Bulk matter formed in Pb-Pb collisions at the LHC

- Introductory remarks – is quark matter at LHC in equilibrium?
- 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

FIAS-Frankfurt

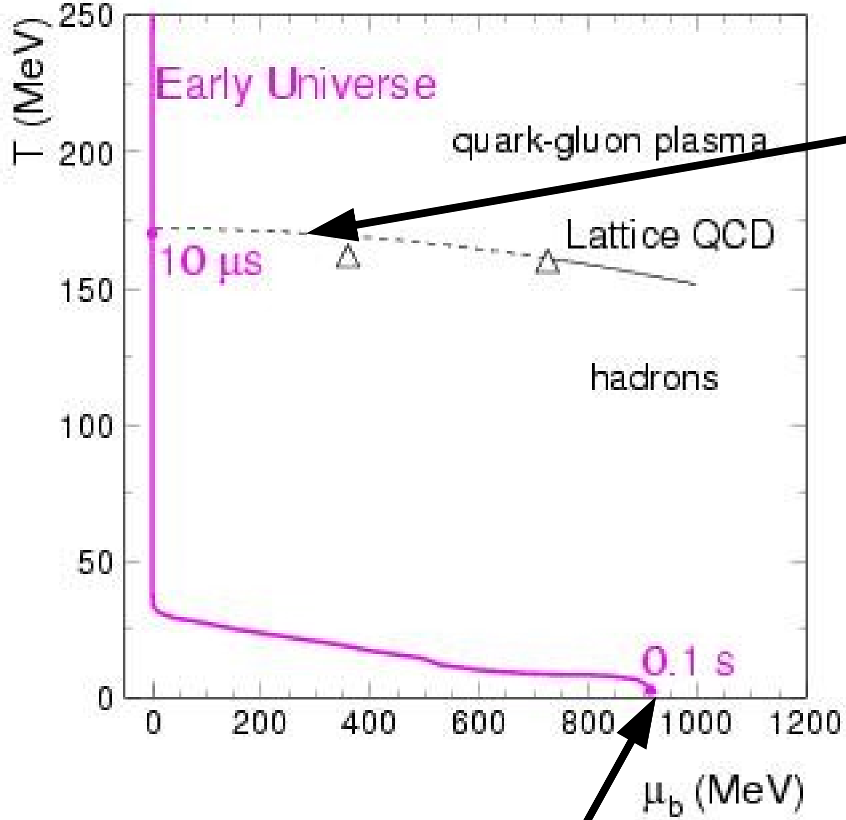
34th Course in Nuclear Physics:

Probing the Extremes of Matter with Heavy Ions

Erice-Sicily: 16 - 24 September 2012

Peter Braun-Munzinger

Evolution of the Early Universe



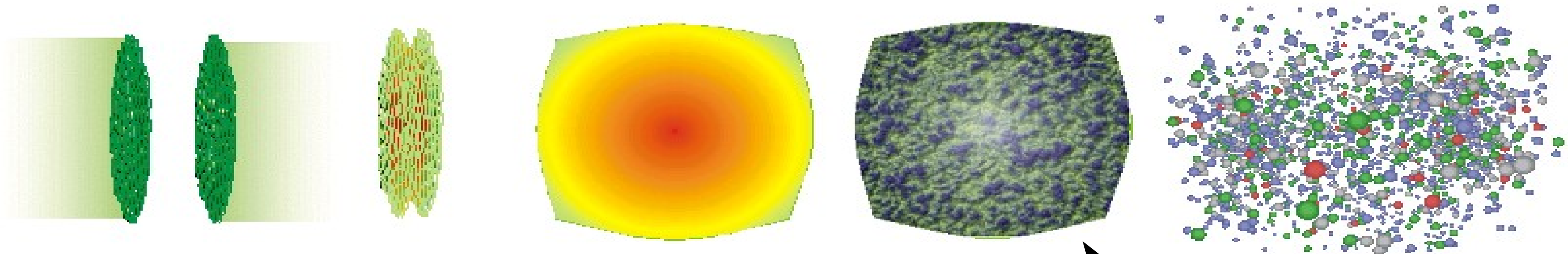
QCD Phase Boundary

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

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

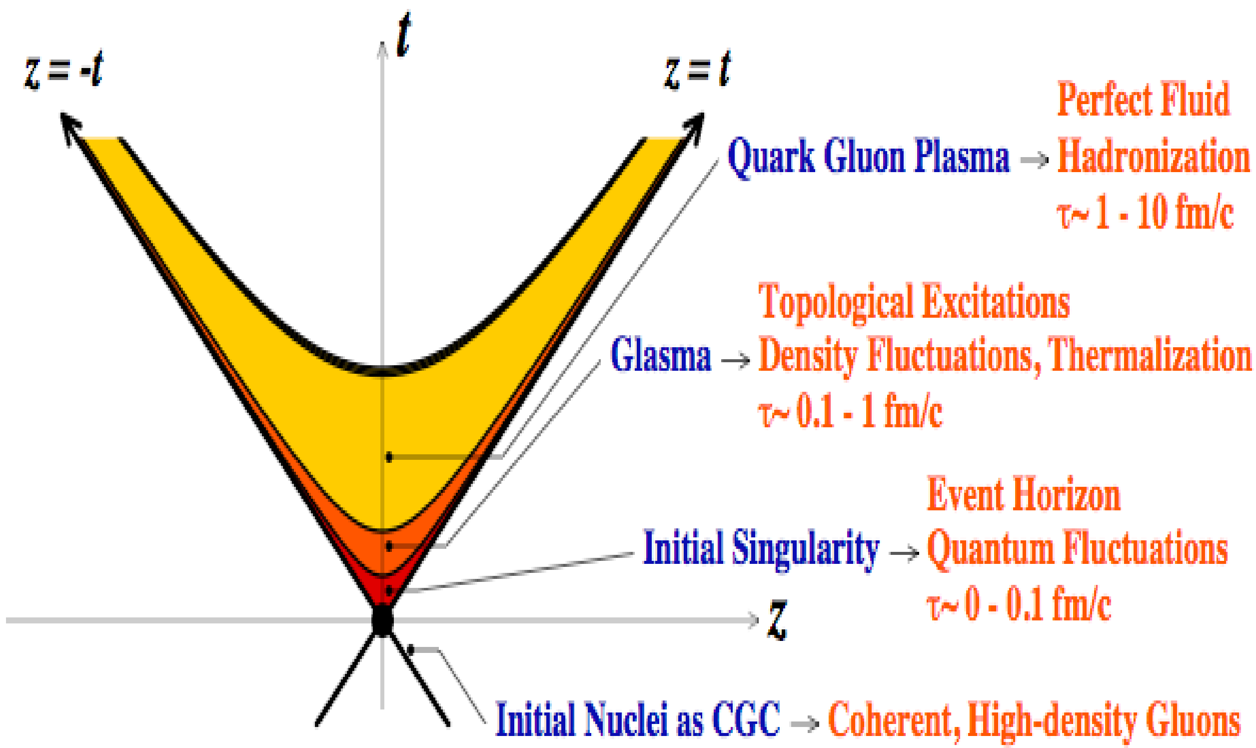
neutrinos decouple and light nuclei begin to be formed

The Space-Time Evolution of a Relativistic Nuclear Collision



CGC | Initial Singularity | Glasma | sQGP | Hadron Gas

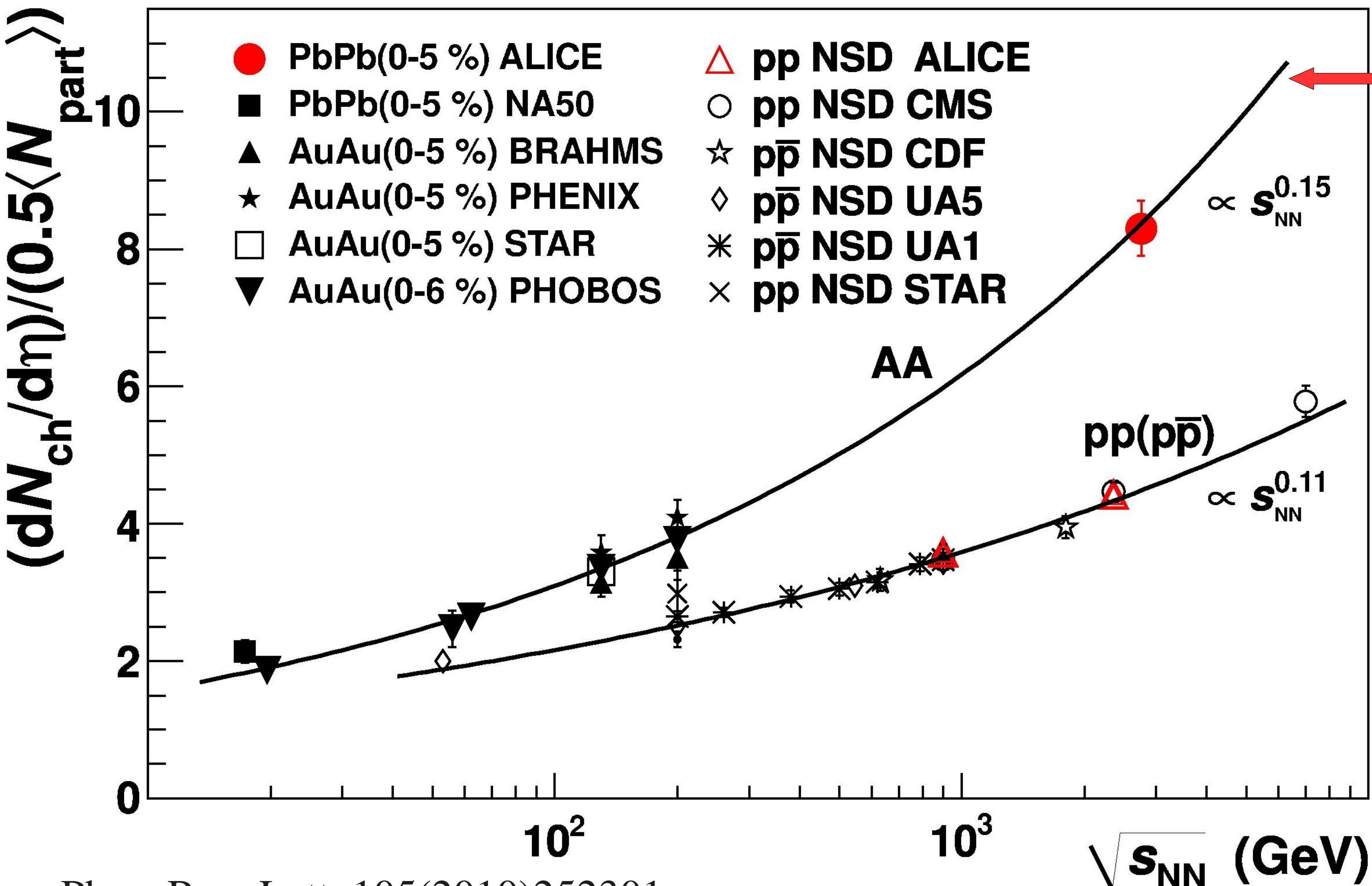
Hot fireball, equilibrized matter



one possible view
(courtesy
Larry McLerran)

Charged particle multiplicity in central PbPb collisions

analysis based on Silicon pixel detector tracklets within η < 0.5
corrected for acceptance, tracklet efficiency and random comb. background

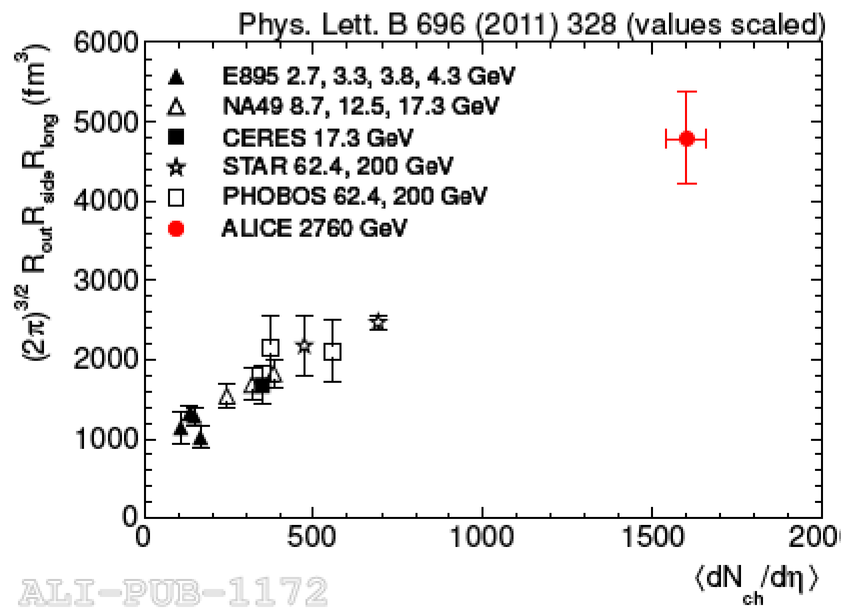


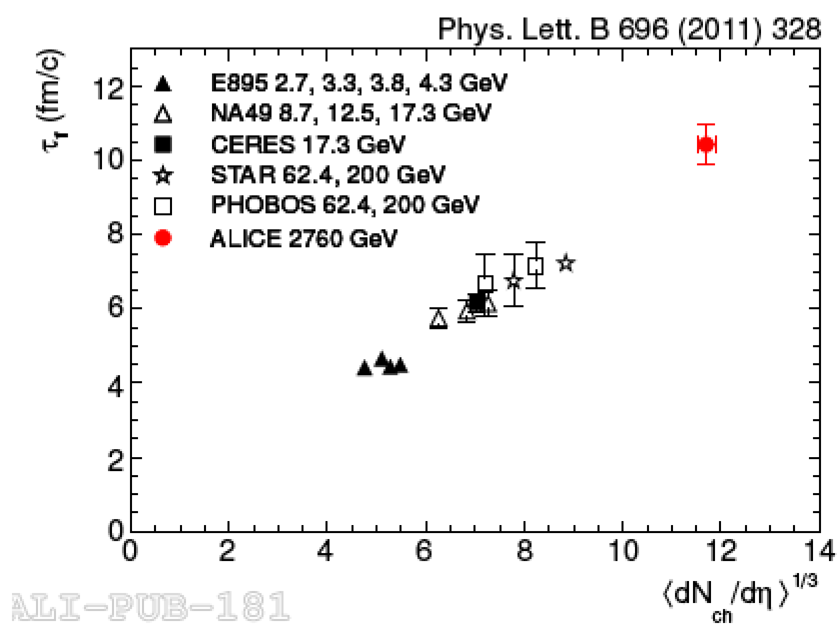
increase with beam energy significantly steeper than in pp

Phys. Rev. Lett. 105(2010)252301

Fireball at LHC energy has much large size and lives

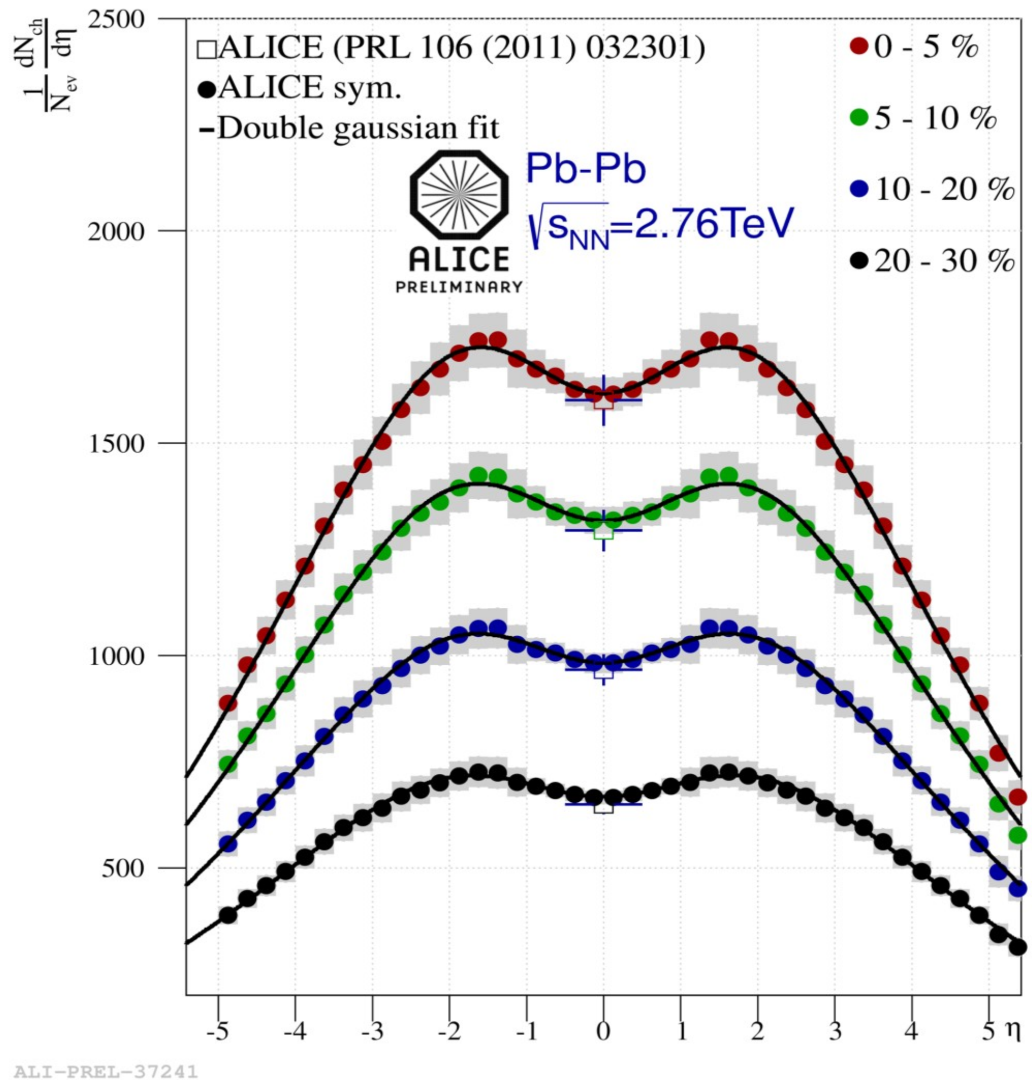
volume and lifetime
from HBT analysis





Complete angular (pseudo-rapidity) distributions

complete angular distr.
between 1 and 179 deg



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?

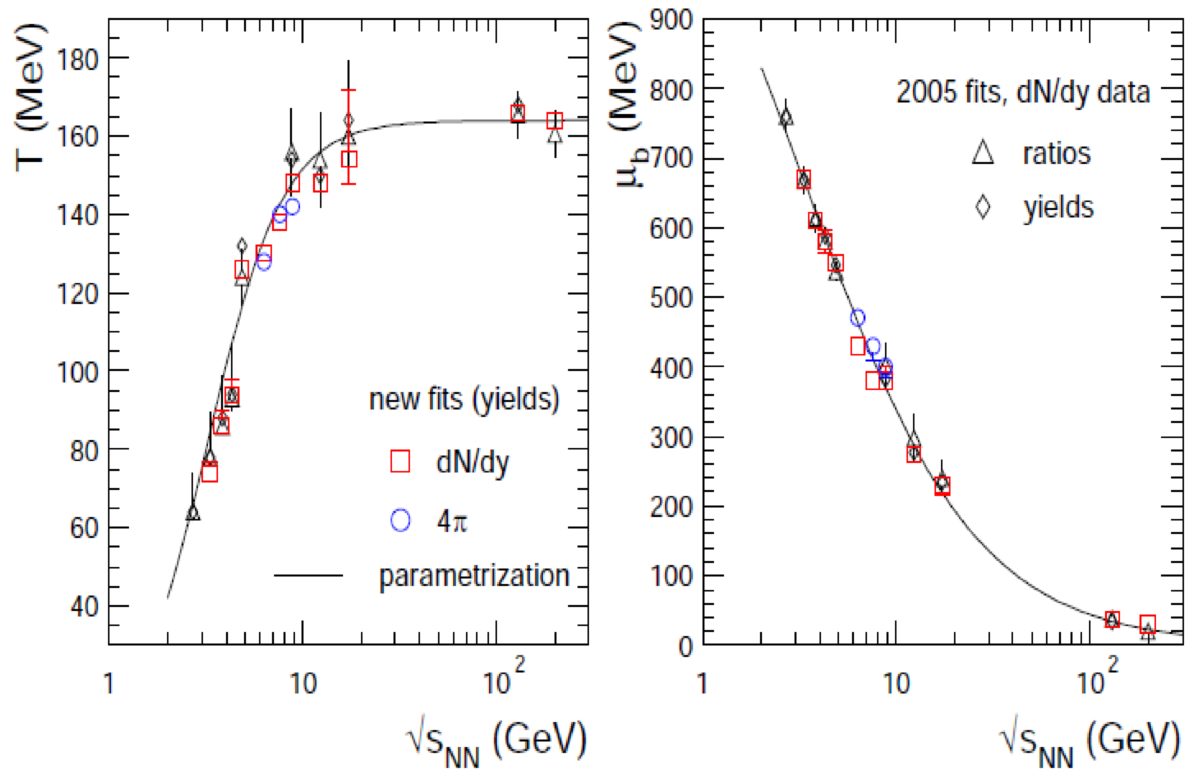
Parameterization of all freeze-out points before LHC data

note: establishment of limiting temperature

T_{lim} = 164 +/- 4 MeV

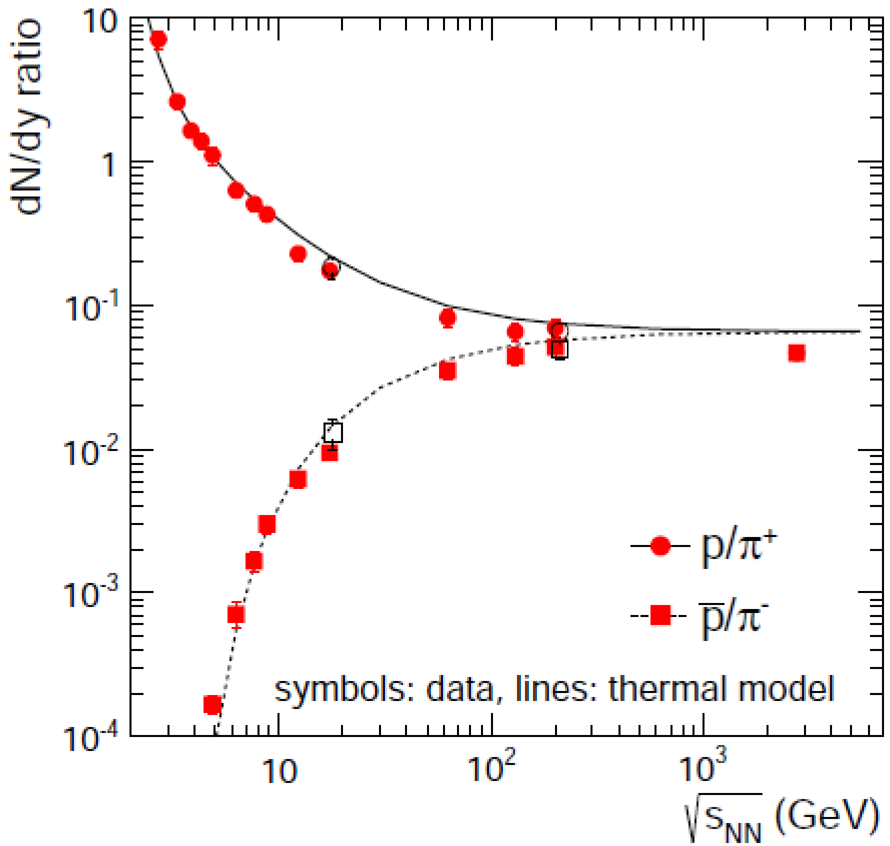
get T and μ_B for all energies

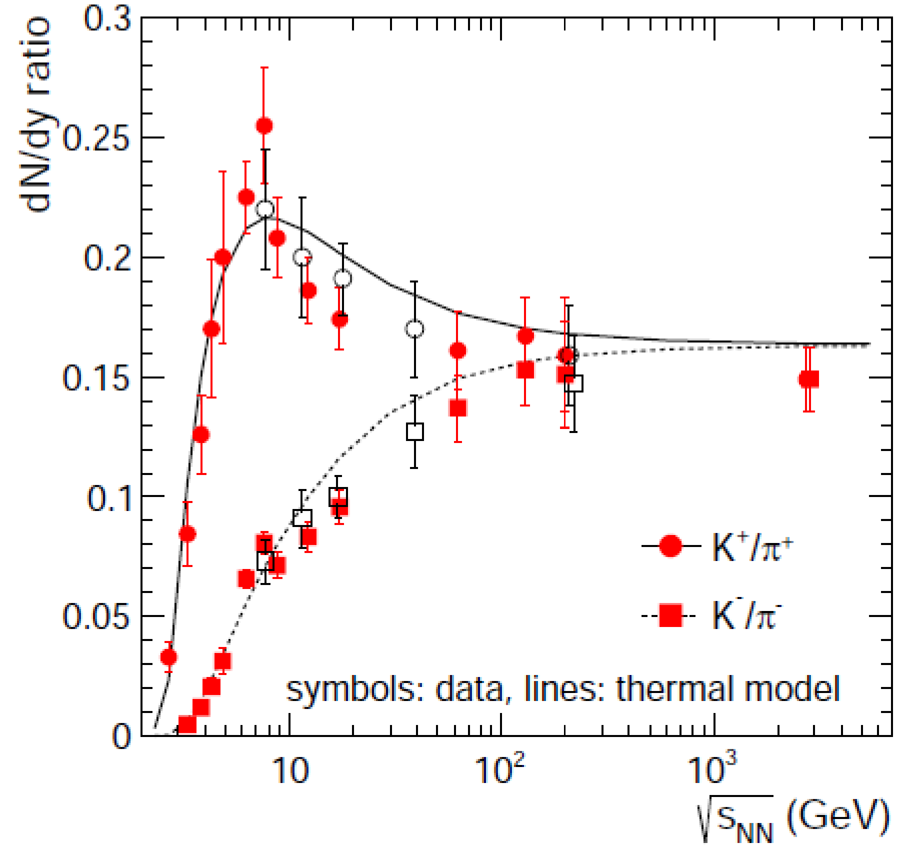
for LHC predictions we picked T = 164 MeV



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

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





Important note: corrections for weak decays

All ALICE data do not contain hadrons from weak decays of hyperons and strange mesons – correction done in hardware via ITS inner tracker

The RHIC data contain varying degrees of such weak decay hadrons. This was on average corrected for in previous analyses.

In light of high precision LHC data the corrections done at RHIC need to be revisited.

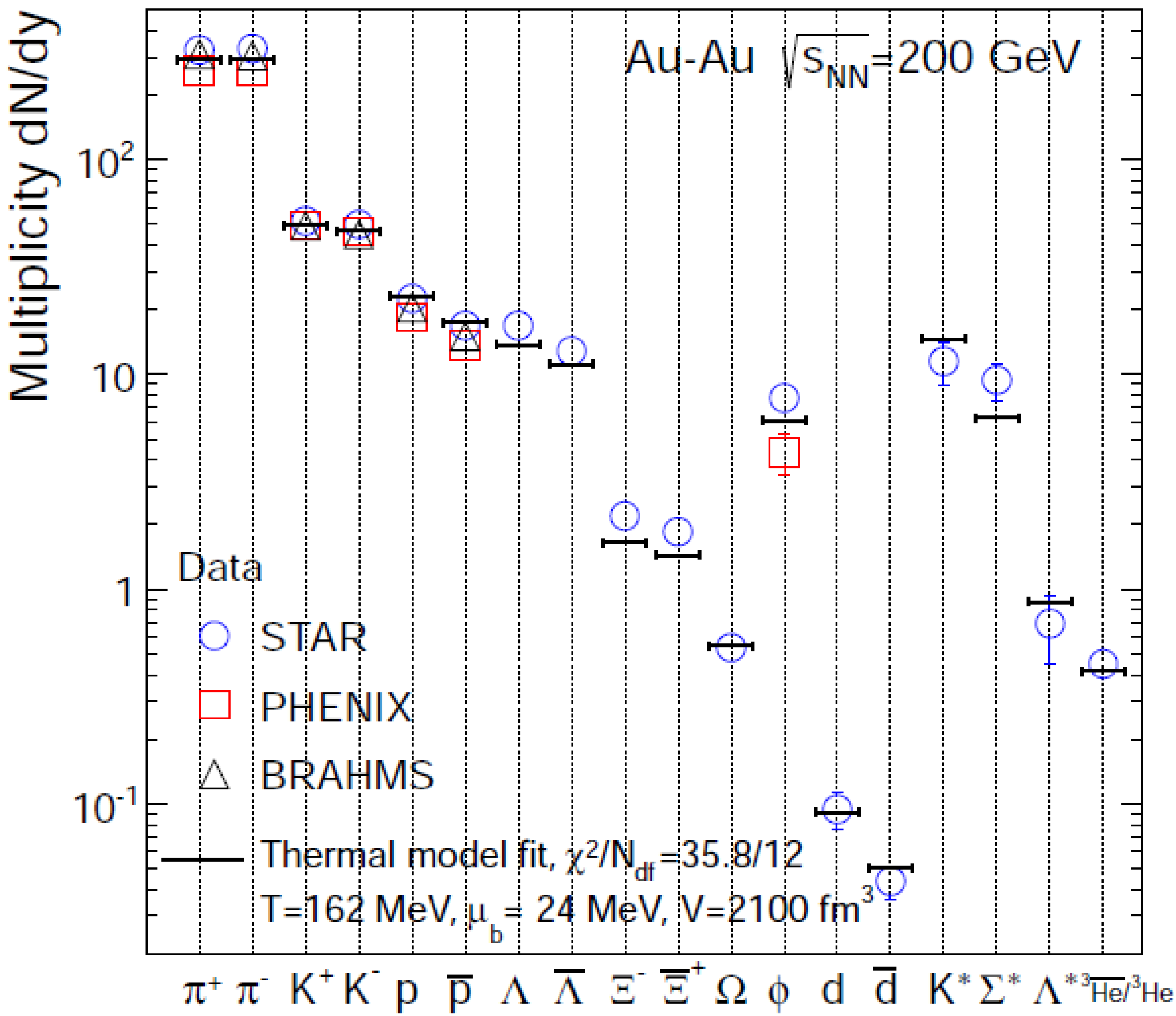
Re-evaluation of fits at RHIC energies – special emphasis on corrections for weak decays

Note: corrections for protons and pions from weak decays of hyperons depend in detail on experimental conditions

RHIC hadron data all measured without application of Si vertex detectors

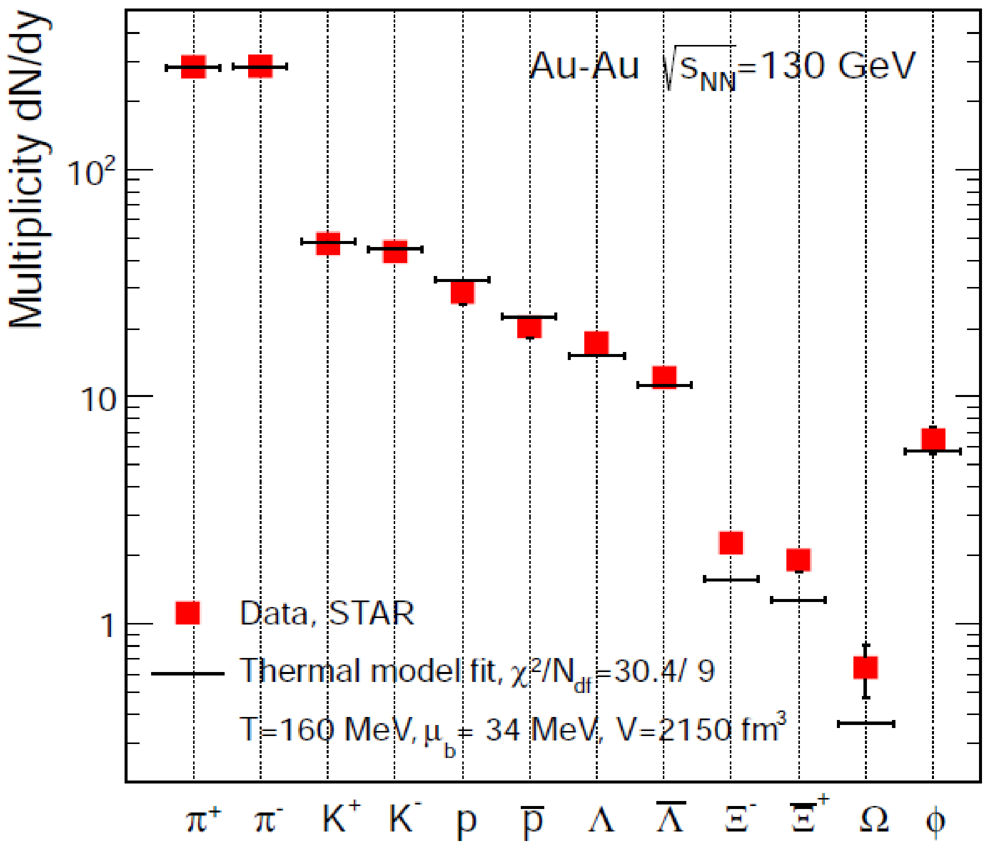
In the following, corrections were applied as specified by the different RHIC experiments

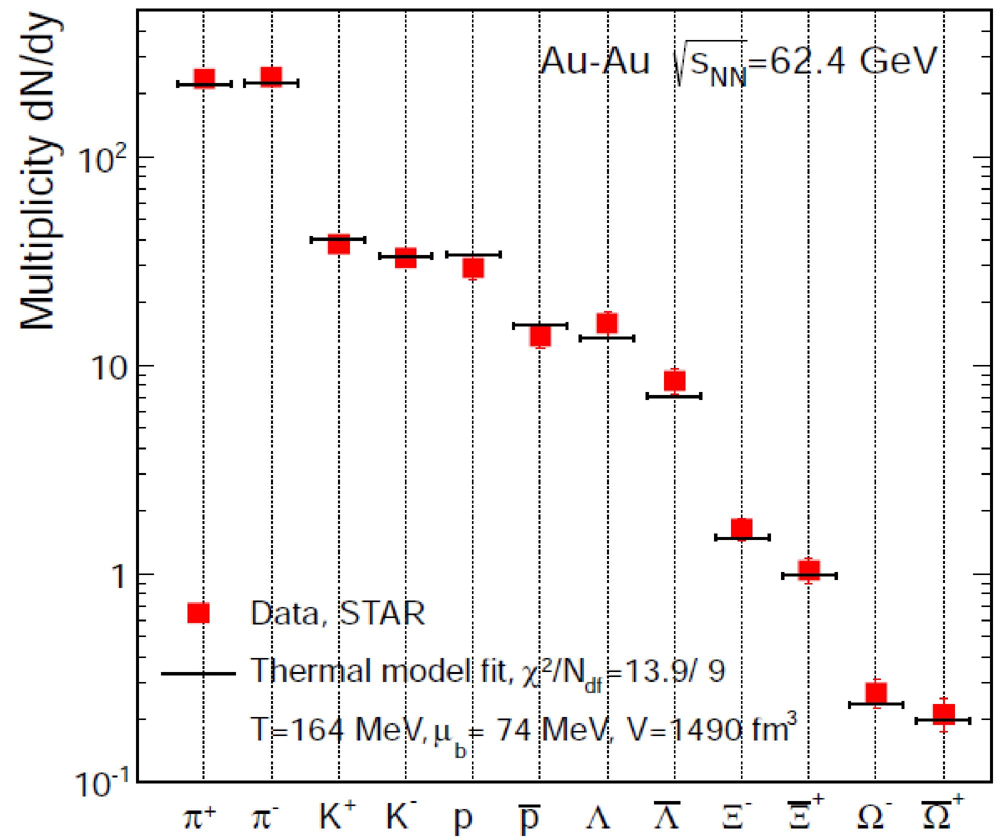
Au+Au central at 200 GeV, all experiments combined



T = 162 MeV

RHIC lower energies, STAR data alone



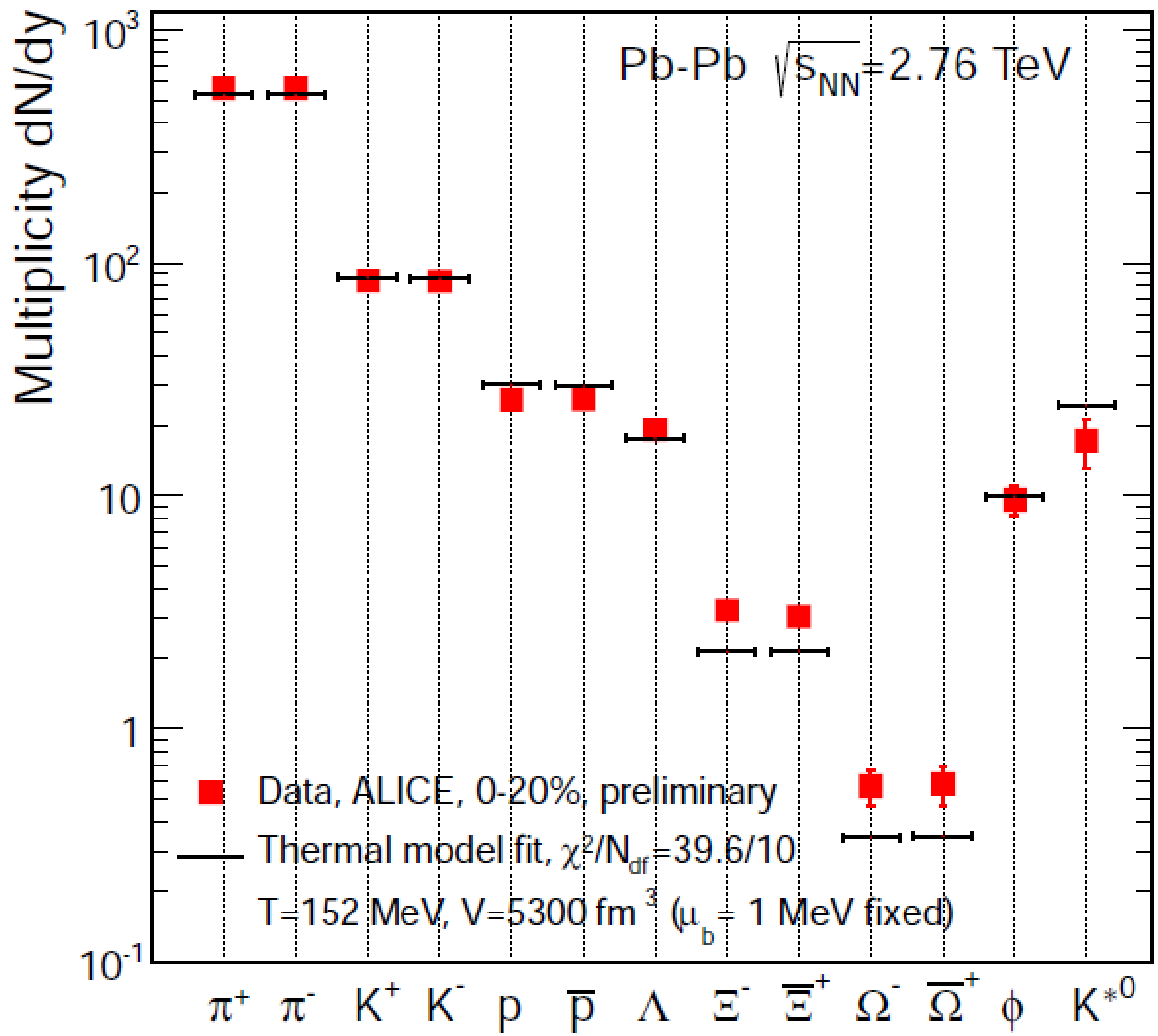


reasonable fits, T = 160 – 164 MeV

now new ALICE data at LHC energy
arXiv:1208.1974 [hep-ex]

rather poor fit,
low T = 152 MeV,
all hyperons
underestimated

is there no equilibrium
near T_c?



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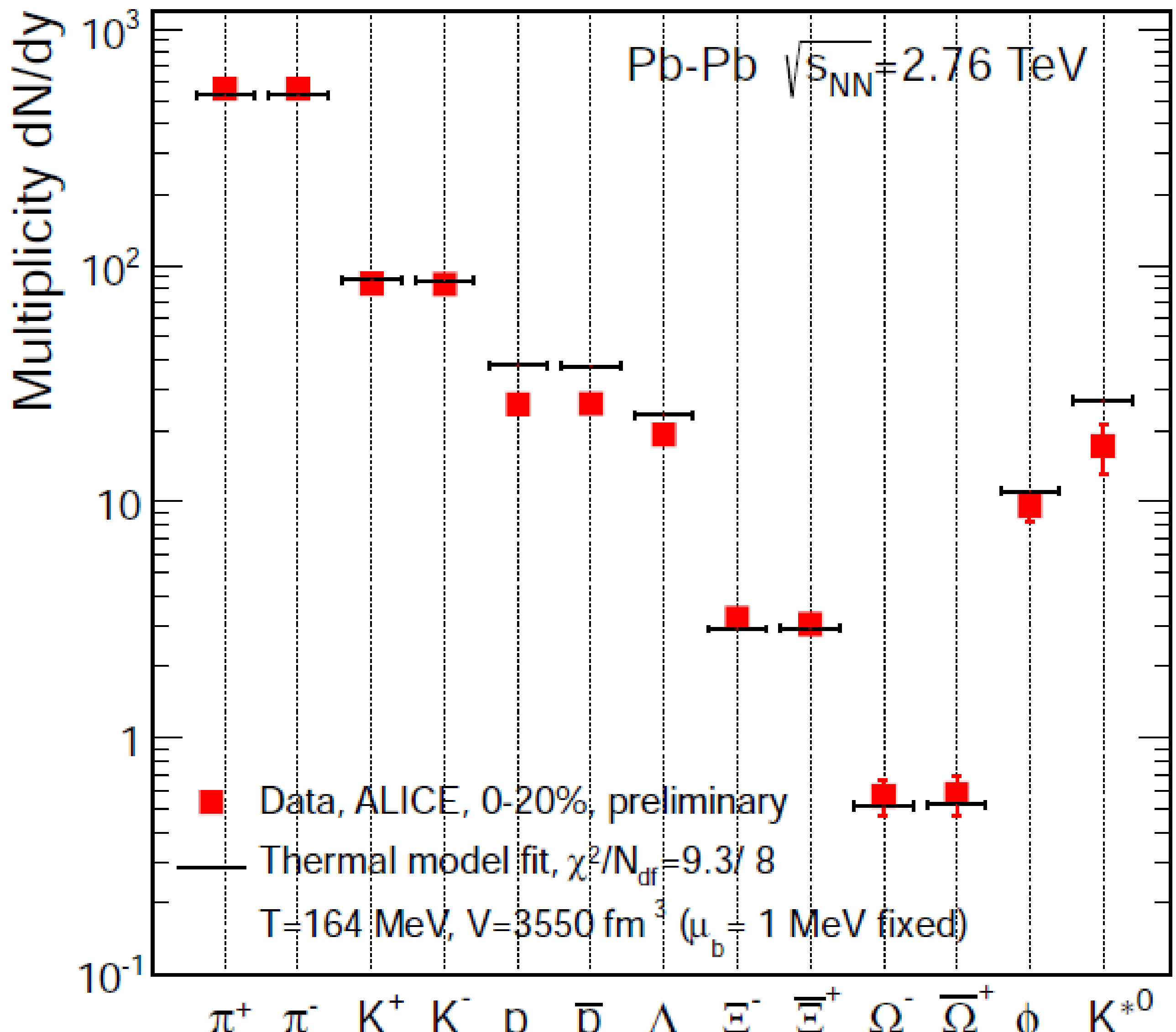
fitting the data without protons and antiprotons

good fit, T = 164 MeV

is there a proton anomaly?



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could it be weak decays from charm?

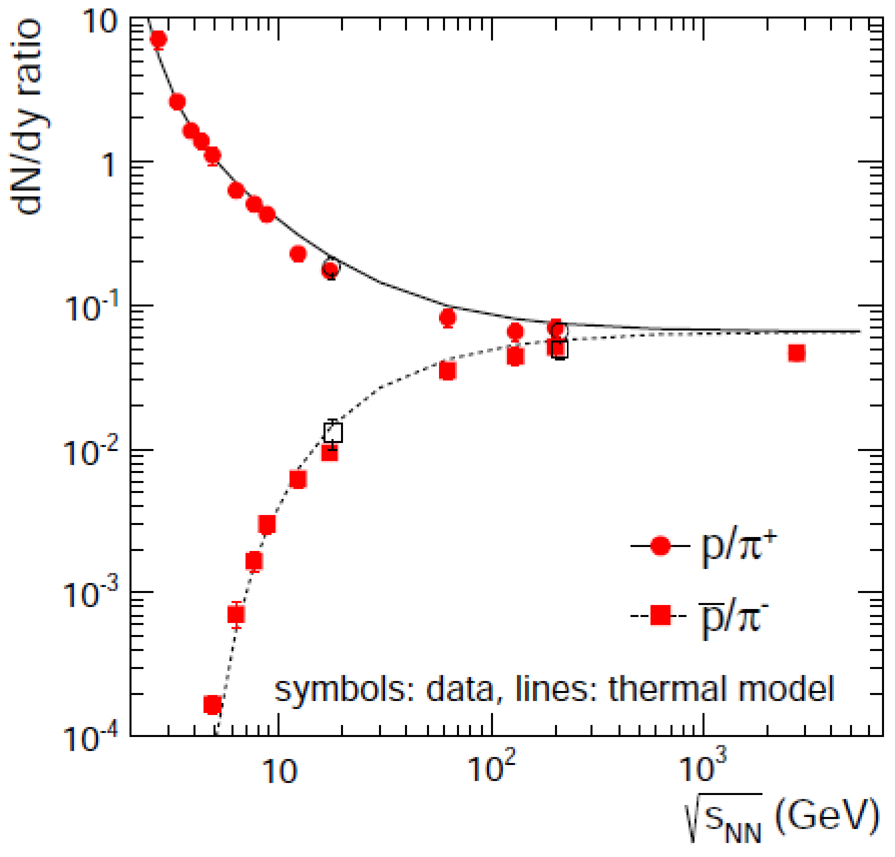
weak decays from charmed hadrons are included in the ALICE data sample

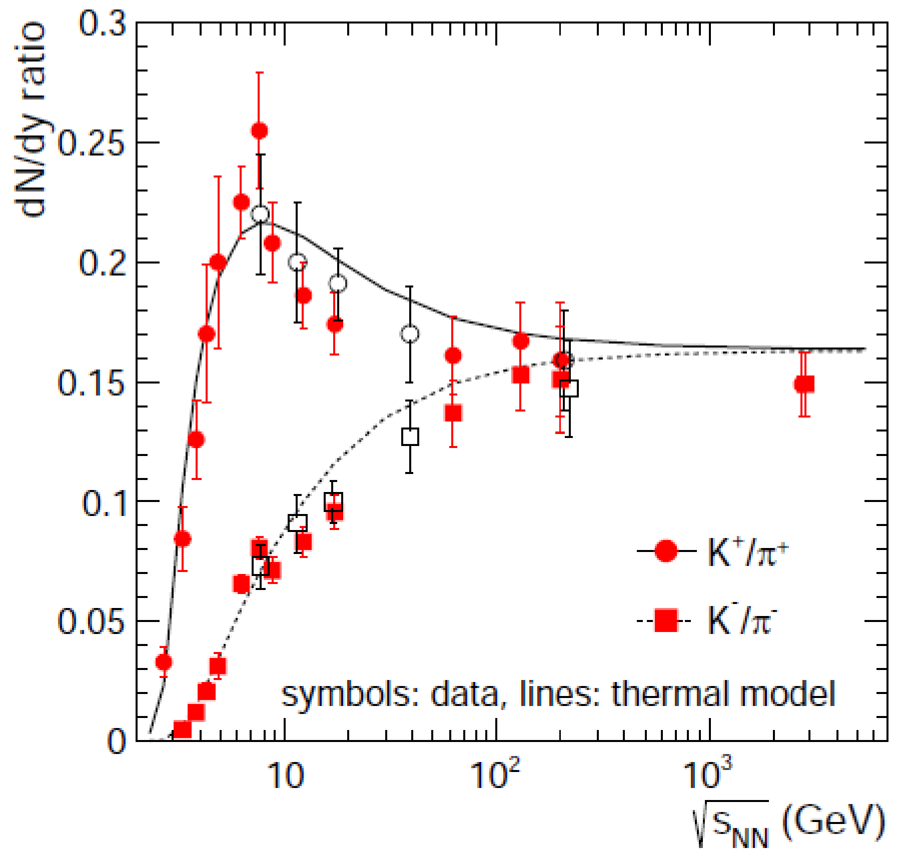
at LHC energy, cross sections for charm hadrons is increased by more than an order of magnitude compared to RHC

first results including charm and beauty hadrons indicate changes of less than 3%, mostly for kaons

not likely an explanation

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





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Summary, light flavors (i)

- with more precision data, differences to thermal model 'predictions begin to appear, especially for protons and hyperons. Note that data precision at LHC is about 6% including systematic and statistical errors.

- at RHIC energies, differences of data for different experiments are of the order of the observed deviations, fits including weak decay corrections yield T close to 160 MeV and good chi2

- all thermal model fits at RHIC energies closely follow the systematics established previously

- fits to ALICE data are poor and yield anomalously low T (152 MeV)

- fits to ALICE data excluding protons are excellent and yield T $\approx$164 MeV

Summary, light flavors (ii)

- one scenario: flavor chemistry of QGP matter at LHC is established close to T_c as at RHIC but protons and anti-protons are anomalous

- maybe result of annihilation in hadronic phase close to T_c

- modelling annihilation in hadronic phase needs detailed balance (Rapp and Shuryak, Phys.Rev.Lett. 86 (2001) 2980-2983)

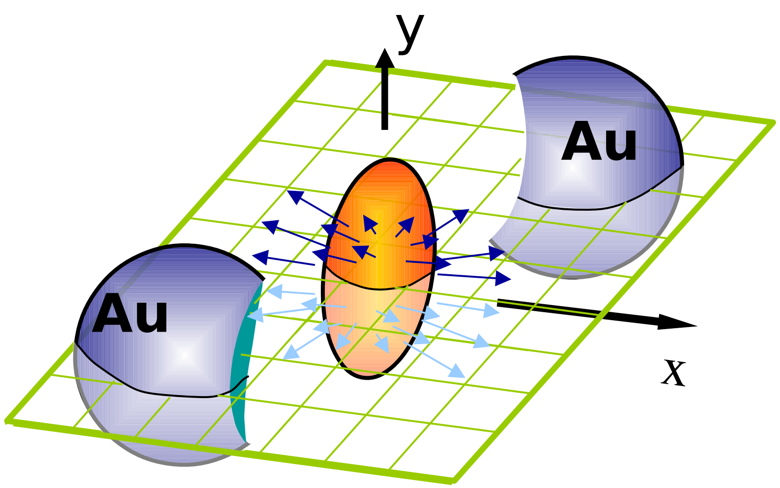
- what is the role of the 'quasi-mixed phase' and the asymmetry between protons and hyperons?

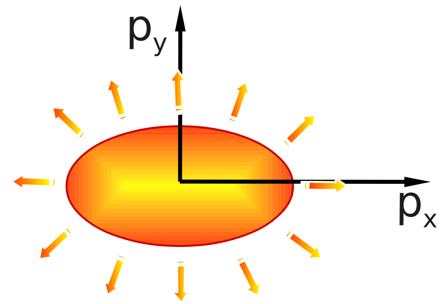
- what is the role of the 2x longer QGP lifetime at LHC energy compared to that at RHIC?

- simultaneous description of protons and all hyperons is required to settle the issue - **a challenge to theory**

hydrodynamic expansion of fireball

Lesson from RHIC: fireball expands collectively like an ideal fluid

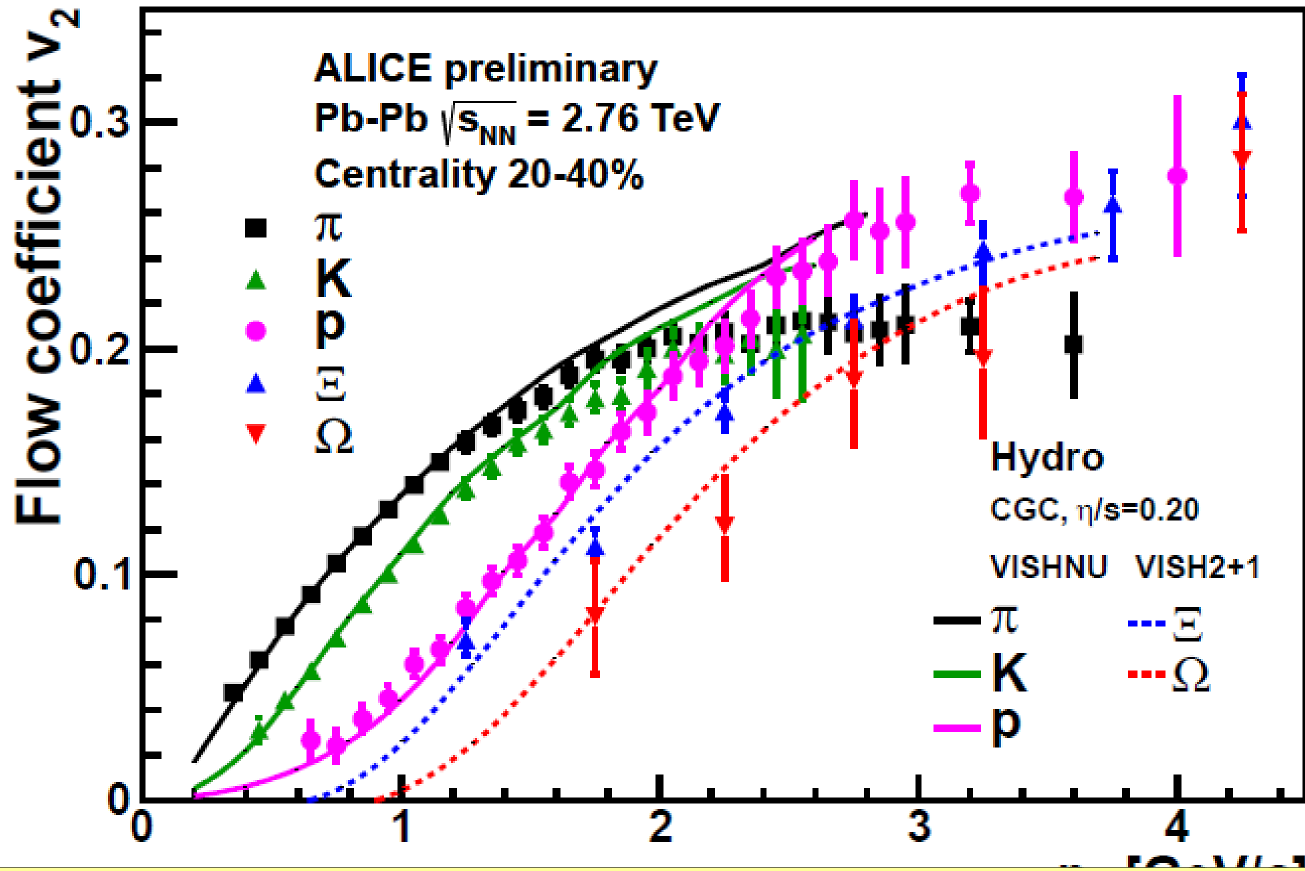




$$dN/d\phi = 1 + 2\,V_2 \cos 2\,(\phi - \psi) + \ldots$$

hydrodynamic flow characterized by azimuthal anisotropy coeffient v_2 + higher orders, sensitivity to eta/s

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



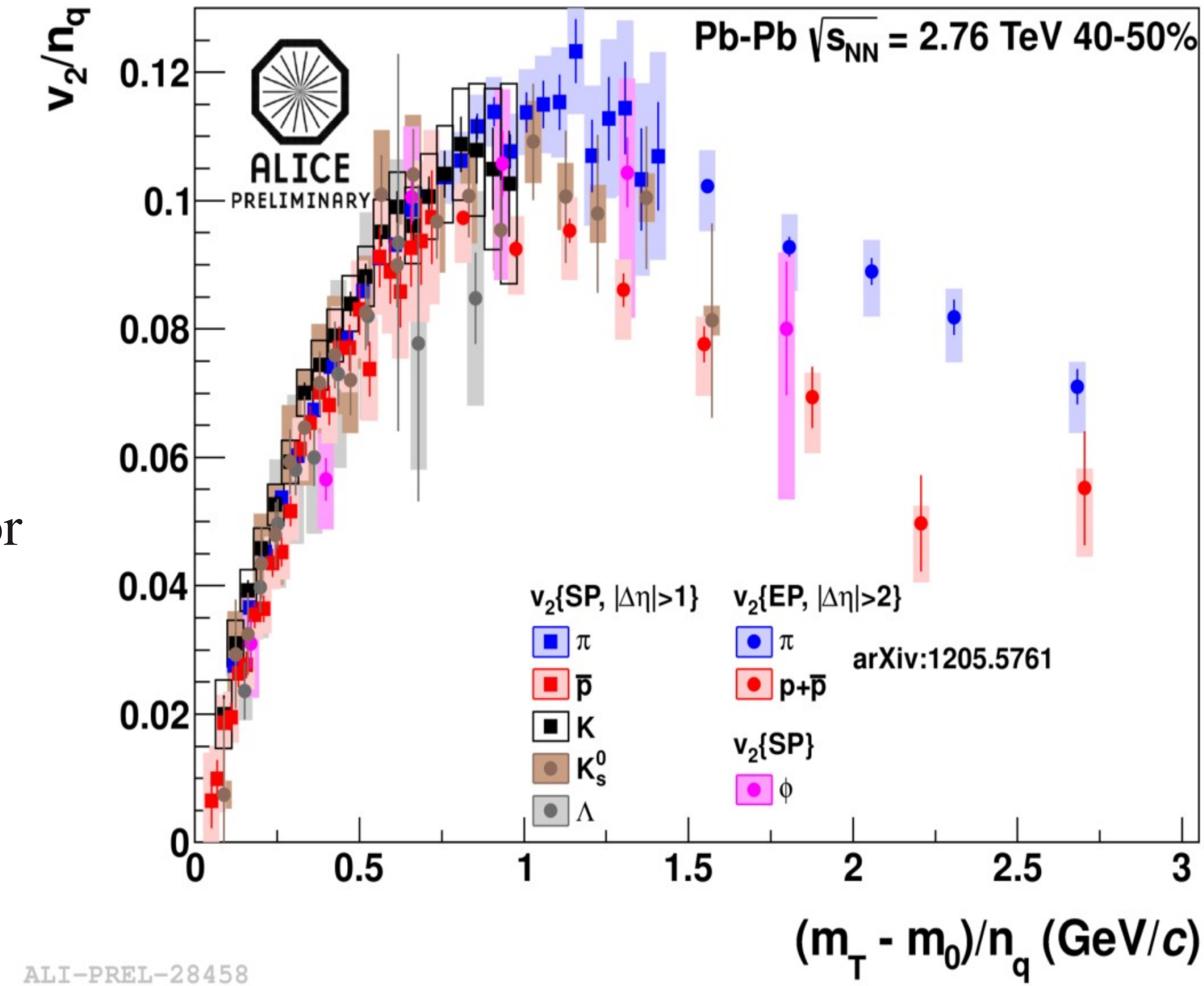
rapidly rising v_2 with p_t and mass ordering are typical features of hydrodyn. expansion

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

Is there valence quark scaling?

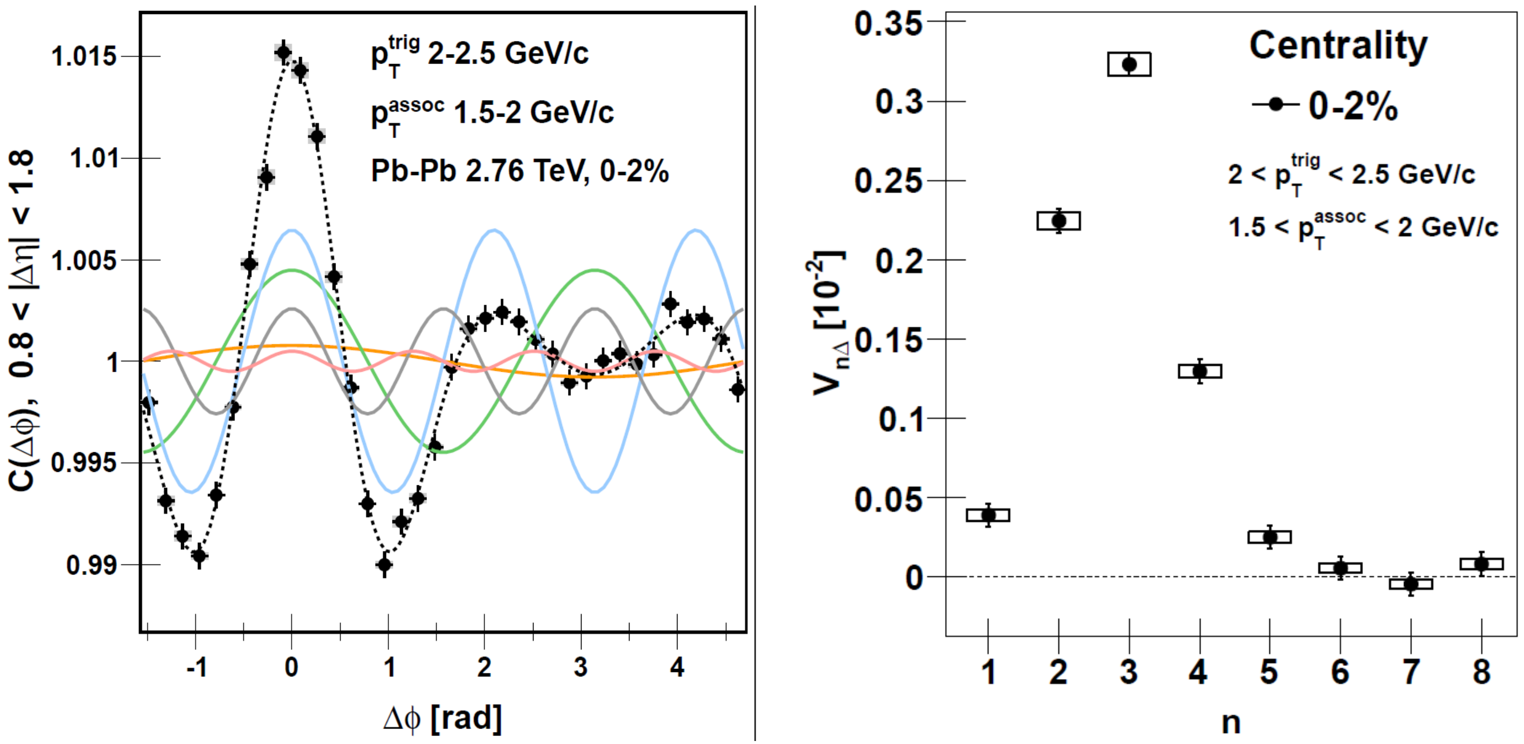
significant scaling violations at LHC energy

this is not a signal for partonic collectivity



The 2-particle correlation function – higher moments

ALICE, PRL 107 (2011) 032301



measurement of the first 8 harmonic coefficients

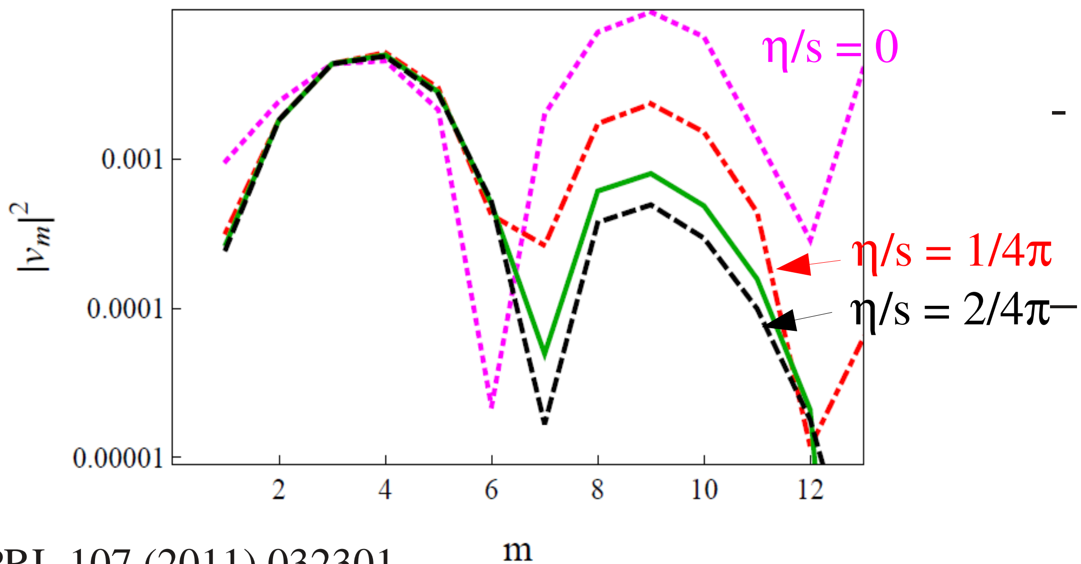
v_1-v_5 significantly larger than 0, maximum at v_3

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

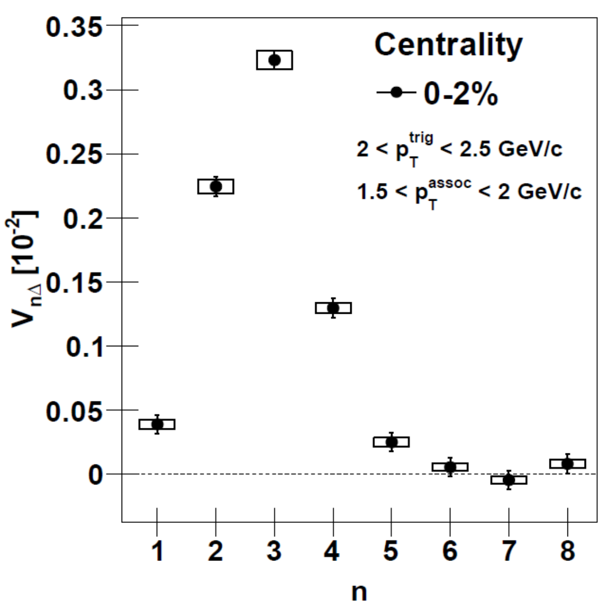
Propagation of sound in the quark-gluon plasma

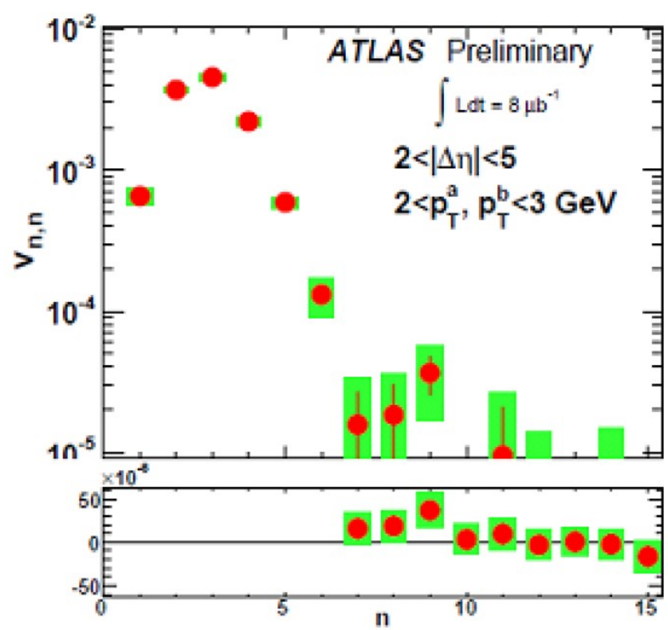
Staig & Shuryak arXiv:1109.6633



- 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

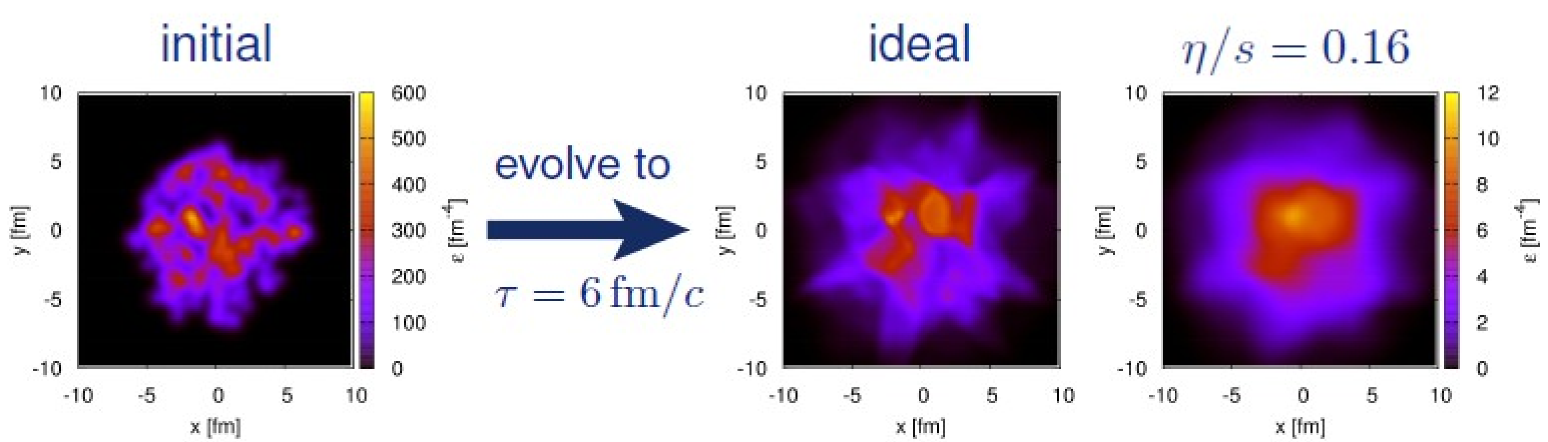
B. Schenke, QM2012

Given the initial energy density distribution we solve

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

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

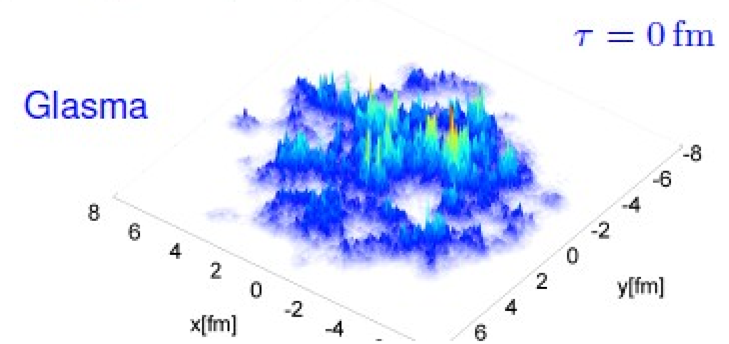
using only shear viscosity: $\pi^\mu_\mu = 0$

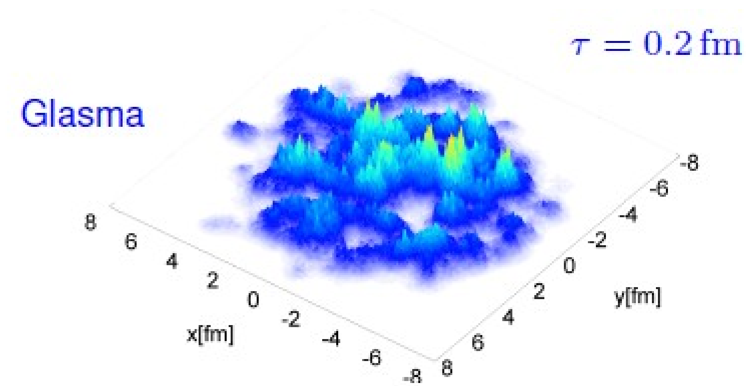


Note: alternate
means to
determine eta/s

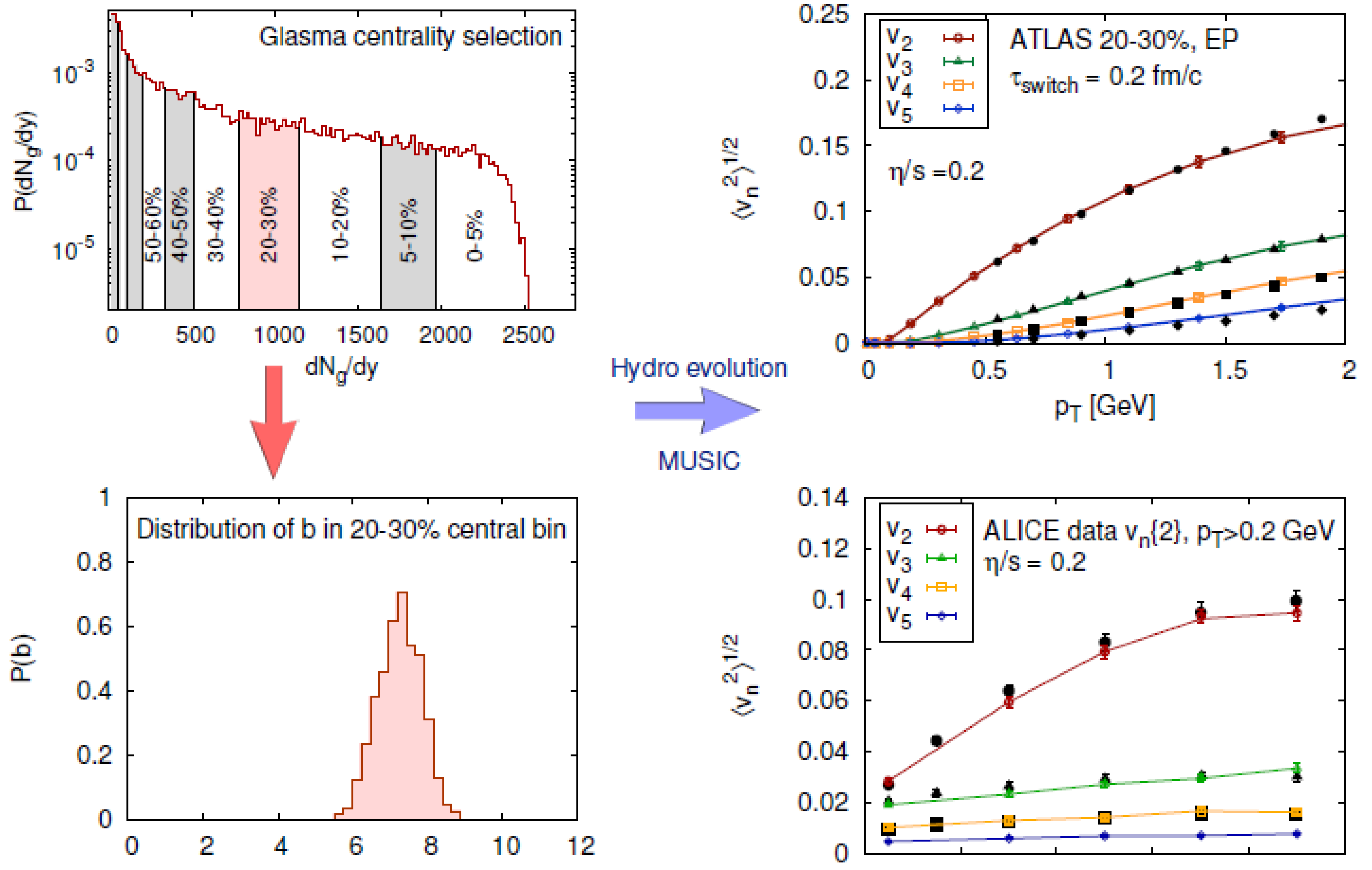
Energy density B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett. 108, 252301 (2012)

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 dscription of ATLAS and ALICE data

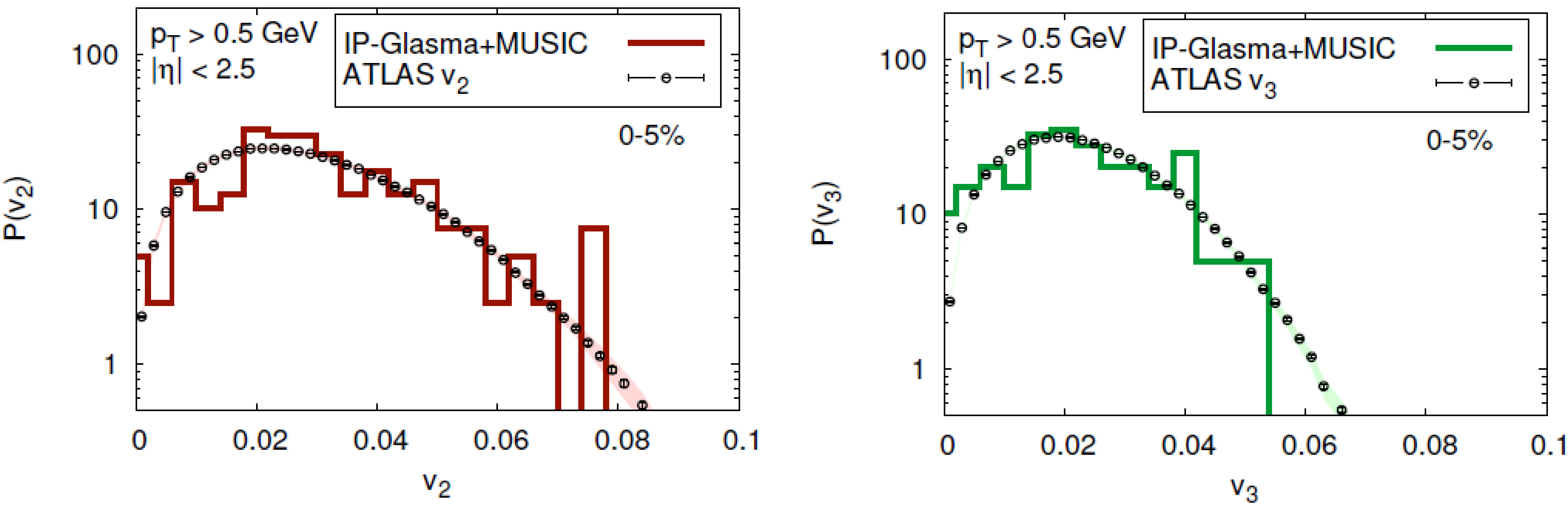


Experimental data:
ATLAS collaboration, Phys. Rev. C 86, 014907 (2012)
ALICE collaboration, Phys. Rev. Lett. 107, 032301 (2011)

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

Excellent description of event-by-event flow fluctuations

B. Schenke et al., QM2012



Determination of eta/s of fireball

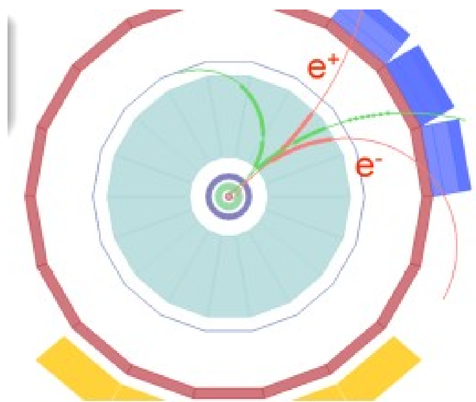
Model-independent determination of eta/s still outstanding

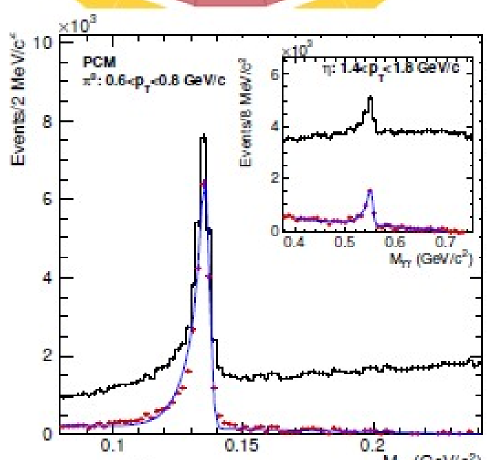
Current best limits: 0.07 < eta/s < 0.43

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

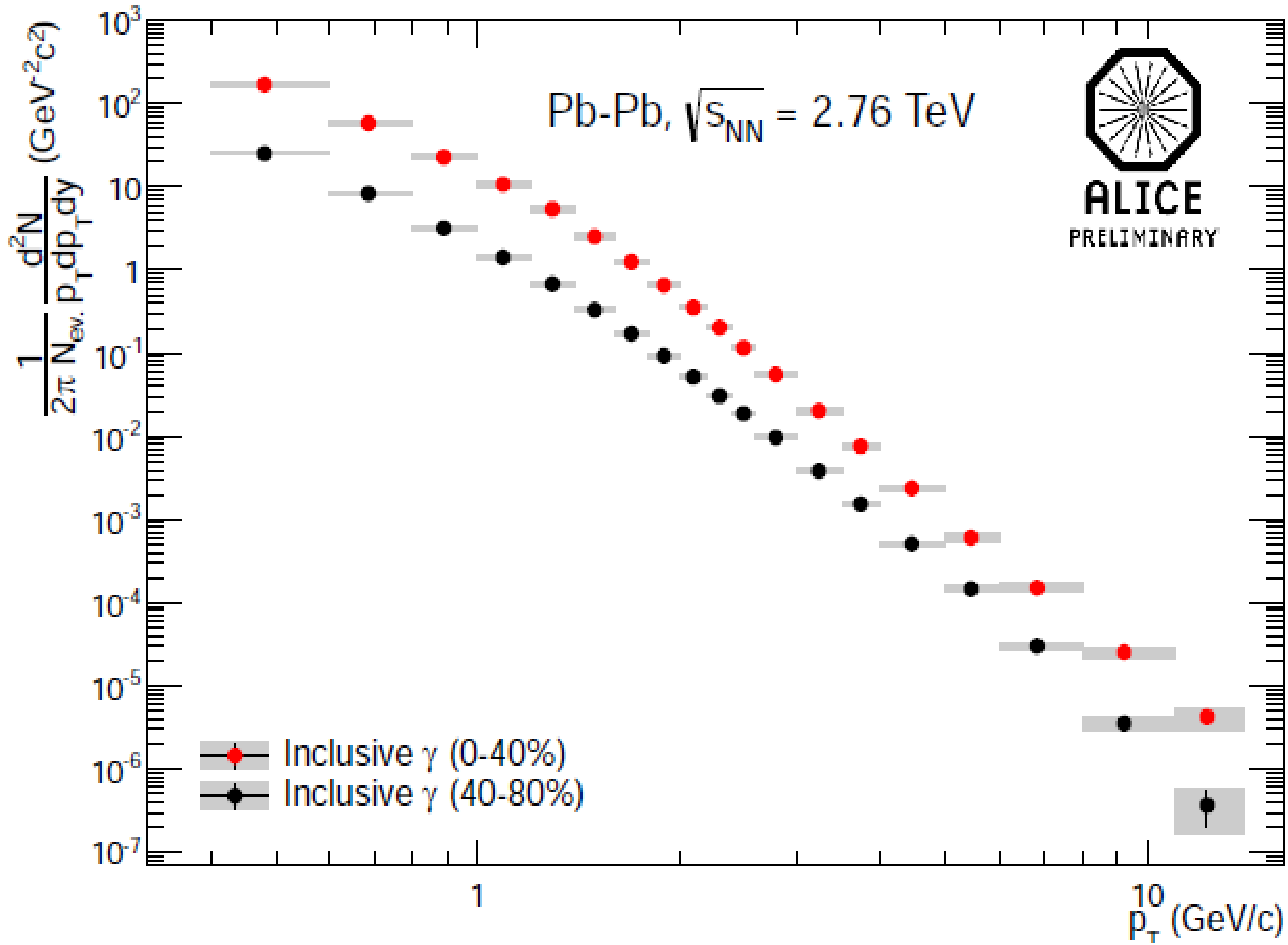
- Direct Photon Signal: $\gamma_{direct} = \gamma_{inc} - \gamma_{decay} = (1 - \frac{\gamma_{decay}}{\gamma_{inc}}) \cdot \gamma_{inc}$

- 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

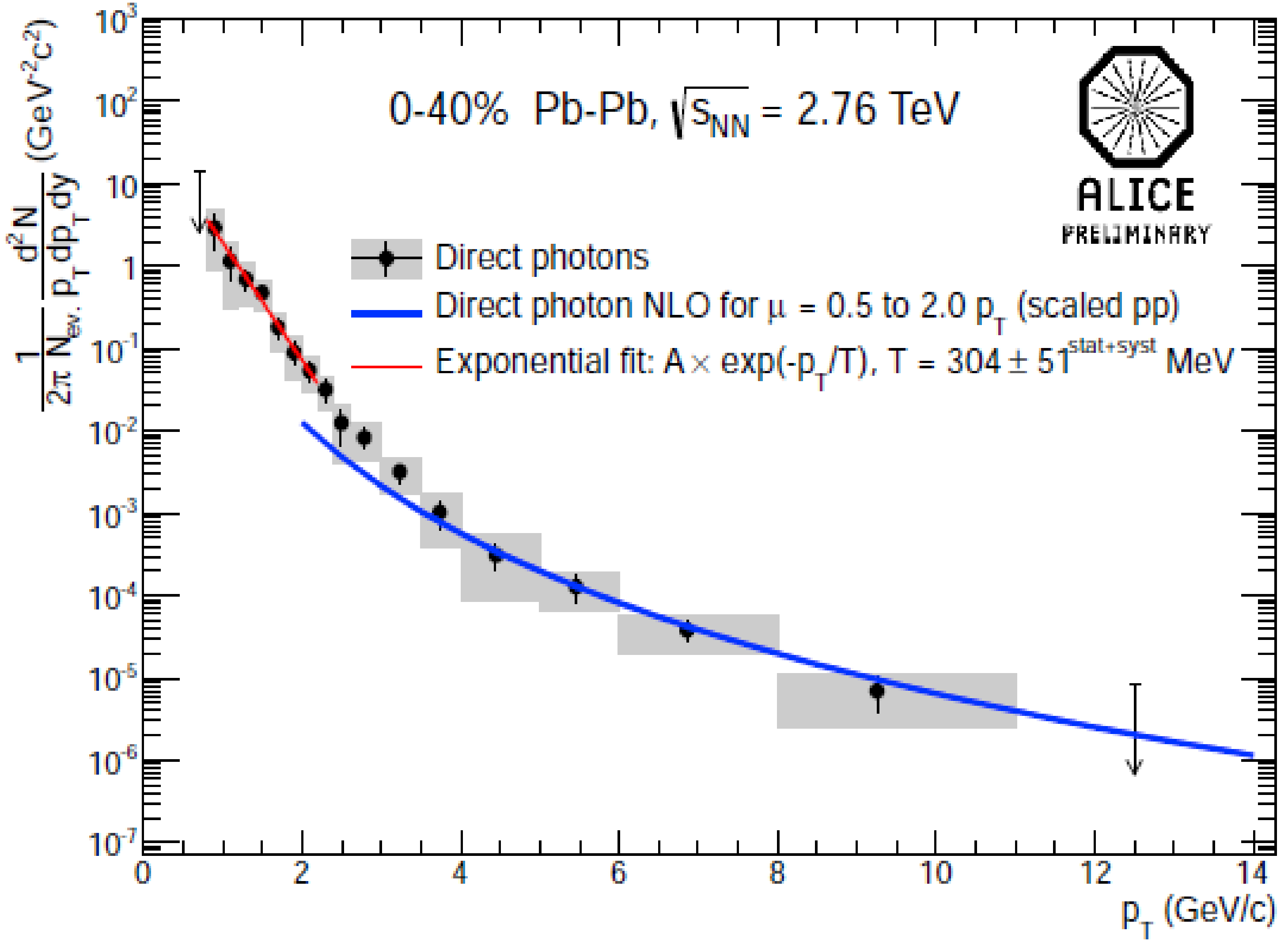
- Numerator: Inclusive γ spectrum per π^0
- Denominator: Sum of all decay photons per π^0
  Decay photons are obtained by a cocktail calculation

- 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

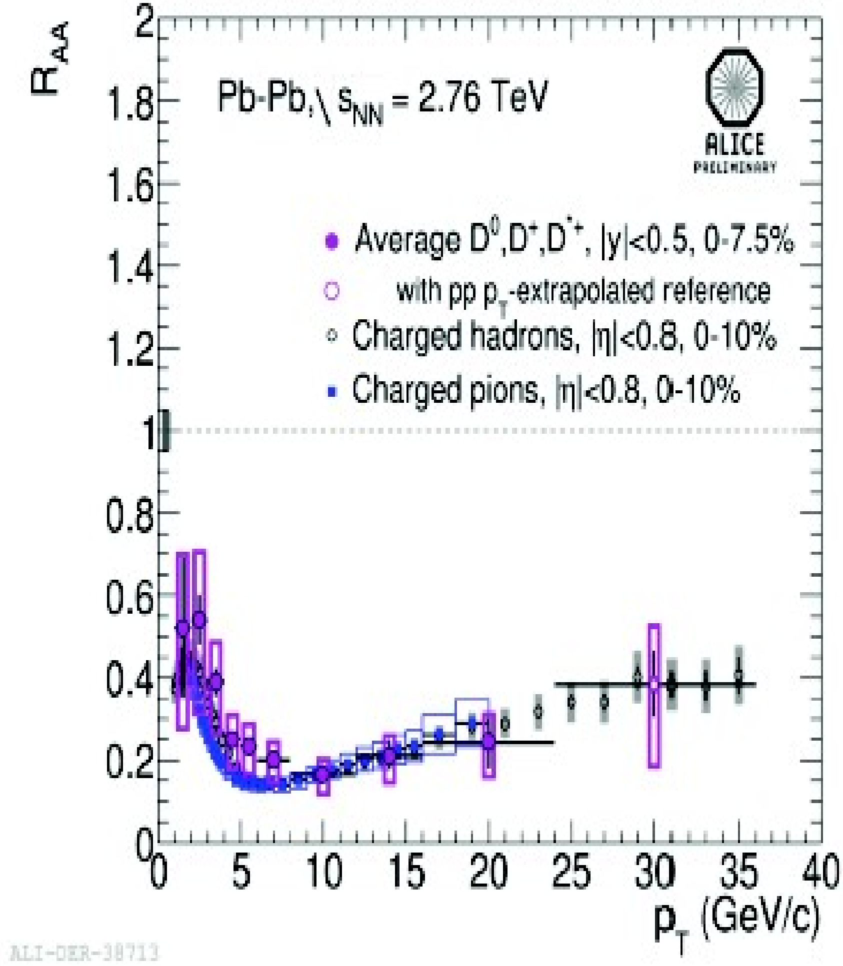


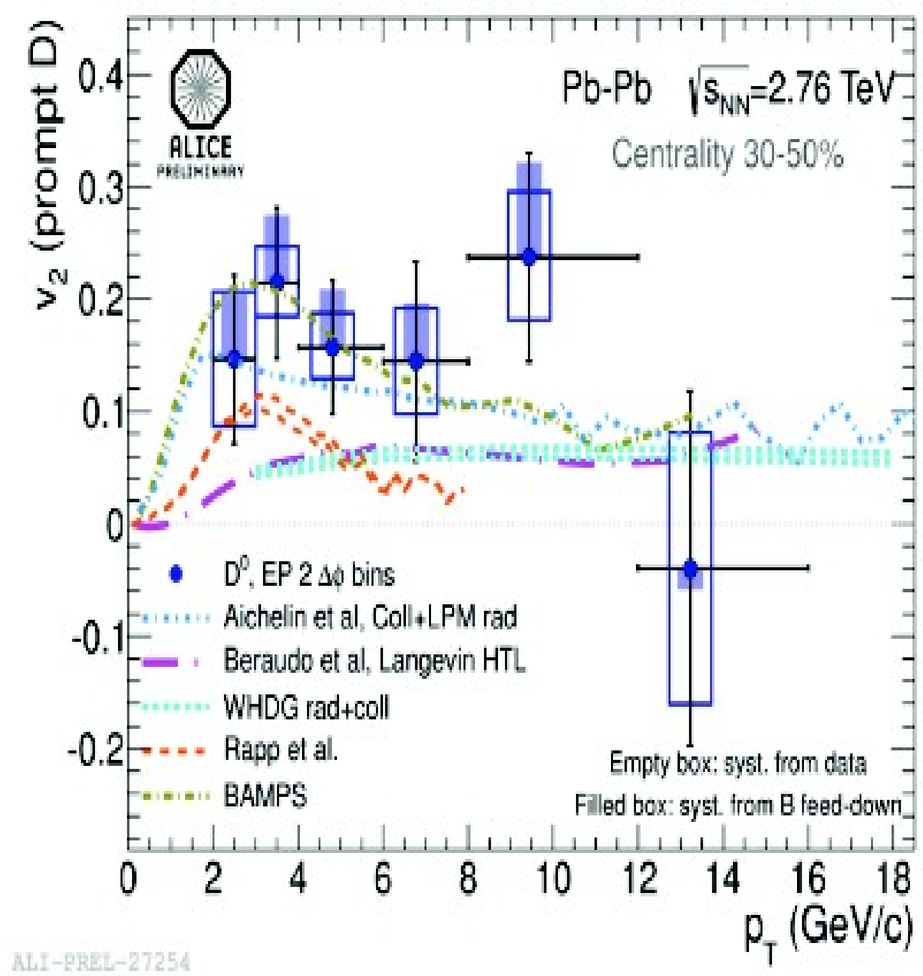
Final result



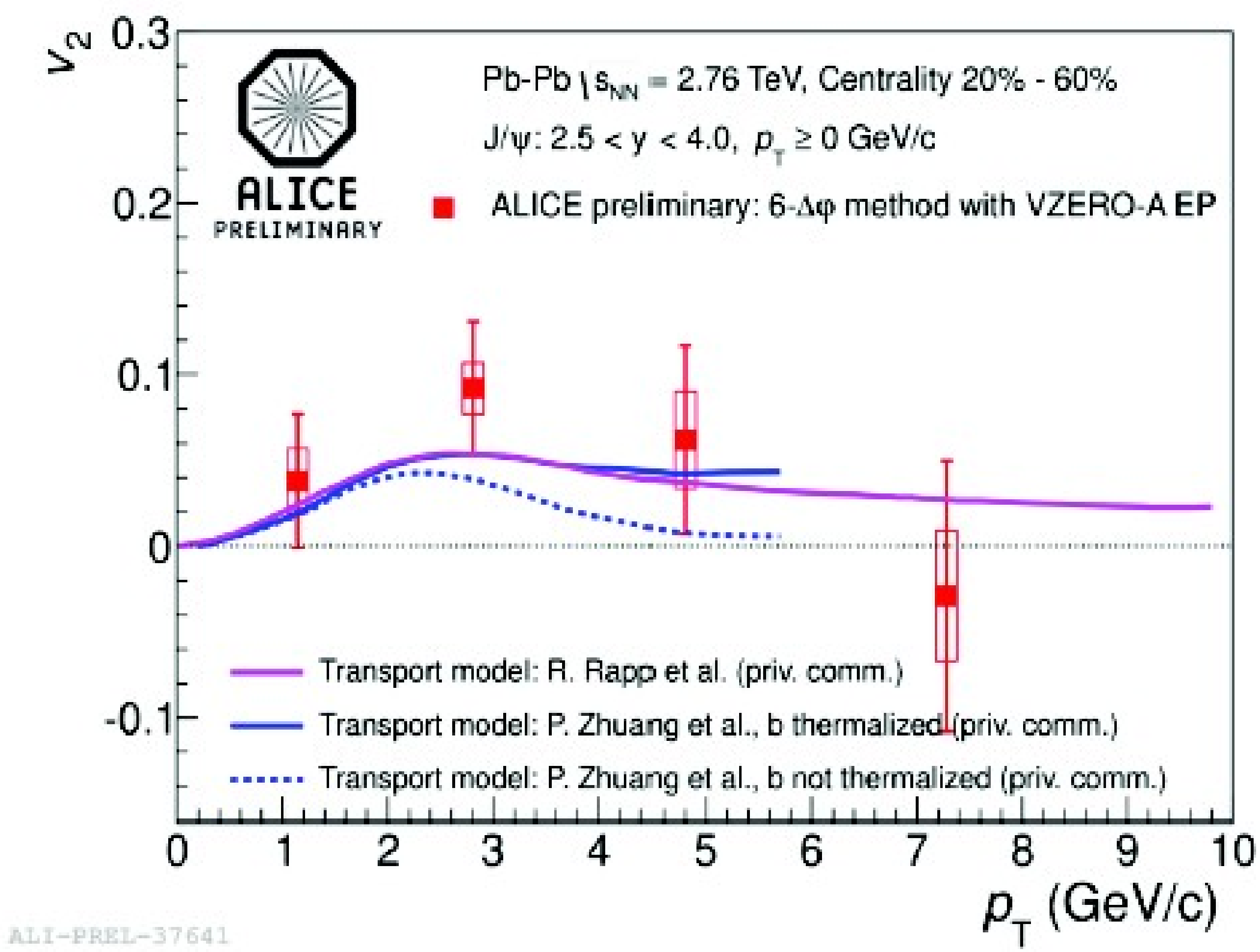
average T = 304 +/- 51 MeV highest ever measured temperature

Thermalization of heavy quarks

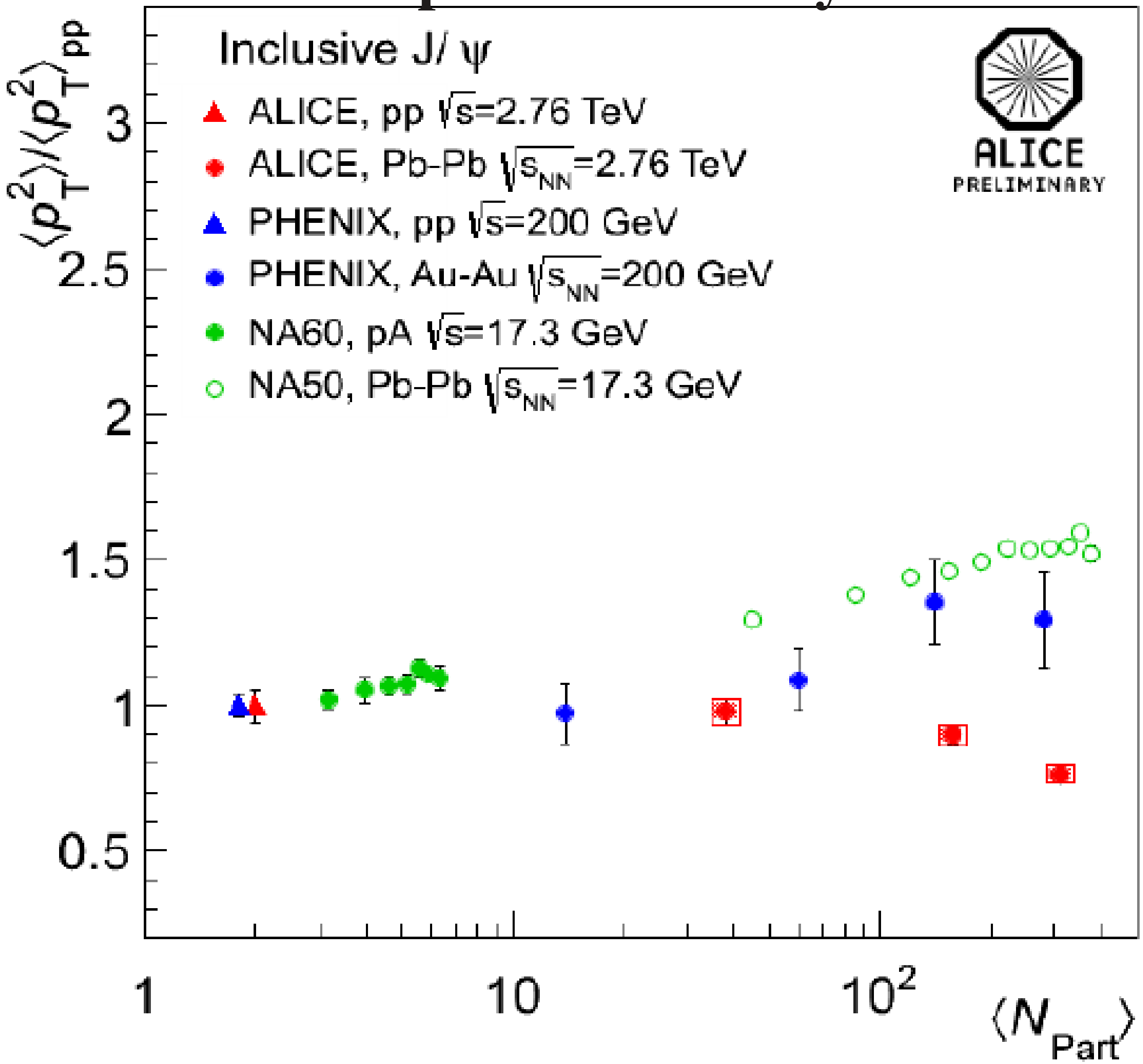




Thermalization of heavy quarks

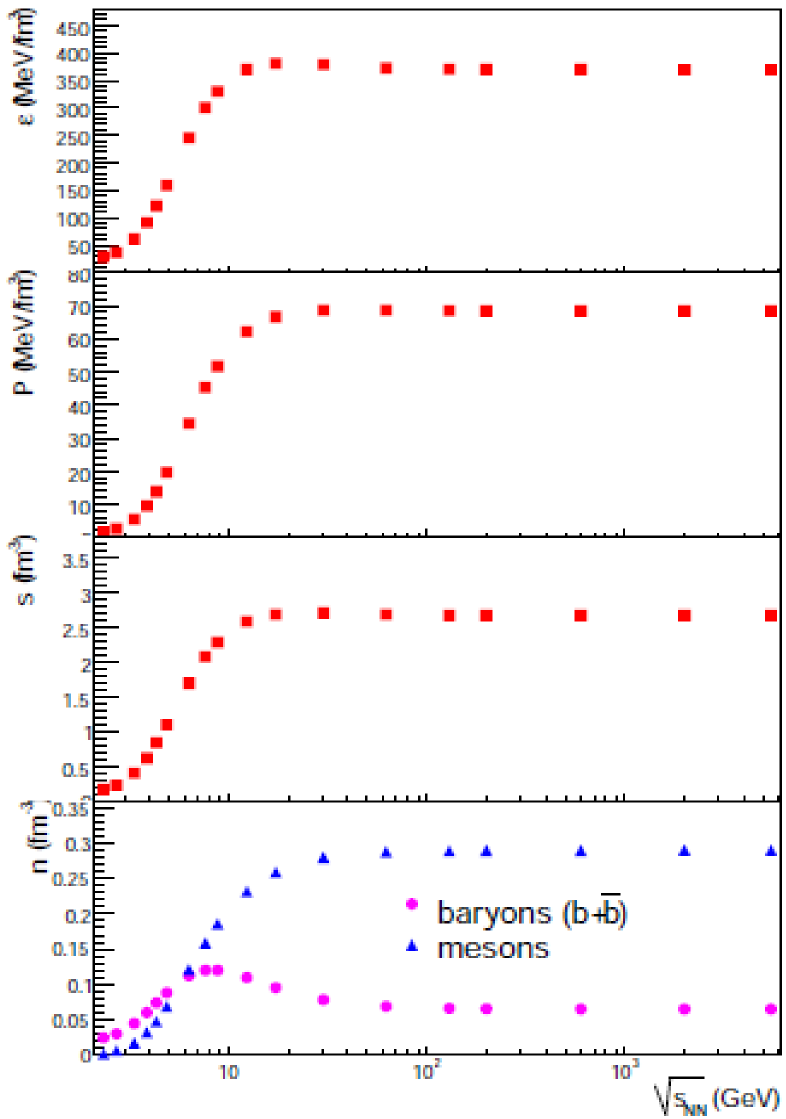


Evolution of J/psi transverse momentum spectra – evidence for thermalization and charm quark coalescence at the phase boundary

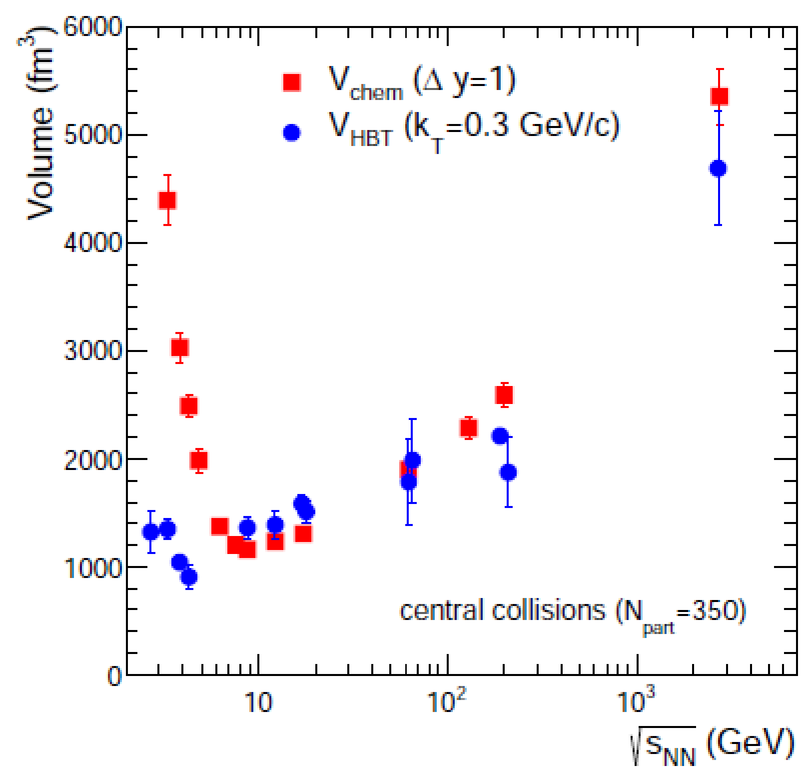


Summary of fireball parameters at LHC energy

Andronic, pbm, Stachel, Winn
arXiv:1201.0693



Fireball parameters at chemical freeze-out



Summary of fireball parameters at LHC energy

T_{gamma} = 305 MeV

T_{ini} > 400 MeV

T_{chem} = 160 MeV

V = 5200 fm^3

entropy = 12100 per unit rapidity

energy density = 315 MeV/fm^3

pressure = 59 MeV/fm^3

0.07 < eta/s < 0.43