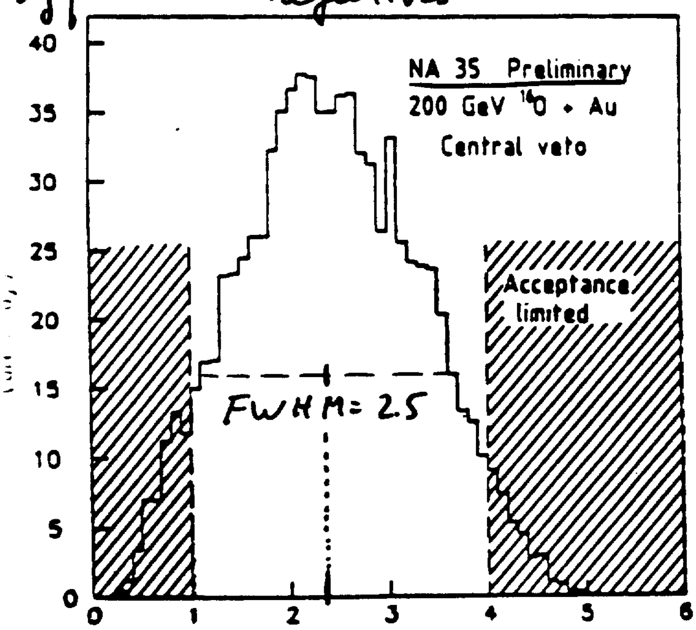
η →

- EMU01 & KLM data agree

  if $n_{ch} \sim A_T^{1/3}$ (1st lecture) ⇒ via ^{16}O Pb data: $b \approx 3$ central

$\frac{dn}{dy}$ ↑

negatives



y_{lab} →

- One finds

  $y_{lab}(max) \approx 2.4$

  $y_{lab}(max, pp) = 3$

- Note: $y_{lab}(max) = y_{lab}(max, pp) \underbrace{- \frac{1}{2} \ln (\bar{P}_T / A_P)}_{\Delta}$

$\Delta \approx -0.6$ for 16 + 55 nucleons !

beam target

geometry

FWHM (NA35) ≈ 2.5 ?

FWHM (Emulsion) ≈ 3.25

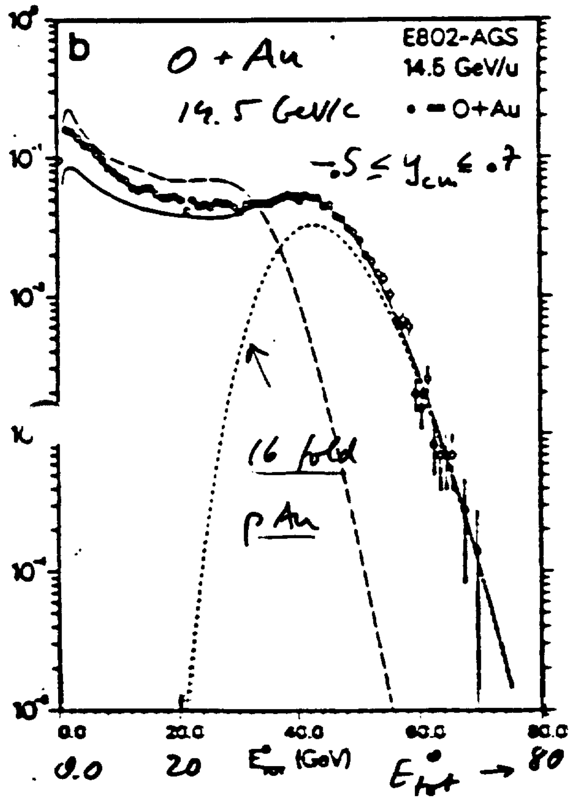
Rafelski

UCT-TP 81/1987

c) Production of transverse energy E_T

Abbott, subm. to PL

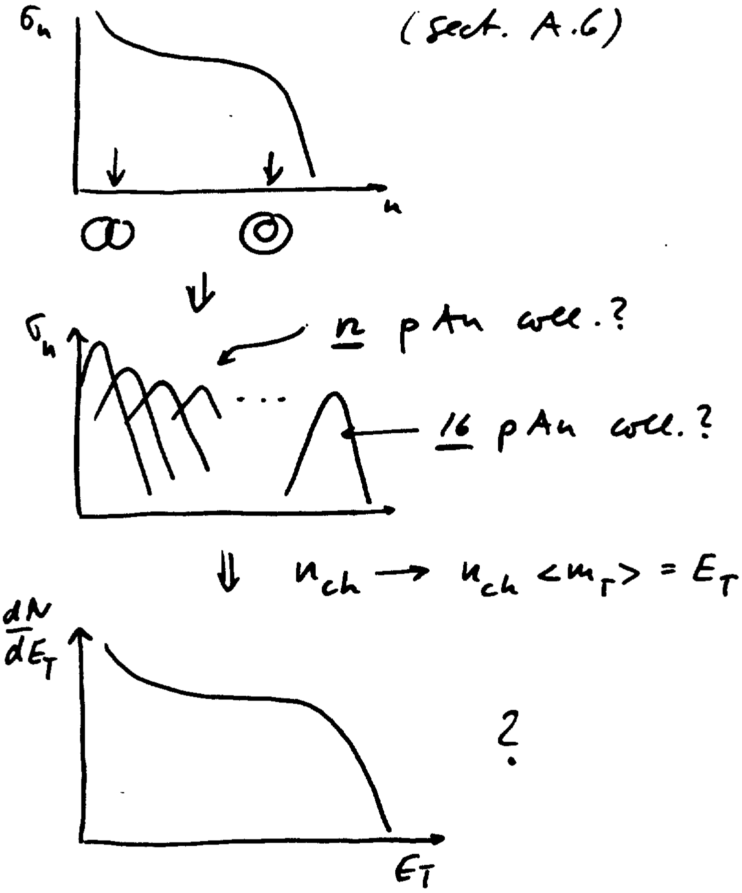
E802 / BNL



$\langle \sin\Theta \rangle \approx 0.29$

• shape mult. distribution

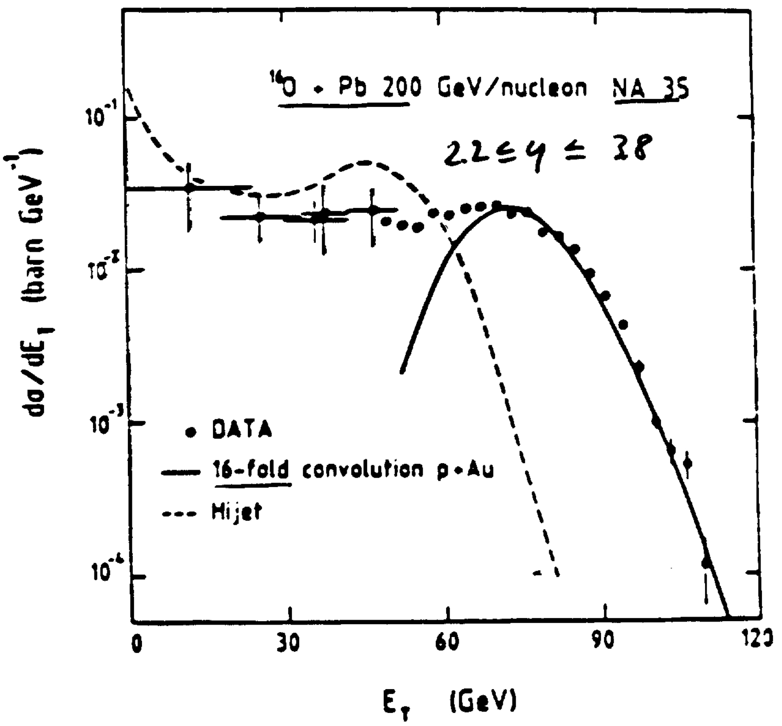
(sect. A.6)



• – Overall shape probably determined by geometry

• But, obvious that indep. pAu coll. fit ^{16}O A coll. ??

Bamberger PL B184, 271



$2.4 \le y \le 3.9$

central → coll. rare

more frequent central coll.

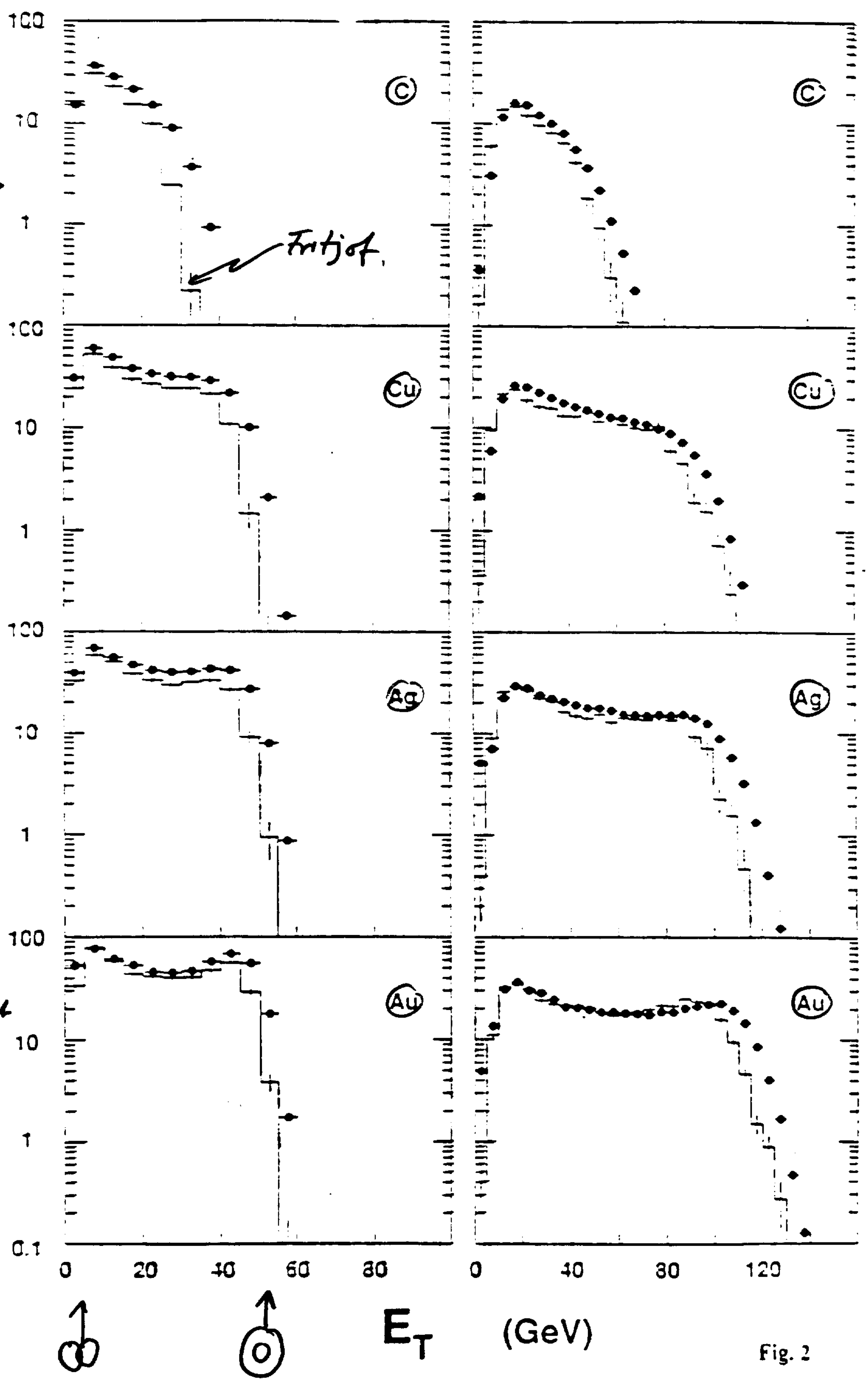
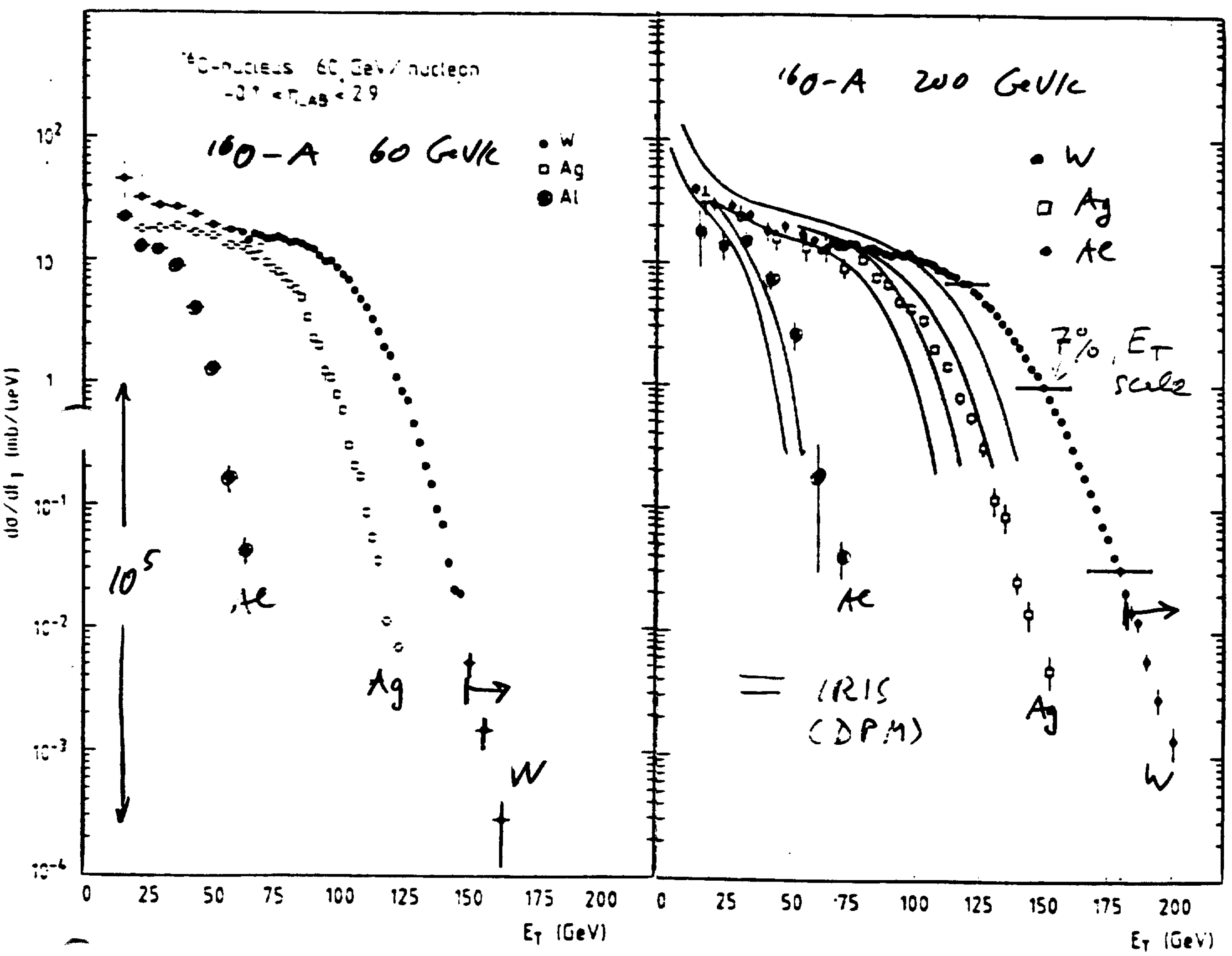


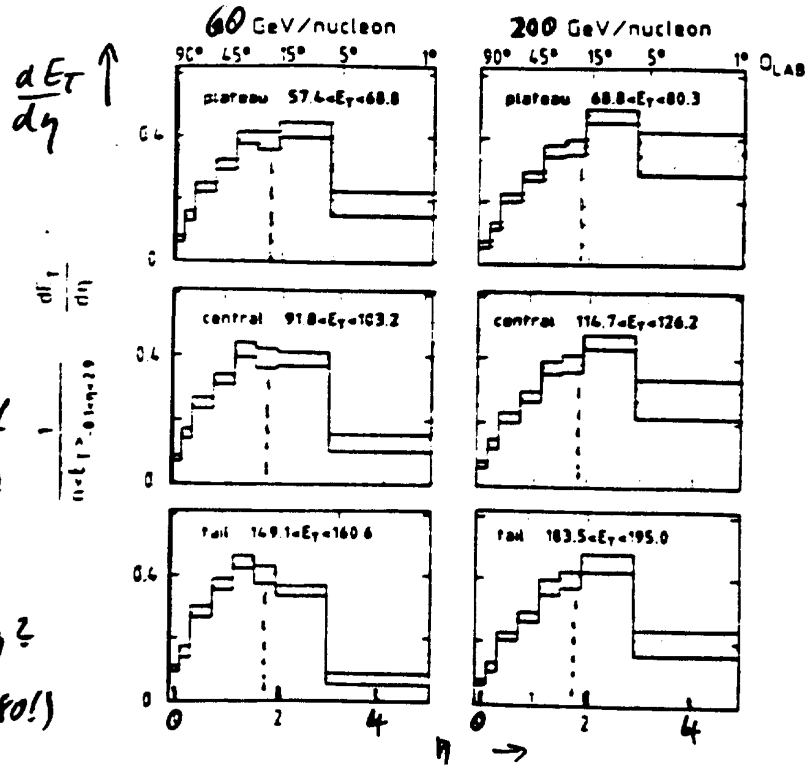
Fig. 2

- data exceed MC systematically at large E_T
- cannot determine '$\sqrt{s}$ scaling' since Δy fixed

(• $\sqrt{s}$ and A-dependence also from NA35)

$-0.1 \le y \le 2.9$





cascading ??

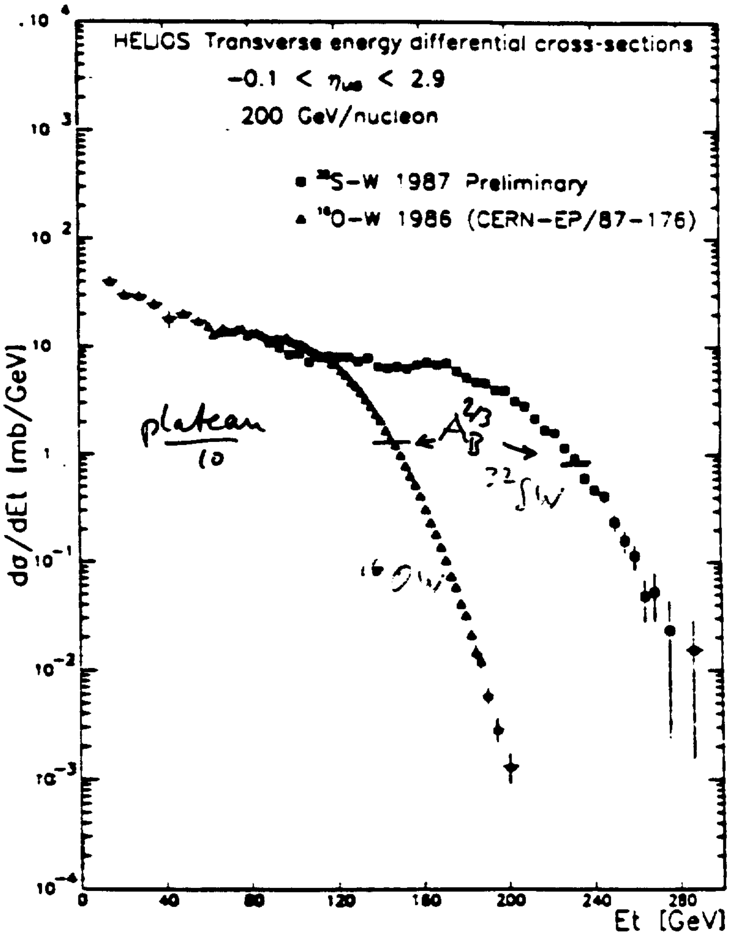
small number of tgt spect.? ⇒ little cascading? ($\langle h_{ch} \rangle$ WA80!)

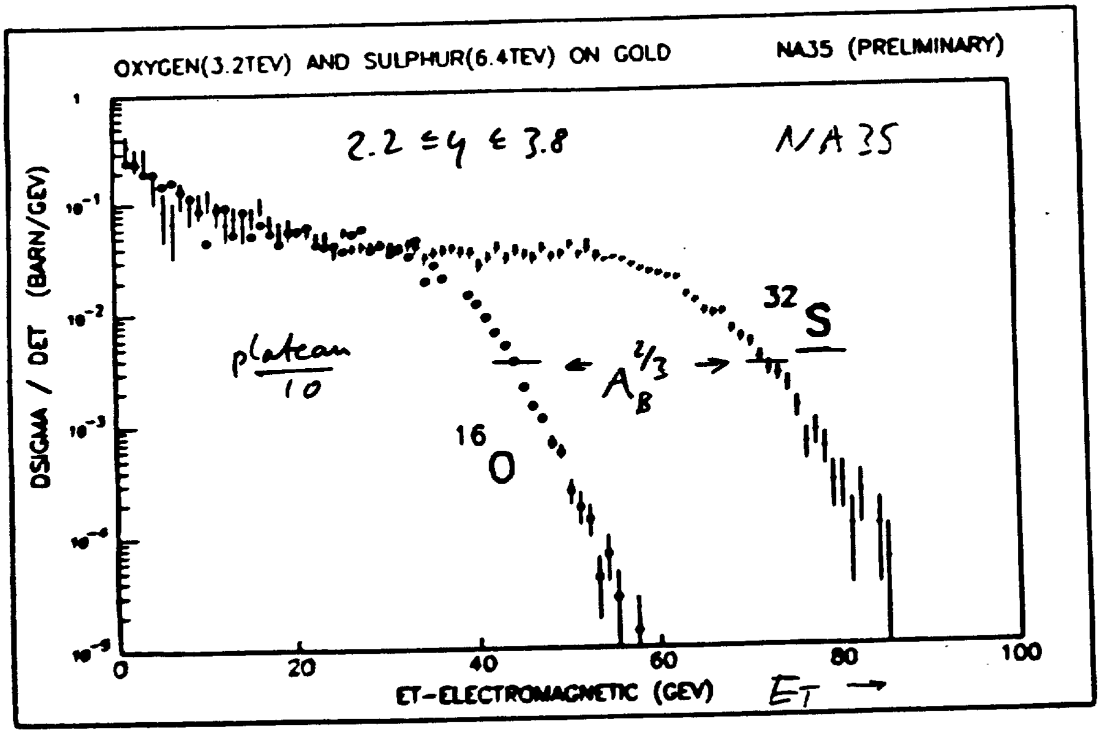
plateau

central

tail ↦

NA 34


HELIOS Transverse energy differential cross-sections
$-0.1 < \eta_{lab} < 2.9$
200 GeV/nucleon
■ ^{32}S–W 1987 Preliminary
▲ ^{16}O–W 1986 (CERN–EP/87–176)
dσ/dEt [mb/GeV]
Et [GeV]
plateau/10
$A_B^{2/3}$
^{32}S W
^{16}O W


OXYGEN(3.2TEV) AND SULPHUR(6.4TEV) ON GOLD
NA35 (PRELIMINARY)
$2.2 \le y \le 3.8$
NA 35
DSIGMA / DET (BARN/GEV)
ET–ELECTROMAGNETIC (GEV)
$E_T \rightarrow$
plateau/10
$A_B^{2/3}$
^{32}S
^{16}O

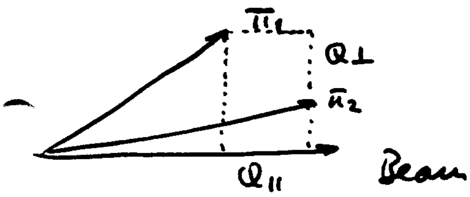
d) Size of Source

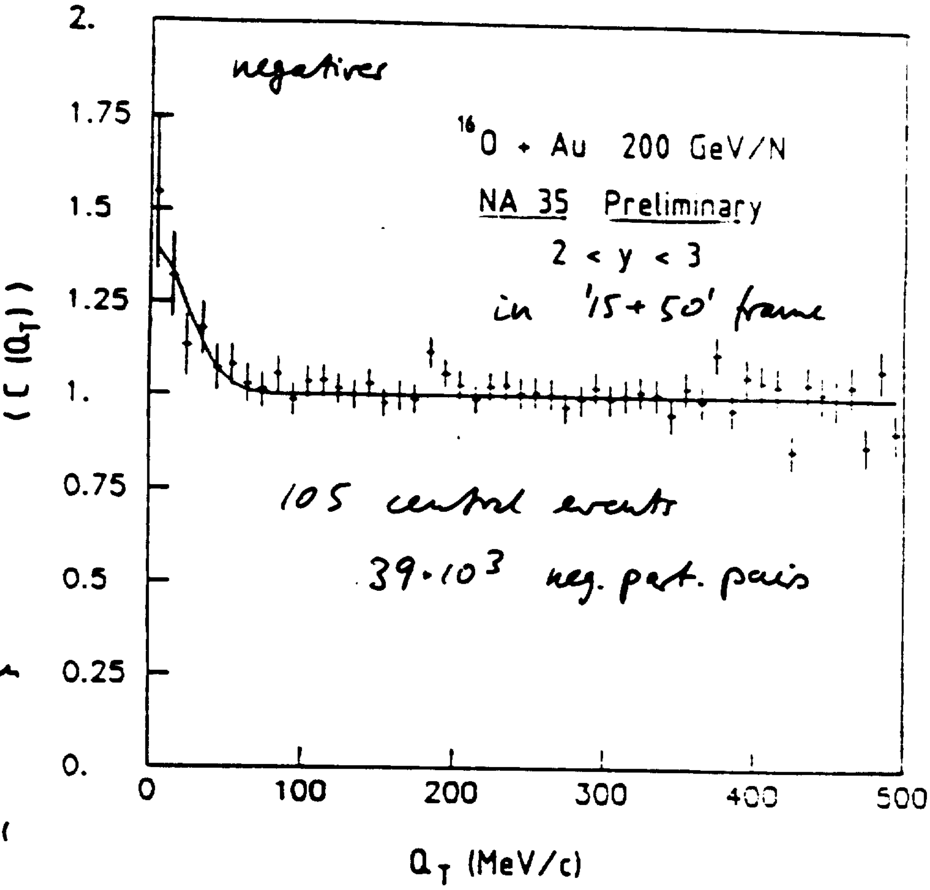
Pion Interferometry

Correlation function

$$C(\Delta q) \sim \frac{N_{\pi\pi}}{N_{BG}}$$

$$\sim 1 + \alpha f(\Delta Q_\perp) g(\Delta Q_\parallel)$$





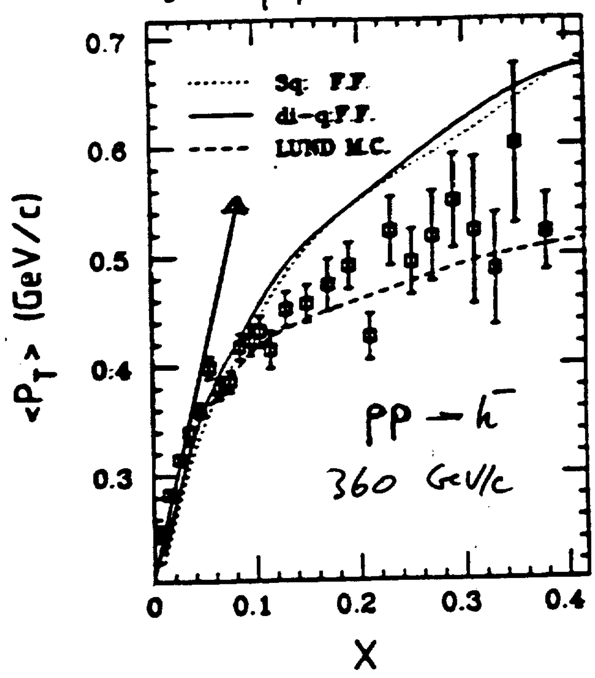
$Q_\perp \rightsquigarrow R_\perp$, $Q_\parallel \rightsquigarrow R_\parallel$

Result: $R_\perp = (8.1 \pm 1.6)$ fm $\quad R_\parallel = (5.6 \pm^{1.2}_{0.8})$ fm $\quad \alpha = 0.77 \pm 0.19$

($R_{^{16}O} \approx 3$ fm) consistent with isotropy

'chaoticity'

Bailey, CERN-EP/87-42



→ expected from isotropy at $|y| \lesssim 0.6$

2.) QGP Signatures: a) Thermalization & T from γ, γ^*

In QGP: $\ell\bar{\ell}$ and γ are expected from

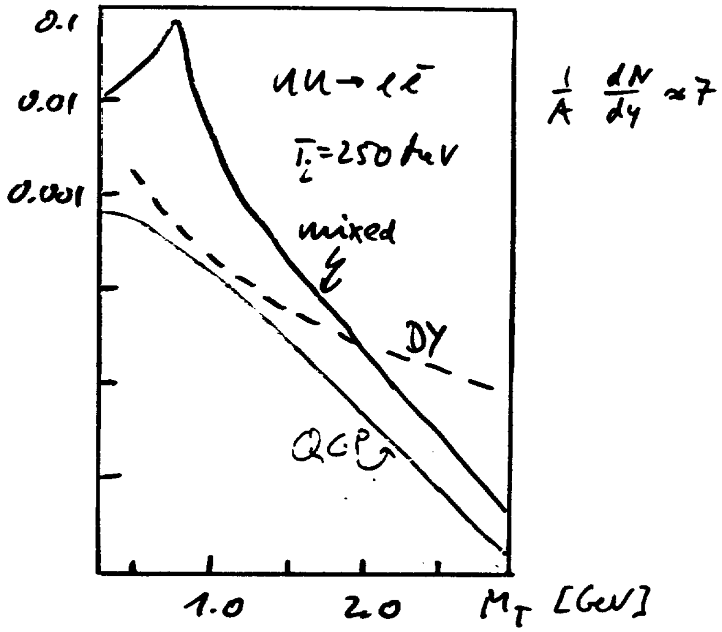
e.g. $q\bar{q} \to \ell\bar{\ell}$ $\quad qg \to \gamma q$ { McLerran, PRD 31, 545; Cleymans, PRD 35, 2153 }

Since $\bar{E}$/parton $\sim T$ (lecture 2): $\underline{M_{\ell\bar{\ell}} \longleftrightarrow T}$

in rest frame { Rate for $\ell\bar{\ell}$ production: $\frac{dN}{d^4x} = \frac{10}{9\pi^2}\alpha^2 T^4$ [Kajantie, PRD 34, 2746]
Rate for γ production: $\sim T^4$ [Kajantie, Z. Phys. C 9, 341] }

$\Rightarrow$ γ^*, γ good thermometers; escape without reinteraction

Kajantie, PRD 34, 811



- Prediction: yield may be low

- There may be a way out (in principle): So far, expansion neglected:

Now: $dN(\gamma) \sim \int d^4x\, R = \int d^2x_\perp\, \underbrace{\tau\, d\tau\, dy}_{\text{long. scaling}}\, R$

$\uparrow$ rate

Remember: scaling hydrodyn.:

$$\frac{dN(\pi)}{dy} = \frac{1}{c} A_\perp \tau s \sim \frac{1}{c} A_\perp \tau T^3 \qquad \text{entropy conserv.}$$

$$\Rightarrow \frac{d\tau}{dT} \sim \frac{dN(\pi)}{dy} T^{-3} \sim \frac{dN(\pi)}{dy} T^{-4}$$

Therefore:
$$\int R \, \tau \, d\tau \, dy \sim \left(\frac{dN(\pi)}{dy}\right)^2 \int dT \cdot T^{-7} \int dy \; R$$

i.e.
$$\# \text{ of } \gamma, \gamma^* \sim \left[\frac{dN(\pi)}{dy}\right]^2 \quad \circledast$$

or
$$\frac{d\sigma(\gamma,\gamma^*)}{\left[\frac{dN(\pi)}{dy}\right]^2} \sim T_c \quad \circledast\circledast$$

Hwa, PRD 32, 1109
Gorenstein, Phys. Lett 192 B, 198
Kajantie, PRD 34, 2746

$\otimes$ for hard γ, γ^* production: yield $\sim F_1(x_1) * F_2(x_2)$

structure fctn.

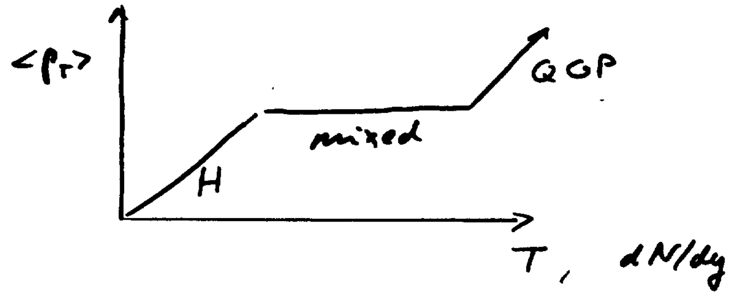
for thermal γ, γ^* production: yield $\sim s * s$

$\otimes\otimes$ The normalized γ, γ^* yield should give a handle on T_c, $\frac{dN}{dy}(\pi)$ should yield T_i $(\sim T_i^3)$!

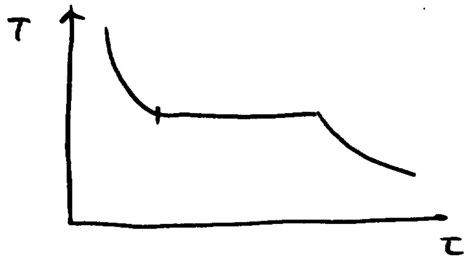
Comments:
- in pp collisions at ISR:
  low mass e pairs depend on $\left[\frac{dN}{dy}(\pi)\right]^2$
  [AFS, Åkesson, prelim. / Åkesson, Phys. Lett. 192 B, 463]
- Potential danger from semileptonic decay of charm:
  $D_1\bar{D}_2 + D_3\bar{D}_4$ events may give very large
  $l\bar{l}$-masses from $D_1\bar{D}_4$ [Fischer, WG, Z. Phys. C 10, 159]
  Rate ??
- $\gamma^* \to l\bar{l}$ unpolarized [Hoyer, CERN-TH 4591/86]

2) Hydrodynamic Flow

2^{nd} lecture: $\langle p_T \rangle \sim T$ in rest frame



This is neglecting long. / radial expansion

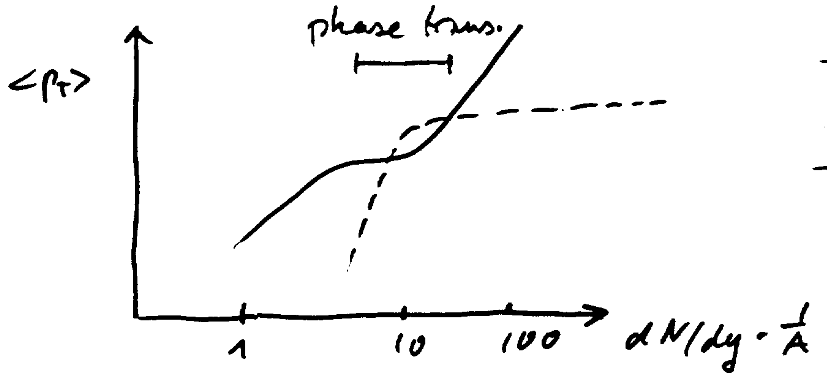


$T(\tau)$ determined by T_i, τ_i and type of phase trans. ...

i.e. cooling: $T(\tau) \to$ flow $\to p_T$, flow $\to T(\tau)$

As a consequence measured $\langle p_T \rangle$ cannot easily be related to any T, $\langle p_T \rangle$ <u>reflects whole history</u>

$\langle p_T \rangle$ vs dN/dy depends on details of hydrodynamical treatment:

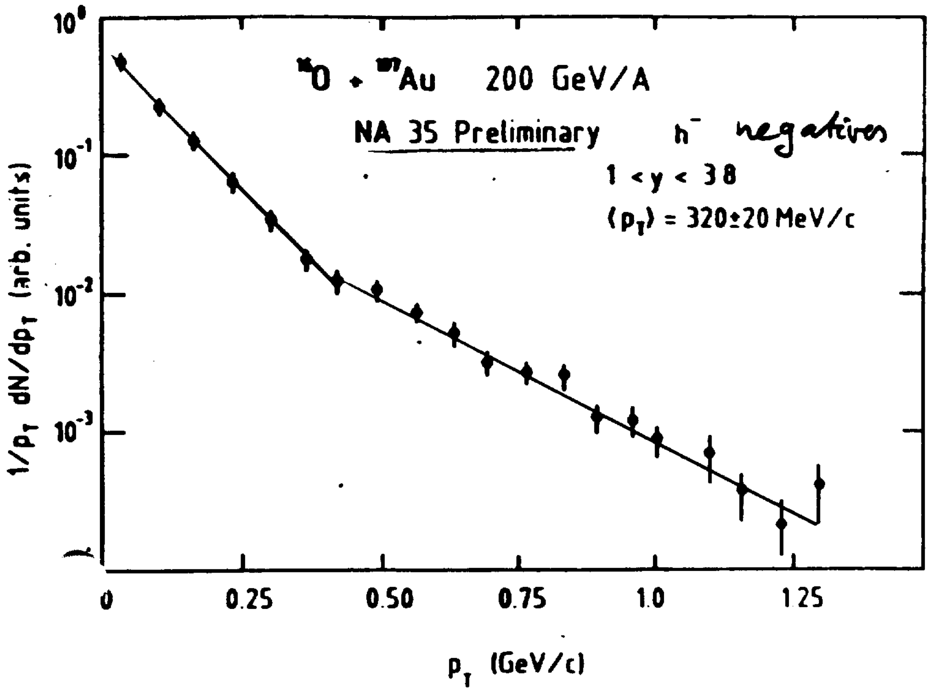


—— Kataja, PRD 34, 2755

- - - - Wang, PRD 35, 3409

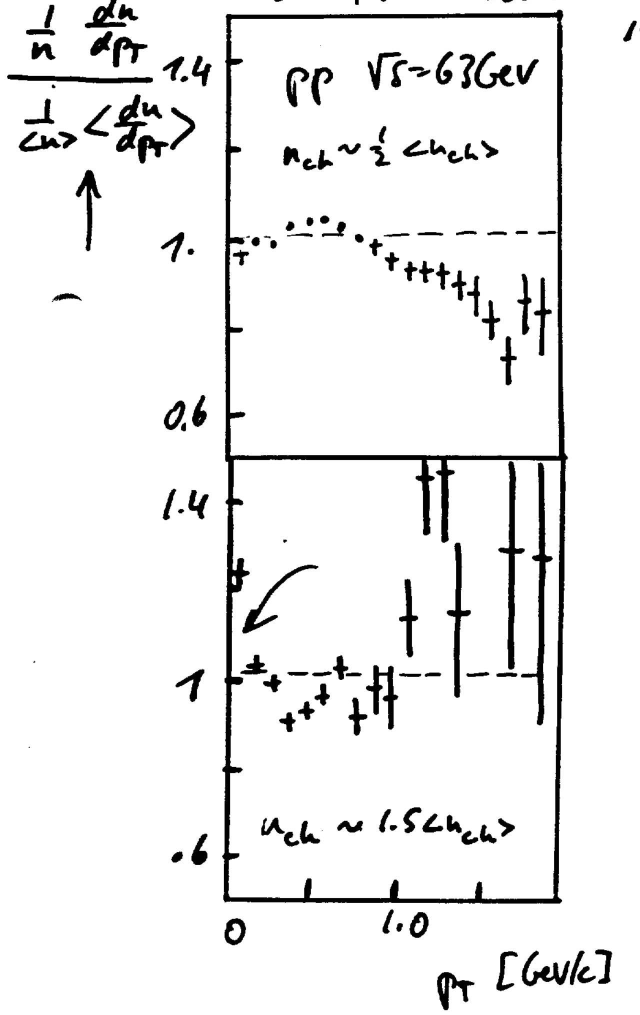
- Still: <u>larger</u> masses should receive <u>larger</u> p_T contribution from flow (flow → velocity)

Guidance from experiment needed

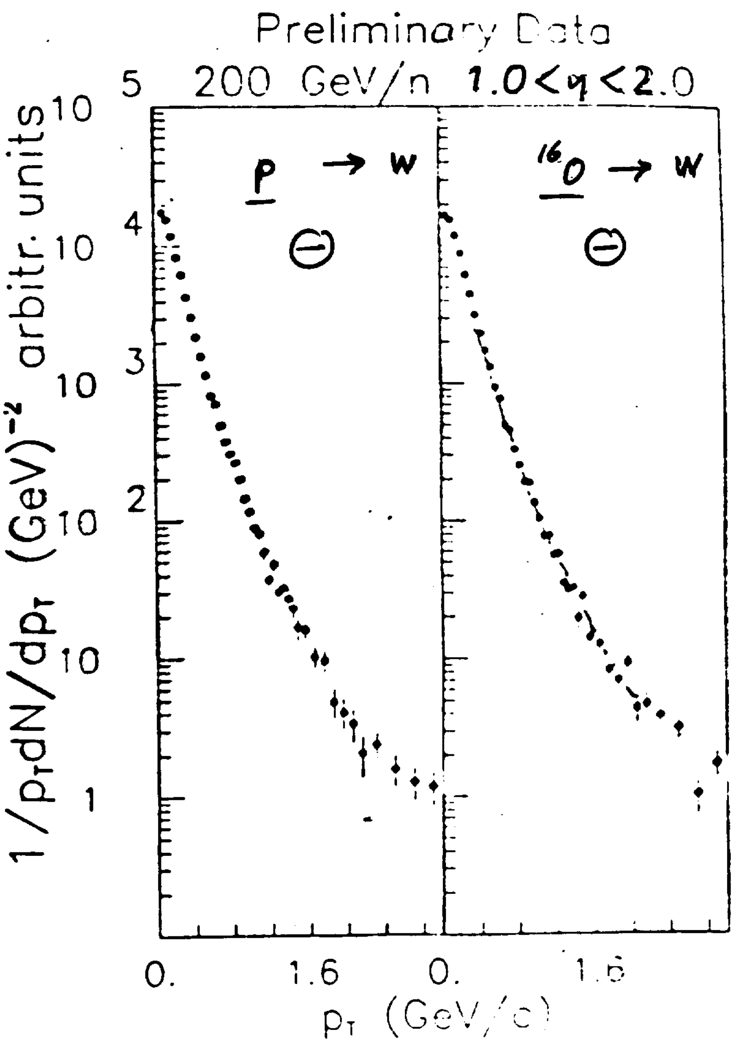


explanation?

SFM/ISR: Bell. Z.Phys.C 27, 191



NA 34



→ Chemical equilibrium : strangeness

- Charm : m_c probably to heavy

- Strangeness : From q to hadrons:
  - $q, \bar{q}, g \to s, \bar{s}$ (kinetic equations)
  - equilibration & expansion
  - hadronization:

    recombination and/or fragmentation ↑ changes flavor content
  - approach to equilibrium in the hadron phase

Predictions have to be done including all these steps and also for a scenario without QGP formation:

- Conclusion (probably): [Koch, Phys. Rep. 142]

K/π not the most sensitive quantity to QGP anyway: $K^* \to K\pi$ 'lowers' K/π from $\lambda = \#s/\#q$

$\bar{\Lambda}, \bar{\Xi}, \bar{\Omega}$ probably best§ signatures, especially for $\mu \neq 0$

exotic: s-retention in QGP → strange matter ??

[see also: Heinz, Mod. Phys. Lett. A 2, 153; Rafelski, Phys. Lett 190B, 167; Kajantie, Phys. Lett. 179B, 153]

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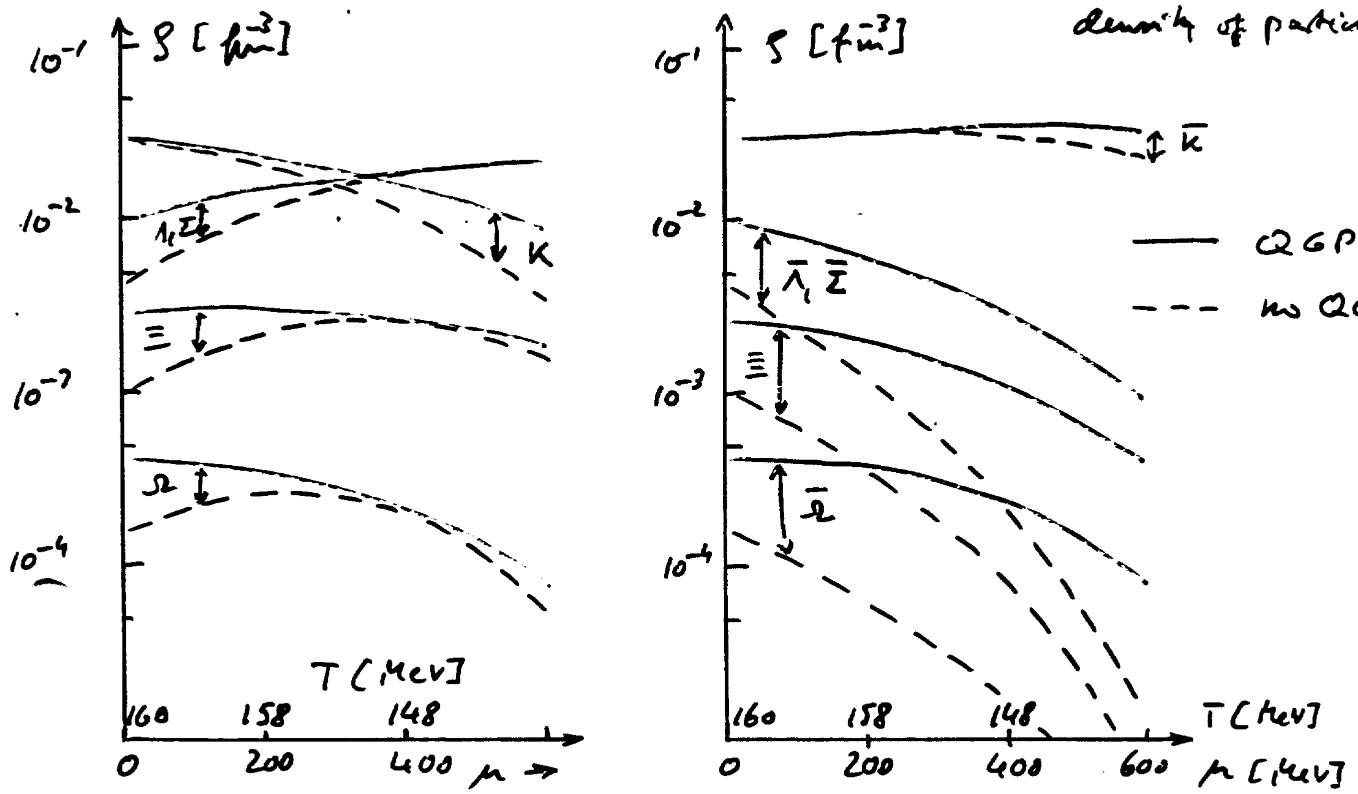
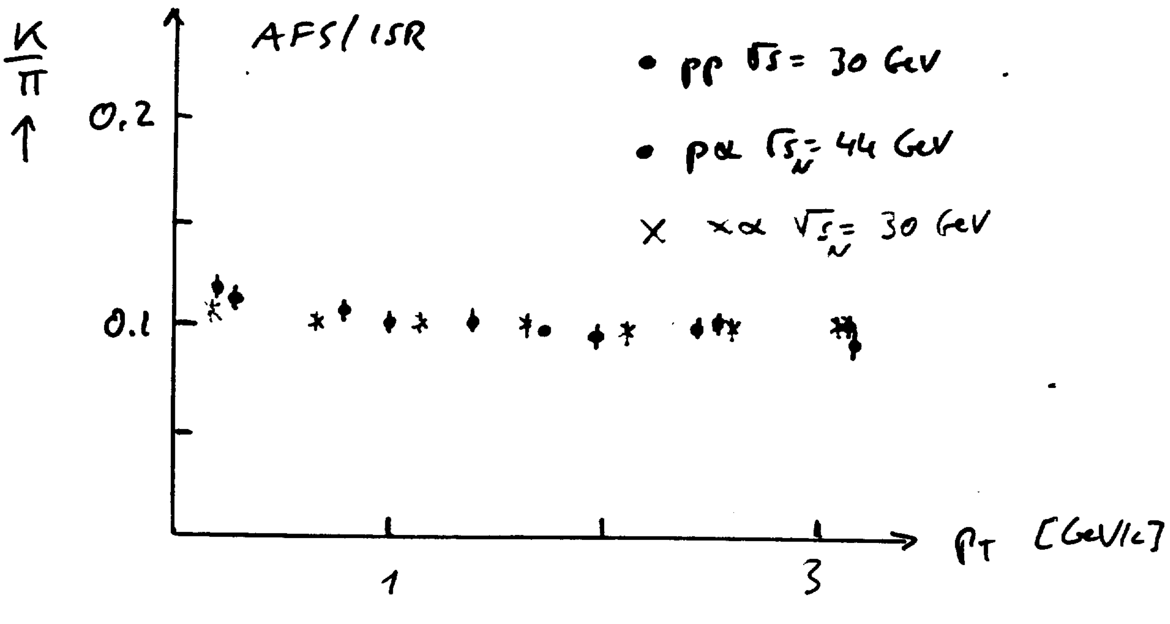
§ experimentally via polarization: Jacob, Phys. Lett. 190B, 173

[Koch, Phys. Rep. 142]

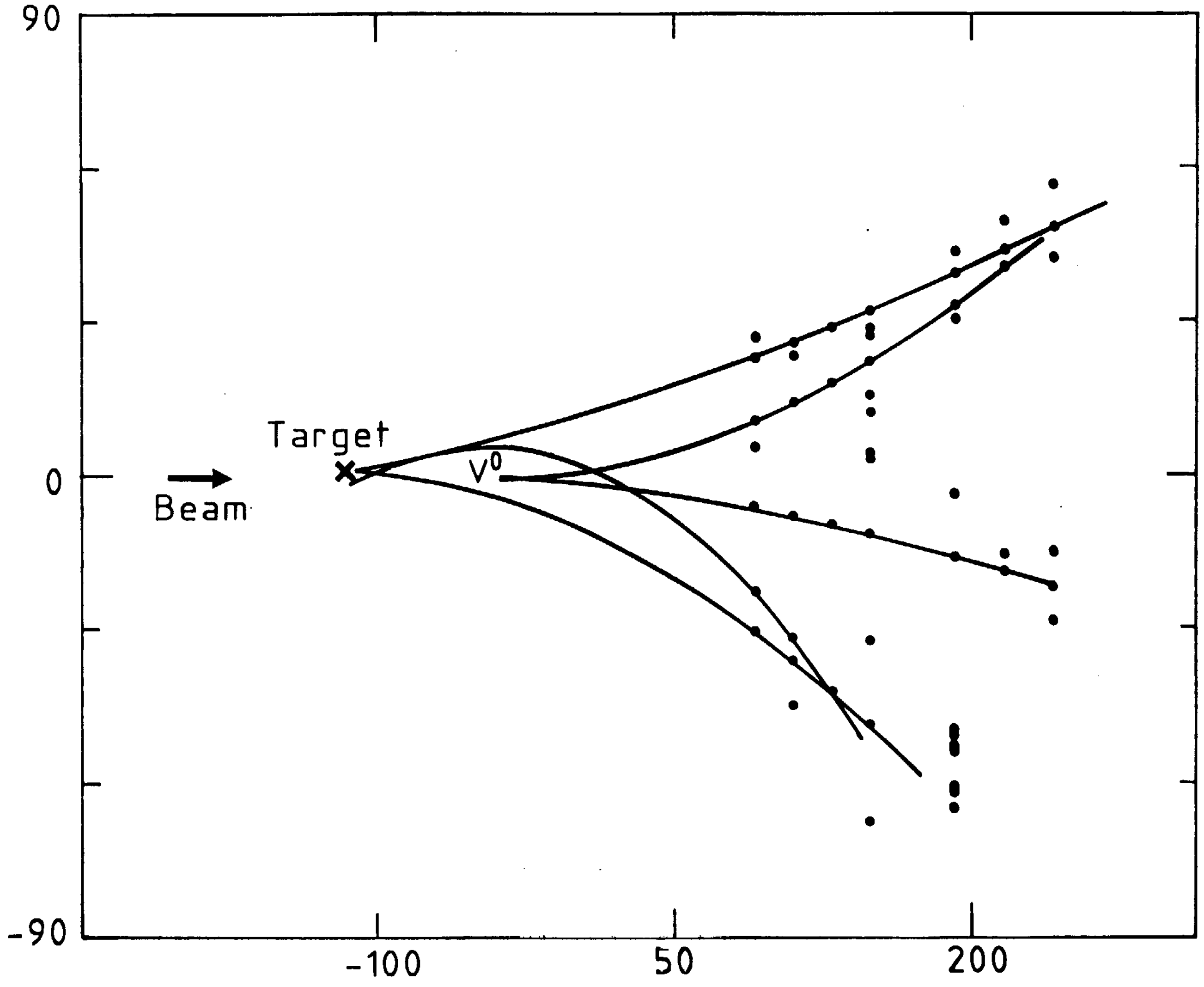
density of particles

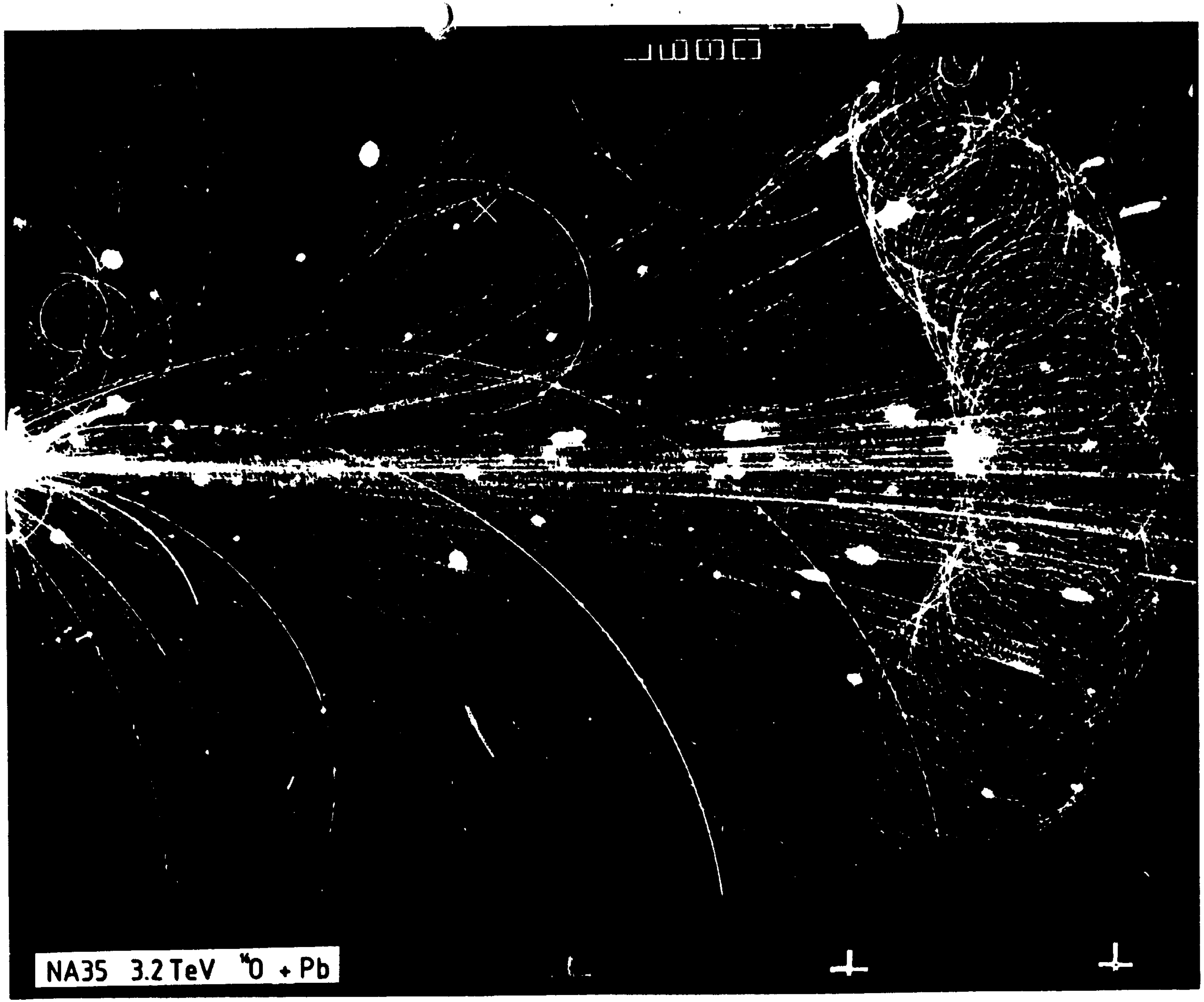


↑ <u>very conservative</u> estimate: includes: • gl.-fragm.
• slow long. expansion
• assumes chem. equilibration of hadron phase:
therefore: ϱ for <u>no</u> <u>QGP</u> <u>overestimated 10^1-10^2</u>



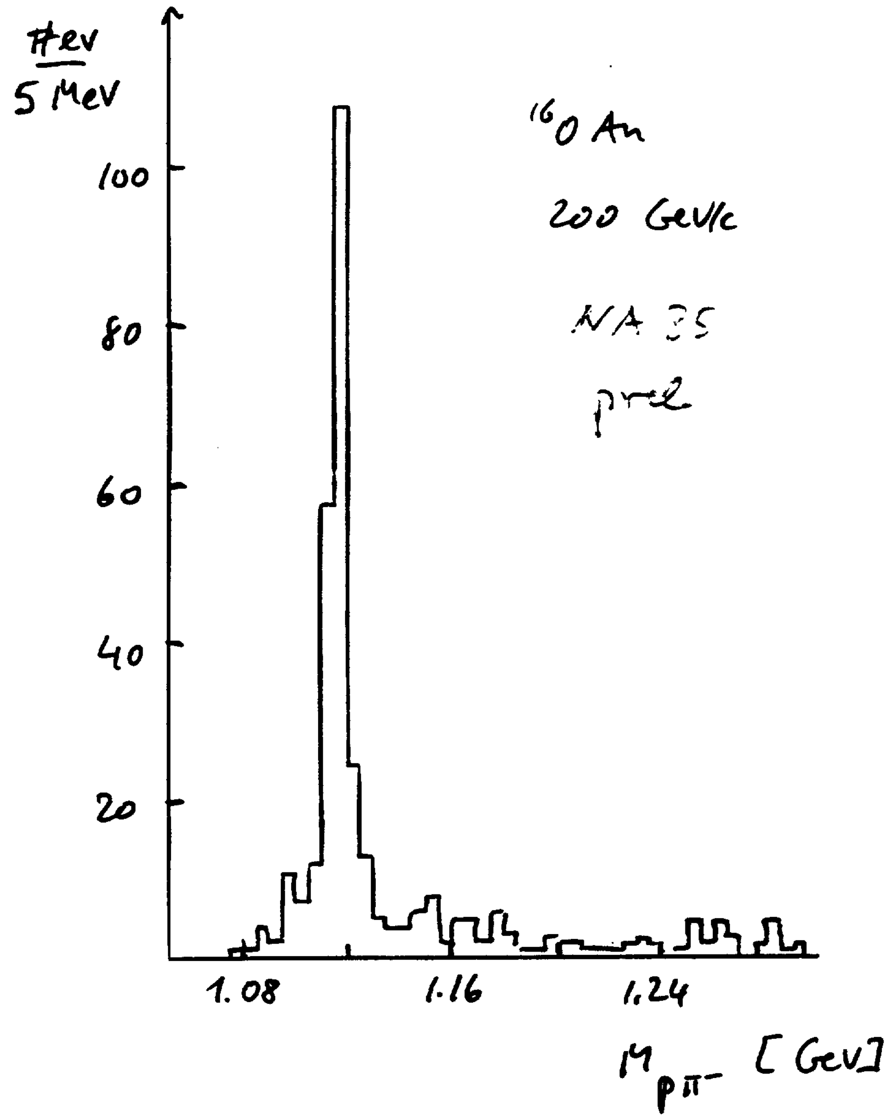
WA 85 (Ω)





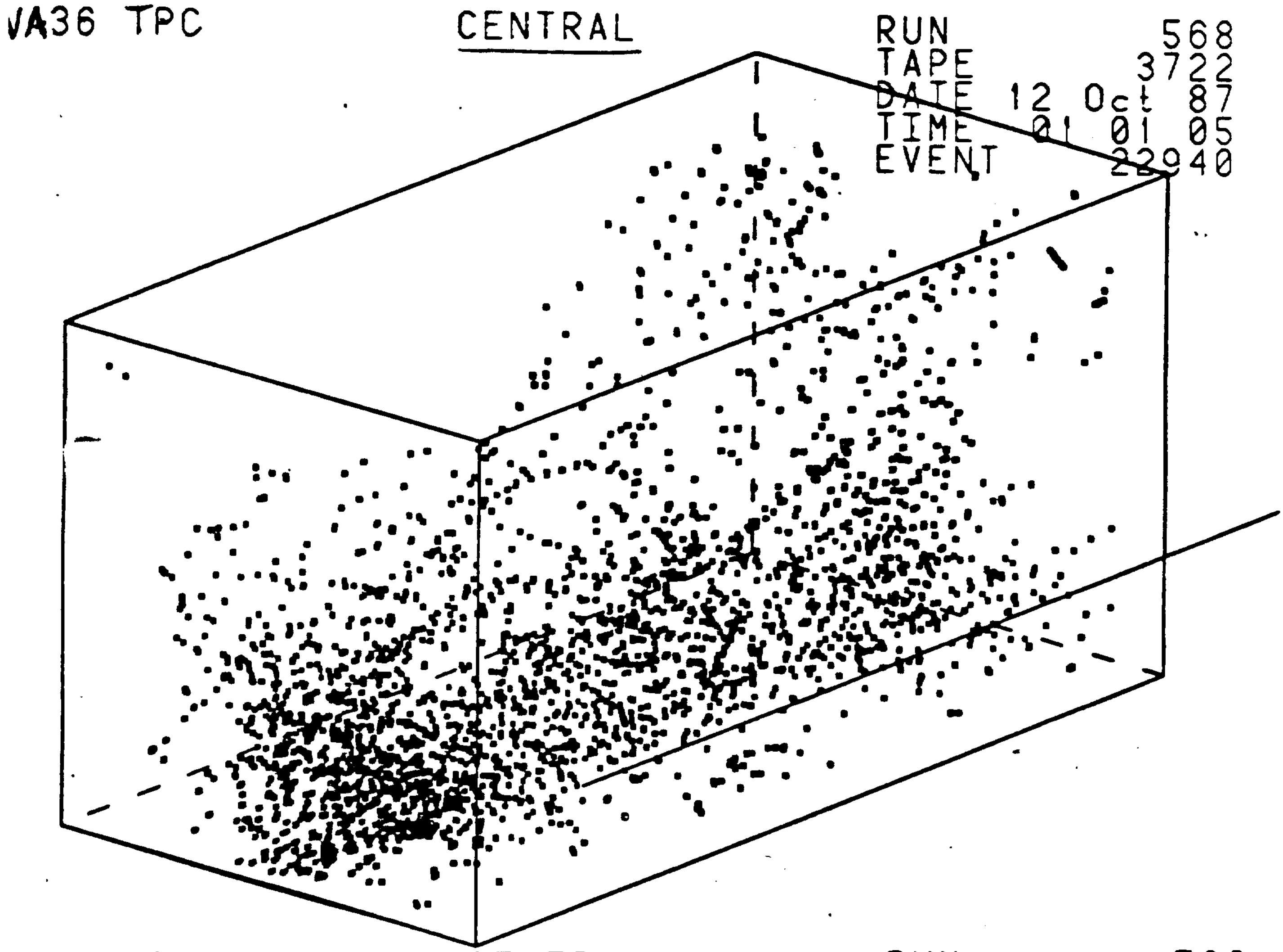
III 17

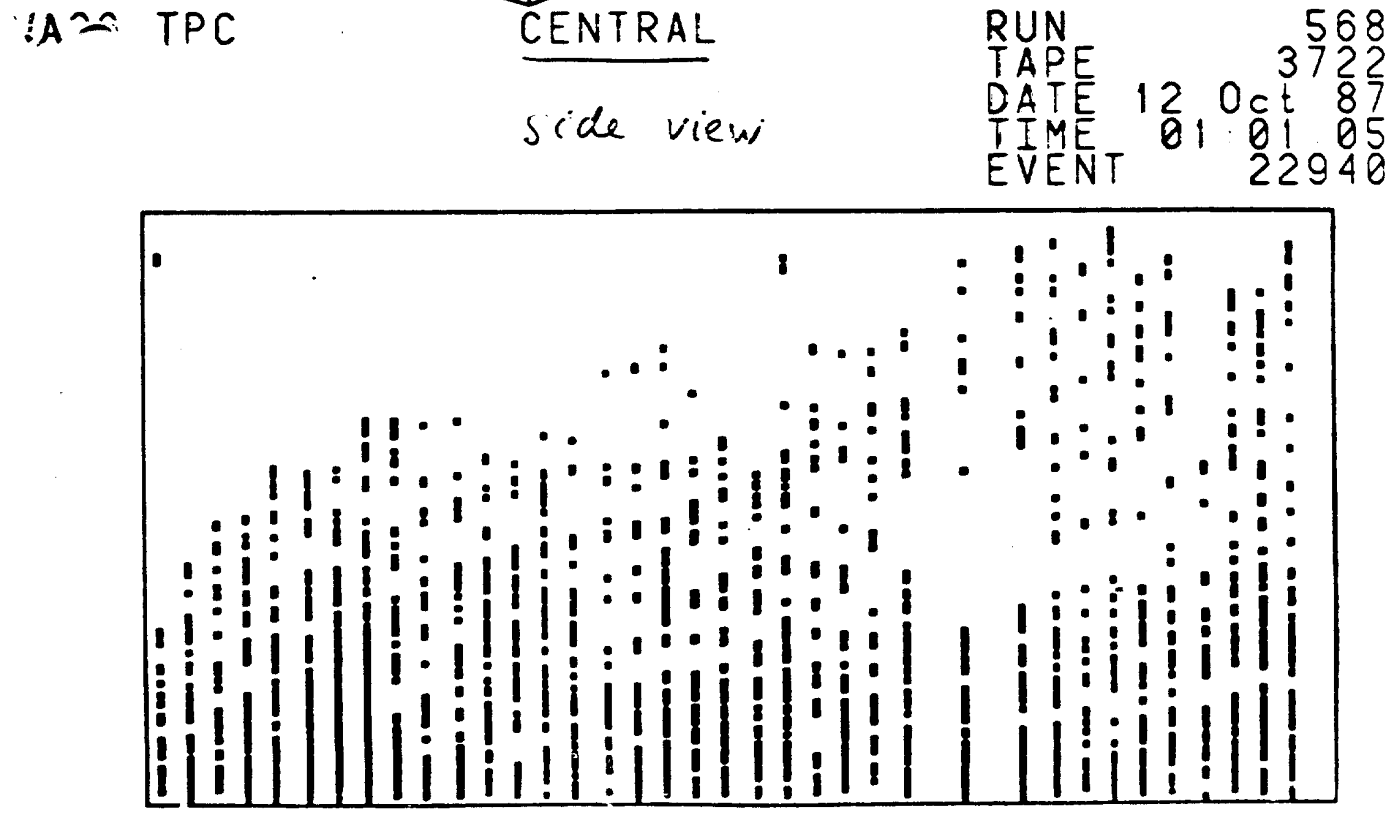
15.10.86



#ev / 5 MeV
100
80
60
40
20
1.08
1.16
1.24
$M_{p\pi^-}$ [GeV]
^{16}O Au
200 GeV/c
NA 35
prel

^{32}S 200 GeV/c


NA36 TPC
CENTRAL
RUN 568
TAPE 3722
DATE 12 Oct 87
TIME 01 01 05
EVENT 22940


NA36 TPC
CENTRAL
side view
RUN 568
TAPE 3722
DATE 12 Oct 87
TIME 01 01 05
EVENT 22940

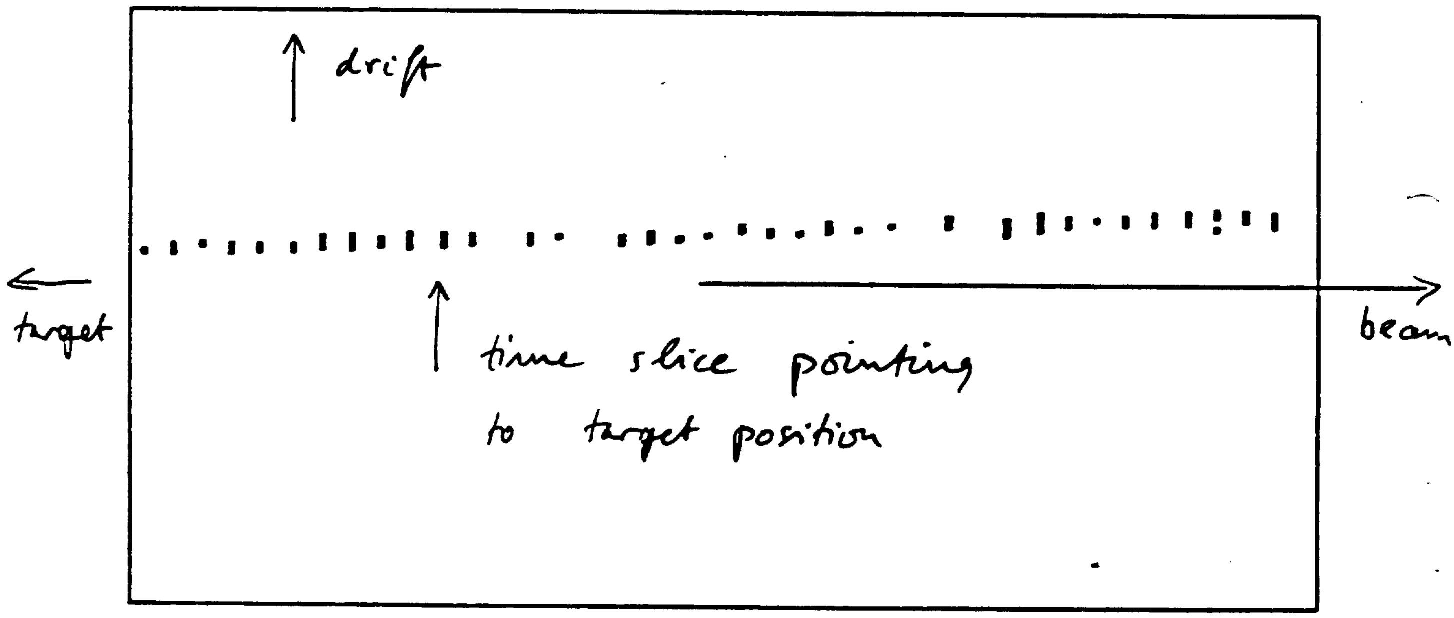
NA36 TPC

CENTRAL

top view

RUN 568
TAPE 3722
DATE 12 Oct 87
TIME 01 01 05
EVENT 22940

on-line

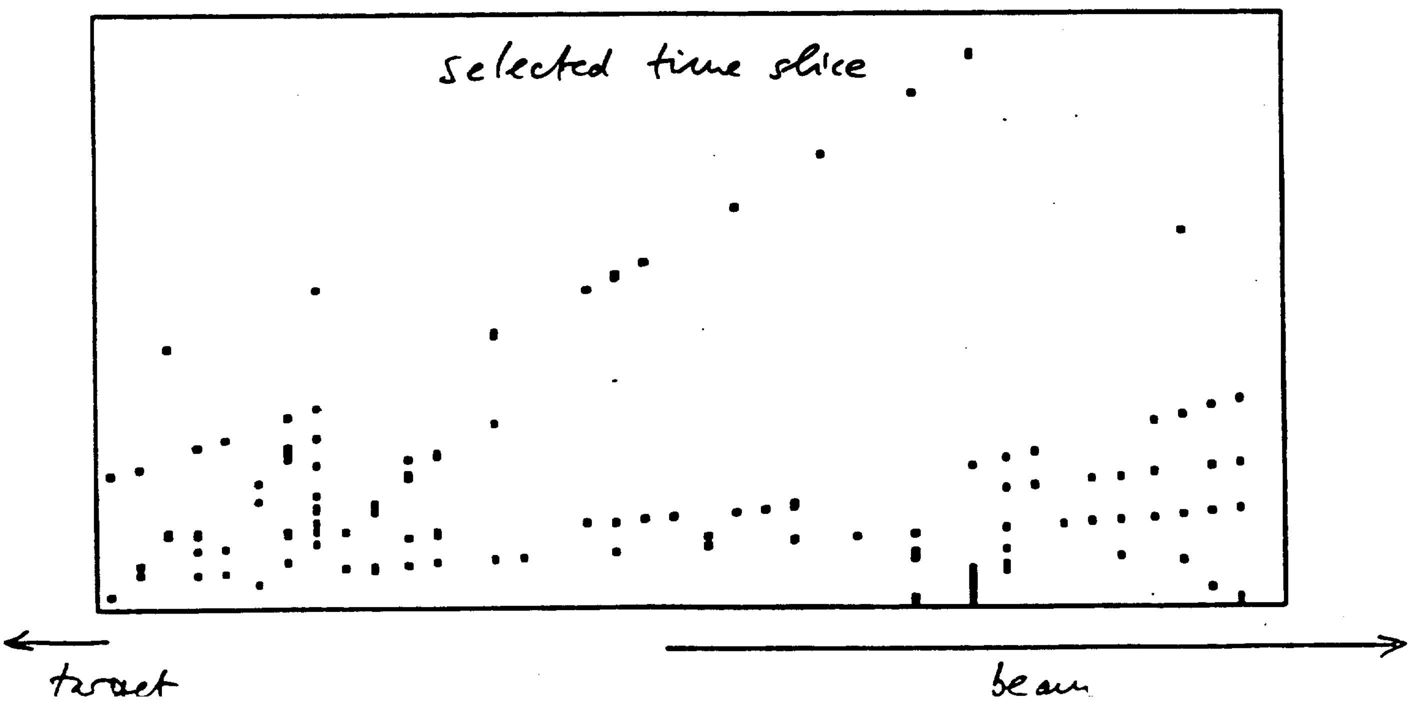


NA36 TPC

CENTRAL

side view

RUN 568
TAPE 3722
DATE 12 Oct 87
TIME 01 01 05
EVENT 22940



1) Deconfinement: J/ψ suppression (Matsui, PL178B, 416)

If Debye screening radius > radius of particle

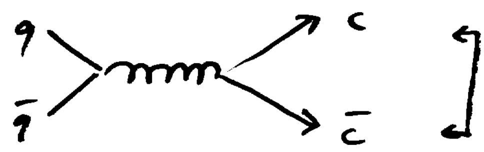
$\Rightarrow$ no binding: suppression

- Cannot reappear at hadronization: $c + \bar{c} \to J/\psi$ since c/q small

- J/ψ not absorbed in nuclear matter around QGP: $\sigma_{\psi N} \sim 1\,mb$ [Sokoloff PRL57, 3003]

- Cannot be formed abundantly before QGP ($\tau_0 \sim 1\,fm/c$, too short)

- However, if $c\bar{c}$ formed in QGP



have to move into the correct relative position: $r_{J/\psi}$

$\Rightarrow$ if $\vec{p}\,(c+\bar{c})$ small:
$r_{J/\psi}$ reached inside QGP but no binding

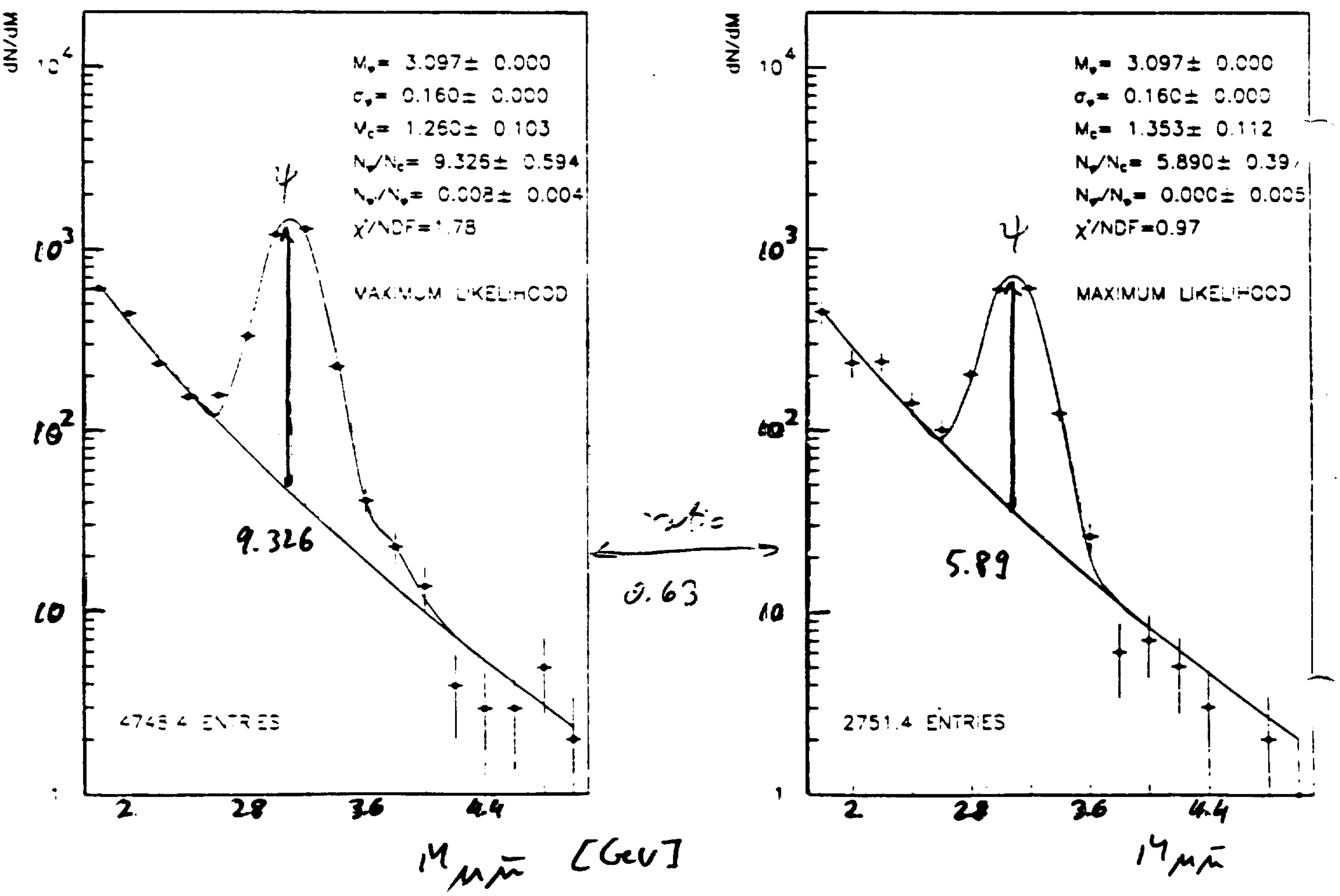
if $\vec{p}\,(c+\bar{c})$ large (large x_F / p_T):
$r_{J/\psi}$ reached outside QGP: binding
less suppression

[Karsch, CERN-TH 4699/87]

NA 38 : 9 U at 200 GeV/c

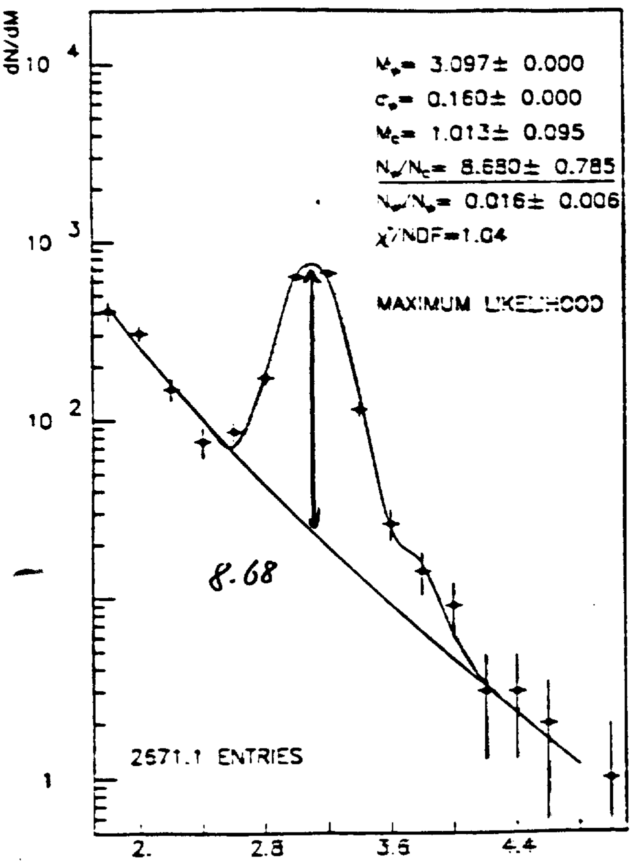
$E_T^0 < 28$ GeV (no QGP!) $E_T^0 > 50$ GeV (QGP?)

all $p_T(J)$ all $p_T(J)$

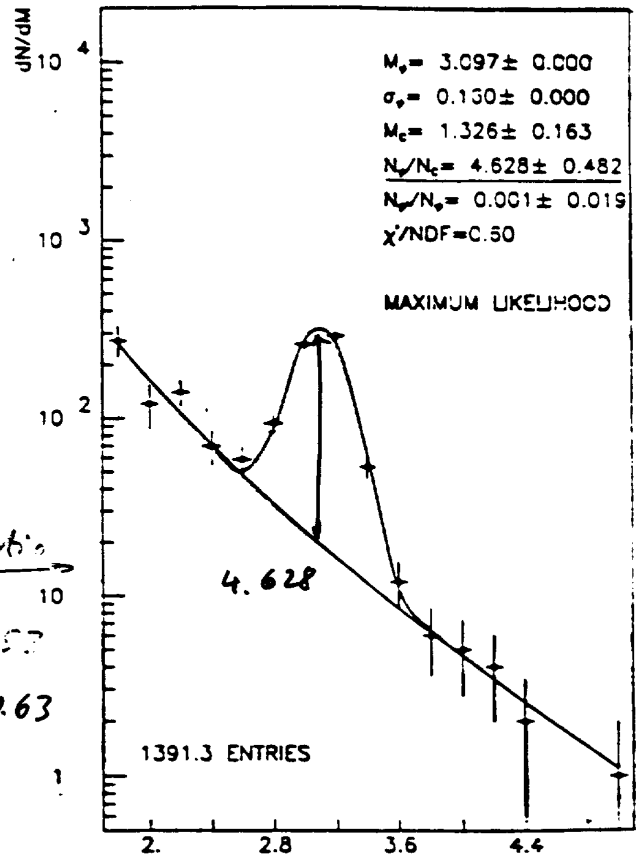


$E_T^0 < 28$ GeV, $p_T(\psi) < 1$ GeV

$E_T^0 > 50$ GeV, $p_T(\psi) < 1$ GeV
↑ central



ratio
0.53
< 0.63



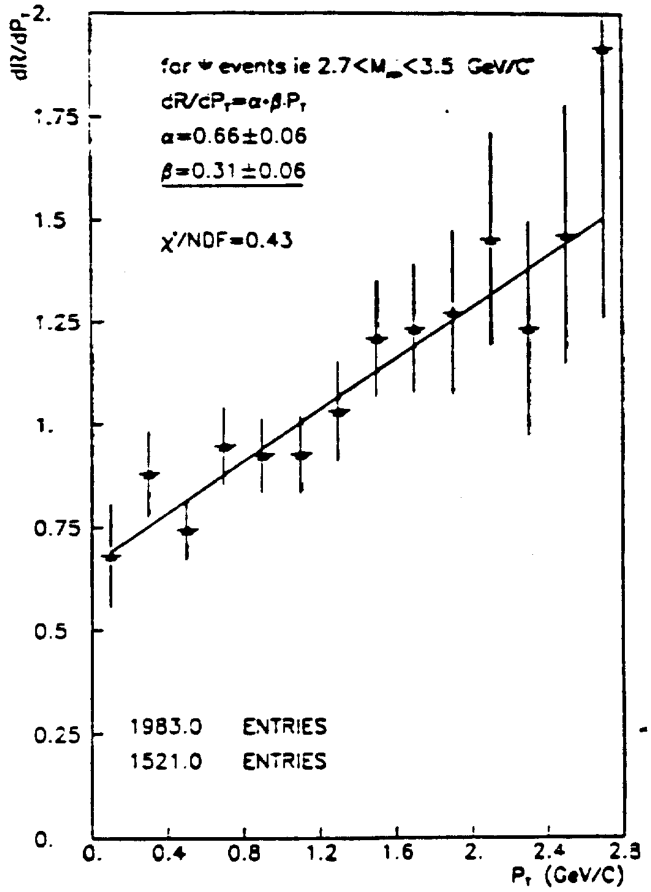
$M_{\mu\mu}$ [GeV]

more suppression

$M_{\mu\mu}$ [GeV]

$$R = \frac{\psi(\text{hi } E_T)}{\psi(\text{lo } E_T)}$$

↑ R

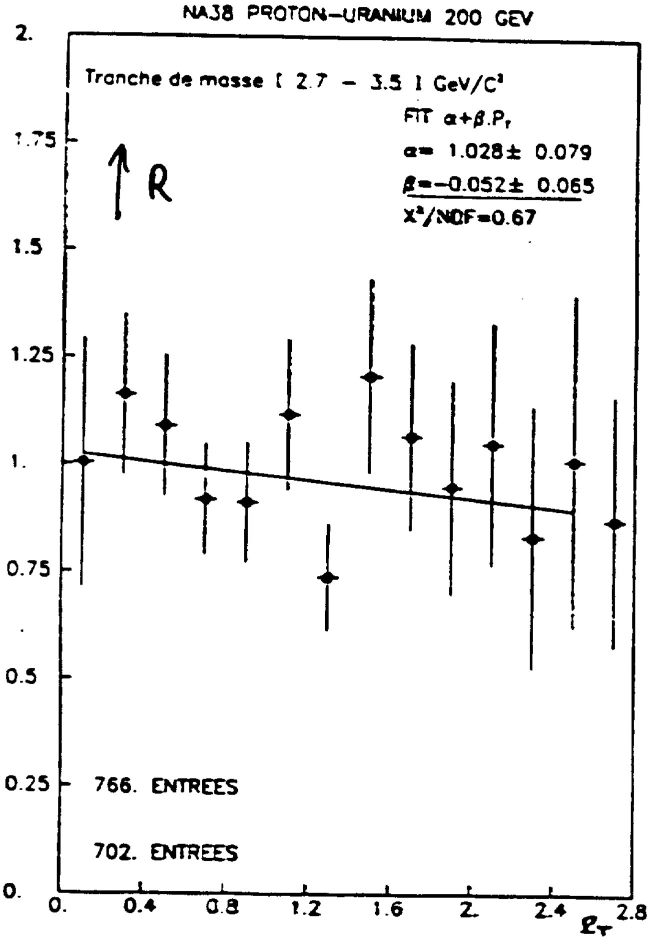


suppression at low p_T!

→ $p_T(\psi)$

II 2:

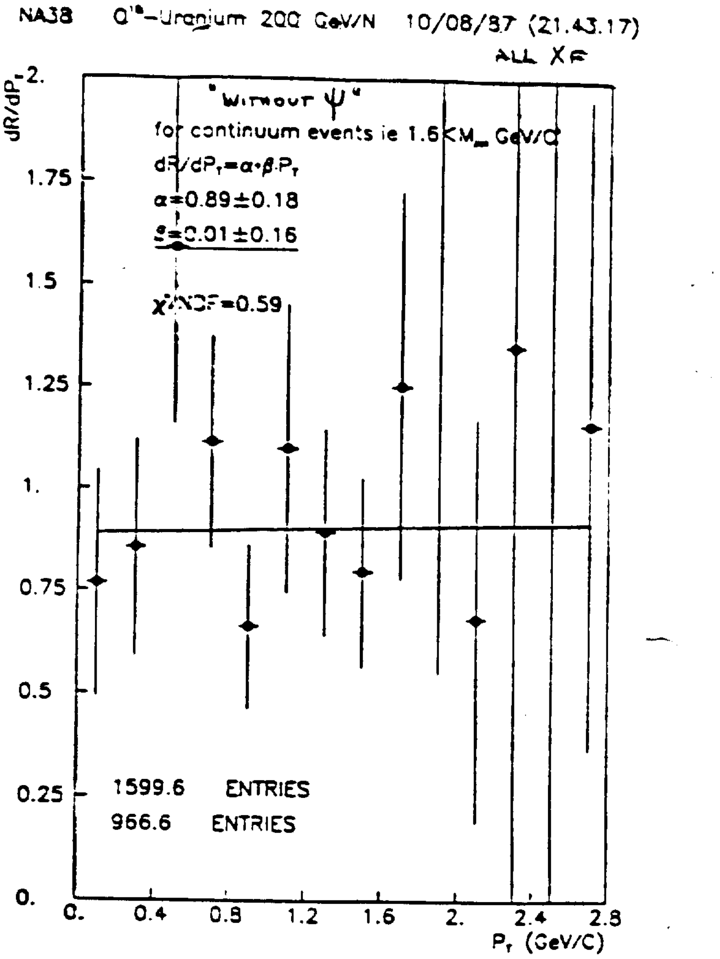
p U 200 GeV/c



↑ R

→ $p_T(\psi)$

O U 200 GeV/c



→ p_T ($1.6 < M_{\mu\mu}$)

no ψ

no evidence for suppression

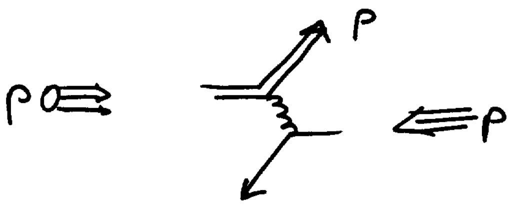
- <u>Other</u> potential signatures of <u>deconfinement</u>

  - In case of <u>recombination</u>:

    q and $\bar{q}$ recombine randomly

    $\Rightarrow$ <u>no</u> $\pi^+\pi^-$ <u>short range</u> correlations

  - At ISR: high p_T p production via 'valence dig'



$\underline{\frac{\# p}{\# \bar{p}} \sim 5} \quad p_T \gtrsim 4$ GeV/c

[Breakstone, Phys. Lett. 147B, 237]

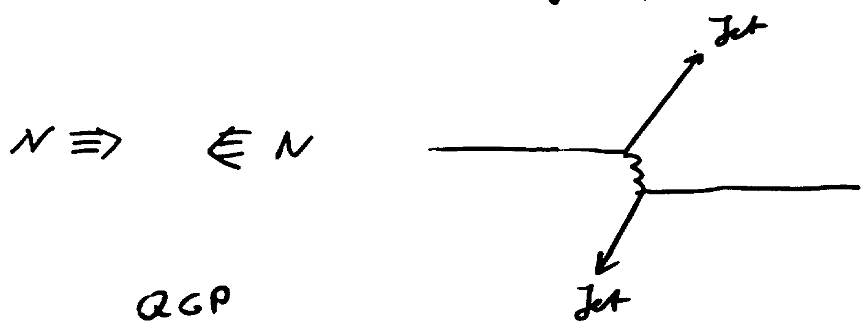
while propagating through QGP $\Rightarrow$ unbound?

$\Rightarrow \frac{p}{\bar{p}} \; \underline{\rightarrow 1}$??

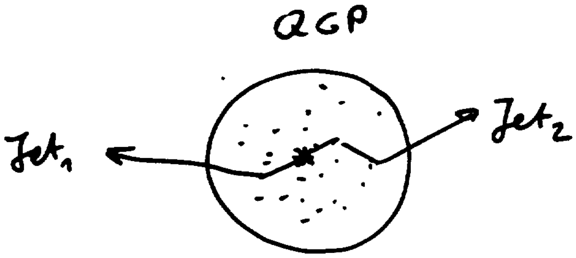
e) <u>Mean free path</u>

informative to know $\underline{\lambda_q, \lambda_{gl}}$ in QGP

if hard parton scattering at $t \approx 0$



Jets $\approx$ collinear



view along beam

[Blaizot, PRD34, 2739]

- Jets <u>non-collinear</u>
- Jets <u>may get stopped</u>
- Maybe one can <u>flavor tag</u> the jets: λ_q vs λ_{gl}

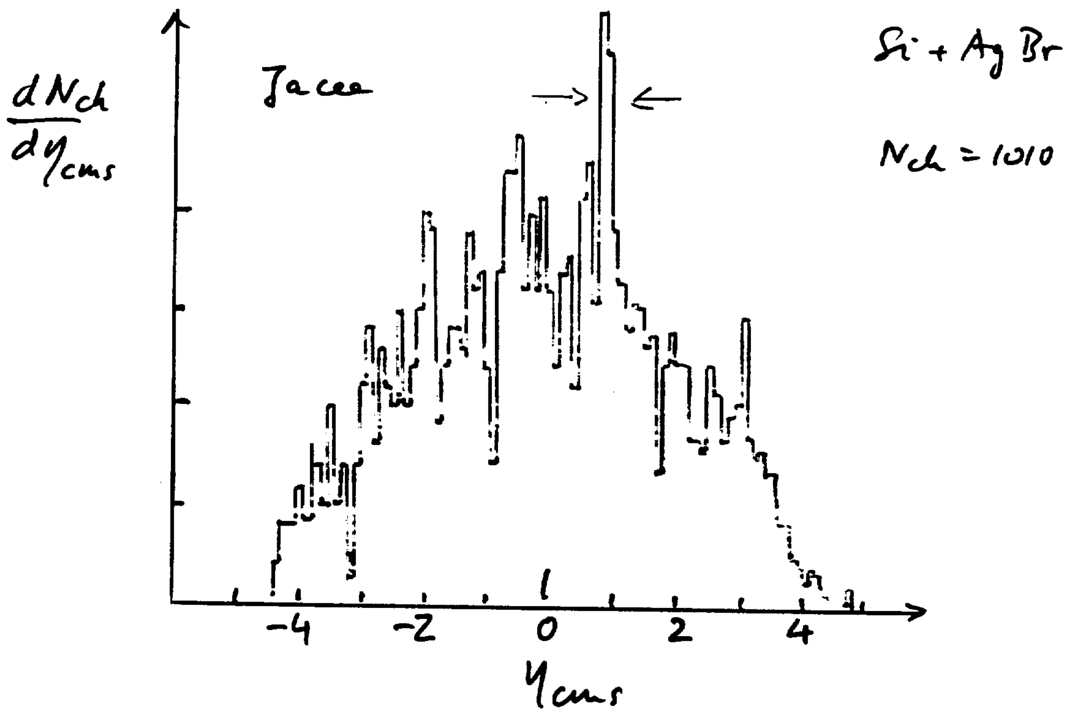
[Gaist, CERN-EP/85-192]

- Fluctuations

explosive hadronization of QGP bubbles

$\Rightarrow$ rap. of hadrons close to rap. of bubble

$\Rightarrow$ fluctuations in $\frac{dN}{dy}$ of width $\Delta y \doteq 1$



[v. Hove, Z. Phys. C27, 135; Gyulassy, NP B237, 477]

III Look into Future

RHIC at BNL : $\tilde{\approx}$ 1995

$\leq$ Au + Au at $\doteq$ 100 + 100 GeV/c

$$\Rightarrow \frac{dN^{ch}}{dy} \approx 2.5 \cdot 200 = \underline{500} \quad \text{at } y=0$$

$$\frac{dN^{ch}}{dy} (\underline{\text{central}}) \gtrsim 3 \cdot 500 = \underline{1500 \text{ at } y=0}$$

compare: $S_{p\bar{p}}S$: $\langle n_{ch} \rangle \approx \underline{22}$

LHC : $\langle n_{ch} \rangle \approx \underline{50}$ (?)

e^+e^- 2 TeV: $\langle n_{ch} \rangle \approx \underline{70}$ (?)

From discussion of signatures:

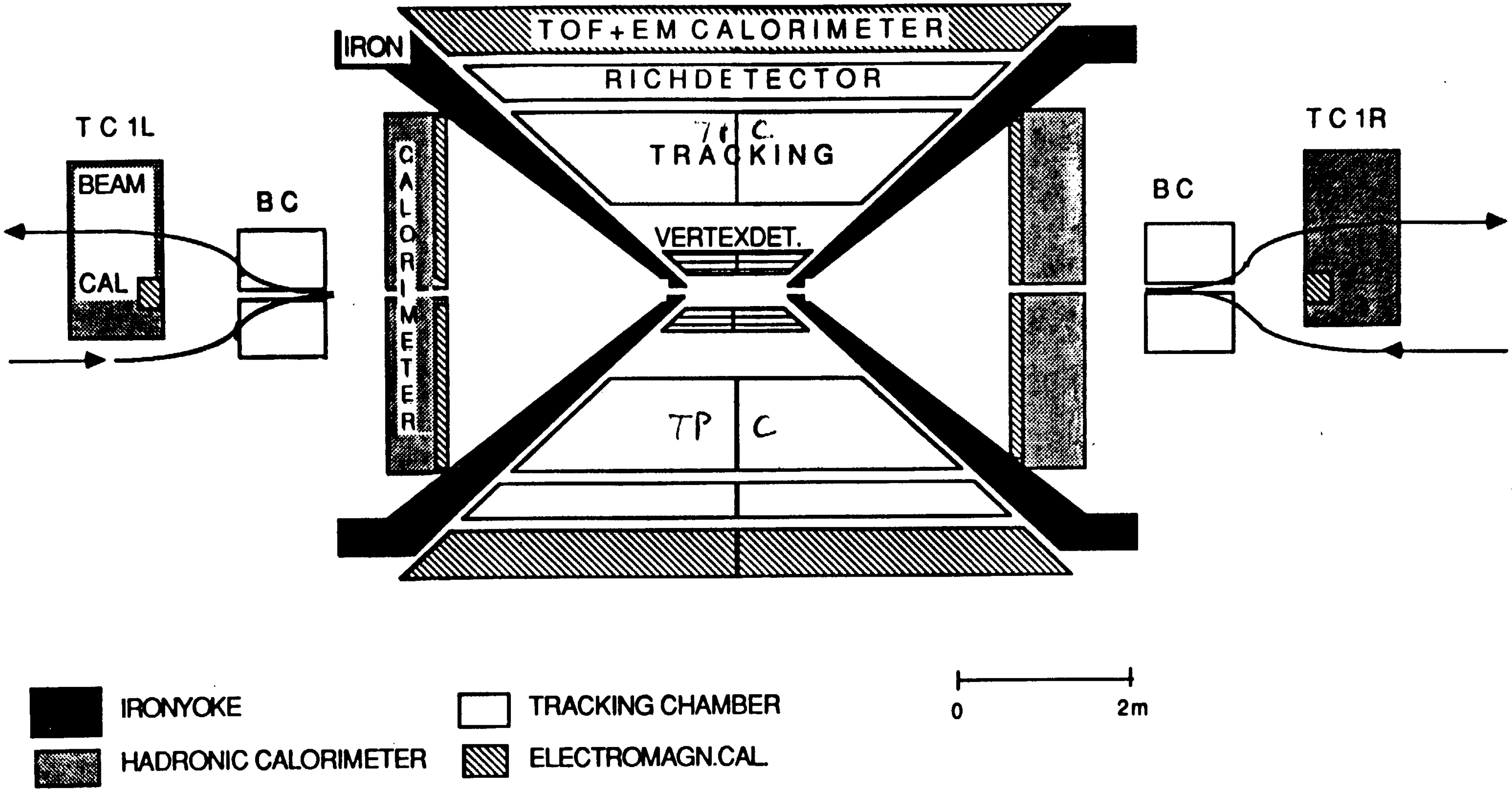
- tracking
- lepton pairs
- calorimetry

Comment: tracking : extremely ambitious

calorimetry : general flow measurements
and $\Delta y \lesssim 1$ fluctuations
no jet spectroscopy
$\Rightarrow$ 'thin calorimeters'

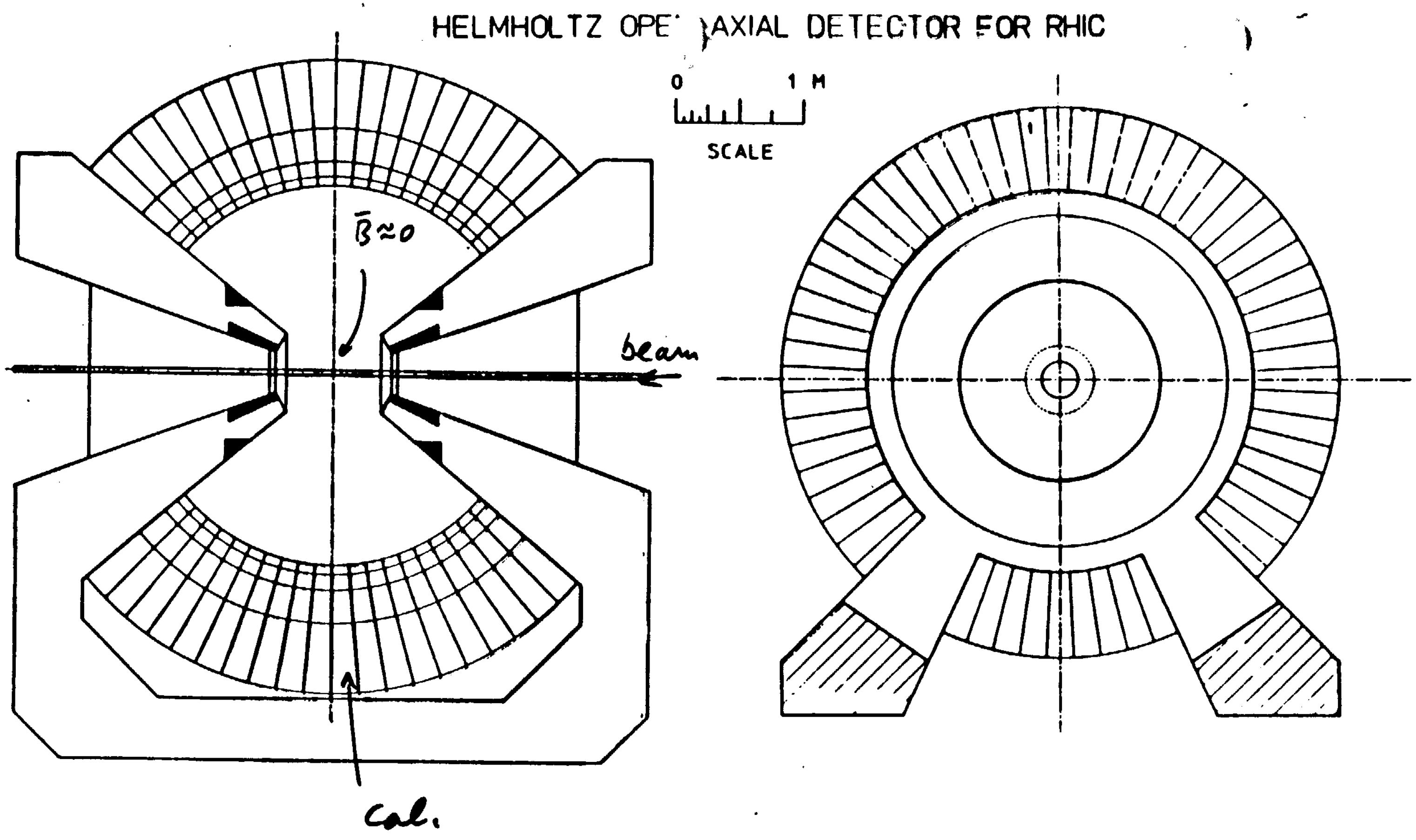
G4TBROD
Proceedings
RHIC Workshop
LBL 1987

PHOTON & HADRON SPECTROMETER FOR RHIC



III 27

Ahrens
Proceedings
RHIC Workshop
LBL 1987



(an e^+e^- - RICH may fit in)

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Conclusions

- Search for QGP of <u>fundamental</u> interest
  (also cosmology ...)
- ∙∙ Theoretical & experimental work
  very challenging but tedious
- ∙∙∙ NA38 result seems to contradict
- ∷ Good pp data needed (and pA)
- Experiments are well on their way
- Ideas for RHIC experiments exist

Anaxagoras: 'Phenomena are views of
the Invisible'