Exploring the QCD Phase Diagram at the LHC

- the phases of strongly interacting matter
  - introductory remarks
- LHC and ALICE experiment
- entering the world of strongly coupled matter
  selected results of PbPb collisions
  - Multiplicity and the initial condition
  - Production of hadrons and the phase diagram
  - Quarkonia as probe for deconfinement

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BMBF Forschungsschwerpunkt ALICE Experiment 201

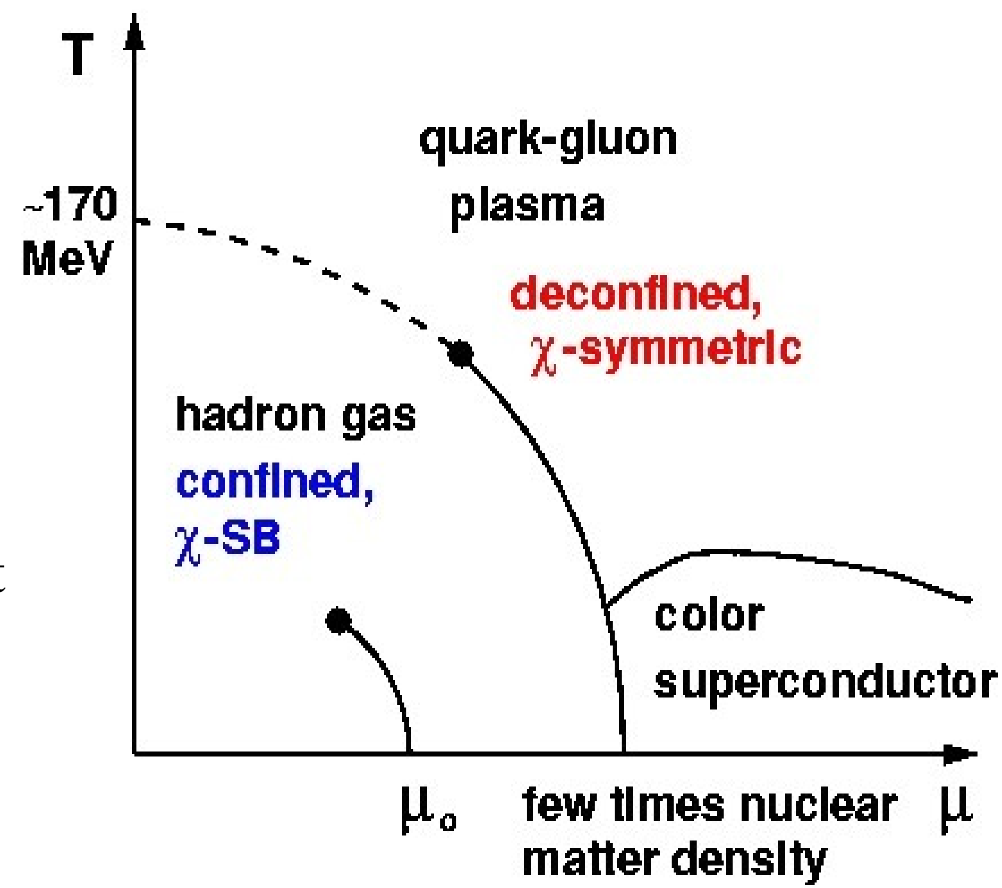
RUPRECHT-KARLS-UNIVERSITÄT HEIDELBERG

the Phase Diagram of Strongly Interacting Matter

at low temperature and normal density
colored quarks and gluons are bound in colorless hadrons - confinement
chiral symmetry is spontaneously broken (generating 99% of proton mass e.g.)
1972 QCD (Gross, Politzer, Wilczek)
asymptotic freedom at small distances

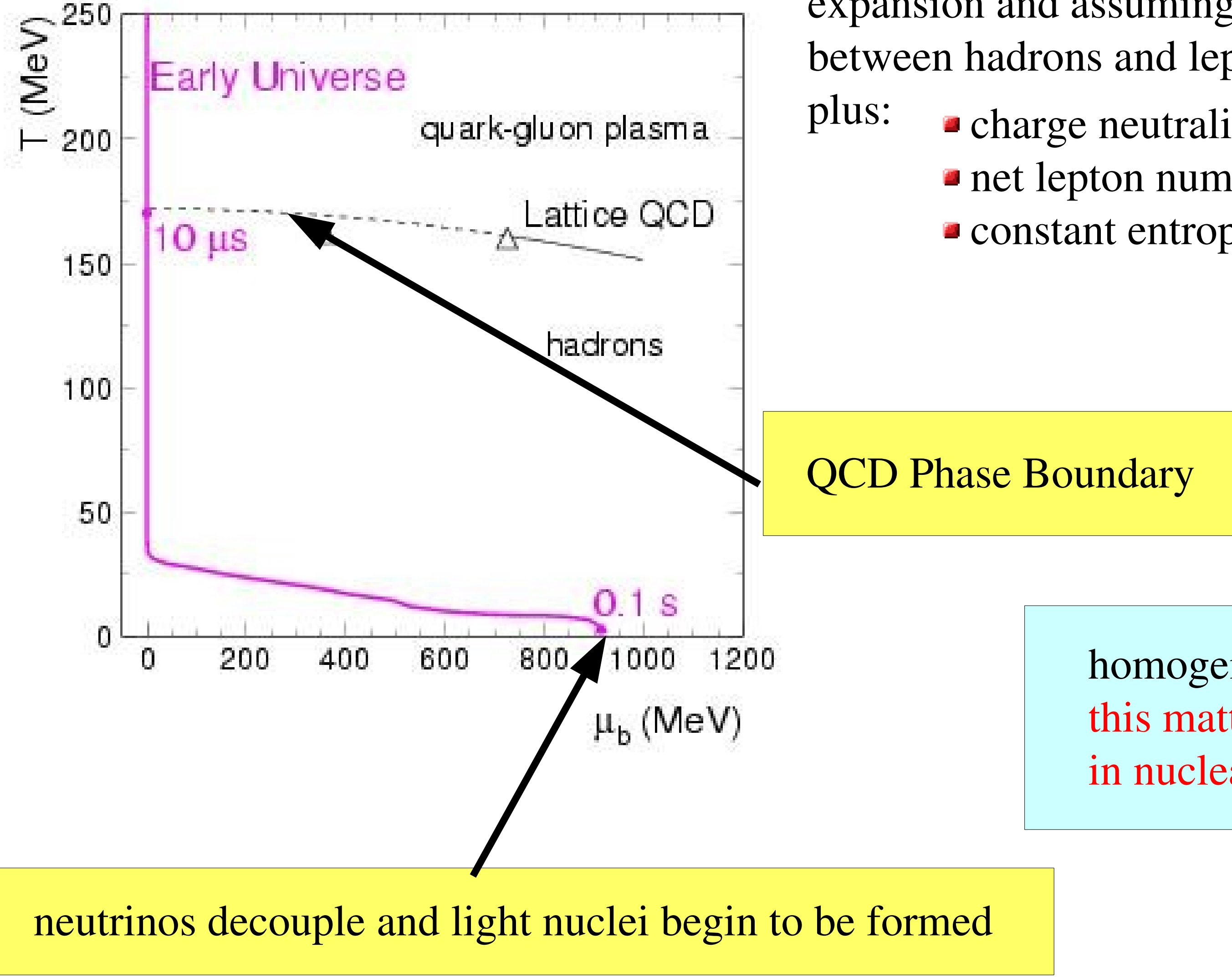
at high temperature and/or high density
quarks and gluons freed from confinement
-> new state of strongly interacting matter
1975 (Collins/Perry and Cabibbo/Parisi)

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



Evolution of the Early Universe

Braun-Munzinger, Wambach
Rev. Mod. Phys. 81 (2009) 1031



Evolution of early universe calculated for isentropic expansion and assuming full chemical equilibrium between hadrons and leptons until neutrinos freeze out plus:

- charge neutrality
- net lepton number = net baryon number
- constant entropy/baryon

homogeneous universe in equilibrium, this matter can only be investigated in nuclear collisions at high energies

SPS : 1986 - 2003

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

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

LHC : from 2009

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

E_{cm}^* = 1150 TeV

at 574 TeV - 20000 prod. hadrons

AGS : 1986 - 2000

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

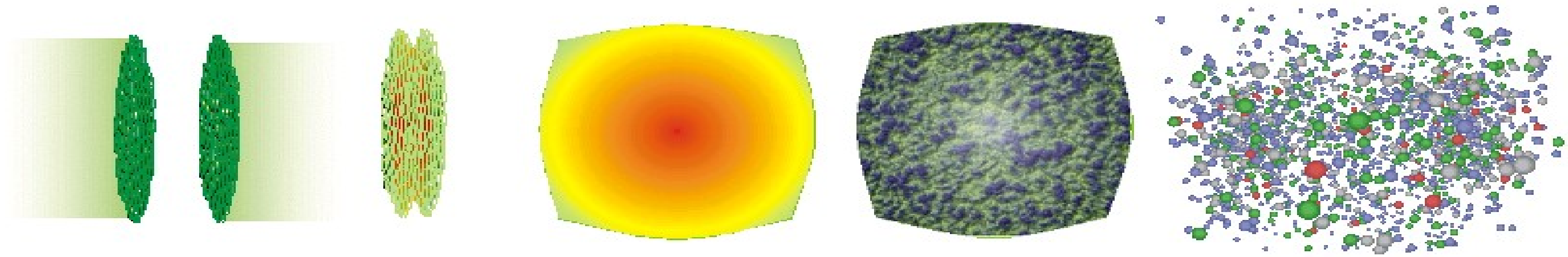
E_{cm}^* = 600 GeV - 1000 produced hadrons

RHIC : from 2000

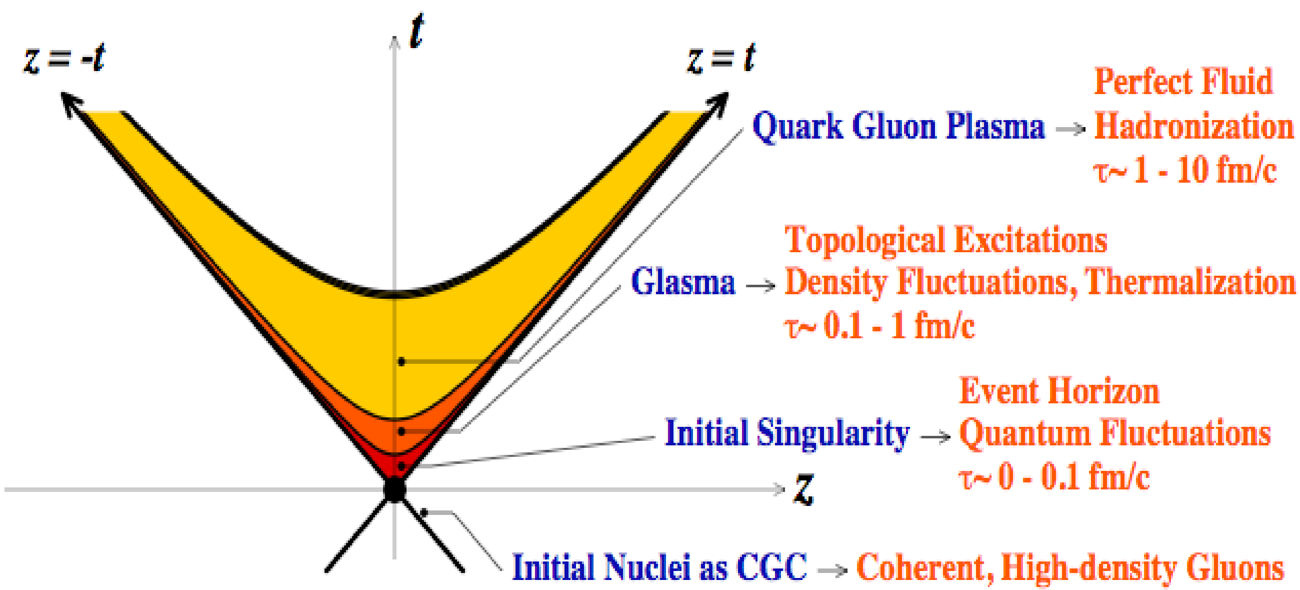
- Au ; up to $\sqrt{s}$ = 200 GeV /nucl pair

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

The Space-Time Evolution of a Relativistic Nuclear Collision at LHC Energy



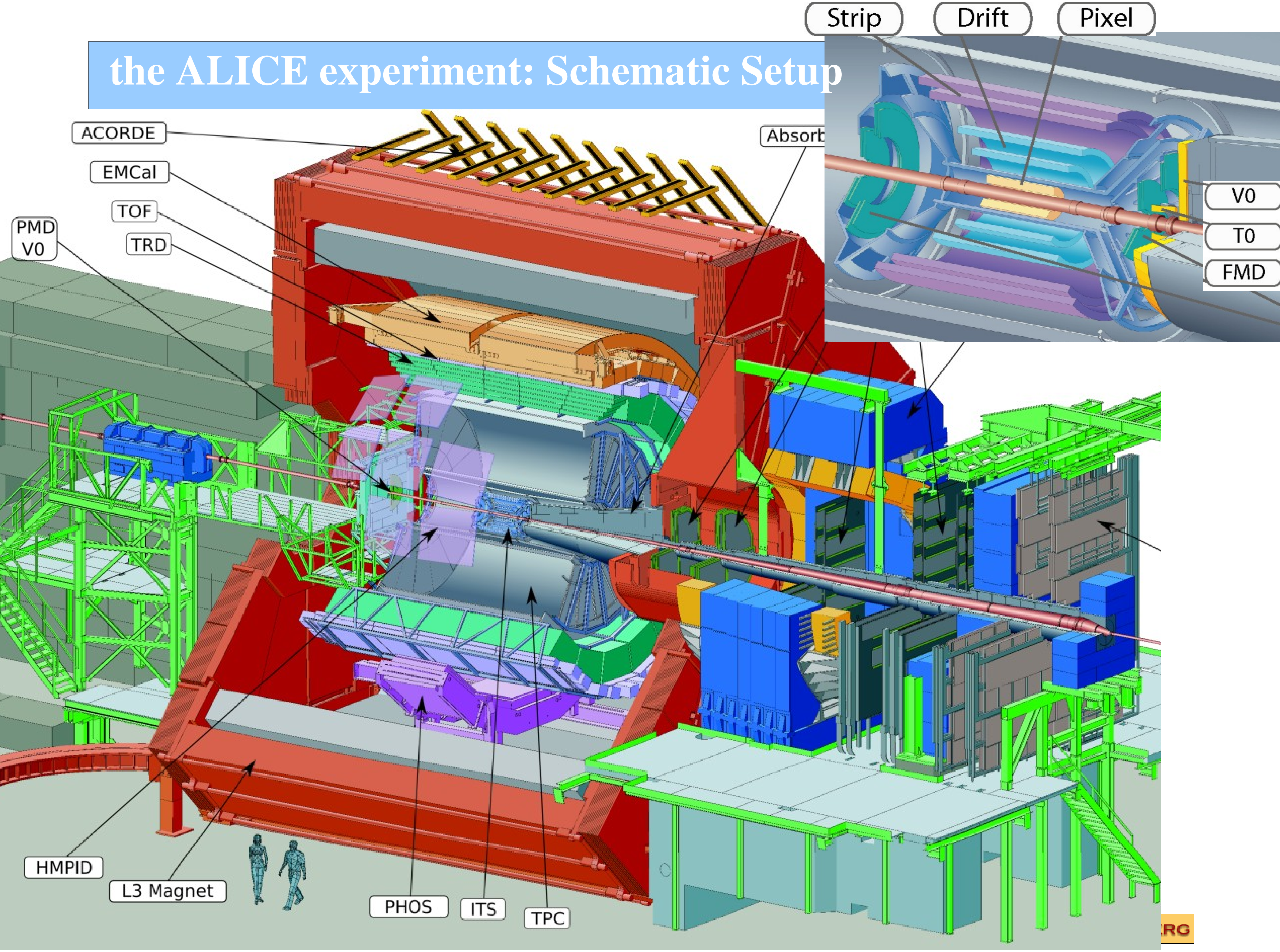
CGC | Initial Singularity | Glasma | sQGP | Hadron Gas



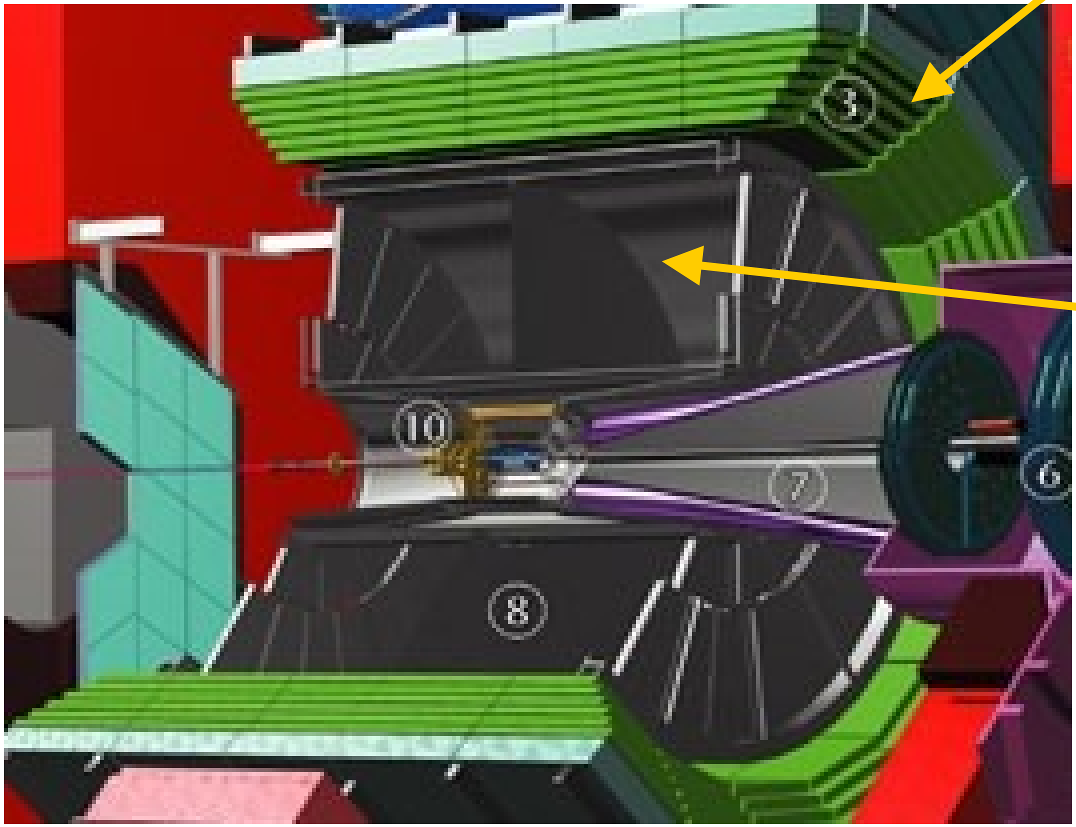
similar to early universe, fluctuations observed in the much later phase may allow to deduce early singularities

one possible view (courtesy L. McLerran)

the ALICE experiment: Schematic Setup



German Contributions to ALICE
GSI and universities of Frankfurt, Heidelberg, Münster



TRD
large area Transition Radiation Detector for electron identification

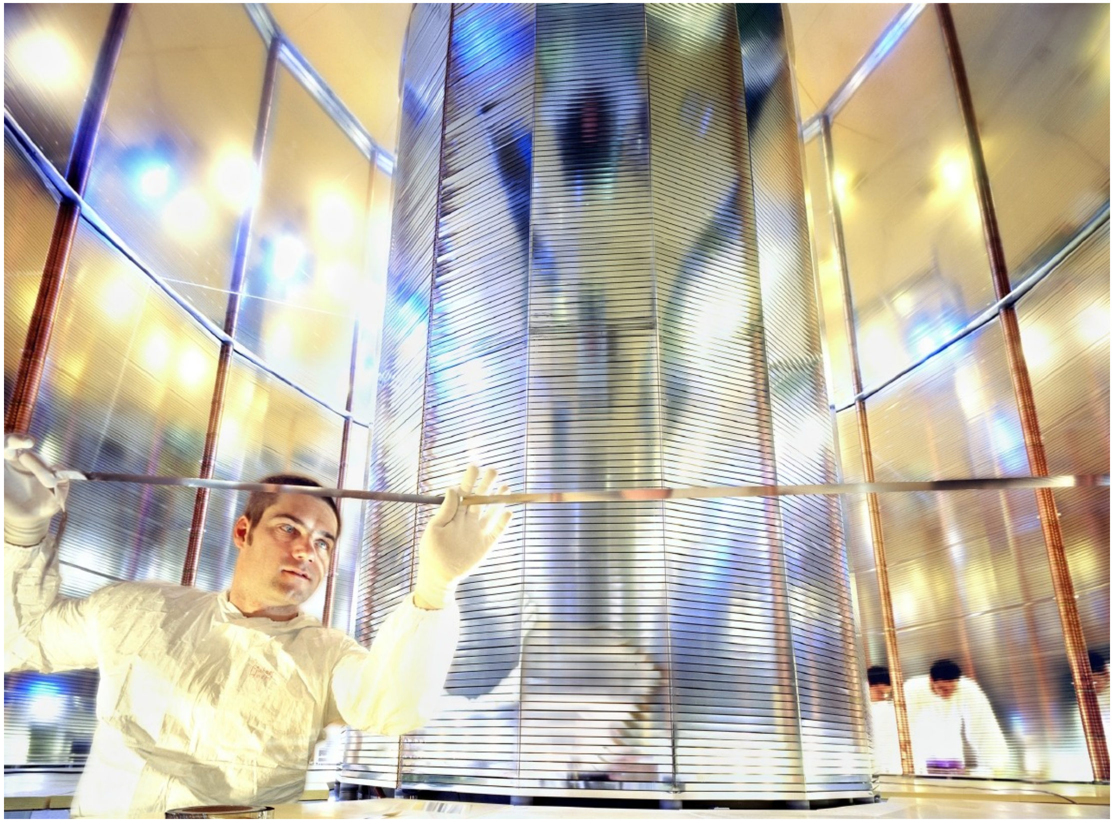
TPC
Time Projection Chamber
large volume, high resolution and high rate tracking device

HLT
Processor farm for rapid online data reconstruction and compression

intense R&D followed by construction - since 1996
about 500 person years - 1/5 of ALICE

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.

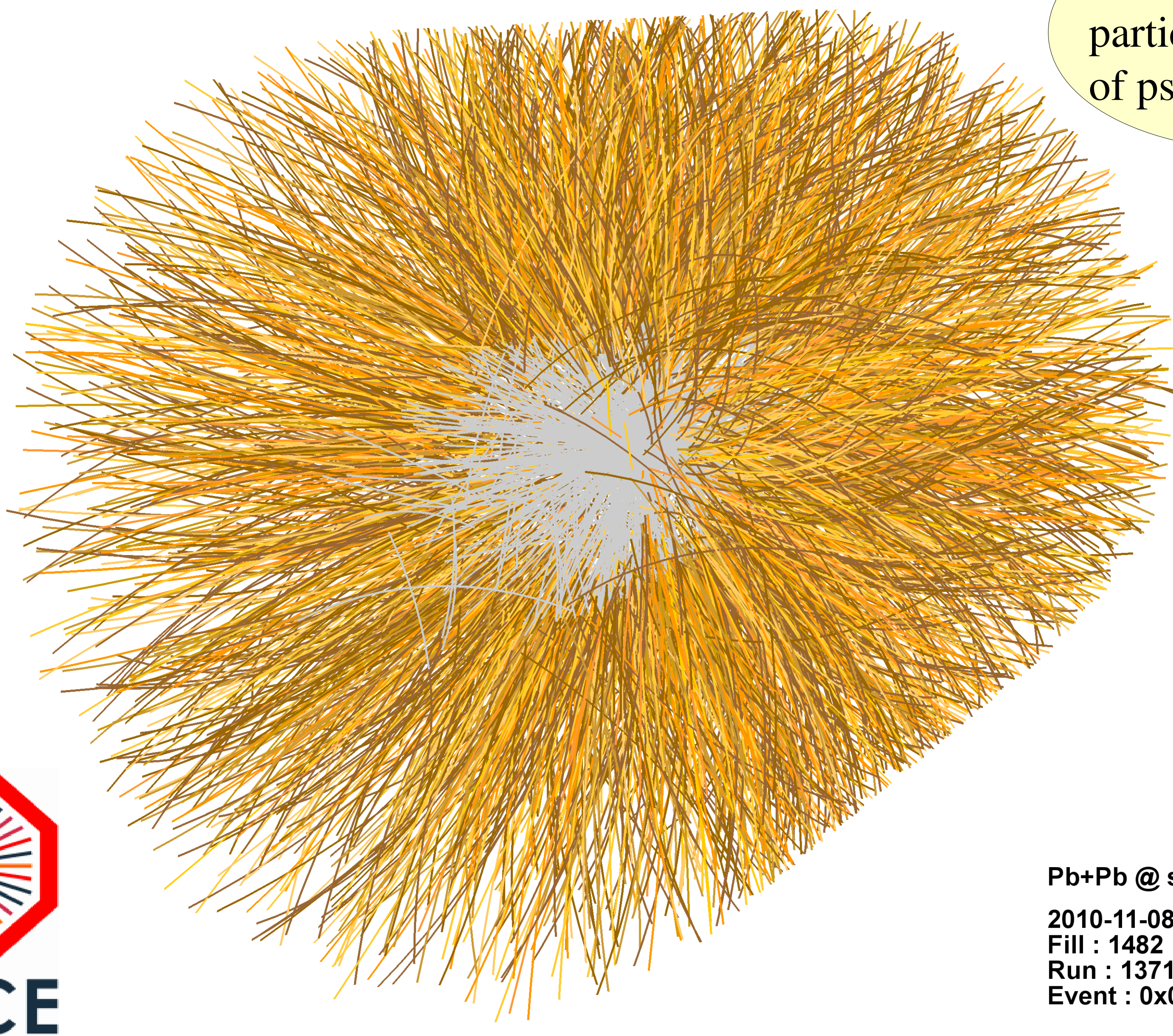
180 space and charge points per track


a look into the interior of the TPC

first PbPb collisions at LHC at $\sqrt{s}$ = 2.76 A TeV

first collisions with stable beams:
Nov 8 - Dec 6, 2010

about 3000 charged particles in 1.8 units of pseudorapidity



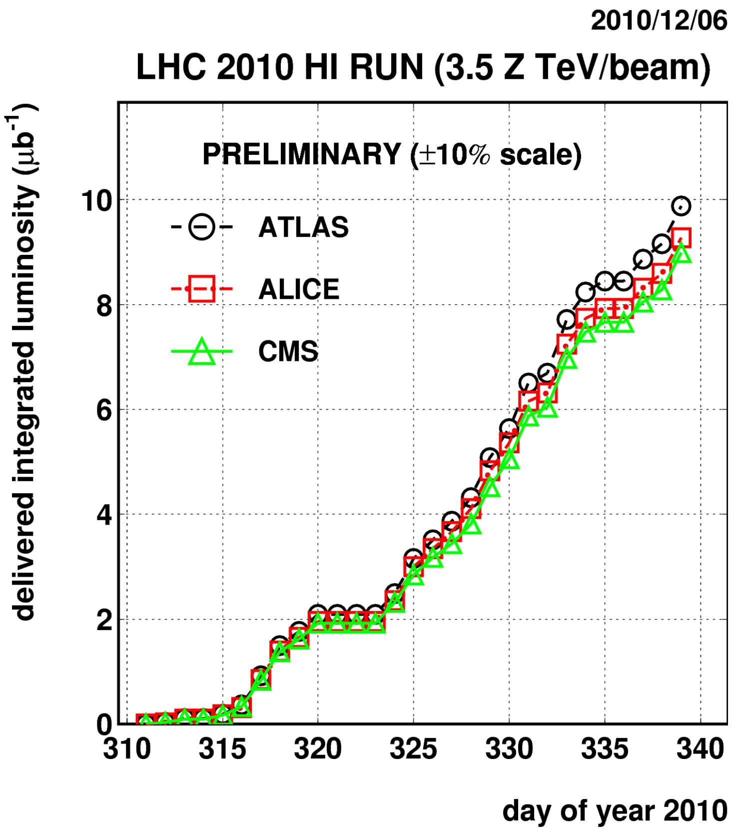
Pb+Pb @ sqrt(s) = 2.76 ATeV

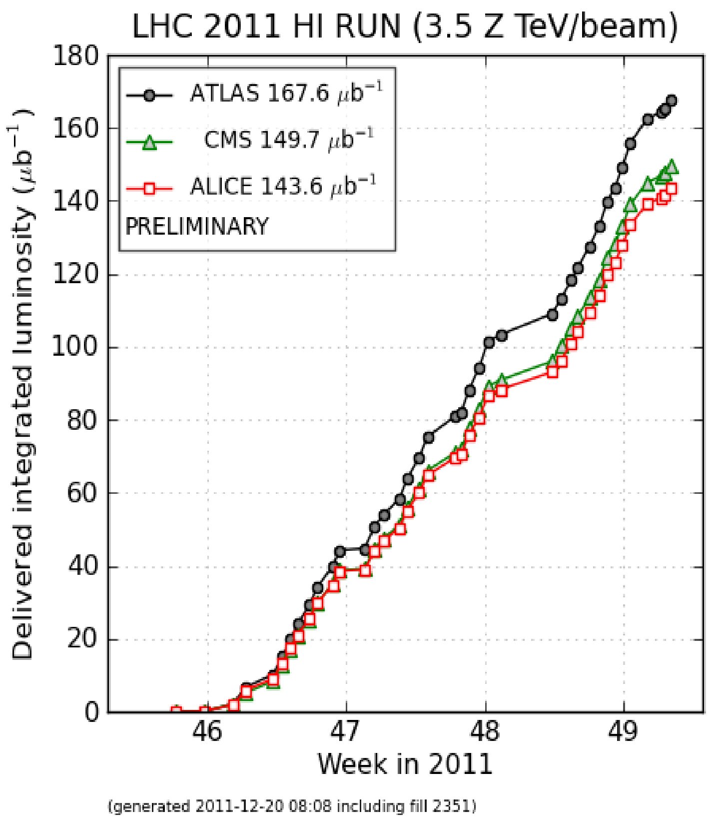
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

ALICE

Heavy Ion Running at the LHC

2 good Pb+Pb runs in 2010 and 2011,
2011 already exceeding design luminosity for 3 experiments and this beam energy





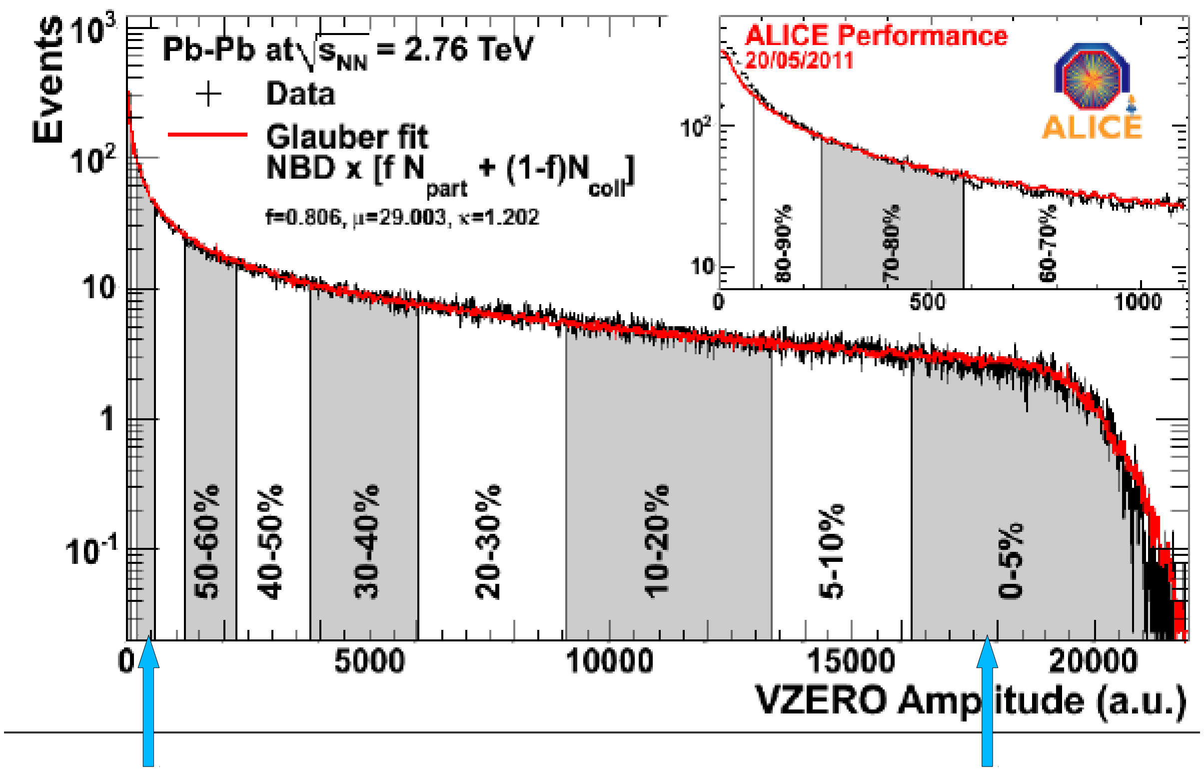
$$N = L \cdot \sigma$$

$$7\mathrm{b} \cdot 140\mu\mathrm{b}^{-1} \approx 10^9$$

Jan/Feb 2013: p + Pb run - about 30 nb^{-1} or $5{\cdot}10^{10}$ coll. were sampled

Determining the Collision Geometry

beams can be steered with micrometer precision, but lead nuclei have diameters of 15 femtometers



several observables scale with the impact parameter of the collision and thereby the number of nucleons participating in the collision
e.g. central collisions produce more particles

grazing collisions

central collisions:
384 nucleon participants

Charged Particle Multiplicity

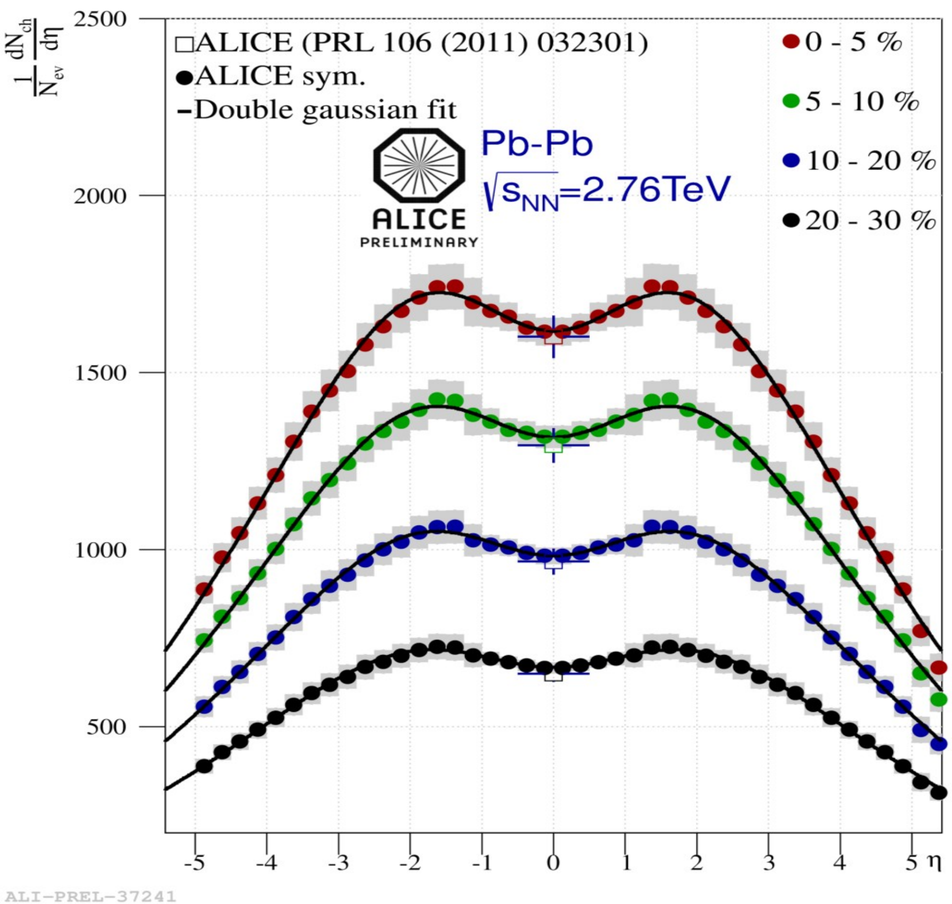
probes density of gluons initially liberated from the colliding nucleons

expect order of 10 000 (question of shadowing and of gluon saturation)

in a statistical ensemble measure of initial entropy density

each gluon (boson) contributes 3.6 units to the entropy

preserved for isentropic expansion



central PbPb at 2.76 TeV

$dN_{ch}/d\eta = 1600$

using arguments by Bjorken

initial energy density

$\varepsilon_0 = 146$ GeV/fm^3

$T \approx 0.68$ GeV $\approx 4\ T_c \approx 10^{13}$ K

pressure P ≈ 49 GeV/fm^3 = 7.9 10^{36} Pa

entropy density ≈ 290/fm^3

total entropy of fireball: 36 000

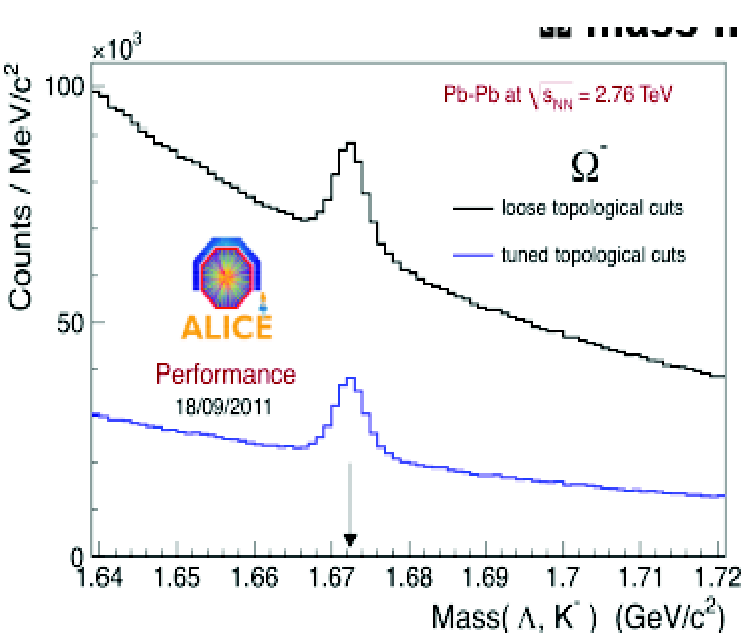
the Hadro-Chemical Composition of the Fireball

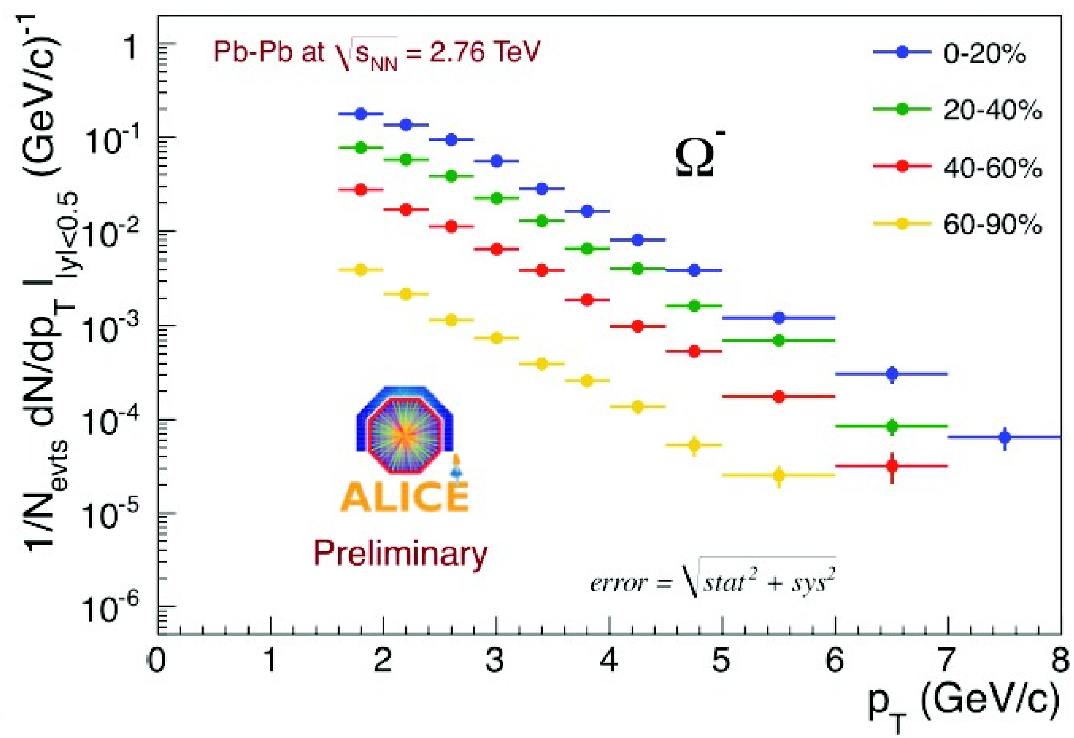
what are the 20 000 hadrons observed in final state at LHC?

Production of Different Hadron Species

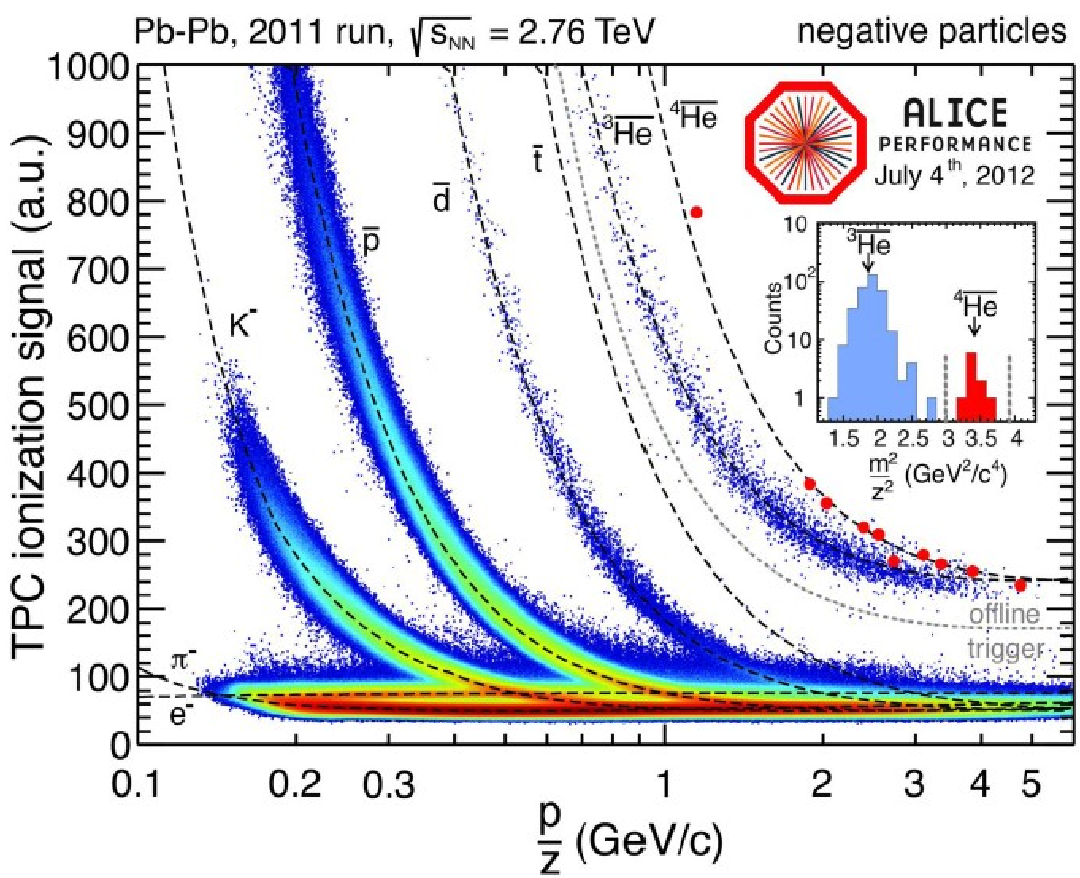
measure and integrate spectra of identified hadrons

- specific energy loss and time-of-flight
- hadrons reconstructed from weak decay products (Λ, Ξ, Ω)

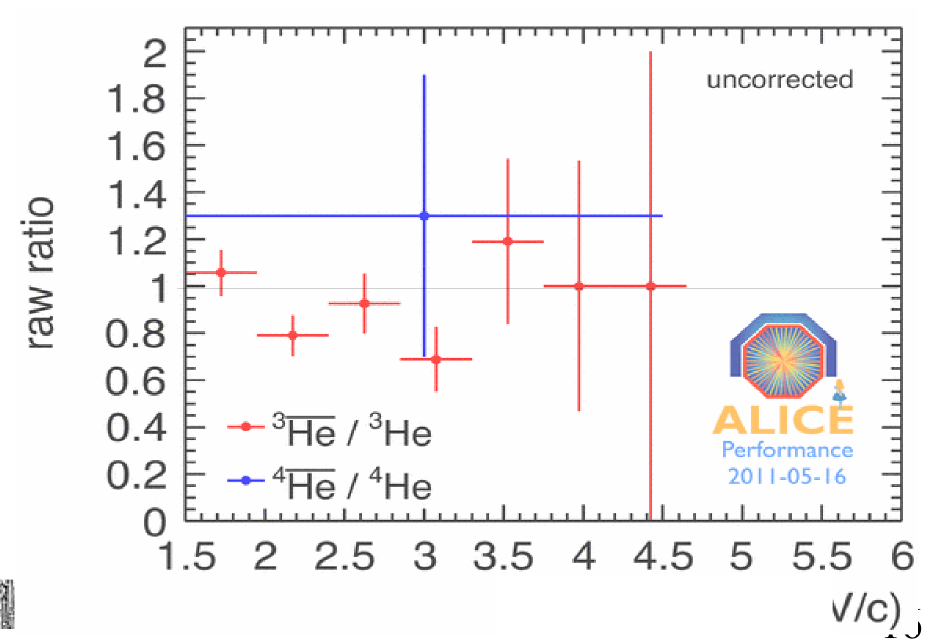




Particle Identification via dE/dx in the TPC and Observation of anti-4He Production



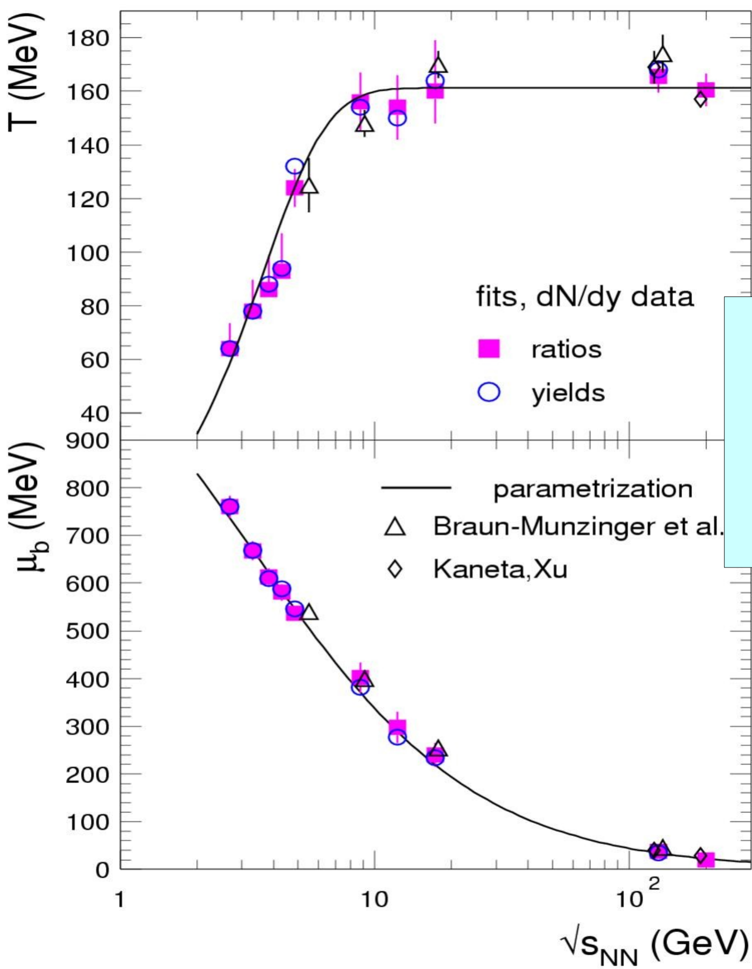
- all particles from electrons to ^{4}He can be identified with the TPC – resolution 5%
- full statistics of 2011 run 2.3 10^7 events – 10 anti-^{4}He
- anti-matter and matter produced in equal proportions
- consistent with baryon-free central region at LHC (μ_b = 1 MeV)



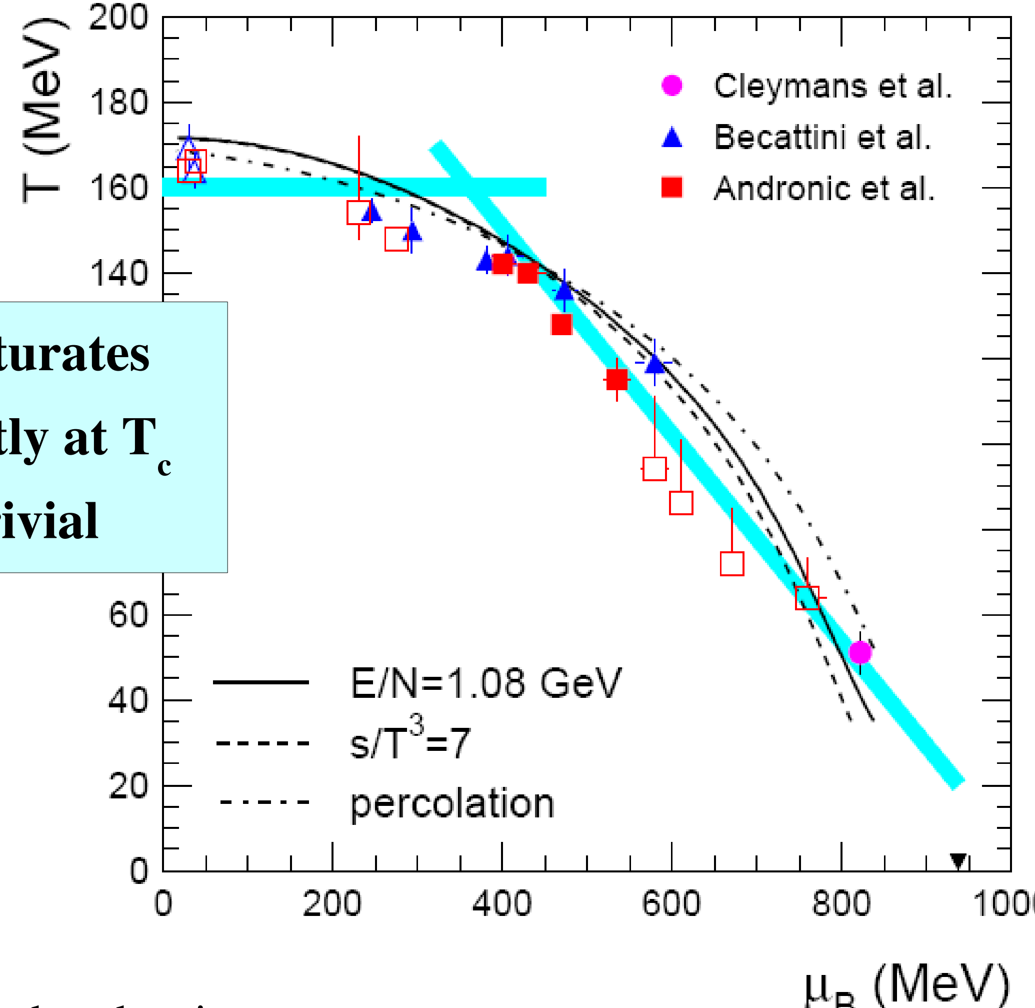
Experimental Knowledge of the QCD Phase Diagram

- agreement between groups doing finite temperature lattice gauge theory: $T_c(\mu=0) = 160\pm10$ MeV

Bazavov & Petreczky, arXiv:1005.1131 [hep-lat]   S. Borsanyi et al., arXiv:1005.3508 [hep-lat]



T_{chem} saturates apparently at T_c not trivial



- data points 'chemical' freeze-out of hadrons from abundancies

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

Starting Point: the 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:

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

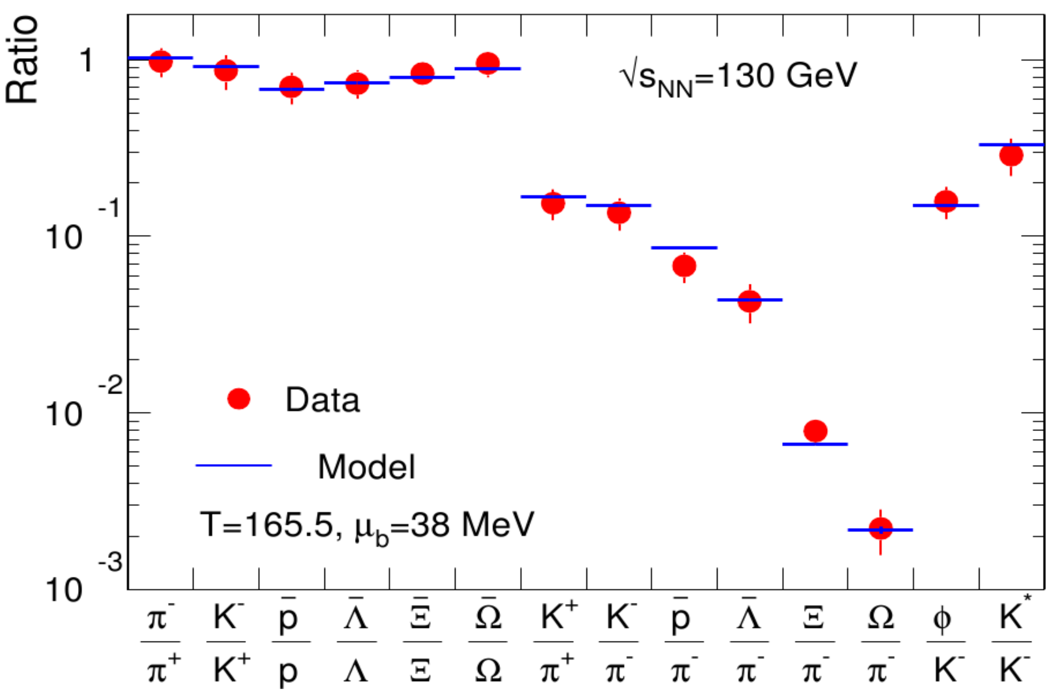
but can use conservation laws to constrain V, μ_S, μ_{I_3}

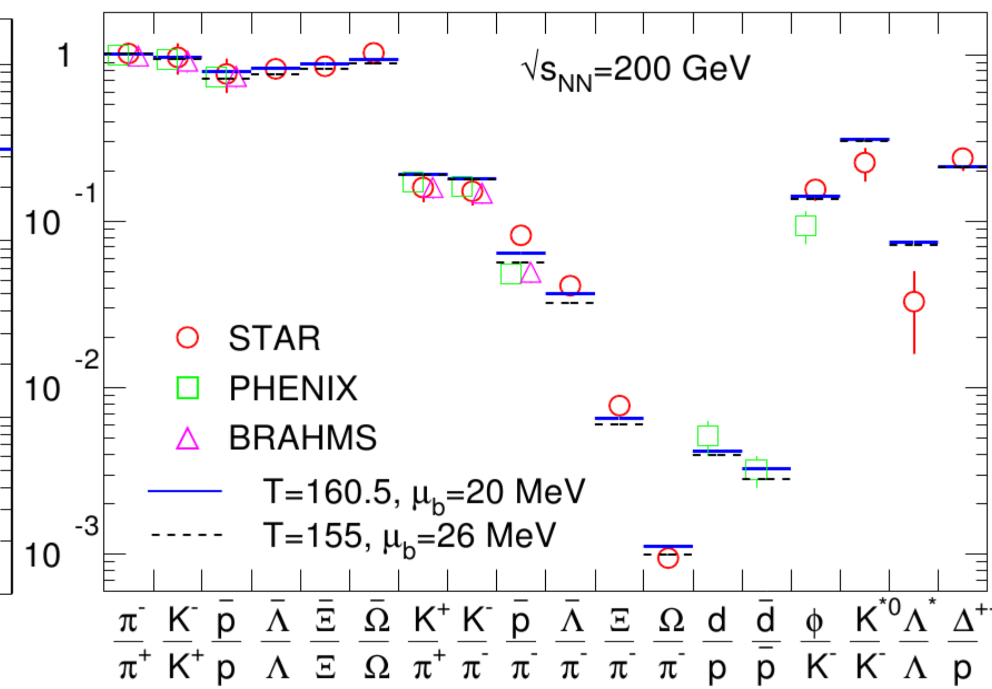
→ **Fit at each energy provides values for T and μ_b**

RHIC Hadron Yields reproduced really well 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
confirmed by Xu and Kaneta and by F. Becattini

Top AGS Energy Data

GC statistical model applied first time successfully to 10.7 A GeV/c Au + Au collisions P. Braun-Munzinger, J.S., J.P. Wessels, N.Xu, Phys. Lett. B344 (1995) 43

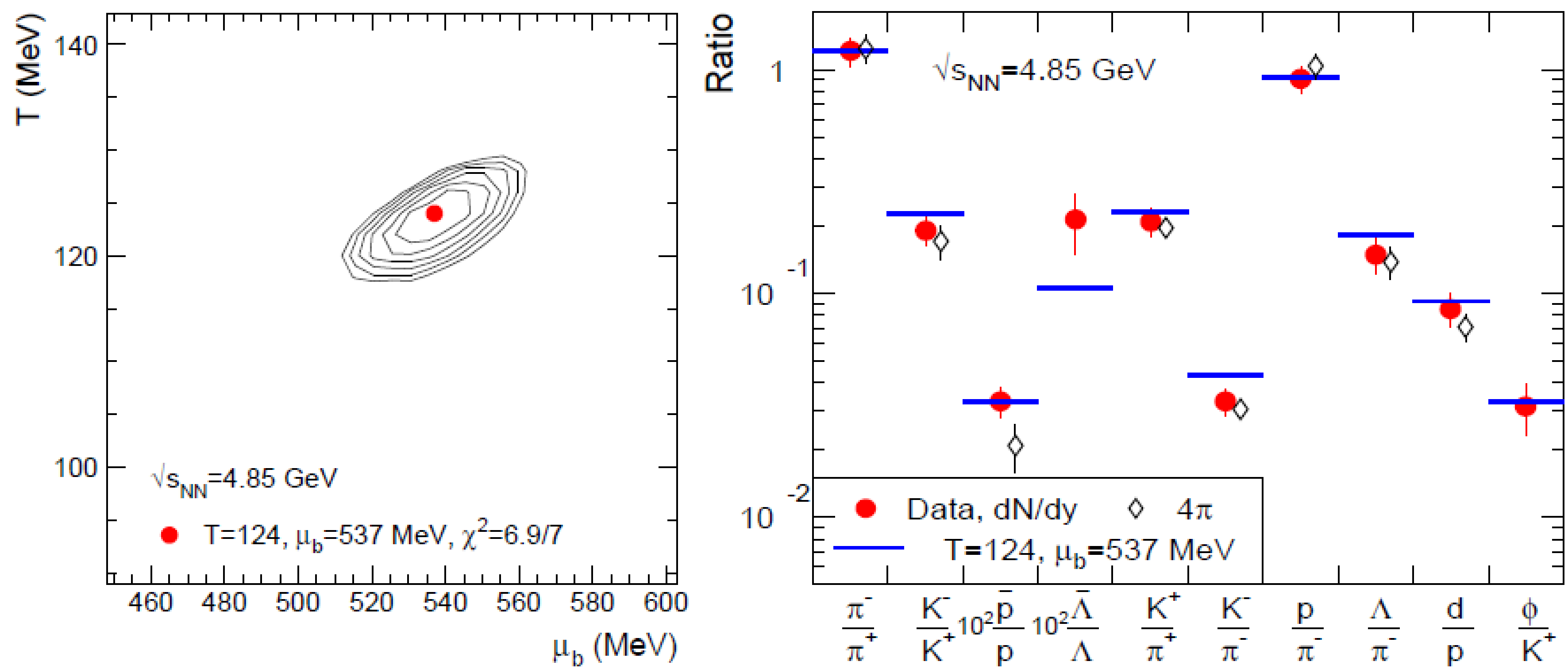
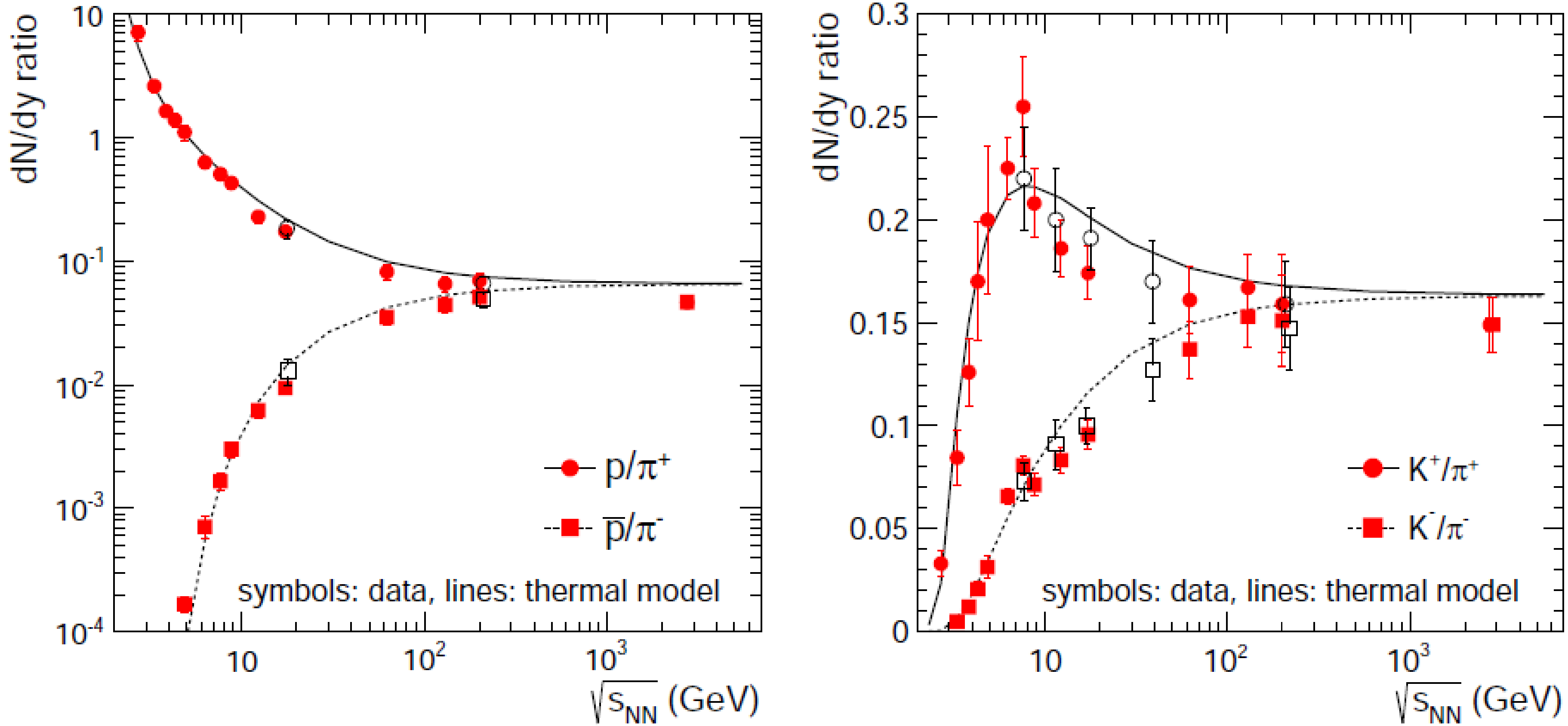


Figure from A. Andronic, P. Braun-Munzinger, J.S. Nucl. Phys. A772 (2006) 167

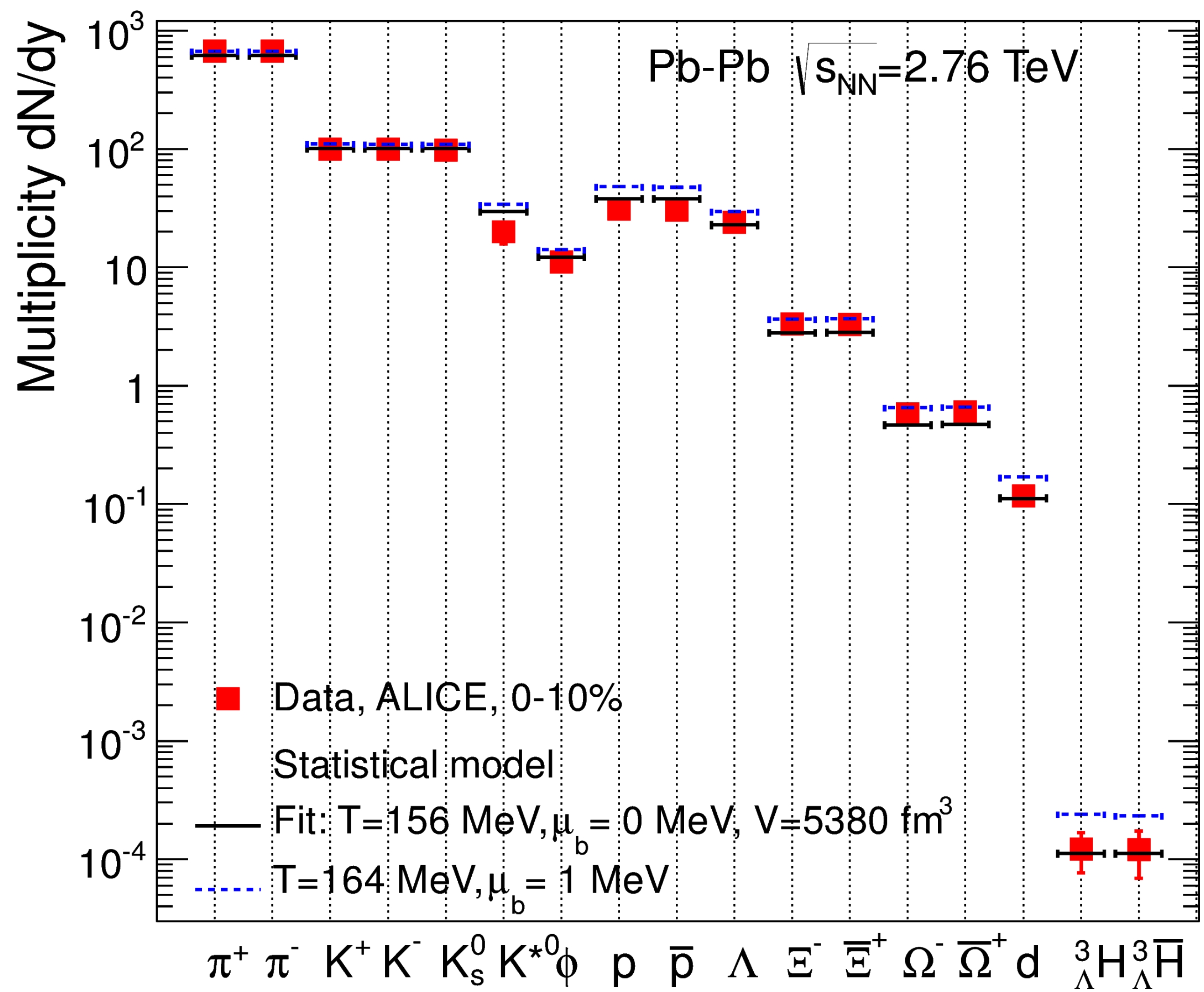
Beam energy dependence of hadron yields from AGS to LHC

following the above T and μ_b evolution, features of proton/pion and kaon/pion ratios reproduced in detail



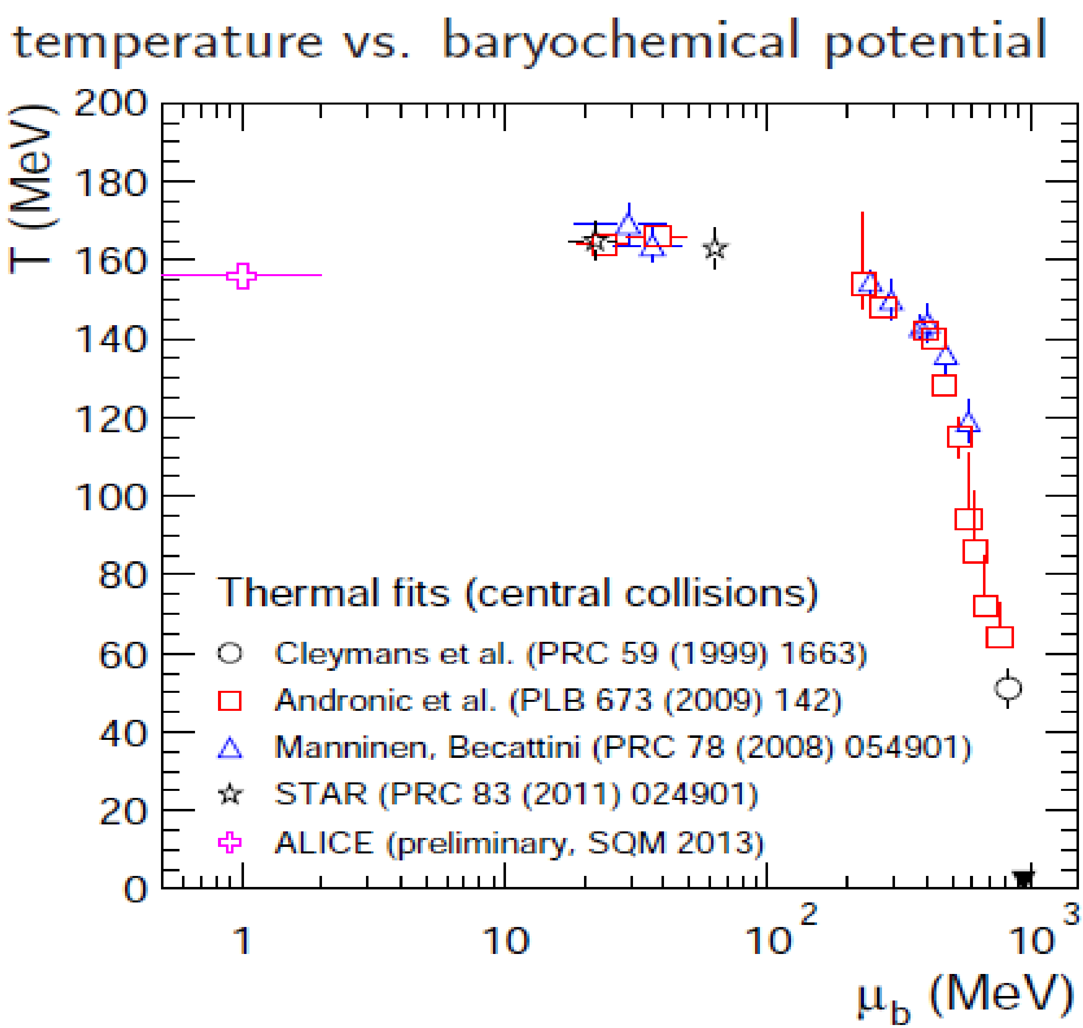
Hadrochemistry at the LHC

J.S., A. Andronic, P. Braun-Munzinger, K. Redlich, arXiv: 1311.4662



good fit over nearly 7 oom
with grand canonical
statistical ensemble
T = 156 MeV
protons somewhat low

The newest T-mu plot



hadron yields for Pb-Pb central collisions from LHC run1 are well described by assuming equilibrated matter at

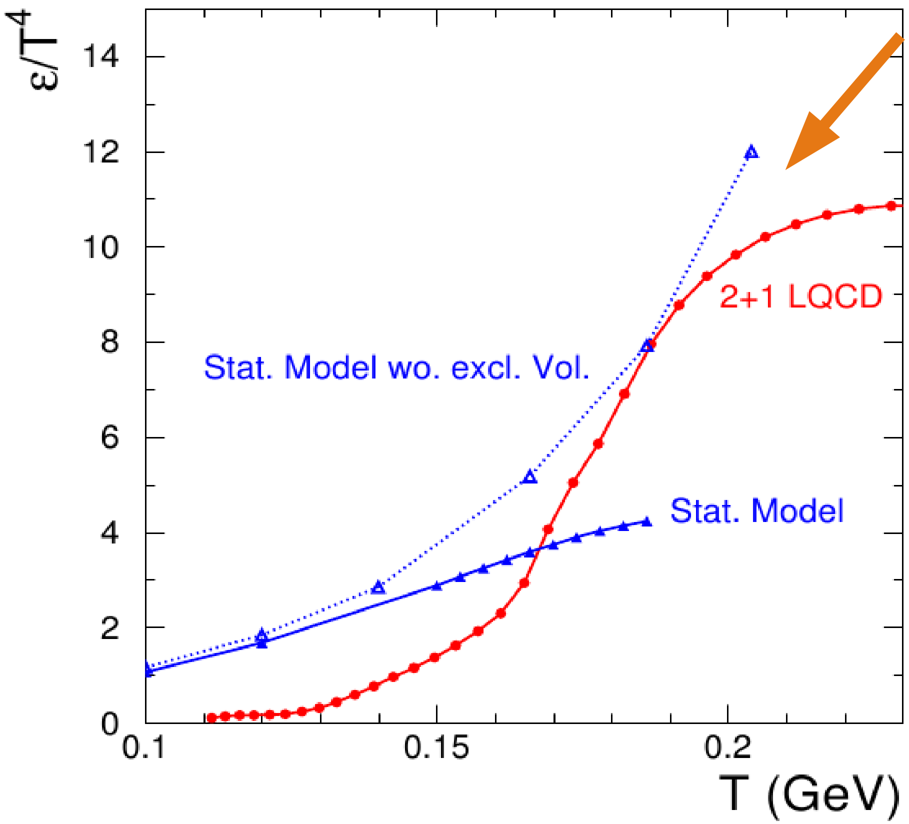
$T = 156$ MeV and $\mu_b < 1$ MeV,

very close to predictions from lattice QCD for T_c

Equilibration Driven by High Densities near T_c

rapid equilibration within a narrow temperature interval around T_c by multi-particle collisions due to steep temperature dependence of densities

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

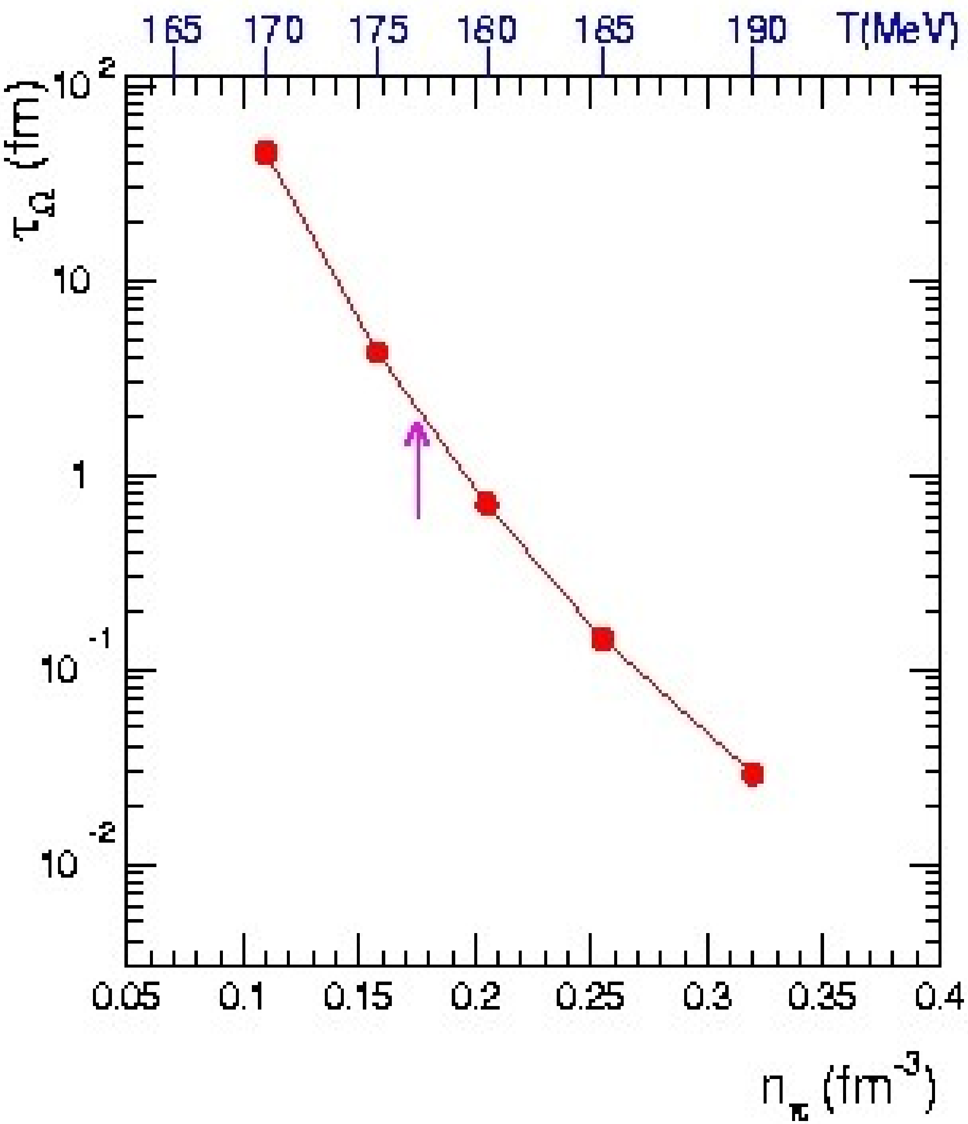


for T_{ch} 20-30 MeV below T_c very hard to maintain scenario of simultaneous freeze-out of all hadron species

estimate upper limit of $T_c - T_{ch} = 5$ MeV

→ requires T_c = 160 - 170 MeV experimental determination!

Density Dependence of Characteristic Time for Strange Baryon Production



- near phase transition particle density varies rapidly with T (see previous slide)
- for SPS energies and above reaction such as 2π+KKK→ Ω Nbar bring multi-strange baryons close to equilibrium rapidly
- in region around T_c equilibration time $\tau_\Omega \propto T^{-60}$!
- increase n_π by 1/3: τ = 0.2 fm/c (corresponds to increase in T by 8 MeV) decrease n_π by 1/3: τ = 27 fm/c

→ all particles freeze out within a very narrow temperature window due to the extreme temperature sensitivity of multi-particle reactions

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

Charmonia as a probe of Deconfinement

Charmonia: bound states of charm and anticharm quarks, e.g. →

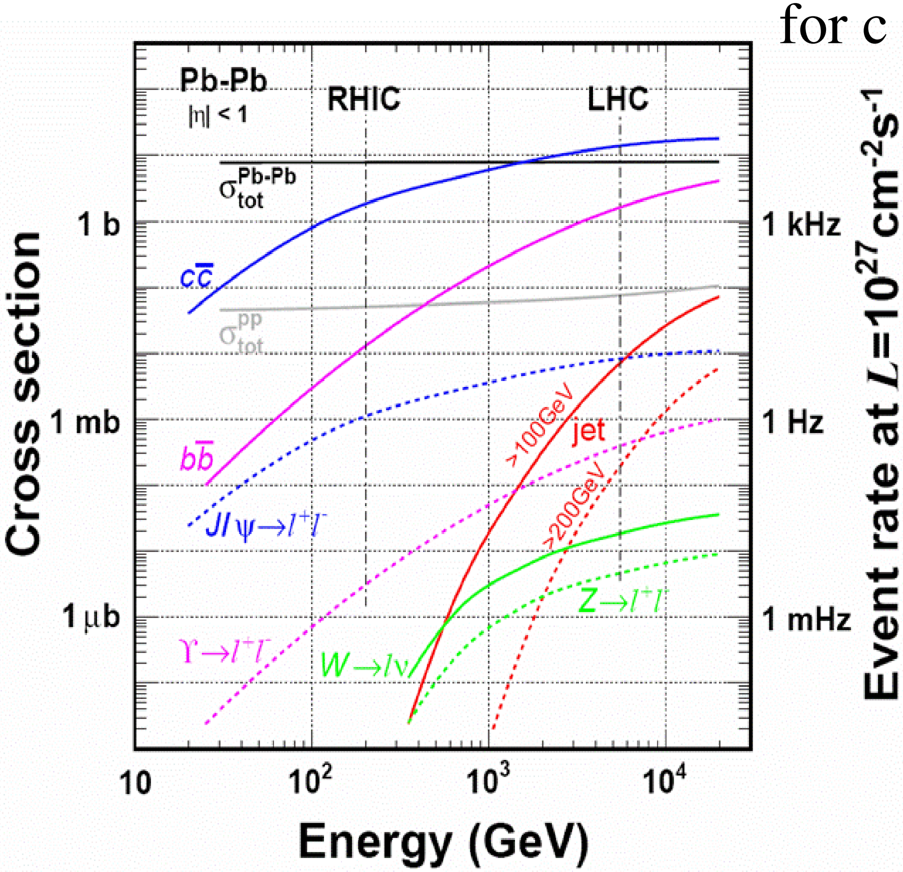
J/ψ 1s state of ccbar
mass 3.1 GeV
radius 0.45 fm

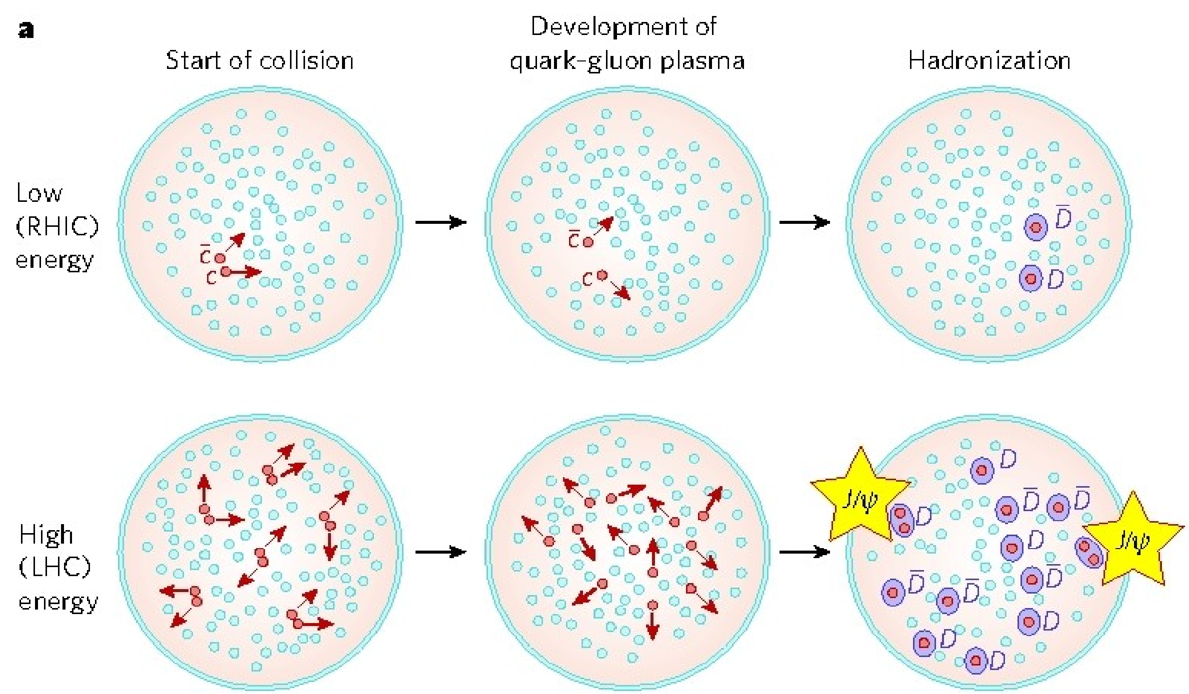
the original idea (Matsui and Satz 1986): implant charmonia into the QGP and observe their modification (Debye screening of QCD), in terms of suppressed production in nucleus-nucleus collisions with or without plasma formation – sequential melting

new insight (Braun-Munzinger, J.S. 2000): QGP screens all charmonia, but charmonium production takes place at the phase boundary, enhanced production at colliders – signal for deconfinement

what happens to deconfined charm quarks at higher beam energy?

as more and more charm quarks produced, probability for c and cbar to hadronize into J/psi grows quadraticaly





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

high energy: many " " → **enhancement** "

unambiguous signature for QGP!

extension of statistical model to include charmed hadrons

- 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

number of charm quarks fixed by a charm-balance equation containing fugacity g_c

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

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 same for all other charmed hadrons

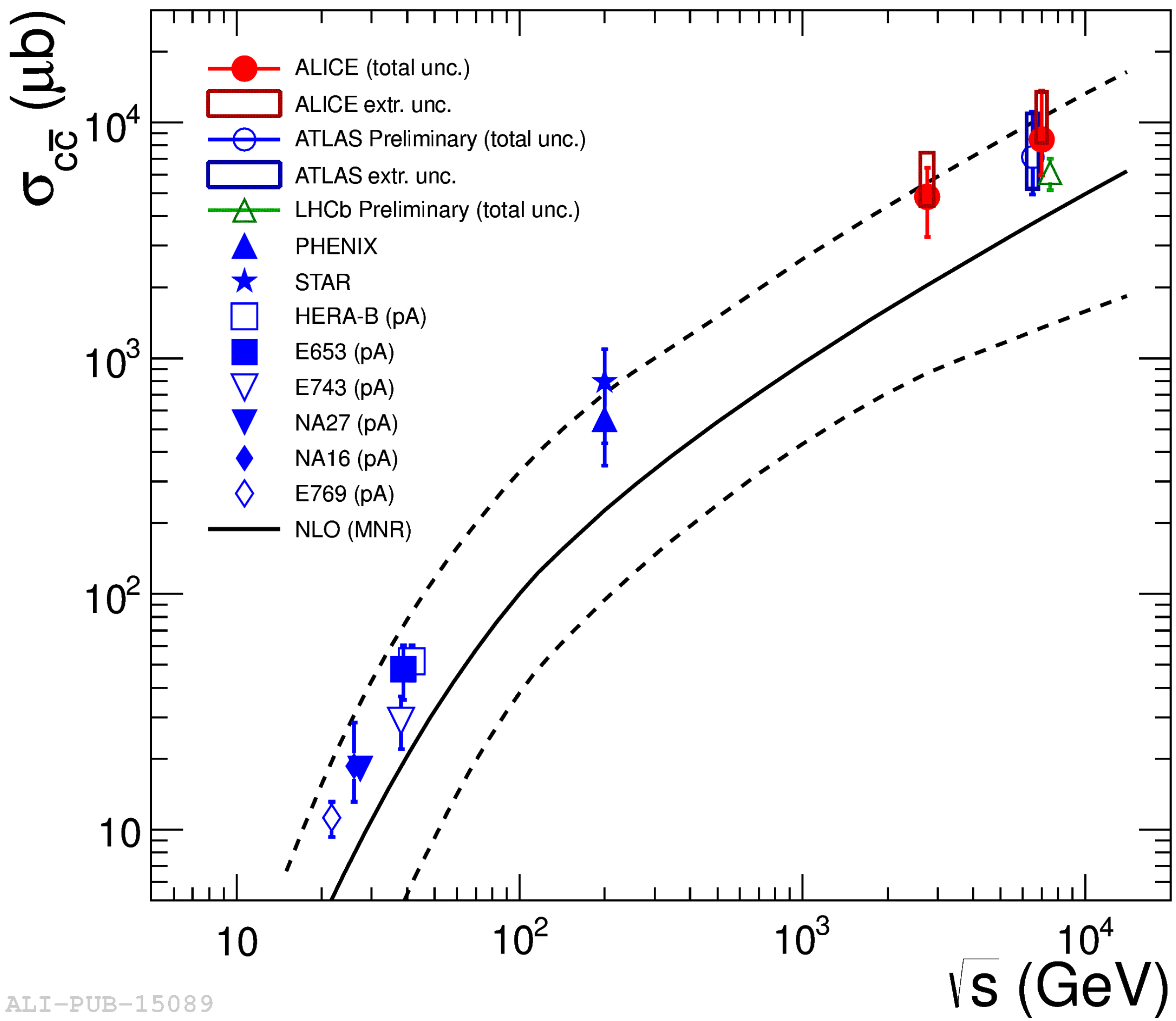
additional input parameters: V, $N_{c\bar{c}}^{direct}$

Volume fixed by $dN_{ch}/d\eta$

$N_{c\bar{c}}^{direct}$ from pQCD as long as precision data are lacking

a first try at the total ccbar cross section in pp at LHC

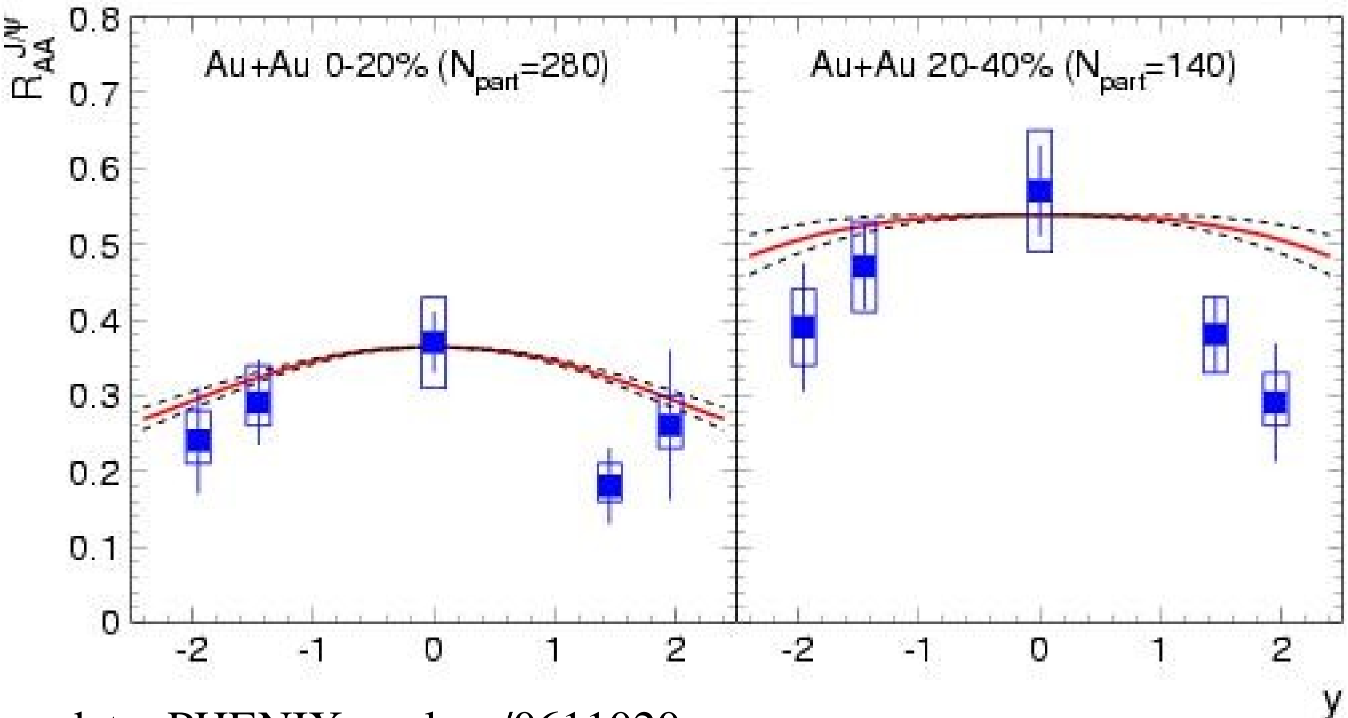
JHEP 1207 (2012) 191



- good agreement between ALICE, ATLAS and LHCb
- large syst. error due to extrapolation to low pt, need to push measurements in that direction
- data factor 2 ± 0.5 above central value of FONLL but well within uncertainty
- beam energy dependence follows well FONLL
- soon more accurate 4pi extrapolation at 7 TeV

comparison of model predictions to RHIC data:

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



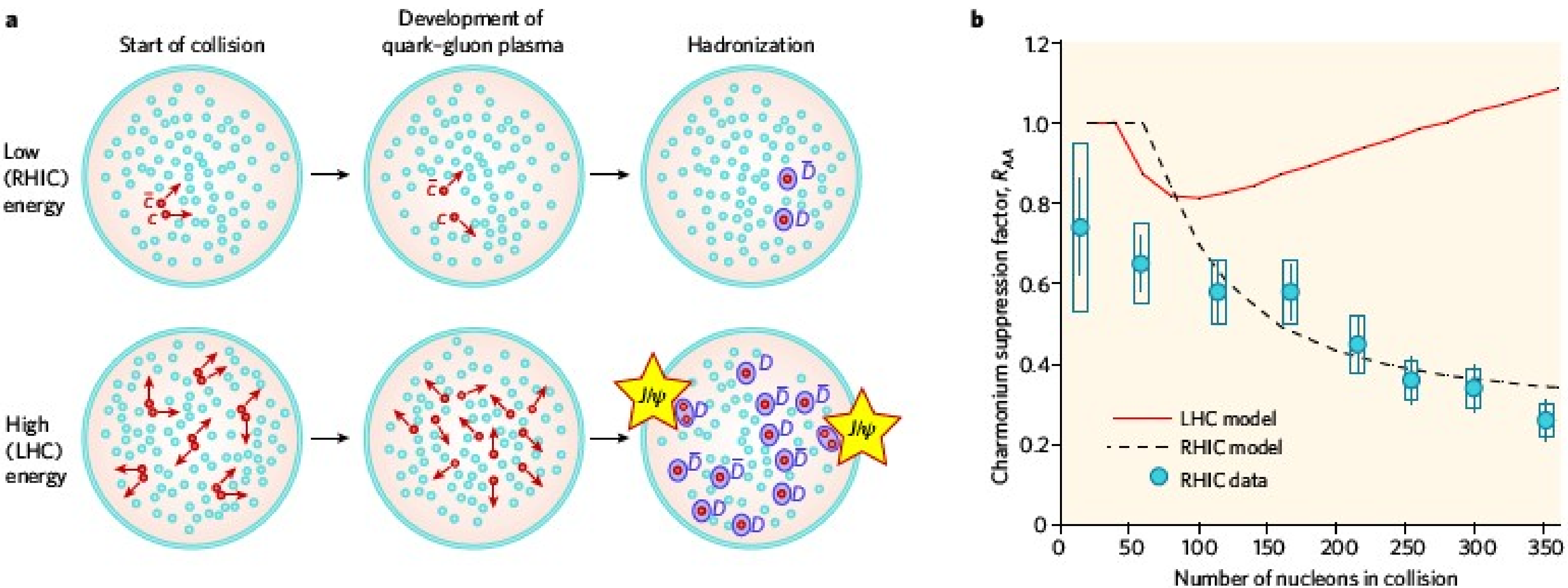
good agreement, no free parameters

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)

Quarkonium as a Probe for Deconfinement at the LHC the Statistical Hadronization Picture



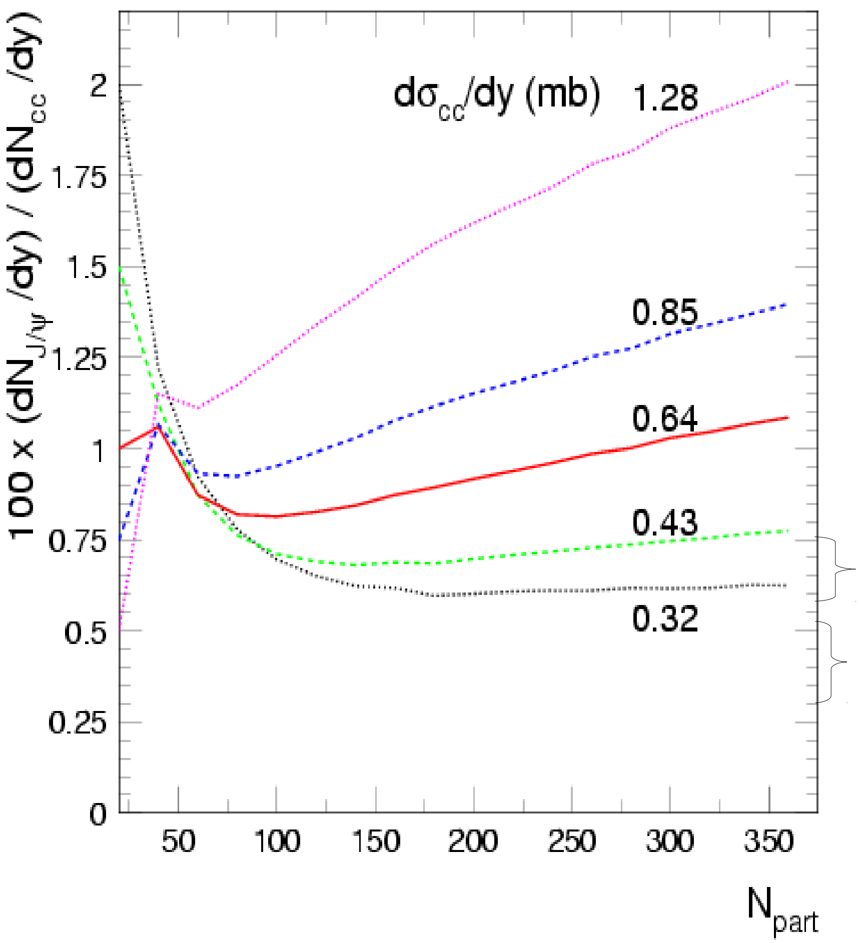
charmonium enhancement as fingerprint of deconfinement at LHC energy

only free parameter: open charm cross section in nuclear collision

Braun-Munzinger, J.S., Phys. Lett. B490 (2000) 196 and

Andronic, Braun-Munzinger, Redlich, J.S., Phys. Lett. B652 (2007) 659

Predictions for LHC energies



open charm is natural and essential normalization

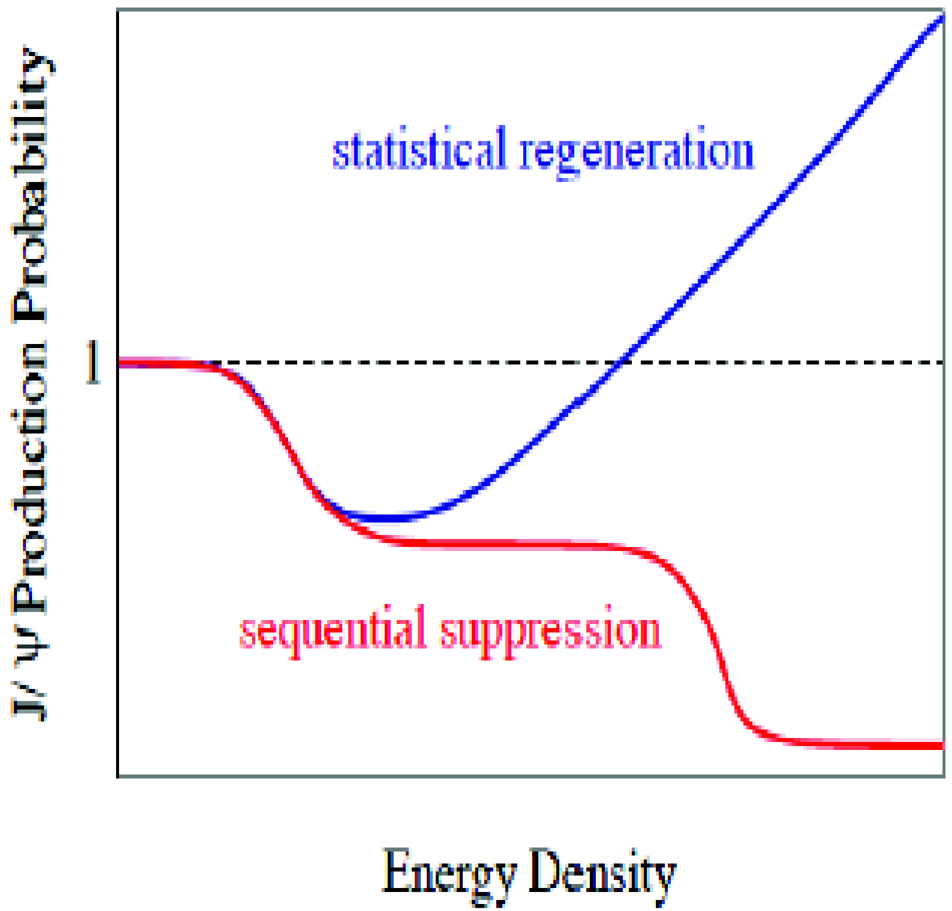
precision measurement needed

mid-y LHC 2.76 TeV including shadowing

forward-y LHC 2.76 TeV including shadowing

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

Decision on Regeneration vs. Sequential Suppression from LHC Data

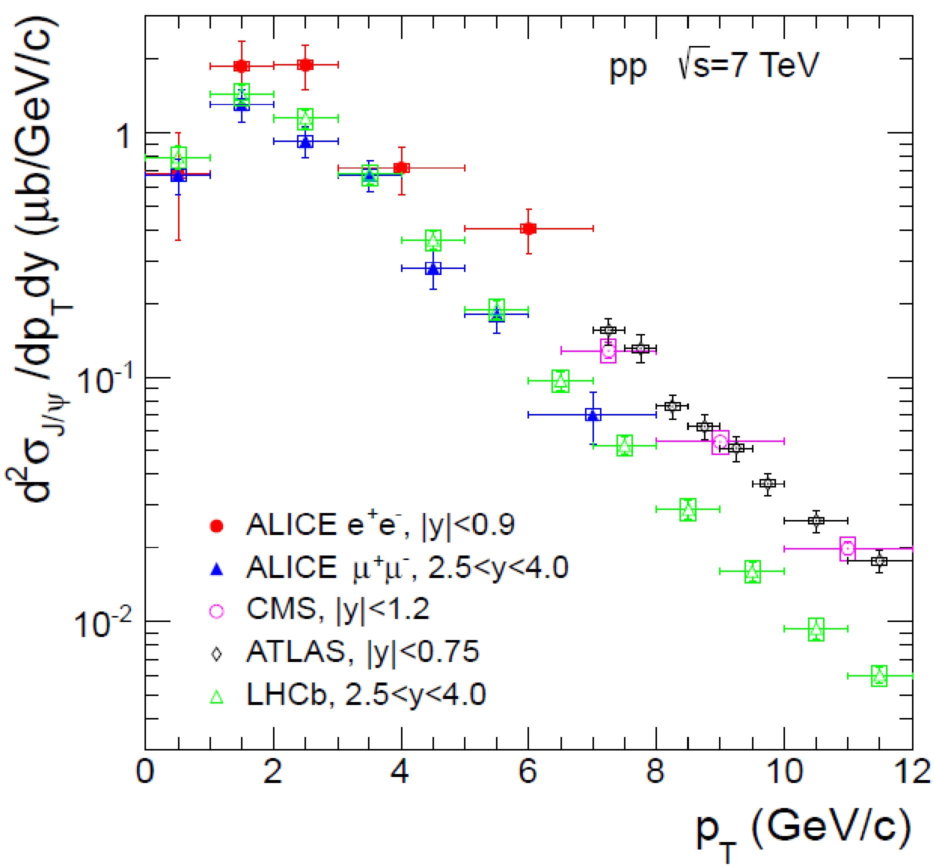


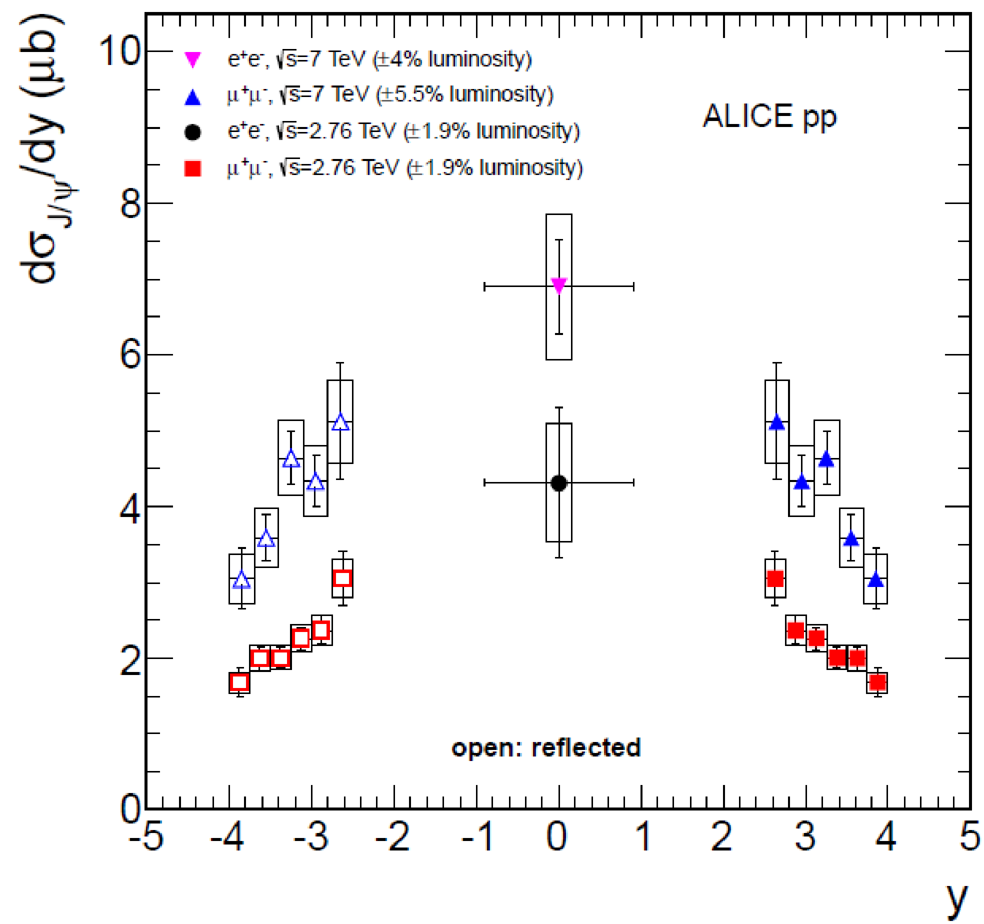
SPS RHIC LHC

Picture:
H. Satz 2009

J/psi spectrum and cross section in pp collisions

ALICE PLB704 (2011) 442 arXiv:1105.0380 and PLB718 (2012) 295





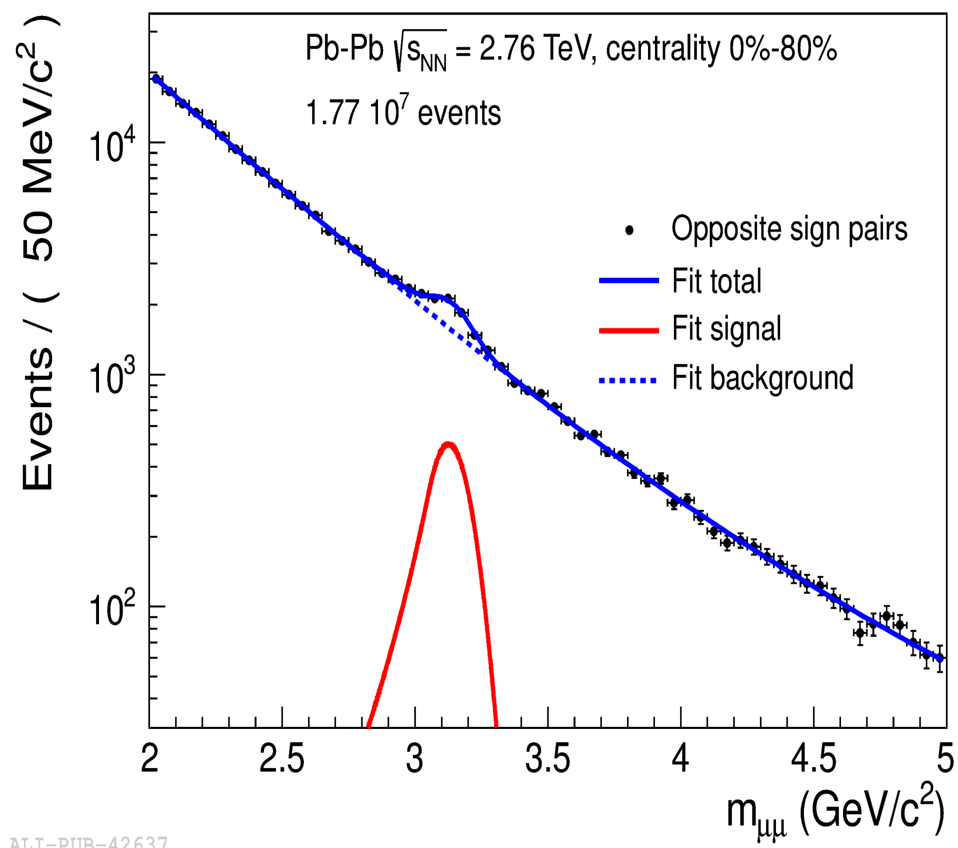
- good agreement between experiments
- complementary in acceptance: only ALICE has acceptance below 6 GeV at mid-rapidity

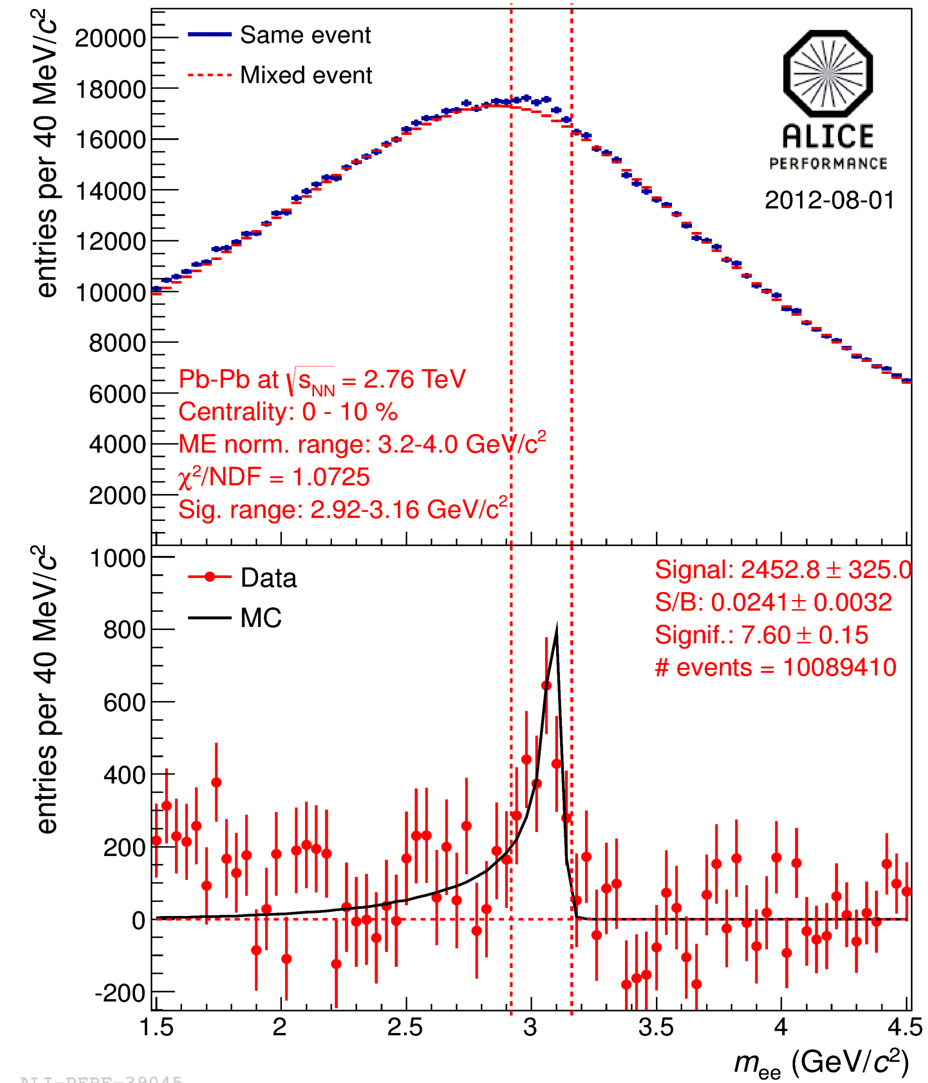
measured both at 7 and 2.76 TeV

<u>open issues:</u> statistics at mid-rapidity

polarization (biggest source of syst error)

Reconstruction of J/psi via mu+mu- and e+e- decay

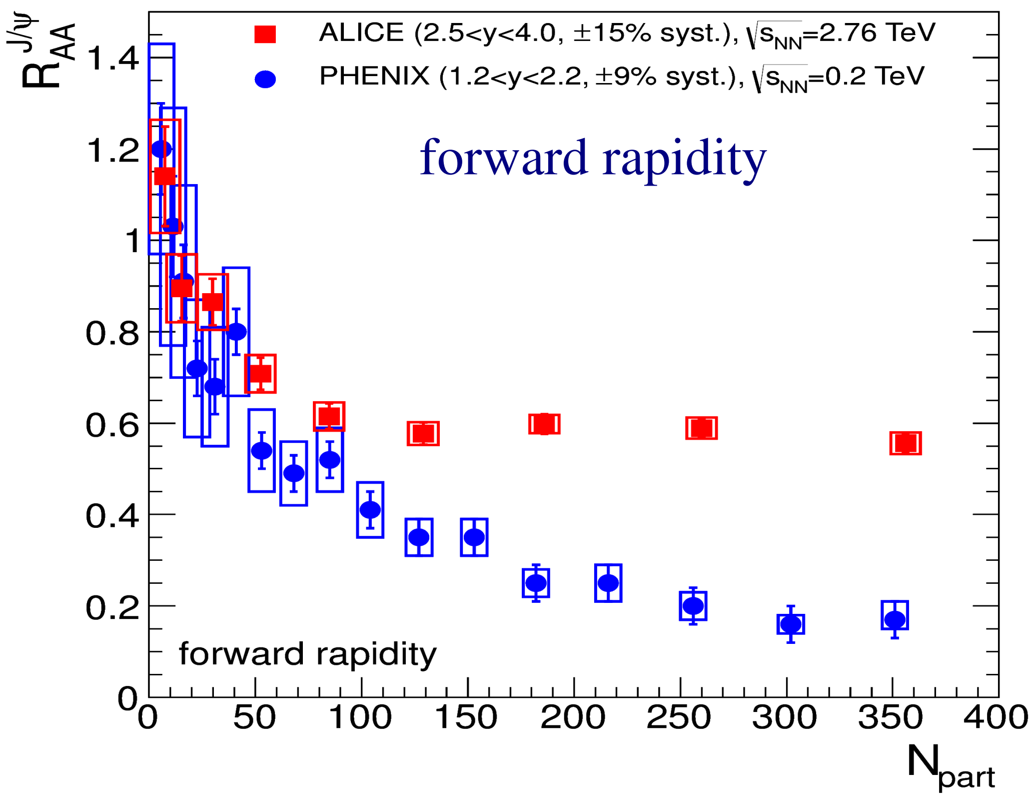


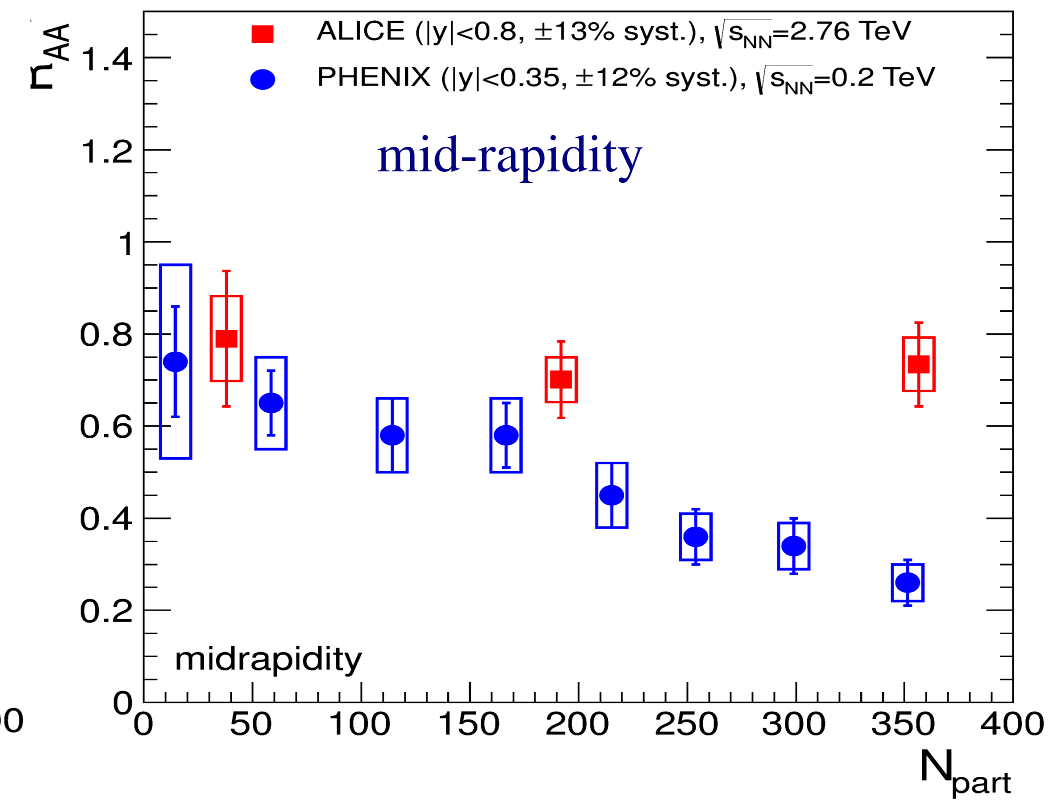


<u>most challenging:</u> PbPb collisions
in spite of significant combinatorial background
(true electrons, not from J/ψ decay but e.g. D- or B-mesons) resonance well visible

J/psi production in PbPb collisions: LHC relative to RHIC

$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta\, dp_T}{\langle N_{coll}\rangle\, (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta\, dp_T}$$



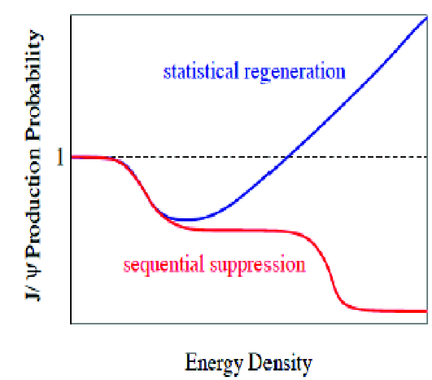


energy density -->

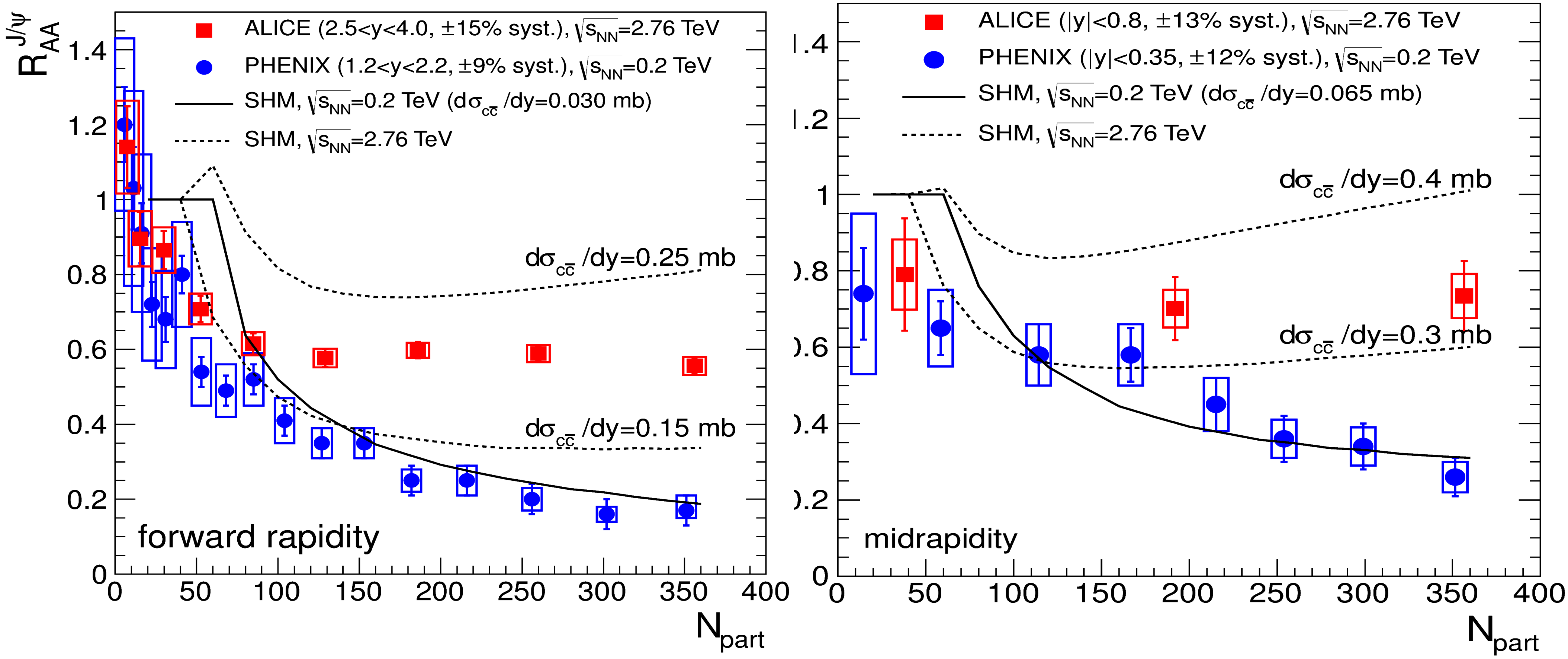
melting scenario not observed

rather: enhancement with increasing energy density!

(from RHIC to LHC and from forward to mid-rapidity)

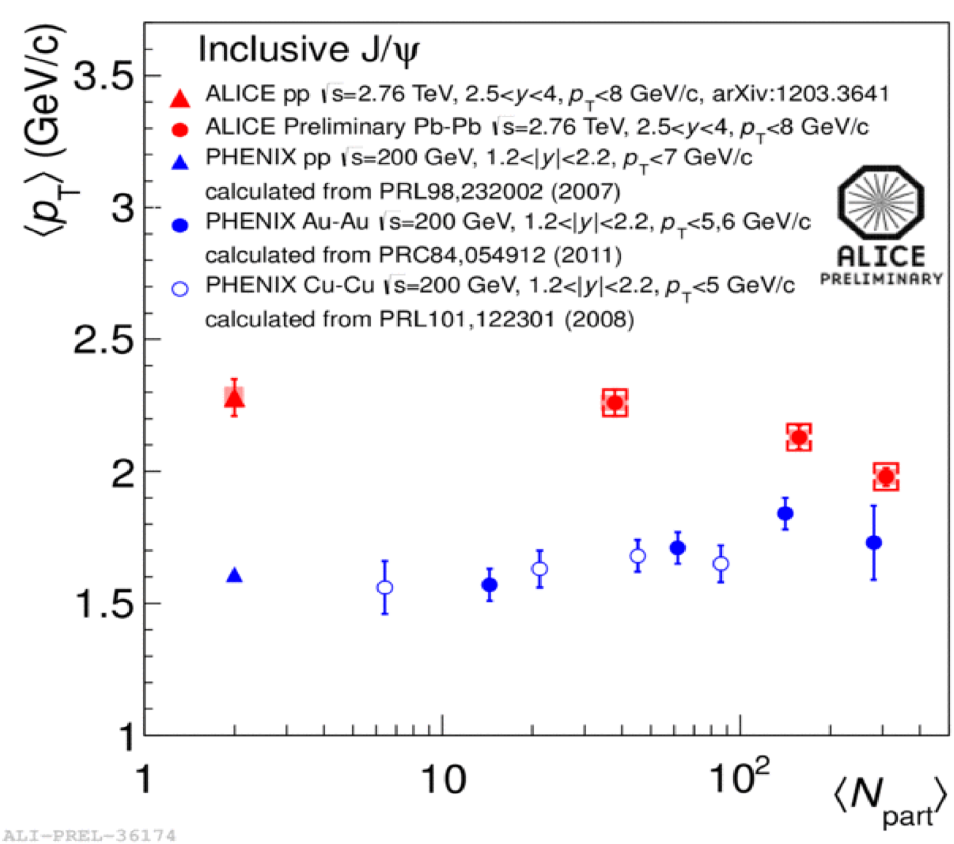


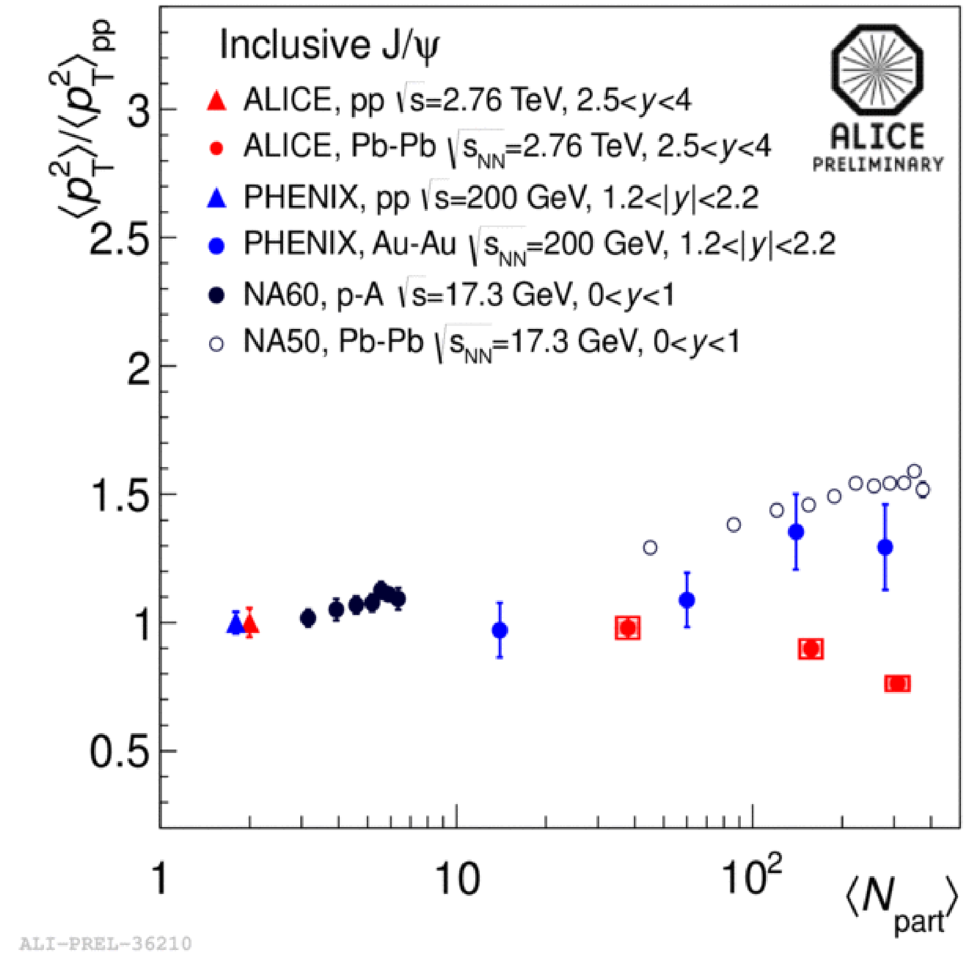
J/psi and Statistical Hadronization



- production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties
- main uncertainties for models: open charm cross section, shadowing in Pb
- shadowing from pPb collisions: forward y: R_{AA} = 0.76(12) mid-y R_{AA} (estim) =0.72(15)

Softening of J/psi p_t distributions for central PbPb coll.

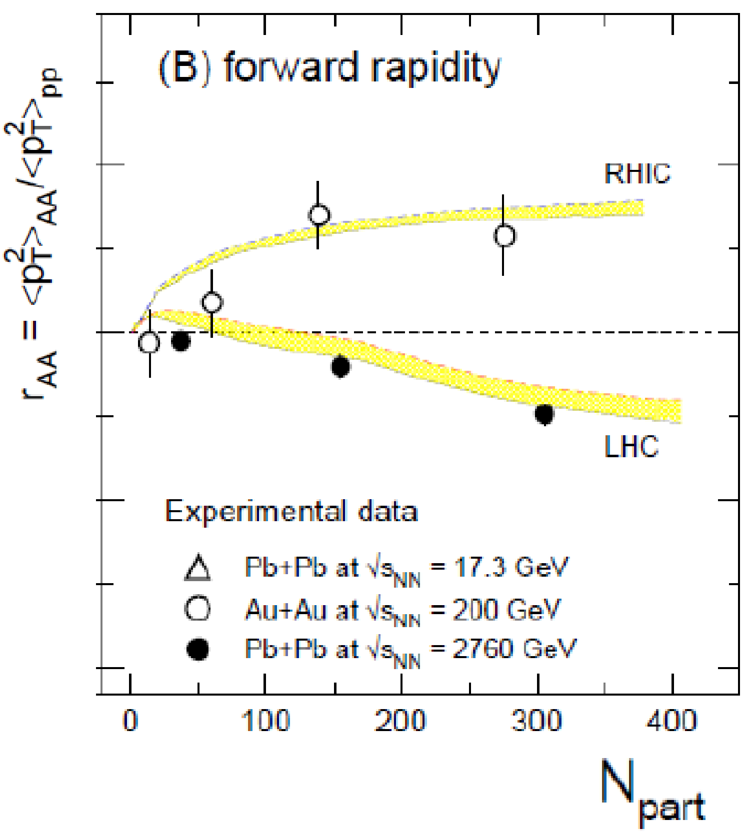


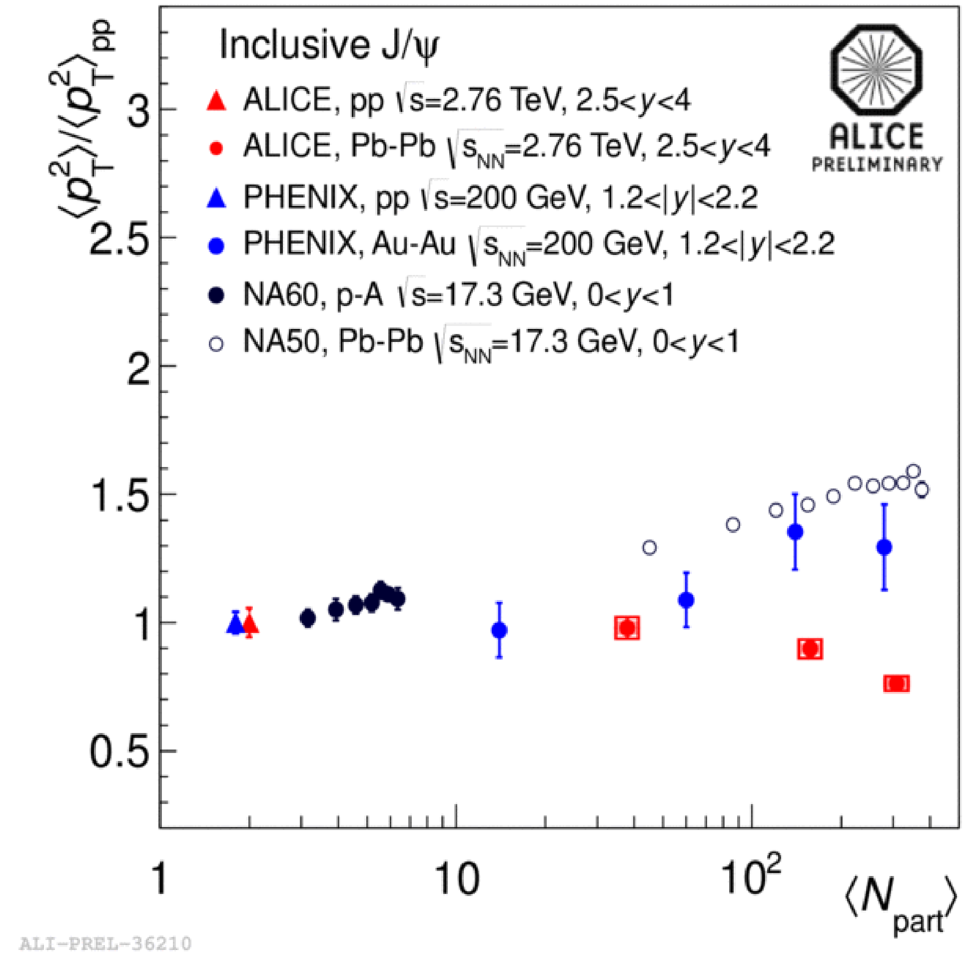


At LHC for central collisions softening relative to peripheral collisions and relative to pp (opposite trend to RHIC) - consistent with formation of J/psi from thermalized c-quarks

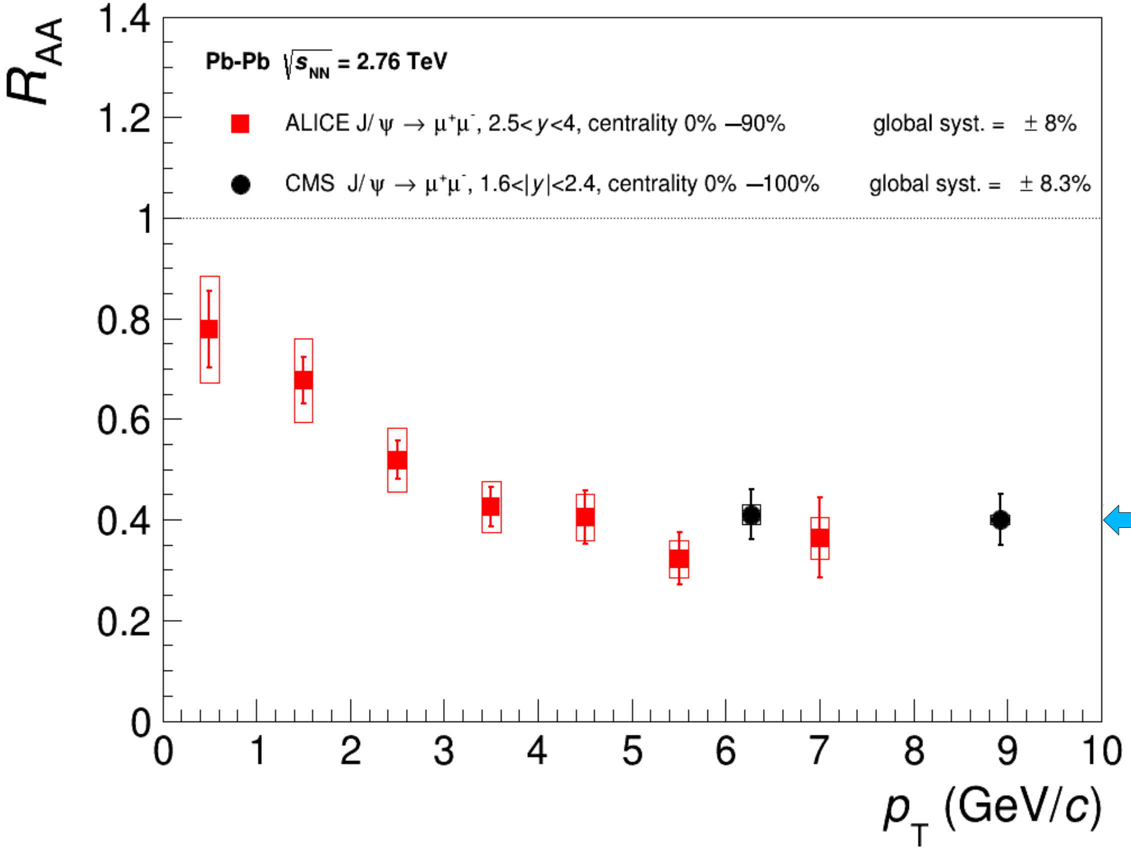
Softening of J/psi p_t distributions for central PbPb coll.

P.Zhuang et al. regeneration of J/psi
90% at mid-y, > 60% at forward y





p_t dependence of R_{AA}

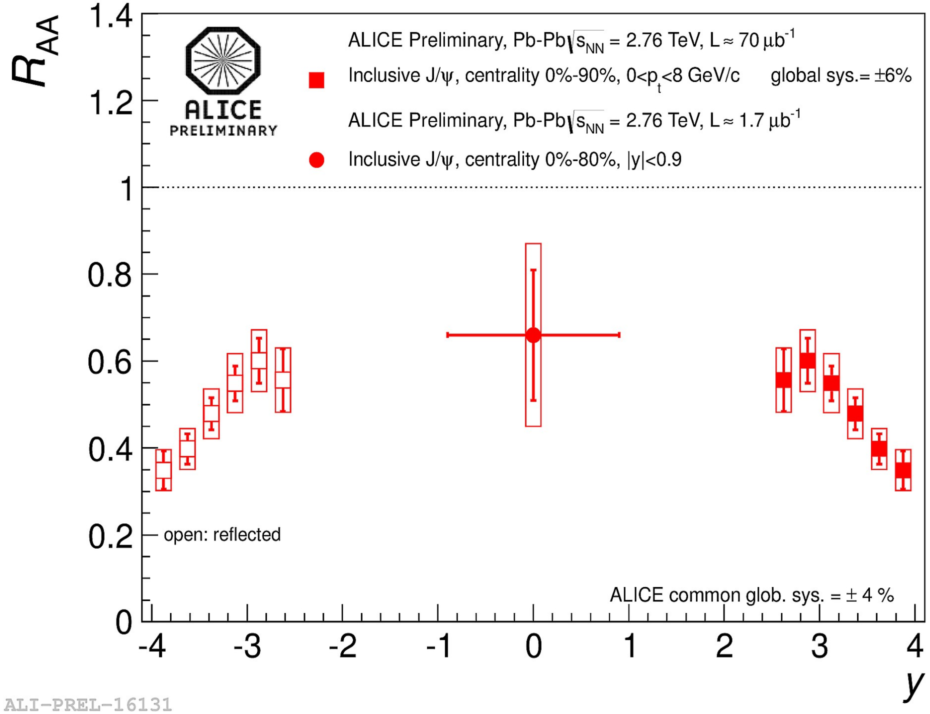


relative yield larger at low p_t in nuclear collisions

good agreement with CMS at high p_t

argument: thermalized deconfined charm quarks hadronize into J/ψ

Rapidity Dependence of J/psi R_{AA}

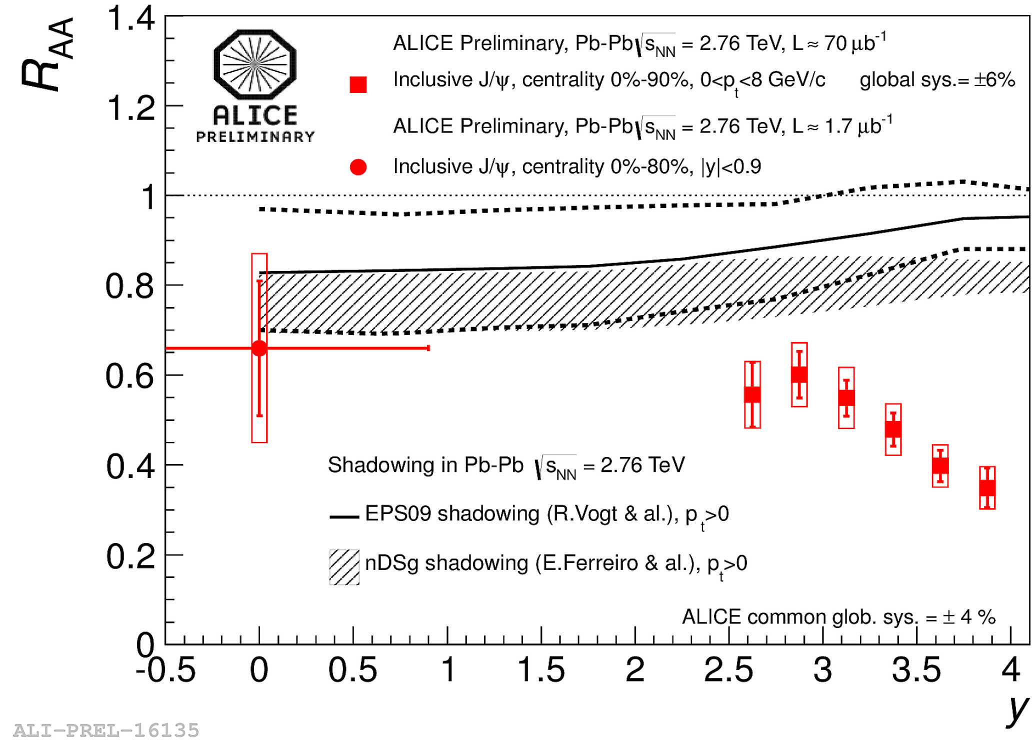


for statistical hadronization J/ψ yield proportional to N_c^2

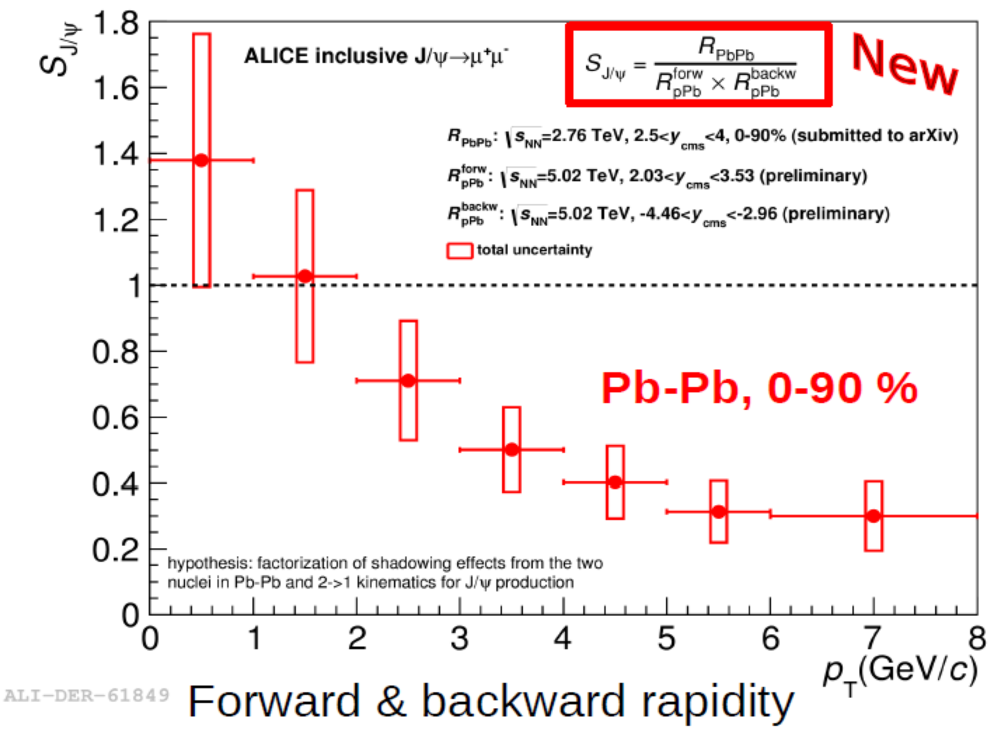
higher yield at mid-rapidity predicted in line with observation

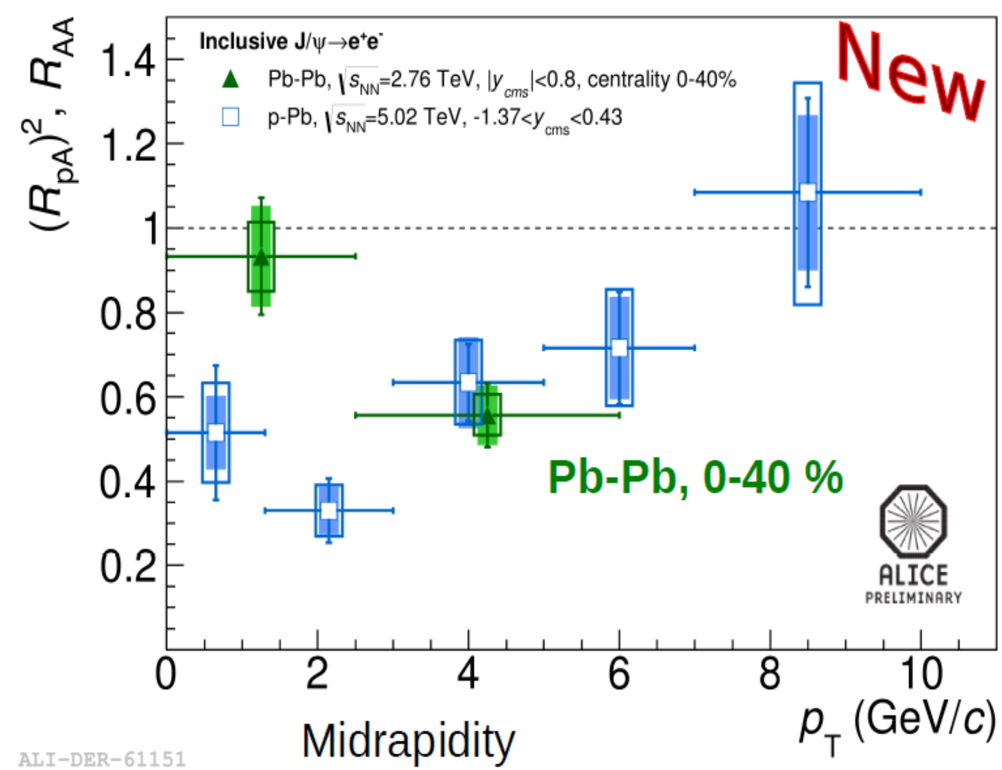
comparison to shadowing calculations:

- at mid-rapidity suppression could be explained by shadowing only
- at forward rapidity there seems to be additional suppression
- need to measure shadowing



J/psi vs pt in PbPb collisions relative to pPb collisions





at low pt yield in nuclear collisions above pPb collisions

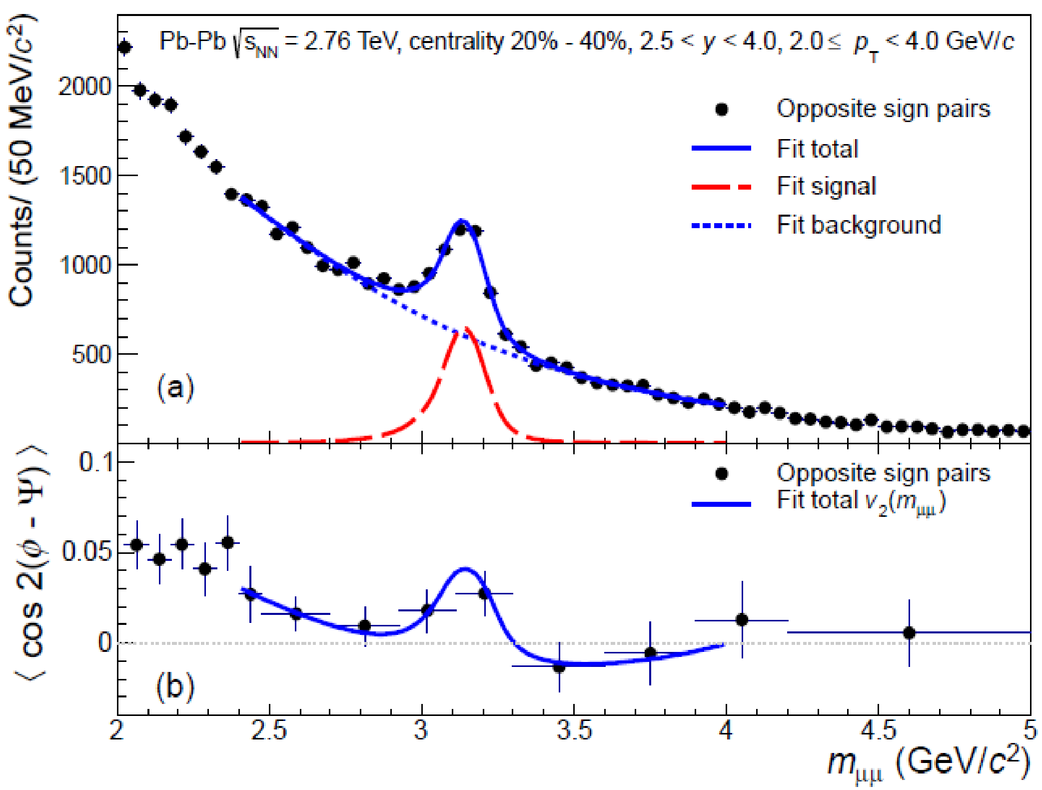
J/psi production **enhanced** in nuclear collisions over mere shadowing effect

Elliptic Flow of J/psi

charm quarks thermalized in the QGP should exhibit the elliptic flow generated in this phase

ALICE data analysis in 4 centrality bins
arXiv:1303.5880 and PRL (2013)

Centrality	$\langle N_{part} \rangle$	EP resolution ± (stat.) ± (syst.)
5%–20%	283 ± 4	0.548 ± 0.003 ± 0.009
20%–40%	157 ± 3	0.610 ± 0.002 ± 0.008
40%–60%	69 ± 2	0.451 ± 0.003 ± 0.008
60%–90%	15 ± 1	0.185 ± 0.005 ± 0.013
20%–60%	113 ± 3	0.576 ± 0.002 ± 0.008



analyze opposite sign muon pairs relative to the V0 event plane as function of mass and for each pt bin

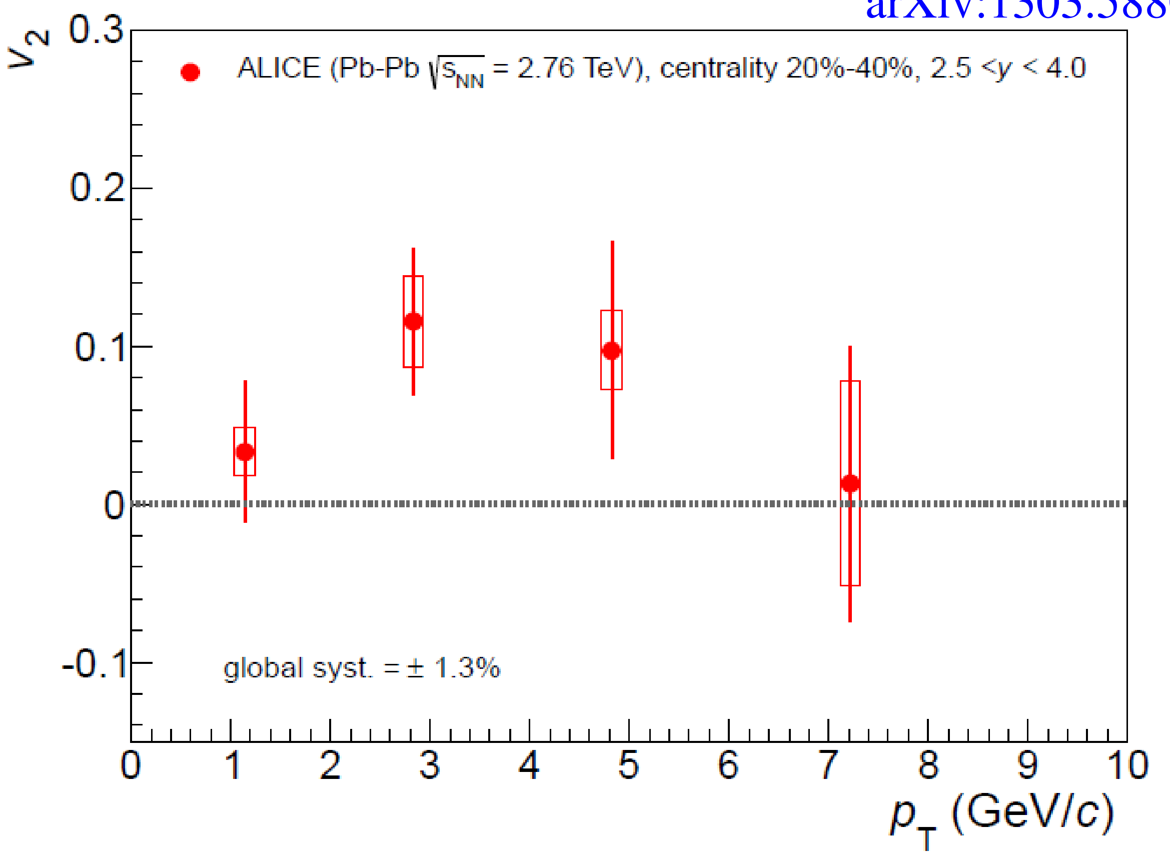
- fit distribution with

$$v_2(m_{\mu\mu}) = v_2^{sig}\alpha(m_{\mu\mu}) + v_2^{bkg}(m_{\mu\mu})[1-\alpha(m_{\mu\mu})]$$

where $\alpha(m_{\mu\mu})$ = S / (S+B) fitted to the mass spectrum

Elliptic Flow of J/psi vs pt

arXiv:1303.5880

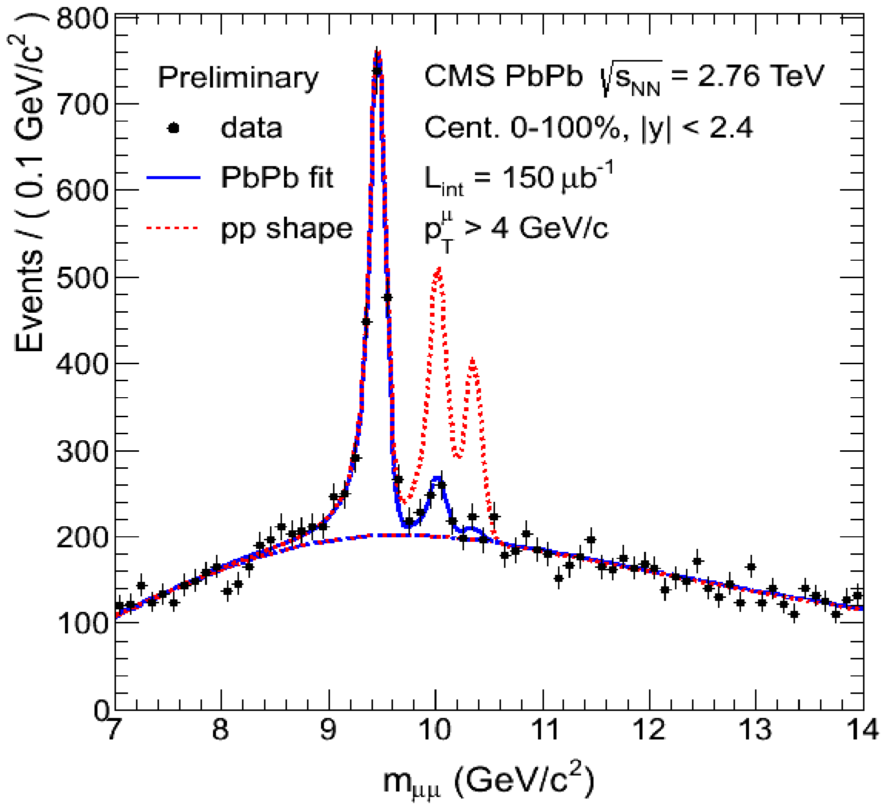


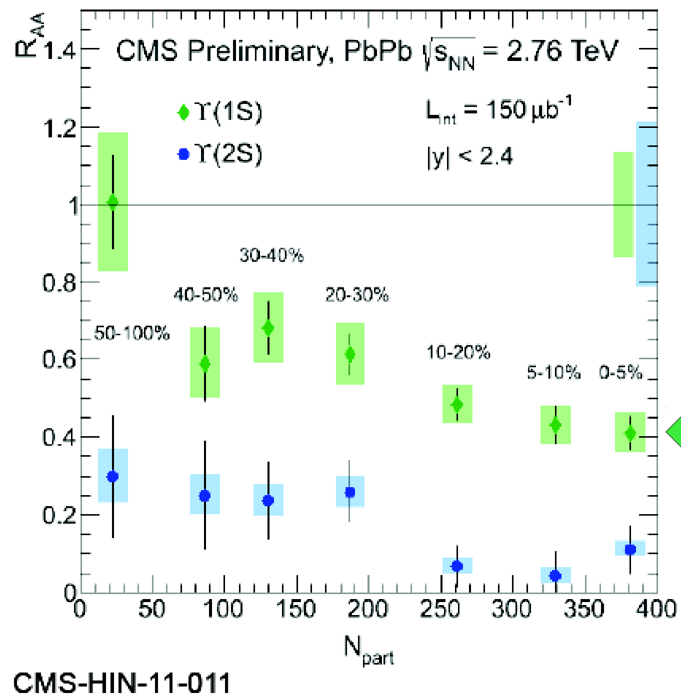
charm quarks thermalized in the QGP should exhibit the elliptic flow generated in this phase

- expect build-up with p_t as observed for π, p. K, Λ, … and vanishing signal for high p_t region where J/ψ not from hadronization of thermalized quarks

first observation of J/ψ v_2
in line with expectation from statistical hadronization

Suppression of Upsilon States





consistent with excited state suppression (50% feed-down)

centrality integrated:
2S/1S PbPb relative to pp 0.21+-0.07+-0.02
3S/1S “ < 0.1 95% C.L.

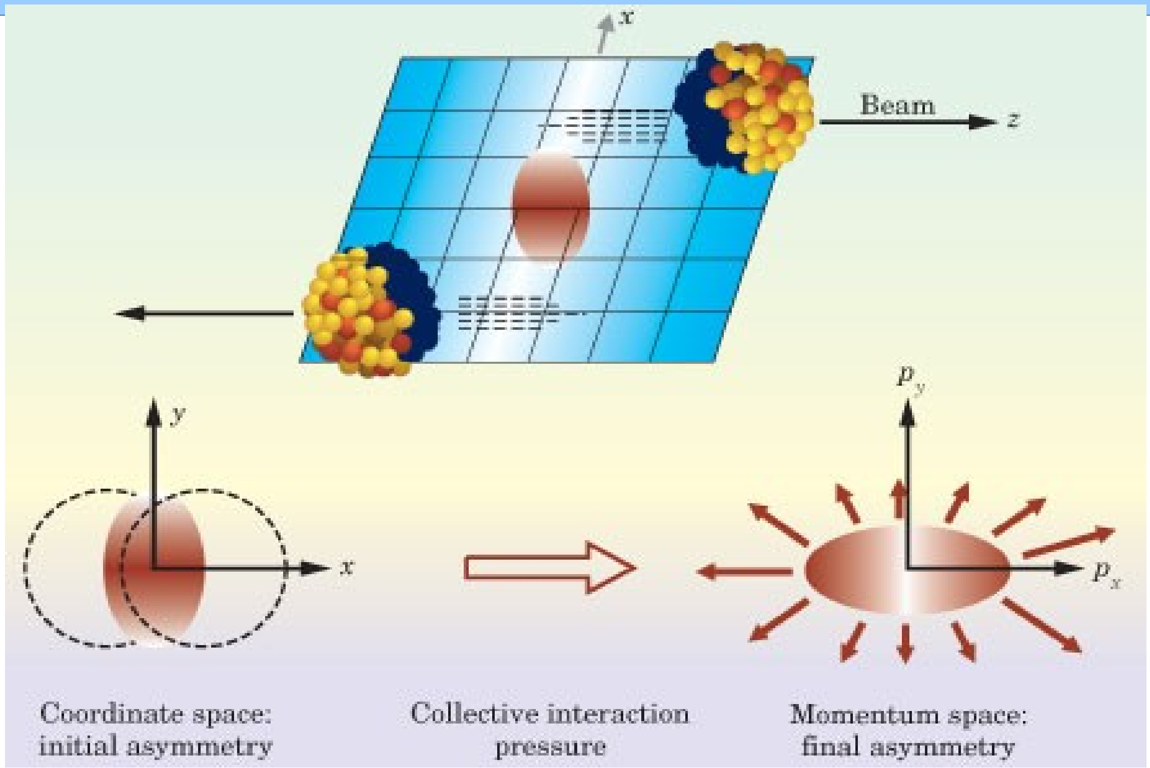
higher upsilon states expected to melt earlier because of larger radius
but also: statistical population much reduced beyond pp value due to Boltzmann factors

Conclusions

- hadron production
  - according to statistical ensemble
  - links hadrochemical freeze-out to phase diagram: experimental determination of phase boundary

- heavy quarks also appear to thermalize (I didn't show this today)
  need total cross section and charm quark observables at low p_t
- J/ψ
  – completely new picture at LHC compared to RHIC:R_{AA}, spectra, and elliptic flow indicate we are well on the way towards proof of deconfinement: thermalized c-quarks form charmonia at hadronization
  need complete story of all charmonia and bottomonia (down to p_t=0)

Azimuthal Anisotropy of Transverse Spectra



Fourier decomposition of momentum distributions rel. to reaction plane:

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

quadrupole component v_2

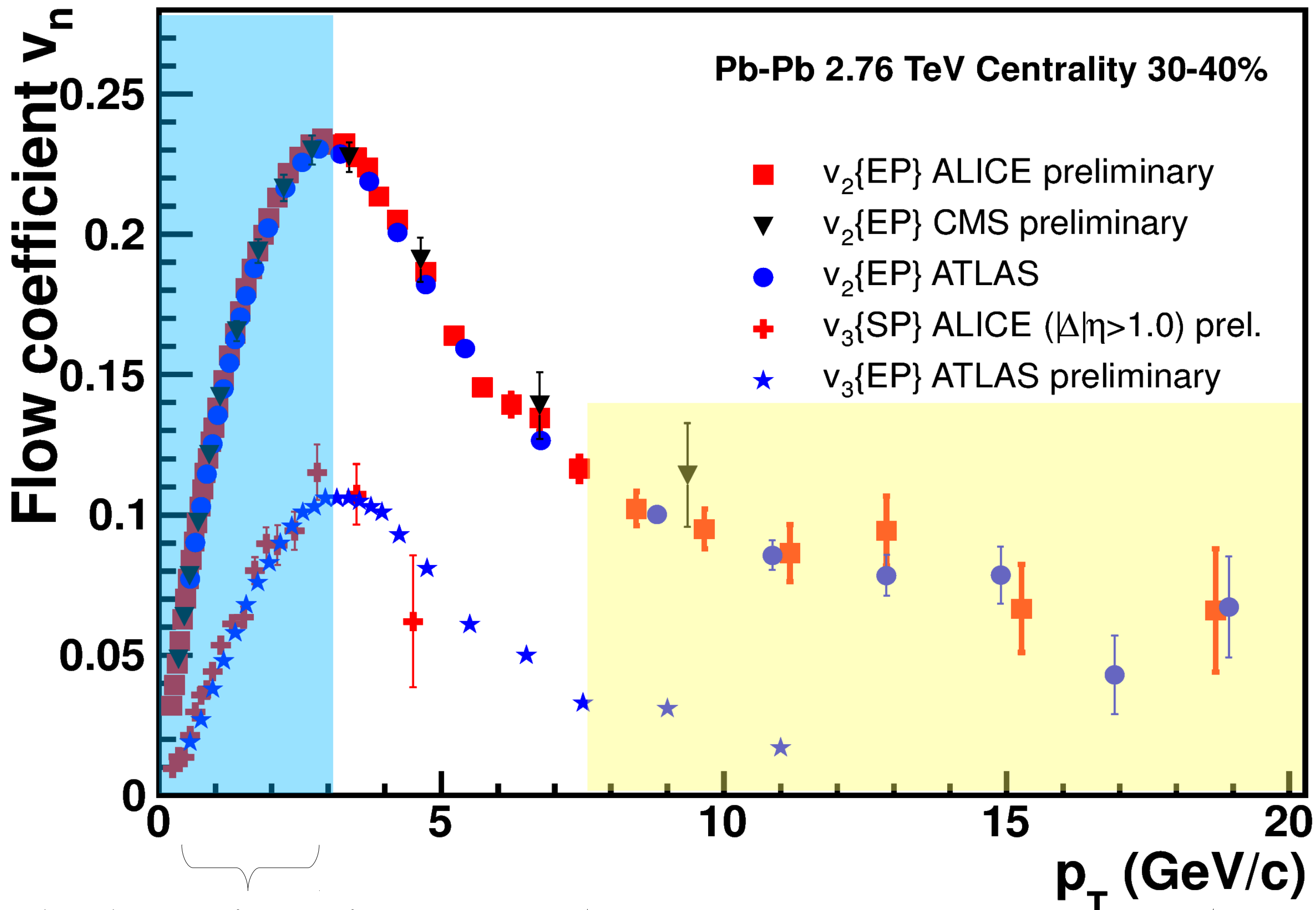
"elliptic flow"

effect of expansion (positive v_2) seen from top AGS energy upwards

the v_n are the equivalent of the power spectrum of cosmic microwave rad.

Elliptic Flow of Charged Particles at LHC

figure modified from B. Muller, J. Schukraft, B. Wyslouch, arXiv:1202.3233v1



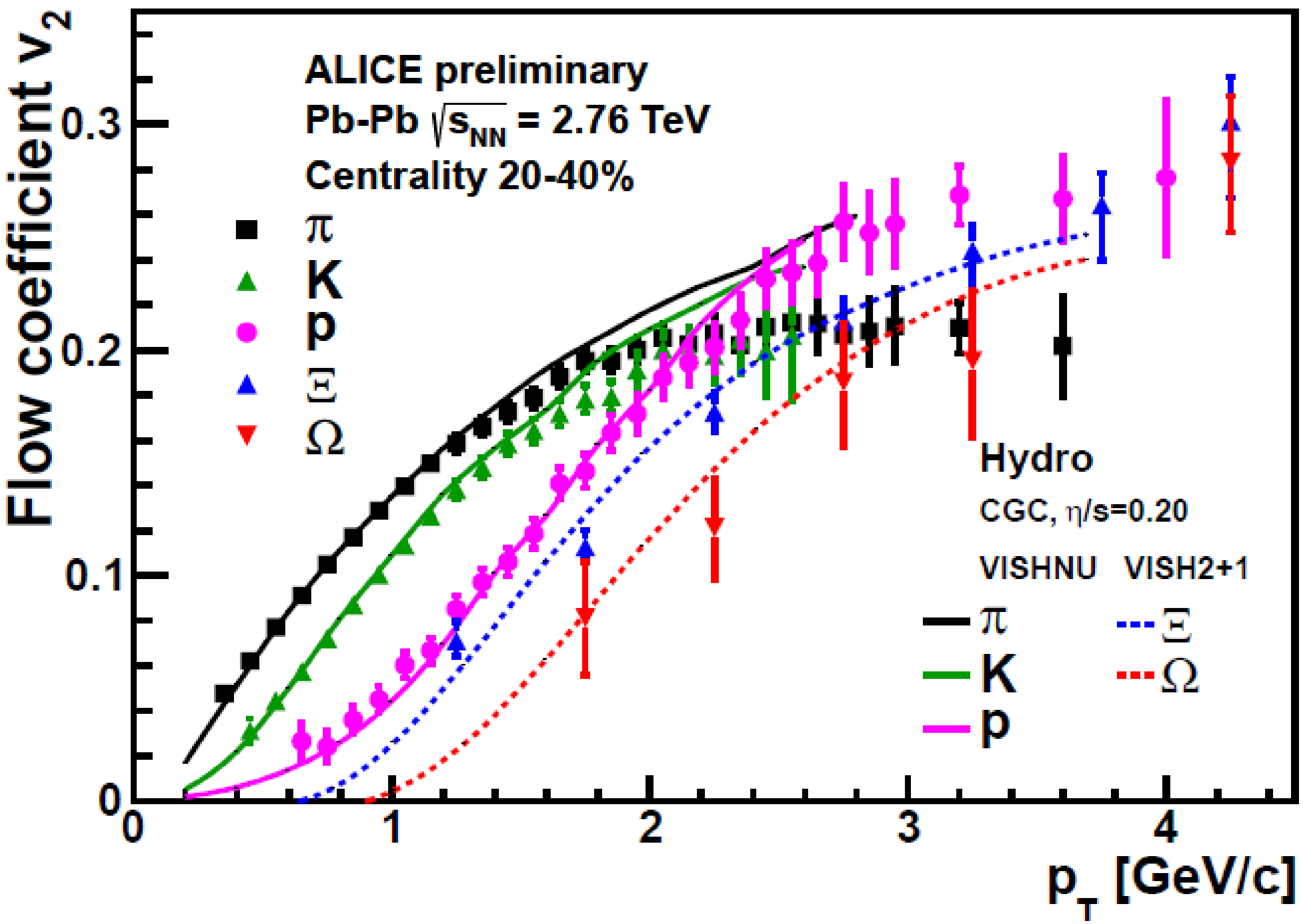
hydrodynamic regime
v2 driven by pressure gradient

jet fragmentation regime
v2 driven by energy loss

elliptic flow (v2) as function of p_t :

- excellent agreement between all 3 LHC experiments
- same for v3

Elliptic Flow in PbPb Collisions at $\sqrt{s}_{NN}$ = 2.76 TeV

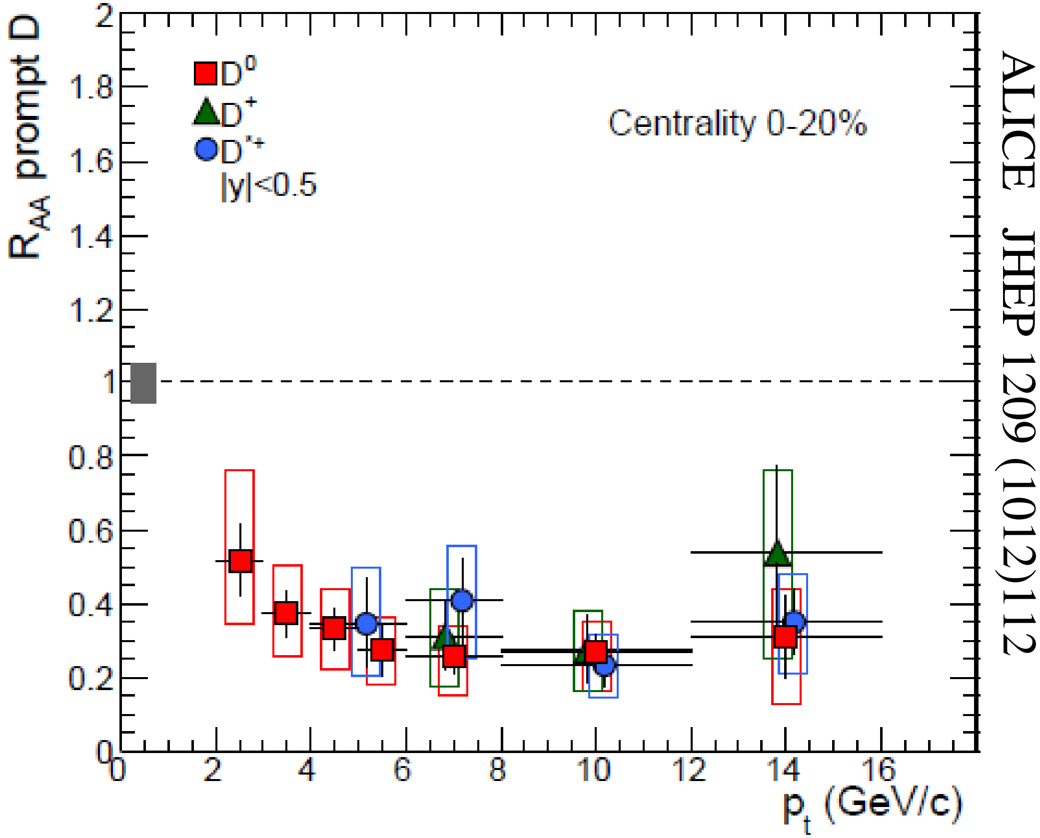


best current value for η/s = 0.20 close to quantum lower bound
hydrodynamics with this small η/s reproduces flow for all particle species

Suppression of charm at LHC energy

$$R_{AA}(p_t) = \frac{1}{\langle T_{AA} \rangle} \cdot \frac{dN_{AA}/dp_t}{d\sigma_{pp}/dp_t}$$

yield in PbPb/(number binary collisions times yield in pp)

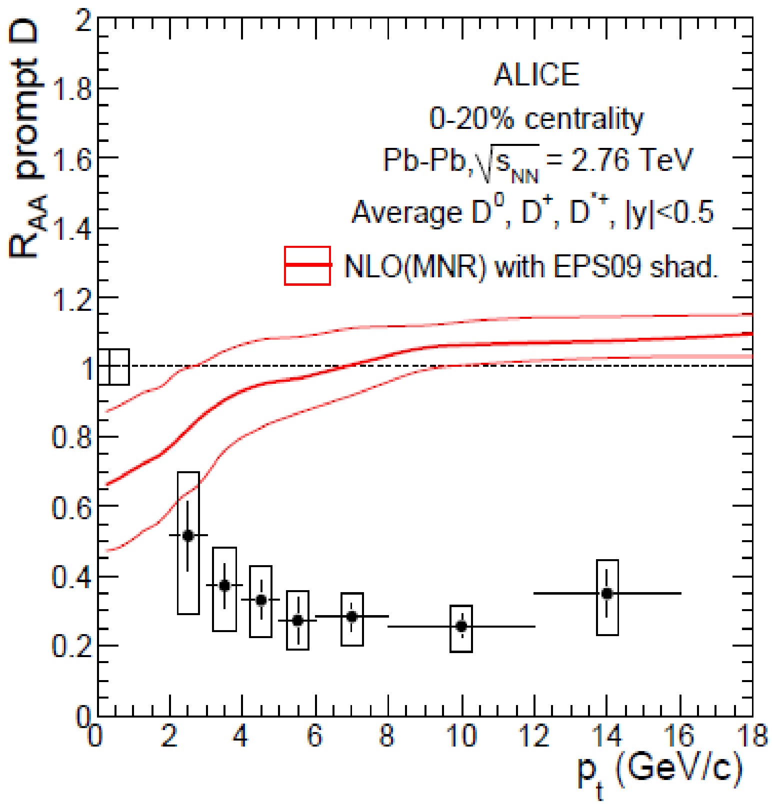


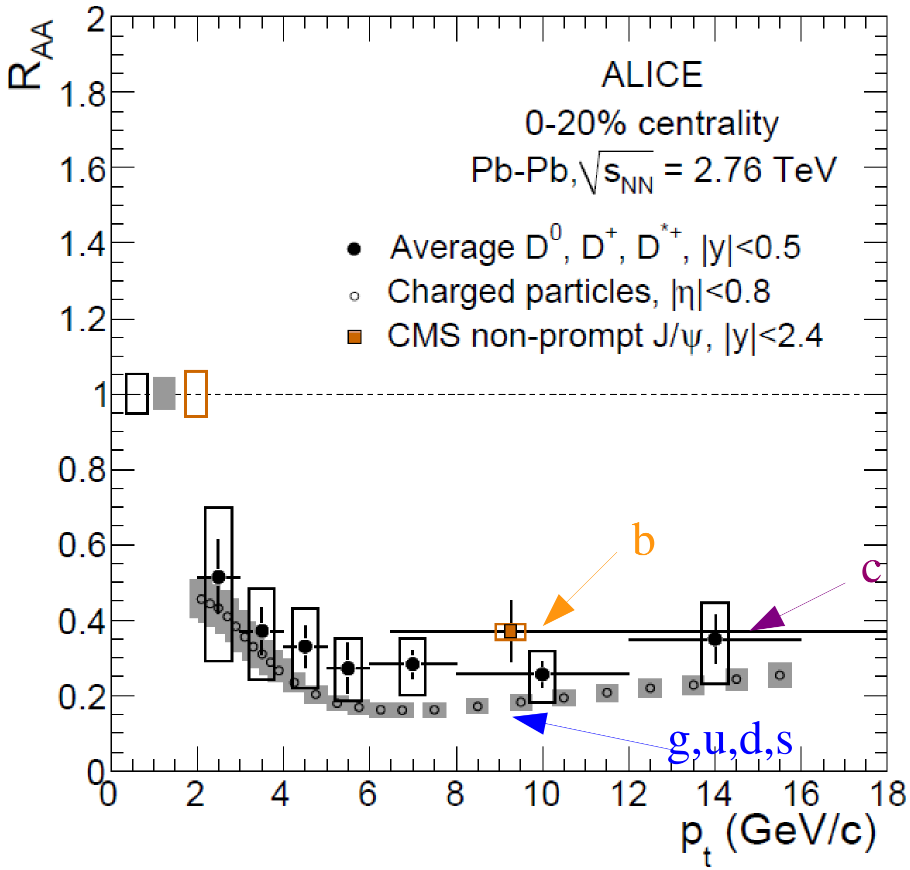
energy loss for all species of D-mesons within errors equal - not trivial

energy loss of central collisions very significant - suppr. factor 4 for 6-12 GeV/c

Suppression of charm at LHC energy

comparison to EPS09 shadowing:
suppression not an initial state effect





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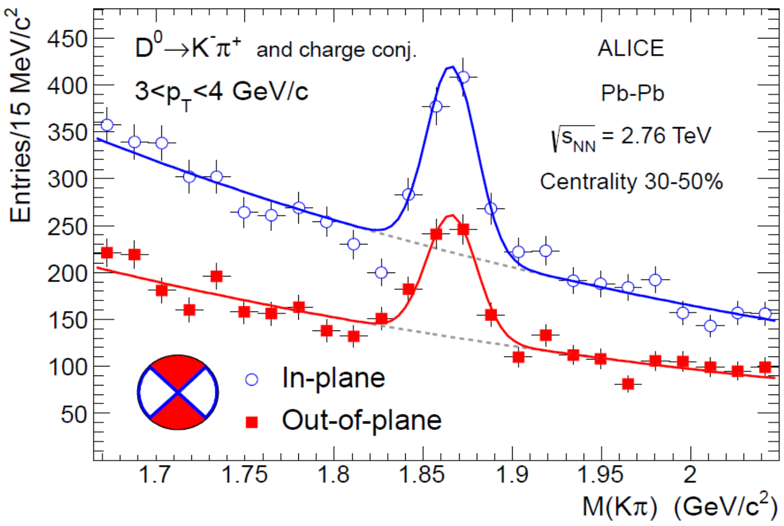
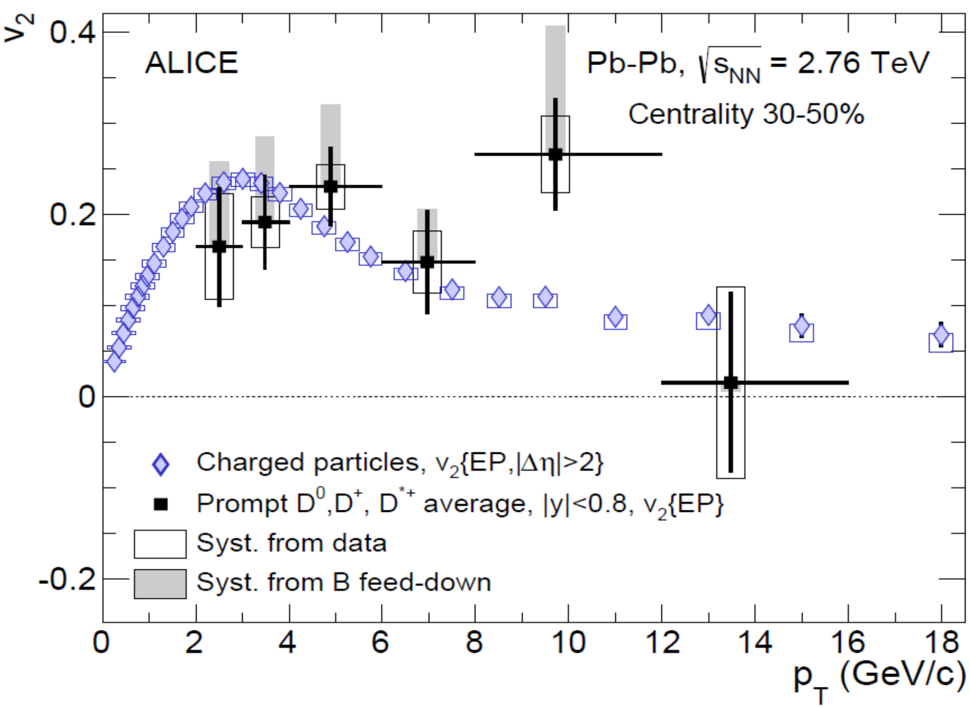
energy loss of charm quarks only slightly less than that for light quark → thermalization

Charm Quarks also Exhibit Elliptic Flow



$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{\text{in-plane}} - N_{\text{out-of-plane}}}{N_{\text{in-plane}} + N_{\text{out-of-plane}}}$$

$$R_2 = 0.8$$

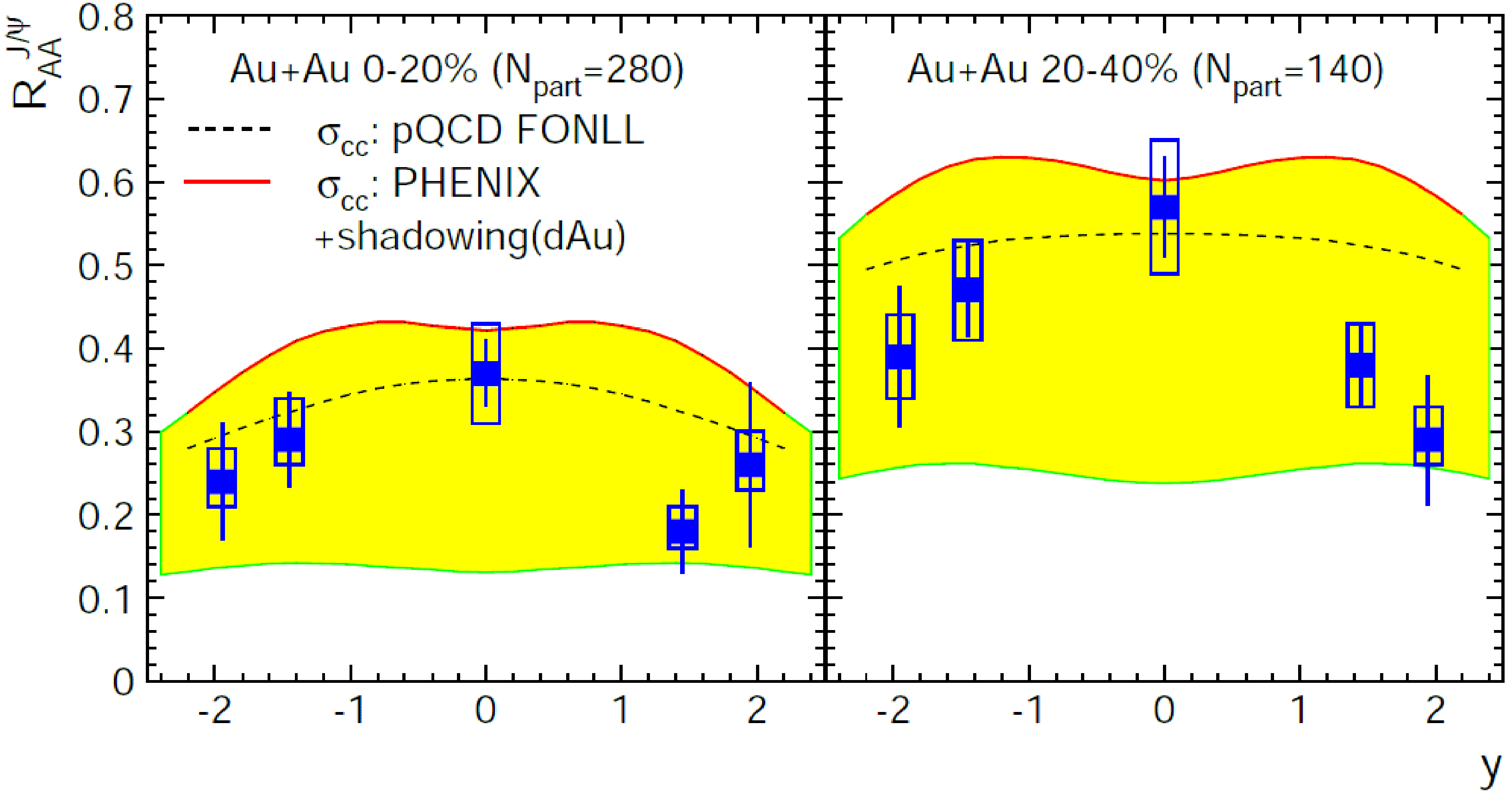


Phys. Rev. Lett. 111 (2013) 102301

2 centrality classes
event plane from TPC
corrected for B-feed down (FONLL)

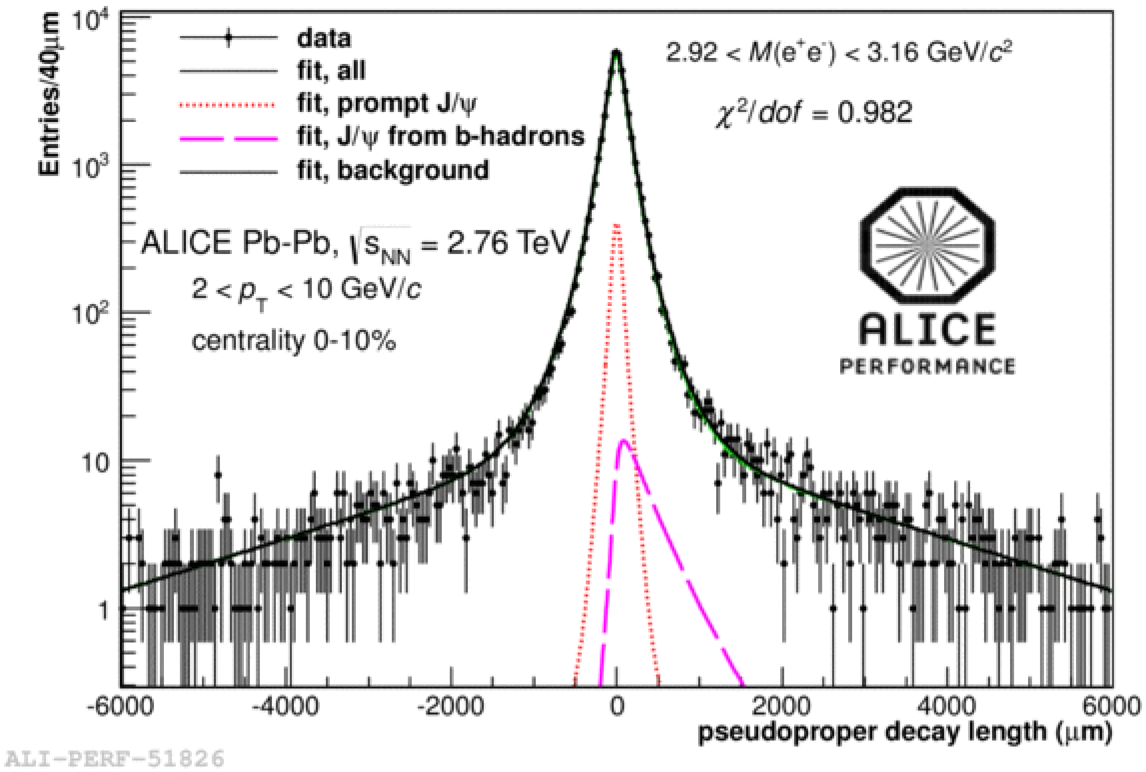
non-zero elliptic flow 5.7 σ effect for D^0 2-6 GeV/c
within errors charmed hadron v_2 equal to that of all charged hadrons

RHIC: shadowing leads to slight modification in shape



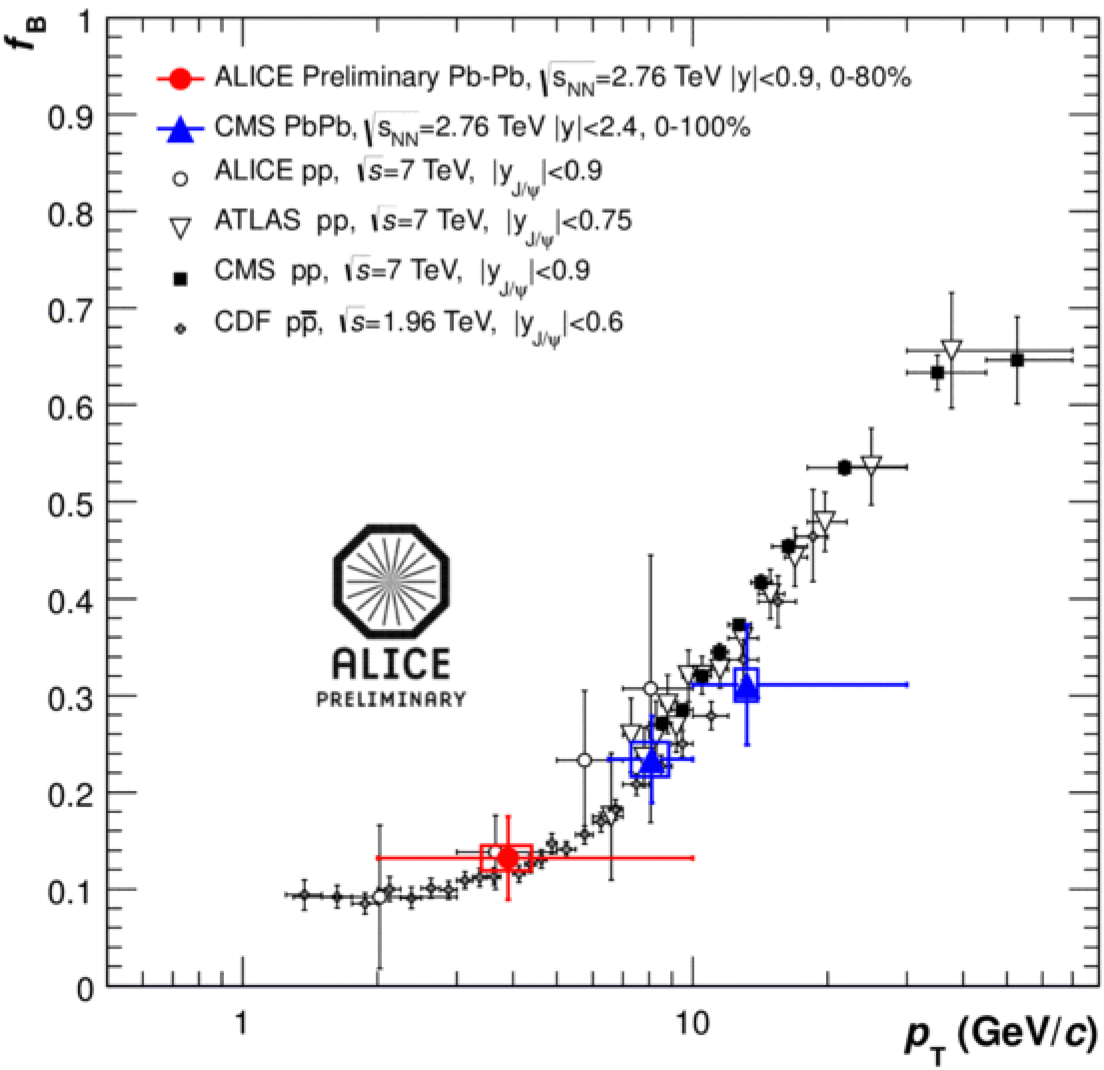
assume PHENIX pA data reflect shadowing
need accurate charm cross section for AuAu!

Fraction of J/psi from B-decays



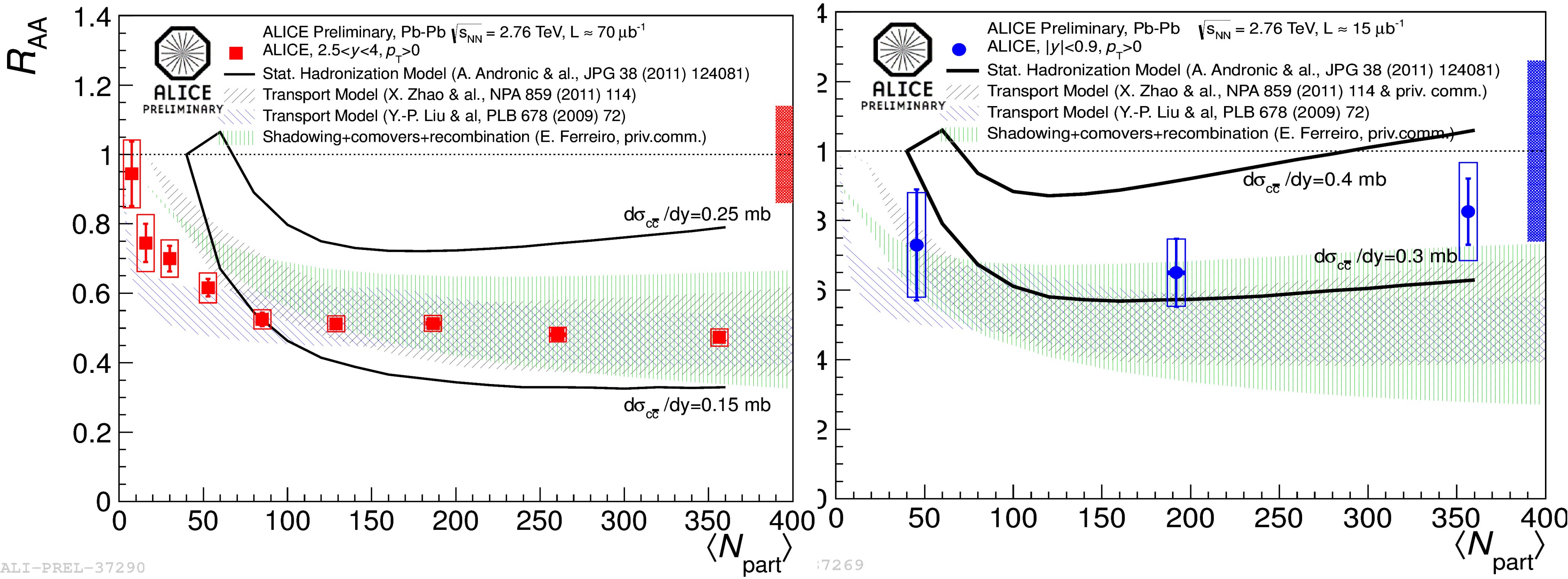
due to displaced decay-vertices, pseudoproper decay length can be used to determine B-fraction

Fraction of J/psi from B-decays



p_t integrated non-prompt B-fraction of small
within current errors no significant difference in pp and PbPb collisions

J/psi and transport models (and stat hadronization)



in transport models (Rapp et al. & P.Zhuang, N.Xu et al.) J/psi generated both in QGP and at hadronization

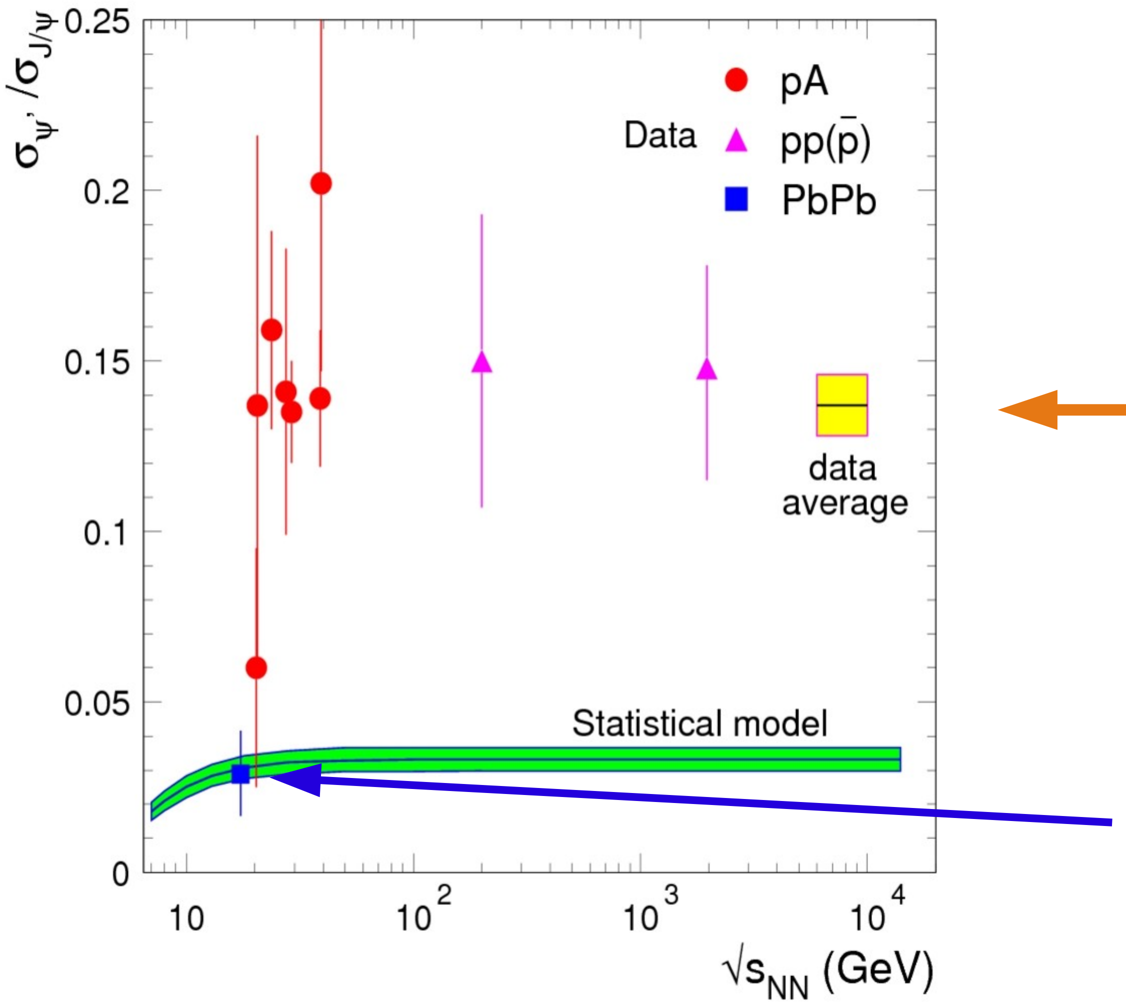
- transport models also well in line with R_{AA}

  part of J/psi from direct hard production, part dynamically generated in QGP

- How to distinguish?

  flow of J/psi and excited state population – precision 2nd and 3rd generation data

Statistical Hadronization Model Predictions for psi'



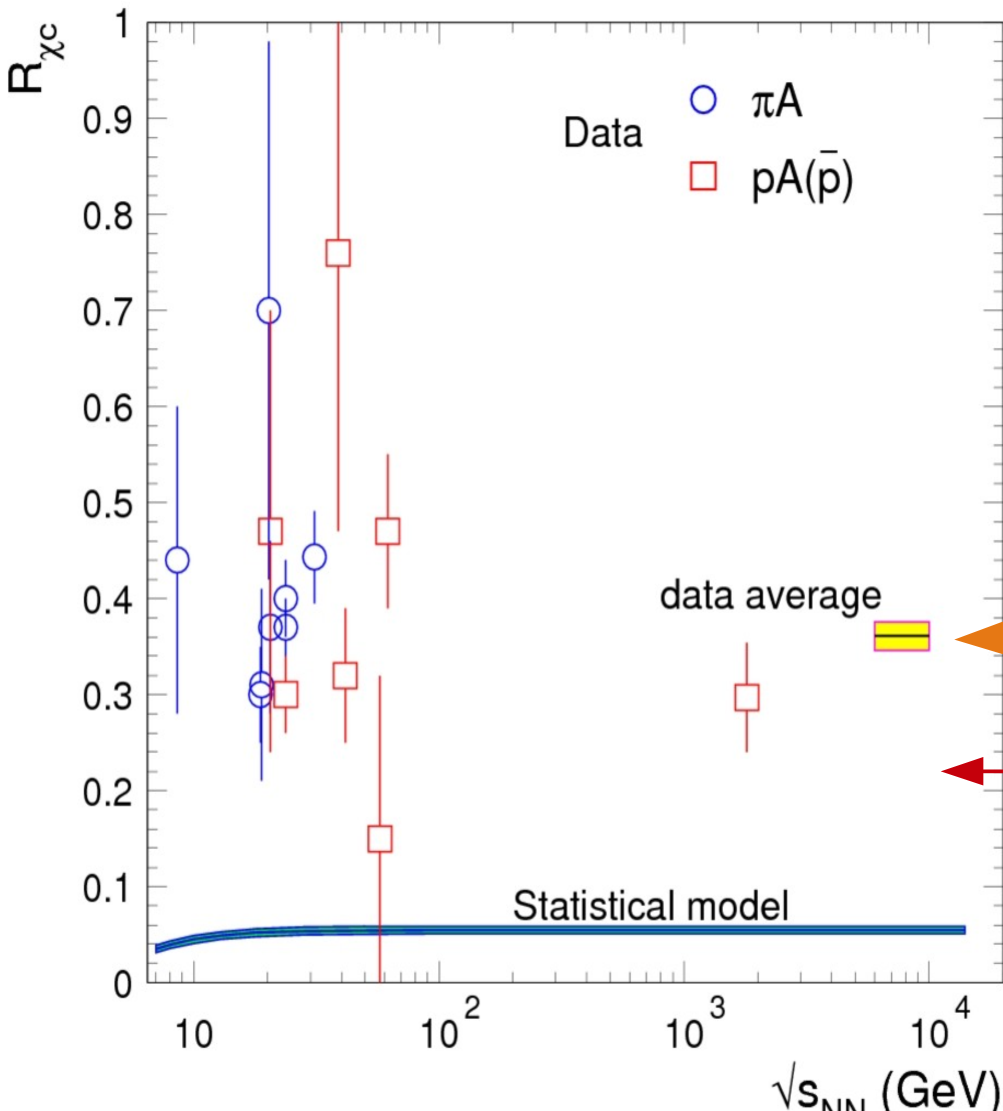
A. Andronic, F. Beutler, P. Braun-Munzinger, K. Redlich, J. Stachel Phys. Lett. B678 (2009) 350

pp and pA data factor 3 above statistical hadronzation value

only result for AA at SPS energy; very close agreement

data at higher energies will be crucial test

Situation even more dramatic for P-states

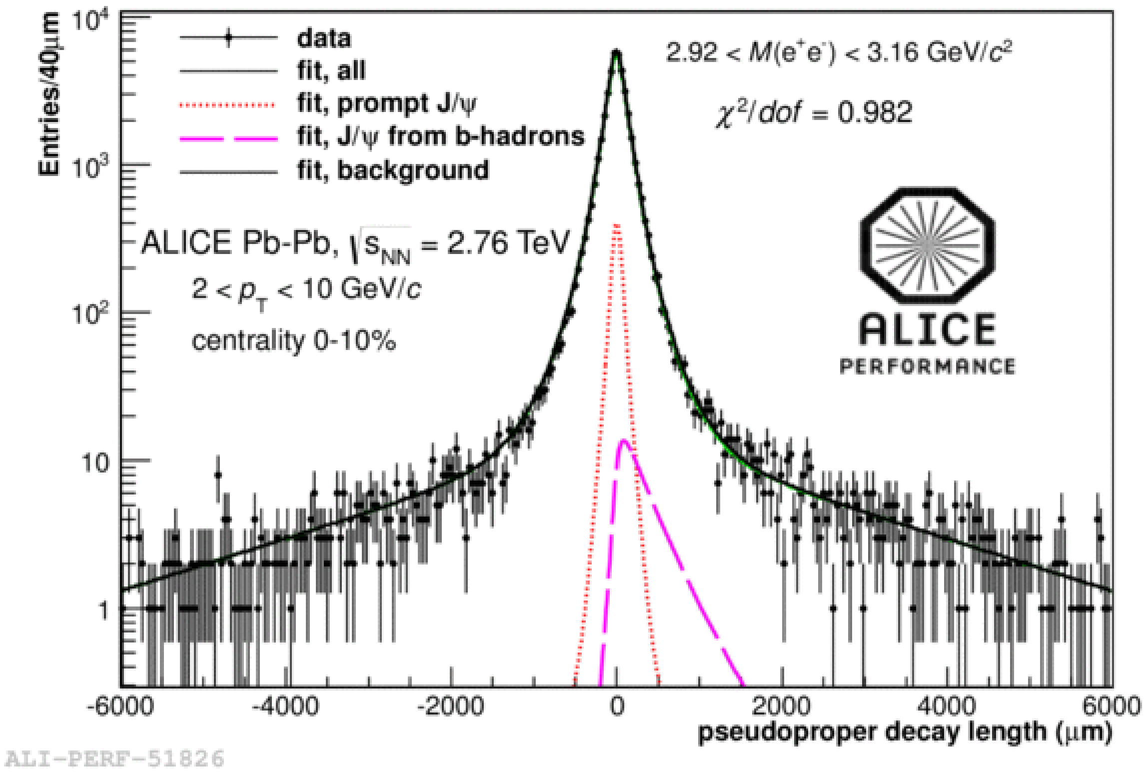


pA and πA data on average factor 7 avove statistical model prediction

Transport model (Rapp)

A. Andronic, F. Beutler, P. Braun-Munzinger, K. Redlich, J. Stachel Phys. Lett. B678 (2009) 350

Fraction of J/psi from B-decays



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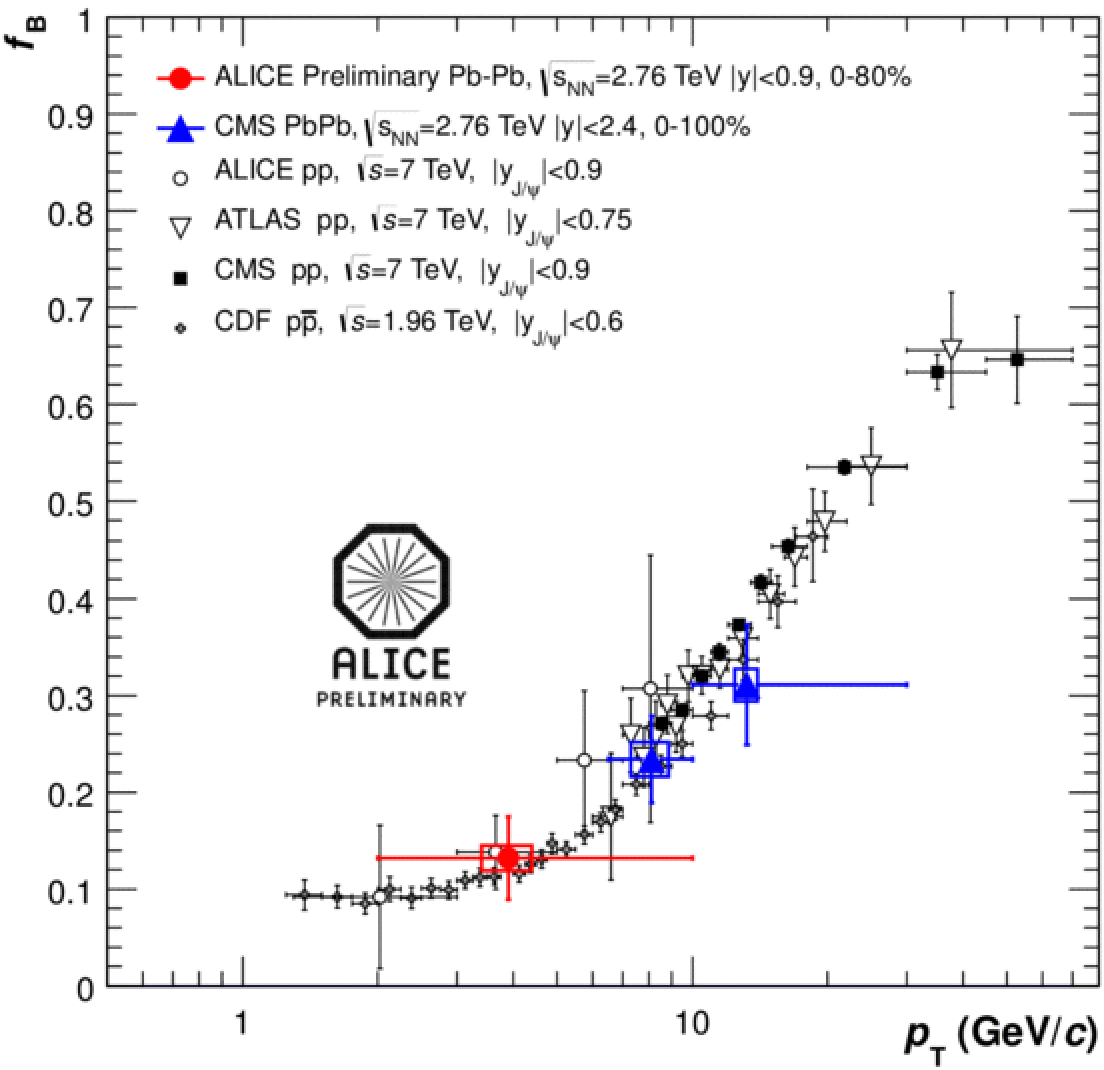

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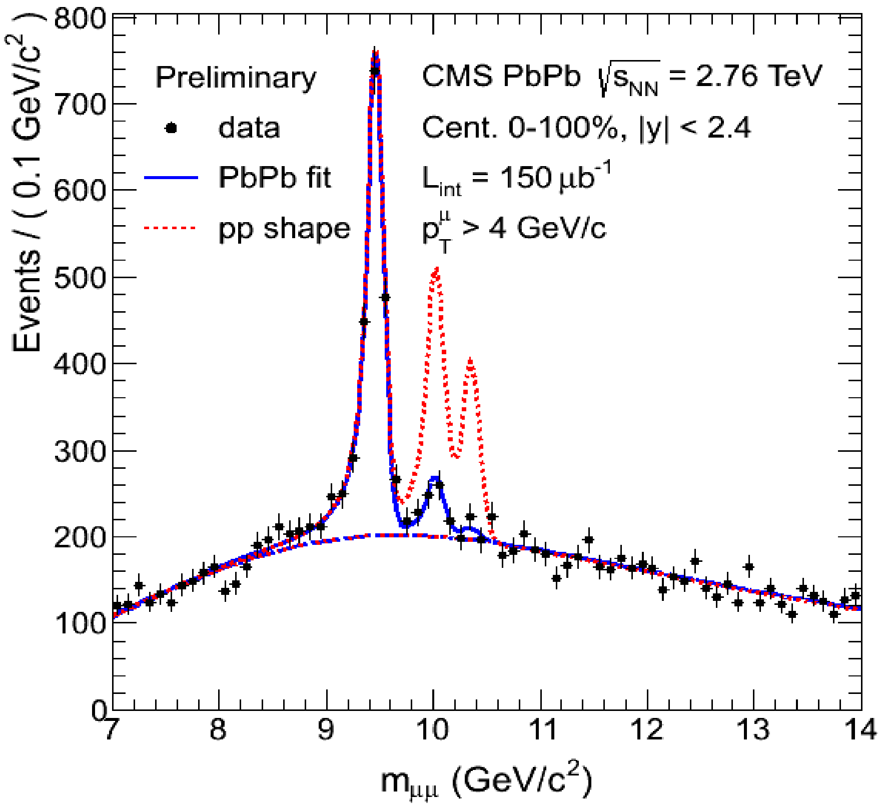

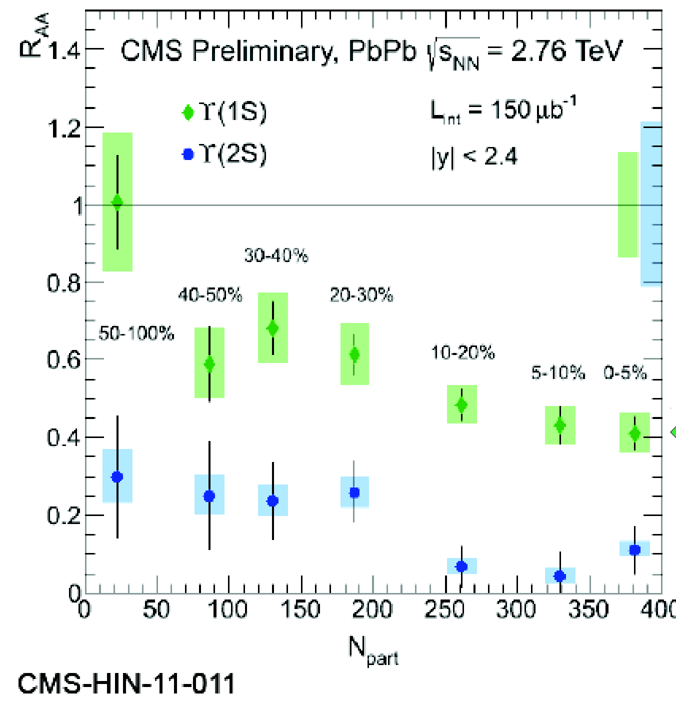

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higher upsilon states expected to melt earlier because of larger radius
but also: statistical population much reduced beyond pp value due to Boltzmann factors