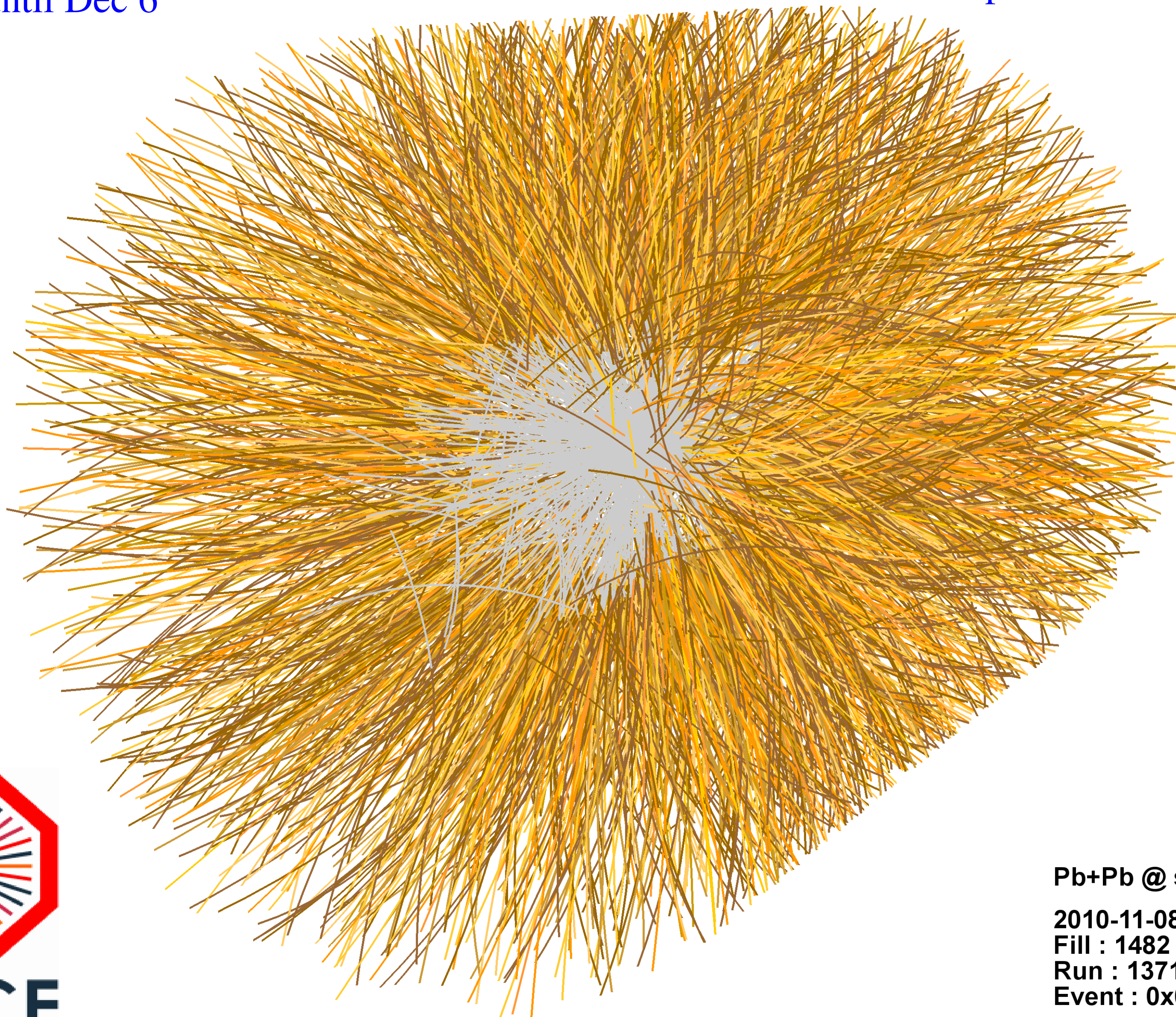
first PbPb collisions at LHC at $\sqrt{s}$ = 2.76 A TeV

setup for ion collisions: November 4
first collisions with stable beams:
November 8 until Dec 6

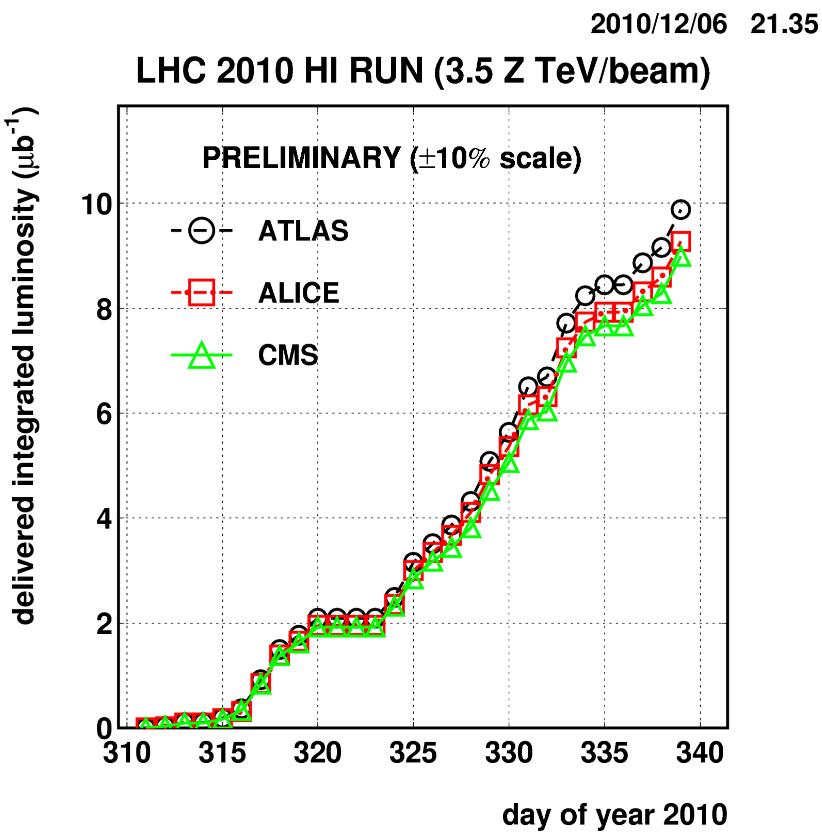
already in Dec 2010
5 publications in PRL and PLB

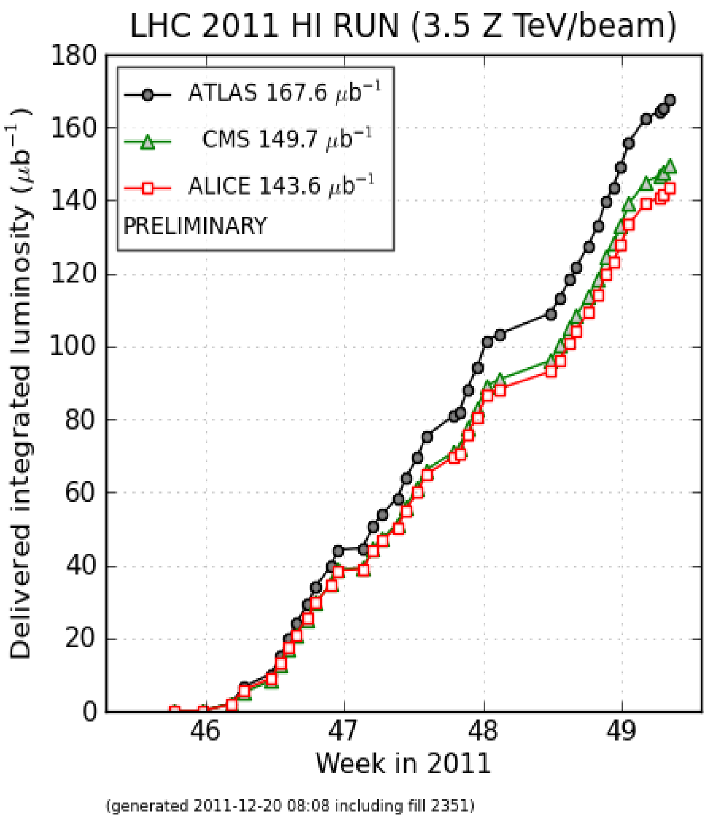


Pb+Pb @ sqrt(s) = 2.76 ATeV

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

Heavy ion running at the LHC





for November 2012: p + Pb run

Mission of the LHC Heavy Ion Program

- after SPS fixed target program 1986-2000 leading to recognition that a deconfined phase of matter is formed (CERN press release Feb. 2000)
- and RHIC program starting to characterize this phase as a dense, strongly coupled liquid (BNL press release April 2005)

→ what is left for LHC?

<u>what is different at LHC?</u>

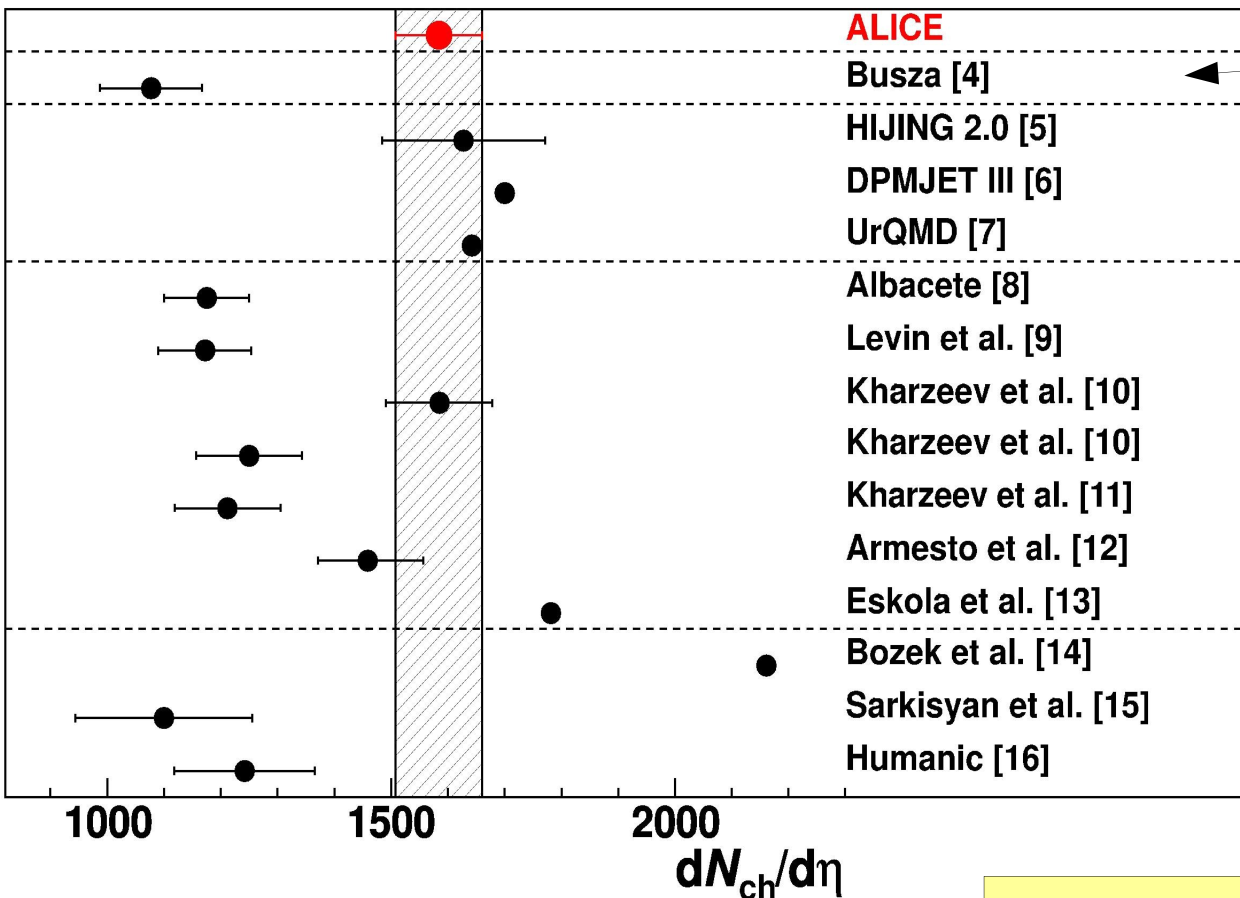
much larger energy (> 20 x RHIC)
very large volumes, temperatures, densities
copious production of jets and heavy quarks

<u>what do we want to learn?</u>

equation of state
number of degrees of freedom
transport coefficients (viscosity etc)
velocity of sound
parton energy loss and opacity
susceptibilities
proof of deconfinement

Charged Particle Pseudo-rapidity Density Compared to Model Predictions

probes density of gluons initially liberated from the colliding nuclei
expect order of 10 000 - depends on shadowing and gluon saturation



Simple logarithmic extrapolation fails

Gluon saturation models mostly underpredict data

predictions cover wide range – many excluded by very first data

Phys. Rev. Lett. 105(2010)252301

Initial Energy Density

$$\epsilon_0 = dE_t/d\eta/A_t \times d\eta/dz = \langle m_t \rangle \times dN_{ch}/d\eta 1.5/A_t \times d\eta/dz$$

Bjorken formula* using Jacobian $d\eta/dz = 1/\tau_0$

ALICE:

$A_t = 150 \text{fm}^2 \quad \langle m_t \rangle = 0.67\,\text{GeV/c} \rightarrow \epsilon_0 \times \tau_0 = 10.7\,\text{GeV/fm}^2$

from saturation momentum $\tau_0 = 1/p_0 = 0.08$ fm

$\rightarrow \quad \varepsilon_0 = 135 \text{ GeV/fm}^3$

estimate temperature to $T \approx 0.665$ GeV $\approx 4\, T_c \approx 10^{13}$ K

pressure $P \approx 45 \text{ GeV/fm}^3 = 7.2\ 10^{36}$ Pa $= 7.2\ 10^{31}$ atm

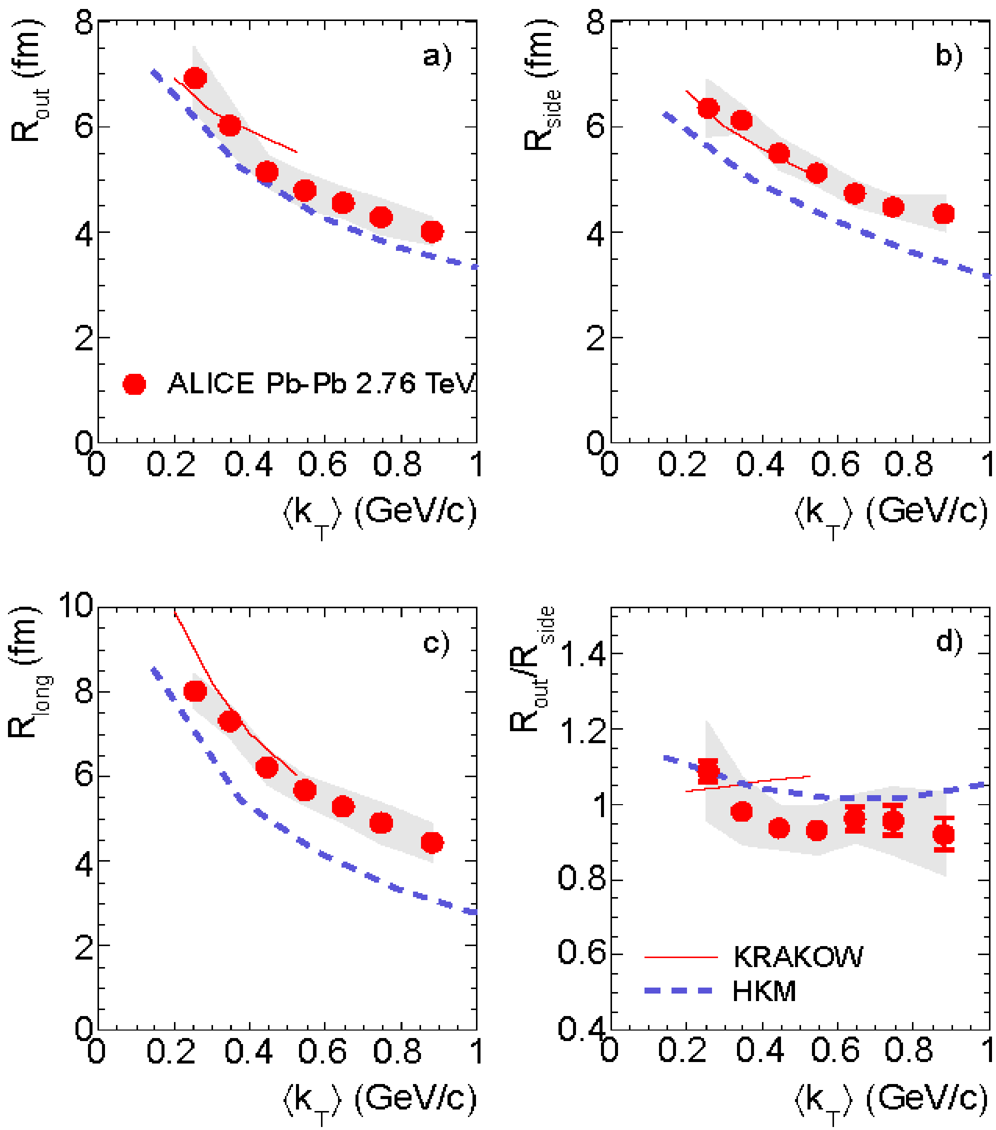
entropy density $\approx 270/\text{fm}^3$ - ok with about 1000 gluons per unit rapidity

total entropy of fireball: 36 000

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

Collision dynamics

Radius Parameters as Function of Pair Transverse Momentum

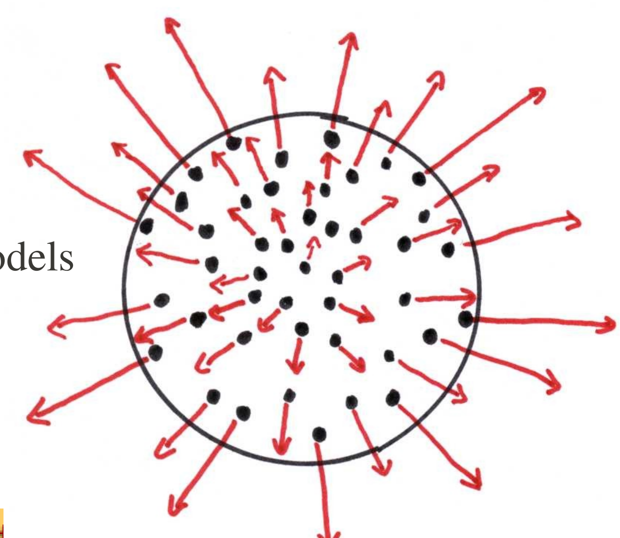


} hydrodynamic models

- Transv. mom. dependence shows
- typical shape for hydrodyn.
- expanding source
- reproduced reasonably well by

Krakow and Kiev hydro models

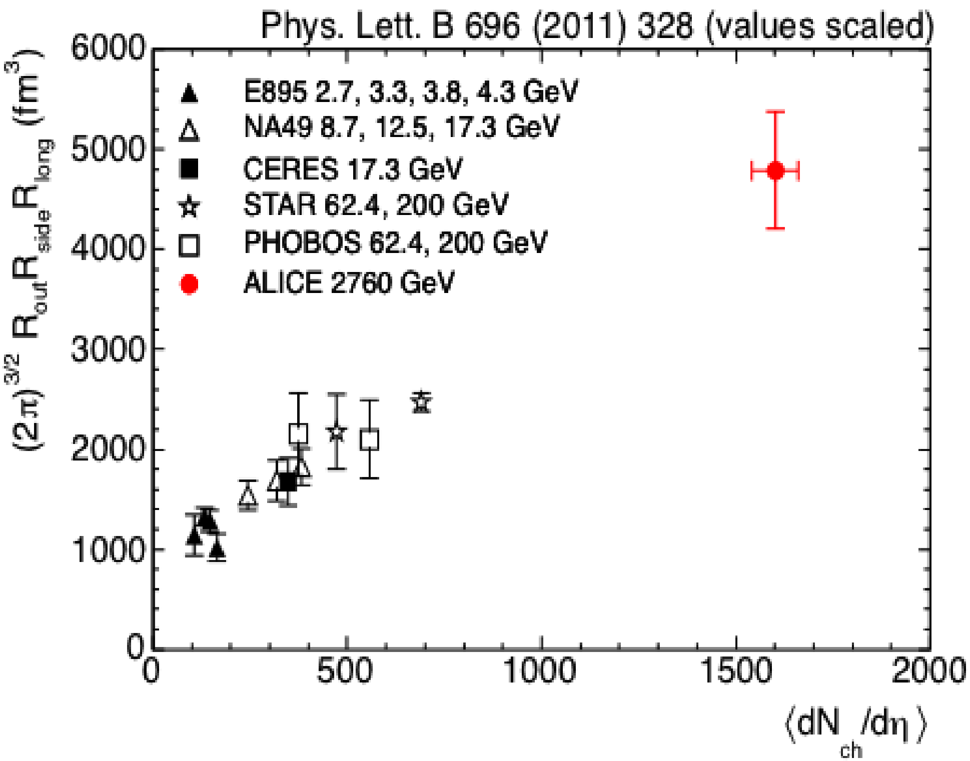
expansion velocity grows linearly
with radius (Hubble-like)
reaches at surface 3/4 c



Phys. Lett. B696(2011)328

Freeze-out Volume and Duration of Expansion

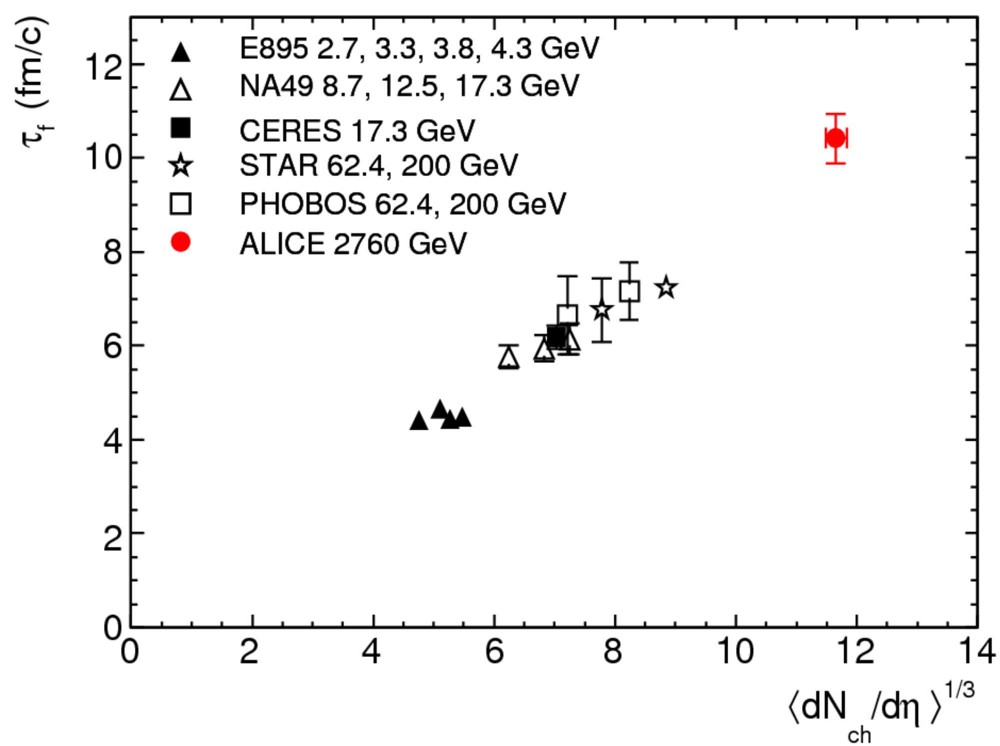
coherence volume $V = (2\pi)^{3/2} R_{side}^2 R_{long}$



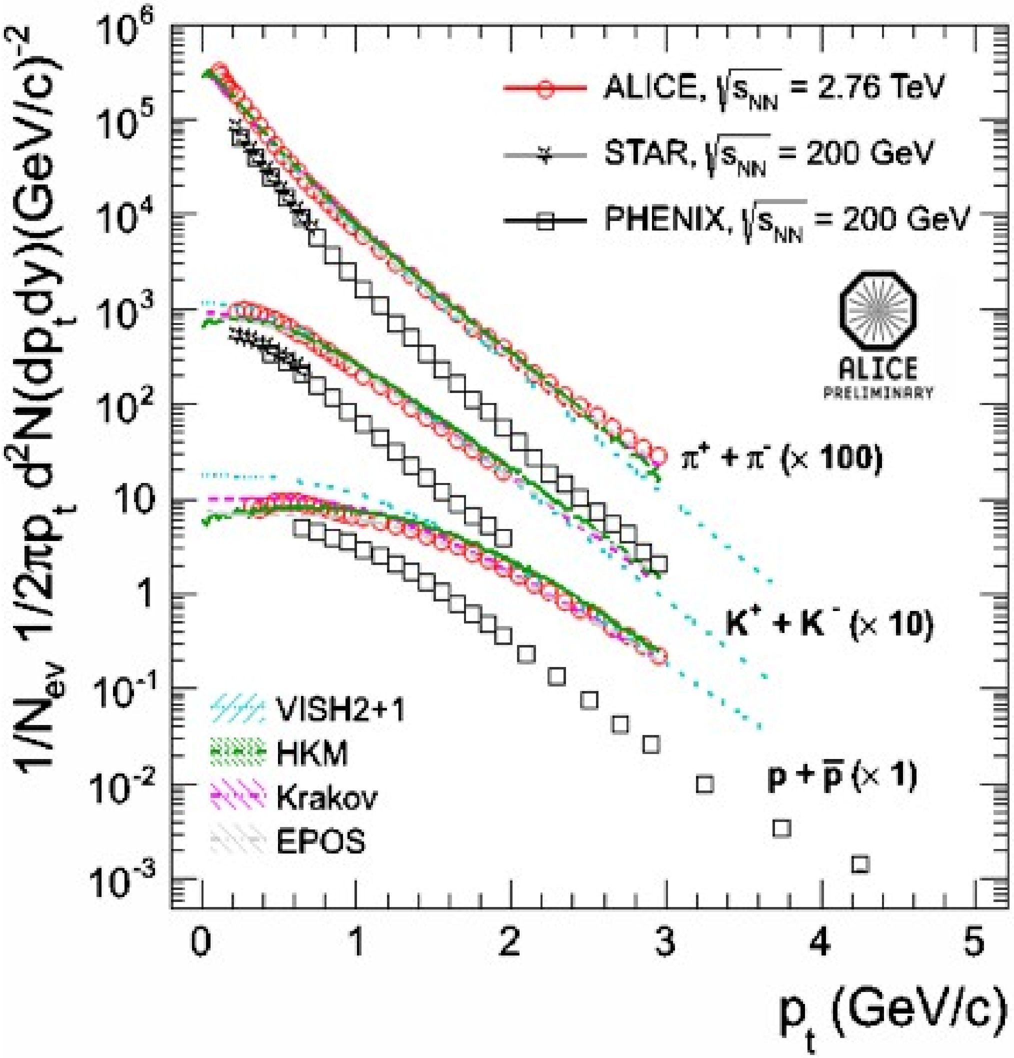
huge growth at LHC

from R_{long}: expansion at LHC 10 fm/c

$$R_{long} = \tau_f \sqrt{T/m_t}$$



spectra of identified hadrons

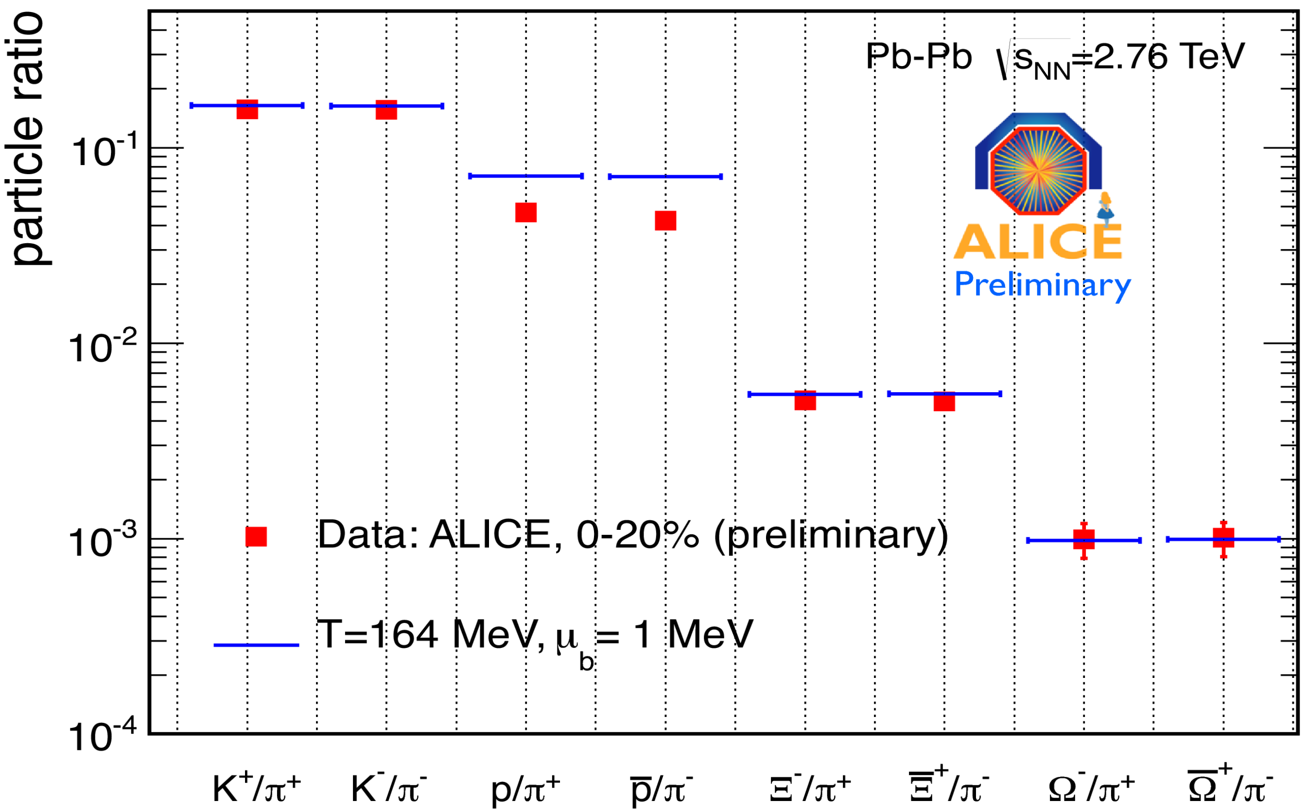


- spectral shapes indicate significantly larger expansion velocity than at RHIC
- hydro calculations that reproduce HBT are also describing spectra very well (HKM, Krakov)

Production of different hadron species

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

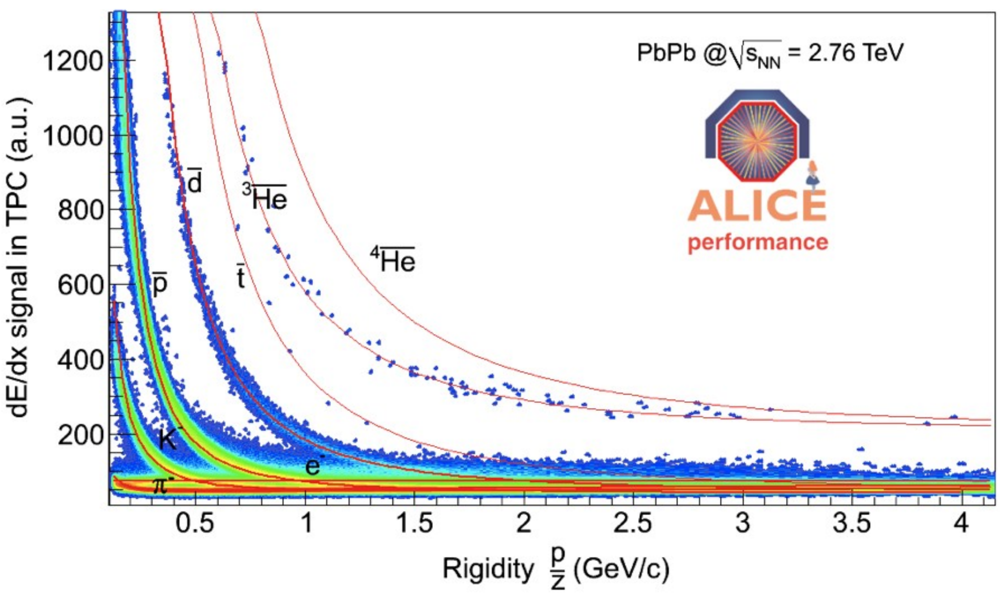
Hadron yields at LHC and statistical model



in agreement with expectations
only: why too few protons?
phi also in perfect agreement with statistical model

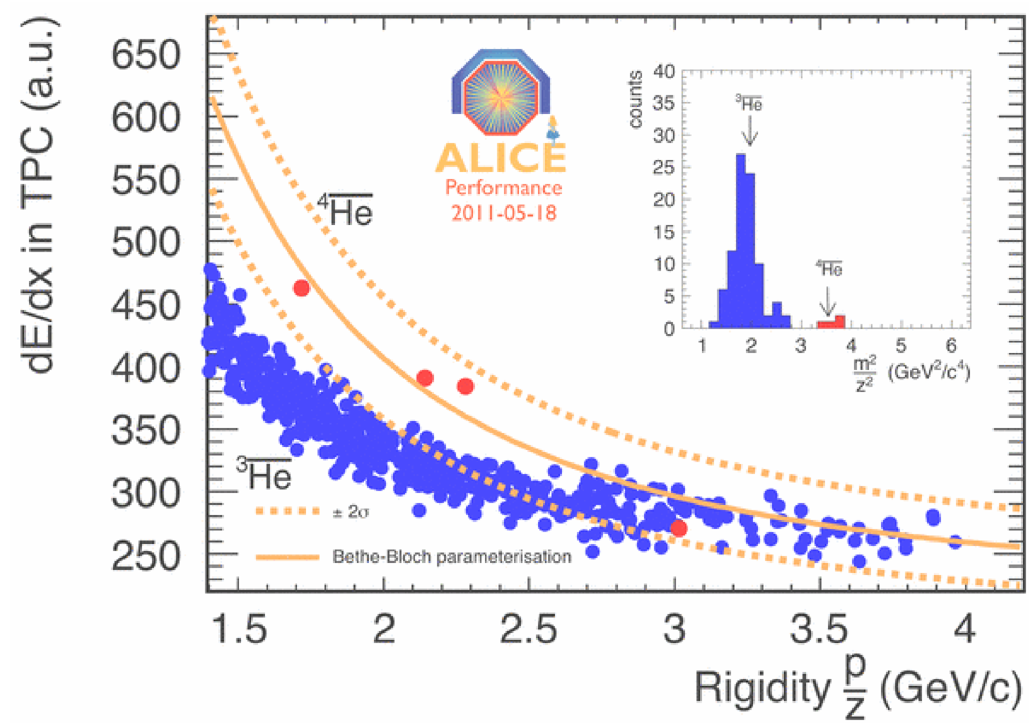
Particle identification via dE/dx in the TPC and observation of anti-4He production

- All particles from electrons to ^{4}He can be identified with the TPC



excellent PID with TPC
dE/dx resolution 5 %
close to theoretical limit

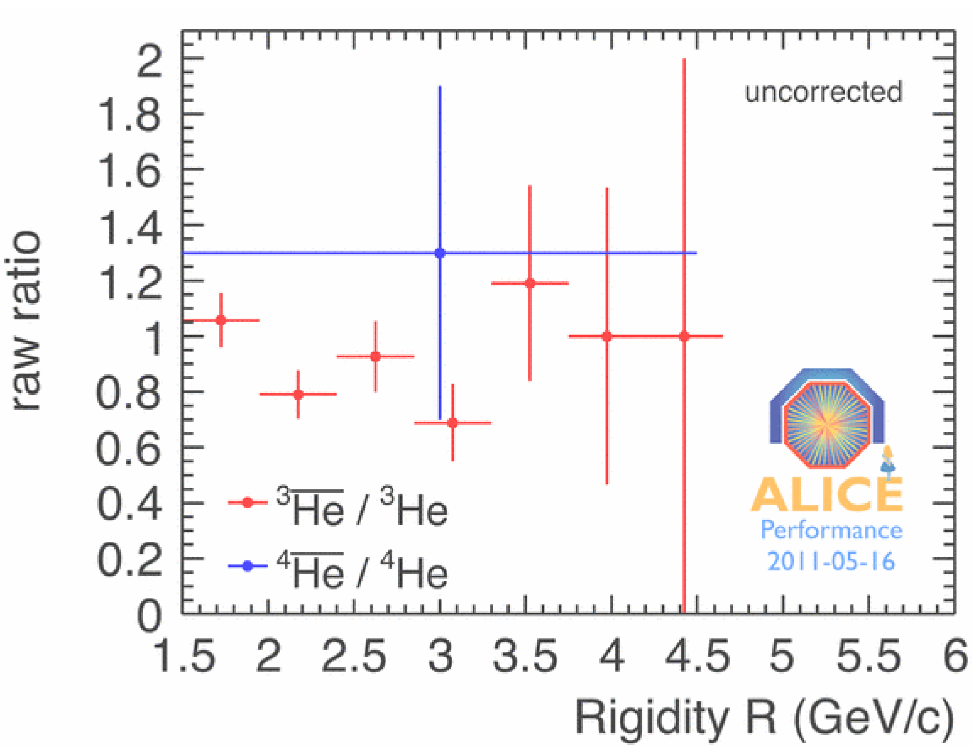
- anti-^{4}He identification



- 4 anti-^{4}He candidates observed so far

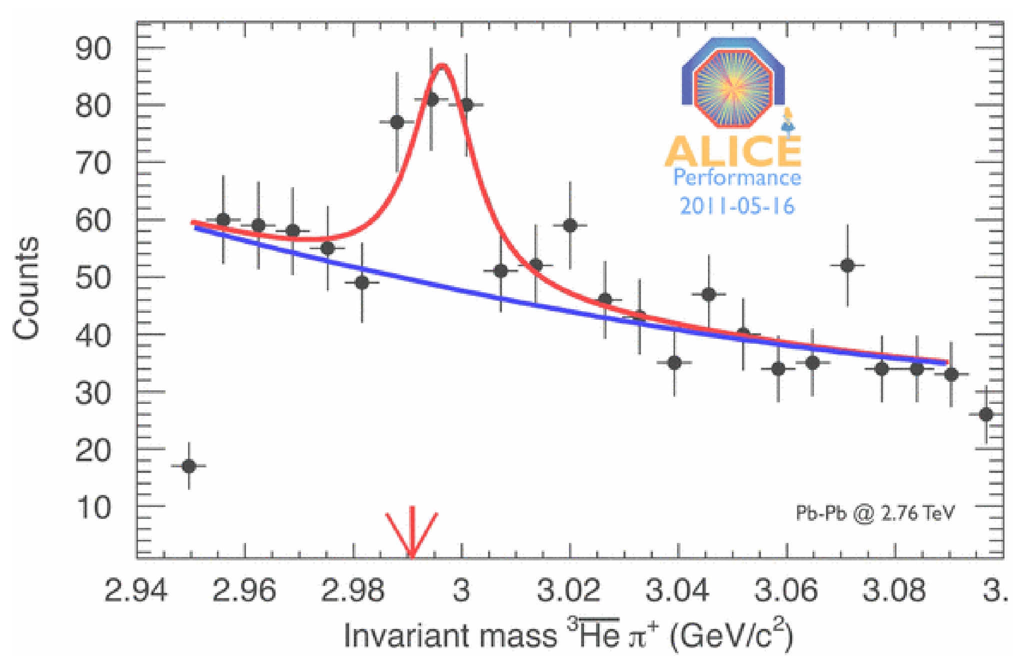
Raw Ratios of anti-^{3}He/^{3}He and anti-^{4}He/^{4}He and anti-hypertriton Observation

- uncorrected raw ratios



- anti-matter and matter seem to be produced in equal proportions
- consistent with baryon chemical potential 1 MeV

- anti-hypertriton

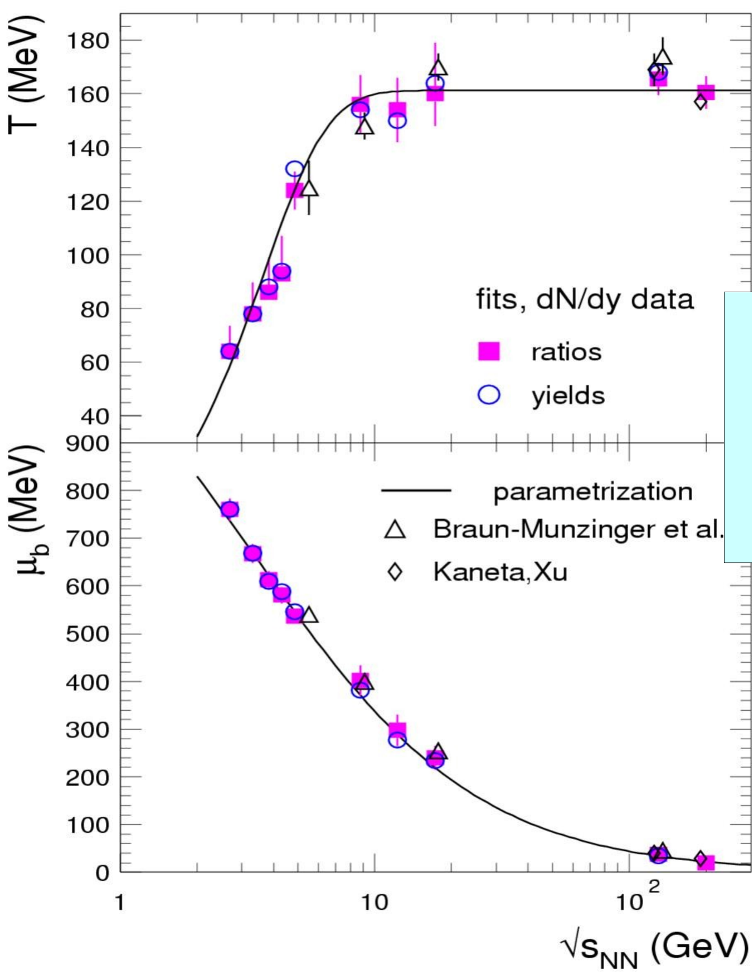


- clear signal observed

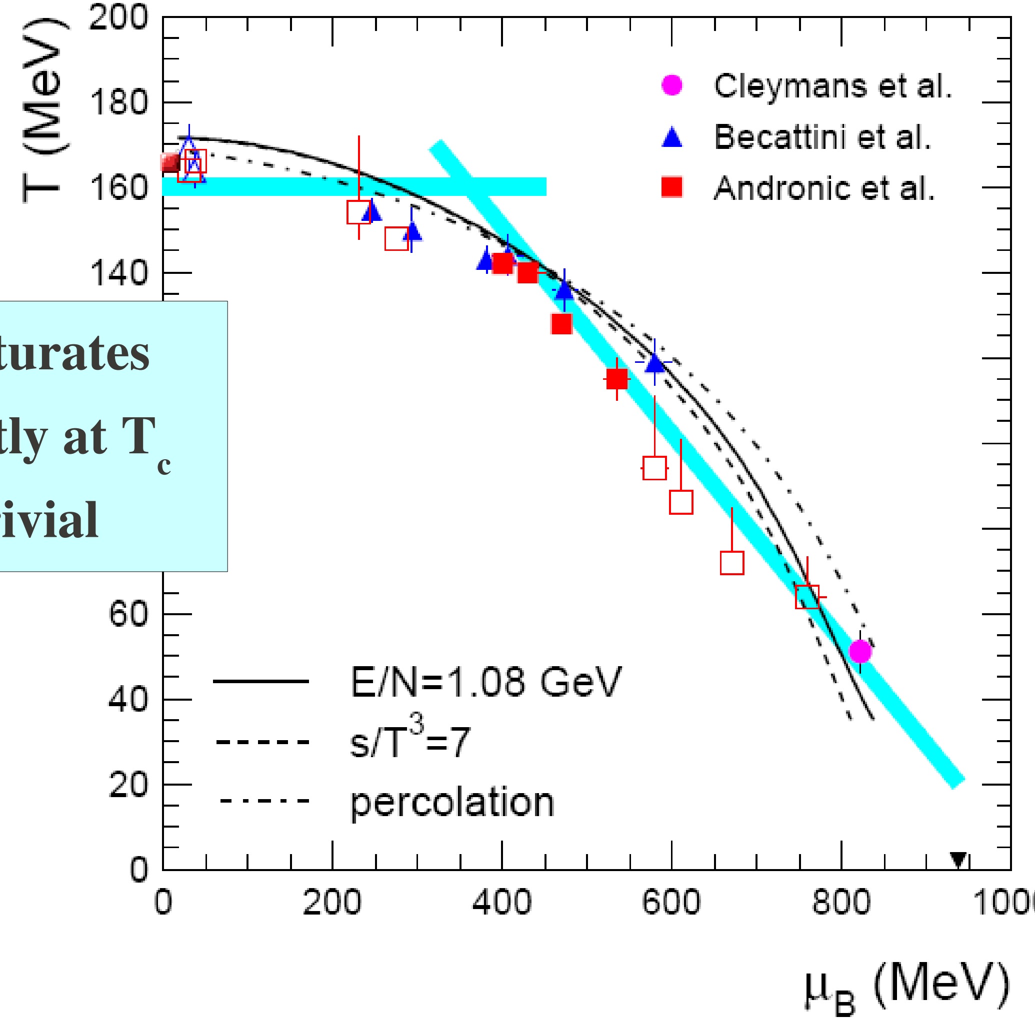
Experimental Knowledge of the QCD Phase Diagram

- agreement between groups doing finite temperature lattice gauge theory: $T_c(\mu=0)$ = 160 - 170 MeV

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



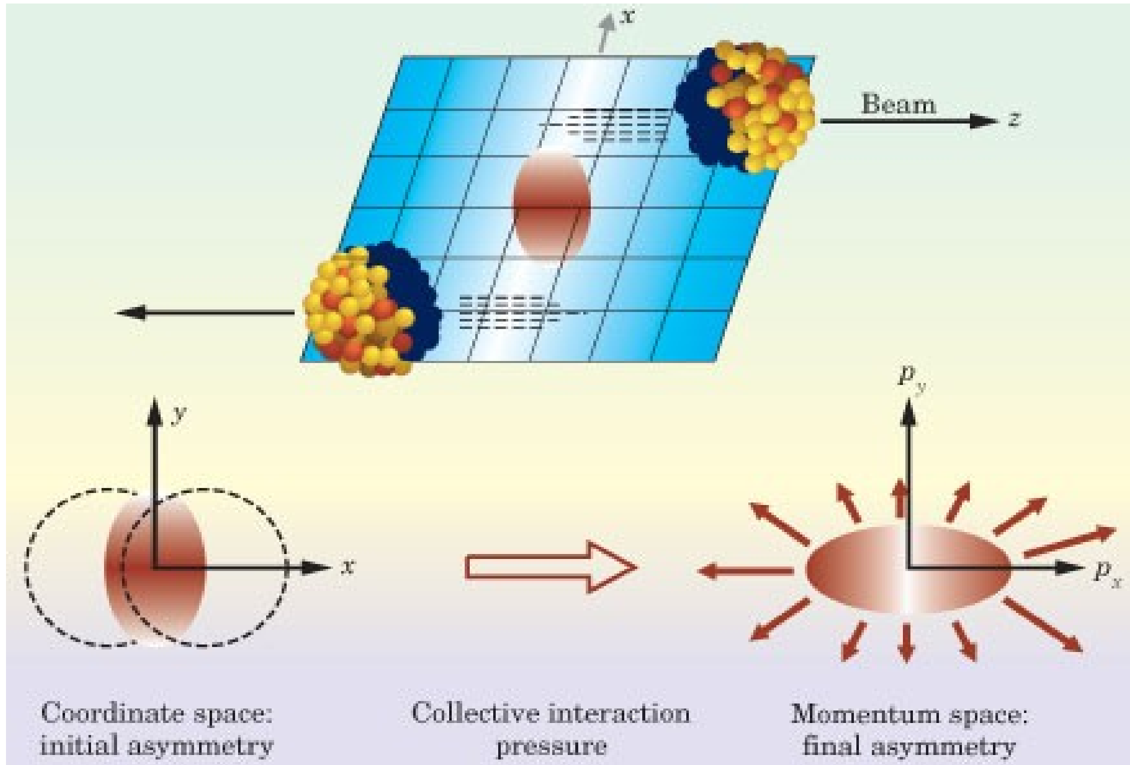
T_{chem} saturates apparently at T_c not trivial



- data points 'chemical' freeze-out of hadrons

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

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

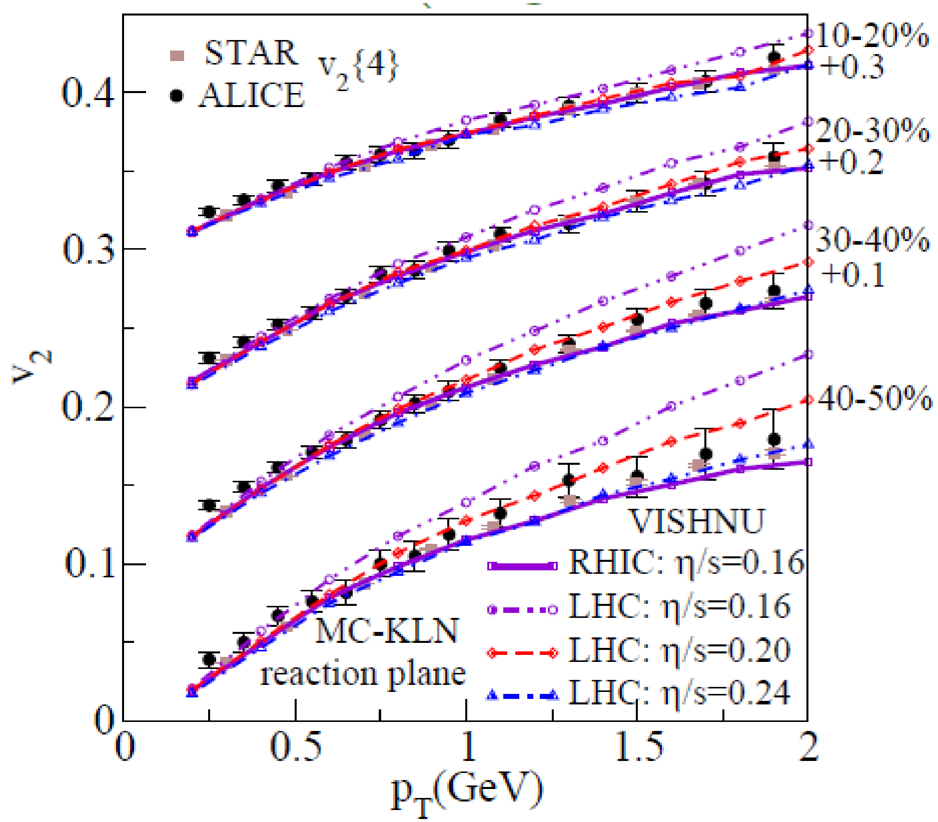
"elliptic flow"

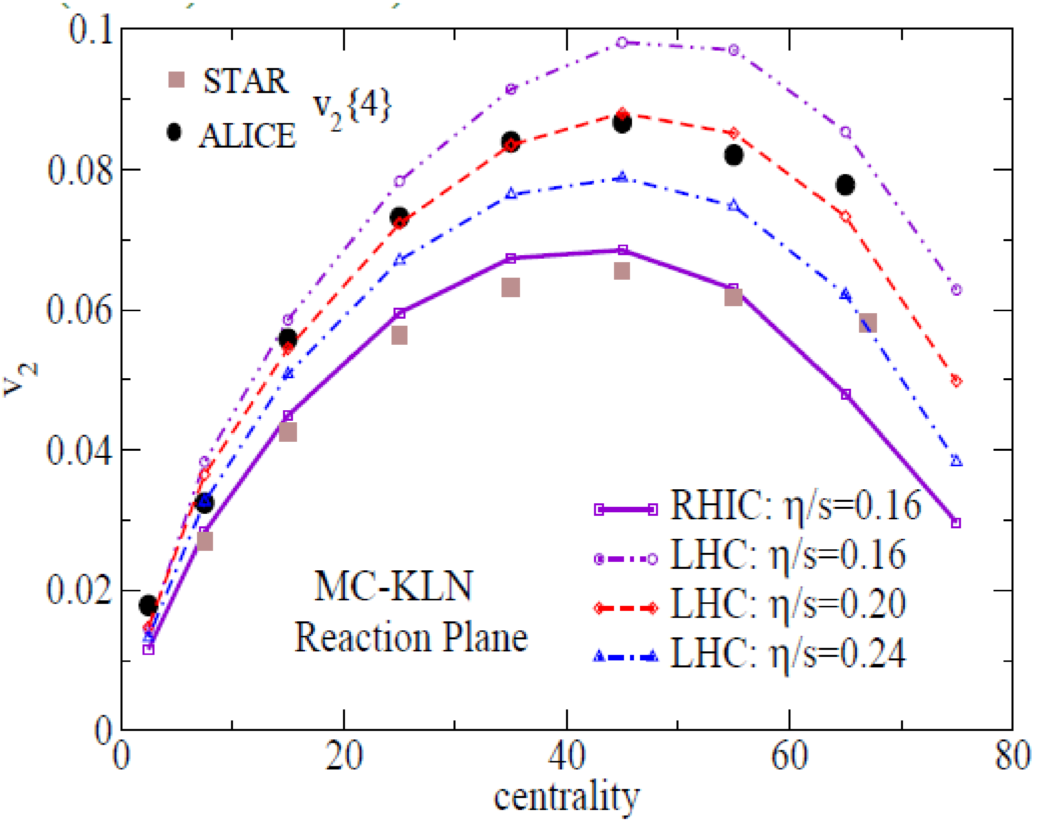
effect of expansion (positive v_2) seen from top AGS energy

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

Elliptic flow of charged particles at LHC

elliptic flow at given p_t very similar to RHIC (not trivially expected) - system also at LHC strongly coupled, indicated by very small ratio of shear viscosity to entropy density pt integrated even stronger due to larger expansion velocity





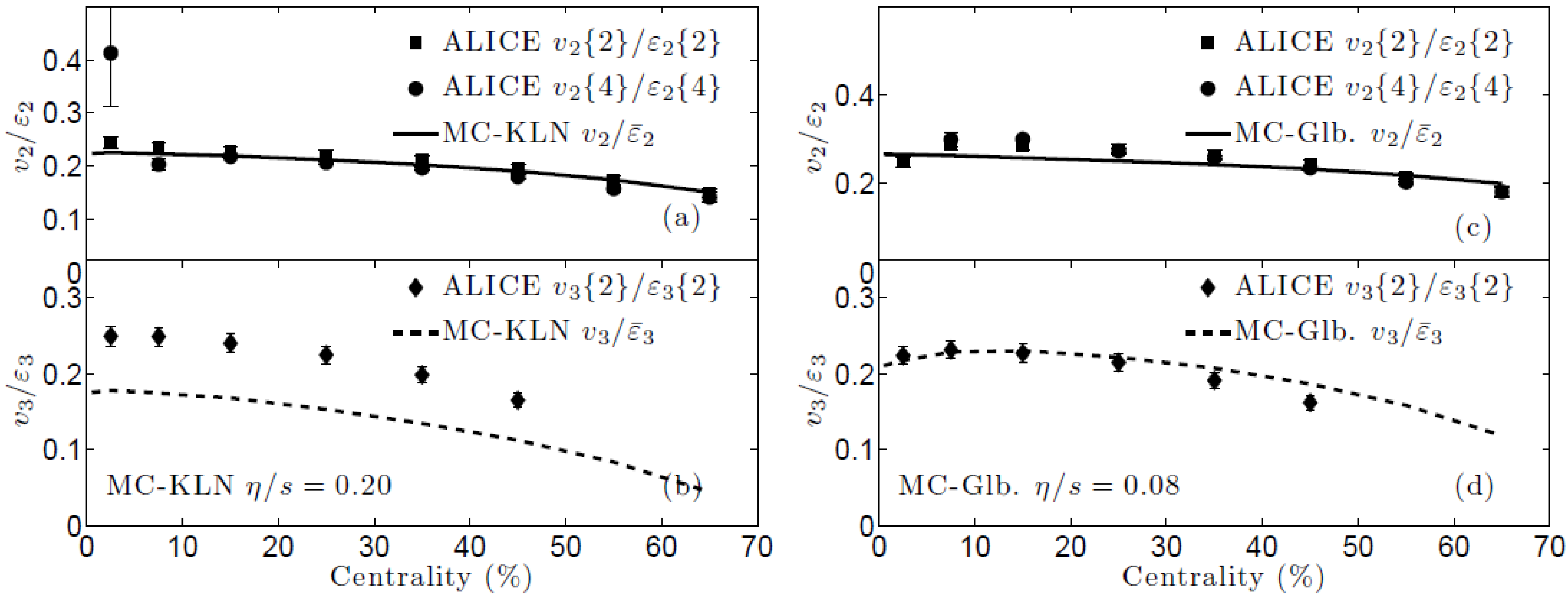
calculations: Song, Bass, Heinz, PRC83 (2011) 054912

2+1 viscous hydrodynamic evolution plus hadronic phase

---- color glass initial condition plus eta/s = 0.20 describe data well

Fitting odd and even moments – obtain initial condition

Z.Qiu, C. Shen. U. Heinz, PLB707 (2012) 151 viscous 2+1 d hydrodynamics

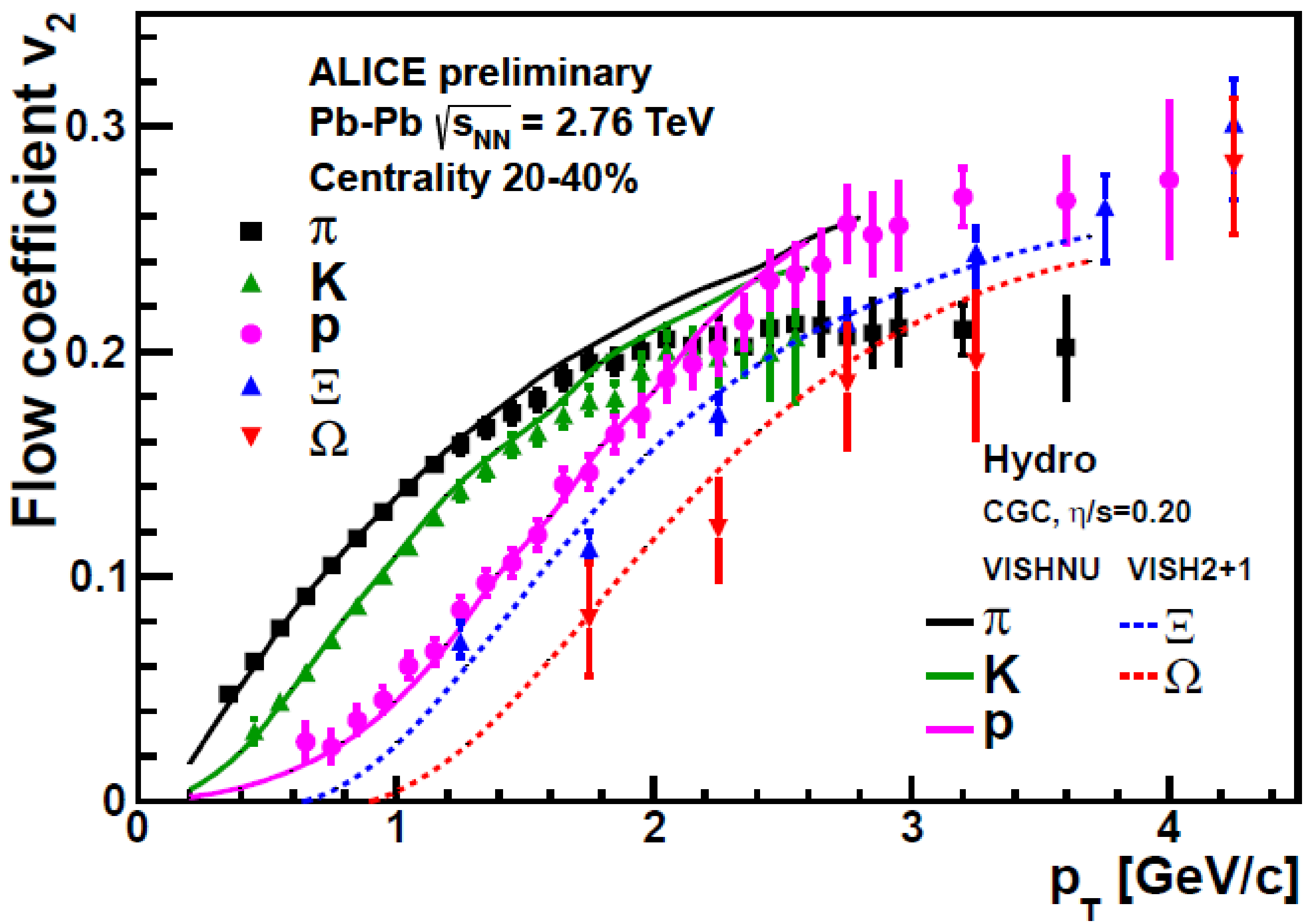


$v_{2,3}$ scaled to initial eccentricity $\varepsilon_x = \frac{\langle\langle y^2 - x^2\rangle\rangle}{\langle\langle y^2 + x^2\rangle\rangle}$

with Glauber initial condition and η/s = 0.08 both v_3/ε and v_2/ε can be described

η/s close to quantum lower limit 1/4π at LHC

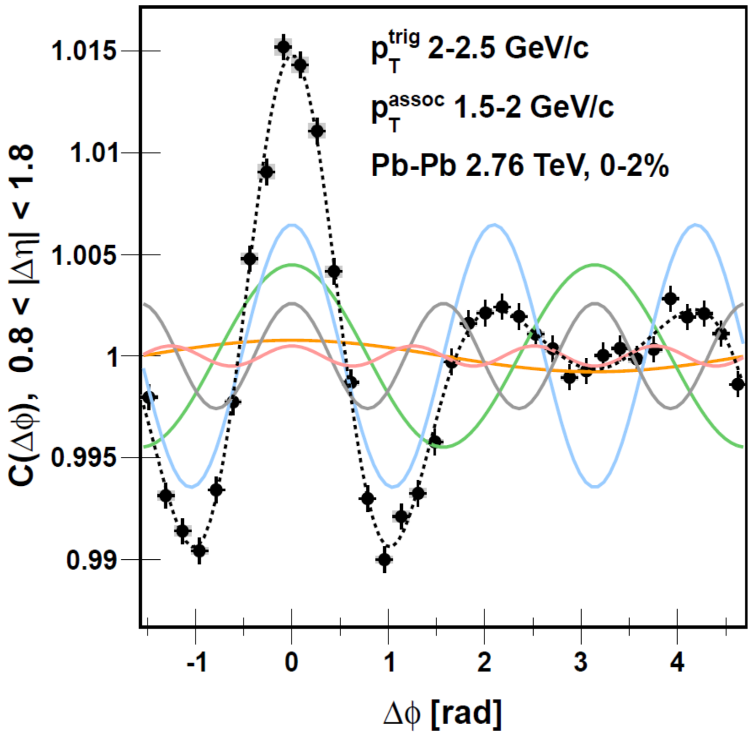
Elliptic Flow in PbPb Collisions at $\sqrt{s}_{NN}$ = 2.76 TeV

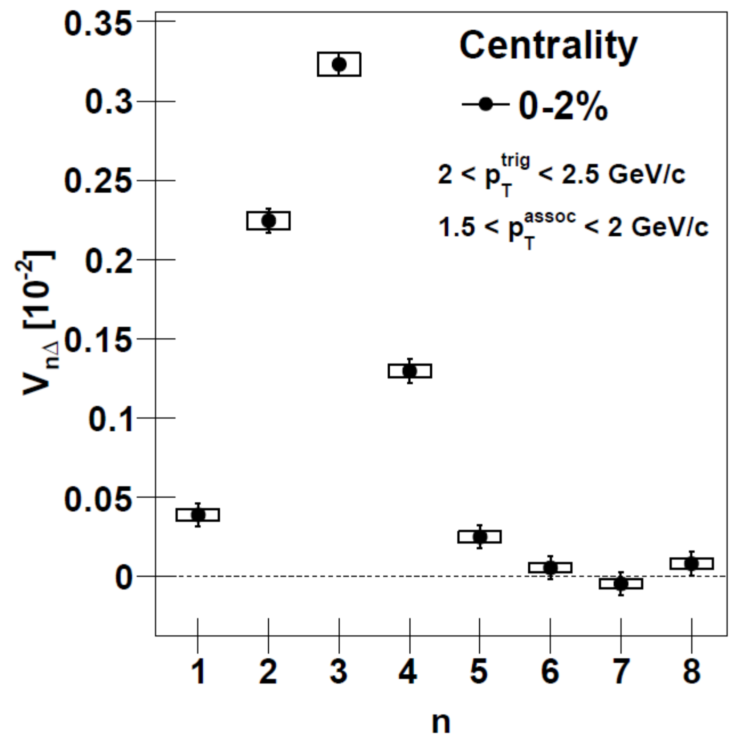


rapidly rising v_2 with p_t and mass ordering typical features of hydrodyn. expansion
nearly ideal (non-dissipative) hydrodynamics reproduces data - surprise!

The 2-particle correlation function – higher moments

ALICE, PRL 107 (2011) 032301 and PLB 708 (2012) 249





measurement of the first 8 harmonic coefficients

v_1-v_5 significantly larger than 0, maximum at v_3

current understanding: higher harmonics (3,4,5,...) are due to initial inhomogeneities caused by granularity of binary parton-parton collisions

Propagation of sound in the quark-gluon plasma

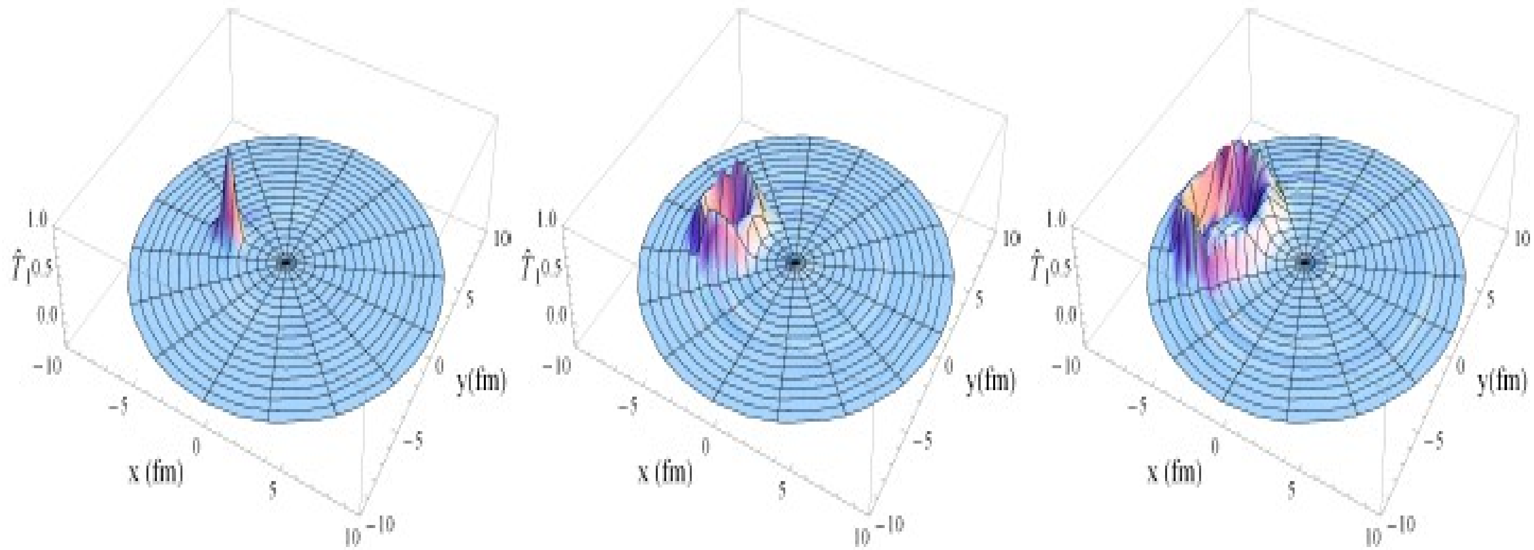
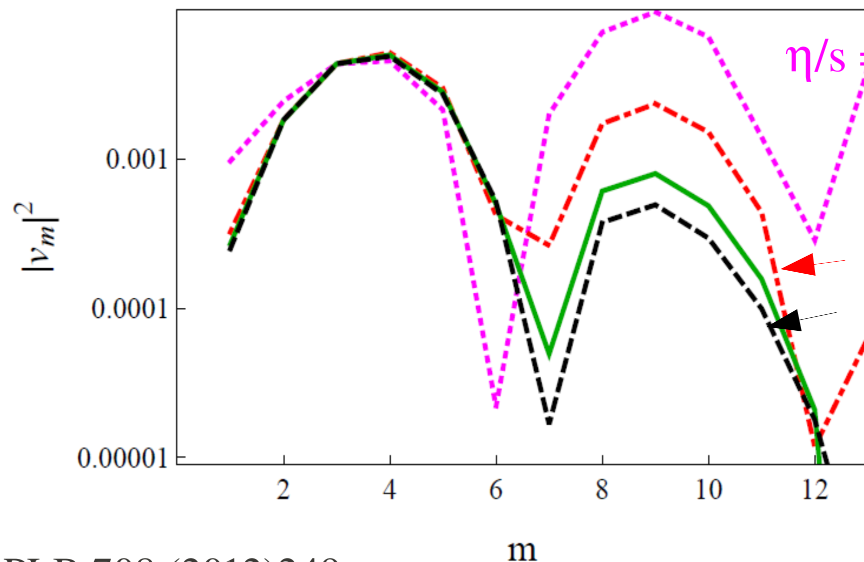


Figure 2: Evolution of the temperature perturbation $\hat{T}_1(\tau, r, \phi)$ in the rescaled frame but in the regular coordinates for $\tau = 1, 4, 6\ fm/c$ from left to right. (Taken from [10])

<u>calculations:</u> Staig & Shuryak arXiv:1106.3243, small initial temperature inhomogeneities due to initial distributions of binary parton collisions evolve in expanding strongly coupled quark-gluon plasma
determine moments of the power spectrum at the decoupling (freeze-out) stage

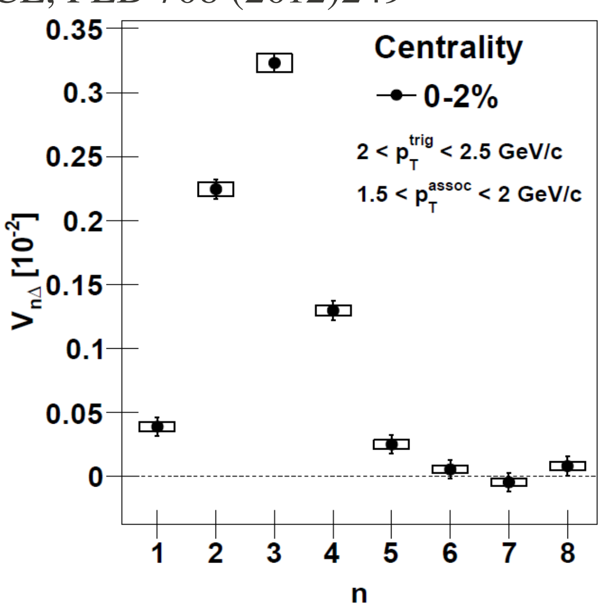
Propagation of sound in the quark-gluon plasma

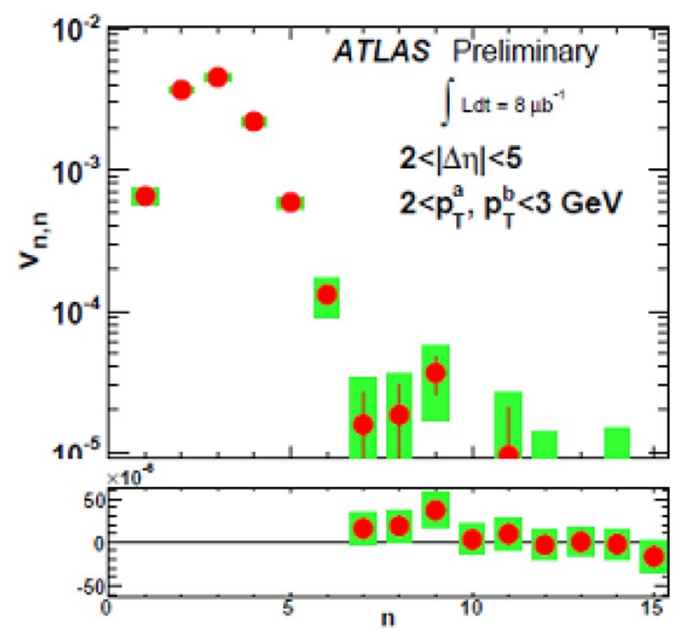


Staig & Shuryak arXiv:1109.6633

- hydrodynamics describes even small perturbations of exploding fireball
- sensitivity to ratio shear viscosity/entropy density and to expansion velocity

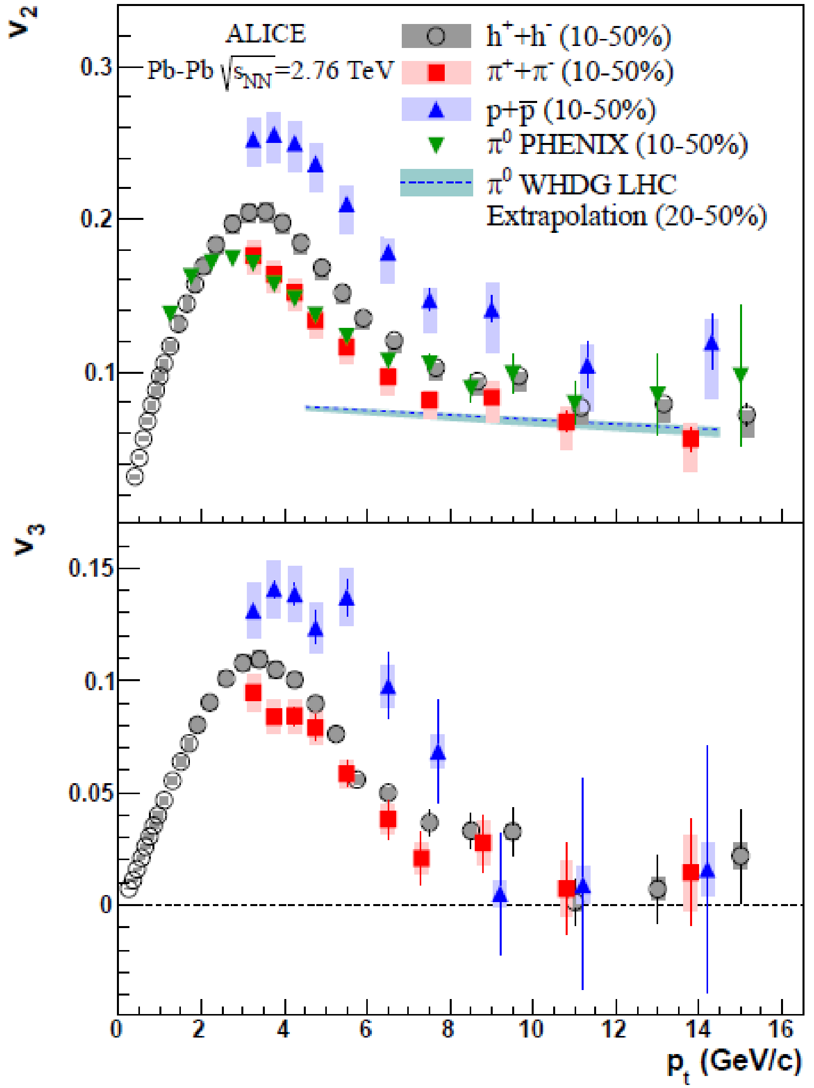
ALICE, PLB 708 (2012)249





Flow at high transverse momentum

arXiv 1205.5761 [nucl-ex]



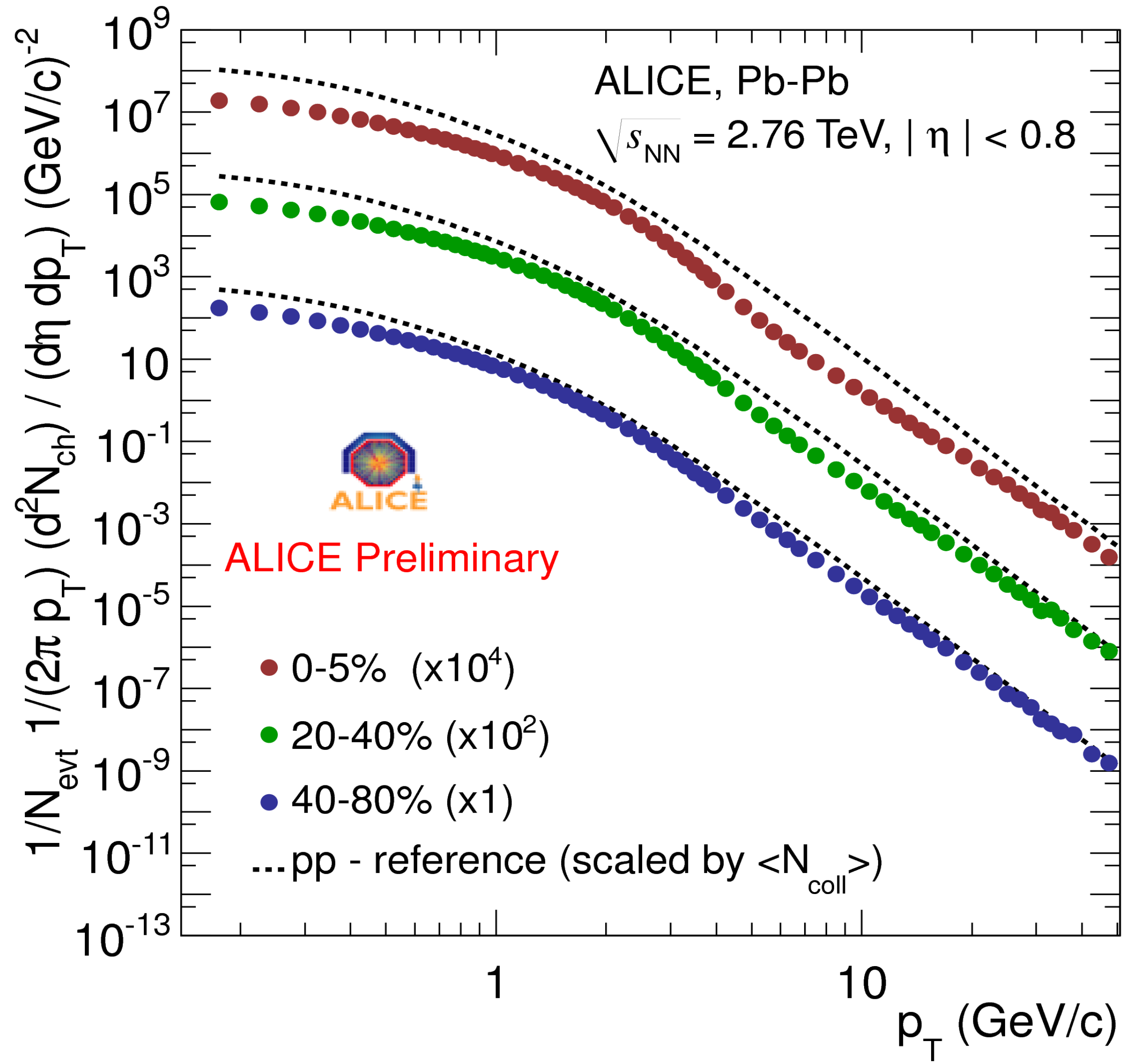
calculations: Horowitz & Gyulassy 2011

elliptic flow:
collective behavior vanishes
universal for all species
small remaining ellipticity due to
- back-to-back dijet structure of events
- energy loss of partons less in plane
(short axis) vs out-of-plane (long axis)

octupole moment:
effects due initial fluctuations and
propagation of sound vanish
coefficient approaches zero for all
hadron species

energy loss of partons in the quark-gluon plasma

spectra in Central and Peripheral PbPb Collisions at LHC



strong suppression relative to pp reference in central PbPb collisions above 3 GeV/c

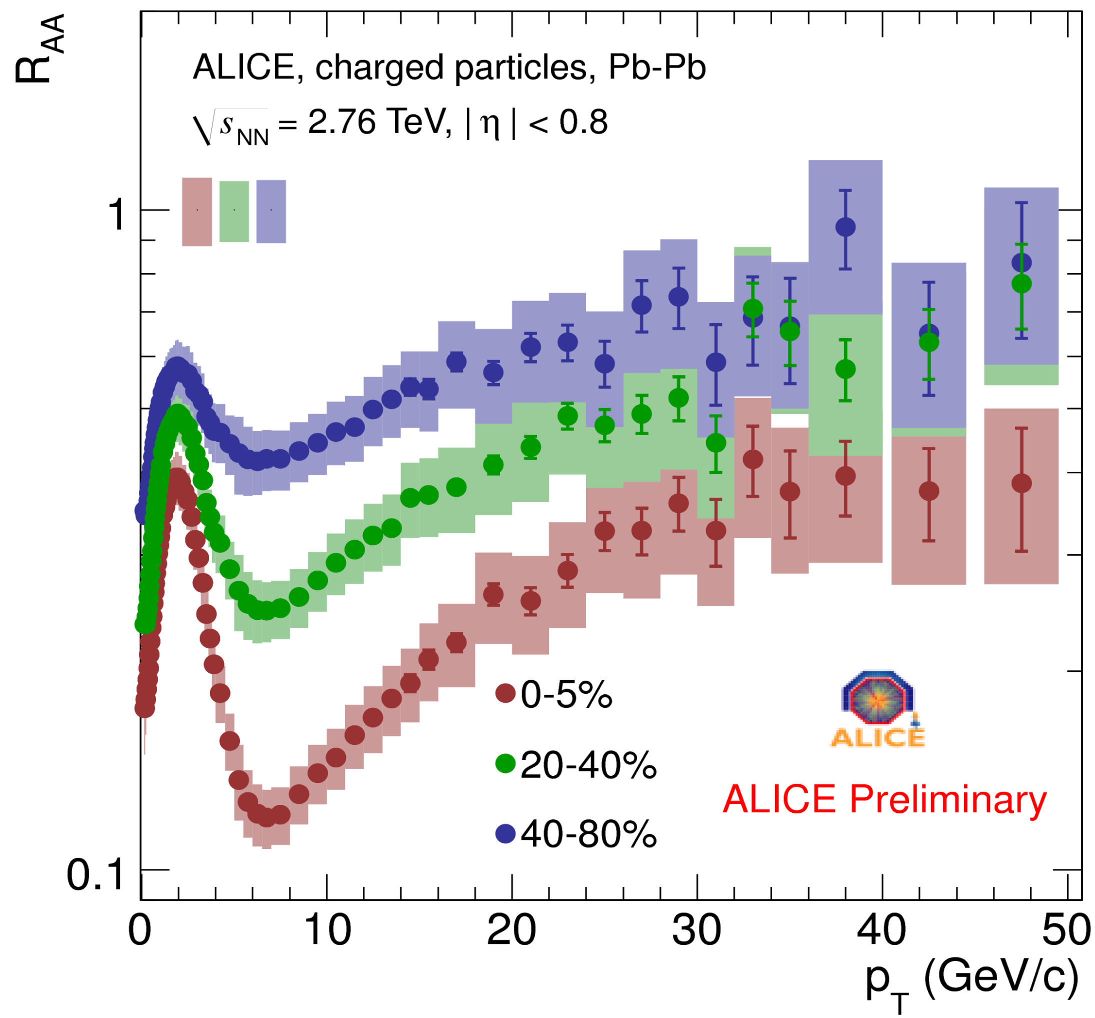
Effect of Very Dense Medium on Jets

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

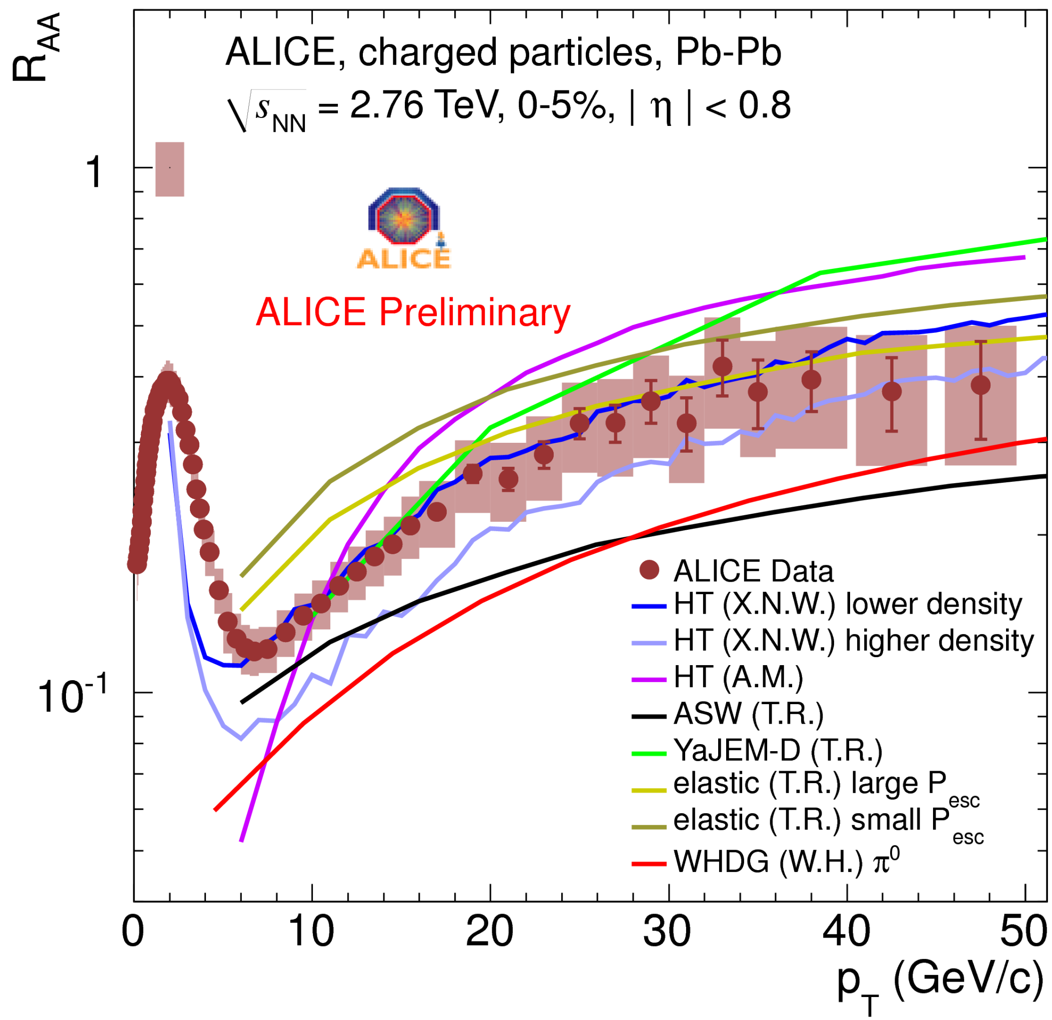
if pQCD is valid at high transverse momentum
$R_{AA} = 1$

- p_T reach 50 GeV/c (soon 100)
- shape of p_T distribution changes with collision centrality → different suppression pattern depending on collision centrality
- strong suppression in central collisions
- hint of leveling off above p_T=30 GeV/c **maybe pQCD limit is never reached**

concept of quasiparticles in dense fireball invalid?



First Comparison to Models
– Goal to Extract Transport Coefficient

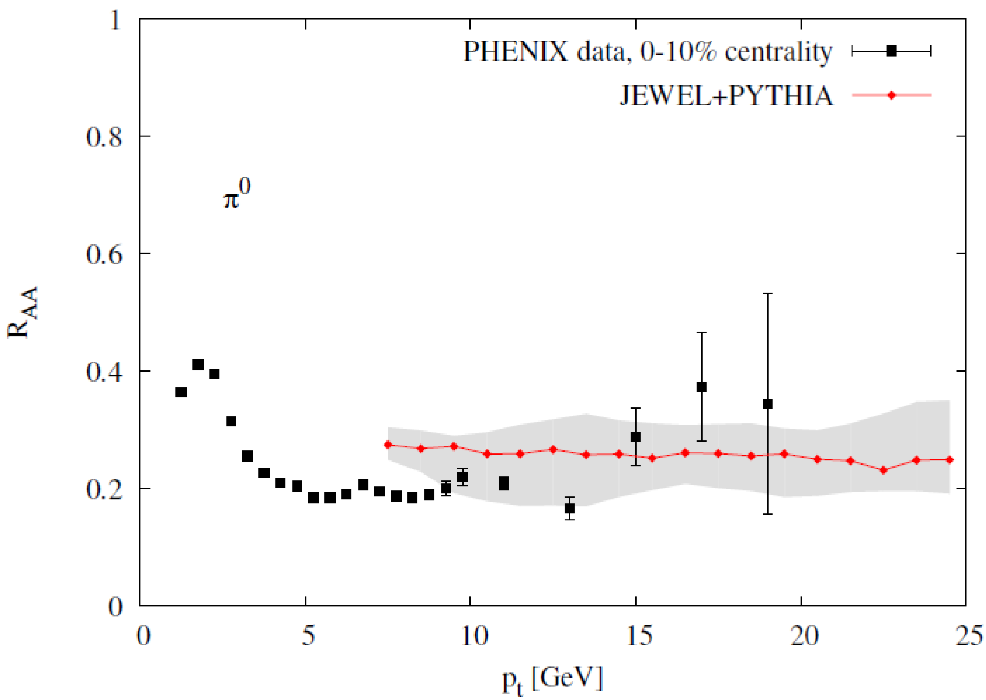


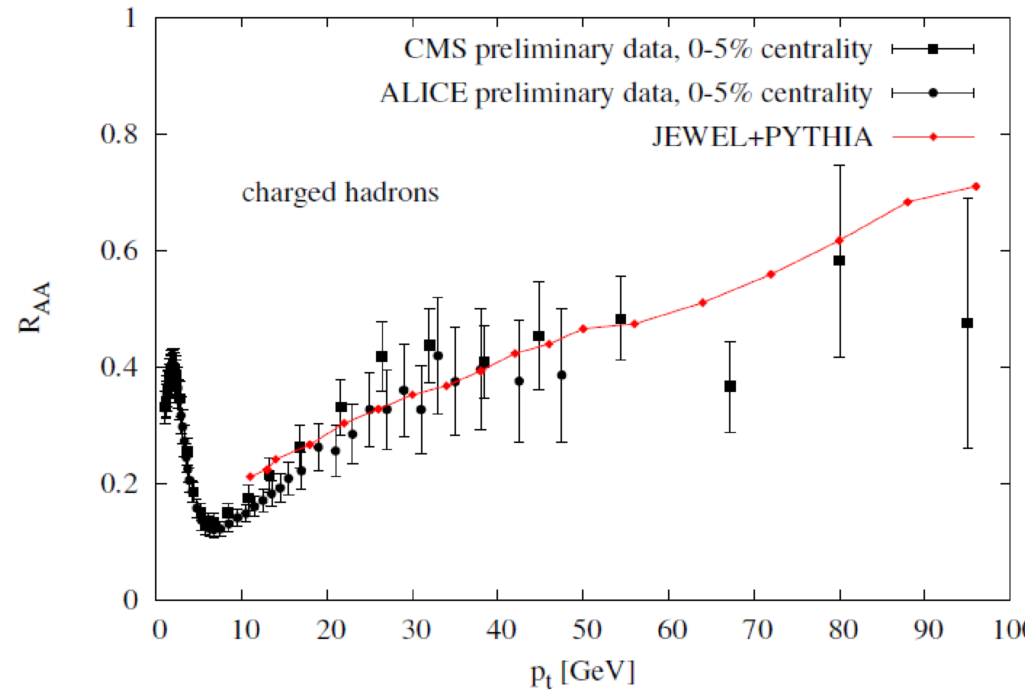
data show sensitivity
program for next years
- precision info for different quark flavors & large kinematic range
- determine effect of medium (QGP) on jets and vice versa

background info: data at RHIC show weak sensitivity to transport coefficients due to very steeply falling spectrum

Evolution of pQCD jet in the QGP medium

K. Zapp, F. Krauss, U. Wiedemann arXiv:1111.6838
modeling of multiple scattering in the medium via infrared continued 2 → 2 scattering matrix element in pQCD and in-medium parton shower for further emissions





RHIC: T_i = 350 MeV τ_i = 0.8 fm/c
scale is set by final state particle multiplicity

LHC: T_i = 530 MeV τ_i = 0.5 fm/c
different shape vs RHIC due to sqrt(s) dependence of hard scattering processes

Reconstructed jets

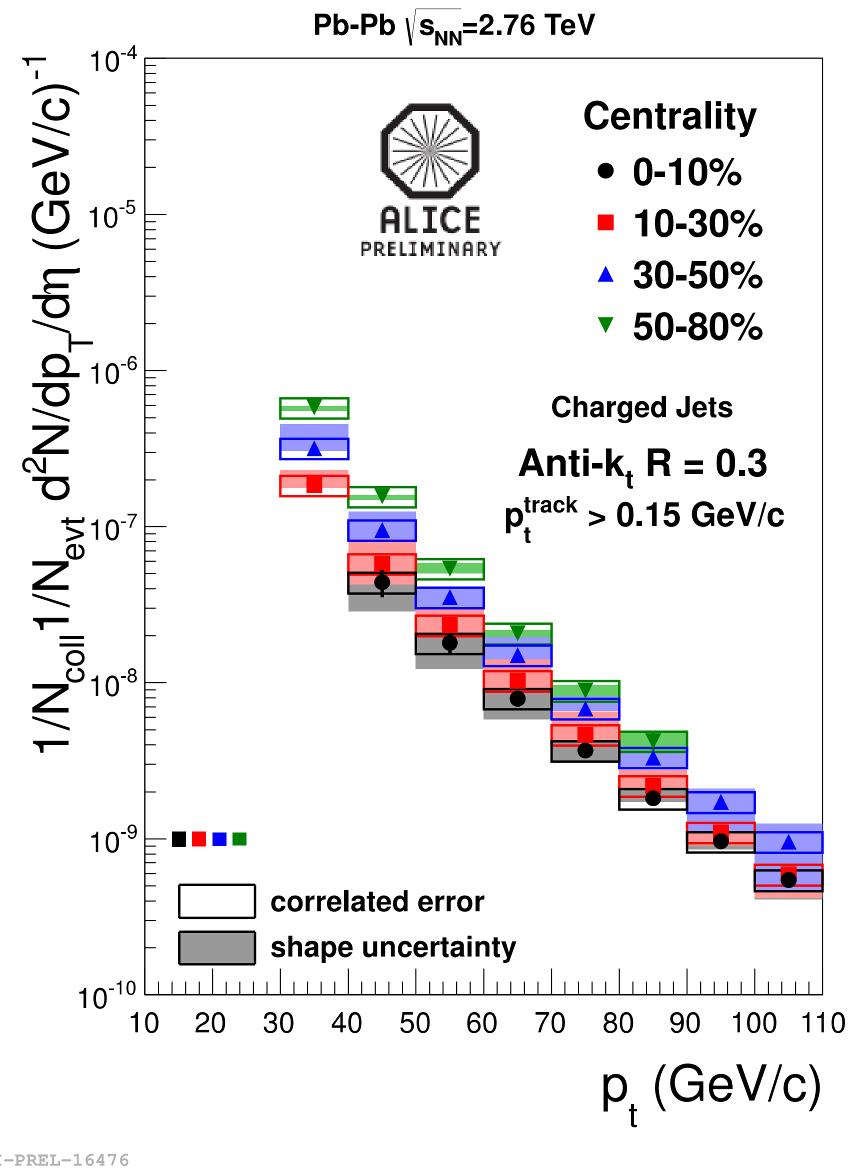
Reconstructed Jets in ALICE

taking into account charged particles down to 150 MeV/c

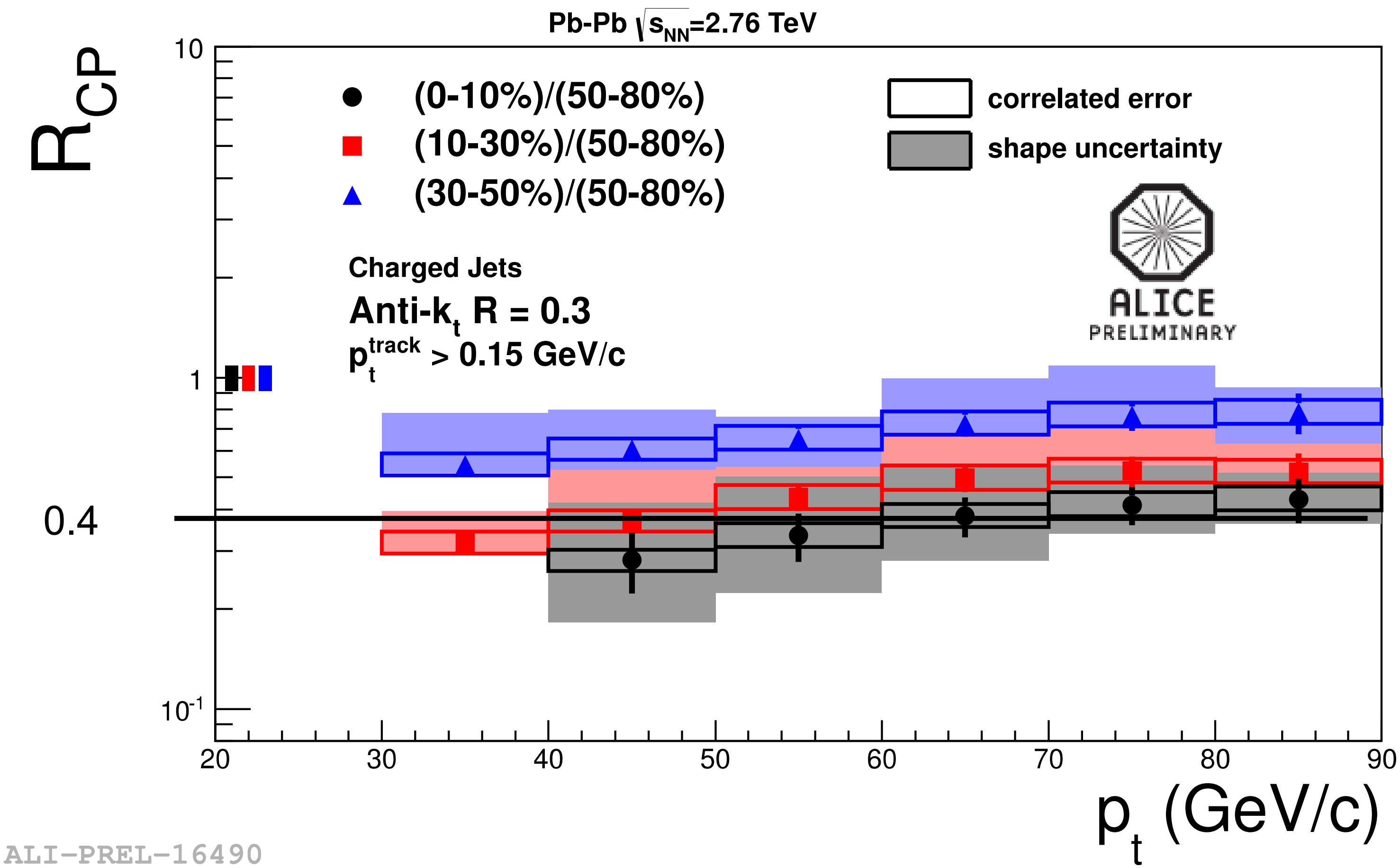
recover redistributed energy

fully corrected for large fluctuations of the underlying Pb Pb event (JHEP 1203 (53), 2012)

reconstructed charged particle jets down to 30 GeV/c

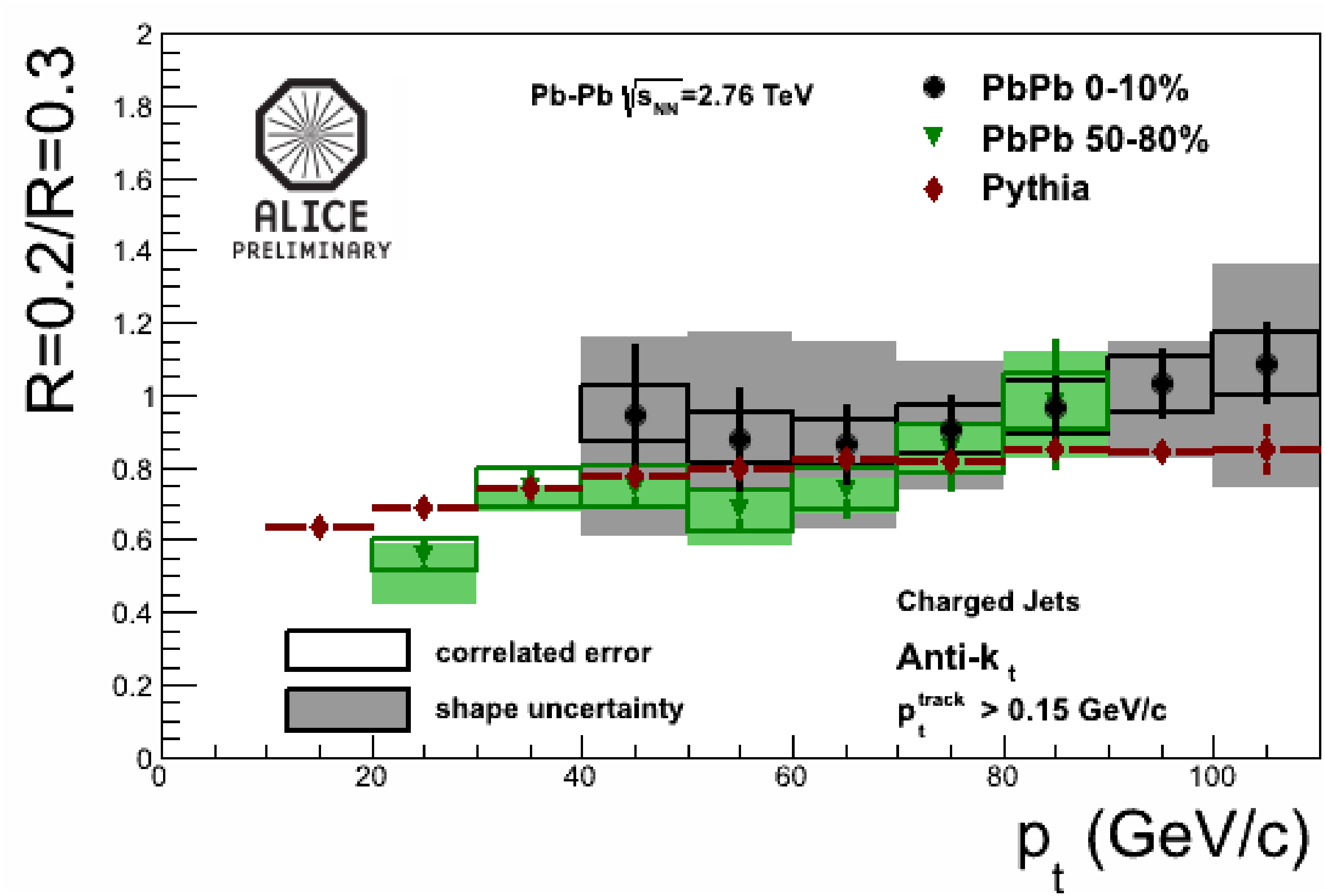


Jet RCP



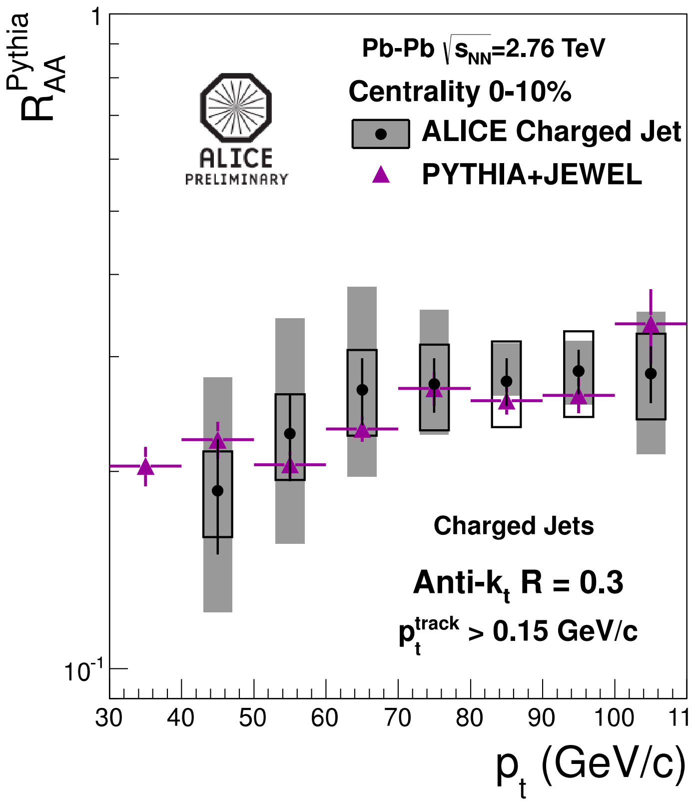
charged jets with R = 0.3 strongly suppressed, despite inclusion of low pt particles.
with higher threshold observed by ATLAS

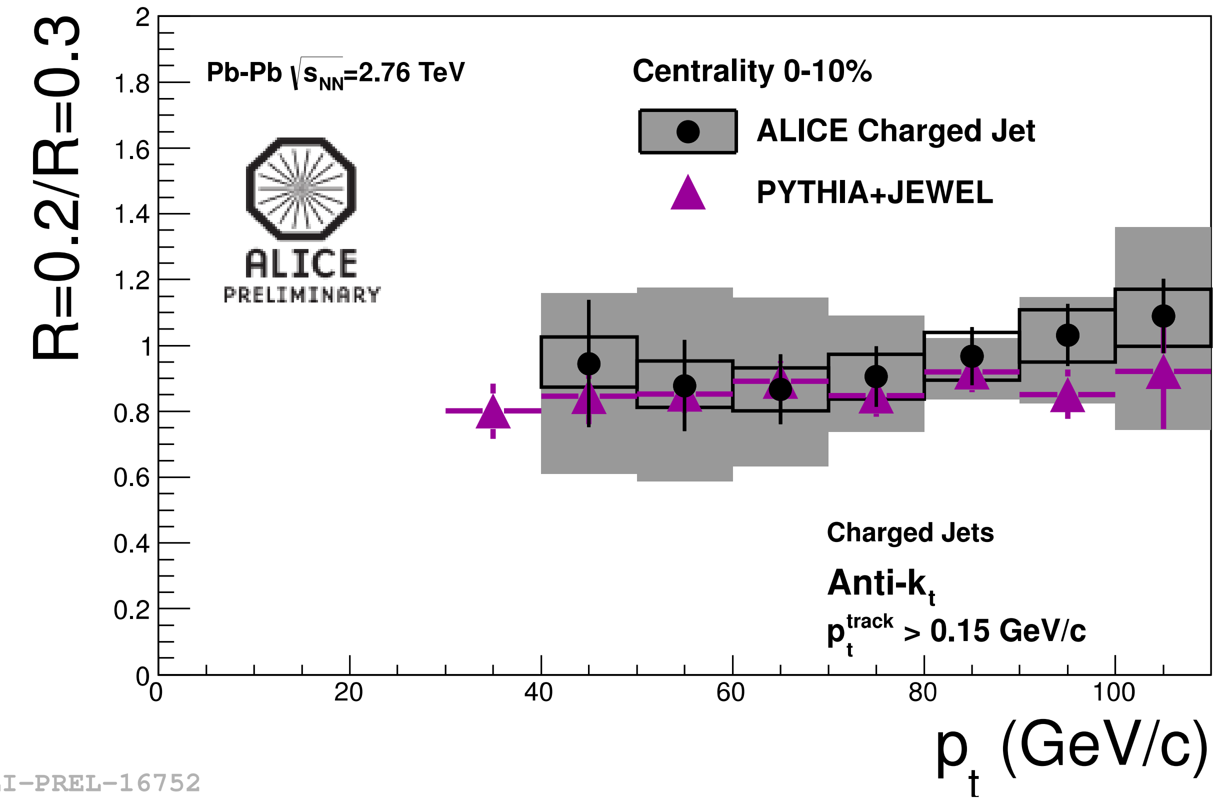
Jet Structure



ratio of cross sections for small cones consistent with vacuum fragmentation.
jet core of reconstructed jets not strongly modified

Model comparison of jet spectrum and shape





ALI-PREL-16745

JEWEL: reproduces charged particle R_{AA} and charged jet R_{AA} and ratio R = 0.2/0.3

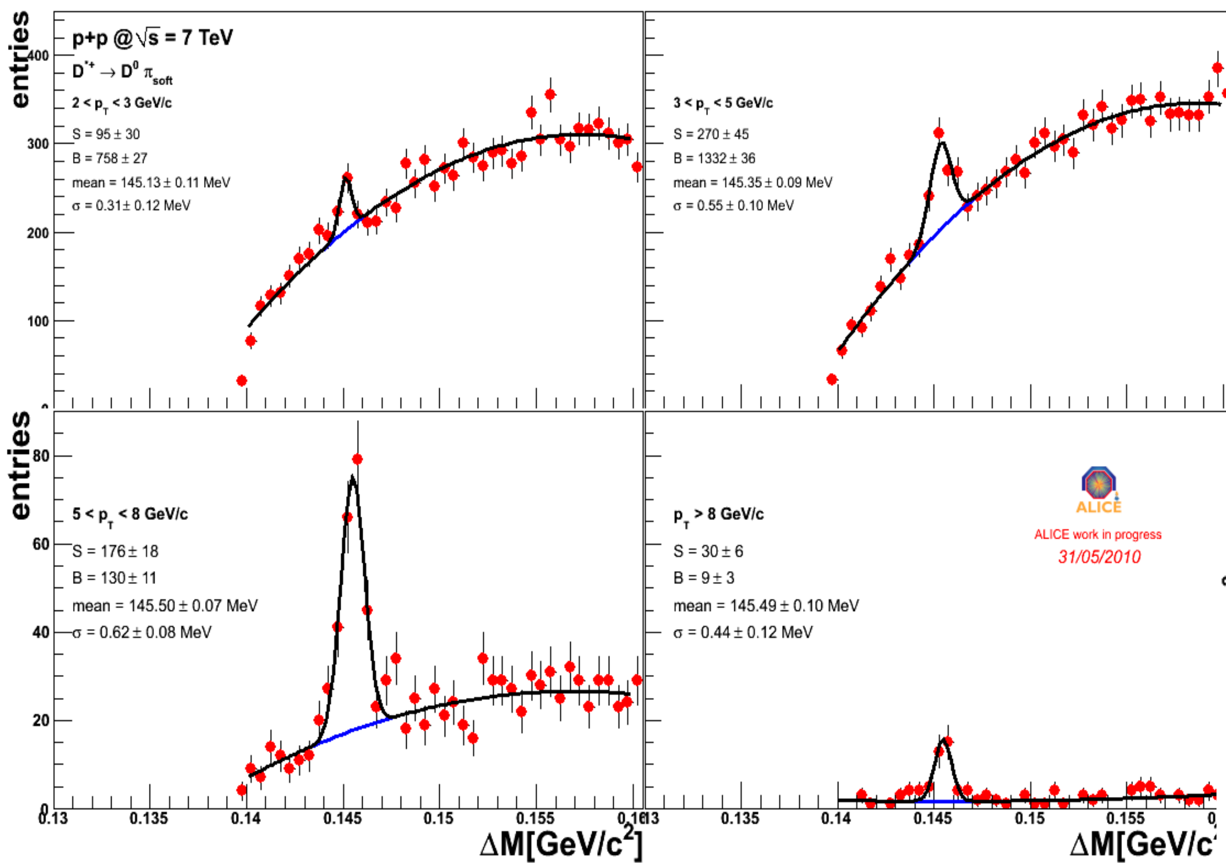
Zapp, Krauss Wiedemann arXiv:1111.6838
JEWEL jet results: private communication

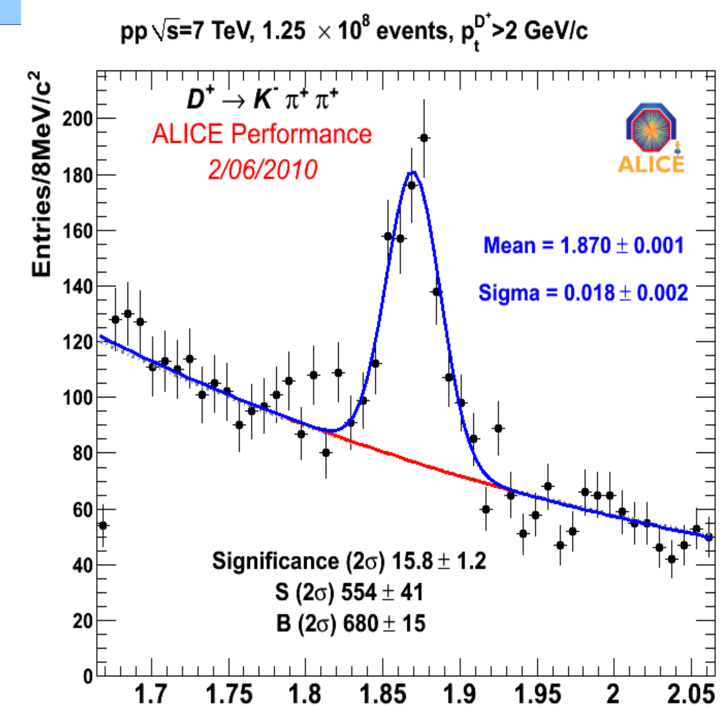
charm quarks in the quark gluon plasma

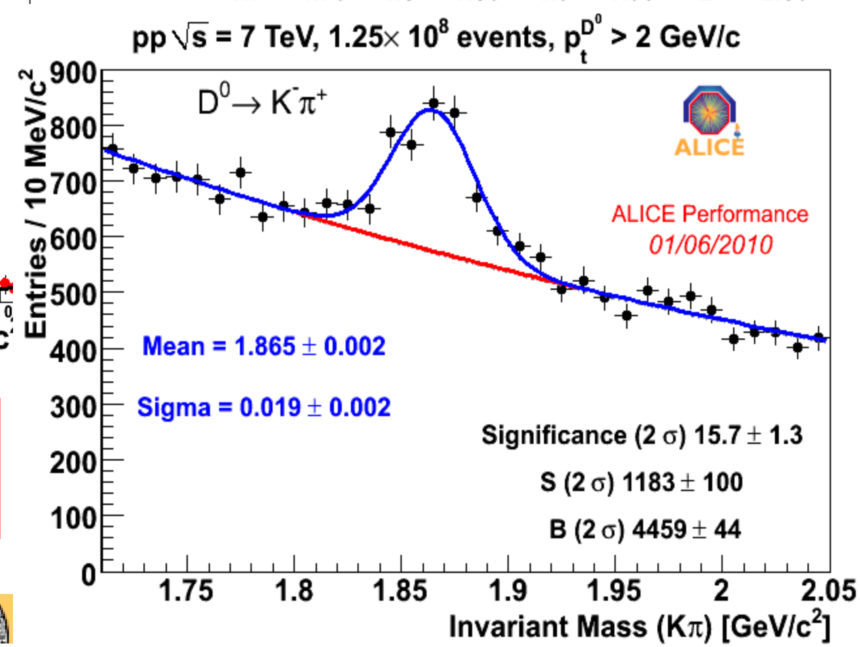
interest 2-fold:
energy loss of heavy quark (radiative energy loss should be suppressed due to large mass (1.2 GeV)
need total charm cross section for understanding of charmonia (ccbar states)

D^0, D^+ and D^{0*} in 7 TeV pp data

$1.25\ 10^8$ events

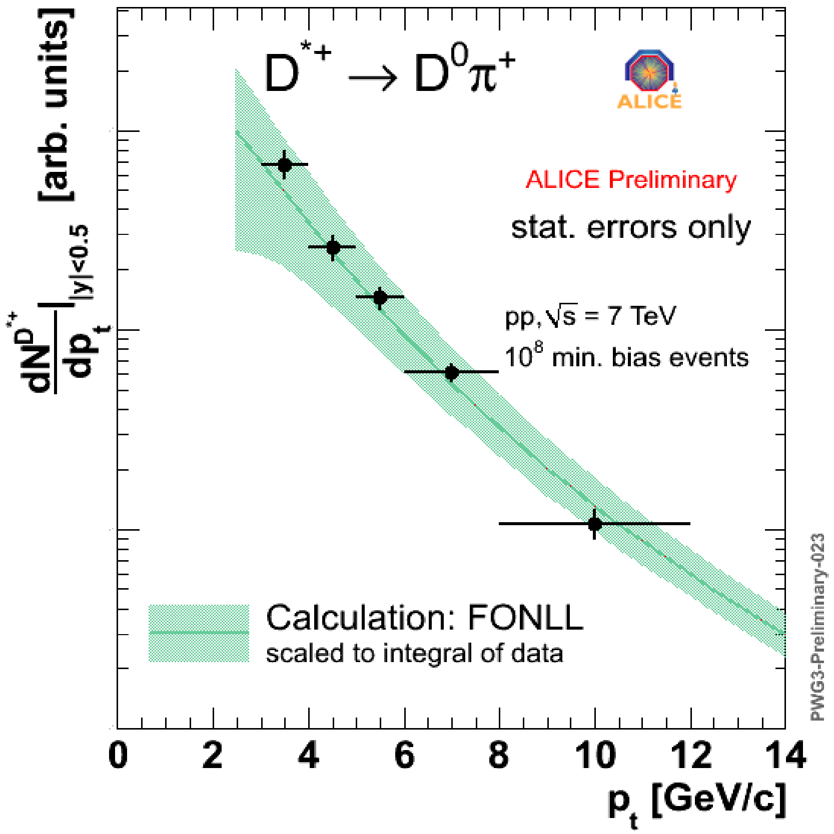


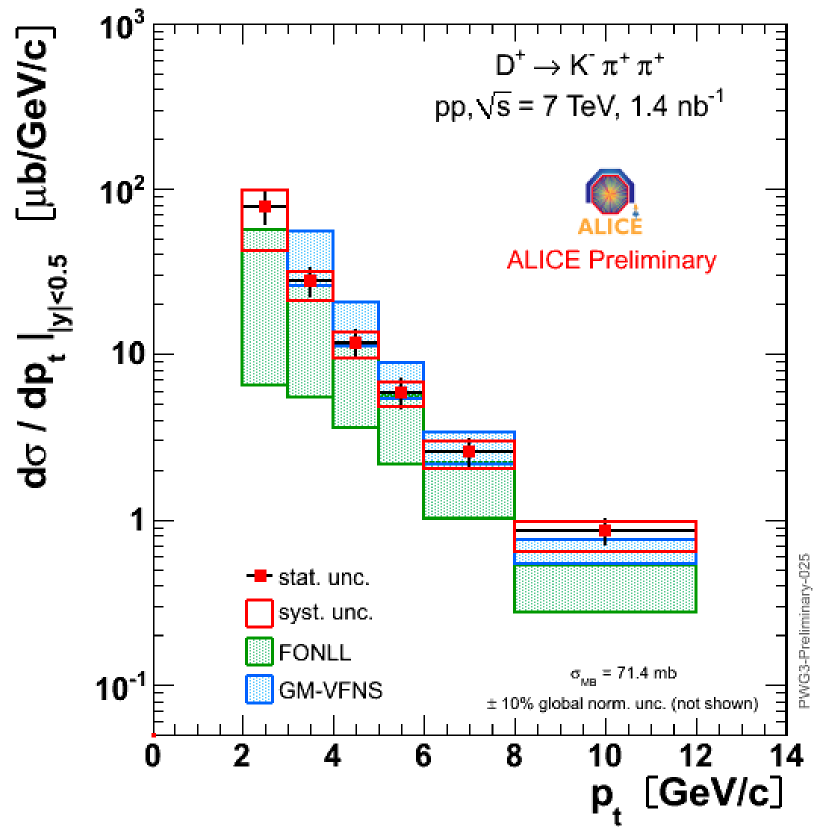




for 10^9 events, expect to measure open charm for $p_t = 0.5 – 15$ GeV/c

Measurements agree well with state of the art pQCD calculations

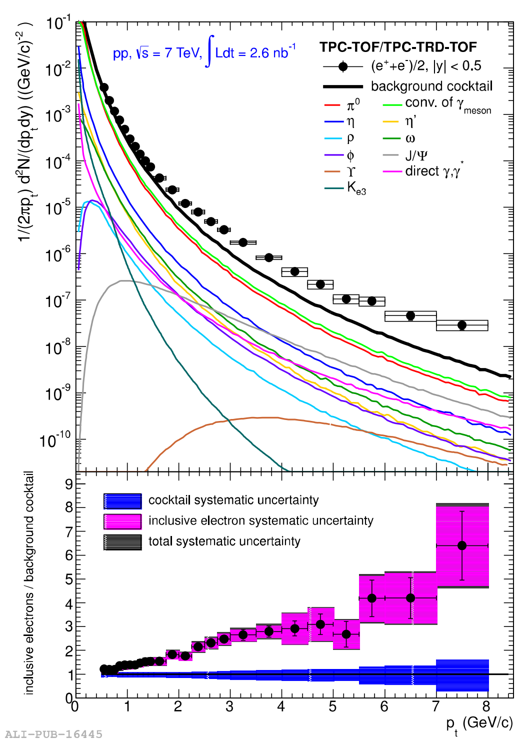


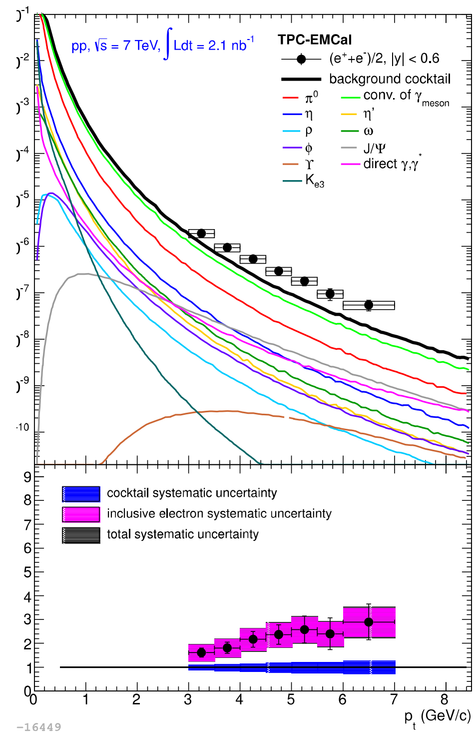


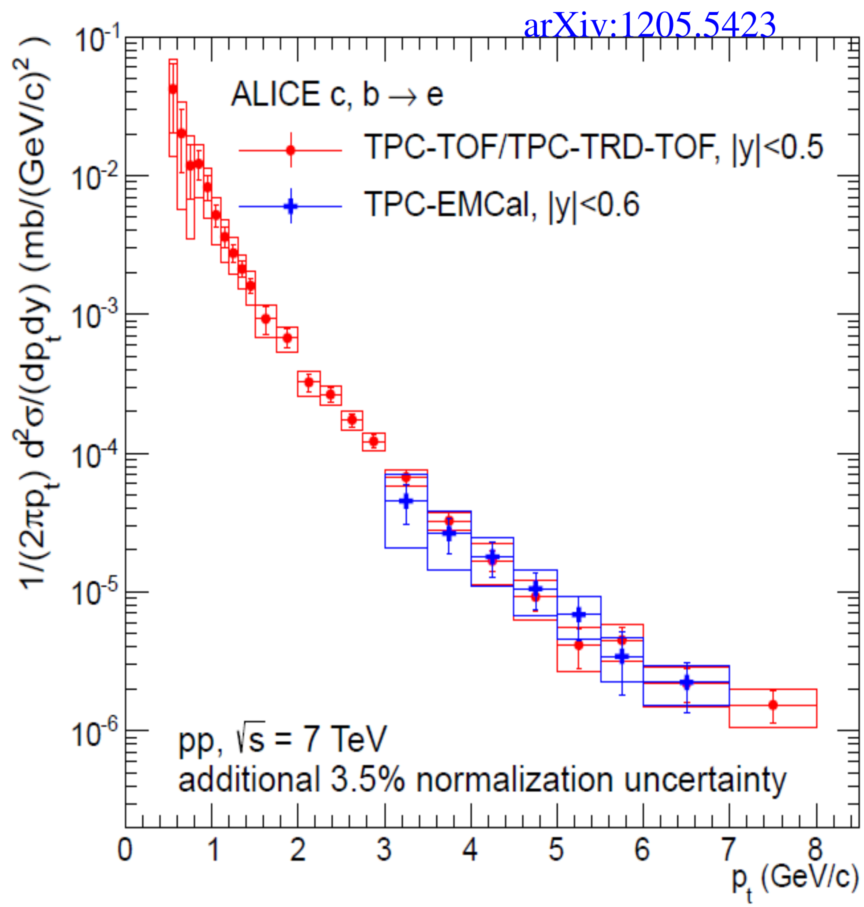
Johanna Stachel

Charm and beauty via semi-leptonic decays

Inclusive electron spectrum from 2 PID methods: TPC-TOF-TRD and TPC-EMCAL



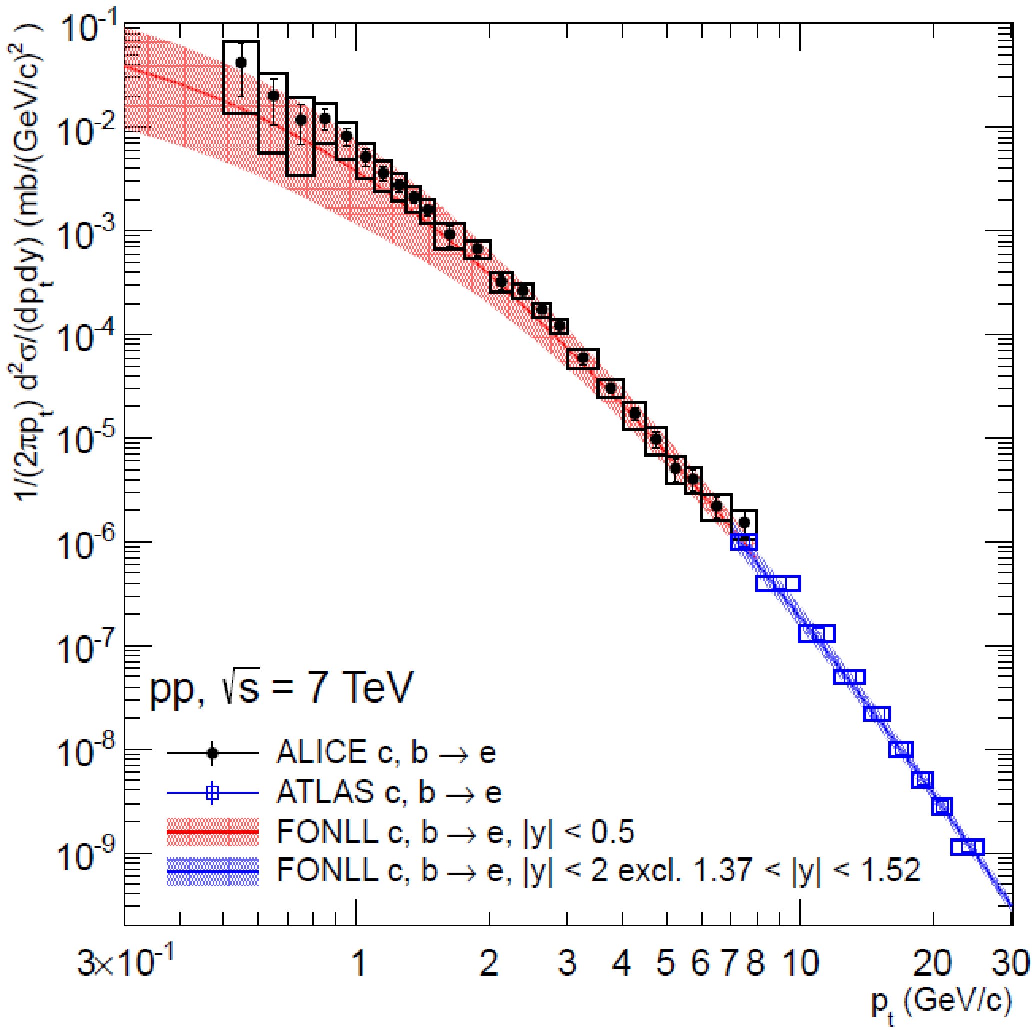




subtract hadronic decay cocktail using measurements where possible (π^0, η, m_t scaling for other mesons, J/ψ), direct γ from pQCD

electrons from c and b decays

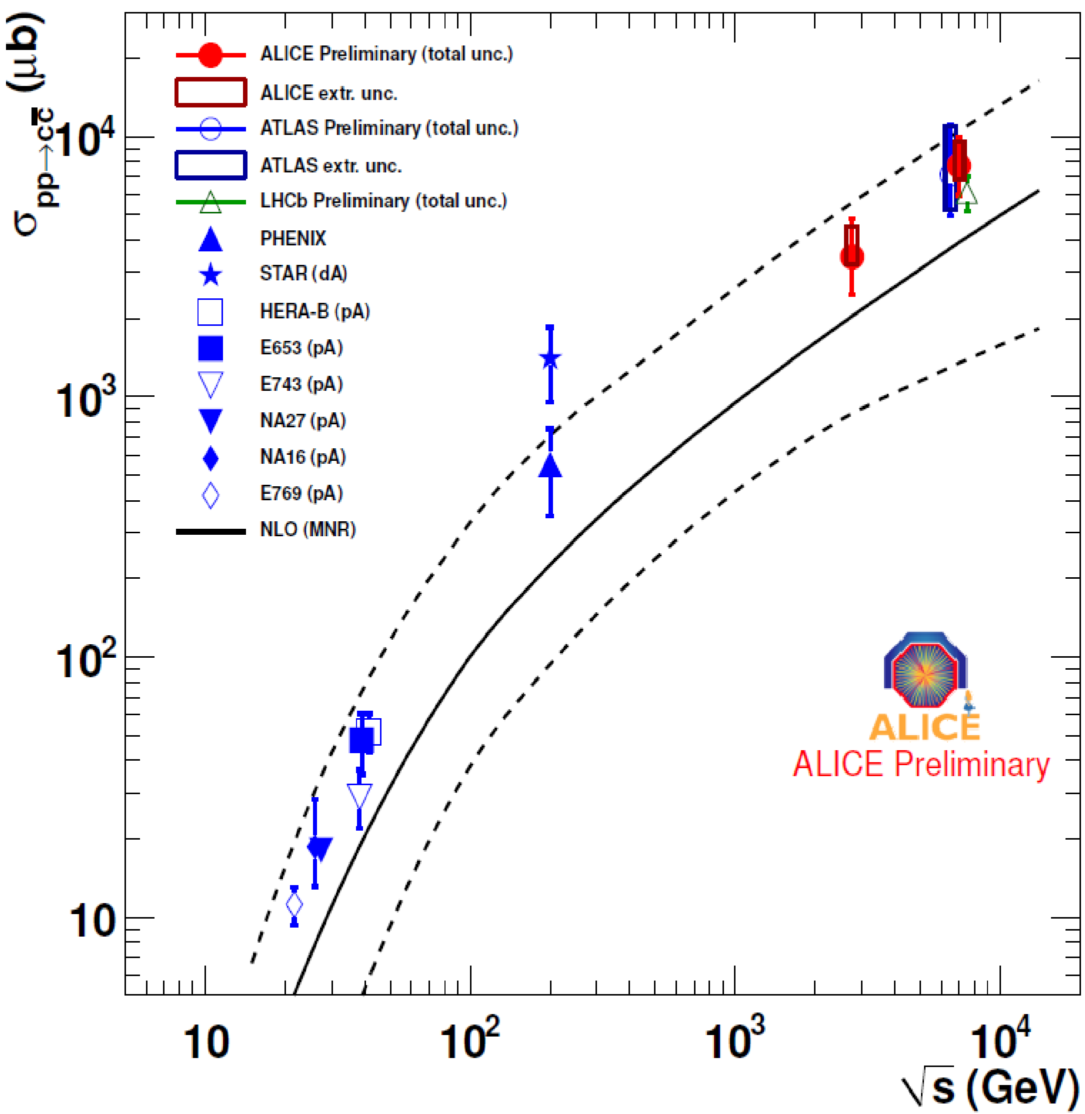
Charm and beauty electrons compared to pQCD



- ALICE data complimentary to ATLAS measurement at higher pt (somewhat larger y-interval)
- good agreement with pQCD
- at upper end of FONLL range for p_t < 3 GeV/c where charm dominates

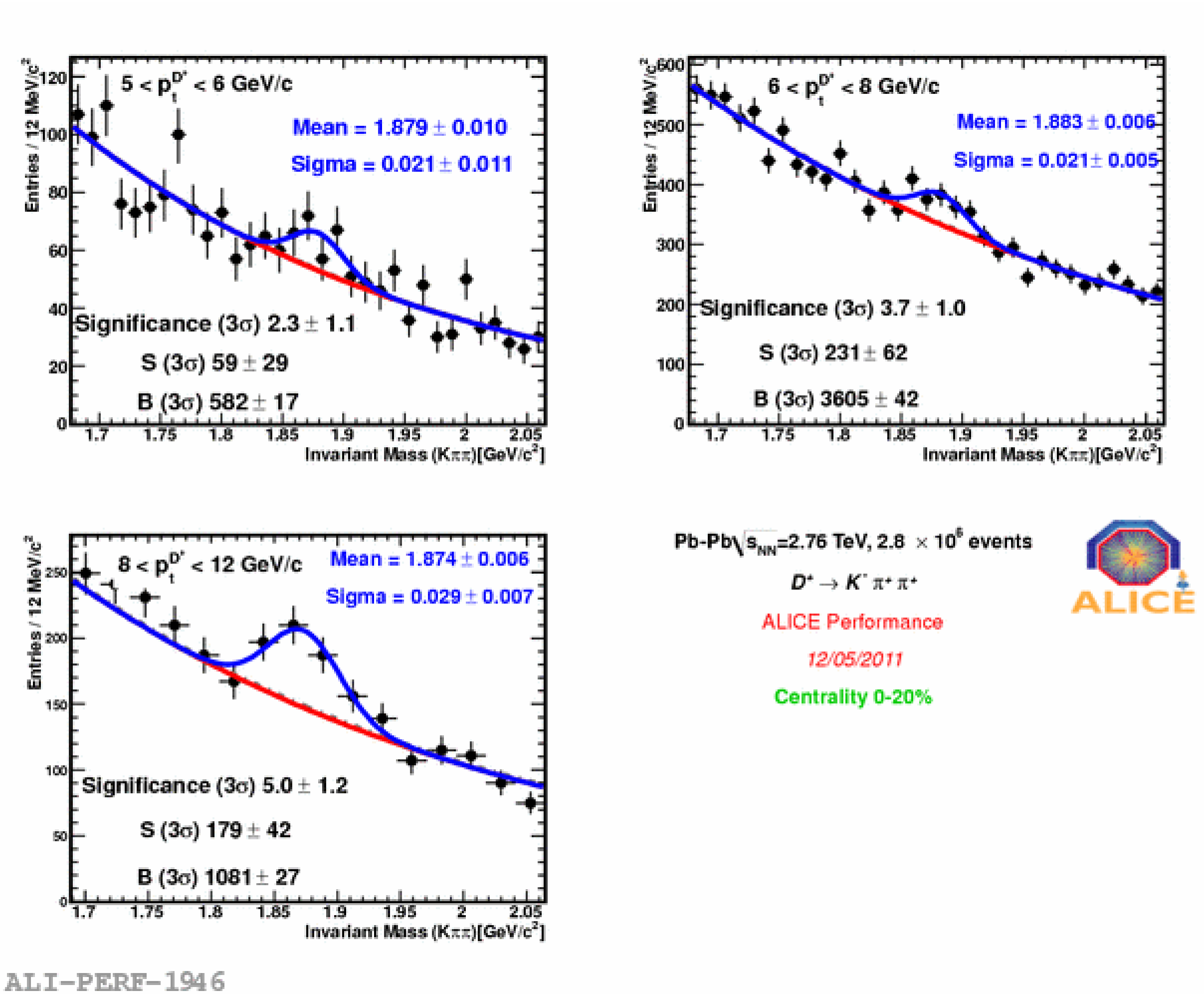
arXiv:1205.5423
ATLAS: PLB707 (2012) 438
FONLL: Cacciari et al., arXiv:1205.6344

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



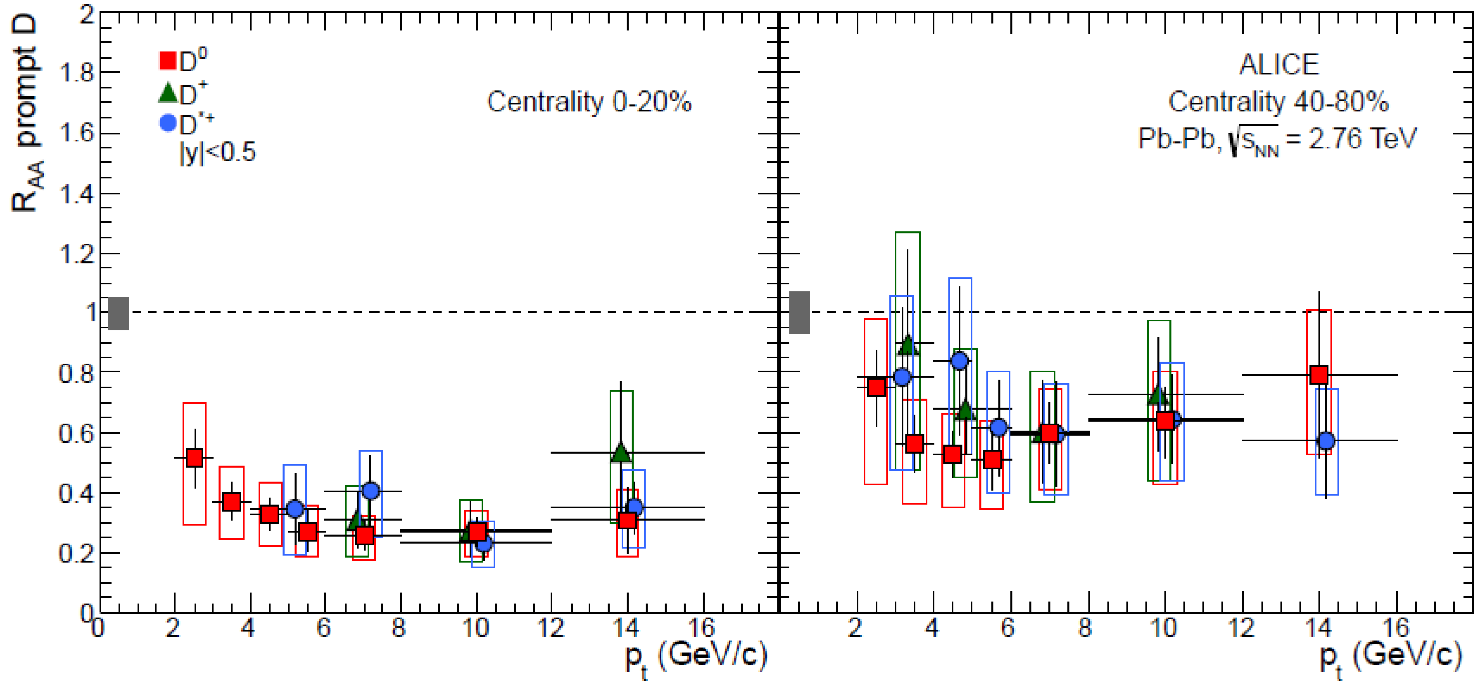
- good agreement with ATLAS and LHCb
- data factor 2 ± 0.5 above central value of FONLL but well within uncertainty
- beam energy dependence follows well FONLL

D meson signals in Pb Pb collisions



Suppression of charm at LHC energy

pp reference at 2.76 TeV: measured 7 TeV spectrum scaled with FONLL
cross checked with 2.76 TeV measurement (large uncertainty due to limited luminosity

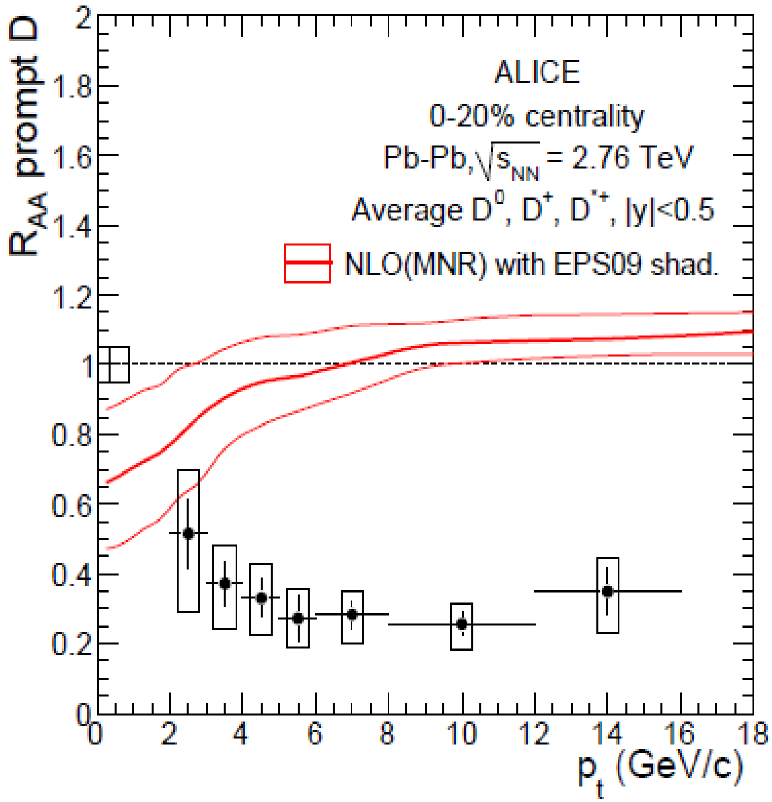


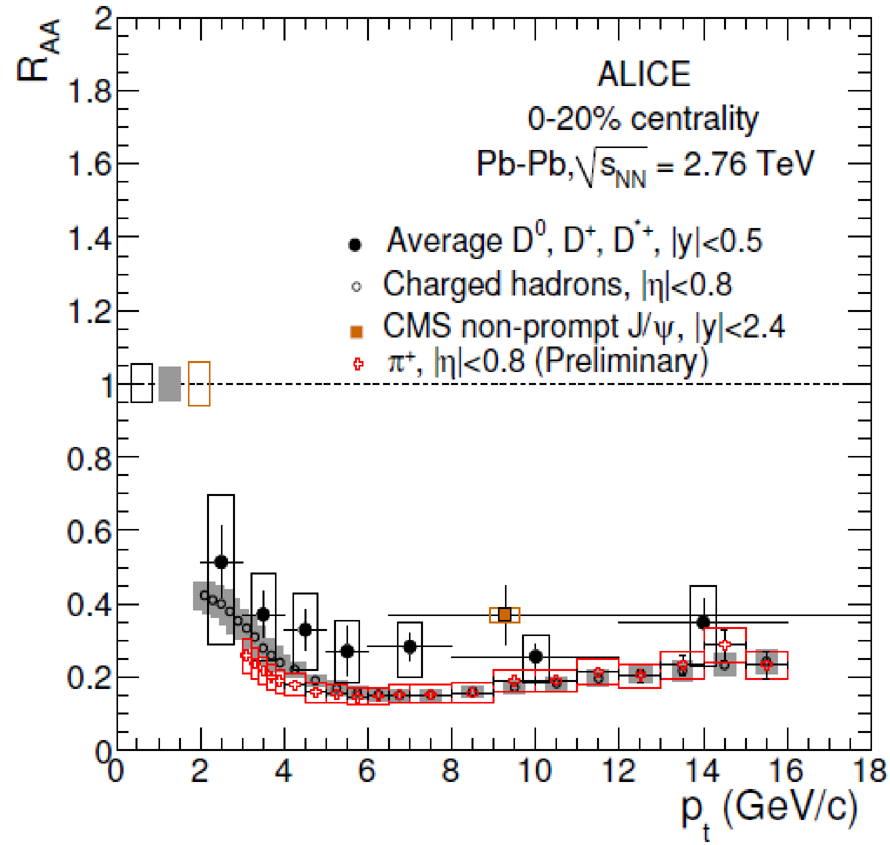
arXiv:1203.2160

energy loss for all species of D-mesons within errors equal - not trivial
energy loss of central collisions very significant - factor 3-4 for 5 GeV/c

Suppression of charm at LHC energy

comparison to EPS09 shadowing:
suppression not an initial state effect
will be measured directly in pPb collisions

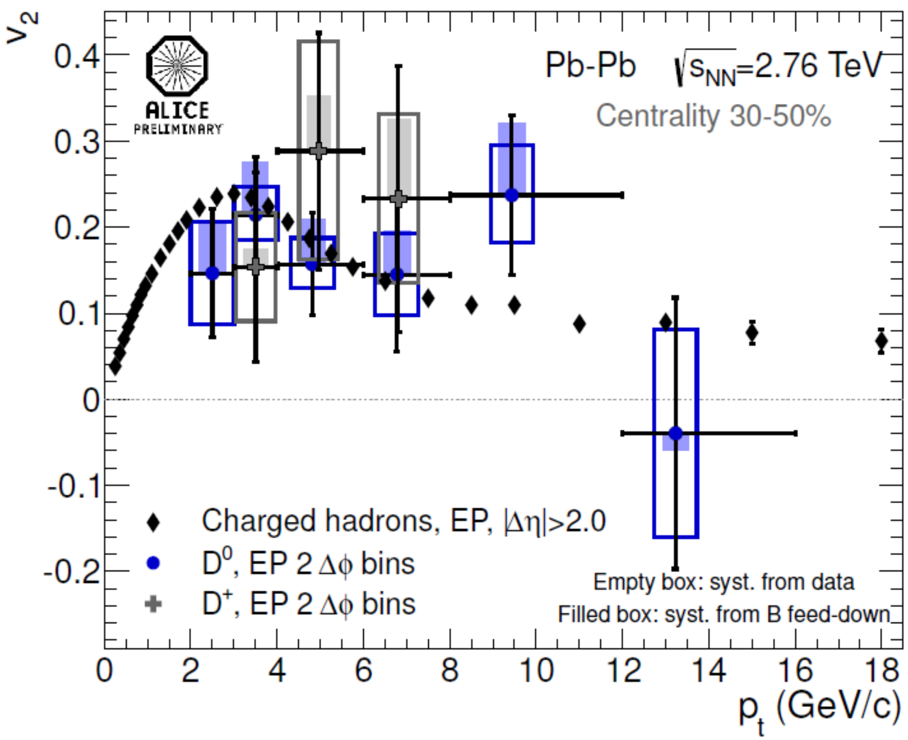




arXiv:1203.2160
arXiv:1201.5069 (CMS)

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

Charm quarks also exhibit elliptic flow

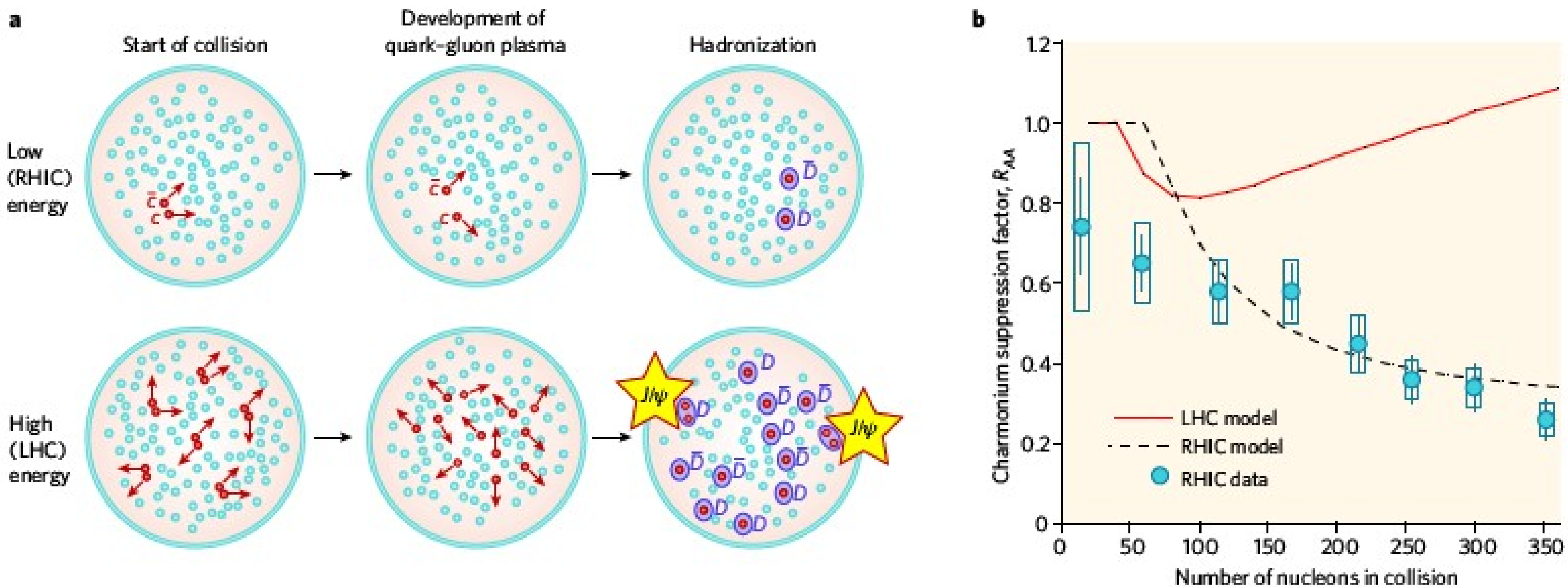


non-zero elliptic flow for 3 σ effect for D^0 2-6 GeV/c

within errors charmed hadron v_2 equal to that of all charged hadrons

J/psi production in PbPb collisions at LHC

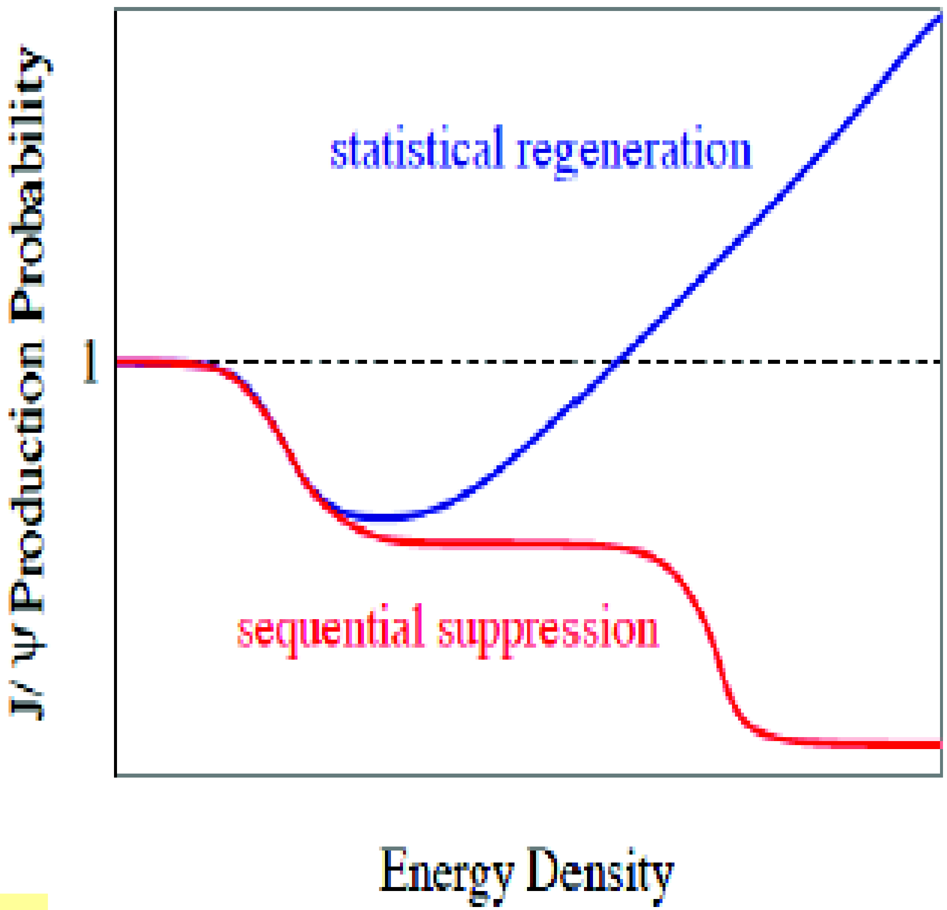
Quarkonium as a Probe for Deconfinement at the LHC
the Statistical (re-)Generation Picture



charmonium enhancement as fingerprint of deconfinement at LHC energy

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

Decision on Regeneration vs. Sequential Suppression from LHC Data

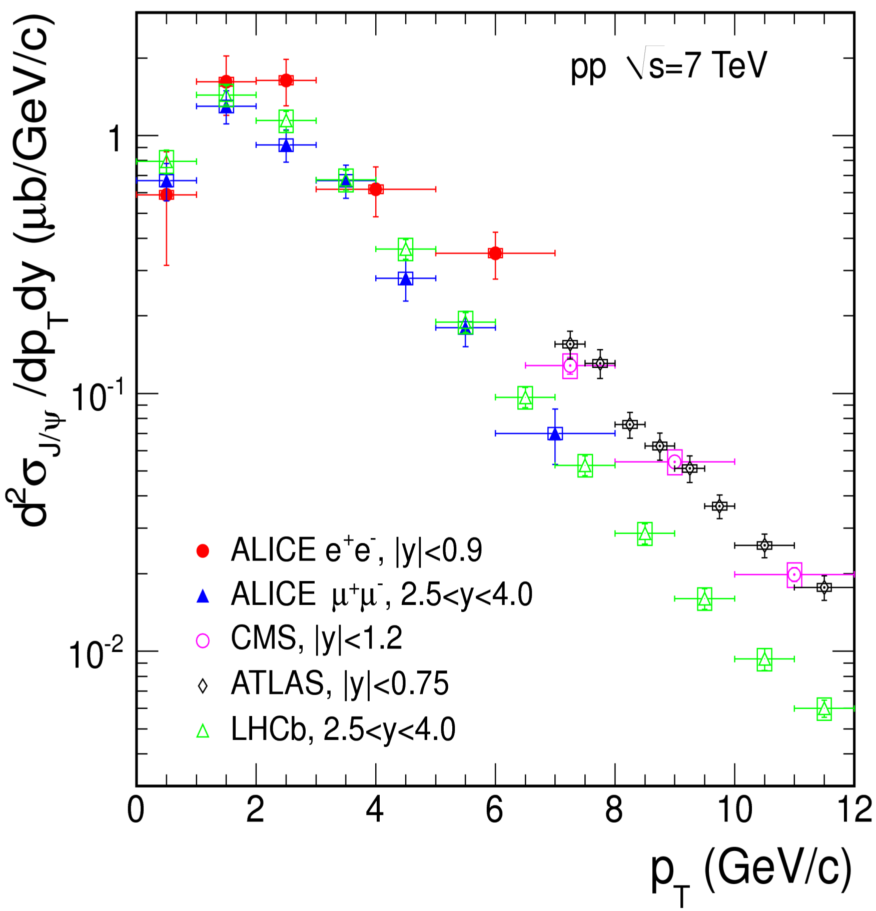


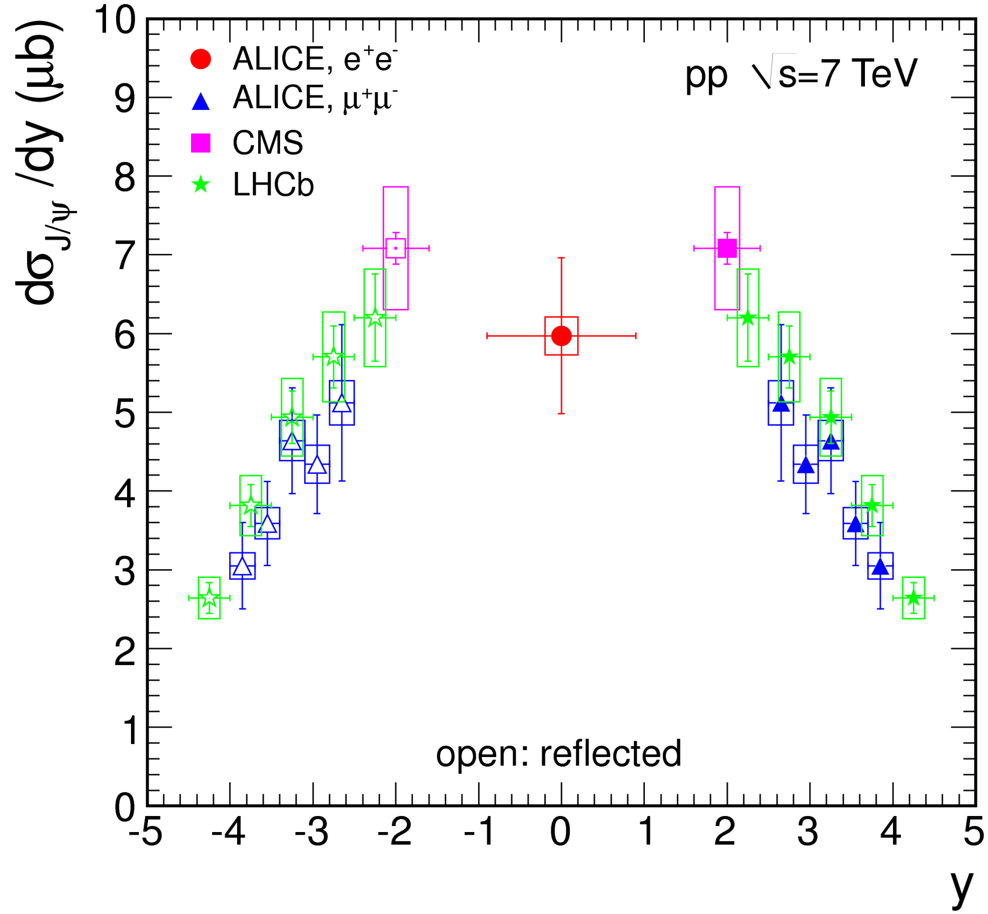
SPS RHIC LHC

Picture:
H. Satz 2009

J/psi spectrum and cross section in pp Collisions

ALICE PRL 704 (2011) 442 arXiv:1105.0380





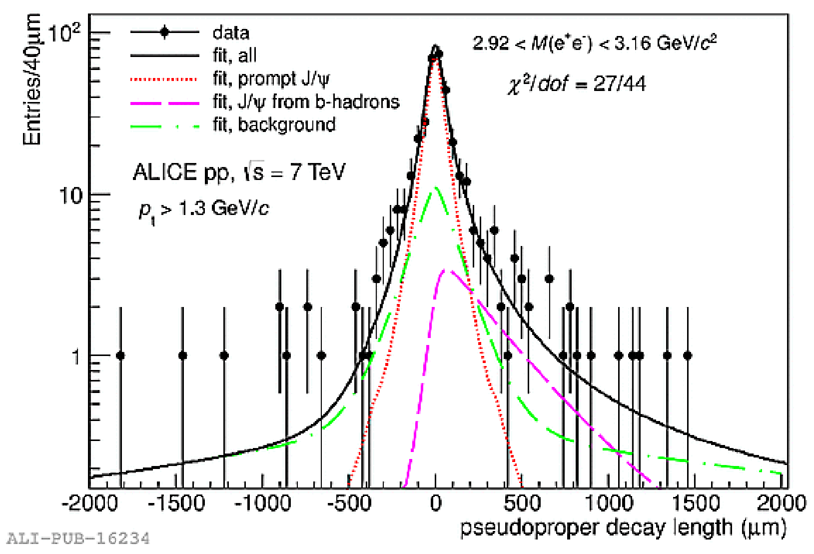
- good agreement between experiments
- complementary in acceptance: only ALICE has acceptance below 6 GeV at mid-rapidity

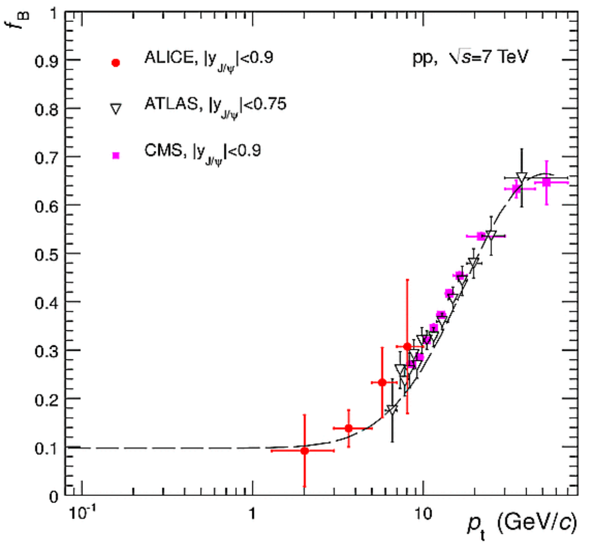
measured both at 7 and 2.76 TeV

open issues: statistics at mid-rapidity

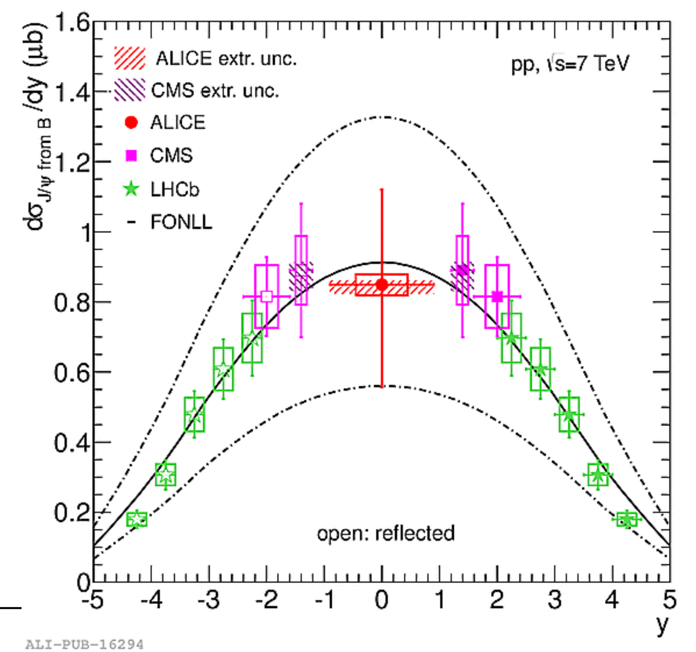
polarization (biggest source of syst error)

J/psi from B-decays in pp collisions



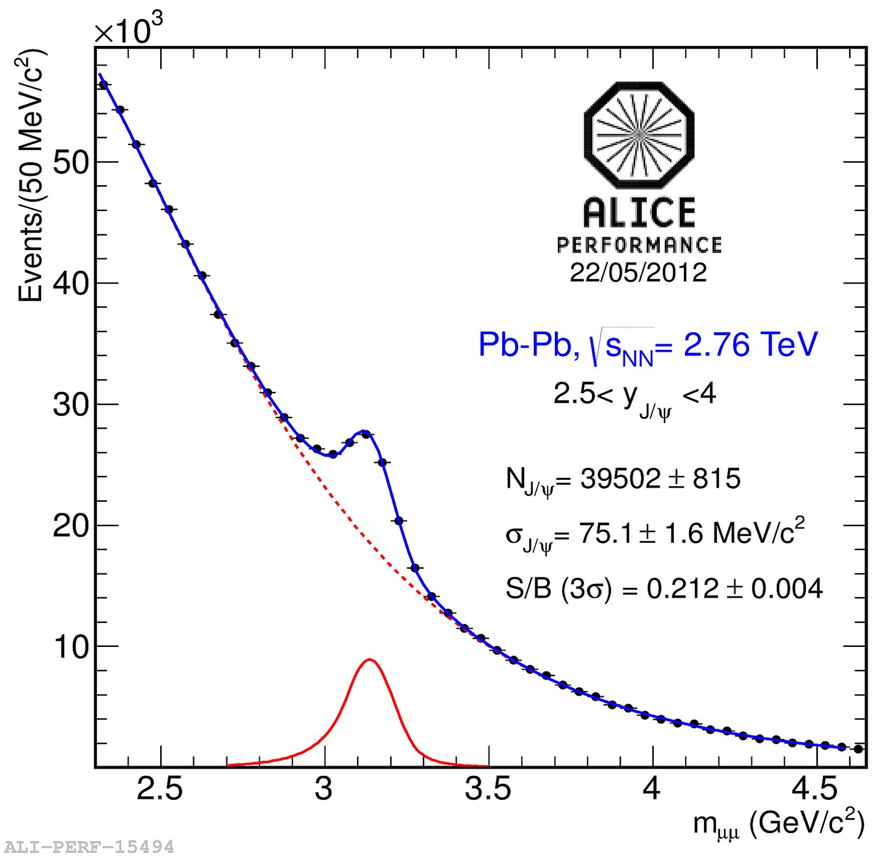


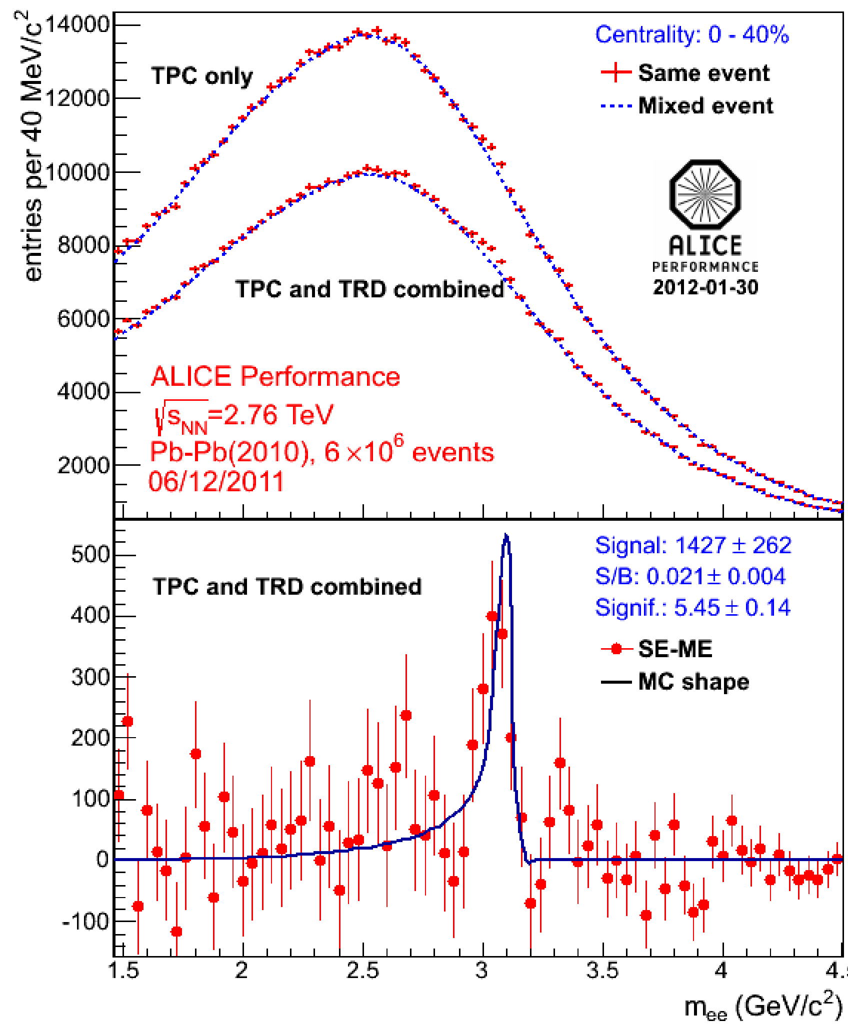
- simultaneous fit of mass spectrum and pseudo-proper decay length
- J/psi from B-decays for pt > 1.3 GeV/c at mid-rapidity - unique at LHC
- obtain prompt J/psi spectrum



arXiv:1205.5880
FONLL: Cacciari et al., arXiv:1205.6344

Reconstruction of J/psi via mu+mu- and e+e- decays in Pb Pb collisions





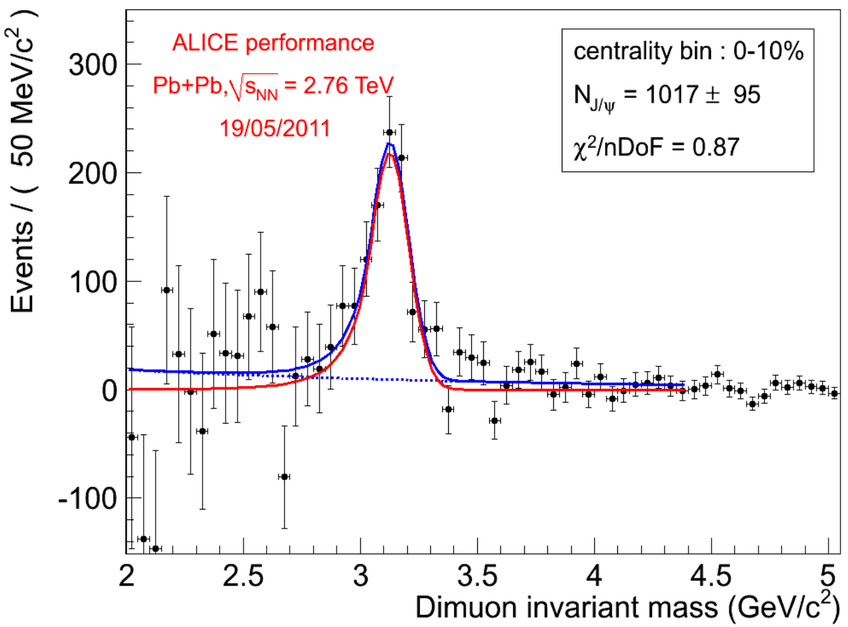
most challenging: PbPb collisions

significant combinatorial background

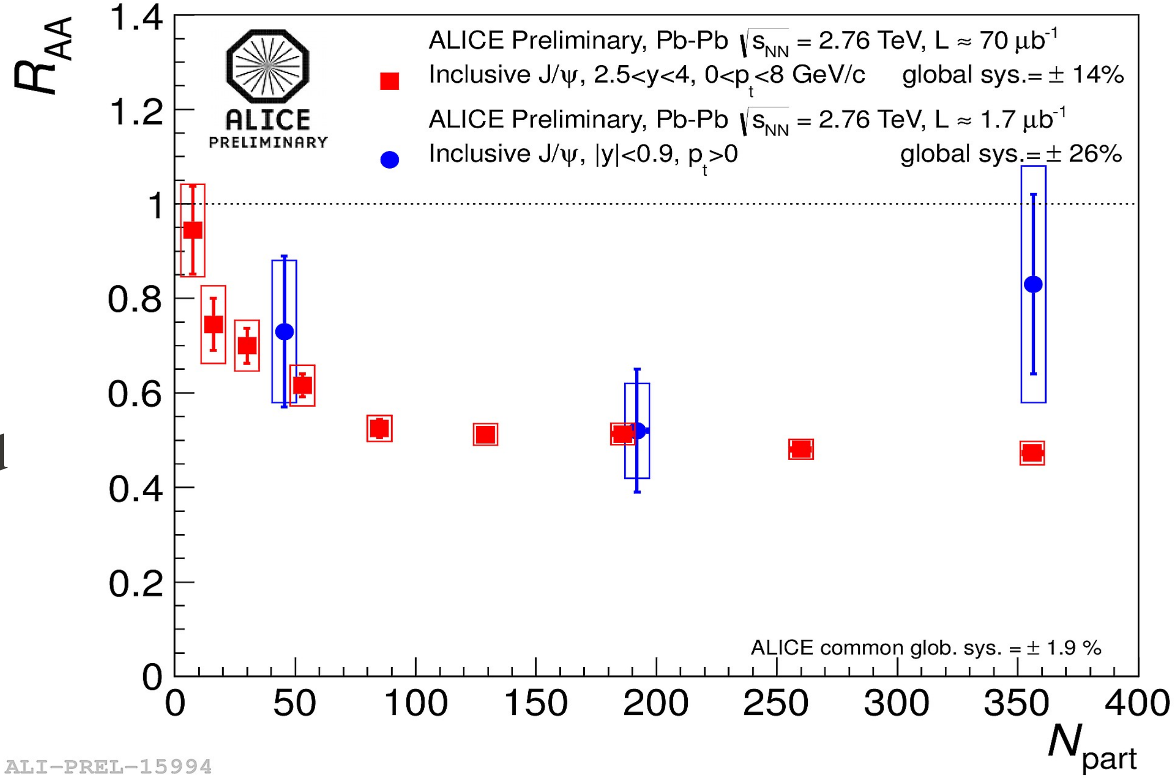
(true electrons, not from J/ψ decay but e.g. D- (

for dimuon channel: triggered events sample hig

J/psi in PbPb collisions relative to pp



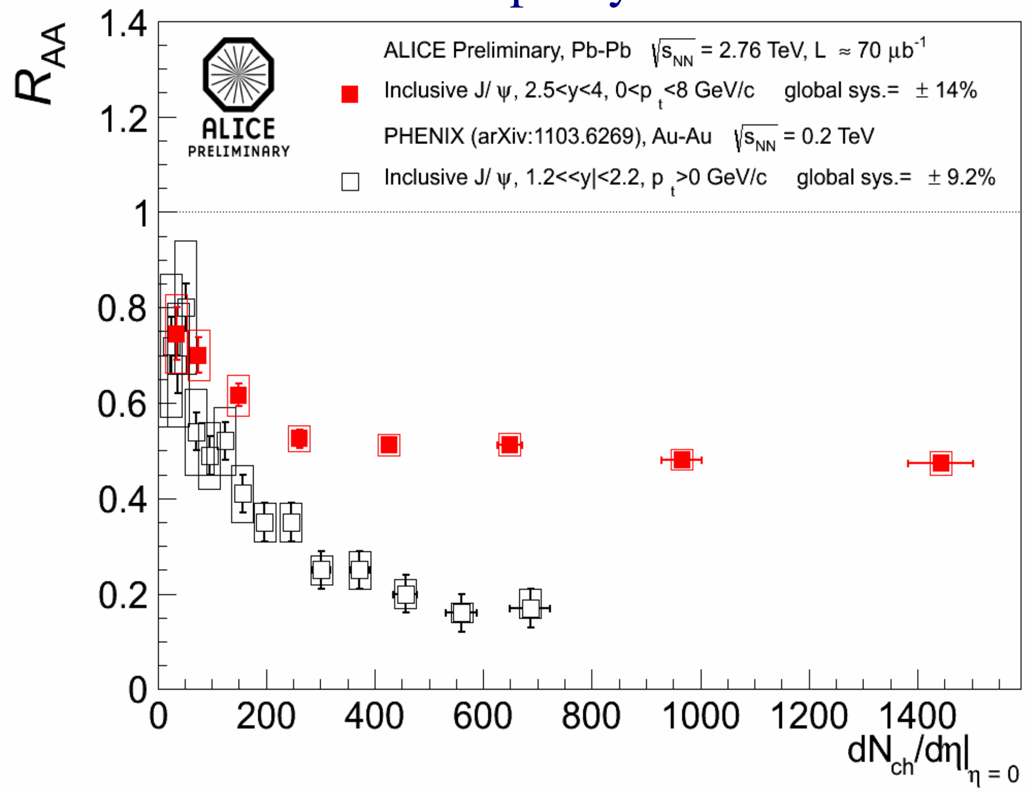
$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$



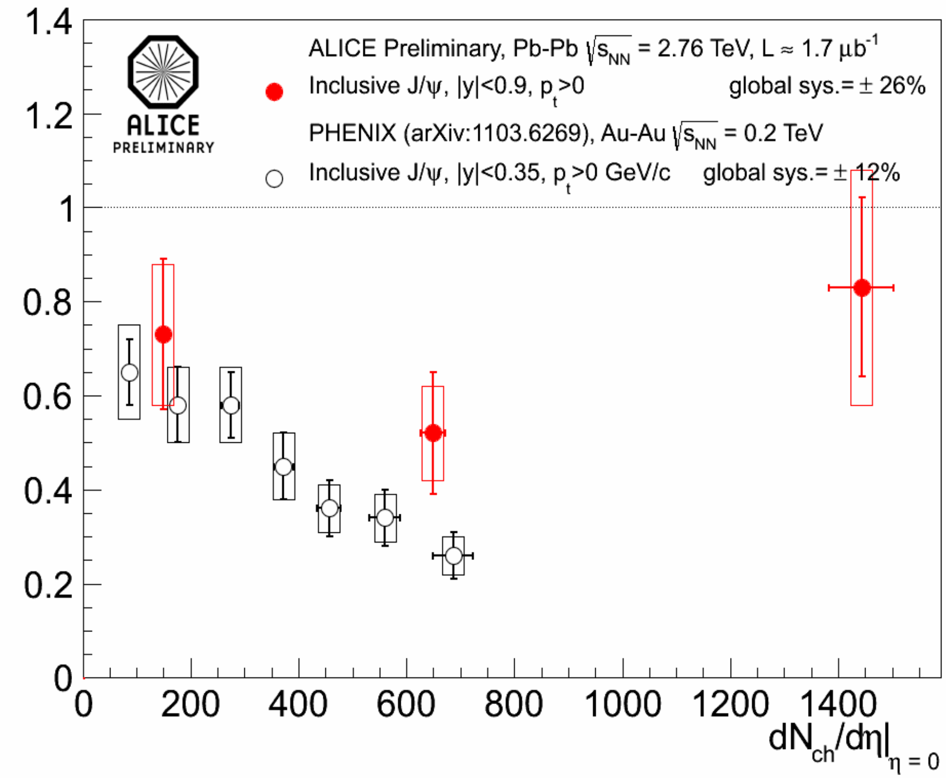
- nearly flat over large centrality range
- indication of rise for most central and mid-rapidity

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

forward rapidity

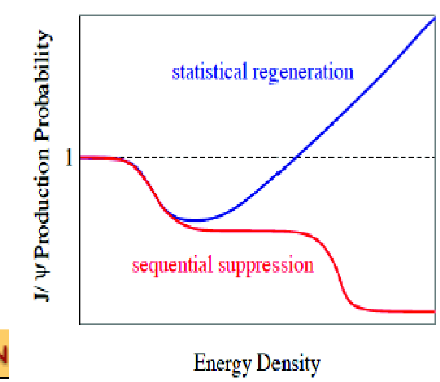


mid-rapidity



energy density -->

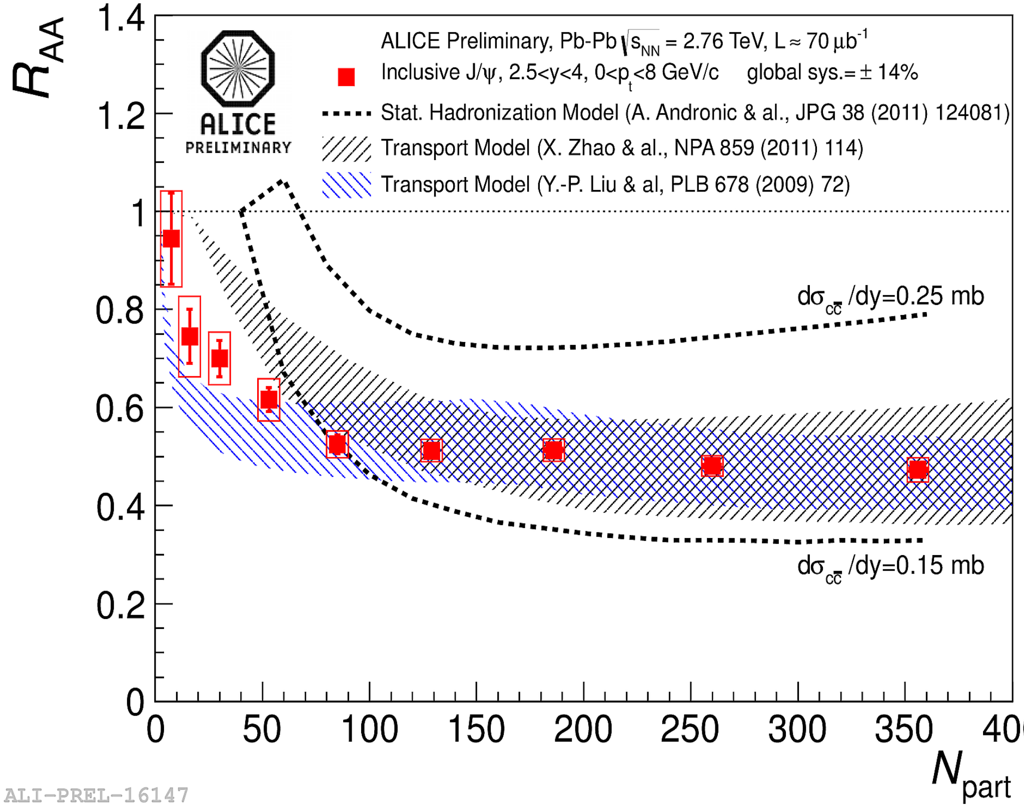
melting scenario not observed
rather: enhancement with increading energy density!
(from RHIC to LHC and from forward to mid-rapidity)

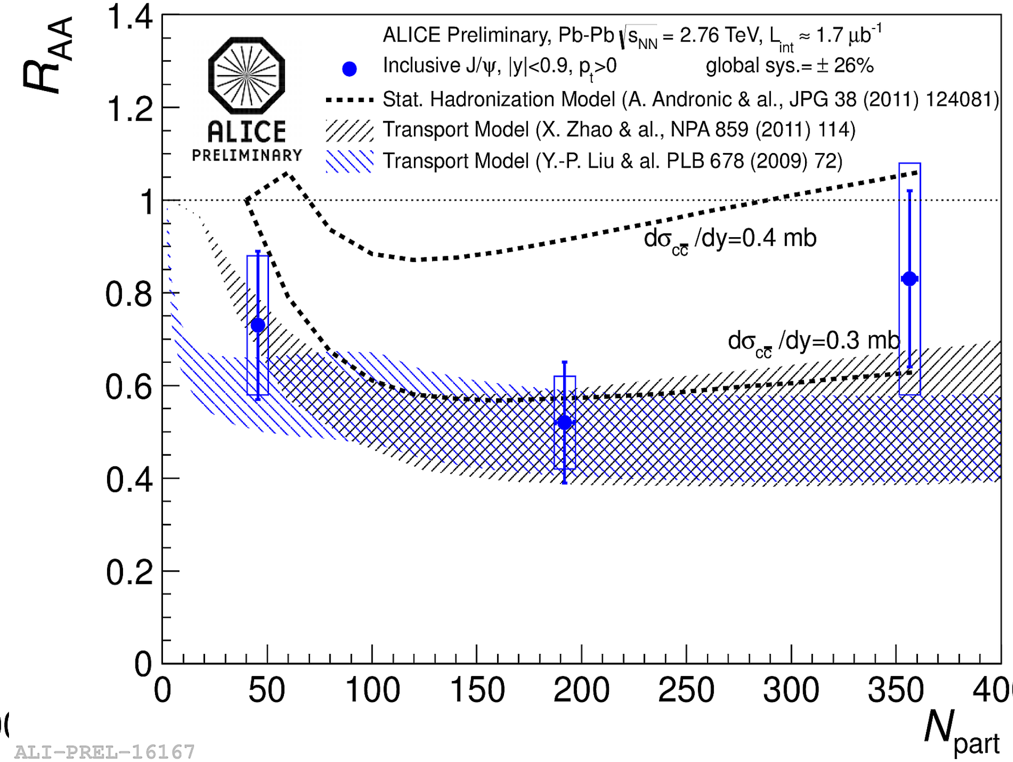


Johanna Stachel

RUPRECHT-KARLS-UN

J/psi and Statistical Hadronization

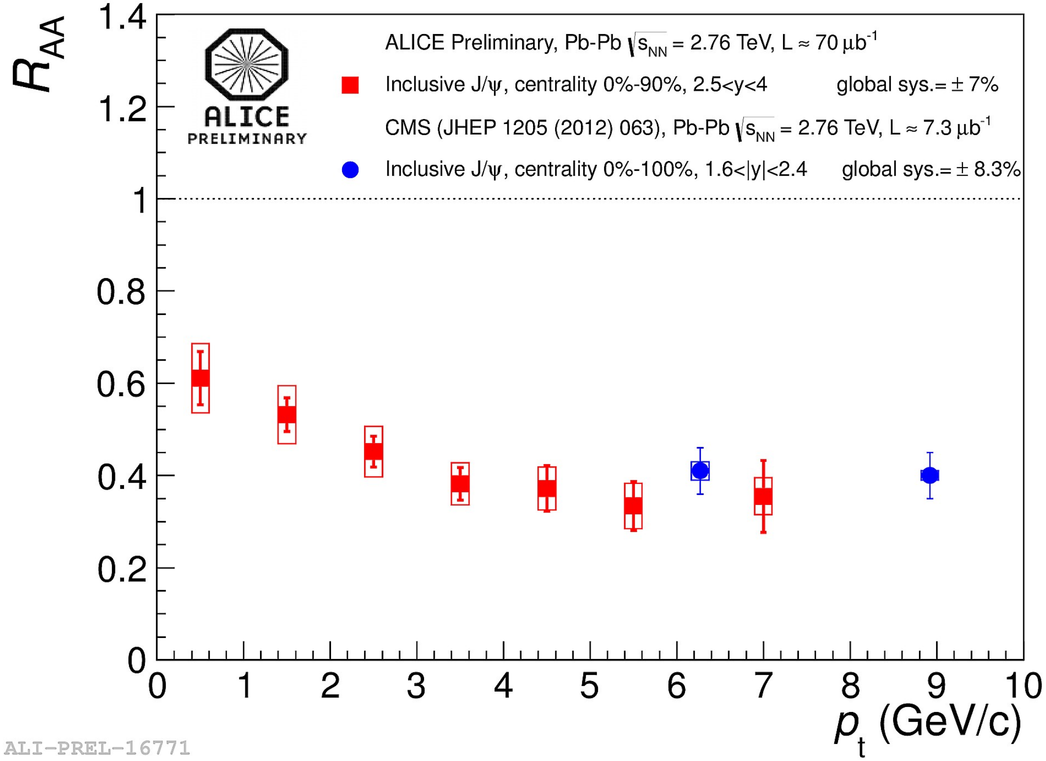




in AA collisions: indication of J/ψ regeneration

- production in PbPb collisions at LHC consistent with statistical hadronization within present uncertainties
- main uncertainties for models: open charm cross section, shadowing in Pb
- need to precisely measure charm cross section in PbPb and pPb collisions

pt dependence of RAA

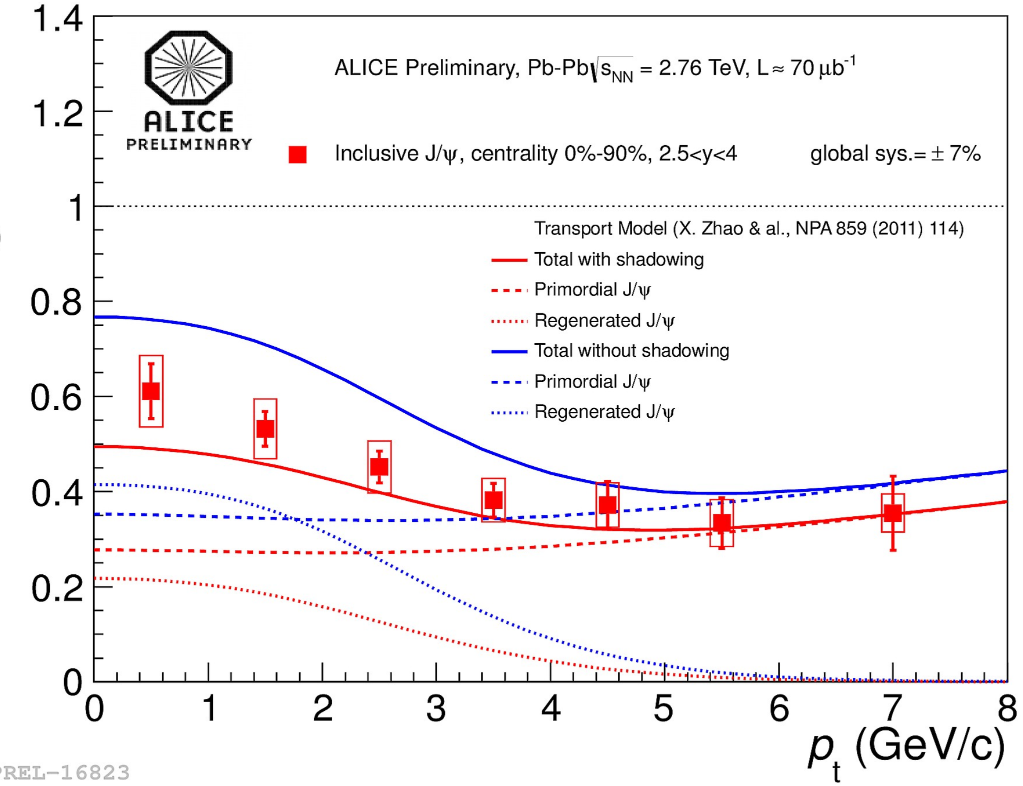


relative yield larger at low p_t in nuclear collisions

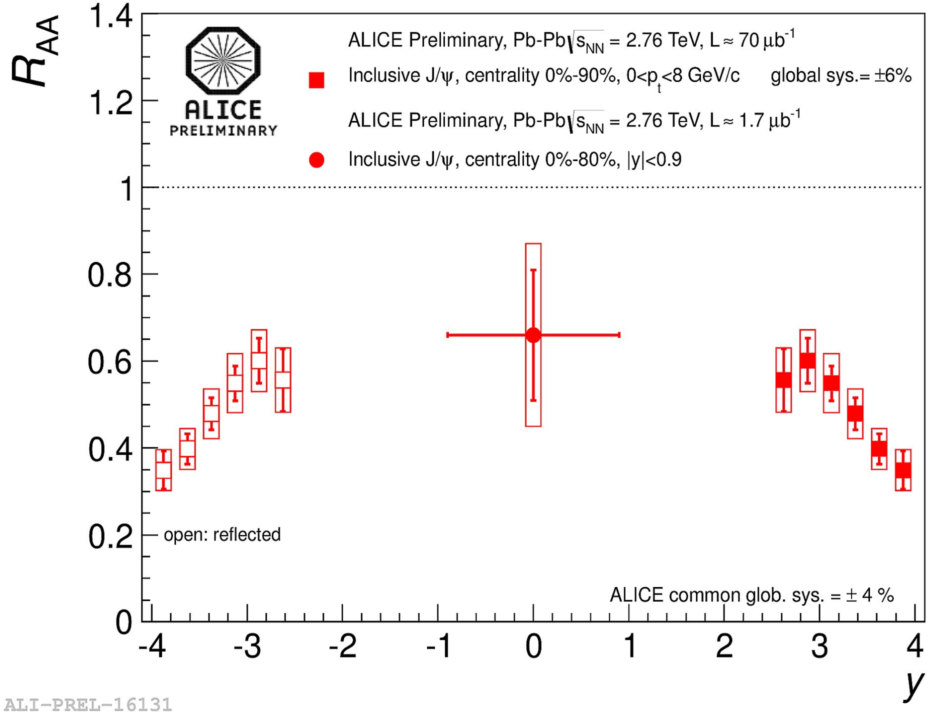
good agreement with CMS at high pt

statistical hadronization only expected for charm quarks thermalized in the QGP

p_t dependence in line with this prediction



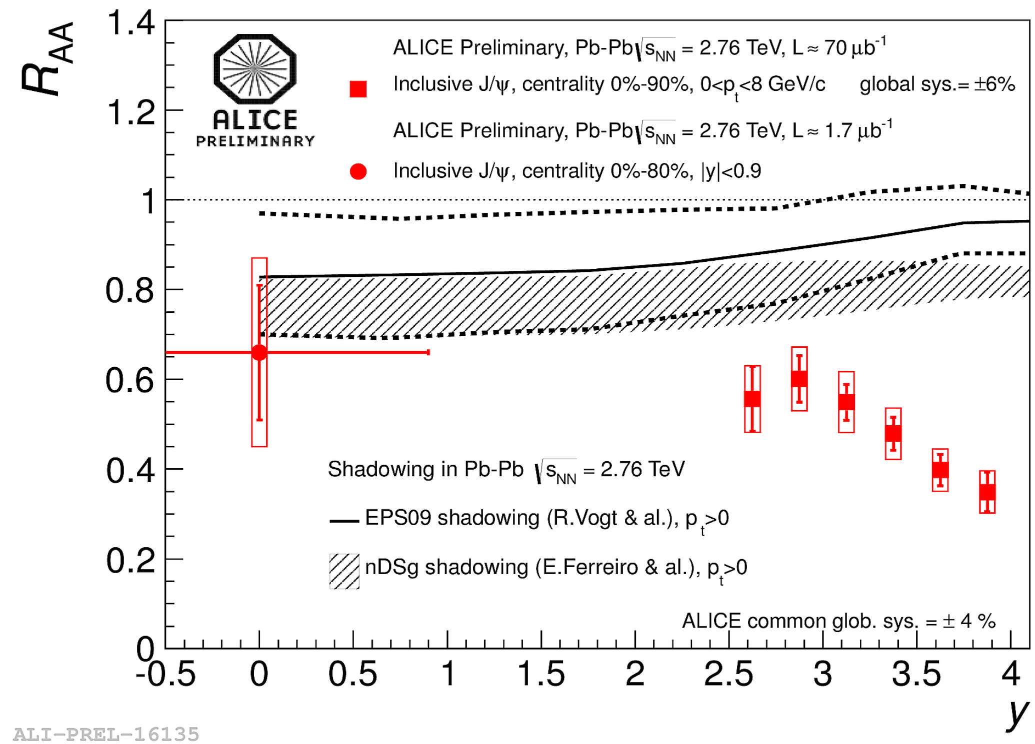
Rapidity dependence of J/psi R_{AA}



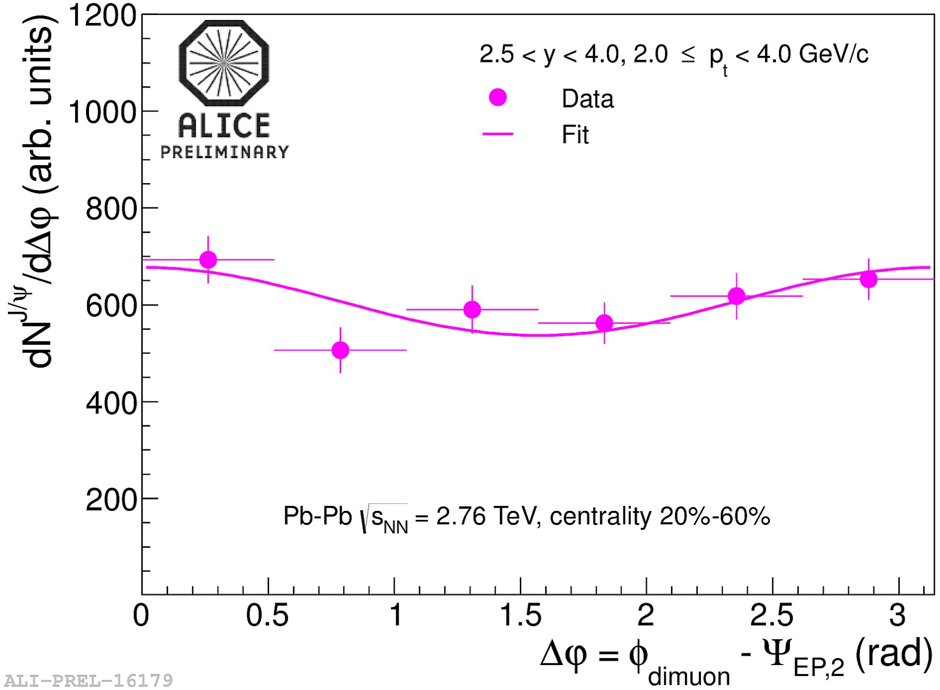
for statistical hadronization J/psi yield proportional to N_c^2

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

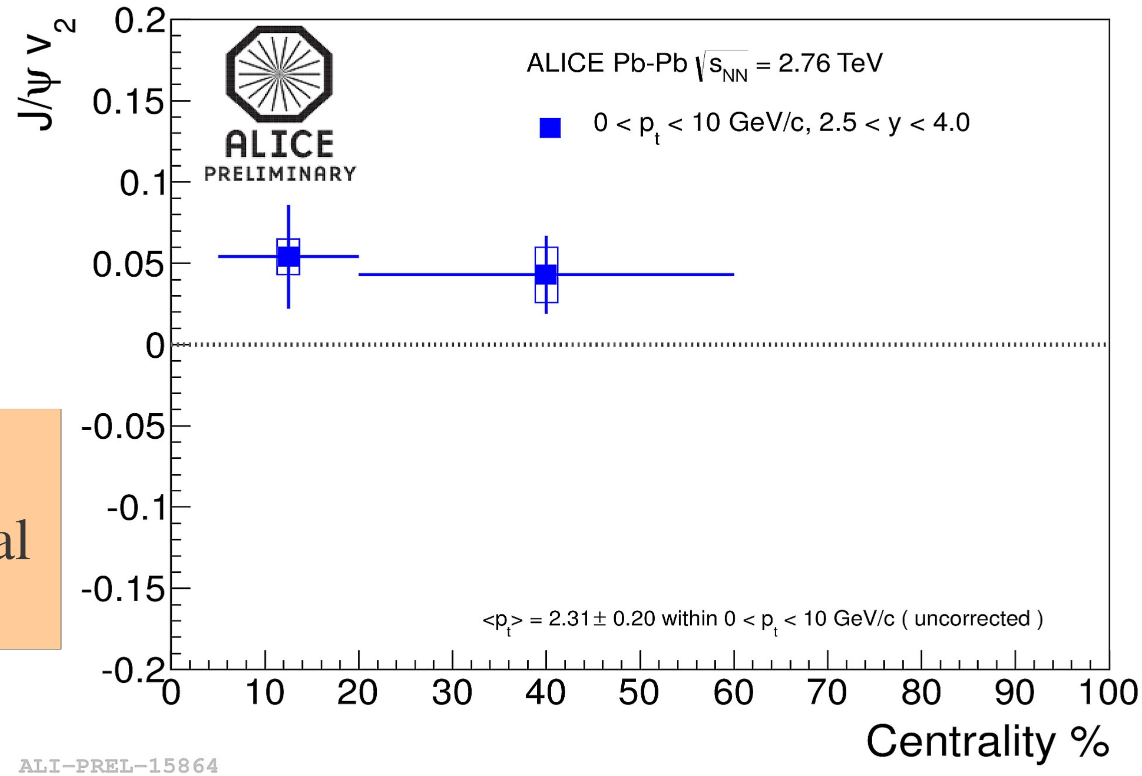


elliptic flow of J/psi

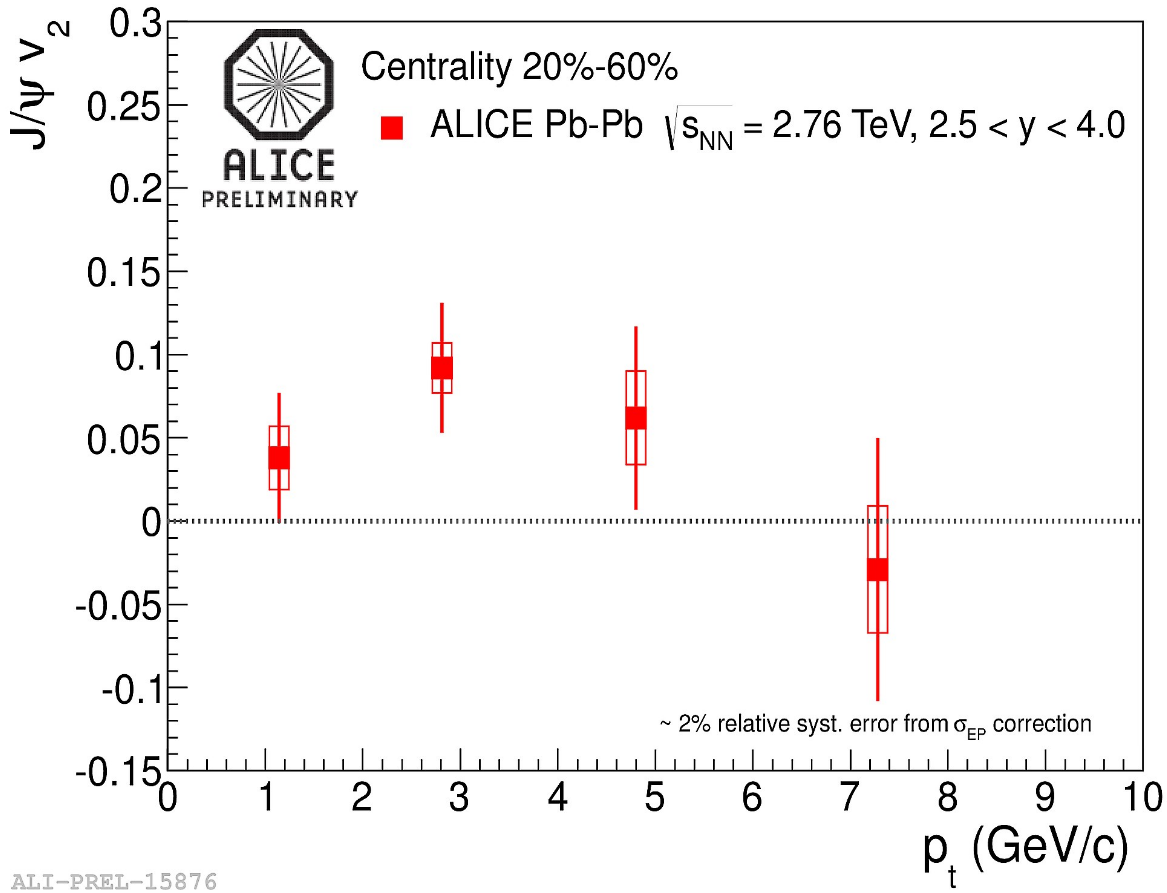


charm quarks thermalized in the QGP should exhibit the elliptic flow generated in this phase

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



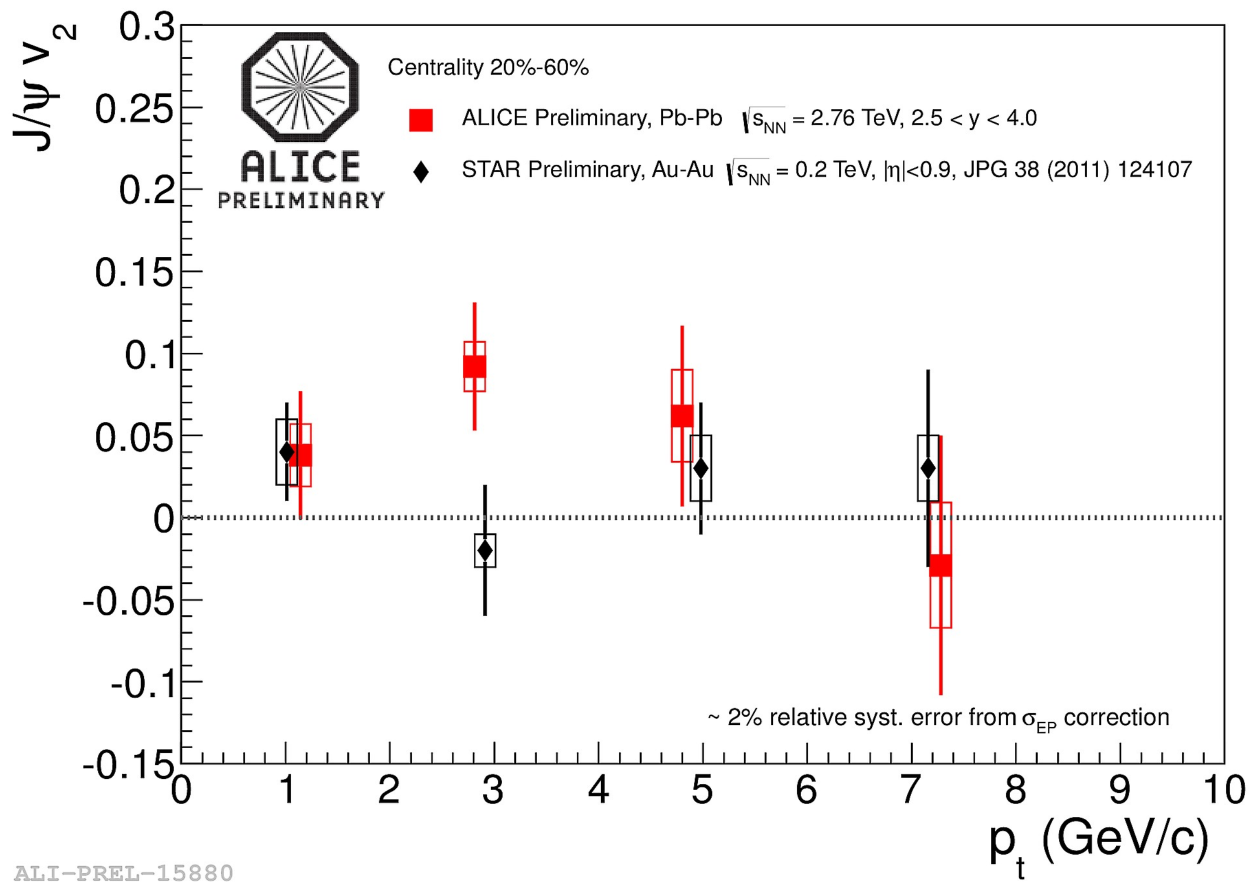
elliptic flow of J/psi



ALI-PREL-15876

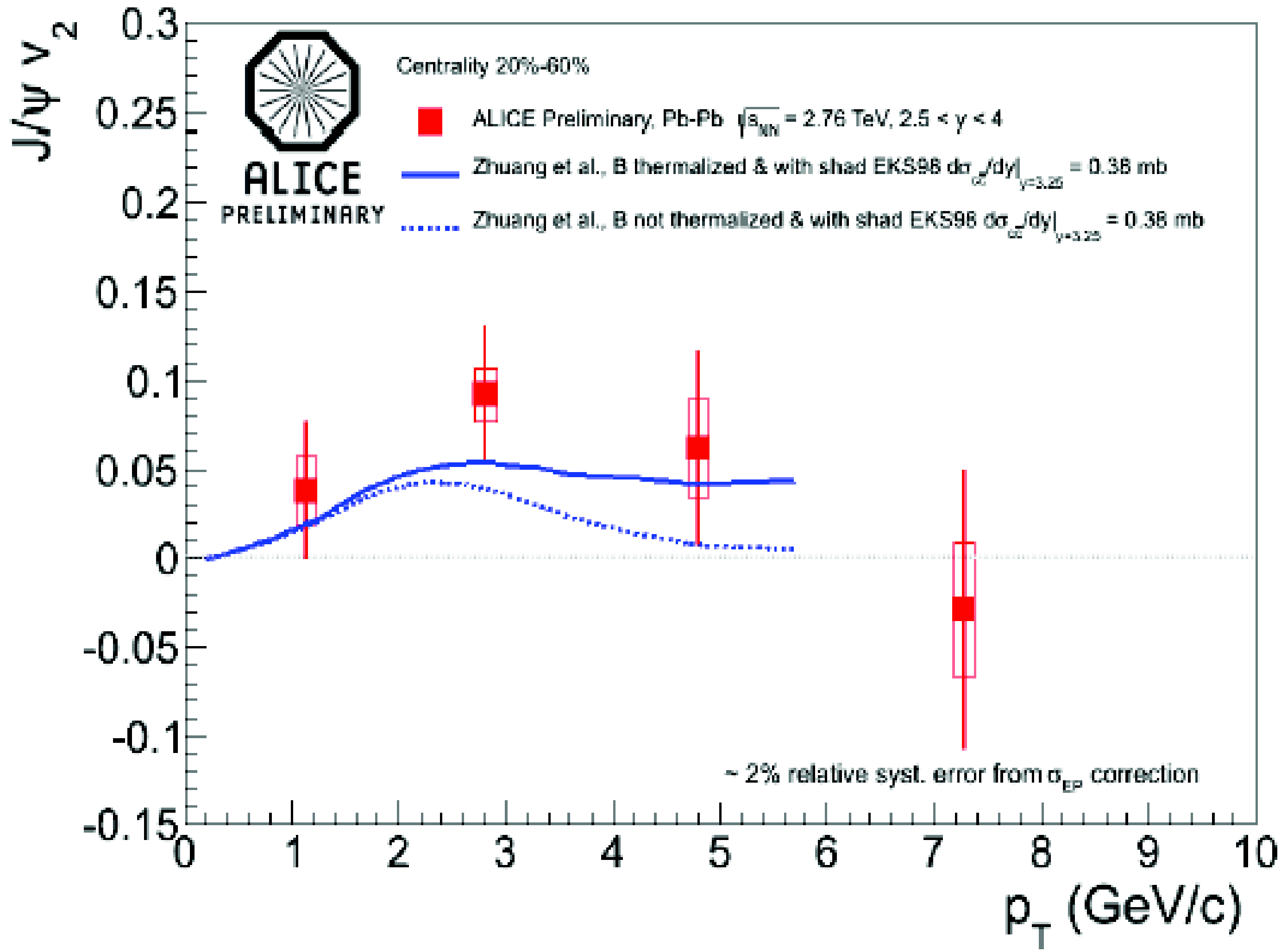
- expect build up with pt as observed for π, p. K, Λ, … and vanishing signal for high pt region where J/psi not from hadronization of thermalized quarks
- observed

elliptic flow of J/psi at LHC compared to RHIC



at RHIC flow signal for J/psi zero within errors, but not very significant
weaker flow in QGP phase?

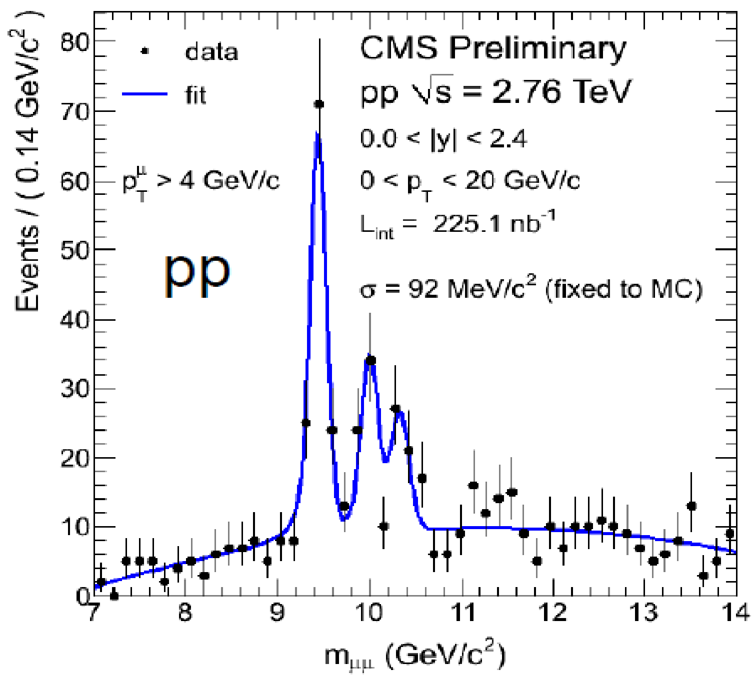
J/psi flow compared to models including (re-) generation

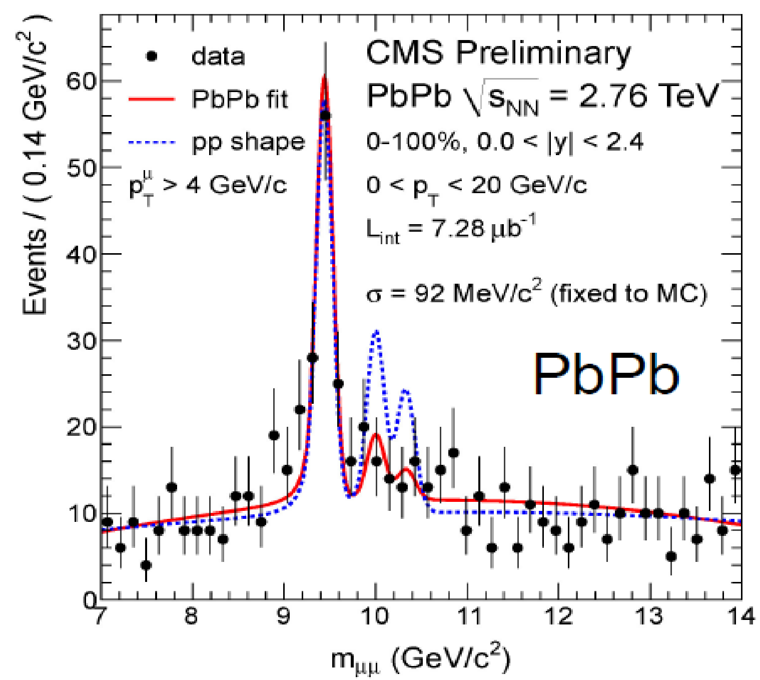


v_2 of J/ψ consistent with hydrodynamic flow of charm quarks in QGP and statistical (re-)generation

Suppression of higher Upsilon states in CMS

in thermal models: expect suppression due to Boltzmann factors





raw ratios: $\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$ $\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$

from CMS cross section measurements:

$$(Y(2S) + Y(3S))/Y(1S)_{PbPb} = 0.14 +0.08 - 0.07$$

vs thermal model at T=170 MeV: 0.046

ok within the current uncertainties

backup

effect of B feed-down and energy loss