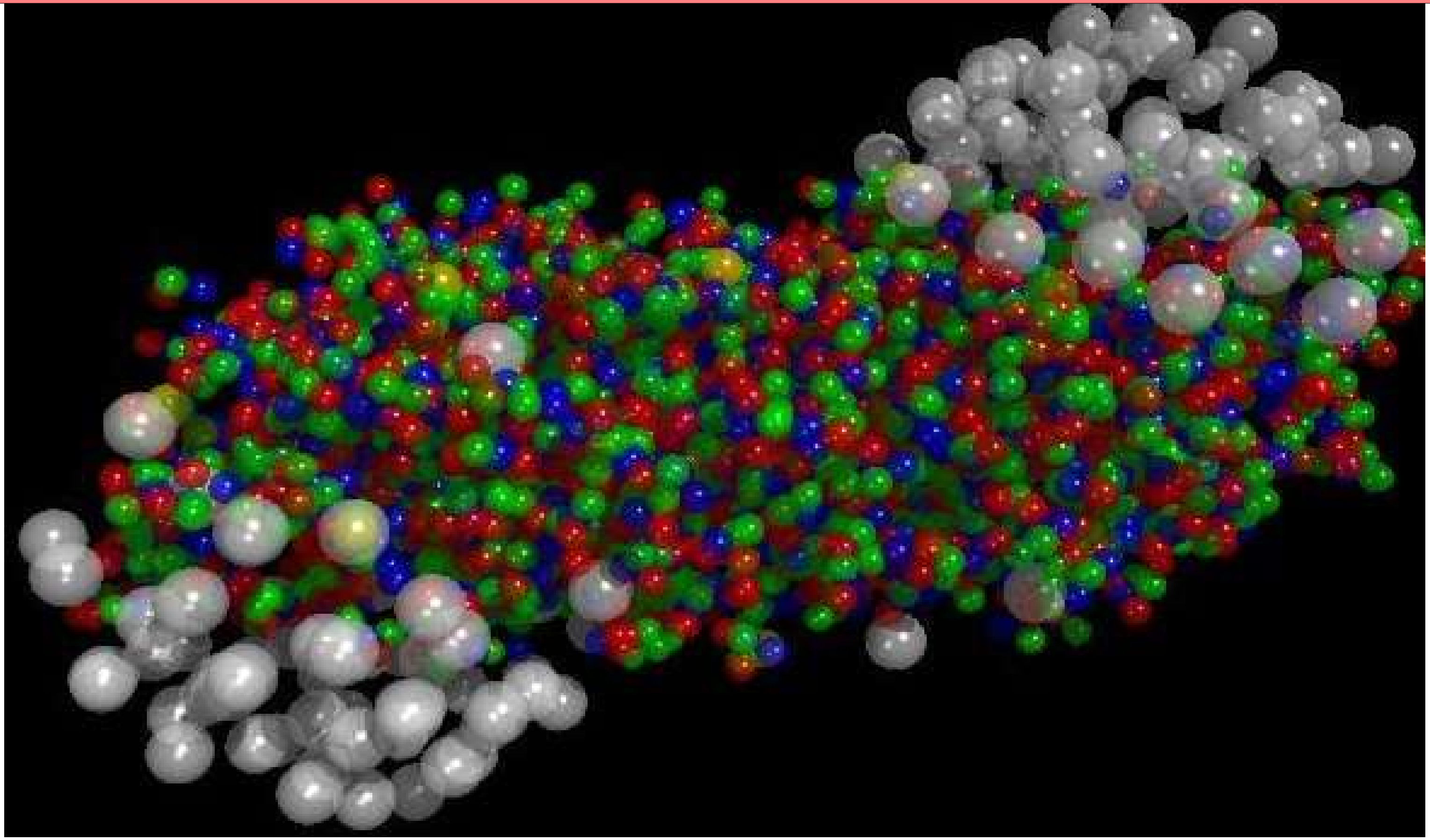
Hard probes to diagnose the QGP at the LHC

- LHC vis-a-vis fixed target program and RHIC
- expectations – initial condition
- diagnozing properties of the QGP with
    - quarkonia
    - jets
    - heavy quarks

(from ALICE point of view)

Where are we 20 years after the start of the high energy heavy ion program?

CERN Press Release Feb. 2000: New State of Matter created at CERN



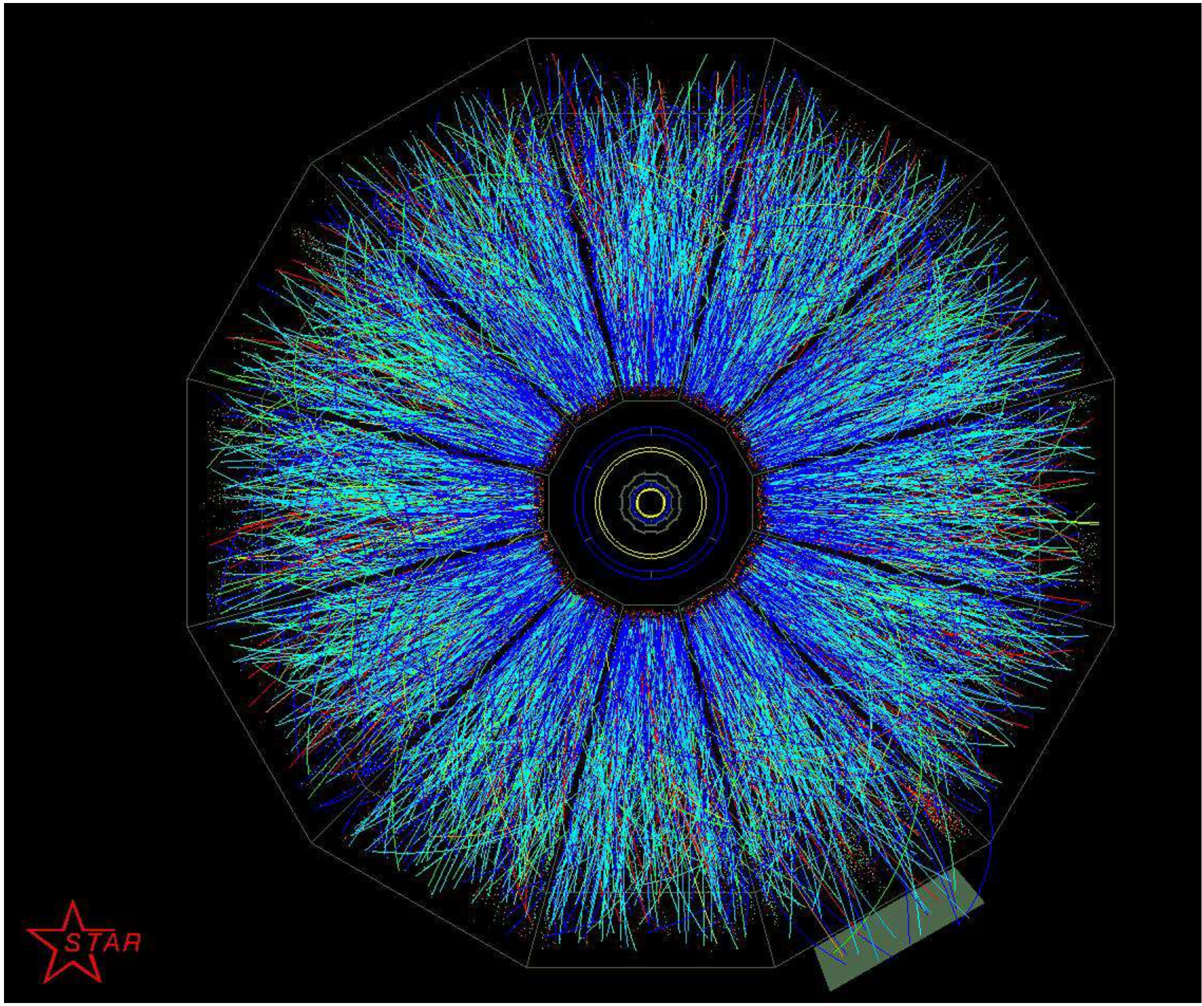
At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

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



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

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 $_0 = 1/p_{sat} = 0.1$

and with Bjorken formula:

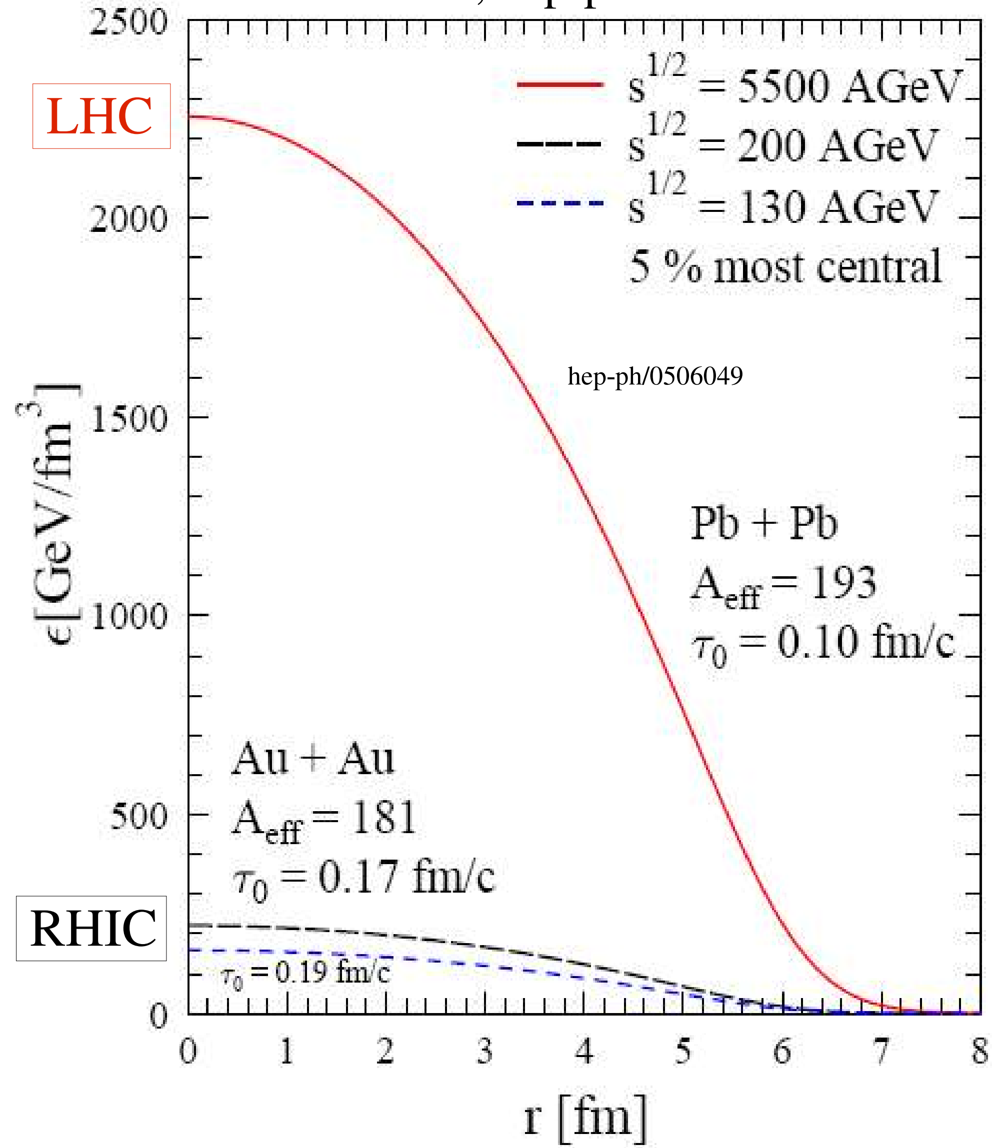
$\varepsilon_0 = dE_t/d\eta/(\tau_0 \pi R^2)$ w. Jacobian $d\eta/dz = \tau_0$

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

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

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

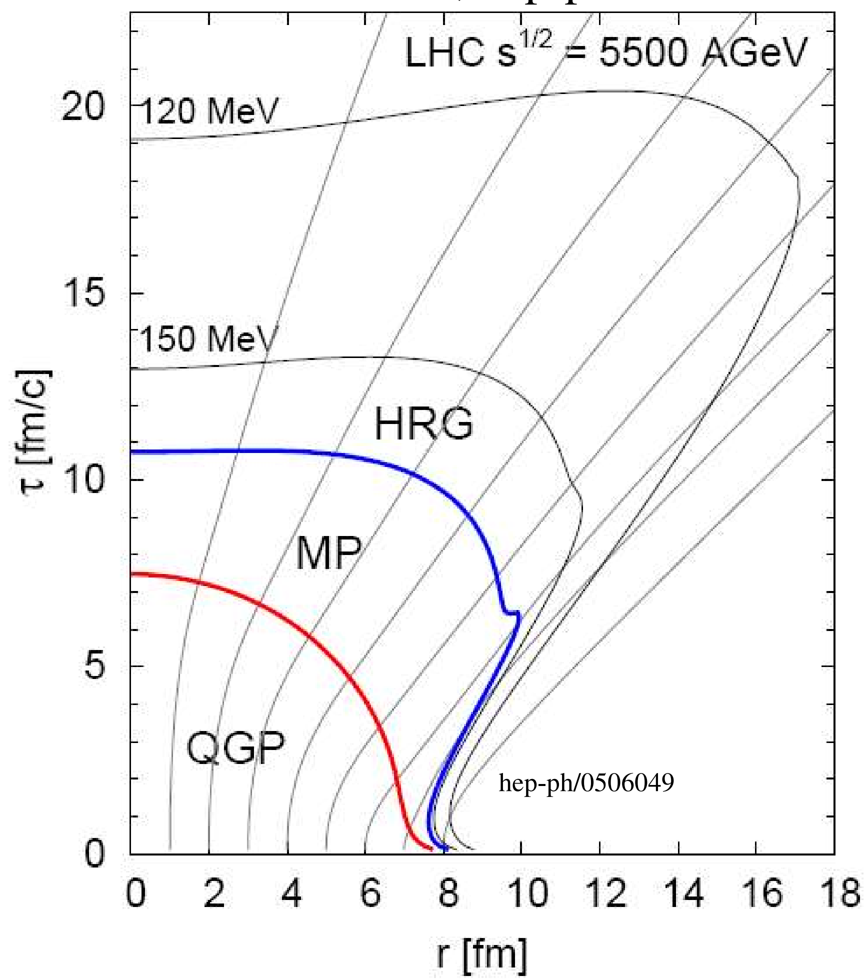
initial N_{AA} determines final multiplicity

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

overall several 10 k hadrons produced

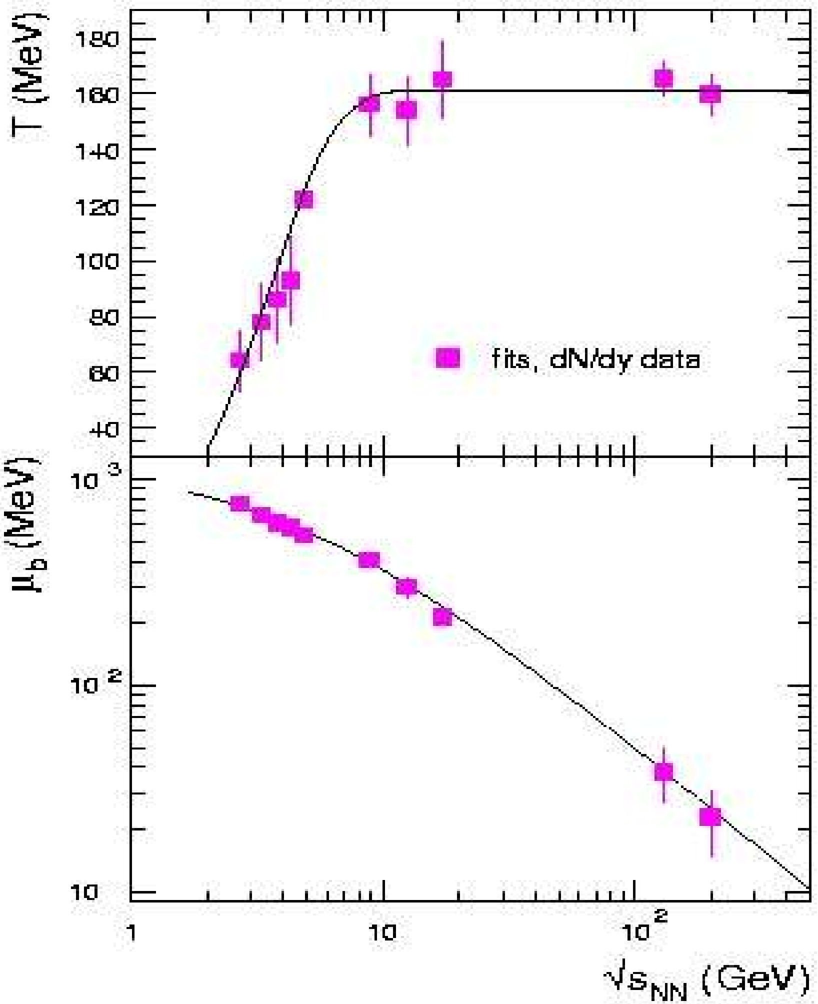
'macroscopic state'

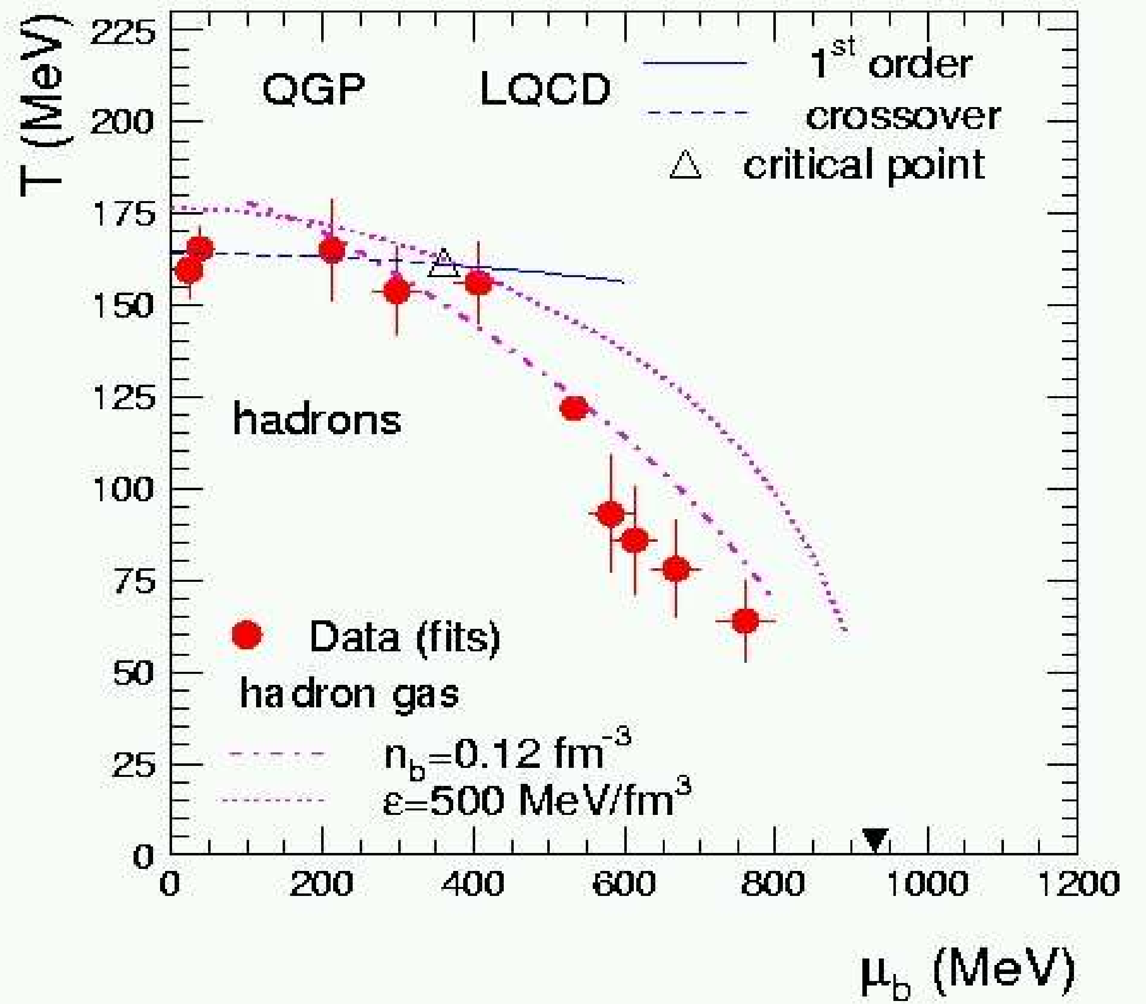
K. Eskola et al., hep-ph/0506049



hadrochemical freeze-out points and the phase diagram AGS to RHIC energies

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





Expectation of thermal parameters for LHC from SPS and RHIC systematics:

T=161±4 MeV and μ_b=$0.8^{+1.2}_{-0.6}$ MeV

Table 1. Predictions of the thermal model for hadron ratios in central Pb+Pb collisions at LHC. The numbers in parantheses represent the error in the last digit(s) of the calculated ratios.

π^-/π^+	K^-/K^+	$\bar{p}/p$	$\bar{\Lambda}/\Lambda$	$\bar{\Xi}/\Xi$	$\bar{\Omega}/\Omega$
1.001(0)	0.993(4)	$0.948^{-0.013}_{+0.008}$	$0.997^{-0.011}_{+0.004}$	$1.005^{-0.007}_{+0.001}$	1.013(4)

p/π^+	K^+/π^+	K^-/π^-	Λ/π^-	Ξ^-/π^-	Ω^-/π^-
0.074(6)	0.180(0)	0.179(1)	0.040(4)	0.0058(6)	0.00101(15)

interesting question: what about strongly decaying resonances – sensitive to existence of hadronic fireball after hadronization

ϕ/K^-	K^{*0}/K^0_S	Δ^{++}/p	$\Sigma(1385)^+/\Lambda$	Λ^*/Λ	$\Xi(1530)^0/\Xi^-$
0.137(5)	0.318(9)	0.216(2)	0.140(2)	0.075(3)	0.396(7)

charmonia as QGP signature

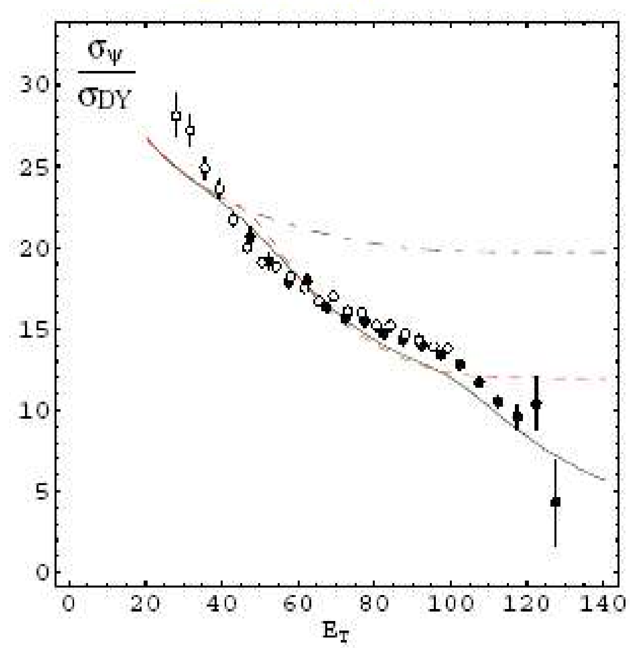
- T. Matsui and H. Satz (PLB178 (1986) 416) predict J/ψ suppression in QGP due to Debye screening
- significant suppression seen in central PbPb at top SPS energy (NA50) in line with QGP expectations

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

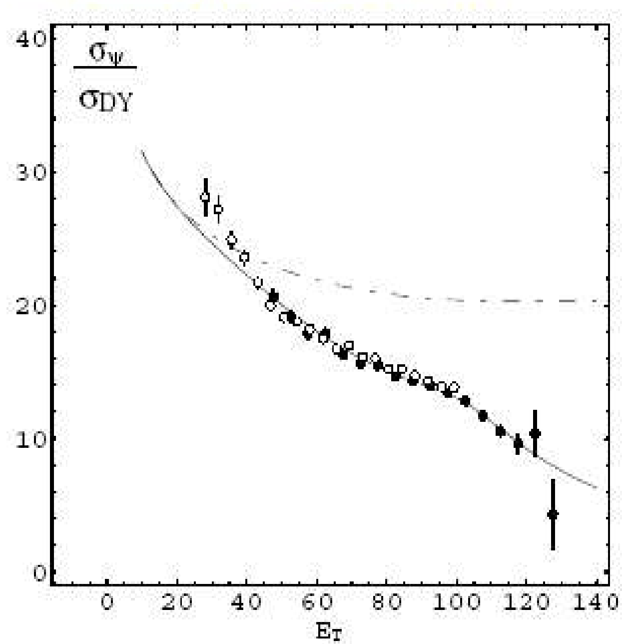
Dissolution in QGP at critical density n_c (dashes)

and with energy density fluctuations (solid)

n_c=3.7/fm^2



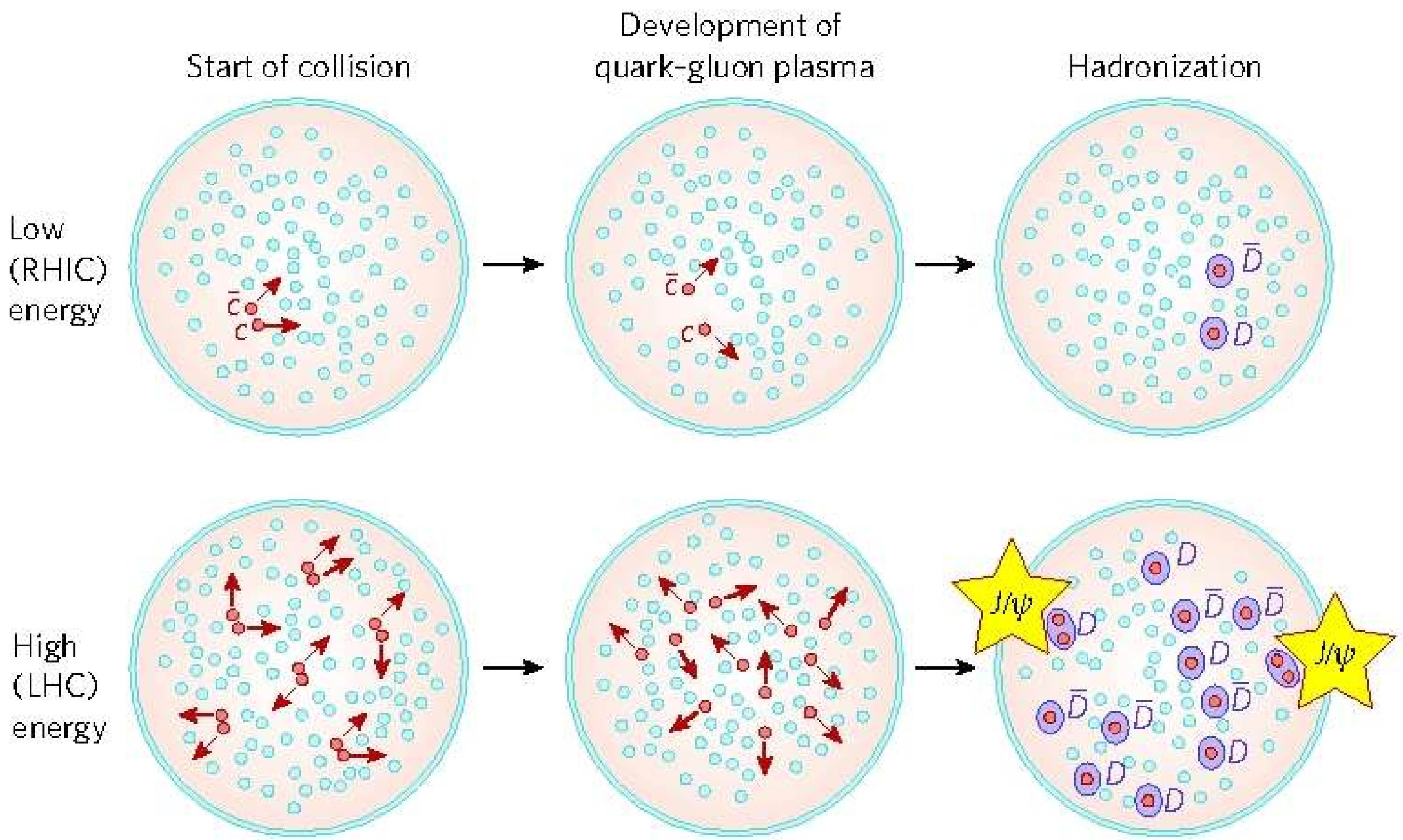
n_{c1}=3.3 and n_{c2}=4.2/fm^2



- 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: $N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{therm} \frac{I_1(g_c N_{oc}^{therm})}{I_0(g_c N_{oc}^{therm})}$

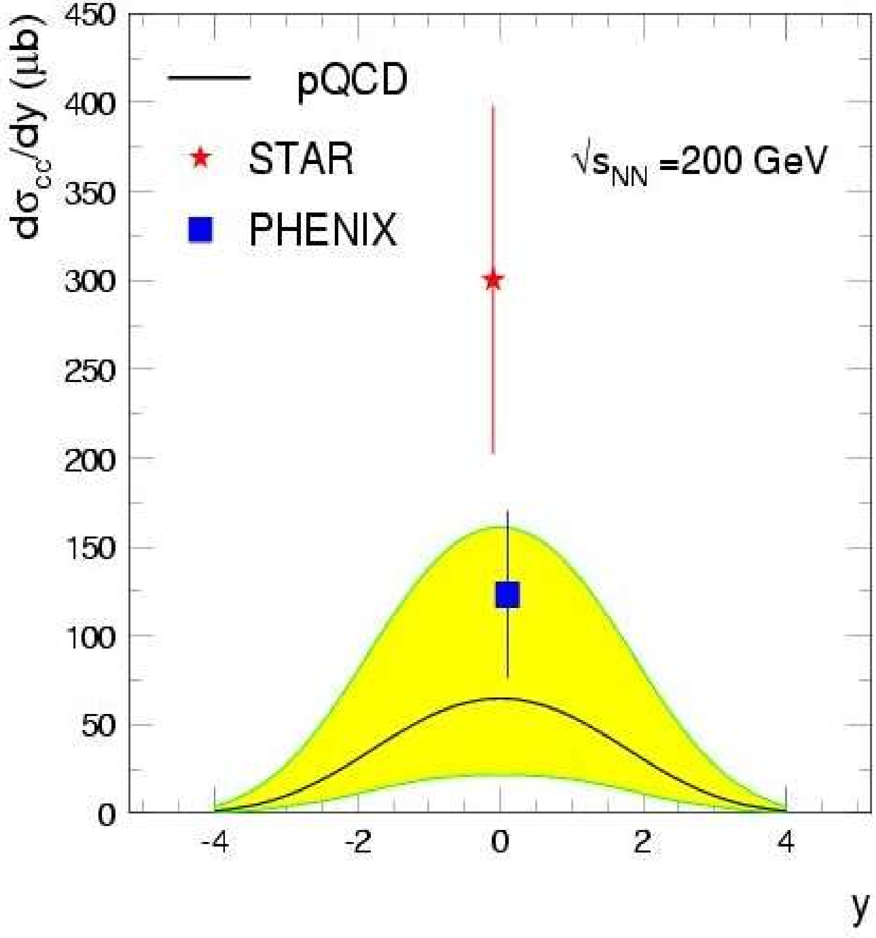
obtain: $N_D = N_D^{therm} \cdot g_c \cdot \frac{I_1}{I_0}$ and $N_{J/\psi} = N_{J/\psi}^{therm} \cdot g_c^2$ and all other charmed hadrons

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 and Phys. Lett. B571 (2003) 36 and nucl-th/0611023 Phys. Lett. B, in print
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

input: open charm pQCD and data

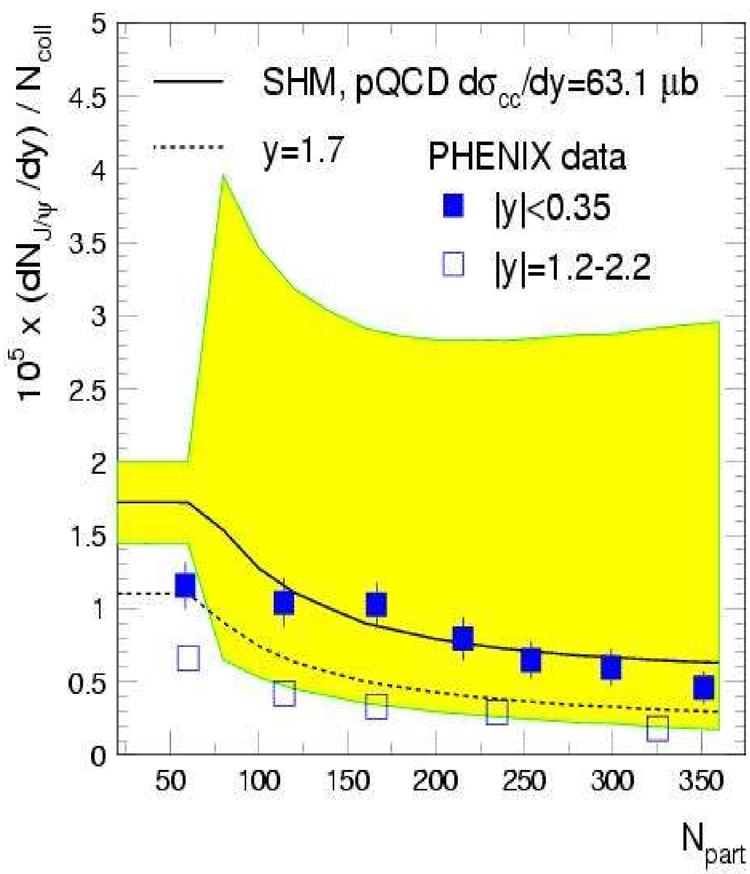
FONLL M. Cacciari et al., hep-ph/0502203

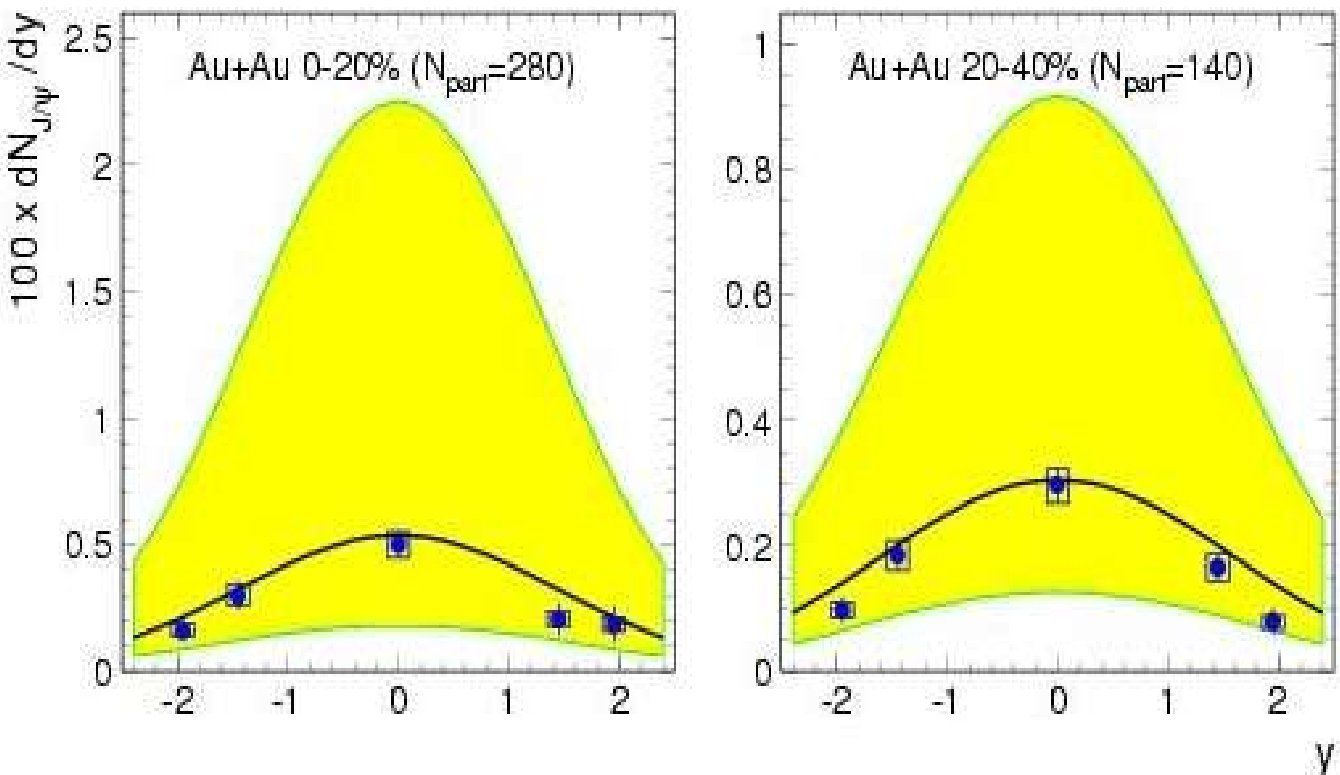


measured values for RHIC energy:
PHENIX somewhat larger than central value of pQCD predictions but well within band
STAR factor 2 above
large uncertainties, need better data!

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

P. Braun-Munzinger, K. Redlich, J. Stachel, nucl-th/0611023 Phys. Lett. B, in print



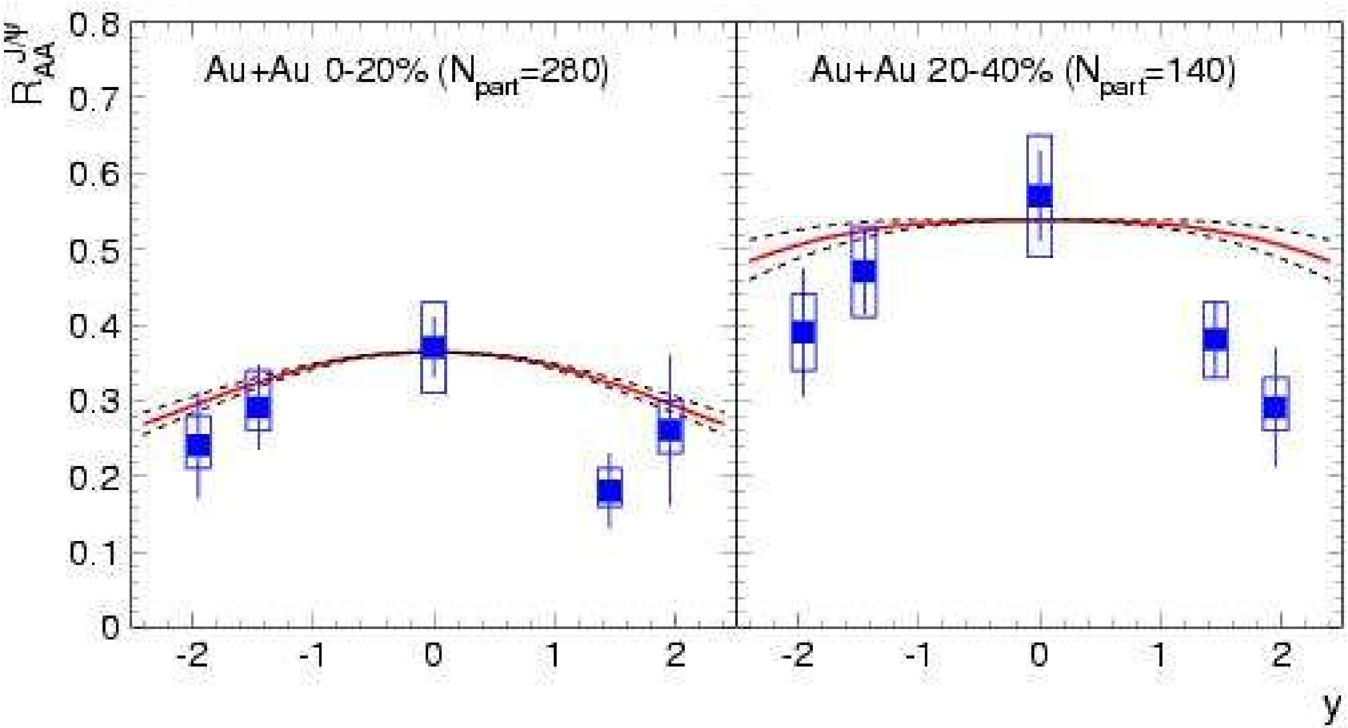


pp open charm cross section FONLL Cacciari et al., PRL 95 (2005) 122001 $\sigma_{cc} = 256^{+400}_{-146}$ μb

good agreement, no free parameters ⟷ but need for good open charm measurement obvious (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!

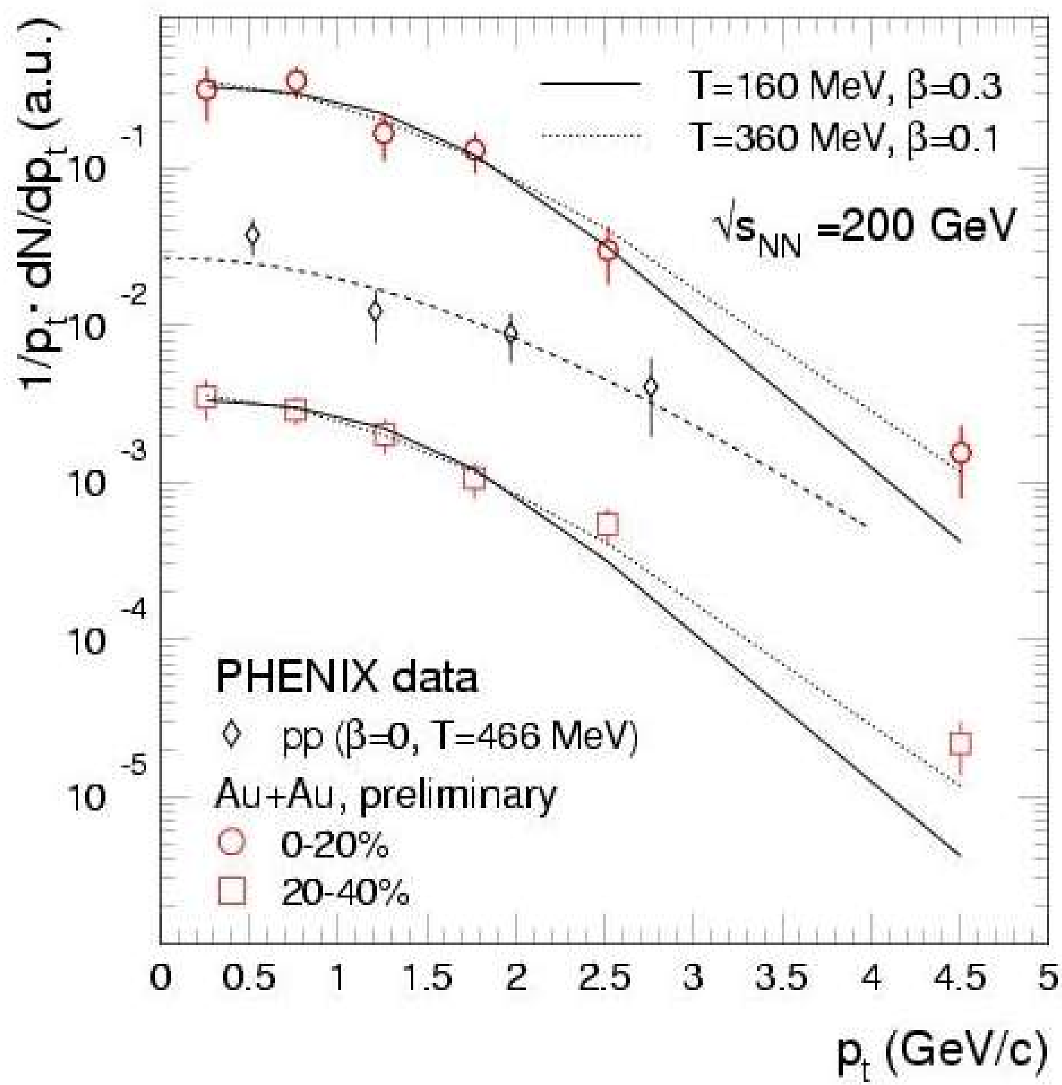
remark: y-dep opposite in 'normal Debye screening' picture; suppression strongest at midrapidity (largest density of color charges)

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

Transverse momentum distributions

PHENIX data:

not yet very conclusive



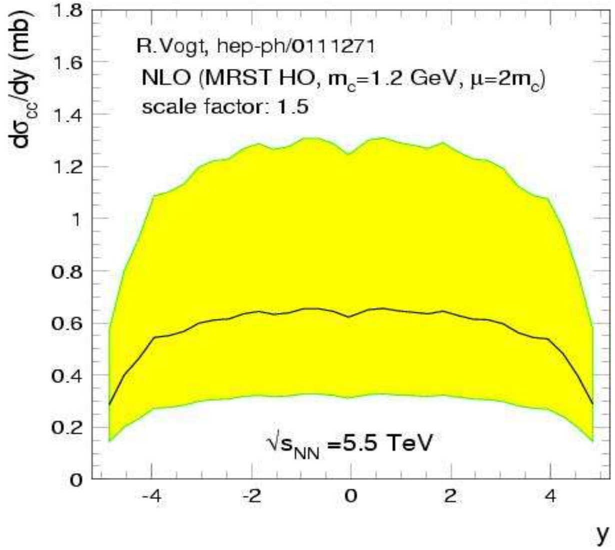
fit with expanding source:

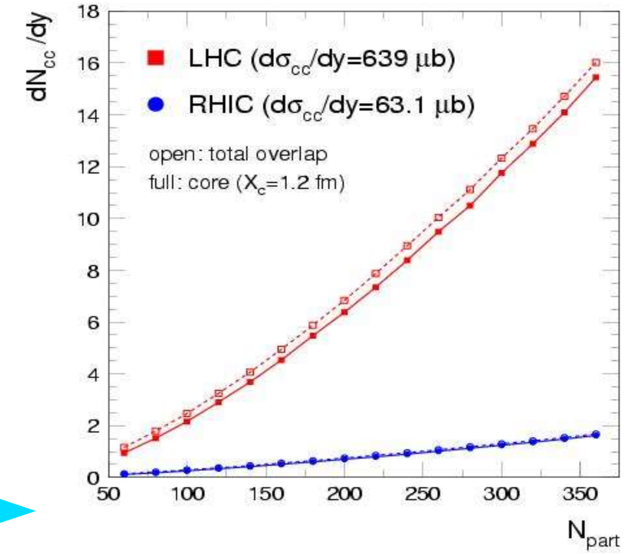
$$\frac{\mathrm{d}N}{\mathrm{d}p_t} \sim p_t \cdot m_t \cdot I_0\left(\frac{p_t \sinh y_t}{T}\right) \cdot K_1\left(\frac{p_t \cosh y_t}{T}\right)$$

$$y_t = \tanh^{-1}(\beta)$$

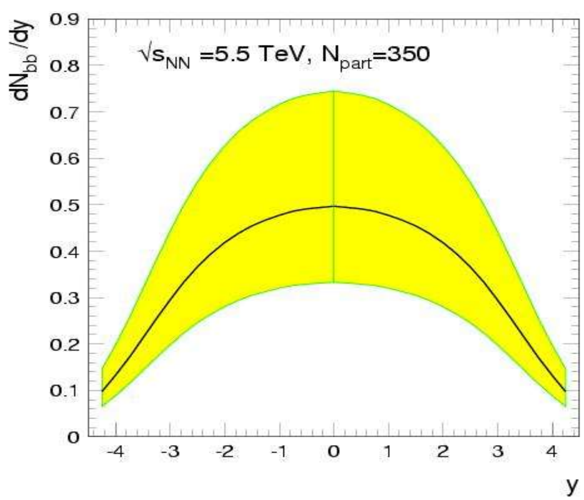
Expectation for charm/beauty production at LHC from pQCD

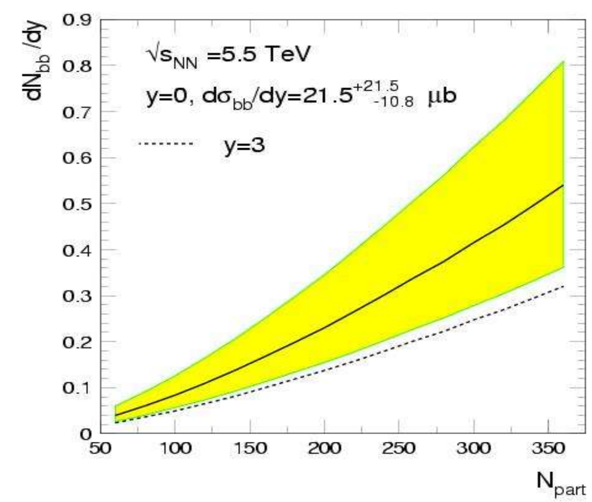
following Cacciari et al., hep-ph/0502203





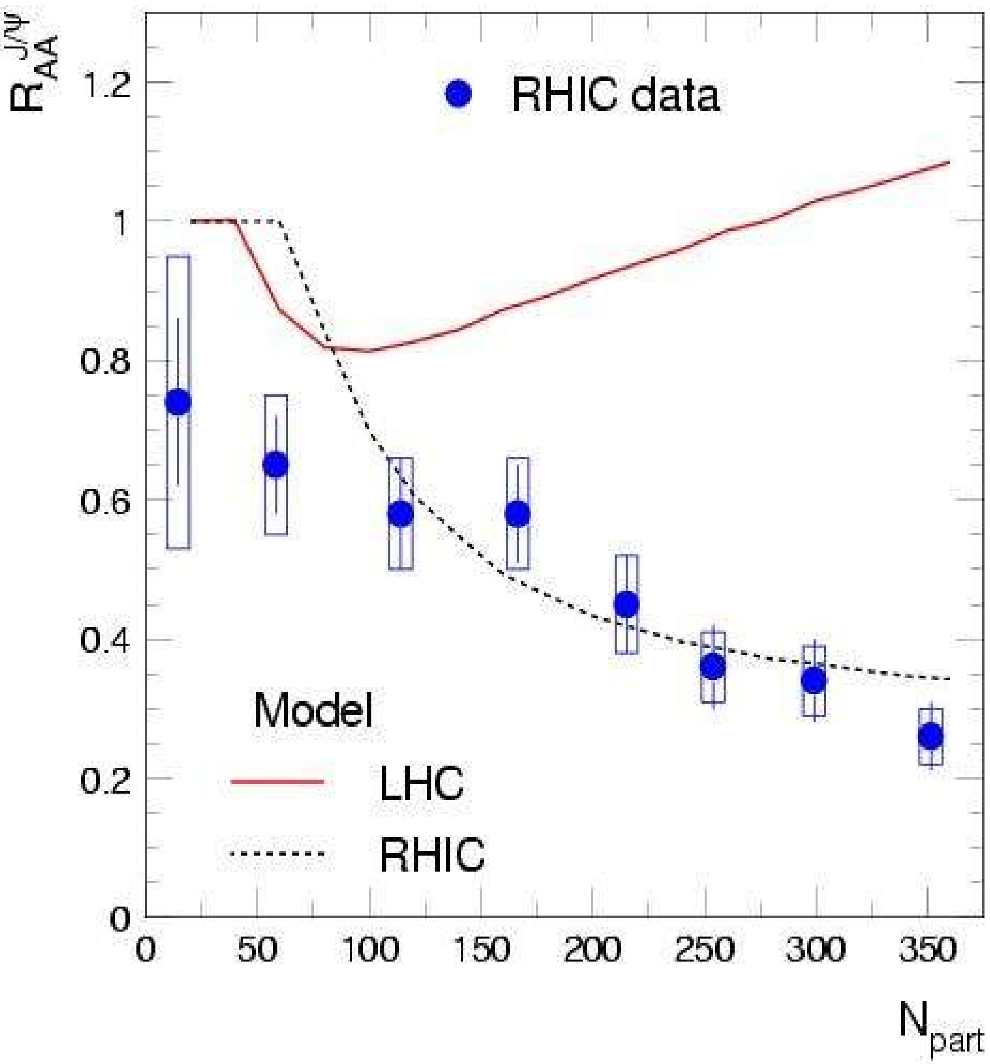
expect for central PbPb collisions 100 (200) ccbar and 5 (10) bbar over all rapidities





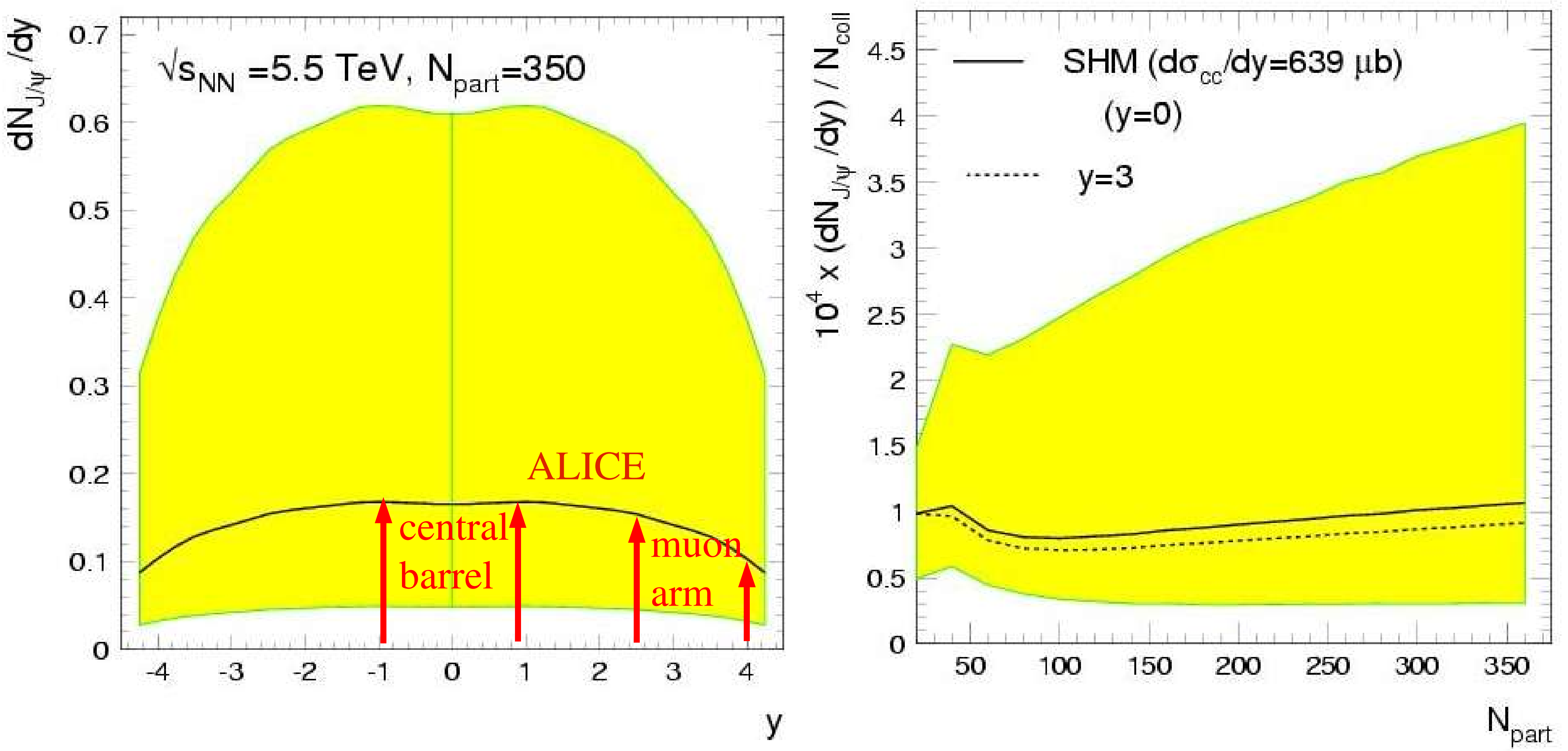
energy dependence of quarkonium production in statistical hadronization model

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, nucl-th/0611023, PLB in print

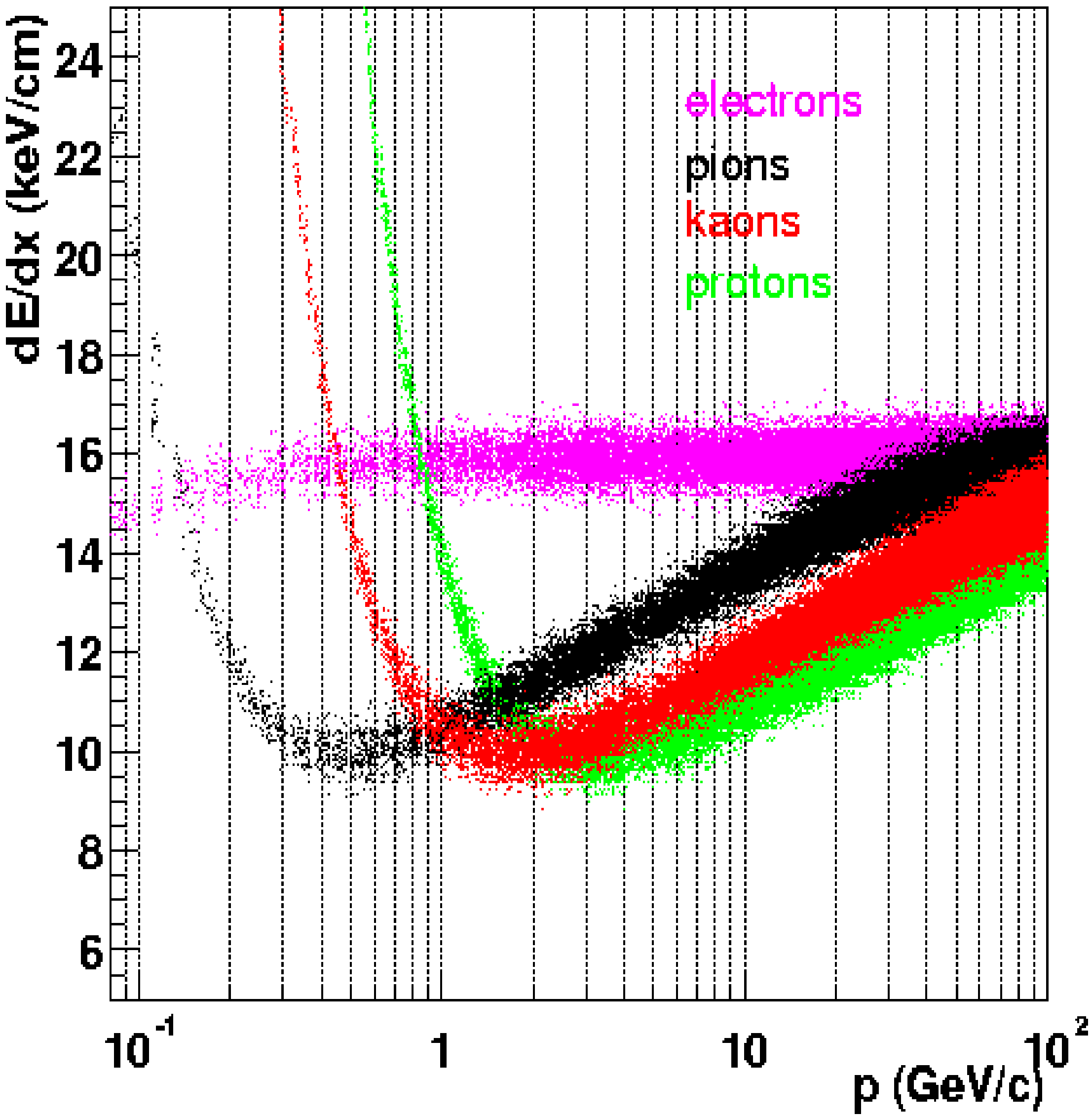


centrality dependence and
enhancement beyond pp value
will be fingerprint
of statistical hadronization at LHC
-> direct signal for deconfinement

predictions for charmonium rapidity and centrality distributions at LHC



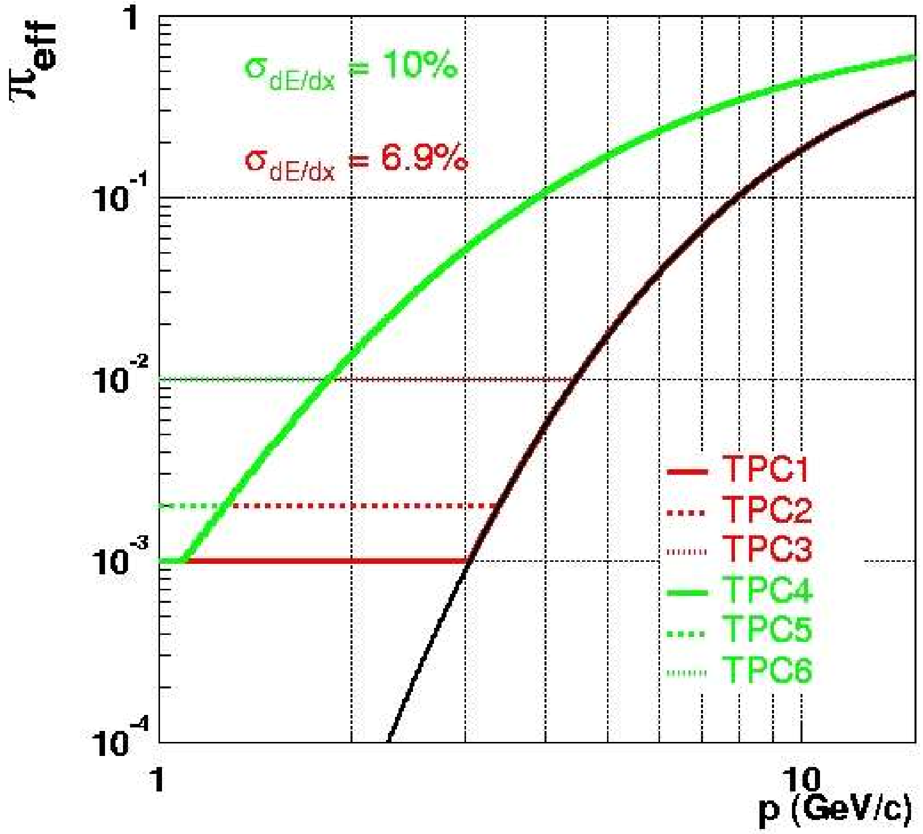
Particle identification by dE/dx - ALICE TPC

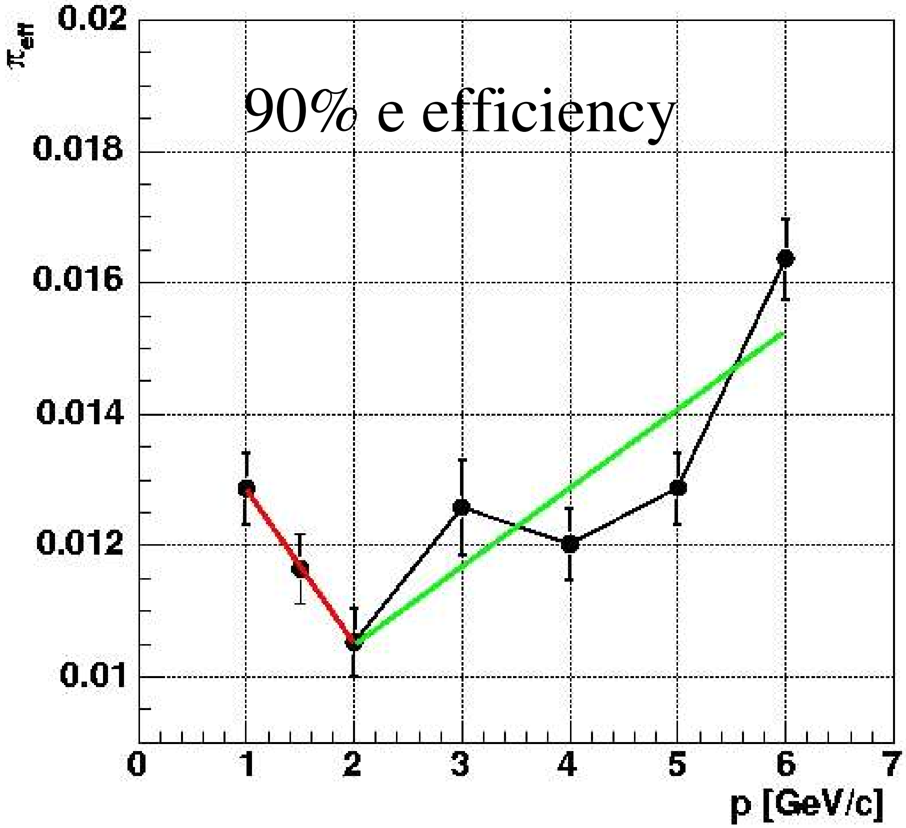


dE/dx resolution 6.9%

crossings: use TOF to resolve ambiguity

ALICE π rejection via TPC dE/dx and TRD

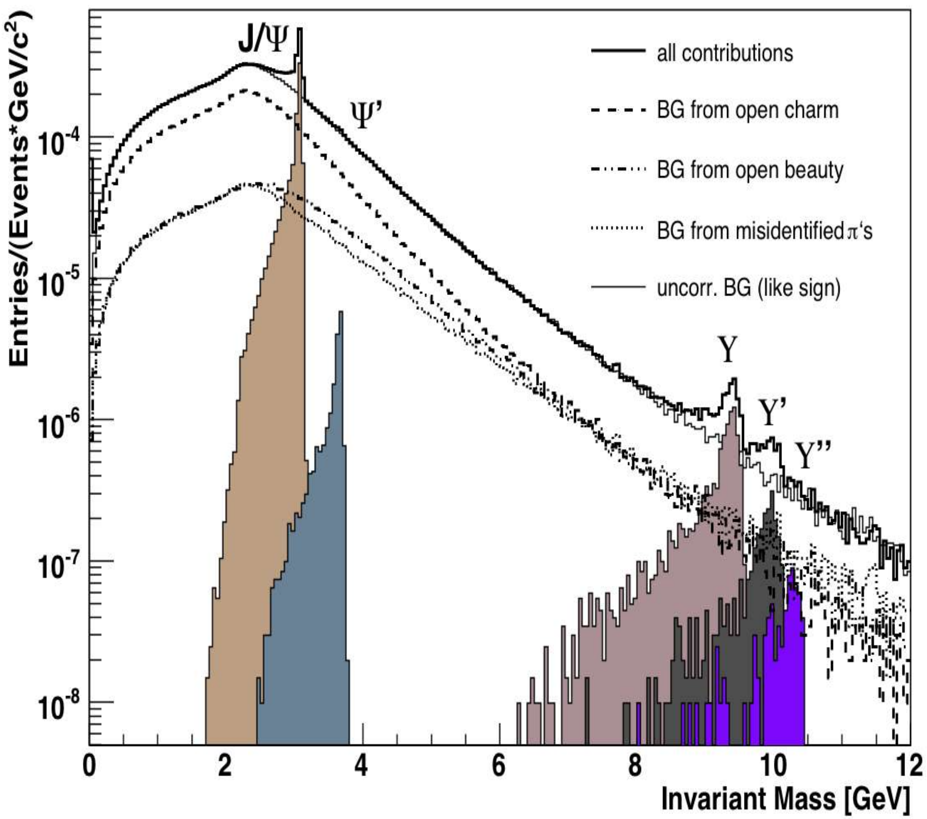


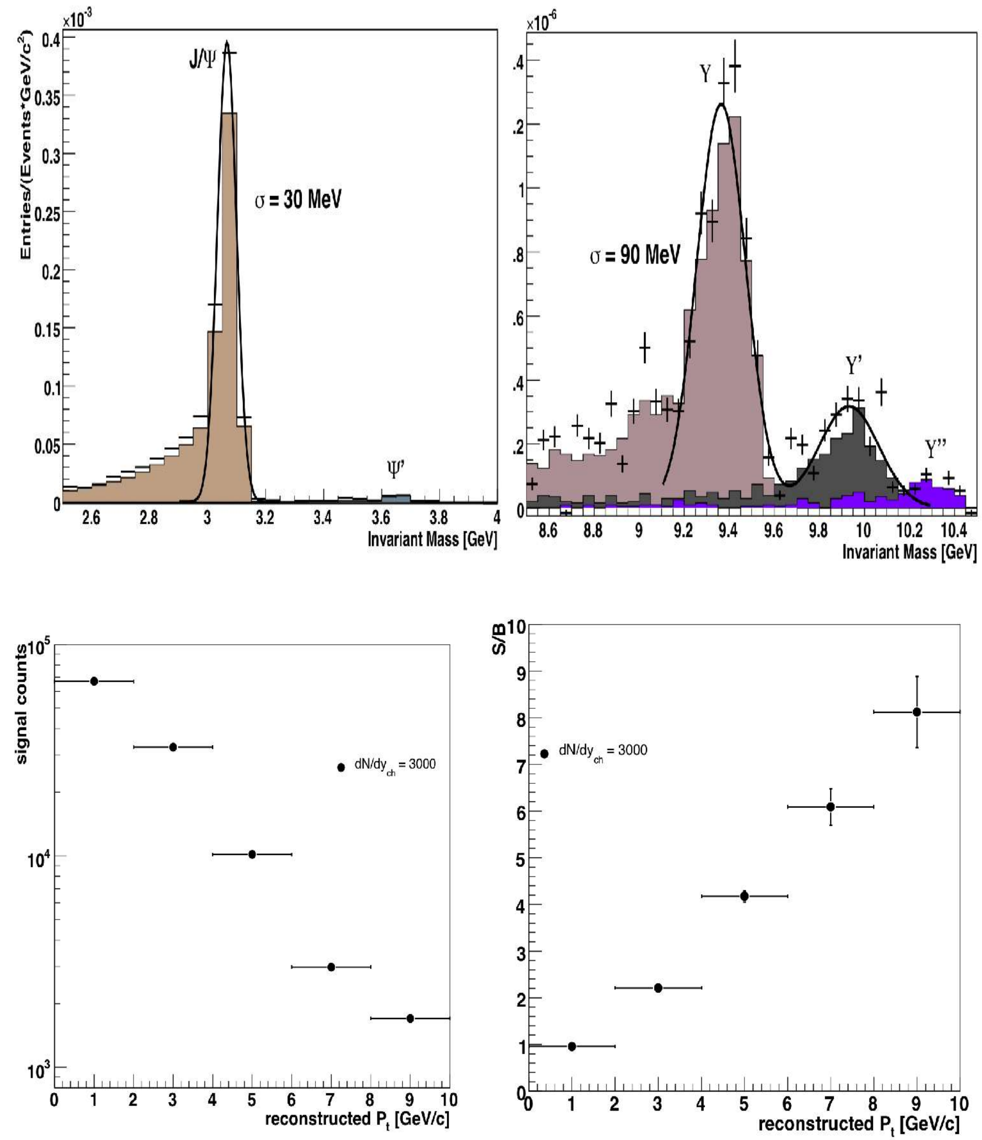


From test beam data: at 2 GeV and 90 % e eff → 10^5 π rejection

charmonia in ALICE at mid-rapidity

electron identification with TPC and TRD





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

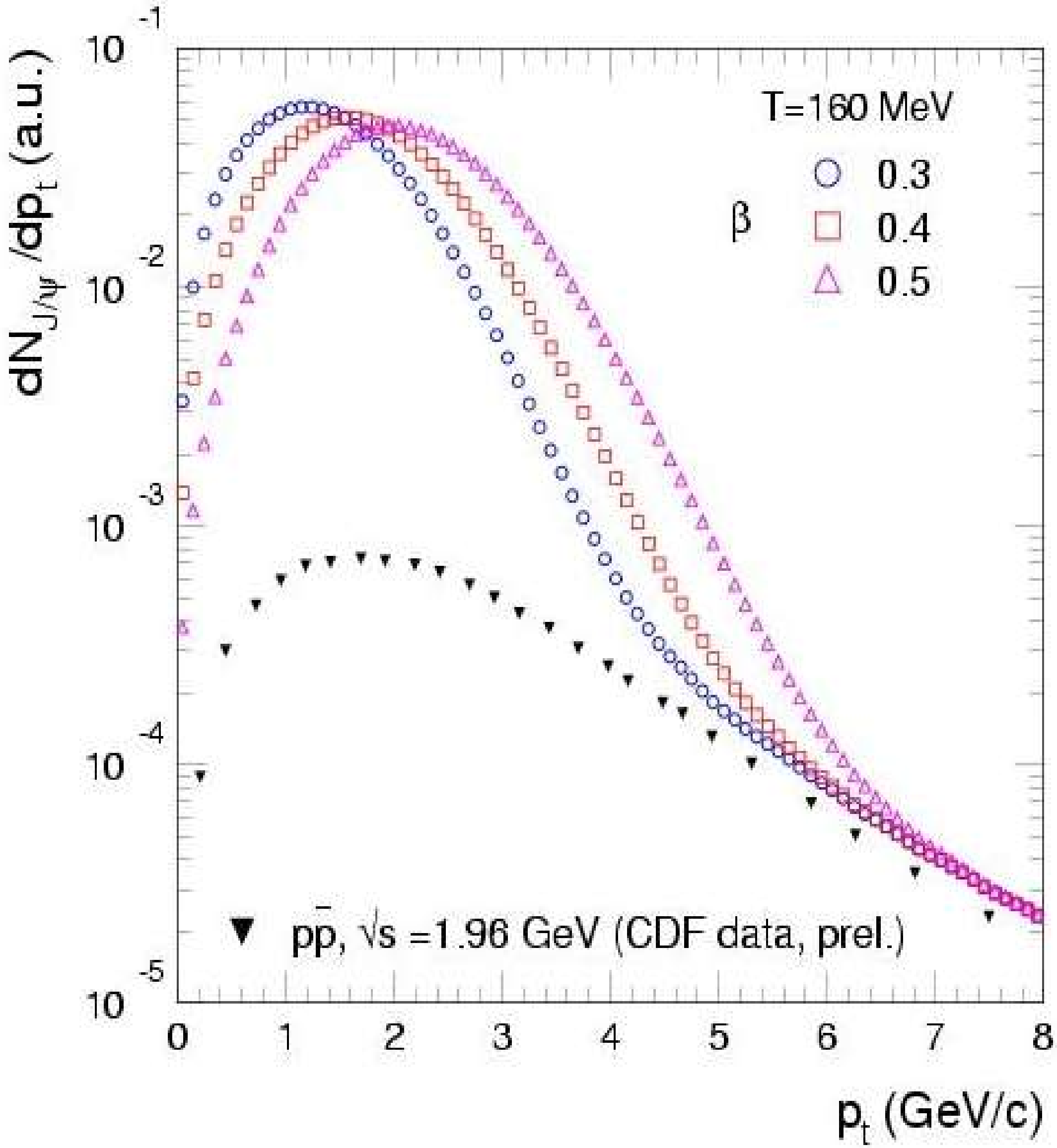
Simulation: W. Sommer 2 10^8 central Pb Pb coll.

flow of quarkonia at LHC?

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

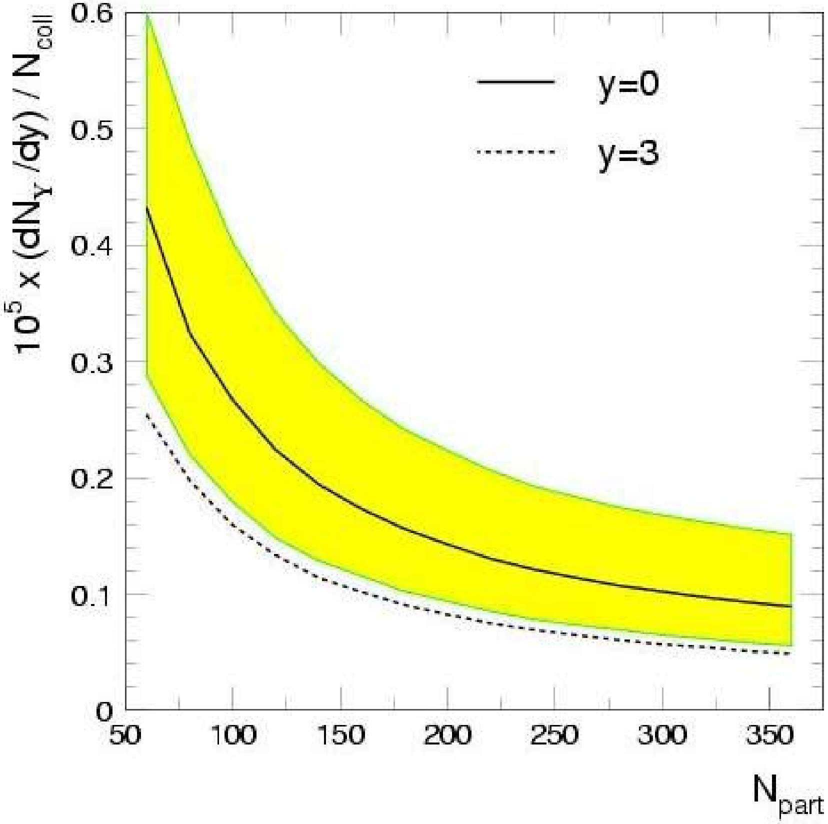
p_t spectra with flow are very different for charmonia from those measured in pp_bar e.g. at Fermilab or expected for pp at LHC

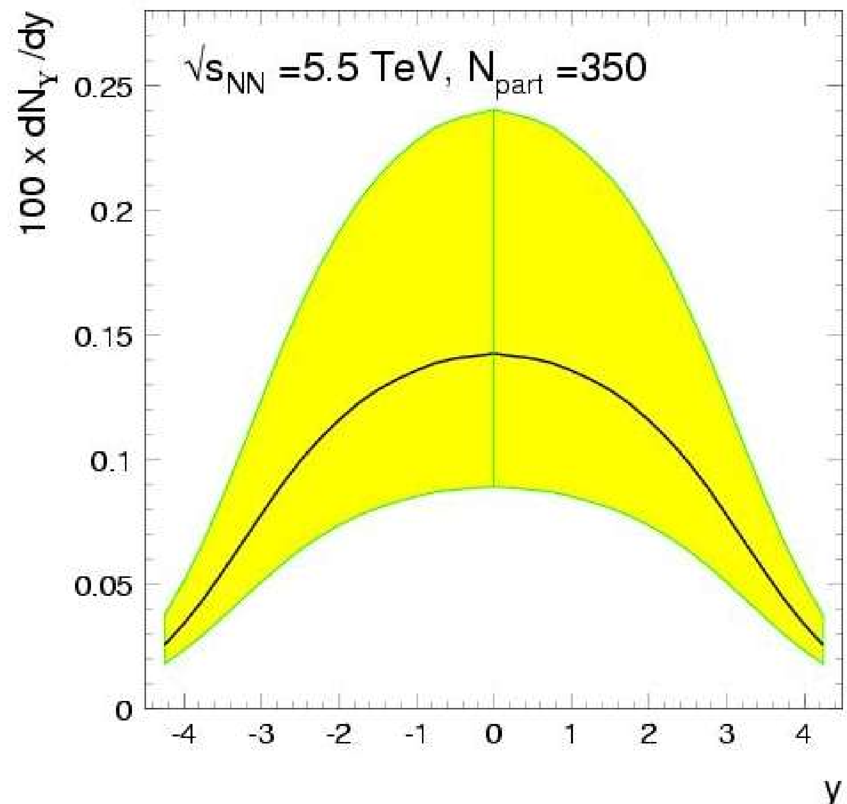
should be easy to discriminate at LHC



bottomonium at LHC

predictions with statistical hadronization model





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

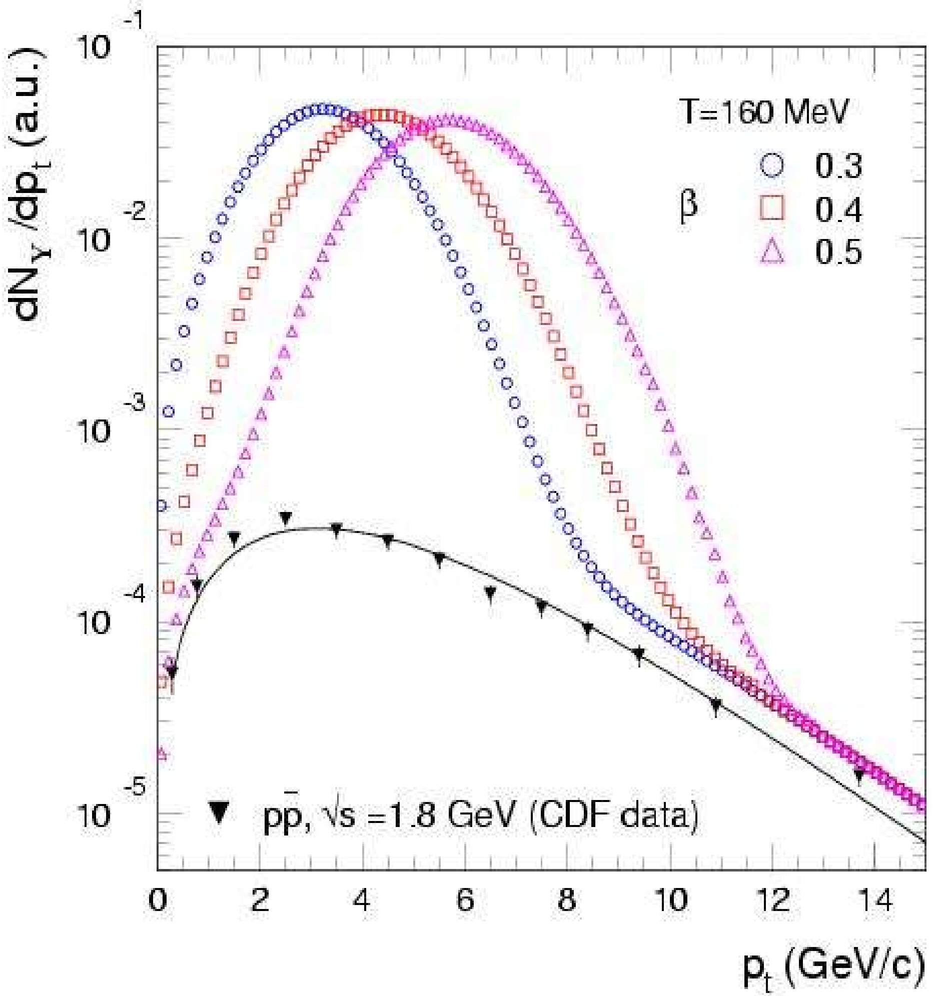
do they thermalize and hadronize statistically??

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

yield ratios Y(2S)/Y(1S) = 0.03 Y(3S)/Y(1S) = 0.04

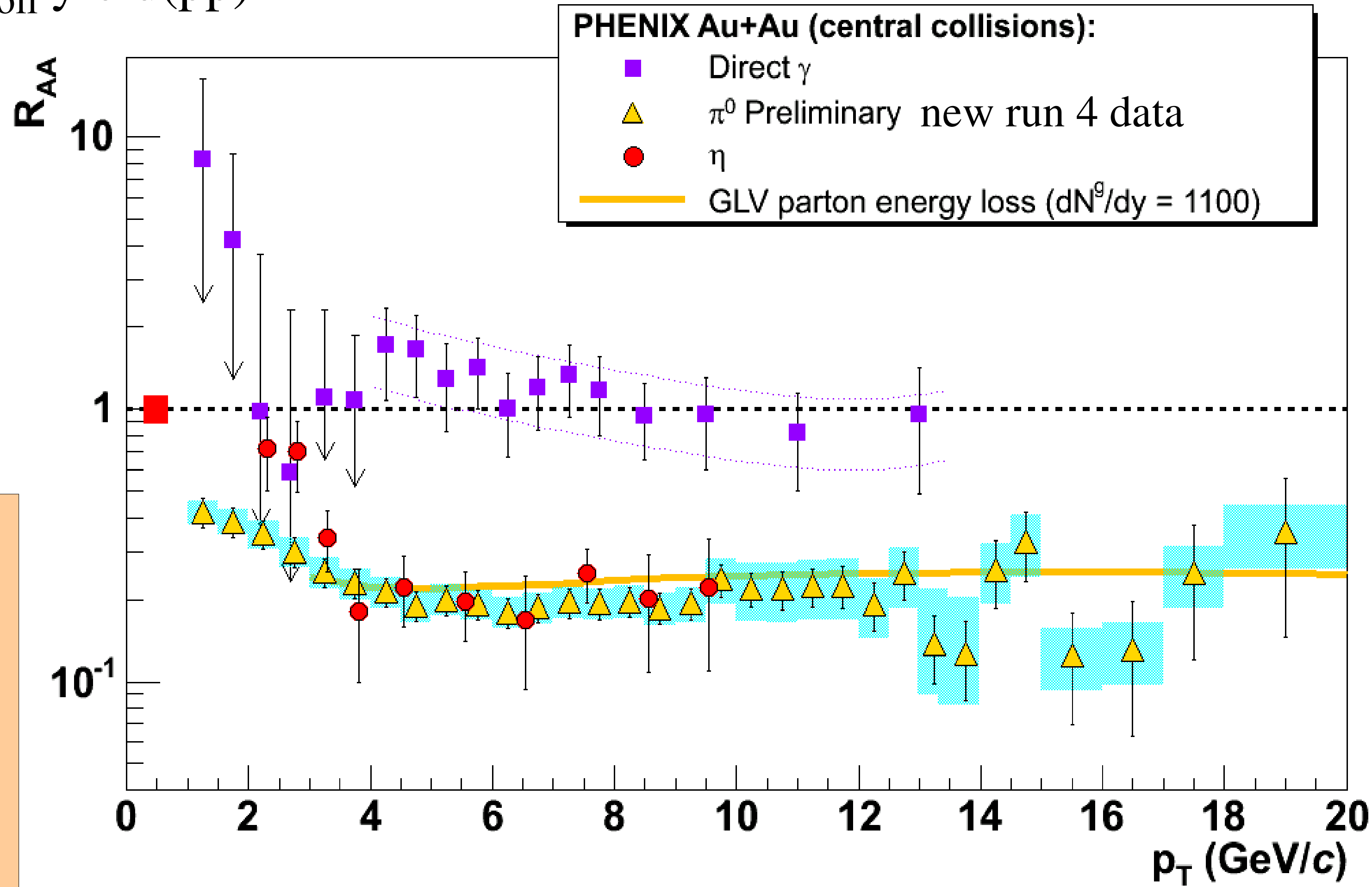
Flow of upsilon at LHC?

difference to ppbar even much more dramatic for Upsilon in case of flow



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 gluon rapidity density

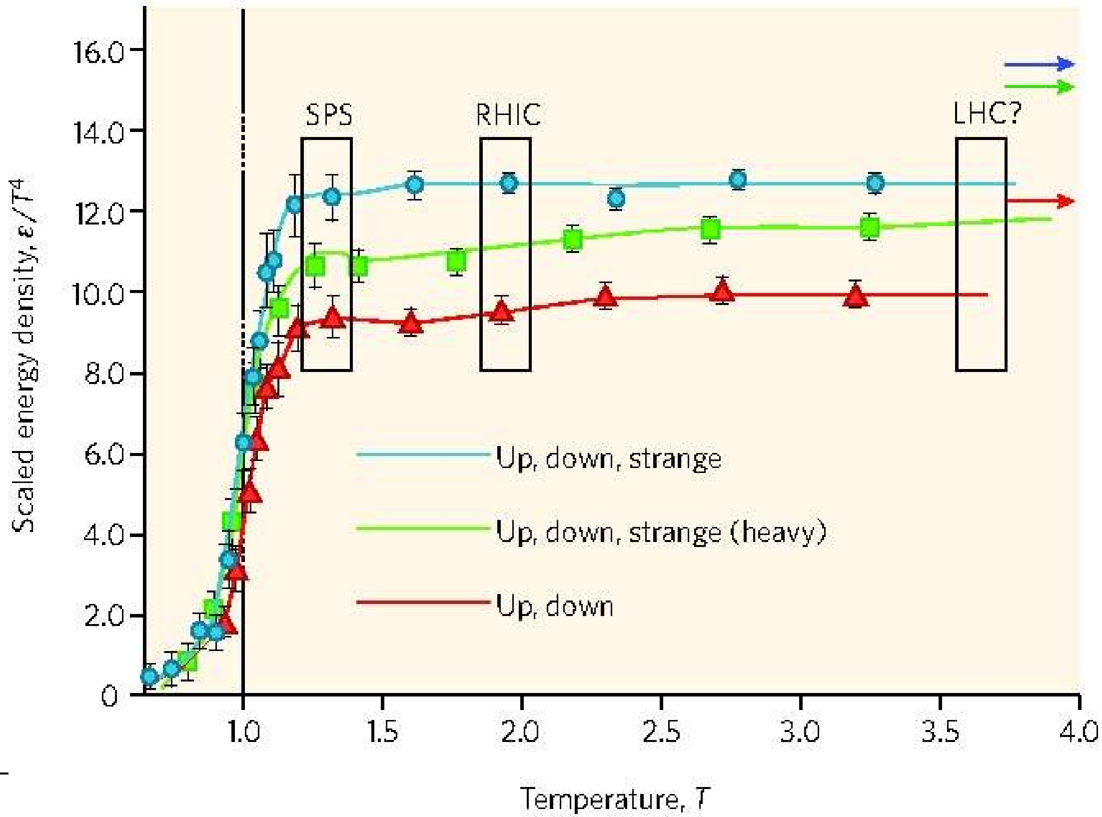
I. Vitev, JPG 30 (2004) S791

	$\tau_0[fm]$	$T[MeV]$	$\varepsilon[GeV/fm^3]$	$\tau_{tot}[fm]$	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**

predictions on jet quenching 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 pt range and measure more (frag. function)



jet measurements in ALICE

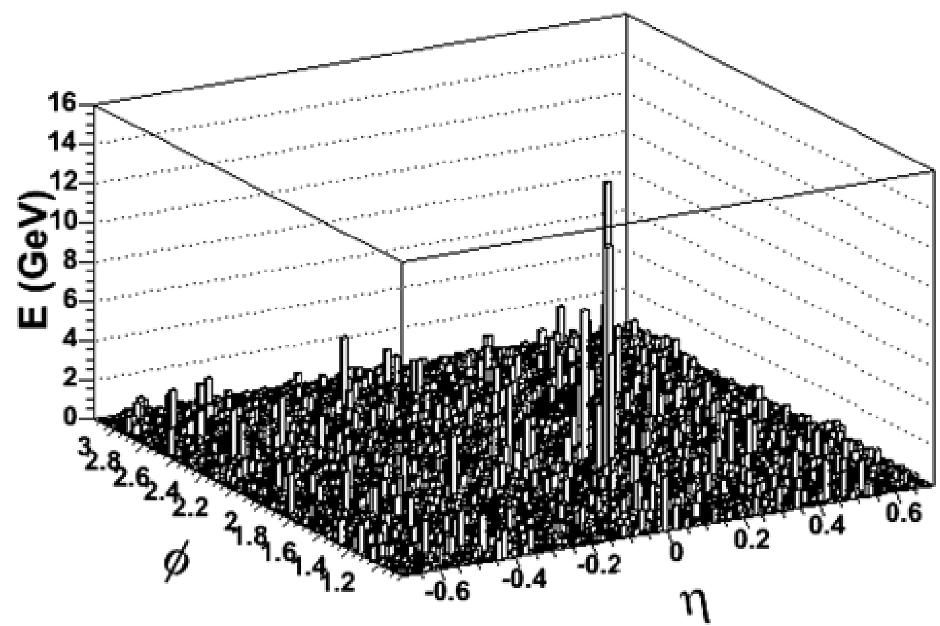
2 GeV | **20 GeV** | **100 GeV** | **200 GeV**

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

event structure and properties:
at p > 2 GeV/c (similar to RHIC)
- leading particle analysis
- correlation studies

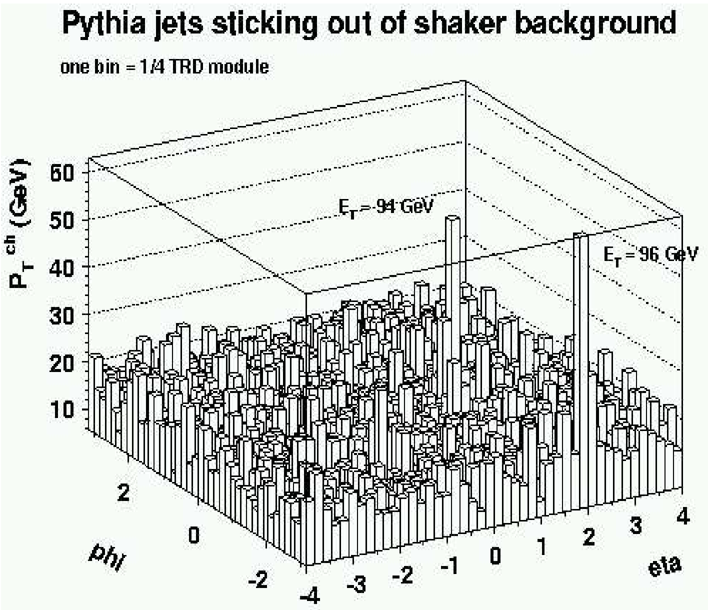
at high p:
- reconstructed jets
- event-by-event well distinguishable objects

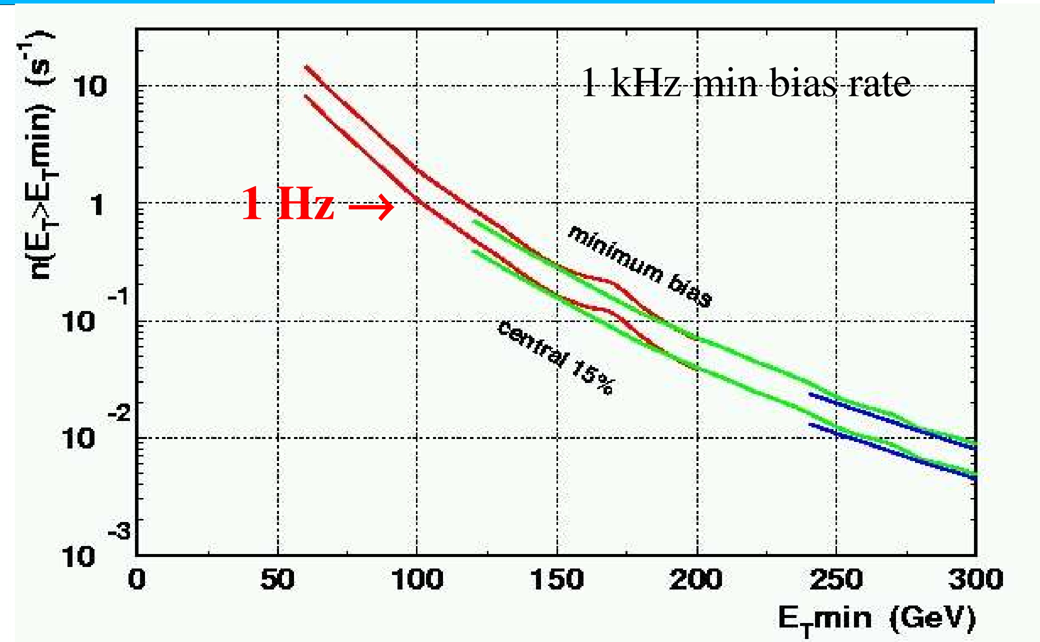
Example :
100 GeV jet +
underlying event

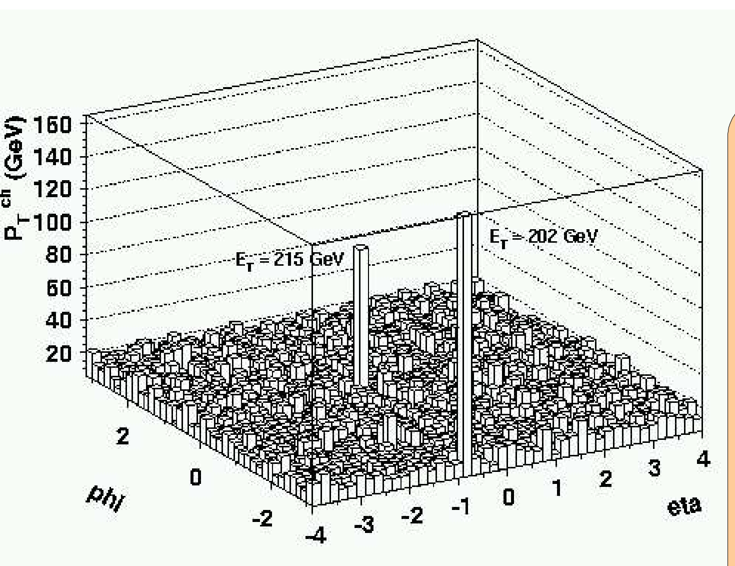


for jet physics recently added EmCal will play important role in conjunction with existing charged particle tracking

jets in ALICE: high rates at very high E_t – need and can trigger





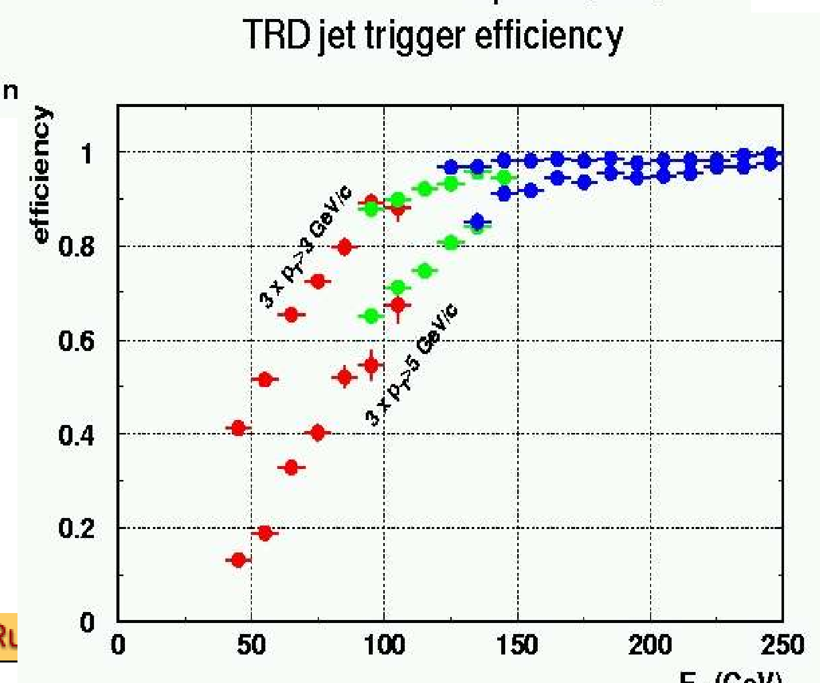


go to very high E_t with trigger

e.g. 3 tracks more than 3 GeV within 0.3 rad (1 TRD stack)

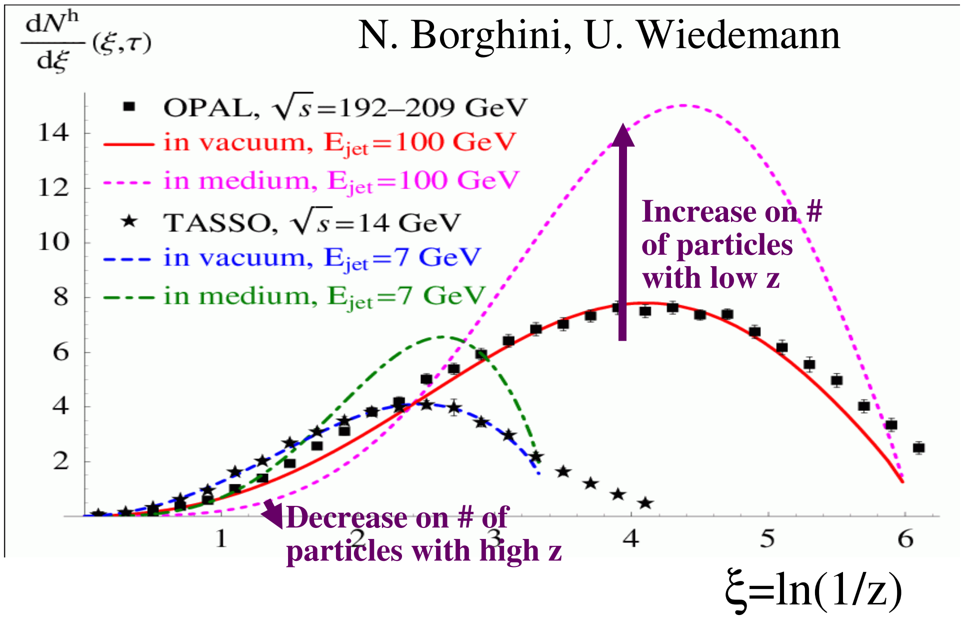
reconstruct actual jet

jet – photon coinc.

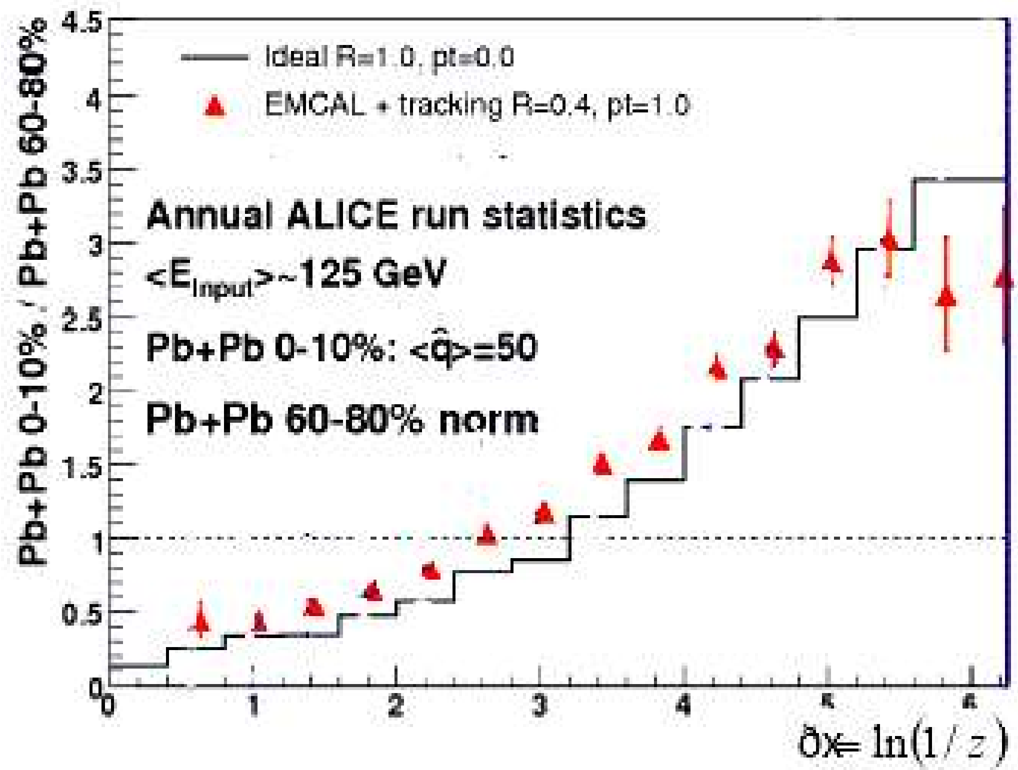


measurement of jet fragmentation function

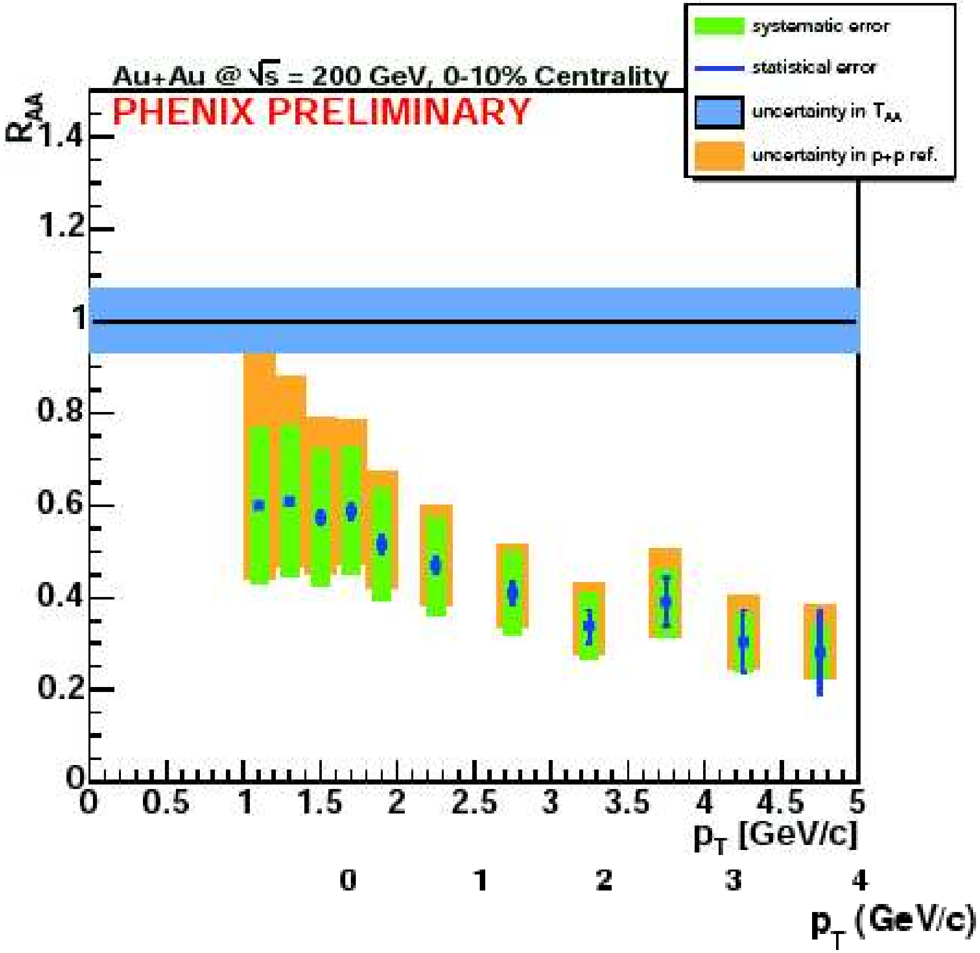
sensitive to energy loss mechanism

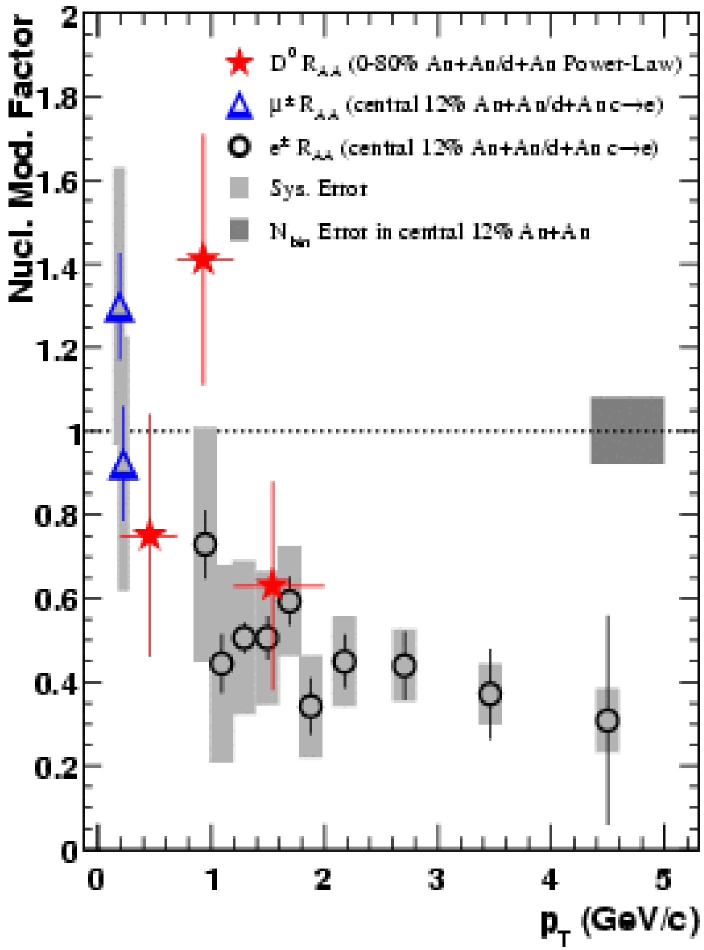


good reconstruction in ALICE



heavy quark distributions from inclusive electron spectra





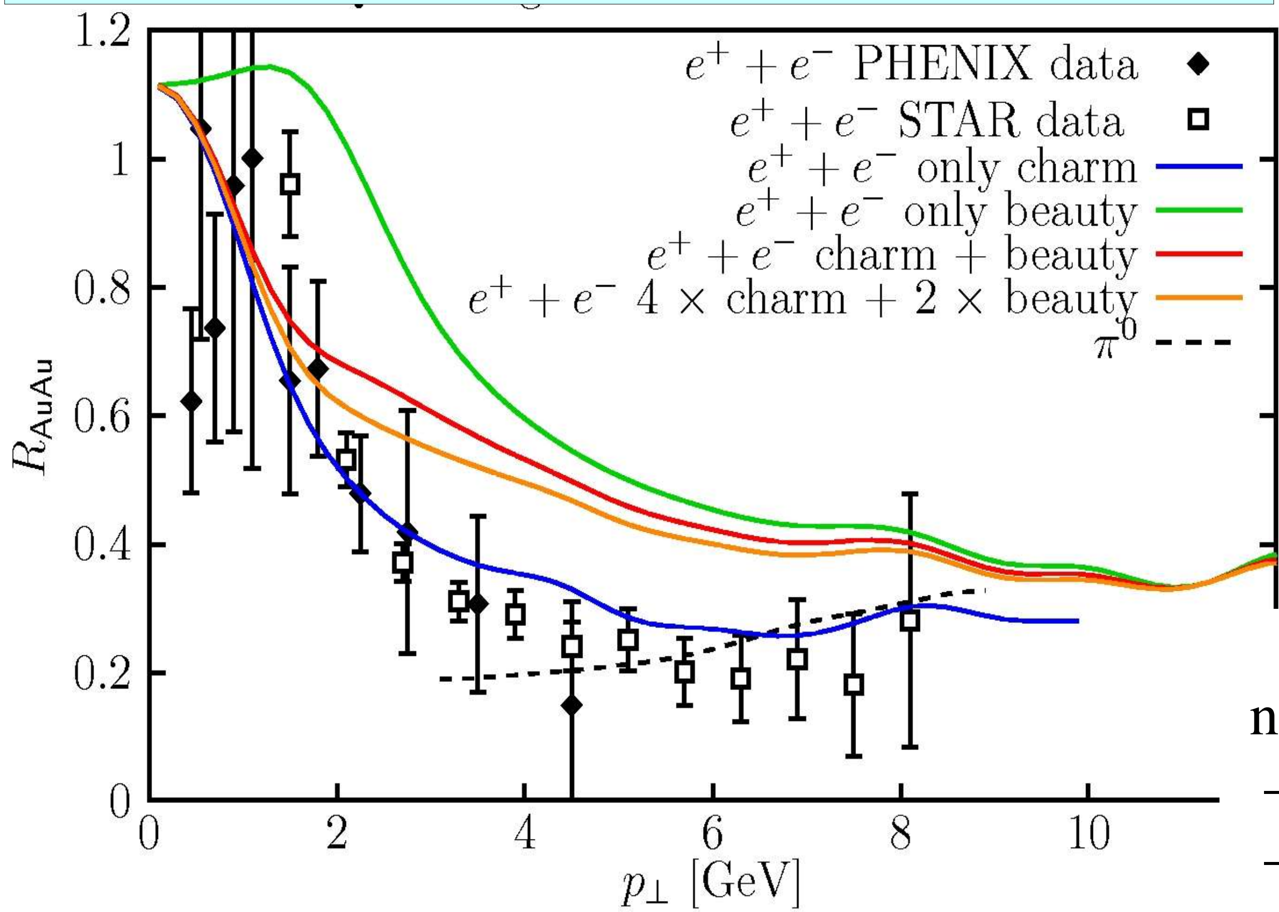
STAR preliminary

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. =5.2 mb ← σ to match pion data



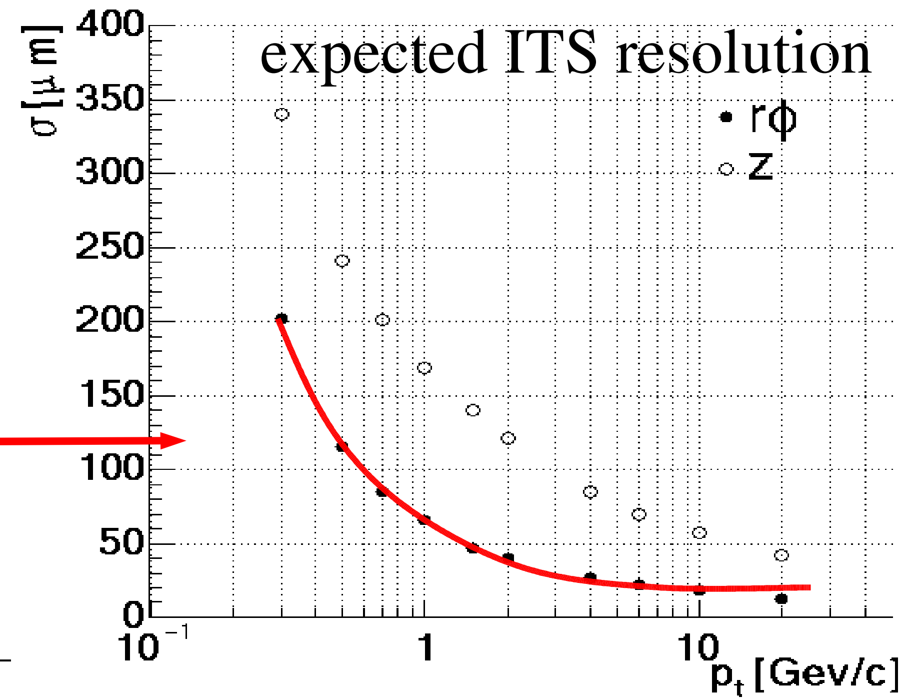
charm contribution indeed suppressed as much as pions but adding beauty data are not reproduced

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

open/hidden heavy flavor measurements in ALICE

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



$D^0 \rightarrow K\pi$ channel

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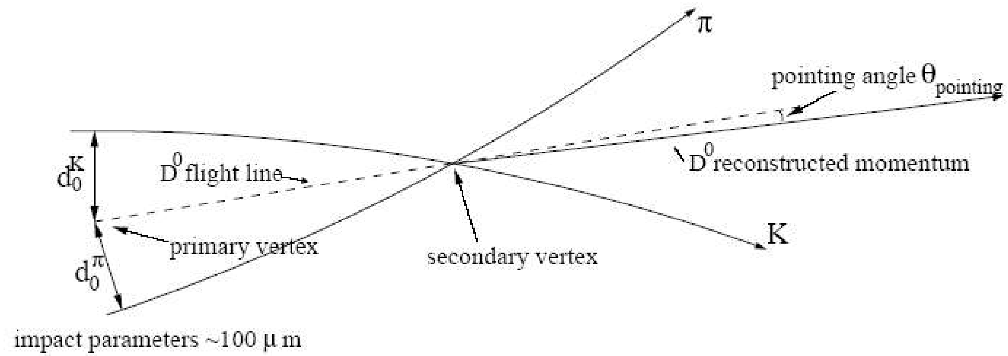
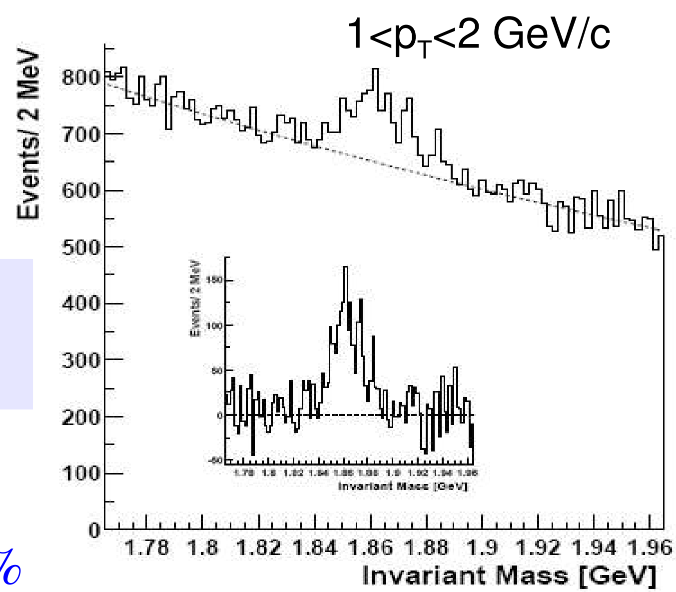
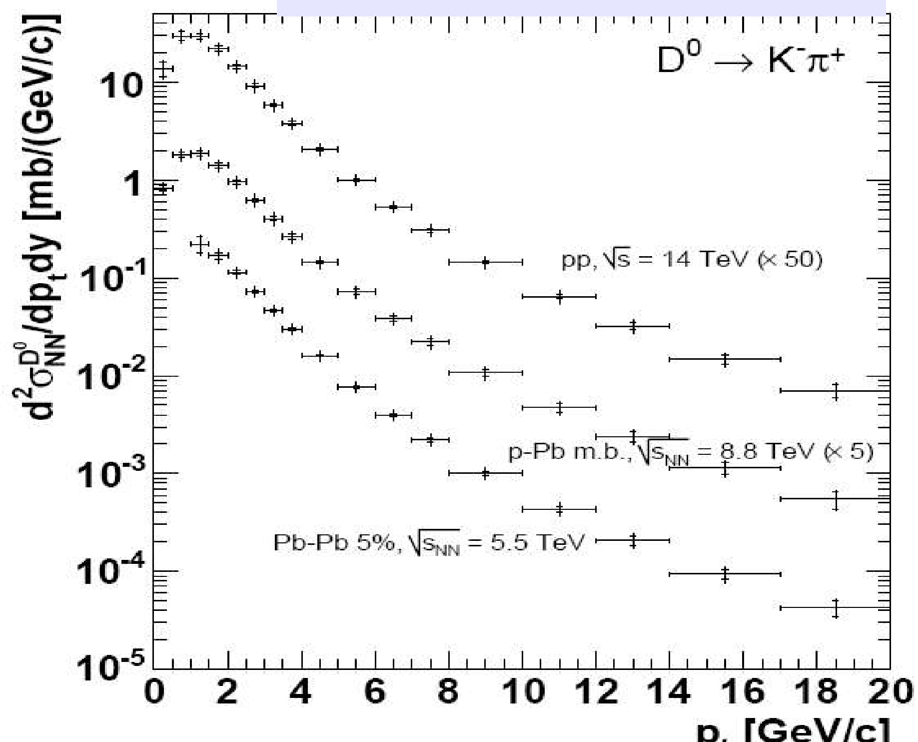
- high precision vertexing, better than 100 μm (ITS)
- high precision tracking (ITS+TPC)
- K and/or π identification (TOF)



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

10^7 central PbPb



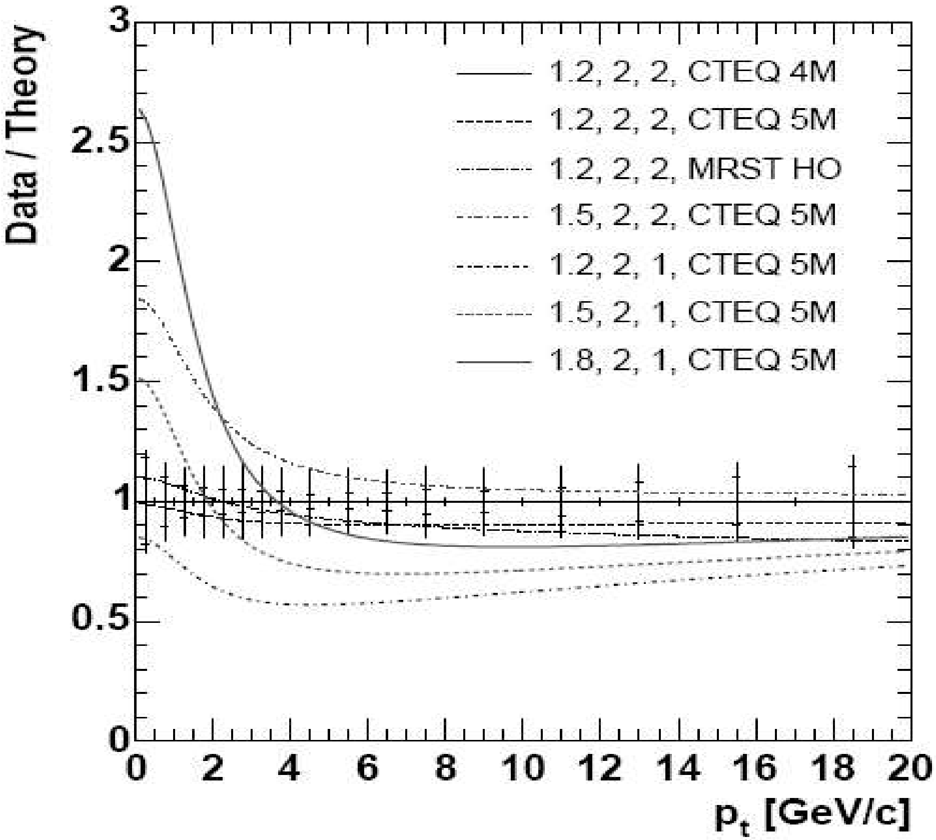


S/B = 10%

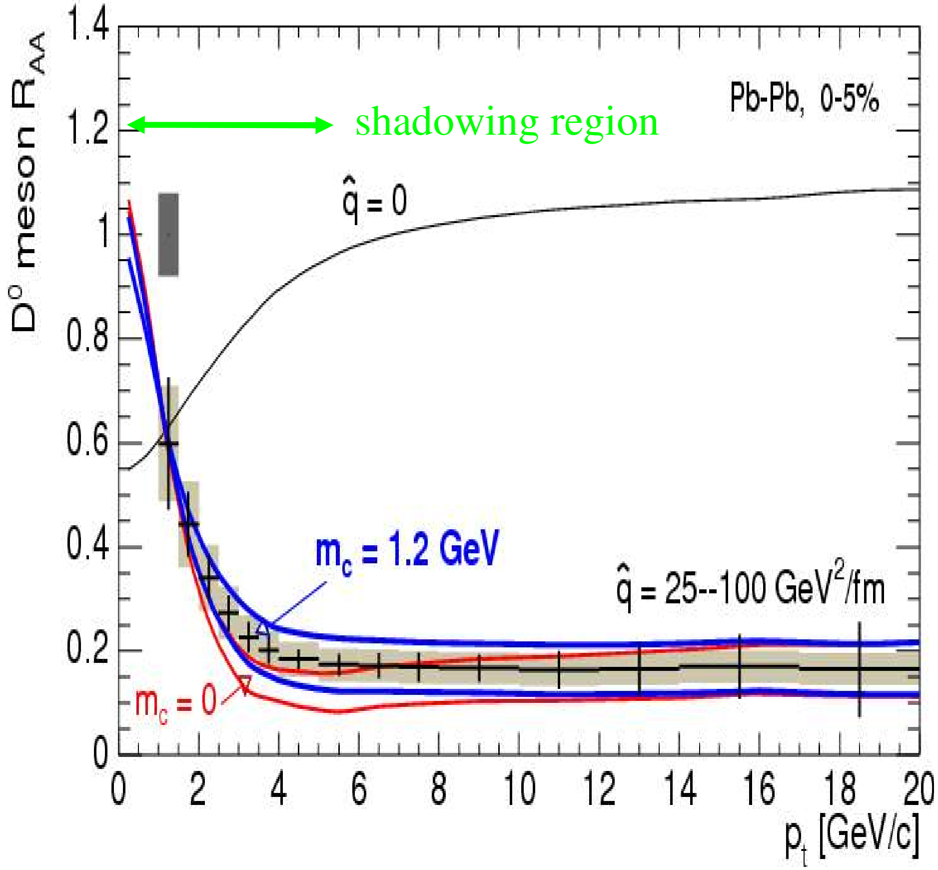
$S/\sqrt{(S+B)} = 40$

high precision charm measurement

pp at 14 TeV
sensitivity to PDF's



Central PbPb
shadowing + k_T + energy loss



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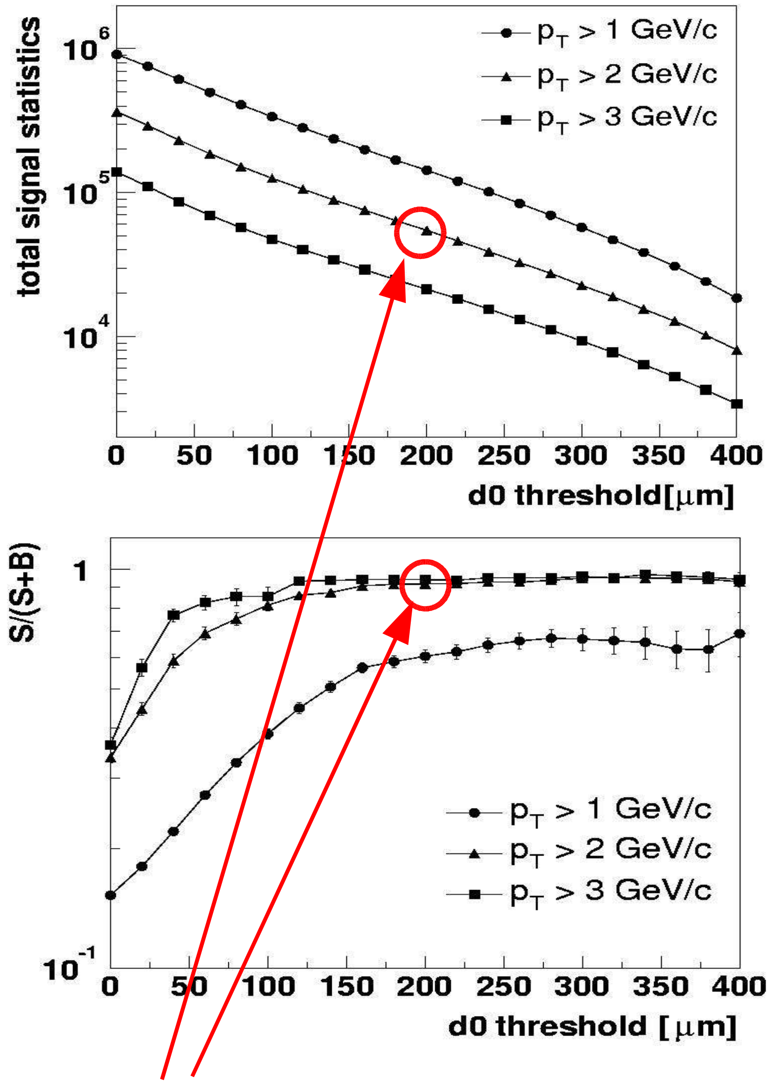
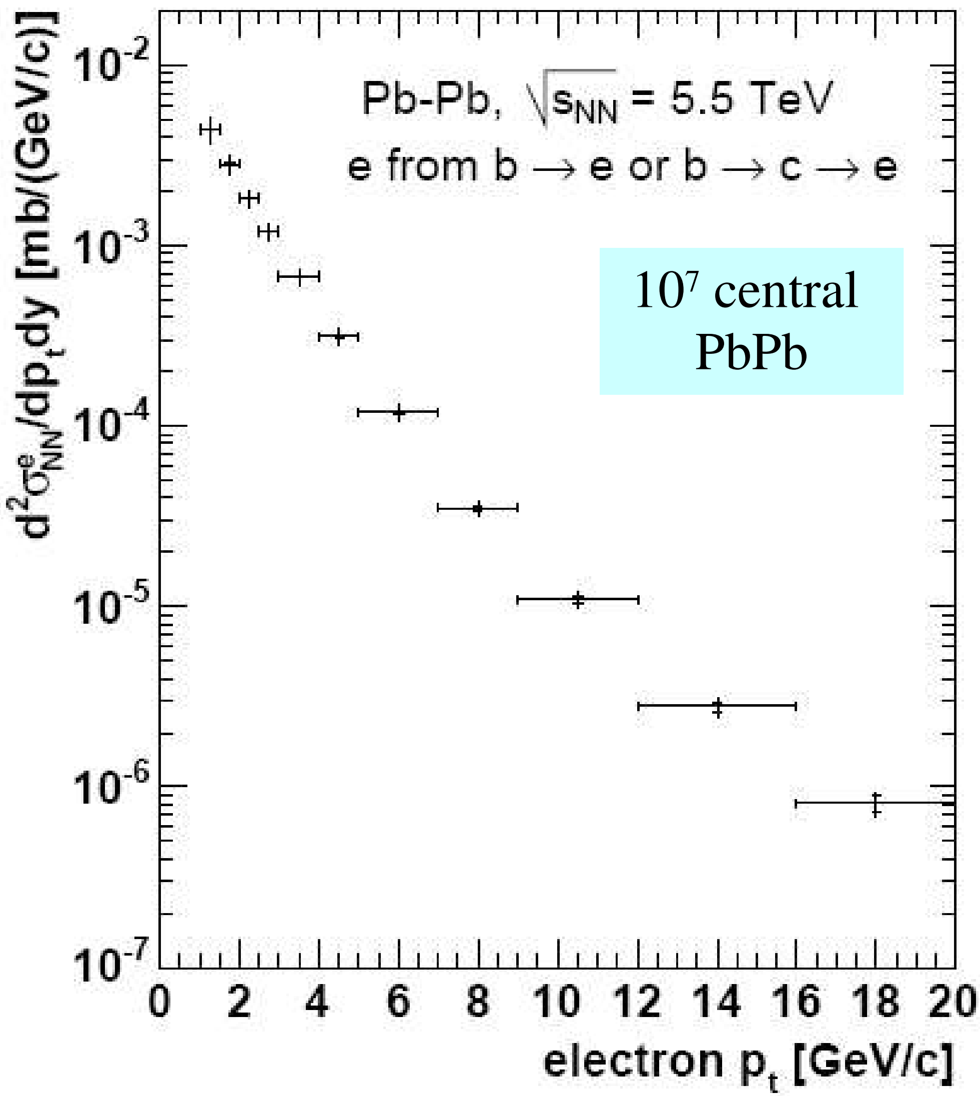
open beauty from single electrons





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%

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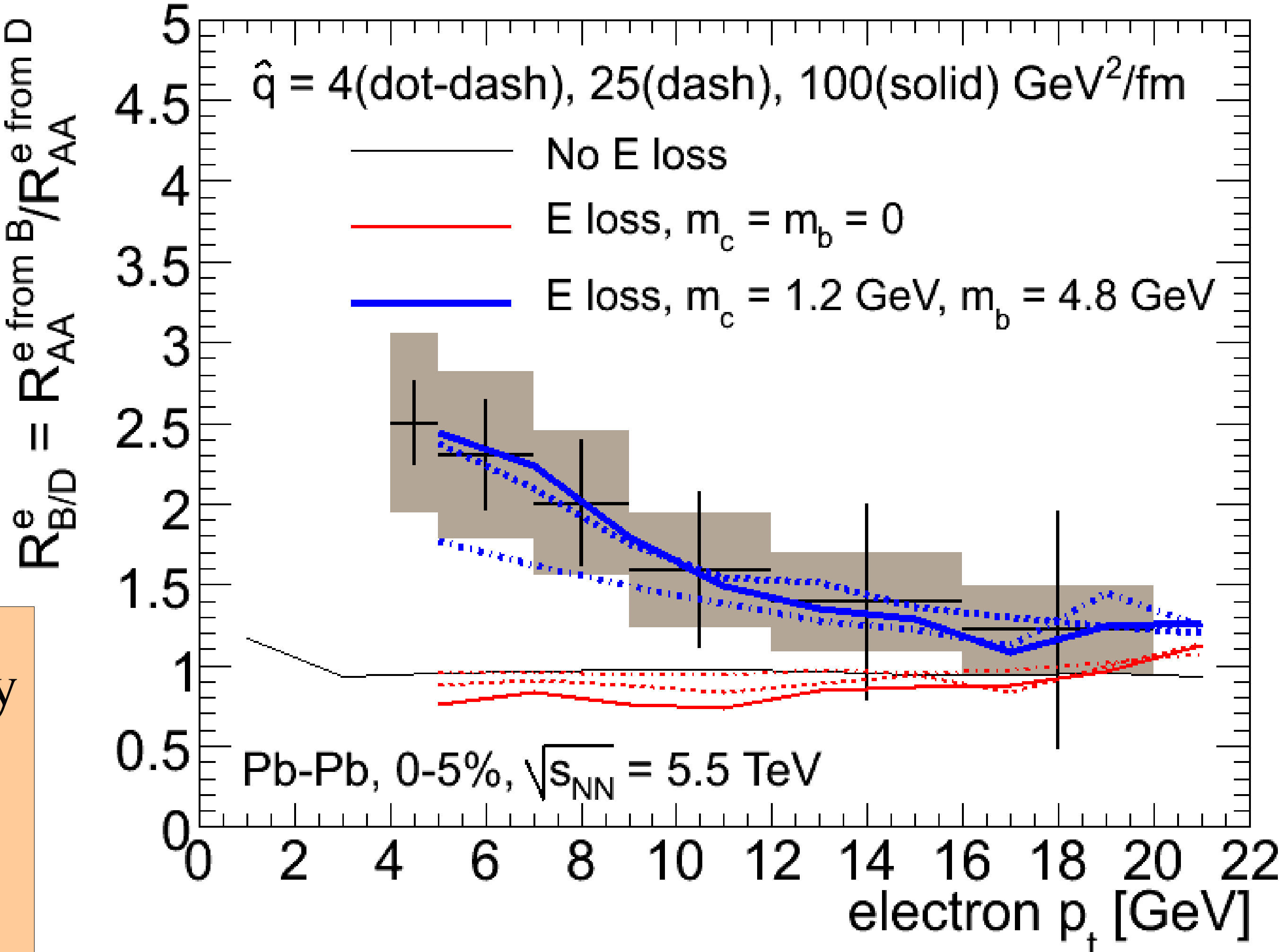
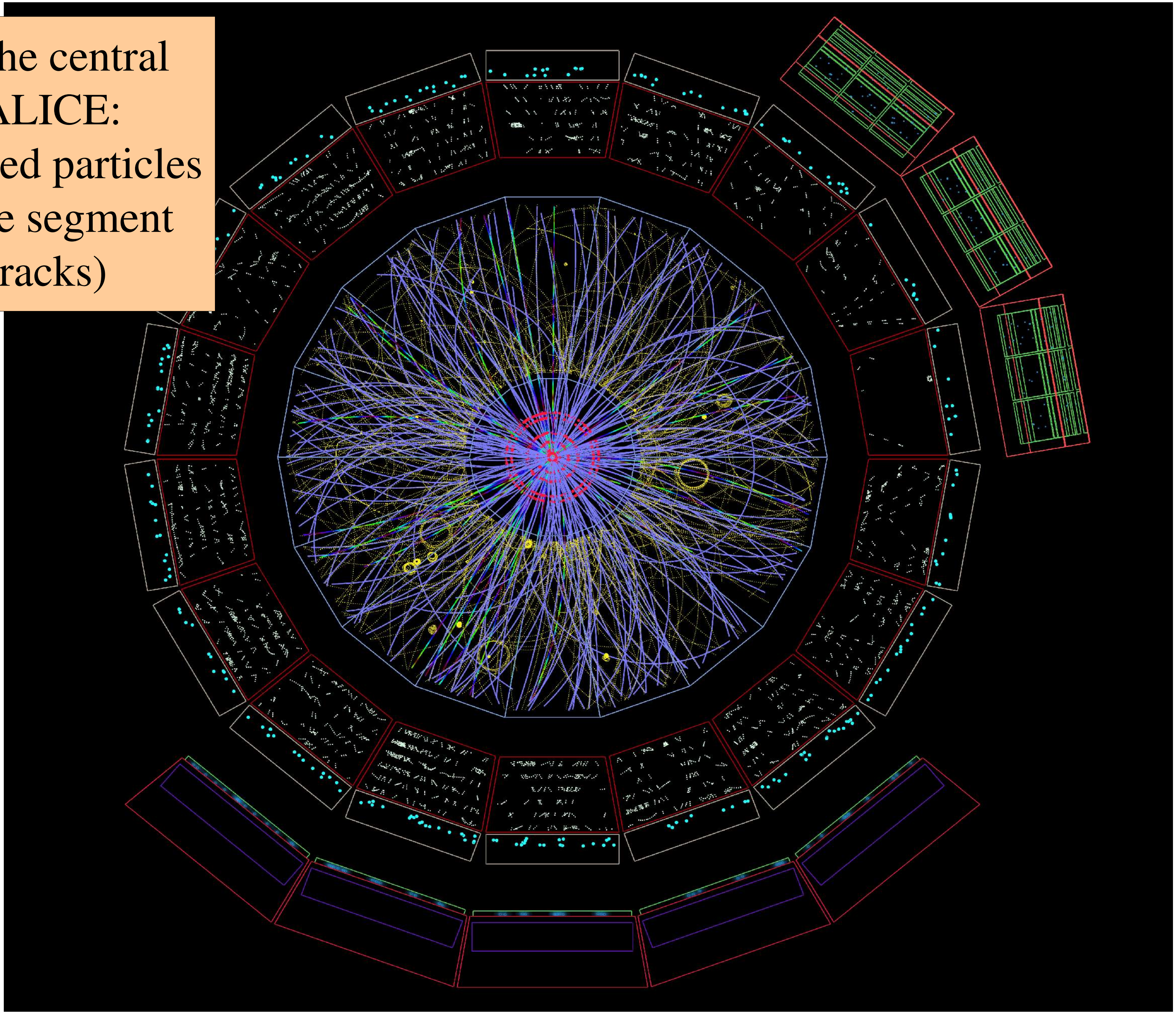
jet quenching for b-quarks relative to c-quarks



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

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)



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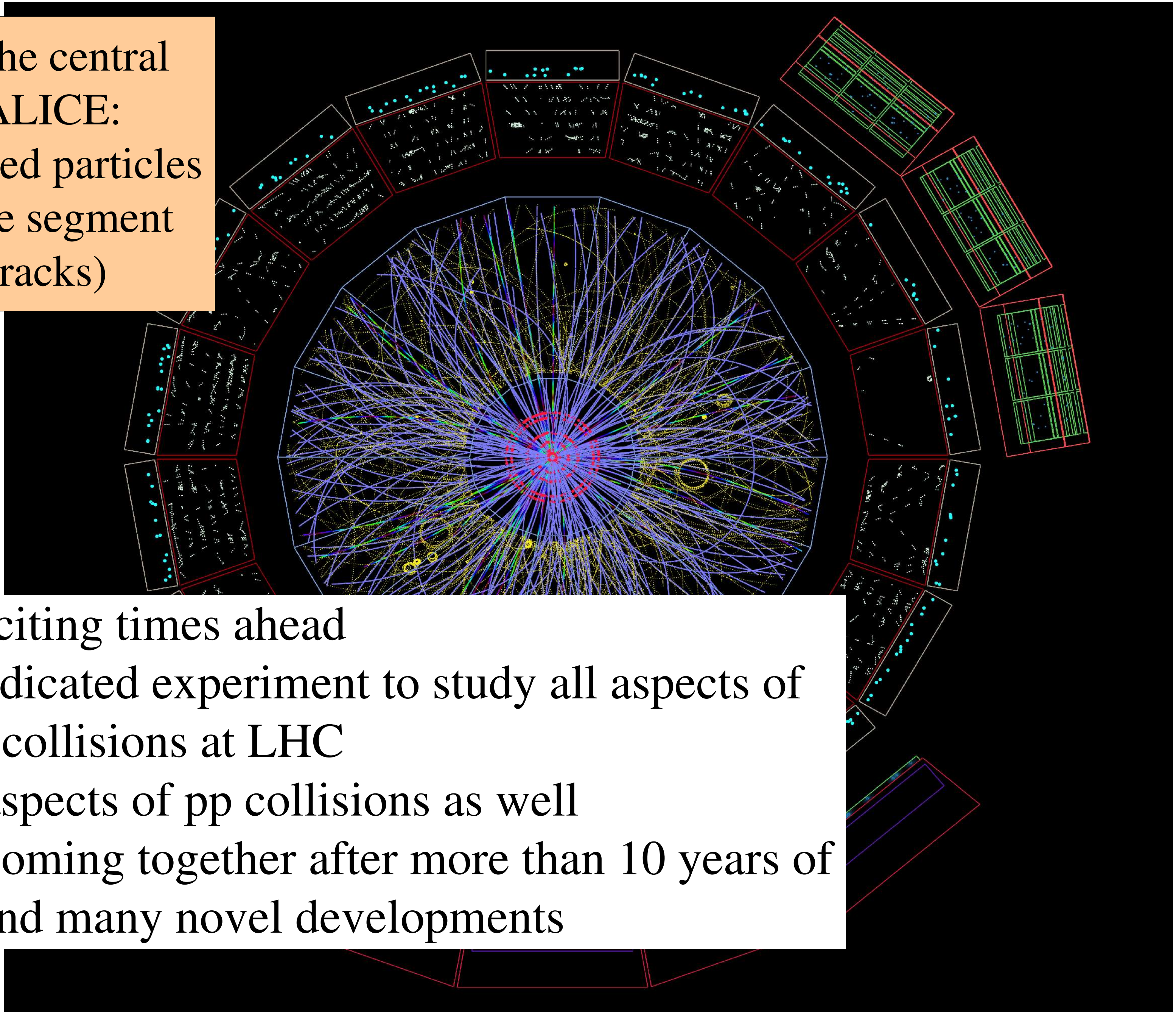
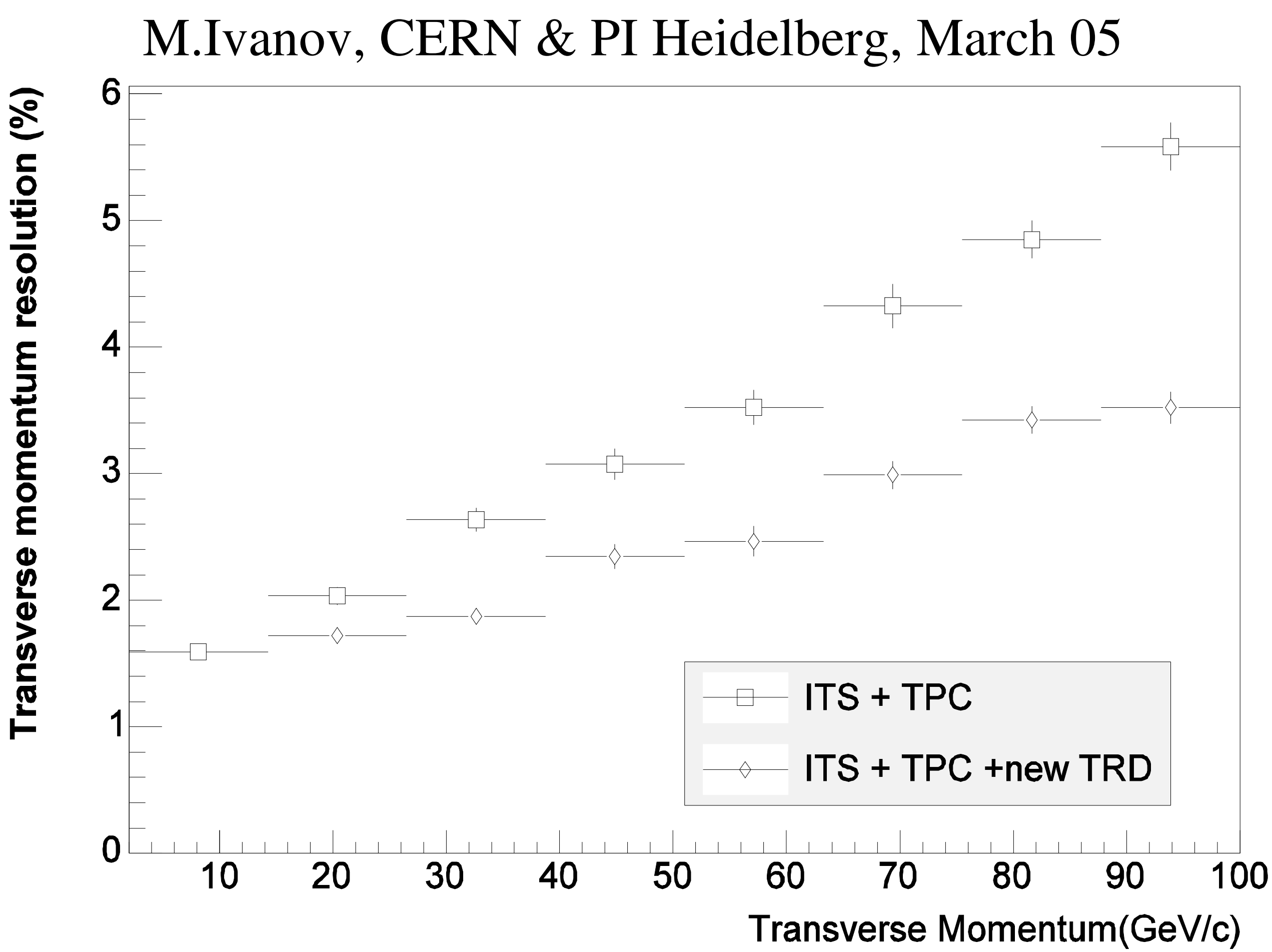


- there are exciting times ahead
- ALICE is dedicated experiment to study all aspects of heavy ion collisions at LHC
- many new aspects of pp collisions as well
- detector is coming together after more than 10 years of hard work and many novel developments

Backup slides

Combined Momentum Resolution in ALICE Central Barrel

$dN_{ch}/dy \sim 5000$

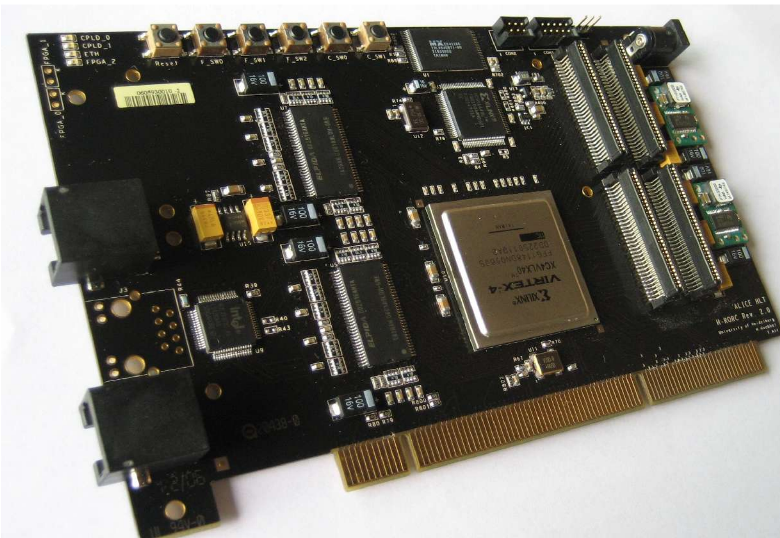


resolution ~ 3% at 100 GeV/c
excellent performance in hard region!

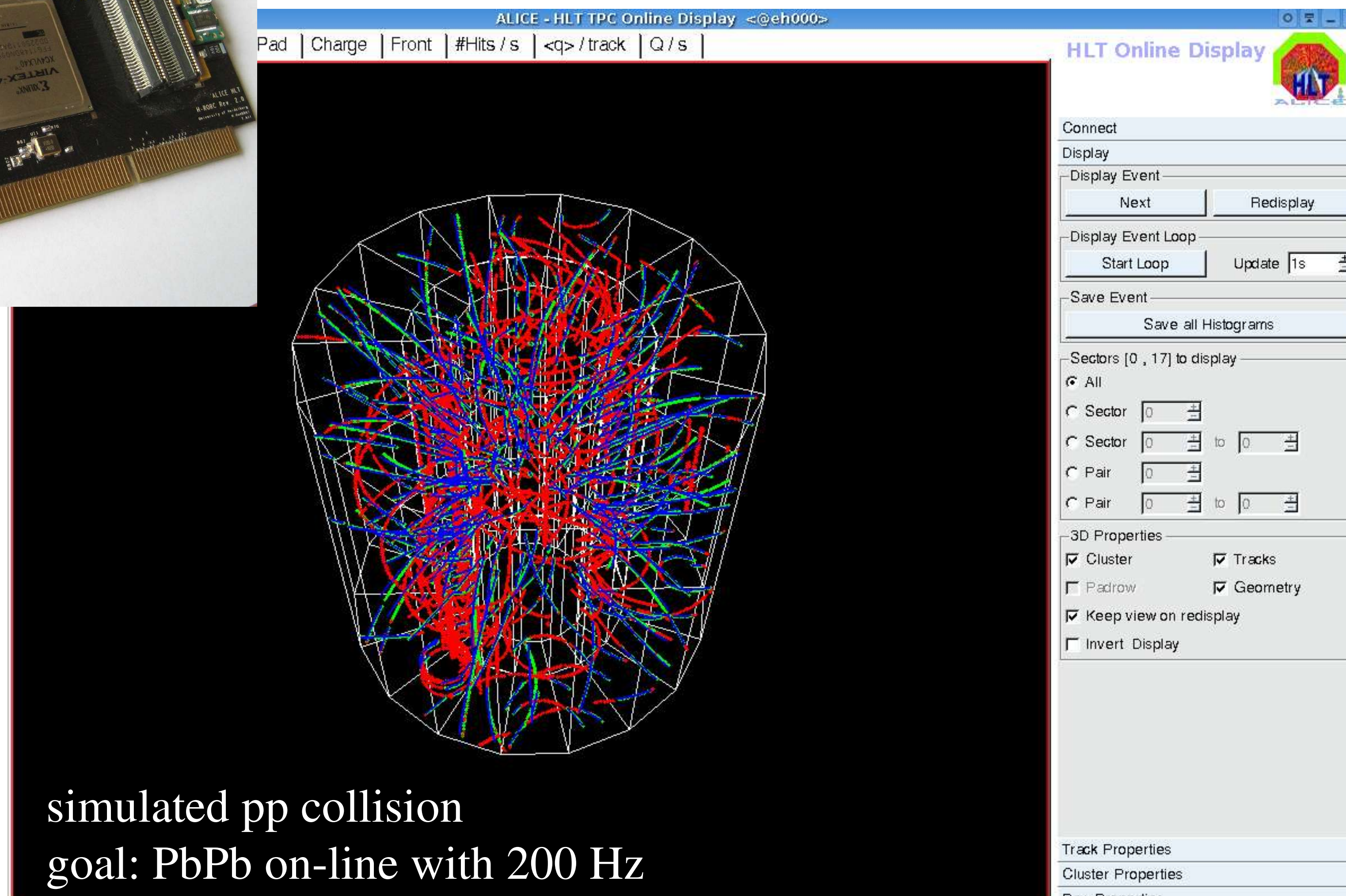
the ALICE High Level Trigger (HLT)

KIP U. Heidelberg, U. Bergen

event selection and compression
(band width for archiving 1.2 Gbyte/s)
method: complete on-line analysis of data
up to 2 million tracks – 360 million track points



1600 processors in
400 compute nodes
with 4 CPUs each
GRID compatible
FPGA co-processors



simulated pp collision
goal: PbPb on-line with 200 Hz

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 $d\eta/dz = \tau_0$

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

$\tau_0 =$ 1 fm/c $\rightarrow$ $\varepsilon_0 = 3$ 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 $\rightarrow$ $\varepsilon_0 = 5.5$ GeV/fm^3

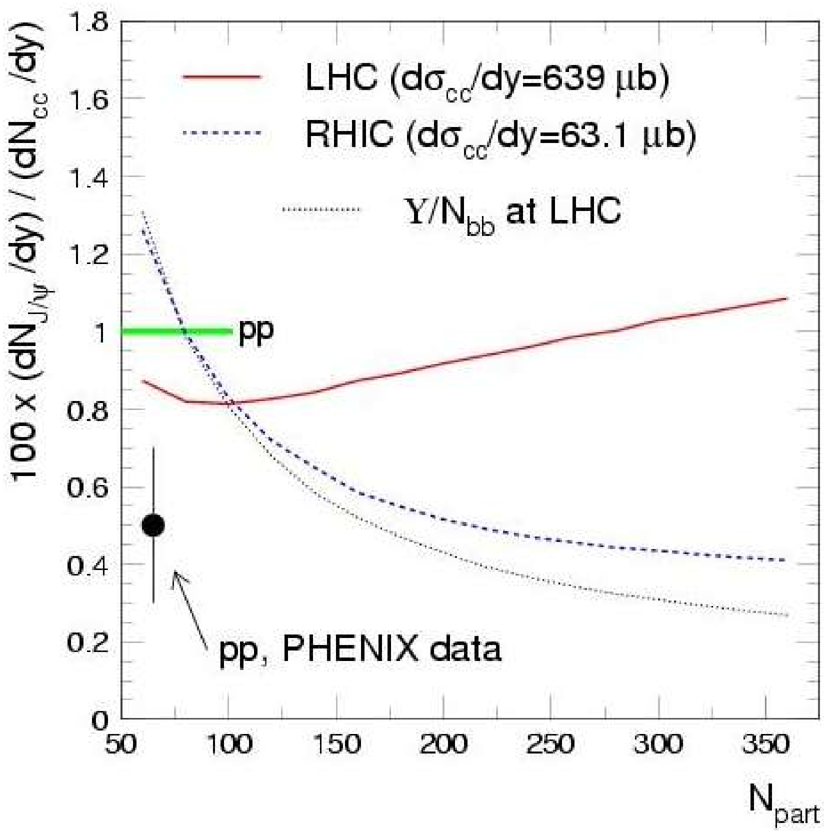
(factor 2 higher than at SPS top energy)

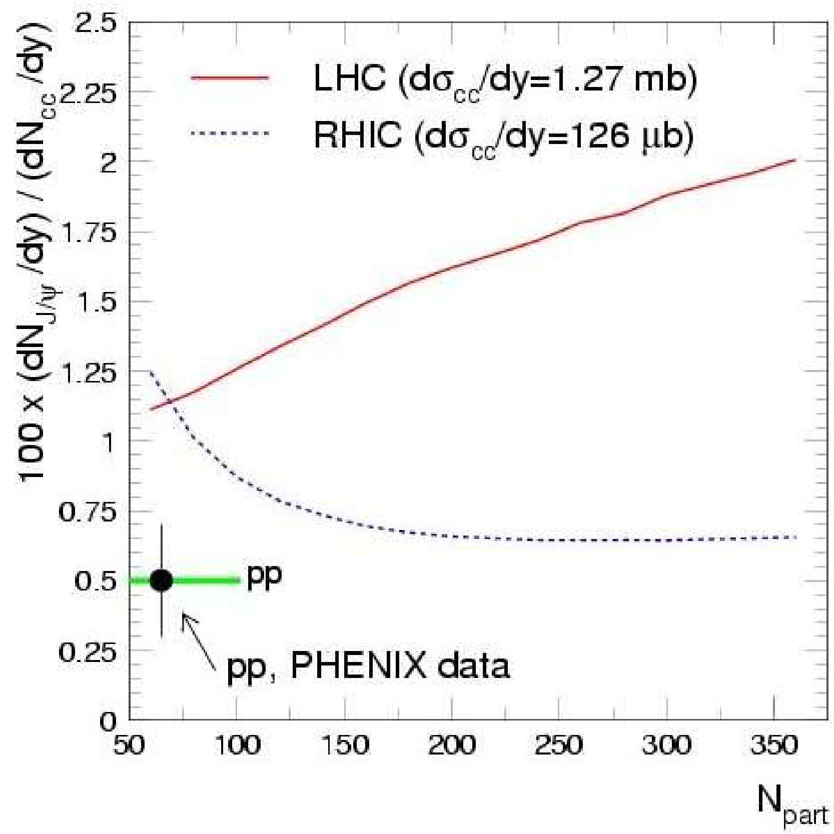
optimistically: $\tau_0 = 1/Q_s = 0.14$ fm/c $\rightarrow$ $\varepsilon_0 = 40$ GeV/fm^3

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

Energy dependence of Quarkonium Production in Statistical Hadronization Model

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, nucl-th/0611023





if more open charm: effect will be larger

the SCI Jet Quenching Model for QGP

Geometry: N_{part}, N_{coll} etc. from simple Glauber - model

Eskola, Kajantie, Lindfors, Nucl. Phys. B 323 (1989)

EOS: ideal relativistic gluon gas

$$\Rightarrow n = \frac{g}{\pi^2}\zeta(3)T^3 \quad \& \quad \epsilon = \frac{\pi^2 g}{30}T^4$$

expansion: boost-invariant longitudinal expansion

$$T(\tau) \propto \tau^{-1/3} \quad \Rightarrow \quad n(\tau) \propto \tau^{-1} \quad \& \quad \epsilon(\tau) \propto \tau^{-4/3}$$

$(\tau = \sqrt{t^2 - z^2})$ Bjorken, Phys. Rev. D 27 (1983)

local energy density: $\epsilon(x,y,\tau) \propto N_{\text{part}}(x,y) \cdot \tau^{-4/3}$

jet production: LO pQCD matrix elements (PYTHIA) + distribution in overlap region according to $N_{\text{coll}}(x,y)$