High Enery Heavy Ion Collisions

Edoardo Amaldi (center) at the first session of the provisional CERN Council (1952)

Johanna Stachel - Physikalisches Institut, Universität Heidelberg

Int. Conf. 'The Legacy of Edoardo Amaldi in Science and Society'

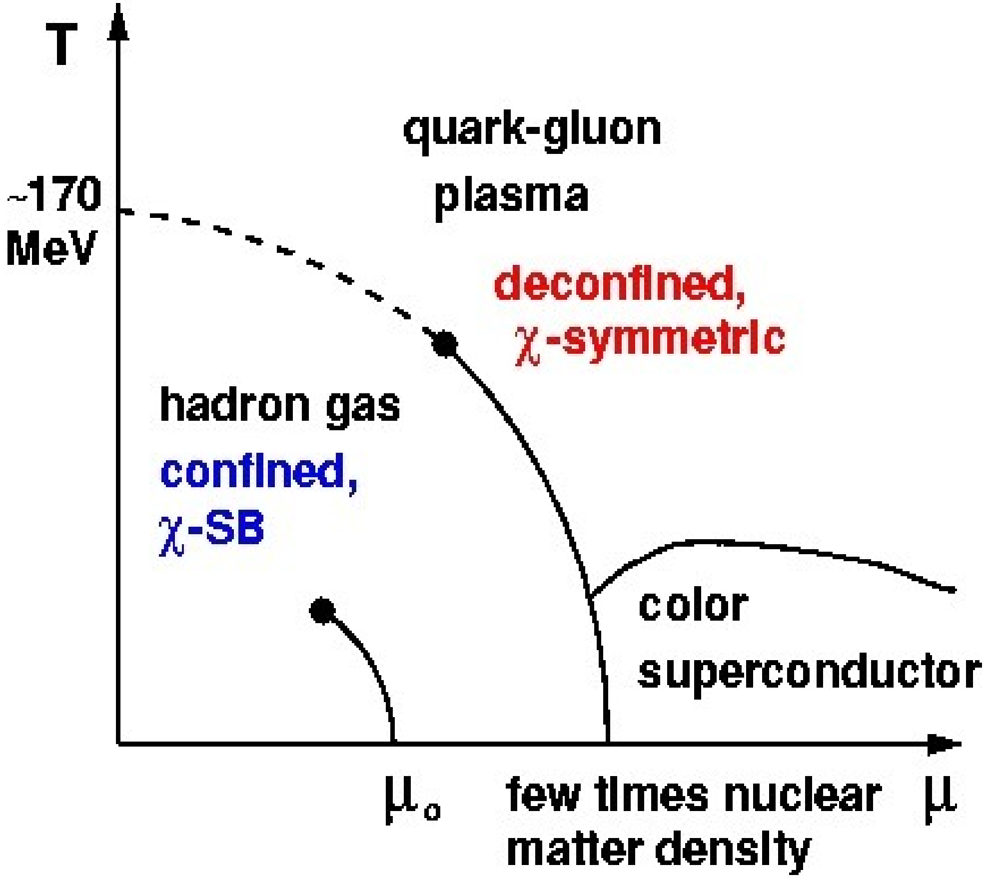
Rome, October 23-25, 2008

the phase diagram of strongly interacting matter

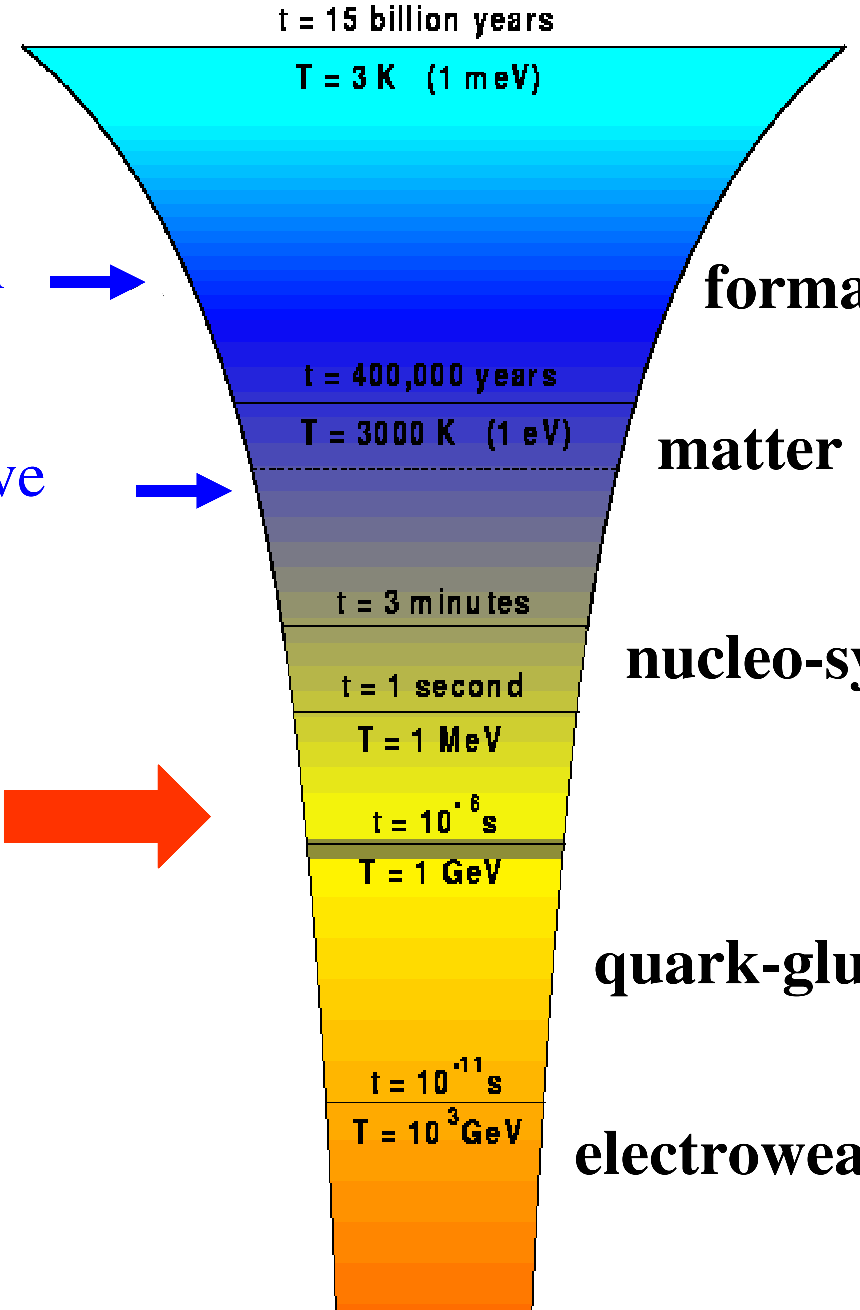
at low temperature and normal density
quarks and gluons are bound in hadrons
color is confined and chiral symmetry is spontaneously broken (generating 99% of proton mass e.g.) 1972

at high temperature and/or high density
quarks and gluons freed from confinement
-> new state of strongly interacting matter
1975 (Collins/Perry and Cabibbo/Parisi)

now called **Quark-Gluon Plasma (QGP)**



Tracing Back the Big Bang



today

formation of galaxies

matter dominated

nucleo-synthesis

quark-gluon matter

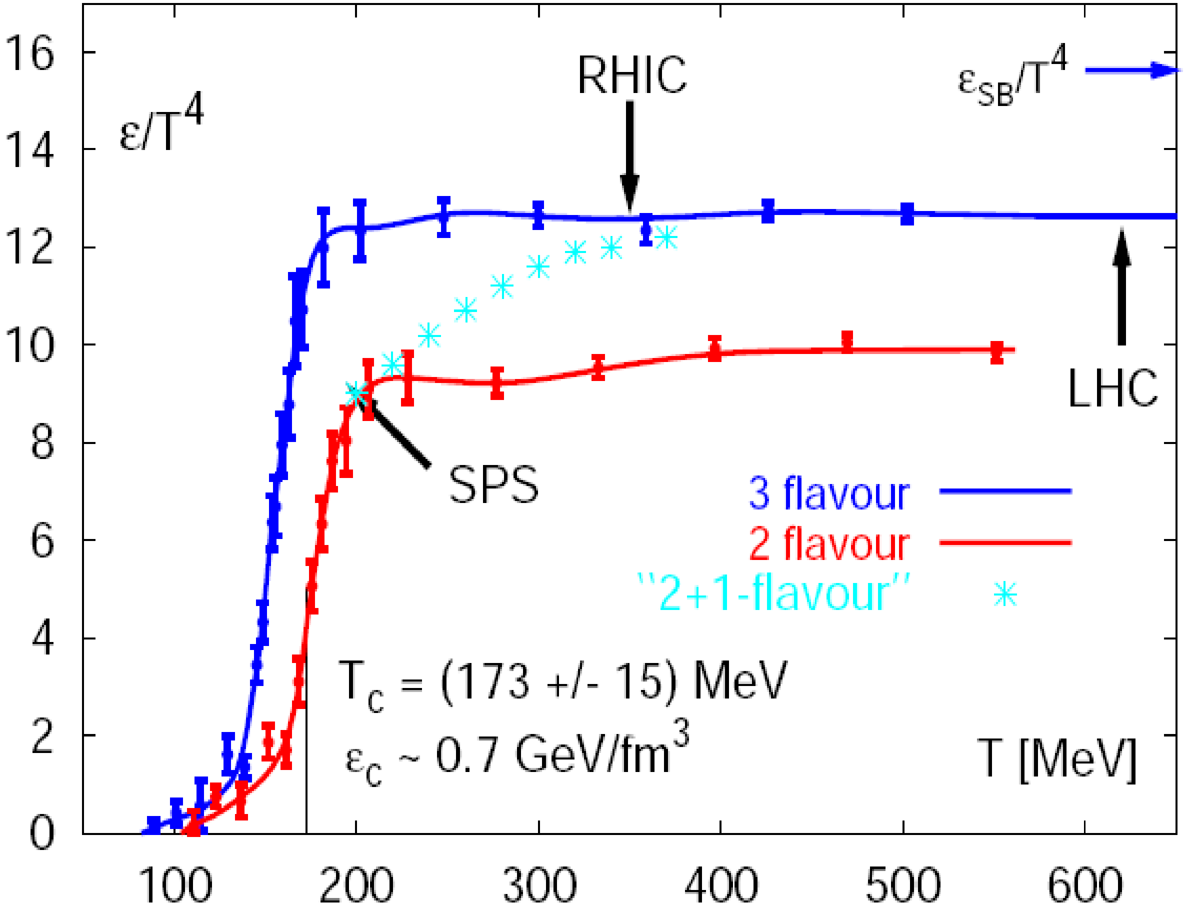
electroweak phase transition

Hubble expansion →

cosmic microwave radiation →

quark hadron phase transition →

phase transition between hadrons and deconfined quark gluon matter in lattice QCD



Lattice QCD calculations for $\mu_b = 0$

Karsch & Laermann, hep-lat/0305025

T_c = 173 +- 12 MeV

ε_c = 700 +- 200 MeV/fm^3

for the (2 + 1) flavor case

the phase transition to the QGP and its parameters are quantitative predictions of QCD

order of transition not yet definitively determined

continuous cross over?

but diGiacomo suggests first order

SPS : 1986 - 2003

- S and Pb ; up to $\sqrt{s}$ =20 GeV/nucl pair

E_{cm}^* = 3200 GeV - 2500 prod. hadrons

LHC : starting 2008

- Pb ; up to $\sqrt{s}$ = 5.5 TeV/nucl pair

E_{cm}^* = 1150 TeV - 40000? prod. hadrons

AGS : 1986 - 2000

- Si and Au ; up to $\sqrt{s}$ =5 GeV /nucl pair

E_{cm}^* = 600 GeV - 1000 produced hadrons

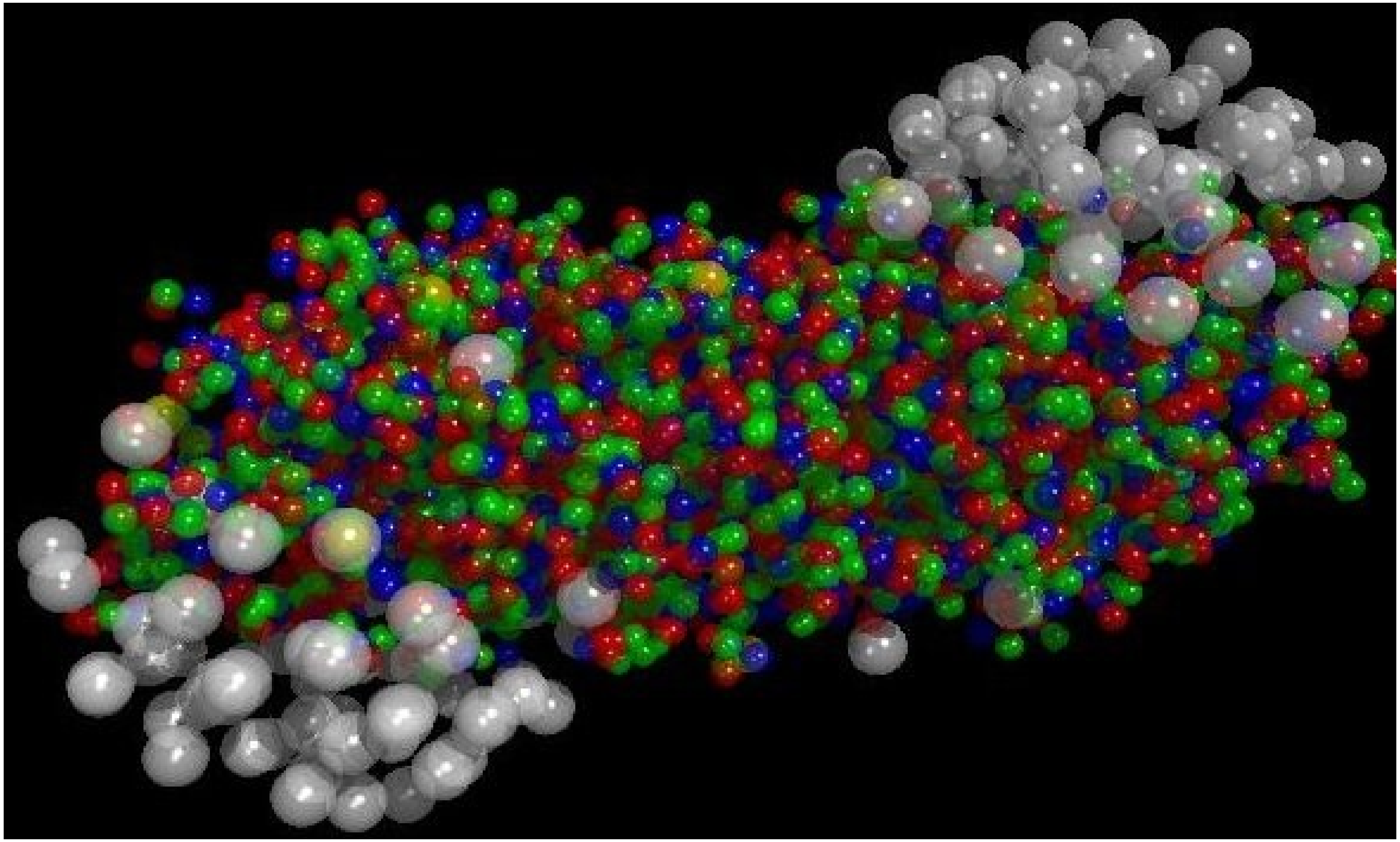
RHIC : 2000

- Au ; up to $\sqrt{s}$ = 200 GeV /nucl pair

E_{cm}^* = 40 TeV - 7500 prod. hadrons

CERN Press Release February 2000:

New State of Matter created at CERN

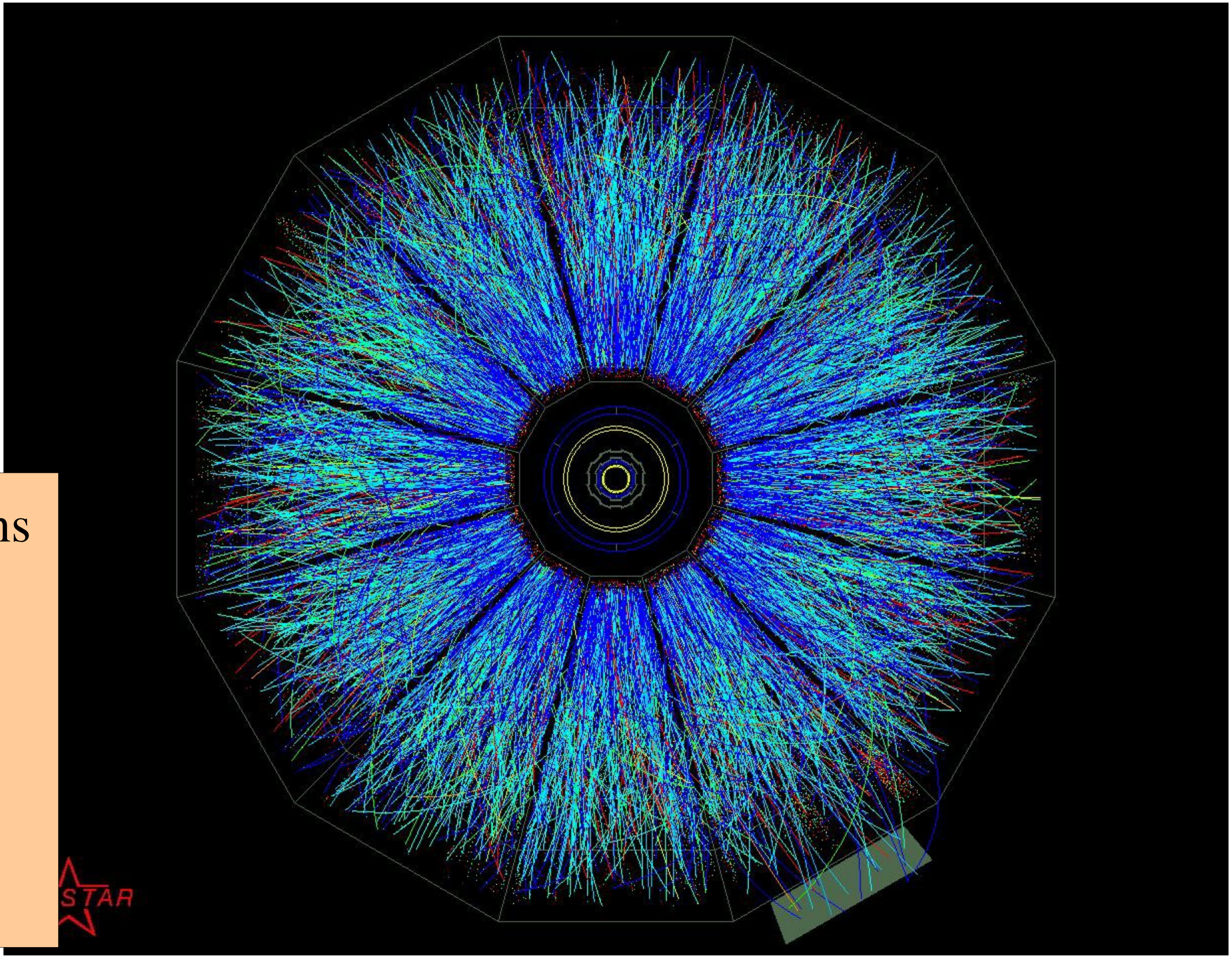


At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

BNL press release April 2005:

RHIC Scientists Serve Up “Perfect “ Liquid

New state of matter more remarkable than predicted
– raising many new questions



in central AuAu collsions
at RHIC √s = 38 TeV
about 7500 hadrons
produced (BRAHMS)

about three times as
many as at CERN SPS

initial energy density from transverse energy

from transverse energy rapidity density using Bjorken formula[*]:

$\epsilon_0 = dE_t/d\eta/(\tau_0 \pi R^2)$ using Jacobian $d\eta/dz = 1/\tau_0$

SPS 158 A GeV/c Au-Au collisions: $dE_t/d\eta \approx 450\text{GeV}$

$\tau_0 = 1$ fm/c (0.3 10^{-23} s) → $\varepsilon_0 = 3\ \text{GeV/fm}^3$

PHENIX & STAR central Au-Au collisions: $dE_t/d\eta \approx 600\text{GeV}$

(nucl-ex/0407003 and nucl-ex/0409015)

conservatively: $\tau_0 = 1$ fm/c → $\varepsilon_0 = 5.5\ \text{GeV/fm}^3$

optimistically: $\tau_0 = 1/p_0 = 0.14$ fm/c → $\varepsilon_0 = 40\ \text{GeV/fm}^3$

in any case this is significantly above critical energy density from lattice QCD of 0.7 GeV/fm^3

[*] this is lower bound; if during expansion work is done (pdV) initial energy density higher (indications hydrodynamics: factor 3)

expected initial conditions in central nuclear collisions at LHC

initial conditions from pQCD+saturation of produced gluons

$$N_{AA}(\mathbf{0}, p_0, \Delta y = 1, \sqrt{s}) \cdot \pi / p_0^2 = \pi R_A^2$$

using pQCD cross sections find for central PbPb at LHC $p_0 = p_{sat} = 2$ GeV

and a formation time of $\tau_0 = 1/p_{sat} = 0.1$ fm/c

and with Bjorken formula:

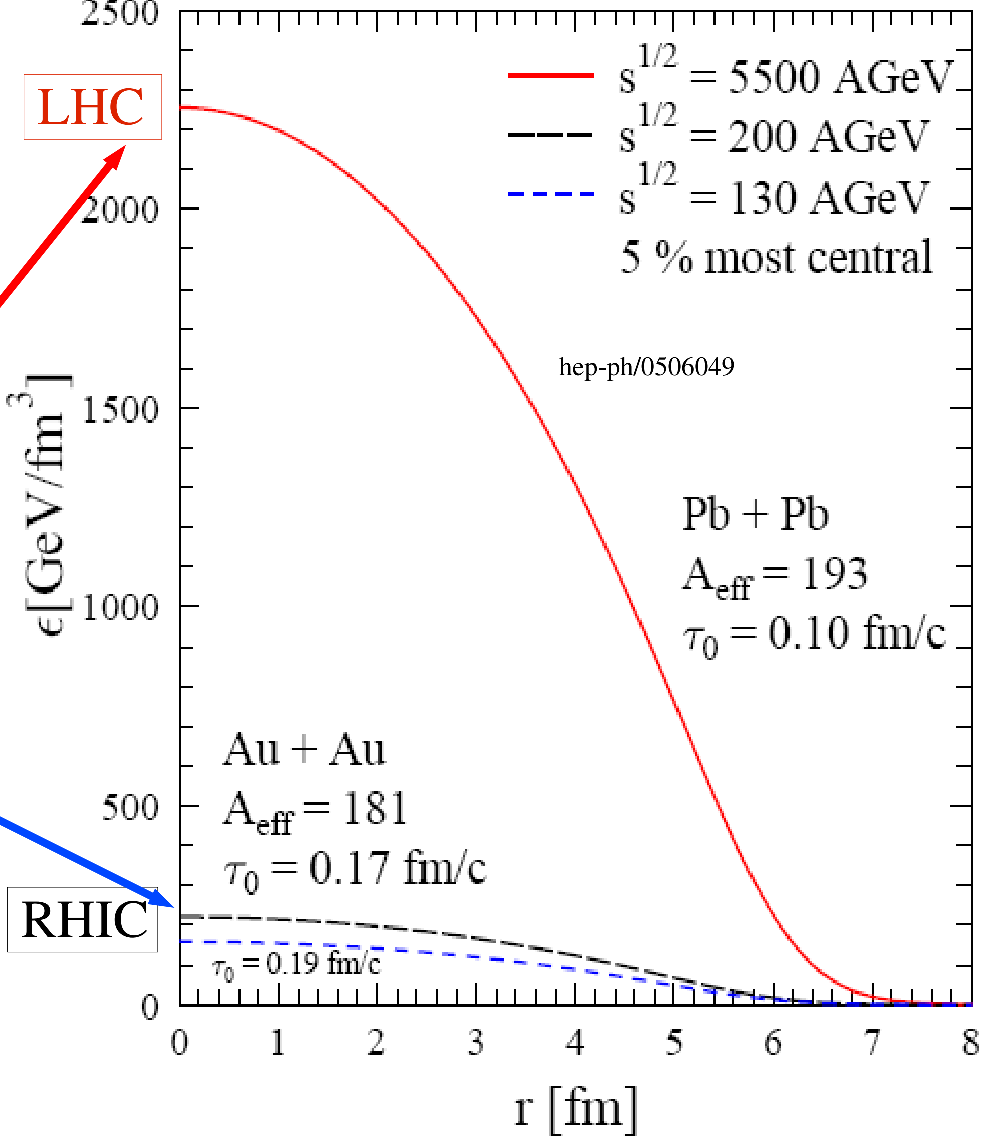
$$\epsilon_0 = \mathrm{dE_t/d\eta/(\tau_0 \pi R^2)}$$

as compared to RHIC: more than order of magnitude increase in intial energy density

initial temperature $T_0 \approx 1$ TeV

(factor 2-3 above RHIC)

K. Eskola et al., hep-ph/0506049



expected evolution of QGP fireball at LHC

- after fast thermalization hydrodynamic expansion of fireball and cooling $T \propto \tau^{-1/3}$ (only long. expansion)
- hadronization starts at when T_c is reached

  duration hadronization: # degrees of freedom drops by factor 3.5

  -> volume has to grow accordingly -> 3-4 fm/c
- maybe further expansion (now increasingly 3-dim) and cooling in hadronic phase until elastic collisions stop (thermal freeze-out)

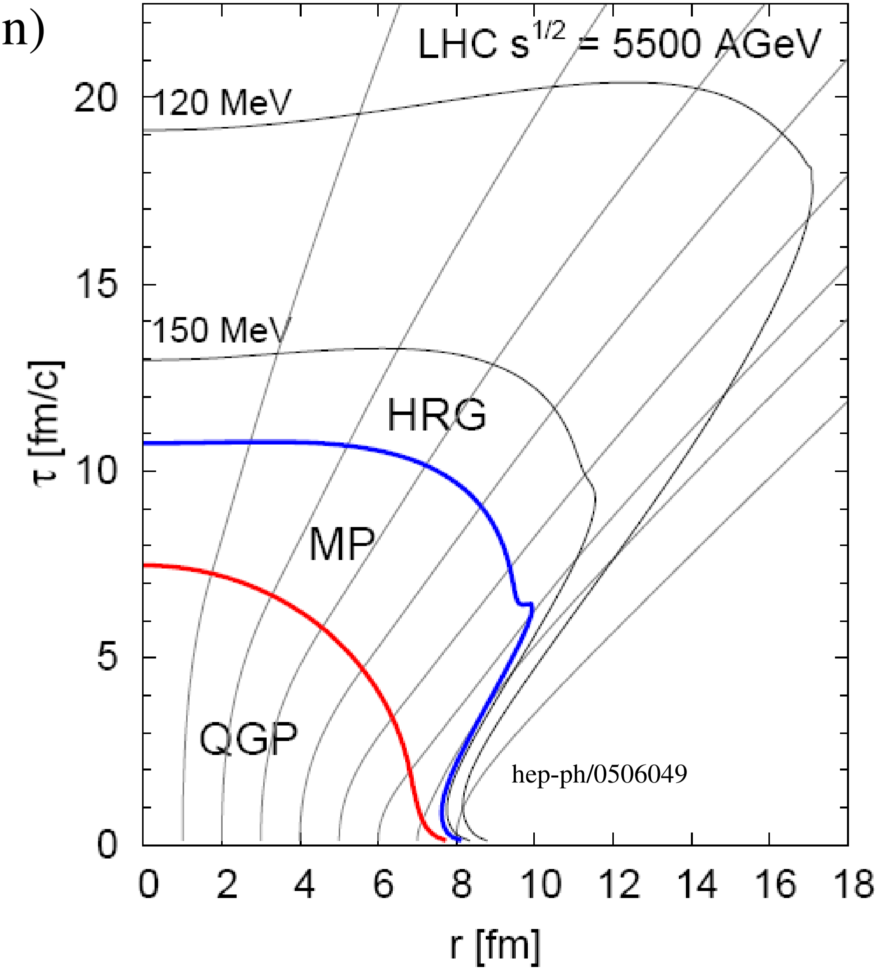
initial N_{AA} determines final multiplicity

estimate (Eskola) $dN_{ch}/d\eta = 2600$

overall several 10 k hadrons produced

'macroscopic state'

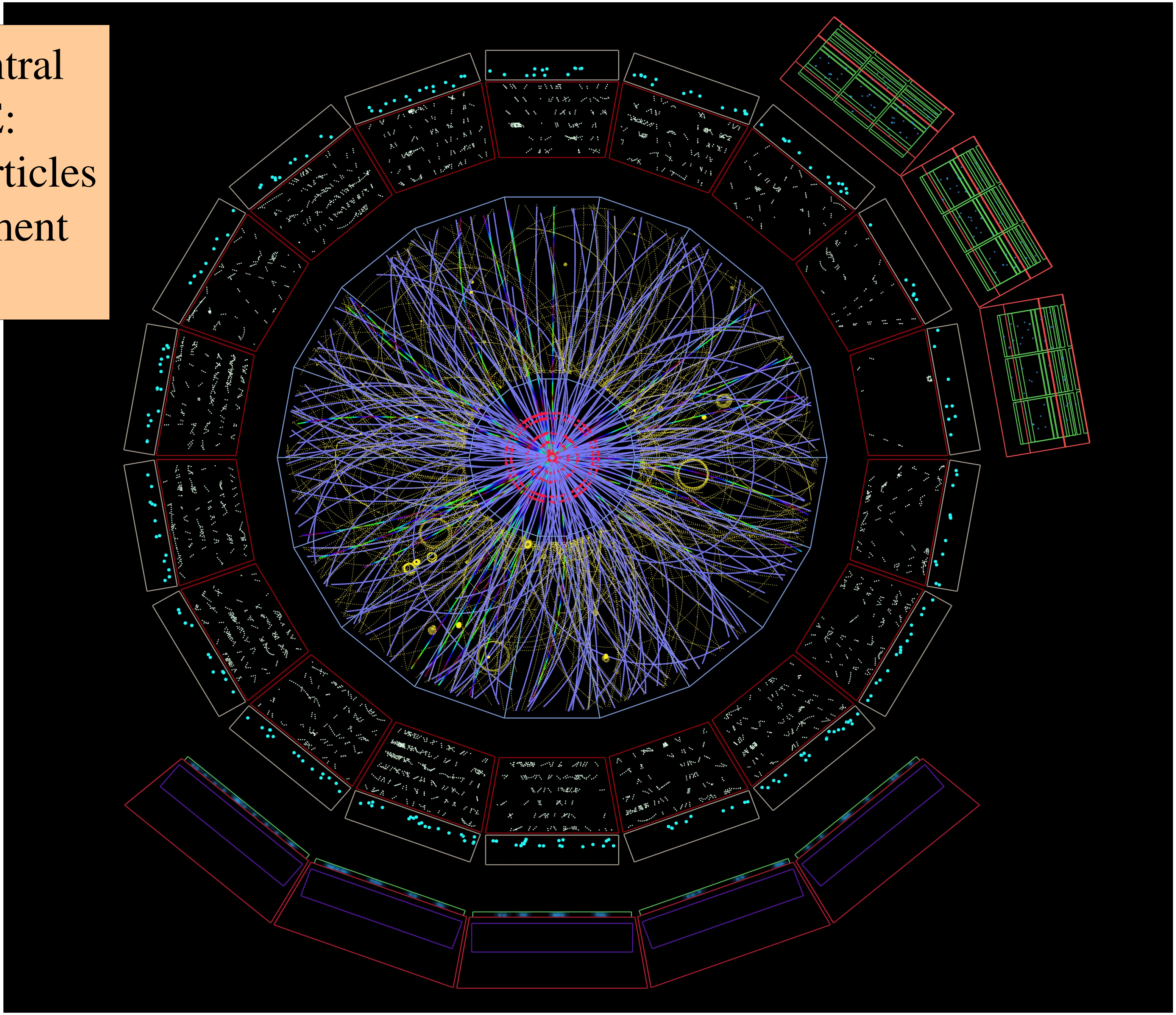
K. Eskola et al.



hep-ph/0506049

the challenge: identification and reconstruction of 5000 (up to 15000) tracks of charged particles

cut through the central
barrel of ALICE:
tracks of charged particles
in a 1 degree segment
(1% of tracks)



task of heavy ion program at LHC

- unambiguous proof of QGP
- determine properties of this new state of matter

equation of state – energy density ↔ temperature ↔ density ↔ pressure
heat capacitance /entropy – number degrees of freedom
viscosity (Reynolds number) – flow properties under pressure gradient
velocity of sound – Mach cone for supersonic particle
opacity / index of refraction / transport coeff. - parton-energy loss
excitations / quasi particles - correlations
susceptibilities – fluctuations
characterisation of phase transition
....

unusual quantities in particle physics – but we want to characterize matter!

- be open for the unexpected

1. The hadro-chemical composition of the fireball

what are the 7500 hadrons observed in final state at RHIC?

analysis of yields of produced hadronic species in statistical model – grand canonical

partition function: $\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 dp \ln(1 \pm \exp(-(E_i - \mu_i)/T))$

particle densities: $n_i = N/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 \, \mathrm{d}p}{\exp((E_i - \mu_i)/T) \pm 1}$

for every conserved quantum number there is a chemical potential:

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_i^3$$

but can use conservation laws to constrain V, μ_S, μ_{I_3} →

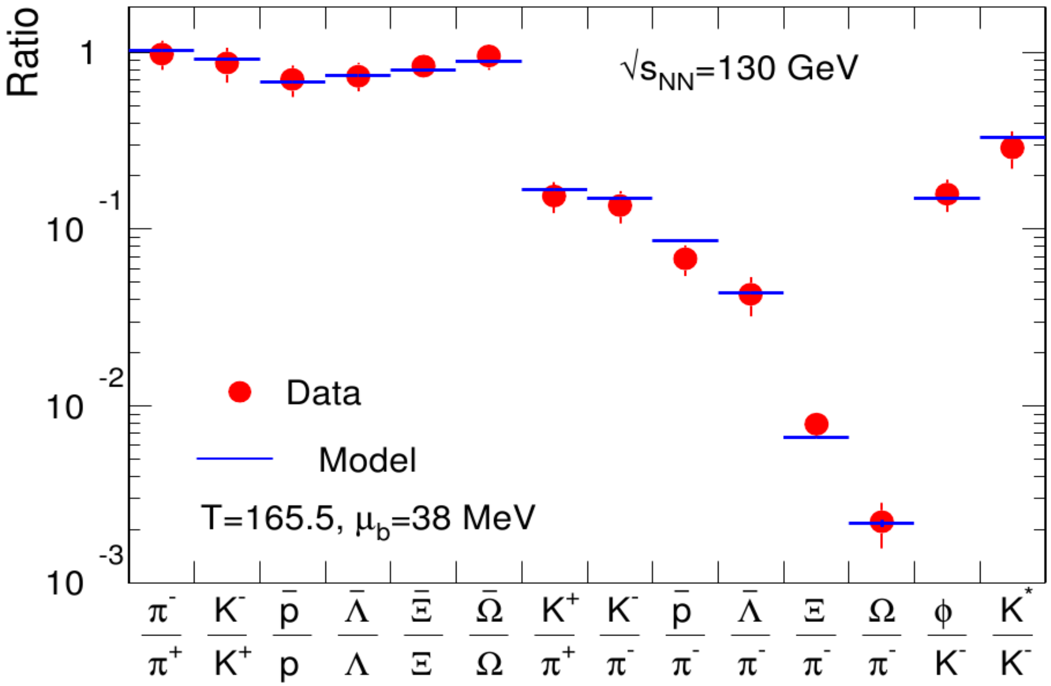
Fit at each energy provides values for T and μ_b

- from AGS energy upwards all hadron yields in central collisions of heavy nuclei reflect grand canonical equilibration
- strangeness suppression known from pp and e^+e^- is lifted

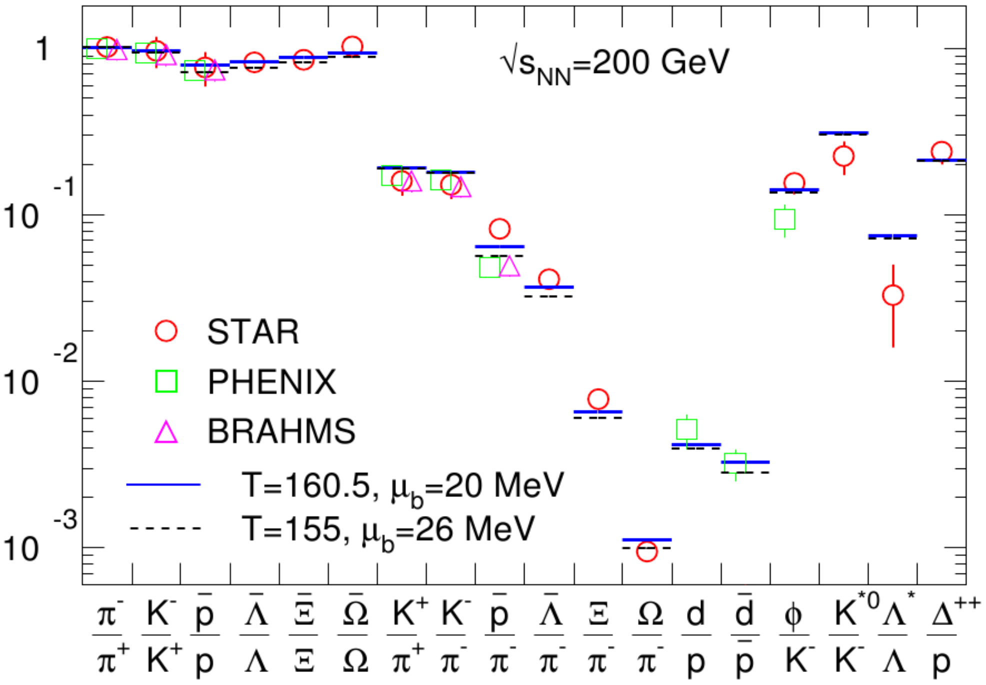
for a review: Braun-Munzinger, Stachel, Redlich, QGP3, R. Hwa, ed. (Singapore 2004) nucl-th/0304013

hadron yields at RHIC compared to statistical model (GC)

130 GeV data in excellent agreement
with thermal model predictions



prel. 200 GeV data fully in line
still some experimental discrepancies

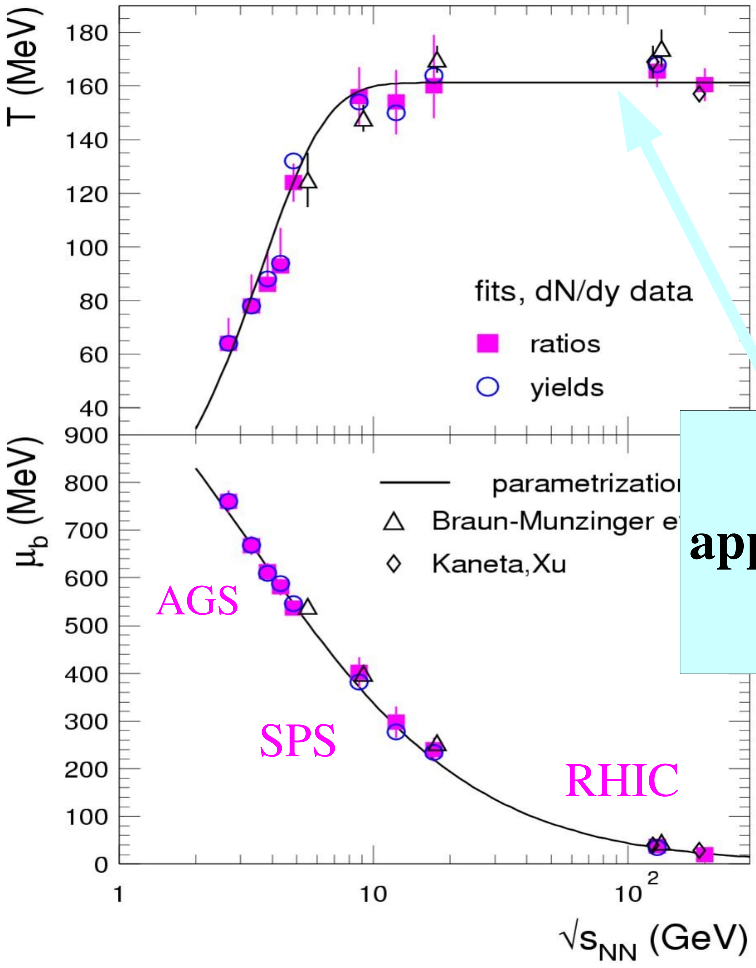


chemical freeze-out at: T = 165 ± 5 MeV

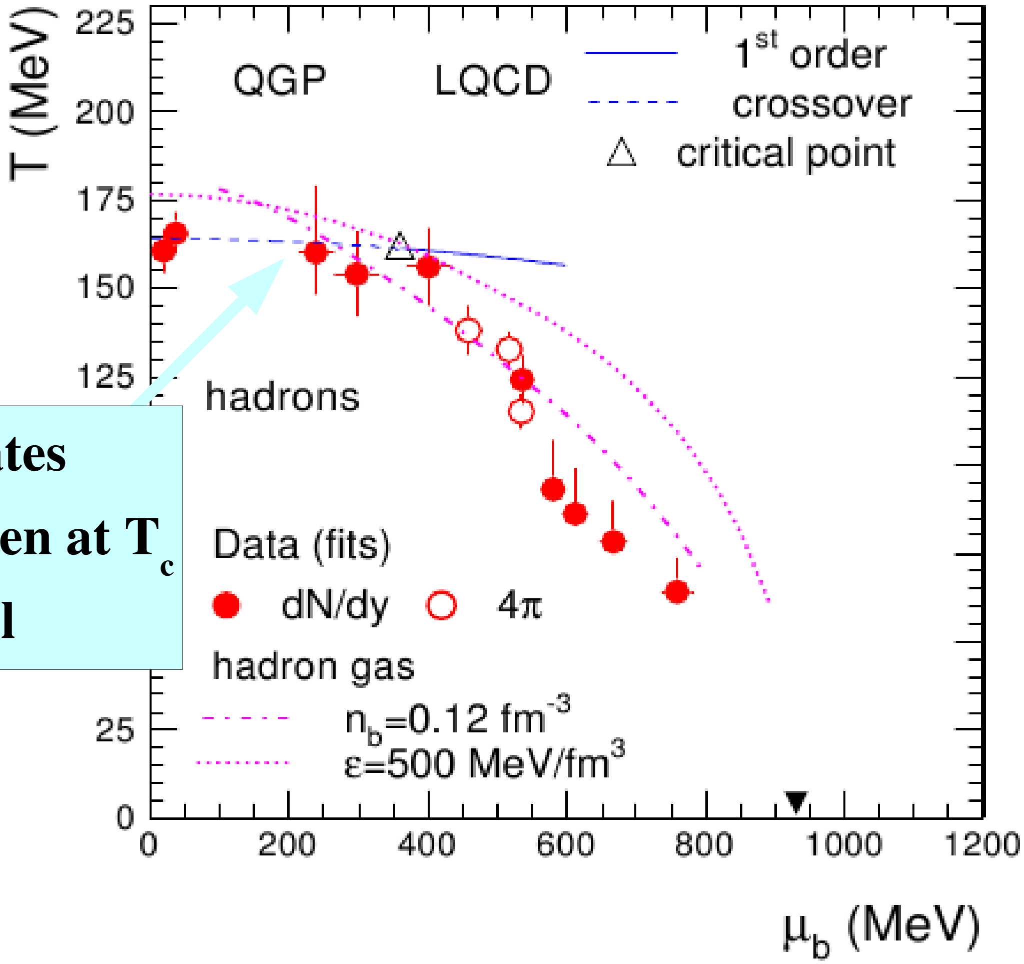
P. Braun-Munzinger, D. Magestro, K. Redlich, J. Stachel, Phys. Lett. B518 (2001) 41
A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A772 (2006) 167

hadrochemical freeze-out points and the phase diagram

A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A772 (2006) 167



T_{chem} saturates appears to happen at T_c not trivial



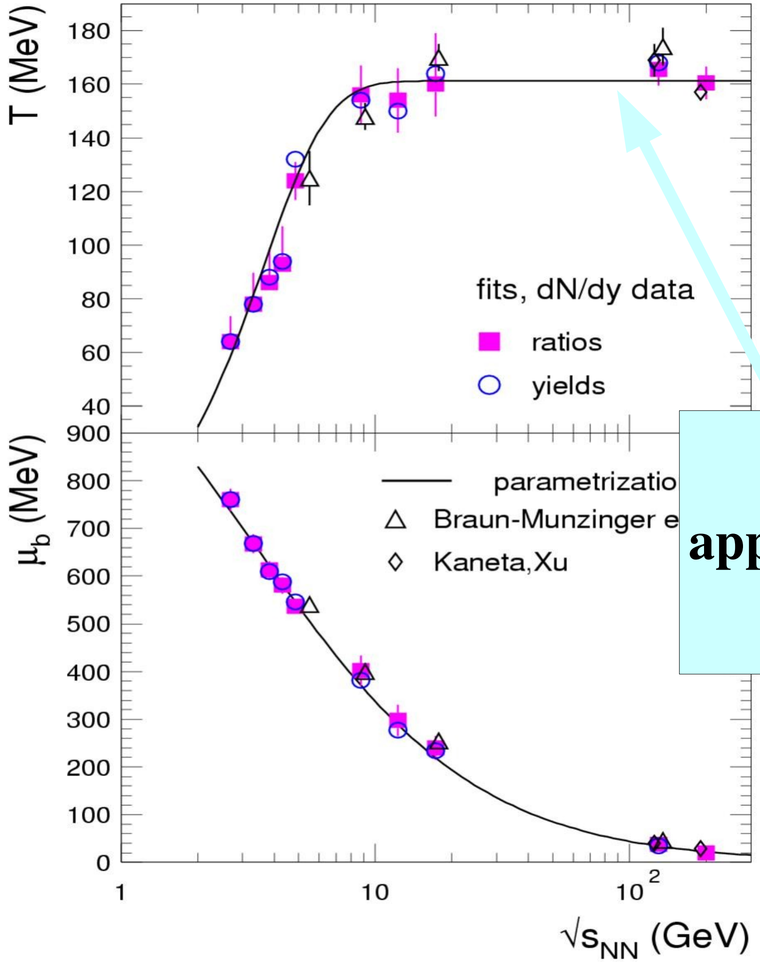
rapid equilibration within a narrow temperature interval around T_c by multiparticle collisions

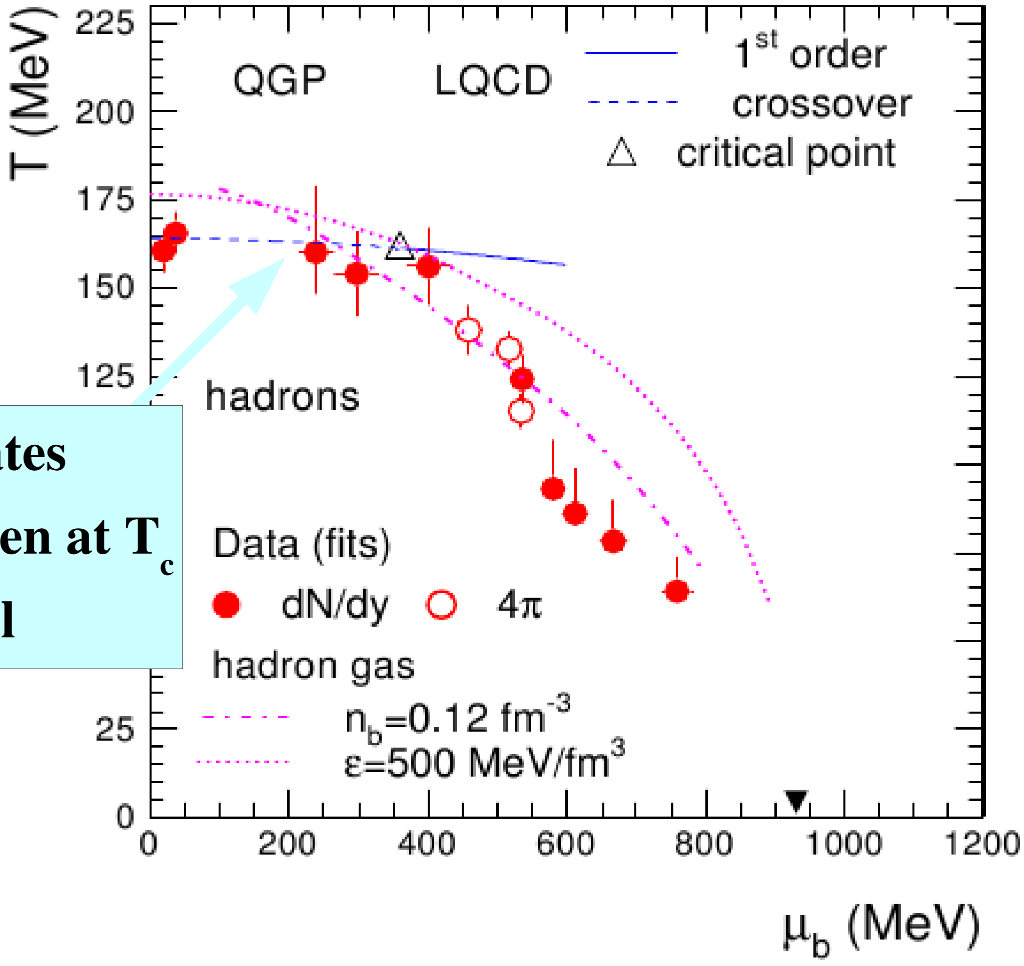
requires $T_c \approx 170$ MeV

P. Braun-Munzinger, J. Stachel, C. Wetterich, Phys. Lett. B596 (2004)61

hadrochemical freeze-out points and the phase diagram

A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A772 (2006) 167





T_{chem} saturates
appears to happen at T_c
not trivial

expectations for LHC: again equilibrium, same $T=T_c$=165 MeV, very small μ_b
interesting question: what about strongly decaying resonances –
sensitive to existence of hadronic fireball after hadronization of QGP

2. Indications for hydrodynamic expansion

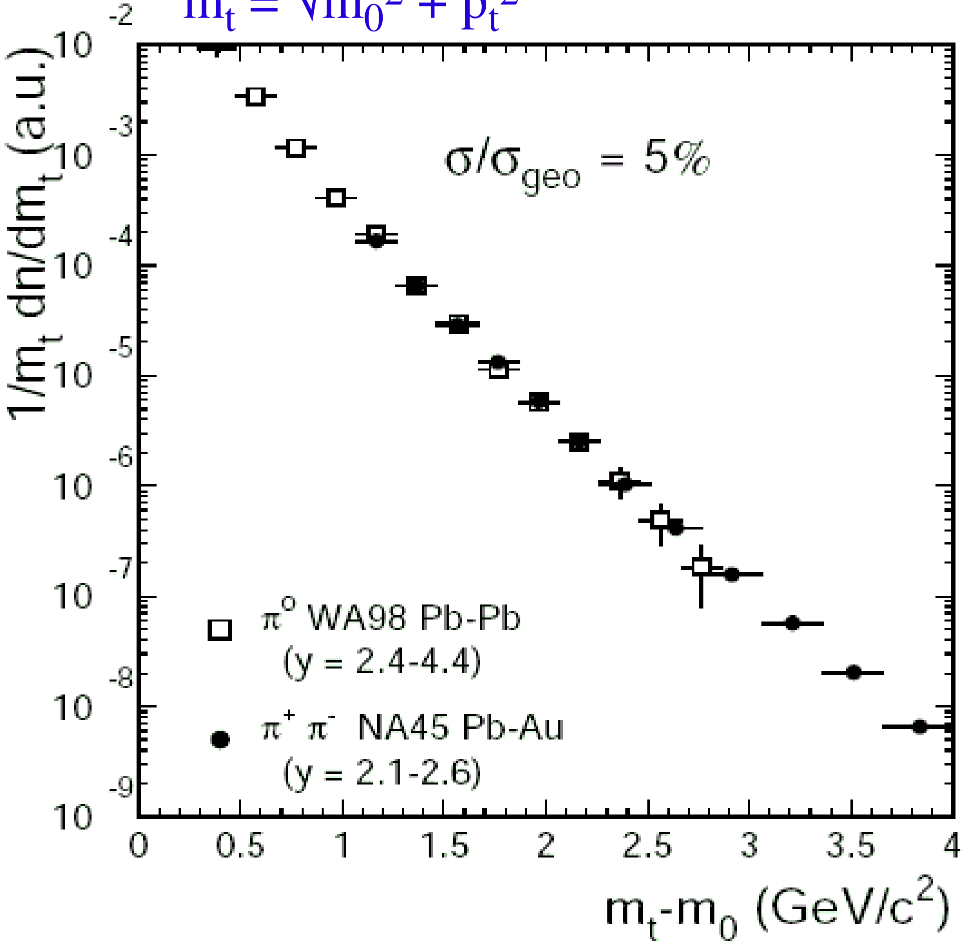
consider

particle transverse momentum spectra
momentum correlations
azimuthal correlations

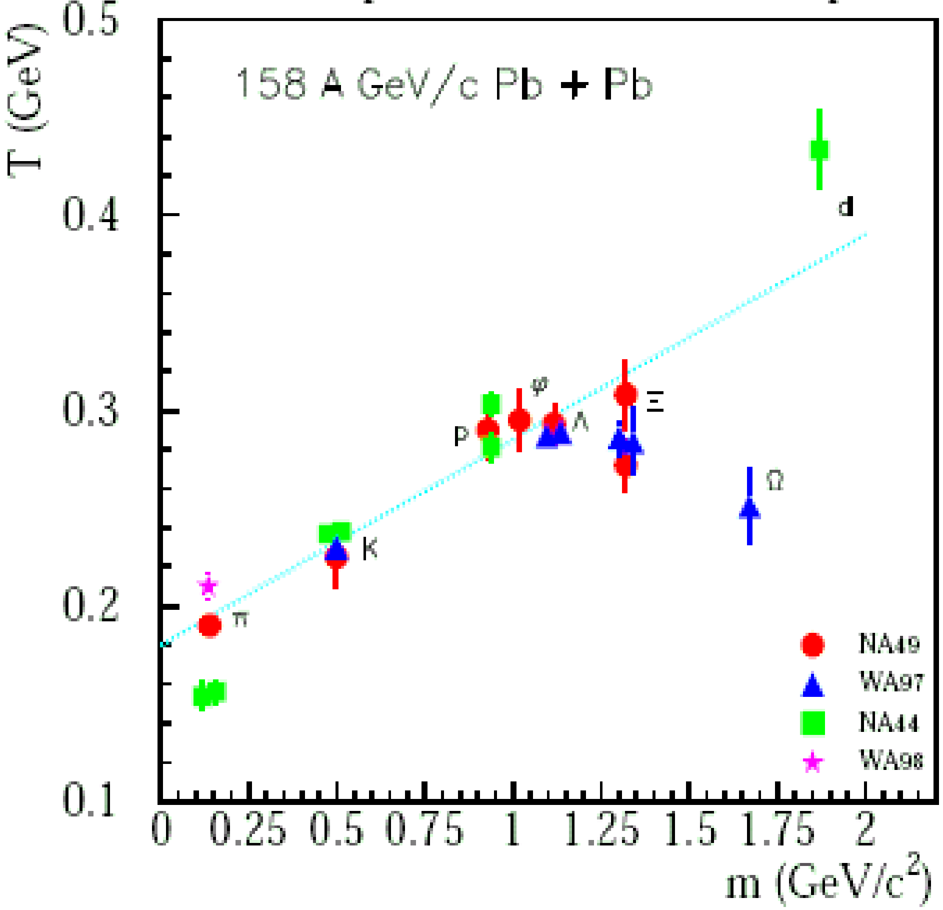
QGP signature: hydrodynamic expansion - transverse spectra

typical transverse mass spectrum

$m_t = \sqrt{m_0^2 + p_t^2}$



mass dependence of inverse slopes



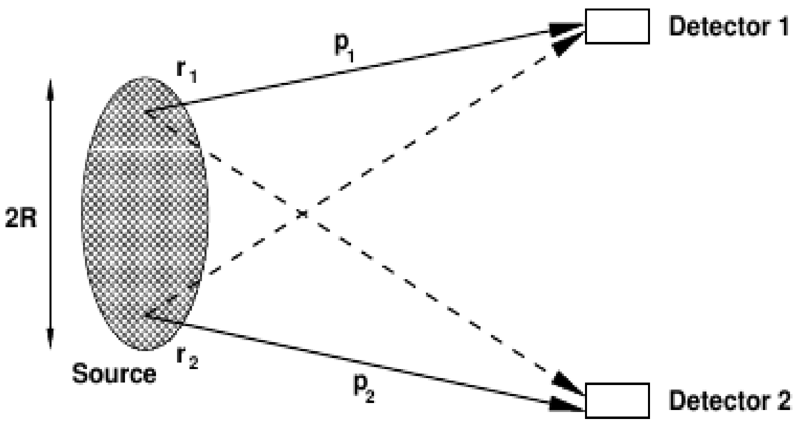
slope constants grow with mass - much too large to be temperatures!

Hubble Expansion of Nuclear Fireball

expansion velocity at surface 2/3 c at SPS, 4/5 c at RHIC

Information about space-time extent of fireball from 2-particle momentum correlations

When phase space volume smaller than $\Delta p_x \Delta x \approx \hbar$ is considered, chaotic system of identical non-interacting particles exhibits quantum fluctuations following Bose-Einstein or Fermi statistics

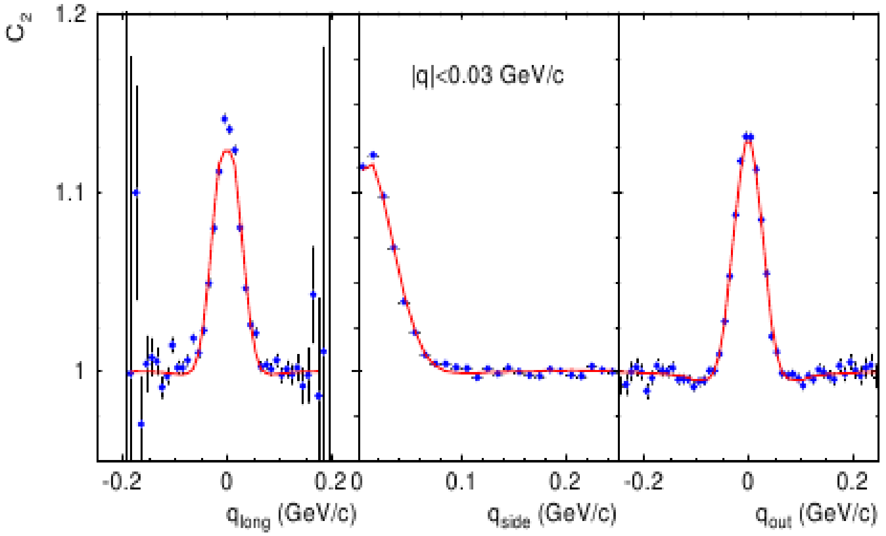


First application in astrophysics (Hanbury Brown and Twiss) → size of stars

$$C_2 \propto \frac{P_2(\vec{p_1},\vec{p_2})}{P_1(\vec{p_1})P_2(\vec{p_2})} = 1 \pm \chi(\vec{p_1} - \vec{p_2})$$

$$\Delta r = \frac{\hbar c}{q} = \frac{197\mathrm{MeV}}{q}\mathrm{fm}$$

in heavy ion physics typical dimensions 1-10 fm → momentum differences of 20-200 MeV/c



more complications, but also more information for non-static source:
duration of emission, space-momentum correlations due to expansion, strong & EM interaction, decays of resonances . . .
measure C_2 as function of
Δp_x, Δp_y, Δp_z for all y, p_t, m

at what stage of it's evolution do we study nuclear fireball with HBT correlations:

typically pions are studied
learn about space-time extent and dynamics at time when pions decouple, i.e. cease to scatter even elastically

'thermal freeze-out'

R_{long} - Longitudinal Expansion of Fireball

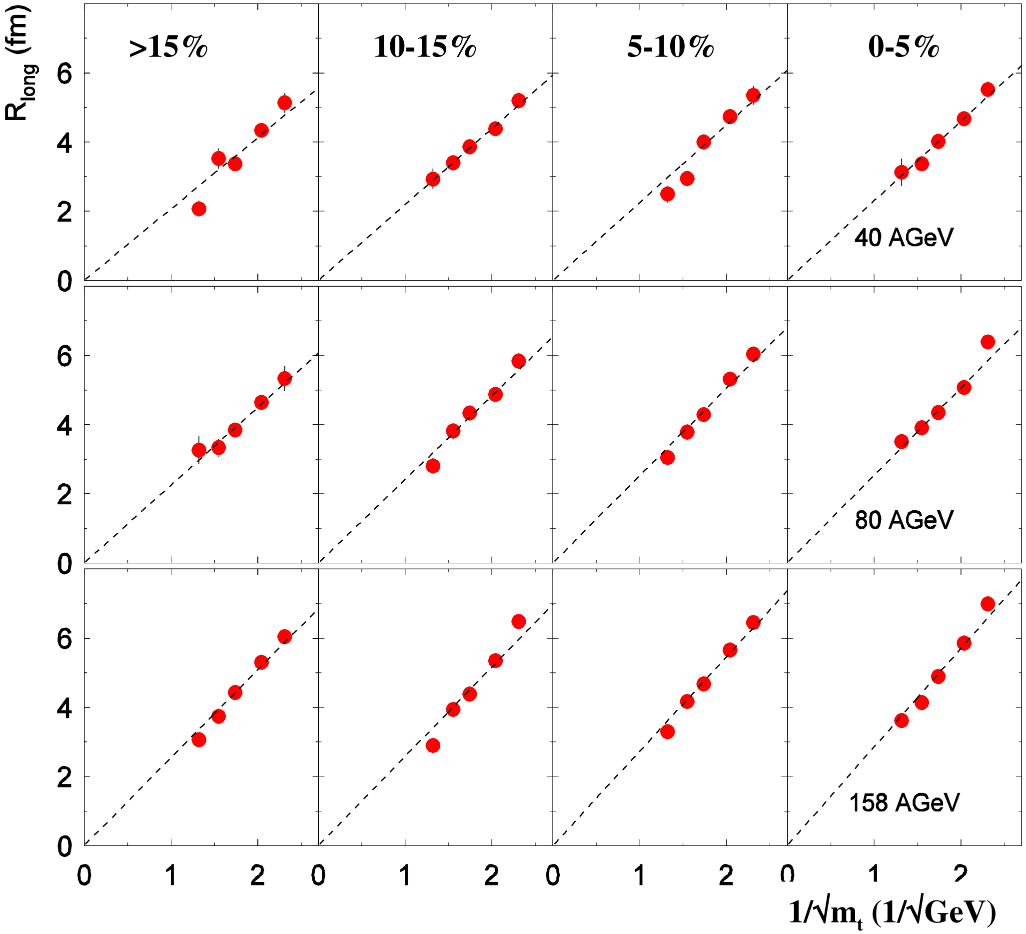
Duration of expansion (lifetime) τ of the system can be estimated from the transverse momentum dependence of R_{long}

$$R_{long} \approx \tau \underbrace{\sqrt{T_f/m_t}}_{\text{thermal velocity}}$$

Y.Sinyukov

$$\tau = 6 - 8 \text{ fm/c}$$
$$\text{for } T_f = 120 - 160 \text{ MeV}$$

CERES Pb-Au *Nucl. Phys. A714 (2003) 124*



Hubble plot of nuclear fireball

R_{side} – transverse expansion and geometry

$$R_{side} = R_{geo}/\sqrt{1+\eta_f^2 m_t/T_f}$$

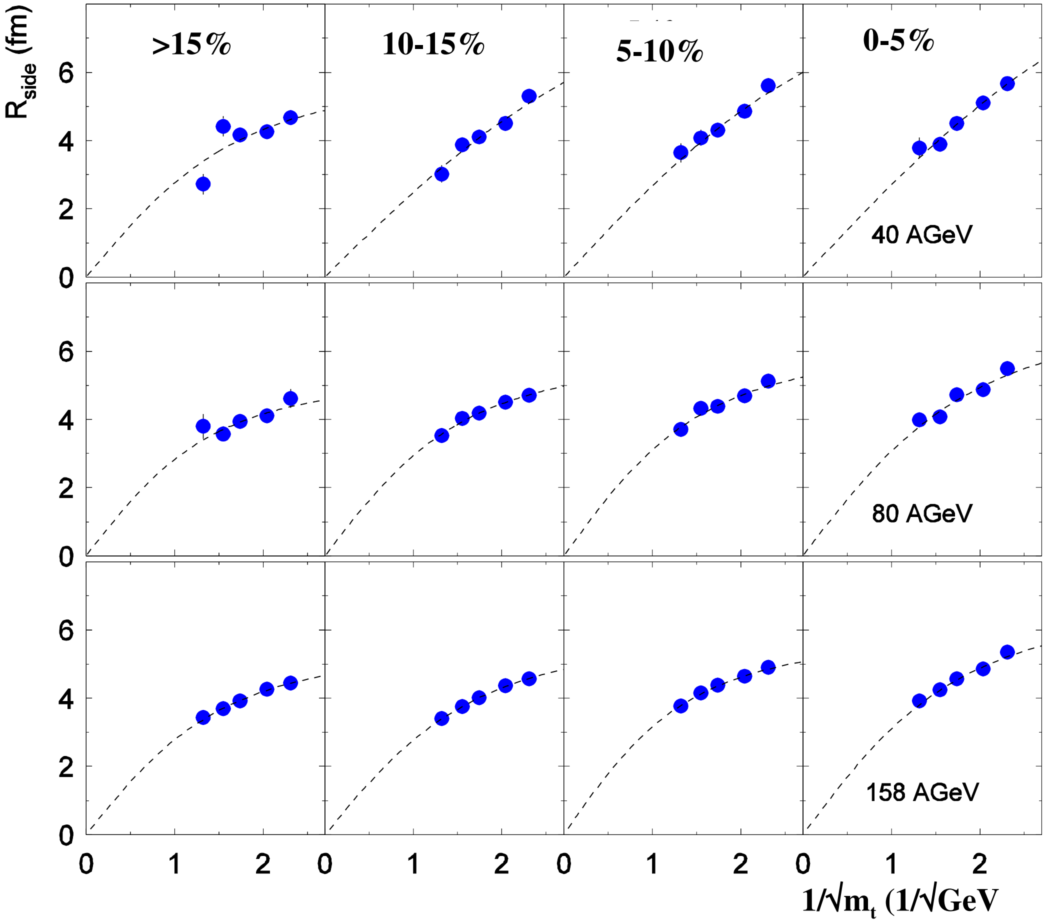
η_f^2 : strength of transverse expansion

(U. Heinz, B. Tomasik, U. Wiedemann)

$$\langle \beta_t \rangle = 0.5 - 0.6$$
$$\text{for } T_f = 160\text{-}120 \text{ MeV}$$

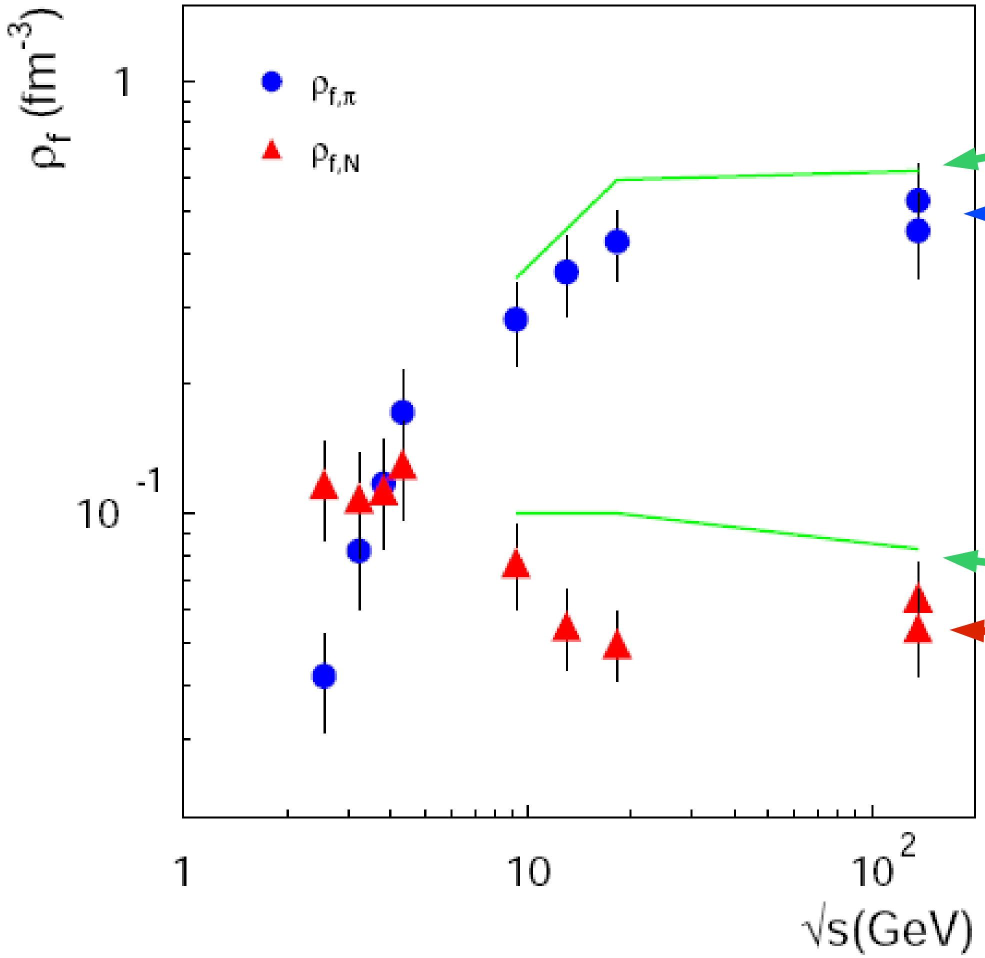
$$R_{geo} = 5.5 - 6 \text{ fm}$$

CERES Pb-Au Nucl. Phys. A714 (2003) 124



Densities at chemical and thermal freeze-out

HBT gives density at thermal freeze-out



pion density at chemical freeze-out

pion density at thermal freeze-out

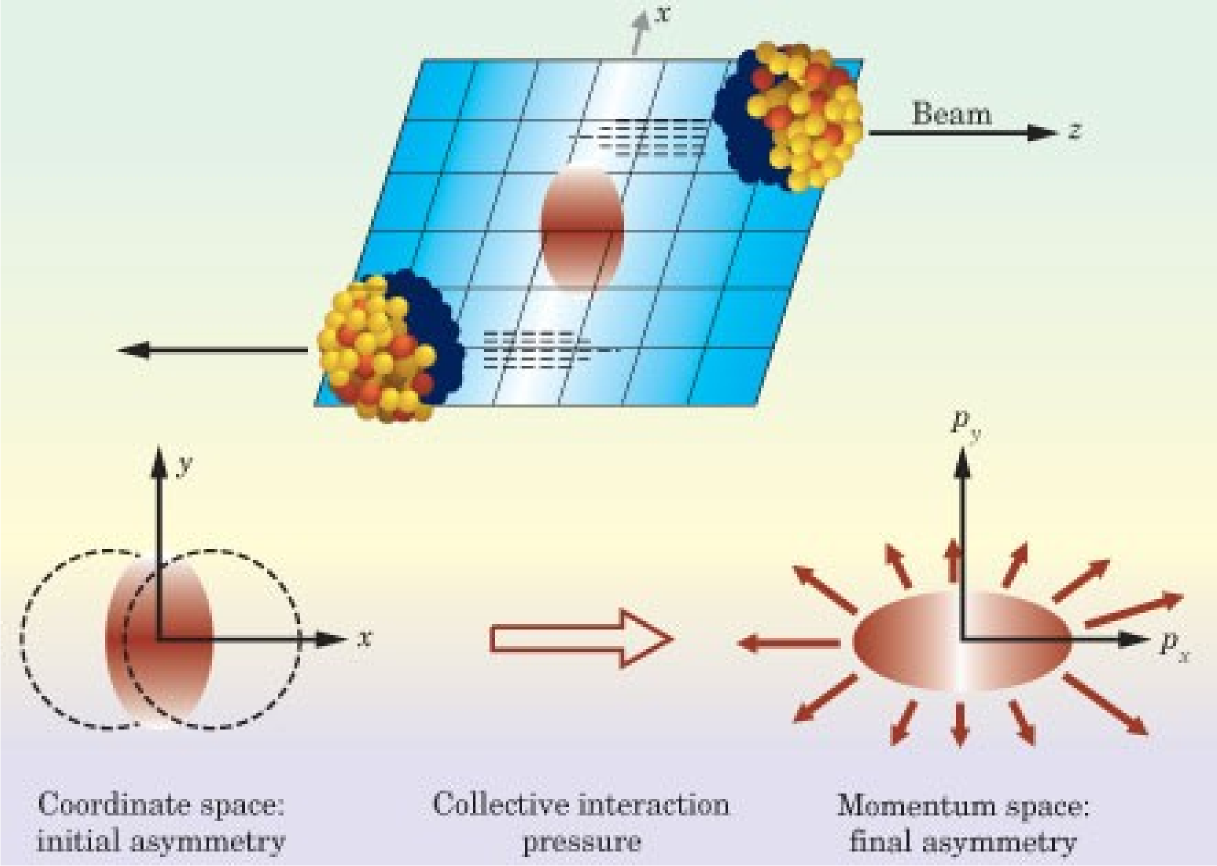
nucleon density at chemical freeze-out

nucleon density at thermal freeze-out

$1/2 - 1/3\rho_0$

Volume appears only to grow 30 % between chemical and thermal freeze-out

Azimuthal Anisotropy of Transverse Spectra



Fourier decomposition of momentum distributions rel. to reaction plane:

$$\frac{dN}{dp_t\, dy\, d\phi} = N_0 \cdot \left[1 + \sum_{i=1} 2\, v_i \left(y, p_t \right) \cos\left(i\, \phi \right) \right]$$

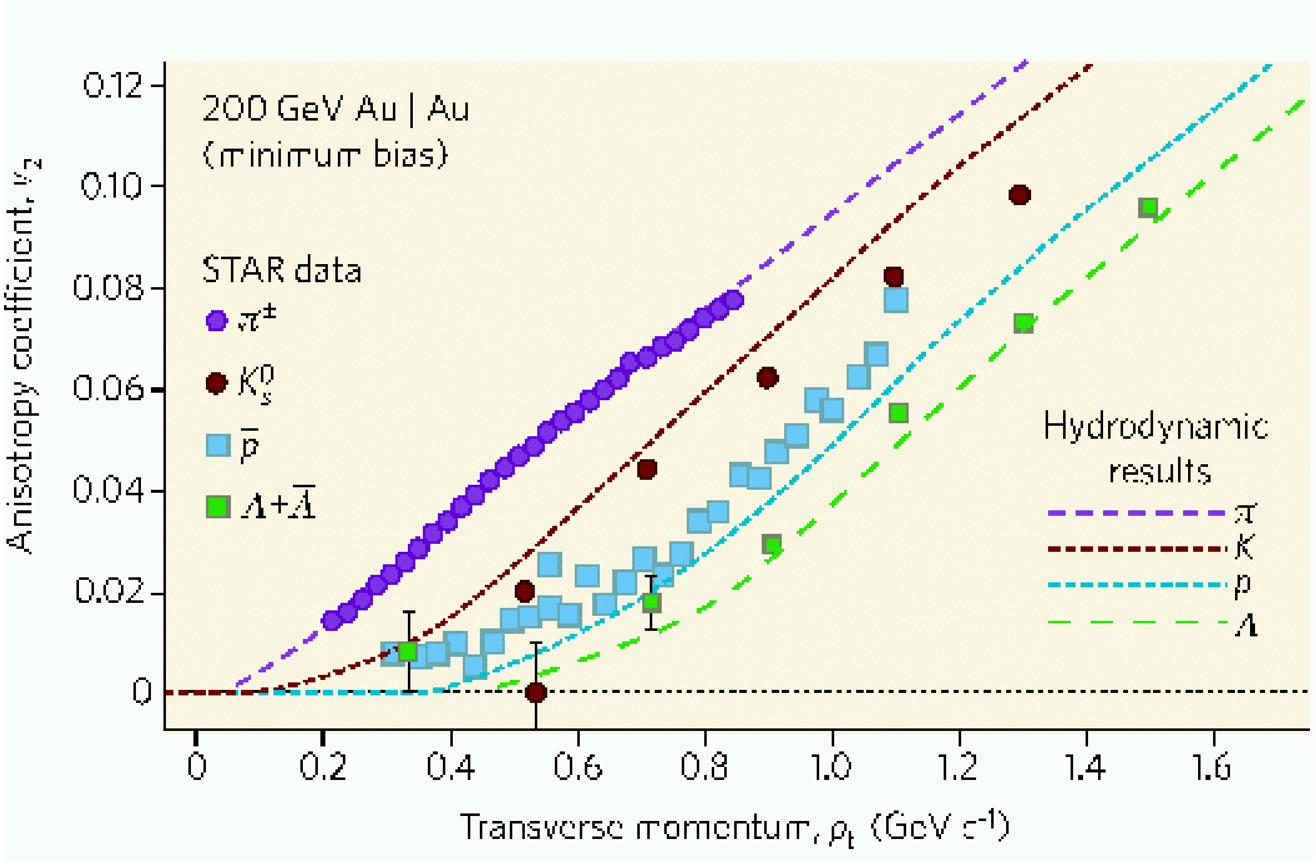
quadrupole component v_2

“elliptic flow”

effect of expansion (positive v_2) seen

from top AGS energy upwards

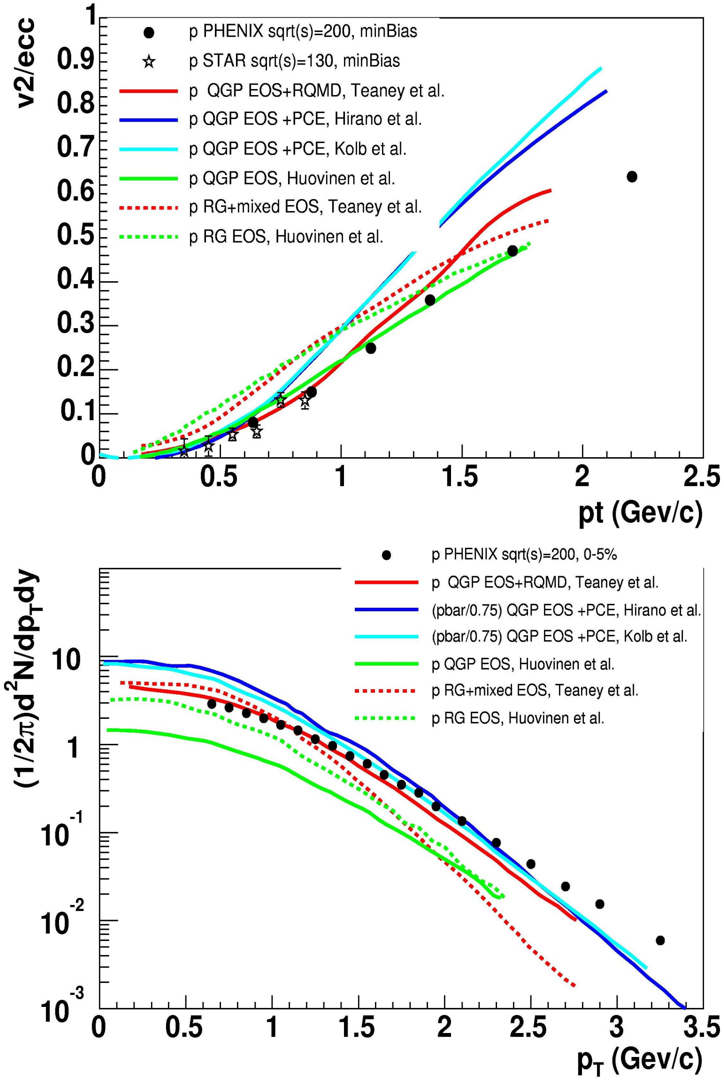
elliptic flow for different particle species and p_t at RHIC



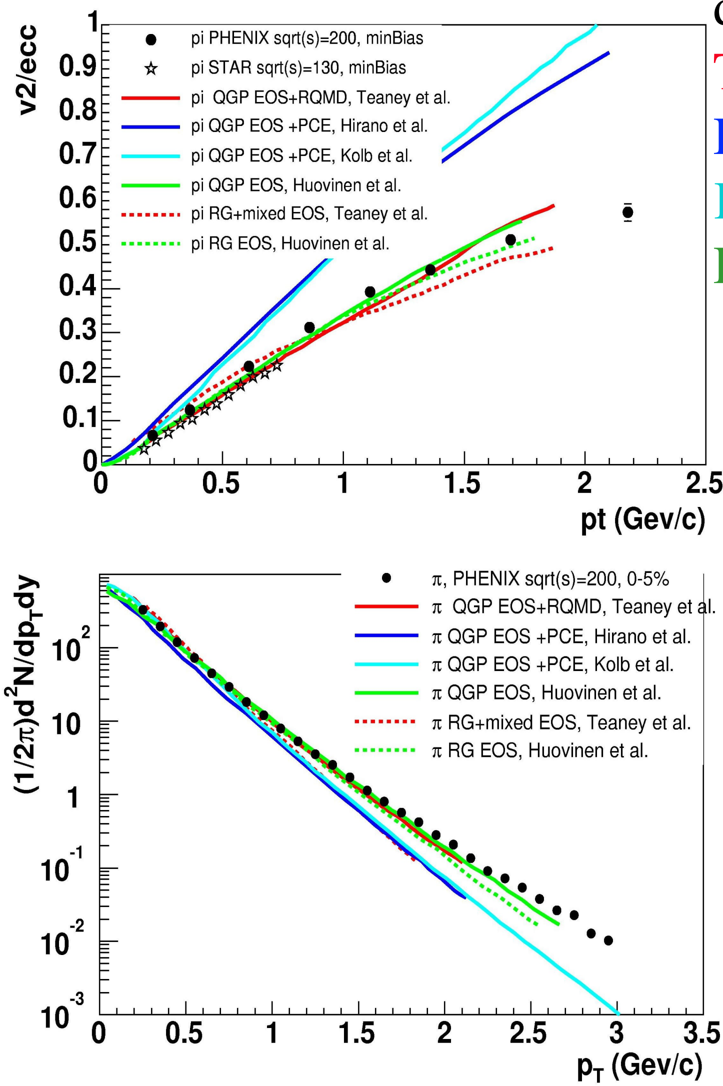
mass ordering typical effect of hydrodynamic expansion
ideal (nonviscous) hydrodynamics describes azimuthal asymmetries up to about 2 GeV/c at % level

hydrodynamics describes spectra and elliptic flow

proton



pion

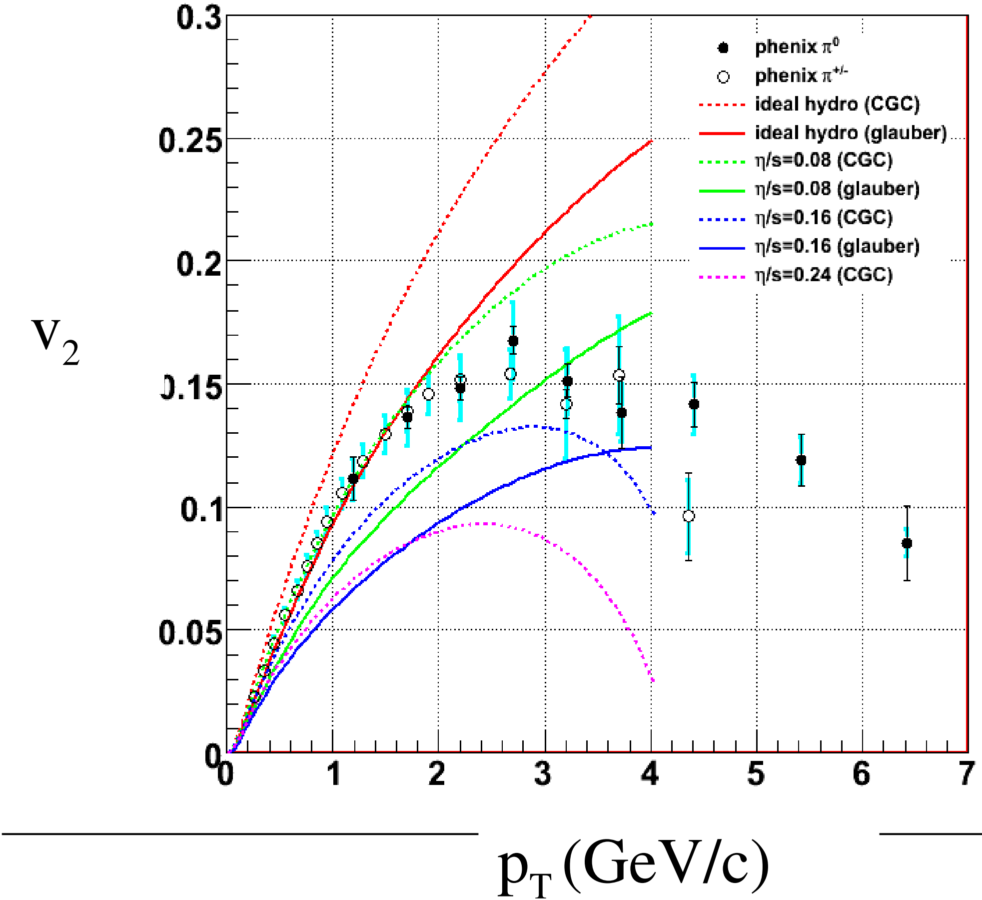


different hydrodyn. models:
Teaney *(w/ & w/o RQMD)*
Hirano *(3d)*
Kolb
Huovinen *(w/& w/oQGP)*

works up to $\simeq$ 2 GeV/c
but not perfectly
requires very fast equilibration (< 1 fm/c)
strong interactions
at short times
origin?

sQGP – strongly interacting quark-gluon plasma

low viscosity (maybe zero?) implies strong interactions
not ideal gas - actually this was realized from lattice results a long time
conjecture: QGP produced at RHIC is strongly interacting
lately a lot of excitement connected to AdS/CFT equivalence
suggested lower bound on ratio shear viscosity/entropy density $\eta/s = 1/4\pi$



viscous hydro very challenging
serious work is starting ...
see e.g. Romatschke arXiv 0706.1522

qualitative trends established
still many open issues when it comes to quantitative comparison to data

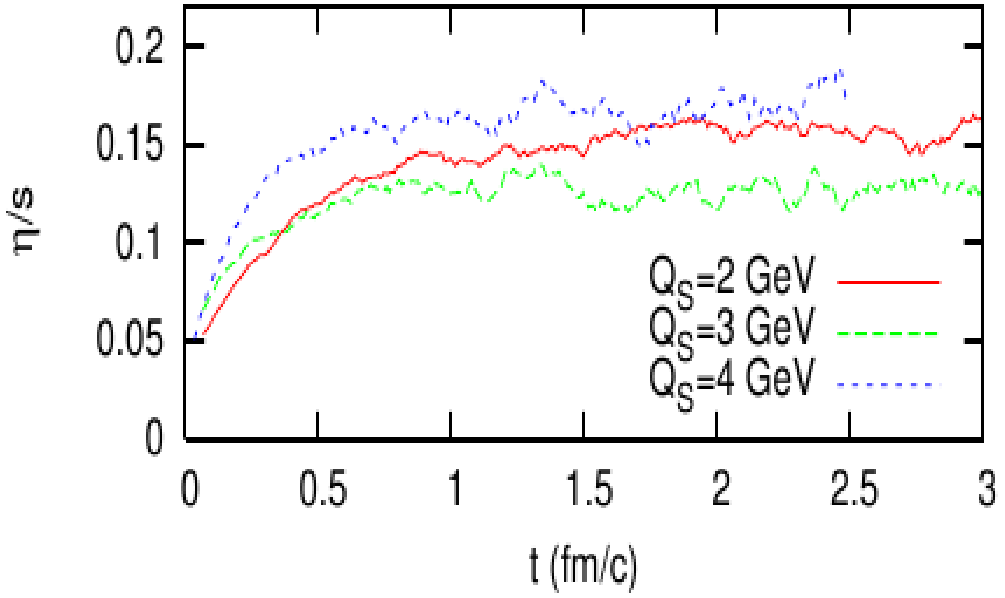
alternatively: theoretical determination of viscosity

determination of viscosity/entropy density from lattice QCD via correlation function of energy-momentum tensor

H.B.Meyer arXiv 0704.1801 [hep-lat]

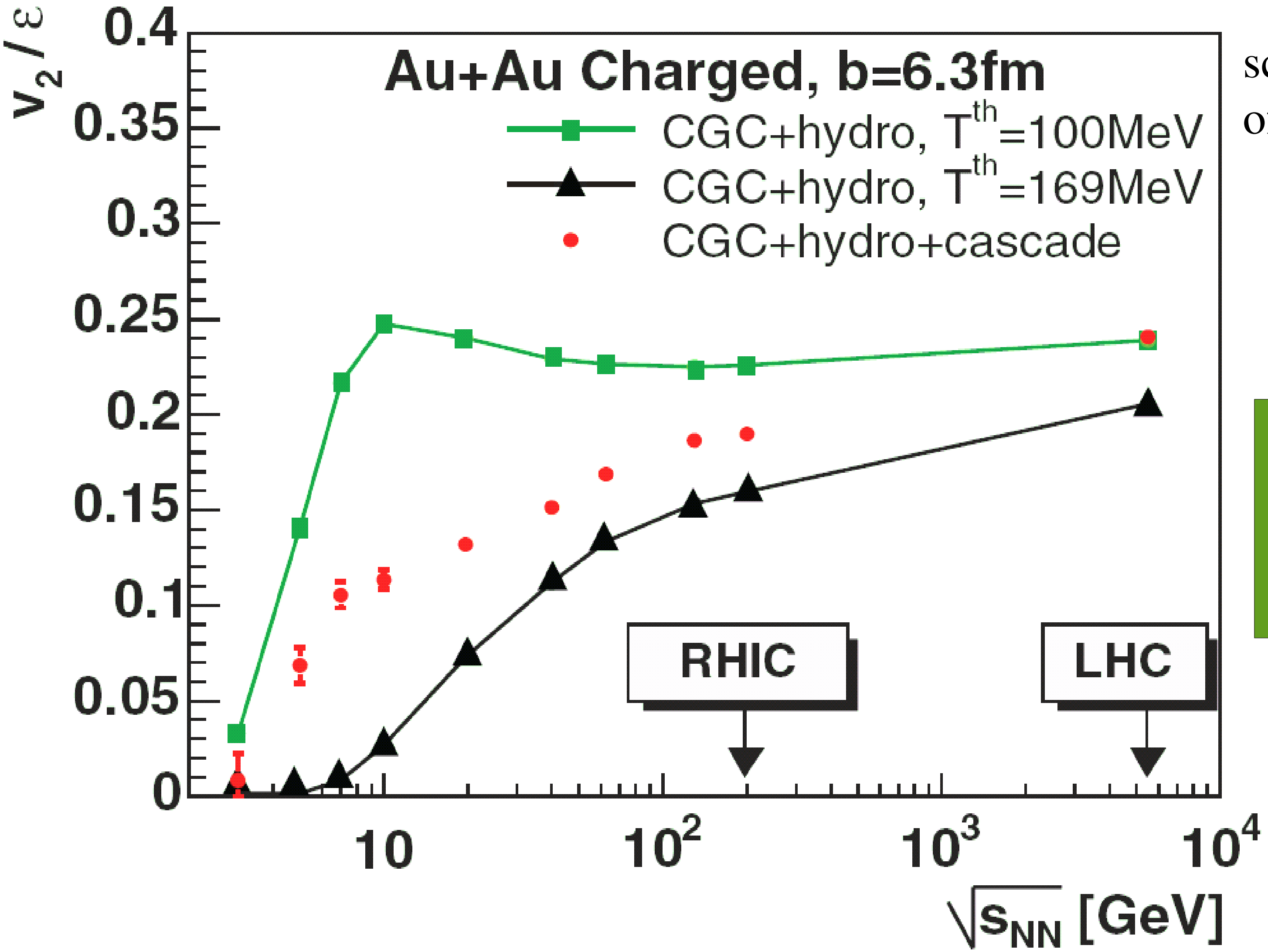
$\eta/s =$ 0.134(33) at T=1.65 Tc
0.101(45) 1.24

C. Greiner et al. using perturbative kinetic parton cascade get $\eta/s = 0.15$



at present all indications are:
for QGP $\eta/s < 0.2$
comparison: He close to critical point $\eta/s \simeq 1$

elliptic flow at LHC: most models predict stronger effects – sensitivity to initial and final condition and to EOS



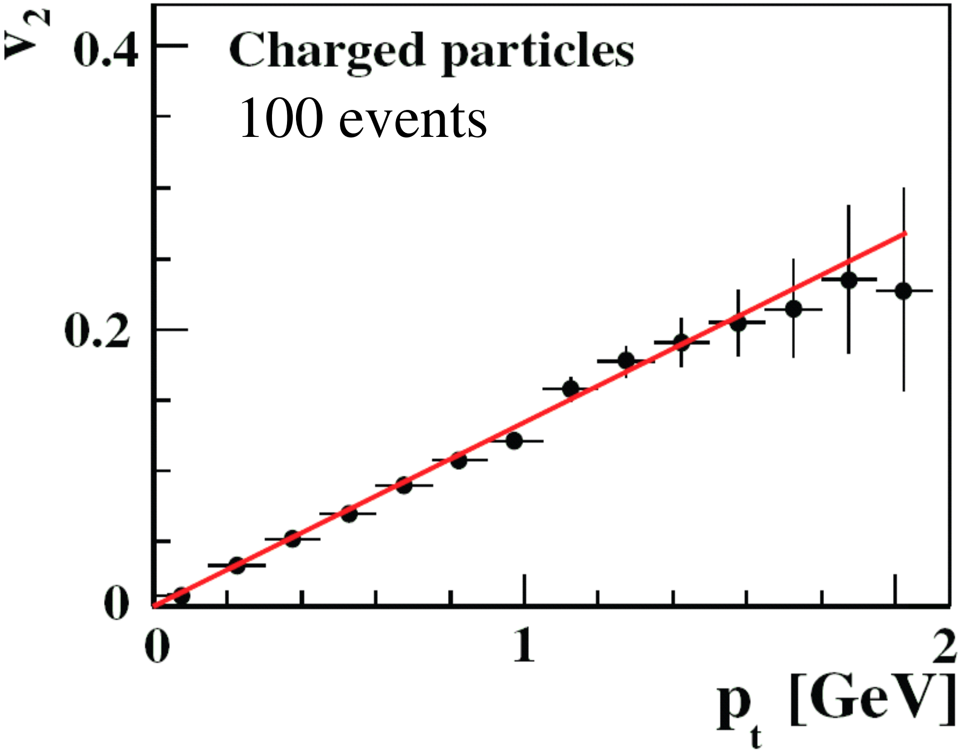
scaled to eccentricity of overlap region

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

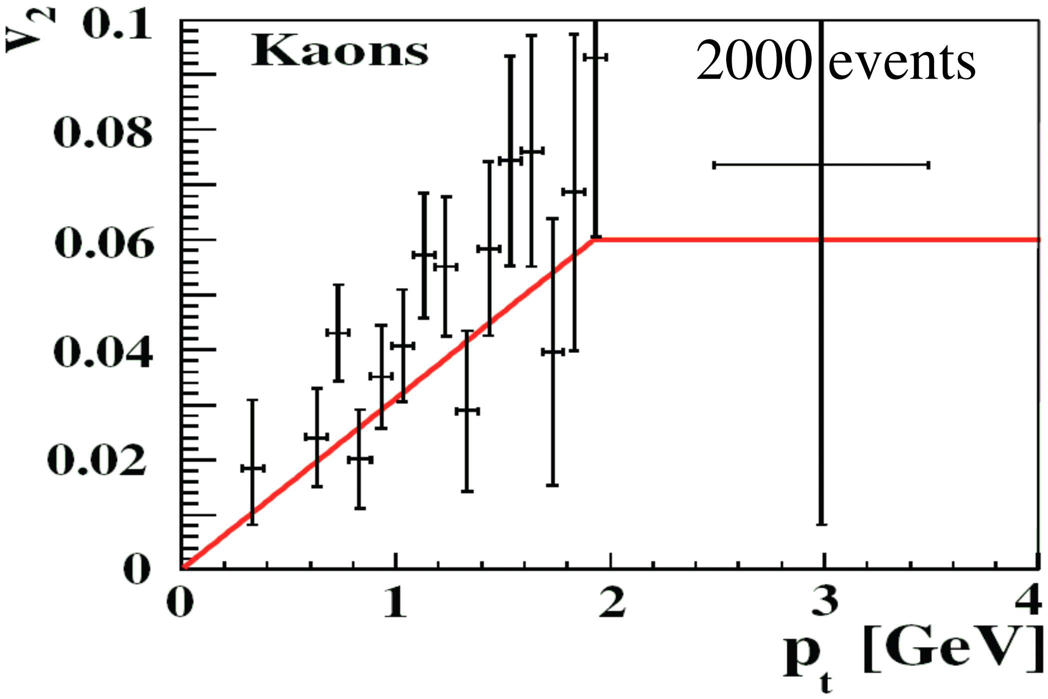
but at very high T the plasma could become weakly interacting

T. Hirano et al., J.Phys.G34 (2007)S879

how well will elliptic flow be measured in ALICE at LHC?



for 2000 charged particles:
reaction plane resolution 8°
statistics plentiful
good particle identification



3. charmonia as signature for deconfinement

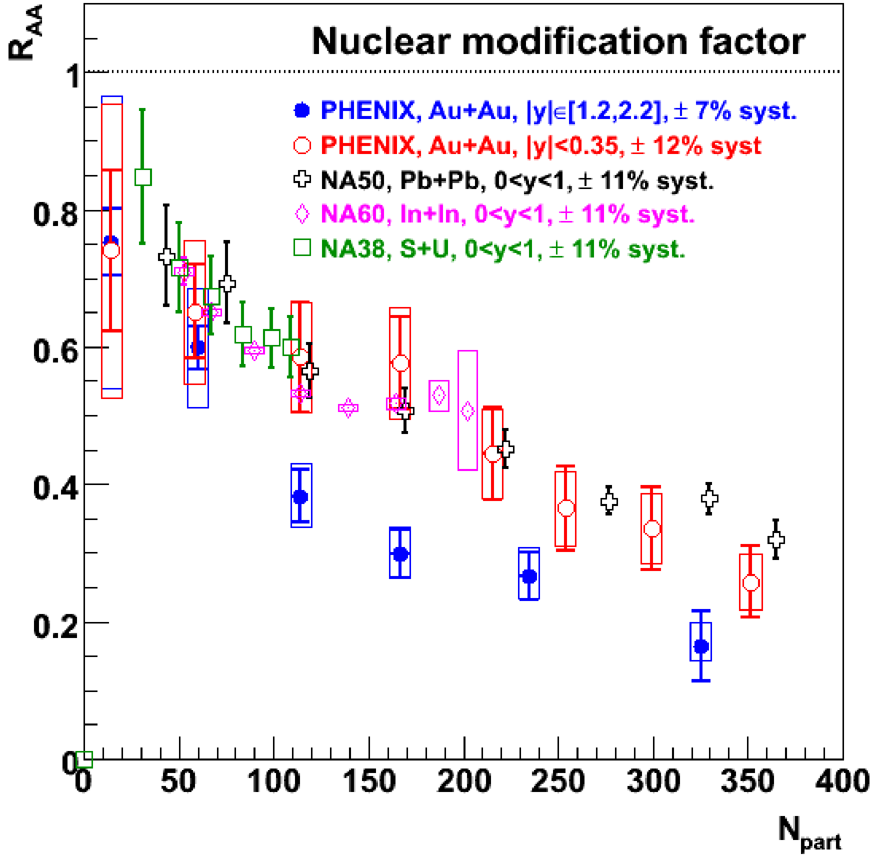
- T. Matsui and H. Satz (PLB178 (1986) 416) predict J/ψ suppression in QGP due to Debye screening

J/ψ 1 s state of ccbar
mass 3.1 GeV
radius 0.45 fm

- significant suppression seen in central PbPb at top SPS energy (NA50) in line with QGP expectations

J/ψ production in AuAu collisions at RHIC

PRL 98 (2007) 232301



R_{AA}: J/ψ yield in AuAu / J/ψ yield in pp times N_{coll}

at mid-rapidity suppression at RHIC very similar to SPS

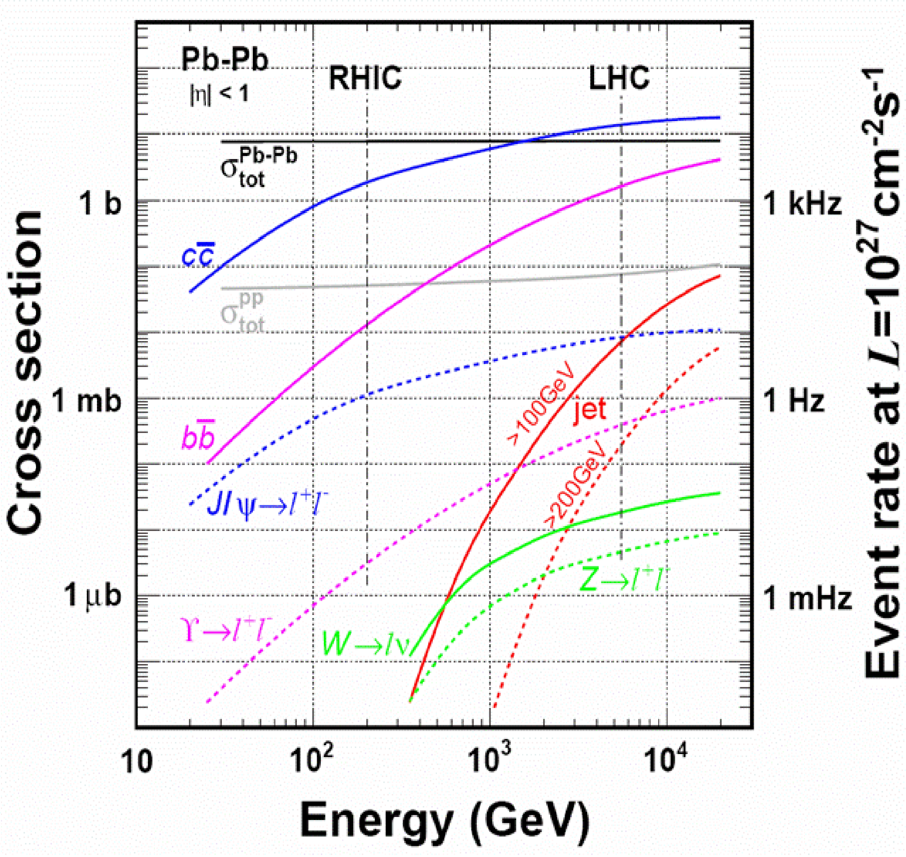
suppression at forward/backward rapidity stronger!

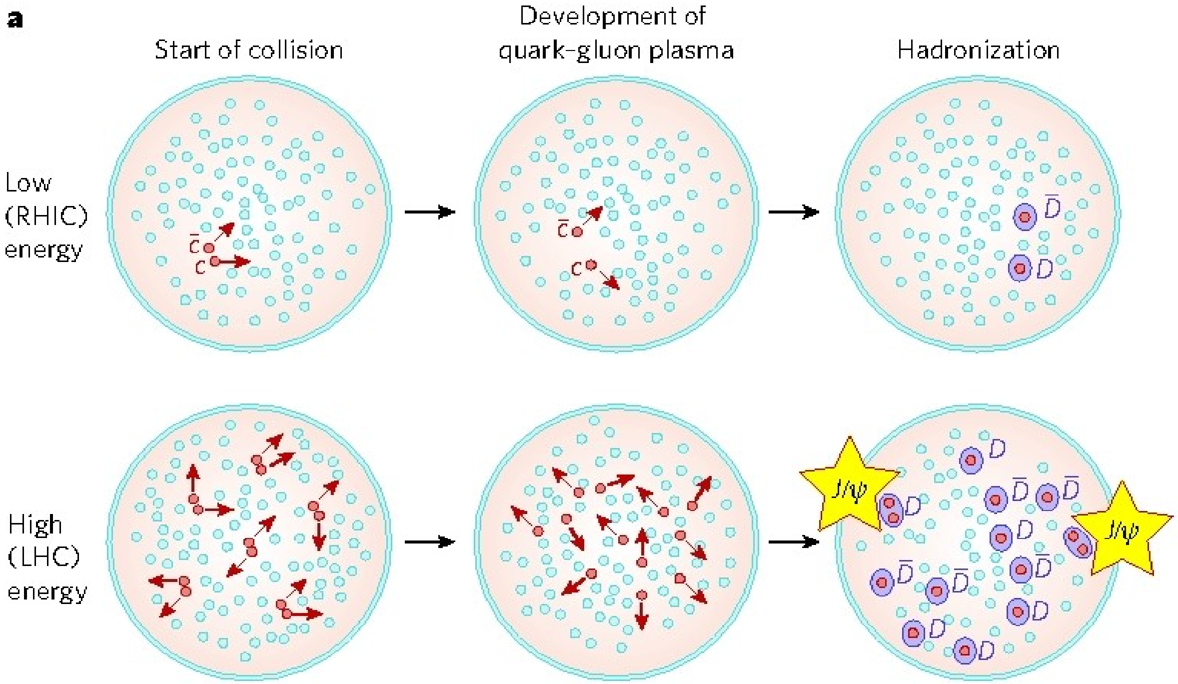
- but prediction:
  at hadronization of QGP
  J/ψ can form again
  from deconfined quarks,
  in particular if number of
  ccbar pairs is large

$$N_{J/\psi} \propto N_{cc}^{2}$$

(P. Braun-Munzinger and
J.Stachel, PLB490 (2000) 196)

what happens at higher beam energy when more and more charm-anticharm quark pairs are produced?





low energy: few c-quarks per collision → **suppression** of J/ψ

high energy: many “ “ → **enhancement** “

unambiguous signature for QGP!

quarkonium production through statistical hadronization

- assume: all charm quarks are produced in initial hard scattering; number not changed in QGP
- hadronization at T_c following grand canonical statistical model used for hadrons with light valence quarks (fugacity g_c to fix number of charm quarks)

$$N_{c\bar{c}}^{direct} = \frac{1}{2} g_c V (\sum_i n_{D_i}^{therm} + n_{\Lambda_i}^{therm}) + g_c^2 V (\sum_i n_{\psi_i}^{therm}) + \ldots$$

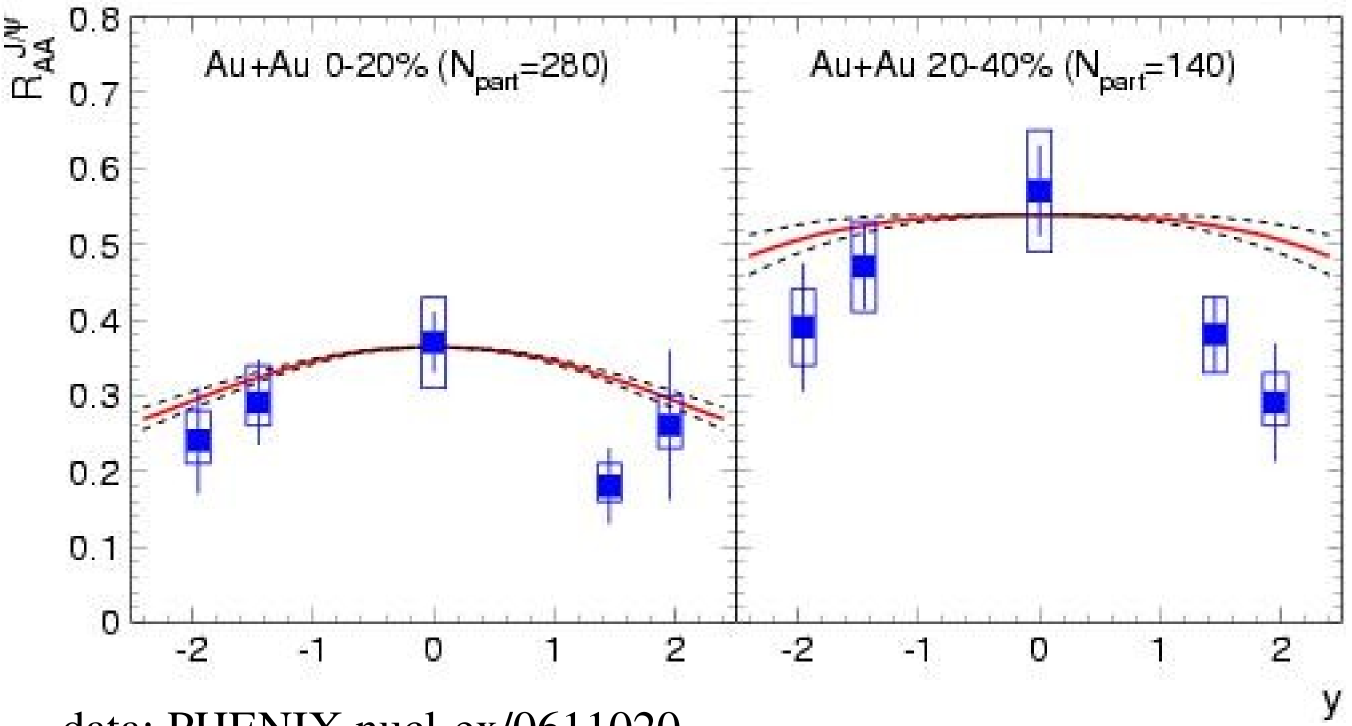
and for $N_{c,\bar{c}} << 1 \rightarrow$ canonical: $N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{therm} \frac{I_1(g_c N_{oc}^{therm})}{I_0(g_c N_{oc}^{therm})}$

obtain: $N_D = N_D^{therm} \cdot g_c \cdot \frac{I_1}{I_0}$ and $N_{J/\psi} = N_{J/\psi}^{therm} \cdot g_c^2$ and all other charmed hadrons

additional input parameters: $V, N_{c\bar{c}}^{dir}(pQCD)$

comparison of model predictions to RHIC data:

R_{AA}: J/ψ yield in AuAu / J/ψ yield in pp times N_{coll}



good agreement, no free parameters

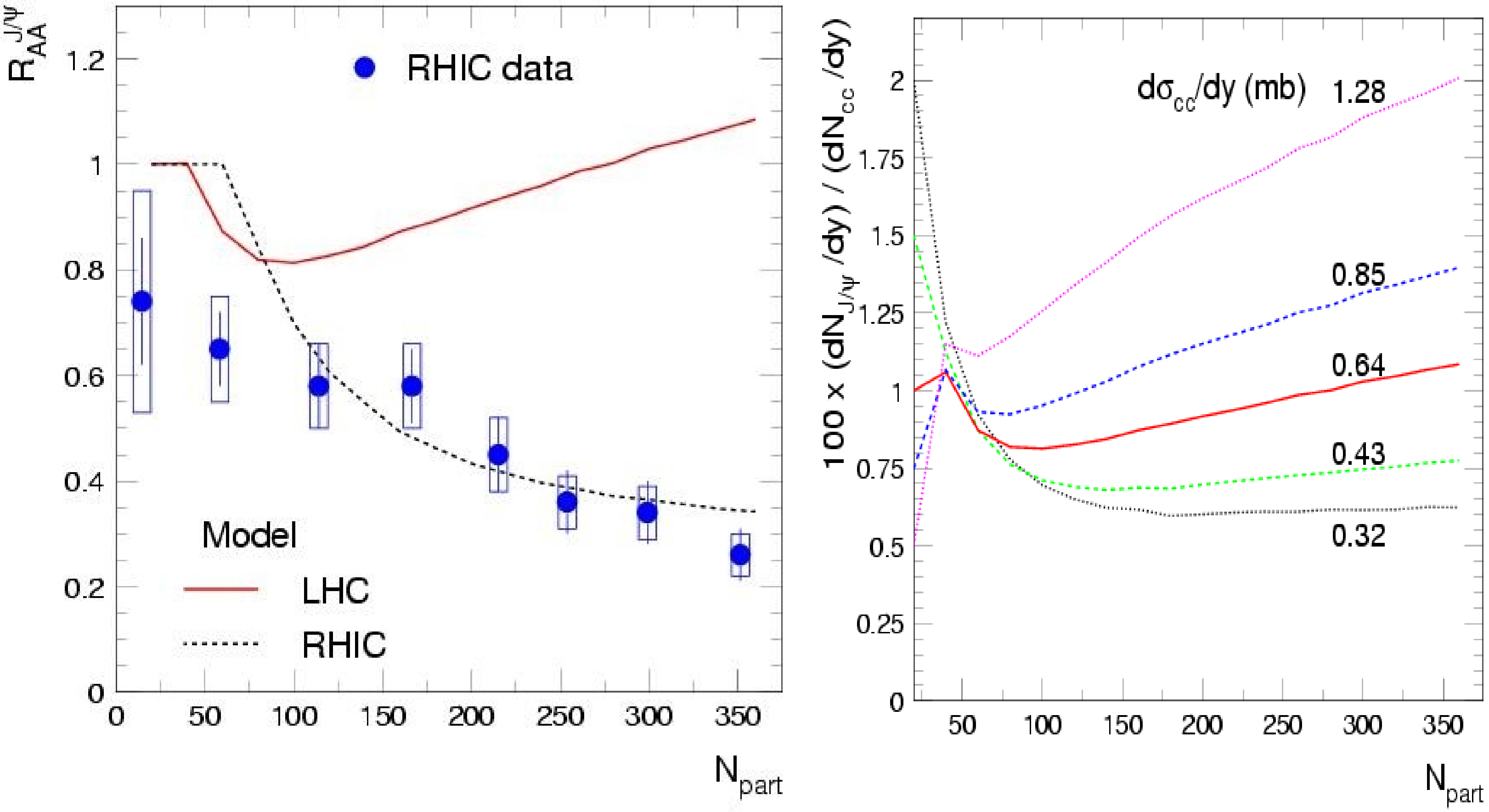
data: PHENIX nucl-ex/0611020
additional 14% syst error beyond shown

model: A. Andronic, P. Braun-Munzinger, K. Redlich,
J. Stachel Phys. Lett. B652 (2007) 259

remark: y-dep opposite in 'normal Debye screening' picture; suppression strongest at midrapidity (largest density of color charges)

energy dependence of quarkonium production in statistical hadronization model

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel Phys. Lett. B652 (2007) 259

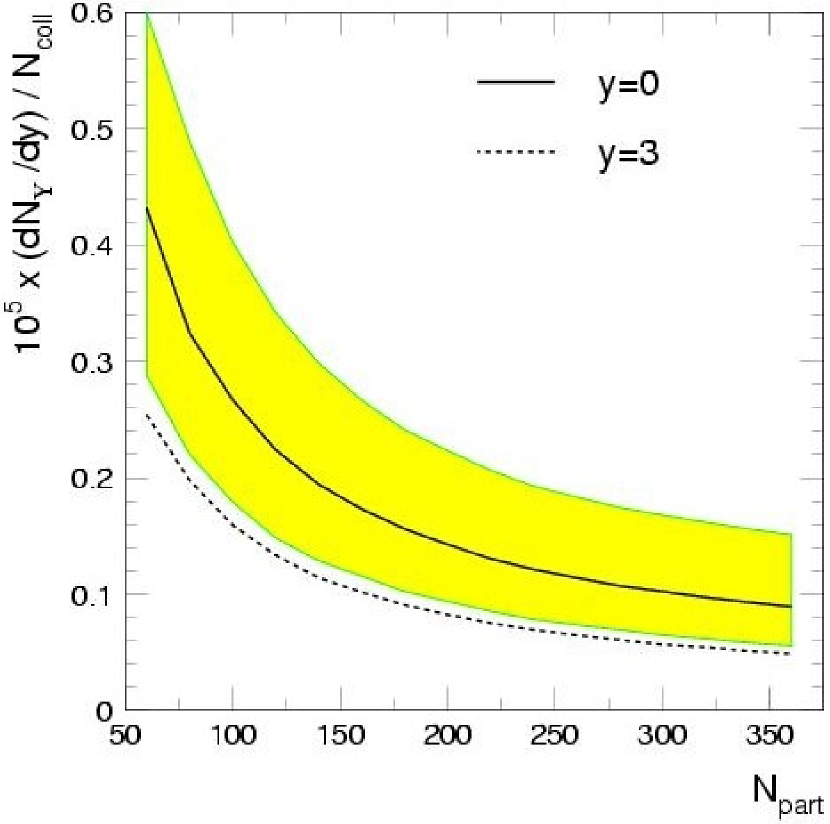


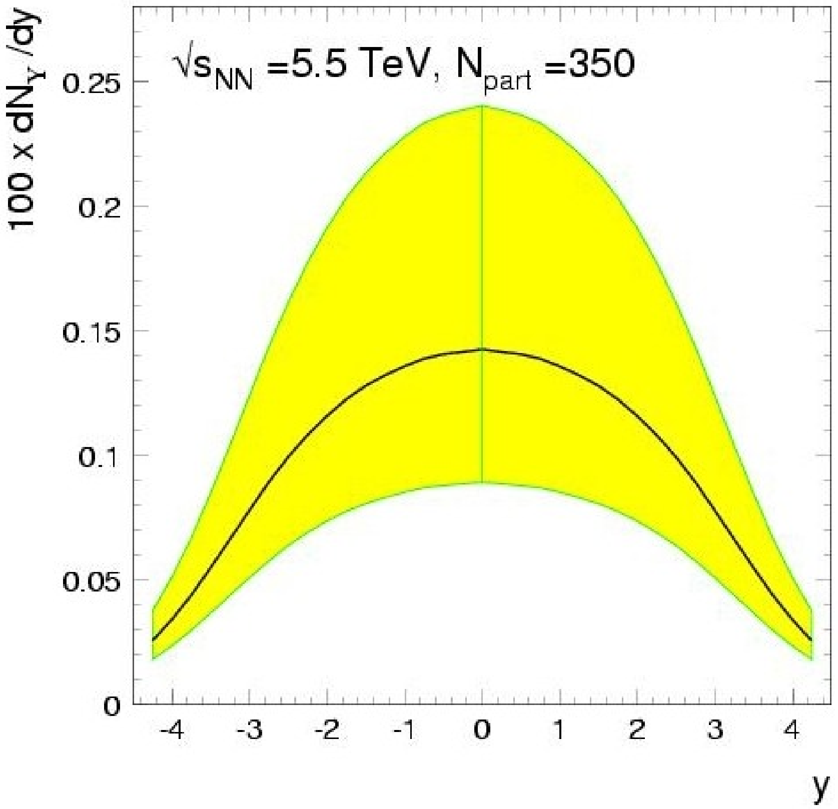
centrality dependence and enhancement beyond pp value will be fingerprint of statistical hadronization at LHC

-> direct signal for deconfinement

bottomonium at LHC

predictions with statistical hadronization model





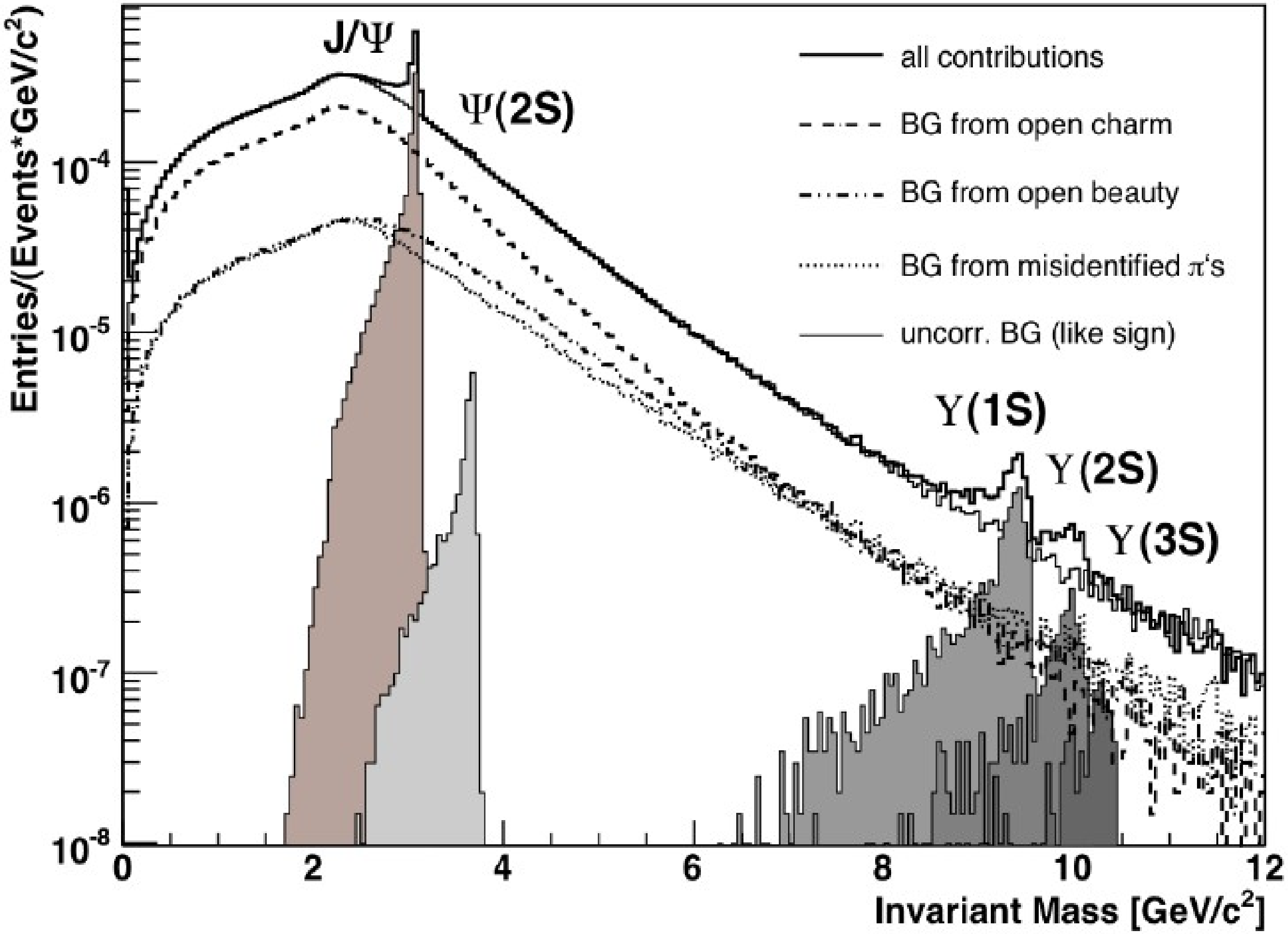
in terms of number of produced quarks, beauty at LHC like charm at RHIC

do they thermalize and hadronize statistically??

if yes, population of 2s and 3s states completely negligible (exp-Δm/T)

charmonia in ALICE at mid-rapidity

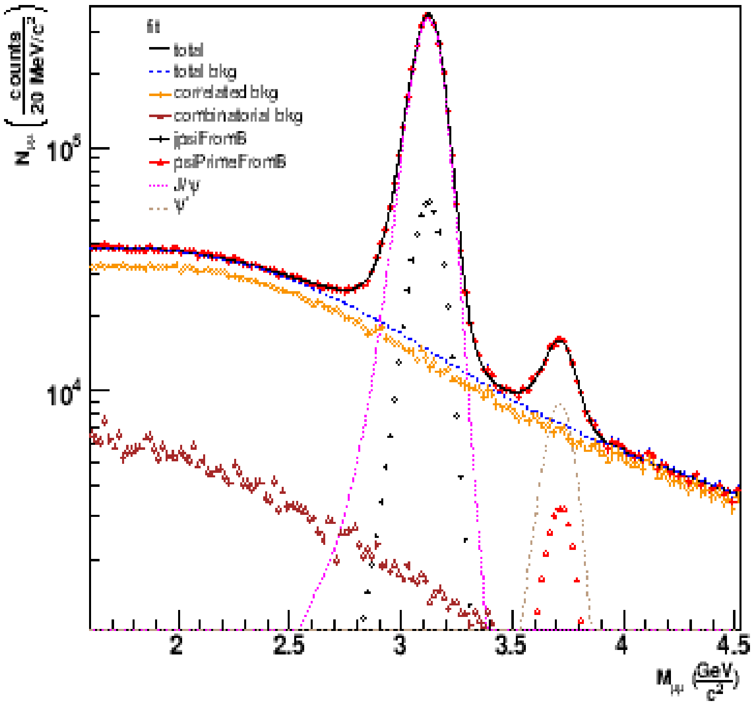
electron identification with TPC and TRD



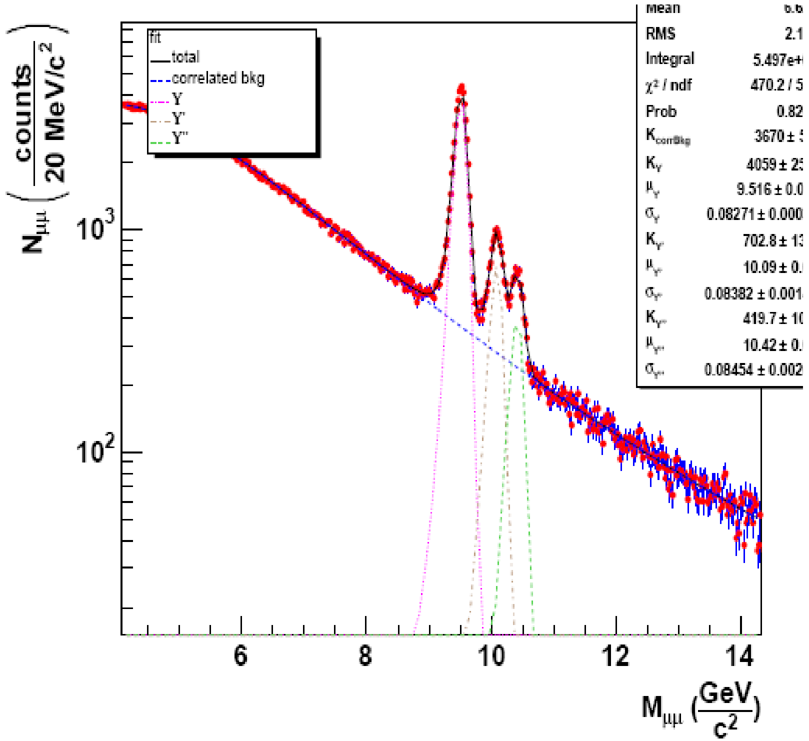
Simulation: W. Sommer (Frankfurt) $2 \cdot 10^8$ central PbPb coll.
corresponding to 1 month of LHC heavy ion running

Charmonia in the di-muon channel at y=2.4-4.0

700 000 J/psi and 6800 Upsilon for 2 10^8 PbPb collisions (1 month)



resolution 74 MeV



resolution 109 MeV

4. jet energy loss as probe of the QGP

jet: a parton (quark or gluon) from an initial hard scattering
hadronizes into a collimated cone of hadrons
typical cone angle < 1 rad
leading hadron carries 10-20 % of jet momentum, rest softer

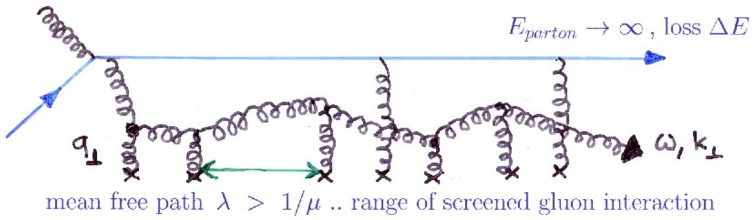
prediction: in dense partonic matter a jet is losing energy rapidly
order several GeV/fm

quark or gluon in medium with free color charge carriers

$$\mathrm{dE/dx} \propto \rho\, \sigma \langle \mathrm{k_t^2} \rangle\ \mathrm{L}$$

density of color charge carriers

transport coefficient $\hat{\mathrm{q}} \propto \rho\, \sigma \langle \mathrm{k_t^2} \rangle$



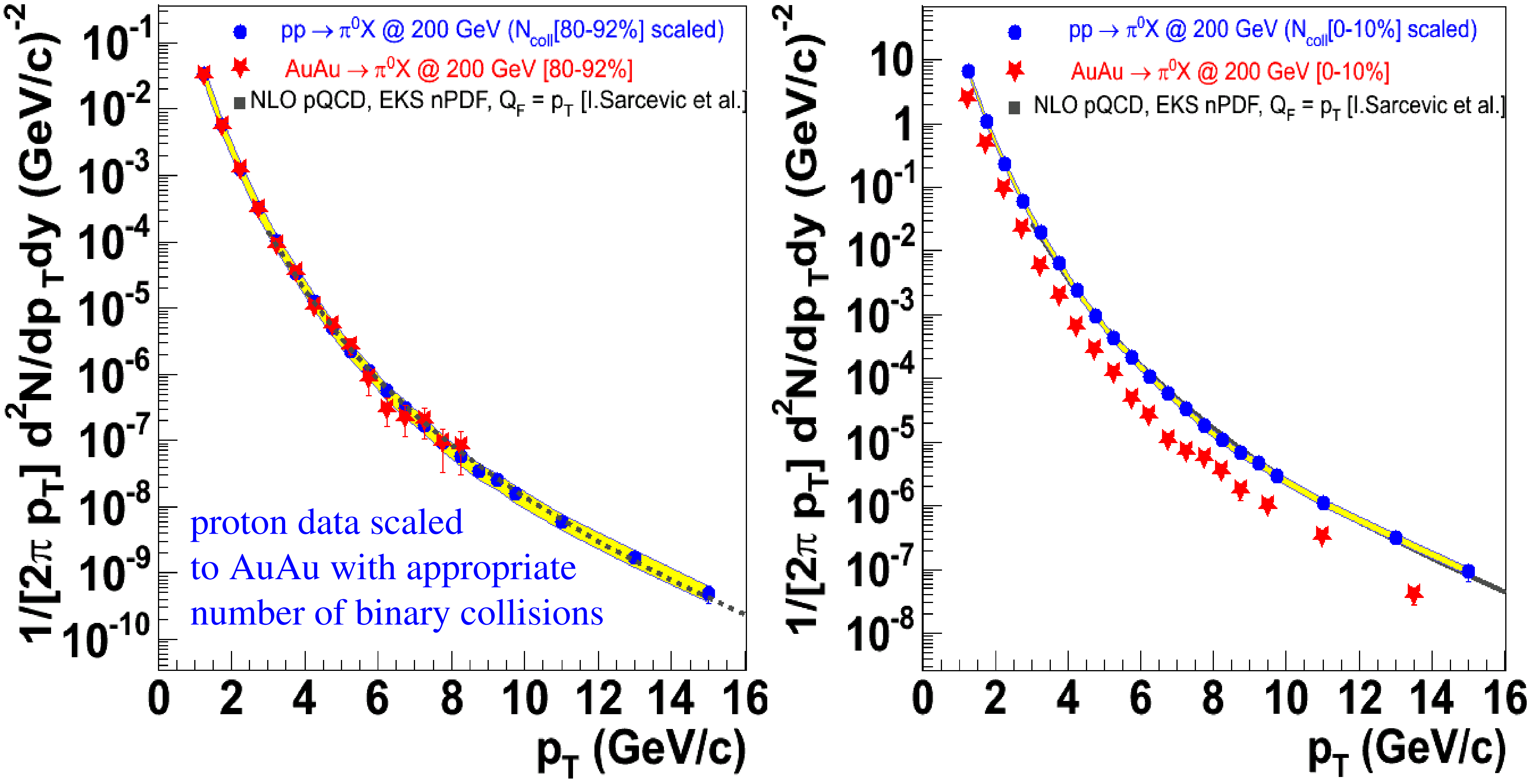
mean free path $\lambda > 1/\mu$ .. range of screened gluon interaction

vs QED (Bethe Bloch formula)

$$\mathrm{dE/dx} \propto \mathrm{n_e} \sigma_{\mathrm{ion}}$$

leading hadron distribution in pp and AuAu

PHENIX PRL 91 (2003) 072305 and 241803

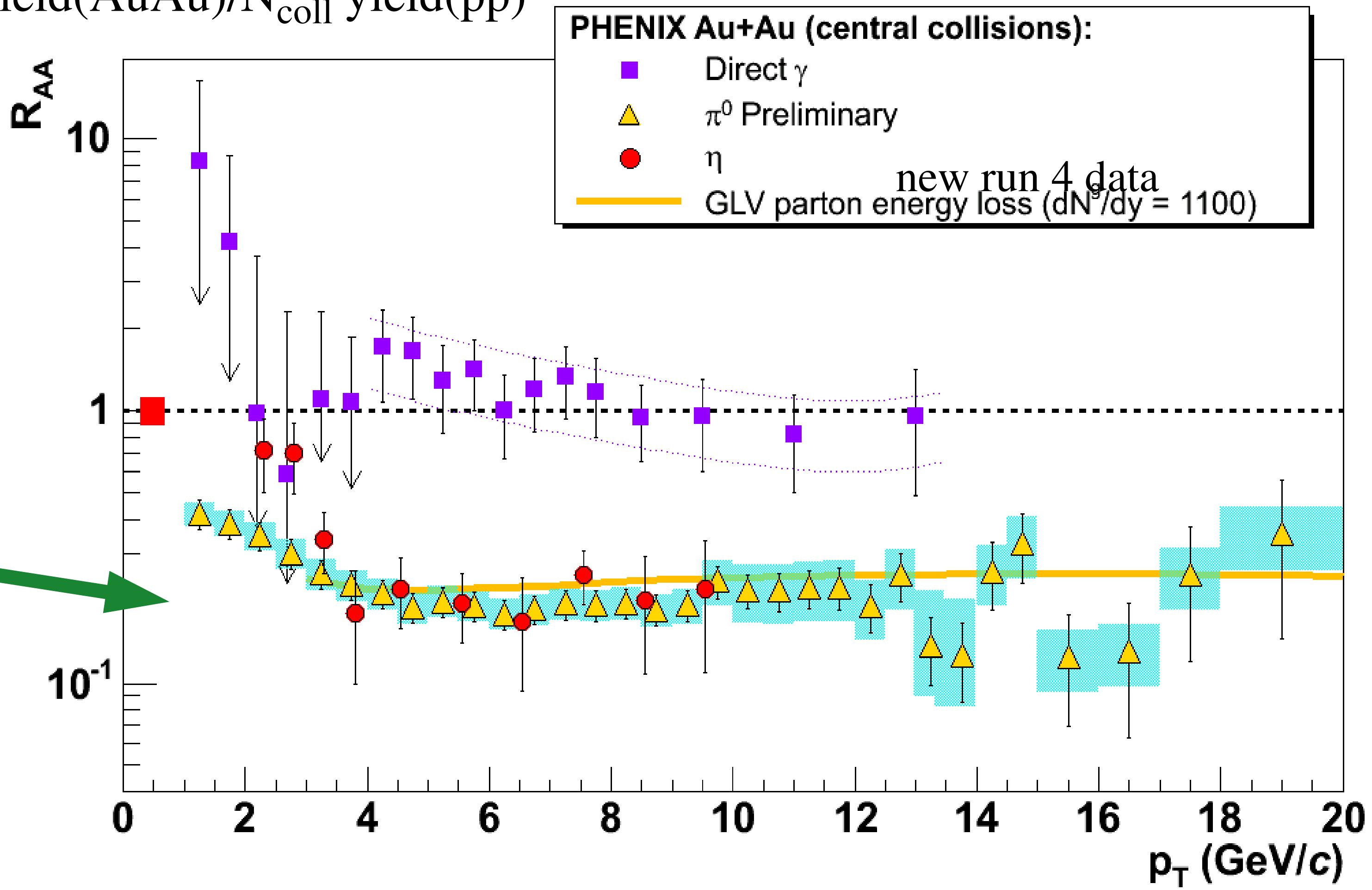


proton data scaled
to AuAu with appropriate
number of binary collisions

at high p_t: spectra suppressed in AuAu relative to pp

RHIC result: jet quenching

R_{AA}=yield(AuAu)/N_{coll} yield(pp)



high gluon density of the plasma induces energy loss of partons

most calculations based on radiation

photons: $R_{AA} \simeq 1$ initial hard interactions understood

jet quenching indicative of high gluon rapidity density

I. Vitev, JPG 30 (2004) S791

	$\tau_0[fm]$	$T[MeV]$	$\varepsilon[GeV/fm^3]$	$\tau_{tot}[fm]$	dN^g/dy
SPS	**0.8**	**210-240**	**1.5-2.5**	**1.4-2**	**200-350**
RHIC	**0.6**	**380-400**	**14-20**	**6-7**	**800-1200**
LHC	**0.2**	**710-850**	**190-400**	**18-23**	**2000-3500**

- **Consistent estimate with hydrodynamic analysis**

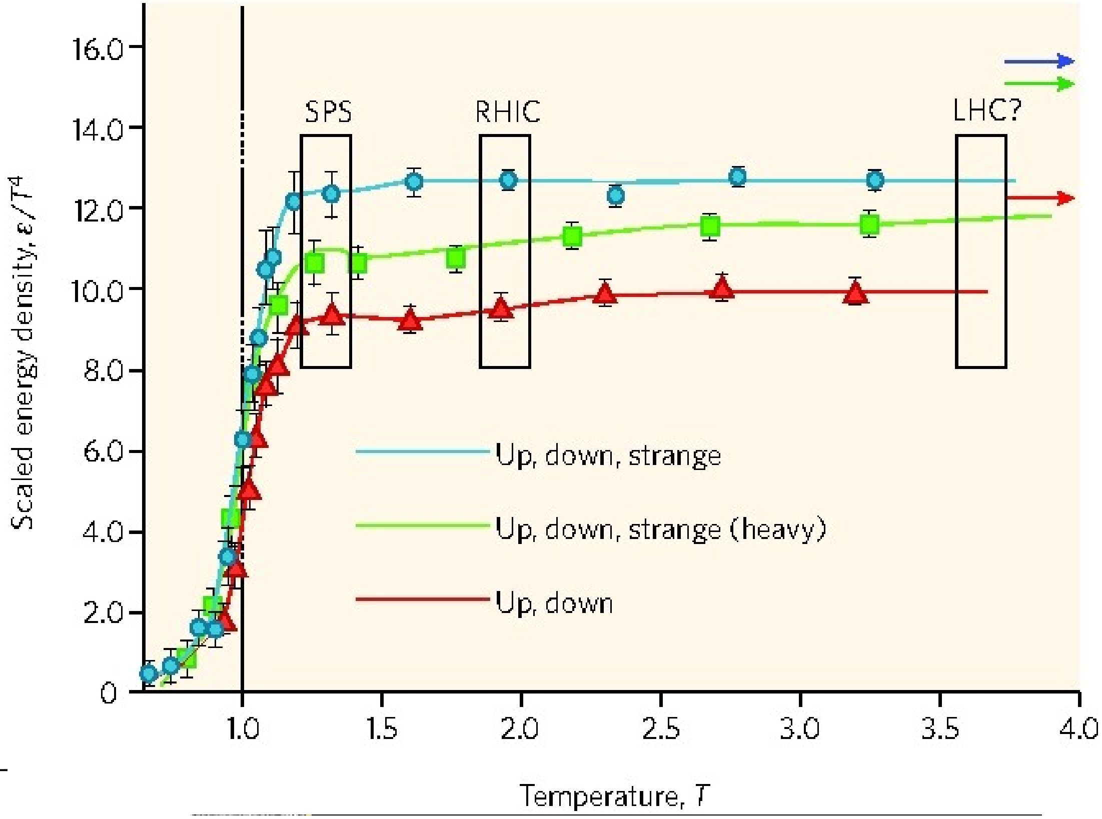
several mechanisms describe jet quenching at RHIC -> predictions for LHC span very wide range

- R_{AA} stays at 0.2 out to 100 GeV or so
- R_{AA} rises slowly toward high pt
- R_{AA} much smaller than at RHIC

need to cover large p_t range

go beyond leading particle analysis

identified jets, frag. function, ...



jet measurements in ALICE

Mini-Jets 100/event 1/event 1 Hz 100k/month

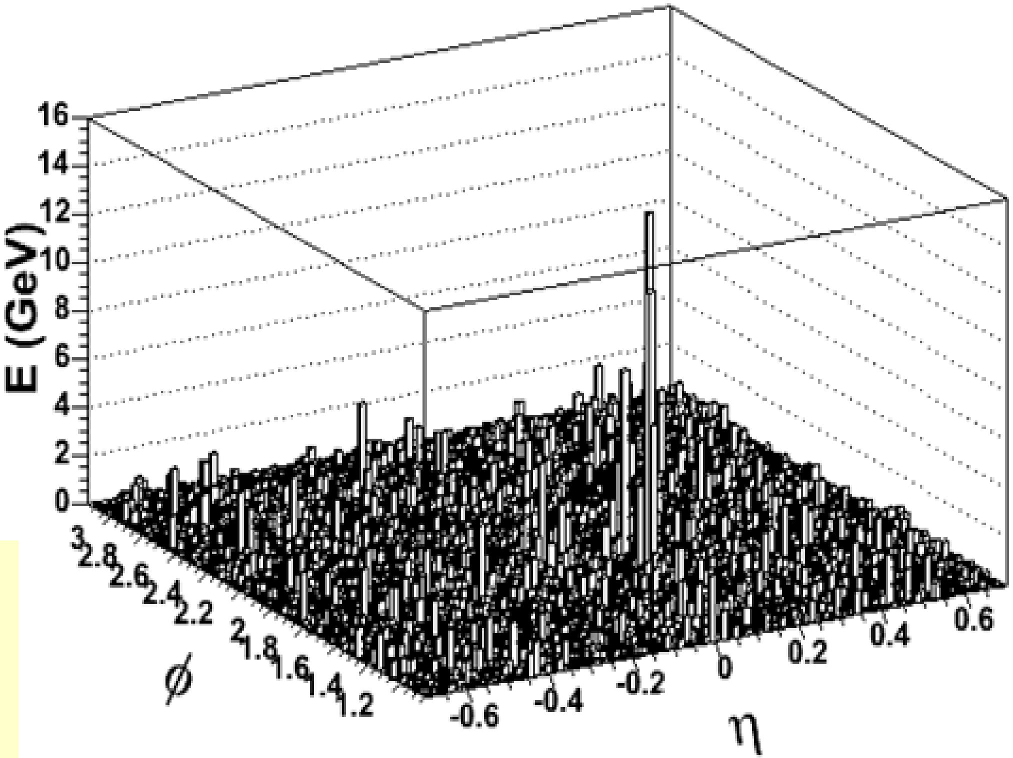
at p > 2 GeV/c :

- leading particle analysis
- correlation studies (similar to RHIC)

at high p:

- reconstructed jets
- event-by-event well distinguishable objects

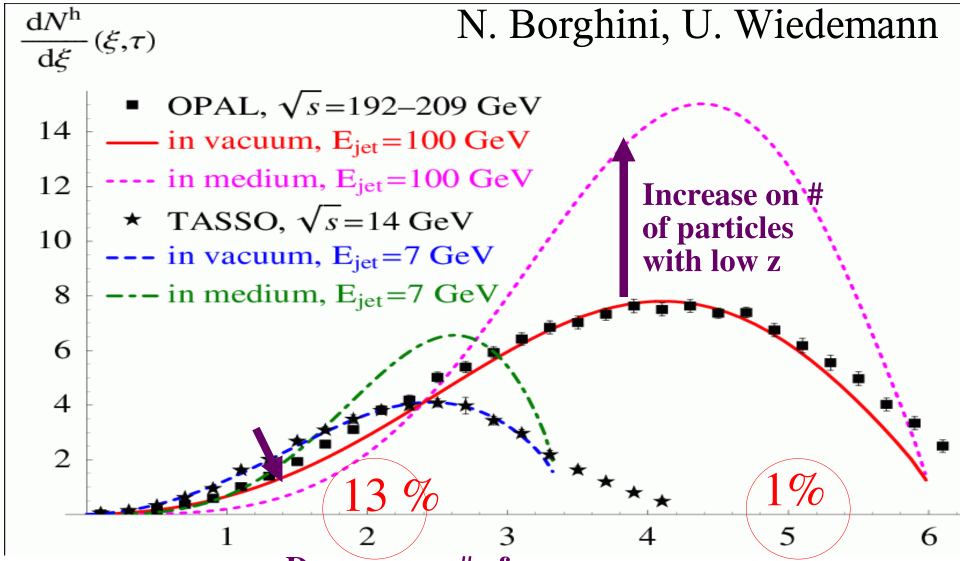
Example :
100 GeV jet +
underlying event



for jet physics recently added EmCal will play important role in conjunction with existing charged particle tracking

measurement of jet fragmentation function

z: energy fraction carried by leading hadron - sensitive to energy loss mechanism

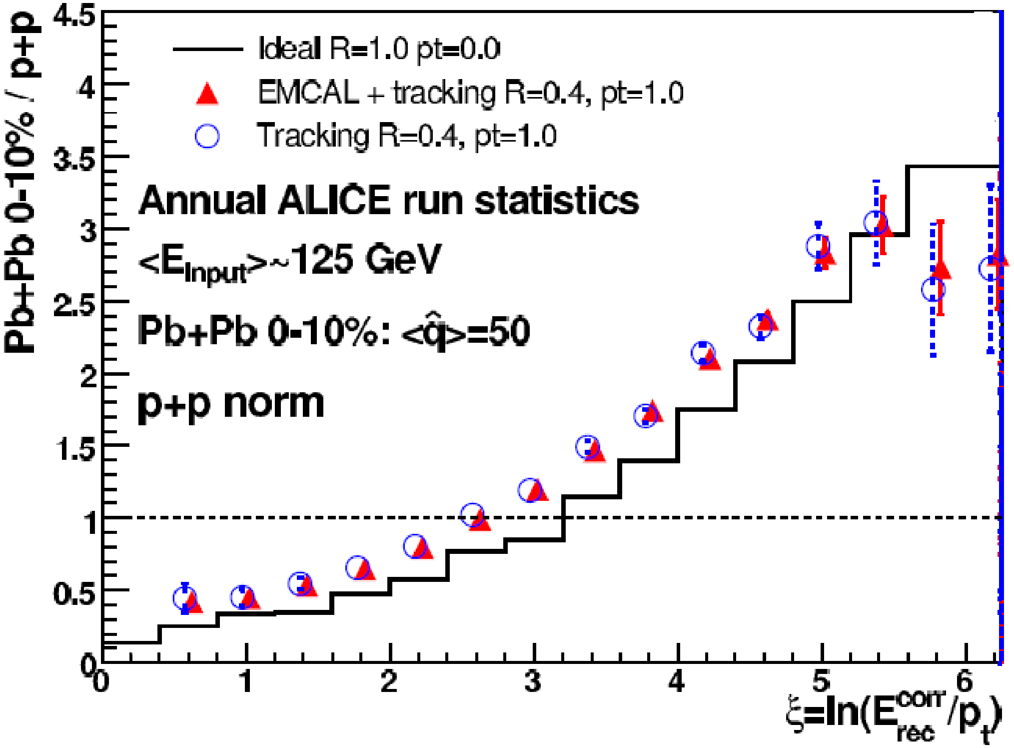


N. Borghini, U. Wiedemann

Increase on # of particles with low z

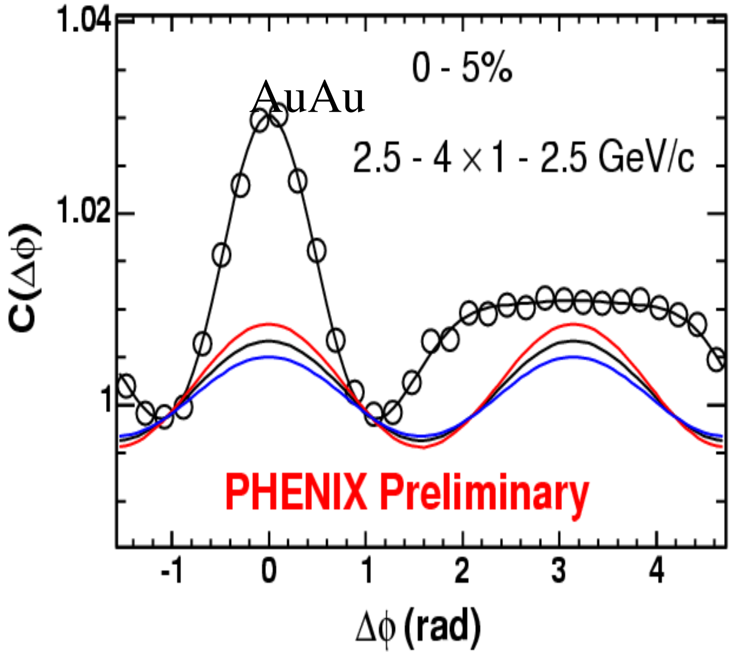
Decrease on # of particles with high z

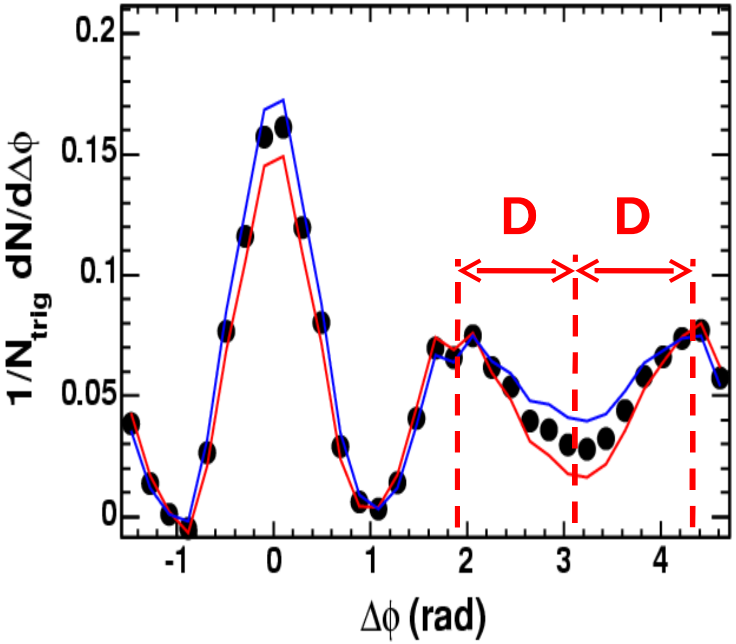
$\xi = \ln(1/z)$



good reconstruction
in ALICE

correlations between 2 leading particles from jets
response of the medium to jet energy loss





expect: back to back peaks - but after subtraction of elliptic flow background find hole of width 2D in middle of 180 deg peak

possibility: sonic shock waves – supersonic ($v>c_s$) partons produce shock waves propagating at a Mach angle w.r.t. the parton direction: cos(D)~ c_s

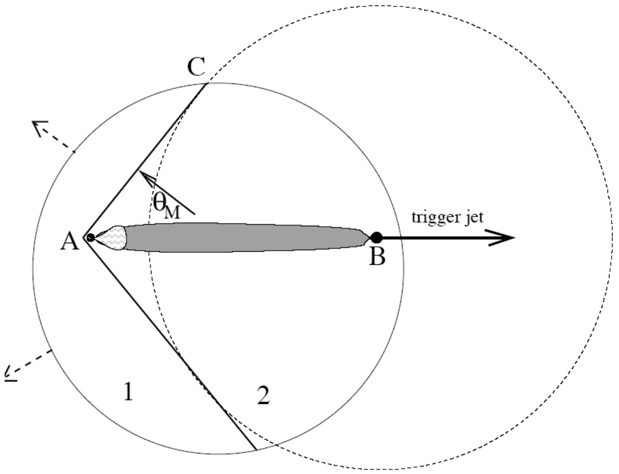
sound velocity is related to the EOS of the medium: $c_s^2 = \partial p/\partial \varepsilon$

ideal gas has c_s^2

original idea: Stöcker/Greiner 1976 for nuclear reactions

Stöcker 2004: 60º cone for jets in QGP and simultaneously

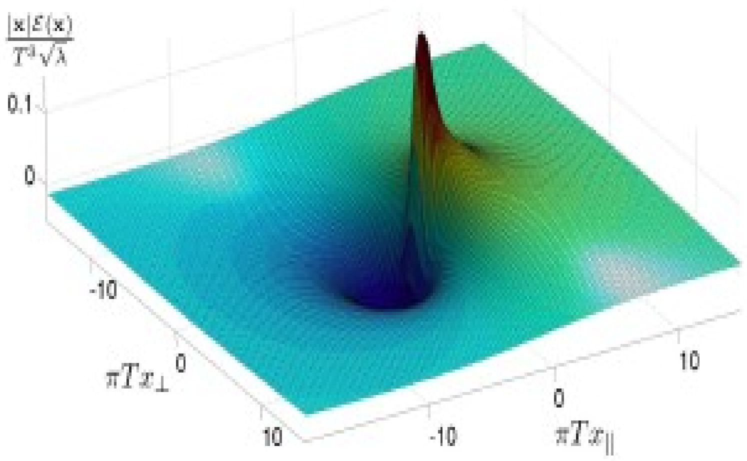
–J.Casalderrey-Solana,E. Shuryak, D. Teaney,hep-ph/0411315



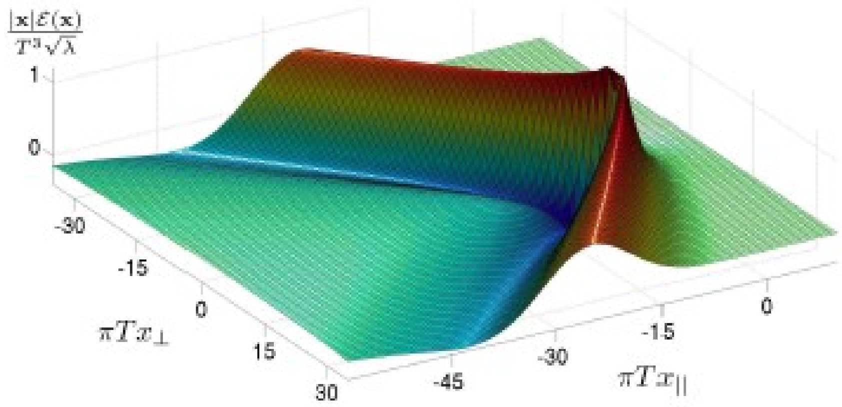
application of gauge/string duality

allows to compute observables probing nonequilibrium dynamics of thermal N=4 supersym. Yang-Mills theory, such as rate of energy loss of heavy quark moving through SYM plasma

compute energy transferred from moving quark to plasma



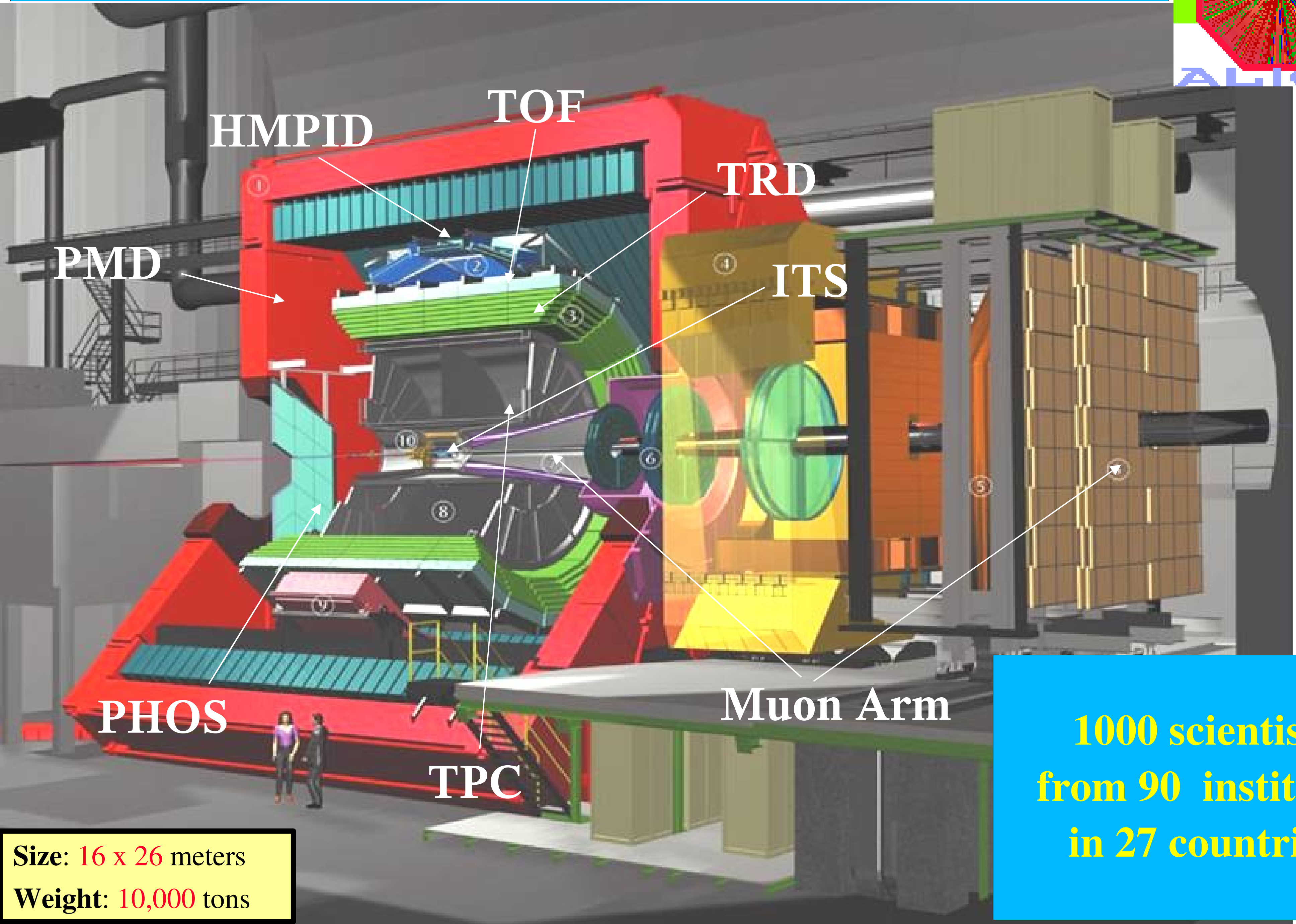
subsonic



supersonic

P.M.Chesler & L.G. Yaffe arXiv: 0706.0368 [hep-th]

ALICE

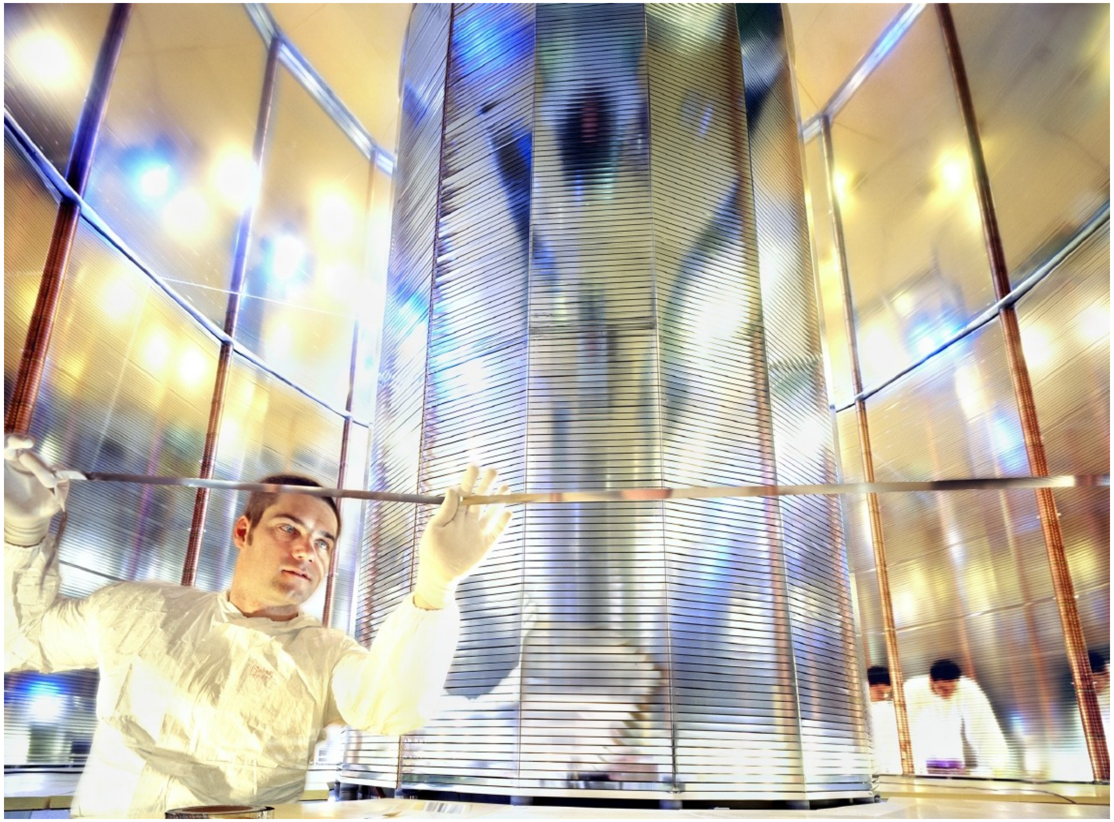


Size: 16 x 26 meters
Weight: 10,000 tons

1000 scientists
from 90 institutes
in 27 countries

the TPC (Time Projection Chamber) - 3D reconstruction of up to 15 000 tracks of charged particles per event

with 95 m^3 the largest TPC ever

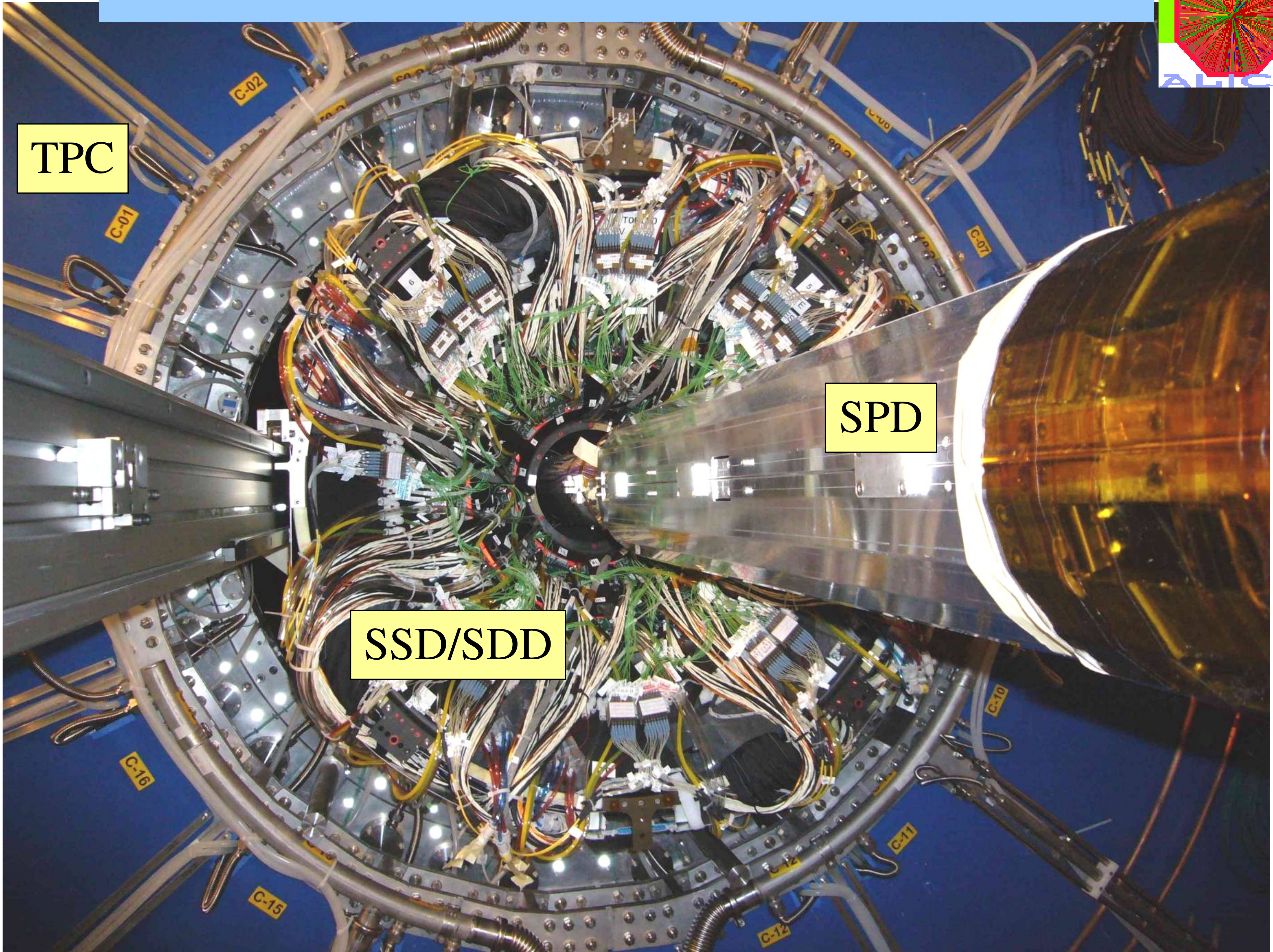


560 million read-out pixels!

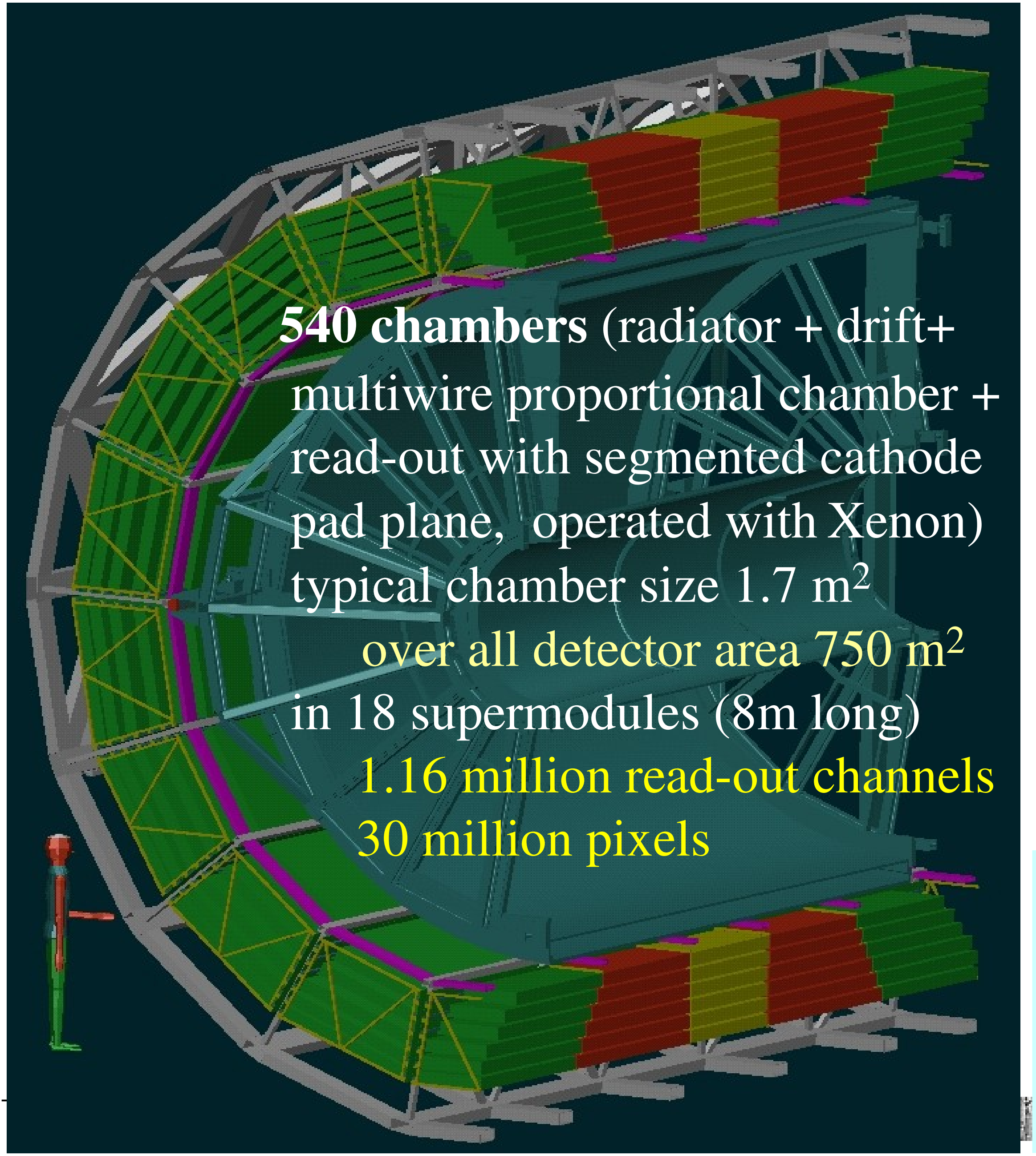
precision better than 500 µm in all 3 dim.

180 space and charge points per track

ITS Russian Dolls - Sliding the SSD/SDD over the SPD



the TRD (Transition Radiation Detector) identifies electrons at the trigger level



540 chambers (radiator + drift+ multiwire proportional chamber + read-out with segmented cathode pad plane, operated with Xenon)

typical chamber size 1.7 m^2

over all detector area 750 m^2

in 18 supermodules (8m long)

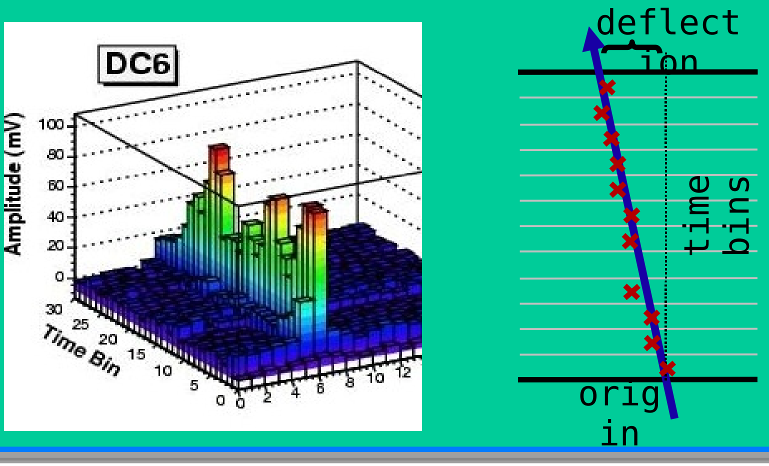
1.16 million read-out channels

30 million pixels

read-out electronics: 2 custom ASICS on multichip modules developed at PI and KIP in Heidelberg

from charge-clustern zu track segments

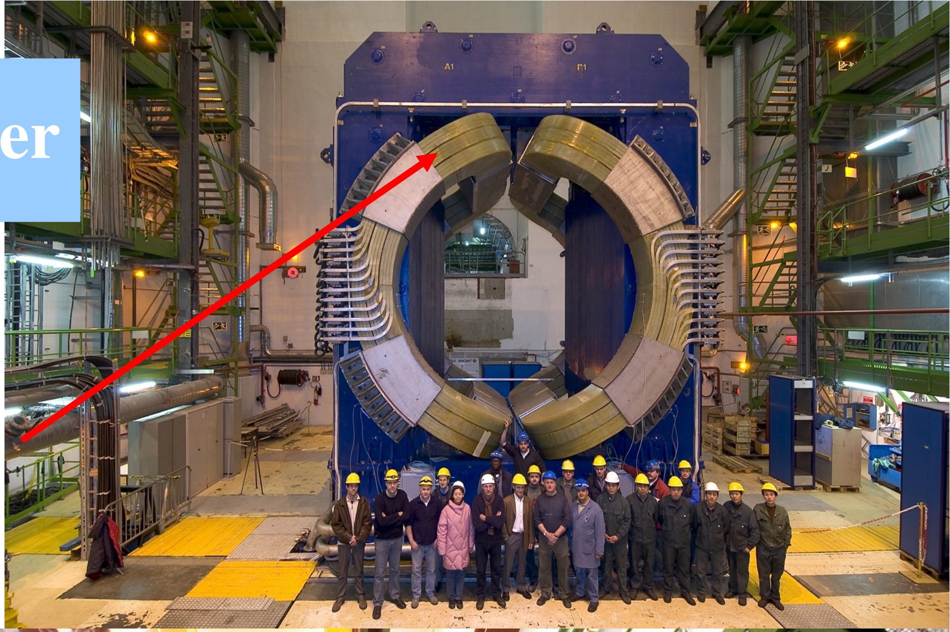
500 cpu Local Tracking Unit on each chamber:



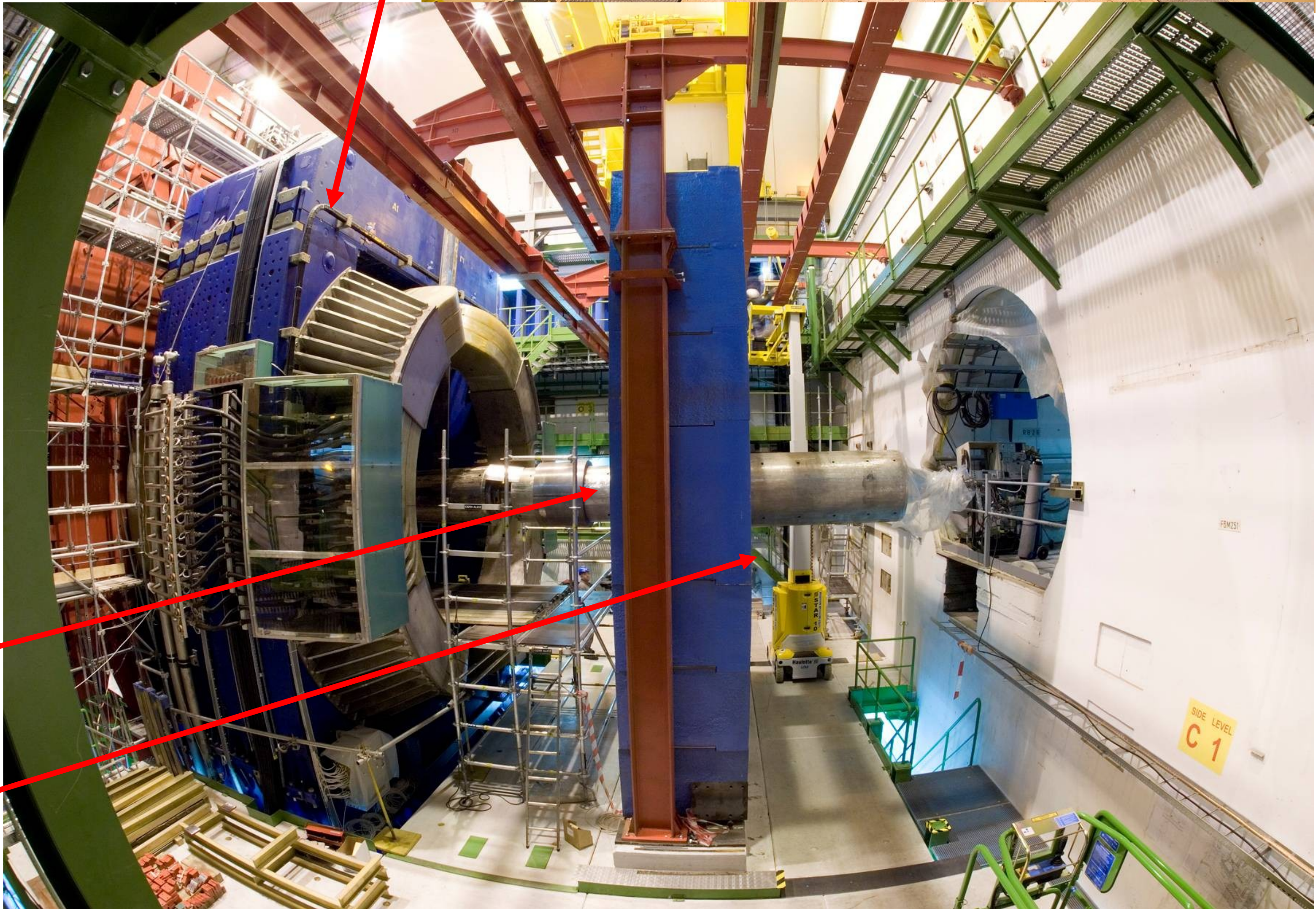
275 000 CPU's process raw data of 65 Mbyte to reconstruct tracks (of 6 segments) in 6.5 µs for trigger decision:

high momentum electron pair

ALICE (Di)-Muon Spectrometer



dipole magnet

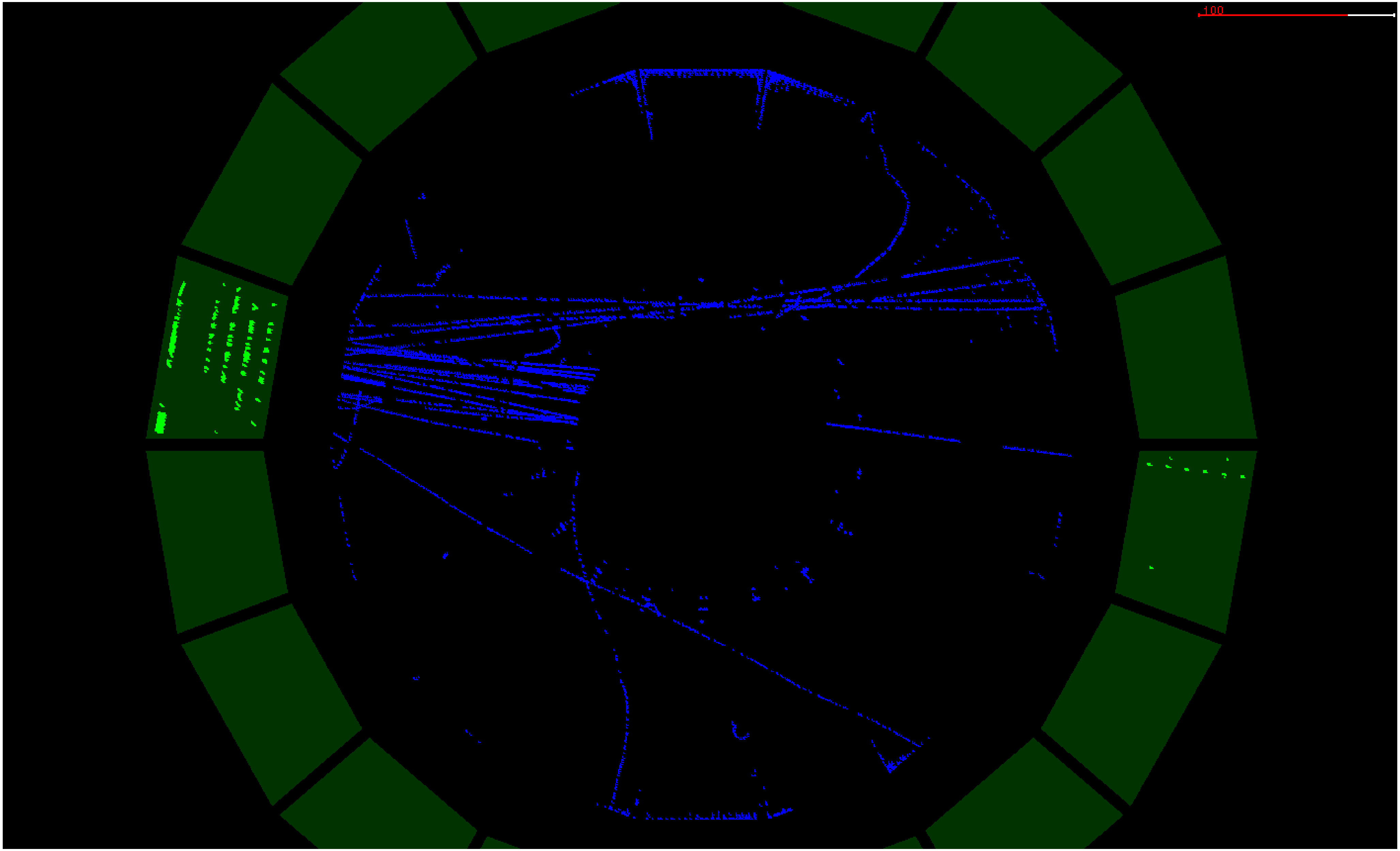


muon chambers

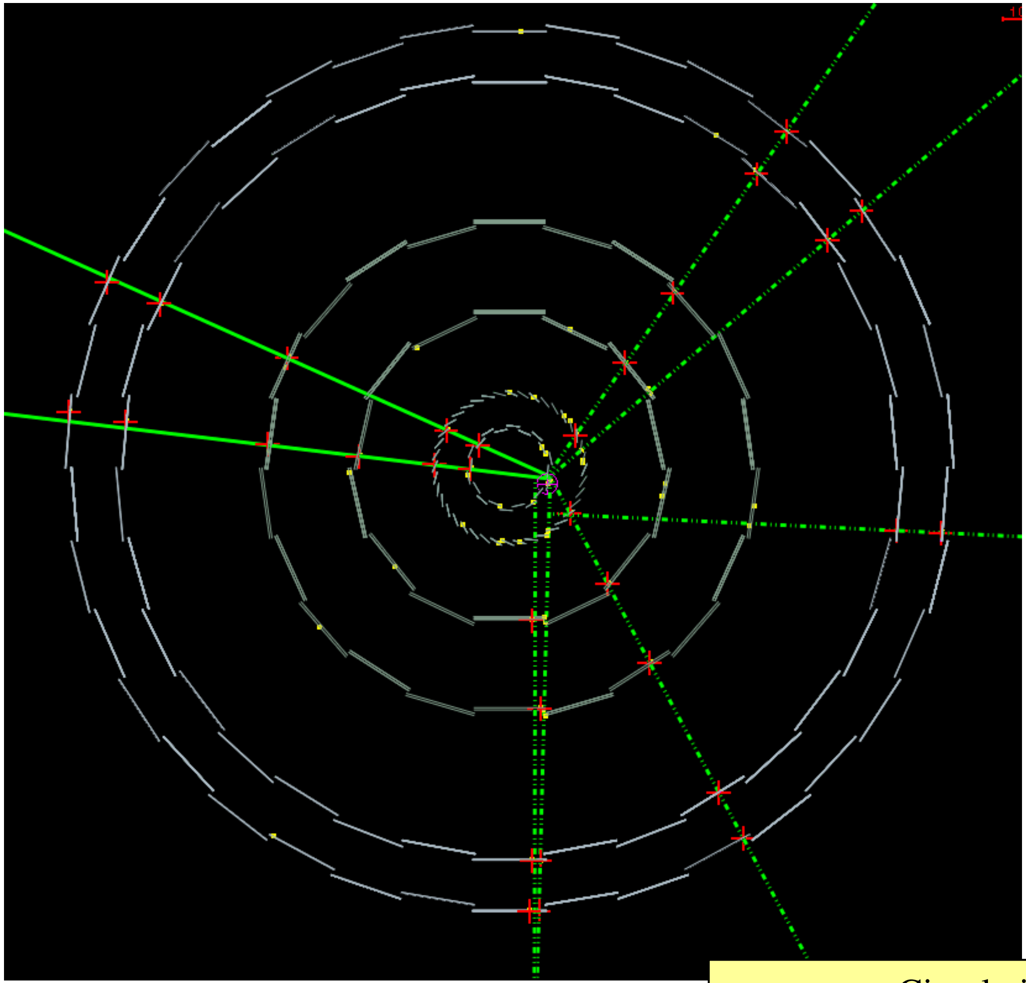
muon absorber

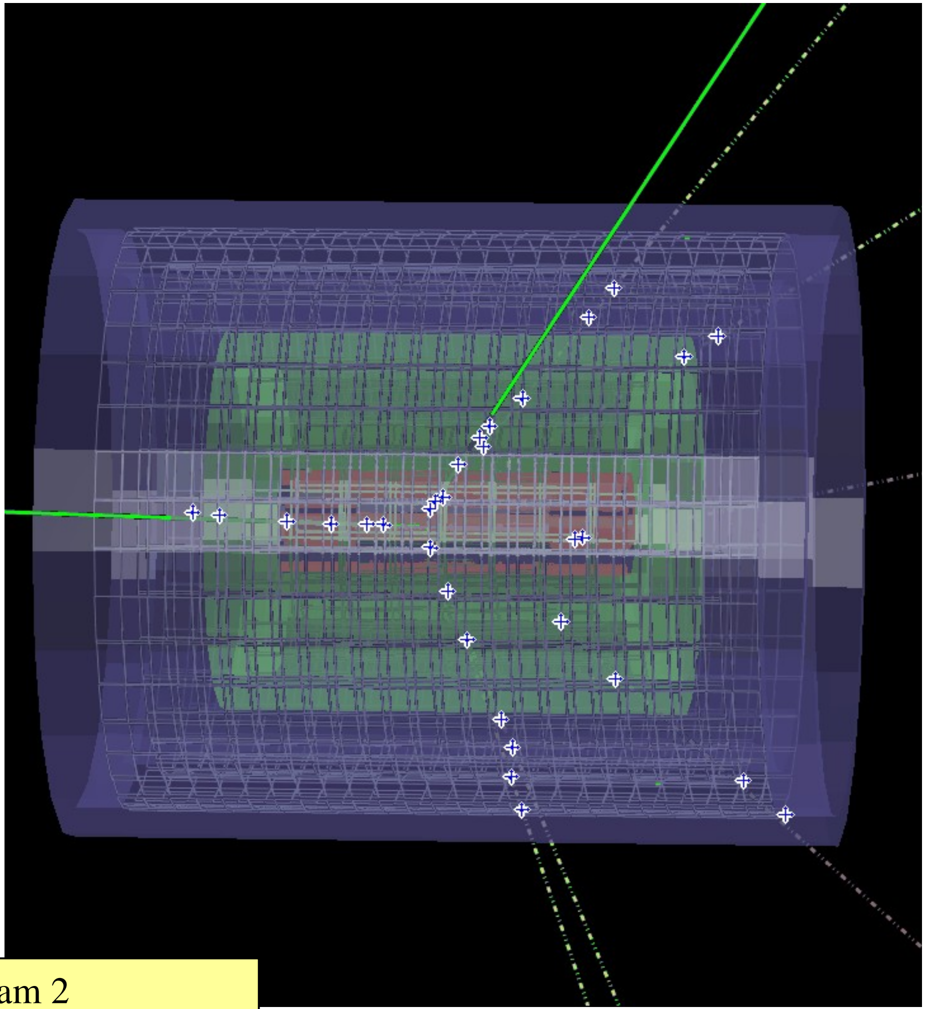
muon filter

cosmic ray induced shower, coincidene TRD and TPC



First interactions on Sept 12, 2008

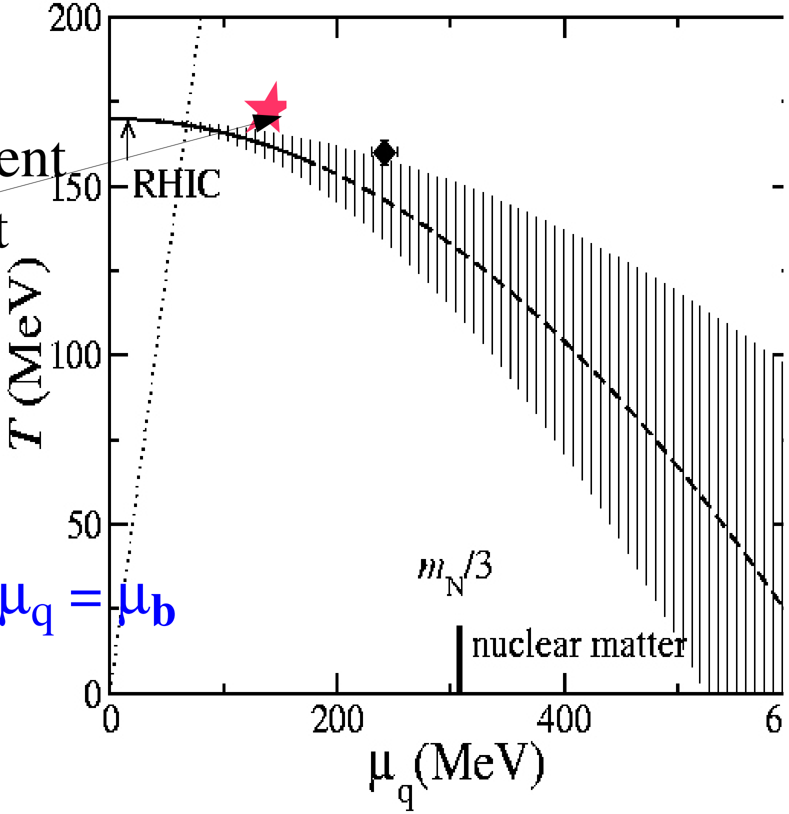




Circulating beam 2
stray particle causing an interaction in
the ITS

Backup slides

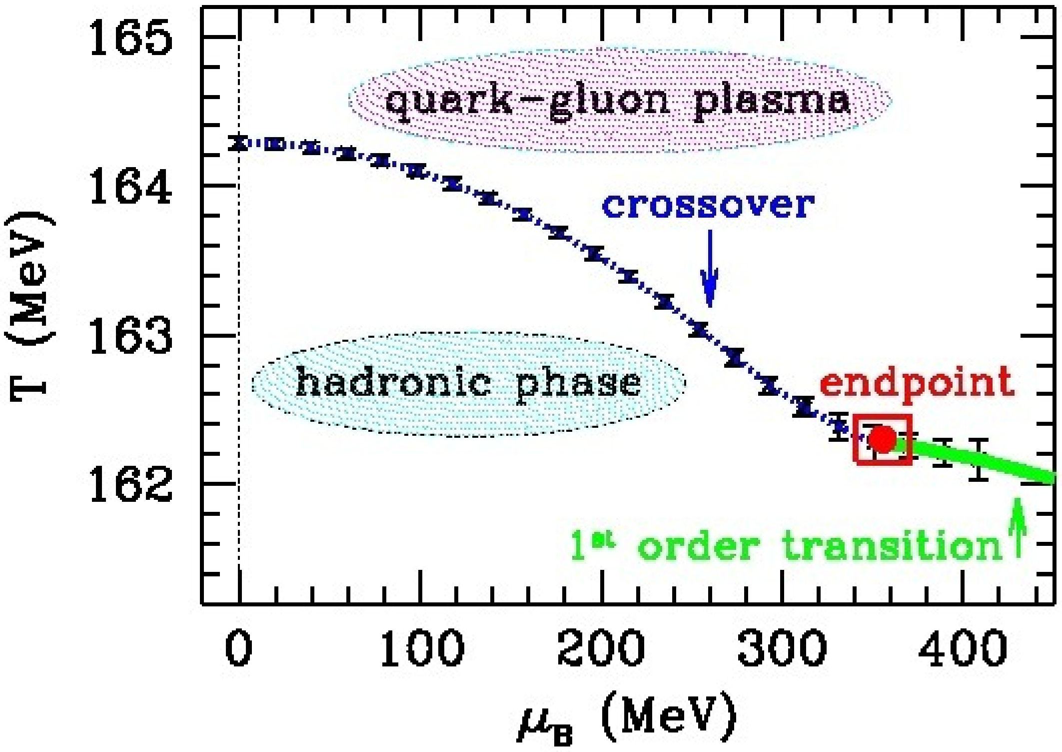
The QCD phase boundary at finite baryon density from lattice QCD



more recent end point

Note: $3\ \mu_q = \mu_b$

S. Ejiri et al, hep-lat/0312006



Z. Fodor, S. Katz, JHEP0404, (2004) 050

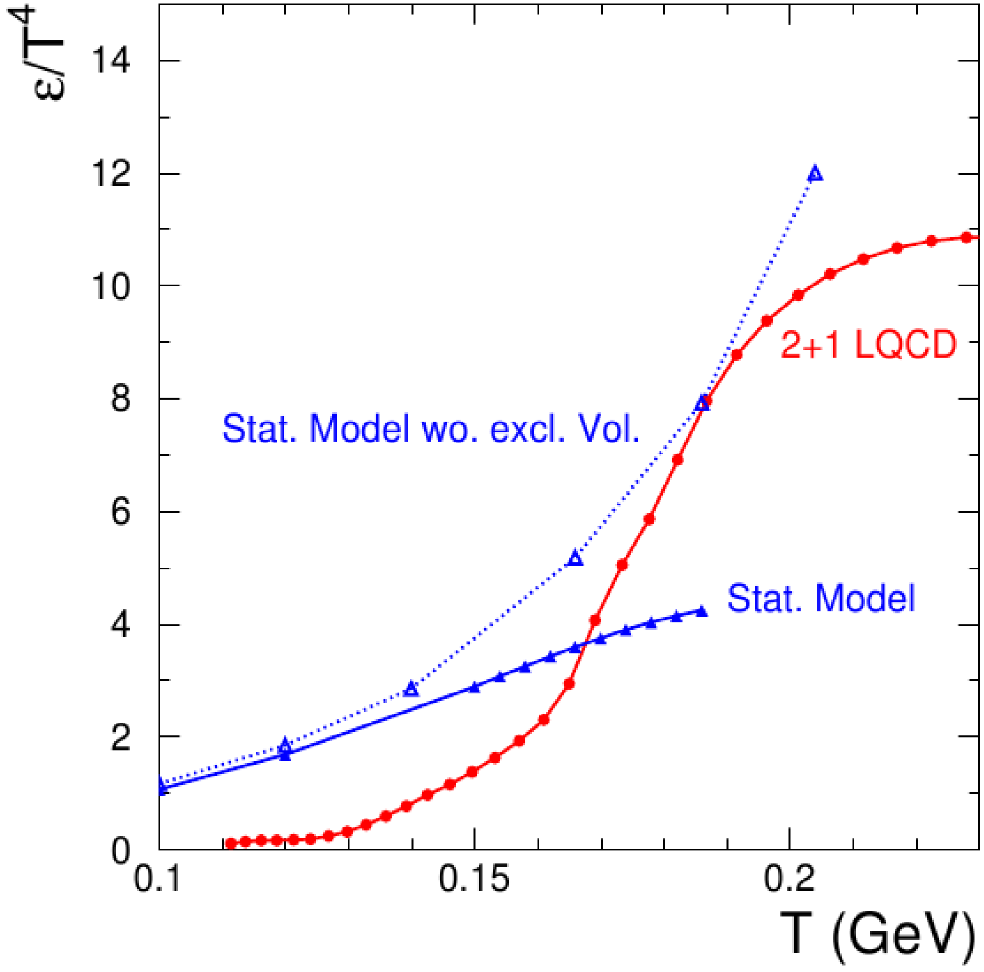
Tri-critical point not (yet) well determined theoretically

Forcrand, Philipsen hep-lat/0607017: maybe no critical end point

why do all particle yields show one common freeze-out T?

- **The density of particles varies rapidly (factor 2 within 8 MeV) with T near the phase transition due to increase in degrees of freedom.**
- **also: system spends time at Tc -> volume has to triple (entropy cons.)**
- **Multi-particle collisions are strongly enhanced at high density and lead to chem. equilibrium very near to T_c**
- **independently of cross section all particles can freeze out within narrow temperature interval**

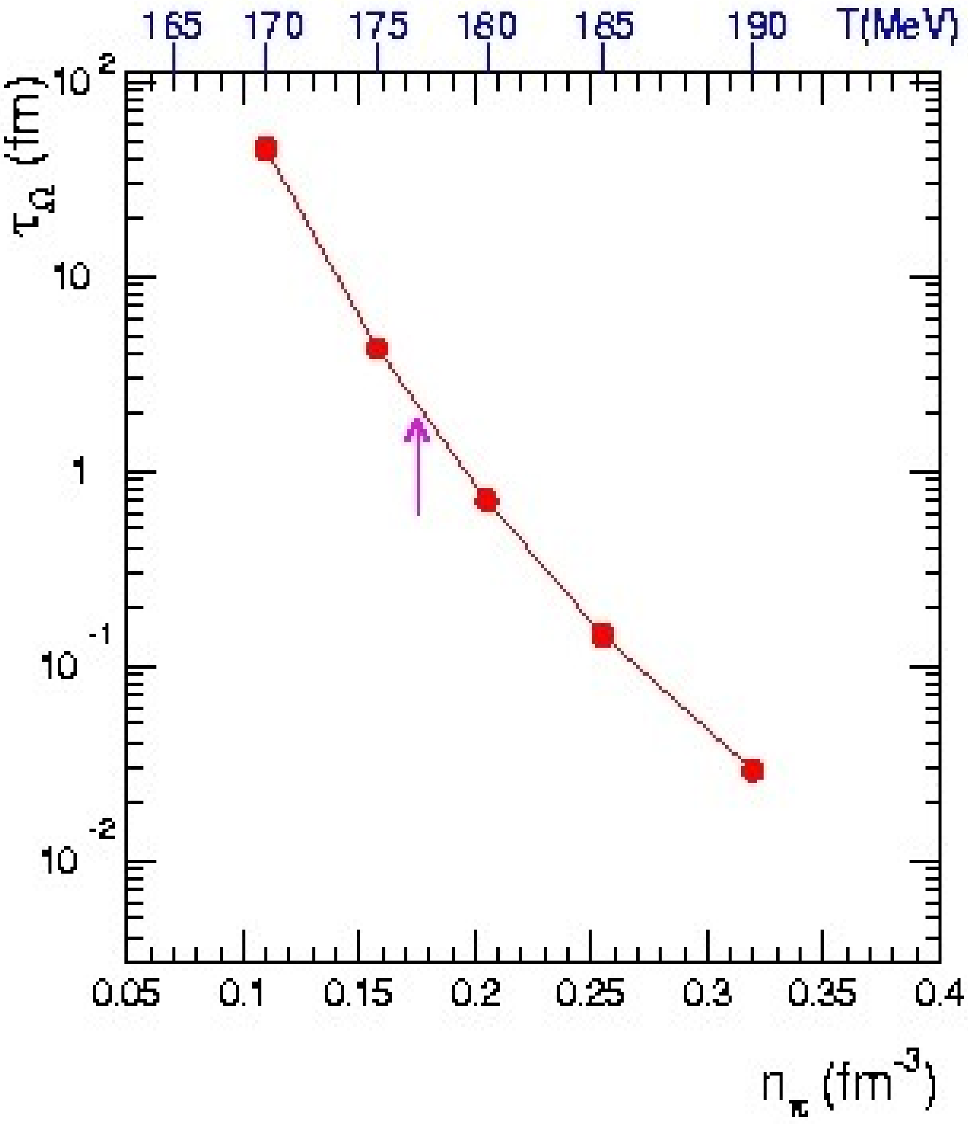
natural consequence that chemical freeze-out takes place at T_c!



Lattice QCD by F. Karsch et al.

P. Braun-Munzinger, J. Stachel, C. Wetterich, Phys. Lett. B596 (2004)61

Density dependence of characteristic time for strange baryon production



- Near phase transition particle density varies rapidly with T
- For small μ_b, reactions such as $2\pi + KKK \rightarrow \Omega$ Nbar bring multi-strange baryons close to equilibrium.
- in region around T_c equilibration time $\tau_\Omega \propto T^{-60}$!
- increase ρ_π by 1/3 or 8 MeV: τ = 0.2 fm/c

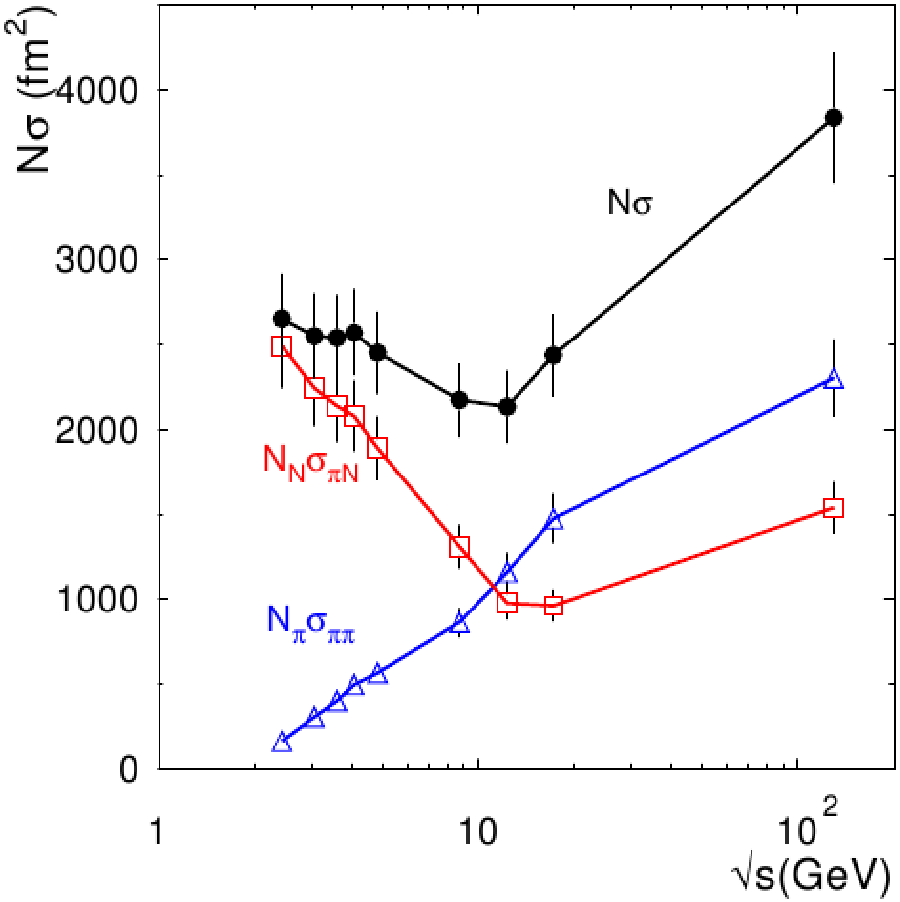
  decrease ρ_π by 1/3: τ = 27 fm/c
- All particles freeze out within a very narrow temperature window.

P. Braun-Munzinger, J. Stachel, C. Wetterich, Phys. Lett. B596 (2004)61

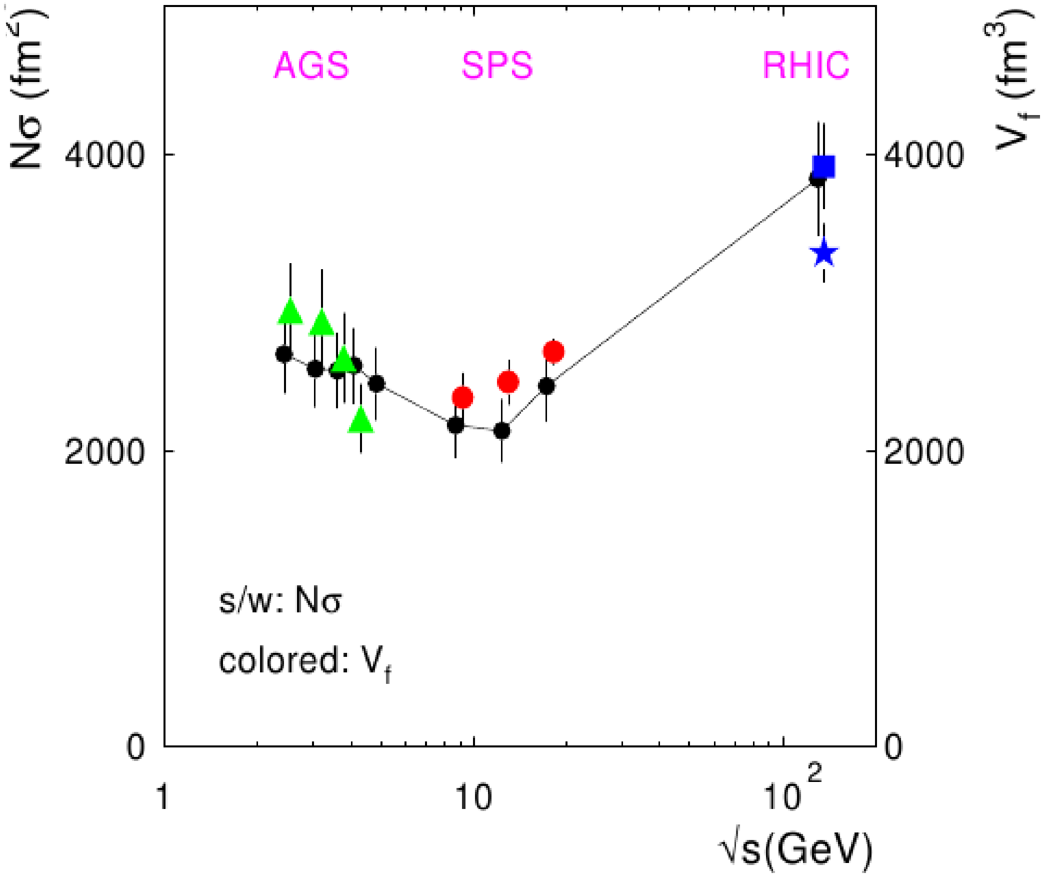
what governs pion freeze-out?

pion mean free path: $\lambda_f = 1/(\rho_f \cdot \sigma) = V_f/(N \cdot \sigma)$

$$N \cdot \sigma \approx N_N \cdot \sigma_{\pi N} + N_\pi \cdot \sigma_{\pi\pi}$$



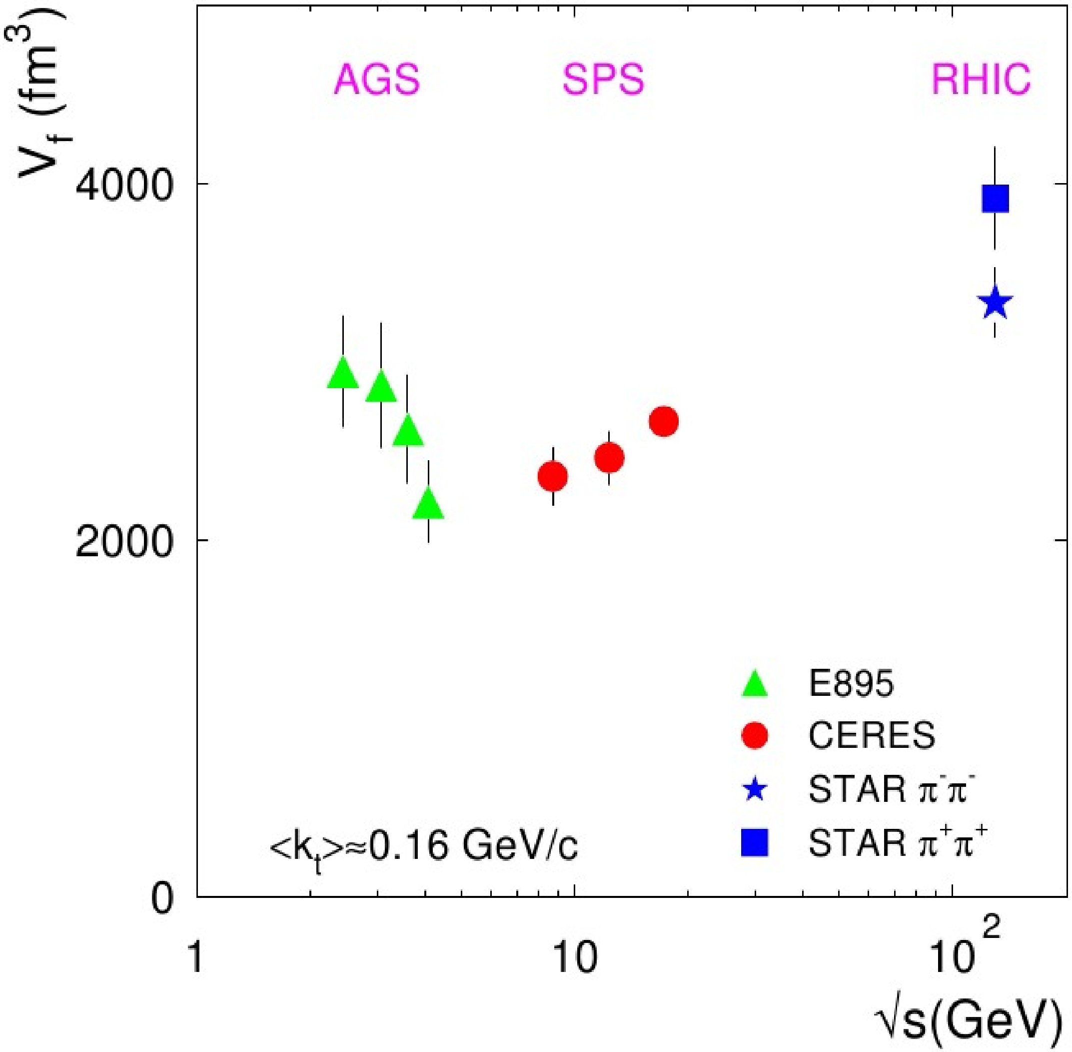
CERES Phys. Rev. Lett. 90 (2003) 022301



Universal freeze-out at mean free path $\lambda_f \approx 1$ fm - small vs system size

Freeze-out volume vs. beam energy

estimate freeze-out volume V_f: $V_f = (2\pi)^{3/2} R_{side}^2 R_{long}$



note: this is volume of 0.88 units of rapidity

surprise: non-monotonic behaviour

minimum between AGS and SPS

rules out freeze-out at constant density

R_{out} – duration of pion emission

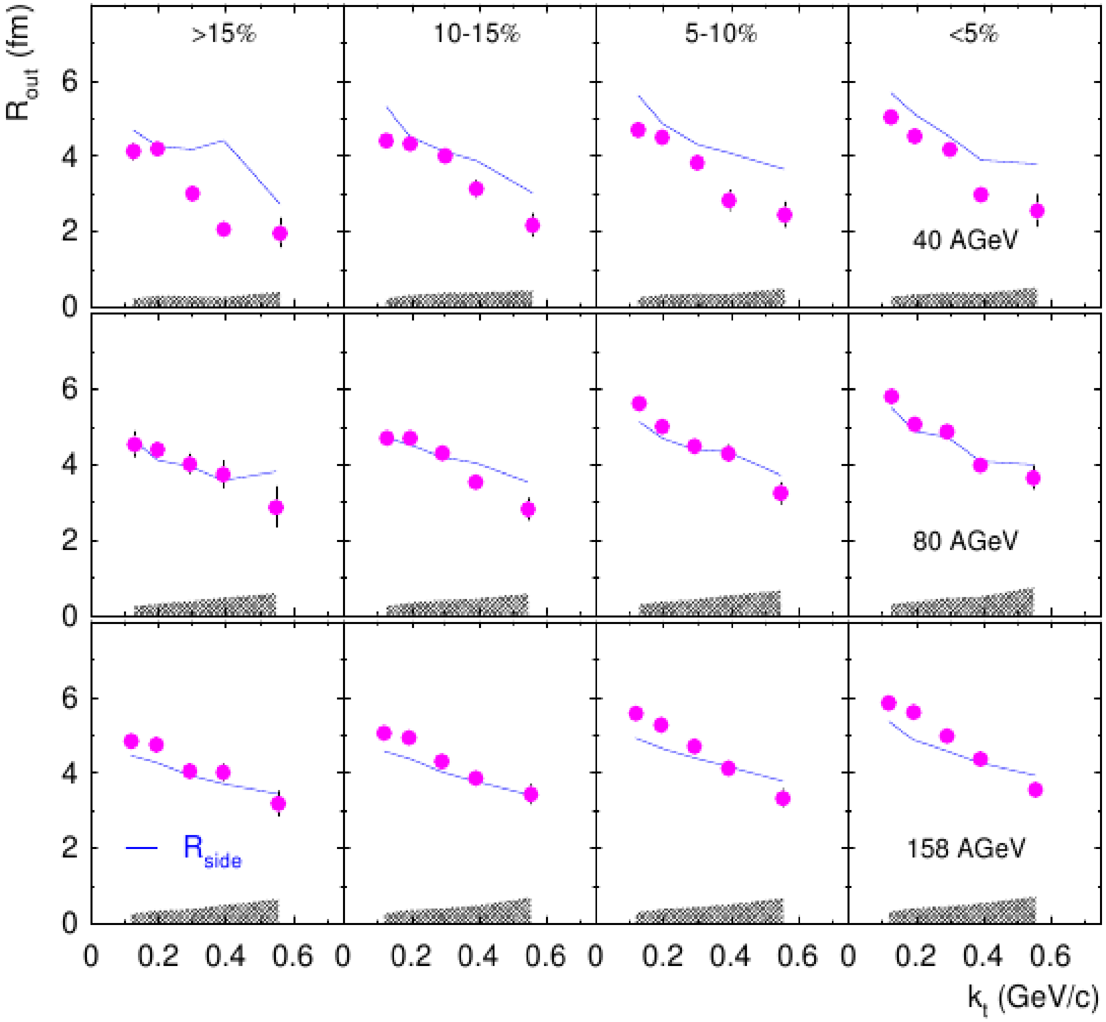
Generally: $R_{out} \approx R_{side}$

At 158 AGeV:
Short but finite emission duration

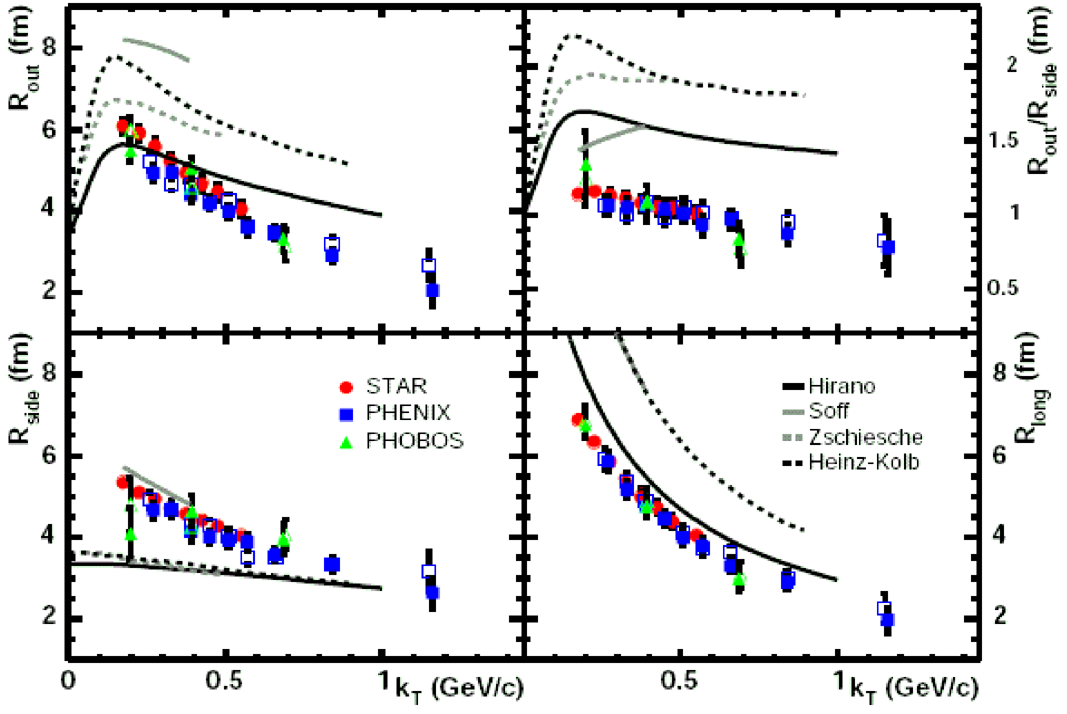
$$\Delta\tau^2 = \frac{1}{\beta_t^2}(R_{out}^2 - R_{side}^2)$$

Δτ ≈ 2 fm/c i.e. short, consistent with small density change

CERES H.Appelshäuser, Nucl.Phys. **A714** (2003) 124

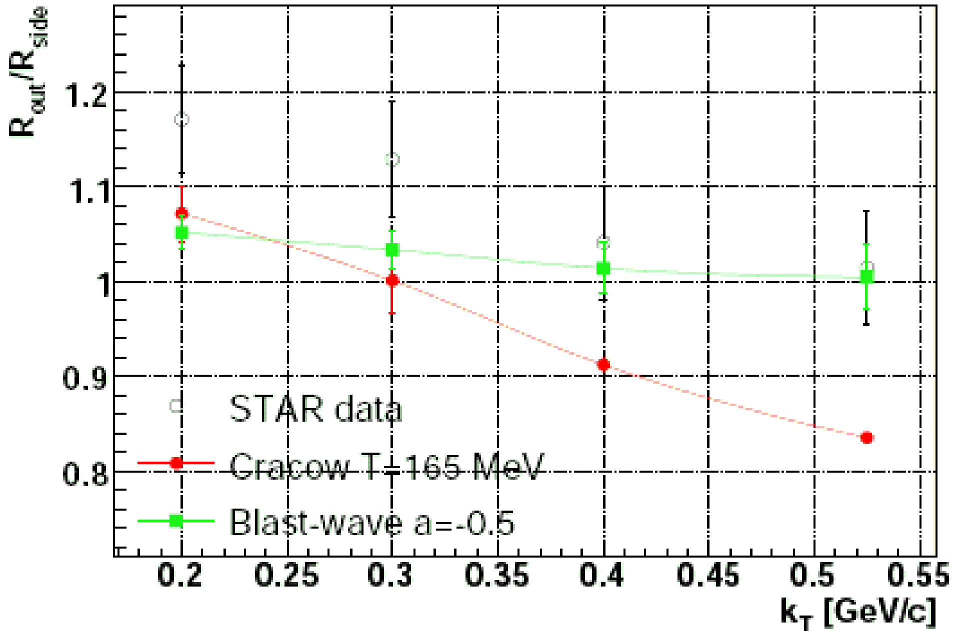


thermal freeze-out condition from pion HBT at RHIC

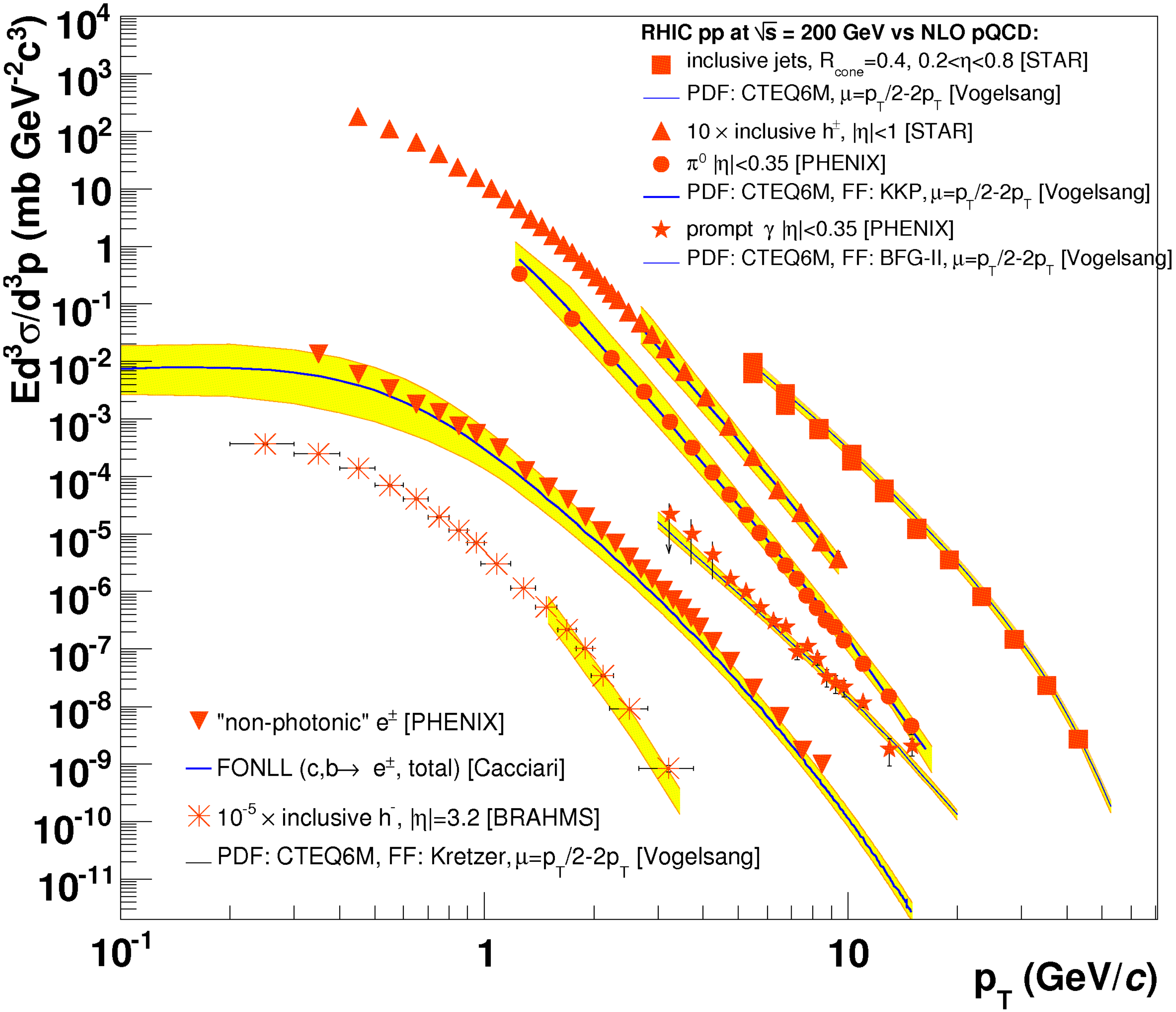


very similar to SPS
again small diff. R_{out} vs R_{side}
difficult for hydro models

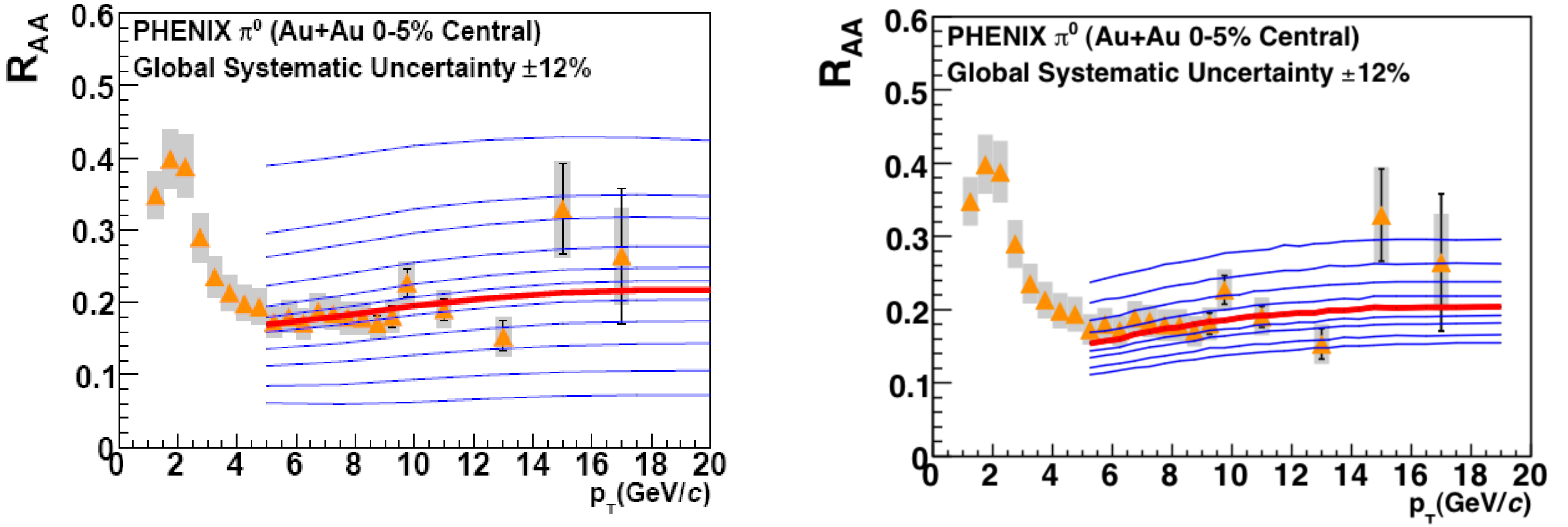
but for thermal freeze-out coinciding with chemical freeze-out ok
Kisiel, Florkowski, Broniowski, Pluta, nucl-th/0602039



High p_T Spectra in p-p Collisions (II)

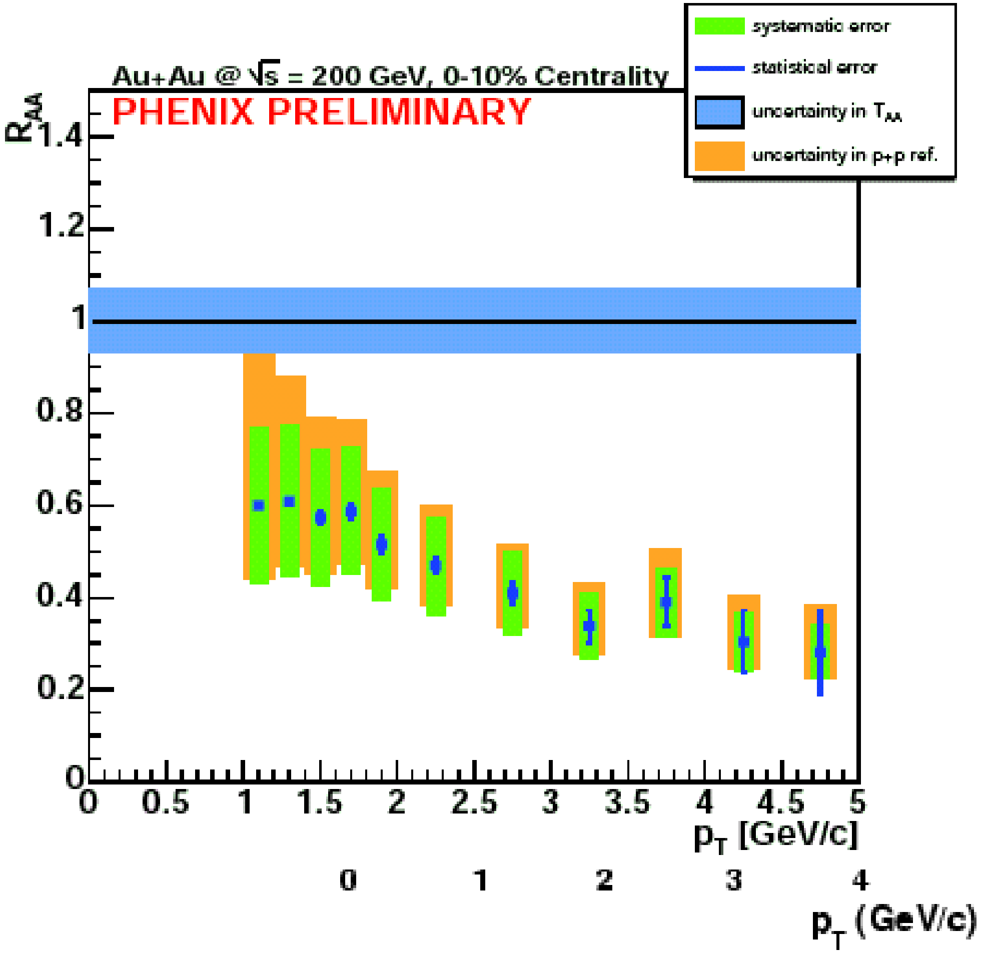


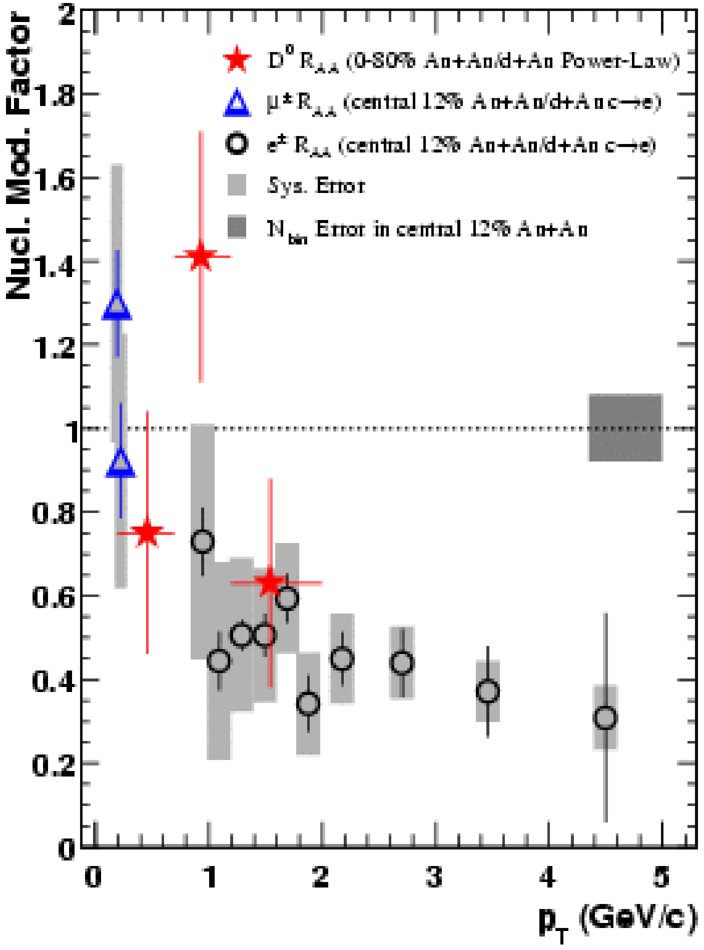
Quantitative Constraints on Medium Parameters



PQM	GLV	WHDG	ZOWW
$\hat{q} = 13.2^{+2.1}_{-3.2}$ GeV^2/fm	$dN^g / dy = 1400^{+270}_{-150}$	$dN^g / dy = 1400^{+200}_{-540}$	$\varepsilon_0 = 1.9^{+0.2}_{-0.5}$ GeV/fm^3

heavy quark distributions from inclusive electron spectra





STAR
preliminary

surprize: suppression very similar to pions

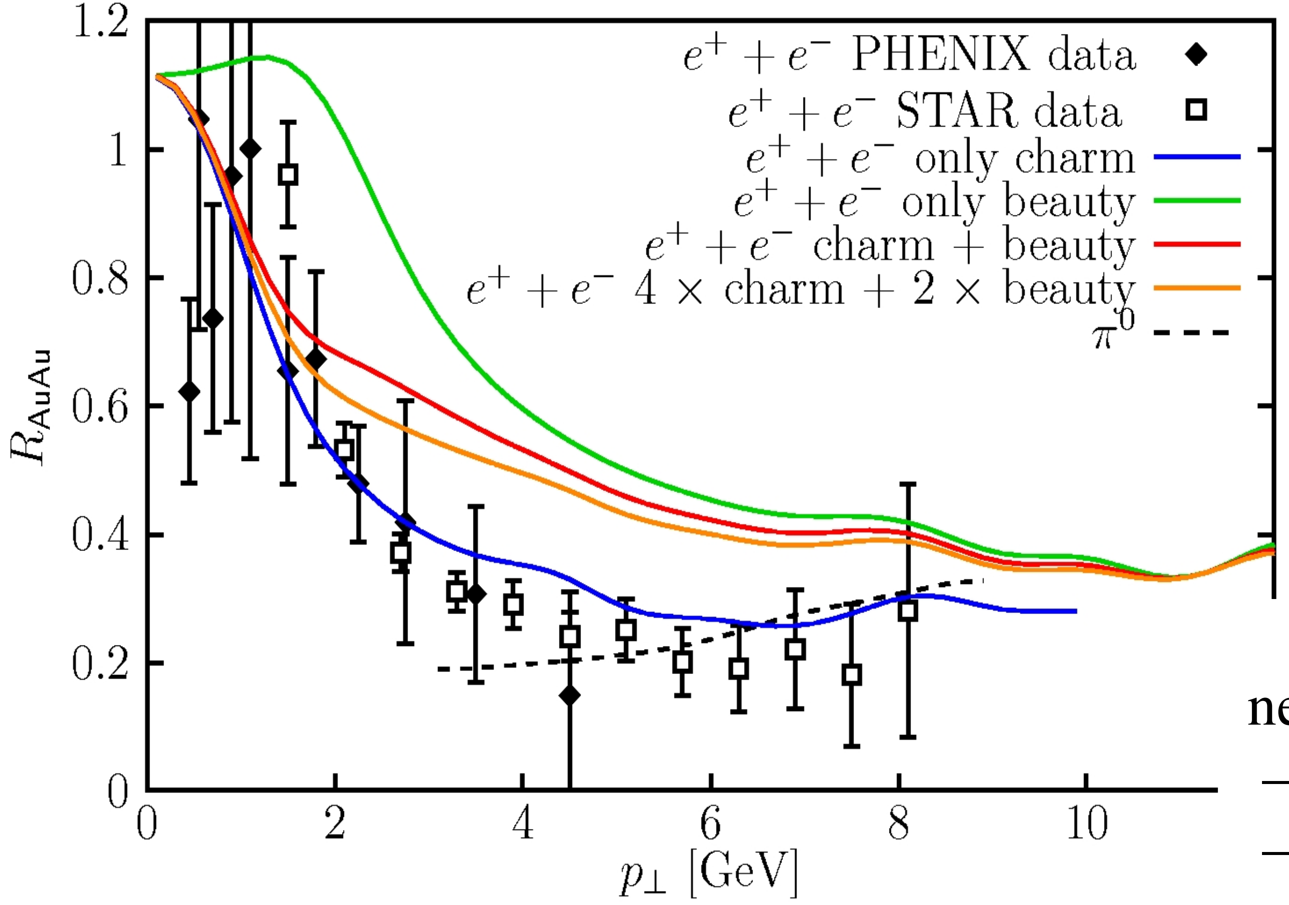
prediction (Dokshitzer, Kharzeev) less energy loss for heavy quarks (radiation suppr.)

radiation fails, is scattering the solution for heavy quarks?

recently shown by Korinna Zapp (U. Heidelberg) that scattering also important for parton energy loss; implementation in nonperturbative approach - SCI jet quenching model (K. Zapp, G. Ingelman, J. Rathsman, J. Stachel, PLB637 (2006) 179

apply same approach to c and b 0-10% centr. σ=5.2 mb

← σ to match pion data

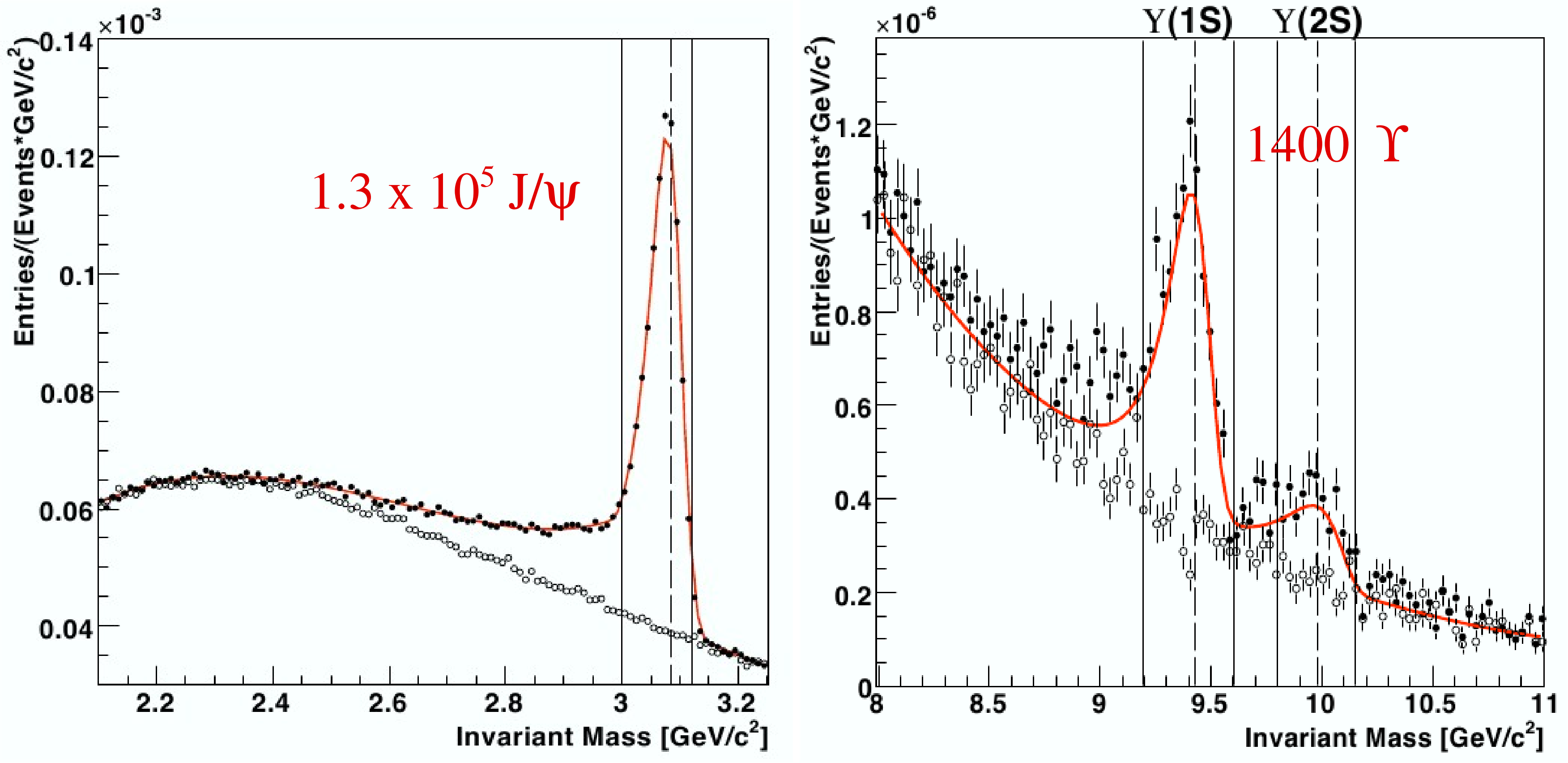


charm contribution indeed suppressed as much as pions but adding beauty data are not reproduced

need improved heavy quark data
- to come with RHIC upgrades
- or even earlier from ALICE

full simulation of central barrel performance

2×10^8 central (10%) events, 10^6 sec (1 year run)

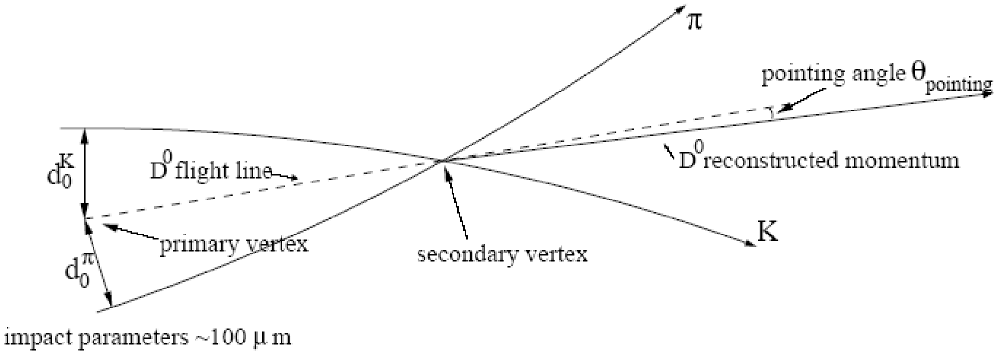


D. Krumbhorn, Heidelberg

$D^0 \rightarrow K\pi$ channel

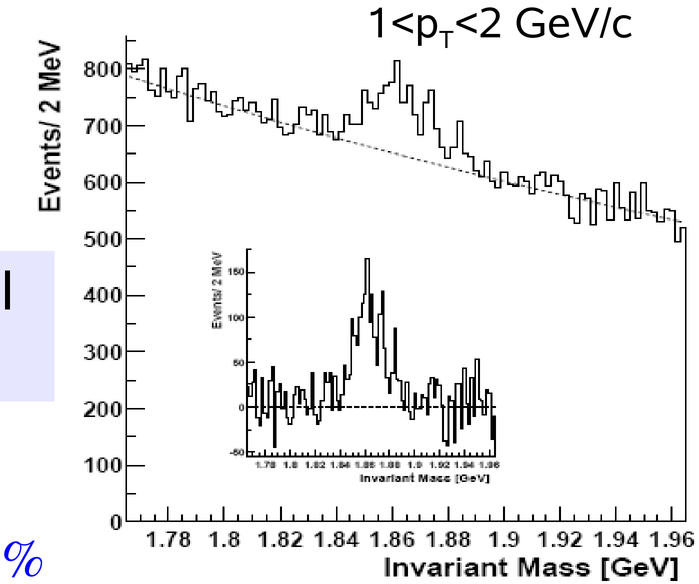
ALICE PPR vol2 JPG 32 (2006) 1295

- high precision vertexing, better than 100 μm (ITS)
- high precision tracking (ITS+TPC)
- K and/or π identification (TOF)



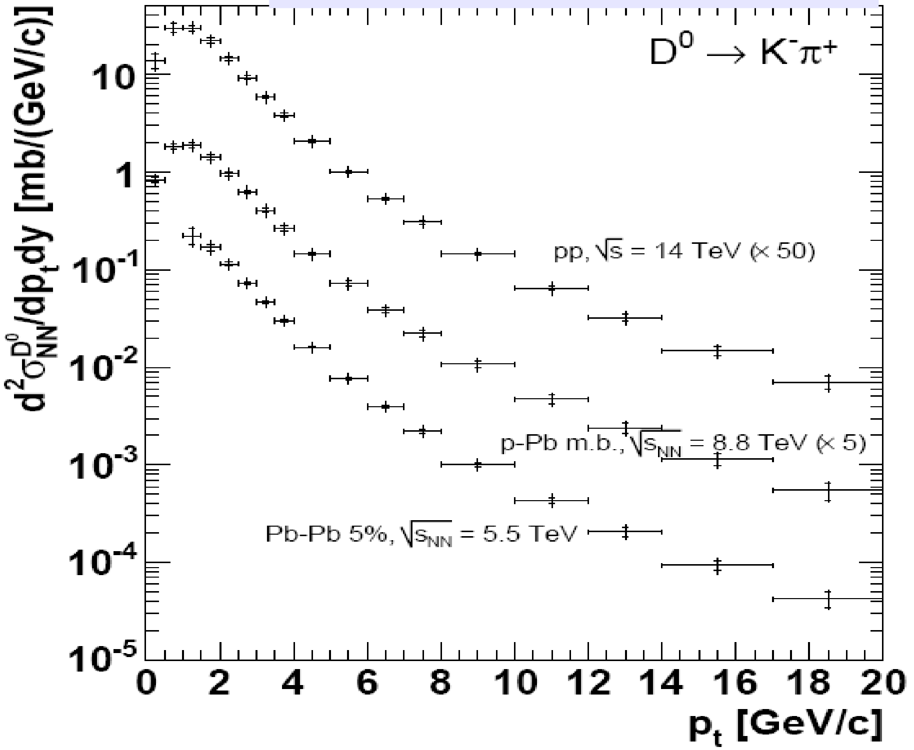
10^9 pp 10^8 pPb 10^7 PbPb

10^7 central PbPb



S/B = 10%

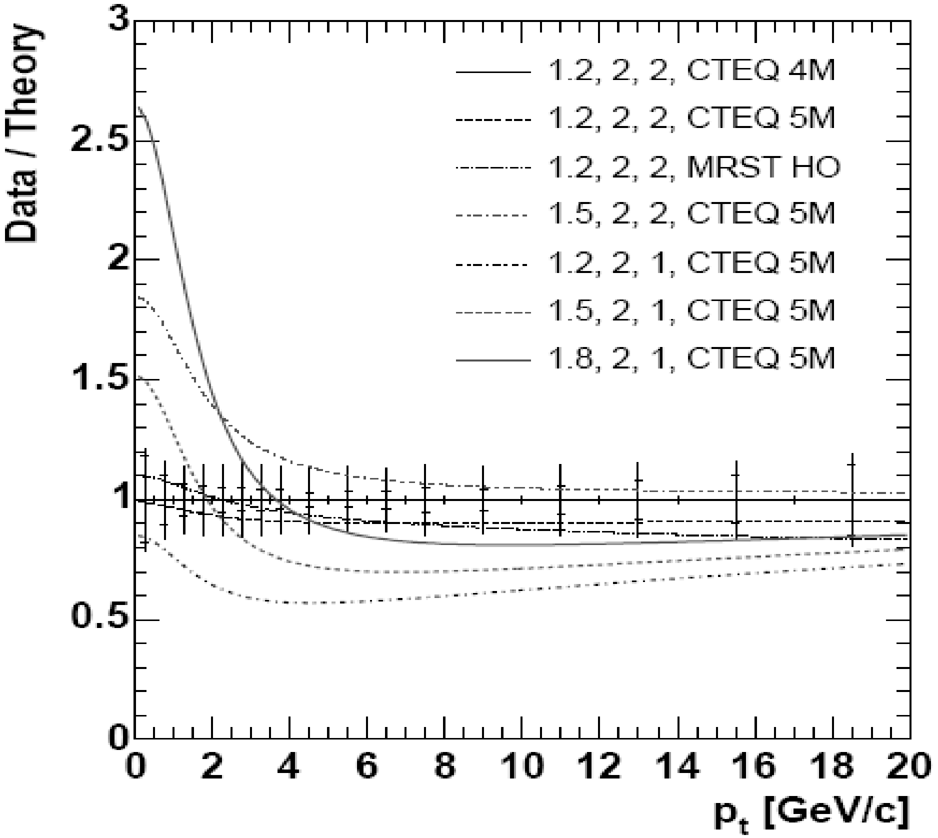
S/√(S+B) = 40

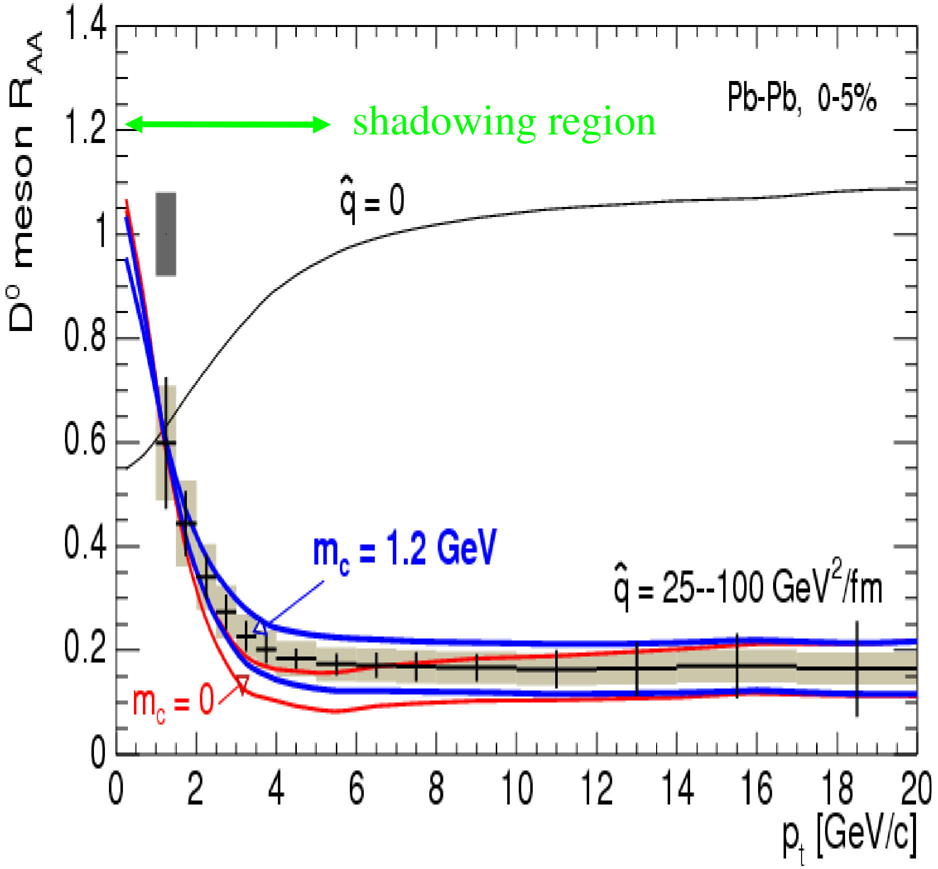


high precision charm measurement

pp at 14 TeV
sensitivity to PDF's

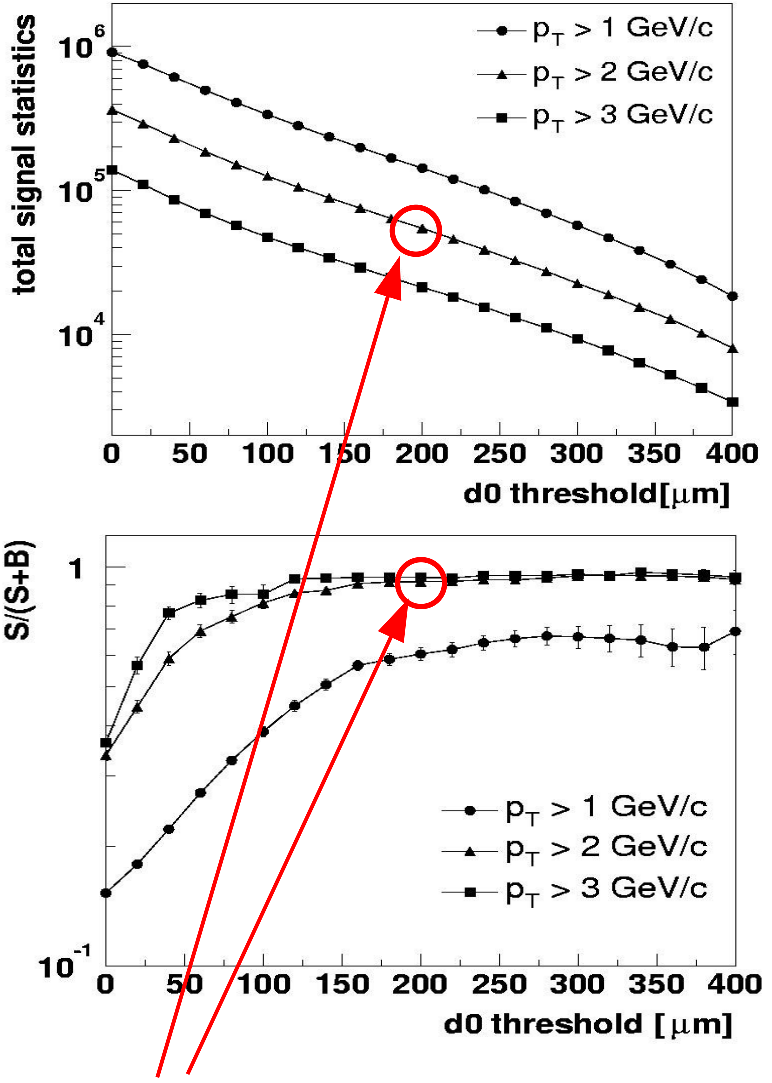
Central PbPb
shadowing + k_T + energy loss



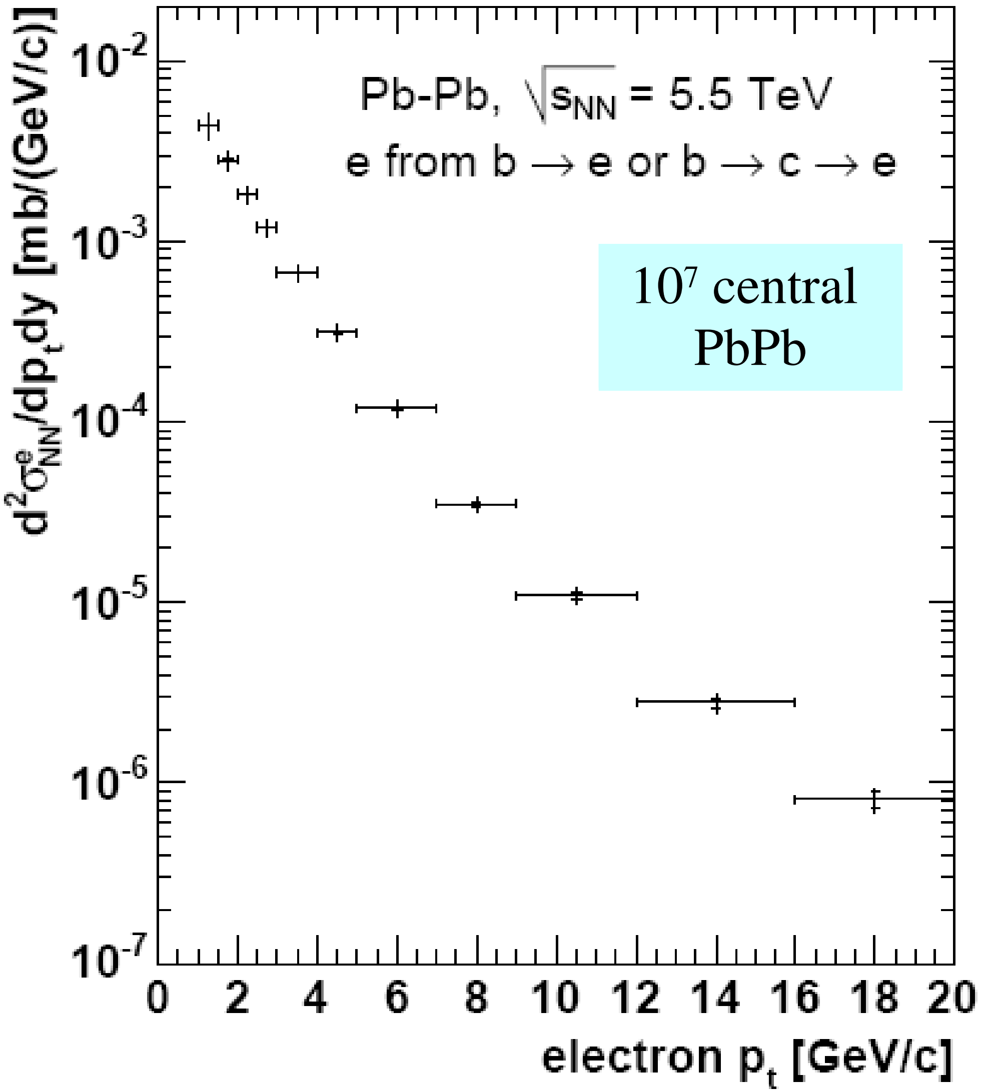


ALICE PPR vol2 JPG 32 (2006) 1295

open beauty from single electrons



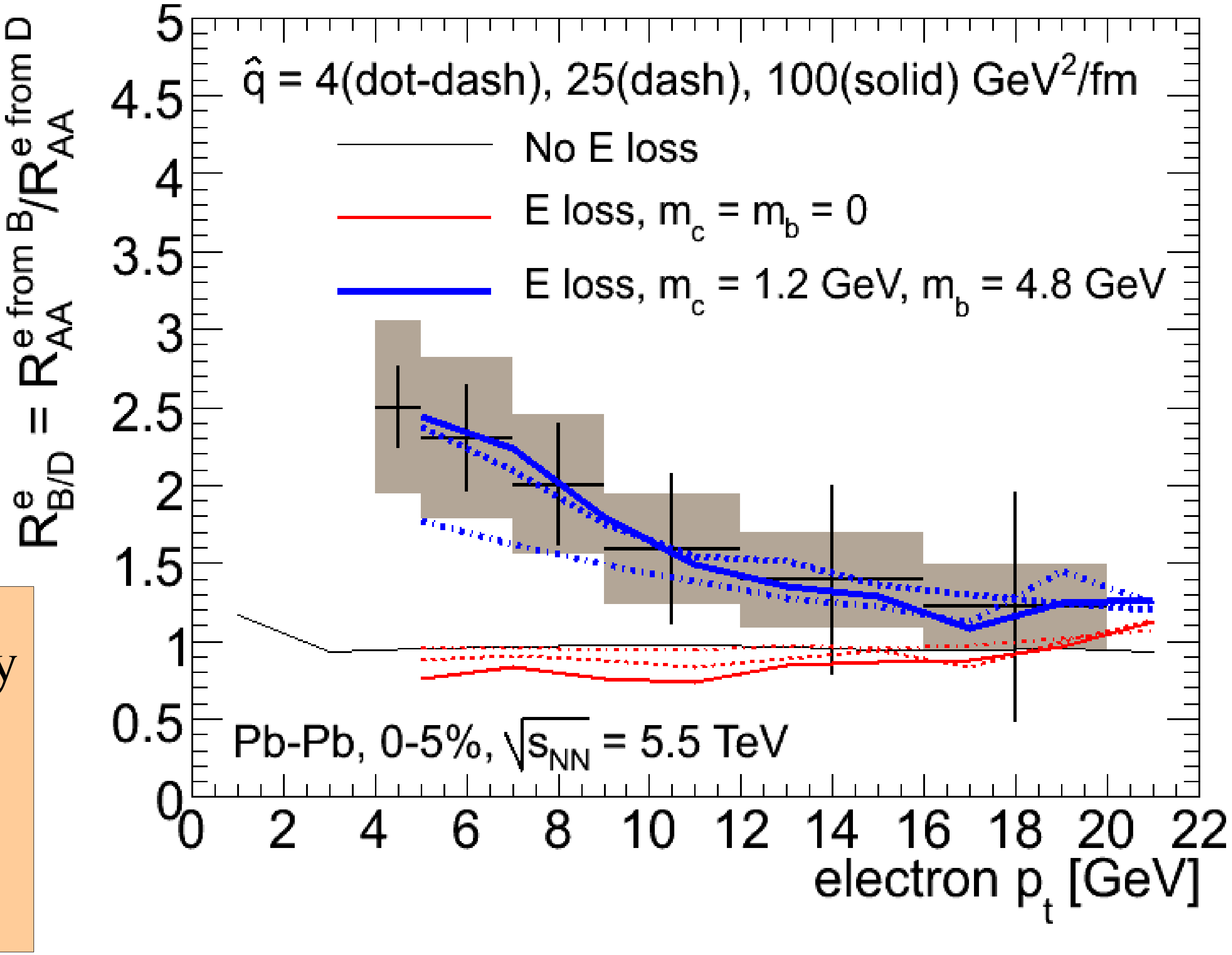
B →fie$^{\overline{P}}$in ALICE ITS/TPC/TRD
$p_t > 2$ GeV/c & $d_0 = 200$ -600 μm:
80 000 electrons with S/(S+B) = 80%



10^7 central PbPb

ALICE PPR vol2 JPG 32 (2006) 1295

jet quenching for b-quarks relative to c-quarks

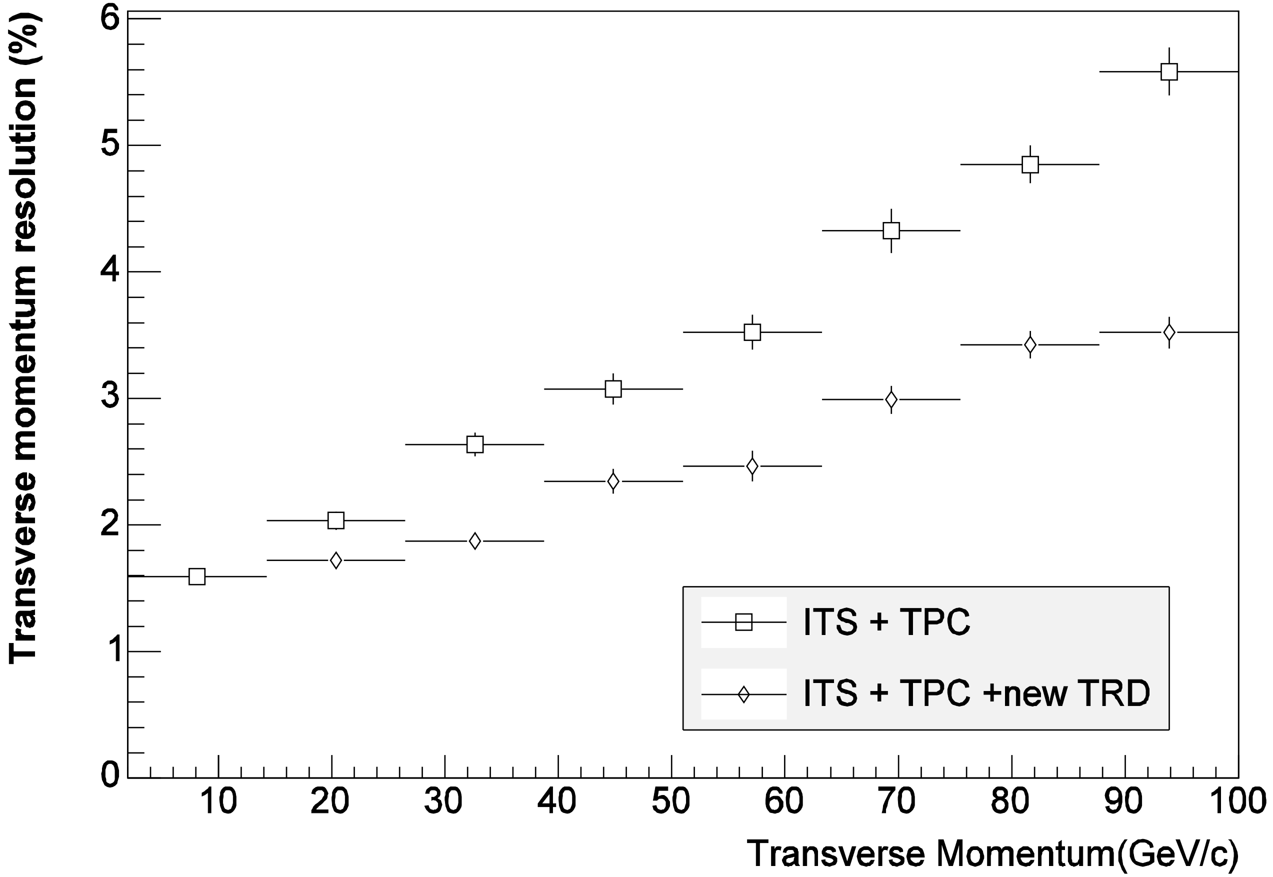


data of one full luminosity PbPb run (10^6 s) should clarify heavy flavor quenching story

Combined Momentum Resolution in ALICE Central Barrel

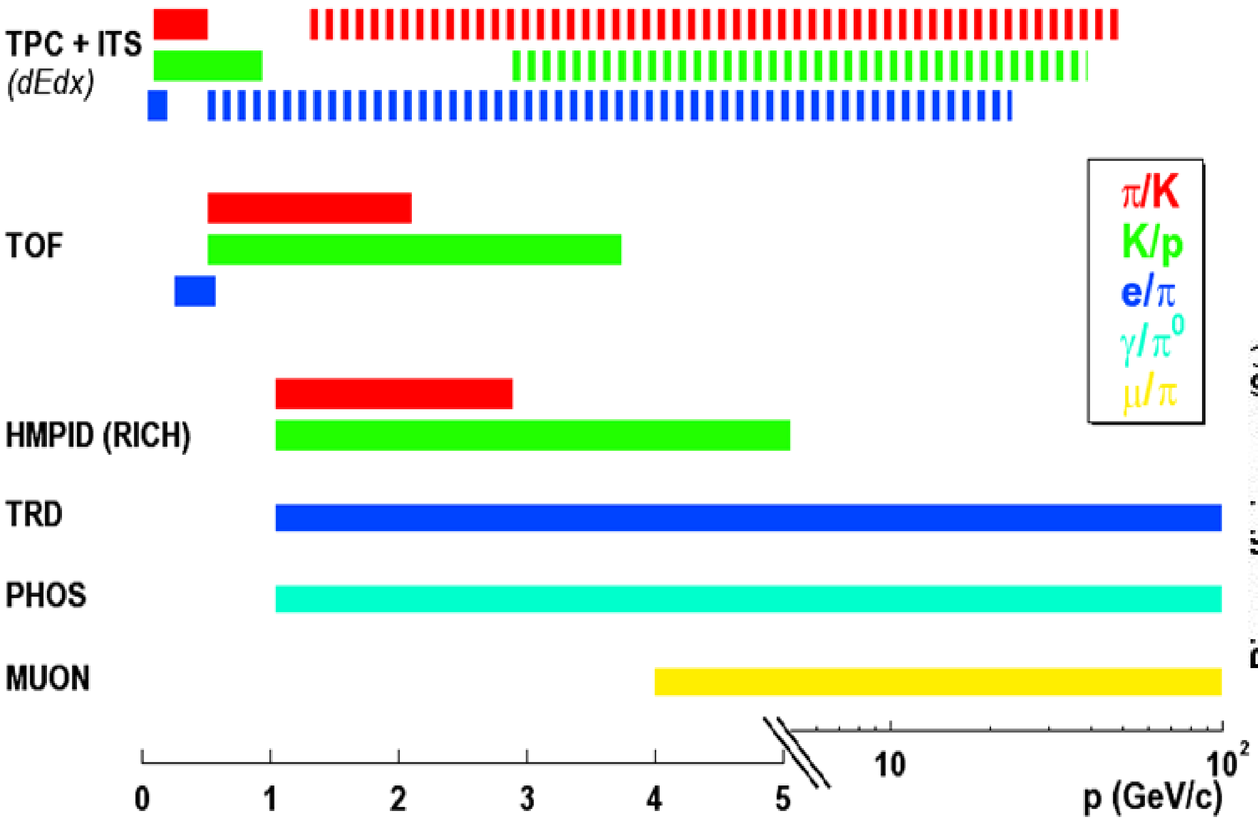
dN_{ch}/dy~5000

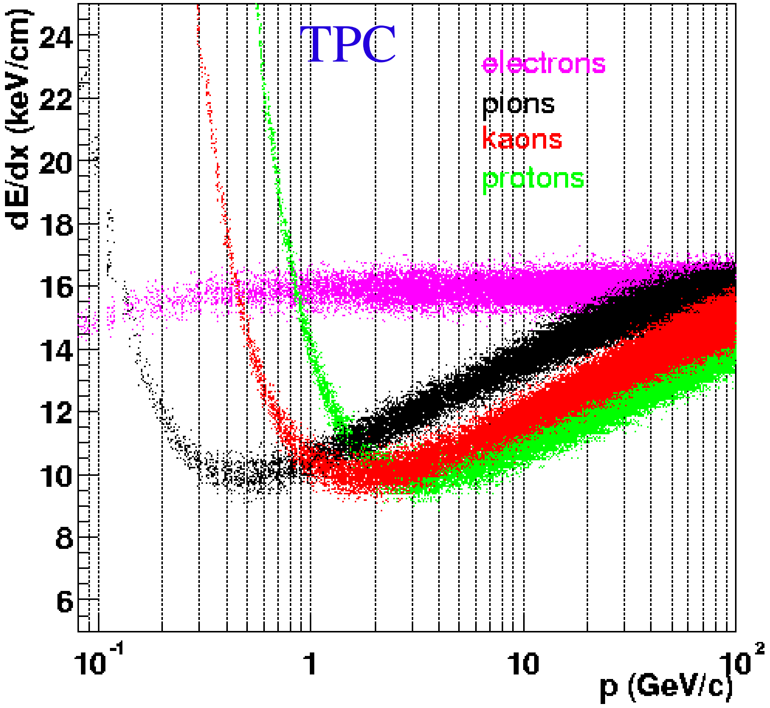
M.Ivanov, CERN & PI Heidelberg, March 05

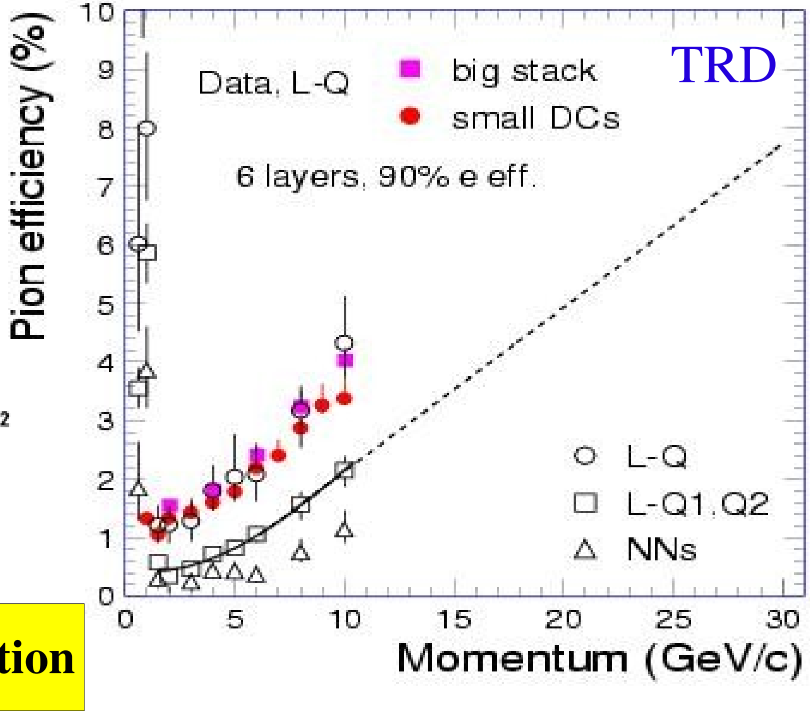


resolution ~ 3% at 100 GeV/c
excellent performance in hard region!

Particle Identification in ALICE







From test beam data: at 2 GeV and 90 % e eff → 10^5 π rejection