Exploring the Quark-Gluon Plasma with ALICE at the LHC

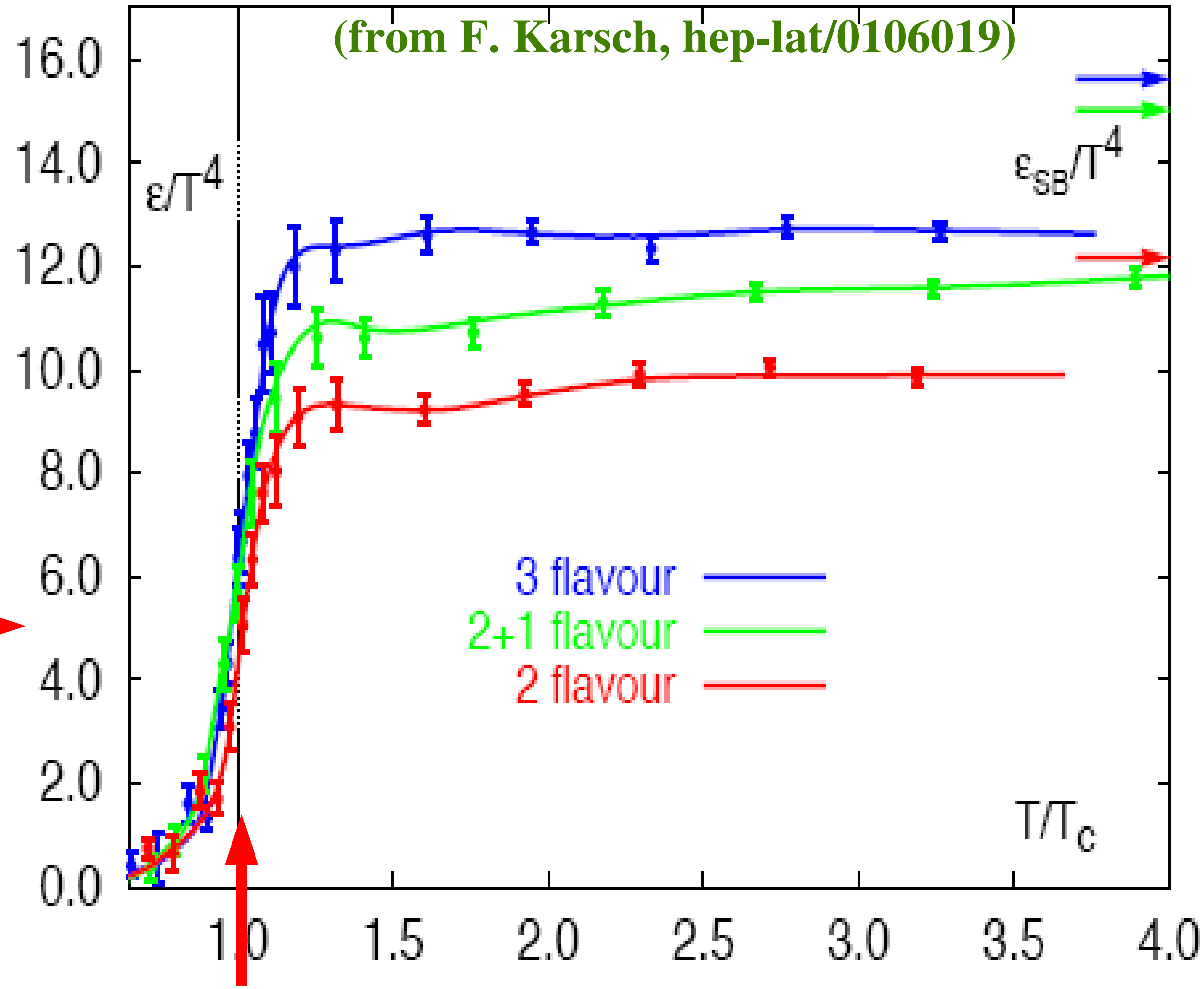
Physics background:
at high temperature and/or high density two phase transitions

- ✯ confined matter ⇔ deconfined matter
- ✯ broken chiral symmetry ⇔ restored chiral symmetry

want to find and characterize this new state of matter

J. Stachel – Physikalisches Institut der Universität Heidelberg
'Physics at the Terascale' - 46th Wilhelm und Else Heraeus Seminar
Bad Honnef, April 29, 2008

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



ideal gas limit

$\epsilon_c = 0.7\ \text{GeV/fm}^3$

for 2 flavors (≅2+1): $T_c = 173 \pm 15$ MeV results rather stable with time but recent debate: 150 - 190 MeV for T_c discussed

SPS : 1986 - 2003

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

LHC : starting 2008

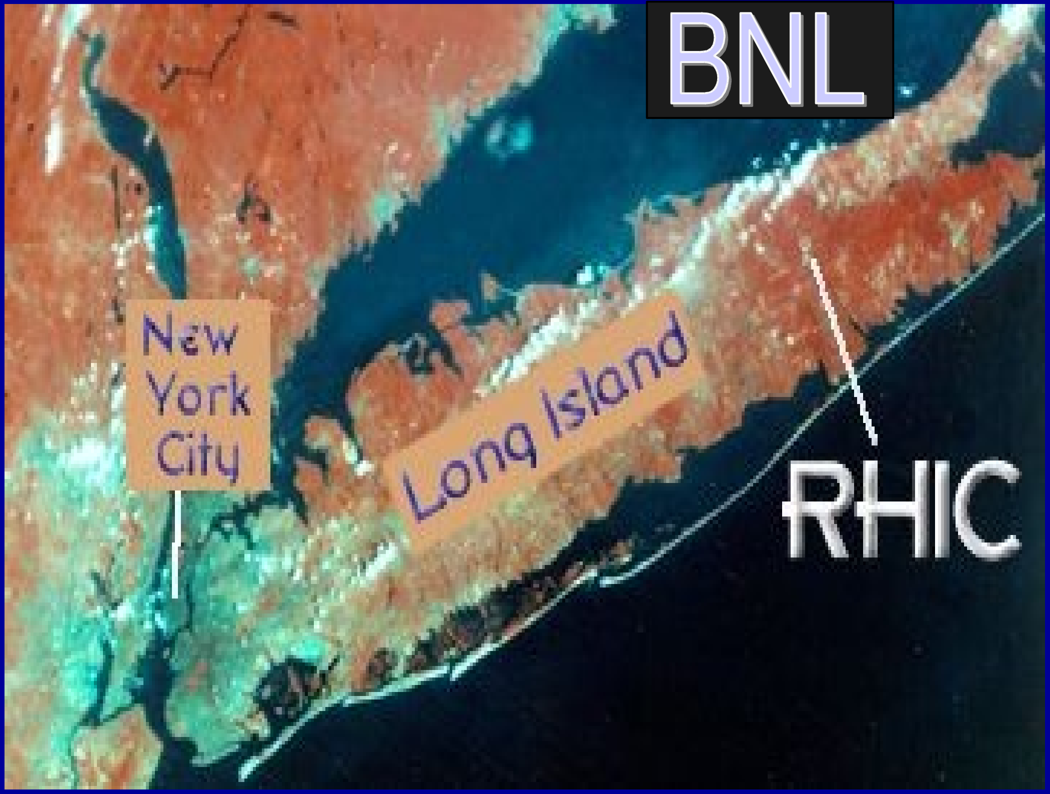
- Pb ; up to $\sqrt{s}$ = 5.5 TeV/nucl pair
- ALICE and CMS experiments

AGS : 1986 - 2000

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

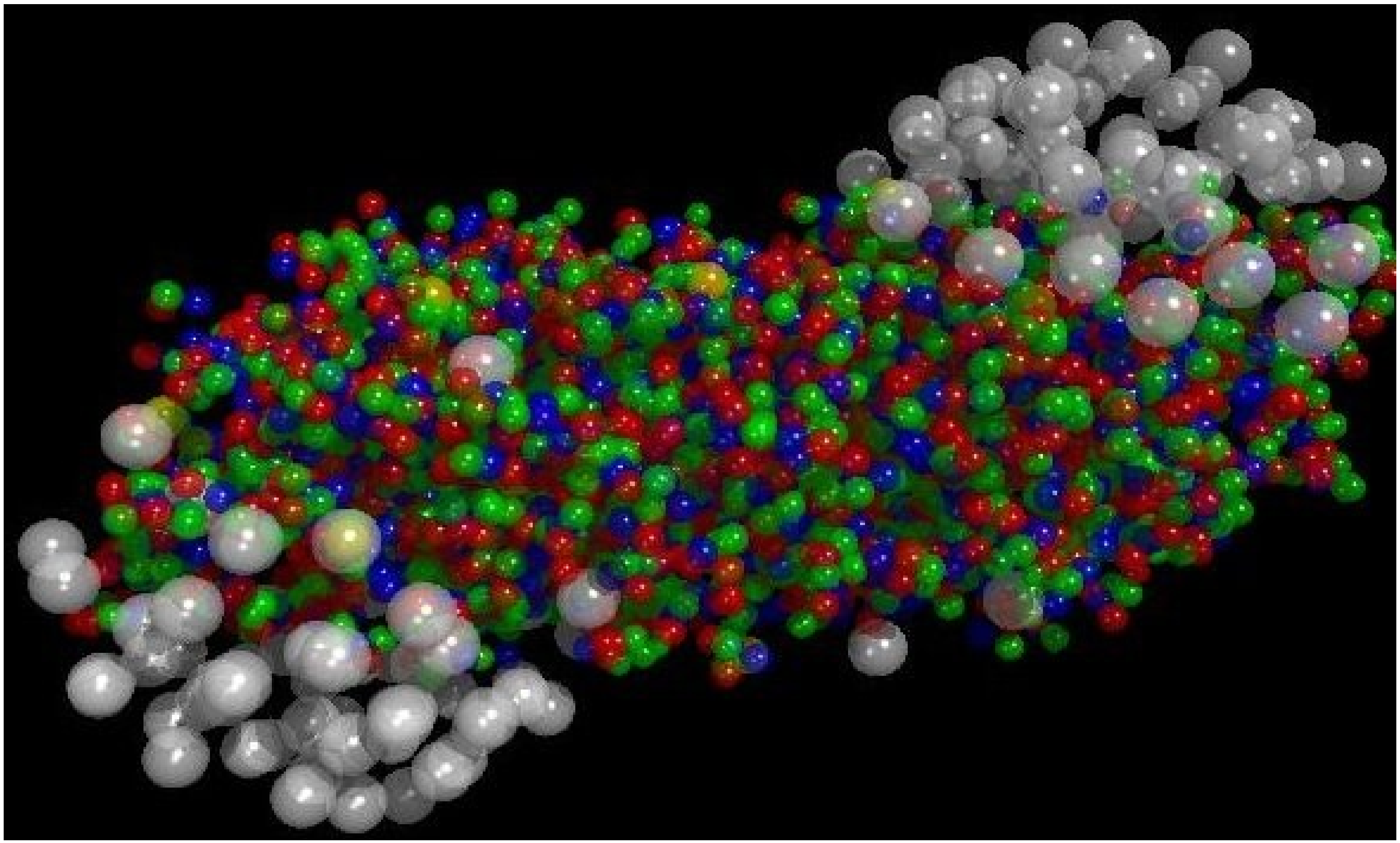
RHIC : 2000

- Au ; up to $\sqrt{\mathbf{s}}$ **=** 200 GeV /nucl pair
- hadrons, photons, dileptons, jets



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:

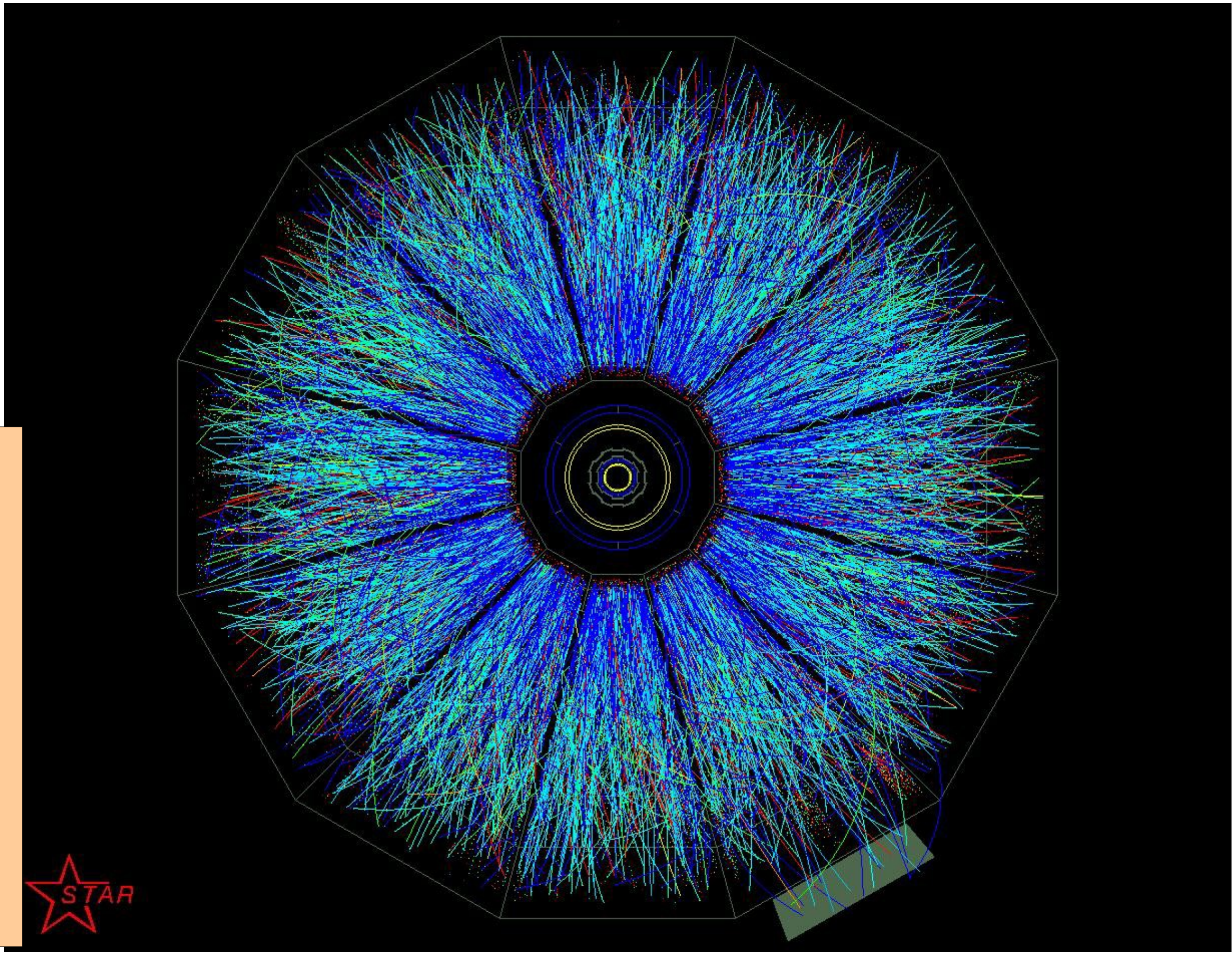
RHIC Scientists Serve Up “Perfect “ Liquid

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

results of first 3 years summarized in 4 large papers:

Nuclear Physics **A757** (2005)

nucl-ex/0410003 (PHENIX)
nucl-ex/0410020 (BRAHMS)
nucl-ex/0410022 (PHOBOS)
nucl-ex/0501009 (STAR)
and references therein



in central AuAu collsions at RHIC $\sqrt{s}$ = 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*:

$\varepsilon_0 = dE_t/d\eta/(\tau_0 \pi R^2)$ using Jacobian $d\eta/dz = 1/\tau_0$

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

$\tau_0 =$ 1 fm/c → $\varepsilon_0 = 3$ GeV/fm^3

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

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

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

optimistically: $\tau_0 = 1/Q_s = 0.14$ fm/c → $\varepsilon_0 = 40$ 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

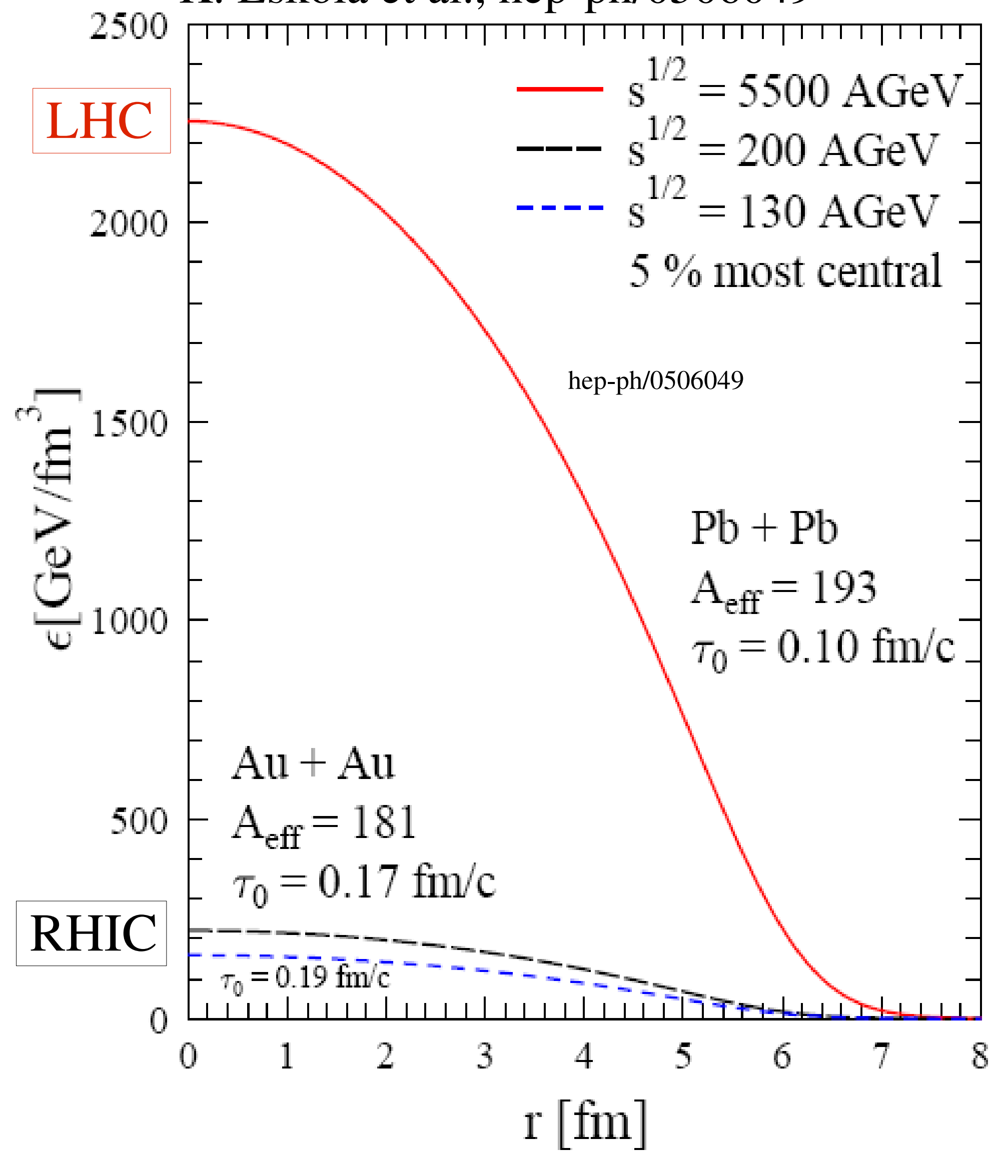
and with Bjorken formula:

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

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

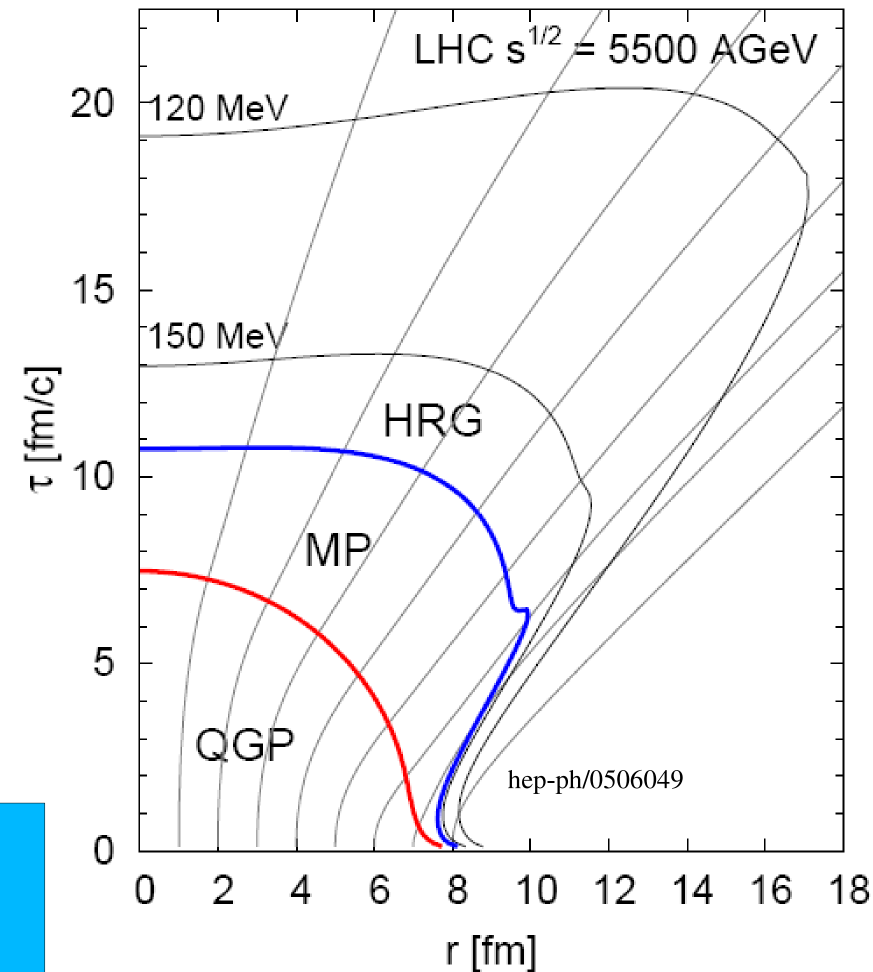
initial temperature $T_0 \approx 1$ TeV
(factor 2-3 above RHIC)

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



expected evolution of QGP fireball at LHC

K. Eskola et al.



after fast thermalization hydrodynamic expansion of fireball and cooling $T \propto \tau^{-1/3}$

hadronization starts at when T_c is reached (165 MeV)

duration hadronization: # degrees of freedom drops by factor 3.5

-> volume has to grow accordingly -> 3-4 fm/c

initial N_{AA} determines final multiplicity

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

overall several 10 k hadrons produced

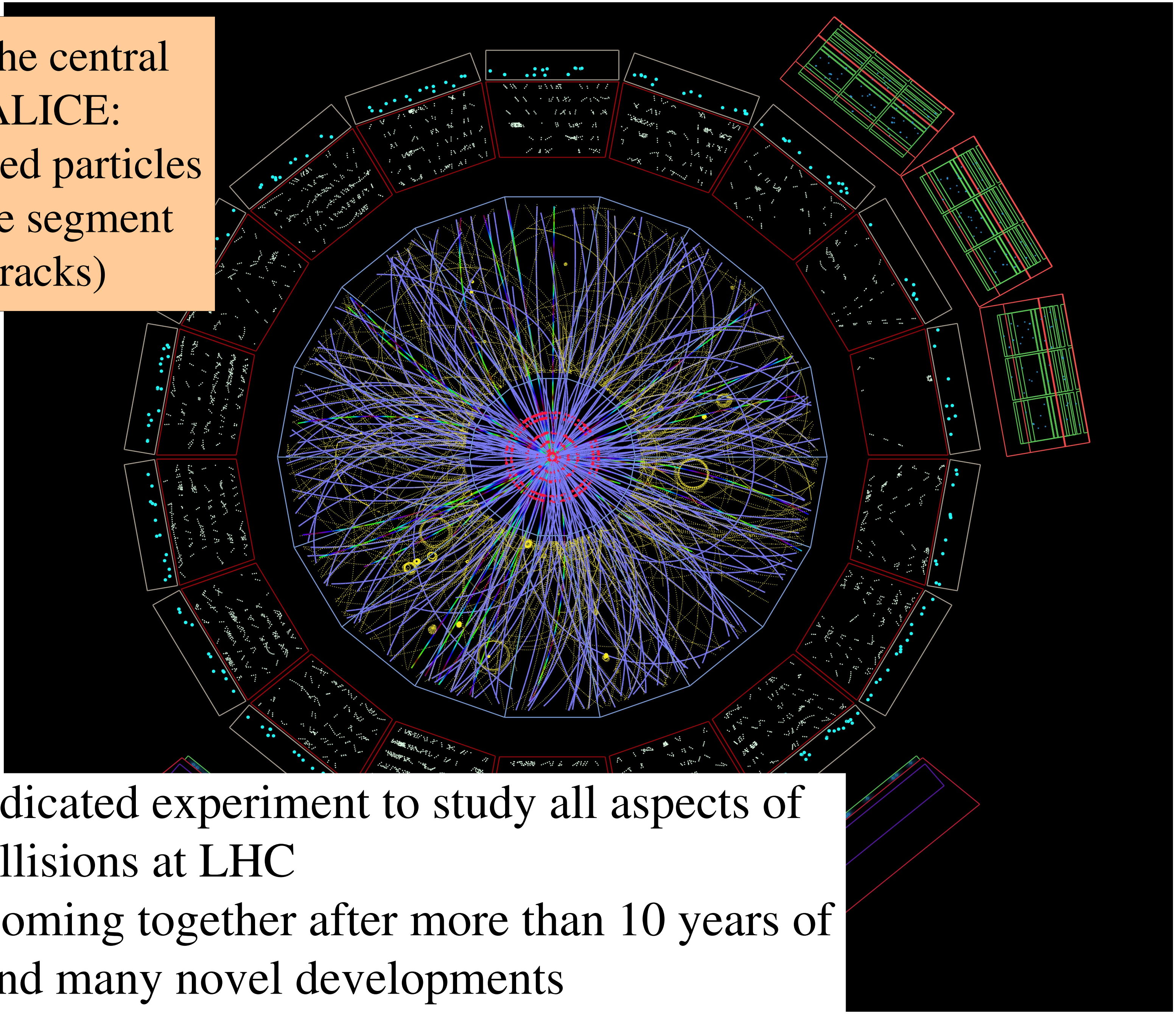
'macroscopic state'

task of heavy ion program at LHC

- unambiguous proof of QGP
- determine properties of this new state of matter
- be open for the unexpected

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)



- ALICE is dedicated experiment to study all aspects of heavy ion collisions at LHC
- detector is coming together after more than 10 years of hard work and many novel developments

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:

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

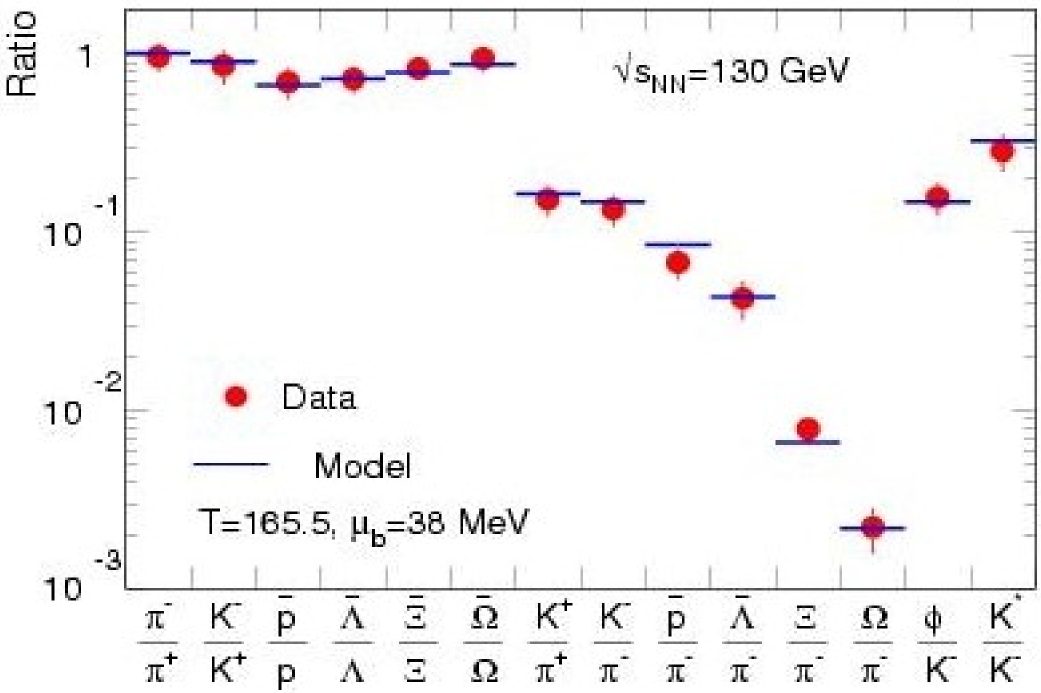
but can use conservation laws to constrain V, μ_S, μ_{I_3} → **Fit at each energy provides values for T and μ_b**

- 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

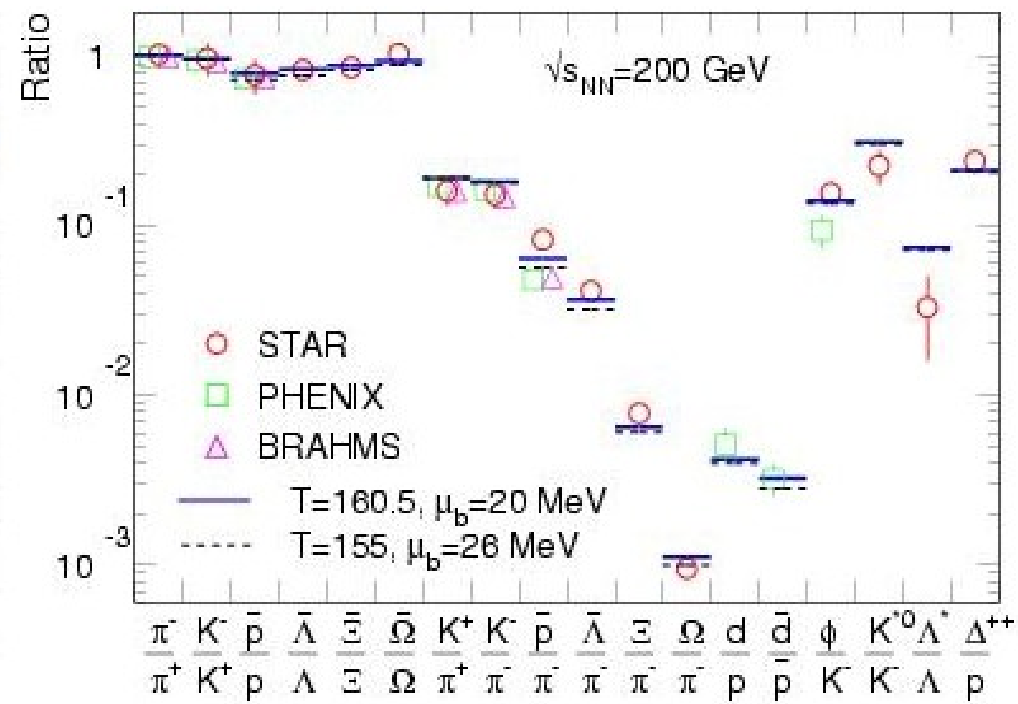
for a review: Braun-Munzinger, Stachel, Redlich, QGP3, R. Hwa, ed. (Singapore 2004) nucl-th/0304013

hadron yields at RHIC compared to statistical model

130 GeV data in excellent agreement
with thermal model predictions



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

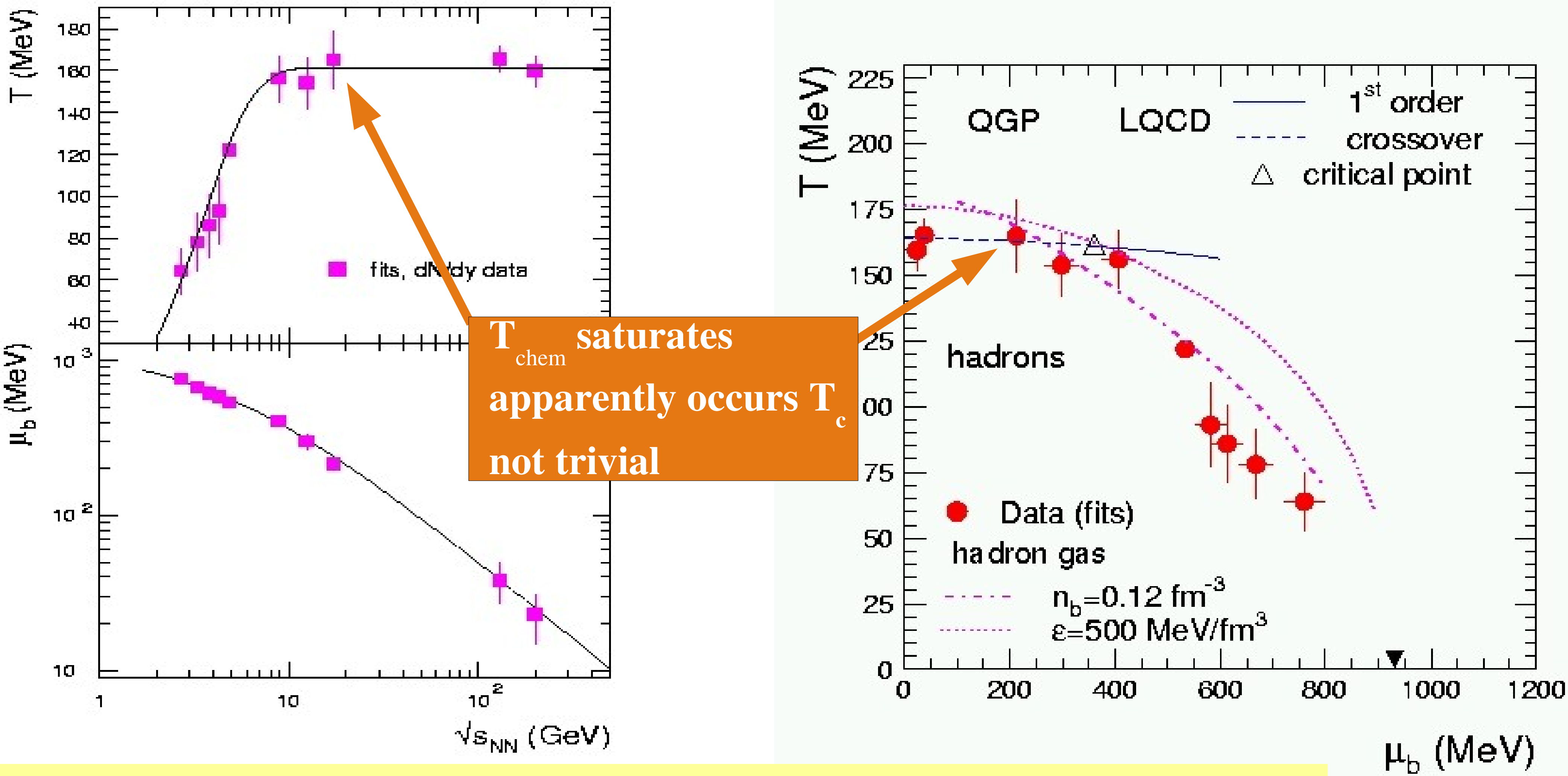


chemical freeze-out at: T = 165 ± 5 MeV

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



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

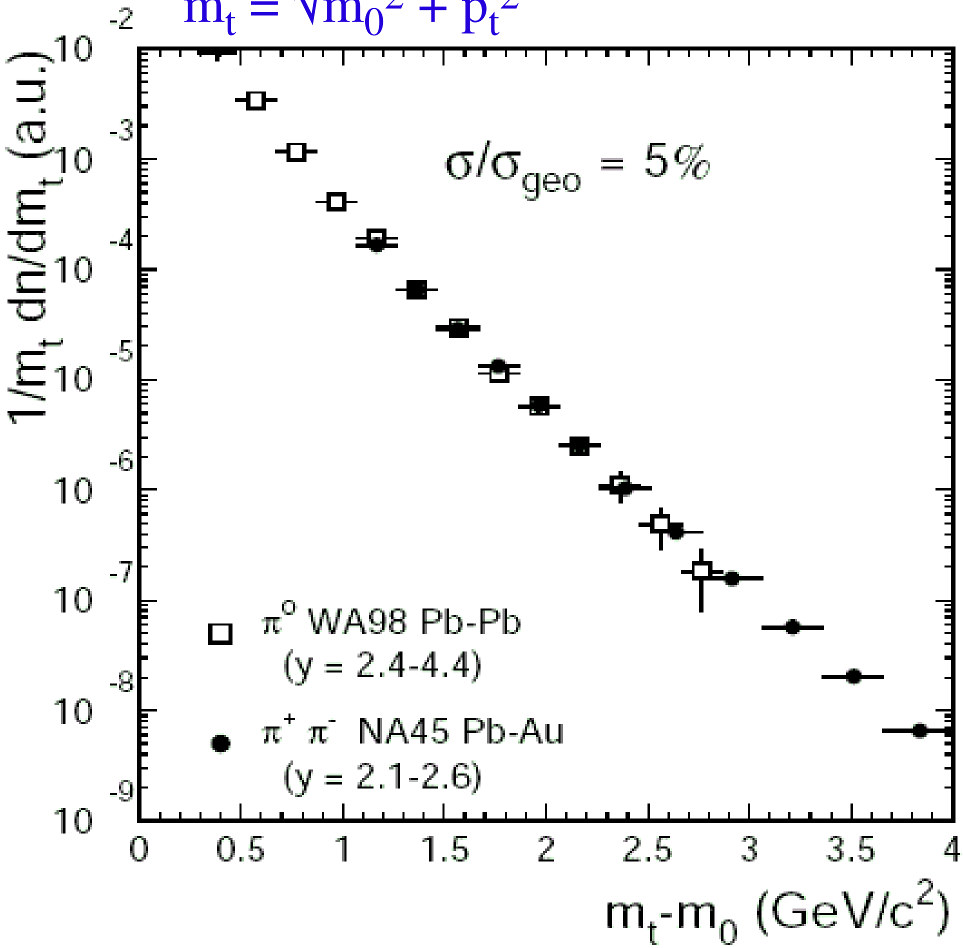
consider

- particle transverse momentum spectra
- azimuthal correlations
- momentum correlations

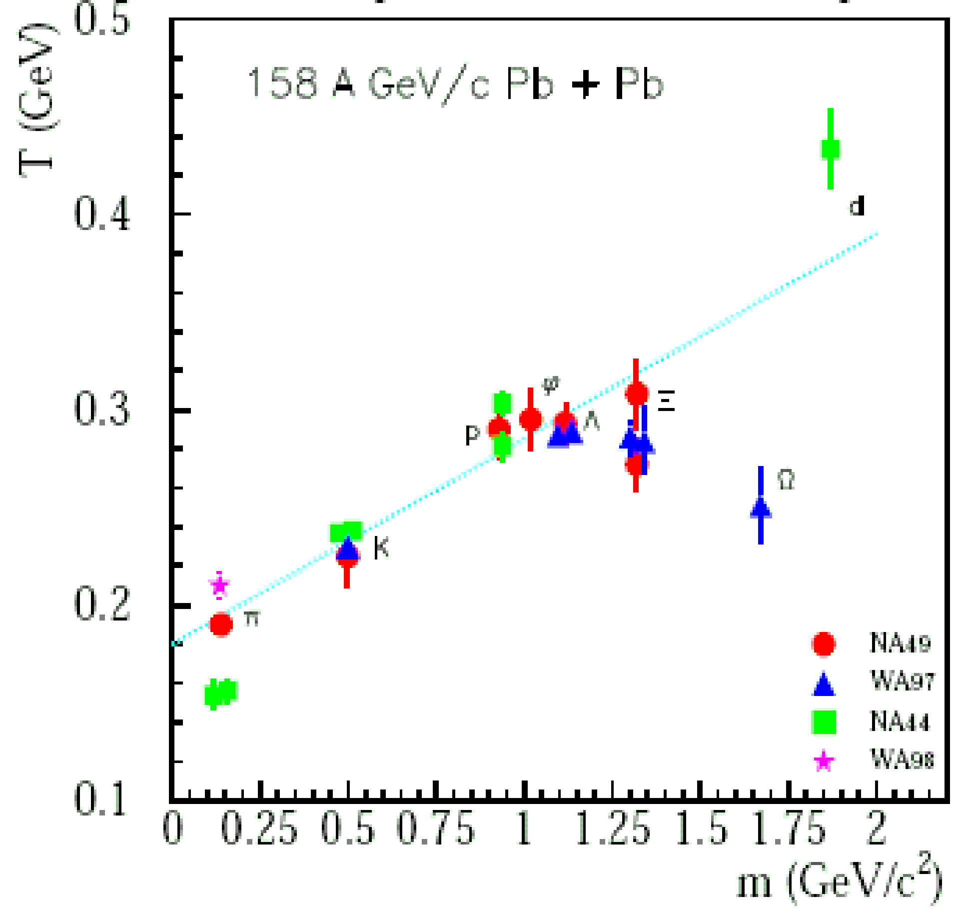
QGP signature: hydrodynamic expansion - transverse spectra

typical transverse mass spectrum

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



mass dependence of inverse slopes

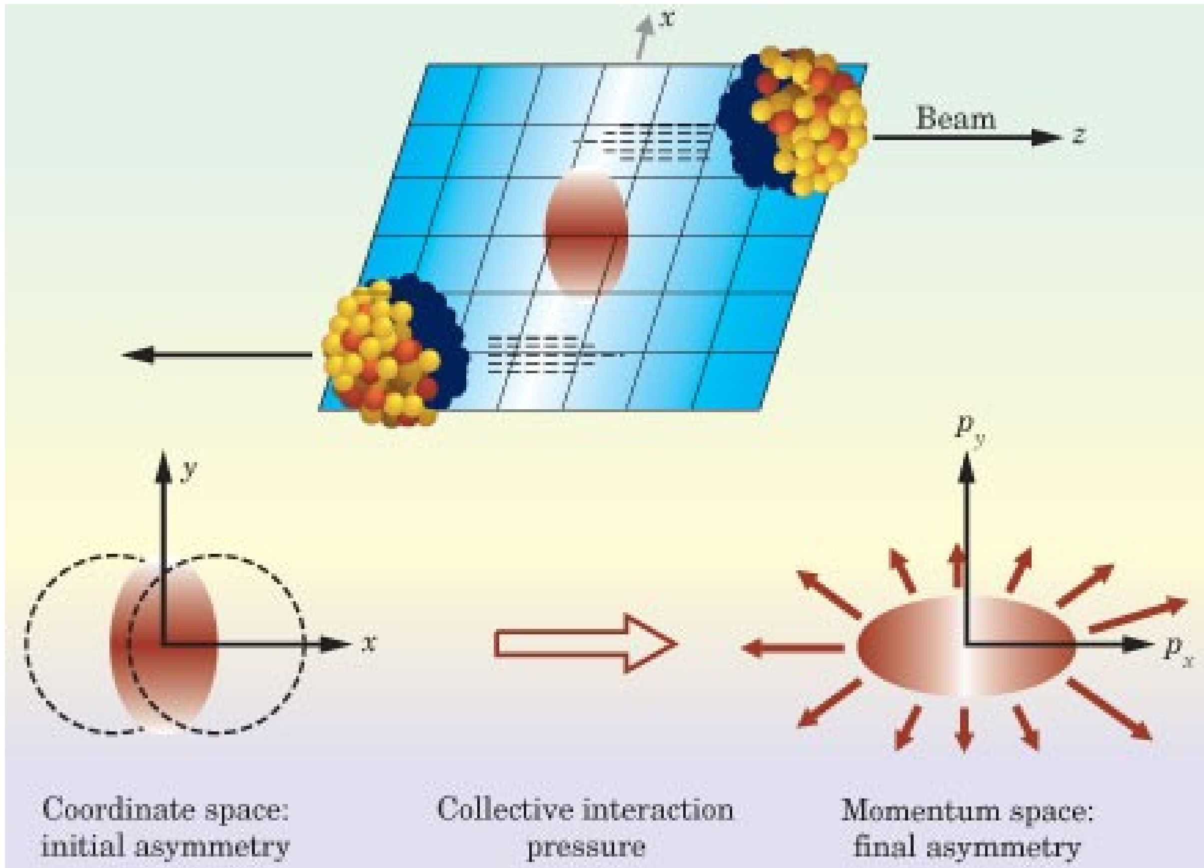


slope constants grow with mass - much too large to be temperatures!

Hubble Expansion of Nuclear Fireball

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

Azimuthal Anisotropy of Transverse Spectra



Fourier decomposition of momentum distributions rel. to reaction plane:

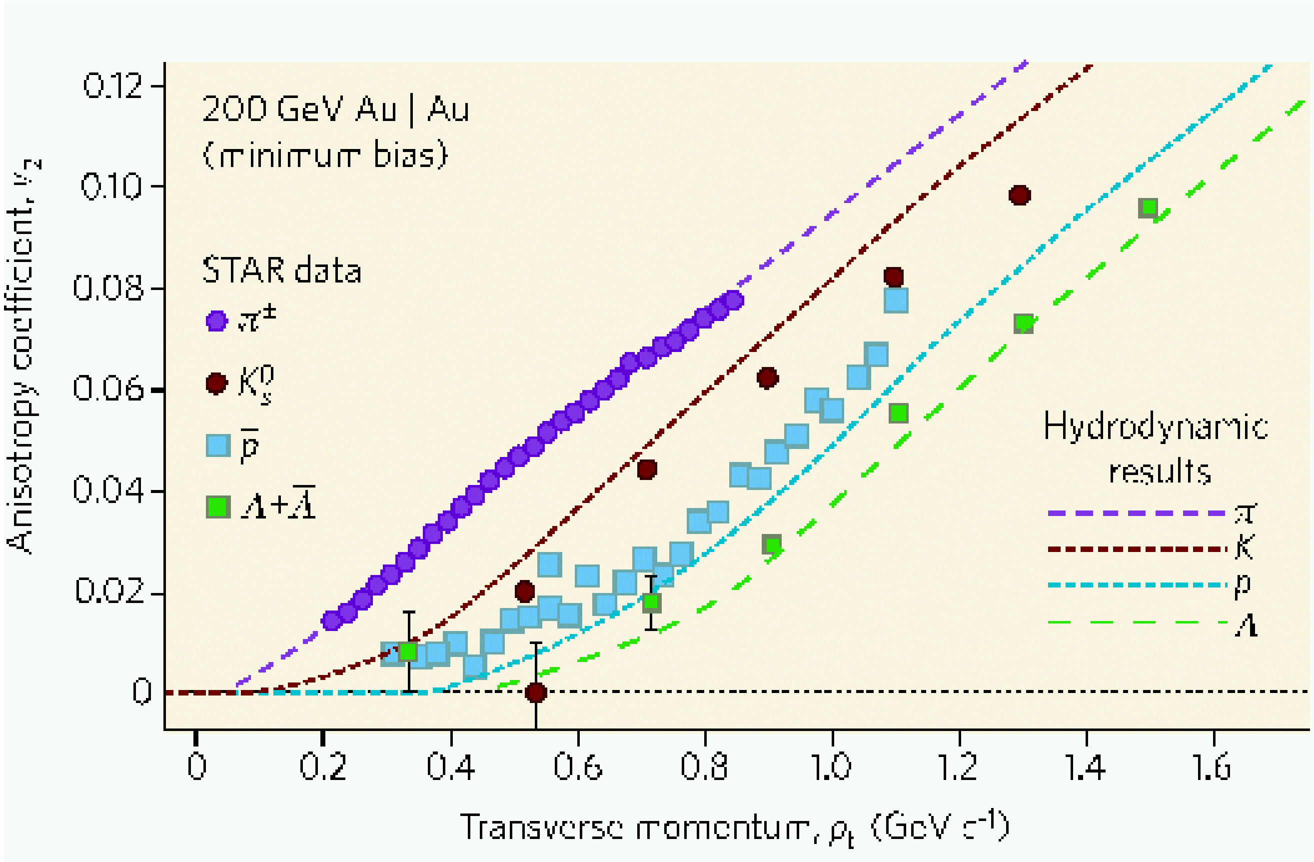
$$\frac{dN}{dp_t\, dy\, d\phi} = N_0 \cdot \left[1 + \sum_{i=1} 2 v_i \left(y, p_t \right) \cos \left(i \phi \right) \right]$$

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



ideal (nonviscous hydrodynamics describes spectra and azimuthal asymmetries up to about 2 GeV/c at sub% level

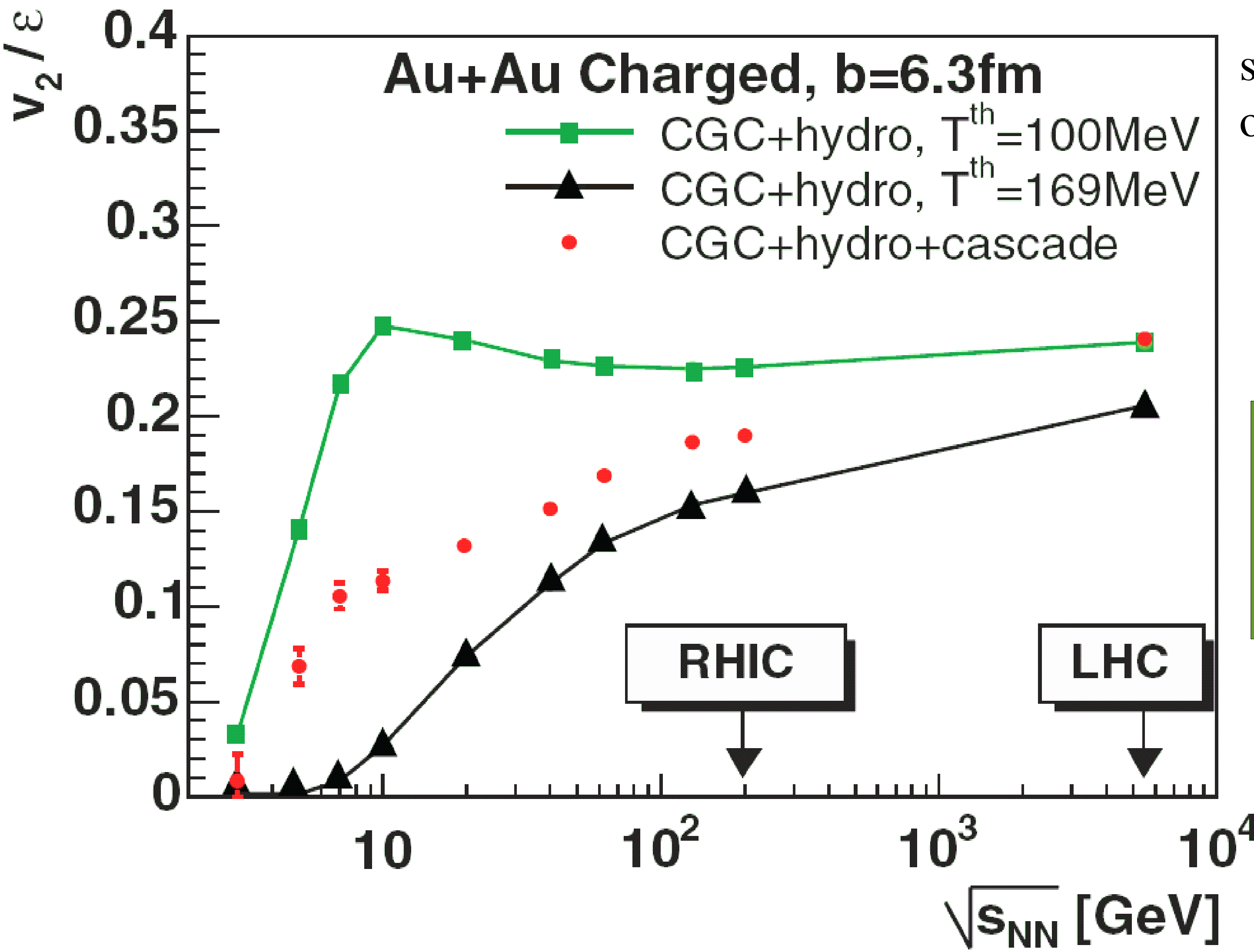
requires strong interactions at short times -> very fast equilibration (< 1 fm/c)

at present mechanism how this happens not yet established!

sQGP

low viscosity (maybe zero?) implies strong interactions
not ideal gas
conjecture: QGP produced at RHIC is strongly interacting

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



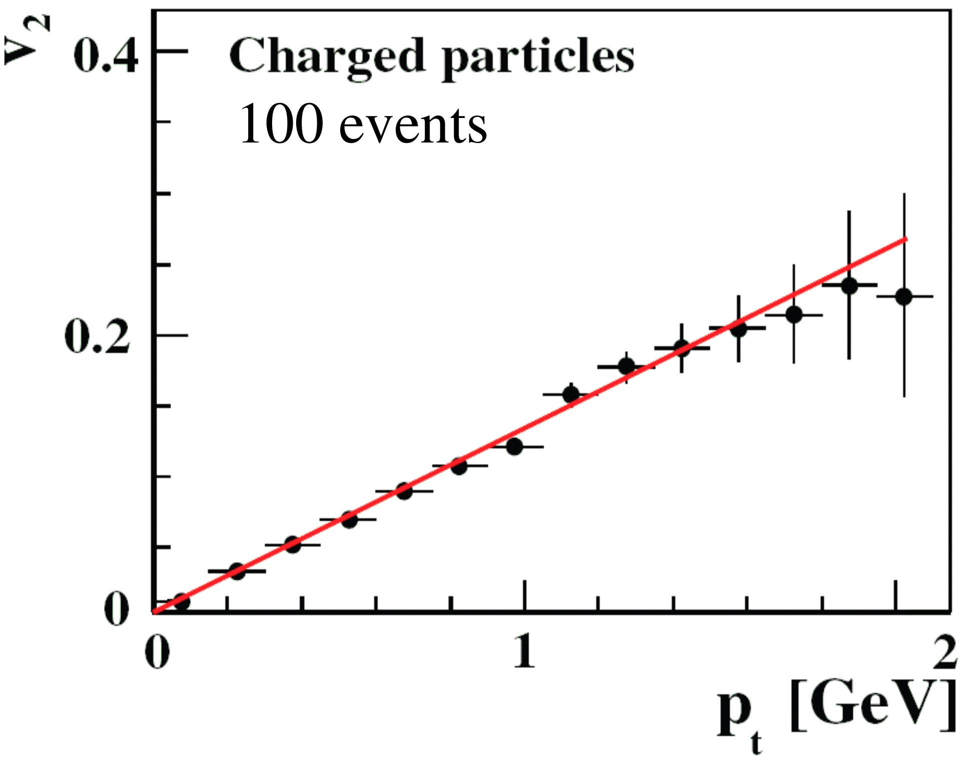
scaled to eccentricity of overlap region

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

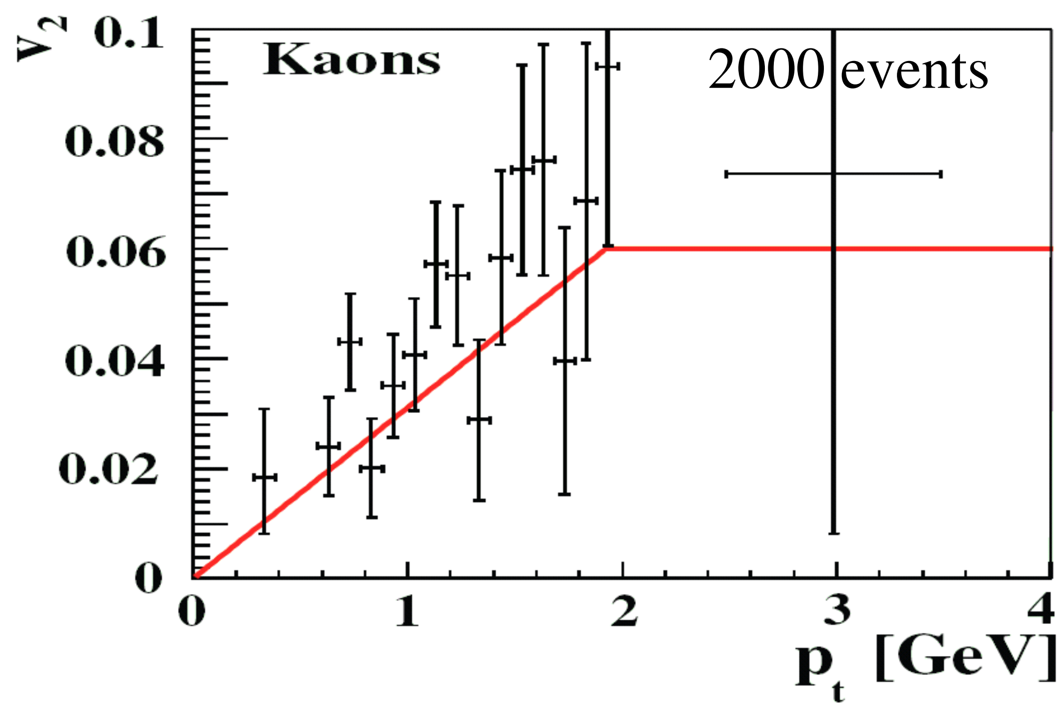
but at very high T the plasma could become weakly interacting

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. Signature for deconfinement

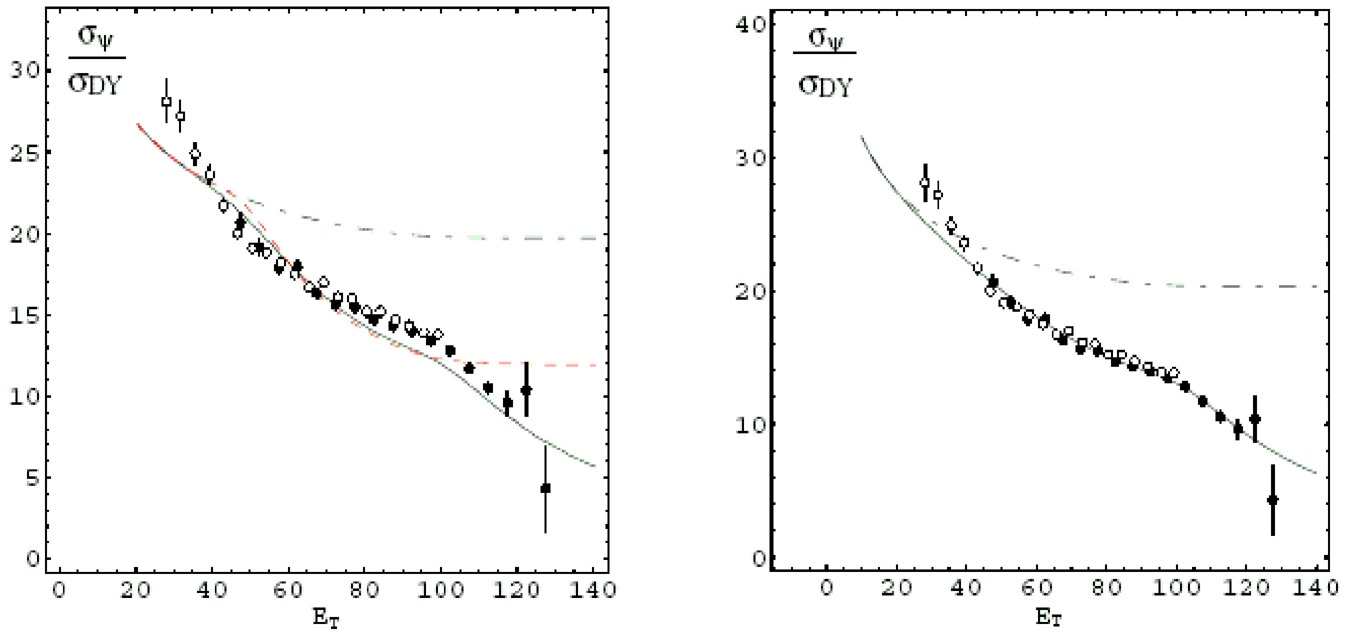
charmonia as QGP signature

- T. Matsui and H. Satz (PLB178 (1986) 416) predict J/ψ suppression in QGP due to Debye screening
- significant suppression seen in central PbPb at top SPS energy (NA50) in line with QGP expectations

J.P. Blaizot, P.M. Dinh, J.Y. Ollitrault, Phys.Rev.Lett.85(2000)4012

Dissolution in QGP at critical density n_c (dashes) and with energy density fluctuations (solid)

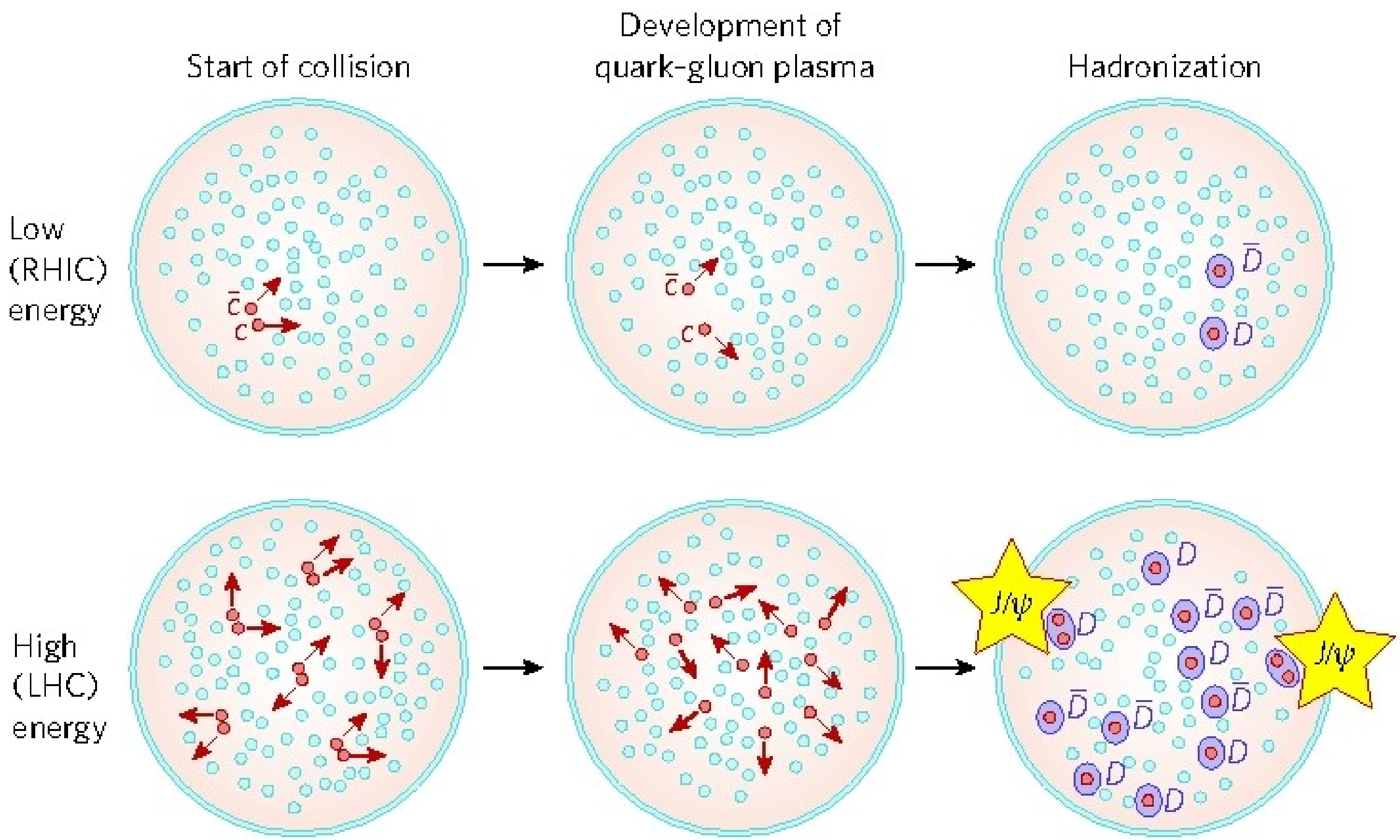
n_c=3.7/fm^2 n_{c1}=3.3 and n_{c2}=4.2/fm^2



- but: at hadronization of QGP J/ψ can form again from deconfined quarks, in particular if number of cc 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: $N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{therm} \frac{I_1(g_c N_{oc}^{therm})}{I_0(g_c N_{oc}^{therm})}$

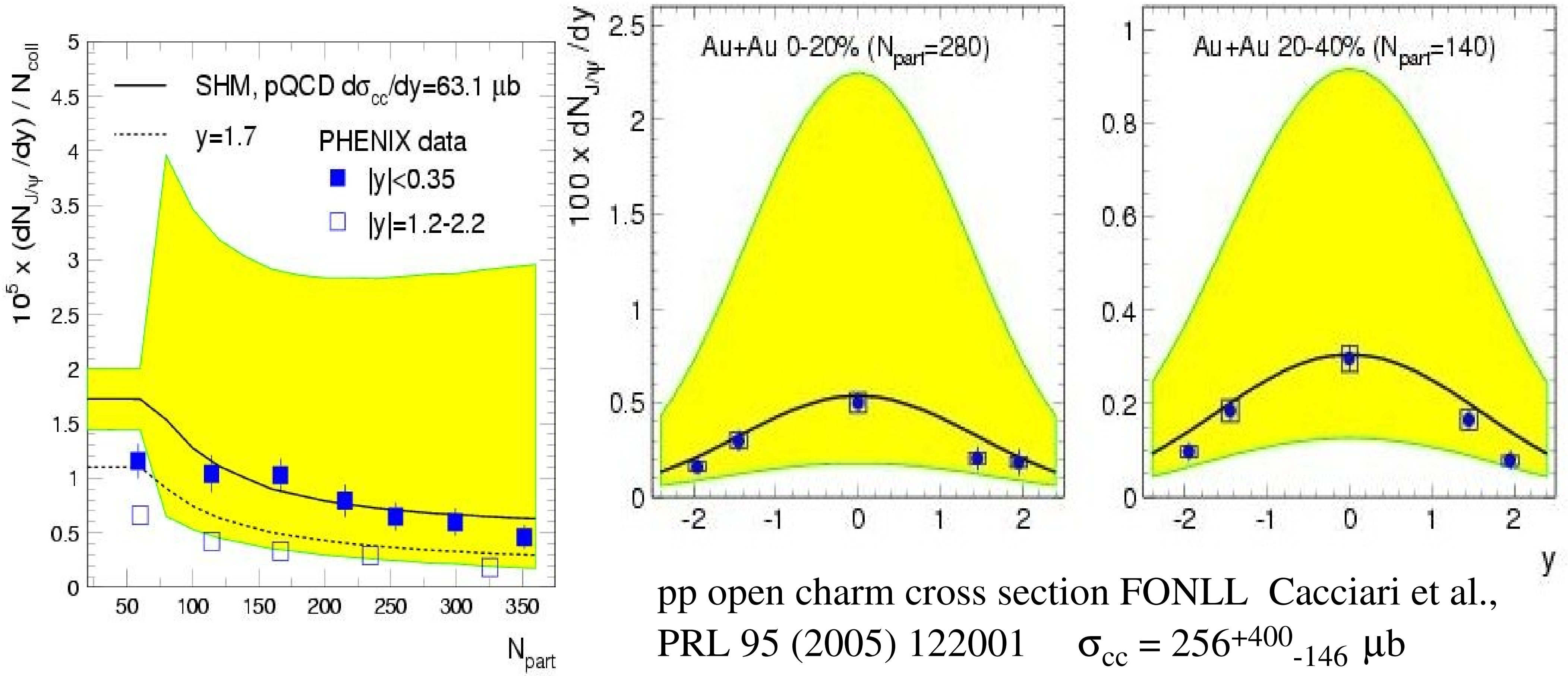
obtain: $N_D = N_D^{therm} \cdot g_c \cdot \frac{I_1}{I_0}$ and $N_{J/\psi} = N_{J/\psi}^{therm} \cdot g_c^2$ and all other charmed hadrons

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

P. Braun-Munzinger, J. Stachel, Phys. Lett. B490 (2000) 196 and Nucl. Phys. A690 (2001) 119
A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nucl. Phys. A715 (2003) 529c,
Phys. Lett. B571 (2003) 36, Nucl. Phys. A789 (2007) 334 and Phys. Lett. B652 (2007) 259
M. Gorenstein et al., hep-ph/0202173; A. Kostyuk et al., Phys. Lett. B531 (2001) 225; R. Rapp and
L. Grandchamp, hep-ph/0305143 and 0306077

comparison of model predictions to RHIC data: centrality dependence and rapidity distribution

P. Braun-Munzinger, K. Redlich, J. Stachel, Nucl. Phys. A789 (2007) 334 nucl-th/0611023

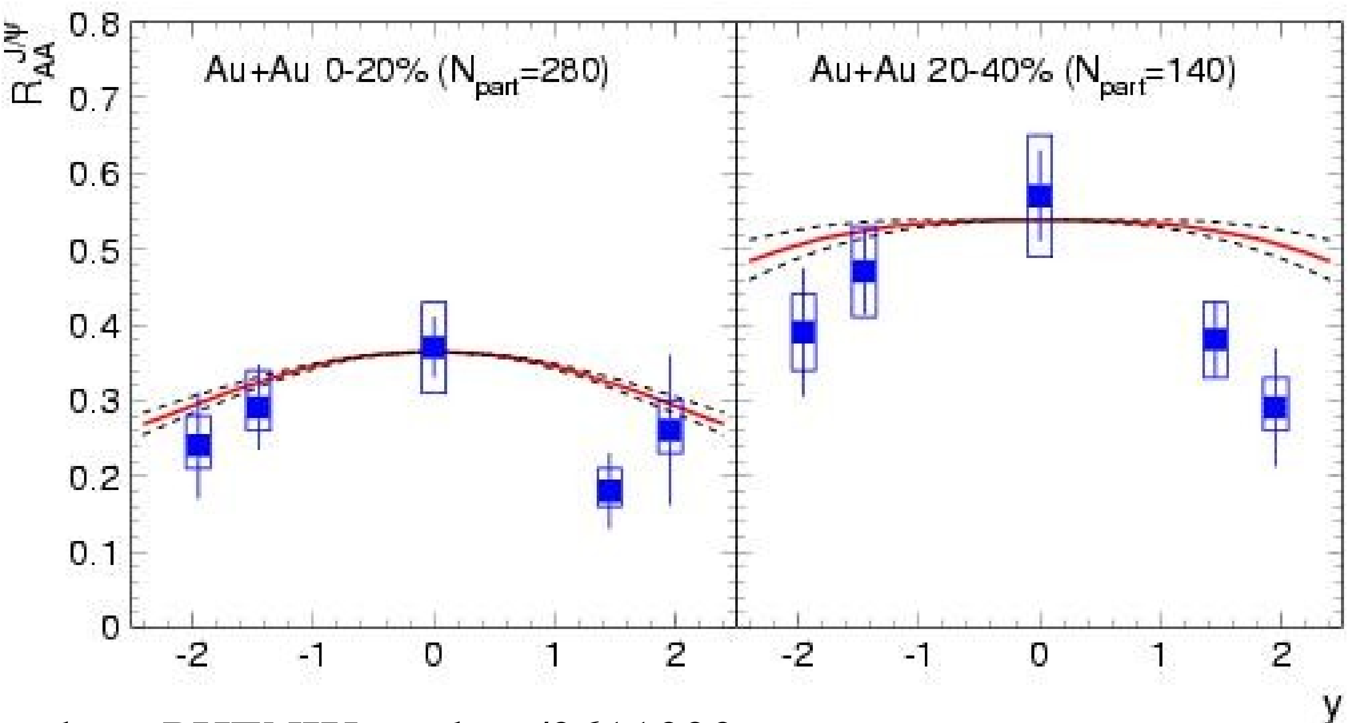


pp open charm cross section FONLL Cacciari et al., PRL 95 (2005) 122001 $\sigma_{cc} = 256^{+400}_{-146}$ μb

good agreement, no free parameters ⟷ but need for good open charm measurement obvious (this is a lesson for LHC as well!)

but there is a more revealing normalization:

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



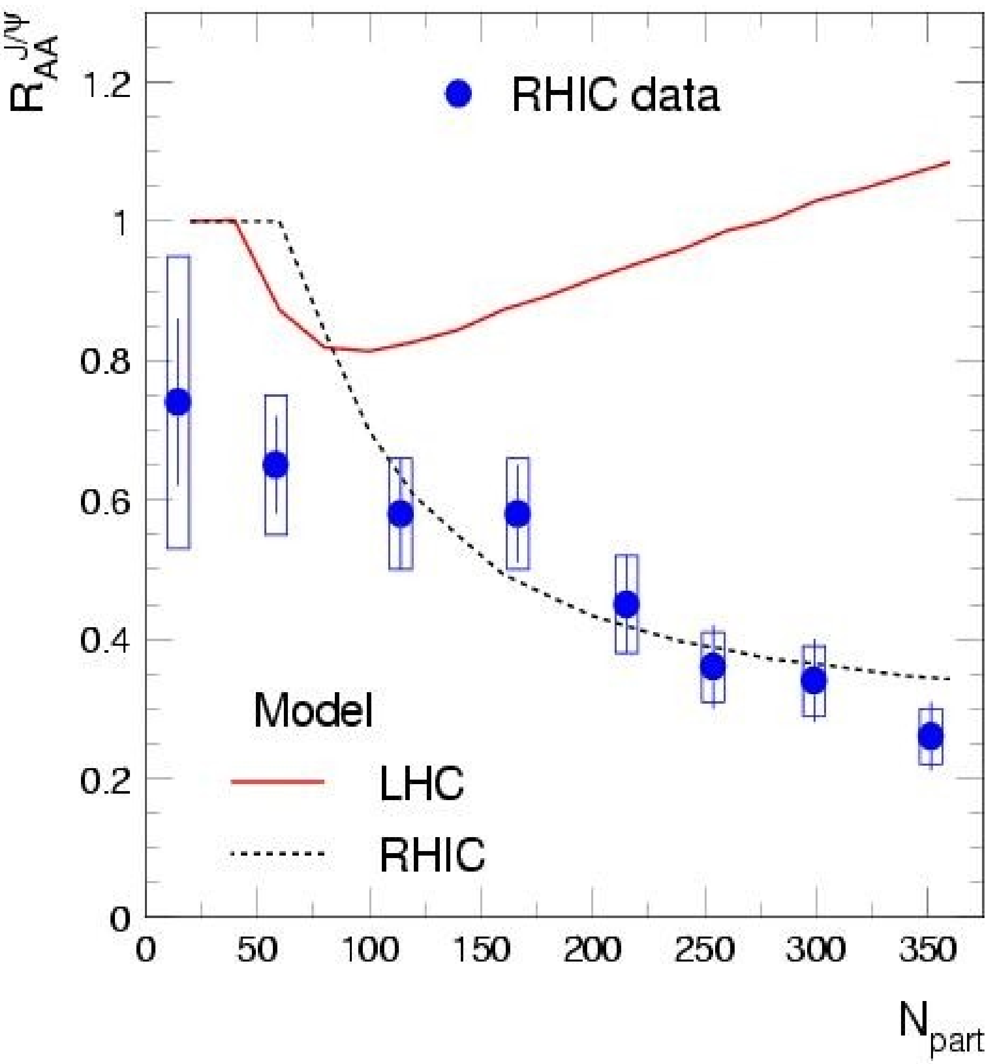
quantitative agreement!

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

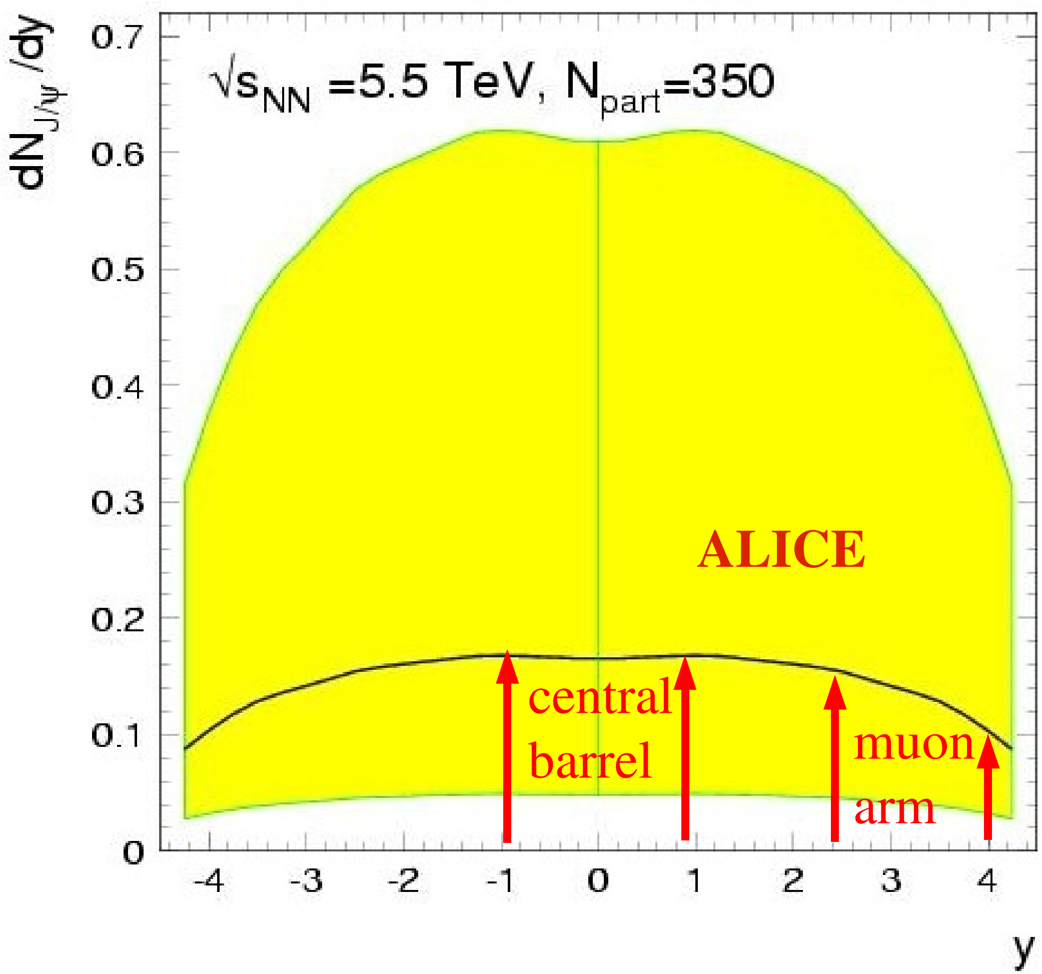
A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel Phys. Lett. B652 (2007) 259

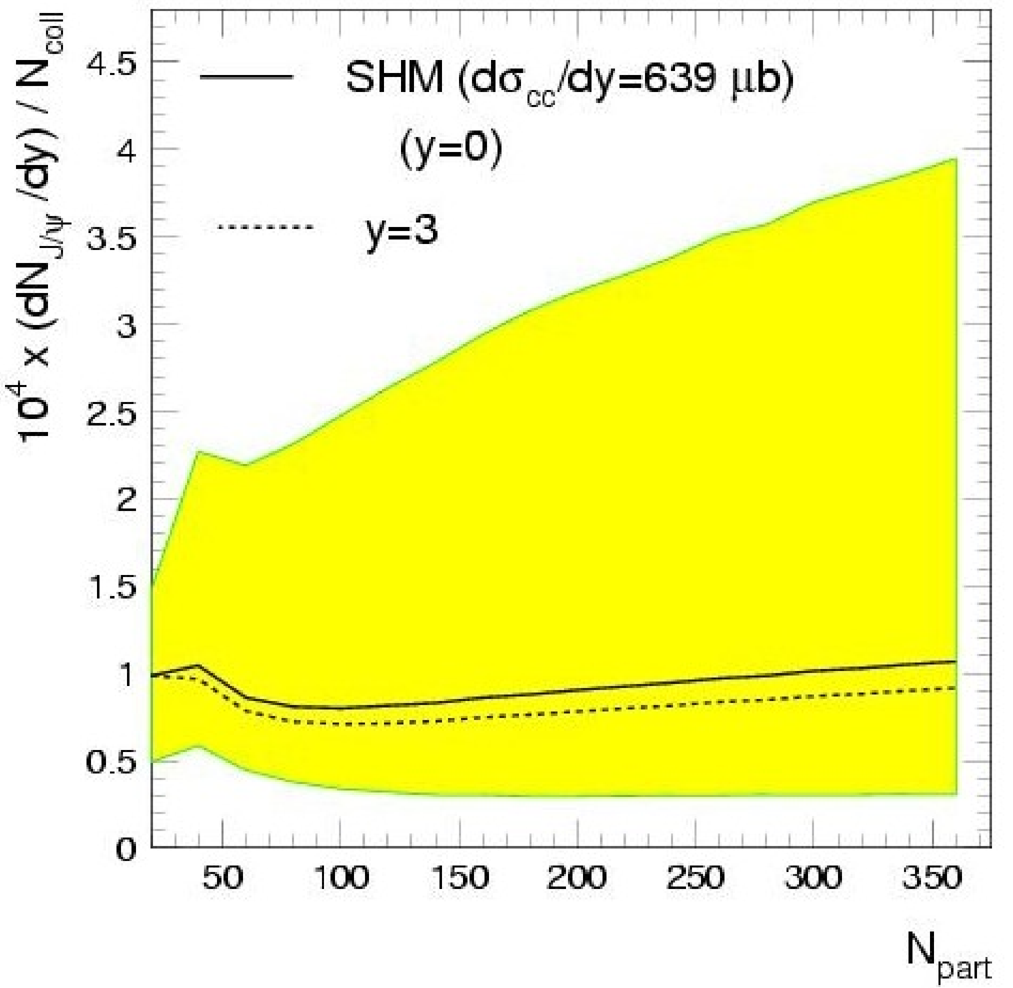


centrality dependence and
enhancement beyond pp value
will be fingerprint
of statistical hadronization at LHC
-> direct signal for deconfinement

predictions for charmonium rapidity and centrality distributions at LHC

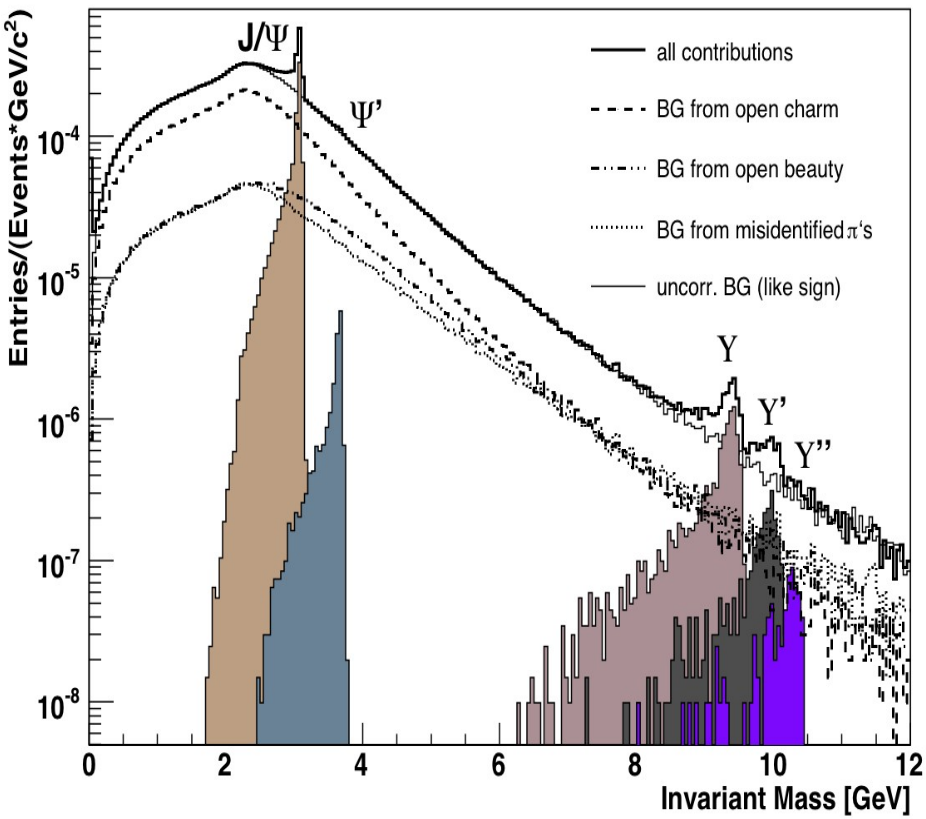
yellow band: uncertainty of pQCD prediction for ccbar prod. line: central value

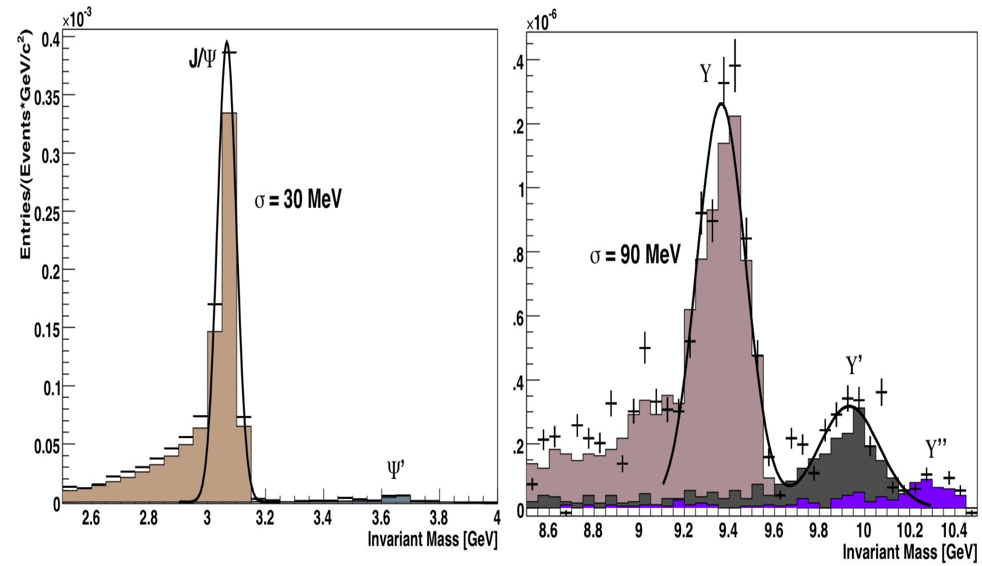


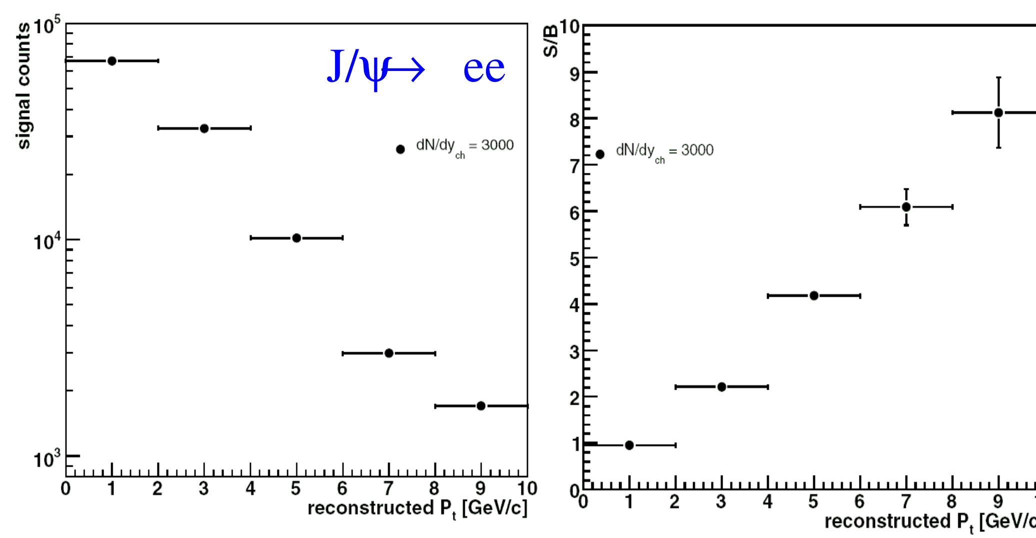


charmonia in ALICE at mid-rapidity

electron identification with TPC and TRD







Simulation: W. Sommer (Frankfurt) $2 \cdot 10^8$ central PbPb coll.

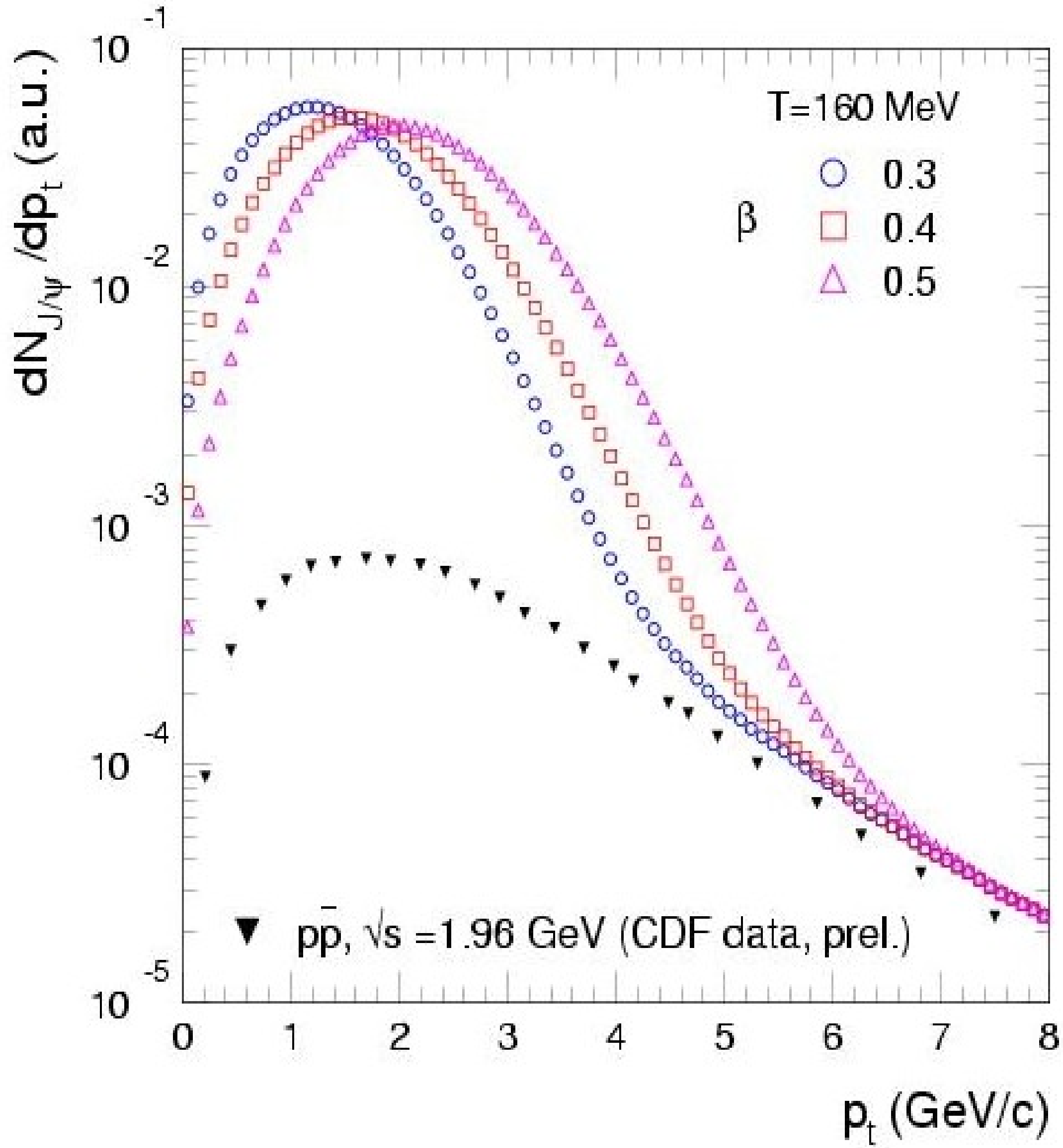
Good mass resolution and signal to background
expect w full TRD and trigger
2500 Upsilon per PbPb year

flow of quarkonia at LHC?

there is evidence from RHIC that fireball is expanding hydrodynamically
do heavy quarks follow?

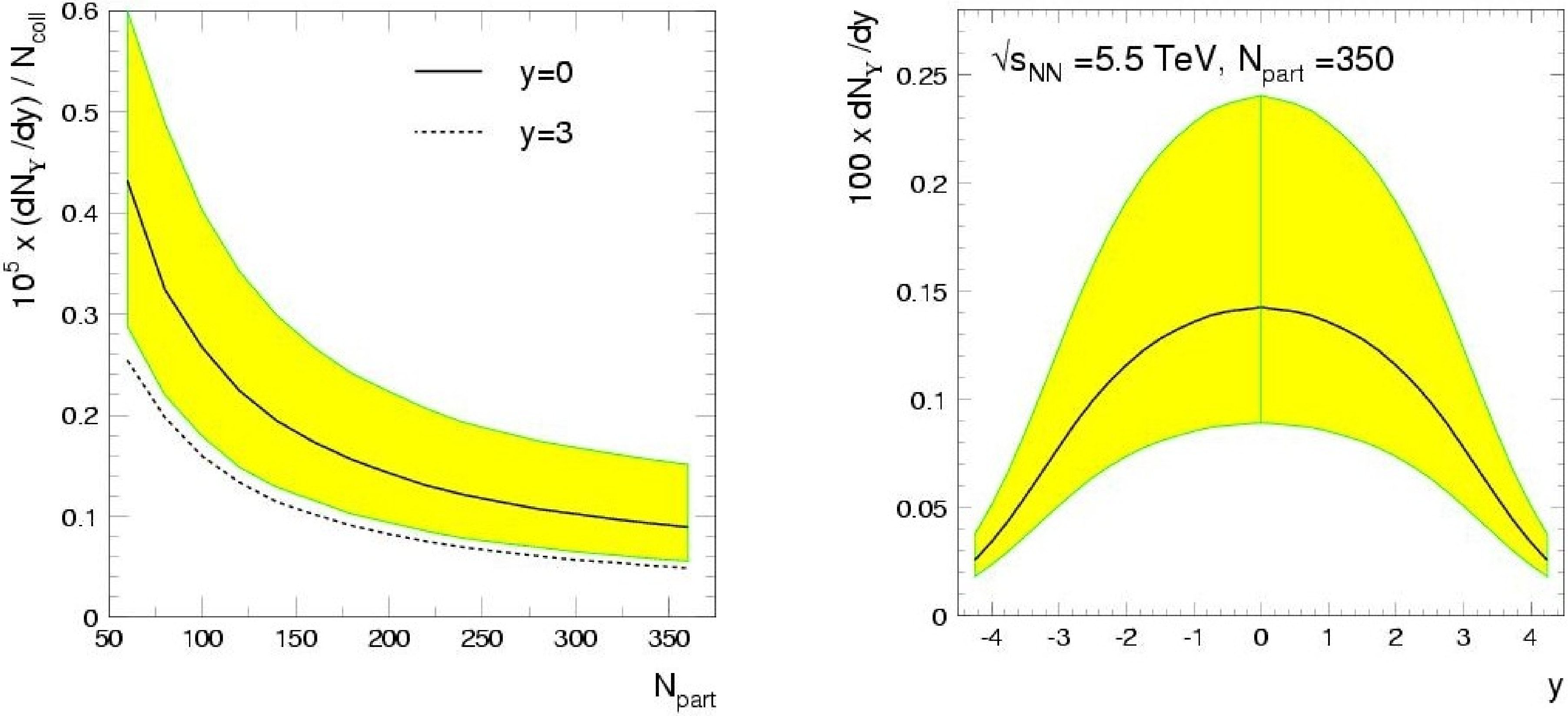
p_t spectra with flow are very different for charmonia from those measured in pp_bar e.g. at Fermilab or expected for pp at LHC

should be easy to discriminate at LHC



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??

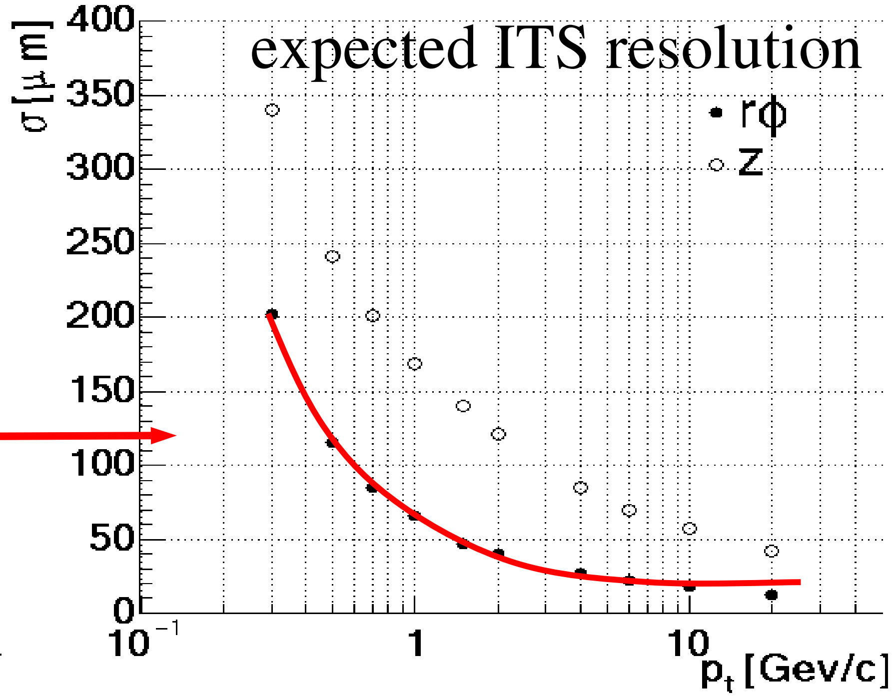
if yes, population of 2s and 3s states completely negligible (exp-Δm/T)

hydrodynamic flow? need to measure spectrum to 15 GeV

open/hidden heavy flavor measurements in ALICE

- Hadronic decays: $D^0 \to K\pi$, $D^{+-} \to K\pi\pi$, $D_s \to K\,K^*$, $D_s \to \phi\pi$, …
- Leptonic decays:
  - $B \to l$ (e or μ) + anything
  - Invariant mass analysis of lepton pairs: BB, DD, BD_{same}, J/Ψ, Ψ', Υ family, B $\to J/\Psi$ + anything
  - BB $\to \mu\,\mu\,\mu$ ($J/\Psi\,\mu$)
  - e-μ correlations

id. hadrons, electrons: $-0.9 < y < 0.9$
muons: $y = 2.5-4.0$
in central barrel: vertex cut effective for heavy quark identification

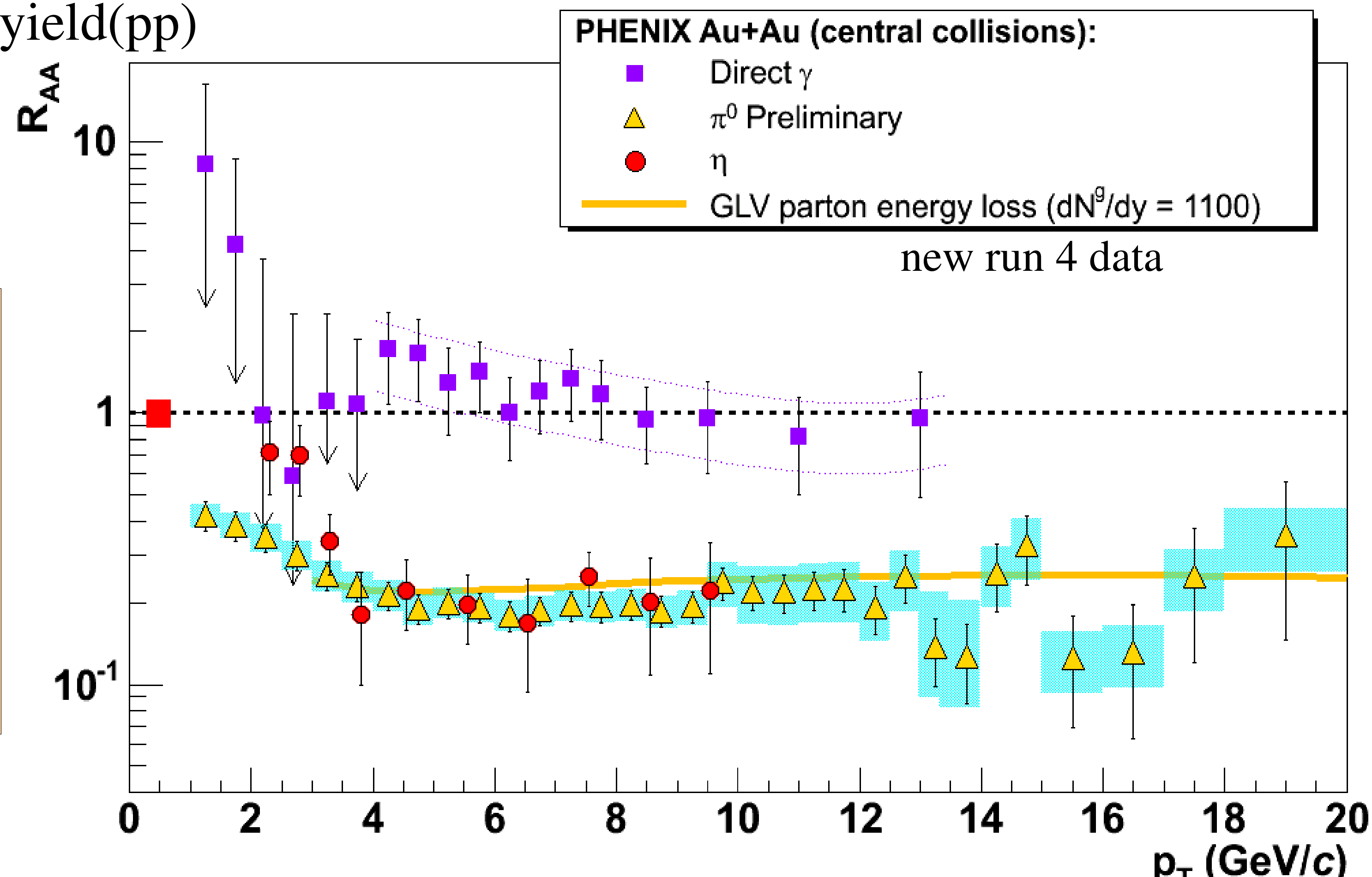


4. high p_t partons as probe of the medium, i.e. the QGP

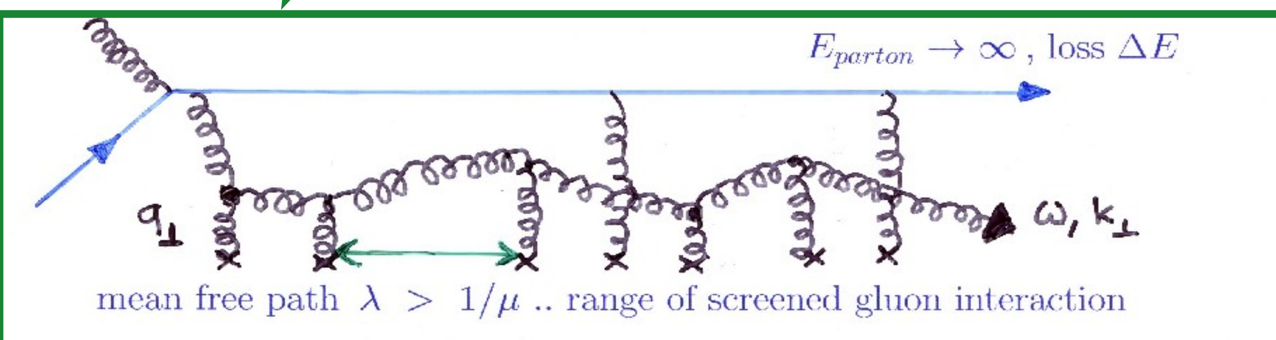
prediction: in dense partonic matter a jet is losing energy rapidly
order several GeV/fm

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



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

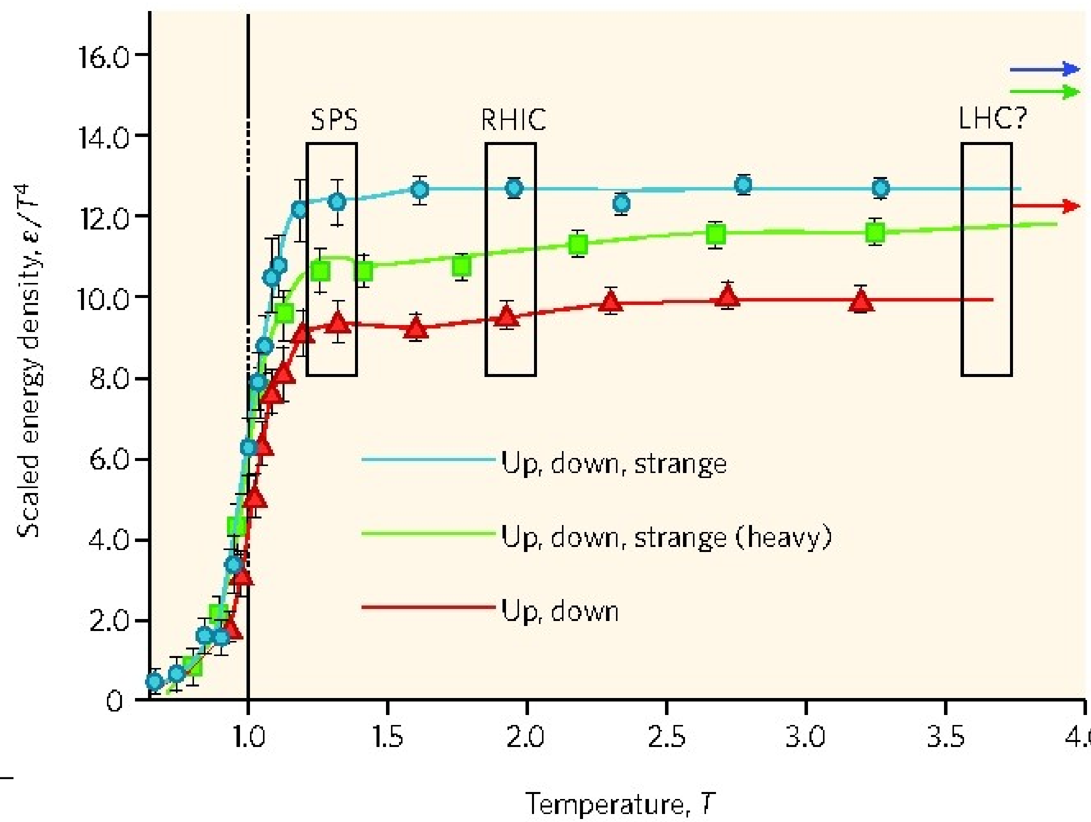
- **Consistent estimate with hydrodynamic analysis**

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

2 GeV 20 GeV 100 GeV 200 GeV

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

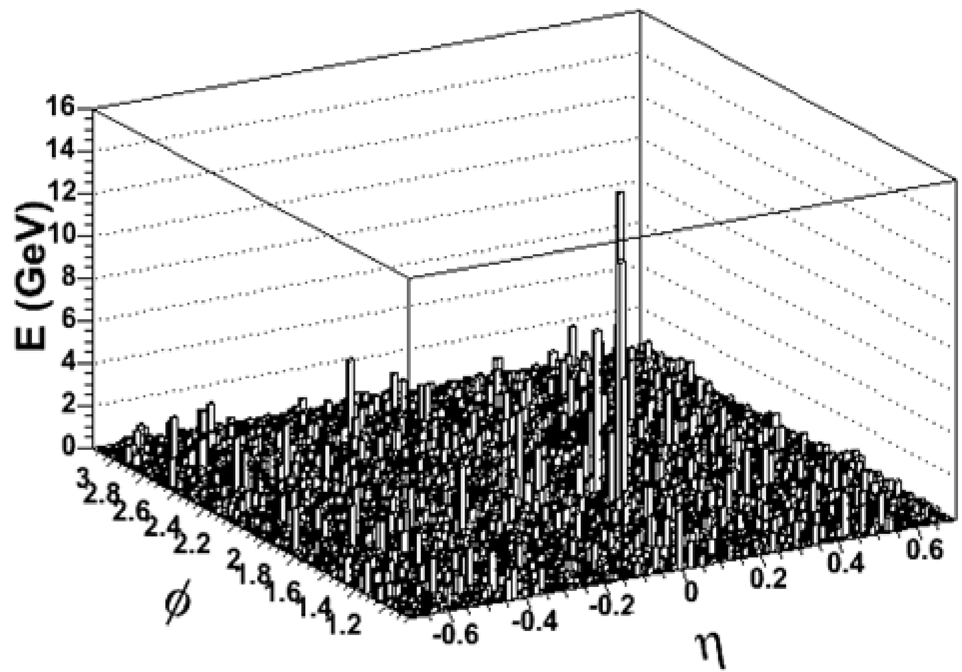
at p > 2 GeV/c :

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

at high p:

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

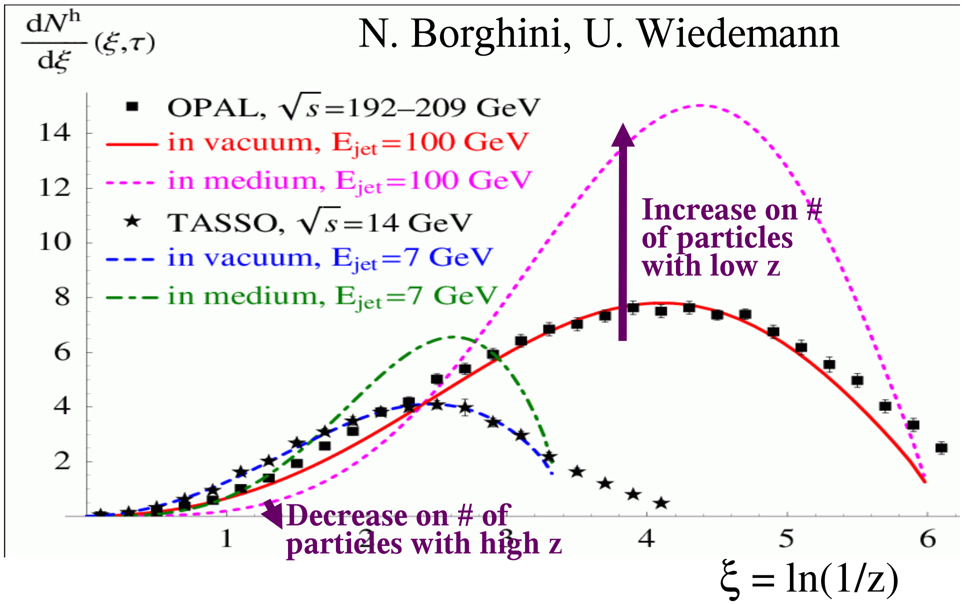
Example :
100 GeV jet +
underlying event

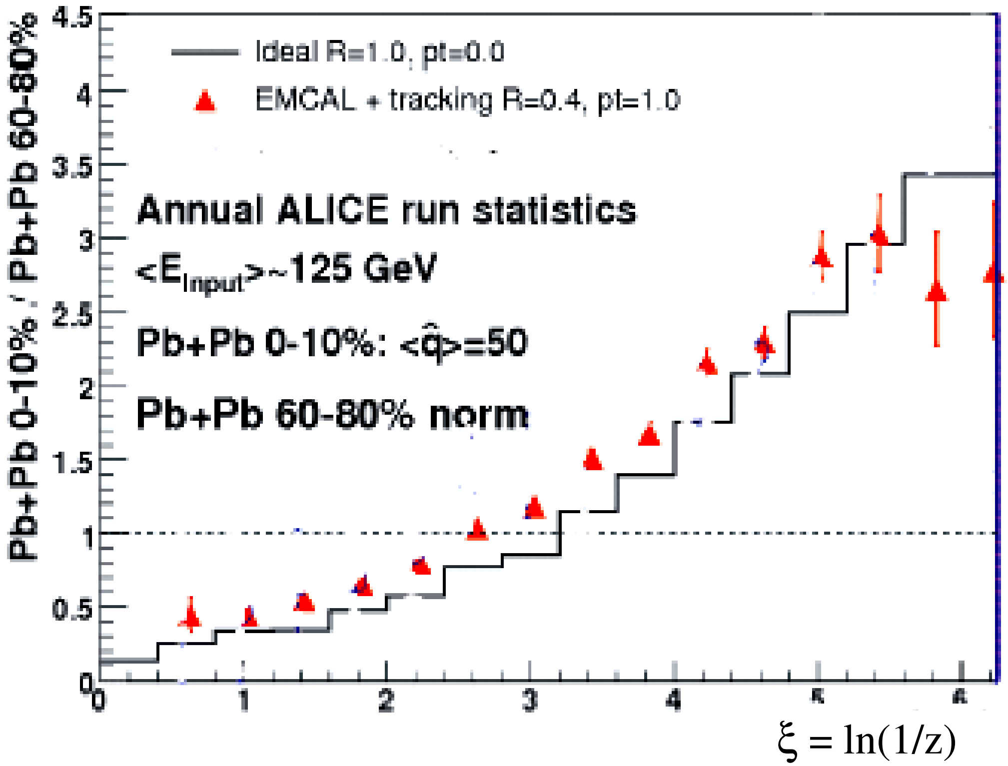


for jet physics recently added EmCal will play important role in conjunction with existing charged particle tracking

measurement of jet fragmentation function

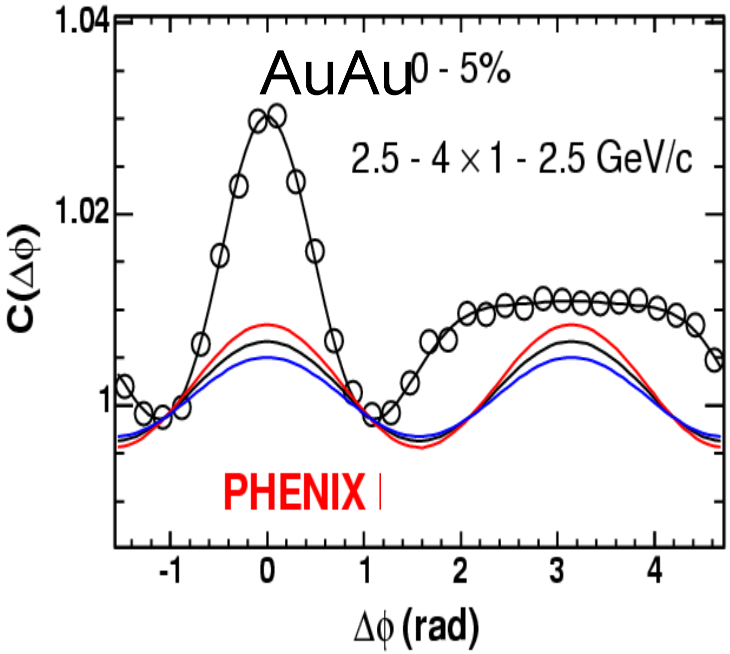
sensitive to energy loss mechanism

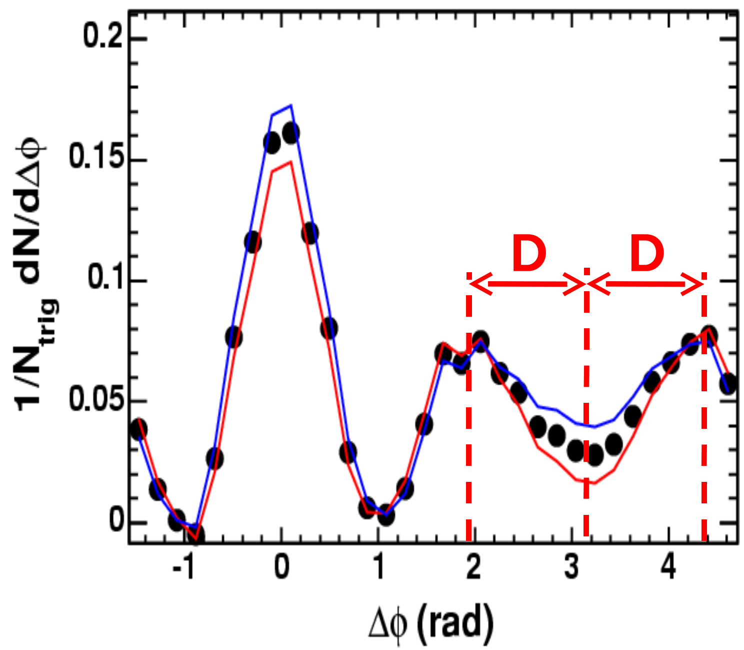




good reconstruction in ALICE

response of the medium to jet energy loss





3-particle correlations confirm cone-like structure

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

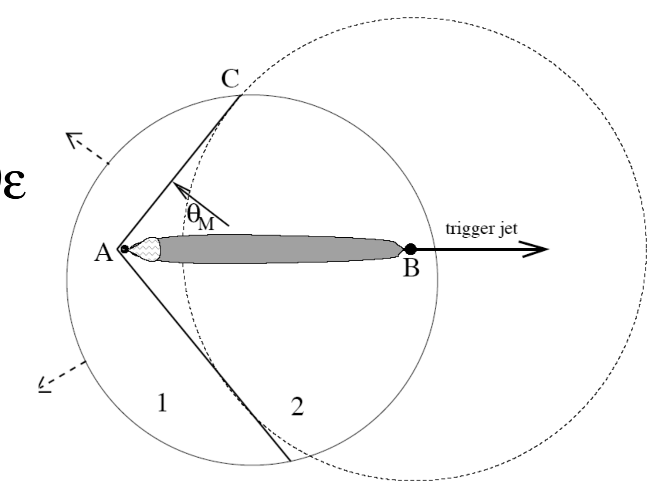
sound velocity is related to the EOS of the medium: $c_s^2 = \partial p/\partial \varepsilon$

ideal gas has c_s^2

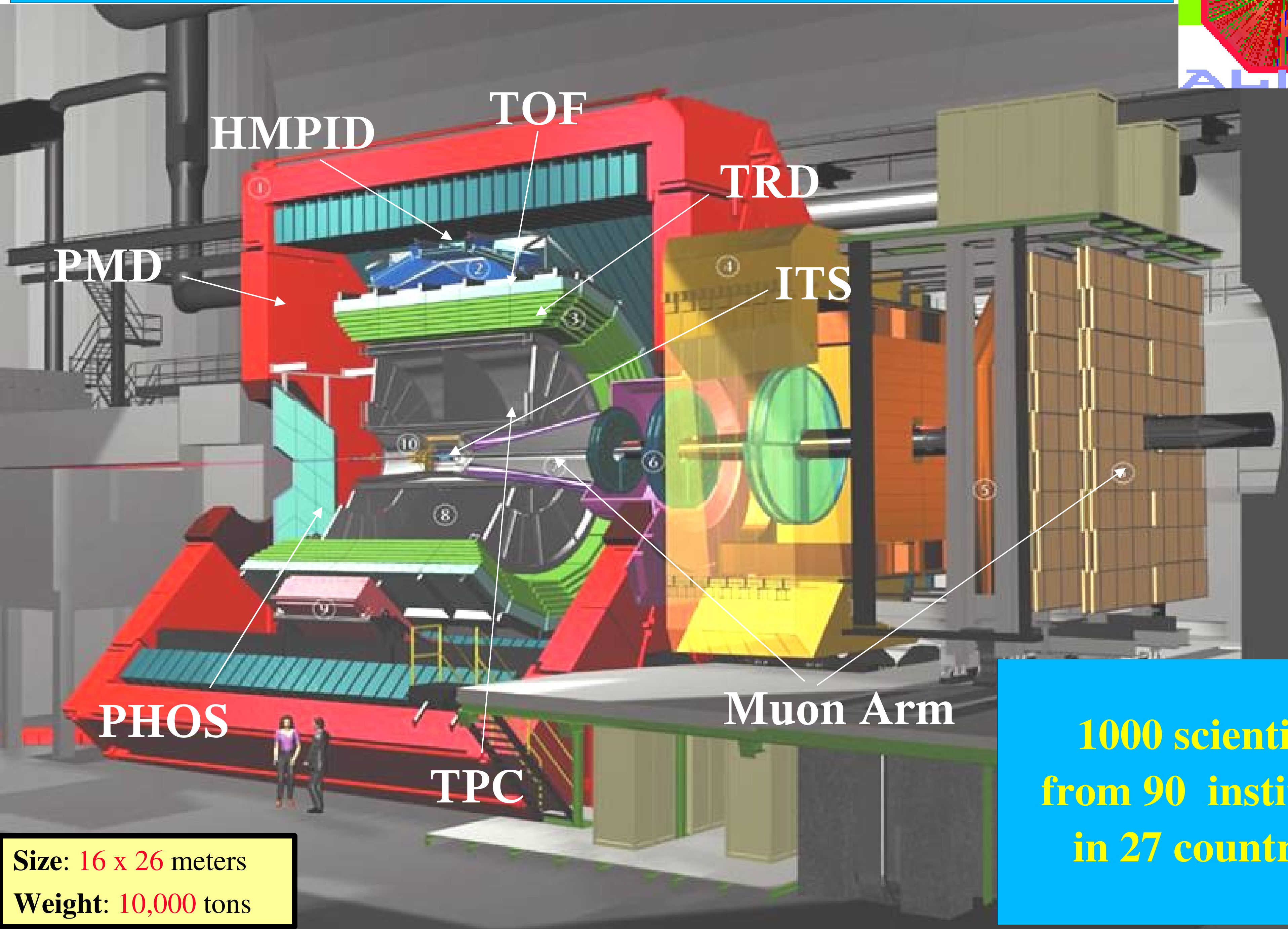
original idea: Stöcker/Greiner 1976 for nuclear reactions

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

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



ALICE

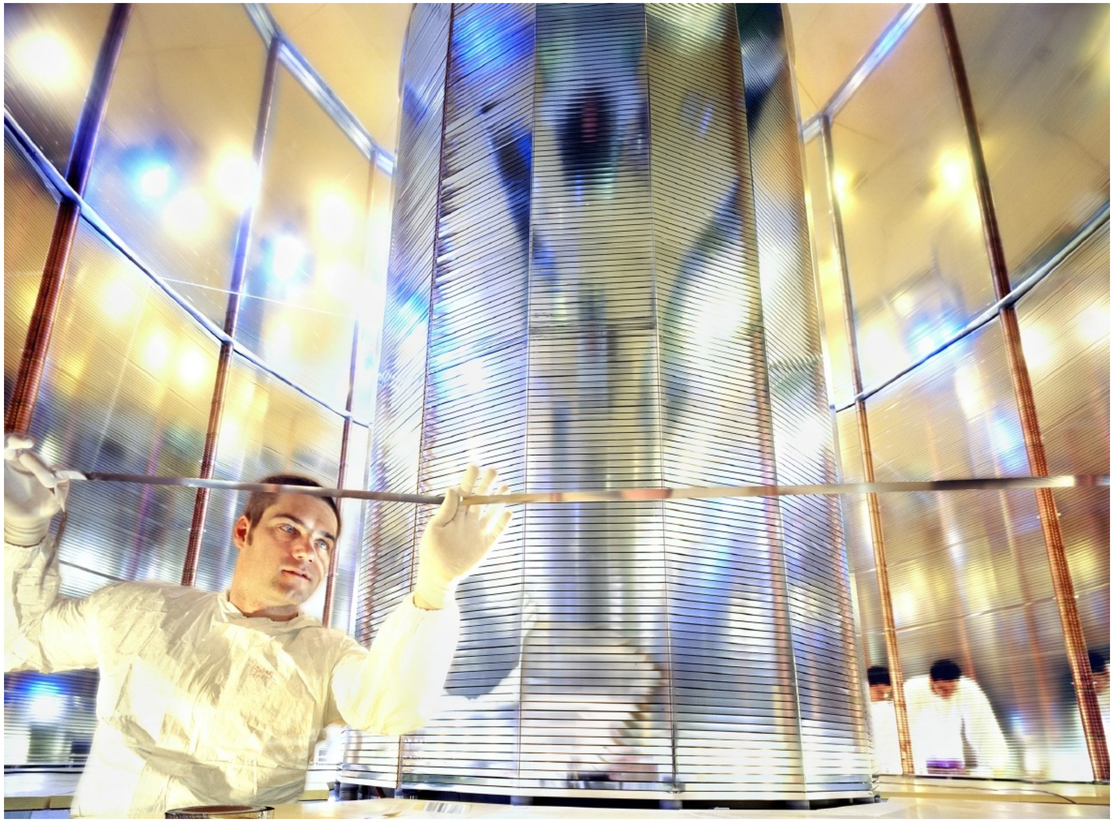


Size: 16 x 26 meters
Weight: 10,000 tons

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

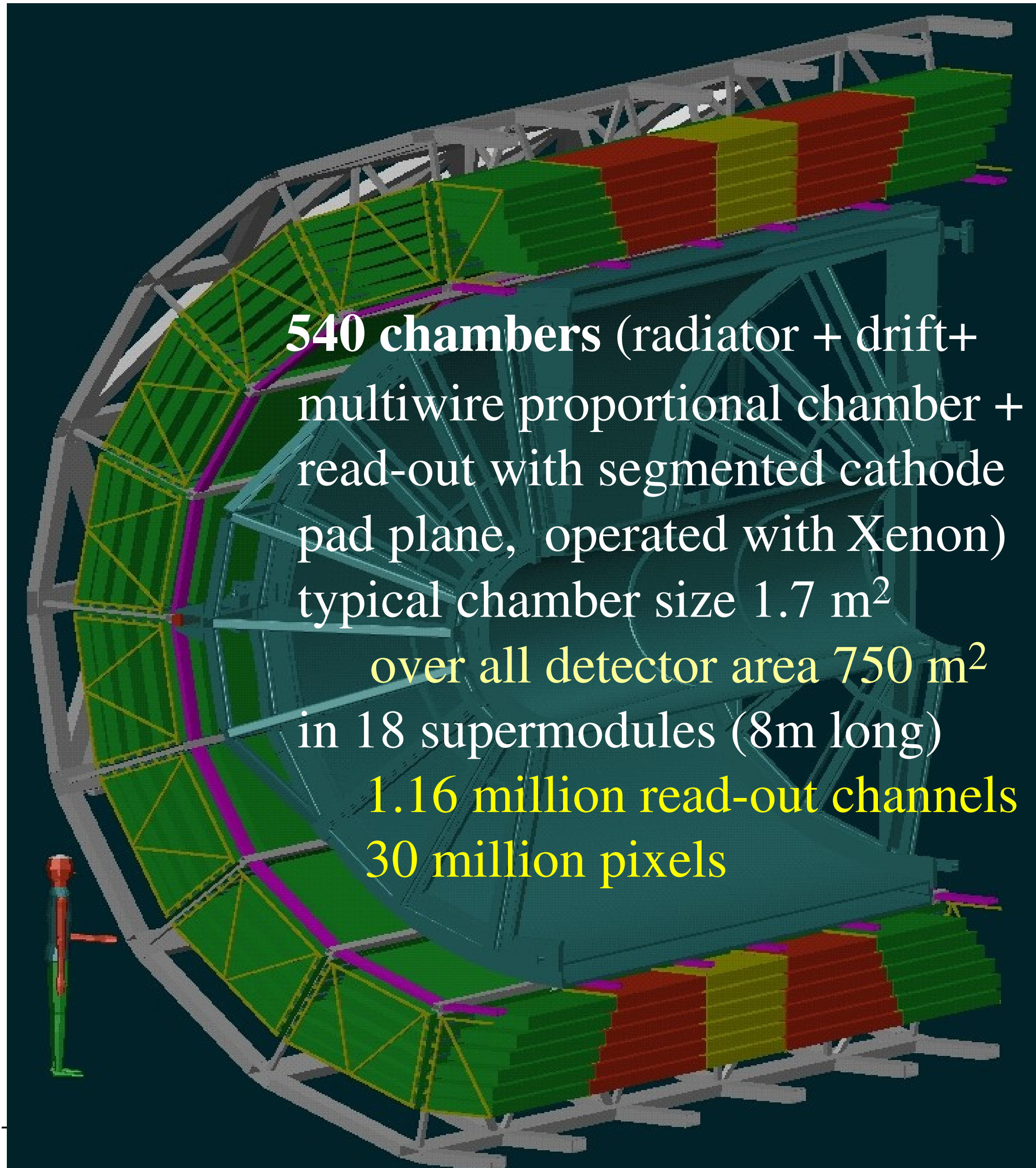


560 million read-out pixels!

precision better than 500 µm in all 3 dim.

180 space and charge points per track

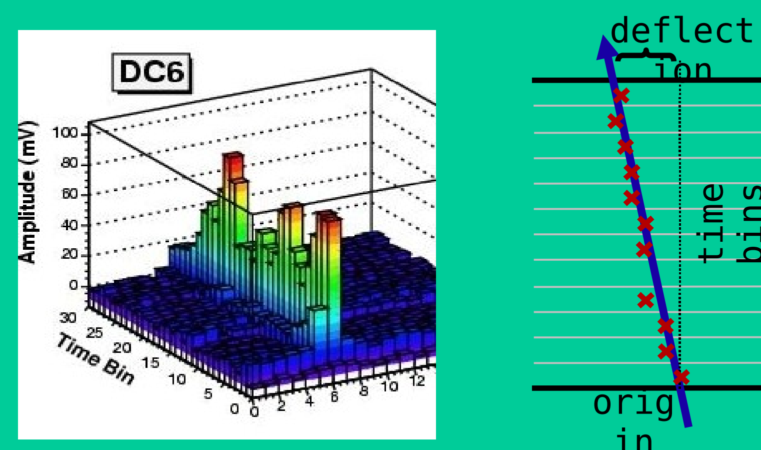
the TRD (Transition Radiation Detector) identifies electrons at the trigger level



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:

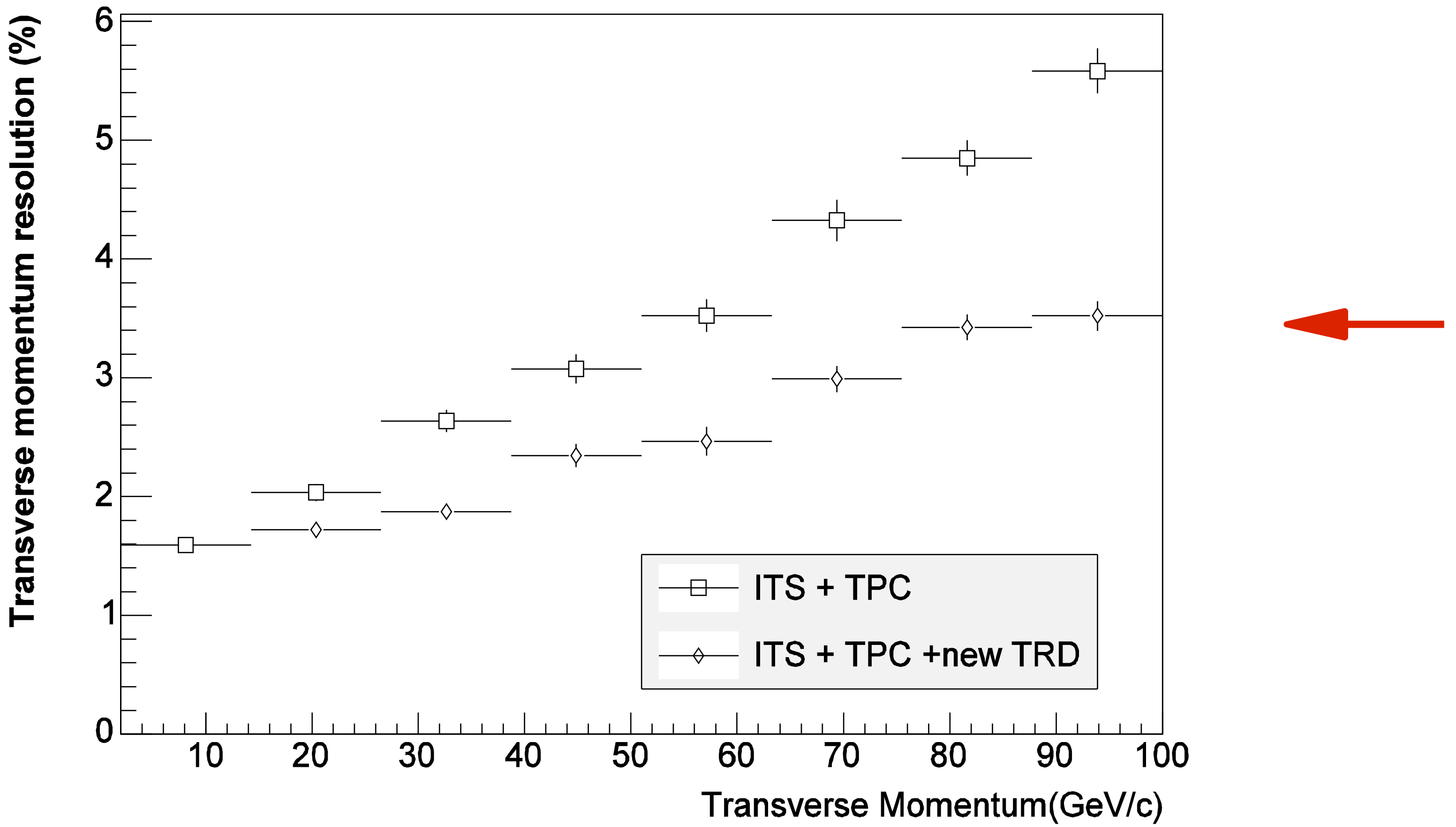


275 000 CPU's process raw data of 65 Mbyte to reconstruct tracks (of 6 segments) in 6.5 µs for trigger decision:
high momentum electron pair

Combined Momentum Resolution in ALICE Central Barrel

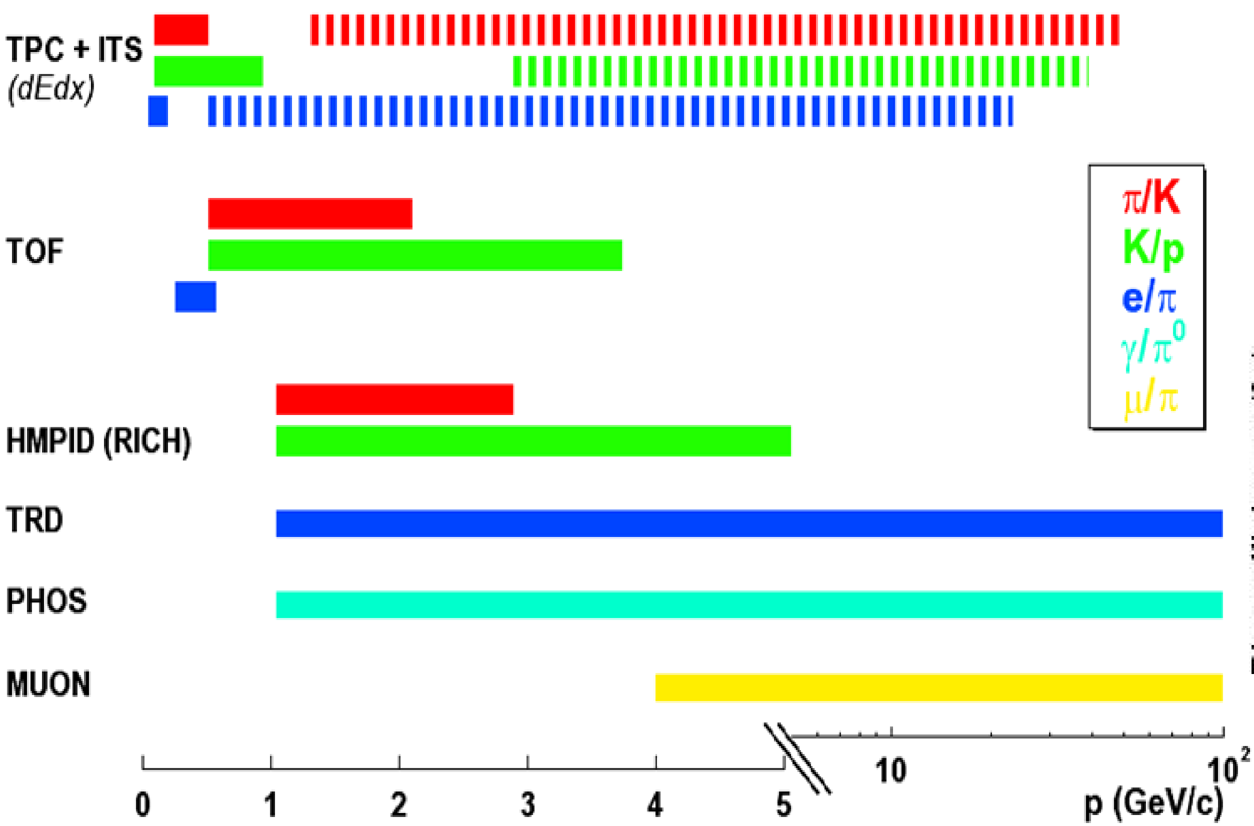
M.Ivanov, CERN & PI Heidelberg, March 05

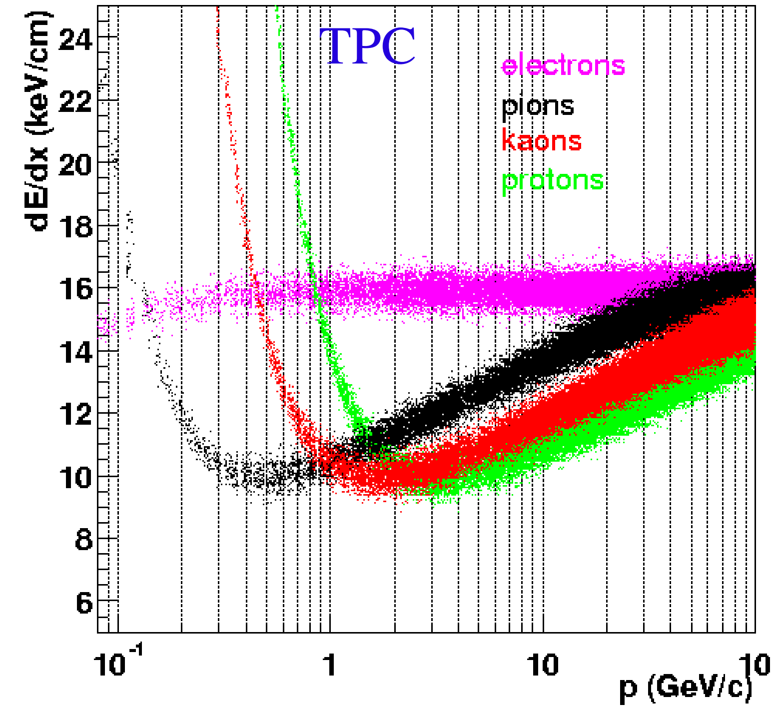
$dN_{ch}/dy \sim 5000$

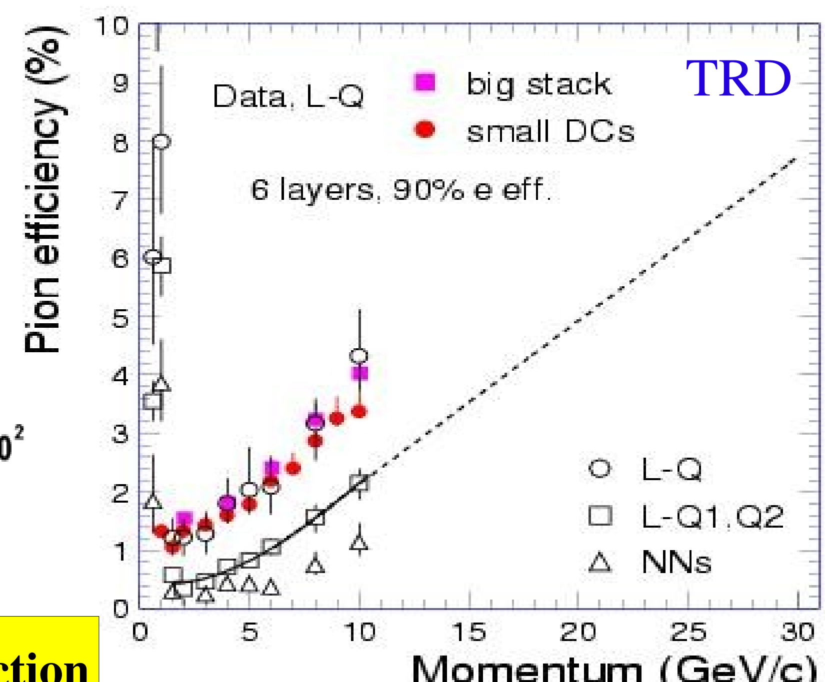


resolution ~ 3% at 100 GeV/c
excellent performance in hard region!

Particle Identification in ALICE



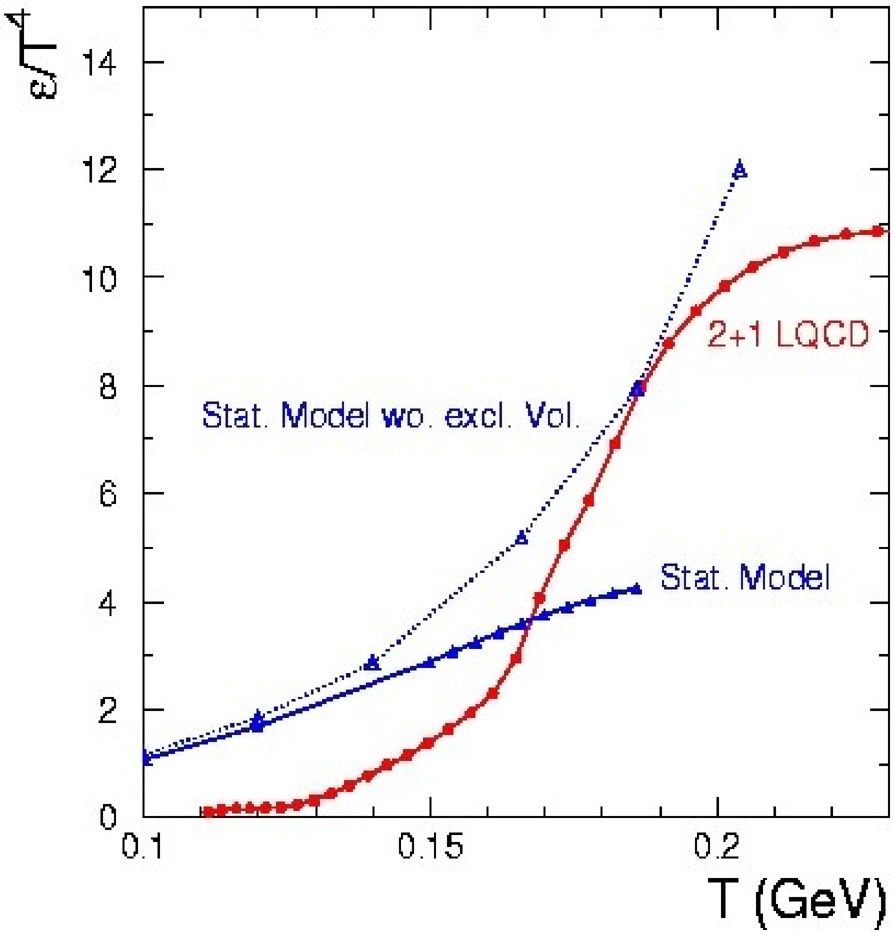




From test beam data: at 2 GeV and 90 % e eff → 10^5 π rejection

Backup slides

rapid hadrochemical equilibration at phase boundary

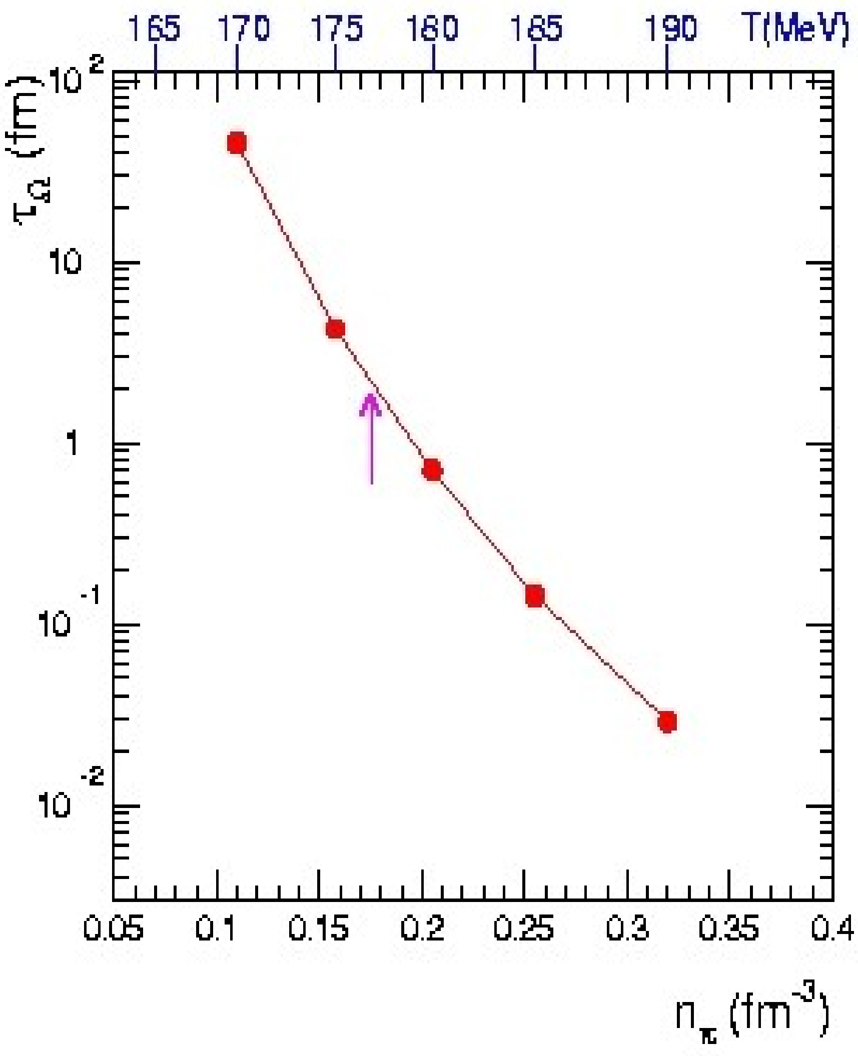


Lattice QCD calcs. F. Karsch et al.

- Known since years: two-body collisions are not sufficient to bring multi-strange baryons into equilibrium.
- The density of particles varies rapidly with T near the phase transition.
- Multi-particle collisions are strongly enhanced at high density and lead to chem. equilibrium very near to $T_{c.}$

P. Braun-Munzinger,
J. Stachel, C. Wetterich
Phys. Lett. B596 (2004) 61
nucl-th/0311005

chemical freeze-out takes place at T_c



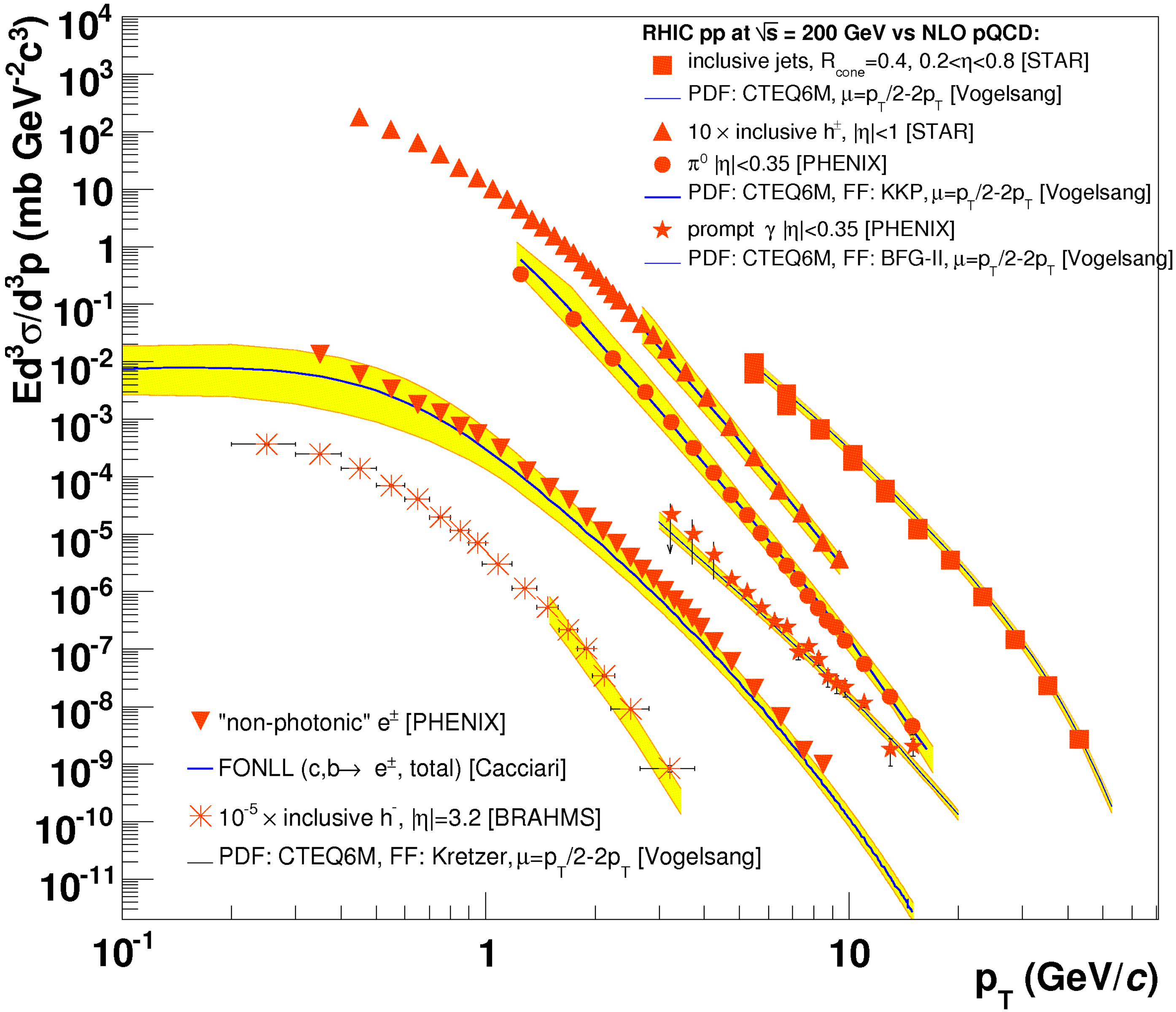
- rate of change of density due to multiparticle collisions $\propto n(T)^{n_{in}} |M|^2 \Phi$
- example: for small μ_b, reactions such as $KKK\pi\pi \rightarrow \Omega N_{bar}$ bring multi-strange baryons close to equilibrium.
- Equilibration time $\tau \propto T^{-60}$!
- All particles freeze out within a very narrow temperature window close to T_c.

P. Braun-Munzinger,
J. Stachel, C. Wetterich
Phys. Lett. B596 (2004) 61
nucl-th/0311005

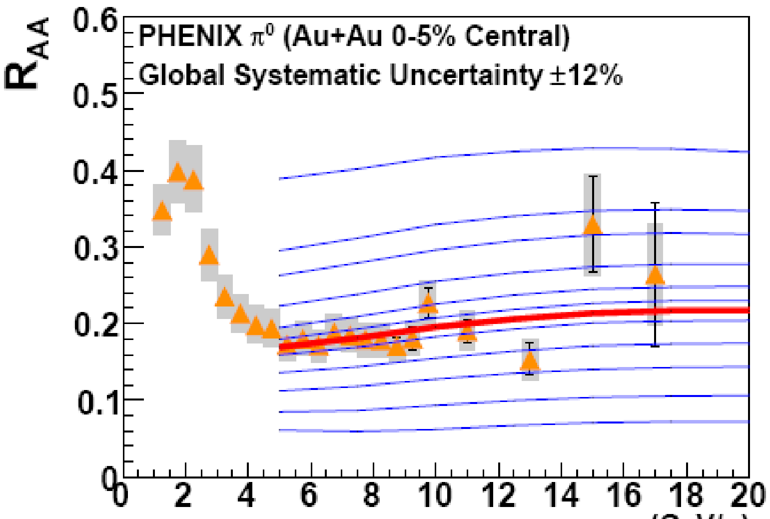
High p_T Spectra in p-p Collisions (II)

NLO pQCD with apropriate FF describes well a wide range of p-p spectra.

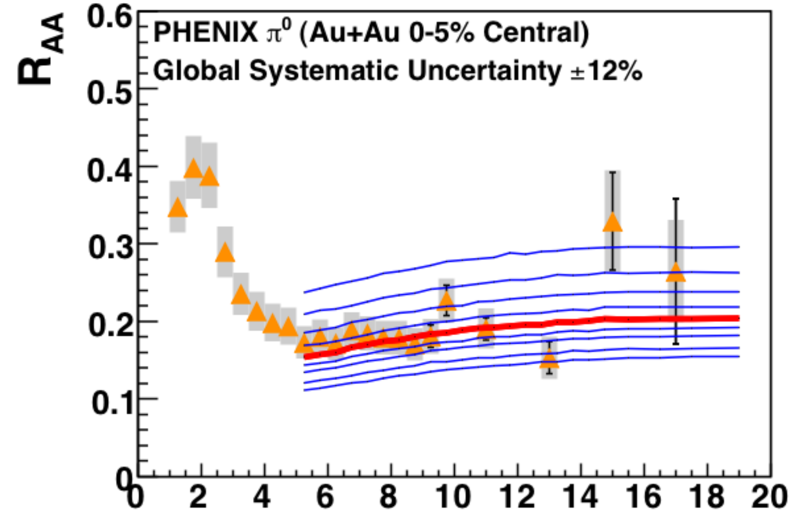
Any cross section modification in nuclear collisions is defined w.r.t. the corresponding p-p cross section by the nuclear modification factor R_{AB}…



Quantitative Constraints on Medium Parameters



Gyulassy, Levai, Vitev



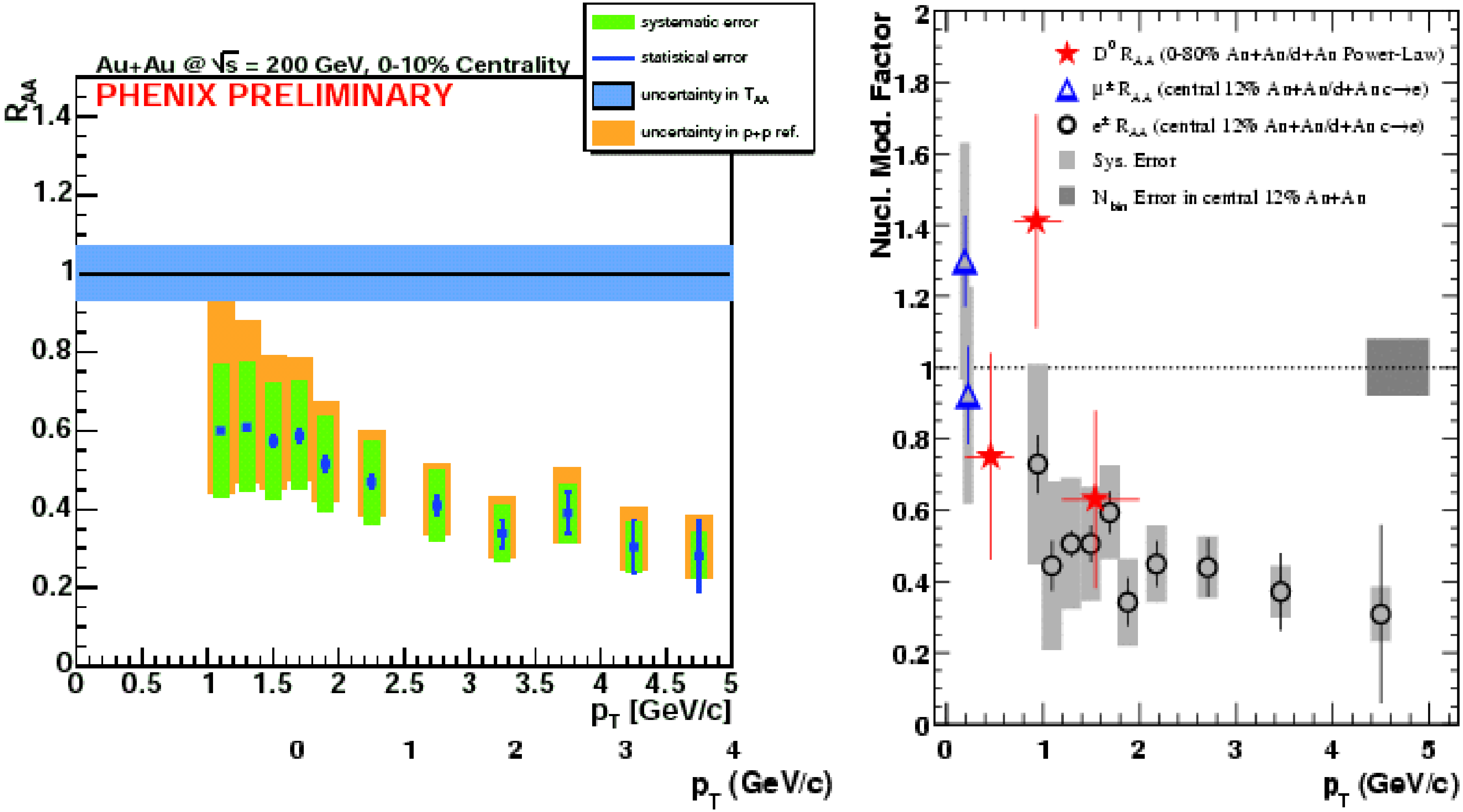
Zhang, Owens, Wang, Wang

- Least square fit of energy loss model parameters to data
- Medium properties indicative of extremely hot, dense, strongly interacting QCD matter
- However, R_{AA} not very sensitive to variations of medium properties
- S... re discriminative power needed.

Medium properties constrained within ± 20-25% at 1σ level

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



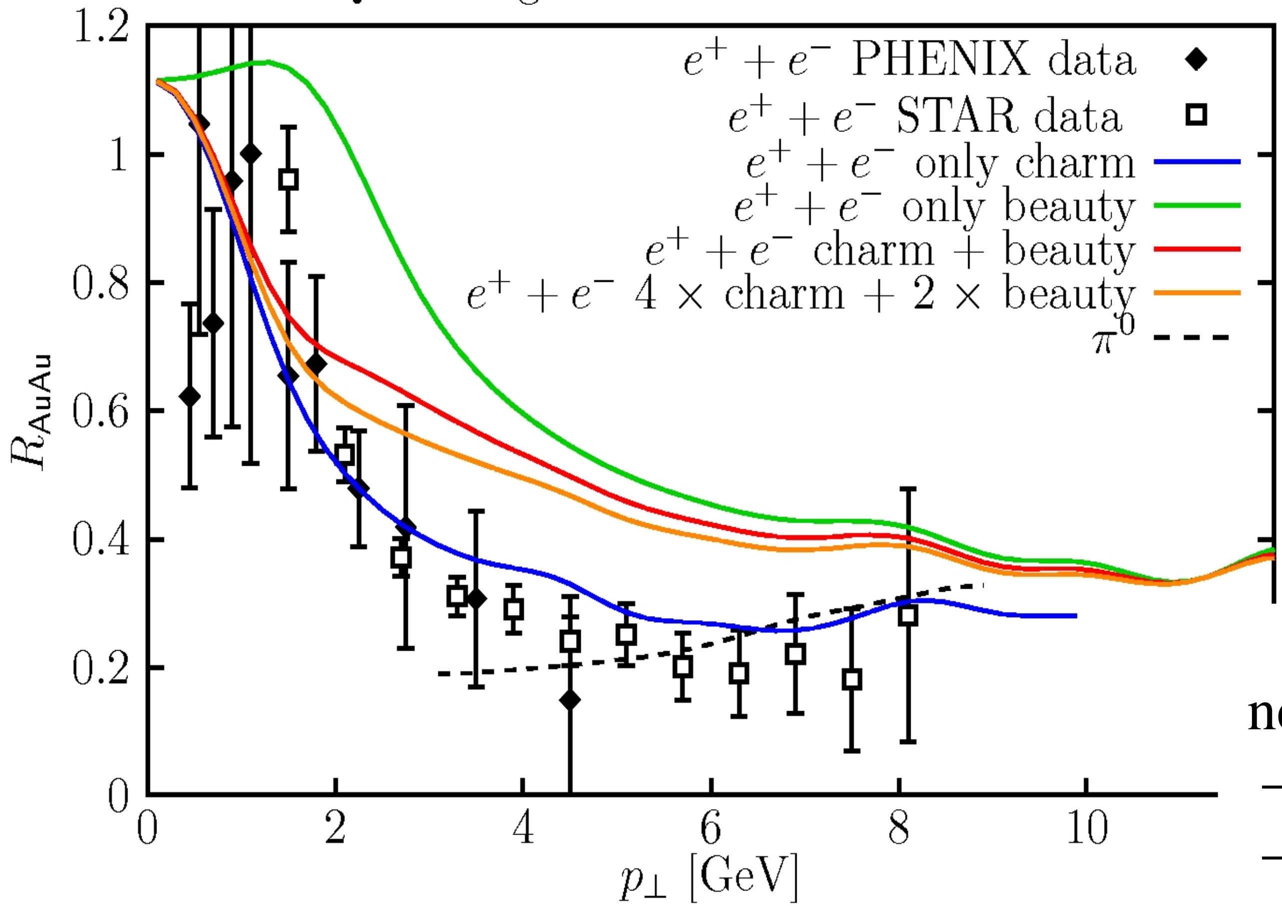
STAR preliminary

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



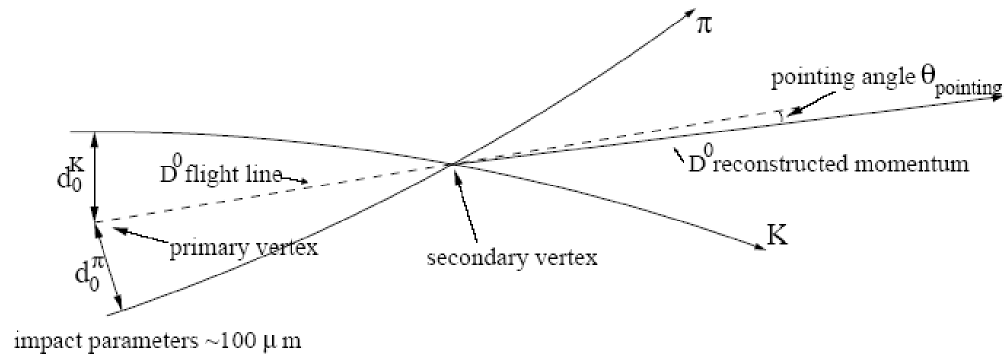
charm contribution indeed suppressed as much as pions but adding beauty data are not reproduced

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

$D^0 \rightarrow K\pi$ channel

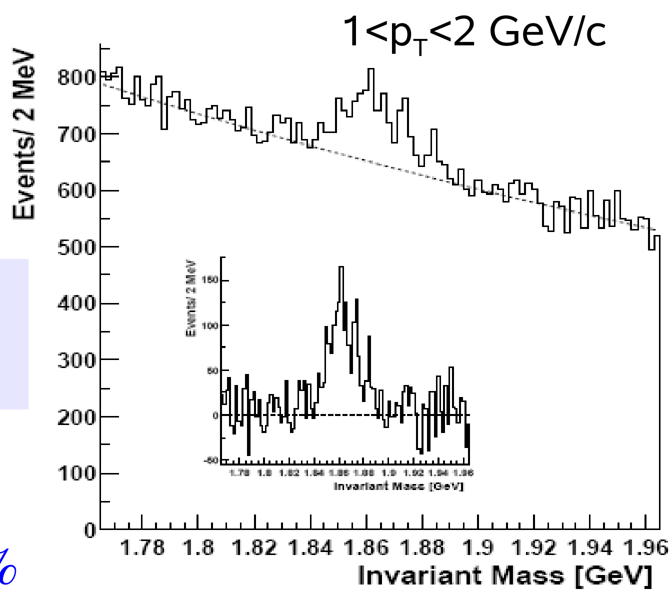
ALICE PPR vol2 JPG 32 (2006) 1295

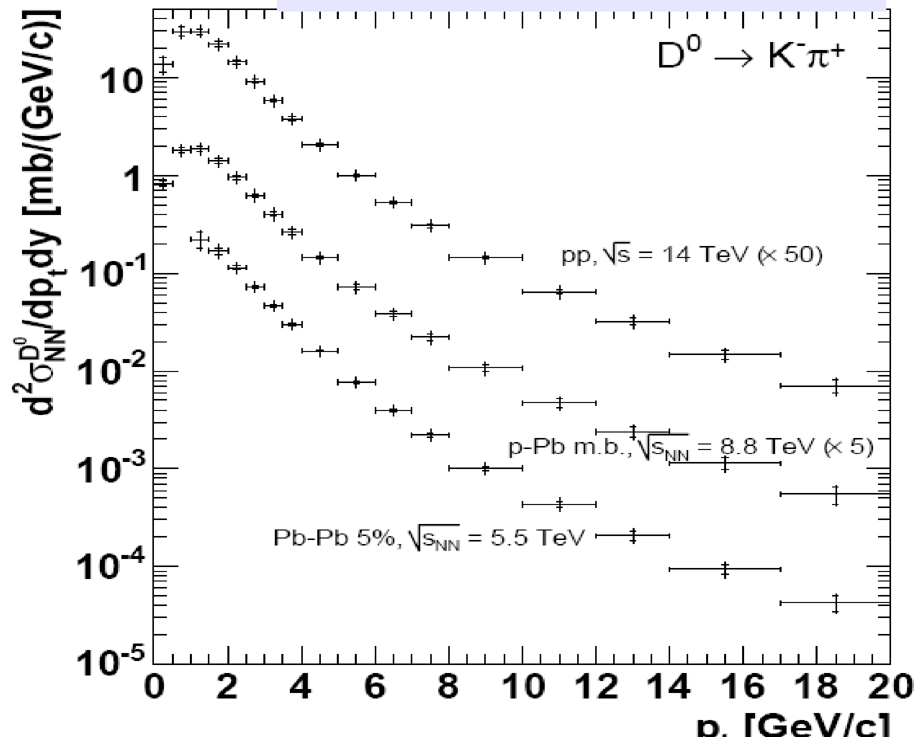
- high precision vertexing, better than 100 μm (ITS)
- high precision tracking (ITS+TPC)
- K and/or π identification (TOF)



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

10^7 central PbPb



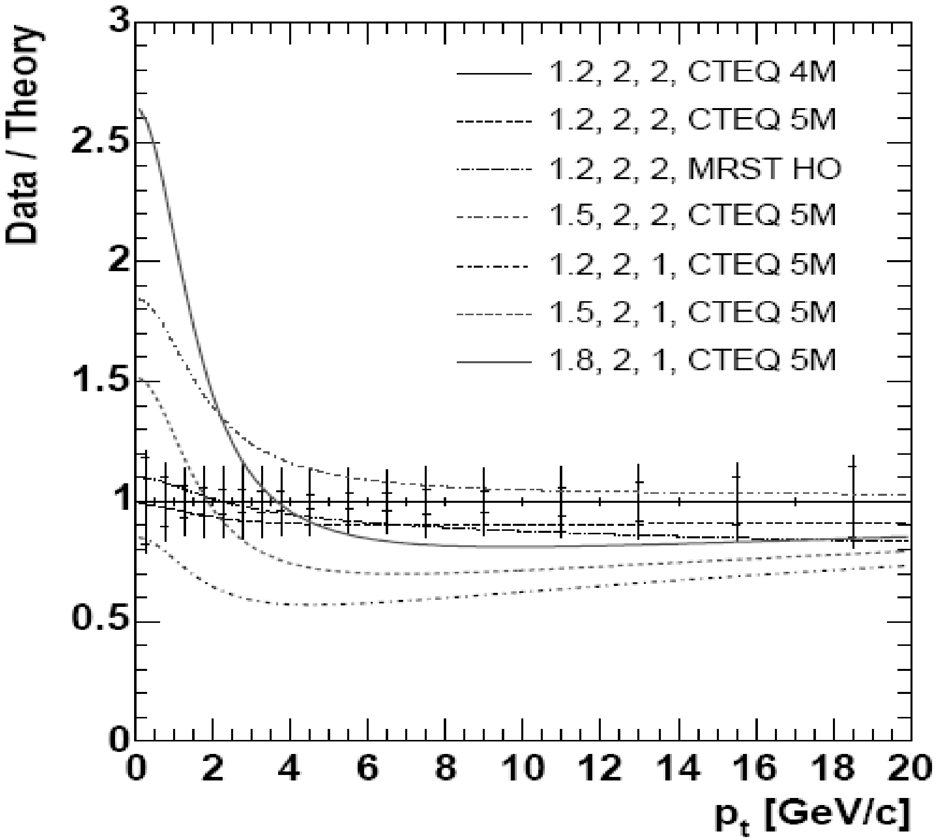


S/B = 10%

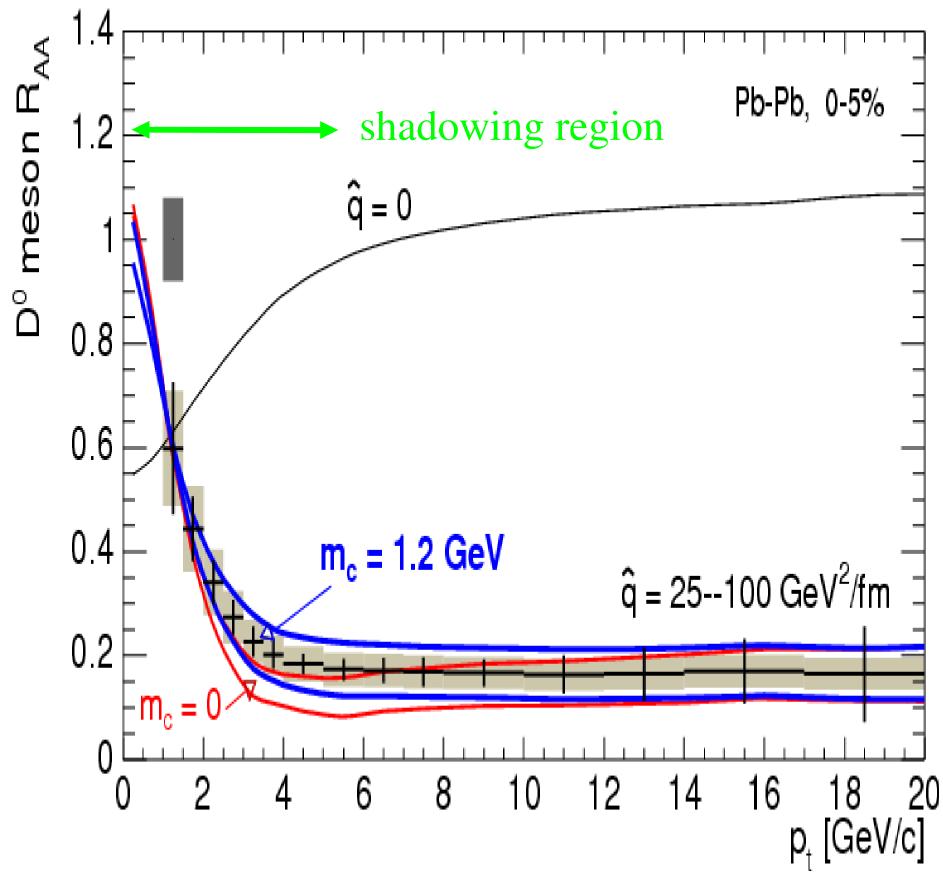
$S/\sqrt{(S+B)} = 40$

high precision charm measurement

pp at 14 TeV
sensitivity to PDF's



Central PbPb
shadowing + k_T + energy loss



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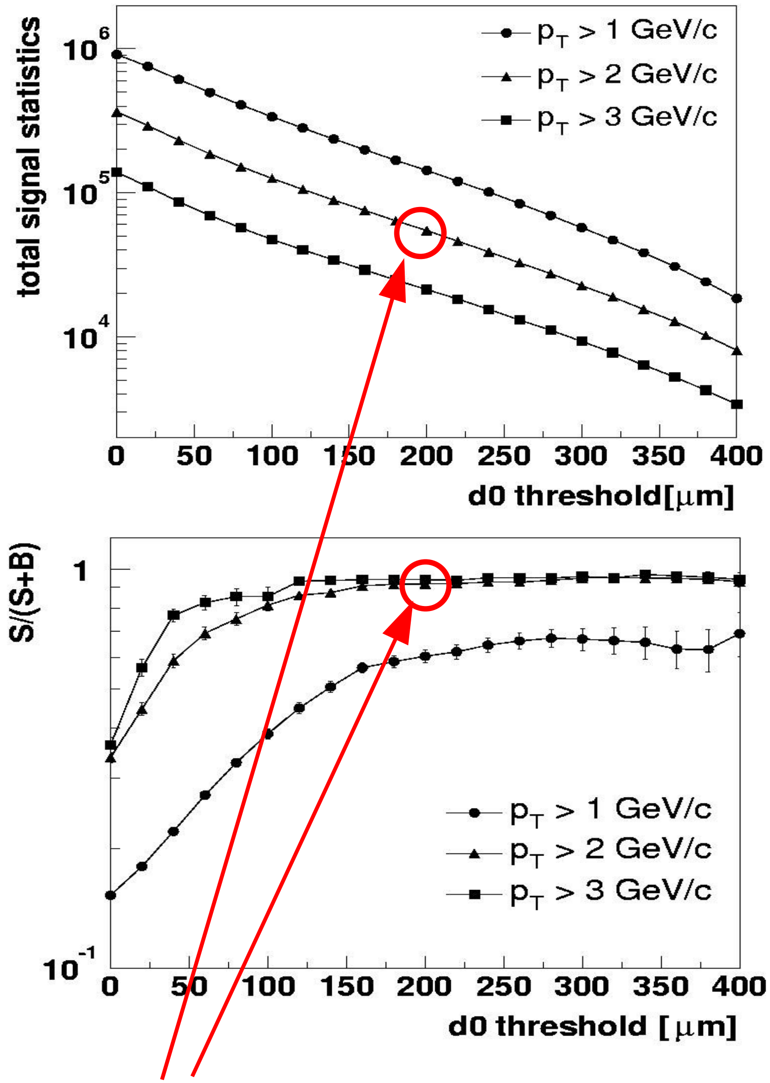
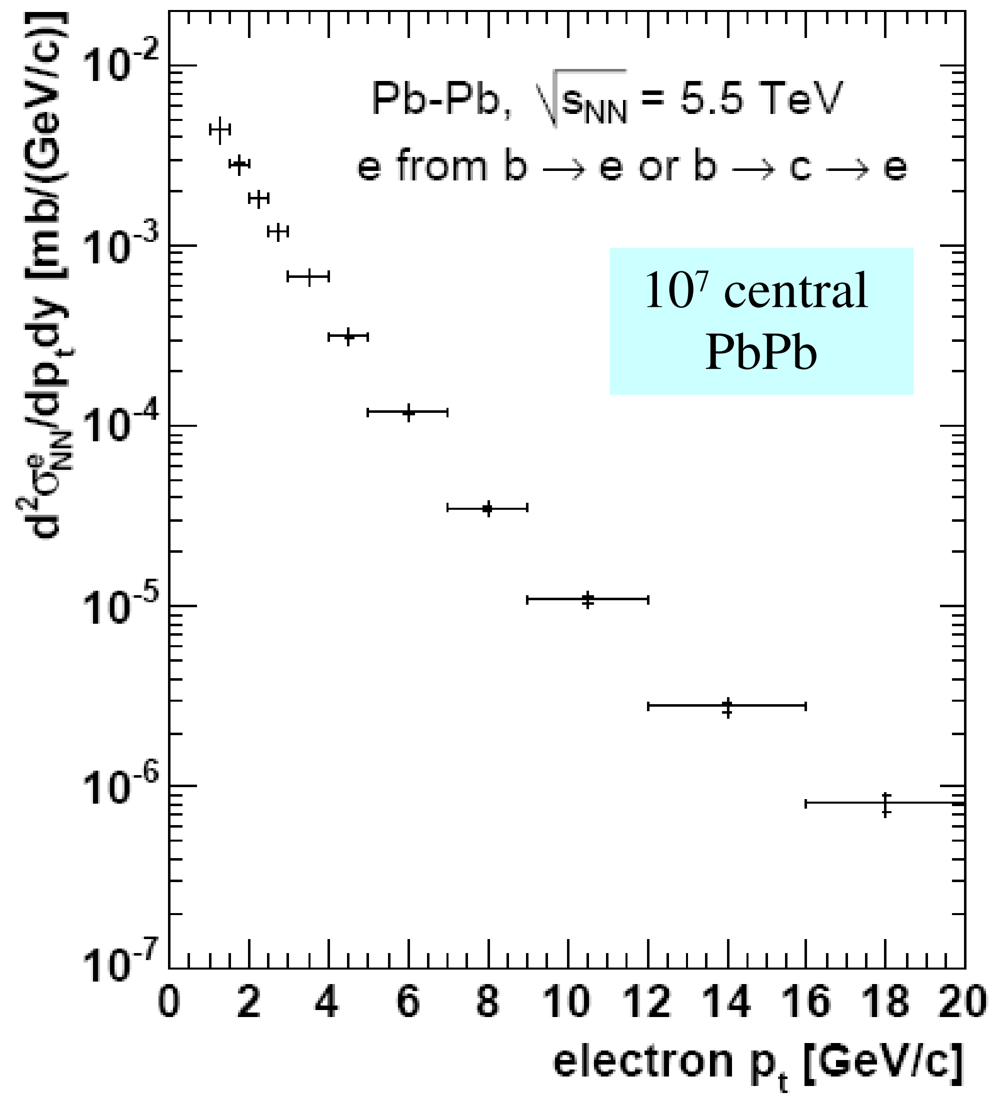
open beauty from single electrons

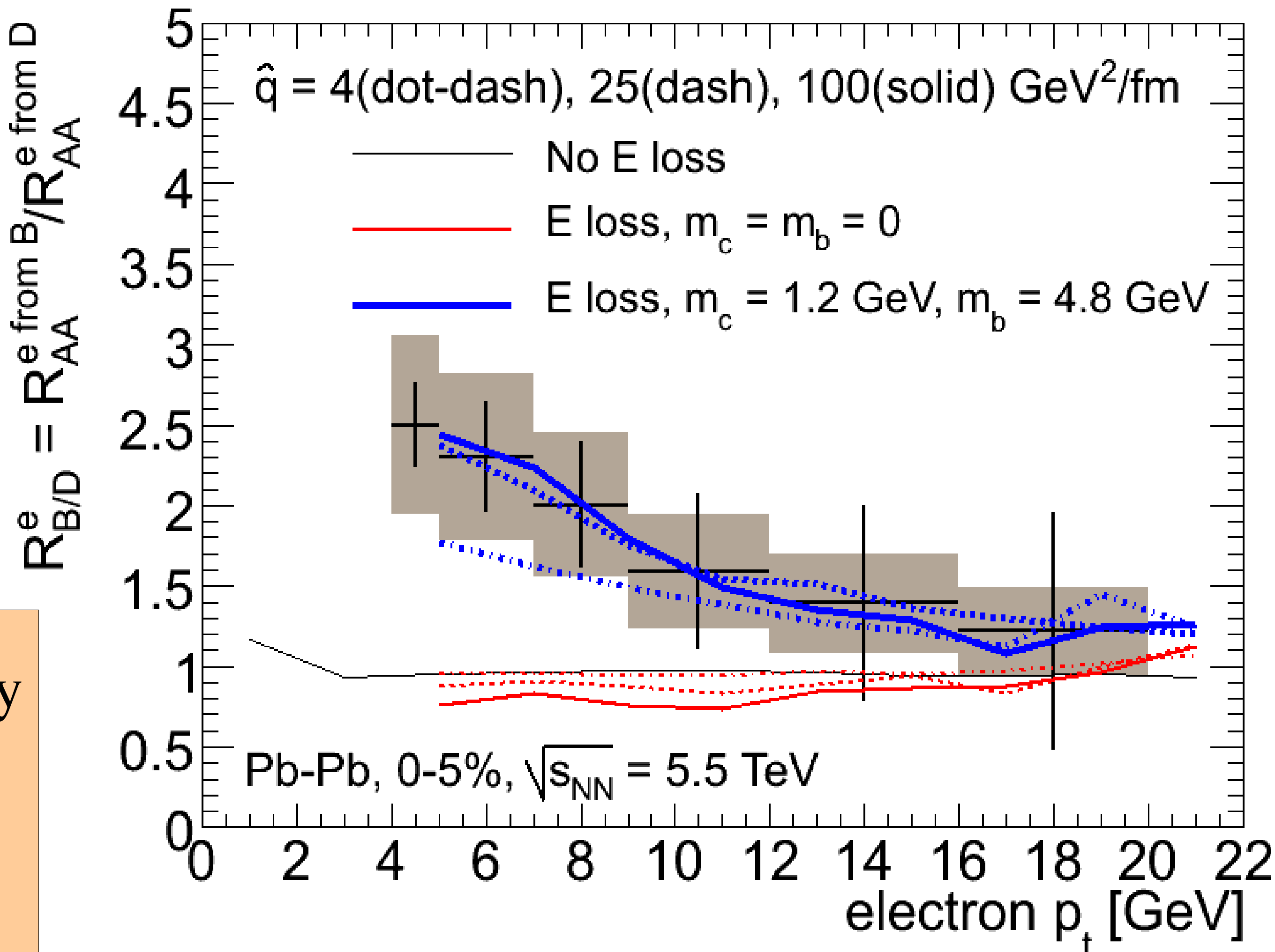




B → e⁻ in ALICE ITS/TPC/TRD
$p_t > 2$ GeV/c & d_0 = 200 -600 μm:
80 000 electrons with S/(S+B) = 80%

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