Quark-gluon plasma research with Pb-beams at the LHC: status and prospects

HELMHOLTZ GEMEINSCHAFT

- Introductory remarks – connection to early universe and other fields
- Energy dependence of hadron production and the quark-hadron phase boundary
- The fireball expands and flows collectively
- The initial temperature of the fireball
- Thermalization of heavy quarks
- Charmonia – probes for deconfinement
- The future of ALICE

FIAS-Frankfurt

EMMI

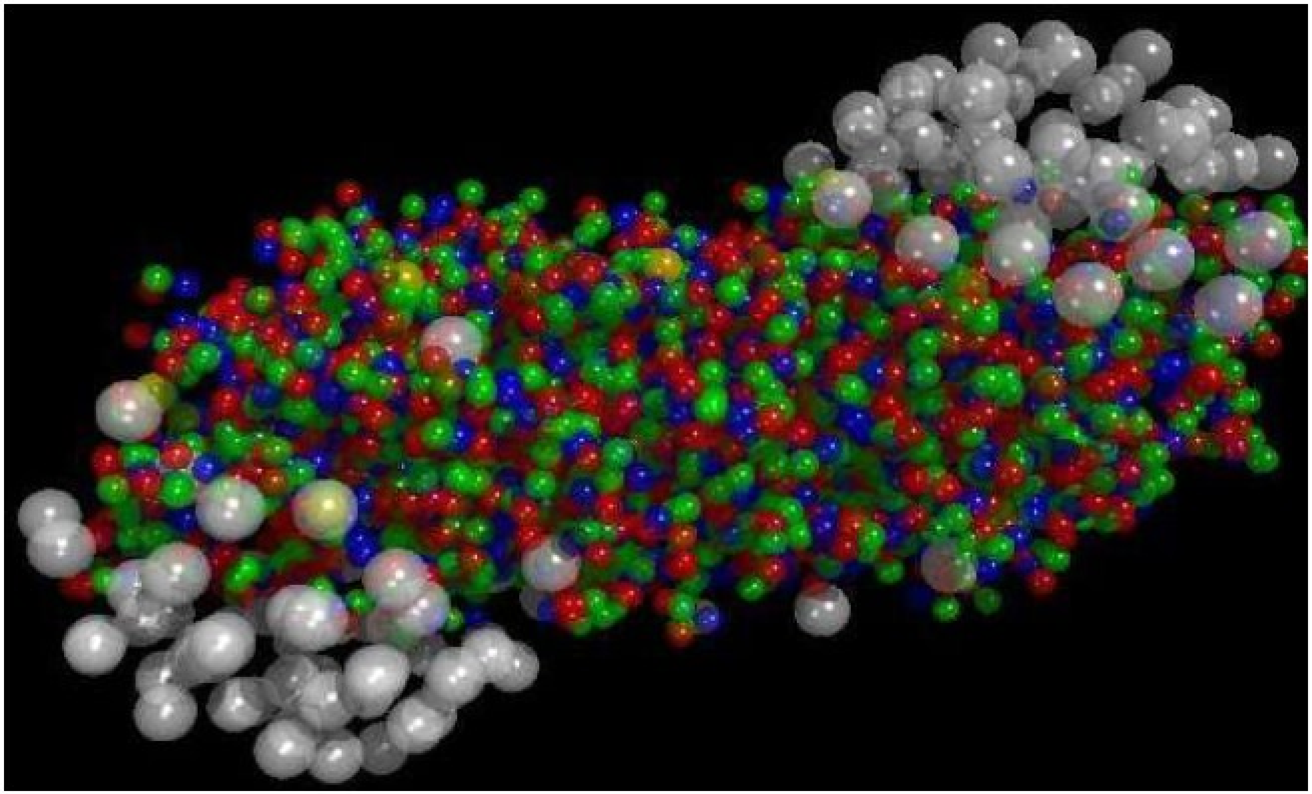
Colloquium Liverpool
Jan. 30, 2013

Peter Braun-Munzinger

GSI

TECHNISCHE UNIVERSITÄT DARMSTADT

Quark-gluon plasma –a new state of matter- deconfined quarks and gluons



in relativistic nucleus-nucleus collisions, a new state of matter is produced, in which colored quarks and gluons roam freely

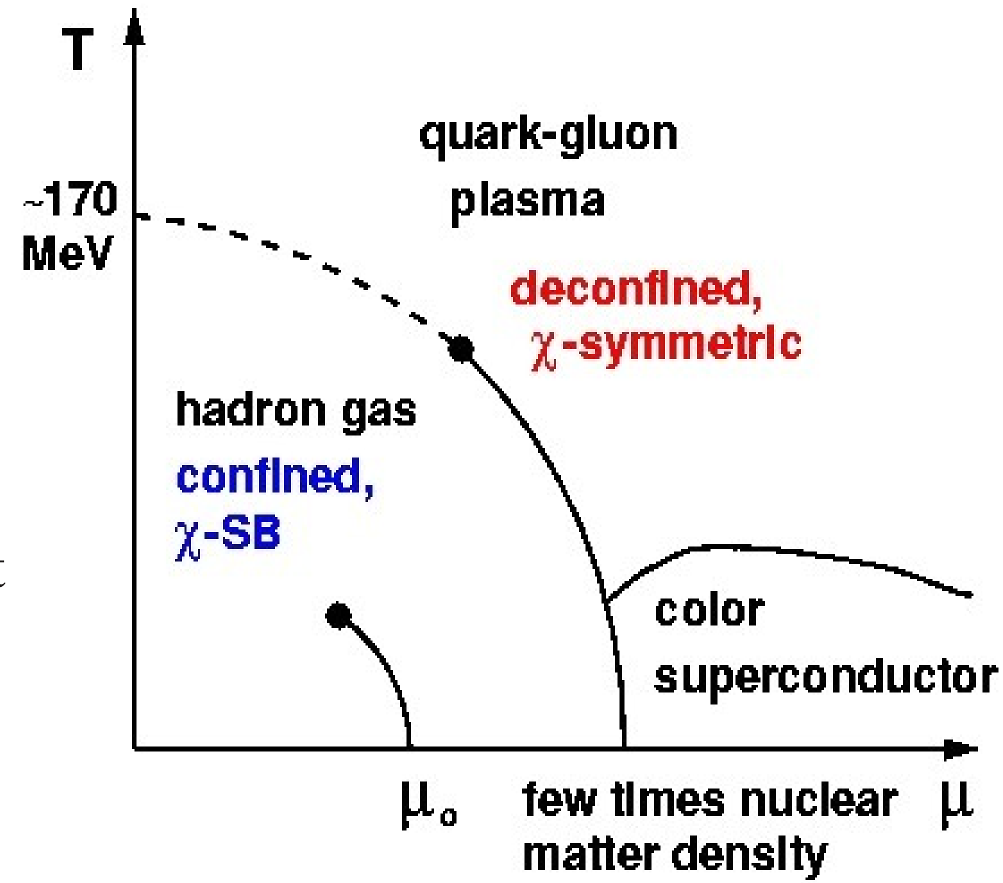
Simulation: UrQMD, Frankfurt

The phase diagram of strongly interacting matter

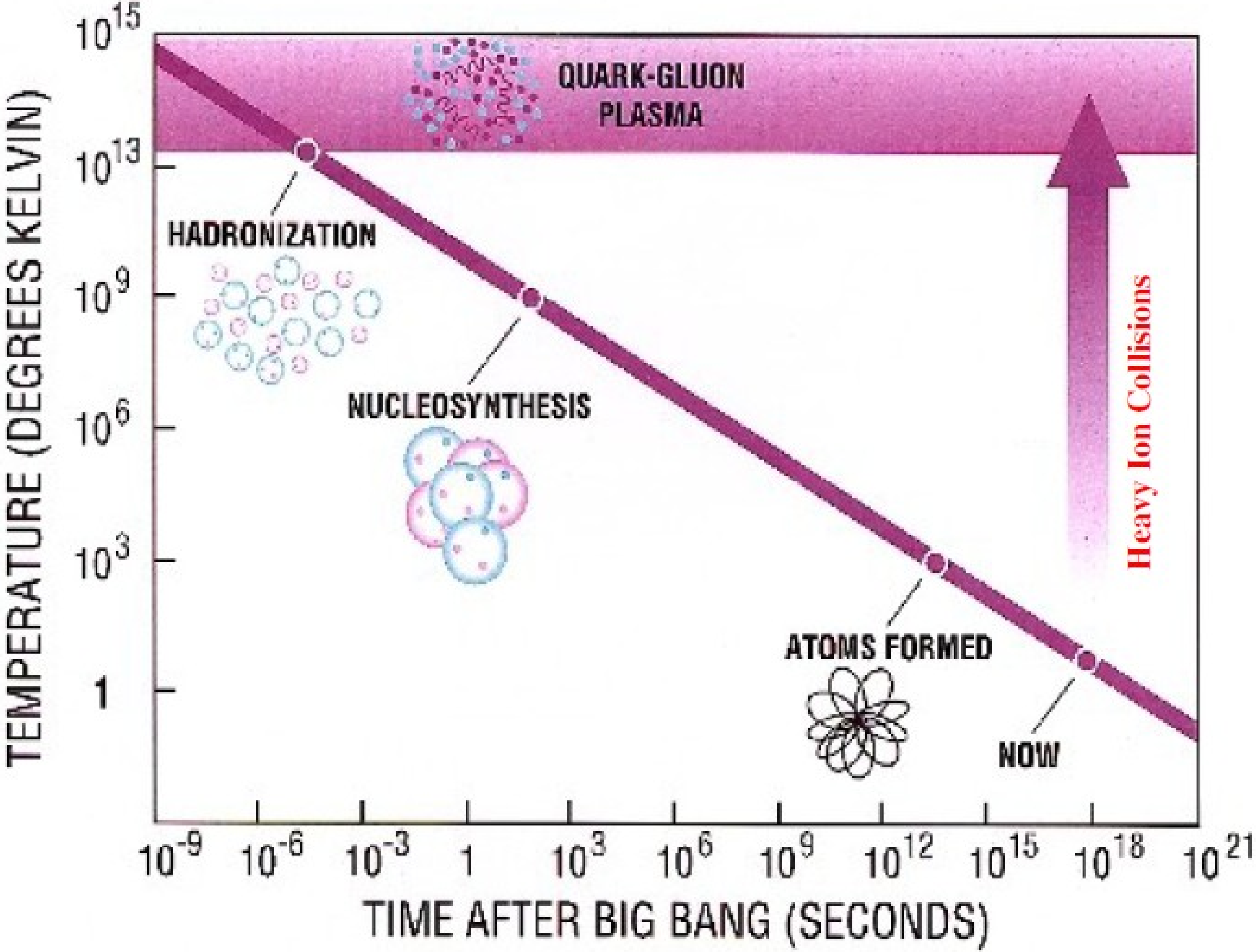
at low temperature and normal density
colored quarks and gluons are bound in colorless hadrons - confinement
chiral symmetry is spontaneously broken (generating 99% of proton mass e.g.)
1972 QCD (Gross, Politzer, Wilczek)
asymptotic freedom at small distances

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)

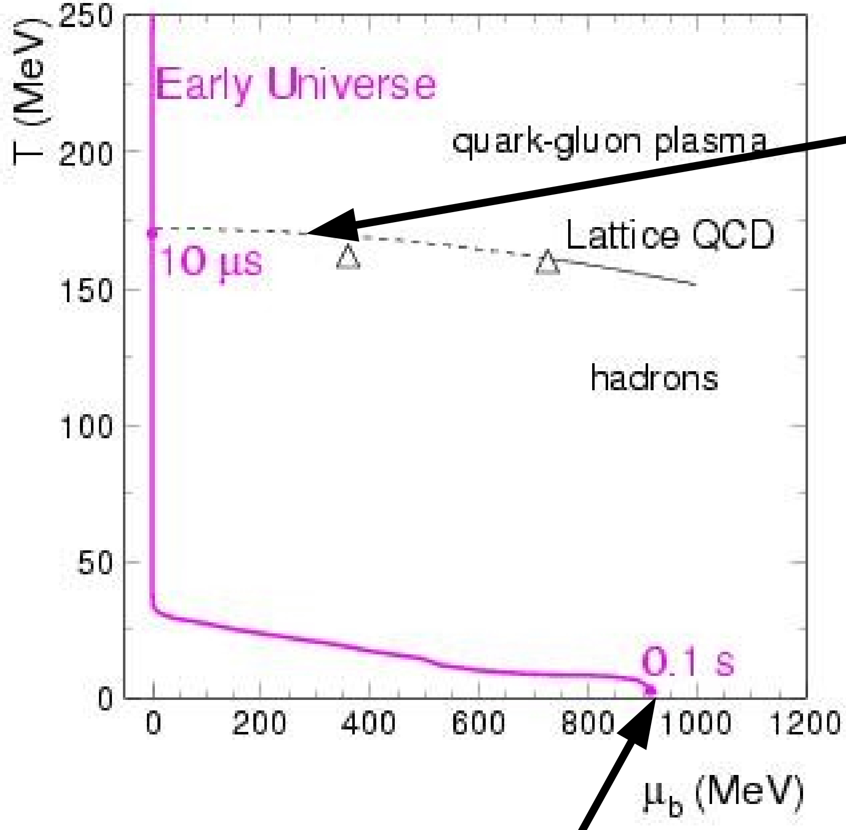
now called **Quark-Gluon Plasma (QGP)**



Quark-gluon plasma and the early universe



Evolution of the Early Universe



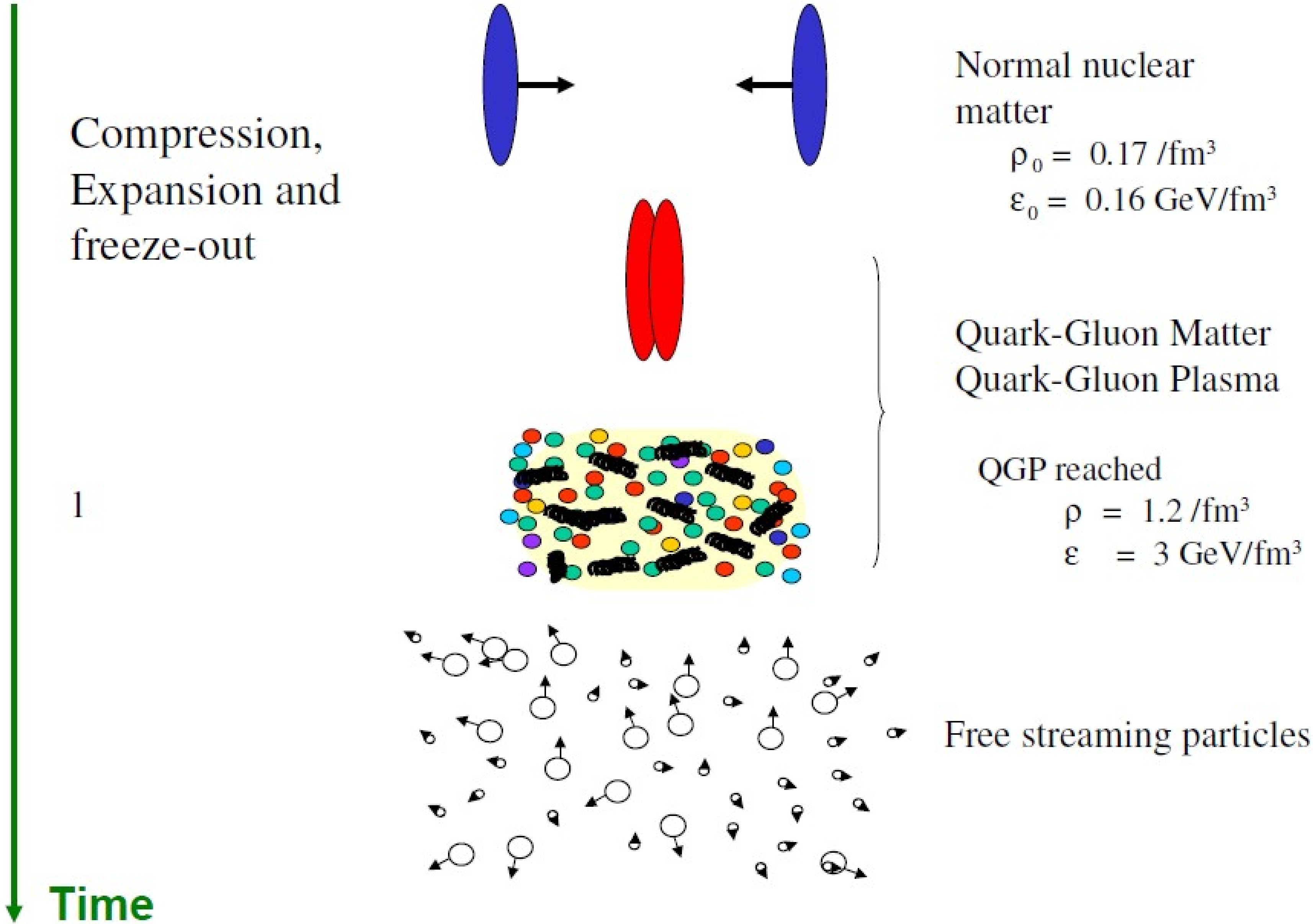
QCD Phase Boundary

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

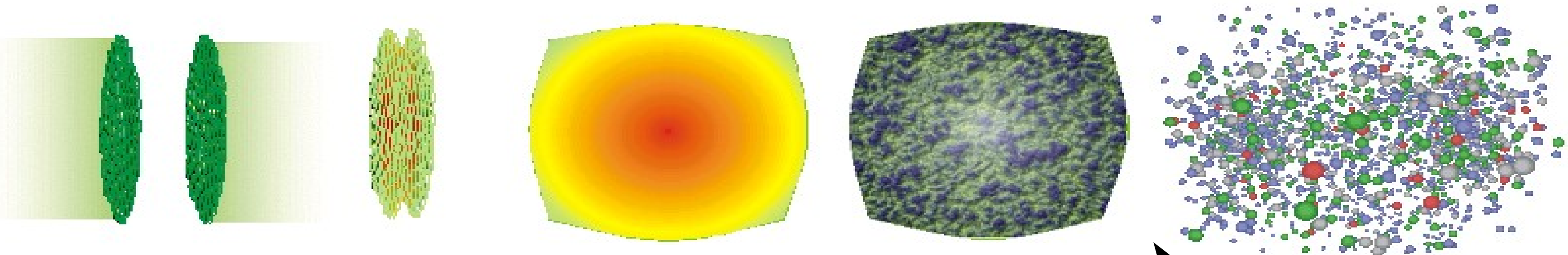
- Charge neutrality
- Net lepton number = net baryon number
- Constant entropy/baryon

neutrinos decouple and light nuclei begin to be formed

How to create QGP in the laboratory?

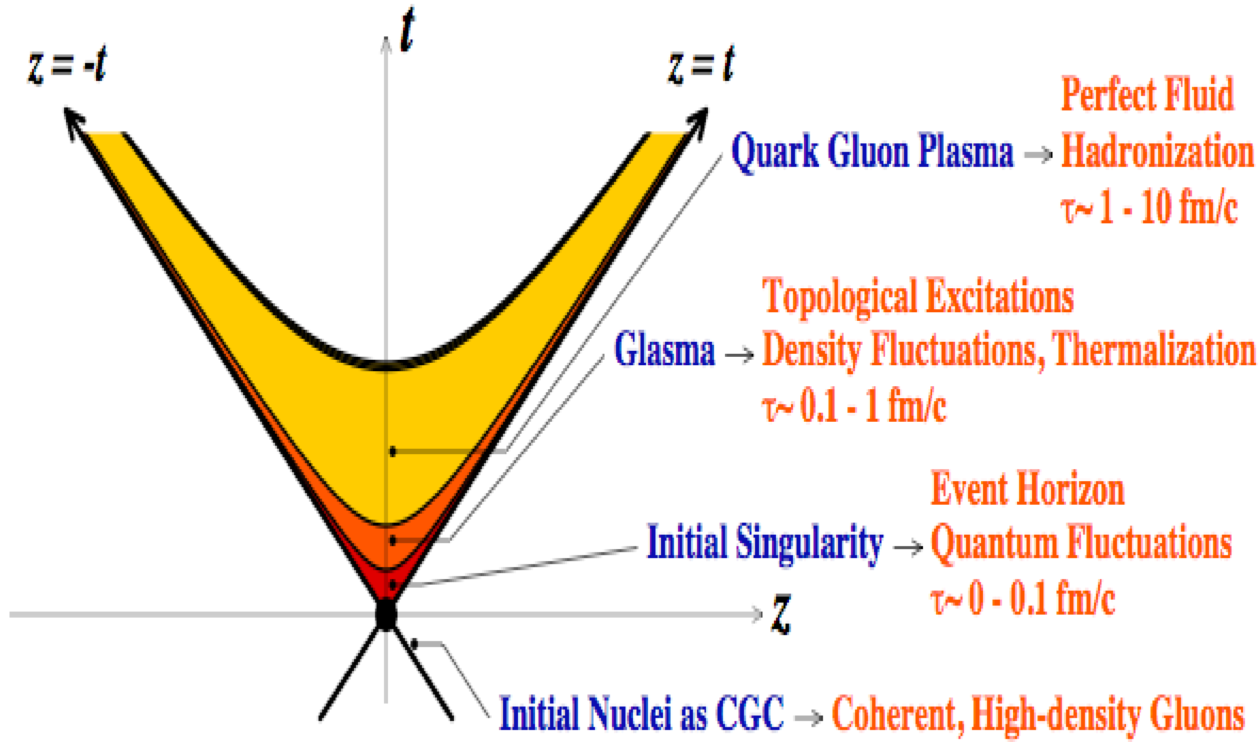


The Space-Time Evolution of a Relativistic Nuclear Collision

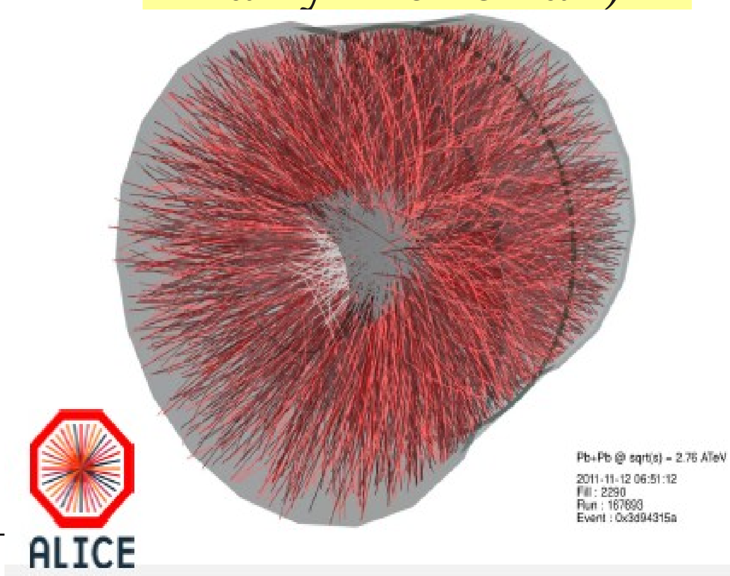


CGC | Initial Singularity | Glasma | sQGP | Hadron Gas

Hot fireball, equilibrized matter

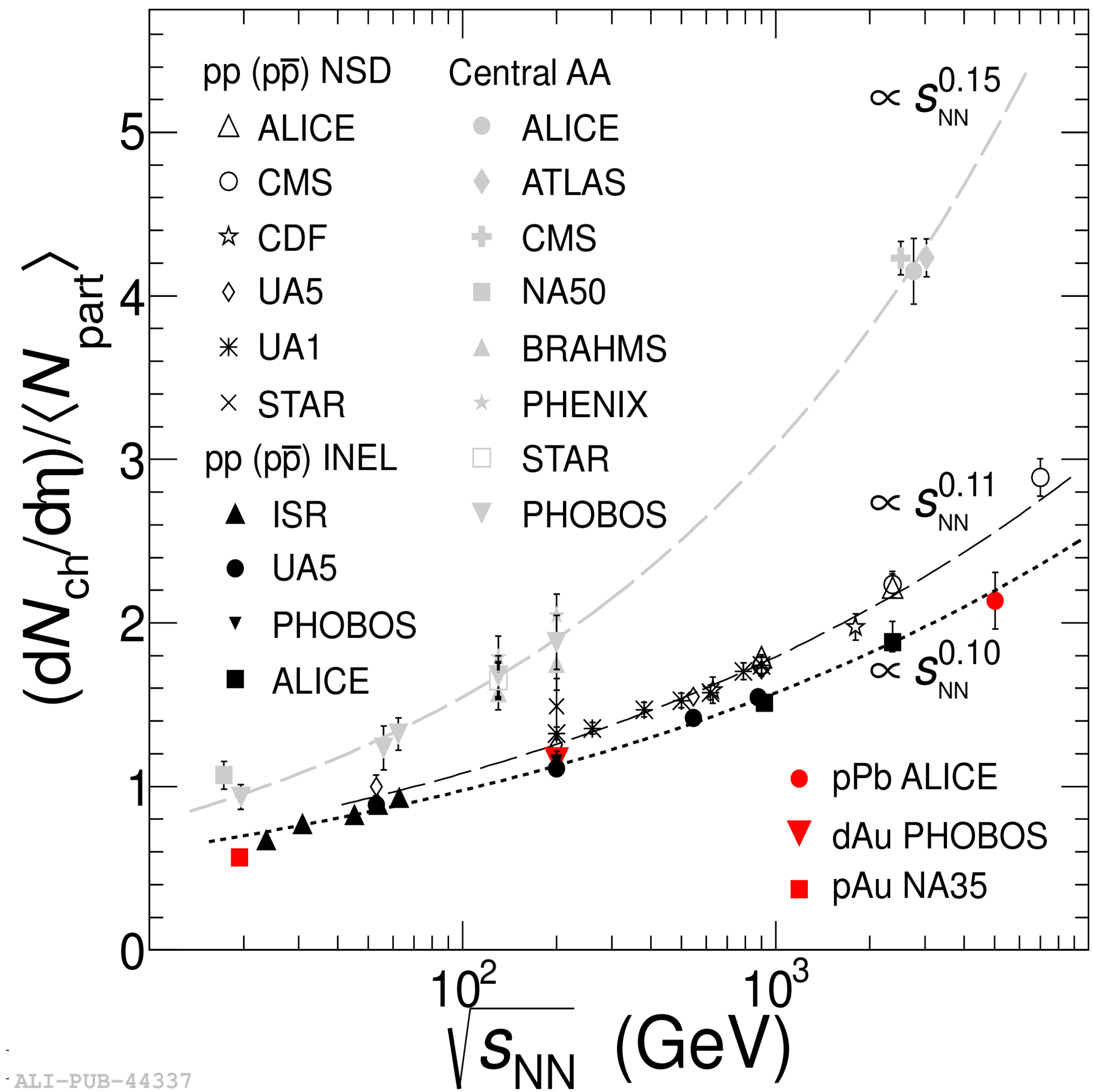


one possible view
(courtesy
Larry McLerran)



Peter Braun-Munzinger

Charged particle multiplicity in pp, pPb and central PbPb collisions

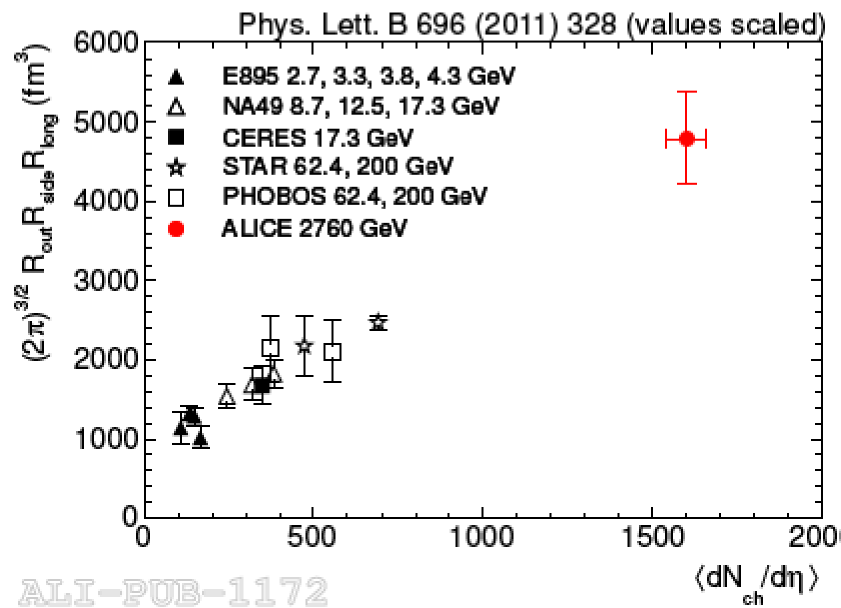


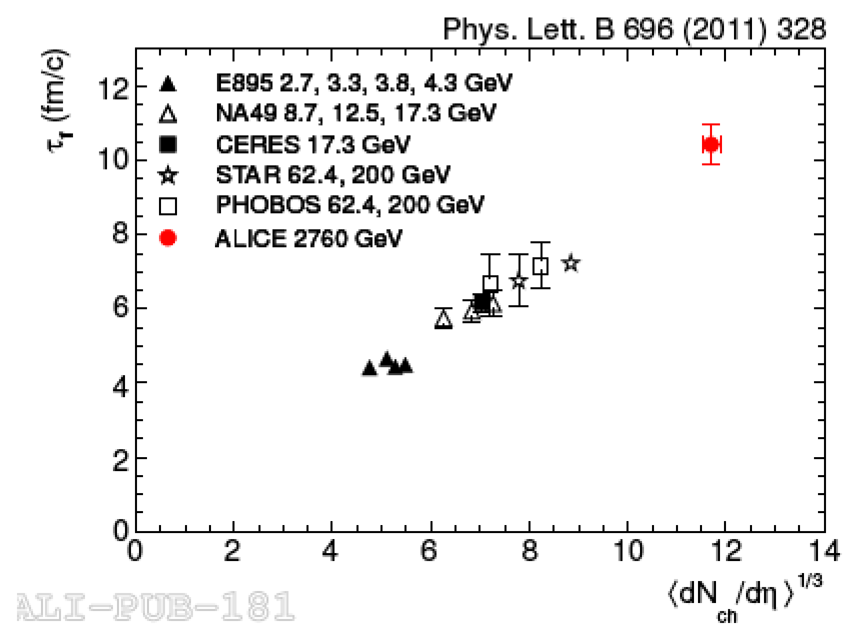
increase with beam energy significantly steeper than in pp

Fireball at LHC energy has much larger size and lives

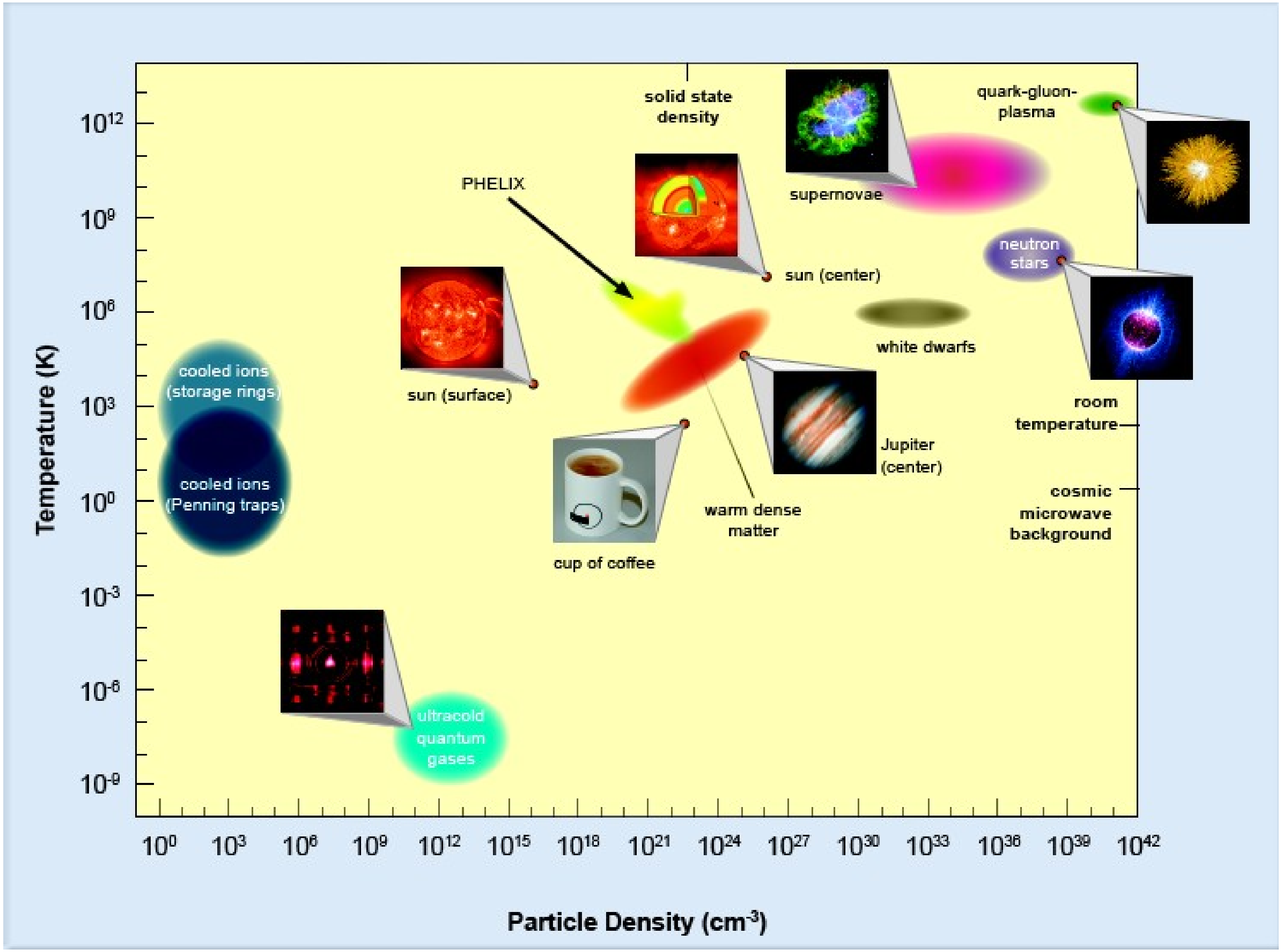
volume and lifetime
from HBT analysis

fireball volume at freeze-out is about 5 x large than volume of a Pb nucleus





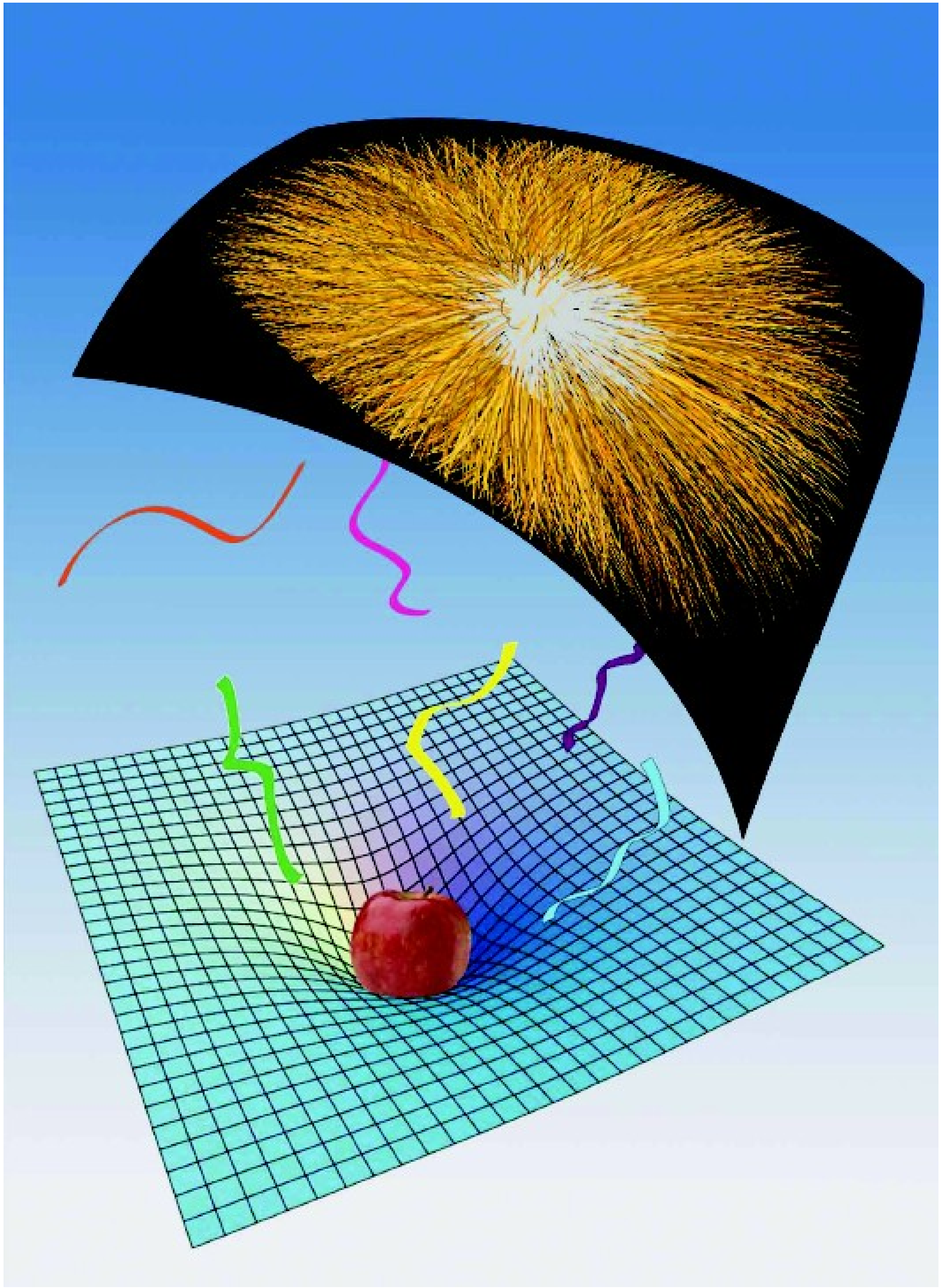
from ultra-cold to ultra-hot



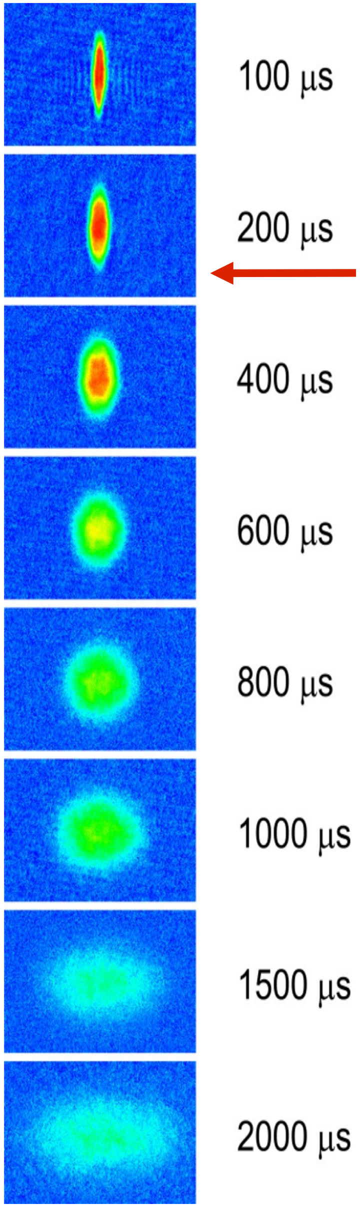
QGP and the 'gauge-gravity' dual

See, e.g. E. Witten, 'Quantum Mechanics of Black Holes, Science 337 (3 August 2012)

The strongly coupled QCD-like gauge theory is dual to weakly coupled gravitation with a large, negative cosmological constant, Kovtun,Son, Starinets, PRL 94 (2005) 111601



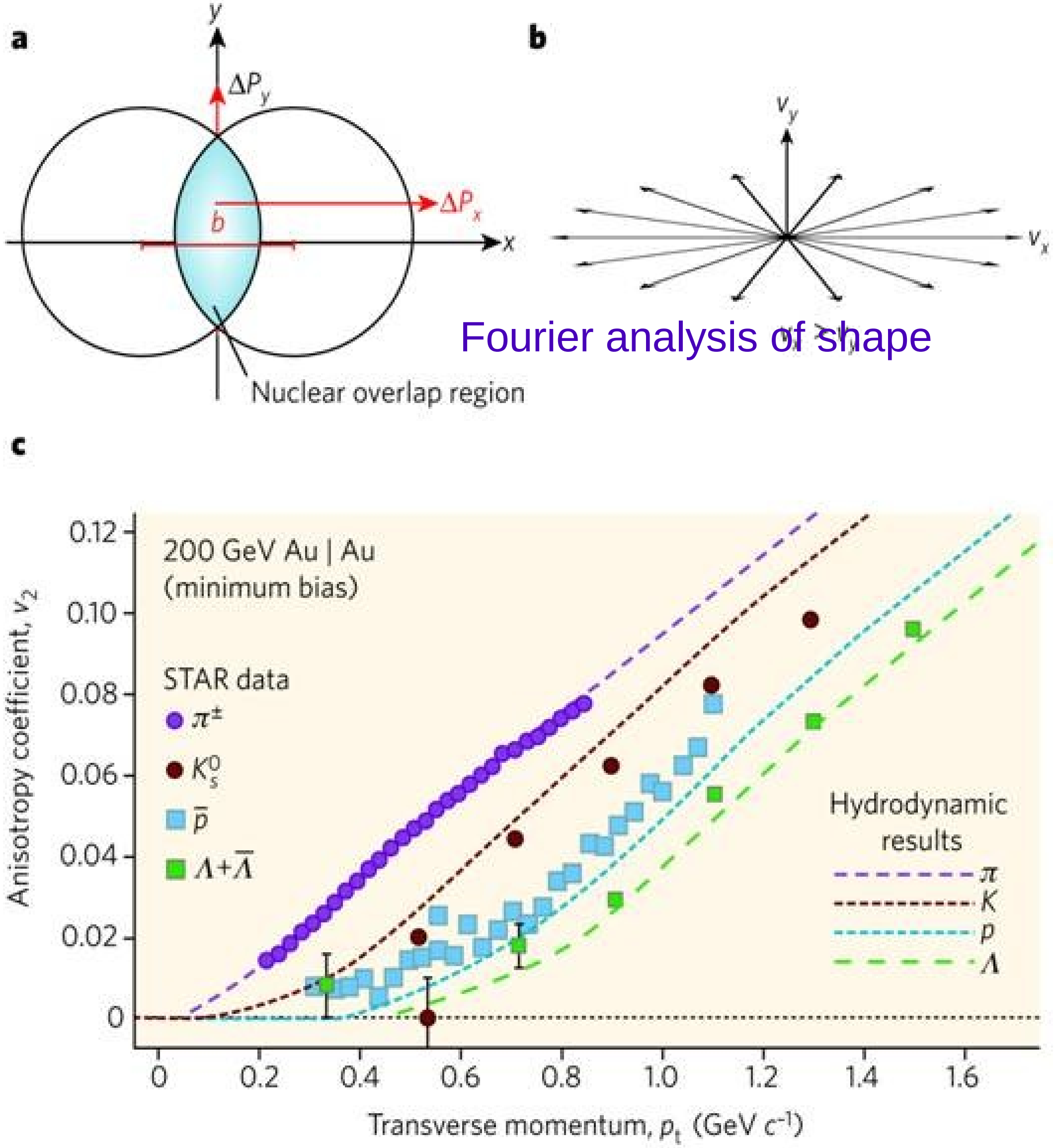
QGP and Ultra-cold Quantum Gases



ultra-cold ^{6}Li
10 nK
~10^{-12} eV

QGP
2.1 TK
~10^8 eV

collective expansion at strong coupling



The Large Hadron Collider (LHC)

27 km long, 8 sectors

1232 **dipole** magnets (15m, 30 tonnes each) to bend the beams

Cooled with **120 tonnes of He at 1.9 K**

pp: 2808 bunches/ring, each 1.15×10^{11} protons (8 min filling time)

Design luminosity: **10^{34} $cm^{-2}s^{-1}$**

PbPb: 592 bunches/ring, each 7×10^{7} Pb ions

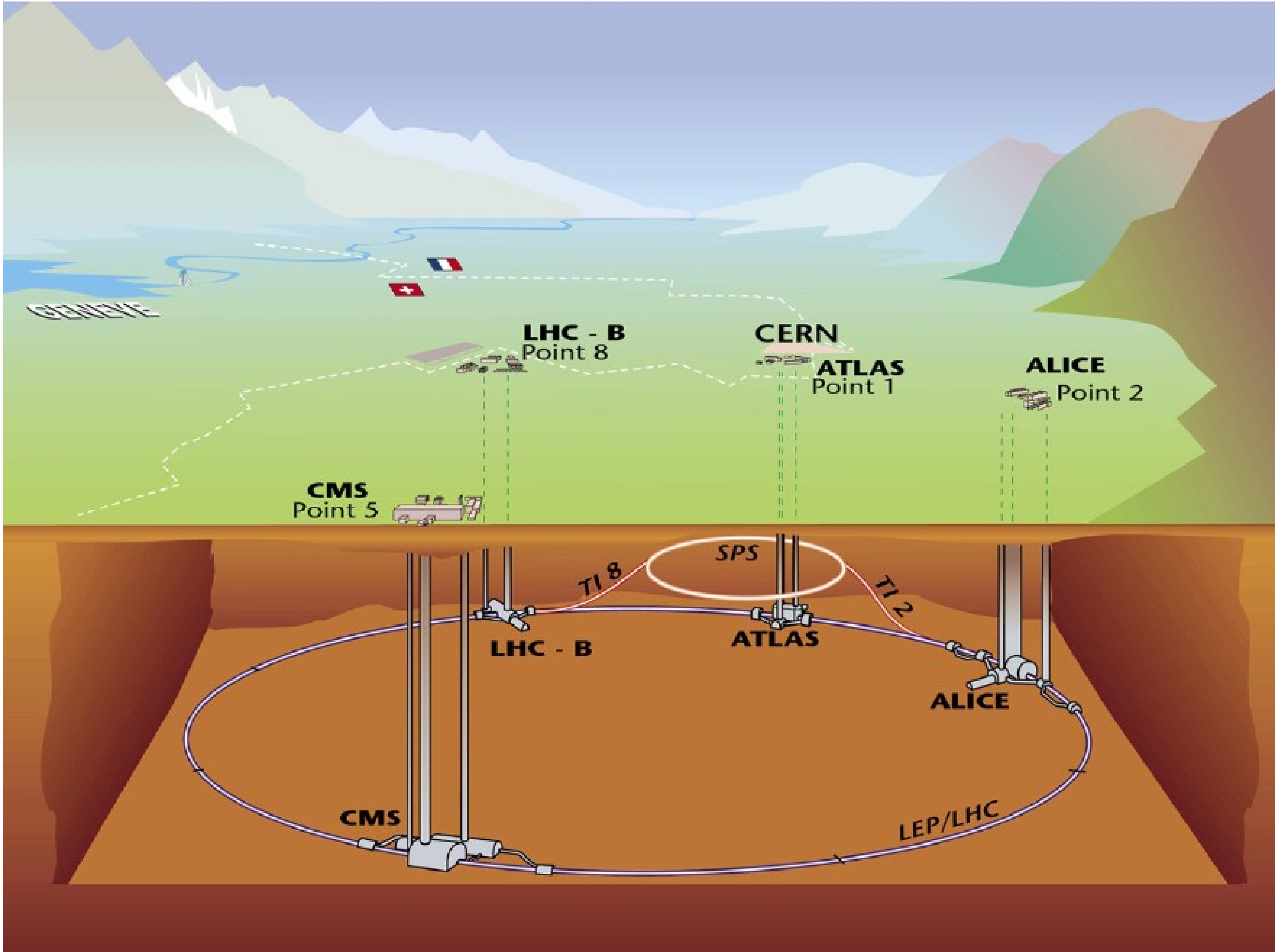
Design luminosity: 10^{27} $cm^{-2}s^{-1}$

Transverse r.m.s beam size: **16 μm**, r.m.s. bunch length: 7.5 cm

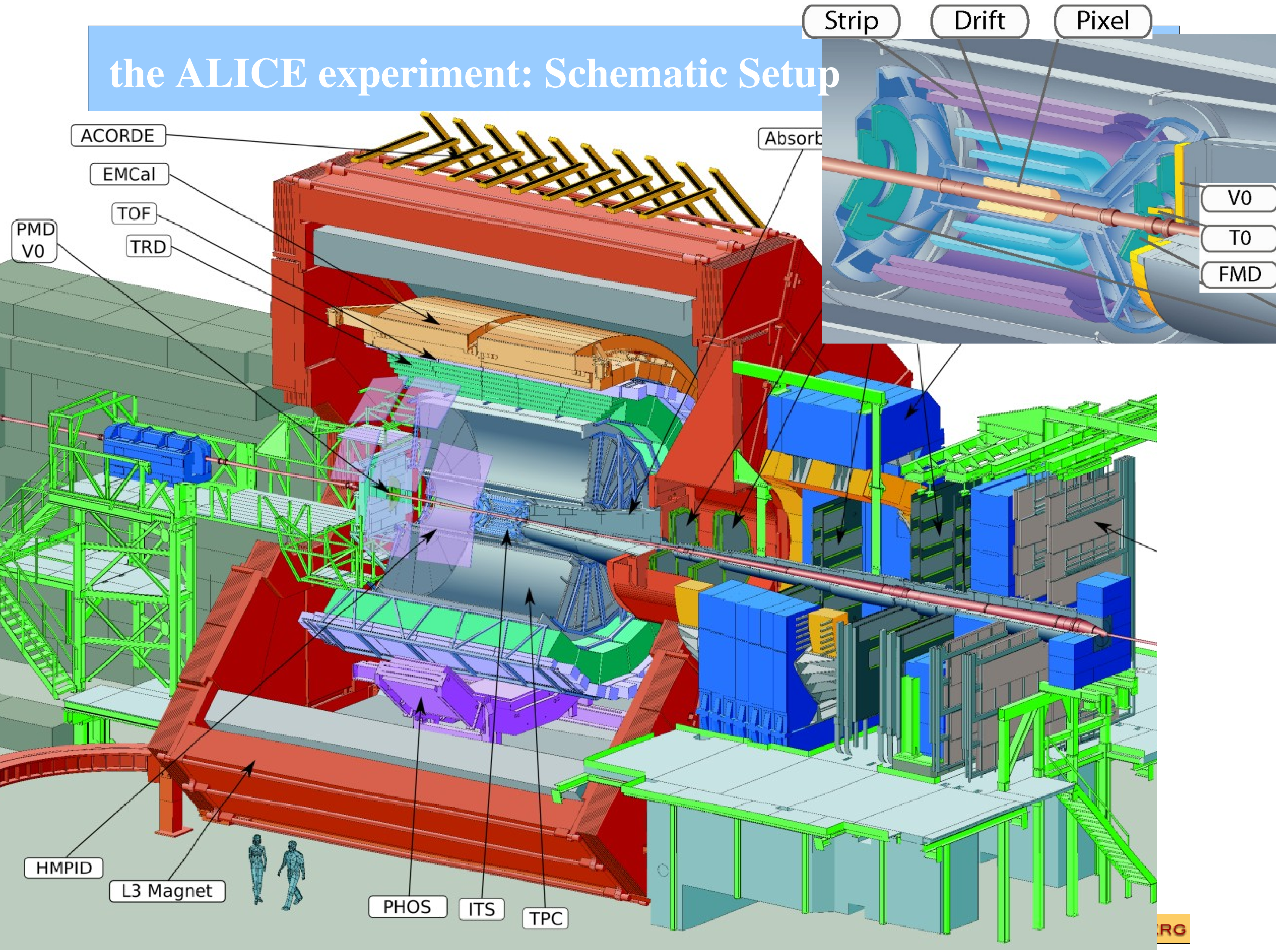
Beam kinetic energy: 362 MJ per beam (1 MJ melts 2 kg copper)

Total stored electromagnetic energy: **8.5 GJ** (dipole magnets only)

Overall view of the LHC experiments.

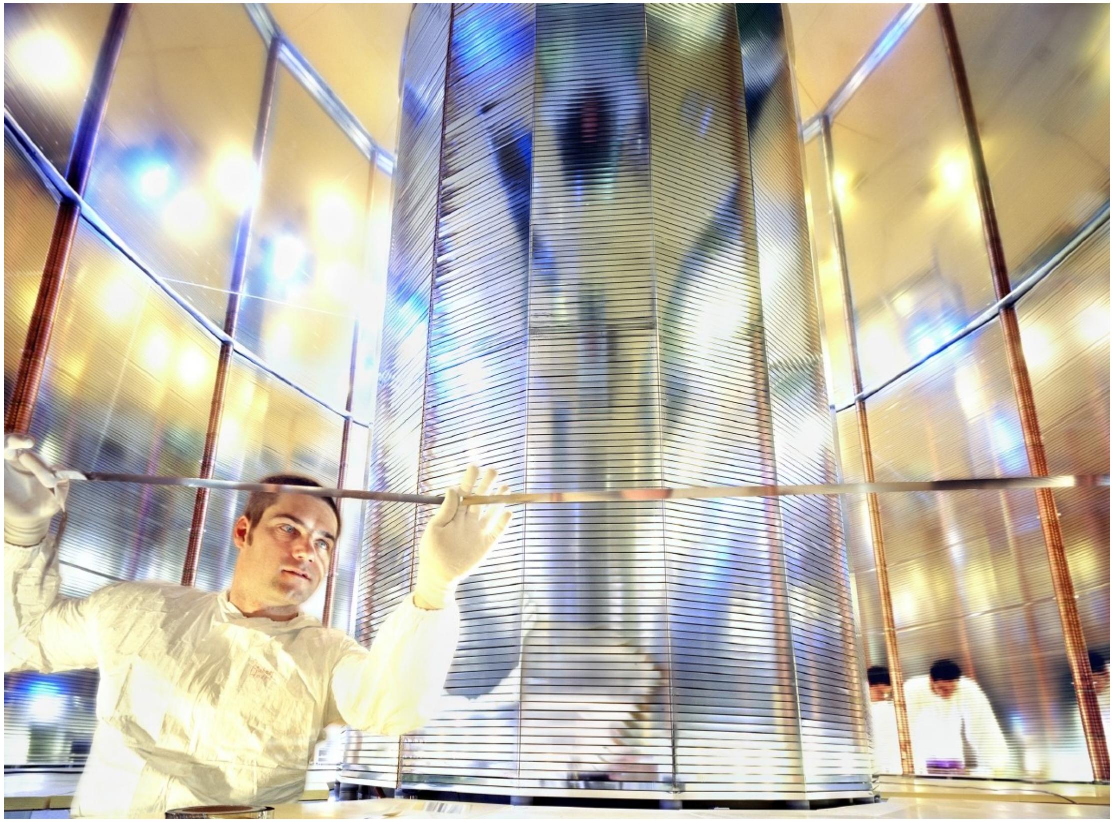


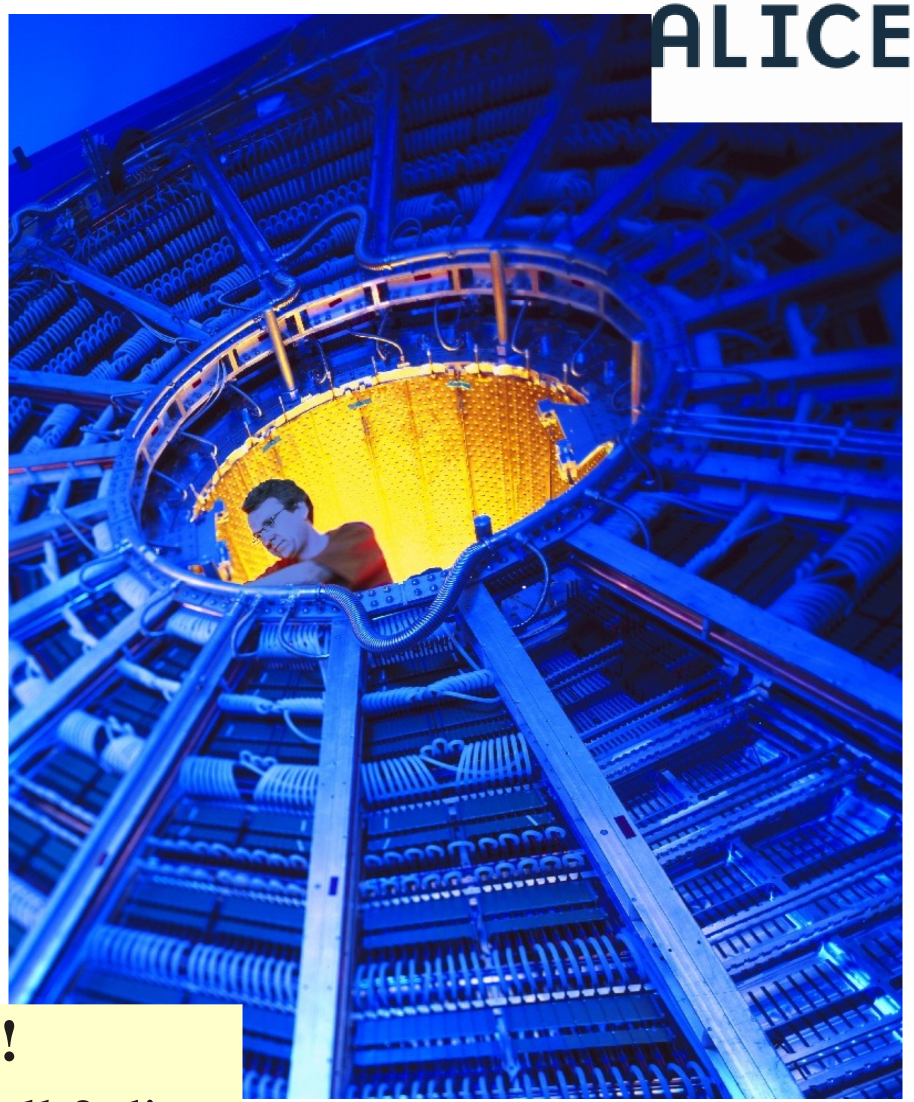
the ALICE experiment: Schematic Setup



the TPC (Time Projection Chamber) - 3D reconstruction of up to 15 000 tracks of charged particles per event

with 95 m^3 the largest TPC ever





560 million read-out pixels!

precision better than 500 µm in all 3 dim.

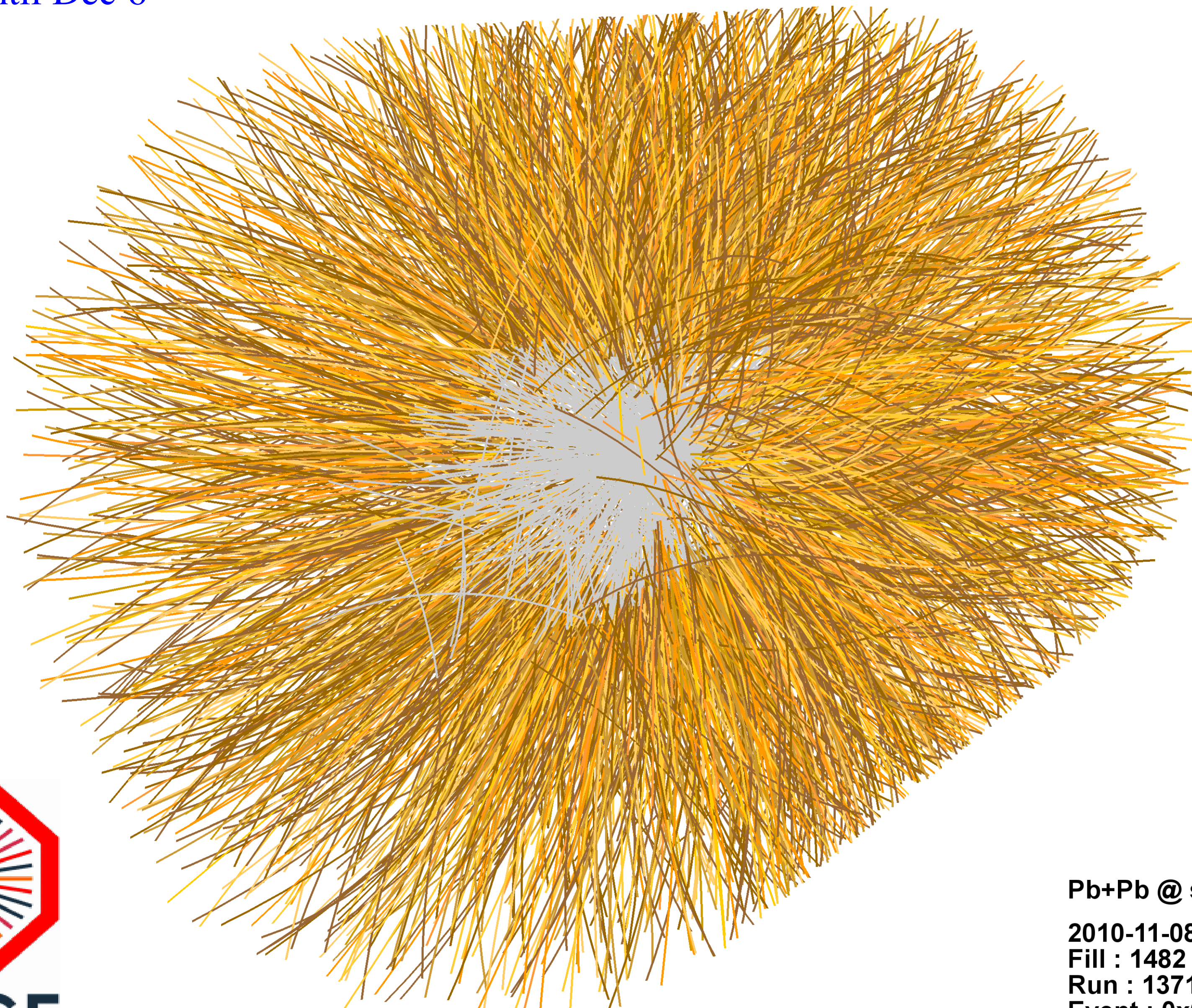
180 space and charge points per track

The interior of the TPC, 2004

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



ALICE

Pb+Pb @ sqrt(s) = 2.76 ATeV

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

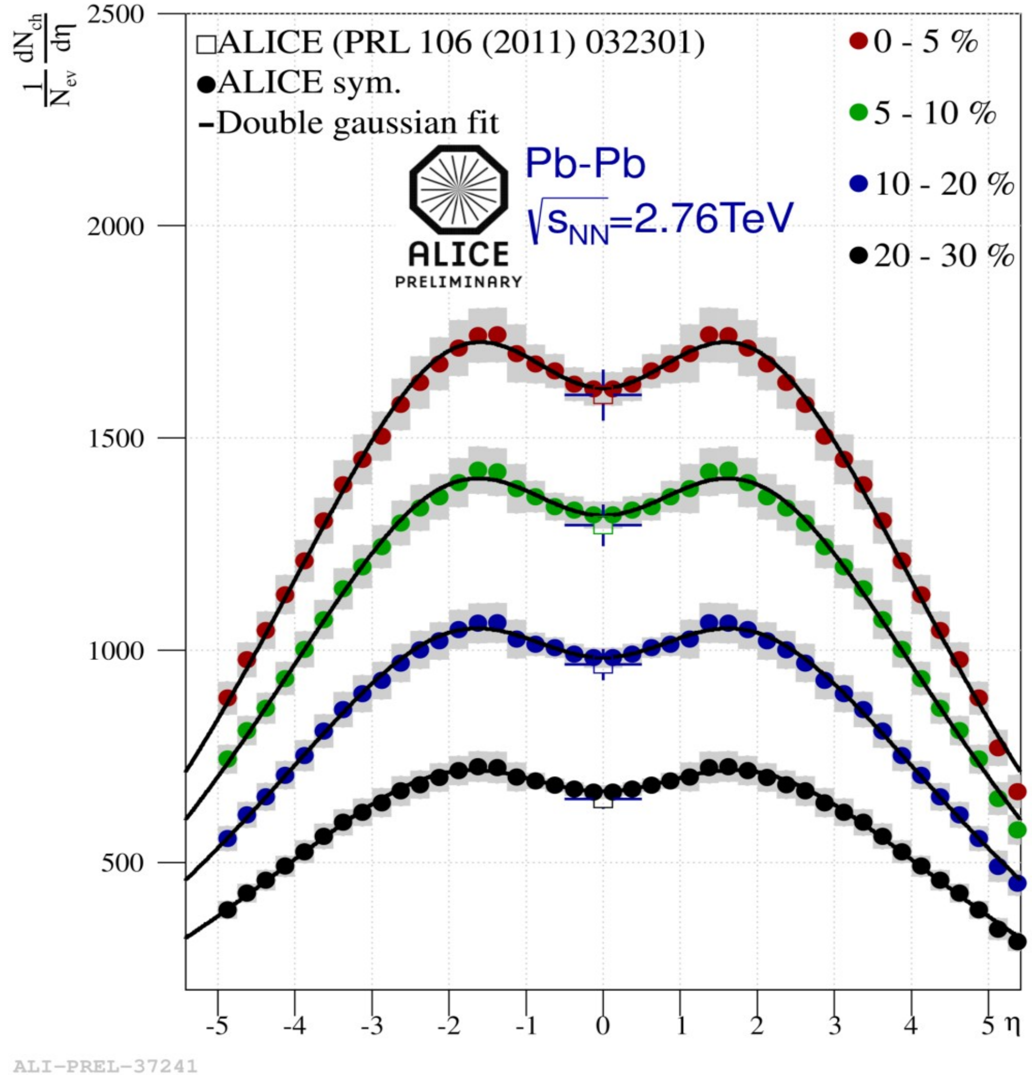
and the fun started

Hadron production and the QCD phase boundary

Complete angular (pseudo-rapidity) distributions

complete angular distr.
between 1 and 179 deg

excellent pseudo-rapidity coverage



Equilibration at the phase boundary

- Statistical model analysis of (u,d,s) hadron production: a test of equilibration of quark matter near the phase boundary
- No (strangeness) equilibration in hadronic phase
- Present understanding: multi-hadron collisions near phase boundary bring hadrons close to equilibrium – supported by success of statistical model analysis pbm, Stachel, Wetterich, Phys.Lett. B596 (2004) 61-69
- This implies little energy dependence above RHIC energy
- Analysis of hadron production → determination of T_c

Is this picture also supported by LHC data?

Parameterization of all freeze-out points before LHC data

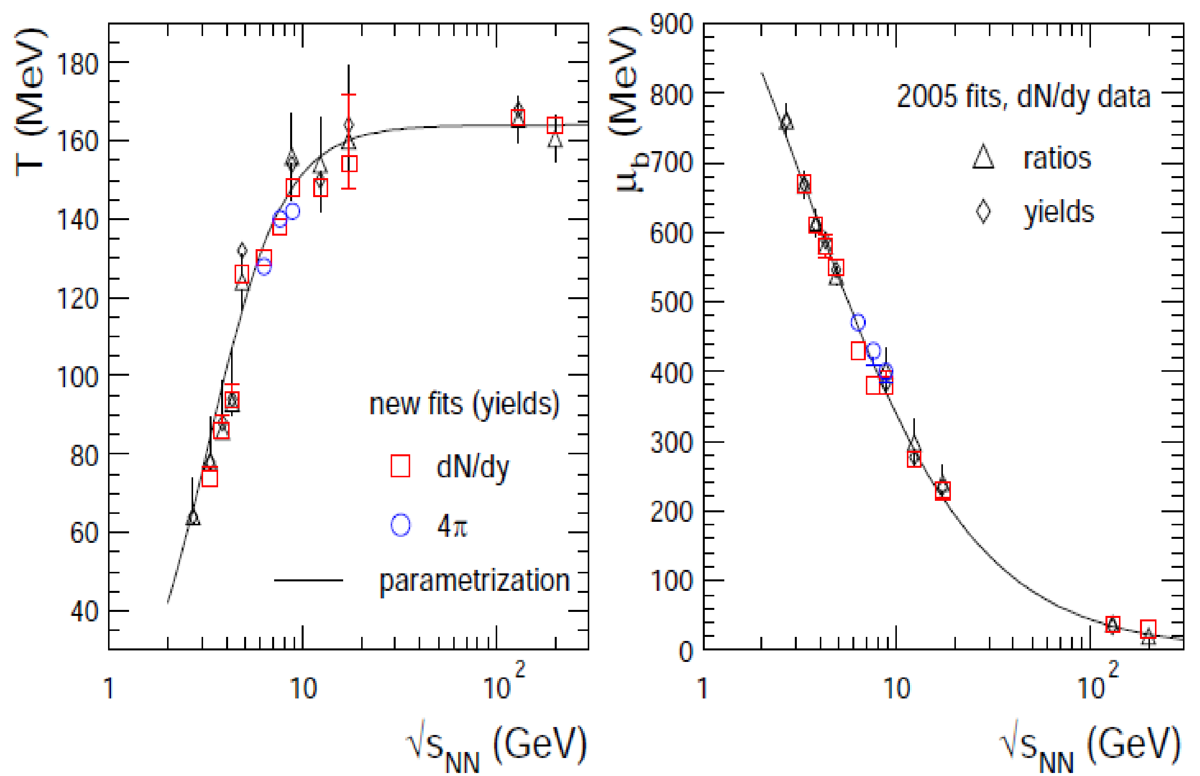
note: establishment of limiting temperature

T_{lim} = 164 +/- 4 MeV

get T and μ_B for all energies

for LHC predictions we picked T = 164 MeV

A. Andronic, pbm, J. Stachel, Nucl. Phys. A772 (2006) 167
nucl-th/0511071



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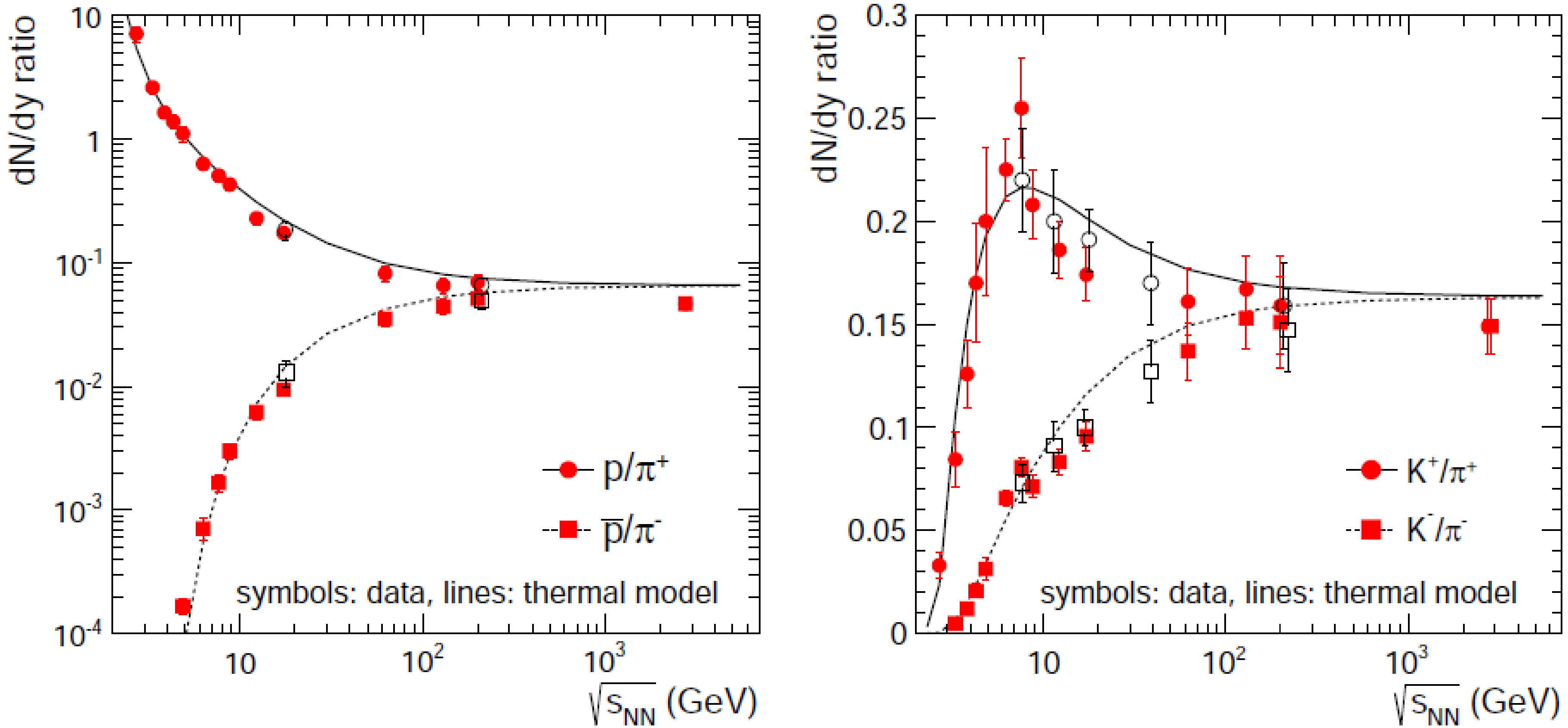
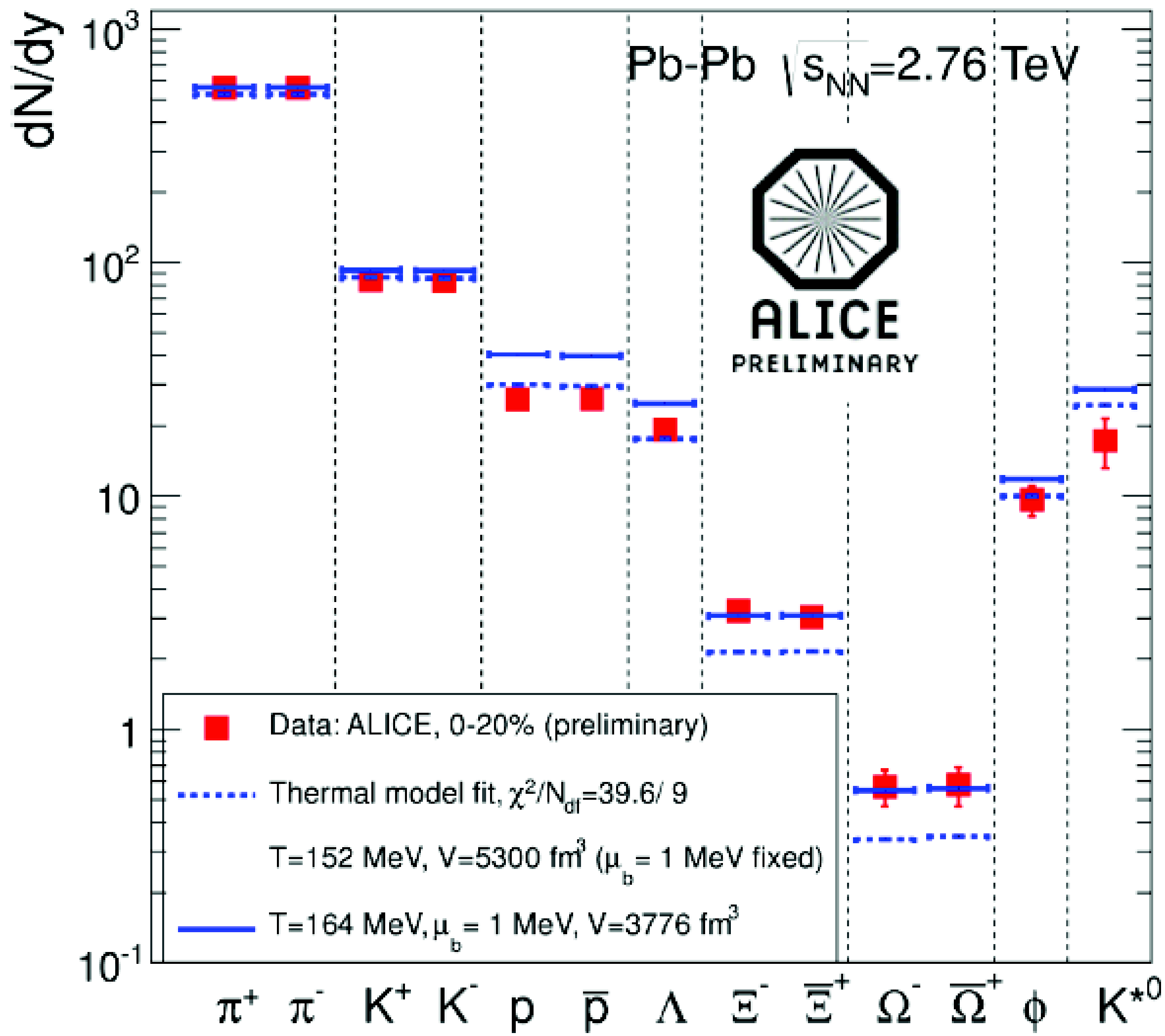
overall systematics, including ALICE data, on proton/pion and kaon/pion ratios



Identified particle yields at LHC energy

rather poor fit and lower temperature than expected

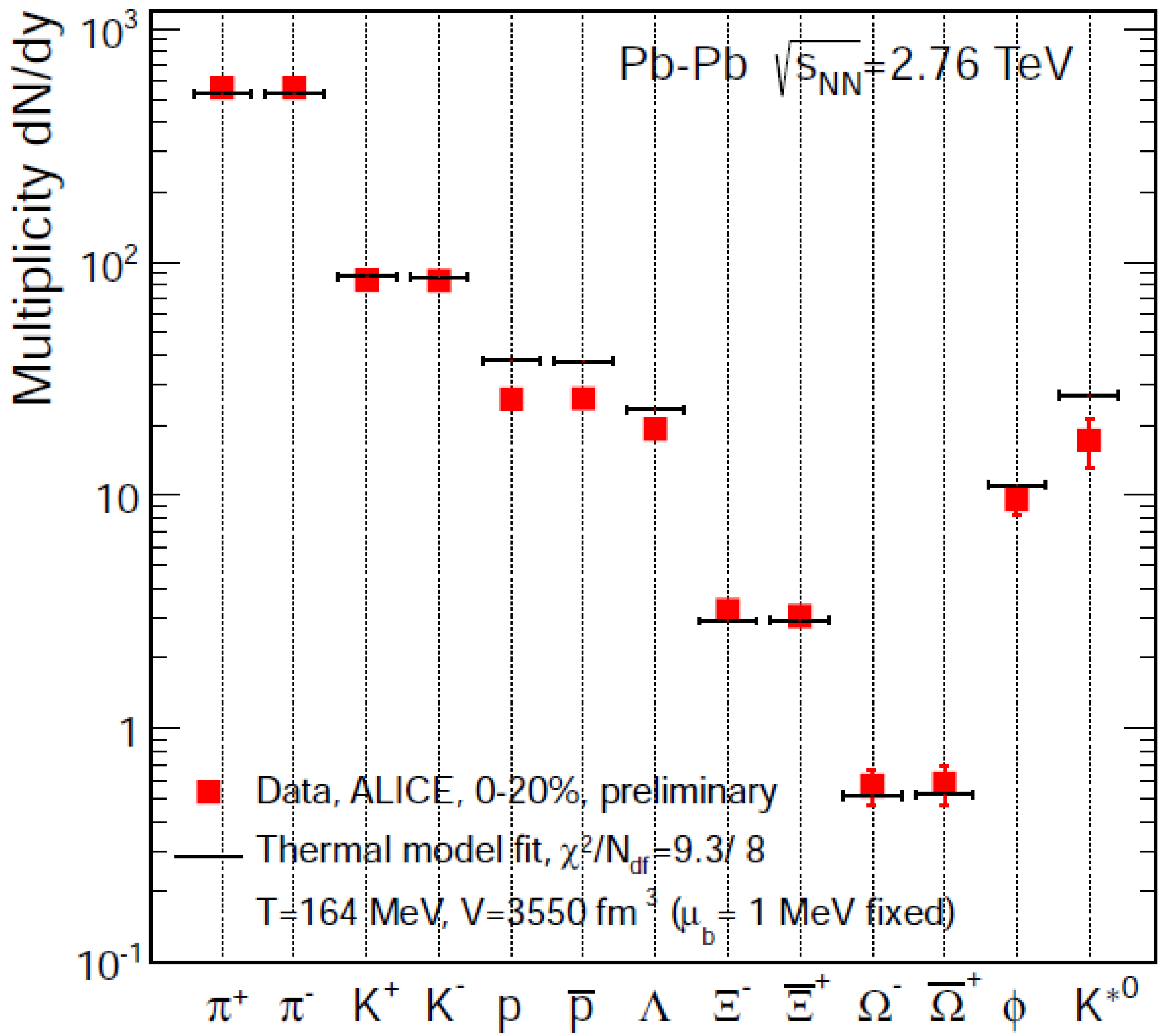


Thermal model analysis:
Andronic, pbm, Redlich, Stachel,
QM2012 arXiv:1210..7724

fitting the data without protons and antiprotons

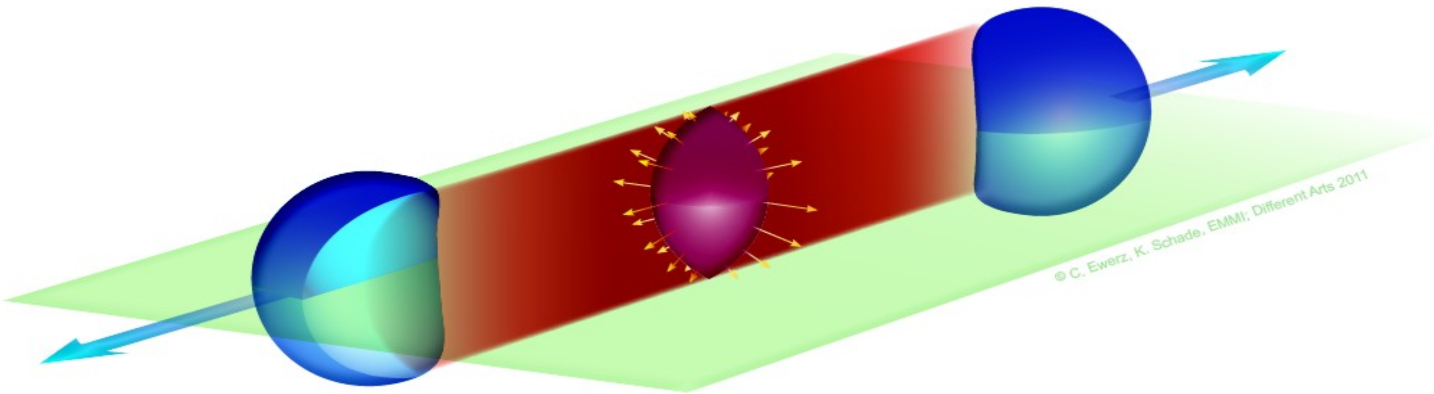
good fit, T = 164 MeV

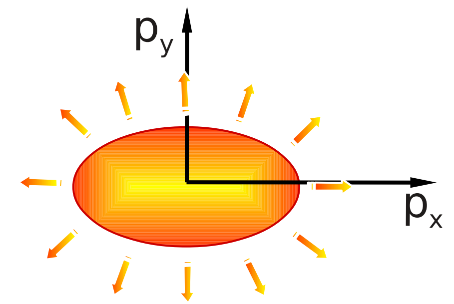
is there a proton anomaly?



hydrodynamic expansion of fireball

fireball expands collectively like an ideal fluid

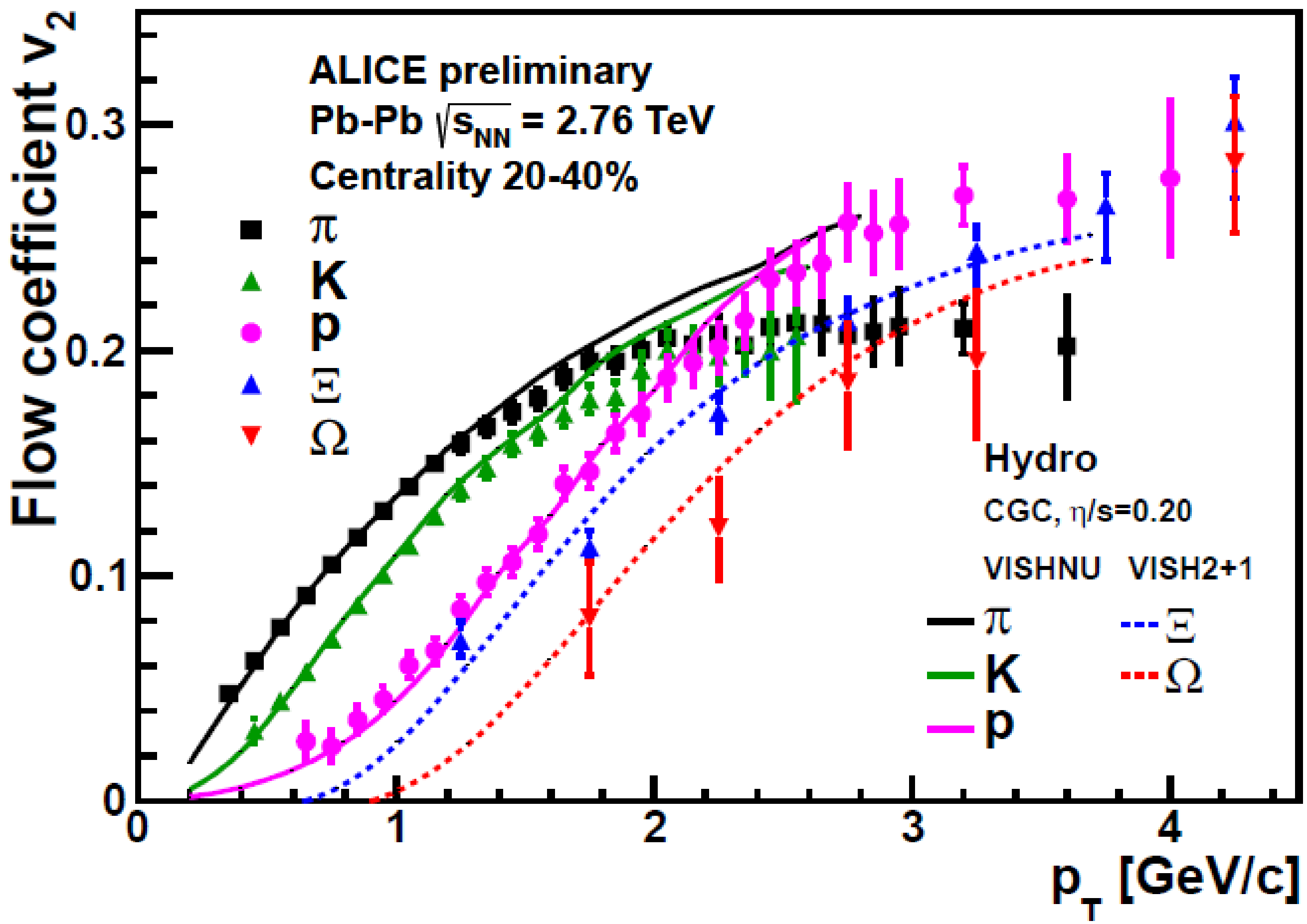




$$\mathbf{dN/d\phi = 1 + 2\, V_2 cos2\, (\phi - \psi) + \ldots}$$

hydrodynamic flow characterized by azimuthal anisotropy coeffient v_2
+ higher orders

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

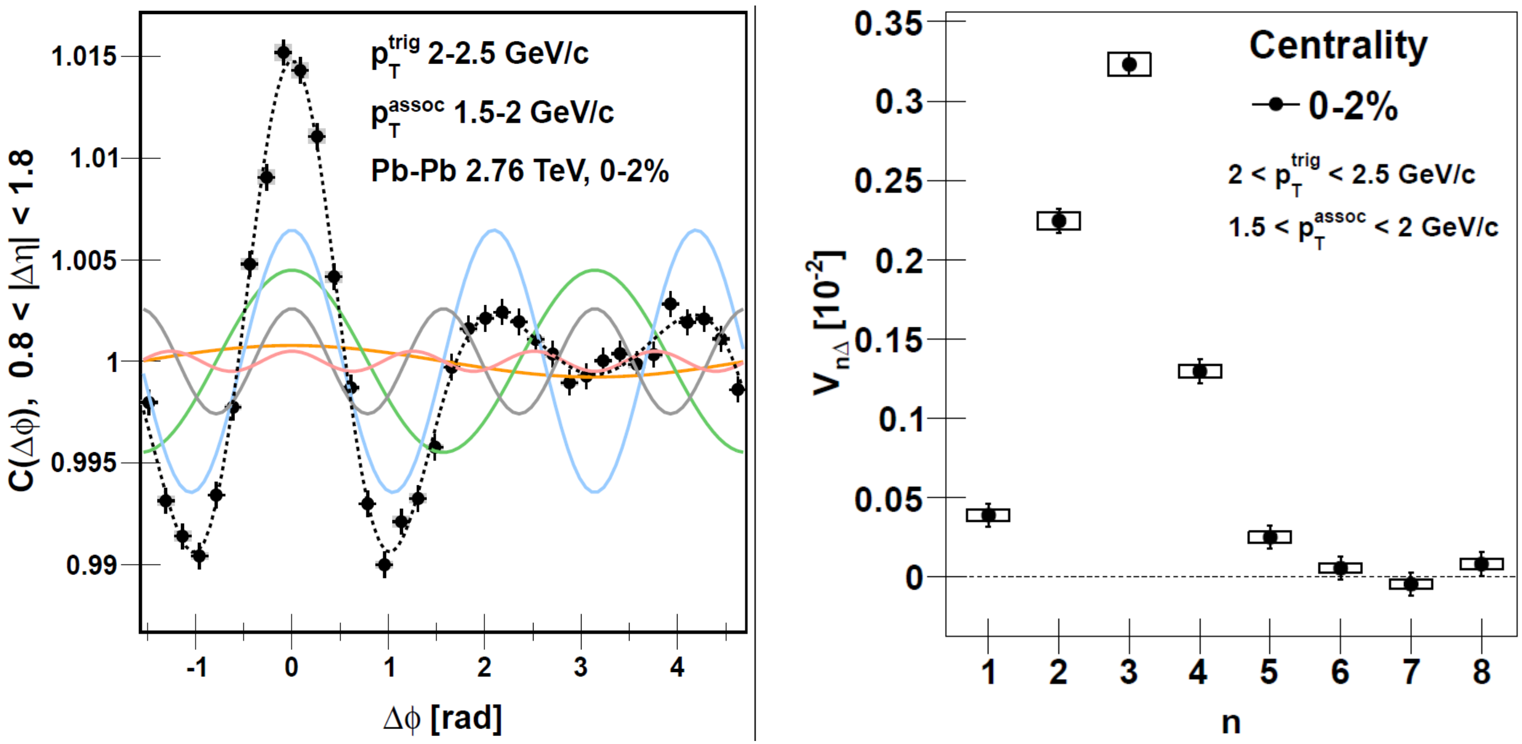


rapidly rising v_2 with p_t and mass ordering are typical features of hydrodyn. expansion

nearly ideal (non-dissipative) hydrodynamics reproduces data, system fairly strongly coupled

The 2-particle correlation function – higher moments

ALICE, PRL 107 (2011) 032301



measurement of the first 8 harmonic coefficients

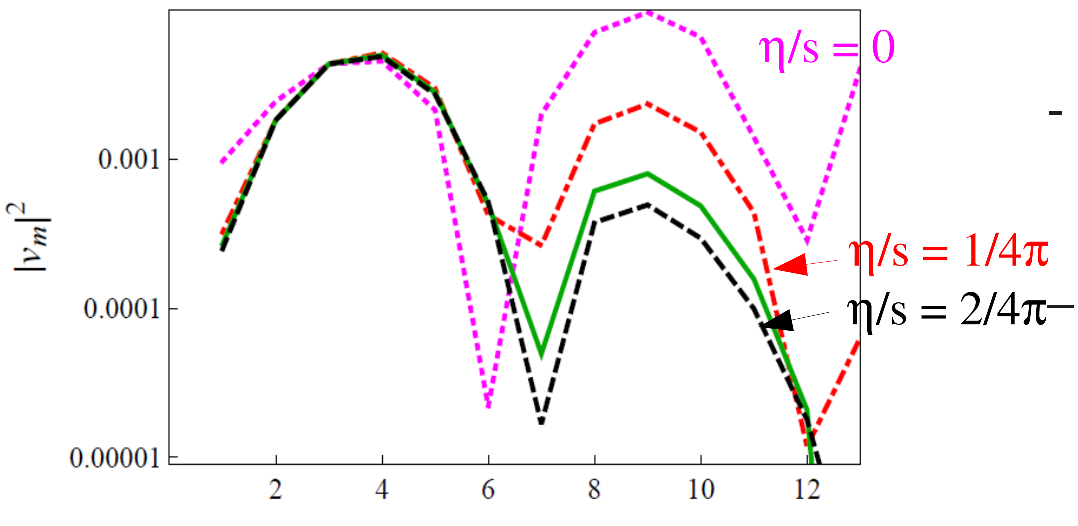
v_1-v_5 significantly larger than 0, maximum at v_3

current understanding: 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

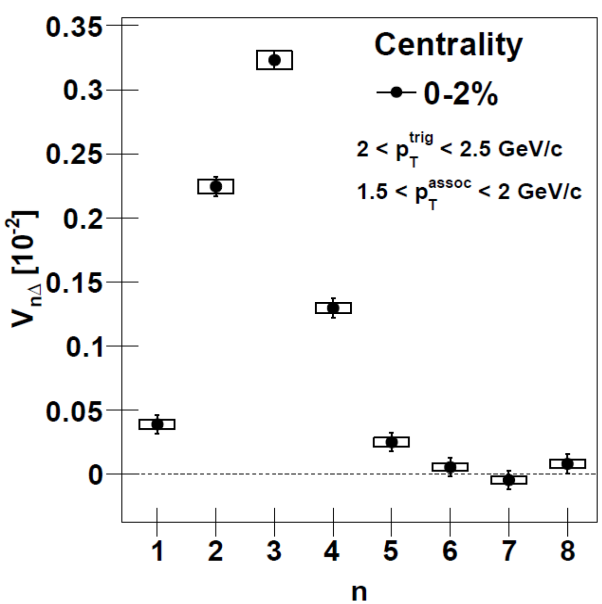
Propagation of sound in the quark-gluon plasma

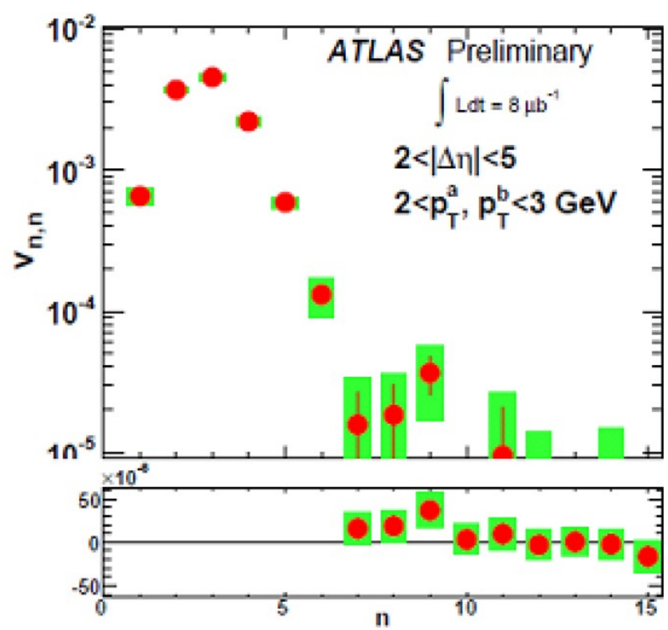
Staig & Shuryak arXiv:1109.6633



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

ALICE, PRL 107 (2011) 032301





Introducing initial quantum fluctuations into calculation

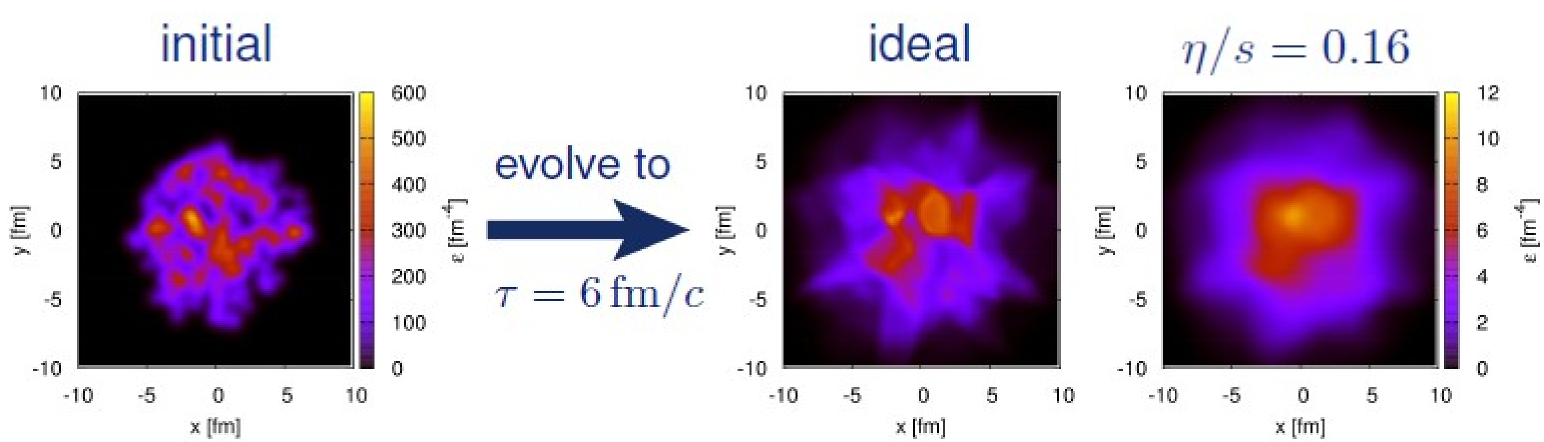
B. Schenke, QM2012

Given the initial energy density distribution we solve

$$\partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \pi^{\mu\nu}$$

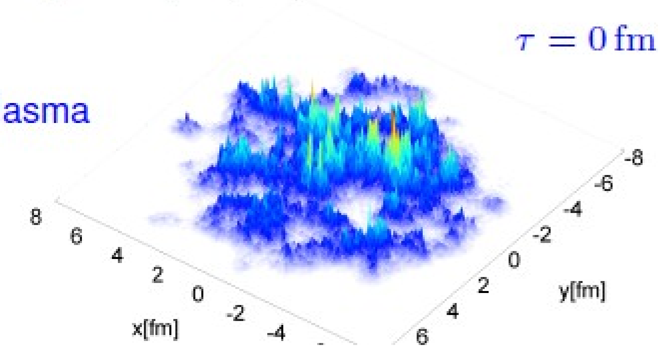
using only shear viscosity: $\pi^\mu_\mu = 0$

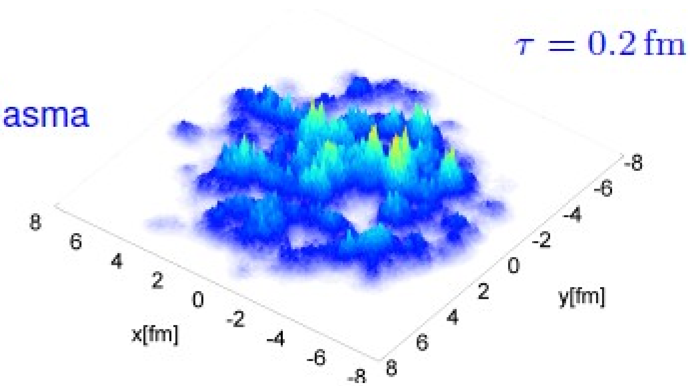


Note: alternate means to determine eta/s

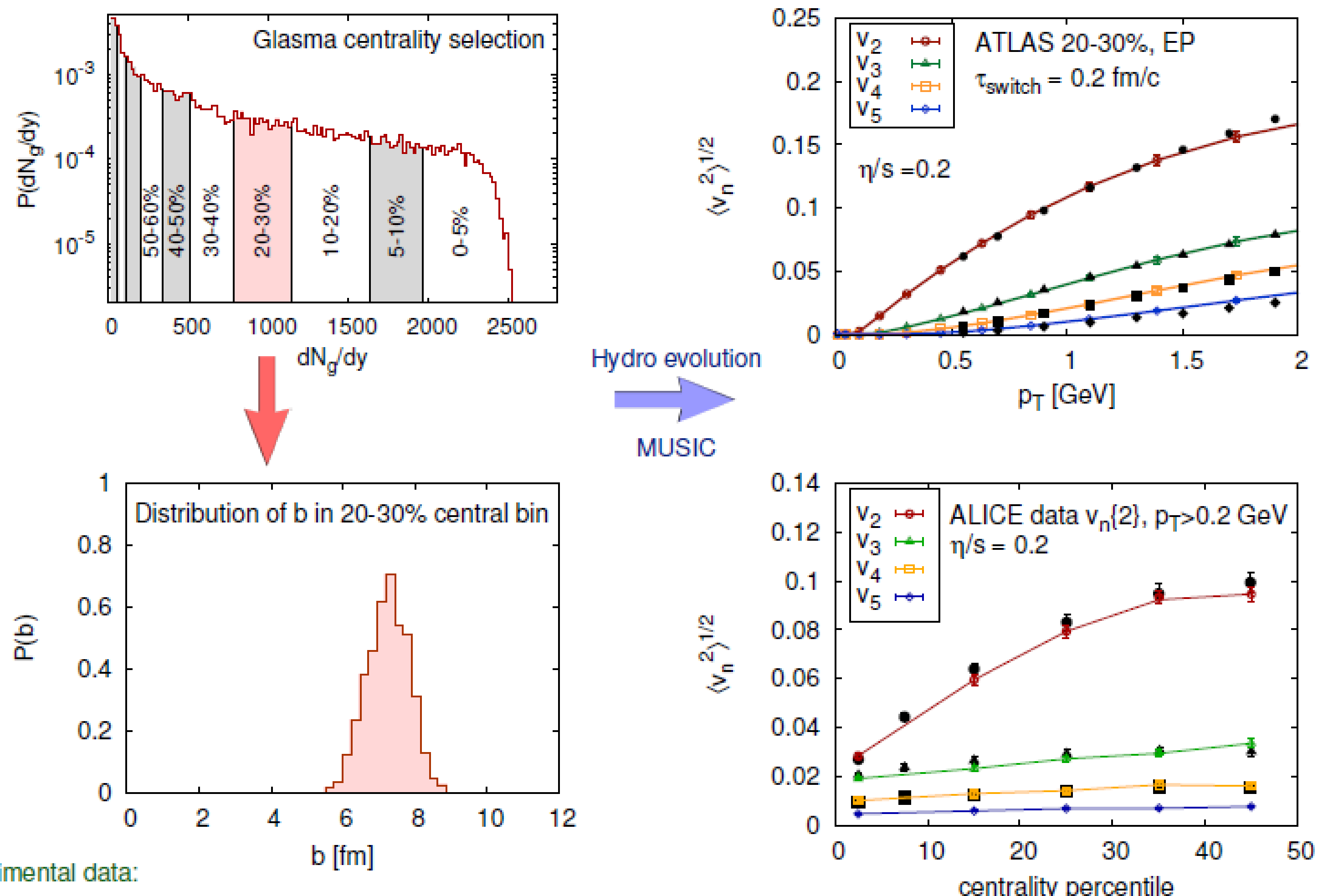
Energy density B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett. 108, 252301 (2012)

Solve for gauge fields after the collision in the forward lightcone
Compute energy density in the fields at $\tau = 0$ and later times with CYM evolution
Lattice: Krasnitz, Venugopalan, Nucl.Phys. B557 (1999) 237





Quantitative description of ATLAS and ALICE data



Experimental data:
ATLAS collaboration, Phys. Rev. C 86, 014907 (2012)
ALICE collaboration, Phys. Rev. Lett. 107, 032301 (2011)

calc.: B. Schenke et al., QM2012, eta/s = 0.2

Determination of eta/s of fireball

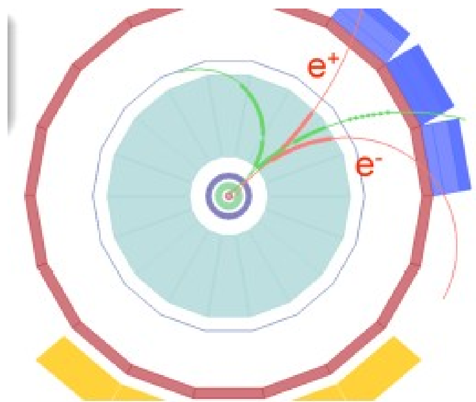
Model-independent determination of eta/s still outstanding

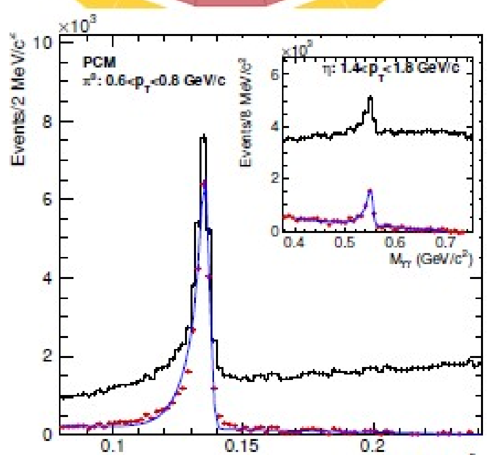
Current best limits: $0.07 < \eta/s < 0.43$

Luzum and Ollitrault, QM2012

Measurement of the fireball temperature via photon emission

Photons and neutral mesons measured via the conversion method in the ALICE TPC, see, .e.g, M. Wilde (ALICE coll.) QM2012



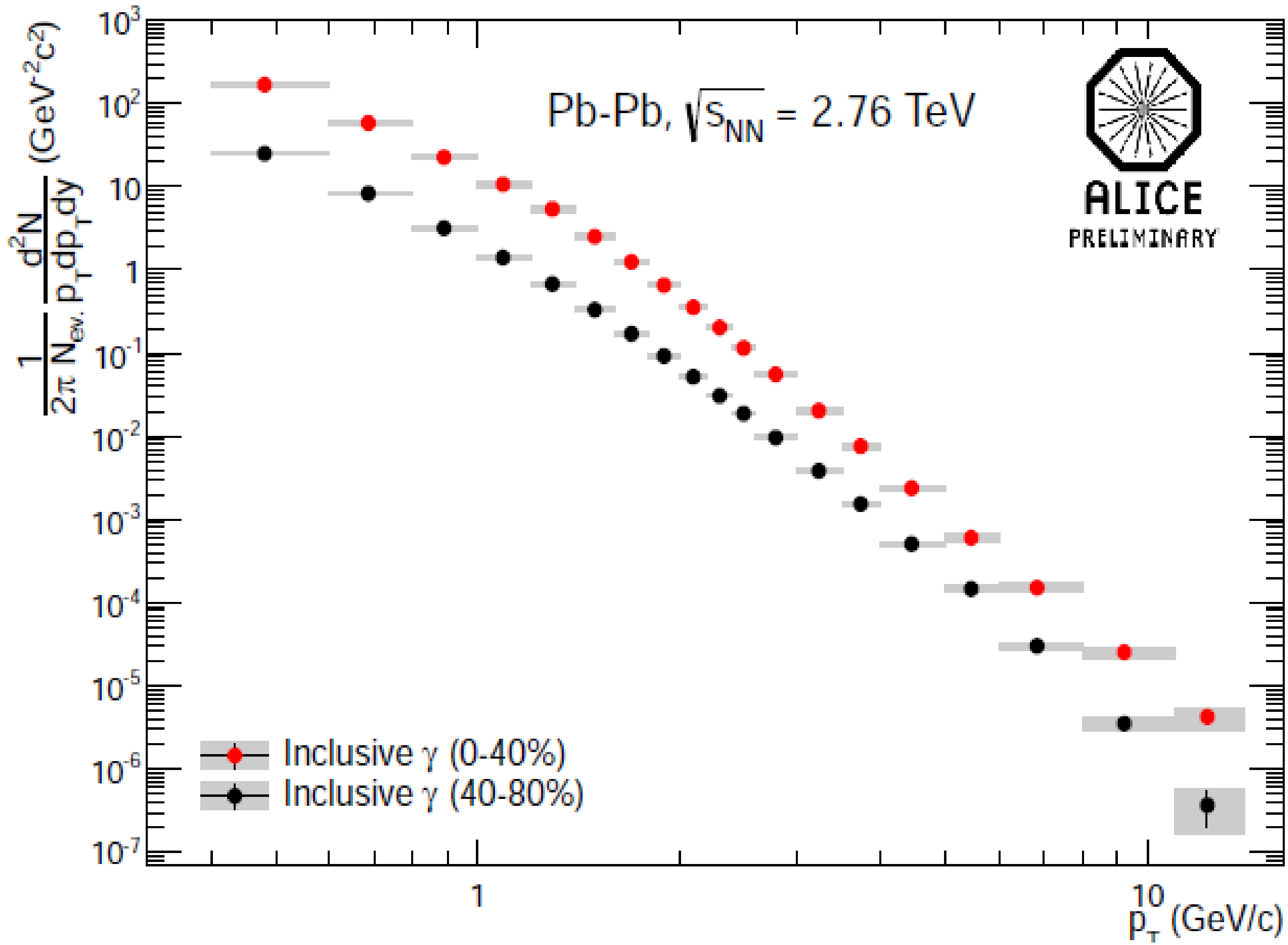


arXiv:1205.5724v1

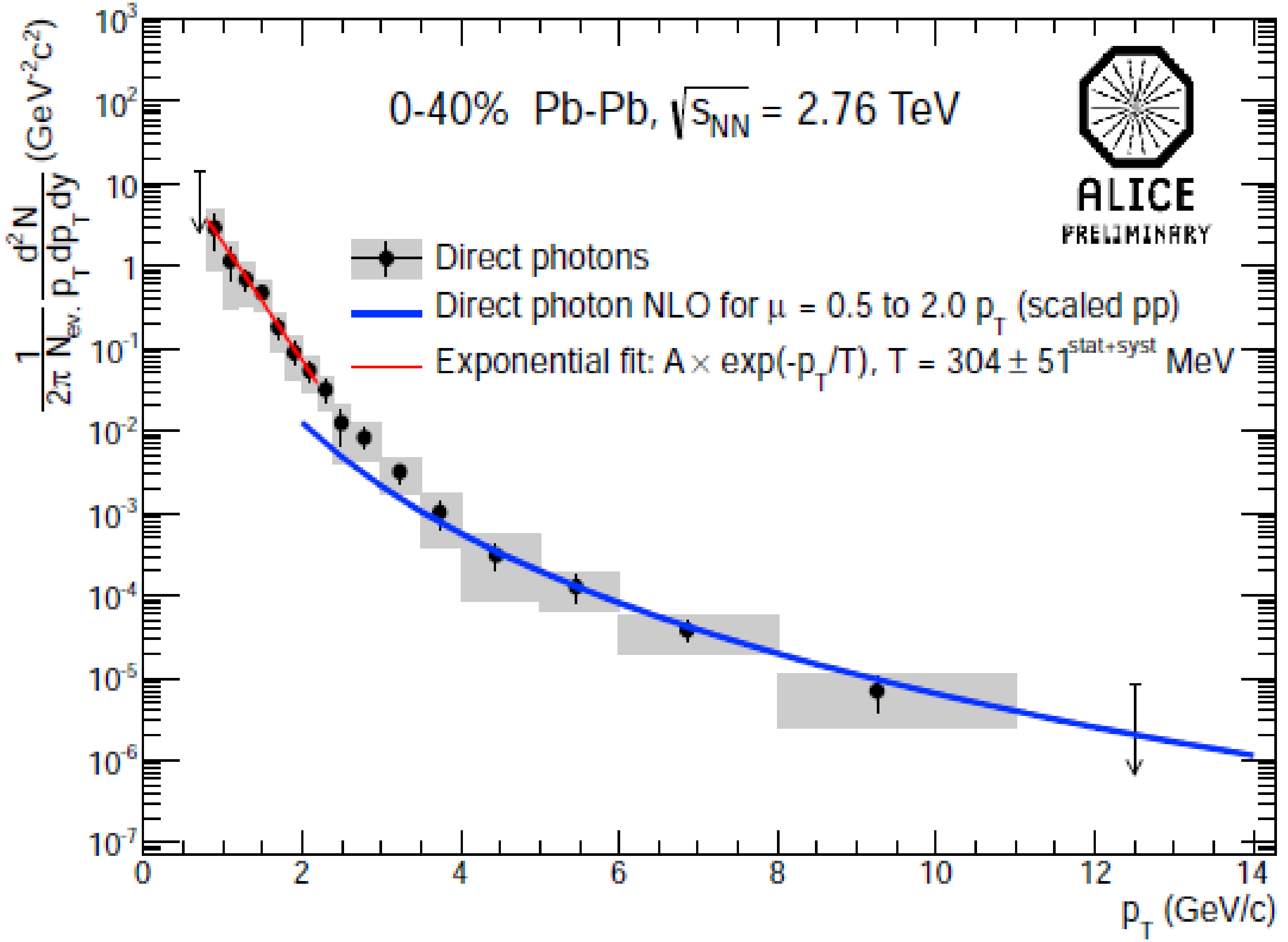
method

- Direct Photon Signal: $\gamma_{direct} = \gamma_{inc} - \gamma_{decay} = (1 - \frac{\gamma_{decay}}{\gamma_{inc}}) \cdot \gamma_{inc}$
- Double Ratio: $\frac{\gamma_{inc}}{\pi^0} / \frac{\gamma_{decay}}{\pi^0_{param}} \approx \frac{\gamma_{inc}}{\gamma_{decay}}$ if > 1 direct photon signal
  $\rightarrow$ cancellation of uncertainties
- Numerator: Inclusive γ spectrum per π^0
- Denominator: Sum of all decay photons per π^0
  Decay photons are obtained by a cocktail calculation
- Photons and π^0s are measured via conversion method
  $\pi^0 \rightarrow \gamma + \gamma$, $\gamma \rightarrow e^+e^-$

Inclusive photon measurement in Pb-Pb collisions



Final result



average T = 304 +/- 51 MeV highest ever measured temperature

The charmonium story

- some historical remarks
- the statistical hadronization model
- comparison to results from RHIC
- charmonium production at LHC energy

Charmonium as a probe for the properties of the QGP

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

new insight (pbm, Stachel 2000) QGP screens all charmonia, but charmonium production takes place at the phase boundary, enhanced production at colliders – signal for deconfined, thermalized charm quarks

work reported here done in coll. with Anton Andronic Krzysztof Redlich Johanna Stachel

recent reviews: L. Kluberg and H. Satz, arXiv:0901.3831

pbm and J. Stachel, arXiv:0901.2500

both published in Landoldt-Boernstein Review, R. Stock, editor, Springer 2010

time scales

for the original Matsui/Satz picture to hold, the following time sequence is needed:

1) charmonium formation
2) quark-gluon plasma (QGP) formation
3) melting of charmonium in the QGP
4) decay of remaining charmonia and detection

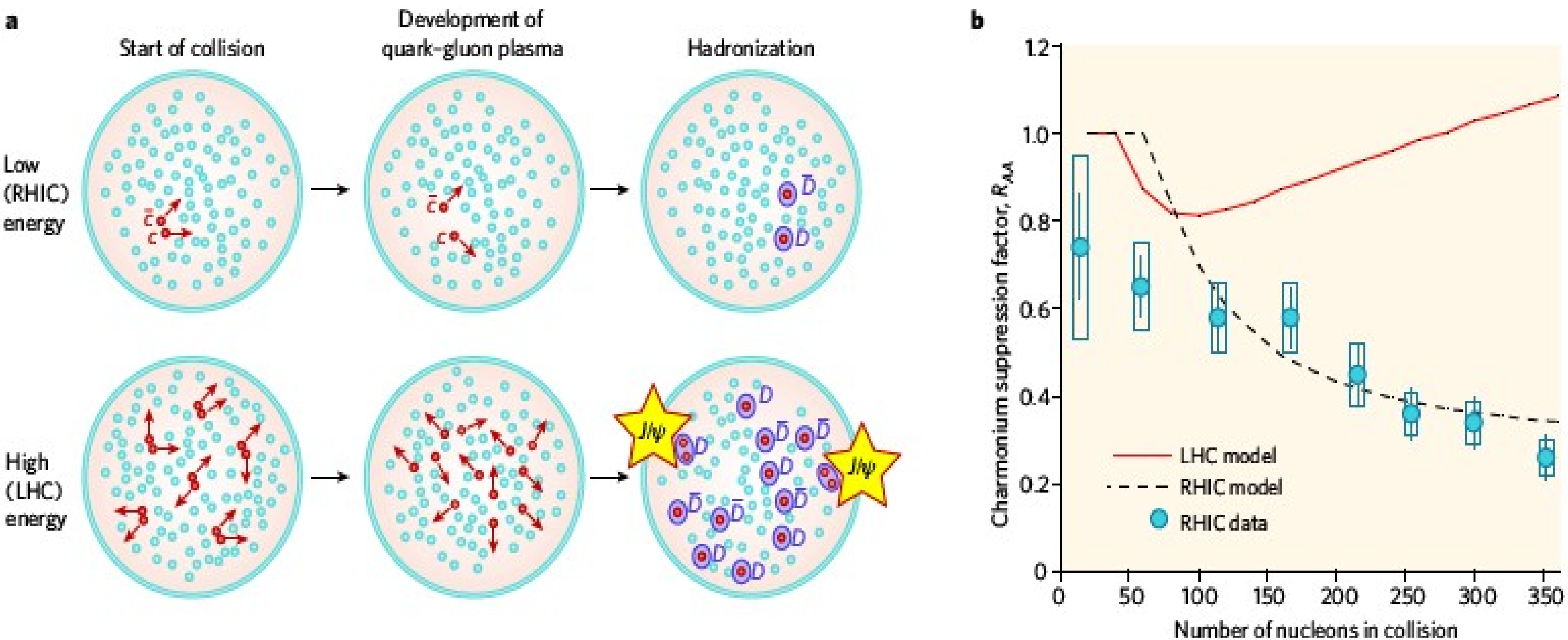
questions:
a) beam energy dependence of time scales
b) what happens with the (many) charm quarks at hadronization, i.e at the phase boundary?

at LHC energy, clean separation of time scales

collision time << QGP formation time < charmonium formation time

quarkonium as a probe for deconfinement at the LHC
the statistical (re-)generation picture

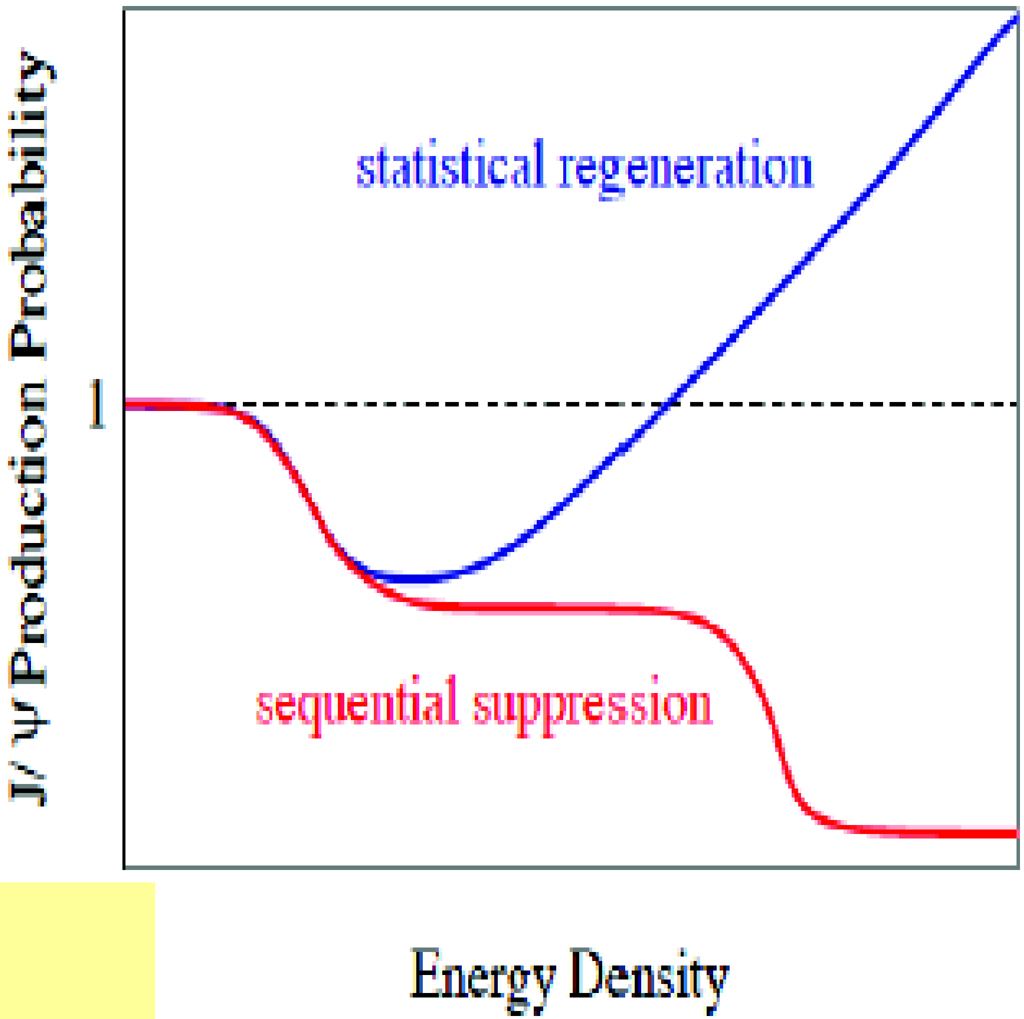
P. Braun-Munzinger, J. Stachel, The Quest for the Quark-Gluon Plasma, Nature **448** Issue 7151, (2007) 302-309.



charmonium enhancement as fingerprint of color screening and deconfinement at LHC energy

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

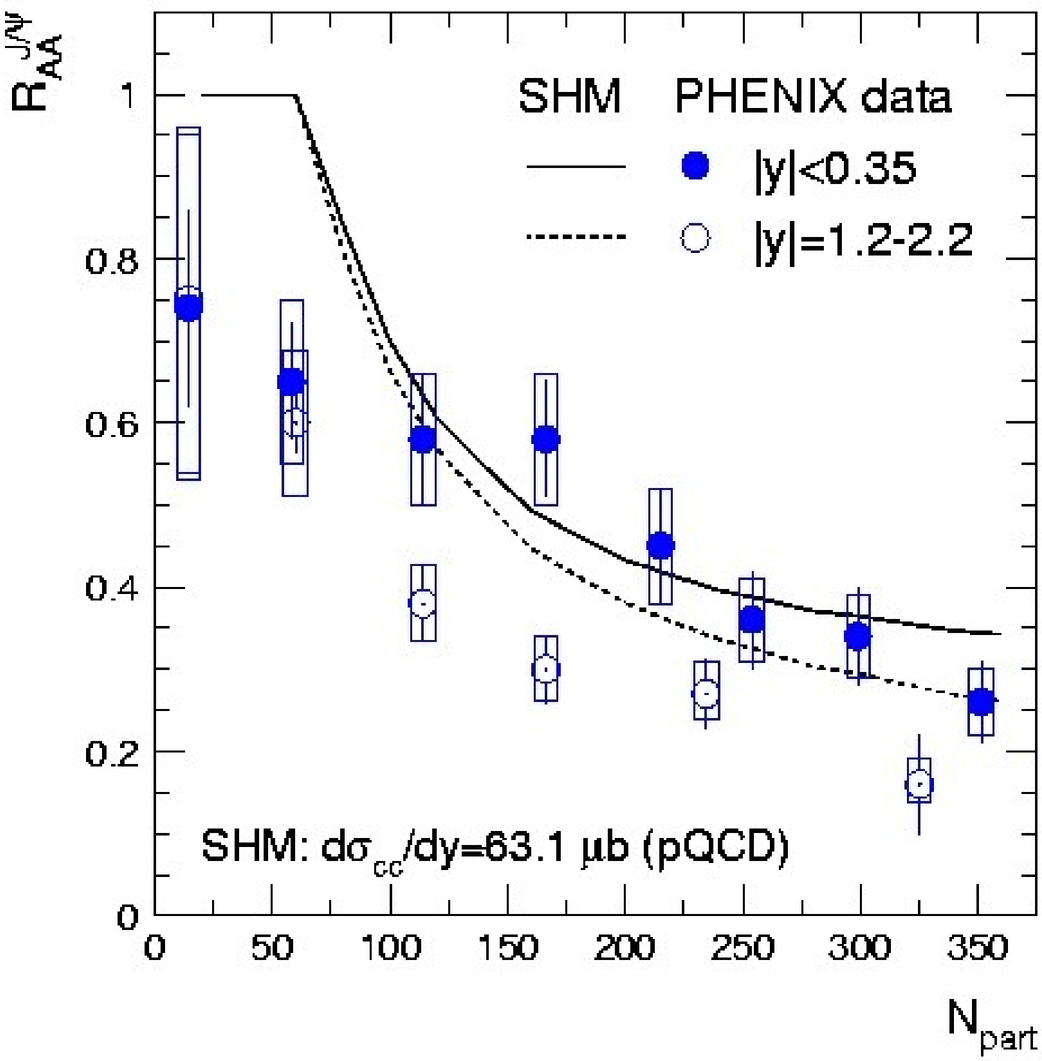
decision on regeneration vs sequential suppression from LHC data



SPS RHIC LHC

Picture:
H. Satz 2009

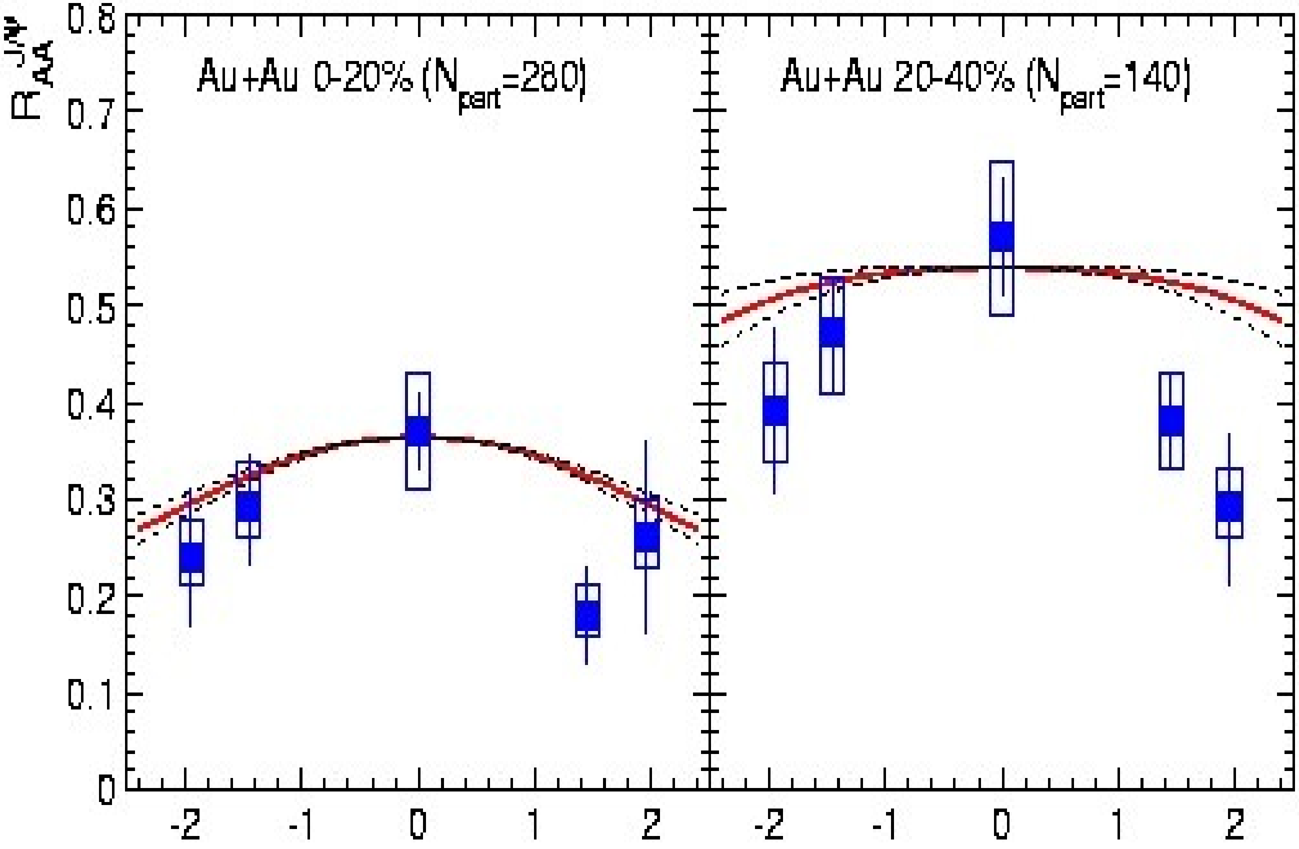
Centrality dependence of nuclear modification factor



data well described
by our regeneration model
without any new
parameters

calcs: Andronic, pbm,Redlich, Stachel
Phys. Lett. B562 (2007) 2591

Comparison of model predictions to RHIC data: rapidity dependence

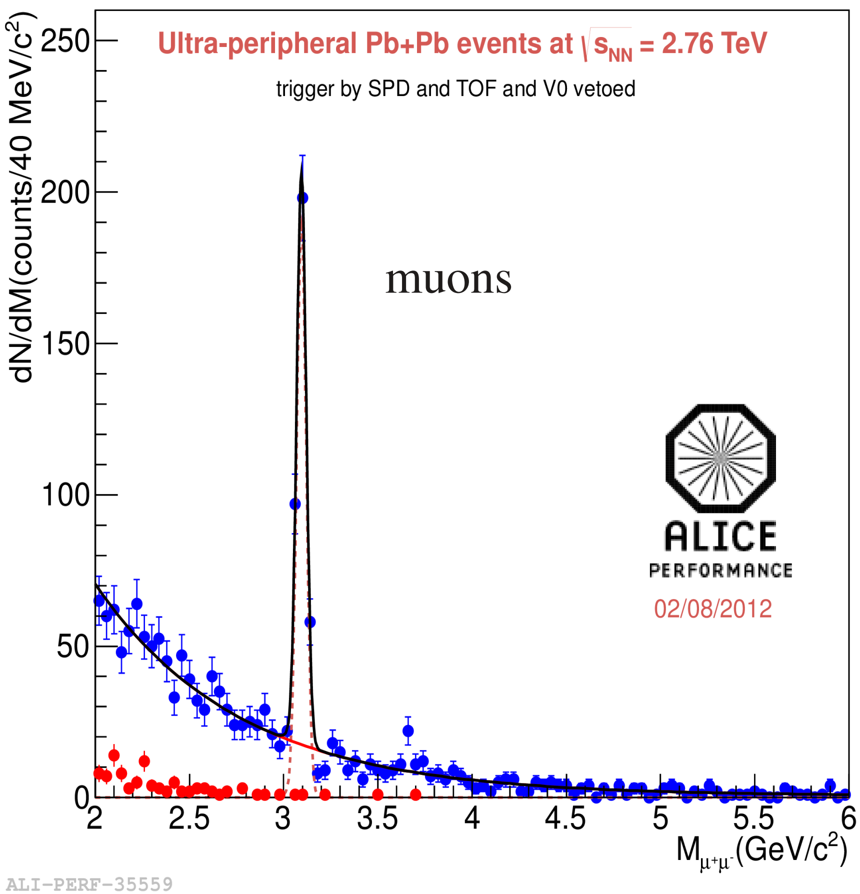


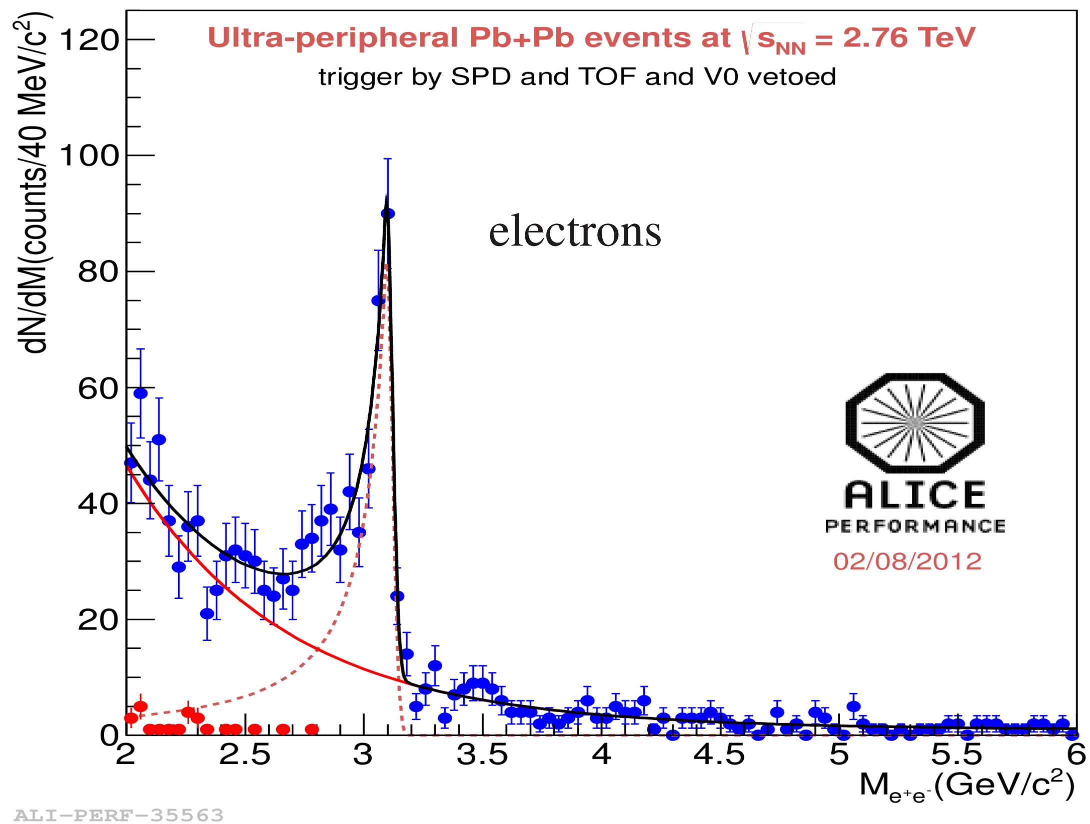
calcs: Andronic, pbm, Redlich, Stachel
Phys. Lett. B562 (2007) 2591

suppression is smallest at mid-rapidity (90 deg. emission)
a clear indication for regeneration at the phase boundary

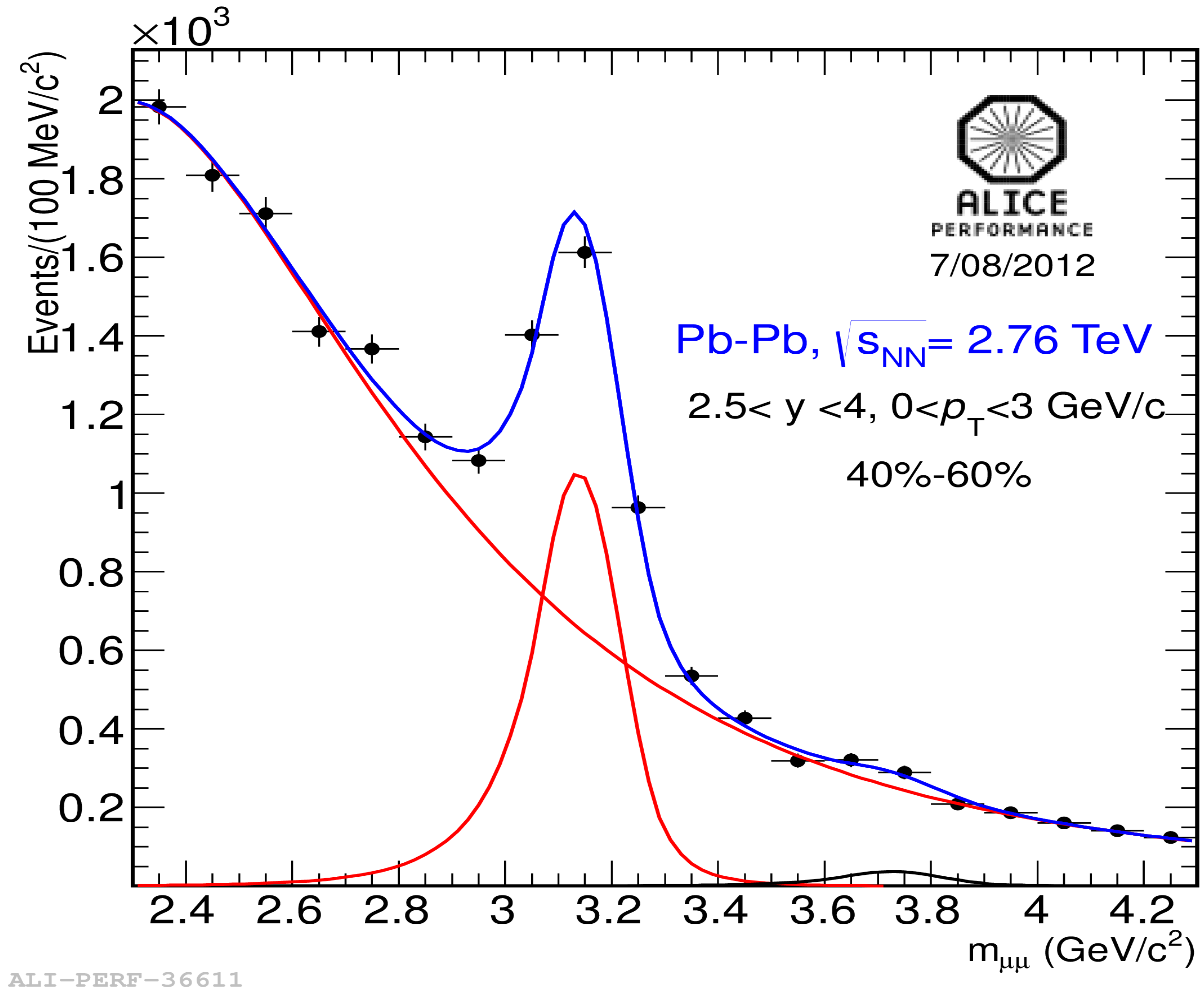
J/psi line shape in ultra-peripheral Pb—Pb collisions

resolution: about 23 MeV for J/psi, precision determination of tail due to internal and external bremsstrahlung



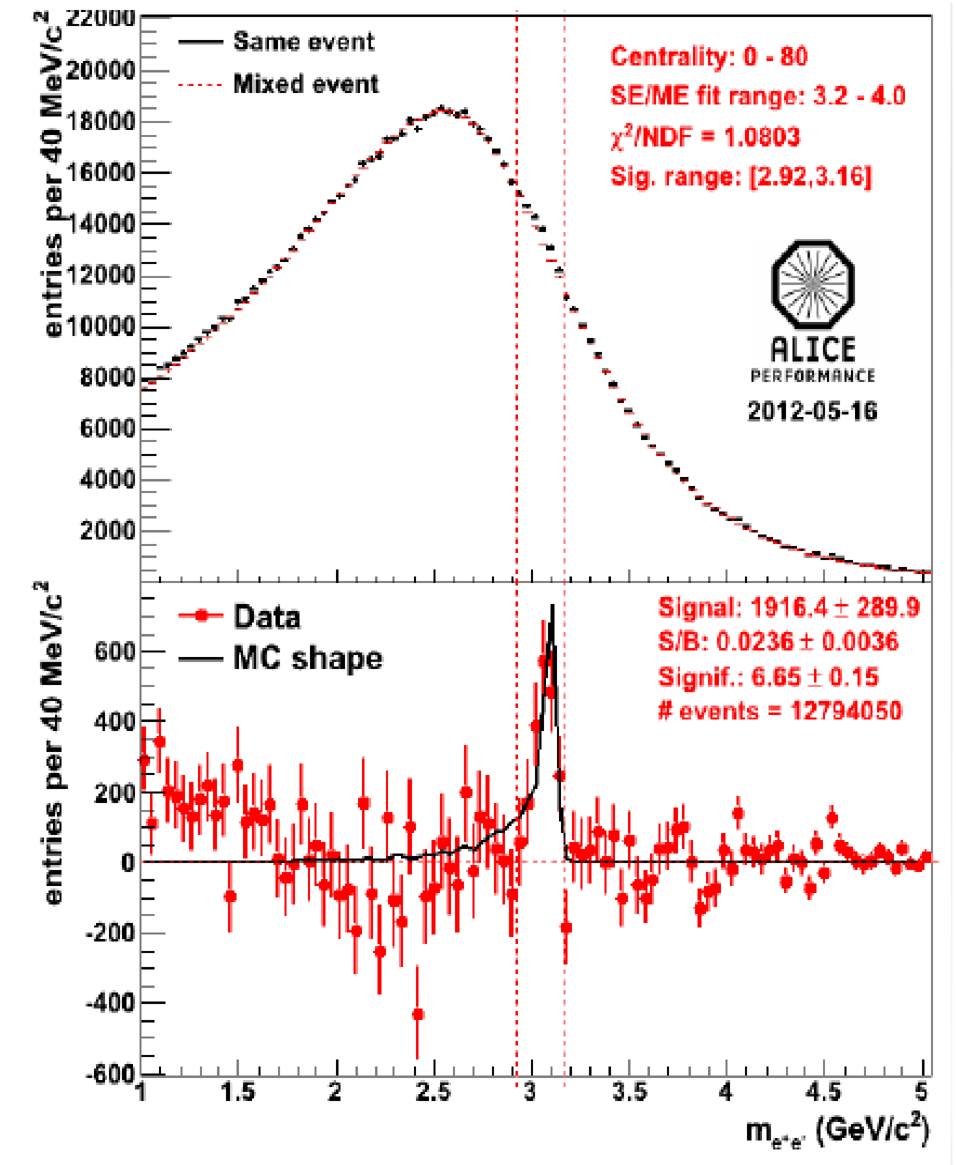


J/psi → mumu in PbPb collisions



note: ALICE measurements include pt(J/psi) = 0

J/psi in e+e- needs electron ID in both TPC and TRD



most challenging: 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

in Pb—Pb collisions 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

Normalization

pp @ 2.76 TeV reference for the nuclear modification factor R_{AA} in Pb-Pb collisions

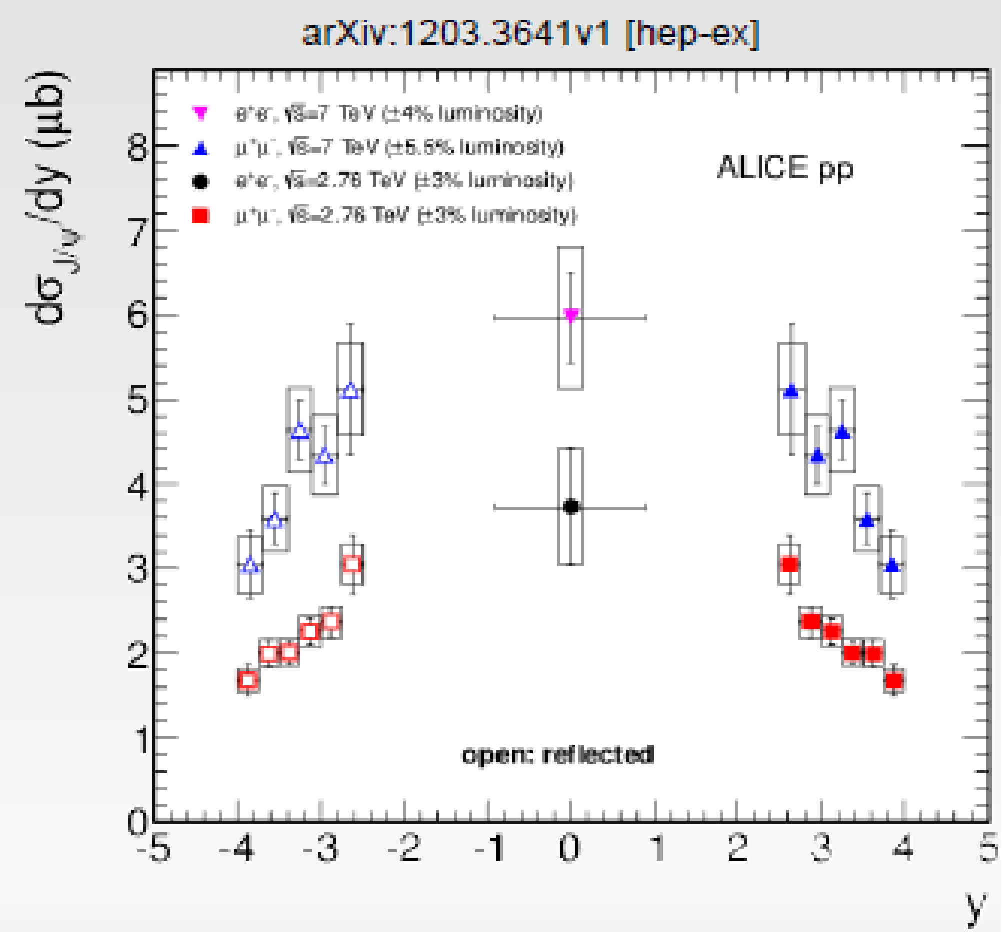
$$R^{i}_{\mathrm{AA}} = \frac{Y^{i}_{\mathrm{J}/\psi}(\Delta p_{\mathrm{t}}, \Delta y)}{\langle T^{i}_{\mathrm{AA}} \rangle \times \sigma^{\mathrm{PP}}_{\mathrm{J}/\psi}(\Delta p_{\mathrm{t}}, \Delta y)}$$

the pp reference is also the main source of systematic uncertainty in the R_{AA} computation:

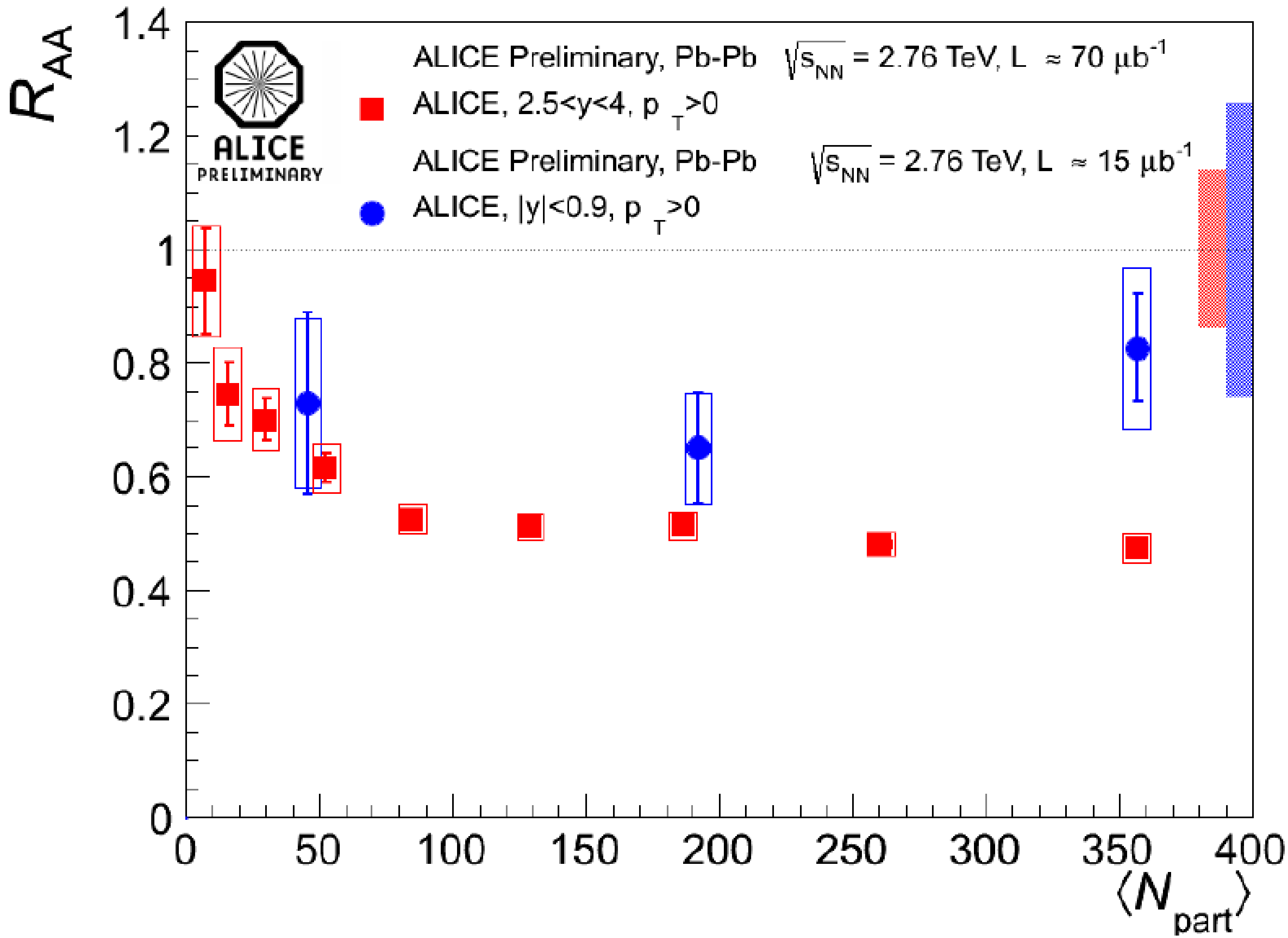
J/Ψ (2.5<y<4), total syst. uncertainty of 9%

J/Ψ (|y|<0.9), total syst. uncertainty of 26%

pp measurement from ALICE data

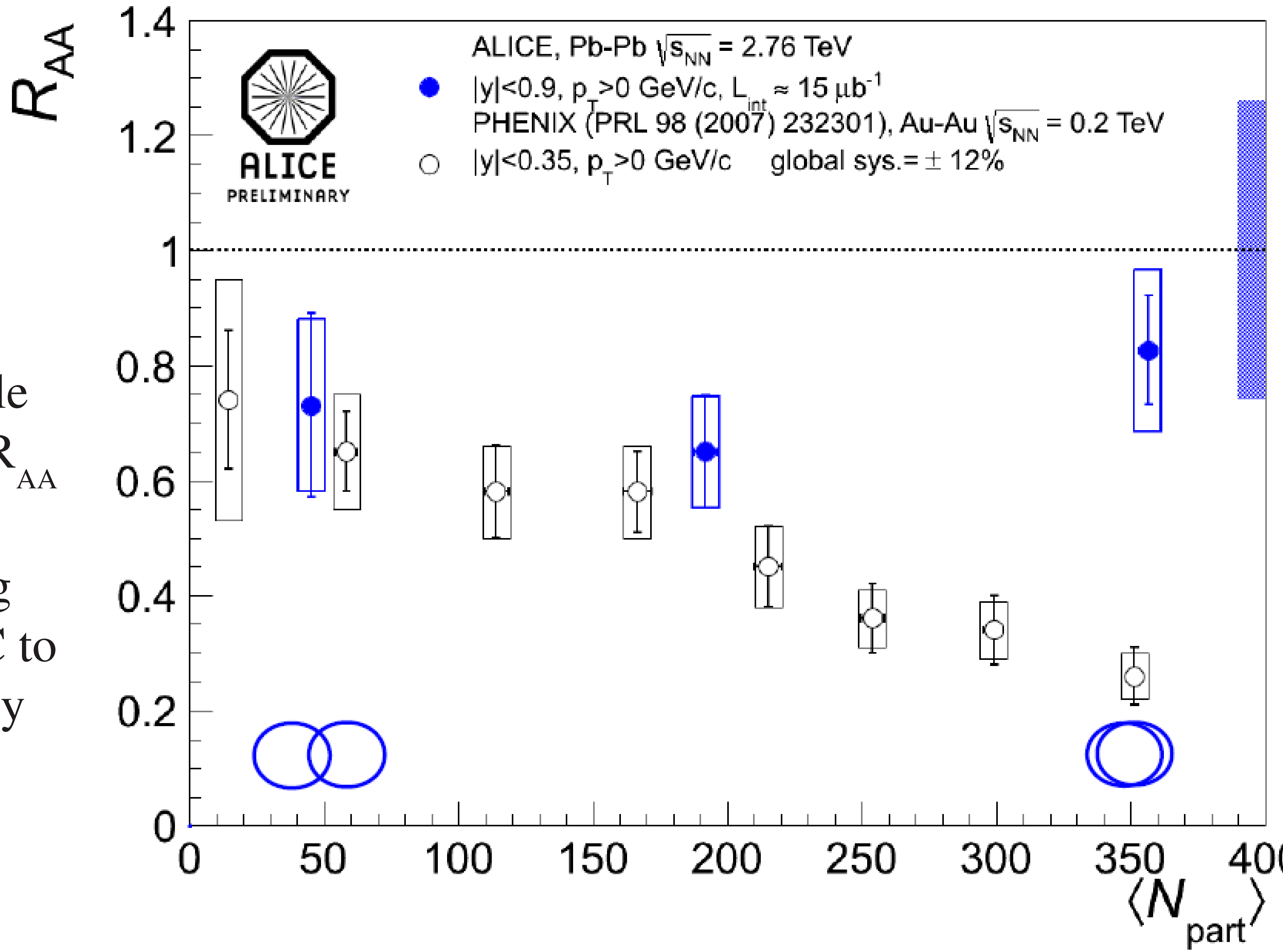


newest ALICE data at central and forward rapidity

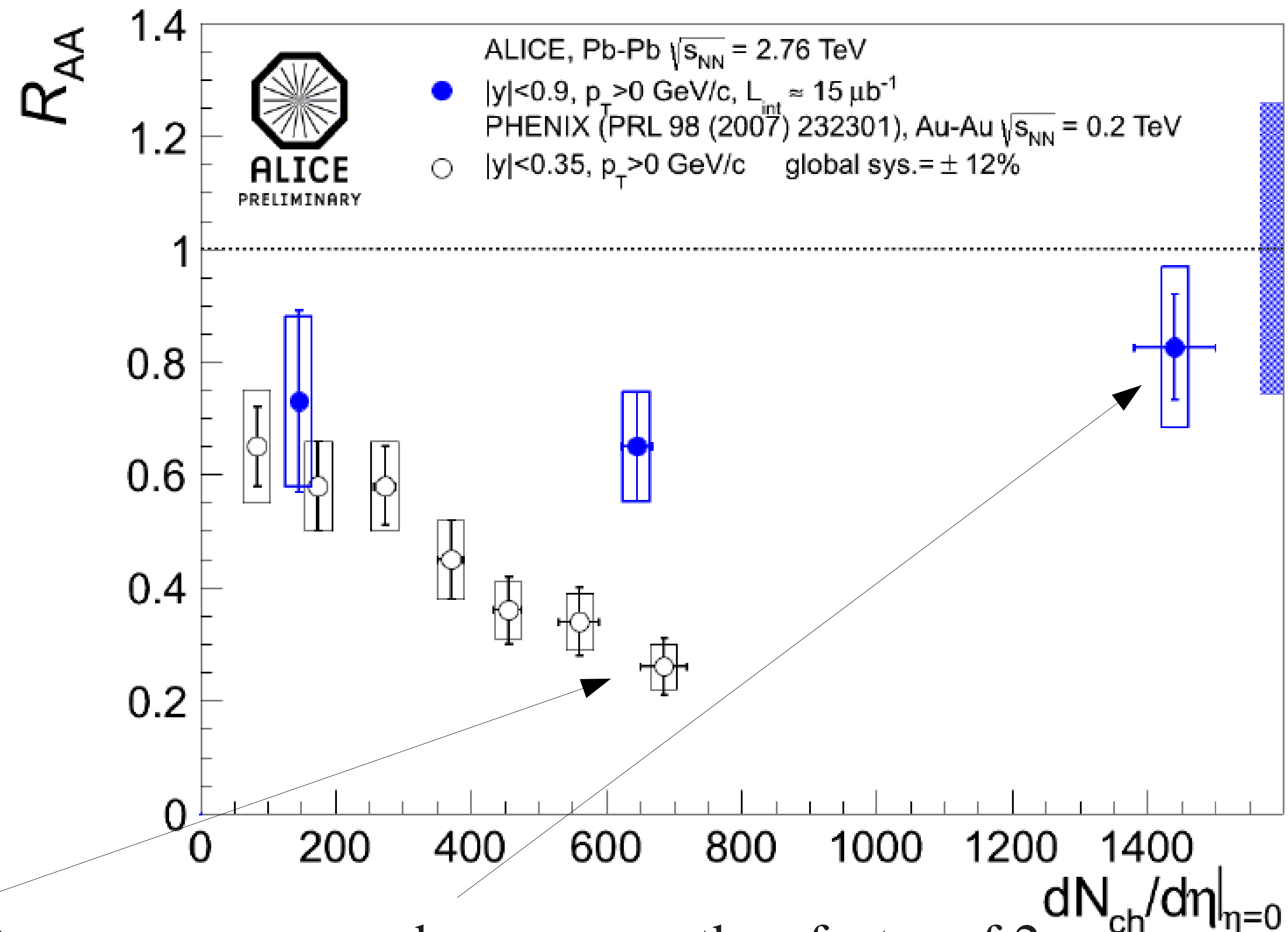


Comparison to PHENIX data

J/psi is the only particle for which R_{AA} increases when going from RHIC to LHC energy

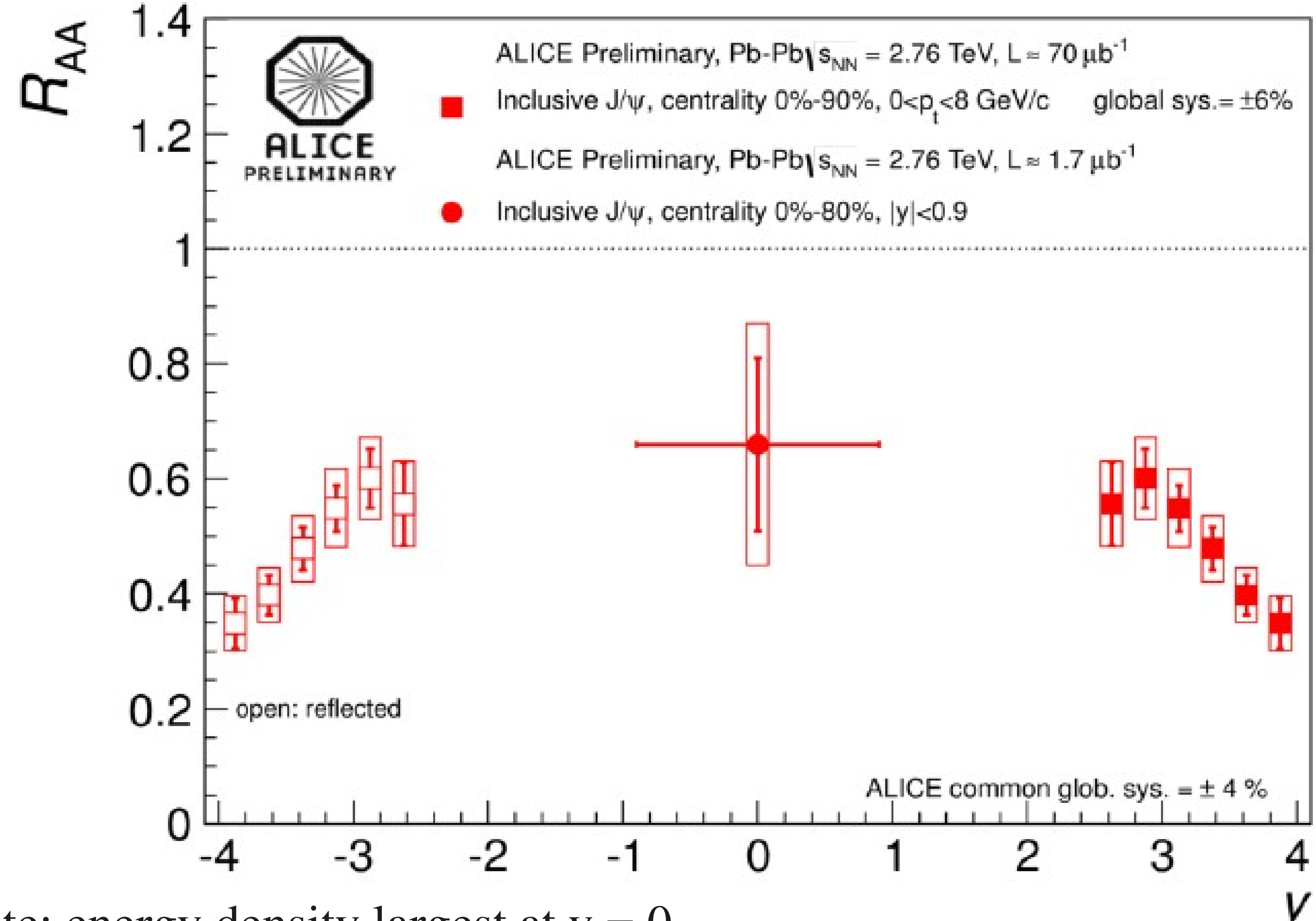


less suppression when increasing the energy density



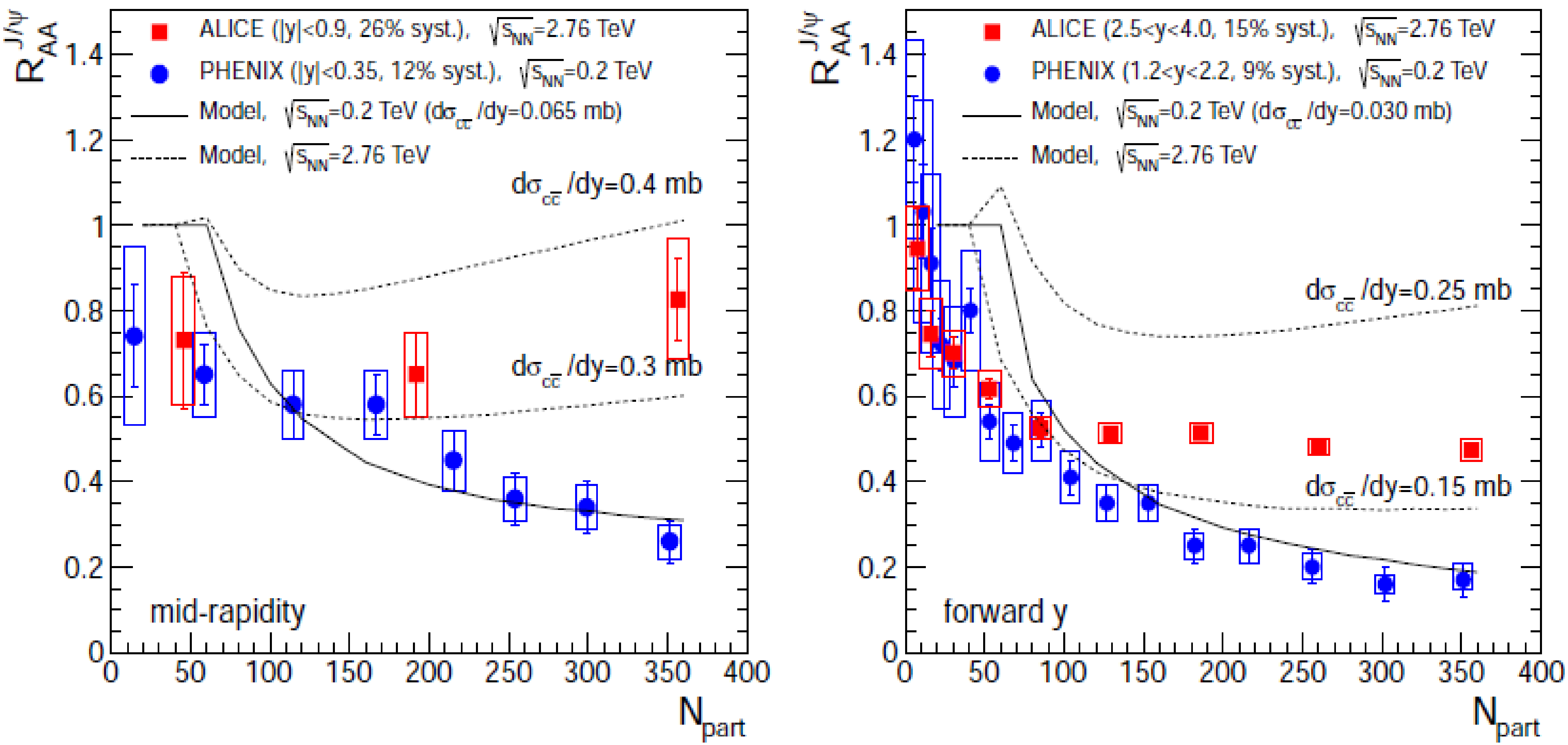
from here to here more than factor of 2 increase in energy density, but R_{AA} increases by more than a factor of 3

Rapidity dependence



note: energy density largest at y = 0

statistical hadronization model



ALICE data and evolution from RHIC to LHC energy described quantitatively

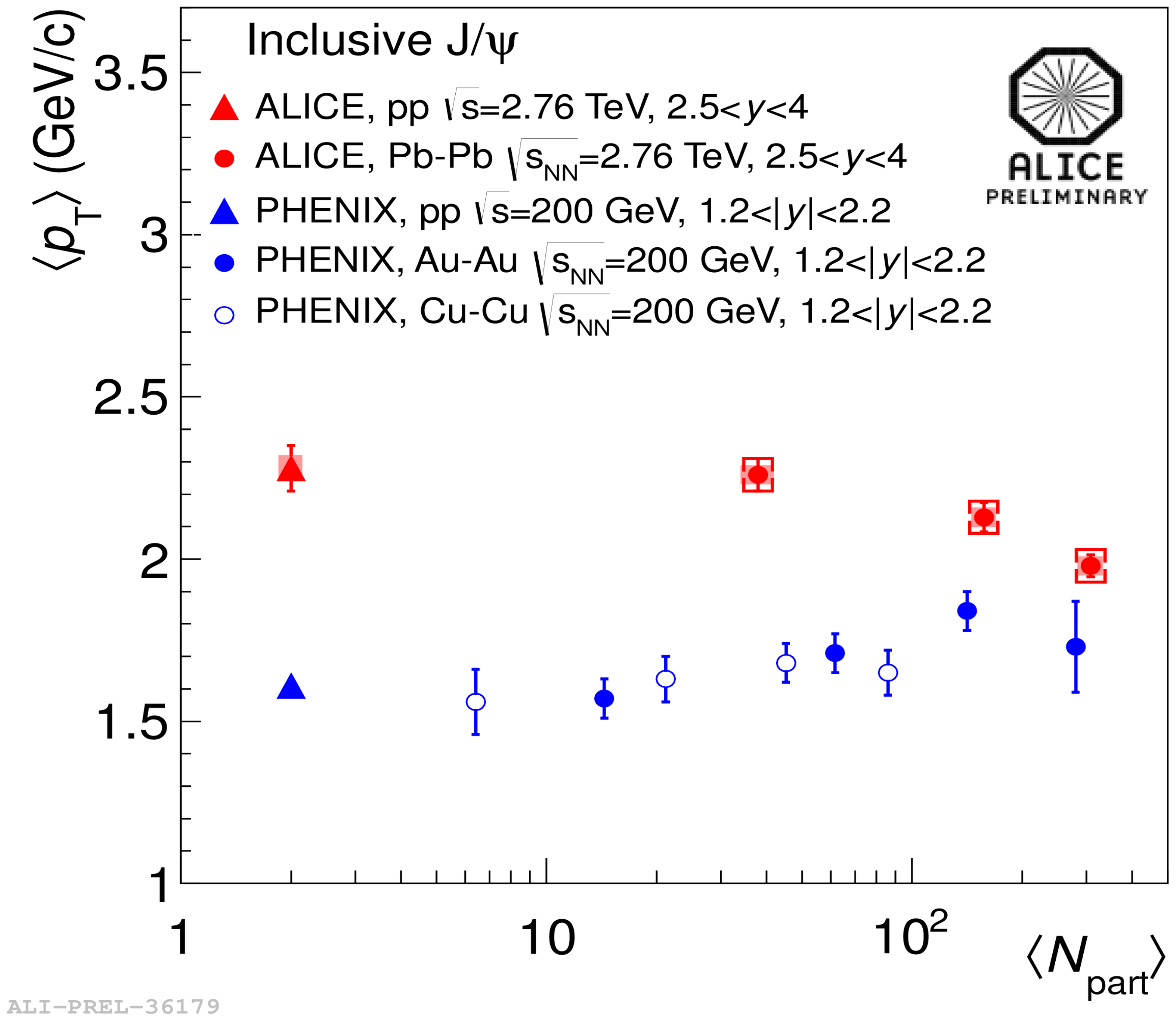
calcs: Andronic, pbm, Redlich, Stachel, arXiv:1210.7724

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

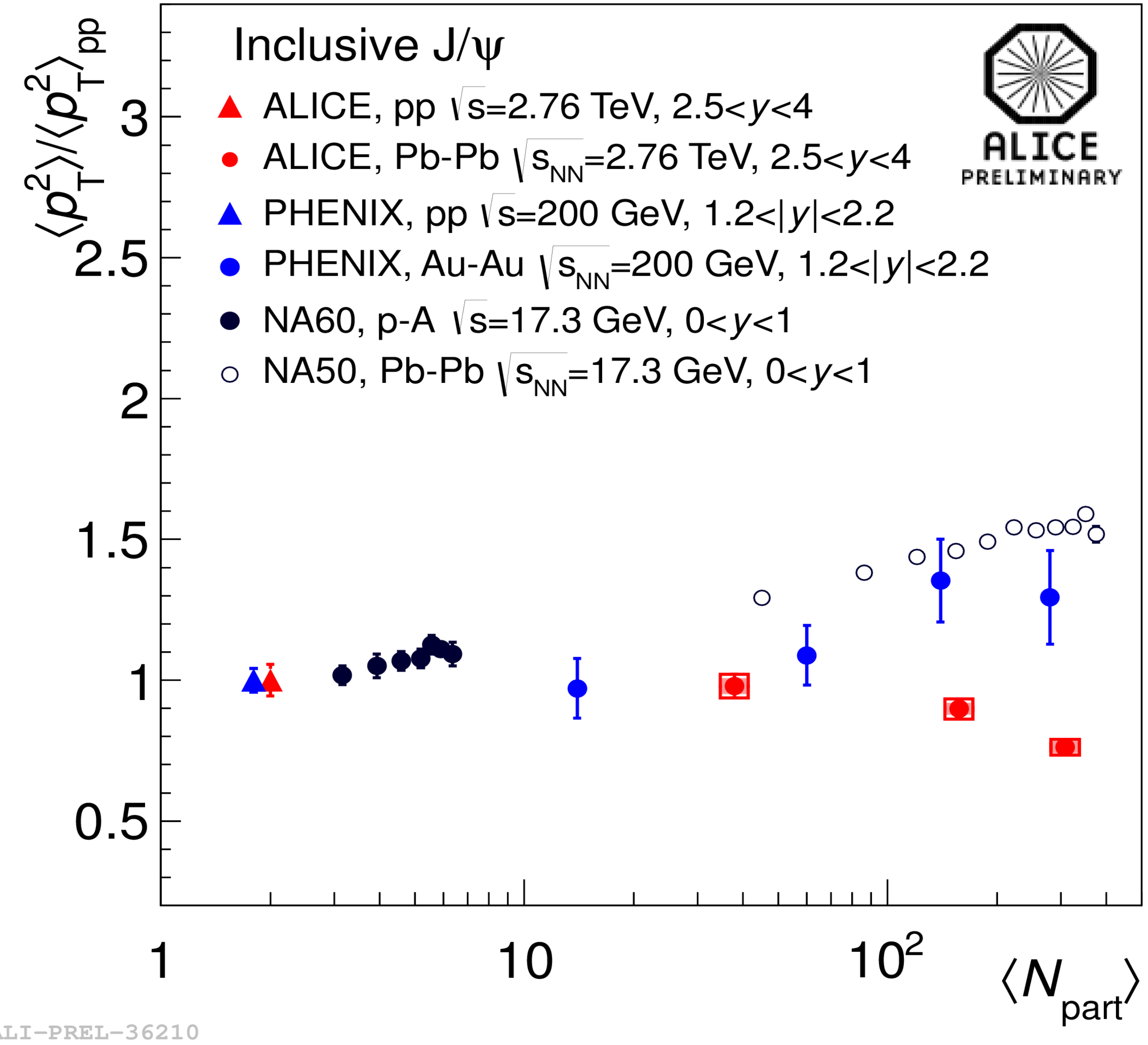
if charmonia are produced via statistical hadronization of charm quarks at the phase boundary, then:

- charm quarks should be in thermal equilibrium
    - low pt enhancement
    - flow of charm quarks
    - flow of charmonia

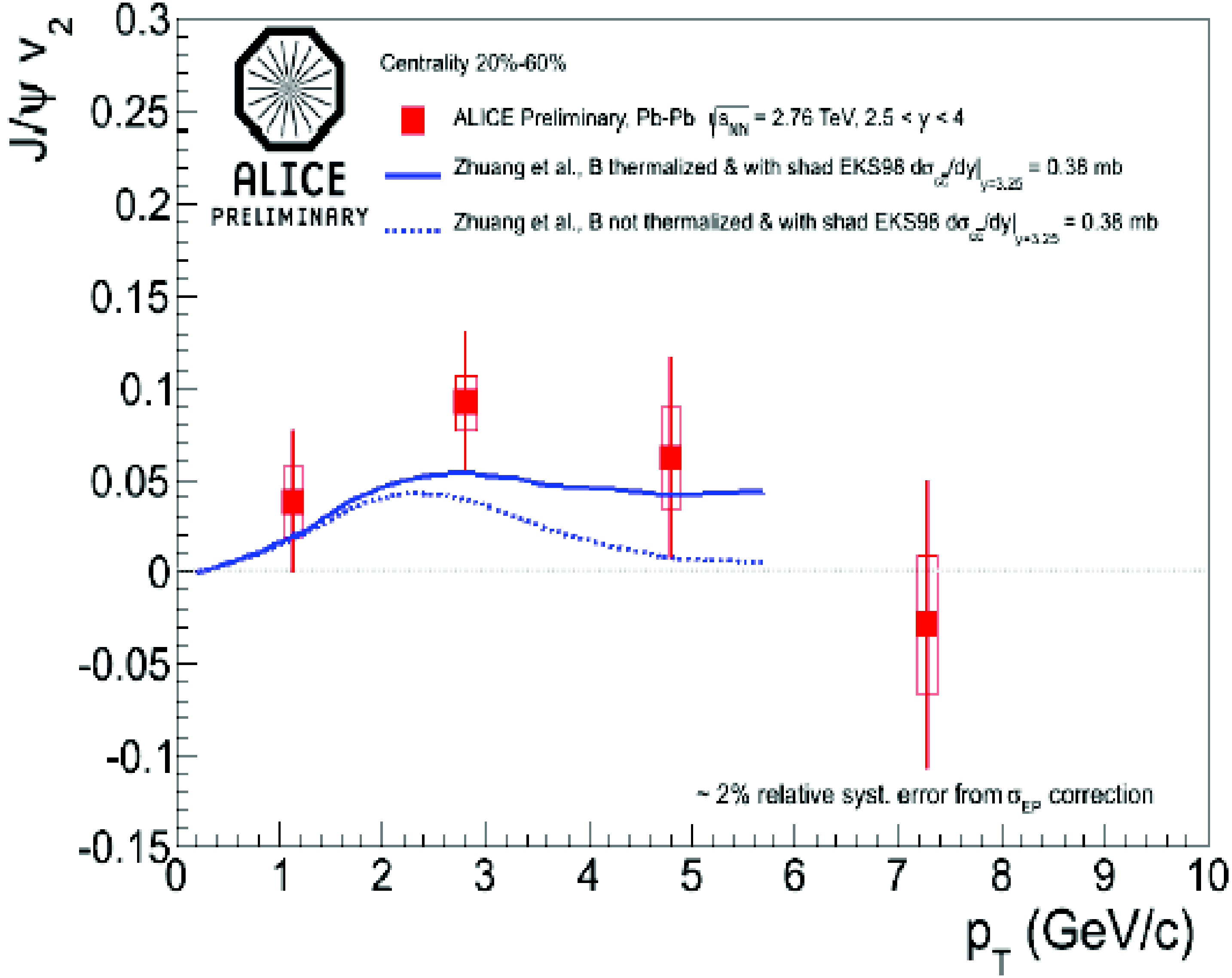
Evolution of J/psi transverse momentum spectra – evidence for thermalization and charm quark coalescence at the phase boundary



Evolution of J/psi transverse momentum spectra – evidence for thermalization and charm quark coalescence at the phase boundary

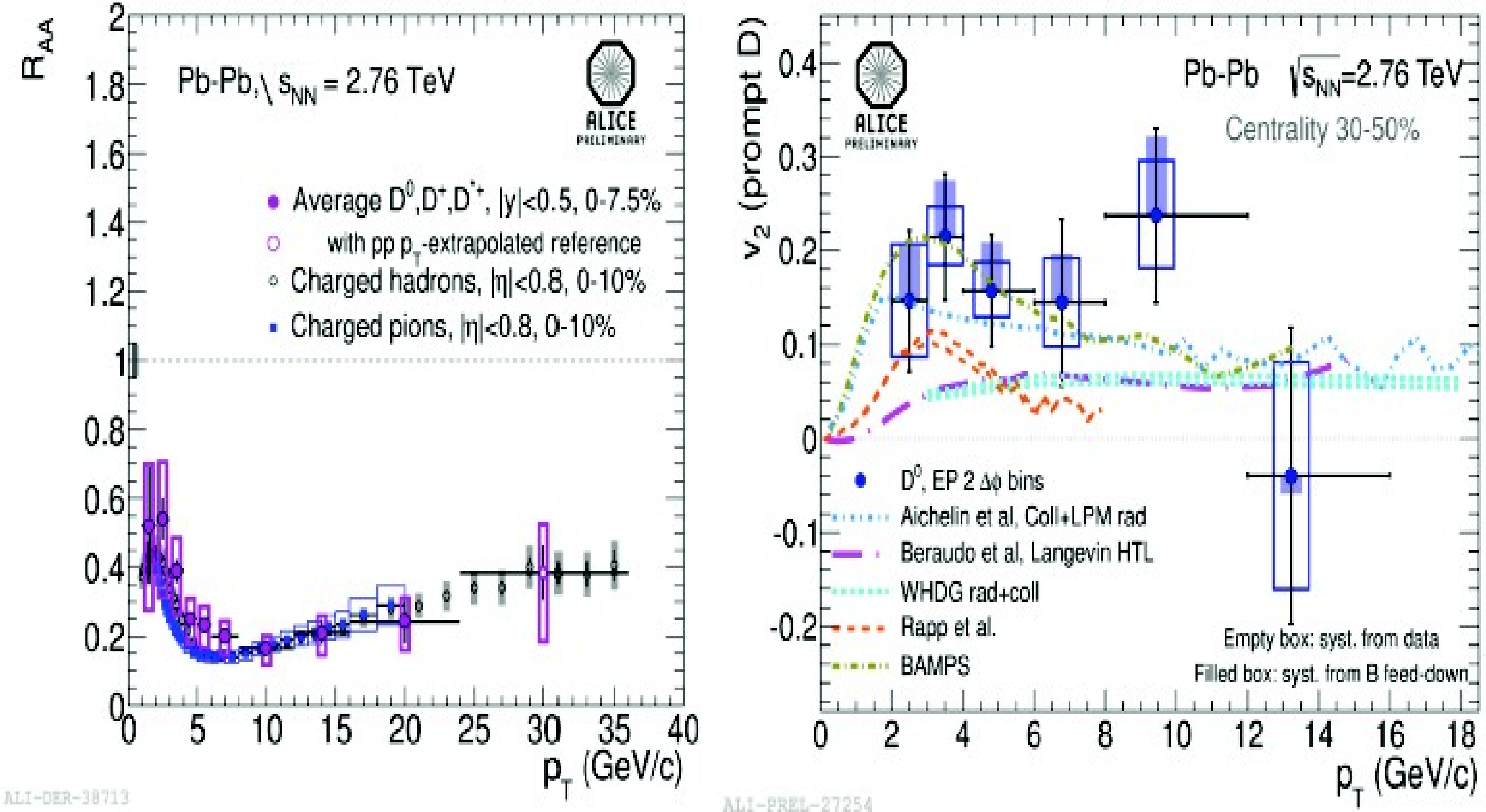


J/psi flow compared to models including (re-) generation



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

Thermalization of heavy quarks



Charmonium production at LHC energy: deconfinement,and color screening

- Charmonia formed at the phase boundary → full color screening at T_c
- Combination of uncorrelated charm quarks into J/psi → deconfinement

statistical hadronization picture of charmonium production provides most direct way towards information on the degree of deconfinement reached as well as on color screening and the question of bound states in the QGP

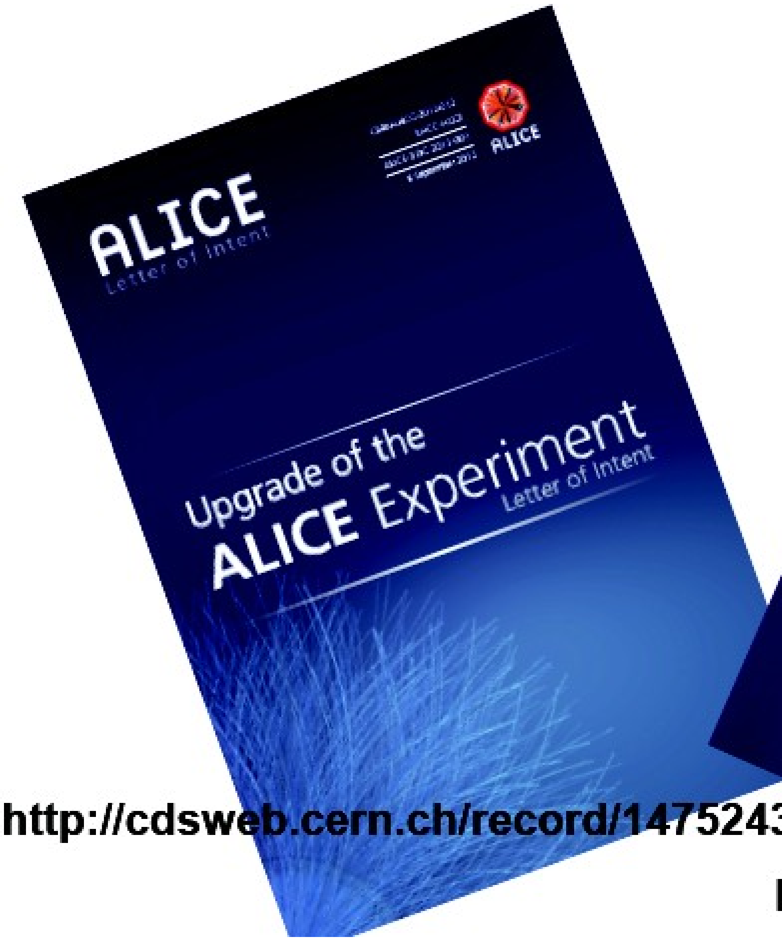
Summary

- Important and new results on bulk observables:
  - thermalization of light flavors → connection to phase boundary
  - hydrodynamic flow to high orders with identified particles → early state fluctuations
  - thermal radiation from the hot fireball → initial temperature
  - thermalization of heavy quarks
- Results on quarkonia and open heavy flavor → deconfinement and color screening

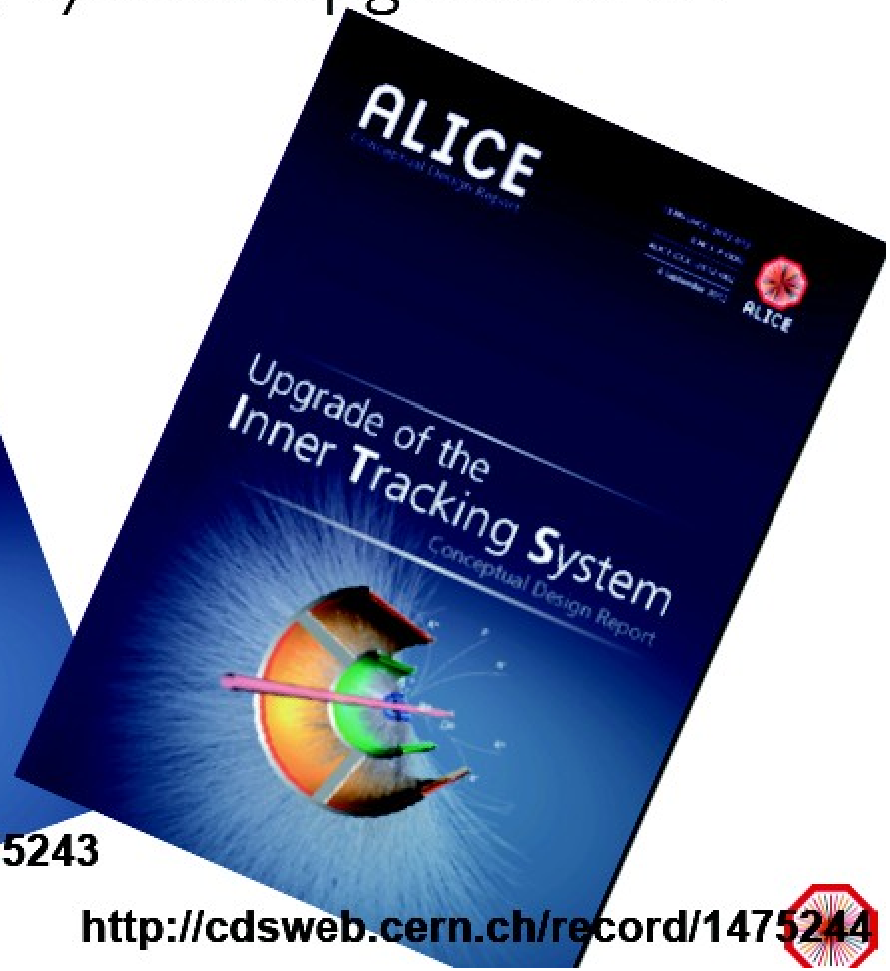
- Next few years: consolidate and deepen understanding at full LHC energy

- Enter R&D and construction phase for ALICE upgrade

ALICE Upgrade Letter of Intent
& Inner Tracking System Upgrade CDR



http://cdsweb.cern.ch/record/1475243



http://cdsweb.cern.ch/record/1475244

main physics motivation for ALICE upgrade

measure Pb—Pb collisions at high rate (50 kHz) to investigate:

- heavy flavor production and transport parameters
- quarkonium production, deconfinement and Debye screening
- low mass lepton pairs and chiral symmetry restoration

this needs approximately 10/nb integrated Pb—Pb lumi

factor of 100 increase in statistical reach
LoI recently endorsed by LHCC and CERN Research Board
ALICE looks forward to continued (until about 2025)
exciting and fundamental experiments with ions in the LHC

Statistical hadronization in one page

Thermal model calculation (grand canonical) T, μ_B: $\rightarrow n_X^{th}$

$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c V (\sum_i n_{D_i}^{th} + n_{\Lambda_i}^{th}) + g_c^2 V (\sum_i n_{\psi_i}^{th} + n_{\chi_i}^{th})$$

$N_{c\bar{c}} << 1 \rightarrow$ Canonical: J.Cleymans, K.Redlich, E.Suhonen, Z. Phys. C51 (1991) 137

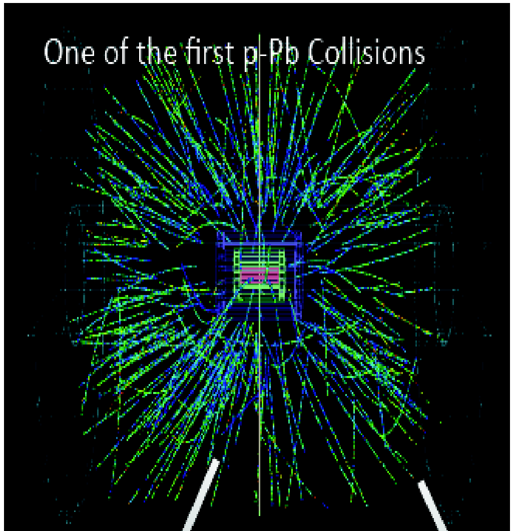
charm balance equation

$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th} \quad \rightarrow g_c$$

Outcome: $N_D = g_c V n_D^{th} I_1 / I_0 \quad N_{J/\psi} = g_c^2 V n_{J/\psi}^{th}$

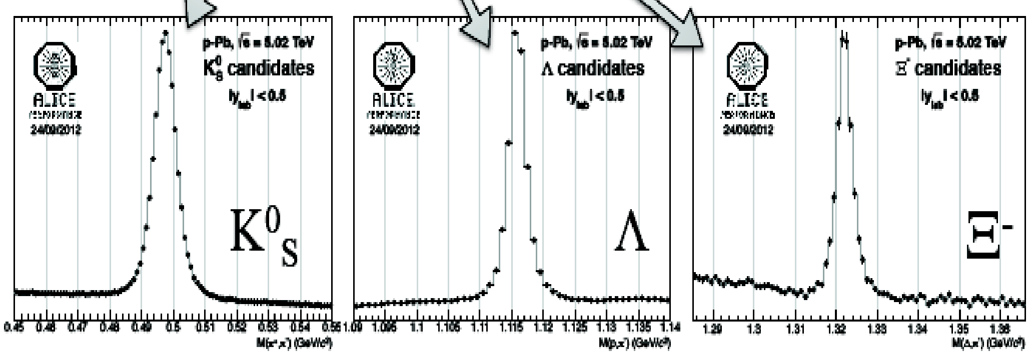
Inputs: T, μ_B, $\quad V = N_{ch}^{exp} / n_{ch}^{th}$, $\quad N_{c\bar{c}}^{dir}$ (pQCD)

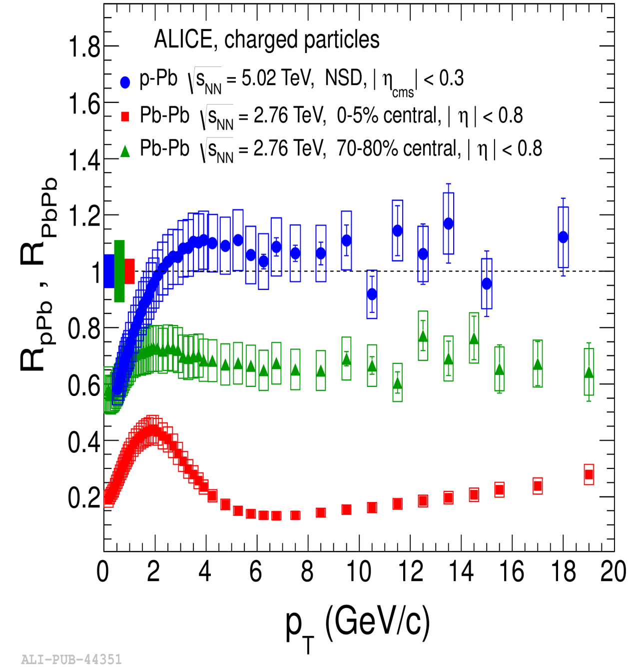
ALICE Data Taking: **p-Pb** at √s = 5.02 TeV

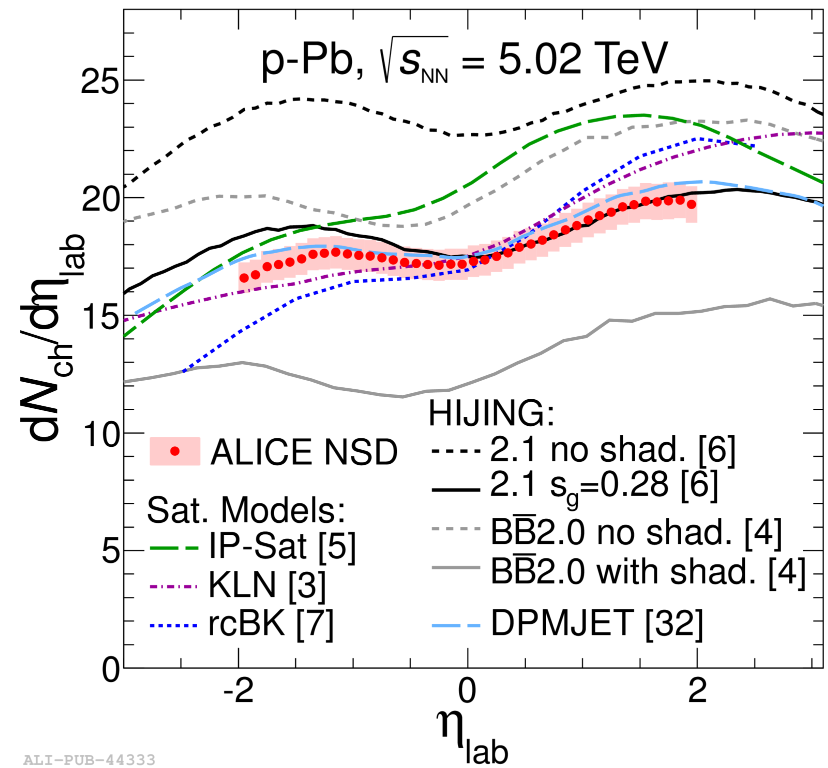


13th September: p-Pb collisions recorded

- Quite successful with higher than predicted luminosity
- Minimum Bias event rate: ~200Hz
- On tape
  - 1.8M min. bias triggers
  - 260K min. bias with disp. vertex, +50 cm
  - 370K min. bias with disp. vertex, -50 cm







First results from ALICE

- **Pseudorapidity density of charged particles p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV**

  arXiv: 1210.3615, accepted by Phys. Rev. Lett

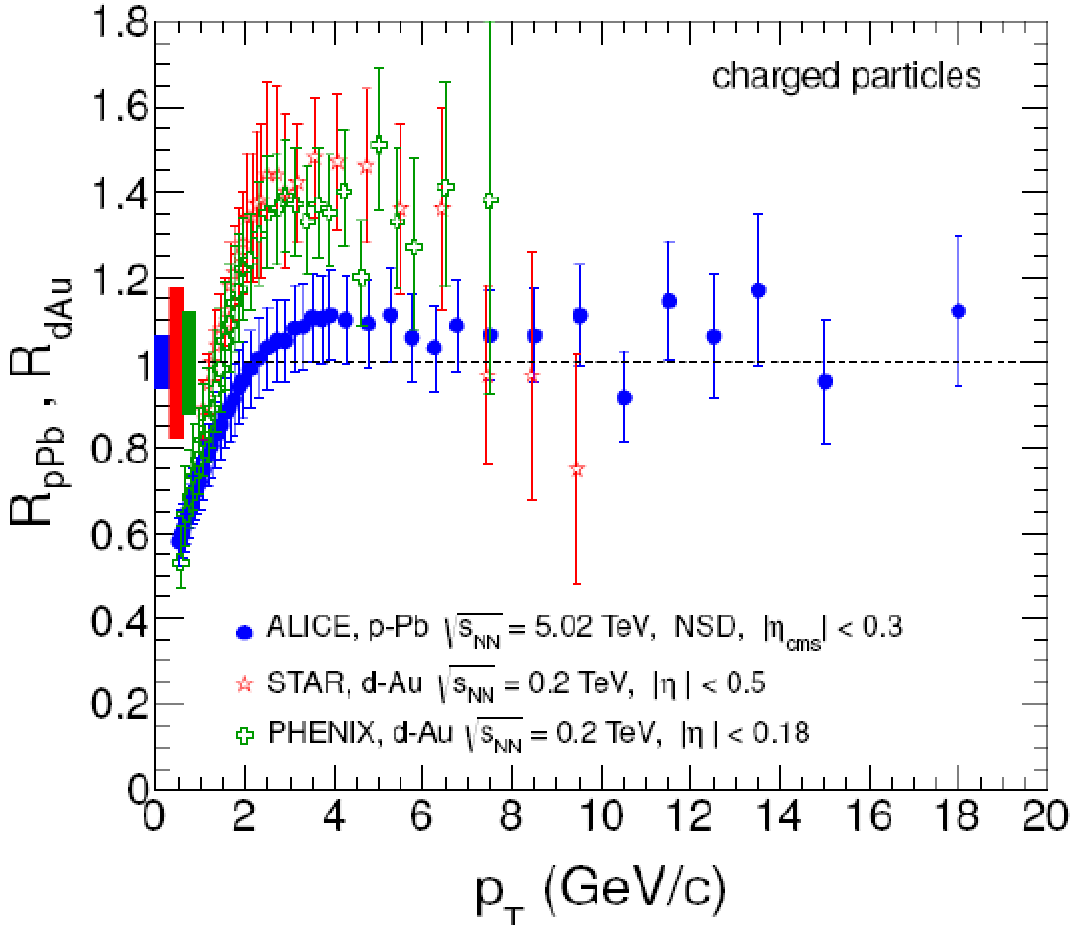
- **Transverse Momentum Distribution and Nuclear Modification Factor of Charged Particles in p-Pb Collisions at $\sqrt{s_{NN}}$ = 5.02 TeV**

  arXiv: 1210.4520, accepted by Phys. Rev. Lett

- **Long-range angular correlations on the near and away side in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV**

  arXiv: 1212.2001, accepted by Phys. Lett. B

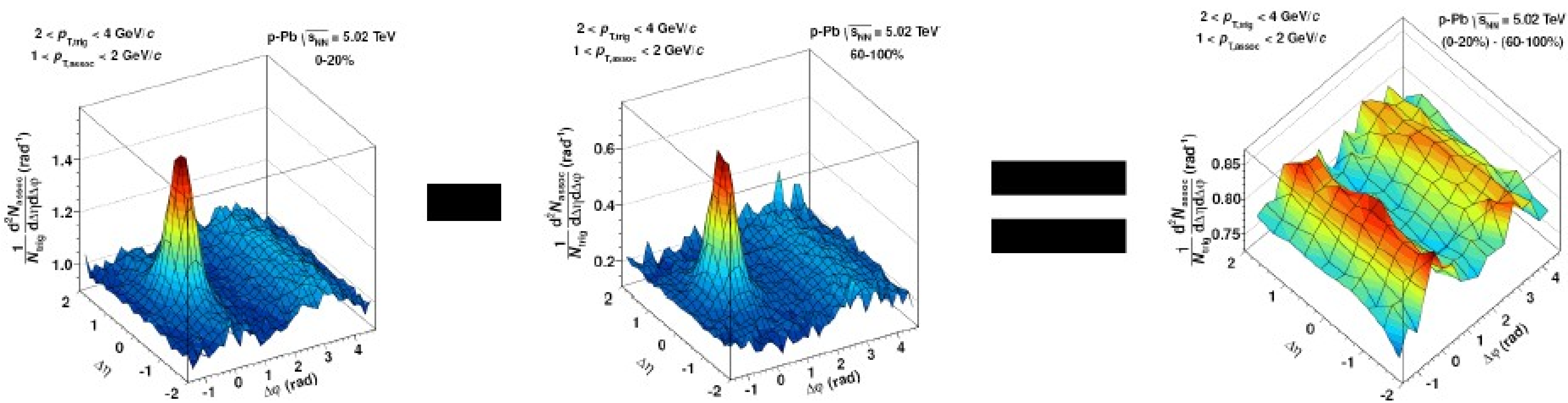
Comparison to data from RHIC



no 'Cronin effect seen at LHC (after 3 hrs of beam)

The big surprize: the 'double ridge'

high multiplicity - low multiplicity = double ridge



- Double ridge structure with excess on near and away side
- Near and away side ridges are similar in magnitude