Quo vadis ultra-relativistic nuclear collisons: Results and prospects at the LHC

- How to characterize Quark-Gluon Plasma at LHC
- Selected results from the first 2 years
- Hydrodynamic flow of the hot fireball
- Parton energy loss in the hot fireball
- Charmonium and heavy quark production at LHC energy
- Prospects for the next decade

ICFP2012,
Kolymbari, Crete, June 16, 2012

TECHNISCHE UNIVERSITÄT DARMSTADT

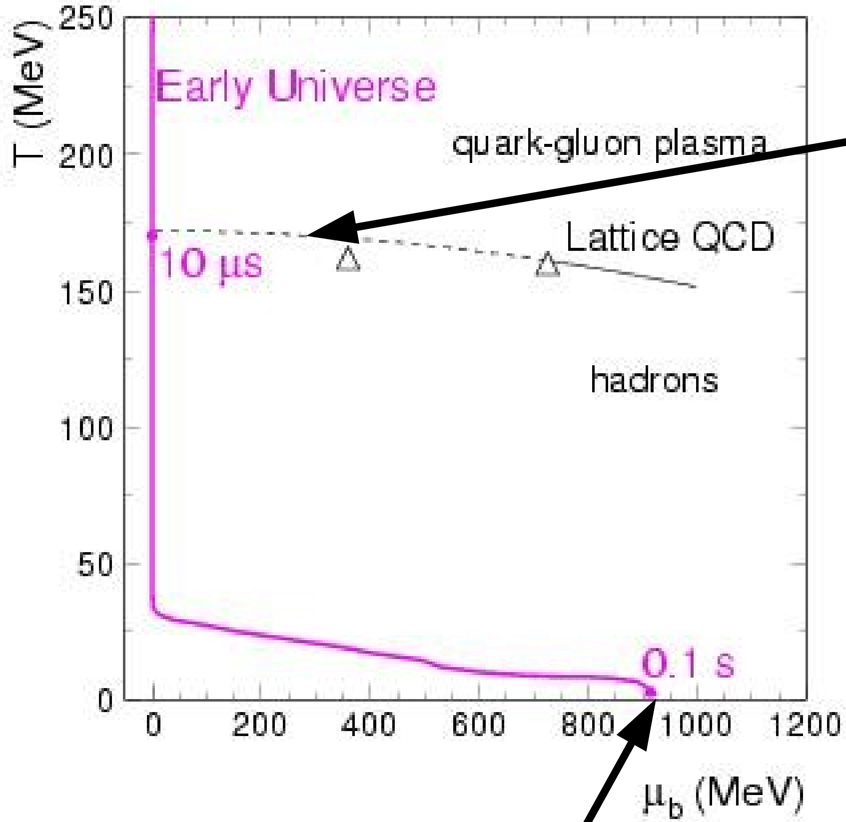
FIAS Frankfurt Institute for Advanced Studies

EMMI

HELMHOLTZ | GEMEINSCHAFT

GSI

Evolution of the Early Universe



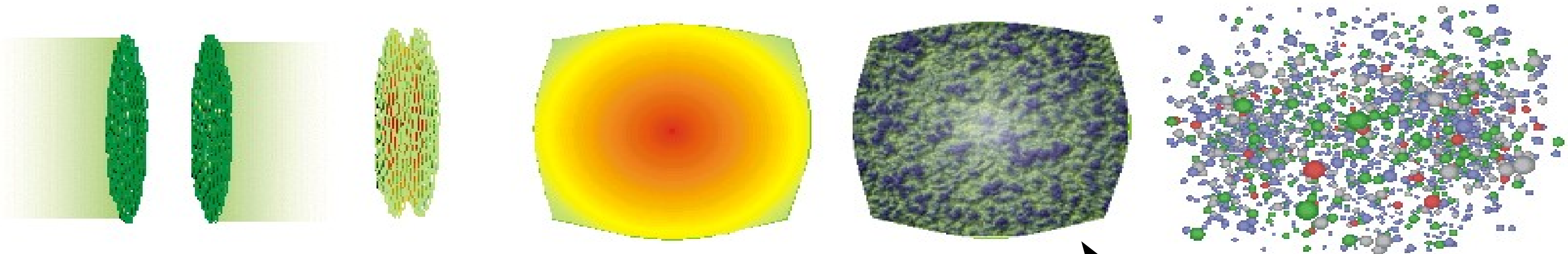
QCD Phase Boundary

Homogeneous Universe in Equilibrium, this matter can only be investigated in nuclear collisions

- Charge neutrality
- Net lepton number = net baryon number
- Constant entropy/baryon

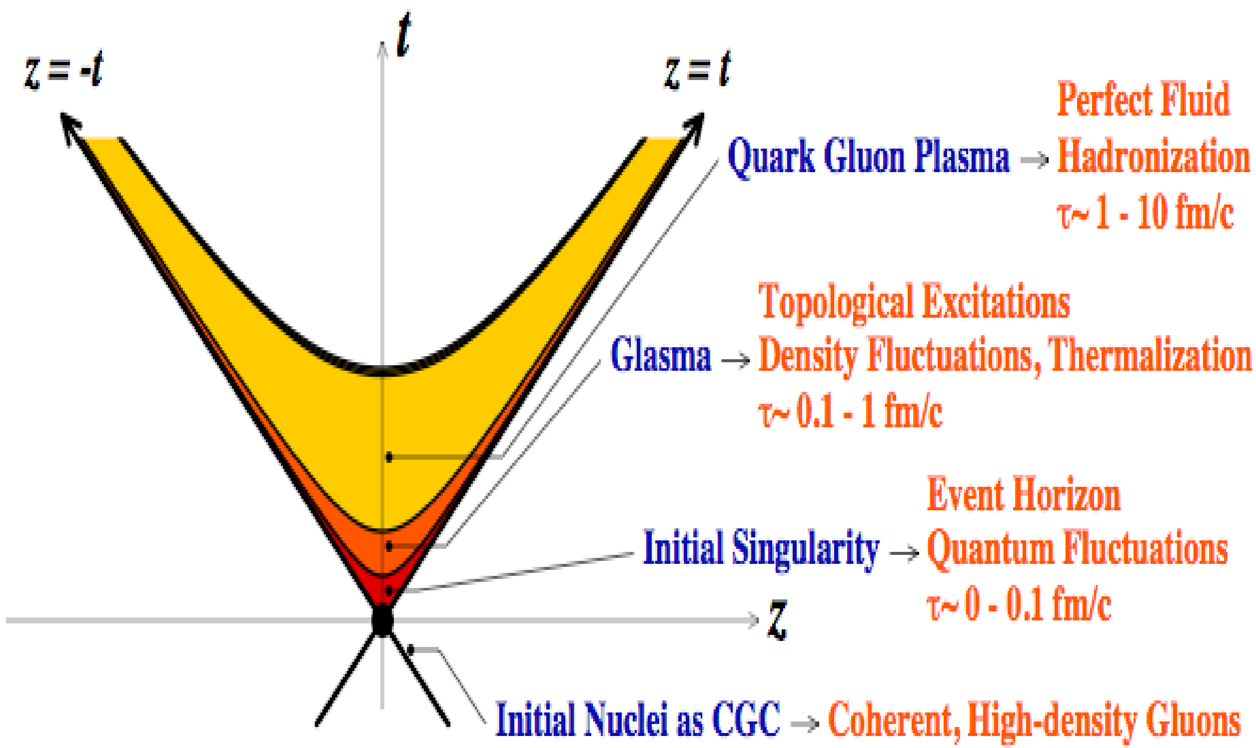
neutrinos decouple and light nuclei begin to be formed

The Space-Time Evolution of a Relativistic Nuclear Collision



CGC | Initial Singularity | Glasma | sQGP | Hadron Gas

Hot fireball, equilibrized matter



one possible view
(courtesy
Larry McLerran)

characterizing QGP matter at LHC

equation of state
critical temperature
number of degrees of freedom
transport coefficients (viscosity etc)
velocity of sound
parton energy loss and opacity
susceptibilities and chiral symmetry restoration
deconfinement
colorless objects inside QGP

but also, look for the unexpected

1. Initial Energy Density of the fireball using measured rapidity densities in Pb-Pb collisions at LHC energy

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

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

ALICE:

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

Upper limit for τ_0 $\tau_0 = 1$ fm $\rightarrow$ $\varepsilon_0 = 13\ GeV/fm^3$

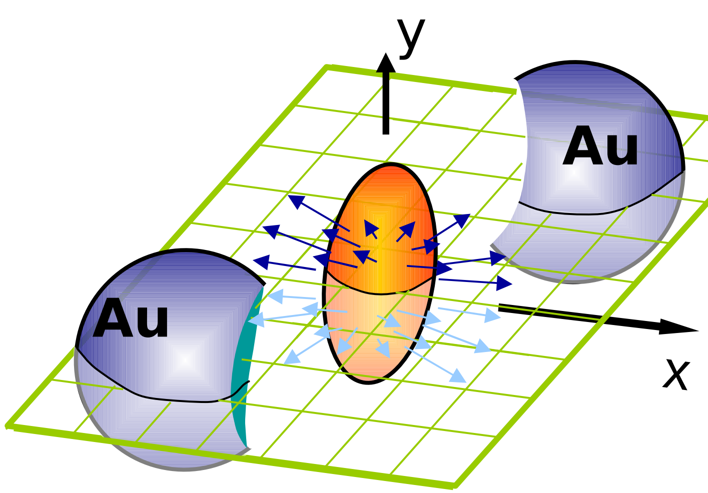
estimate temperature to $T \approx 0.4$ GeV $\approx 2.5\ T_c$

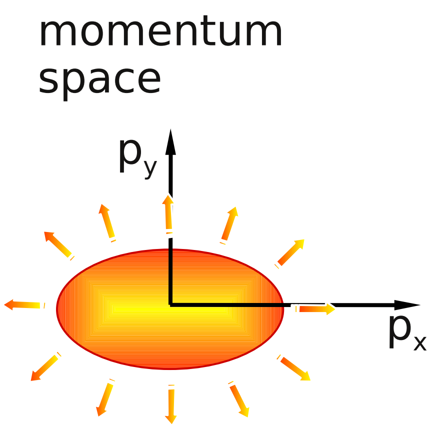
* this is lower bound; if during expansion work is done (pdV) initial energy density higher (indications hydrodynamics: factor 3)

Initial energy density exceeds that in the center of a Pb nucleus by more than a factor of 100!

2. hydrodynamic expansion of fireball

Lesson from RHIC: fireball expands collectively like an ideal fluid

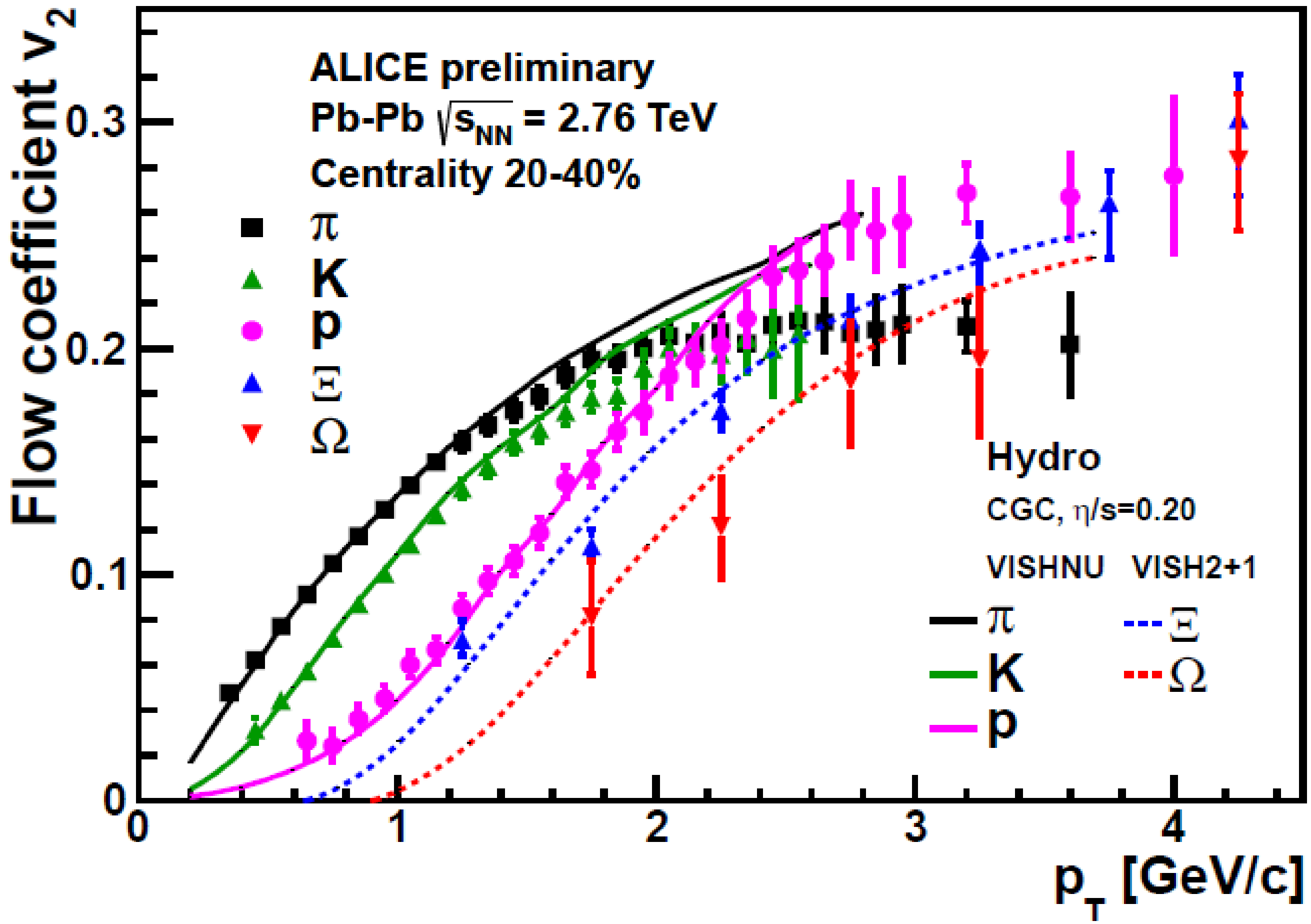




$$dN/d\phi = 1 + 2\, V_2 \cos 2\,(\phi - \psi) + \ldots$$

hydrodynamic flow characterized by azimuthal anisotropy coeffient v_2 + higher orders

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

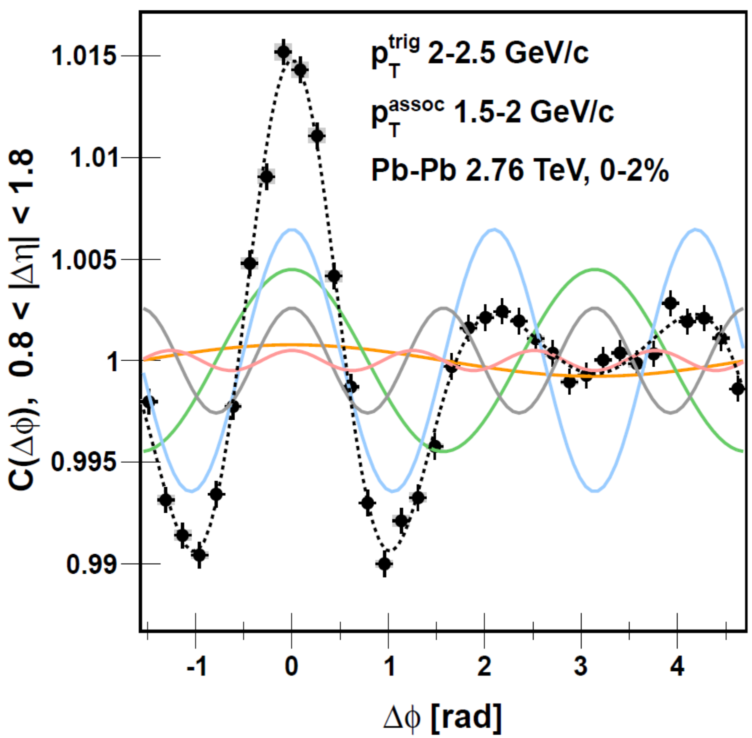


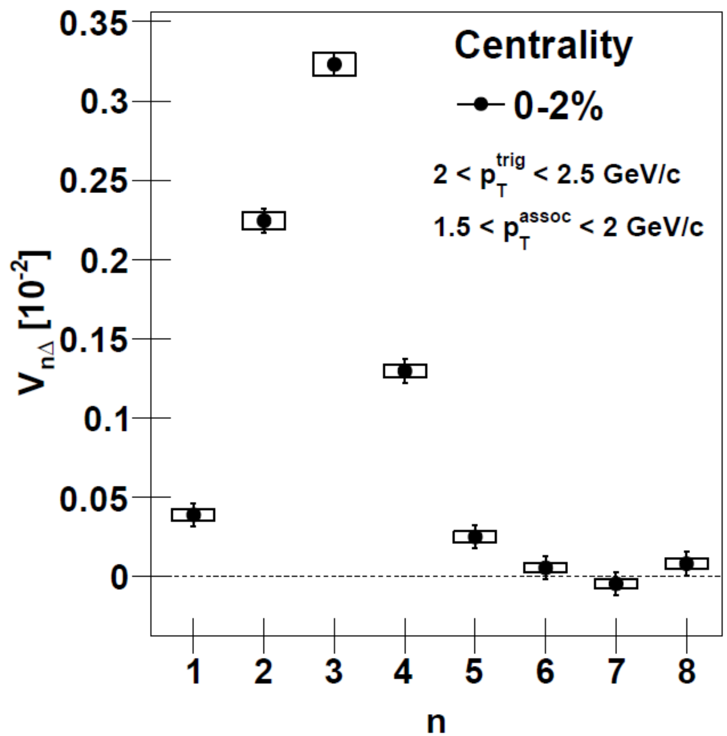
rapidly rising v_2 with p_t and mass ordering typical features of hydrodyn. expansion

nearly ideal (non-dissipative) hydrodynamics reproduces data

The 2-particle correlation function – higher moments

ALICE, PRL 107 (2011) 032301





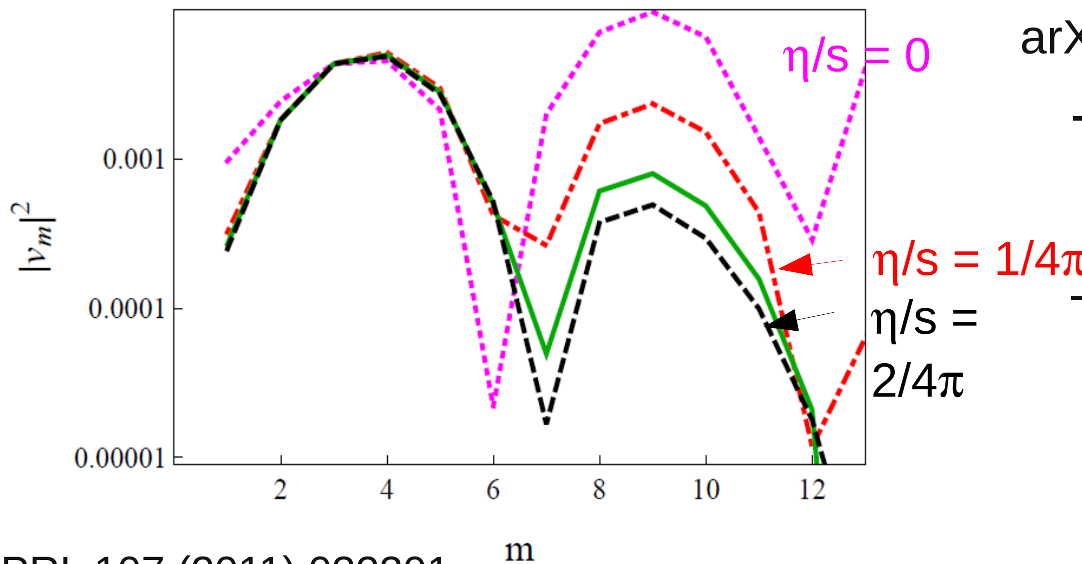
measurement of the first 8 harmonic coefficients

v_1-v_5 significantly larger than 0, maximum at v_3

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

Analogy with early universe power spectrum of CMB

Propagation of sound in the quark-gluon plasma

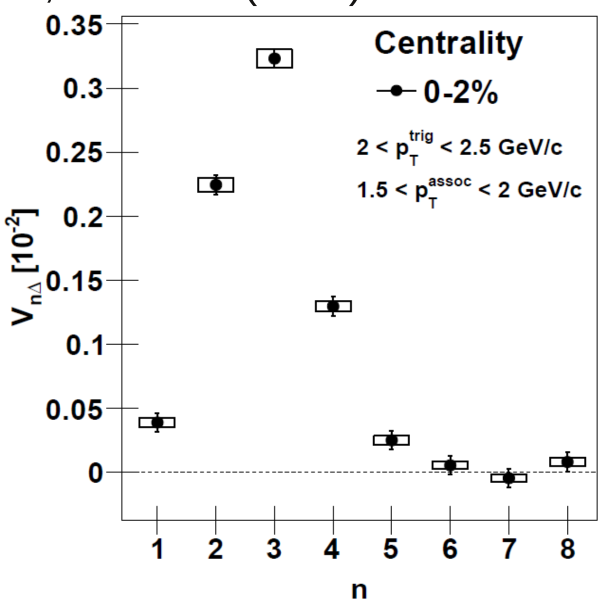


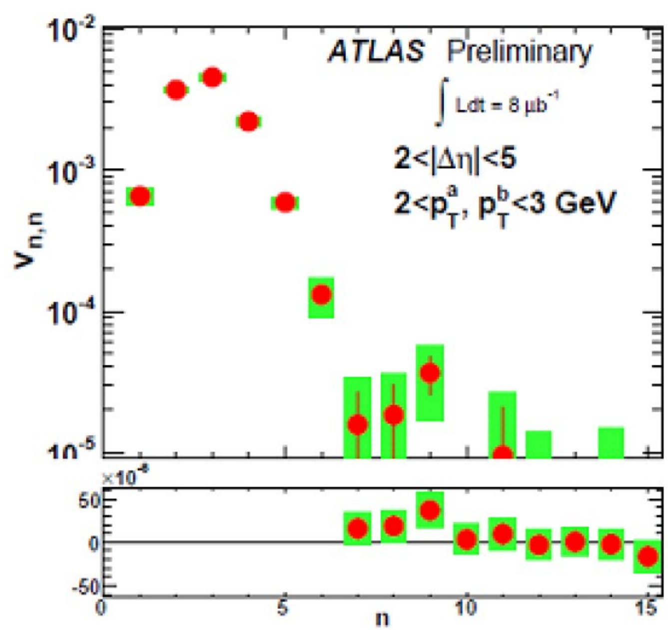
Staig & Shuryak
arXiv:1109.6633

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

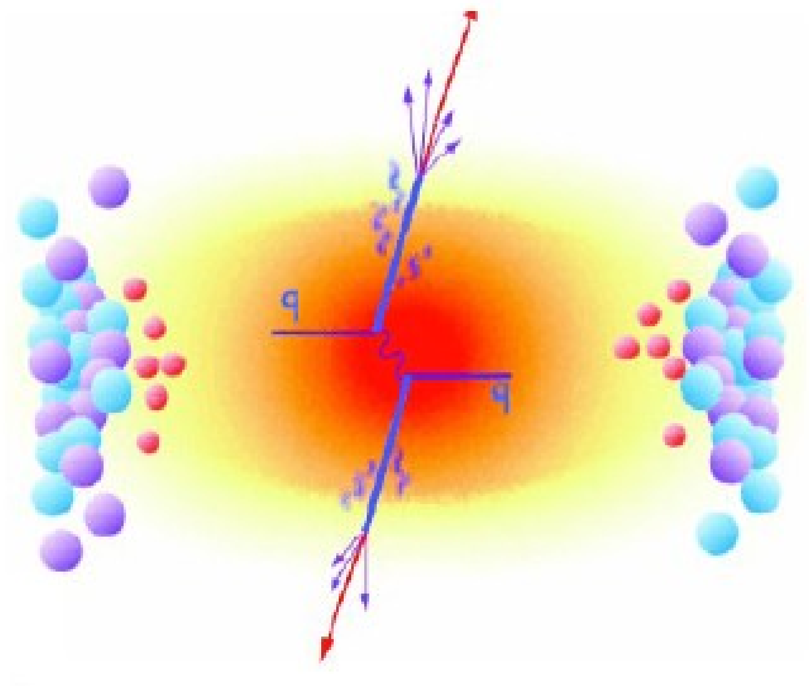
  and to expansion velocity

ALICE, PRL 107 (2011) 032301





3. Parton energy loss



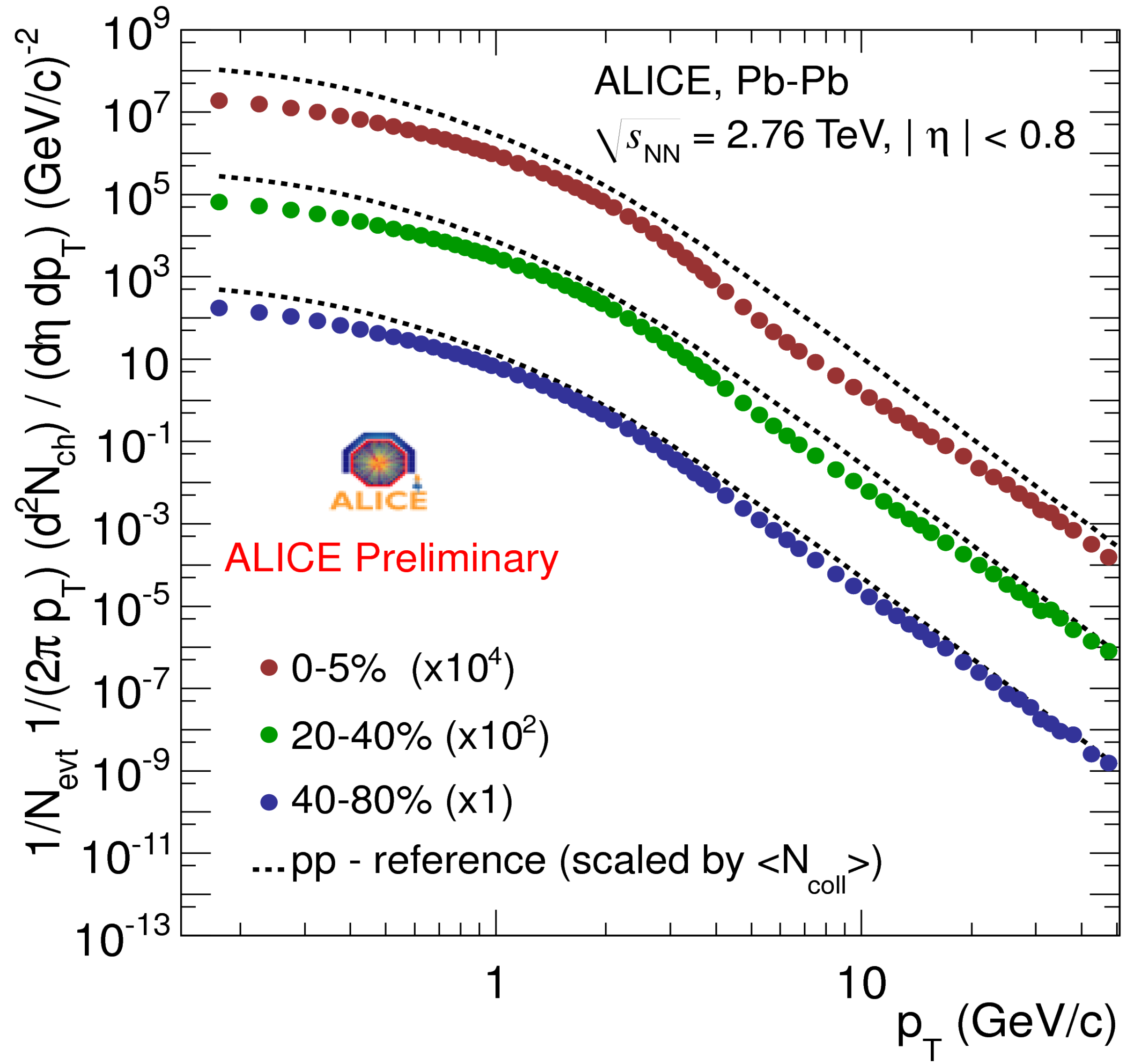
Medium modification quantified via nuclear modification factor

$$R^i_{\mathrm{AA}} = \frac{Y^i_{\mathrm{J}/\psi}(\Delta p_{\mathrm{t}}, \Delta y)}{\langle T^i_{\mathrm{AA}} \rangle \times \sigma^{\mathrm{pp}}_{\mathrm{J}/\psi}(\Delta p_{\mathrm{t}}, \Delta y)}$$

Here, T_{AA} is the nuclear thickness function

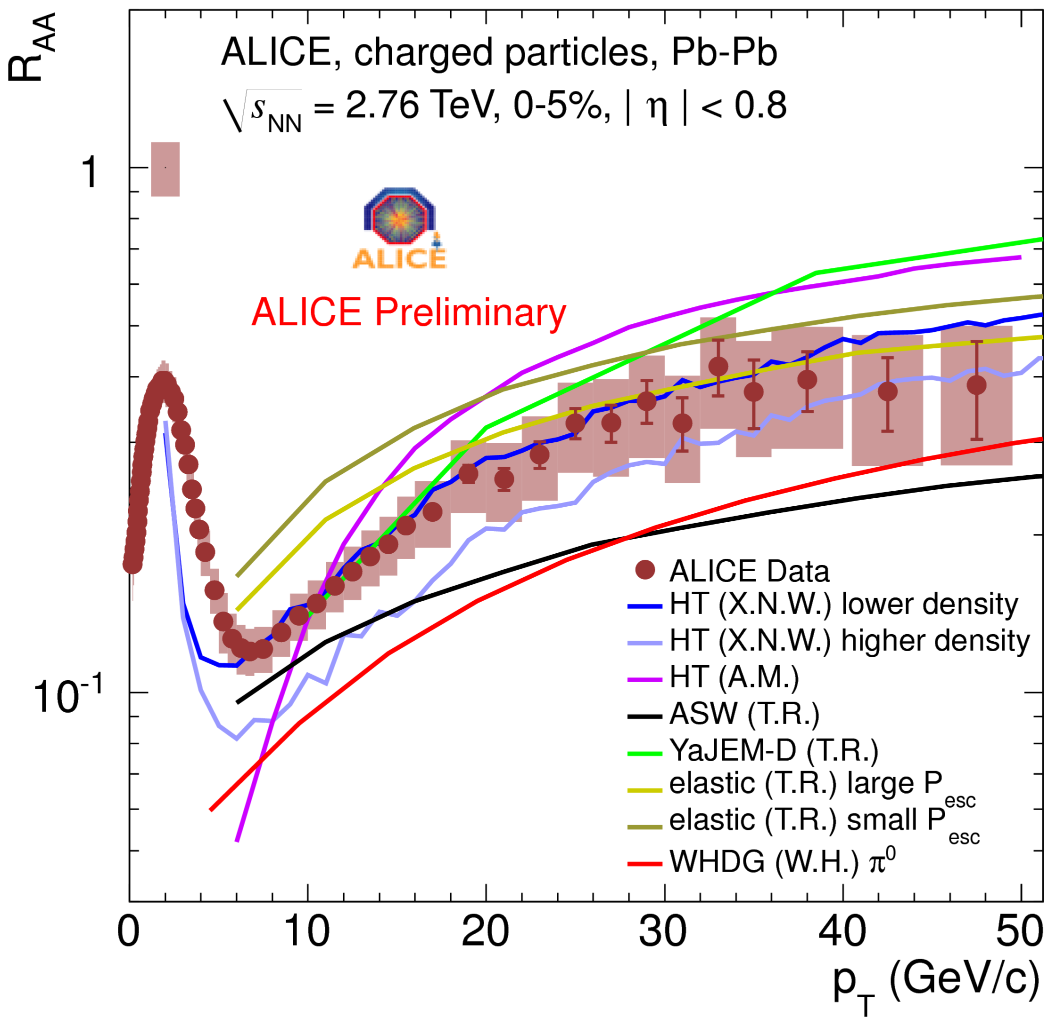
by construction, R_{AA} = medium/vacuum

p_t Spectra in Central and Peripheral PbPb Collisions



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

First Comparison to Models

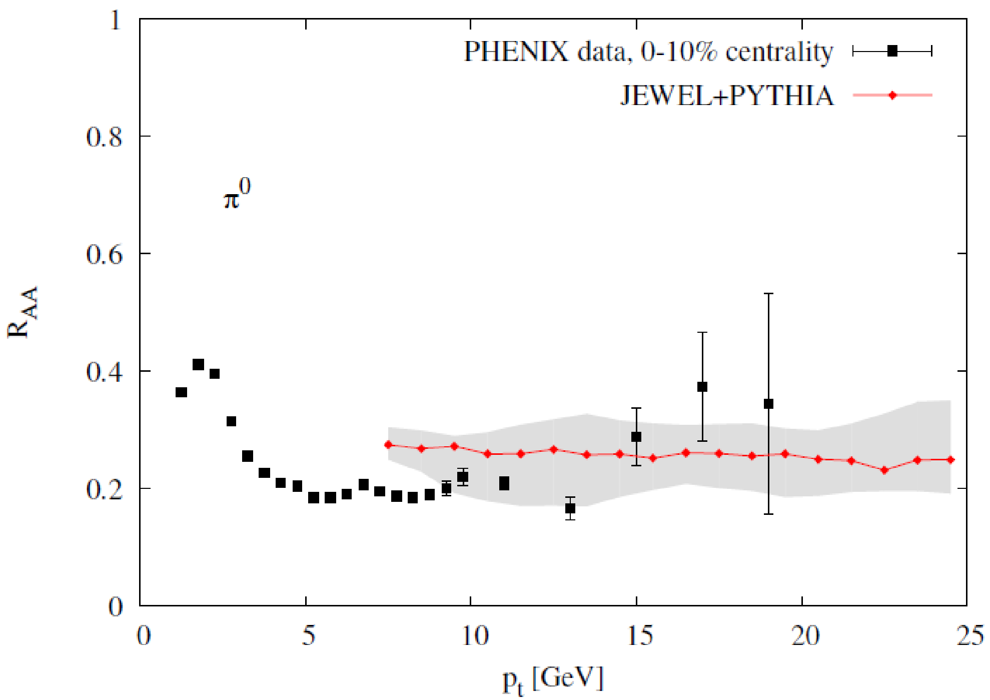


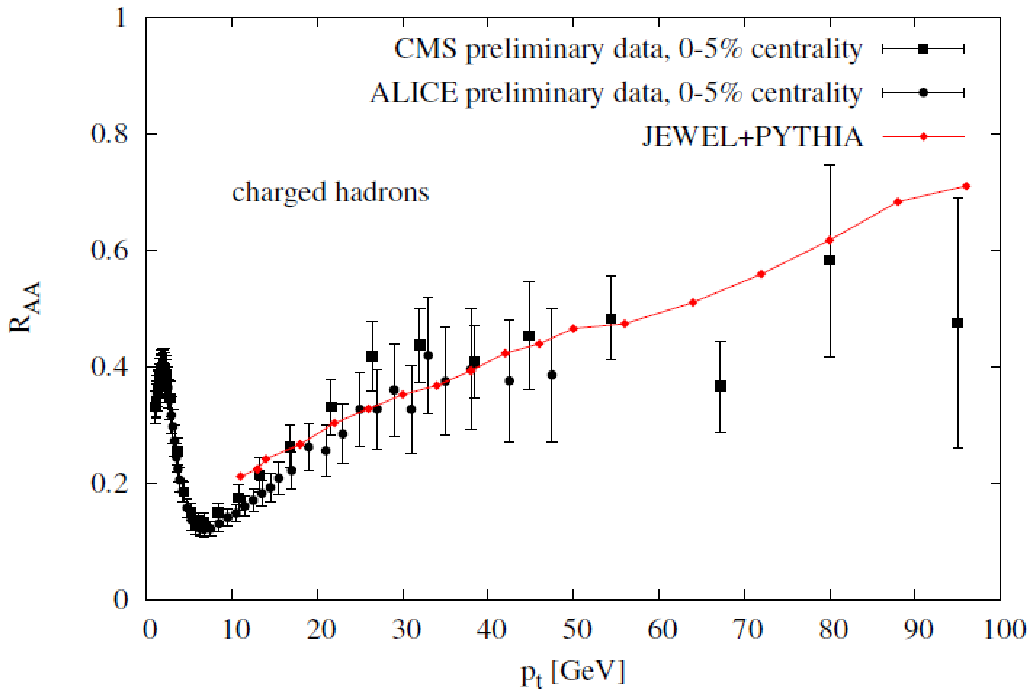
data show sensitivity
program for next years
- precision info for different quark flavors & large kinematic range
- determine effect of medium (QGP) on jets and vice versa

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
modelling of multiple scattering in the medium via infrared continued 2 → 2 scattering matrix element in pQCD and in-medium parton shower for further emissions

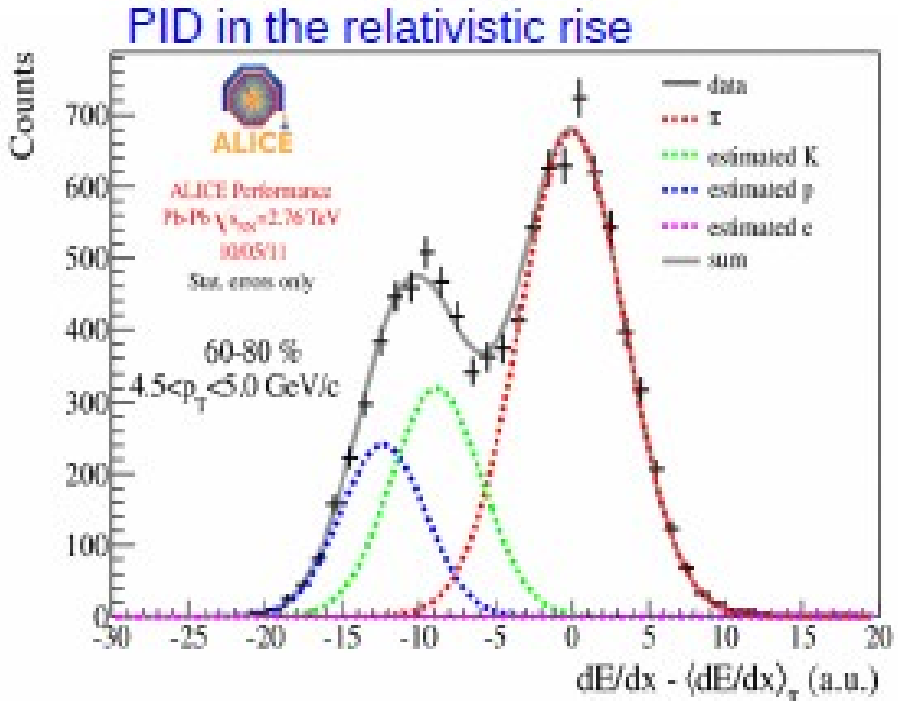


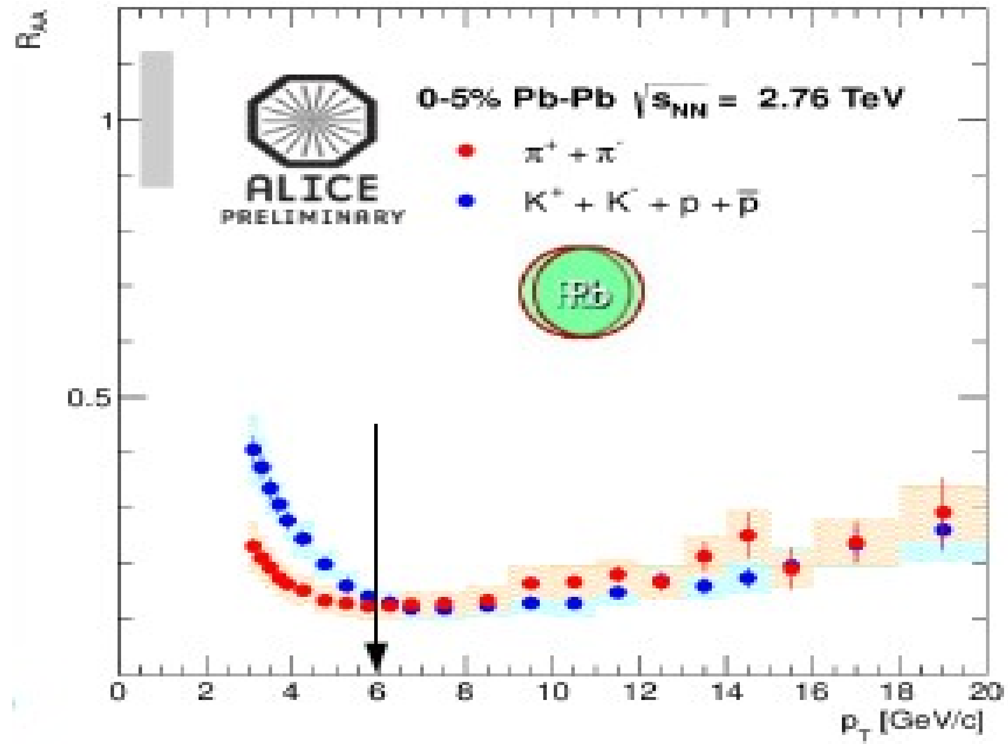


RHIC: T_i = 350 MeV τ_i = 0.8 fm/c
scale is set by final state particle multiplicity

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

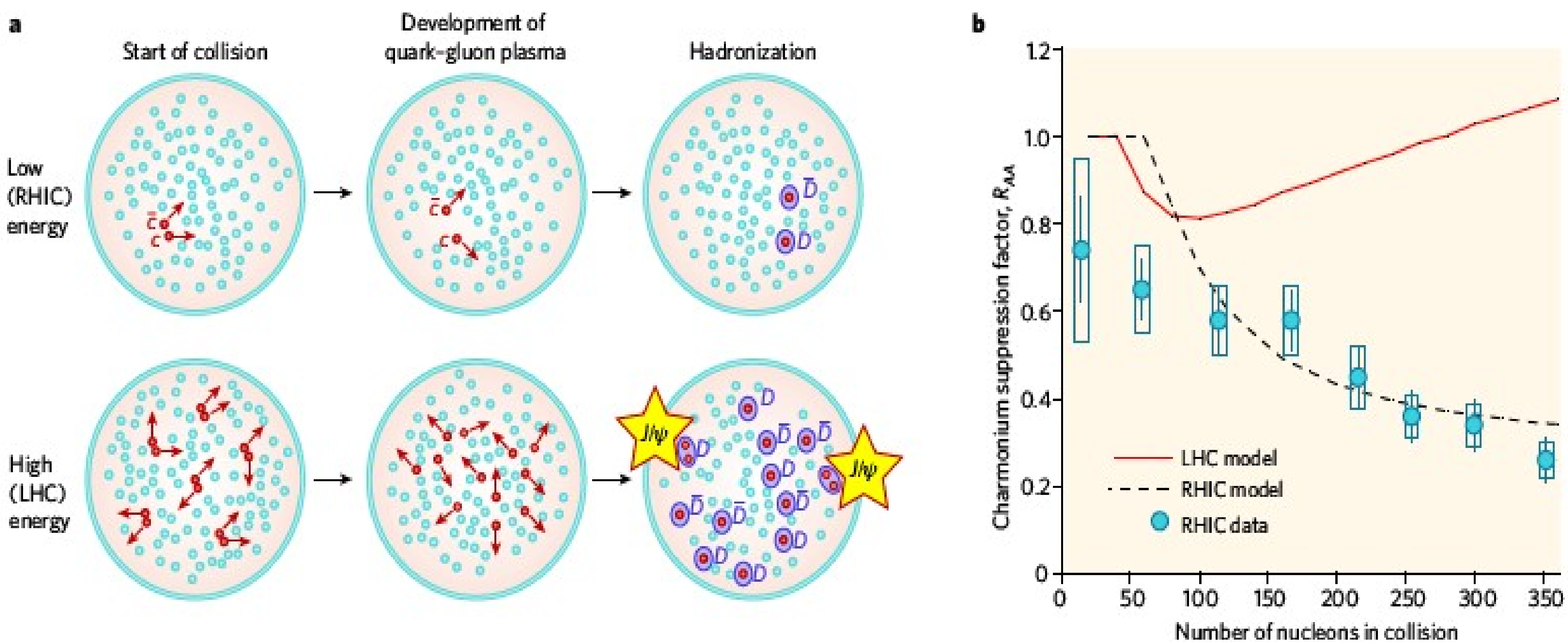
Nuclear modification factor for identified particles





no medium modification of fragmentation functions
data are consistent with energy loss on the parton level and fragmentation into vacuum

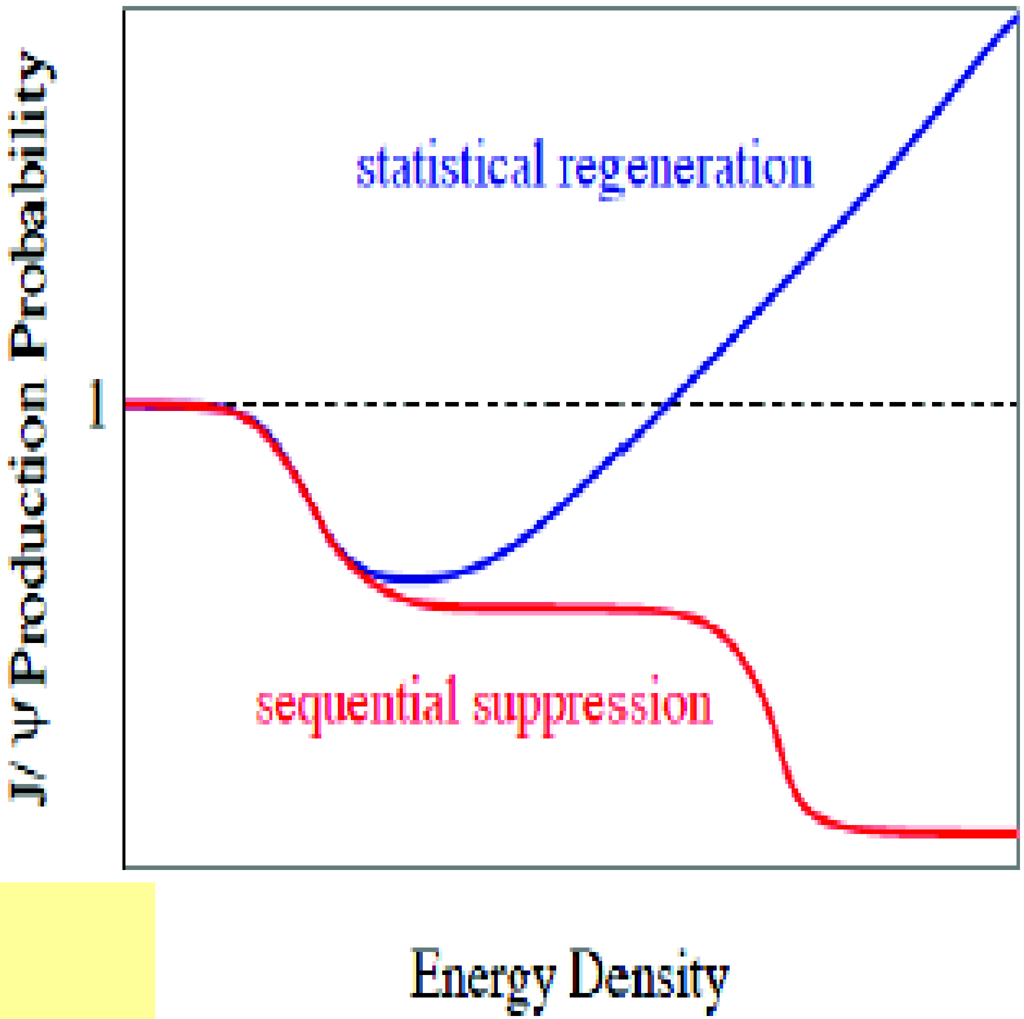
4. quarkonium as a probe for deconfinement at the LHC



charmonium enhancement as fingerprint of deconfinement at LHC energy

pbm, Stachel, Phys. Lett B490 (2000) 196
Andronic, pbm, Redlich, Stachel, Phys. Lett. B652 (2007) 659

decision on regeneration vs sequential suppression from LHC data



Picture:
H. Satz 2009

SPS RHIC LHC

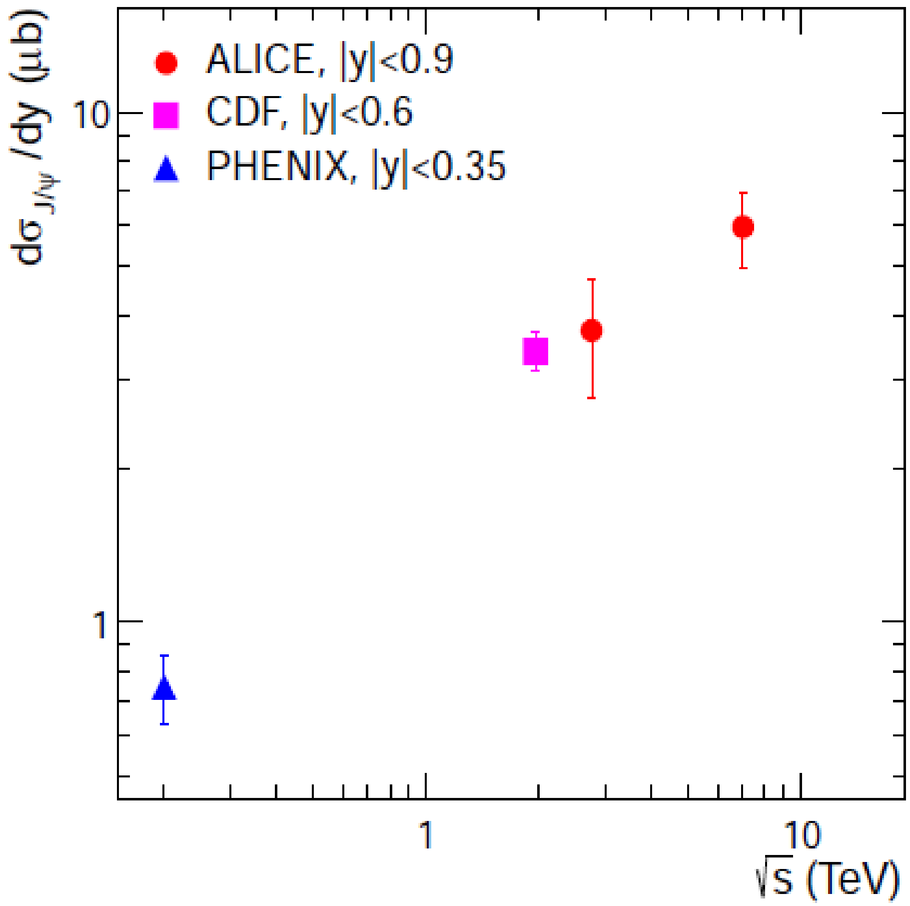
now to LHC data

attempt full measurement of open charm and open beauty
in pp, pPb, PbPb as function of centrality, rapidity and transverse momentum

attempt full measurement including polarization of all quarkonia
in pp, pPb, PbPb as function of centrality, rapidity and transverse momentum

...we are on the way

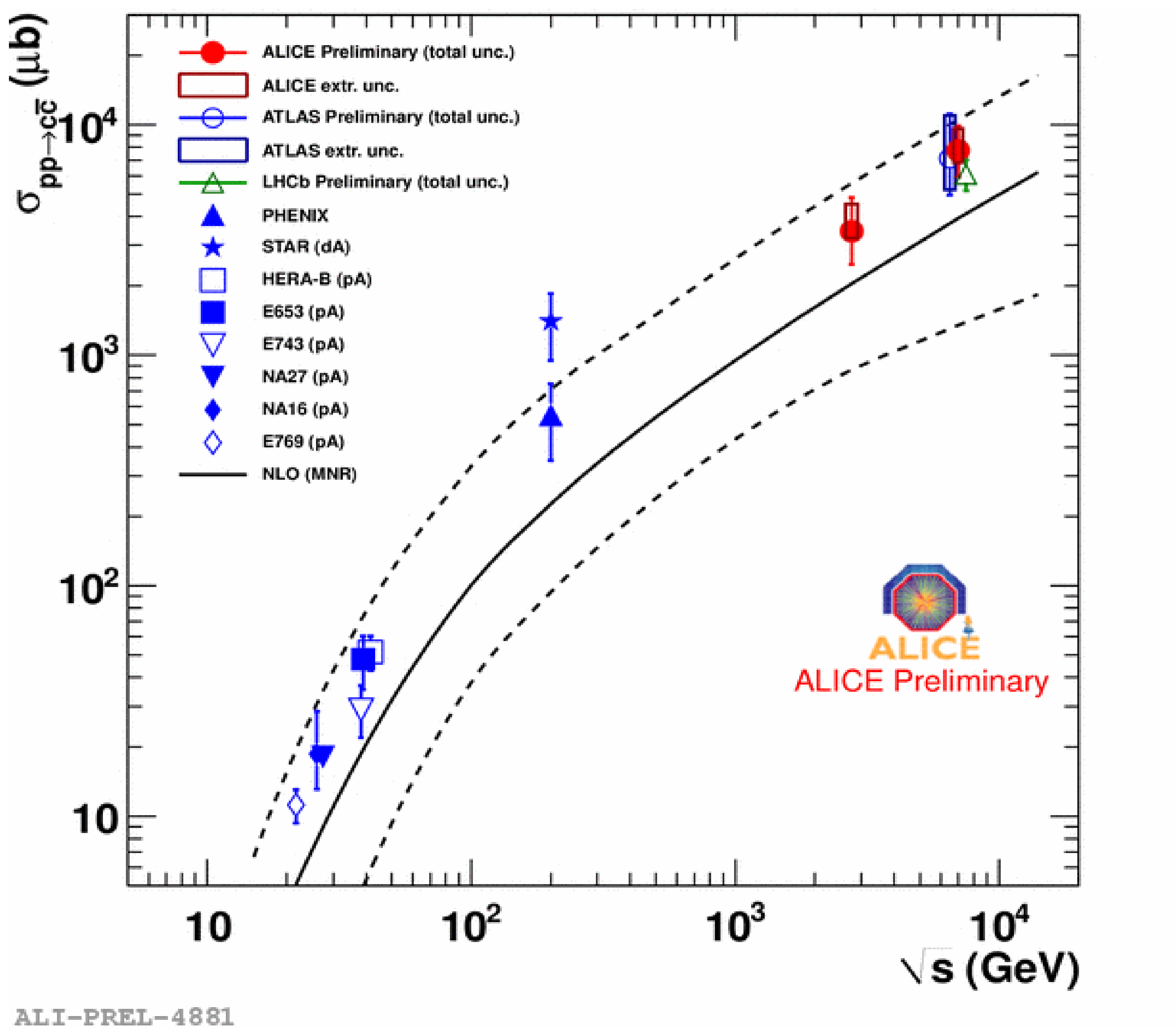
energy dependence of J/psi production in pp collisions – collider energies



arXiv:1203.3641

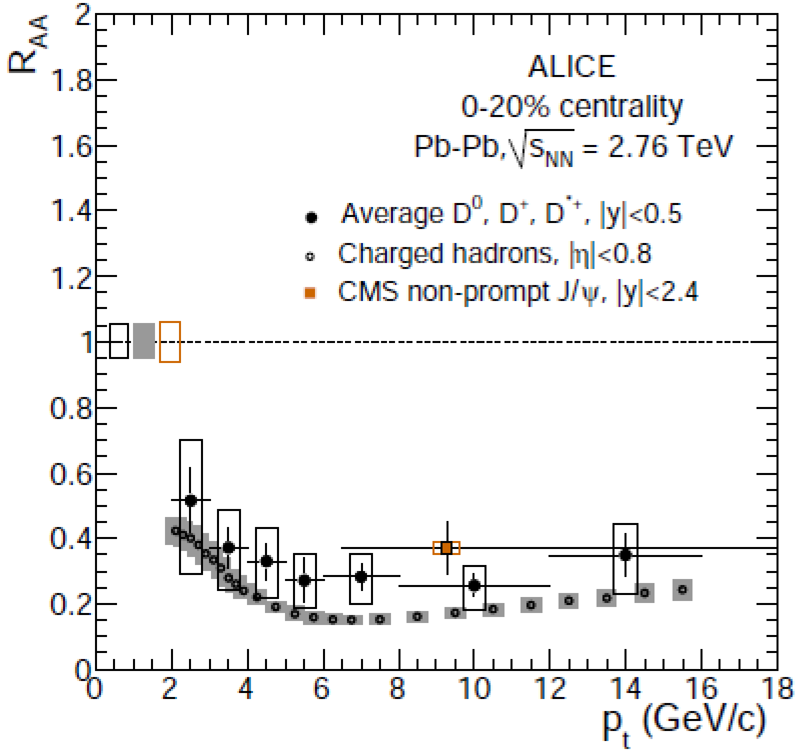
...and more: polarization results (PRL 108 (2012) 082001), $B \to J/\psi$

a first try at the total open charm cross section in pp collisions



Suppression of charm at LHC energy

$$R_{AA} = \frac{\mathrm{d}N^{AA}/\mathrm{d}p_t}{N_{coll} \cdot \mathrm{d}N^{pp}/\mathrm{d}p_t}$$



ALICE, arXiv:1203.2160

Energy loss of charm quarks close to that for light quark → thermalization

charm quarks are suppressed relative to pp collisions

in the pt range 3 < pt < 10 GeV there are much fewer charm quarks compared to expectations from pp collisions

→ **charm quarks in PbPb are at low pt!**

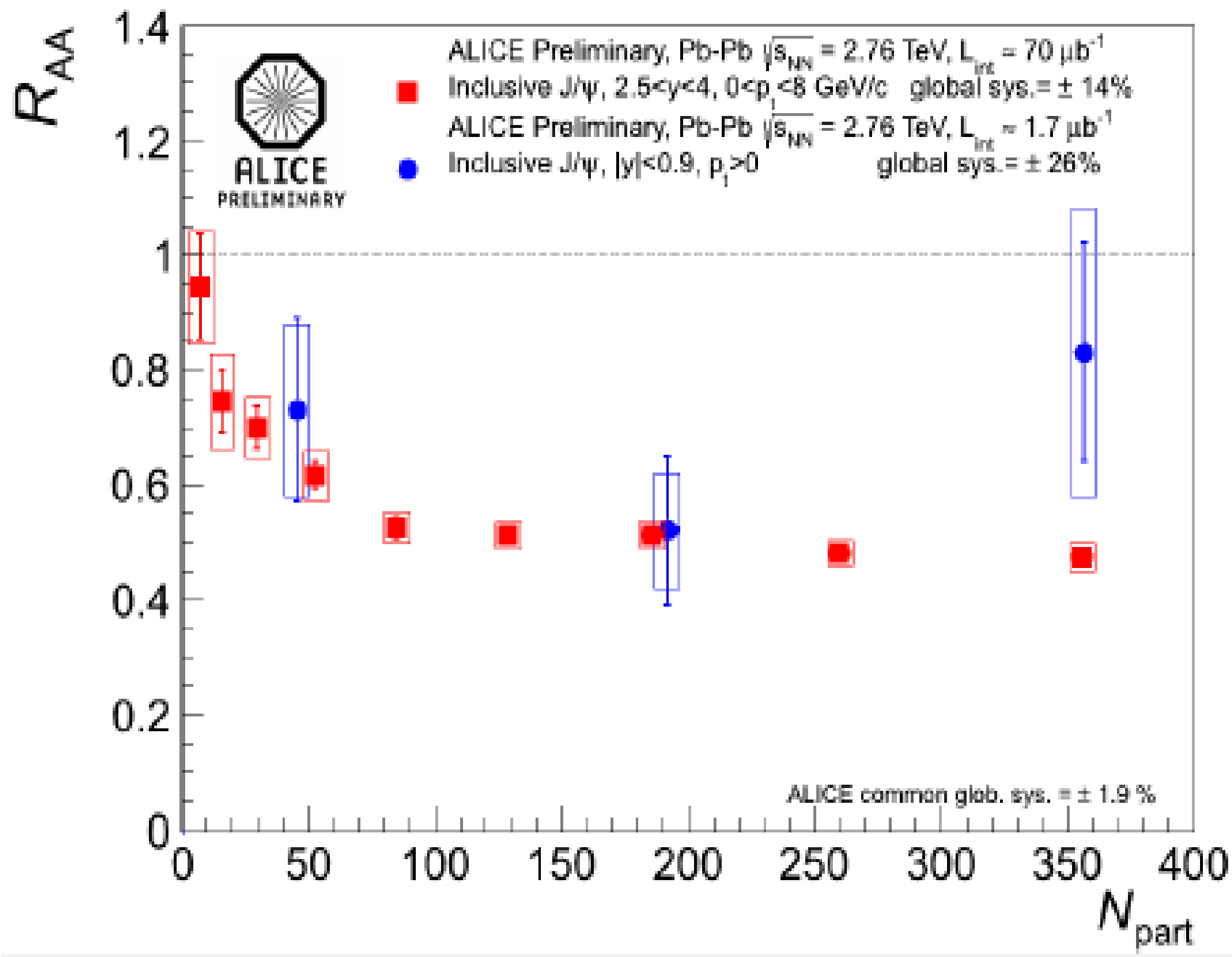
expect that charmonia are suppressed in the pt > 3GeV range

measurements at low pt are absolutely essential for the charmonium story

solution: normalization of J/psi to the open charm cross section in PbPb collisions

first step: (J/psi)/D ratio in PbPb collisions
to come soon from ALICE

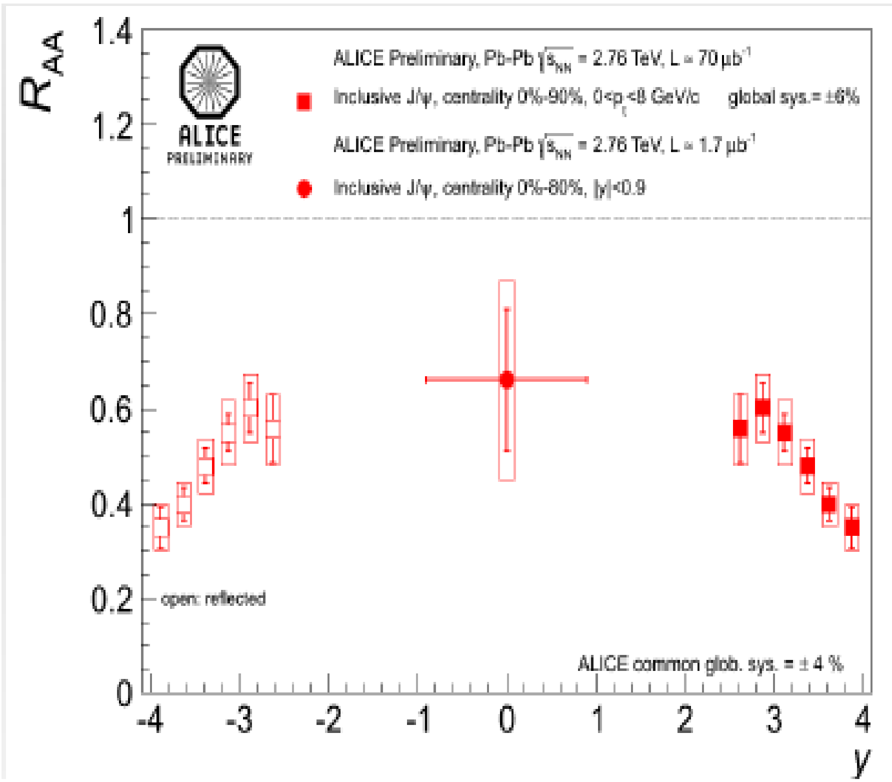
new results from ALICE

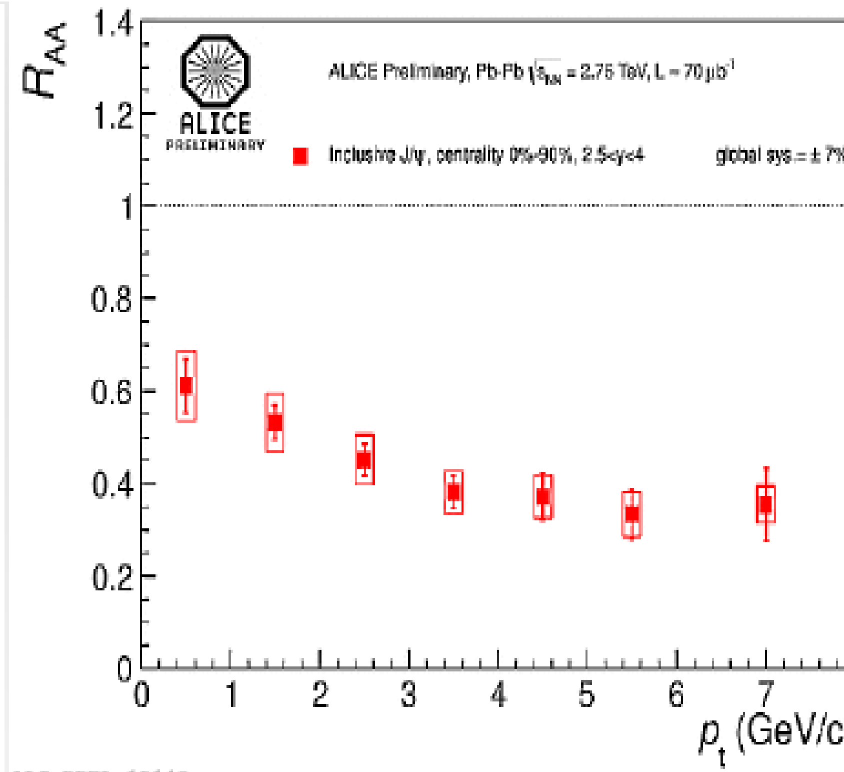


much improved statistics at forward rapidity and first results at mid-rapidity

indication of increase at midrapidity for very central collisions

rapidity and transverse momentum dependence of J/psi nuclear modification factor R_{AA}

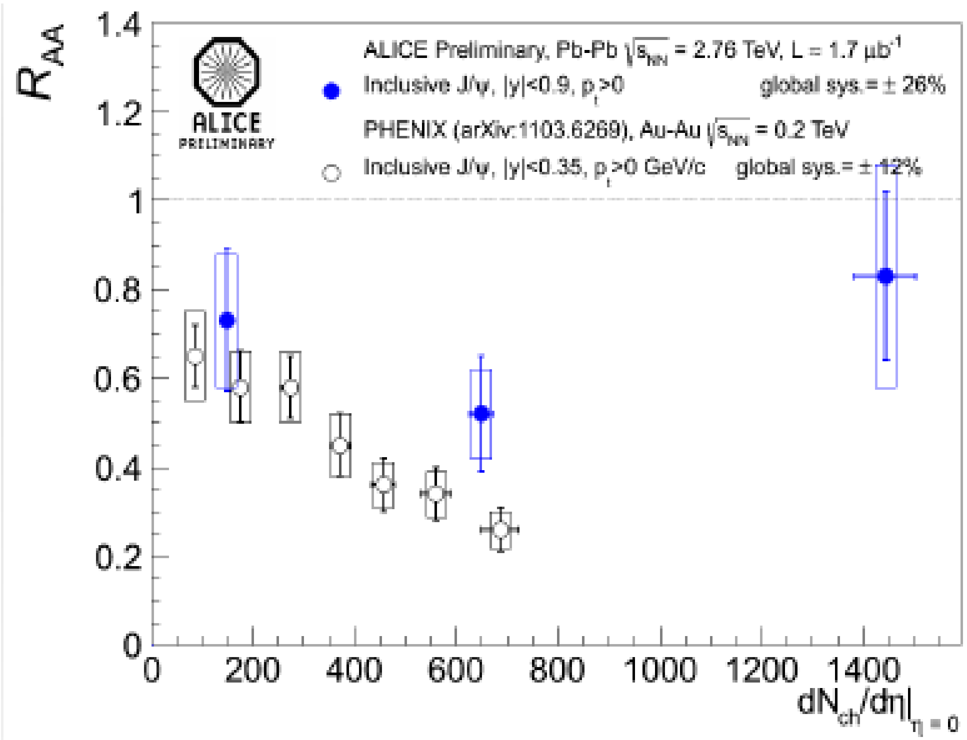


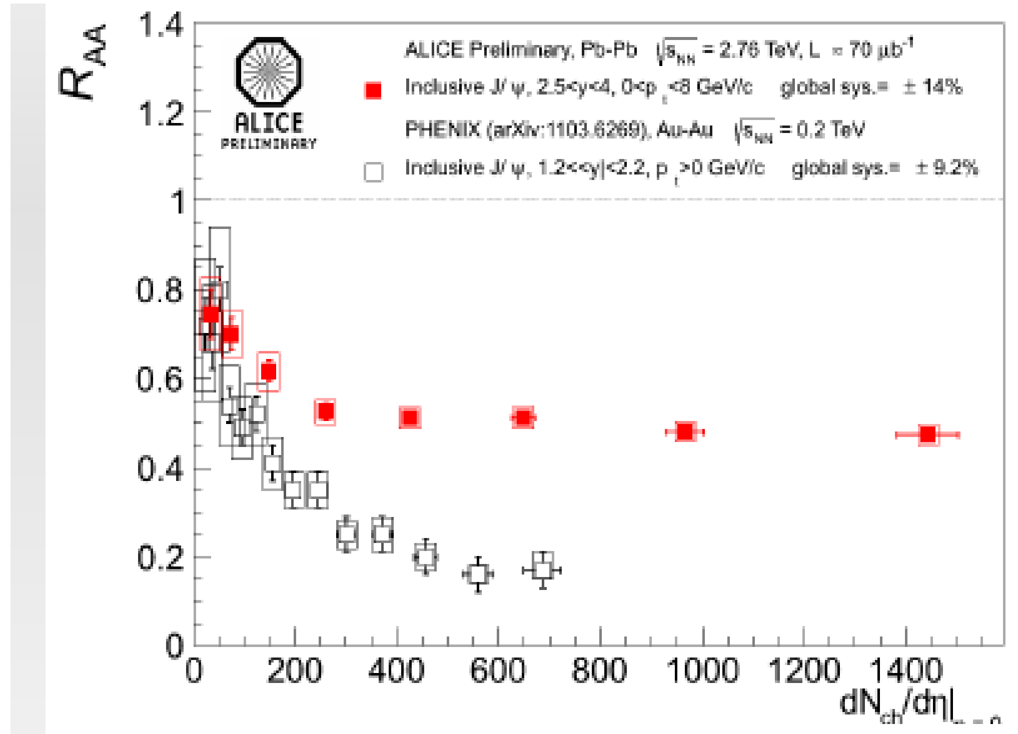


R_{AA} increases towards midrapidity, where energy density is largest

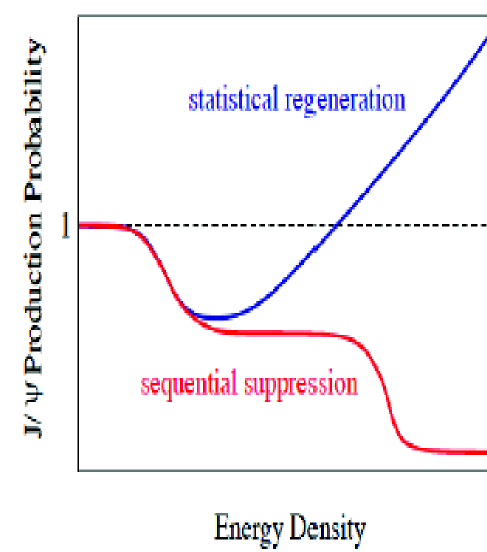
R_{AA} decreases with J/psi transverse momentum – at high p_t there are fewer charm quarks to combine into J/psi, also non-equilibrium contributions

comparison to results from PHENIX at RHIC





energy density →



N_{ch} is proportional to energy density

→ enhancement with increasing energy density!

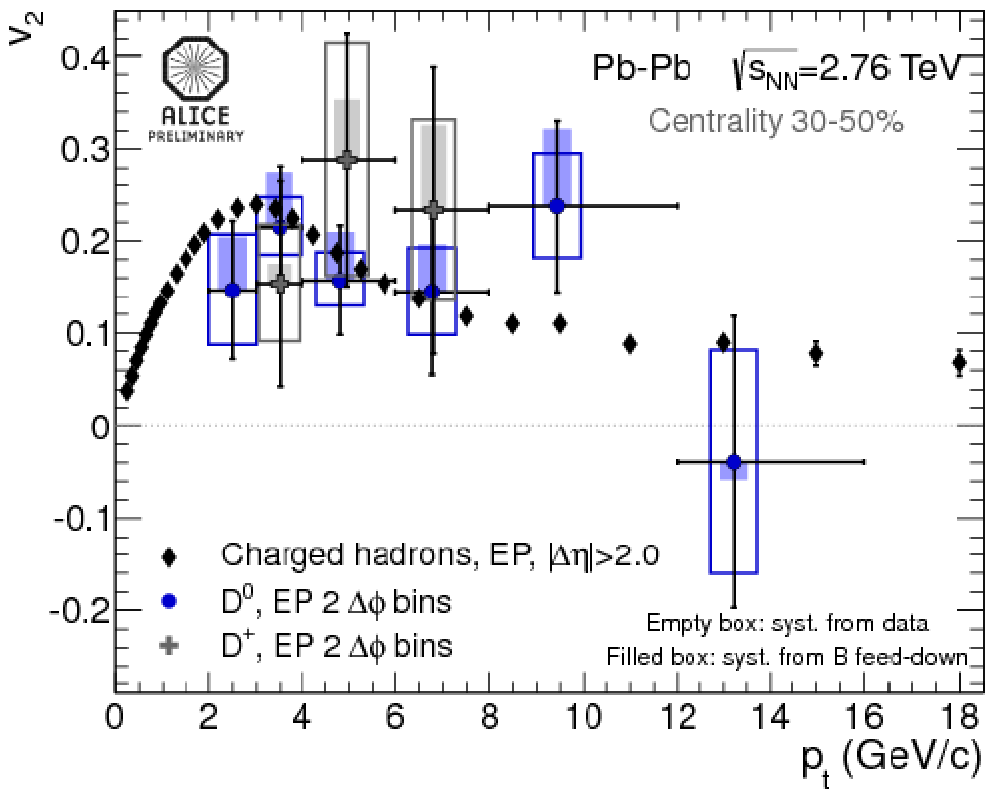
→ increase of suppression with increasing energy density is not observed

back to J/psi data – what about hydrodynamic flow of charm and charmonia?

if charmonia are produced via statistical hadronization of charm quarks at the phase boundary, then:

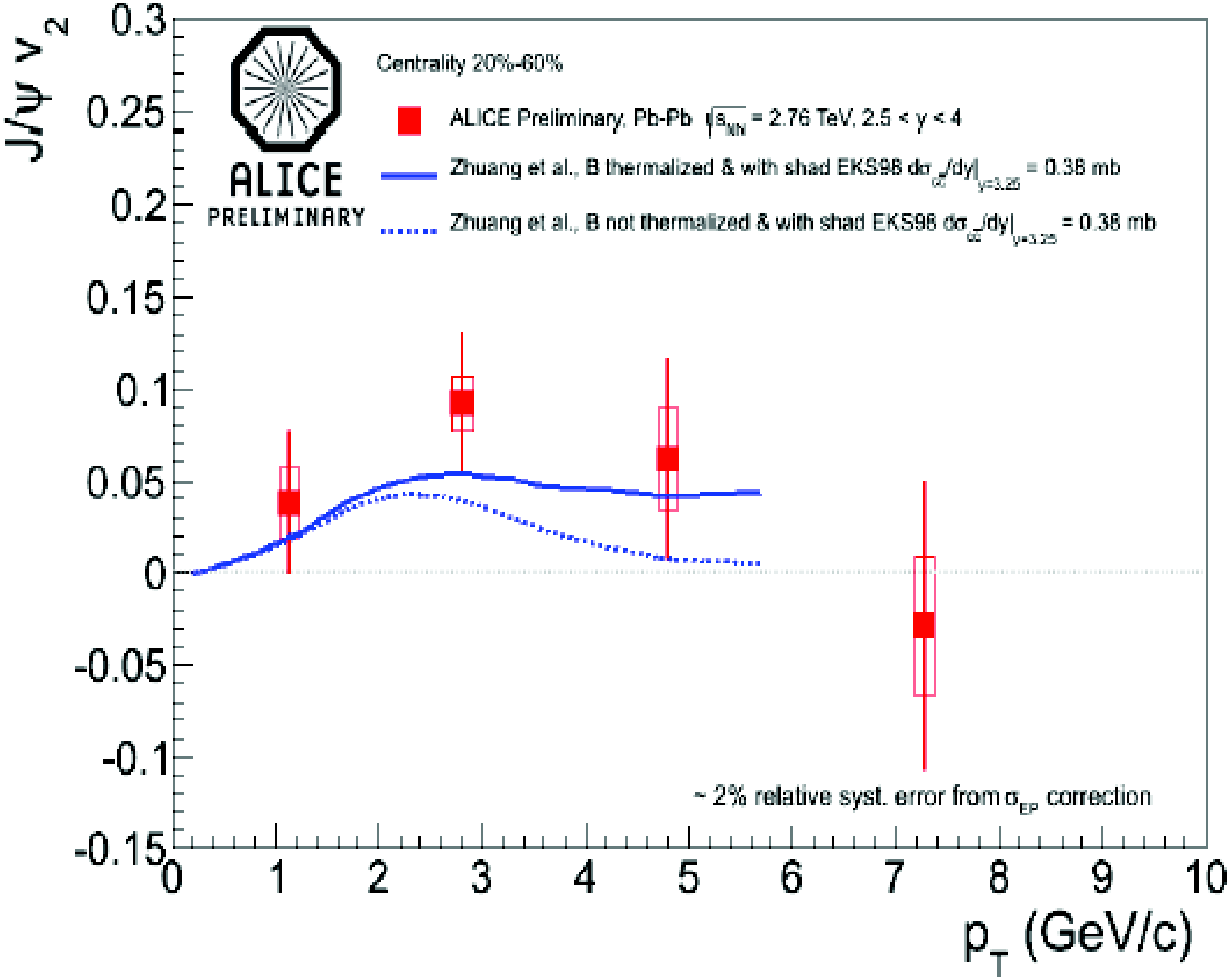
- charm quarks should be in thermal equilibrium
    - flow of charm quarks
    - flow of charmonia

charm quarks flow (nearly) as much as light quarks



results from ALICE at the LHC

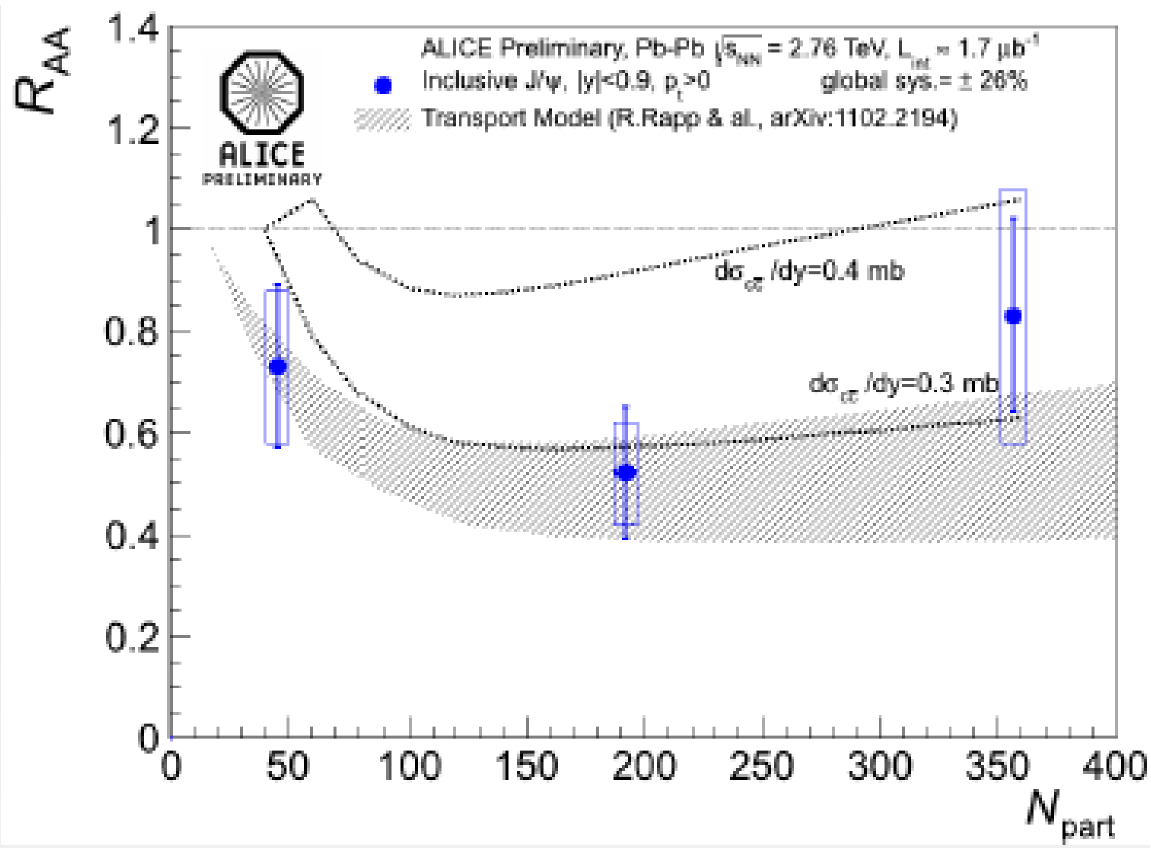
J/psi flow compared to models including (re-) generation



hydrodynamic flow of J/psi consistent with (re-)generation

J/ψ story – generation at the phase boundary

total ccbar cross section
from 7 TeV pp and
scaled to 2.76 TeV
using data



In Pb--Pb collisions at LHC:
signature of J/ψ regeneration

- larger R_{AA} at LHC compared to RHIC, a generic prediction of the statistical model
- R_{AA} has maximum at y=0
- charm quarks and J/ψ exhibit flow

predicted with statistical hadronization scenario

also transport models with regeneration describe data

summary so far

- Energy density in LHC fireball exceeds critical energy density by more than an order of magnitude

- Hydrodynamic flow similar to what has been observed at RHIC → ideal fluid scenario

- Energy loss is partonic, no evidence for medium-modified fragmentation functions

- Charmonium at low pt behaves very differently from what has been seen at RHIC → deconfinement and charm quark recombination at the phase boundary

Program for the next 5 years (up to LS2)

complete measurements with soft probes

hydrodynamic flow
→ shear viscosity and speed of sound

correlations

complete measurements on jets quenching and energy loss

→ opacity, detailed energy loss mechanism

complete 1st phase of measurements on heavy quarks and quarkonia

ALICE Upgrade: target LS2 (2018)

Primary scope:

- precision studies of charm and beauty mesons and baryons and charmonia
- low mass lepton pairs and thermal photons
- gamma-jet and jet-jet with particle identification from low momentum up to > 30 GeV.
- heavy nuclear states

➢ low-transverse momentum observables (complementary/orthogonal to the general-purpose detectors)

- not triggerable => need to examine full statistics.

- **Operate ALICE at high rate while preserving its uniqueness, superb tracking and PID, and enhance its secondary vertex capability and tracking at low-p_T → factor of 100 increase in statistics compared to present set-up**

Summary ALICE

- compelling and unique physics case

  heavy flavor embedded in QGP bulk
  flavor dependence of QCD phase boundary
  deconfinement vs chiral phase transition
  collective response of QGP to high energy and/or heavy quarks

- factor 100 in statistics reach, inspect min bias 50 kHz Pb—Pb

  strongly improved S/B for rare probes due to new ITS and PID

- technically interesting solutions for new ITS, GEM-TPC, and pipelined readout

Note: after upgrades of ATLAS and CMS there will also be improved opportunities for Pb—Pb physics in the multi-purpose detectors

An interesting decade of heavy ion physics at the LHC is ahead of us