Ultra-Relativistic Heavy-Ion Physics: A Brief Introduction

Arbeitstreffen Kernphysik, Schleching, 18 - 25 Feb, 2016

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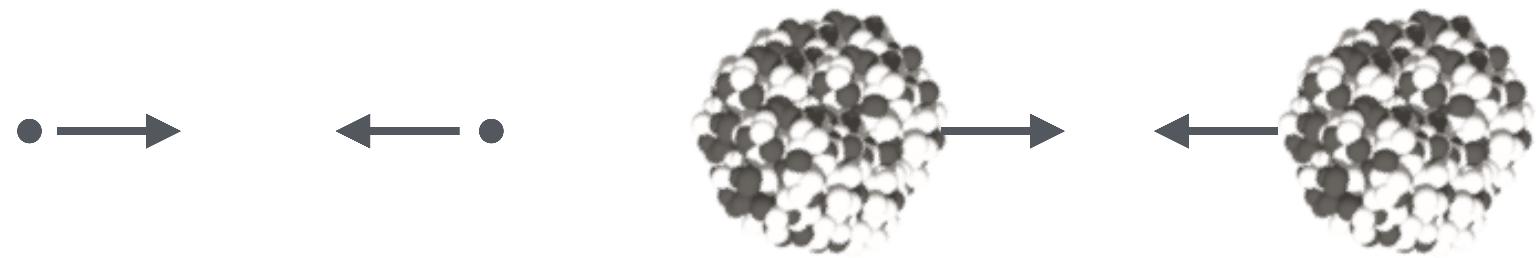
1. Introduction

pp and heavy-ion collisions at the same energy are rather different



A-A collisions:

- More stopping, larger mean transverse momentum
- Relative number of produced strange quarks larger
- Different shape of transverse momentum spectra; different particle distributions in ϕ and η
- Fewer pions at high p_T than expected
- Fewer J/ψ's than expected (depending on $\sqrt{s_{NN}}$)
- More low p_T photons and dileptons

We'll discuss these phenomena and their relation to the formation of quark-gluon plasma

Interestingly, some of these features have now also been observed in (high multiplicity) pp collisions — QGP in pp?

Outline

1. Introduction: Motivation and history
2. Thermodynamics of the QGP
3. Global properties of heavy-ion collisions
4. Strangeness and the statistical model
5. Space-time evolution of the QGP
6. Jet quenching
7. J/ψ and Quarkonia
8. Thermal photons and lepton pairs

lecture 1 (items 1–3)

lecture 2 (items 4–5)

lecture 3 (items 6–8)

Concepts, main experimental results, very little theory

http://www.physi.uni-heidelberg.de/~reygers/lectures/2016/Schleching/

Books

- Used for preparing these lectures
  - H. Satz: Extreme States of Matter in Strong Interaction Physics: An Introduction (2012)
  - S. Sarkar, H. Satz, B. Sinha: The physics of the quark gluon plasma (2010)
  - K. Yagi, T. Hatsuda, Y. Miake: Quark-Gluon Plasma: From Big Bang to Little Bang (2005)
  - C. Y. Wong: Introduction to High-Energy Heavy-Ion Collisions (1994)
- Other books
  - J. Rak, M. J. Tannenbaum: High-pT Physics in the Heavy Ion Era (2013)
  - W. Florkowski: Phenomenology of Ultra-Relativistic Heavy-Ion Collisions (2010)
  - R. Vogt, Ultrarelativistic Heavy-ion Collisions (2007)
  - L. P. Csernai: Introduction to Relativistic Heavy-Ion Collisions (1994) [free pdf]

[underlined words: clickable links]

Recent overview articles

- N. Armesto, E. Scomparin, Heavy-ion collisions at the Large Hadron Collider: a review of the results from Run 1, arXiv:1511.02151
- P. Braun-Munzinger, V. Koch, T. Schäfer, J. Stachel, Properties of hot and dense matter from relativistic heavy ion collisions, arXiv:1510.00442
- J. Rafelski, Melting Hadrons, Boiling Quarks, arXiv:1508.03260
- R. Averbeck, J. Harris, B. Schenke, Heavy-Ion Physics at the LHC, in: The Large Hadron Collider - Harvest of Run 1, 2015
- A. Andronic, An overview of the experimental study of quark-gluon matter in high-energy nucleus-nucleus collisions, arXiv:1407.5003
- G. Roland, K. Safarik, P. Steinberg, Heavy-ion collisions at the LHC, Prog.Part.Nucl.Phys. 77 (2014) 70-127
- E. Shuryak, Heavy Ion Collisions: Achievements and Challenges, arXiv:1412.8393

Older overview articles

- J. Casalderrey-Solana, H. Liu, D. Mateos, K. Rajagopal, U. Wiedemann, A heavy ion phenomenology primer, first chapter of arXiv:1101.0618
- R. Stock (editor), Relativistic Heavy Ion Physics, Landolt-Börnstein, Vol. 23 (2010)
- B. Muller, J. Nagle, Results from the Relativistic Heavy Ion Collider, nucl-th/0602029
- M. Gyulassy, L. McLerran, New forms of QCD matter discovered at RHIC, nucl-th/0405013
- U. Heinz, Concepts of Heavy-Ion Physics, hep-ph/0407360

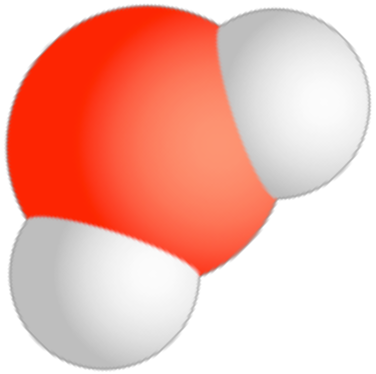
Lectures

- K. Reygers, J. Stachel: Quark-Gluon Plasma Physics (2015)
- P. Braun-Munzinger, A. Andronic, T. Galatyuk,
  Introduction to Relativistic Heavy Ion Collisions (2012)
- C. Loizides, CERN summer student lectures, 2015 (1, 2, 3,)
- J.-F. Grosse-Oetringhaus,
  CERN-Fermilab Hadron Collider Physics Summer School, 2015 (1, 2, 3)
- QM 2015 student lectures
- QM 2014 student lectures

These slides:
http://www.physi.uni-heidelberg.de/~reygers/lectures/2016/Schleching/

Ultra-relativistic heavy-ion physics: Study of emergent phenomena in QCD

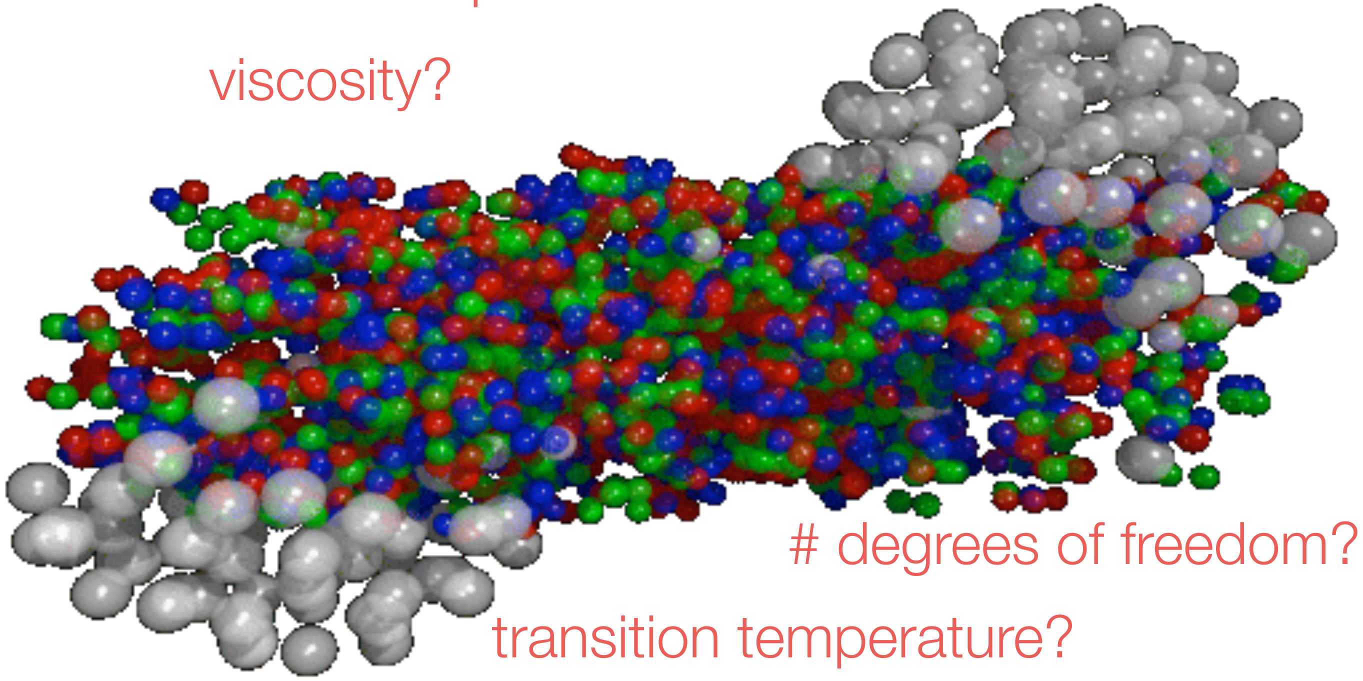
- Theme:
  Properties of matter from known particle properties and interactions
  - Complexity from fundamental laws
  - Example:
    Properties of water and its phases (ice, water, steam) from the known properties of a water molecule



source: de.wikipedia.org

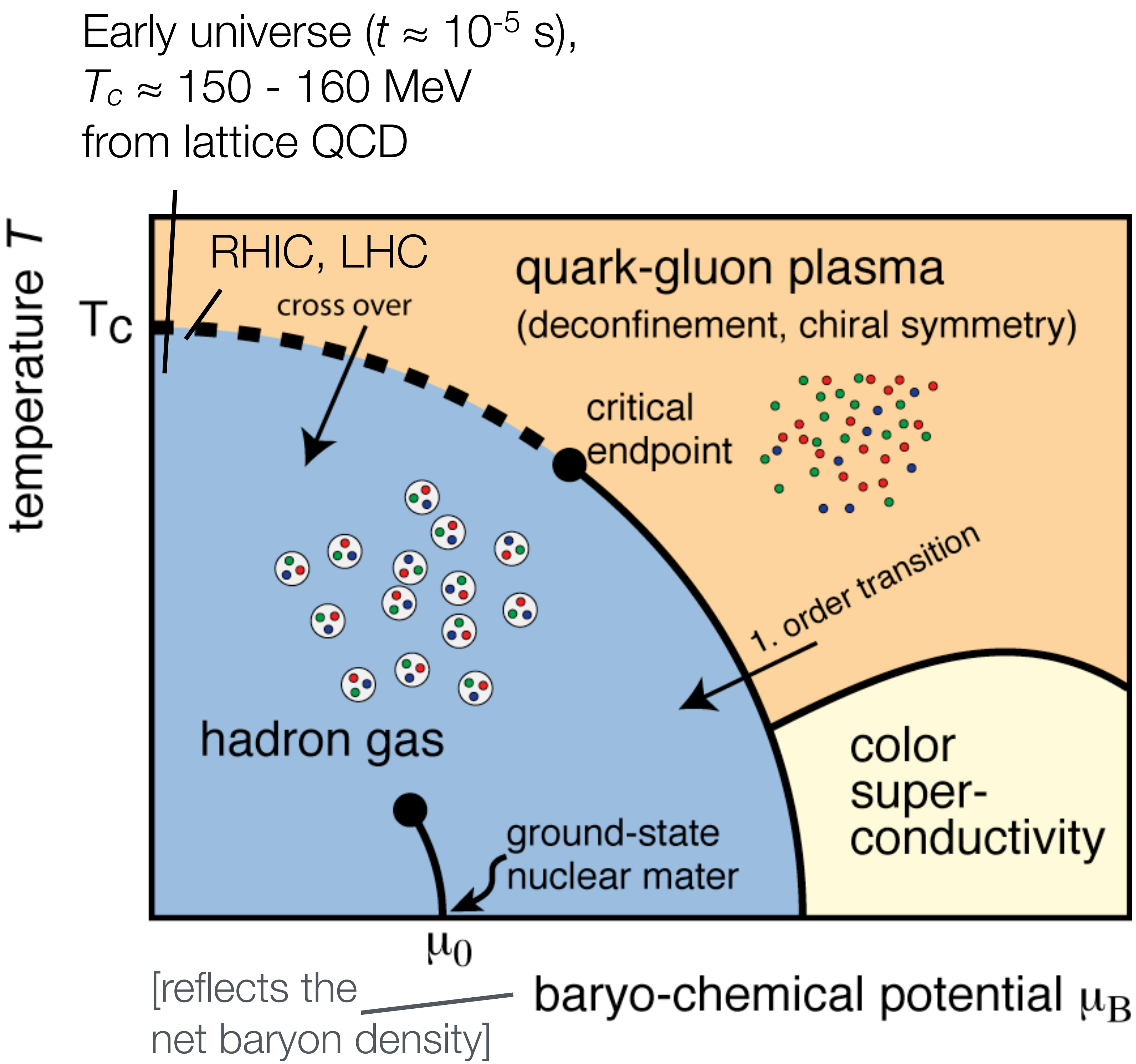
- Ultra-relativistic heavy-ion physics: Study of condensed-matter aspects of QCD at high temperature
  - Complementary to the successful reductionism in particle physics

„More is different“
Philip W. Anderson, Science, 177, 1972, S. 393



source: urqmd.org

QCD in the high temperature & high density sector



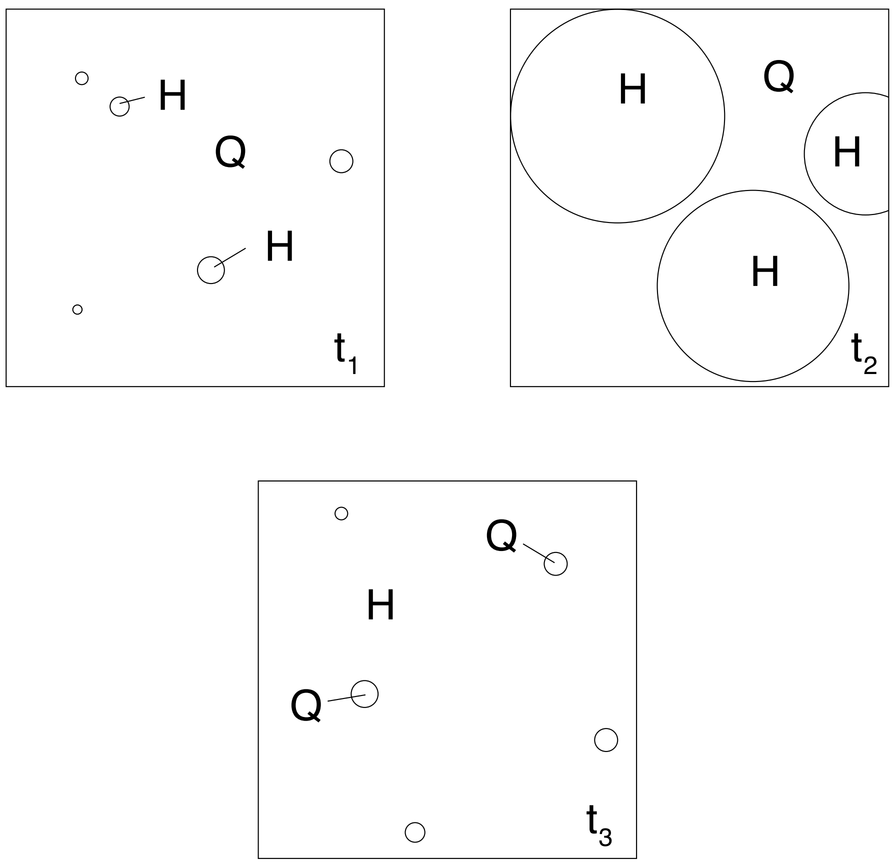
- Weakly coupled sector of QCD well tested (e.g. with jets)
- Heavy-ion physics: Strong coupling at high temperature
- Prediction from first QCD principles (lattice QCD): transition to QGP
  - $T_c \approx$ 150 - 160 MeV
  - $\varepsilon_c \approx$ 0.2 - 0.5 GeV/fm^3
- Deconfinement transition coincides with chiral symmetry restoration

Heavy-ion physics = Experimental QCD thermodynamics

The Cosmological QCD transition a few μs after the Big Bang

D. Boyanovsky, H. J. de Vega, D. J. Schwarz
arXiv:hep-ph/0602002

Sketch of a 1st order phase transition (bubble nucleation):



1. First hadronic bubbles nucleate in supercooled QGP
2. Hadronic bubbles grow, released latent heat quenches formation of new bubbles
3. Shrinking QGP drops separated by a typical distance

- A first order phase transition might have observable consequences
- Conceivable effects
  - Formation of quark nuggets / strangelets
    - Could contribute to dark matter today
  - Cold dark matter clumps
    - Modified yield of light nuclei in Big Bang nucleosynthesis
  - Damping of gravitational waves?
- Still true for sharp cross-over?
- Relating heavy-ion physics to observable properties of the cosmological QCD transition currently seems very difficult

Limits of the hadron gas

Dokl. Akad. Nauk SSSR 78, 889 (1951)

- Pomeranchuk considered the conceptual limit of the ideal pion gas
- He argued that a pion gas makes sense as long as there is some minimum volume available per pion:

$$n_c = \frac{1}{V_0} = \frac{3}{4\pi r_0^3} \qquad r_0 \simeq 1/m_\pi \approx 1.4\,\mathrm{fm}$$

- Partition function for an ideal gas of identical, point-like pions

$$\ln Z_0(T,V) = \frac{V}{(2\pi)^3}\int d^3p \exp\left(-\sqrt{p^2+m^2}/T\right)$$

$$= \frac{VTm^2}{2\pi^2} K_2(m/T)$$

modified Bessel function of 2nd kind

- Pion density: $n(T) = \left(\frac{\partial \ln Z_0(T,V)}{\partial V}\right)_T = \frac{Tm^2}{2\pi^2}K_2(m/T)$
- Critical density: $n(T_c) = n_c \quad \rightarrow \quad T_c = 1.4 m_\pi \approx 190\,\mathrm{MeV}$

The Hagedorn limiting temperature (1)

- Observation ca. 1960:
  Number density of hadronic states ρ(*m*) seemed to grow without limit
- 1965: Hagedorn described this with his statistical bootstrap model
  - "fireballs consist of fireballs, which consist of fireballs, and so on …"
  - Suppl. Nuovo Cim. 3 (1965) 147
- Such self-similar models lead to an exponentially growing mass spectrum of hadronic states

$$\rho(m) = m^{-a} e^{bm}$$

  where 1/*b* = 0.15 - 0.20 GeV.

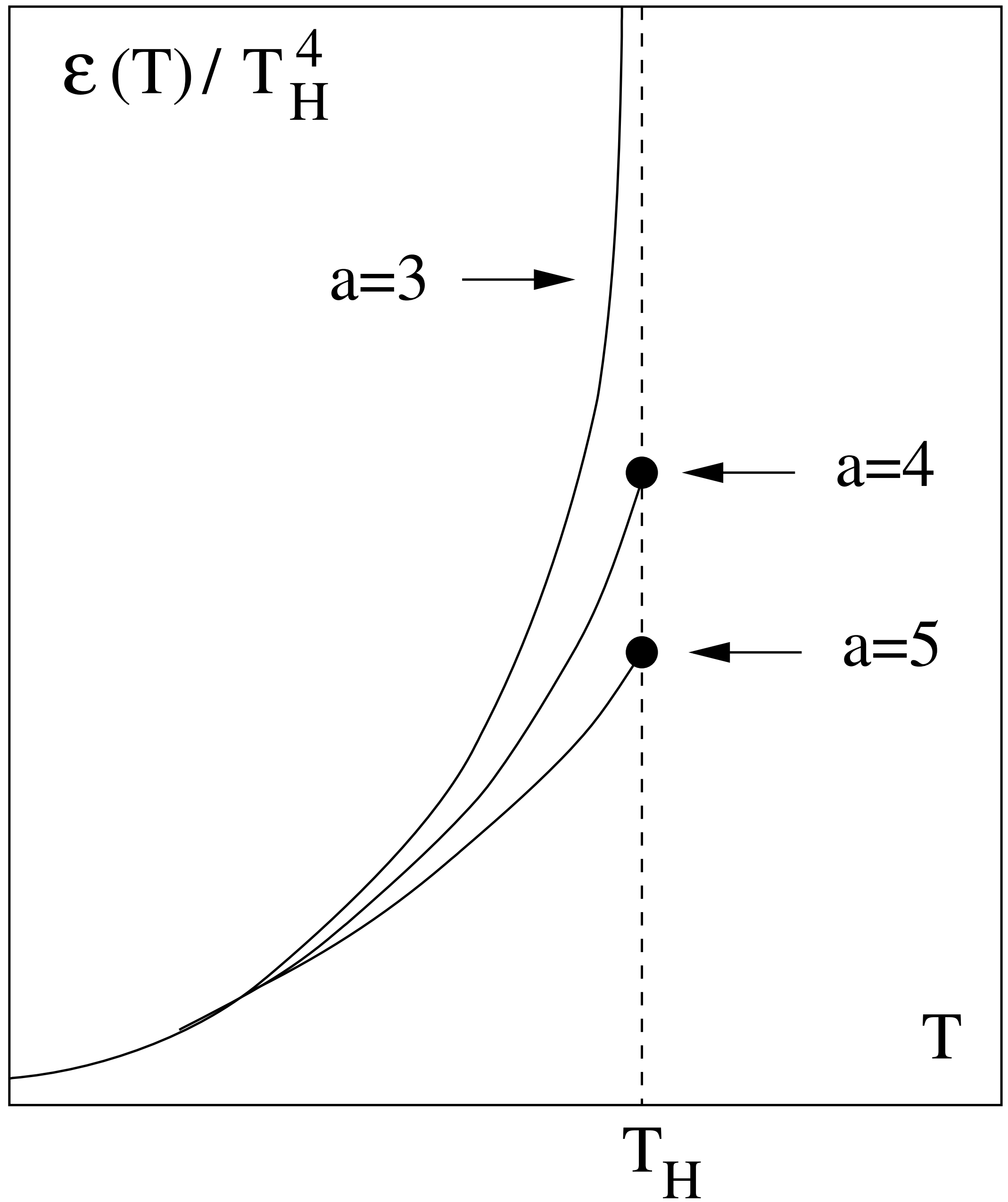
- Resulting energy density of the hadron resonance gas:

$$\varepsilon(m) \sim V T^{7/2} \int_{m_0}^{\infty} \mathrm{d}m \; m^{\frac{5}{2}-a} e^{m(b-\frac{1}{T})}$$

The Hagedorn limiting temperature (2)

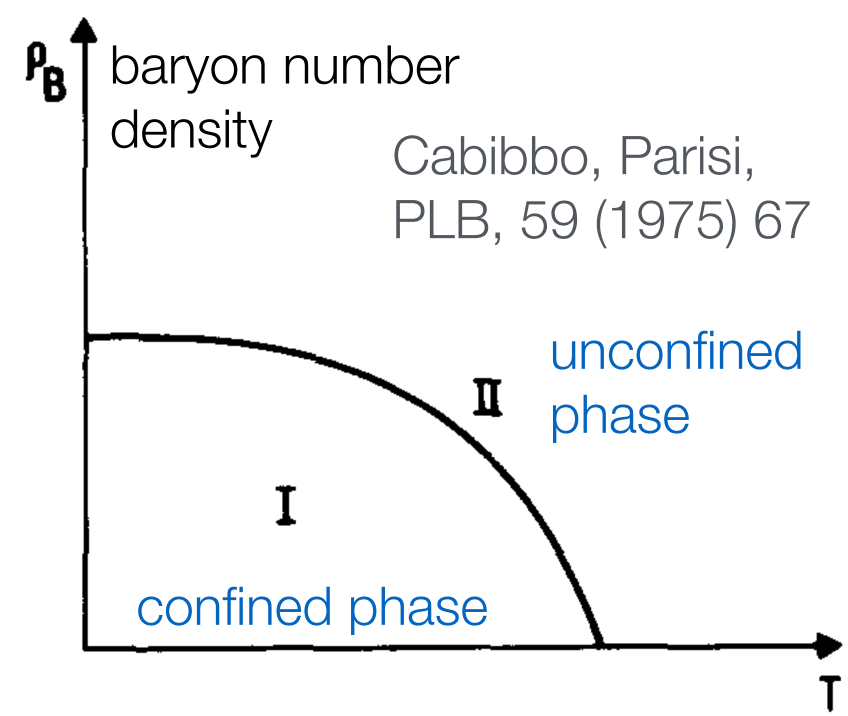
- Hagedorn used a = 3 and concluded that T_H = 0.15 GeV would be the ultimate temperature of all matter
- Physical reason:
  - Energy put into the system excites high-mass resonances
  - This prevents a further increase of the temperature
- However, this conclusion depends on the value of a
  - For a > 7/2 the energy density remains finite
  - In this case temperatures $T > T_H$ could perfectly well exist

H. Satz, Extreme States of Matter in Strong Interaction Physics, Springer, 2012



QGP — the idea

- 1973 — Birth of QCD
  - All ideas in place:
    Yang-Mills theory; SU(3) color symmetry; asymptotic freedom; confinement in color-neutral objects
- 1975 — Idea of quark deconfinement at high temperature and/or density
  - Collins, Perry, PRL 34 (1975) 1353
    - "Our basic picture then is that matter at densities higher than nuclear matter consists of a quark soup."
    - Idea based on weak coupling (asymptotic freedom)
  - Cabibbo, Parisi, PLB, 59 (1975) 67
    - Exponential hadron spectrum not necessarily connected with a limiting temperature
    - Rather: Different phase in which quarks are not confined
- It was soon realized that this new state could be created and studied in heavy-ion collisions



Order-of-magnitude physics of the QGP: Critical temperature at vanishing net baryon number

- Consider an ideal gas of u, d quarks and antiquarks, and gluons
- Calculate temperature at which energy density equals that within a proton
- Energy density in a proton

$$\varepsilon_{\text{proton}} = \frac{m}{V} = \frac{0.94\,\text{GeV}}{4/3\pi(0.8\,\text{fm})^3} \approx 0.44\,\text{GeV}/\text{fm}^3$$

- Energy density of an ideal gas

$$\varepsilon_{\text{id.gas}} = 37\frac{\pi^2}{30}T^4 = 0.44\,\text{GeV}/\text{fm}^3 \rightarrow T \approx 130\,\text{MeV} \qquad (k_B = 1)$$

$$= 1.5 \times 10^{12}\,\text{K}$$

Order-of-magnitude physics of the QGP: Critical density at vanishing temperature

- Baryon density of nuclear matter ($r_0 \approx 1.15$ fm):

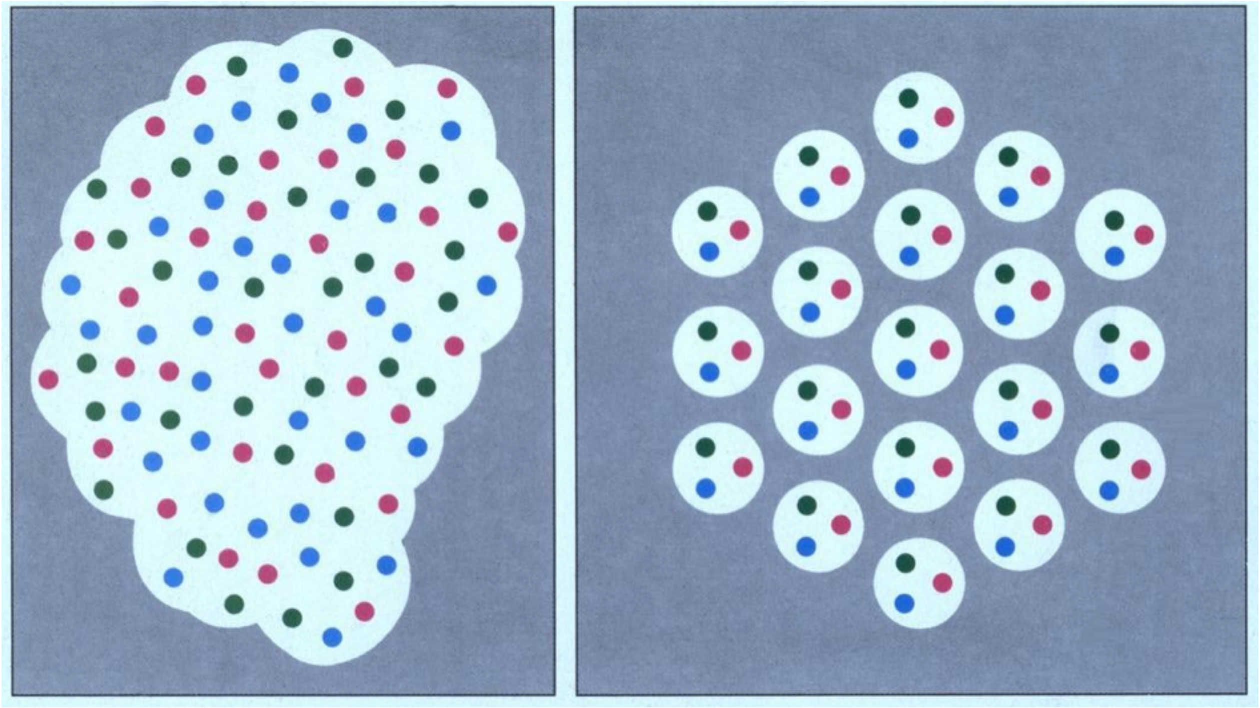
$$\rho_0 = \frac{A}{4\pi/3R^3} = \frac{1}{4\pi/3r_0^3}$$
$$\approx 0.16\,\mathrm{fm}^{-3}$$

- Nucleon start to overlap at a critical density ρ_C if nuclear matter is compressed ($r_N \approx 0.8$ fm):

$$\rho_c = \frac{1}{4\pi/3r_n^3} \approx 0.47/\mathrm{fm}^3 = 3\rho_0$$

- A refined calculation in fact gives a somewhat higher critical density

Figure: CERN



A little bit of history

- 1974 Bear mountain workshop 'BeV/nucleon collisions of heavy ions' [link]
  - Focus on exotic matter states and astrophysical implications
- 1983 long range plan for nuclear physics in US:
  Realization that the just abandoned pp collider project at Brookhaven could be turned into a nuclear collider inexpensively
- 1984: 1-2 GeV/*c* per nucleon beam from SuperHILAC into Bevalac at Berkeley
- 1986
  - beams of silicon at Brookhaven AGS ($\sqrt{s_{NN}} \approx 5$ GeV)
  - beams of oxygen/sulfur at CERN SPS ($\sqrt{s_{NN}} \approx 20$ GeV)
- 1992/1994
  - beams of gold at Brookhaven AGS ($\sqrt{s_{NN}} \approx 5$ GeV)
  - beams of lead at CERN SPS ($\sqrt{s_{NN}} \approx 17$ GeV)
- 2000: gold-gold collisions at RHIC ($\sqrt{s_{NN}} \approx 200$ GeV)
- 2010: lead-lead collisions at the LHC ($\sqrt{s_{NN}} \approx 2760$ GeV)
- 2015: lead-lead collisions at the LHC ($\sqrt{s_{NN}} \approx 5020$ GeV)

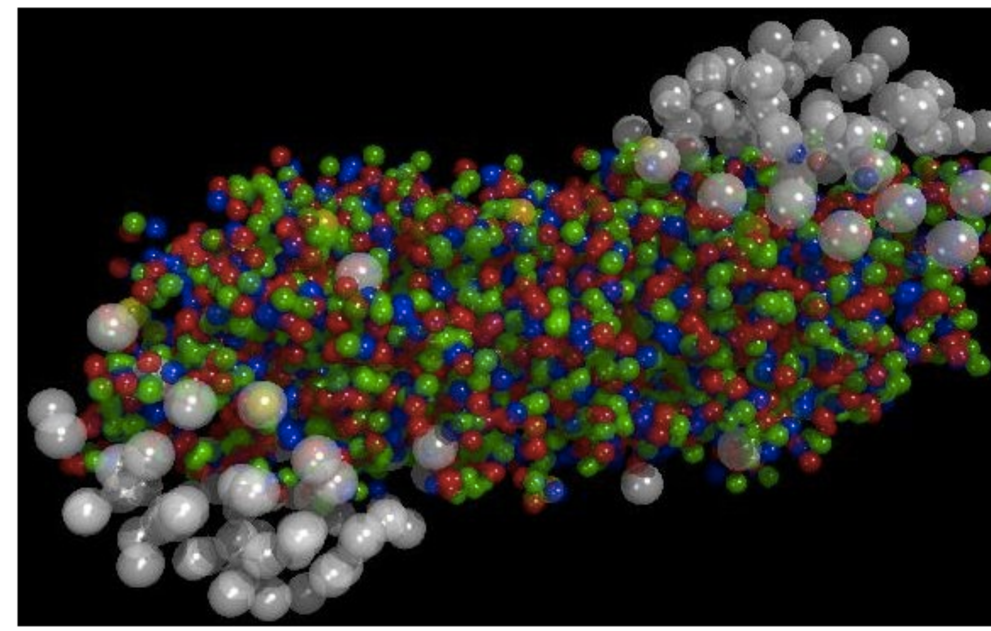
CERN press release in February 2000: New state of matter created at CERN

http://press.web.cern.ch/press-releases/2000/02/new-state-matter-created-cern

- Press release text
  - At a special seminar on 10 February, spokespersons from the experiments on CERN's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.
- Summary in nucl-th/0002042
  - "The new state of matter found in heavy ion collisions at the SPS features many of the characteristics of the theoretically predicted quark-gluon plasma"

New State of Matter created at CERN

10 Feb 2000



- Featured on front page of the NY times
- Mixed reactions among US physicists …

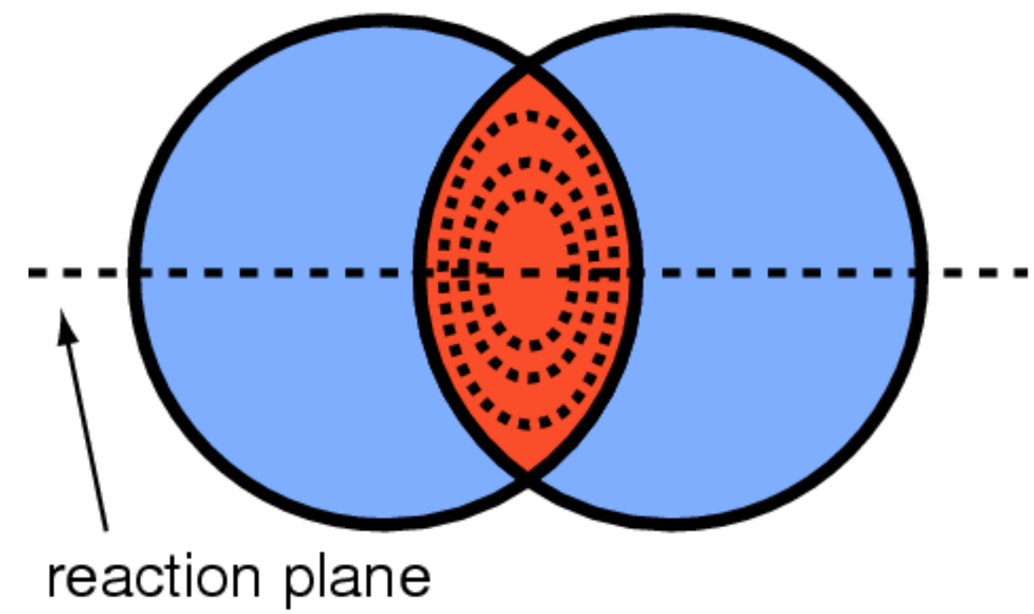
BNL press release April 2005: RHIC Scientists Serve Up "Perfect" Liquid [link]

- Considered to be the announcement of the QGP discovery
- Accompanied by the four papers on the first three years of RHIC running
  - BRAHMS
    - "Quark gluon plasma and color glass condensate at RHIC? The Perspective from the BRAHMS experiment"
  - PHENIX
    - "Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: Experimental evaluation by the PHENIX collaboration"
  - PHOBOS
    - "The PHOBOS perspective on discoveries at RHIC"
  - STAR
    - "Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR Collaboration's critical assessment of the evidence from RHIC collisions"
- QGP near T_C is not a weakly interacting gas, but a strongly correlated liquid (sQGP)
- But: Not easy to find clear statements on QGP discovery in these papers

Important results from the RHIC heavy-ion programme

- Azimuthal anisotropy of particle production at low p_T (< 2 GeV/c)
  - Interpreted as a result of the collective expansion of the QGP
  - Ideal hydrodynamics close to data
  - Small viscosity over entropy density: strongly coupled QGP, "perfect liquid"
  - Evidence for early QGP thermalization ($\tau \lesssim$ 1-2 fm/c)
- Hadron suppression at high p_T
  - Medium is to large extent opaque for jets ("jet quenching")
- Yields of hadron species in chemical equilibrium with freeze-out temperature T_{ch} close to T_c
  - $T_{ch} \approx$ 160 MeV, $\mu_B \approx$ 20 MeV

Elliptic Flow:
Anisotropy in position space



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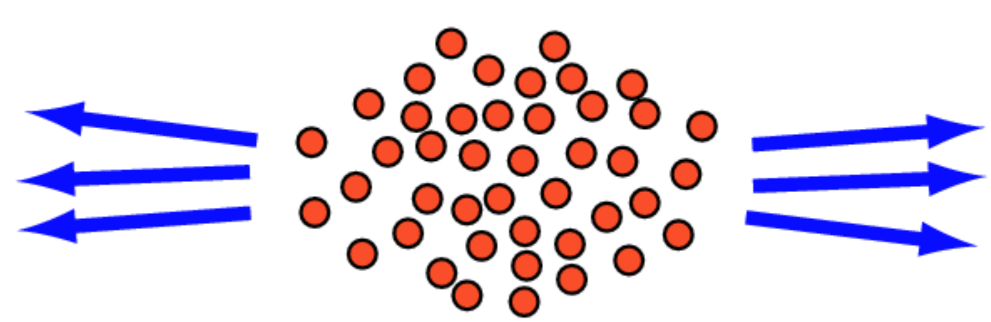
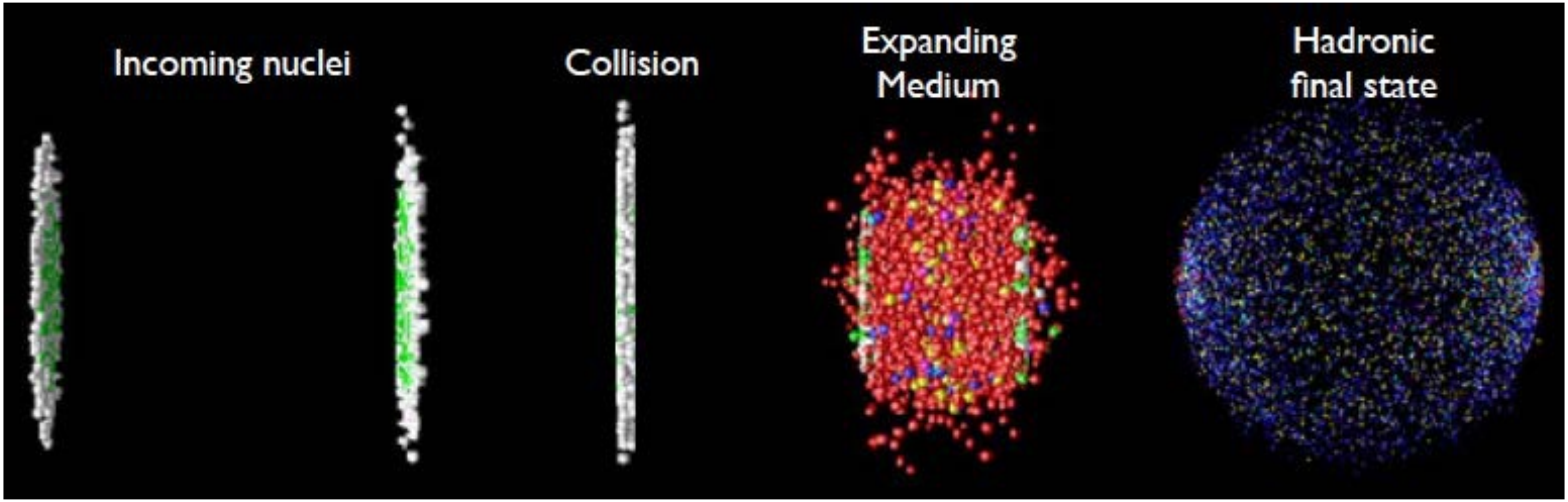
Anisotropy in momentum space



Heavy-ions at the LHC

- Qualitatively similar results in A-A collisions
  - Jet quenching
  - Elliptic flow
  - Particle yields in or close to chemical equilibrium values
- A surprise:
  Observation of elliptic flow and other effects first seen in heavy-ion collisions also in pp and p-Pb collisions
  - QGP in small systems?
  - But no jet quenching seen in small systems
  - Ongoing discussion

Space-time evolution (1):

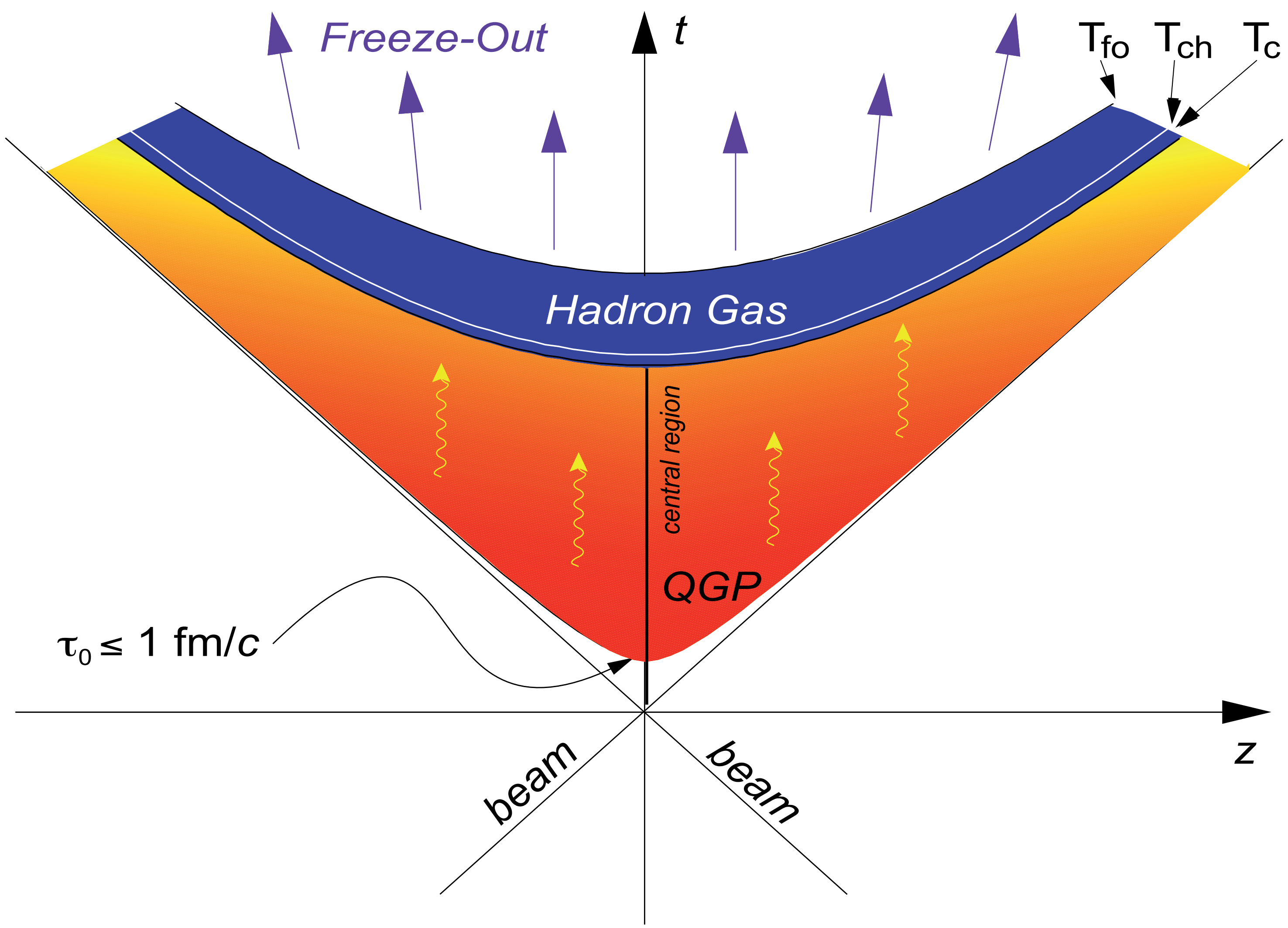


Initial parton wave function described in the Color Glass Condensate model

Central region initially dominated by low-*x* partons (i.e. gluons), then, at some point, quark-antiquarks pairs appear

Expansion, cooling, transition to hadrons

Space-time Evolution (2)



arxiv:0807.1610

- Strong color-electric glue fields between nuclei
- Rapid thermalization: QGP created at ~ 1-2 fm/c
- Expected initial temperatures of 600 MeV or higher
- Cooling due to longitudinal and transverse expansion describable by almost ideal relativistic hydrodynamics ($\eta/s \approx 0$)*
- Transition QGP → hadrons after about 10 fm/c
- Chemical freeze-out at $T_{ch} \approx T_c$ (T_c = 150 - 160 MeV)
- Kinetic freeze-out at T_{fo} ~ 100 MeV

* conjectured lower bound from string theory: $\eta/s|_{min} = 1/4\pi$ (Phys.Rev.Lett. 94 (2005) 111601)

Summary and (some) current questions

- What is the mechanism for the fast thermalization in heavy-ion collisions?
- What is the physical origin of equilibrium particle yields, or, more general, how does hadronization work?
- What are the transport properties of the QGP? Dependence on T and μ_B?
- How can one make contact with ab-initio QCD predictions?
- Can one experimentally determine properties of the QCD phase diagram
  - Nature of the transition at $\mu_B = 0$ (crossover, 1st order)?
  - Is there a critical endpoint? If so, where?
  - Currently explored in the RHIC beam energy scan (BES) programme
- Can one identify the onset of deconfinement in heavy-ion collisions at some $\sqrt{s_{NN}}$?
  - Also studied in the RHIC BES
- Is a strongly-correlated QGP liquid also formed in pp and p-Pb collisions? What about e^+e^- …?

2. Thermodynamics of the QGP

Ideal ultra-relativistic quark and gluon gas

- Quark density (massless quarks, i.e., $E = p$):

$$n_q(\mu_q) = \frac{N_q}{V} = g_q \frac{4\pi}{(2\pi)^3} \int_0^\infty dE \, \frac{E^2}{e^{(E-\mu_q)/T} + 1}$$

"+" for antiquarks

- Gluon density:

$$n_g = g_g \frac{4\pi}{(2\pi)^3} \int_0^\infty dE \, \frac{E^2}{e^{E/T} - 1}$$

- Degrees of freedom

$$g_q = g_{\text{quark}} + g_{\text{anti-quark}} = 2 \times g_{\text{quark}} \\ = 2 \times 2_{\text{spin}} \times 2_{\text{flavor}} \times 3_{\text{color}} = 24$$

$$g_g = 8_{\text{color}} \times 2_{\text{spin}} = 16$$

Ideal QGP with $\mu_q = 0$

- Pressure, energy density, quark and gluon density

$$p_{\mathrm{QGP}} = \left(g_g + \frac{7}{8}(g_q + g_{\bar{q}})\right) \frac{\pi^2}{90} T^4$$

$$\varepsilon_{\mathrm{QGP}} = 3 p_{\mathrm{QGP}}$$

$$n_{\mathrm{q}} = n_{\bar{\mathrm{q}}} = \frac{3}{4} \frac{q_q}{\pi^2} \zeta(3) T^3$$

1.20205

$$n_g = \frac{q_g}{\pi^2} \zeta(3) T^3$$

- Example: T = 200 MeV, two quark flavors

$$\varepsilon_{\mathrm{QGP}}^{\mathrm{id.\,gas}} = 2.55\ \mathrm{GeV/fm^3} \qquad n_q = n_{\bar{q}} = 1.71/\mathrm{fm}^3 \qquad n_g = 2.03/\mathrm{fm}$$

Ideal QGP with $\mu_q \geq 0$

- For $\mu_q \neq 0$ a solution in closed form can be found for $\varepsilon_q + \varepsilon_{\bar{q}}$ but not for ε_q and $\varepsilon_{\bar{q}}$ separately: Chin, PL 78B (1978) 552

$$\varepsilon_q + \varepsilon_{\bar{q}} = g_q \times \left(\frac{7\pi^2}{120} T^4 + \frac{\mu_q^2}{4} T^2 + \frac{\mu_q^4}{8\pi^2} \right)$$

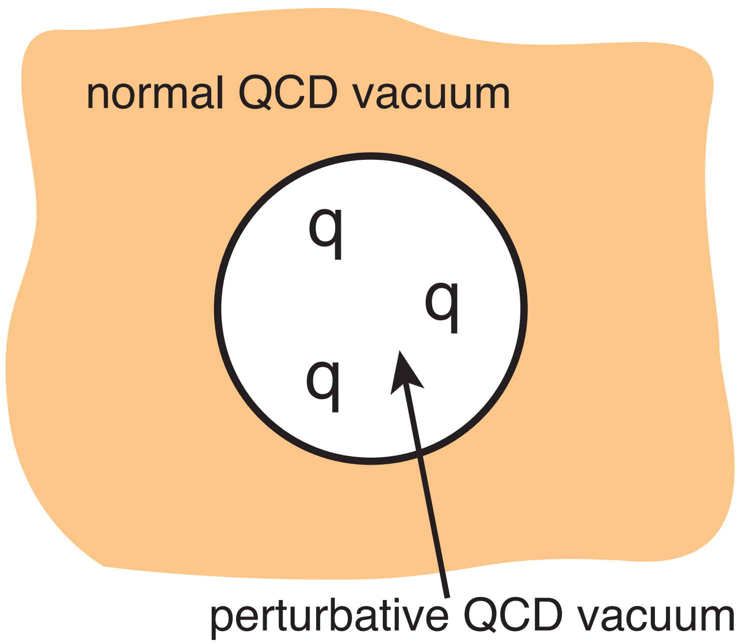
- Accordingly, one finds for the quark density

$$n_q - n_{\bar{q}} = g_q \times \left(\frac{\mu_q}{6} T^2 + \frac{\mu_q^3}{6\pi^2} \right)$$

- The net baryon density can be determined as

$$n_B = \frac{n_q - n_{\bar{q}}}{3} = \frac{2\mu_q}{3} T^2 + \frac{2\mu_q^3}{3\pi^2} = \frac{2\mu_B}{9} T^2 + \frac{2\mu_B^3}{81\pi^2} \qquad (\mu_B = 3\mu_q)$$

The MIT bag model



- Build confinement and asymptotic freedom into simple phenomenological model
- Hadron = „bag“ filled with quarks
- Two kinds of vacuum
- Normal QCD vacuum outside of the bag
- Perturbative QCD vacuum within the bag

Energy density in the bag is higher than in the vacuum: $\varepsilon_{\text{pert}} - \varepsilon_{\text{vacuum}} =: B$

Energy of N quarks in a bag of radius R: $E = \boxed{\frac{2.04 N}{R}} + \frac{4}{3}\pi R^3 B$

kinetic energy of N particles in a spherical box of radius R

Condition for stability: $dE/dR = 0$ (minimum):

$$B^{1/4} = \left(\frac{2.04 N}{4\pi}\right)^{1/4} \frac{1}{R} \quad \overset{N=3,\ R=0.8\ \text{fm}}{\Longrightarrow} \quad B^{1/4} = 206\,\text{MeV} \quad (\hbar = c = 1)$$

Ideal QGP with $\mu_q \geq 0$

- Energy density (two quark flavors)

$$\varepsilon_{\text{QGP}} = \varepsilon_q + \varepsilon_{\bar{q}} + \varepsilon_g = \frac{37\pi^2}{30} T^4 + 3\mu_q^2 T^2 + \frac{3\mu_q^4}{2\pi^2}$$

- $T_c(\mu_q)$ from stability condition:

$$p_{\text{QGP}} = \frac{1}{3}\varepsilon_{\text{QGP}} \stackrel{!}{=} B$$

Alternative condition, sometimes also used: $p_{\text{QGP}} = p_{\text{hadron gas}}$

- Critical temperature at $\mu_q = 0$:

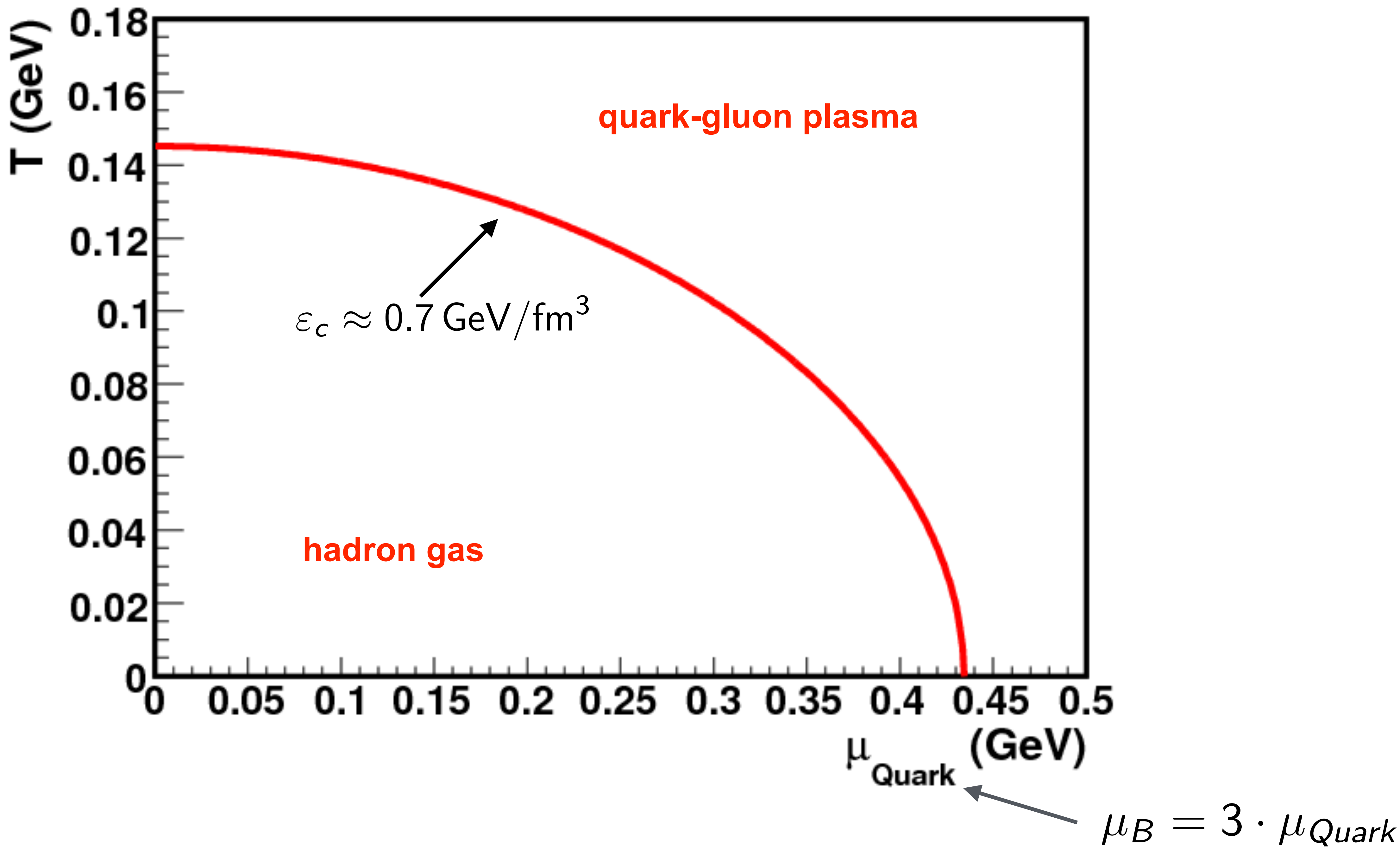
$$T_c(\mu_q = 0) = \left(\frac{90B}{37\pi^2}\right)^{1/4}$$

- Critical quark potential and density at $T = 0$:

$$\mu_q^c(T = 0) = (2\pi^2 B)^{1/4} = 0.43\,\text{GeV}$$

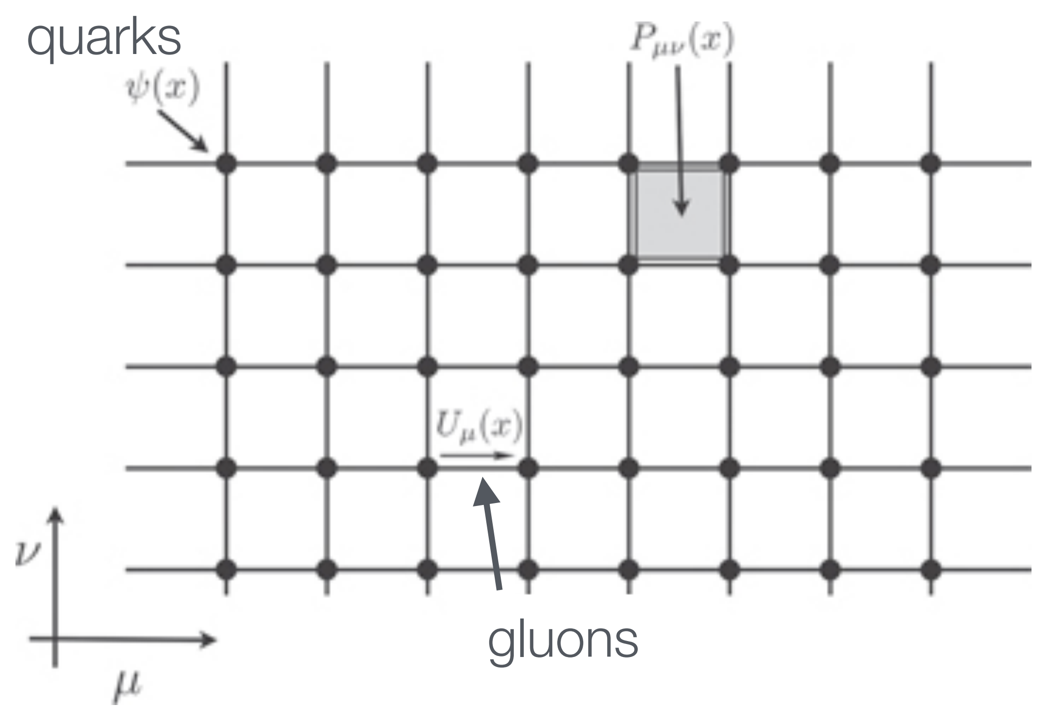
$$n_B^c(T = 0) = \frac{2}{3\pi^2}(2\pi^2 B)^{3/4} = 0.72\,\text{fm}^{-3} \approx 5 \times n_{\text{nucleus}}$$

Phase diagram of the non-interacting QGP



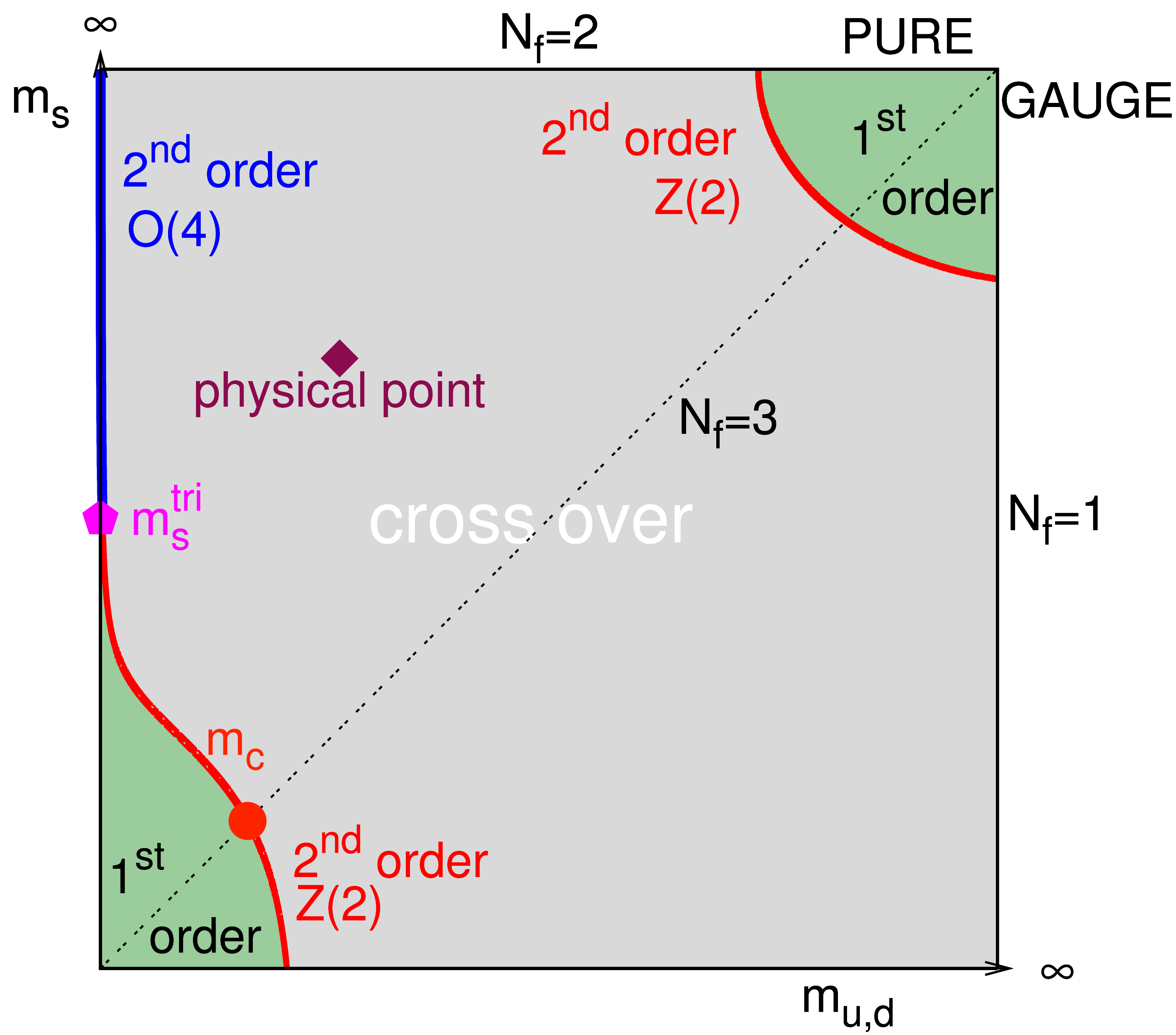
Lattice QCD

- Formulated in 1974 (K. Wilson), numerical Monte Carlo calculations started ca. 1980 (M. Creutz)
- First-principles non-perturbative calculation
- Benefitted from huge increase in computing power
- QCD thermodynamics on the lattice
  - So far restricted to $\mu_B \approx 0$
  - Two major groups (HotQCD coll., Wuppertal-Budapest coll.), results agree
- To be done:
  - Lattice QCD for finite baryon number
  - Transport properties of the QGP
  - Clarify existence and location of critical endpoint (CEP)



Example of a machine for lattice QCD: JUGENE in Jülich (294,912 processor cores, ~ 1 PetaFLOPS)

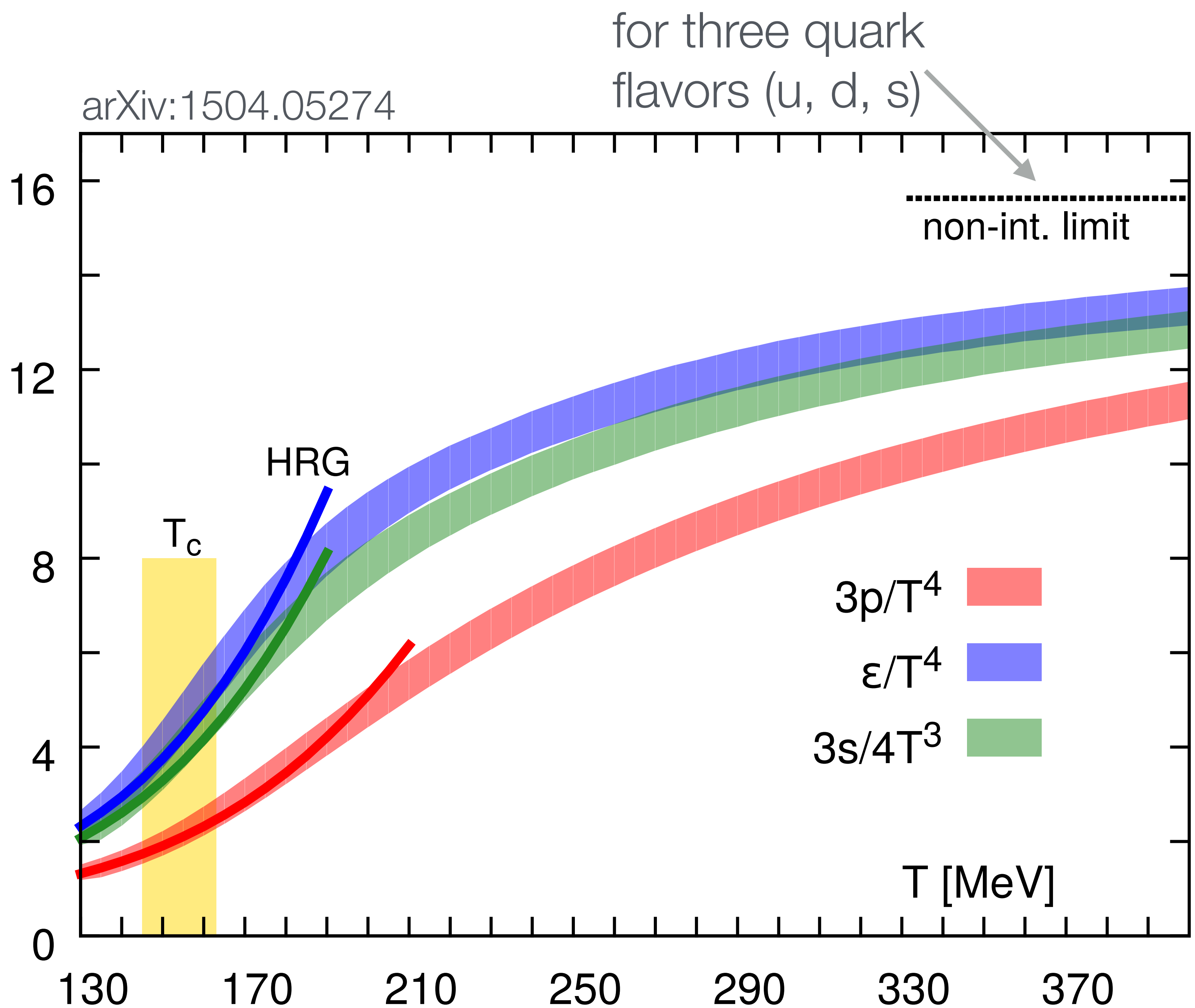
Lattice QCD: Nature of the transition vs. quark mass



Ding, Karsch, Mukherjee, arXiv:1504.05274

- Nature of the transition depends on quark masses
- Infinitely heavy quarks (pure gauge)
  - First order phase transition
  - $T_c \approx 270$ MeV
- Cross over transition for physical quark masses

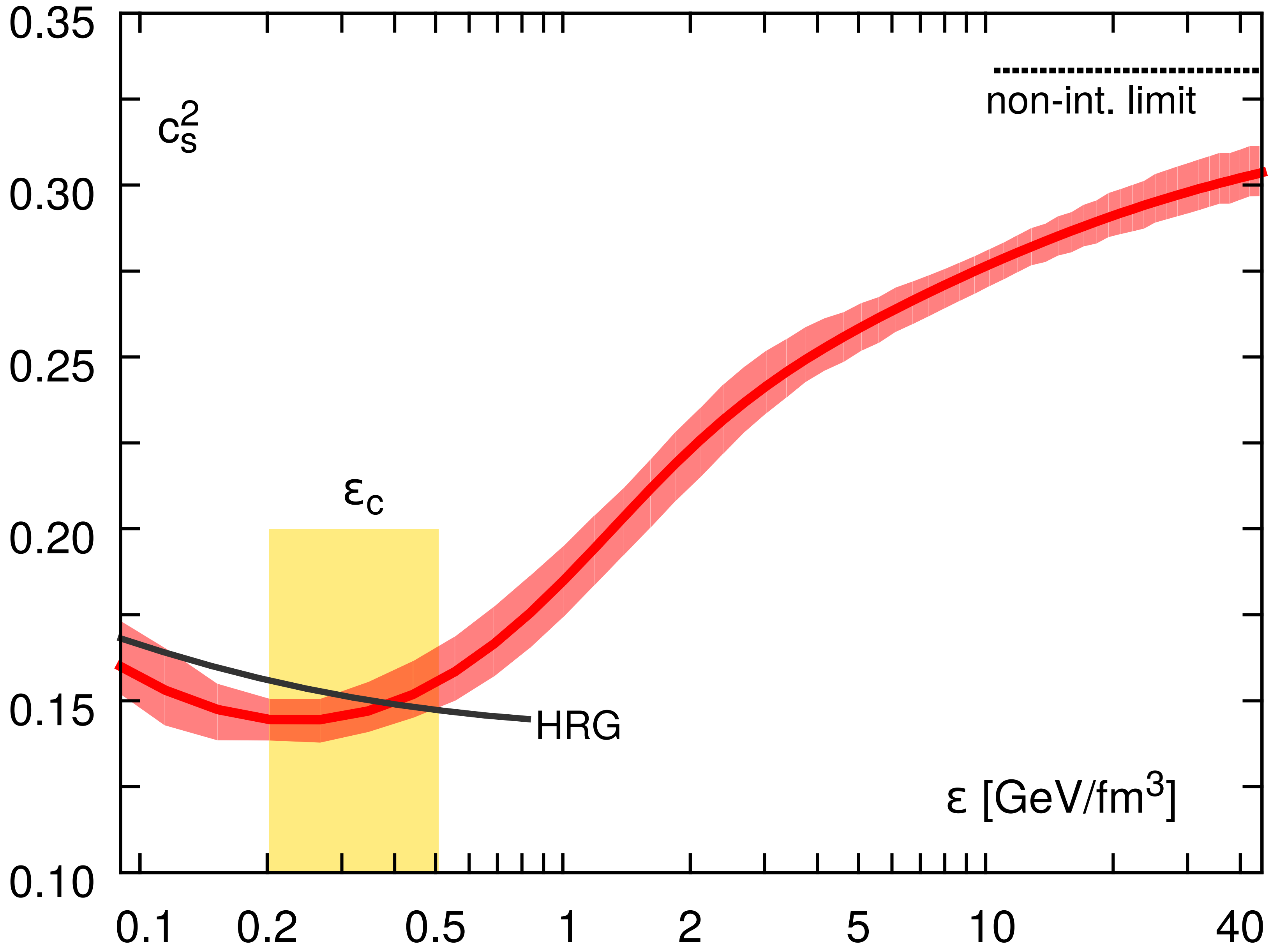
Pressure, energy and entropy density from lattice QCD



- (2+1) flavor QCD
  - two light quarks (u,d) + 1 heavier quark (s)
- Results extrapolated to continuum limit
- Pseudo-critical temperature for chiral crossover transition
  - $T_c = (154 \pm 9)$ MeV
  - $\varepsilon_c \approx (0.34 \pm 0.16)$ GeV/fm^3
- Hadron resonance gas (HRG) agrees with lattice results for $T < T_c$
- State-of-the art hydro calc's use equation of from lattice QCD

Speed of sound

arXiv:1504.05274

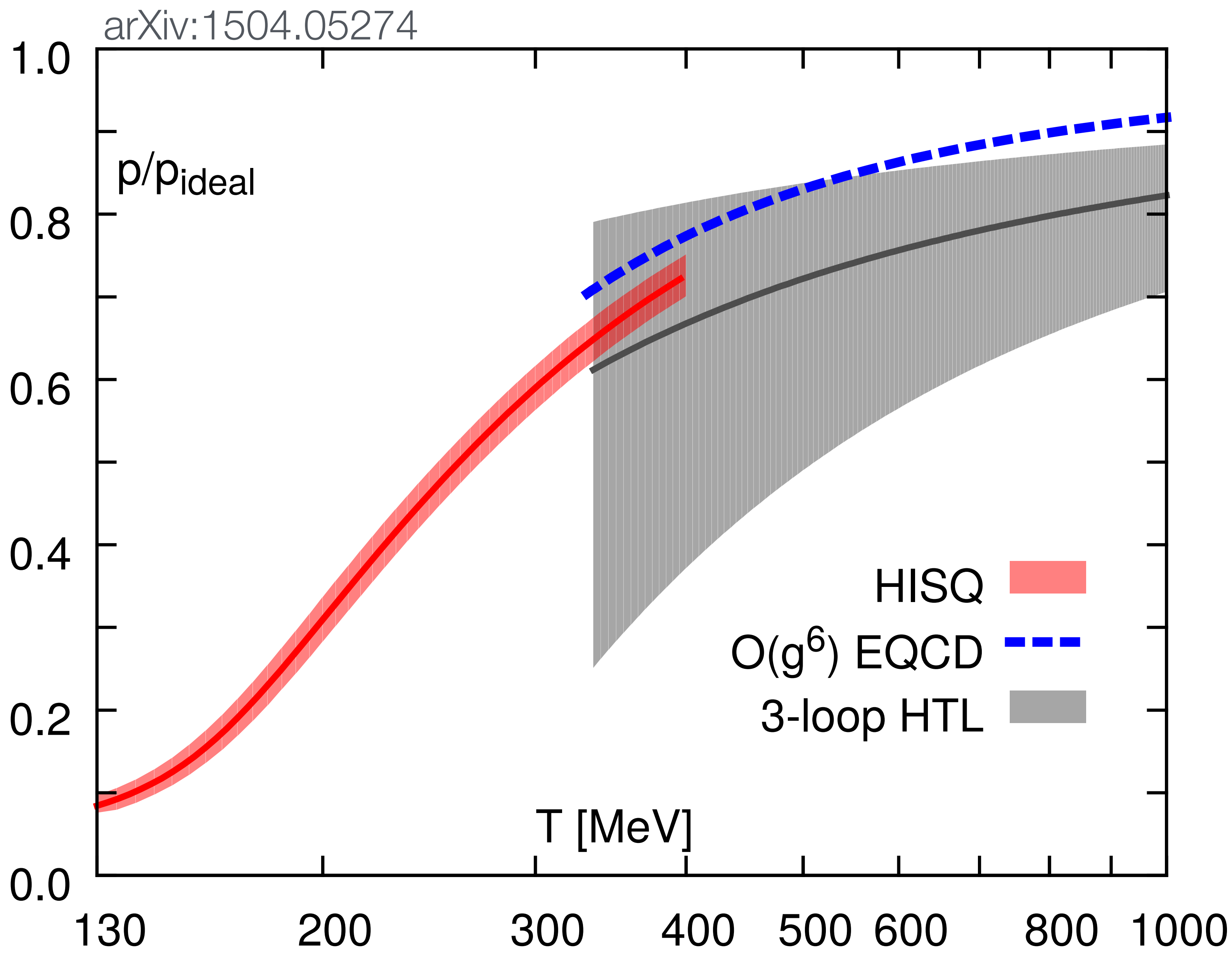


entropy density

$$c_s^2 = \frac{dp}{d\varepsilon} = \frac{dp/dT}{d\varepsilon/dT} = \frac{s}{C_V}$$

specific heat

Lattice QCD vs. perturbation theory



Lattice QCD agrees with perturbation theory (HLT) for T > 400 MeV

Summary QCD thermodynamics

- Toy model based on treating the QGP as a bag in the QCD vacuum filled with an ideal gas of quarks and gluons provides some intuitive insights into the phase diagram
- For T = 400 MeV the energy density of an ideal gas is only 20% above the lattice QCD results
- Lattice QCD results
  - For physical quark masses the transition at $\mu_B = 0$ is a crossover
  - Chiral symmetry transition coincides with deconfinement transition
  - Pseudo-critical temperature and energy density
    - $T_c = (154 \pm 9)$ MeV
    - $\varepsilon_c \approx (0.34 \pm 0.16)$ GeV/fm
- Not covered, but interesting: Thermodynamic fluctuations, especially fluctuations of conserved quantities (charge Q, baryon number B, …)
  - Measured via susceptibilities on the lattice, experimentally accessible

3. Global Properties of Heavy-Ion Collisions

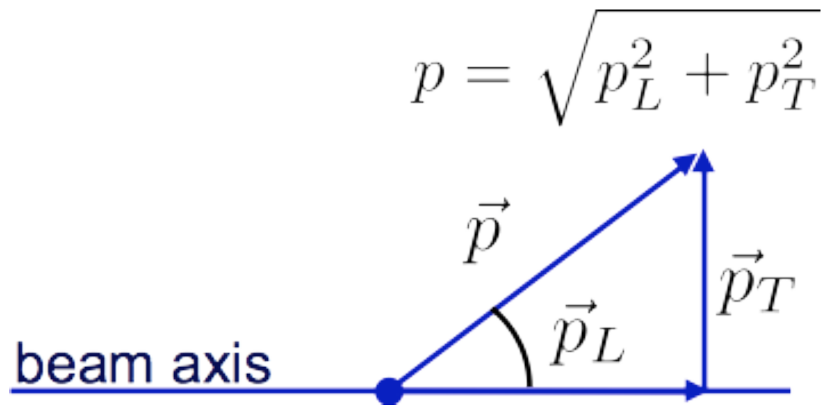
Basic observables

- Transverse momentum

$$p_T = p \sin\theta$$

transverse mass:

$$m_T = \sqrt{p_T^2 + m^2}$$

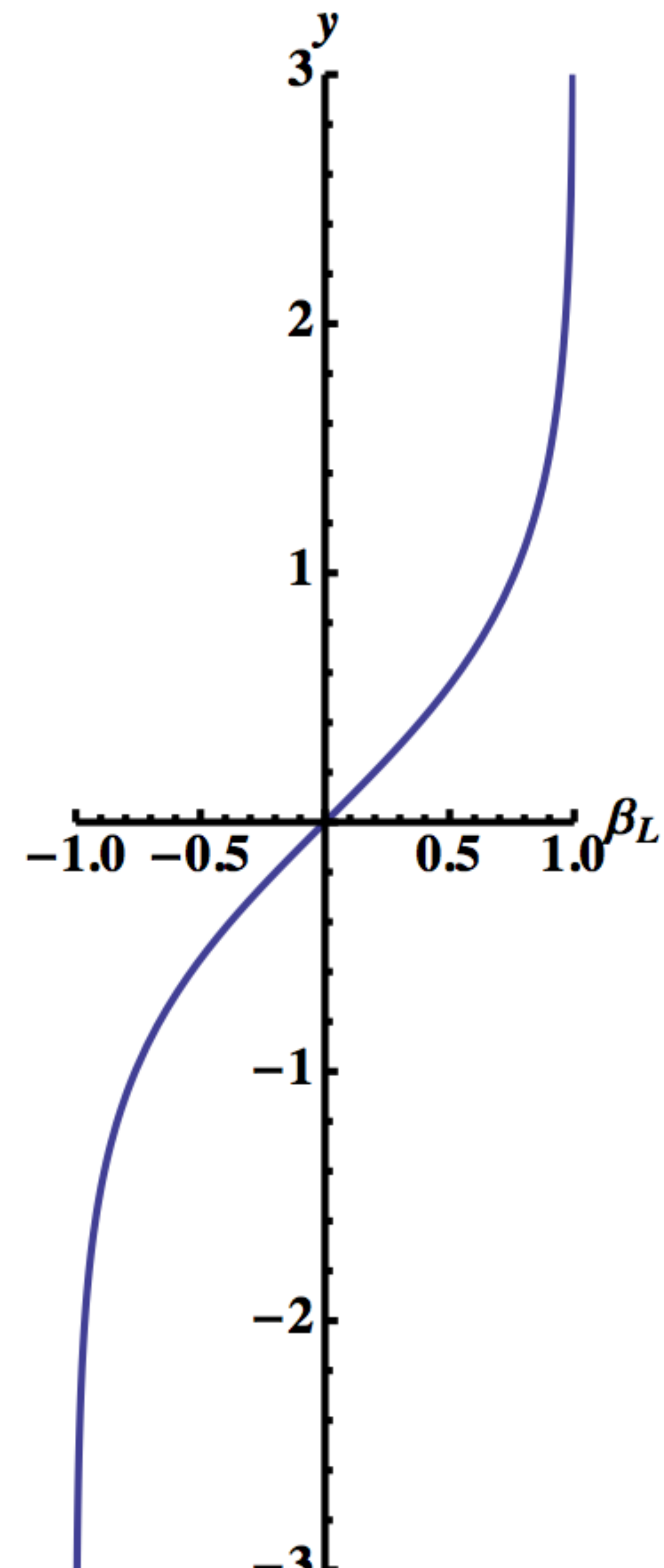


- Rapidity *y* (additive under Lorentz transformation)

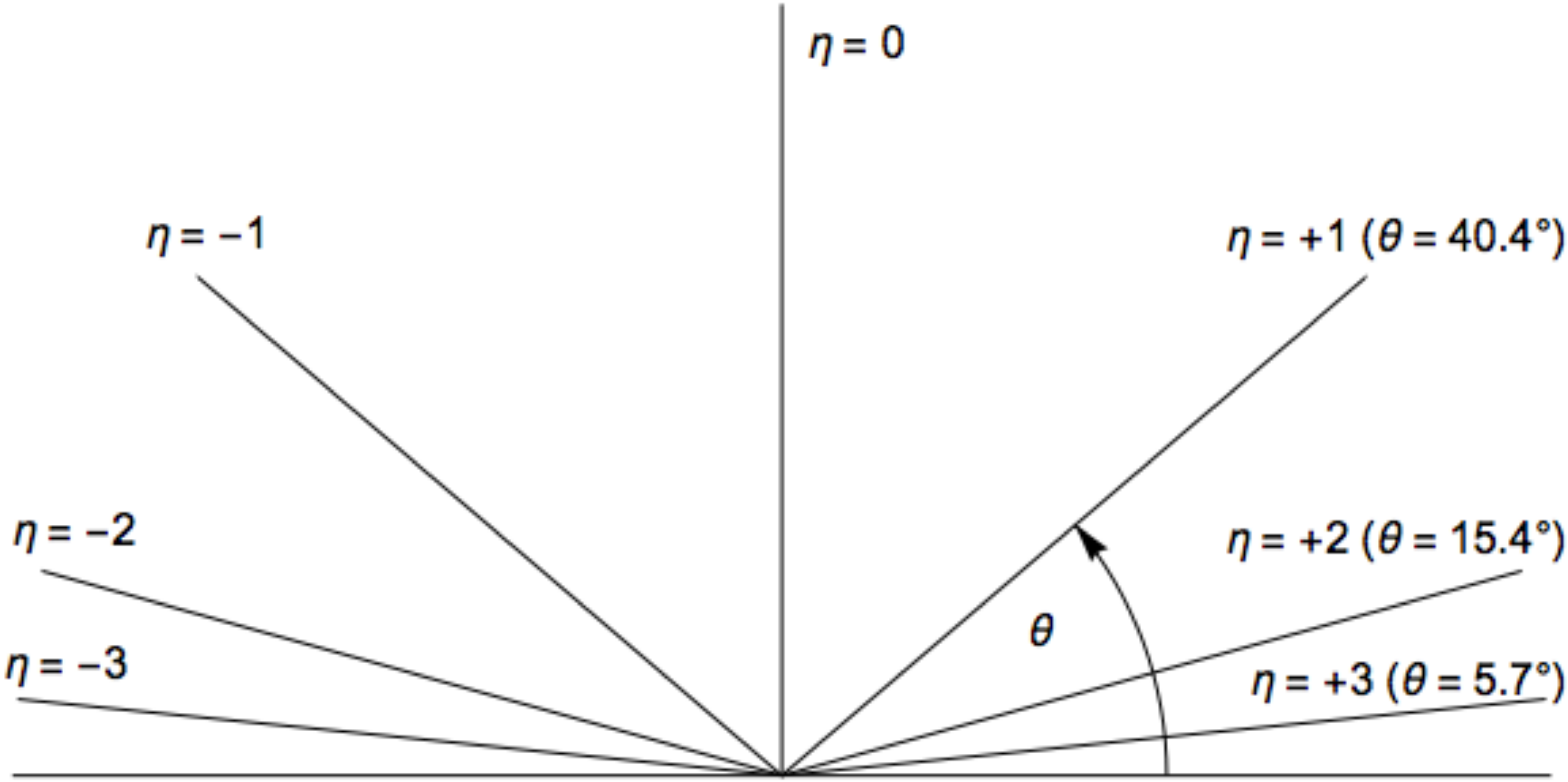
$$y = \operatorname{arctanh} \beta_L = \frac{1}{2} \ln \frac{1+\beta_L}{1-\beta_L} = \frac{1}{2} \ln \frac{E+p_L}{E-p_L}$$

- Pseudorapidity η

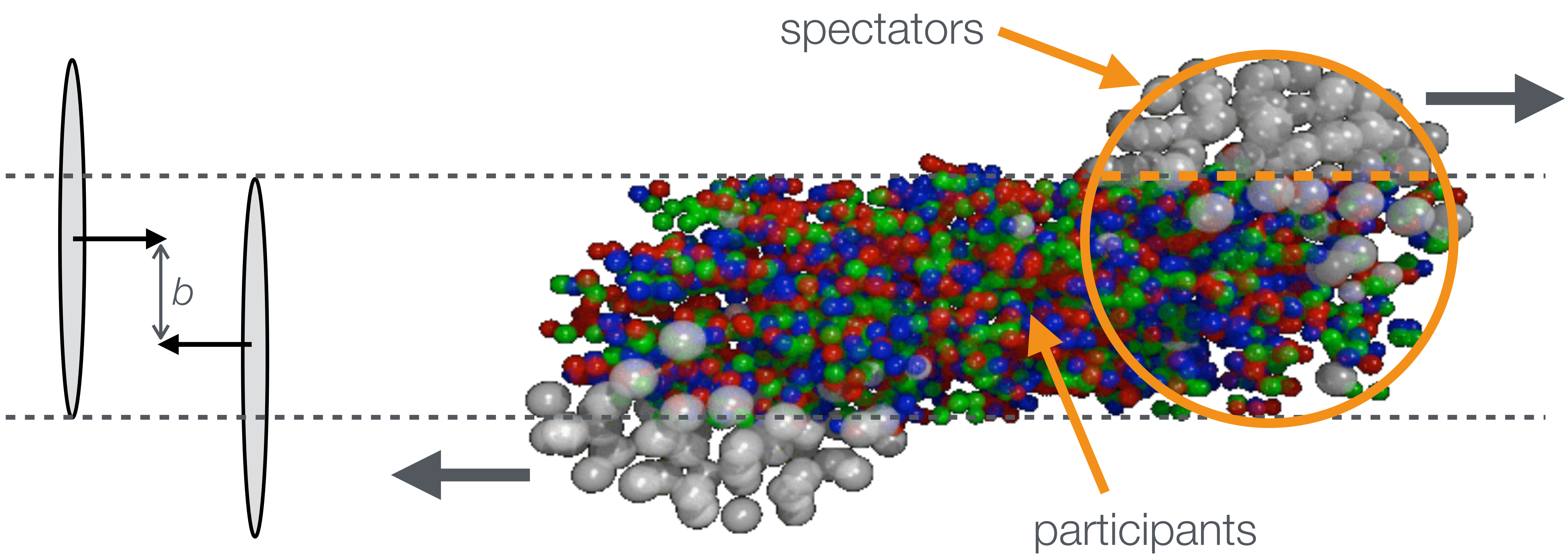
$$y \overset{p \gg m}{\approx} \frac{1}{2} \ln \frac{1+\cos\vartheta}{1-\cos\vartheta} = -\ln\left[\tan\frac{\vartheta}{2}\right] =: \eta$$



Pseudorapidity

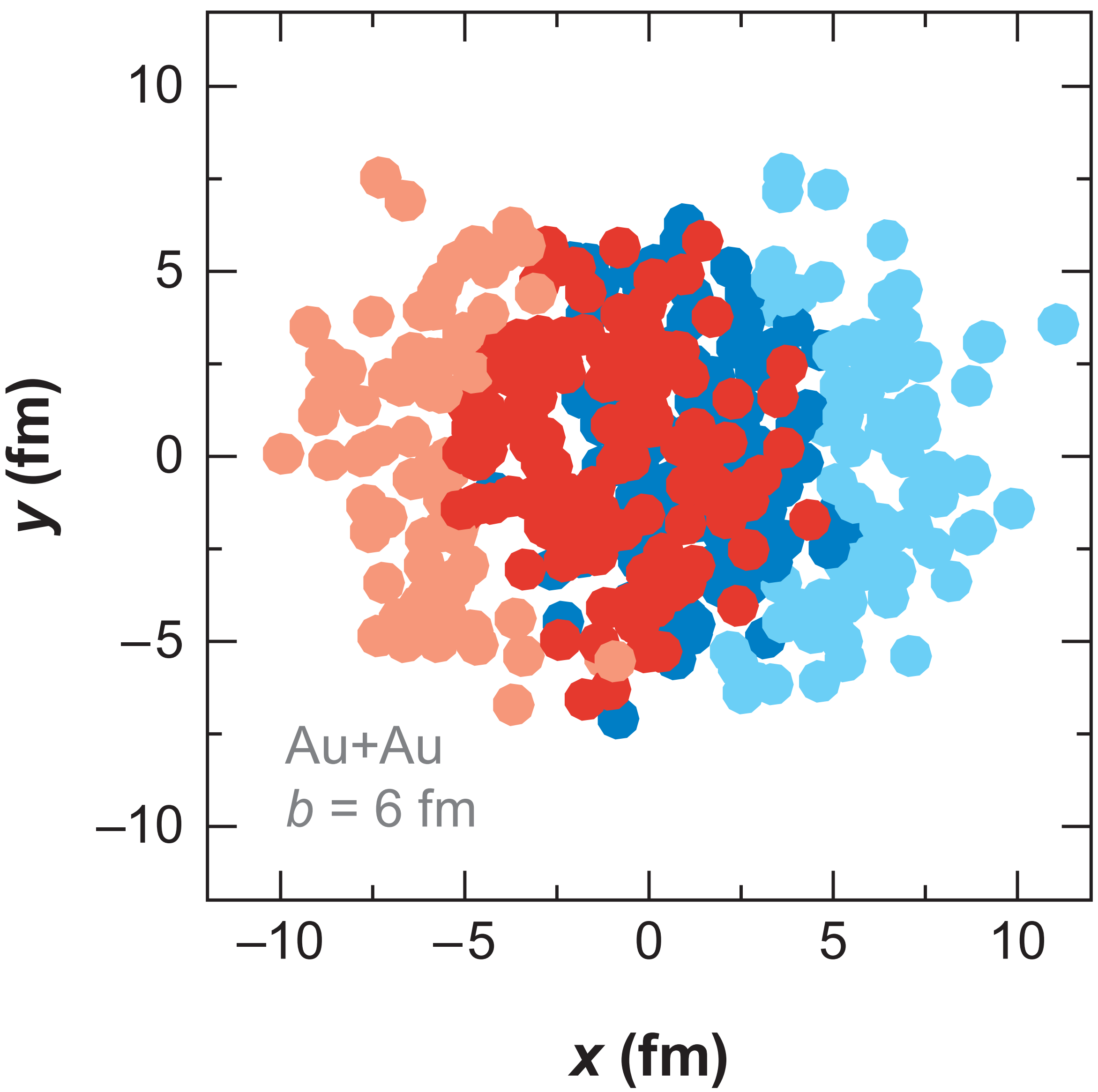


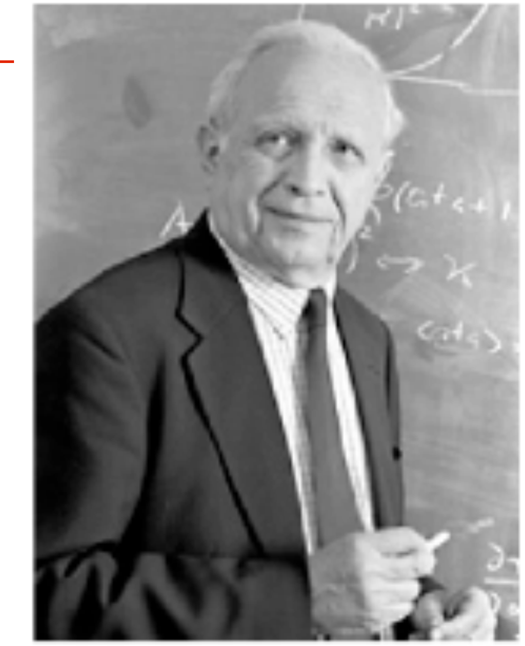
Participants and spectators



- N_{coll}: number of inelastic nucleon-nucleon collisions
- N_{part}: number of nucleons which underwent at least one inelastic nucleon-nucleon collisions

Glauber Monte Carlo calculations: An interface between theory and experiment





Roy J. Glauber

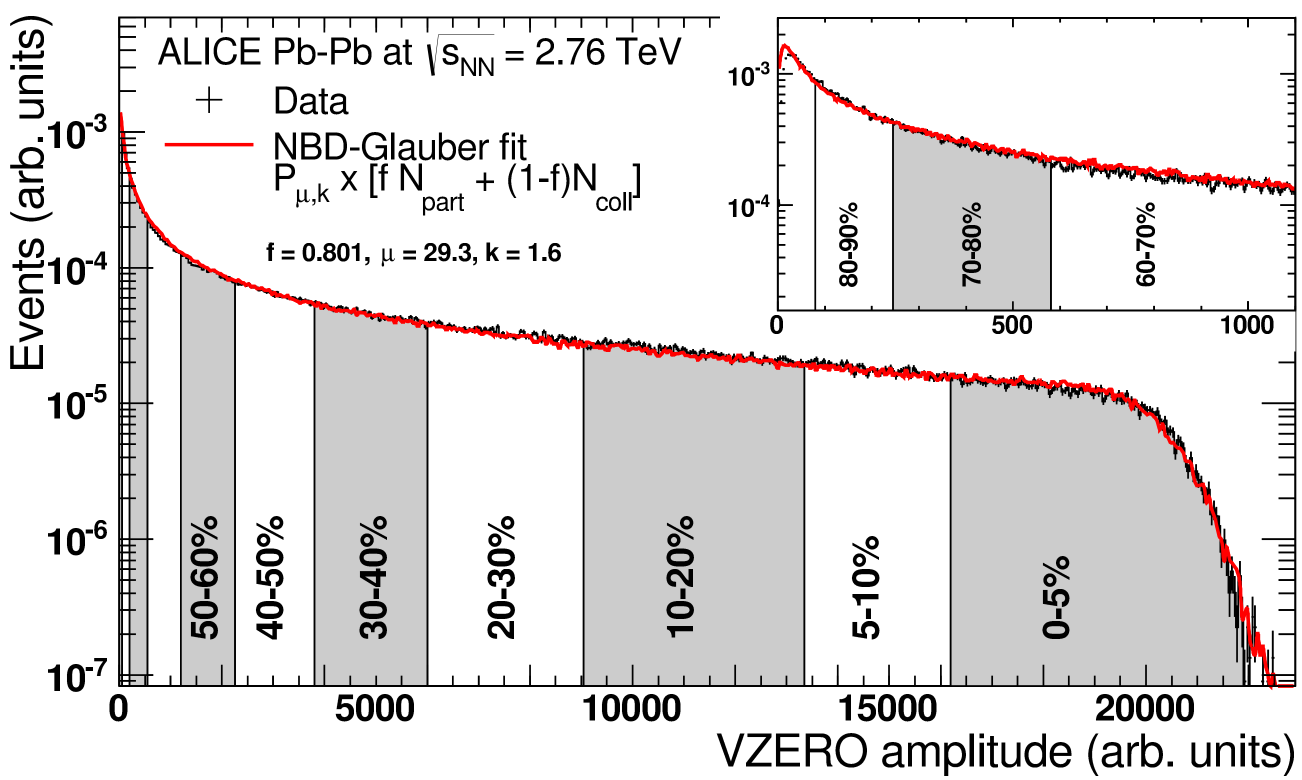
- "Glauber calculation" means a different thing to different people
- In heavy-ion physics
  - Pure geometry, no quantum mechanics
- Procedure
  - Randomly select impact parameter *b*
  - Distribute nucleons of two nuclei according to nuclear density distribution
  - Consider all pairs with one nucleon from nucleus A and the other from B
  - Count pair as inel. n-n collision if distance *d* in *x*-*y* plane satisfies

$$d < \sqrt{\sigma_{\mathrm{inel}}^{\mathrm{NN}} / \pi}$$

- Repeat many times: $\langle N_{\mathrm{part}} \rangle(b)$ $\langle N_{\mathrm{coll}} \rangle(b)$

How $\langle N_{part} \rangle$, $\langle N_{coll} \rangle$, and $\langle b \rangle$ are assigned to an experimental centrality class (1)

ALICE, arXiv:1301.4361v3



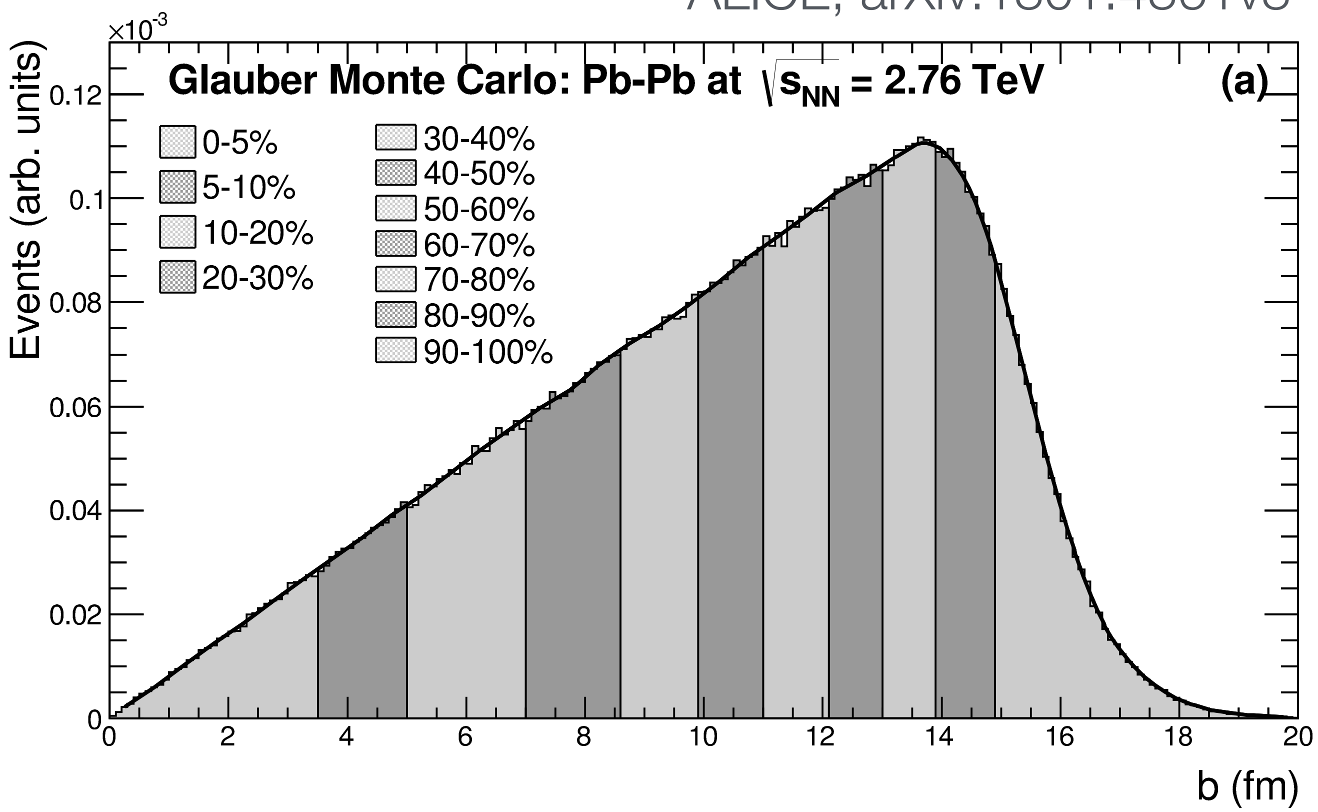
Glauber fit model

- Draw N_{ch} from negative binomial distribution for each “ancestor”
- Assume simple relation btw. $N_{ancestor}$ and N_{part}, N_{coll}

- Measure charged particle multiplicity
  - ALICE: VZERO detectors
    - $2.8 < \eta < 5.1$
    - $-3.7 < \eta < -1.7$
  - Assumption: $\langle N_{ch} \rangle(b)$ increases monotonically with decreasing b
- Define centrality class by selecting a percentile of the measured multiplicity distribution (e.g. 0-5%)
  - Slight complication:
    - Non-hadronic physical background processes contribute at low multiplicities
  - Need Glauber fit to define “100%”

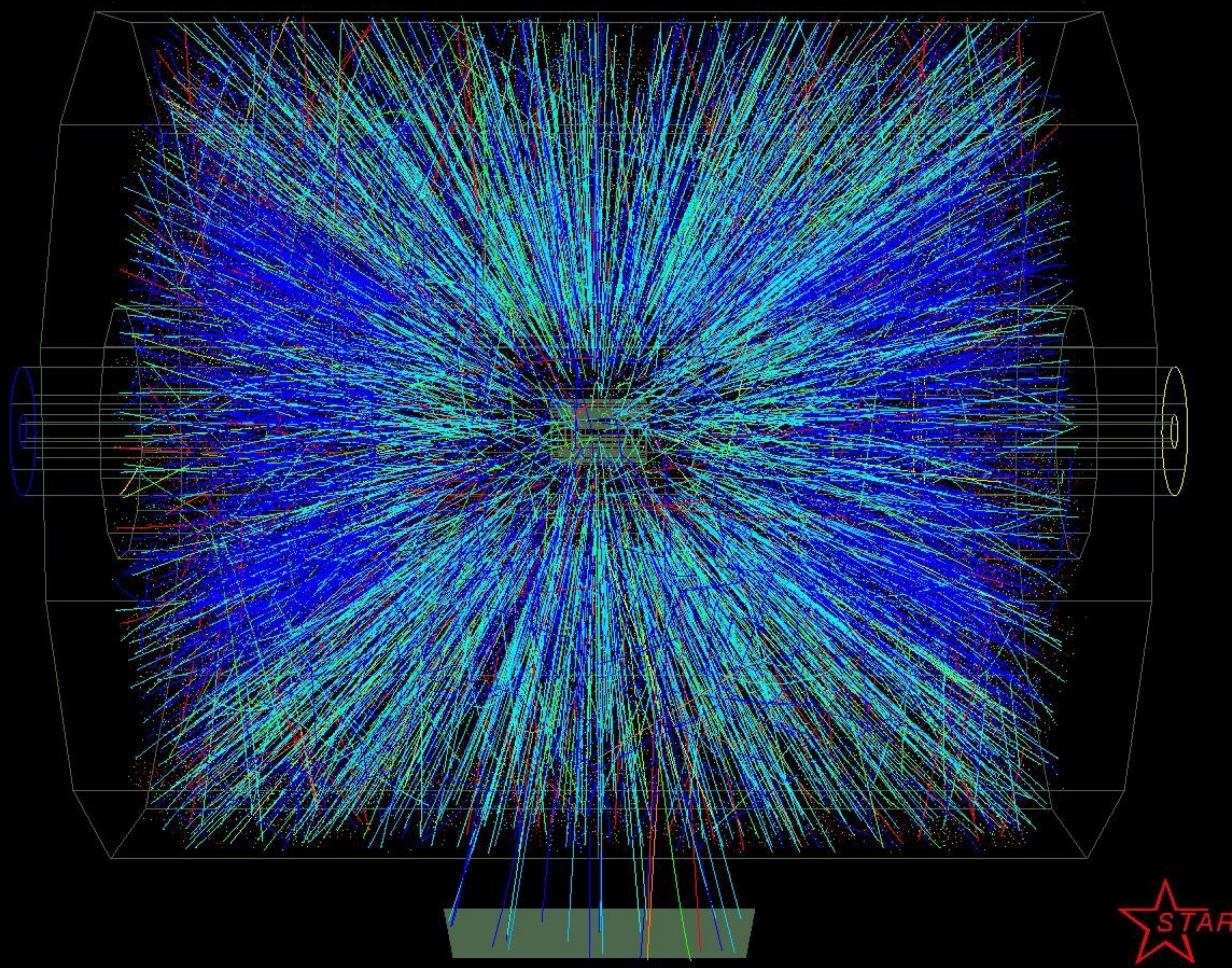
How $\langle N_{part} \rangle$, $\langle N_{coll} \rangle$, and $\langle b \rangle$ are assigned to an experimental centrality class (2)

ALICE, arXiv:1301.4361v3

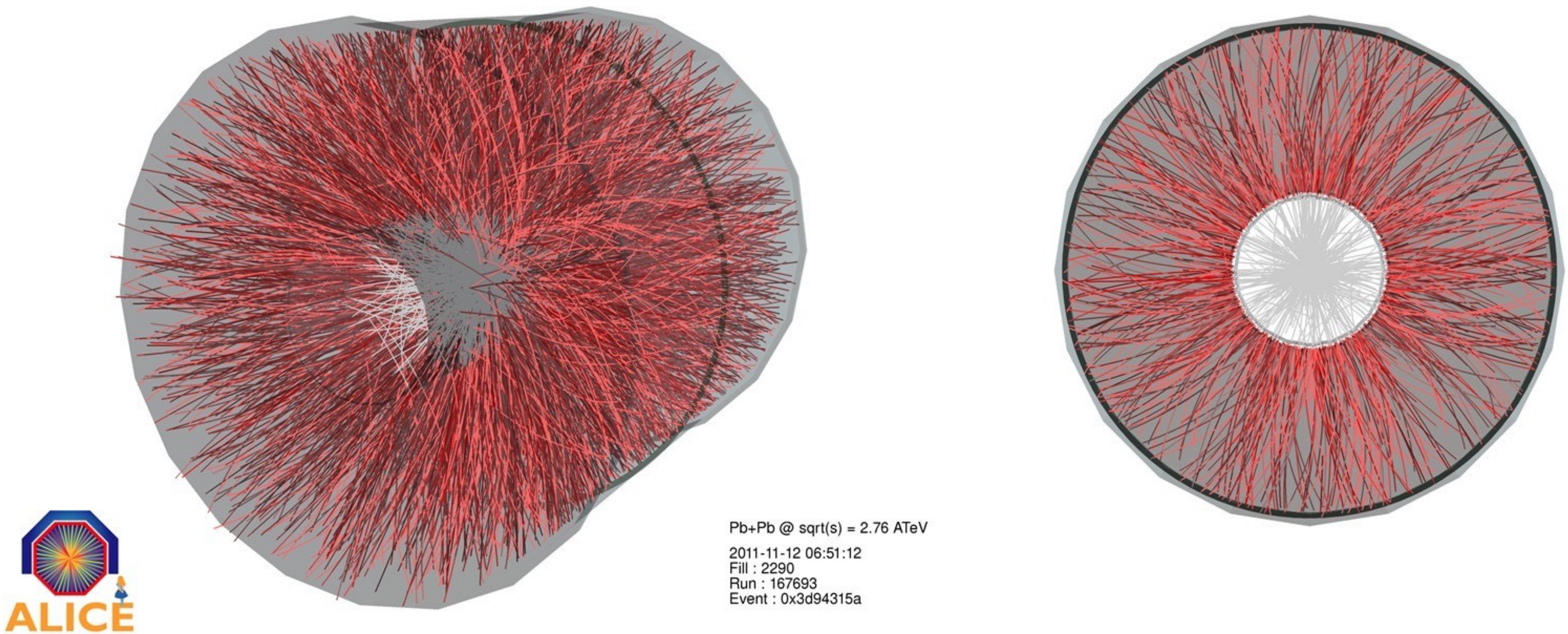


- Glauber Monte Carlo
  - Find impact parameter interval $[b_1, b_2]$ which corresponds to the same percentile
  - Average $N_{part}(b)$, $N_{coll}(b)$, etc over this interval
- Example: Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV
  - $\sigma_{NN}(\text{inel}) = (64 \pm 5)$ mb

Centrality	b_{min} (fm)	b_{max} (fm)	$\langle N_{part} \rangle$	RMS	(*sys.*)	$\langle N_{coll} \rangle$	RMS	(*sys.*)	$\langle T_{AA} \rangle$ 1/mbarn	RMS 1/mbarn	(*sys.*) 1/mbarn
0–5%	0.00	3.50	382.7	17	3.0	1685	140	190	26.32	2.2	0.85
5–10%	3.50	4.94	329.4	18	4.3	1316	110	140	20.56	1.7	0.67
10–20%	4.94	6.98	260.1	27	3.8	921.2	140	96	14.39	2.2	0.45
20–40%	6.98	9.88	157.2	35	3.1	438.4	150	42	6.850	2.3	0.23
40–60%	9.88	12.09	68.56	22	2.0	127.7	59	11	1.996	0.92	0.097
60–80%	12.09	13.97	22.52	12	0.77	26.71	18	2.0	0.4174	0.29	0.026
80–100%	13.97	20.00	5.604	4.2	0.14	4.441	4.4	0.21	0.06939	0.068	0.0055



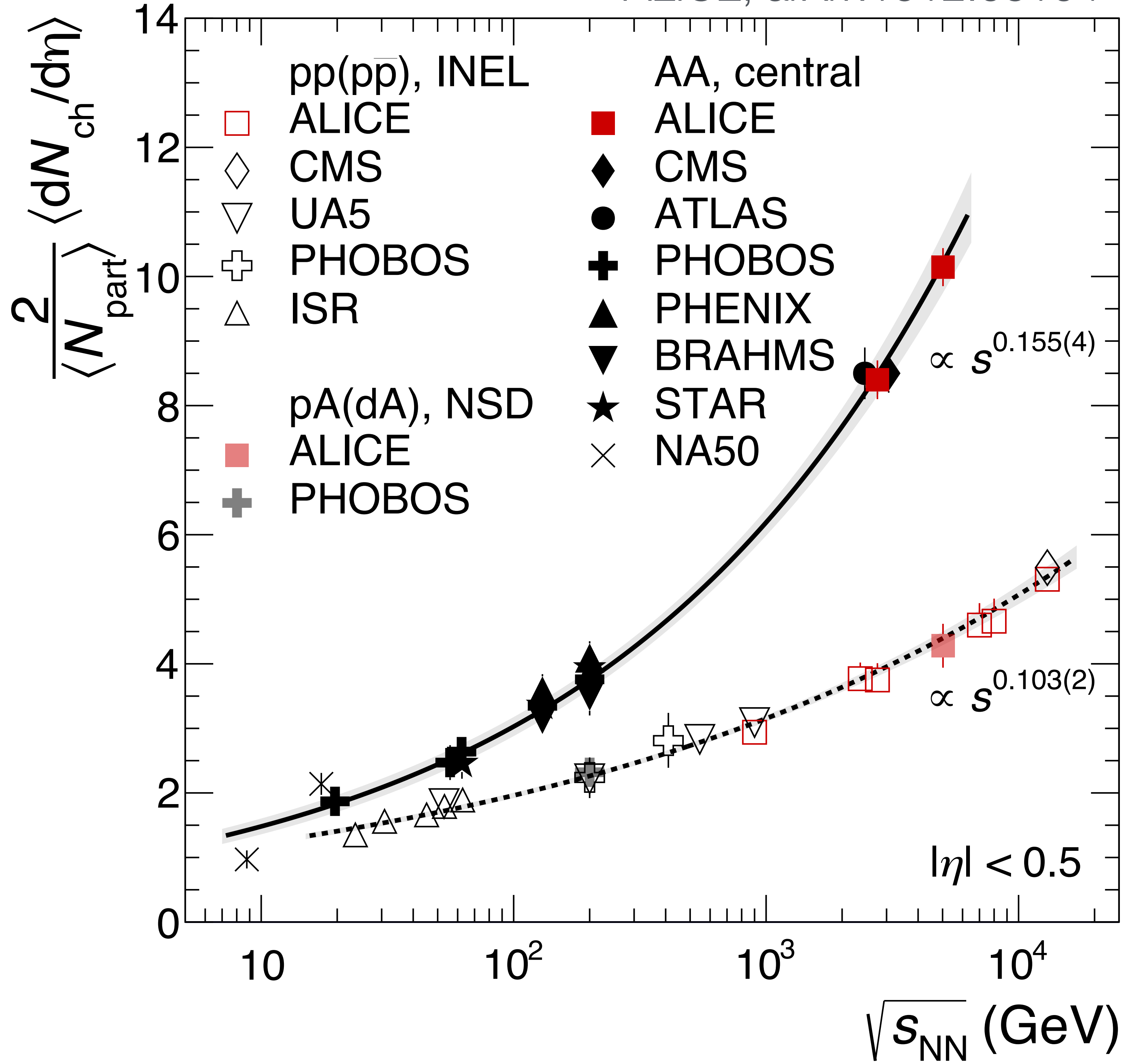
Central Au-Au collisions at $\sqrt{s_{NN}}$ = 200 GeV:
about 5000 charged particles in the full rapidity range



Central Au-Au collisions at $\sqrt{s_{NN}} = 2760$ GeV:
about 18000 charged particles in the full rapidity range

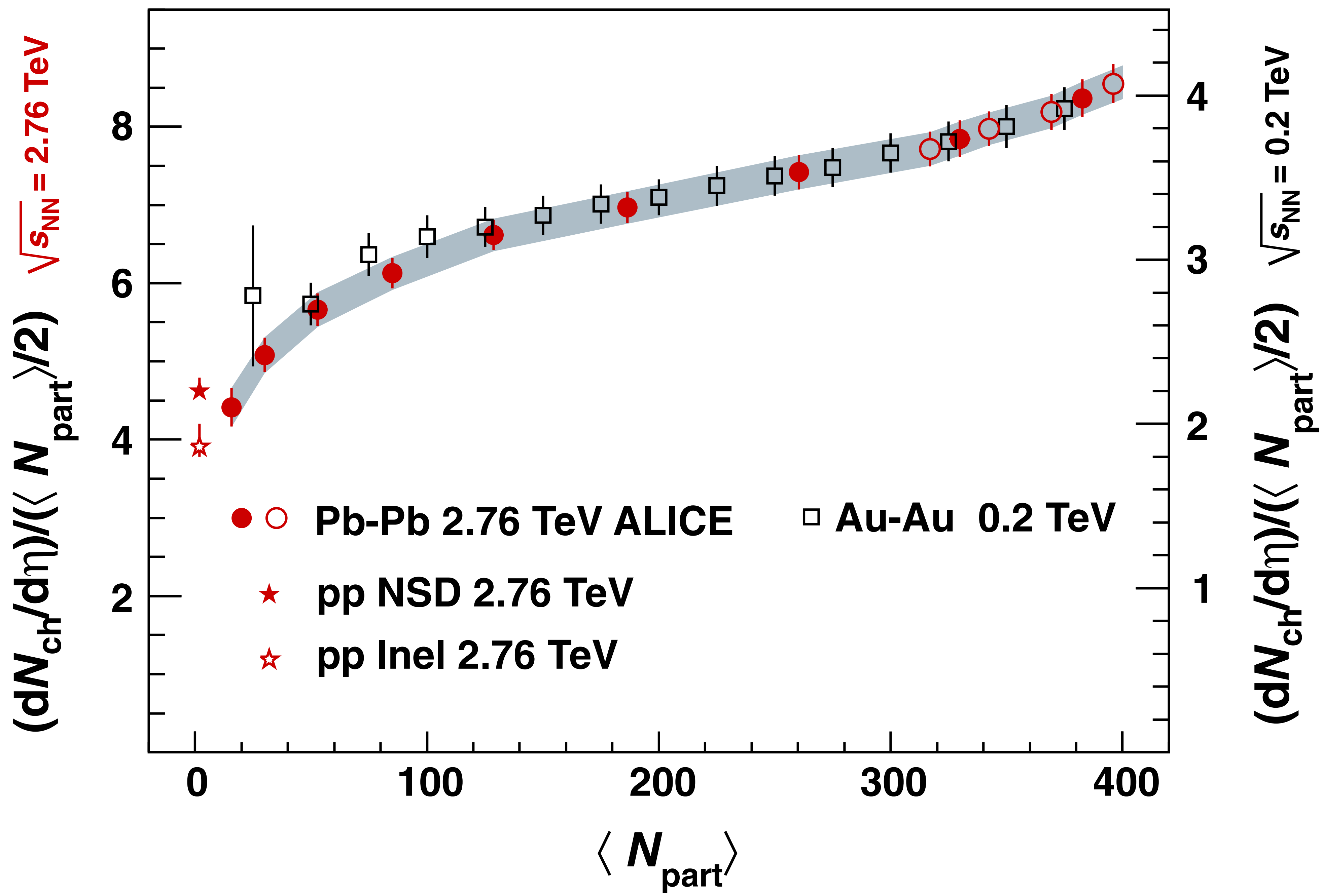
$dN_{ch}/d\eta$ vs $\sqrt{s_{NN}}$ in pp and central A-A collisions

ALICE, arXiv:1512.06104



- $dN_{ch}/d\eta$ scales with s^{α}
- Increase in central A+A stronger than in p+p

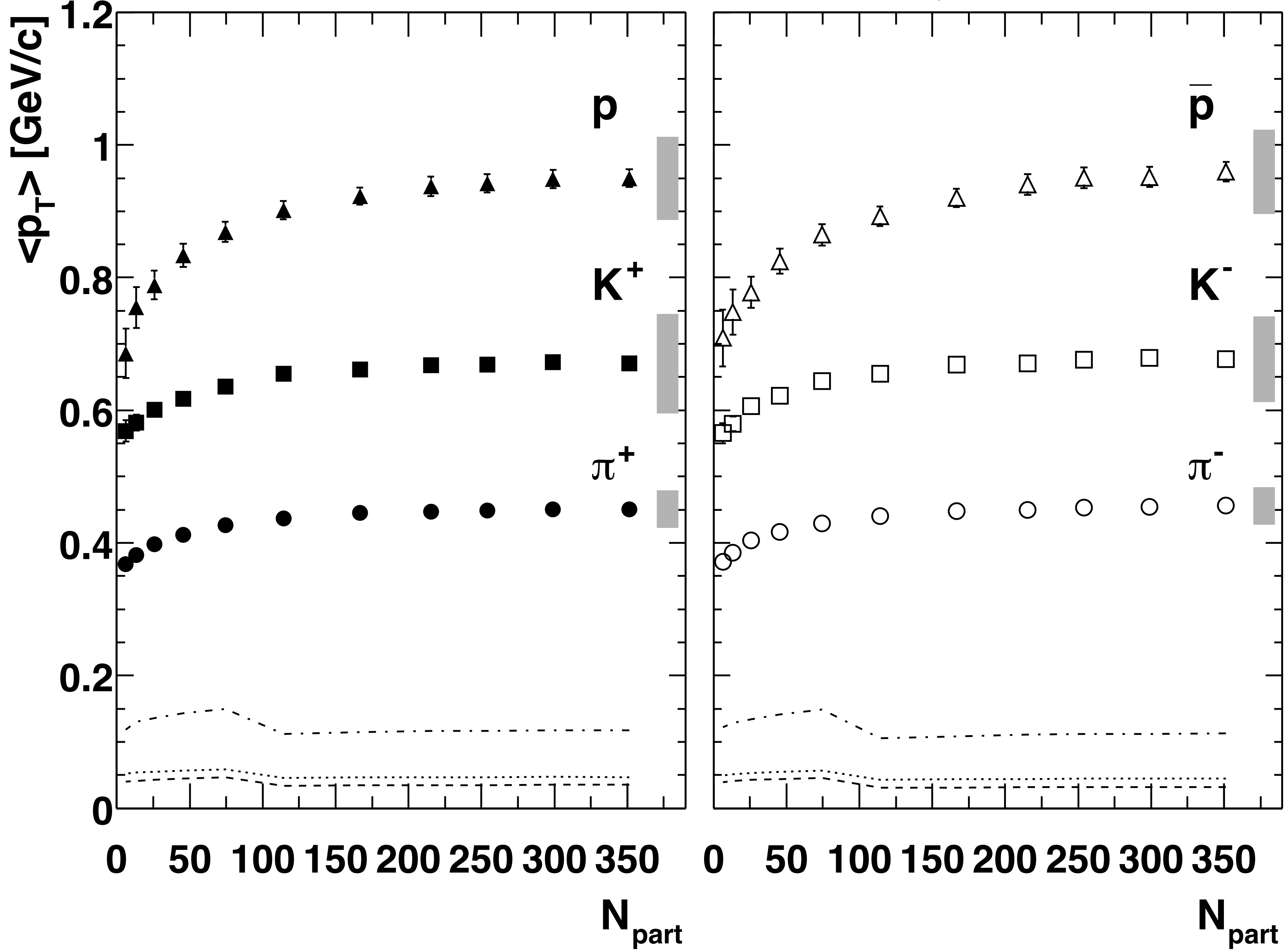
Centrality dependence of dN_{ch}/dη



- dN_{ch}/dη / N_{part} increases with centrality
- Relative increase similar at RHIC and the LHC: Importance of geometry!

Increase of the mean p_T with N_{part} for π, K, p in Au-Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

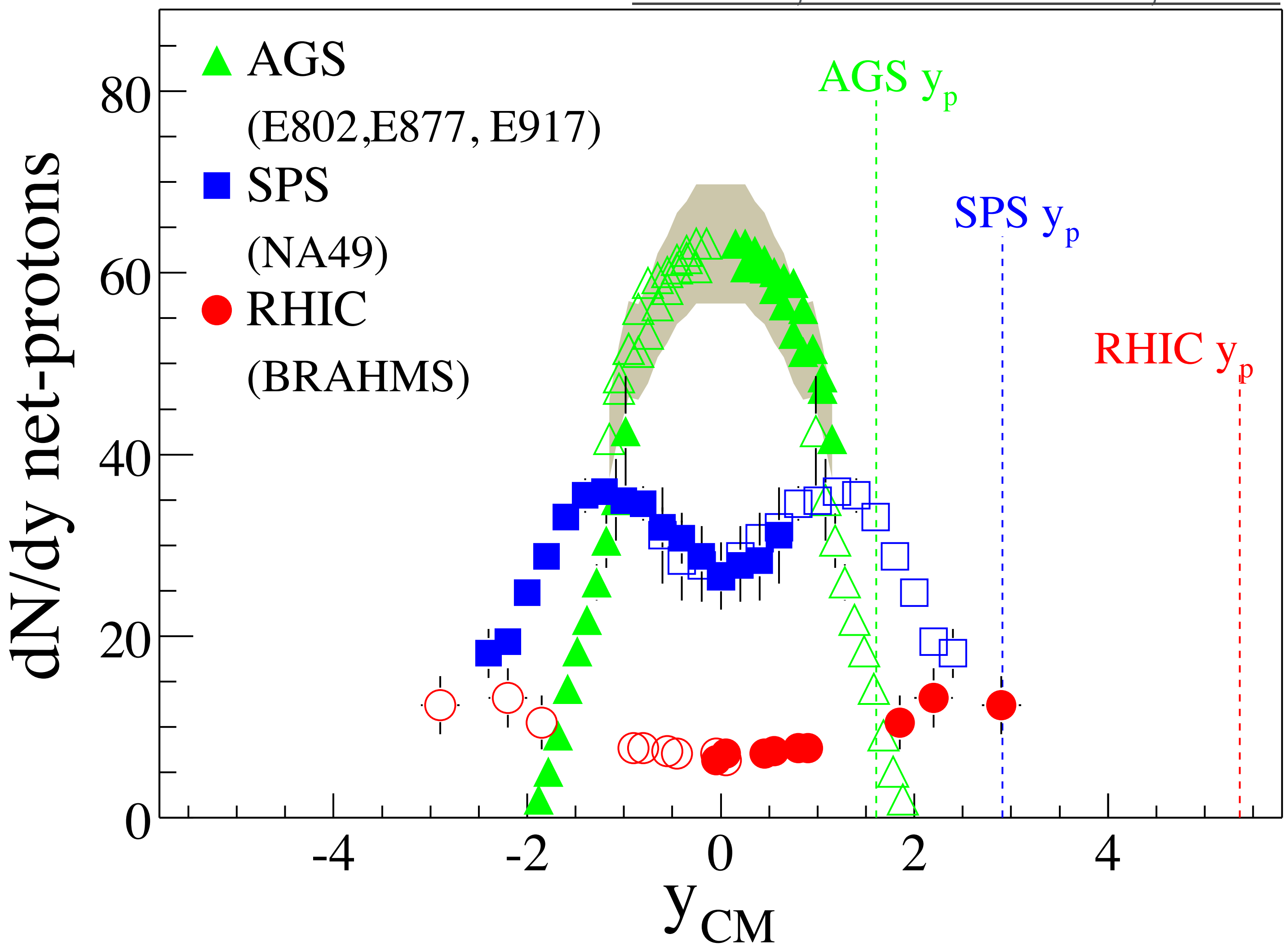
PHENIX, nucl-ex/0410003v3



Strong increase for 2 ≲ N_{part} ≲ 100, relatively constant for larger N_{part}

Nuclear stopping power (Au-Au at $\sqrt{s_{NN}} = 200$ GeV)

Brahms, PRL 93:102301, 2004



- Average rapidity loss

  Initial rapidity:

  $$y_p = 5.36$$

  Net baryons after the collision:

  $$\langle y \rangle = \frac{2}{N_{part}} \int_0^{y_p} y \frac{dN_{B-\bar{B}}}{dy} dy$$

  Average rapidity loss:

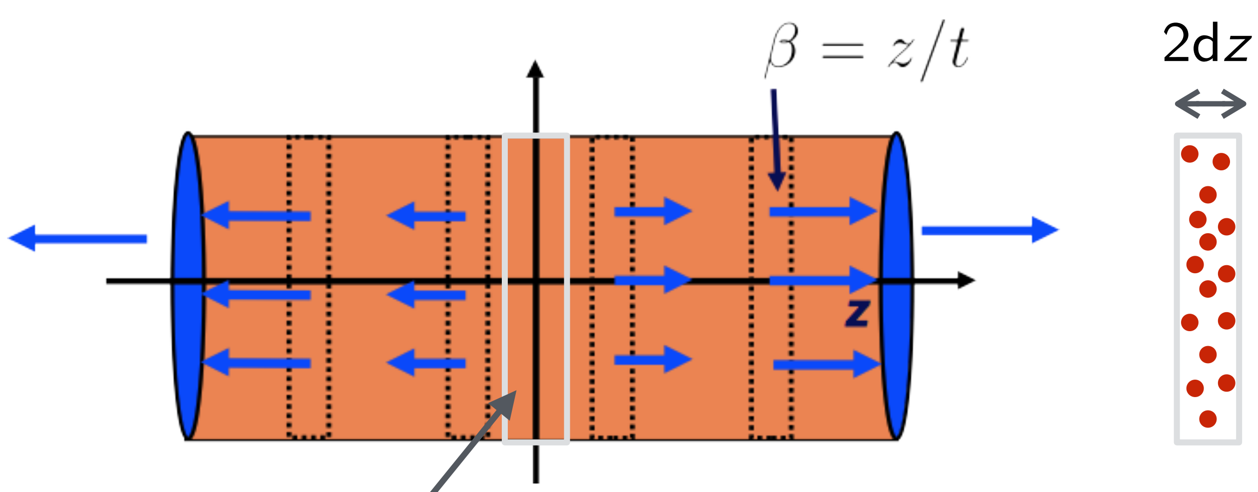
  $$\langle \delta y \rangle = y_p - \langle y \rangle \approx 2$$

- Average energy per (net) baryon

$$E_p = 100\,\text{GeV}, \qquad \langle E \rangle = \frac{1}{N_{part}} \int_{-y_p}^{y_p} \underbrace{\langle m_T \rangle \cosh y}_{E} \frac{dN_{B-\bar{B}}}{dy} dy \approx 27 \pm 6\,\text{GeV}$$

- Average energy loss of a nucleon in central Au+Au@200GeV is 73 ± 6 GeV

Bjorken's formula for the initial energy density



Consider total energy in slice at $z = 0$ at time τ_0

Assumptions:

- Particles (quarks and gluons) materialize at proper time τ_0
- Position z and longitudinal velocity (i.e. rapidity) are correlated
  - So as if particles streamed freely from the origin

$z = \tau \sinh y$

$$\varepsilon = \frac{1}{A} \frac{dE}{dz}\bigg|_{z=0} = \frac{1}{A} \frac{dE_T}{dz}\bigg|_{z=0} = \frac{1}{A} \frac{dE_T}{dy}\bigg|_{y=0} \frac{dy}{dz}\bigg|_{z=0} = \frac{1}{A} \frac{dE_T}{dy}\bigg|_{y=0} \frac{1}{\tau}$$

A = transverse area

$$\varepsilon = \frac{1}{A \cdot \tau_0} \frac{dE_T}{dy}\bigg|_{y=0}, \qquad \tau_0 \approx 1\,\mathrm{fm}/c$$

J.D. Bjorken, Phys.Rev. D27 (1983) 140-151, 2417 citations on inspire.net on Feb. 16, 2016

Energy density in central Pb-Pb collisions at the LHC

$$\varepsilon = \frac{1}{A \cdot \tau_0} \left. \frac{dE_T}{dy} \right|_{y=0}$$

$$= \frac{1}{A \cdot \tau_0} J(y,\eta) \left. \frac{dE_T}{d\eta} \right|_{\eta=0}$$

with $J(y,\eta) \approx 1.09$

Transverse area:

$$A = \pi R_{\mathrm{Pb}}^2 \quad \text{with } R_{\mathrm{Pb}} \approx 7\,\mathrm{fm}$$

Central Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV:

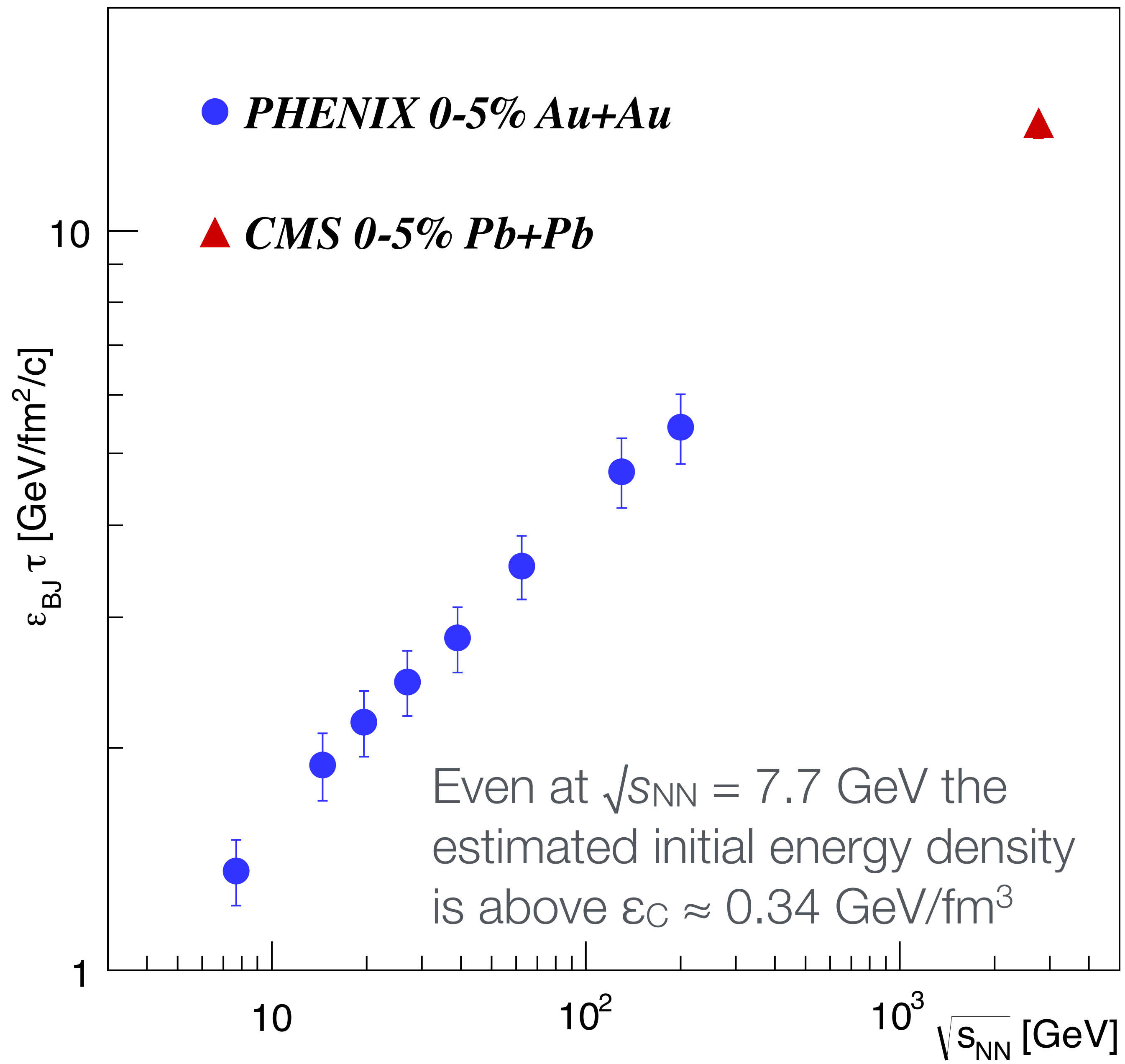
$$dE_T/d\eta = 2000\,\mathrm{GeV}$$

Energy density:

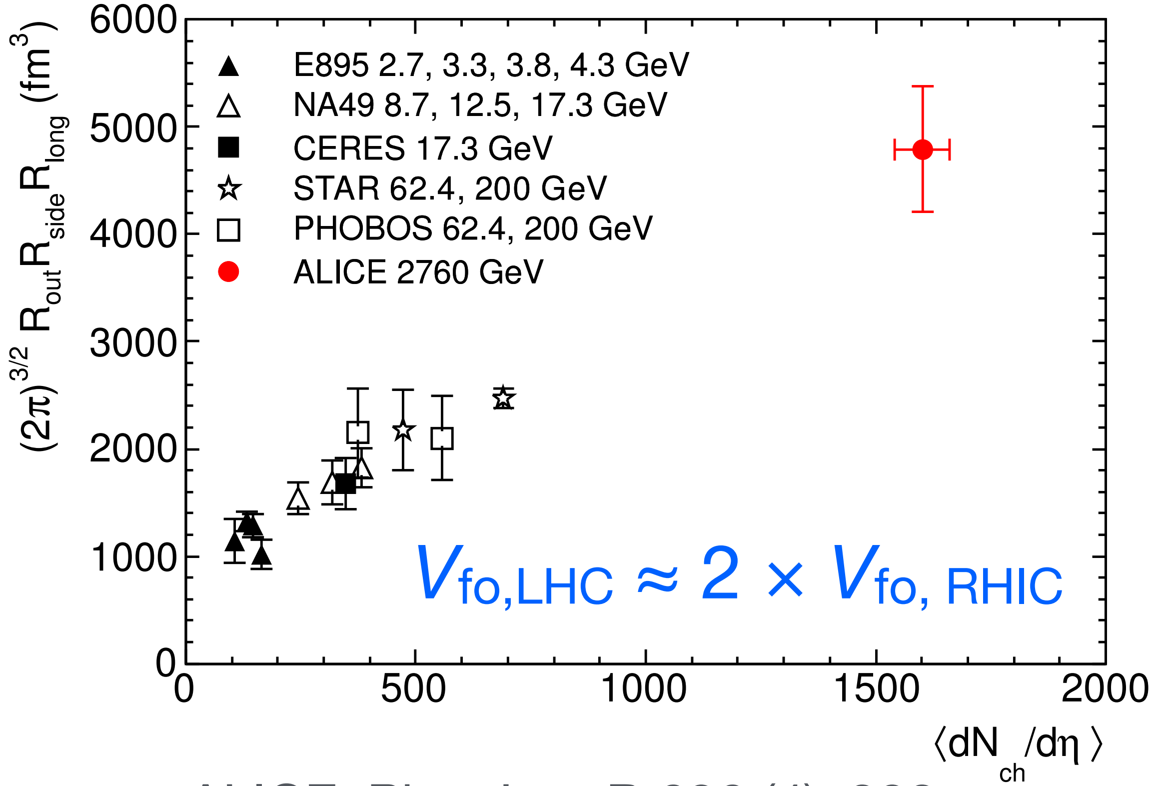
$$\varepsilon_{\mathrm{LHC}} = 14\,\mathrm{GeV/fm^3}$$

$$\approx 2.6 \times \varepsilon_{\mathrm{RHIC}} \text{ for } \tau_0 = 1\,\mathrm{fm}/c$$

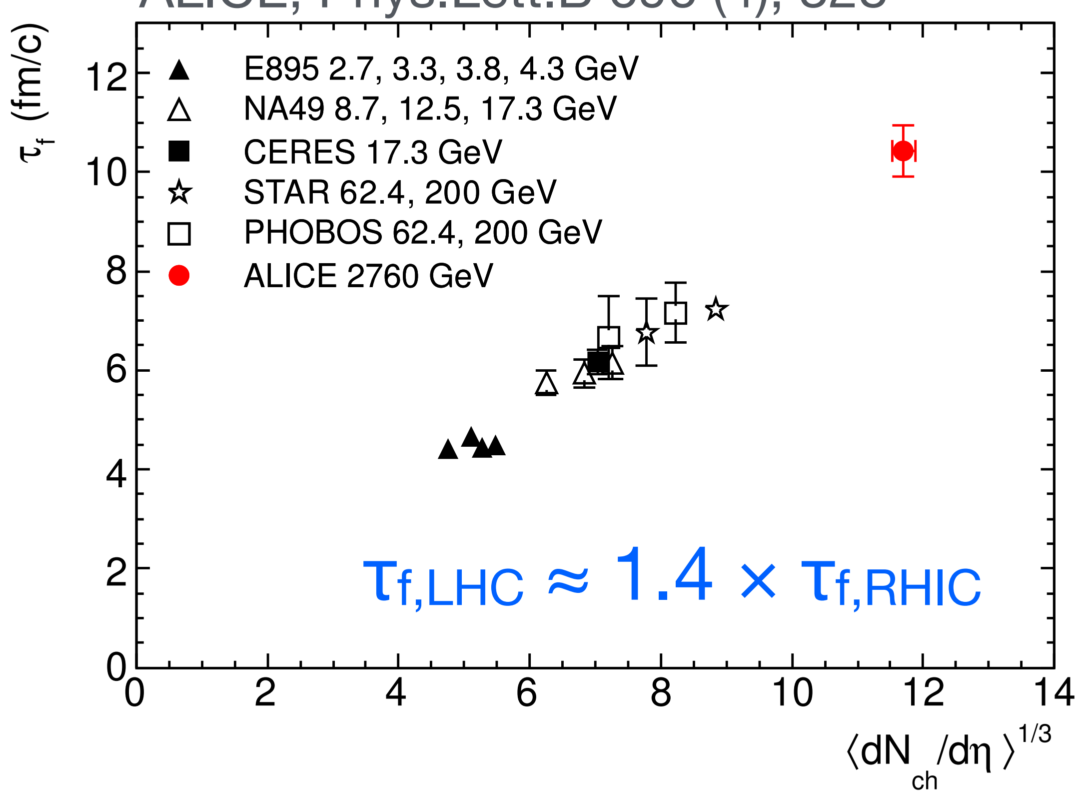
PHENIX, arXiv:1509.06727

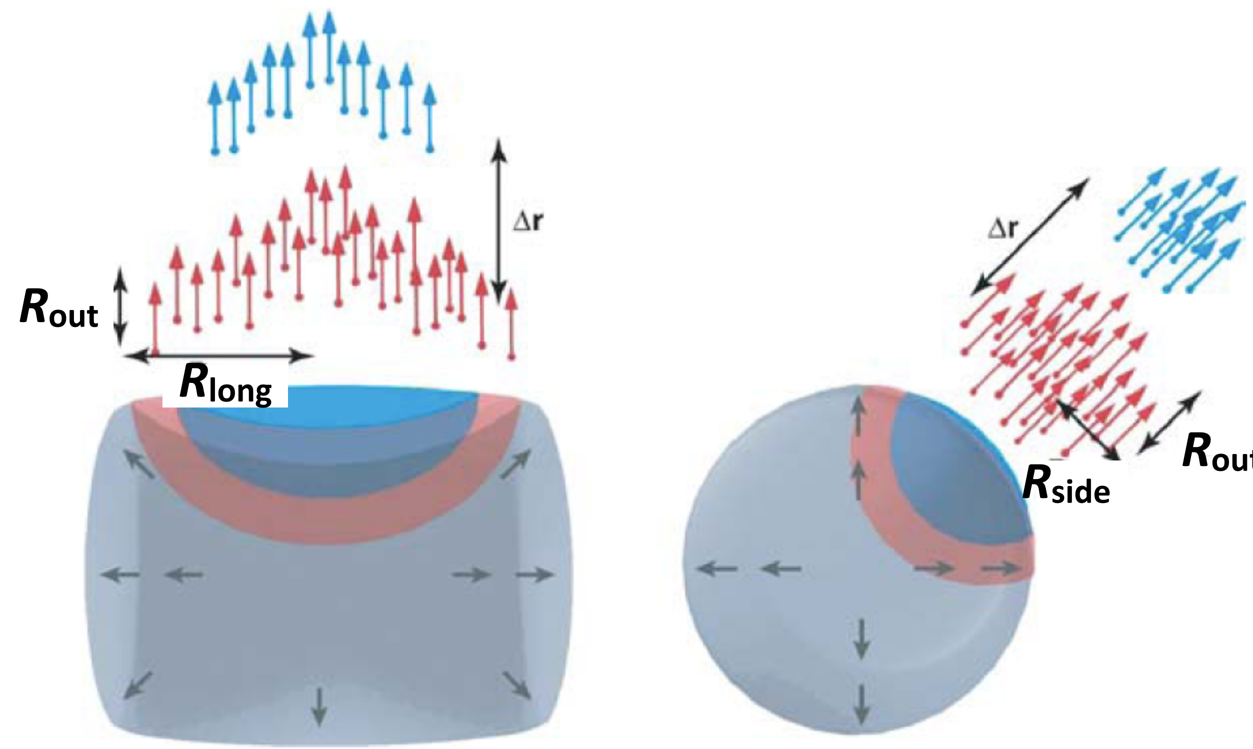


Freeze-out volume and emission time from two-pion Bose-Einstein correlations



ALICE, Phys.Lett.B 696 (4), 328





Freeze-out volume:

$$V_{fo} \sim (2\pi)^{3/2} R_{out} R_{side} R_{long}$$

Emission time: $\tau_f \sim R_{long} \sqrt{m_T / T_f}$

$V_{PbPb,central}$ at the LHC: $\approx 5000\ fm^3$

$V_{Pb} \approx 800\ fm^3$

$\rightarrow\ V_{PbPb,central} \approx\ 6.25 \times V_{Pb}$

Summary: Global properties

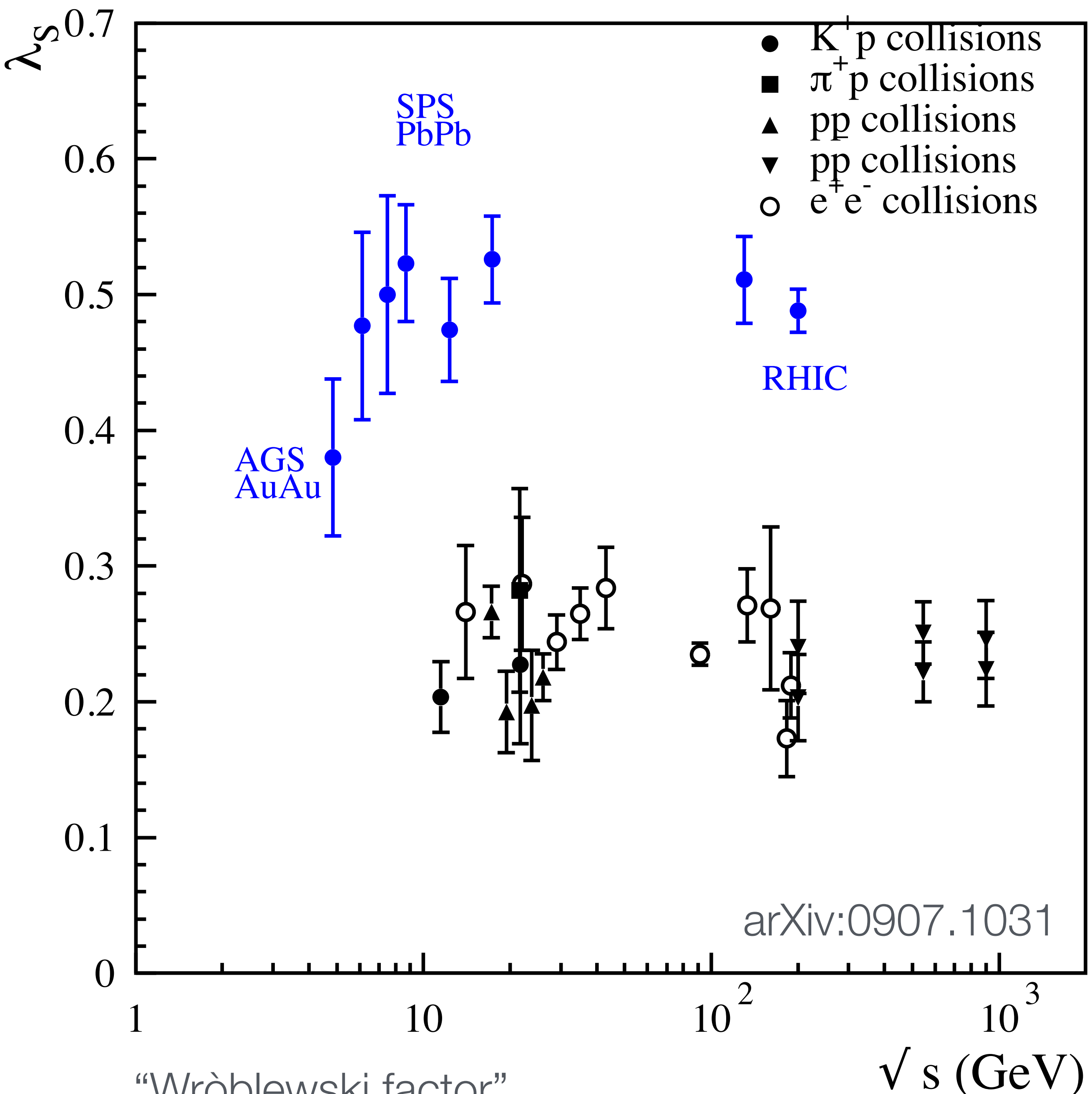
- Up to 18000 charged particles in the full rapidity range in a single central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2760 GeV
- Energy density in heavy-ion collisions at RHIC and the LHC as estimated with Bjorken's formula well above critical energy density
  - Even at $\sqrt{s_{NN}}$ = 7.7 GeV
- Bose-Einstein correlations of identical pions:
  Fireball in Pb-Pb at the LHC lives longer, and expands to a larger size compared to lower energies

4. Strangeness and the statistical model

Is stangeness enhancement a QGP signal?

$$\lambda_s = \frac{2\langle s\bar{s}\rangle}{\langle u\bar{u}\rangle + \langle d\bar{d}\rangle}$$

ratio of newly created valence quark pairs before strong decays (ρ, Δ, …)



"Wròblewski factor", Acta Phys. Pol. B16 (1985) 379

- Bare quark masses in the QGP (chiral symmetry restoration) vs. constituent quark masses in hadronic reactions
  - Easier to produce strange quarks in the QGP

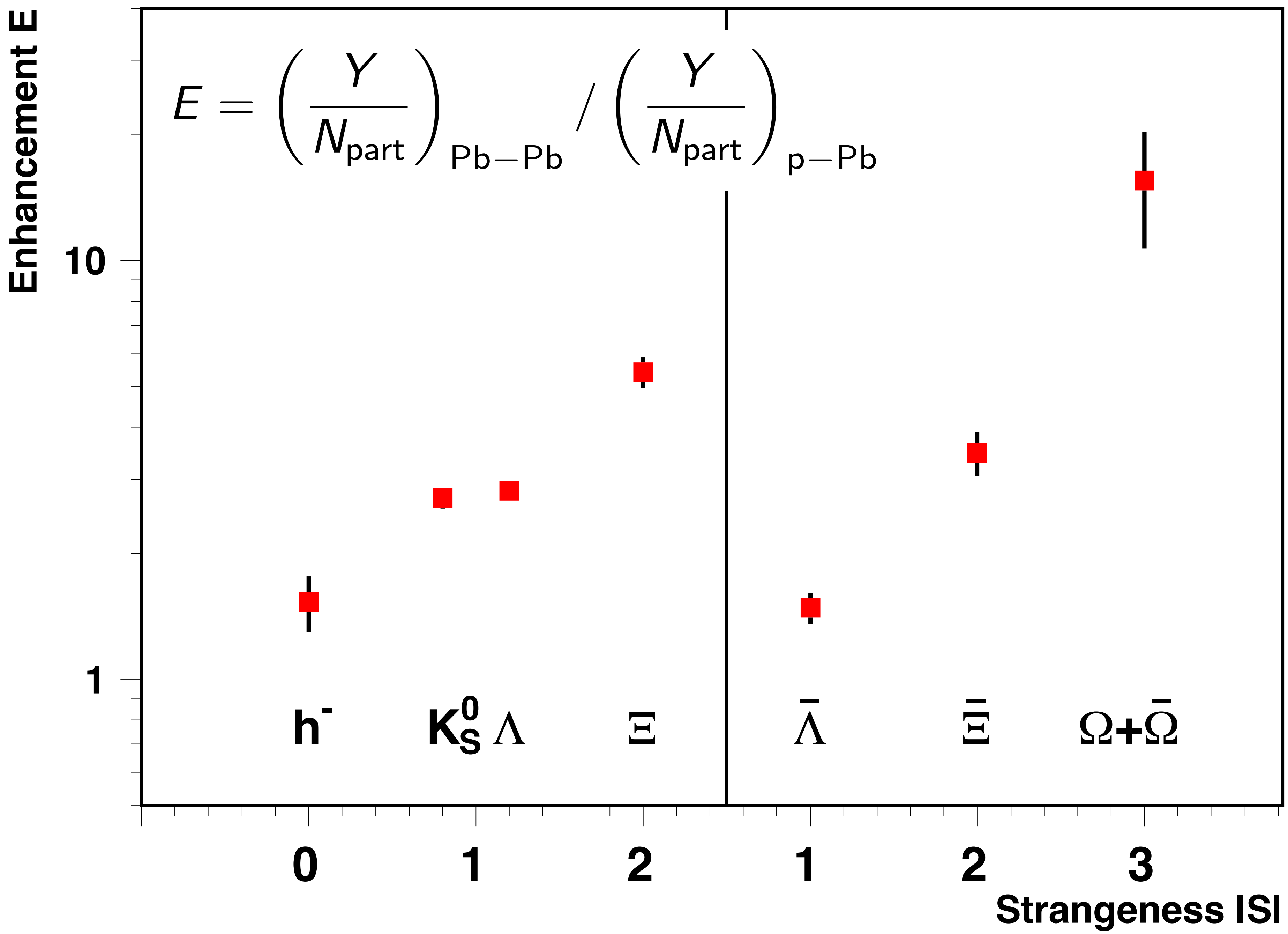
$$g + g \rightleftarrows s + \bar{s}, \quad q + \bar{q} \rightleftarrows s + \bar{s}$$
$$Q \approx 2 m_s \approx 200\,\mathrm{MeV}$$

$$N + N \to N + \Lambda + K,$$
$$Q \approx 670\,\mathrm{MeV}$$

- Strangeness equilibration time in hadron gas too long to reach equilibrium
- Strangeness enhancement: one of the earliest QGP signals

J. Rafelski, B. Müller, PRL 48 (1982) 1066

Strangeness Enhancement in Pb-Pb relative to p-Pb at $\sqrt{s_{NN}}$ = 17.3 GeV



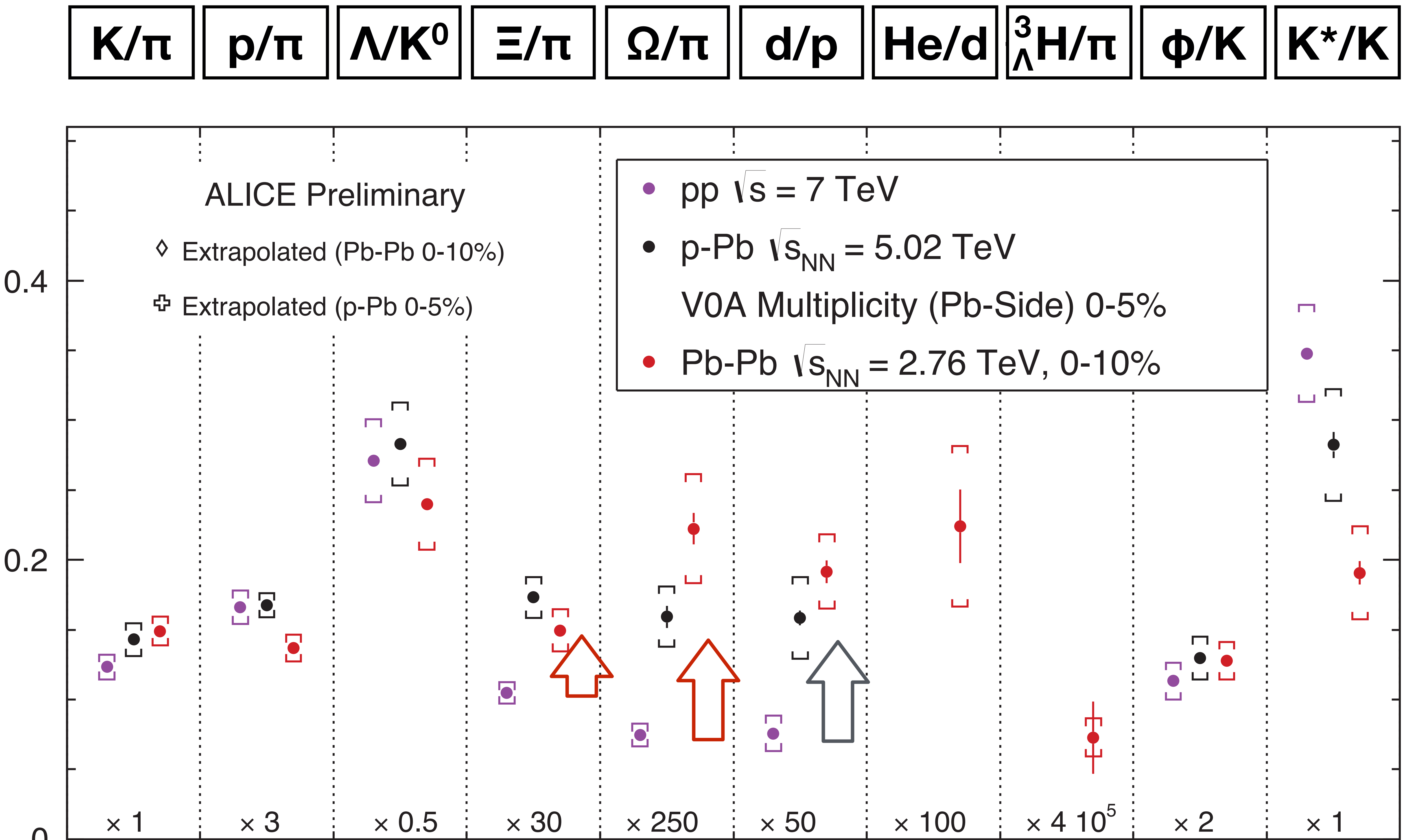
0-40% Pb-Pb
at $\sqrt{s_{NN}}$ = 17.3 GeV

WA97,
PLB 449 (1999) 401,
CERN-EP/99-29

p-Be reference
instead of p-Pb:
similar behavior
(NA57)

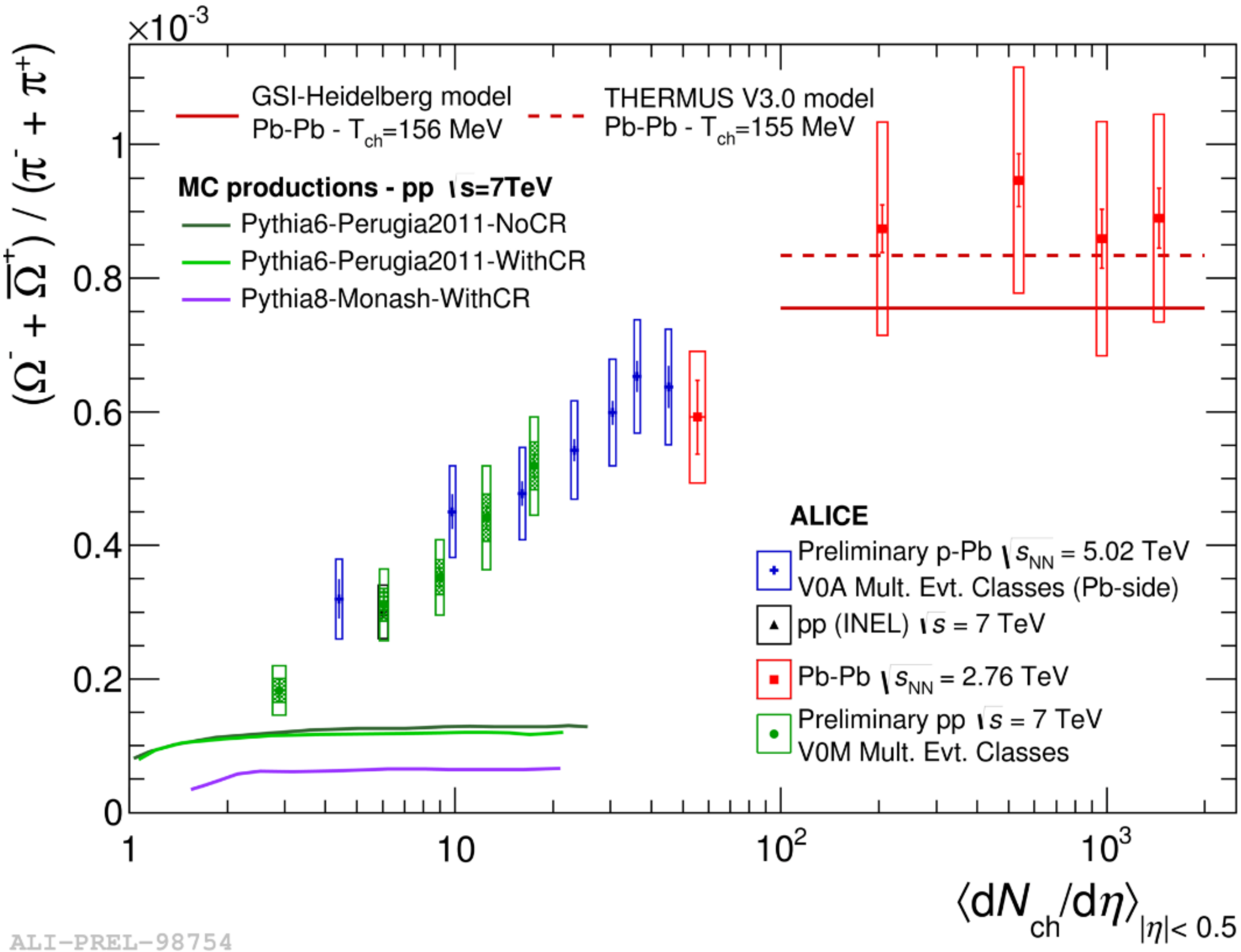
Strangeness enhancement increases with s quark contents
(up to factor 17 for the Ω baryon)

Ξ/π and Ω/π enhancement in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV



Interestingly, ϕ/π very similar in pp, p-Pb, and Pb-Pb

Multiplicity dependence of Ω/π in pp, p-Pb, and Pb-Pb

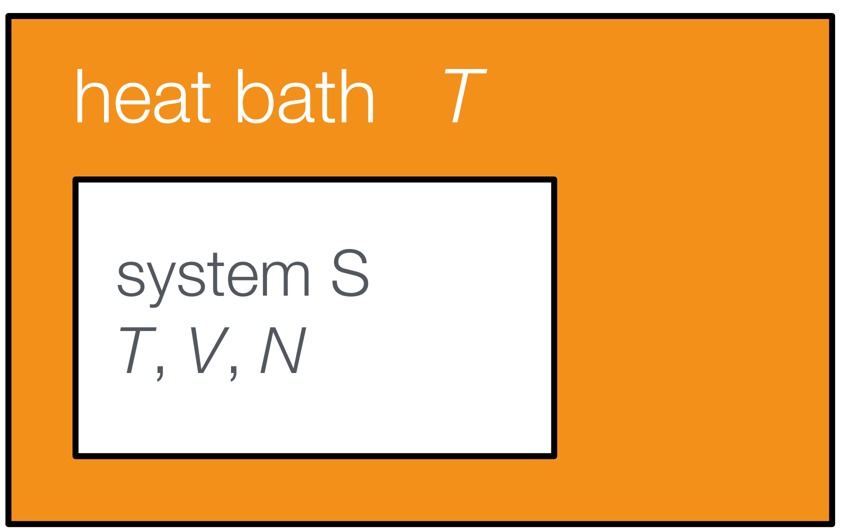


Significant increase in Ω/π with $dN_{ch}/d\eta$ already in pp and p-Pb

Particle yields from the hadron resonance gas

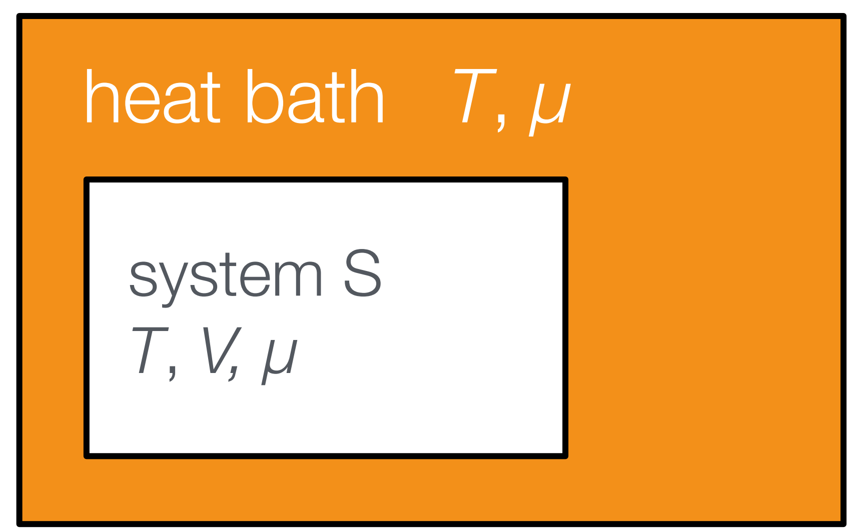
- Idea: Freeze-out of the QGP creates an equilibrated hadron resonance gas
- The HRG then freezes out with a characteristic temperature T_{ch} close to T_c which determines the yields of different particle species
- What is the appropriate statistical ensemble for the theoretical treatment?

canonical ensemble:
N and *V* fixed, energy *E* of the system fluctuates
($E_s + E_b = E$, T is given)



pp collisions, strangeness locally conserved

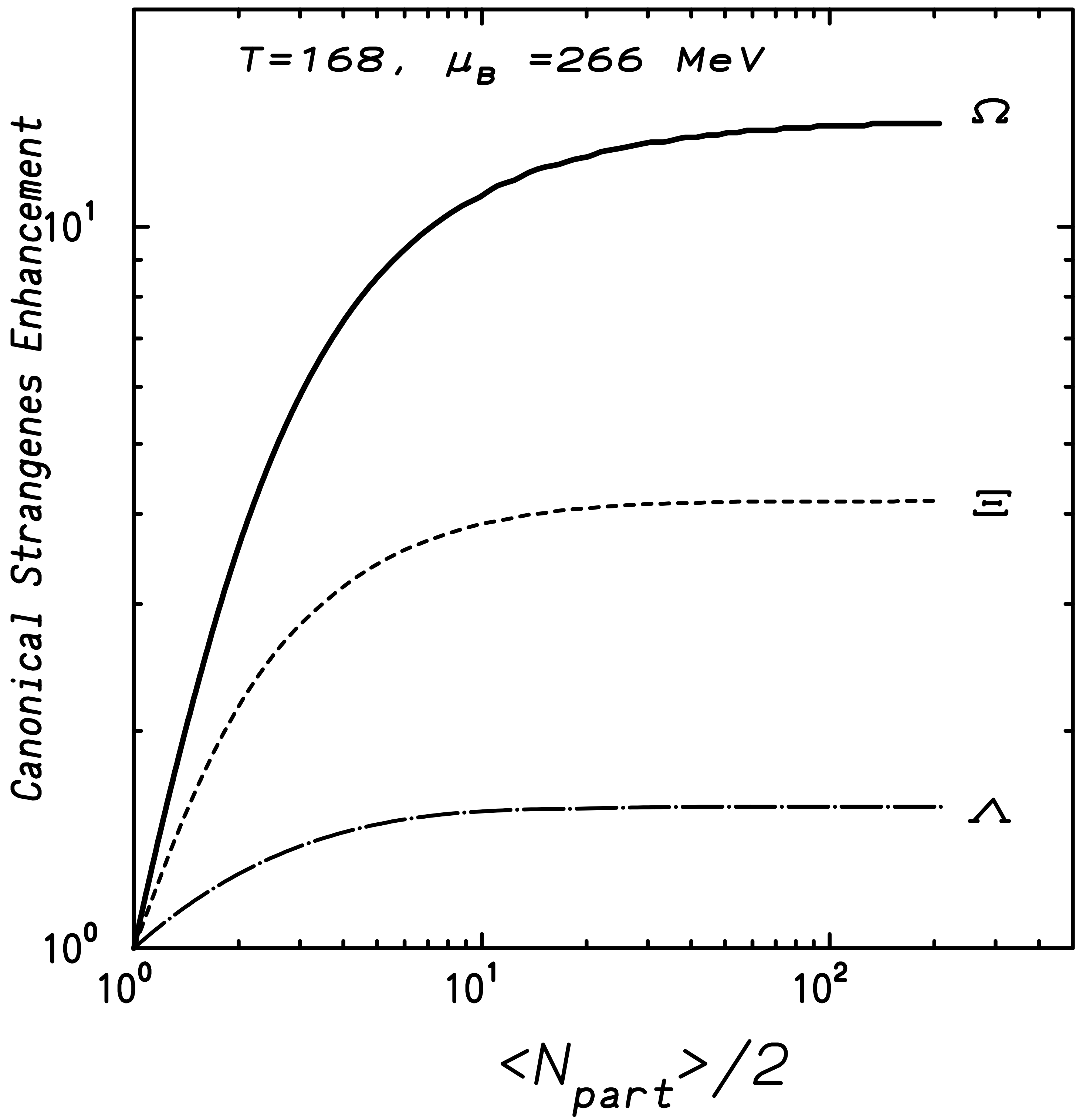
grand-canonical ensemble:
V fixed, energy *E* and particle number *N* fluctuate
(T, μ given)



central A-A collisions, local strangeness fluctuations possible,“there is a medium”

Canonical suppression for small volumes

Braun-Munzinger, Redlich, Stachel, nucl-th/0304013v1



- Particle densities in C and GC approach are related

$$n_K^C = n_K^{GC} \cdot F_S$$

$$F_S = \frac{I_K(2n_K^{GC} V)}{I_0(2n_K^{GC} V)}$$

n_K : Density of particles with strangeness K = |S|, S =-1, -2, -3

I_n : Modified Bessel function of the first kind

- Volume V is assumed to scale as $V \sim N_{\mathrm{part}}$

Particle yields in the grand-canonical ensemble

$g_i = (2\,J_i + 1)$ spin degeneracy factor

$E_i^2 = p_i^2 + m_i^2$

- Partition function (particle species *i*):

$$\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 \mathrm{d}p \, \ln(1 \pm \exp(-(E_i - \mu_i)/T))$$

"-" for bosons, "+" for fermions

- Particle densities:

$$n_i = N/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 \, \mathrm{d}p}{\exp((E_i - \mu_i)/T) \pm 1}$$

- For every conserved quantum number there is a chemical potential:

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3,i}$$

- Use conservation laws to constrain V, μ_s, μ_{I_3}

strangeness: $\sum_i n_i S_i = 0 \quad \to \quad \mu_s$

charge: $V \sum_i n_i I_{3,i} = \frac{Z - N}{2} \quad \to \quad \mu_{I_3}$

baryon number: $V \sum_i n_i B_i = Z + N \quad \to \quad \mu_B$

Only two parameters left (T, μ_B)

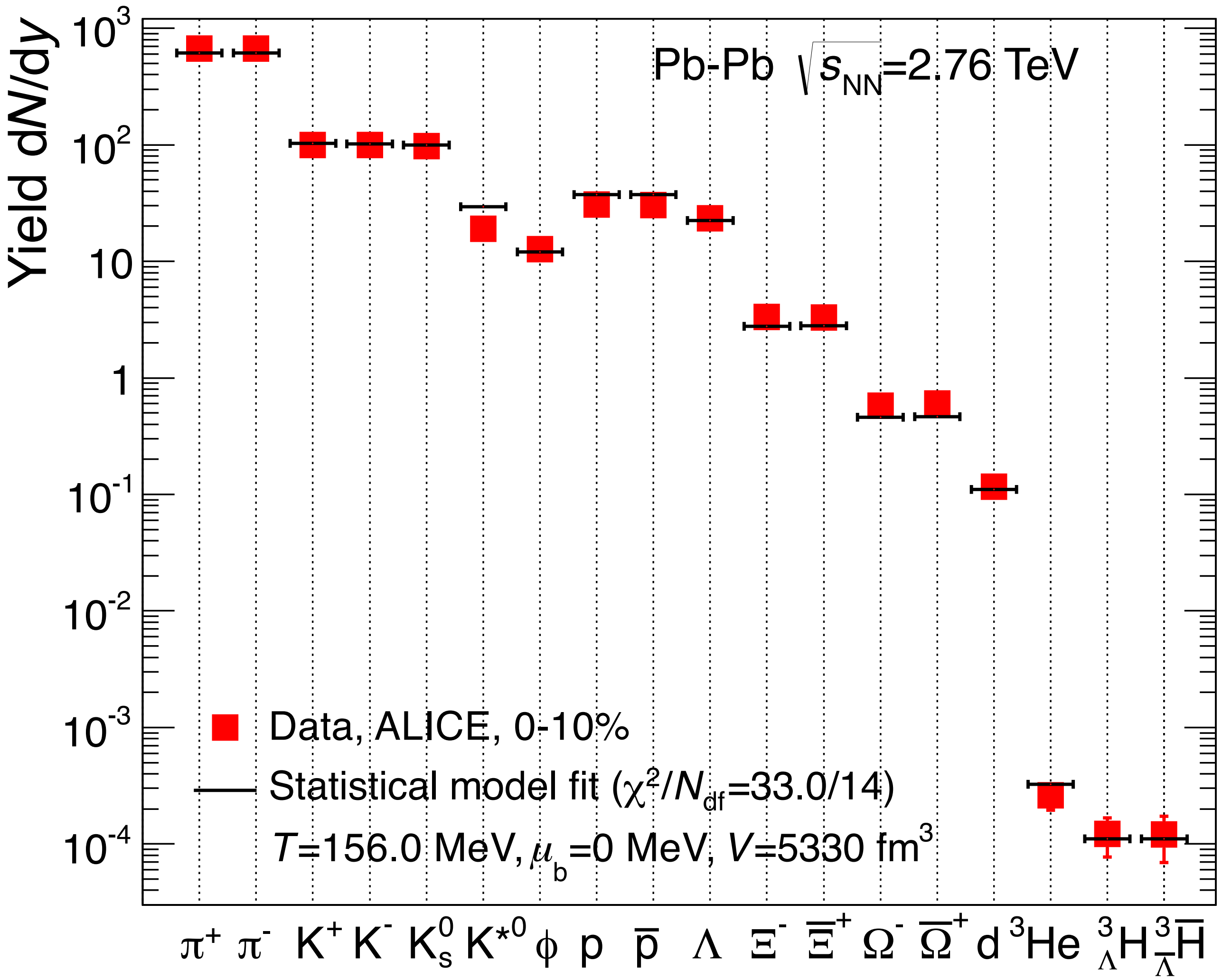
Example: **Boltzmann approximation**

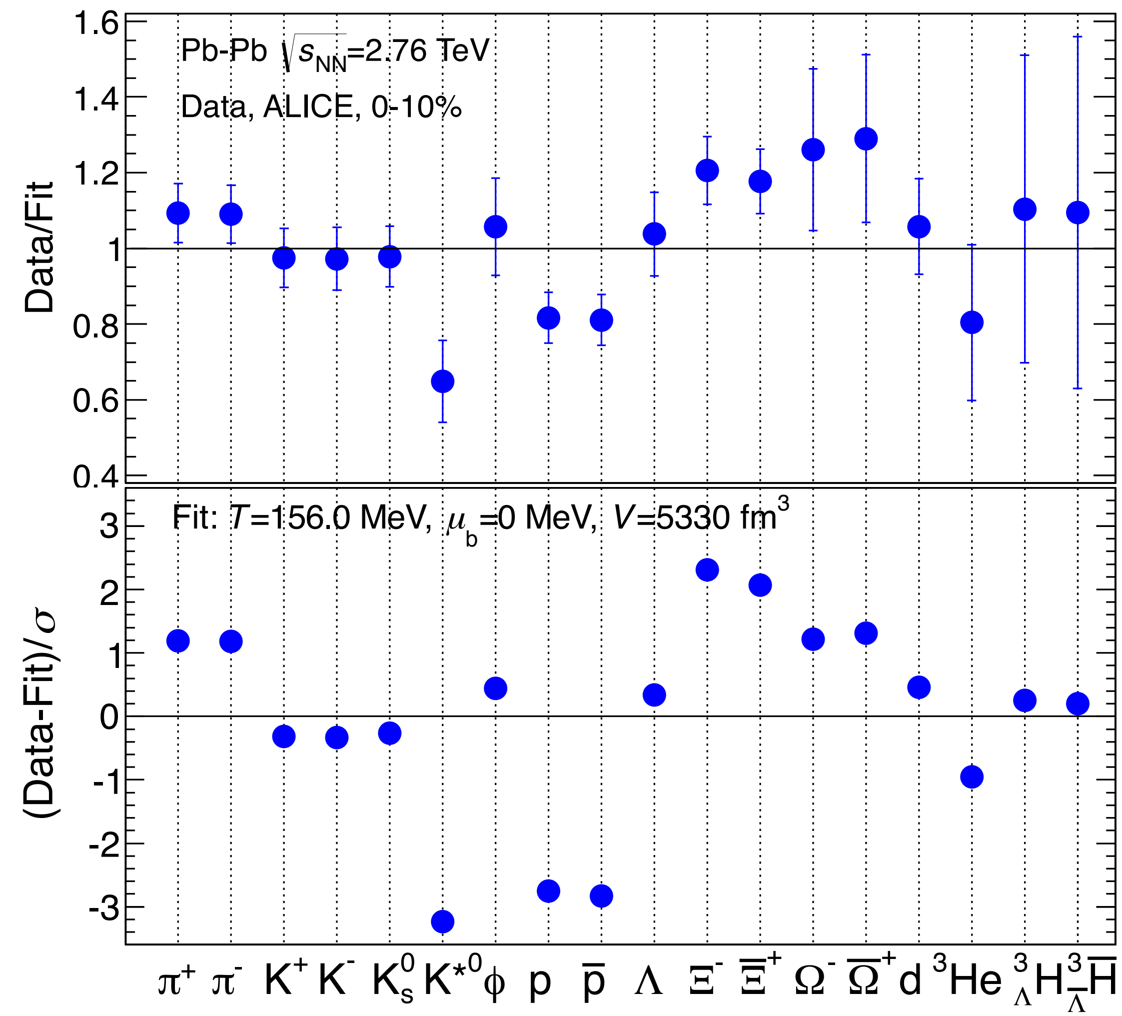
$$n(\bar{p})/n(p) = \exp(-2\mu_B/T)$$

→ determine (T, μ_B) for different $\sqrt{s_{NN}}$ from fits to data

χ^2 fit of the statistical models to LHC data

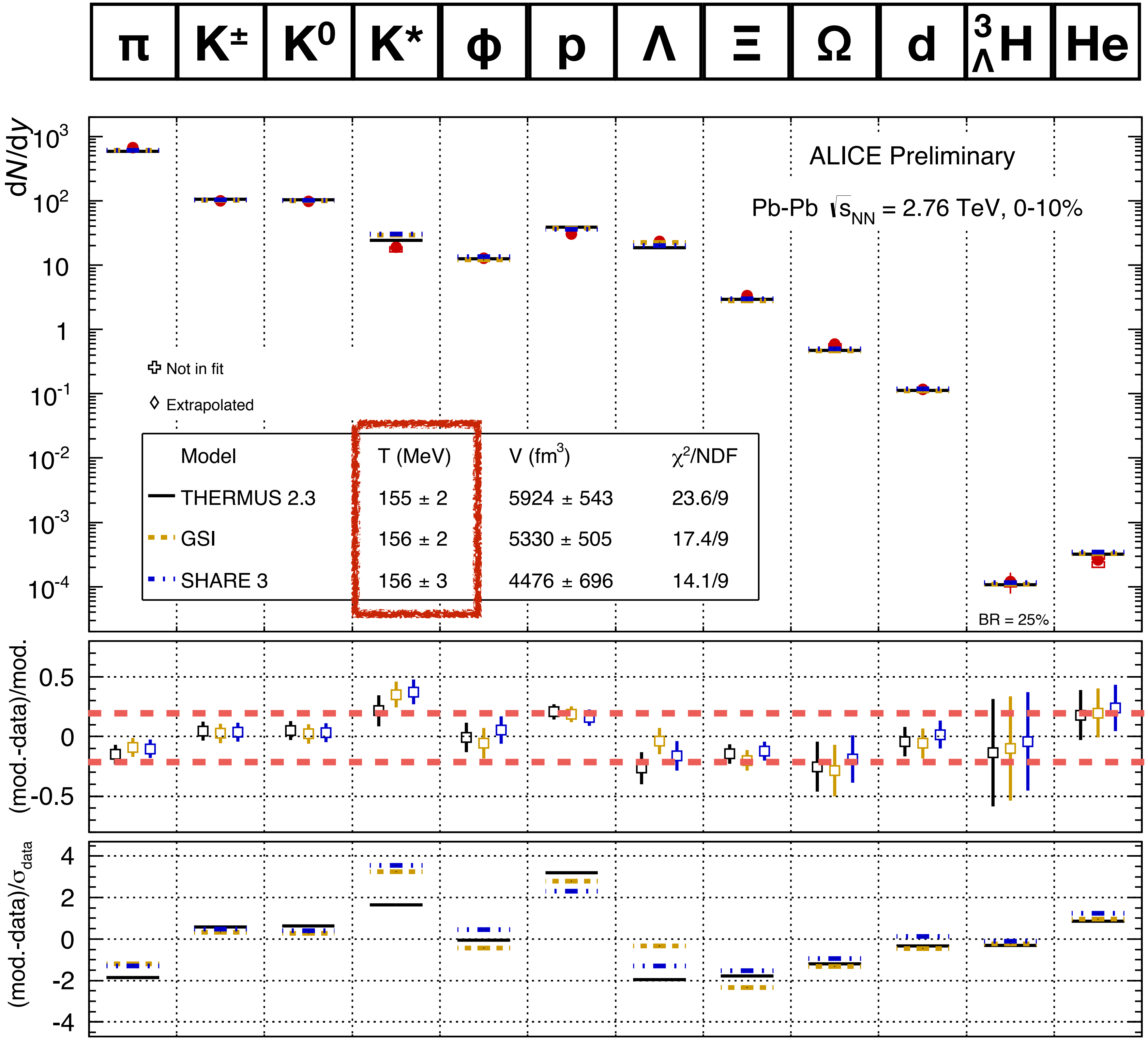
Andronic, Braun-Munzinger, Stachel
arXiv:1106.632, arXiv:1210.7724, arXiv:1311.4662, talk A. Andronic Trento





- Overall good agreement with data
- T = 156 ± 1.5 MeV, μ_B = 0 ± 2 MeV, V = 5330 ± 400 fm^3

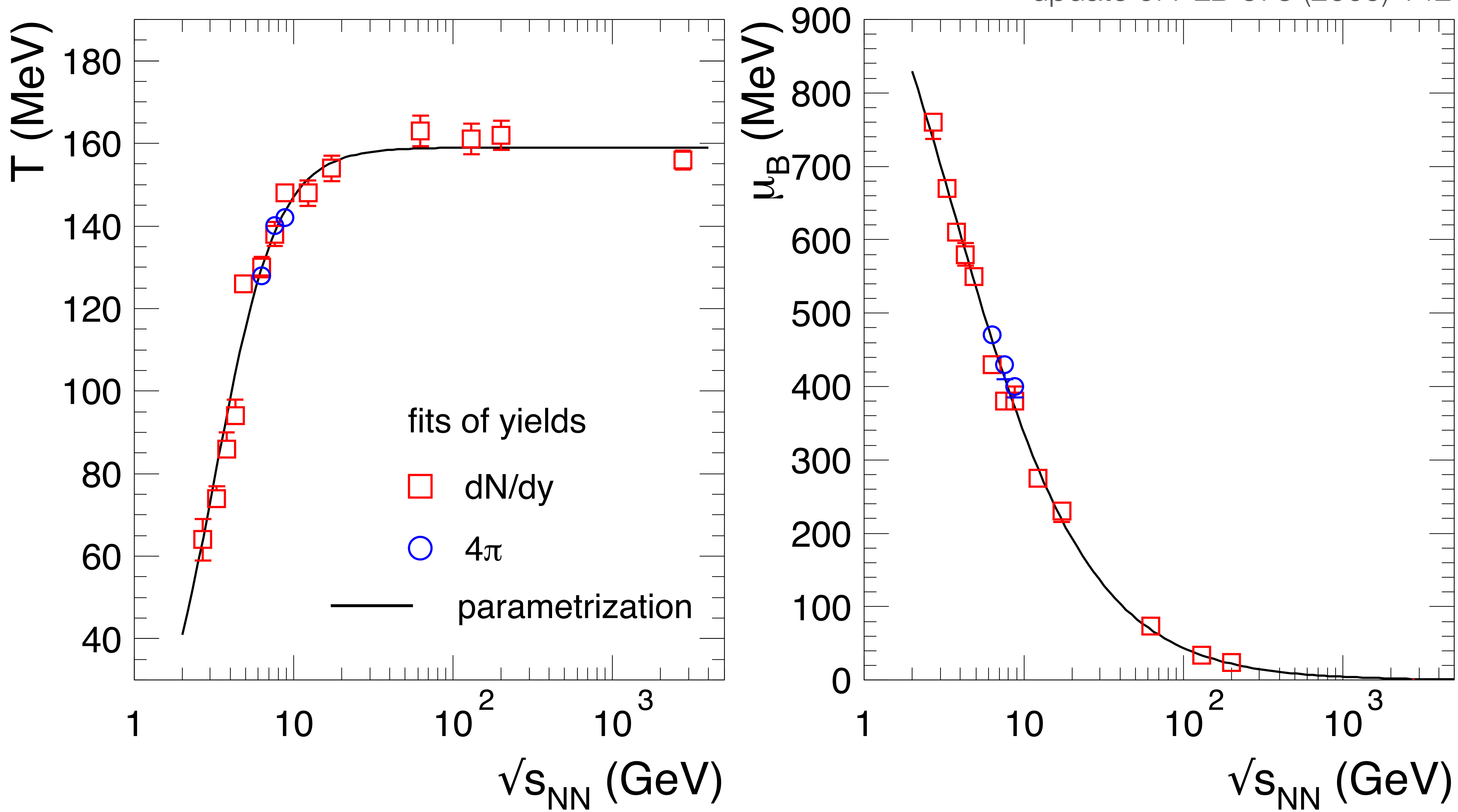
Different thermal models give the same temperature



Model	T (MeV)	V (fm^3)	χ^2/NDF
THERMUS 2.3	155 ± 2	5924 ± 543	23.6/9
GSI	156 ± 2	5330 ± 505	17.4/9
SHARE 3	156 ± 3	4476 ± 696	14.1/9

$\sqrt{s_{NN}}$ dependence of T and μ_B

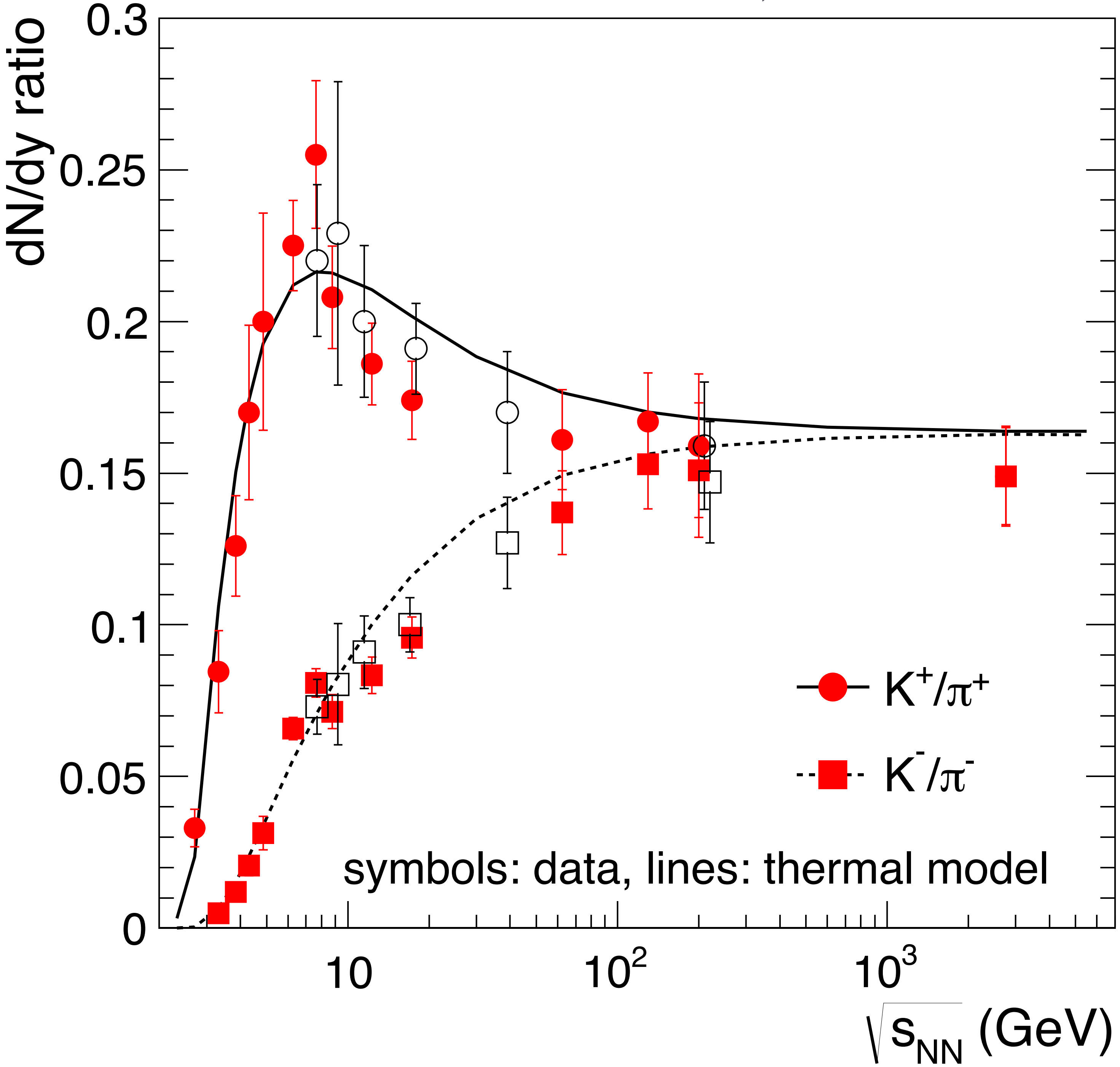
update of PLB 673 (2009) 142



- Smooth evolution of T and μ_B with $\sqrt{s_{NN}}$
- T reaches limiting value of T_{lim} = 159 ± 2 MeV

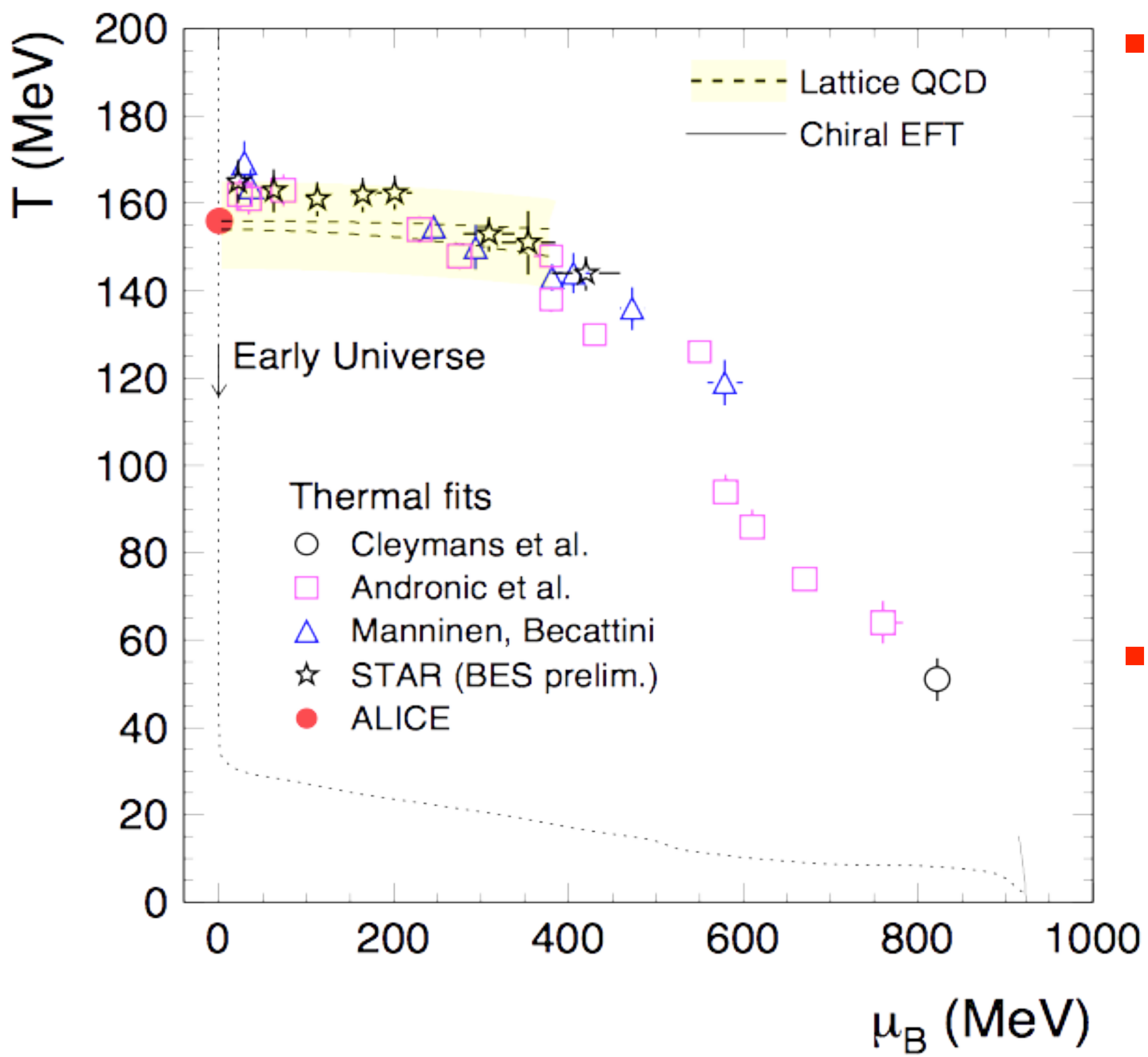
K/π ratio vs. $\sqrt{s_{NN}}$

A. Andronic, arXiv:1407.5003v1



- Maximum in K^+/π^+ ("the horn") was discussed as a signal of the onset of deconfinement at $\sqrt{s_{NN}} \approx$ a few GeV
- However, in the GC statistical model the structure can be reproduced with T, μ_B that vary smoothly with $\sqrt{s_{NN}}$

Freeze-out points for $\sqrt{s_{NN}} \gtrsim 10$ GeV from thermal model fits coincide with T_c from lattice calculations



- What is the origin of equilibrium particle yields?
  - General property of the QCD hadronization process ("particle born into equilibrium")
  - Or does the hadron gas thermalizes via particle scattering after the transition?
- Possible mechanism for fast thermalization after the transition: multi-hadron scattering resulting from high particle densities

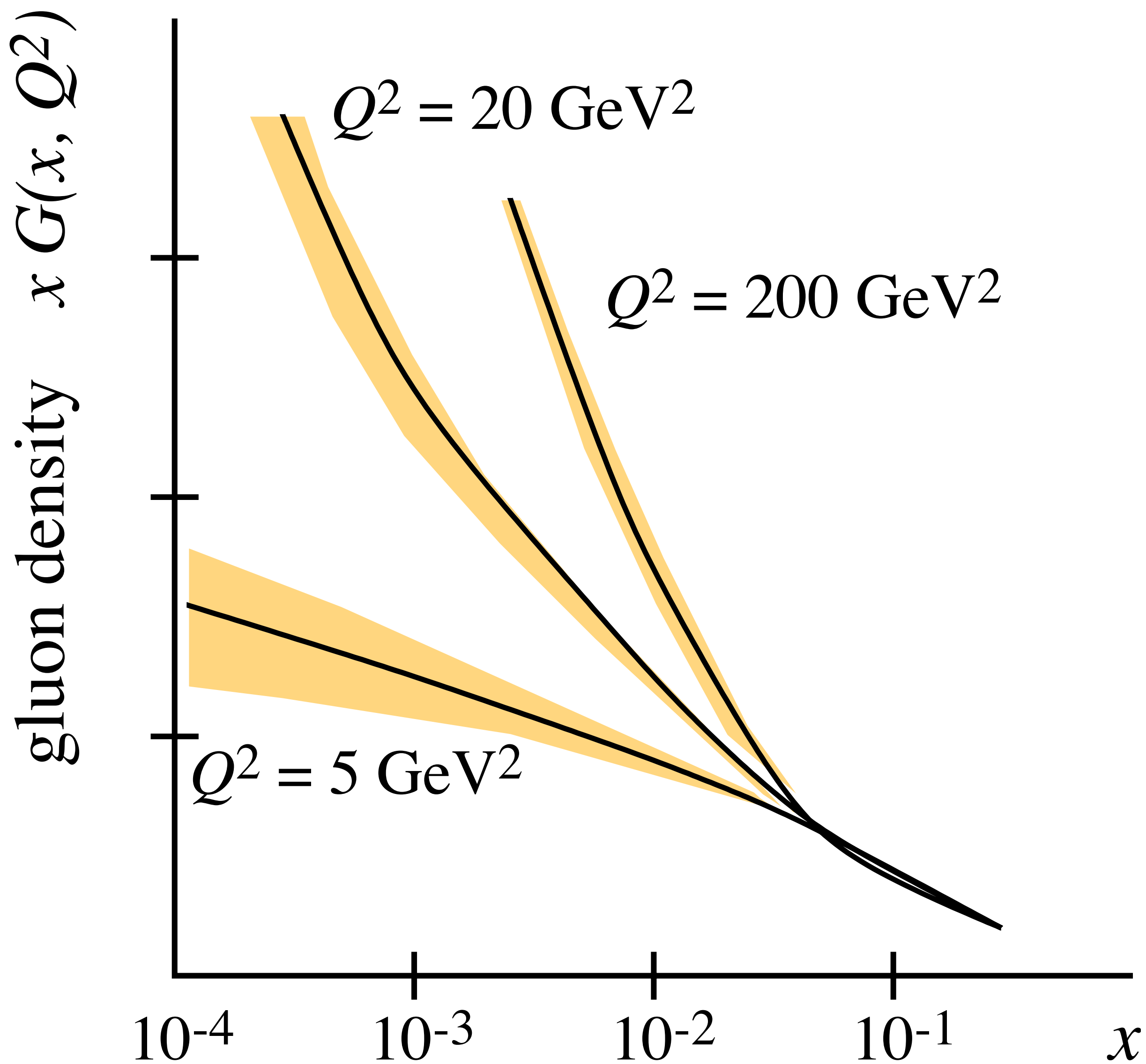
Braun-Munzinger, Stachel, Wetterich, PLB 596 (2004) 61

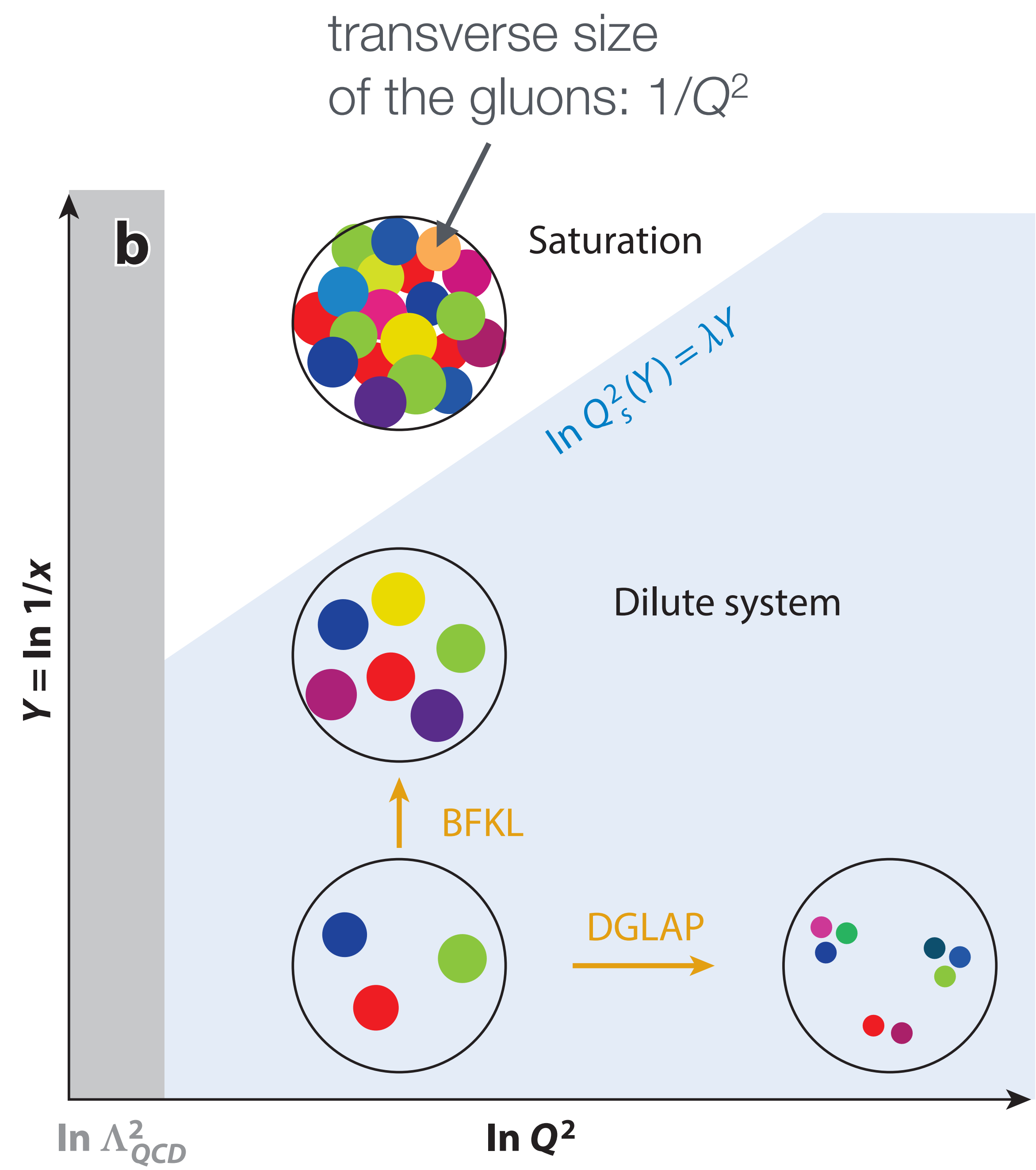
Summary/questions strangeness

- Strangeness is enhanced in A-A collisions relative to e^+e^- and pp
- LHC: Strangeness enhancement in high-multiplicity pp collisions approaches the enhancement in Pb-Pb
  - Not predicted by Pythia
- Origin of the strangeness enhancement?
  - Typical hadronic cascade codes (e.g. UrQMD) cannot explain the enhancement
  - Does the volume associated with strangeness production becomes larger in A-A collisions (relaxation of canonical suppression)?
  - Can one understand the fast thermalization of the hadron gas?
  - Or maybe coalescence of strange quarks from the QGP?
- Strangeness provides important information and probably points to QGP formation
  - However, a better understanding of the mechanisms of strangeness enhancement is needed

5. Space-time evolution of the QGP

The initial parton wave function: Gluon saturation



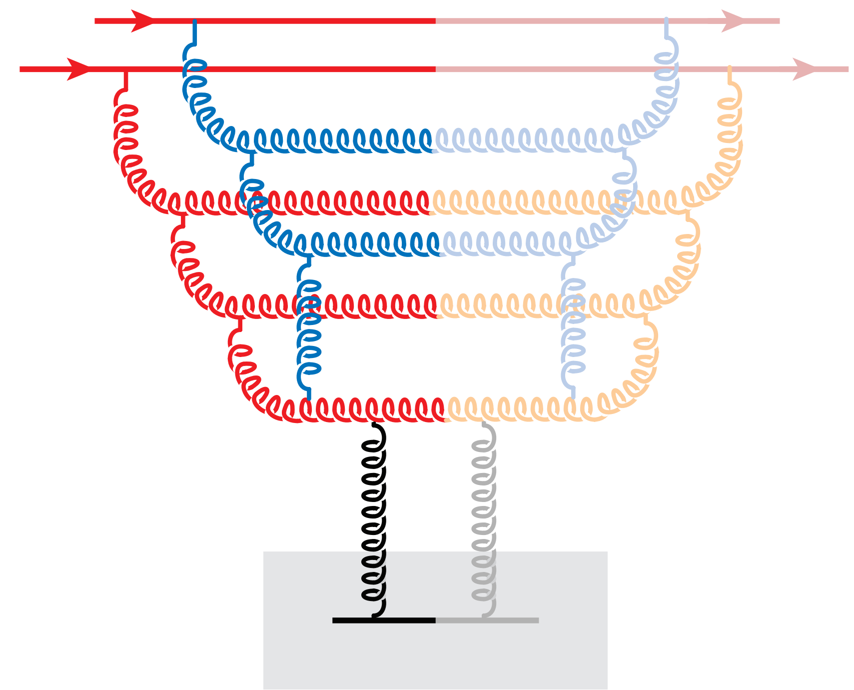


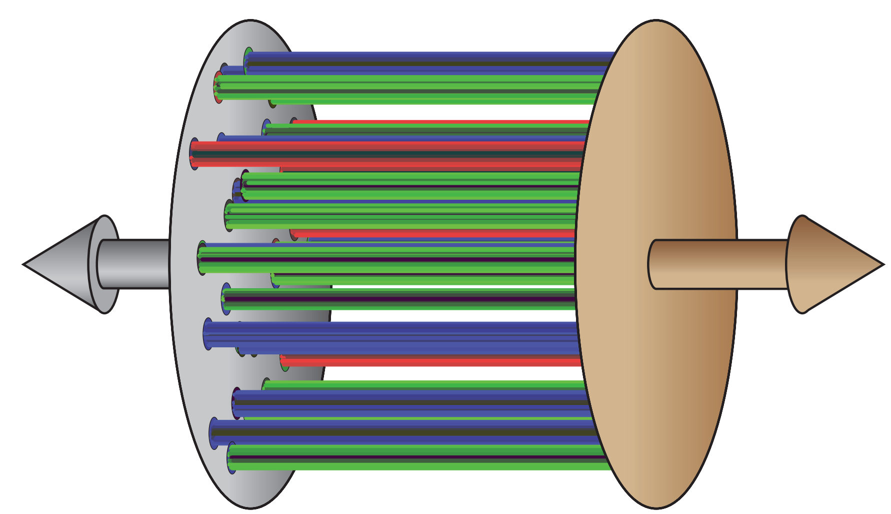
Growth of gluons saturates at an occupation number $1/\alpha_s$. This defines a (semihard) scale $Q_s(x)$, i.e., a typical gluon transverse momentum.

$$\frac{1}{2(N_c^2-1)}\frac{xG(x,Q_s^2)}{\pi R^2 Q_s^2} = \frac{1}{\alpha_s(Q_s^2)}$$

The color glas condensate model

- Color glass condensate:
  Effective field theory, which describes universal properties of saturated gluons in hadron wave functions
- Separation of timescales:
  Dynamical fields coupled to the static color sources
- CGC dynamics produces so-called glasma-field configurations at early times
  - Strong longitudinal chromoelectric and chromomagnetic fields screened on transverse distance scales $1/Q_S$.

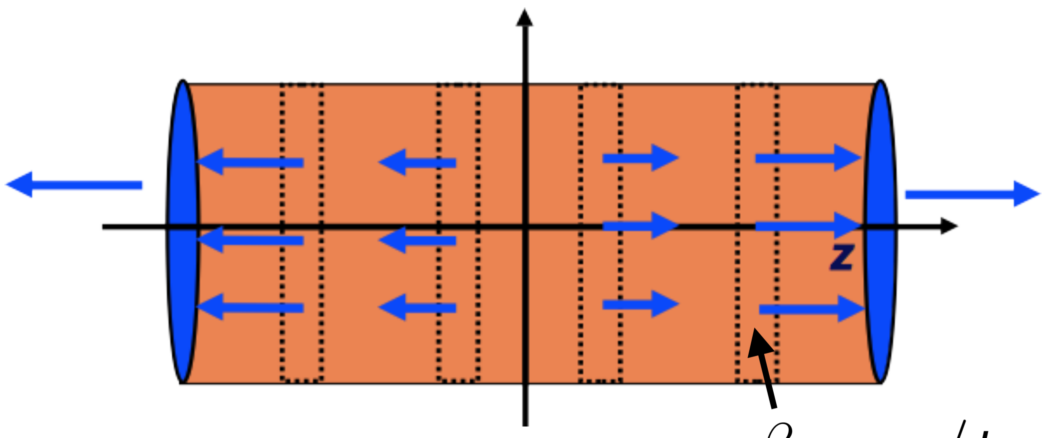




Annu. Rev. Nucl. Part. Sci. 2010.60:463

Longitudinal expansion: 1+1 d ideal hydrodynamics (Bjorken model)

$$\tau = t/\gamma = t\sqrt{1-\beta_z^2} = \sqrt{t^2 - z^2}$$



$\beta_z = z/t$

Thermodynamic quantities depend only on proper time τ (not on (t,z) separately)

Initial conditions:

$$\varepsilon(\tau_0) = \varepsilon_0, \quad u^\mu = \frac{1}{\tau_0}(t,0,0,z) = \frac{x^\mu}{\tau_0}$$

For an ideal gas ($\varepsilon = 3p$, $\varepsilon \sim T^4$) one obtains:

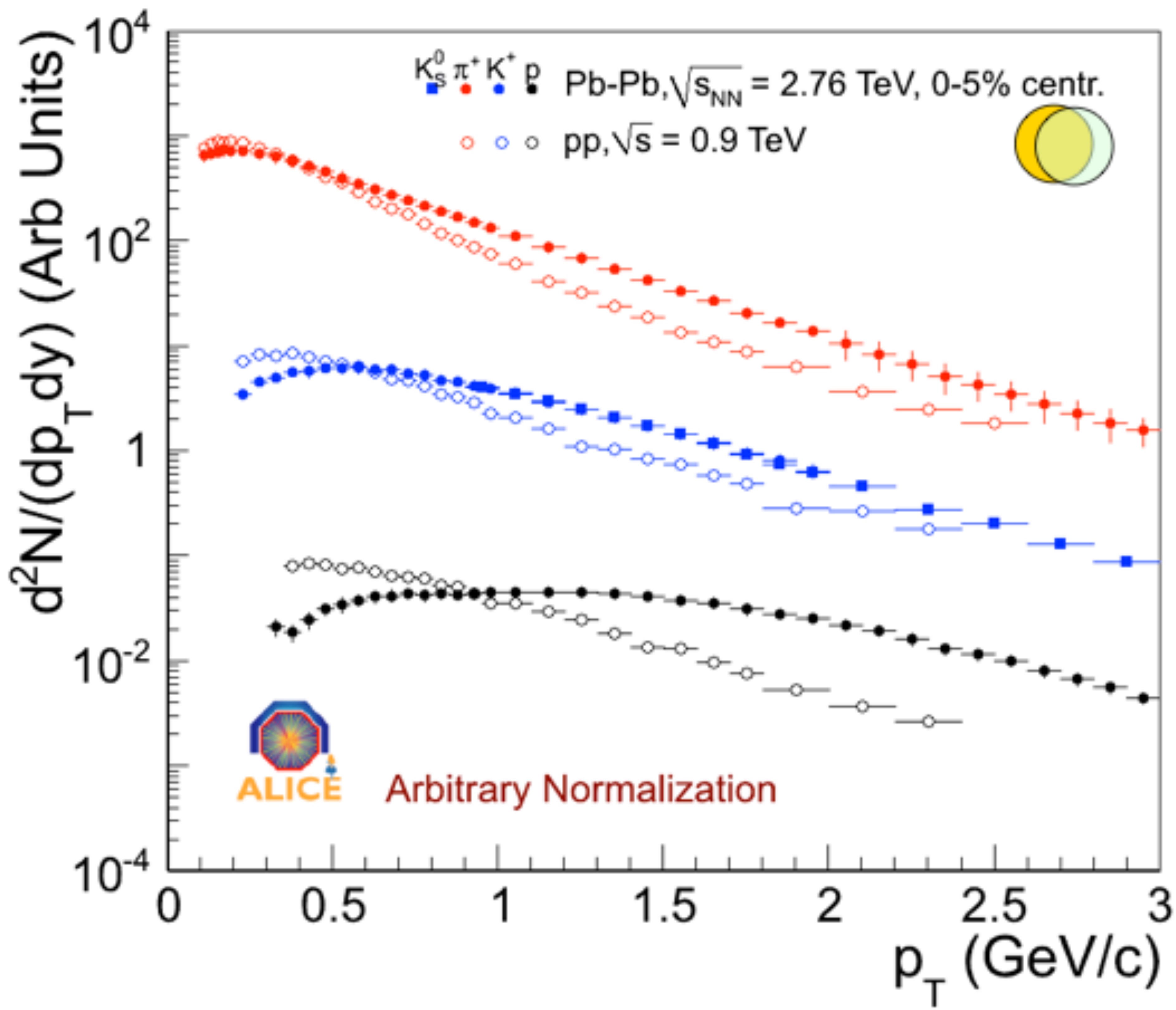
$$\varepsilon(\tau) = \varepsilon_0 \left(\frac{\tau}{\tau_0}\right)^{-4/3}, \quad T(\tau) = T_0 \left(\frac{\tau}{\tau_0}\right)^{-1/3}, \quad s = \frac{\varepsilon + p}{T} = \frac{s_0 \tau_0}{\tau}$$

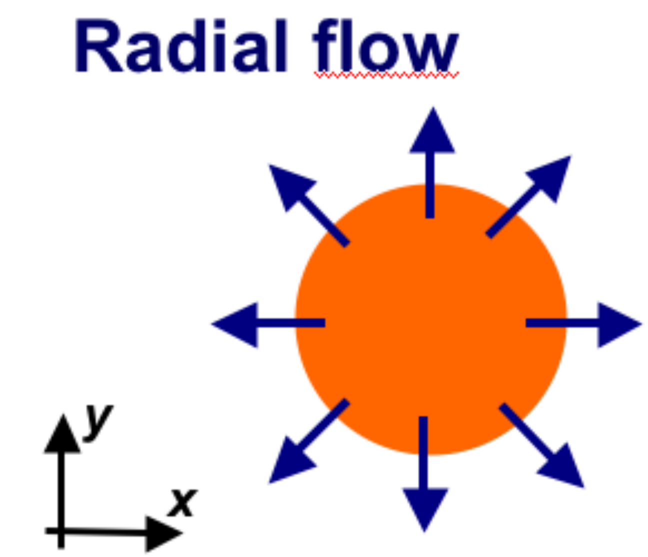
With $dV = dA\,\tau\,dy$ one gets for the entropy S:

$$\frac{dS}{dA\,dy} = s\tau = \text{const.} \quad \rightarrow \quad \frac{d}{d\tau}\left(\frac{dS}{dy}\right) = 0$$

The entropy per unit of rapidity is constant during the hydrodynamical evolution

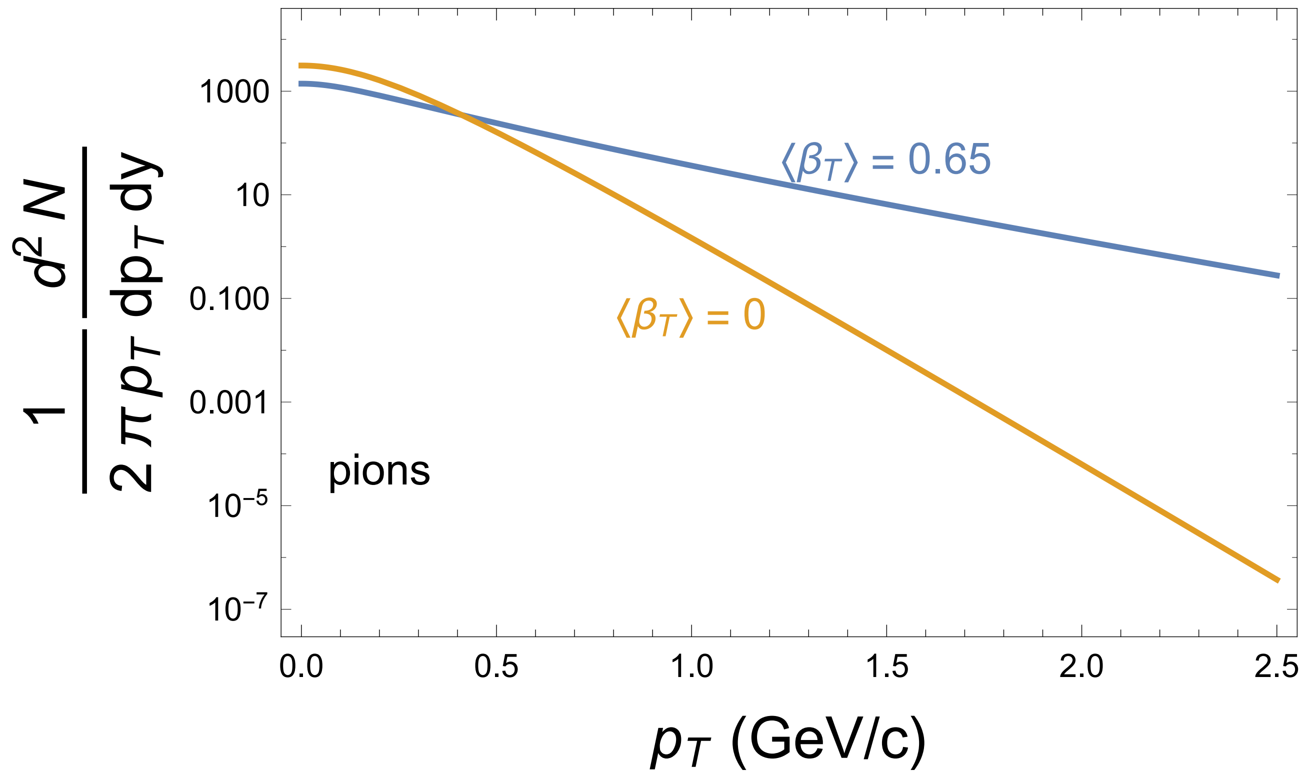
Radial flow

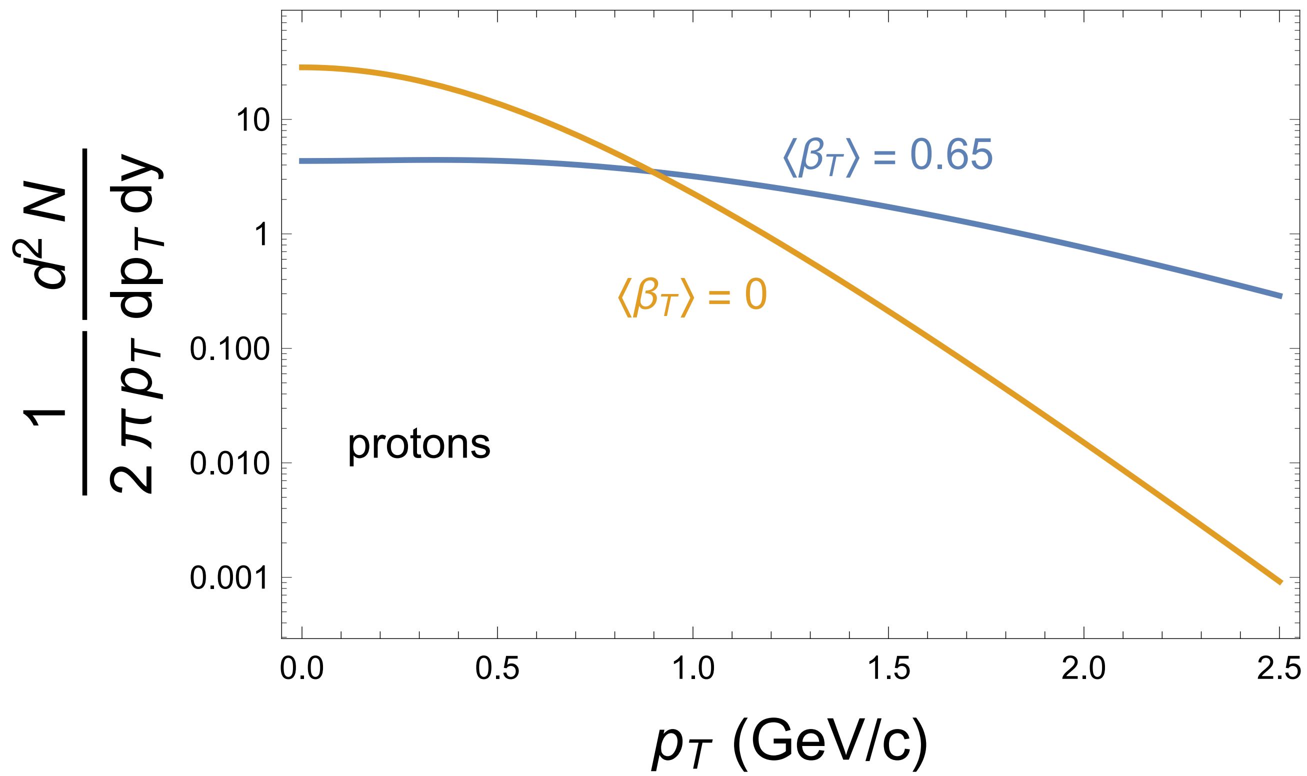




Change of shape of p_T spectra from pp to Pb-Pb as expected from radial flow

Blast-wave model:
Change of slope due to radial flow



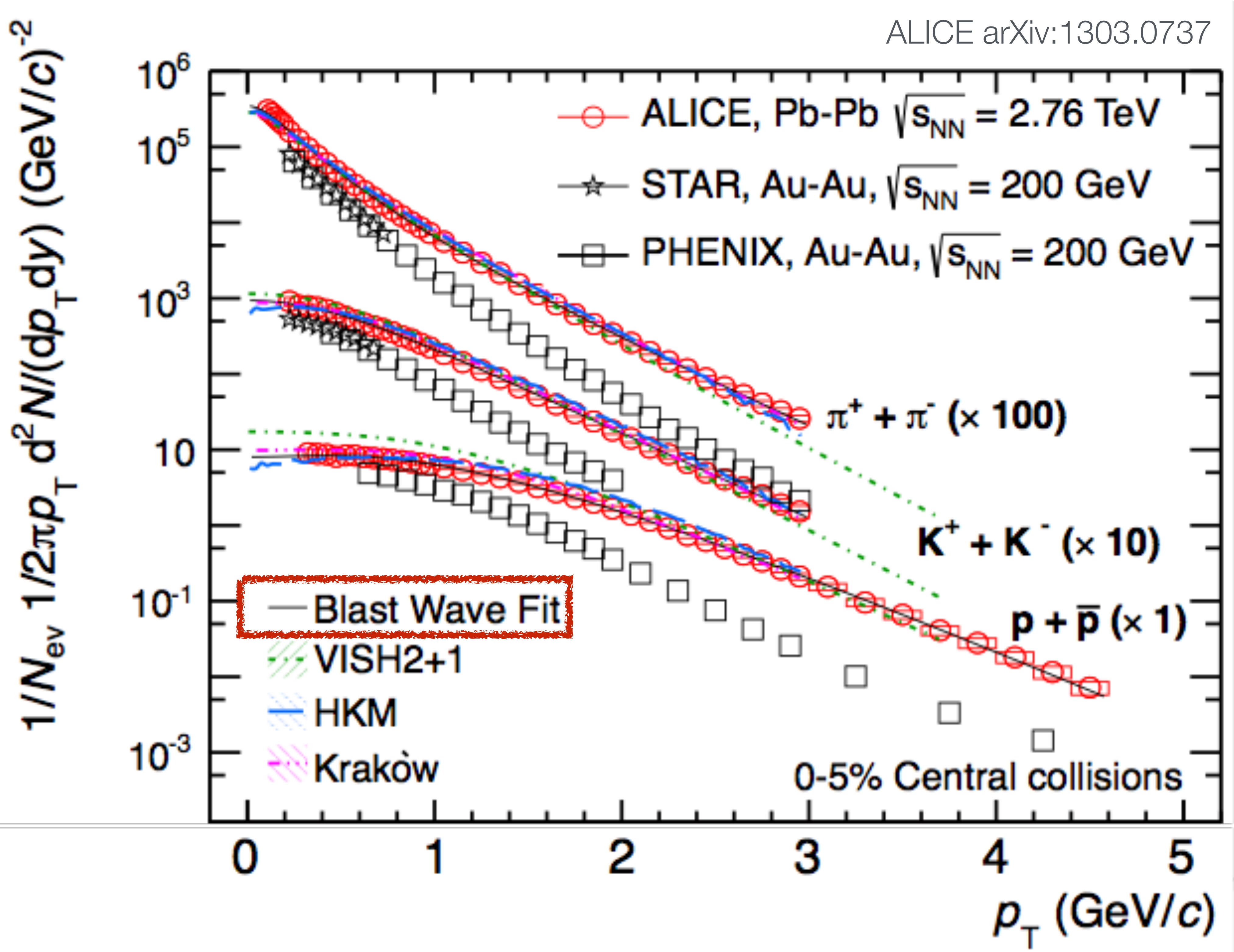


$$\lim_{p_T \to \infty} \frac{\mathrm{d}}{\mathrm{d}p_T} \ln\left(\frac{1}{p_T}\frac{\mathrm{d}n}{dp_T}\right) = -\frac{1}{T}\sqrt{\frac{1-\beta_T}{1+\beta_T}}$$

The apparent temperature, i.e., the inverse slope at high p_T, is larger than the original temperature by the blue shift factor:

$$T_{\mathrm{eff}} = T\sqrt{\frac{1+\beta_T}{1-\beta_T}}$$

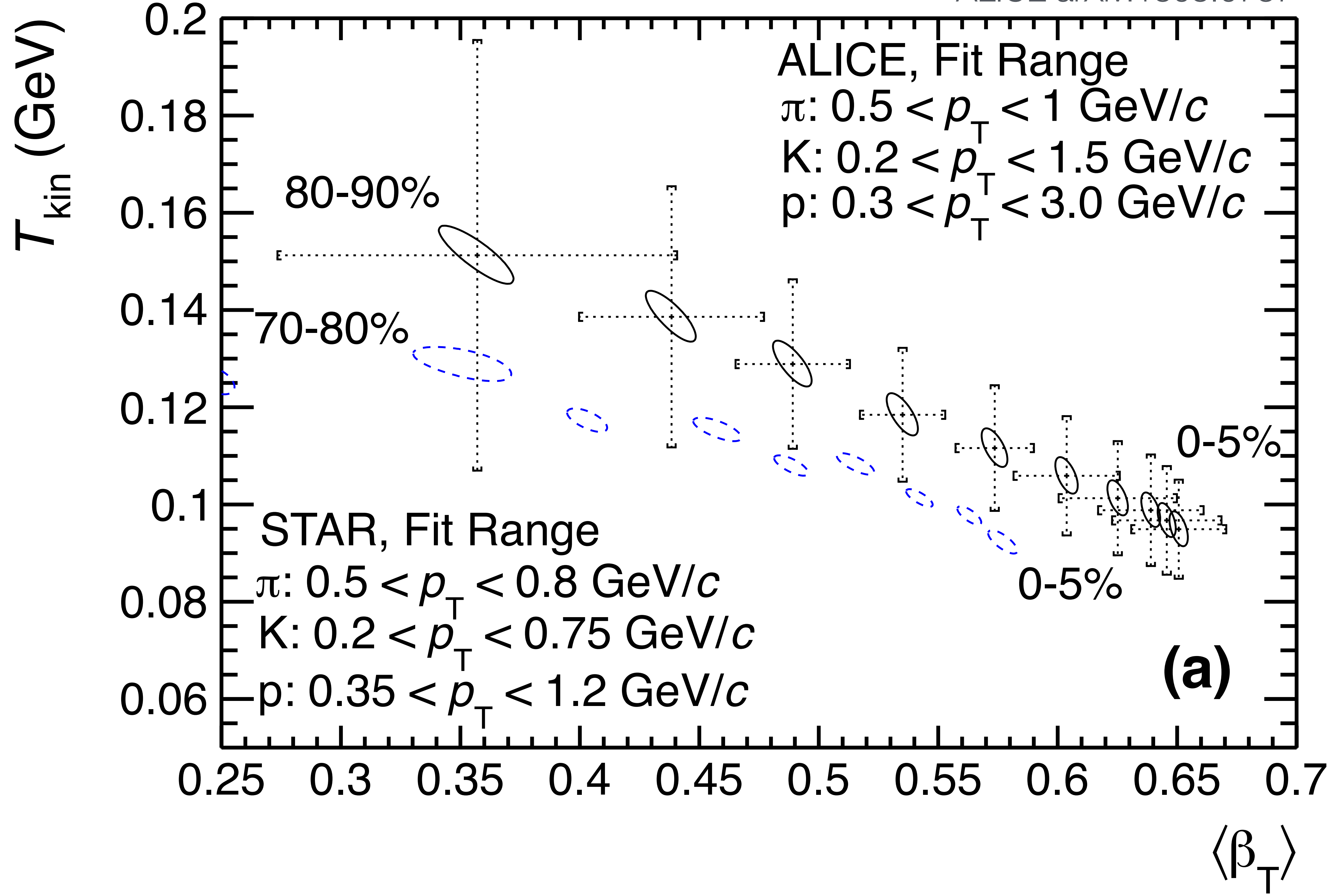
π, K, p Spectra and Blast-wave Fits at the LHC



Can extract T_{kin} and β_T from a simultaneous fit to the π, K, p spectra

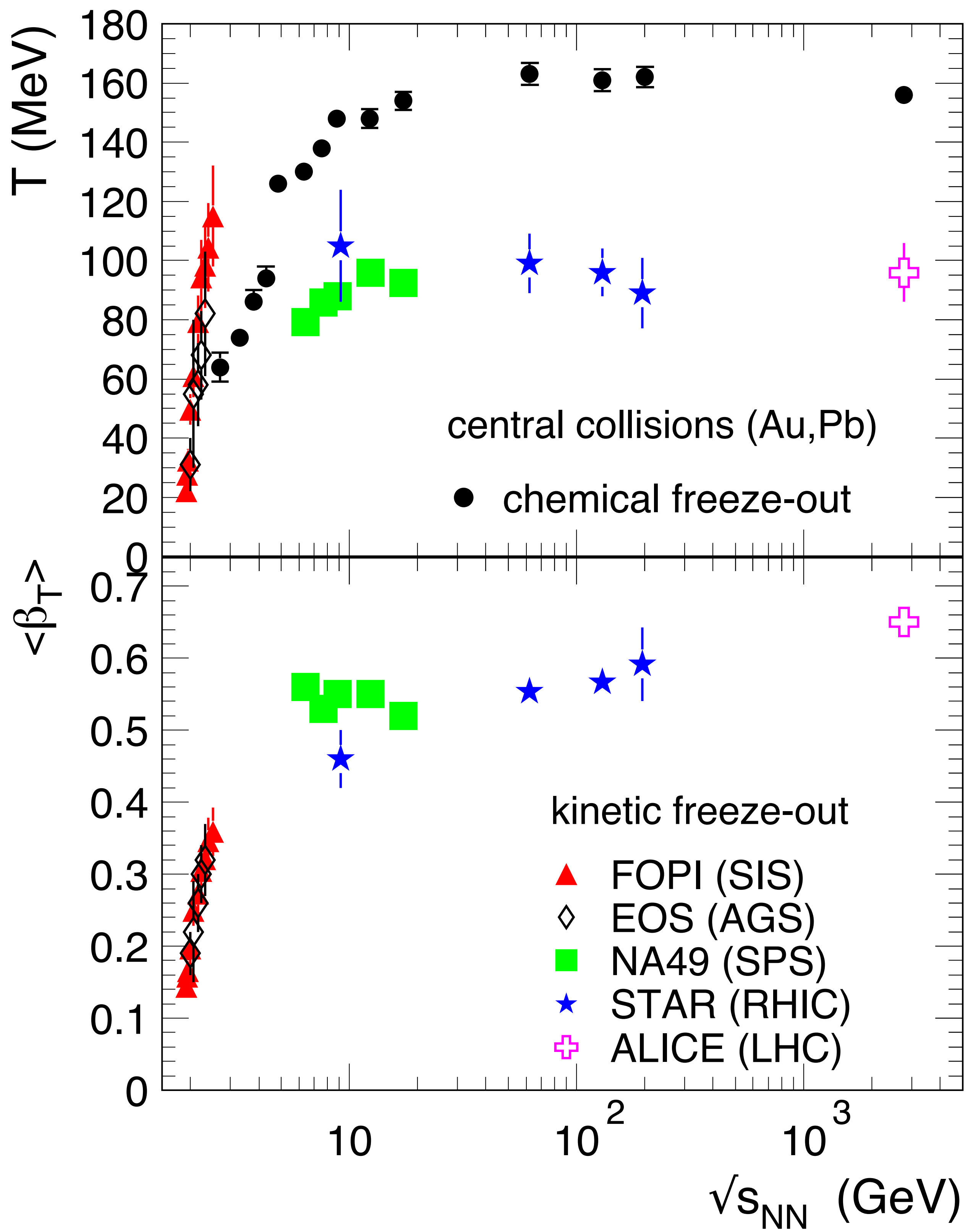
T und $\langle\beta\rangle$ for Different Centralities at RHIC and the LHC

ALICE arXiv:1303.0737



Average radial flow velocity in central Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV: β_T = 0.65

Radial Flow Velocities as a Function of $\sqrt{s_{NN}}$



Rather weak $\sqrt{s_{NN}}$ dependence of T and $\langle\beta_T\rangle$ for $\sqrt{s_{NN}} \gtrsim 10$ GeV

Basics of ideal relativistic hydrodynamics (1)

See e.g. Ollitrault, arXiv:0708.2433

- Hydrodynamics: Effective theory describing the long wavelength limit of the underlying microscopic theory
- Energy momentum tensor

$$T^{\mu\nu} = \begin{pmatrix} \text{energy density} & \text{energy flux density} \\ \text{momentum density} & \text{momentum flux density} \end{pmatrix}$$

in fluid rest frame (ideal hydro)

$$T^{\mu\nu}_{\text{id,R}} = \begin{pmatrix} \varepsilon & 0 & 0 & 0 \\ 0 & P & 0 & 0 \\ 0 & 0 & P & 0 \\ 0 & 0 & 0 & P \end{pmatrix}$$

pressure

- Transformation to the lab frame

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

metric tensor: $\text{diag}(1, -1, -1, -1)$

4-velocity: $u^\mu = \mathrm{d}x^\mu / \mathrm{d}\tau = \gamma(1, \vec{v})$

- Conservation of energy, momentum, and net-baryon current

$$\partial_\mu T^{\mu\nu}_{\text{id}} = 0, \quad \partial_\mu J^\mu_B = 0$$

$$\partial_\mu = (\frac{\partial}{\partial t}, \vec{\nabla})$$

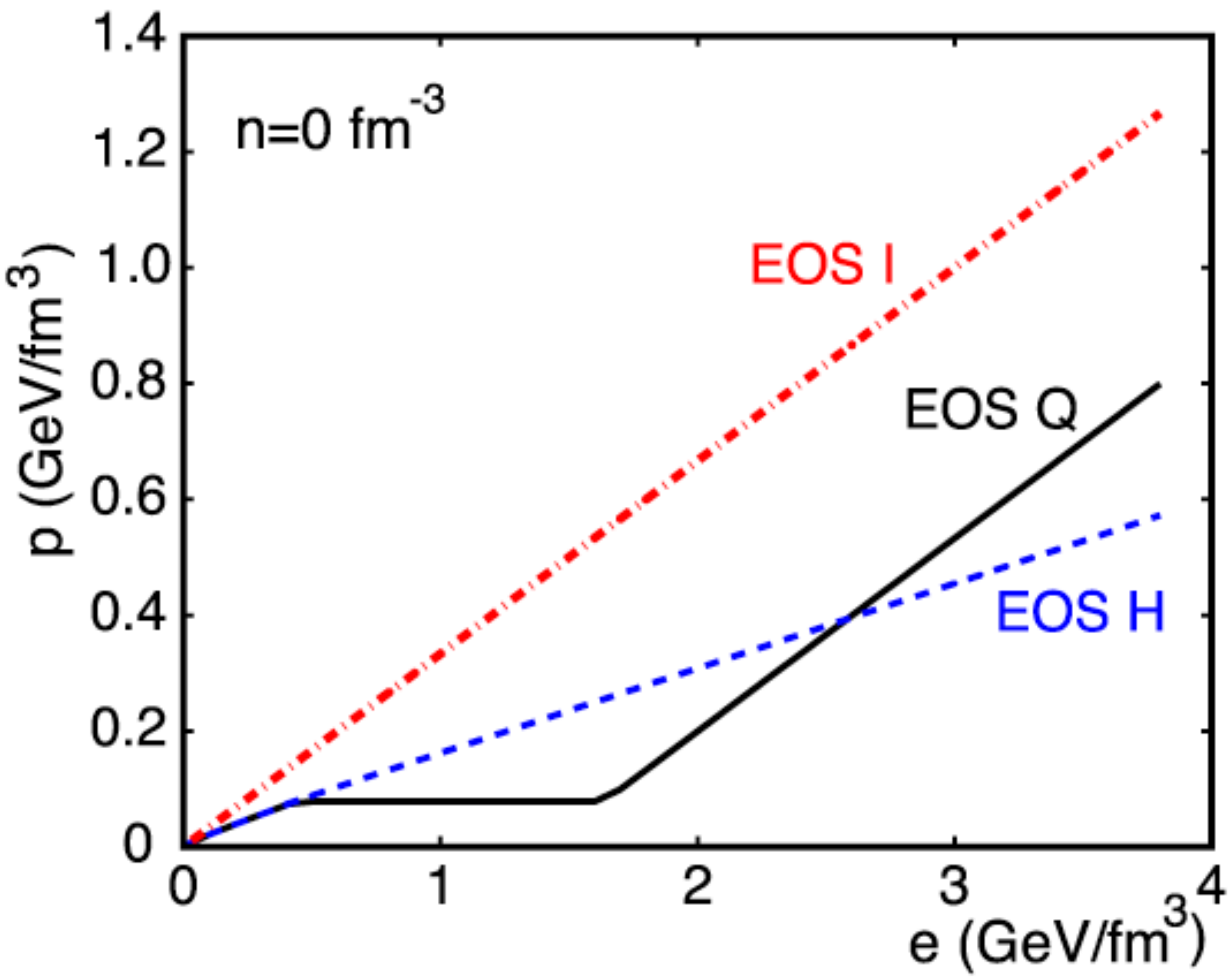
5 equations for 6 unknowns: $(u_x, u_y, u_z, \varepsilon, P, n_\text{B})$

Basics of ideal relativistic hydrodynamics (2)

- Equation of state (EoS) needed to close the system:

$$P(\varepsilon, n_B)$$

- Via the EoS hydrodynamics allows one to relate observables with QCD thermodynamics
- Initial conditions ($\varepsilon(x, y, z)$)
  - Glauber MC
  - Color glass condensate
- Transition to free-streaming particles



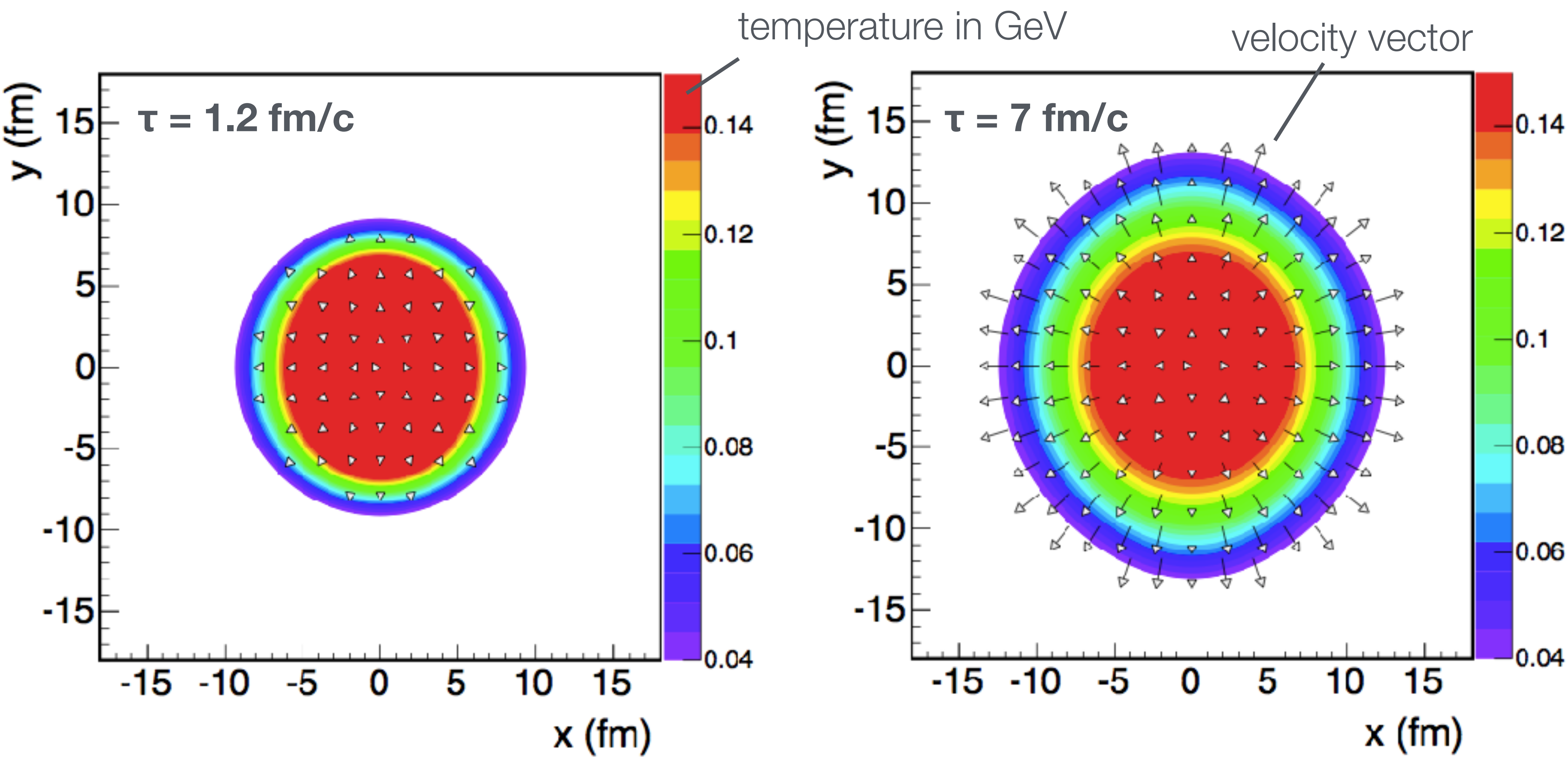
$$E\frac{dN}{d^3p} = \int_\Sigma f(x,p,t)p\,d\sigma(x)$$

$$= \frac{g}{(2\pi)^3}\int_\Sigma \frac{p\,d\sigma(x)}{\exp\left(\frac{p\cdot u(x)-\mu(x)}{T(x)}\right)\pm 1}$$

normal vector to the freeze-out 3d hyper surface Σ in space-time defined e.g. by $T = T_{fo}$

Cooper, Frye, Phys. Rev. D10 (1974) 186

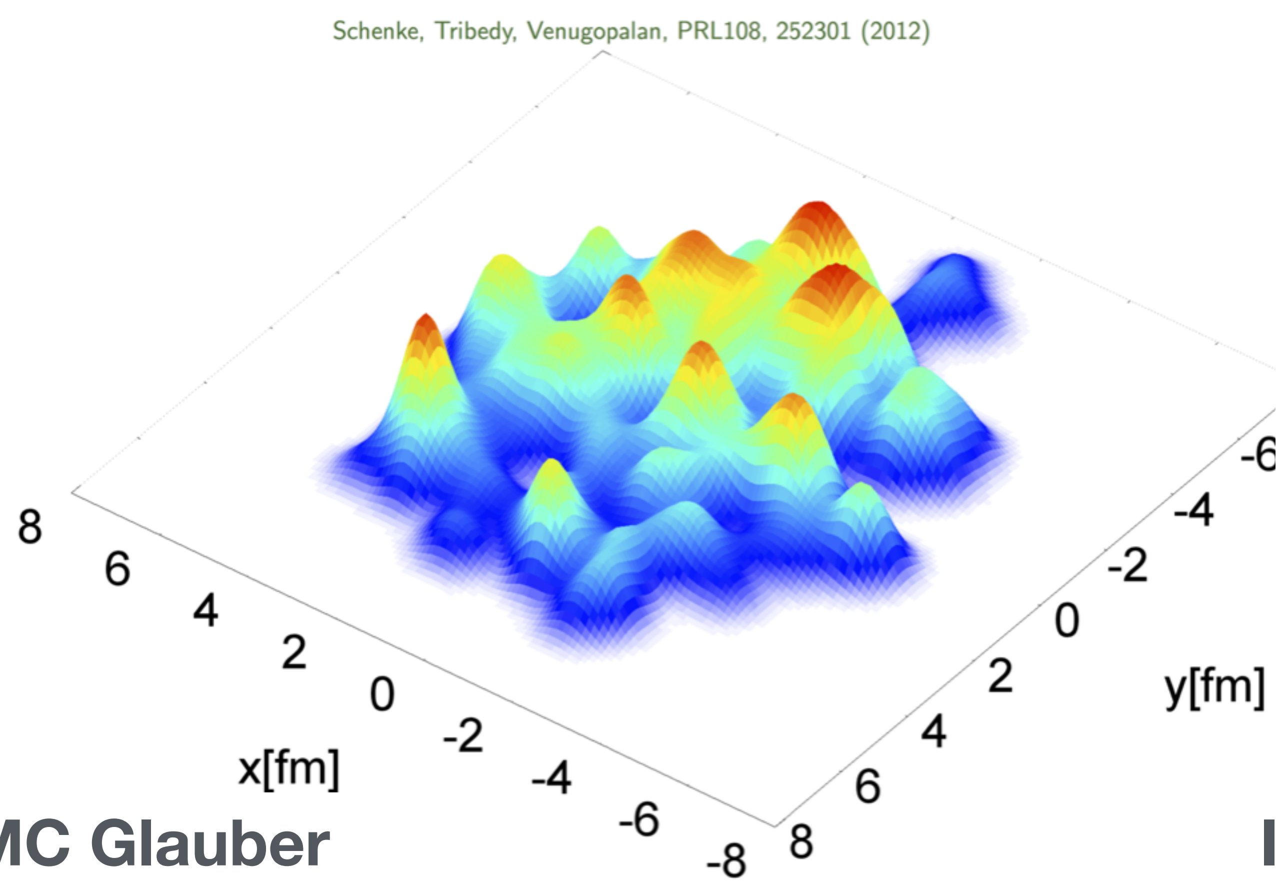
Hydrodynamical modeling of the fireball evolution



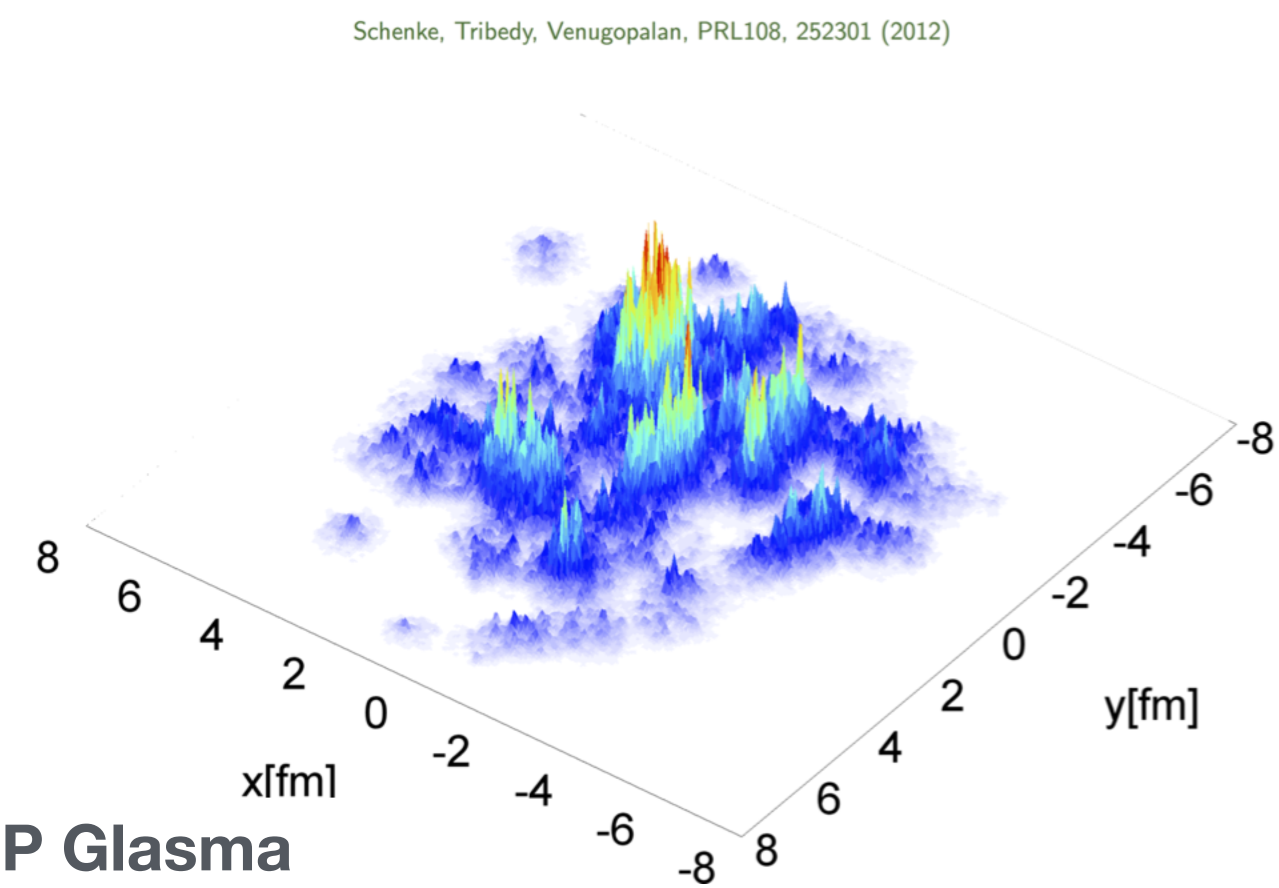
Explosive expansion of the QGP fireball

Hydrodynamic modeling of heavy-ion collisions: State of the art

- Equation of state from lattice QCD
- 2+1 d or 3+1 d viscous hydrodynamics
- Fluctuating initial conditions (event-by-event hydro)
- Hydrodynamic evolution followed by hadronic cascade

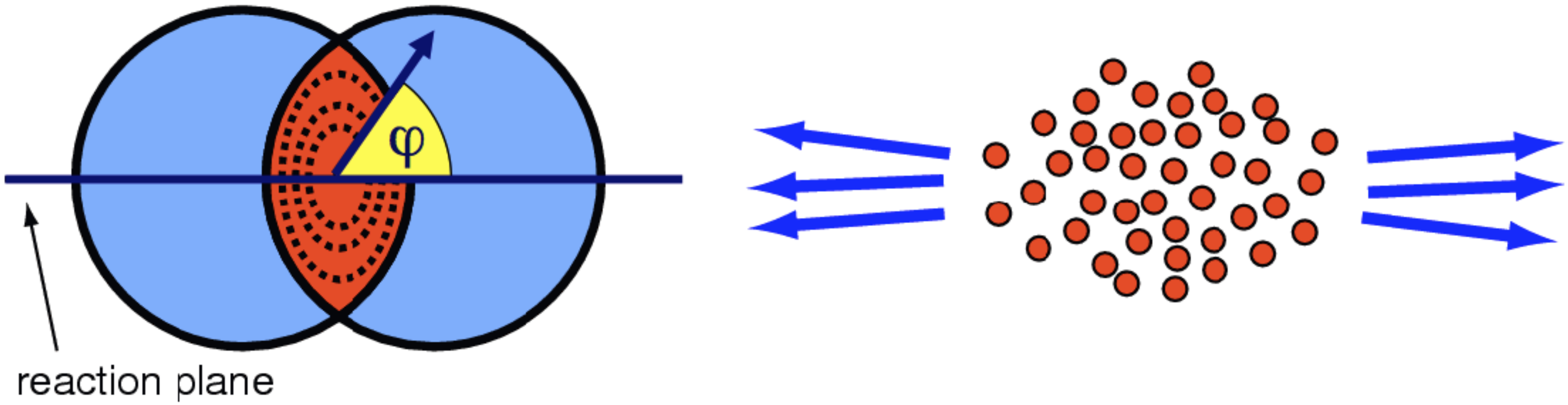


MC Glauber initial condition



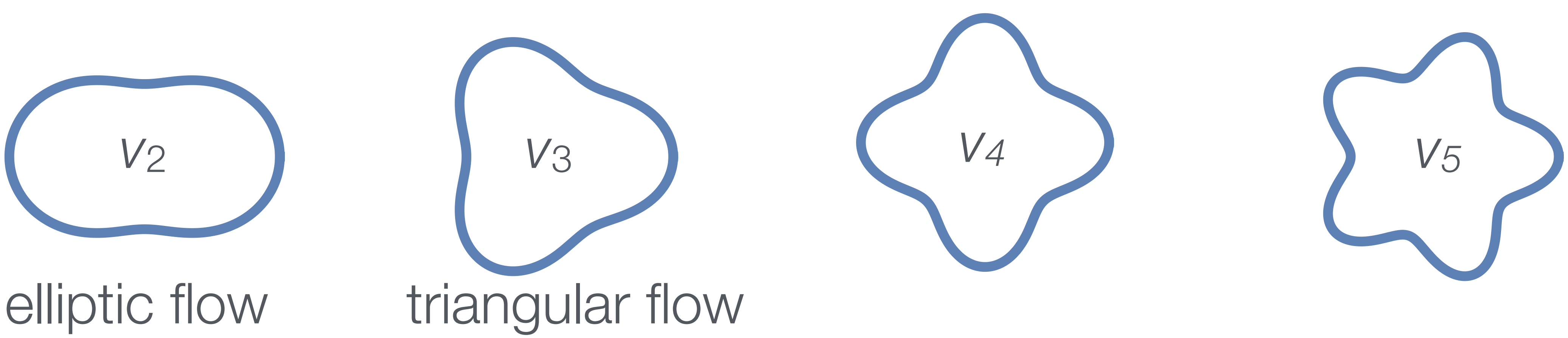
IP Glasma initial condition

Azimuthal distribution of produced particles



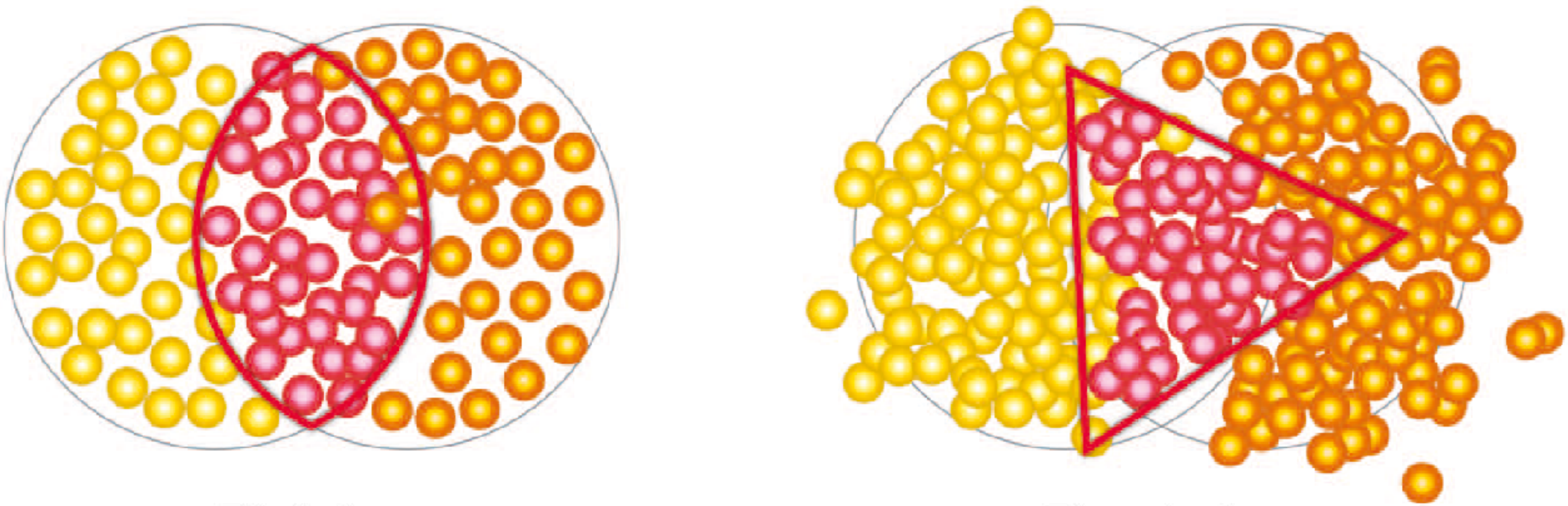
$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]$$

Fourier coefficients: $v_n(p_T, y) = \langle \cos[n(\varphi - \Psi_n)] \rangle$



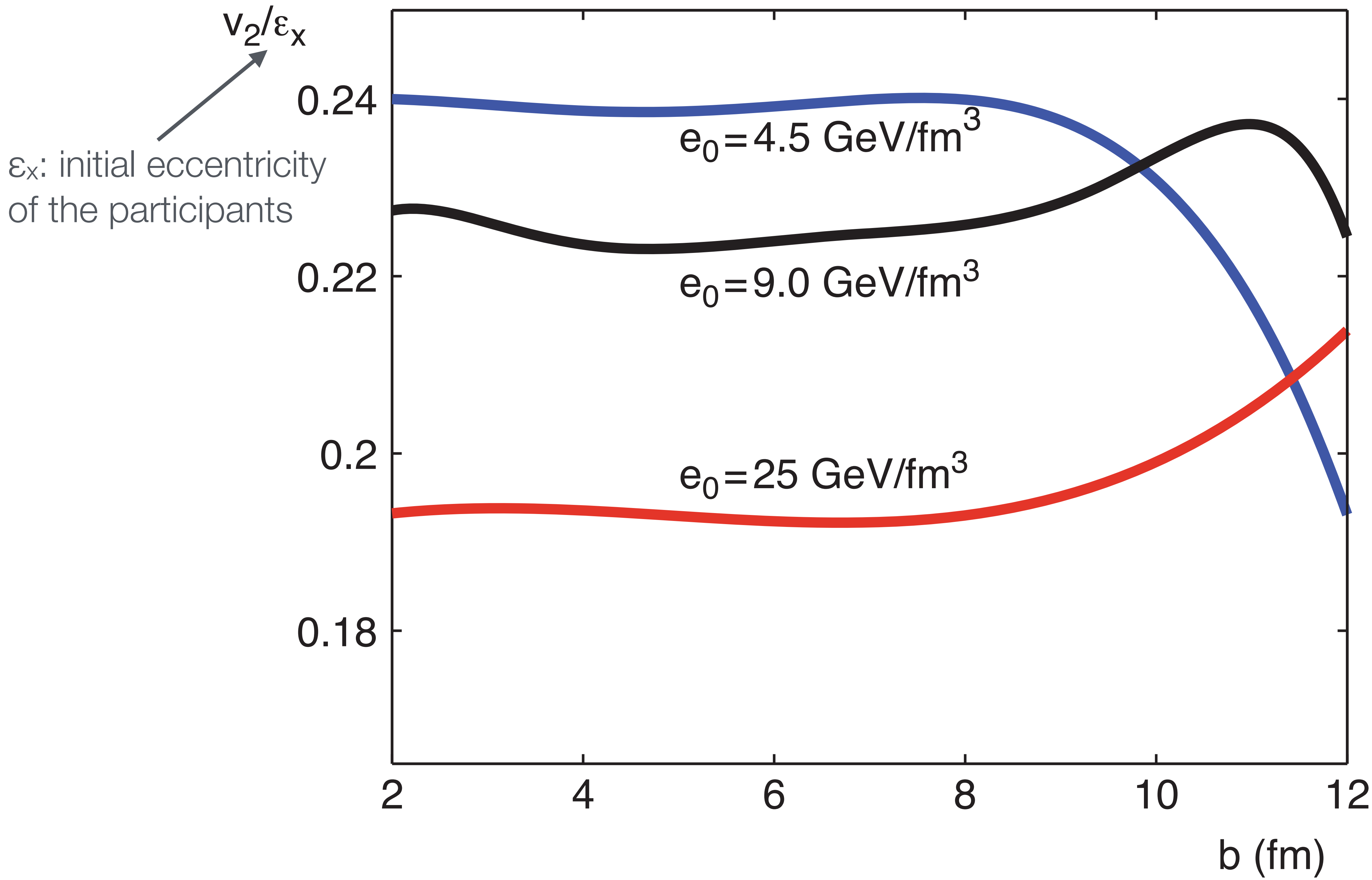
Origin of odd flow components

- v_2 is related to the geometry of the overlap zone
- Higher moments result from fluctuations of the initial energy distribution



Müller, Jacak, http://dx.doi.org/10.1126/science.1215901

Hydrodynamic models: v_2/ε approx. constant



Ideal hydrodynamics gives $v_2 \approx 0.2\ \varepsilon$

How the v_n are measured (1): Event plane method

Event flow vector Q_n e.g., measured at forward rapidities:

$$Q_n = \sum_k e^{in\varphi_k} = |Q_n| e^{in\Psi_{n,rec}} = Q_{n,x} + iQ_{n,y}$$

Event plane angle reconstructed in a given event:

$$\Psi_{n,rec} = \frac{1}{n} \mathrm{atan2}(Q_{n,y}, Q_{n,x})$$

Reconstructed event plane angle fluctuates around "true" reaction plane angle. The reconstructed v_n is therefore corrected for the event plane resolution:

$$v_n = \frac{v_n^{\mathrm{rec}}}{R_n}, \qquad v_n^{\mathrm{rec}} = \langle \cos[n(\varphi - \Psi_n^{\mathrm{rec}})] \rangle, \qquad R_n = \text{"resolution correction"}$$

What the event plane methods measures depends on the resolution which depends on the number of particles used in the event plane determination:

$$\langle v^\alpha \rangle^{1/\alpha} \quad \text{where} \quad 1 \leq \alpha \leq 2$$

Therefore other methods are used today where possible.

How the v_n are measured (2): Cumulants

two-particle correlations

average over all particles within an event, followed by averaging over all events

non-flow contribution (Resonance decays, HBT, jets, ...)

$$c_2\{2\} \equiv \left\langle\left\langle e^{i2(\varphi_1-\varphi_2)}\right\rangle\right\rangle = \langle v_2^2 + \delta_2\rangle$$

$$c_2\{4\} \equiv \left\langle\left\langle e^{i2(\varphi_1+\varphi_2-\varphi_3-\varphi_4)}\right\rangle\right\rangle - 2\left\langle\left\langle e^{i2(\varphi_1-\varphi_2)}\right\rangle\right\rangle^2, \\ = \langle -v_2^4 + \delta_4\rangle$$

$c_n\{4\}$ is a measure of genuine 4-particle correlations, i.e., it is insensitive to two-particle non-flow correlations. It can, however, still be influenced by higher-order non-flow contributions, denoted here by δ_4.

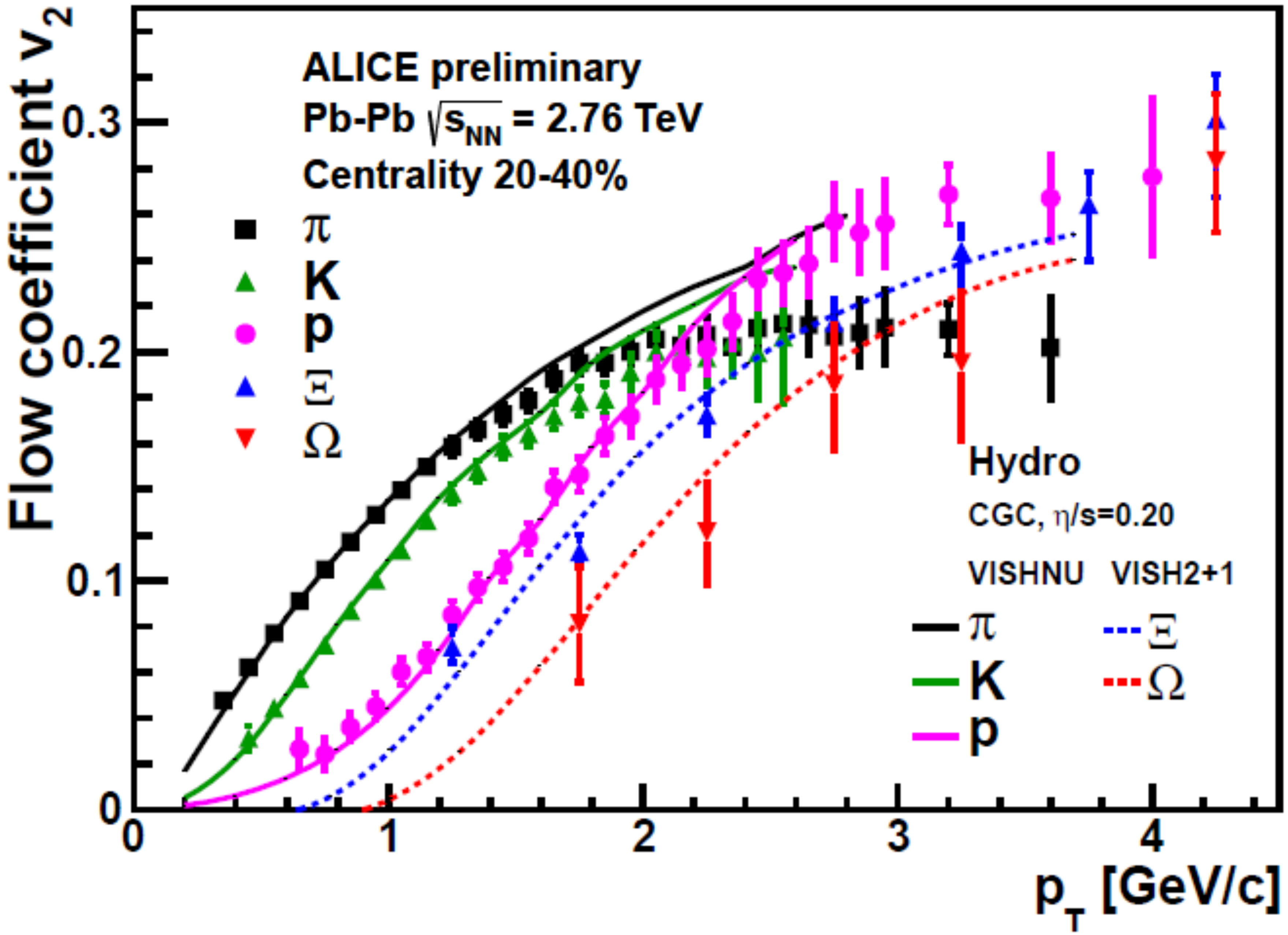
$$v_n\{2\}^2 := c_n\{2\}, \qquad v_n\{4\}^4 := -c_n\{4\}$$

These observables measure (assuming $\sigma \ll \langle v_n\rangle$):

$$v_n\{2\} = \langle v_n\rangle + \frac{1}{2}\frac{\sigma^2}{\langle v_2\rangle}, \qquad v_n\{4\} = \langle v_n\rangle - \frac{1}{2}\frac{\sigma^2}{\langle v_2\rangle}$$

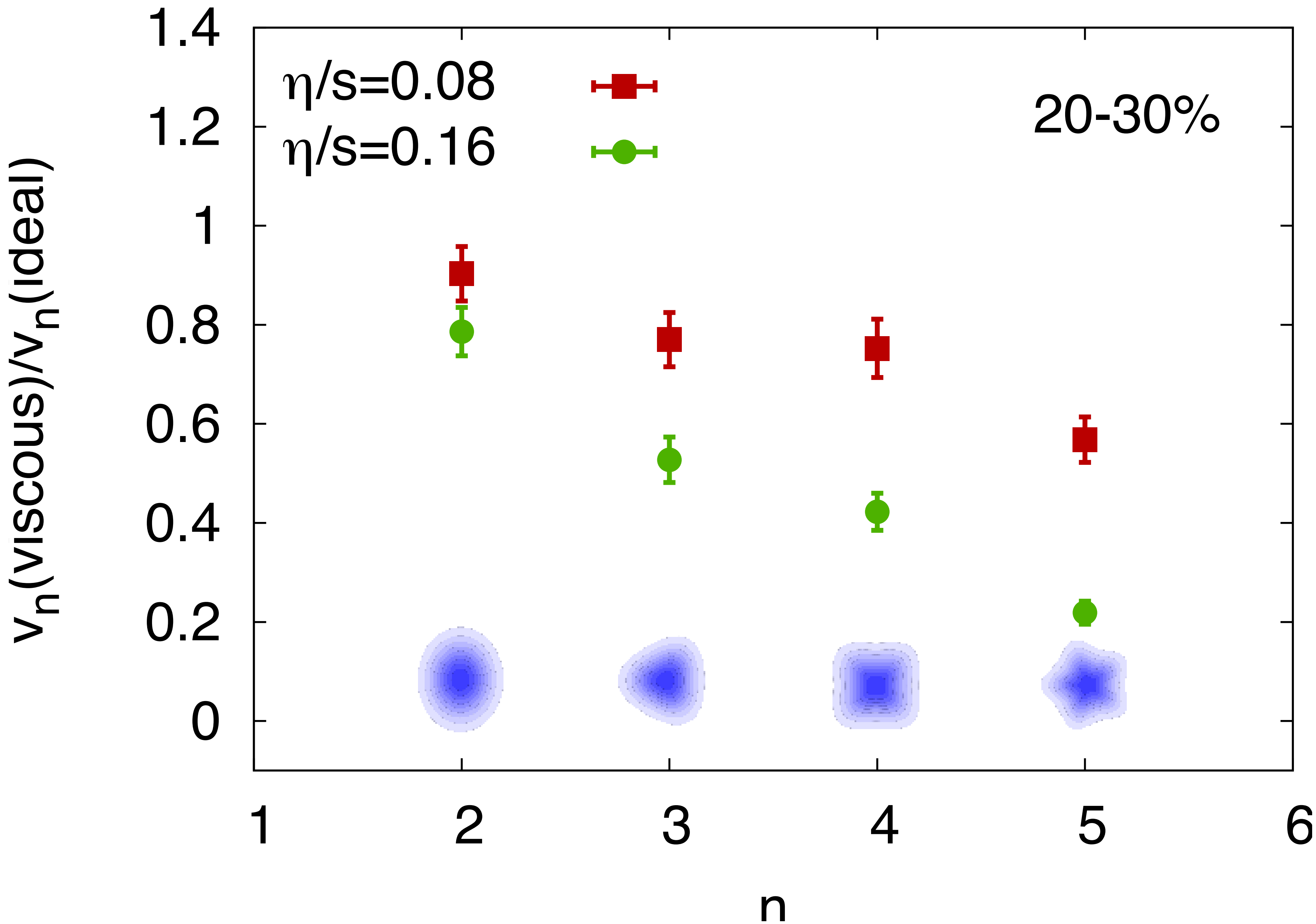
Elliptic flow of identified hadrons: Reproduced by viscous hydro with η/s = 0.2

final results: arXiv:1405.4632



Dependence of v_2 on particle mass ("mass ordering") is considered as strong indication for hydrodynamic space-time evolution

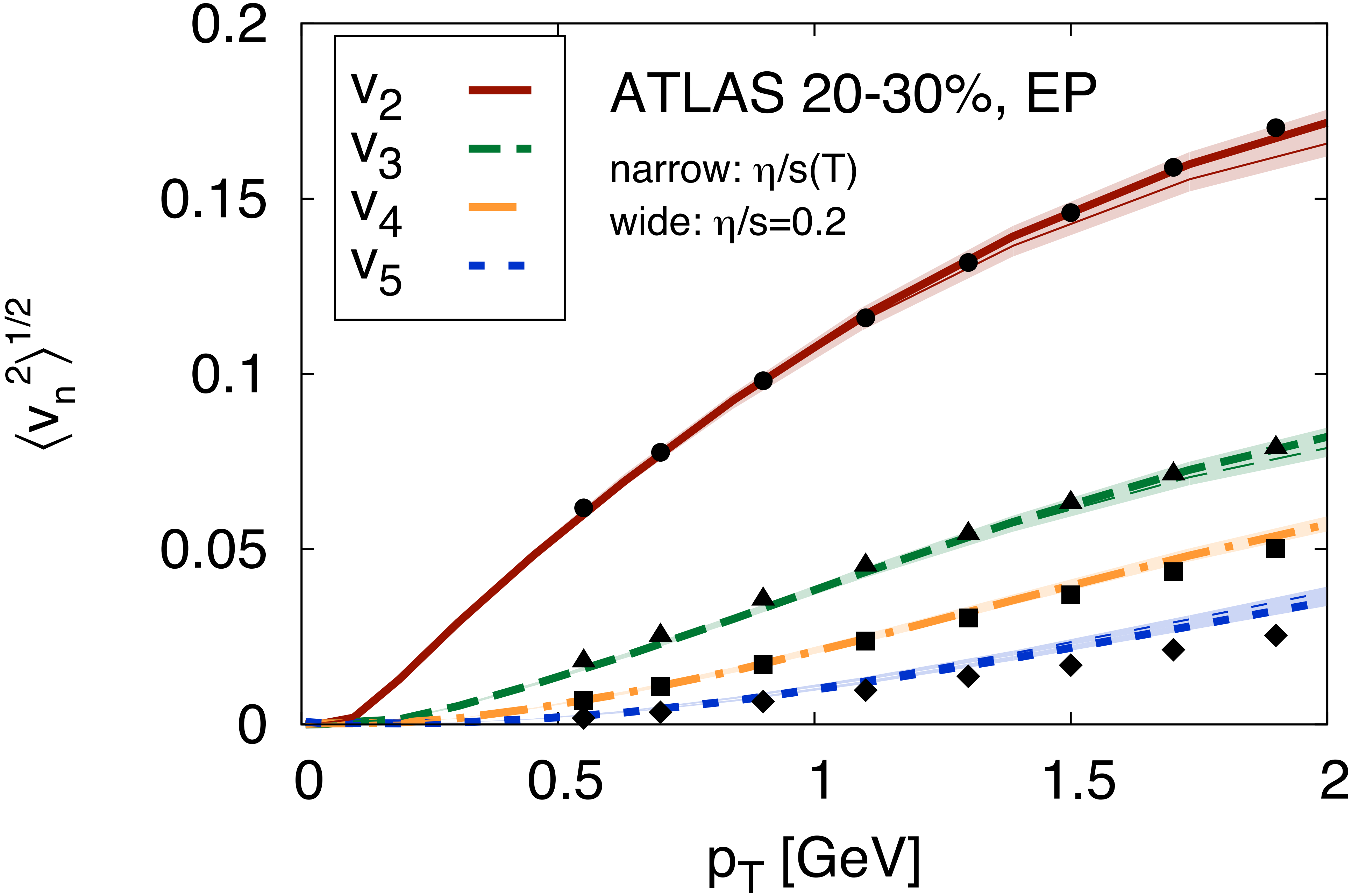
Higher flow harmonics are particularly sensitive to η/s



Major uncertainty in extracting η/s from data: uncertainty of initial conditions

η/s from comparison to data

arXiv:1209.6330

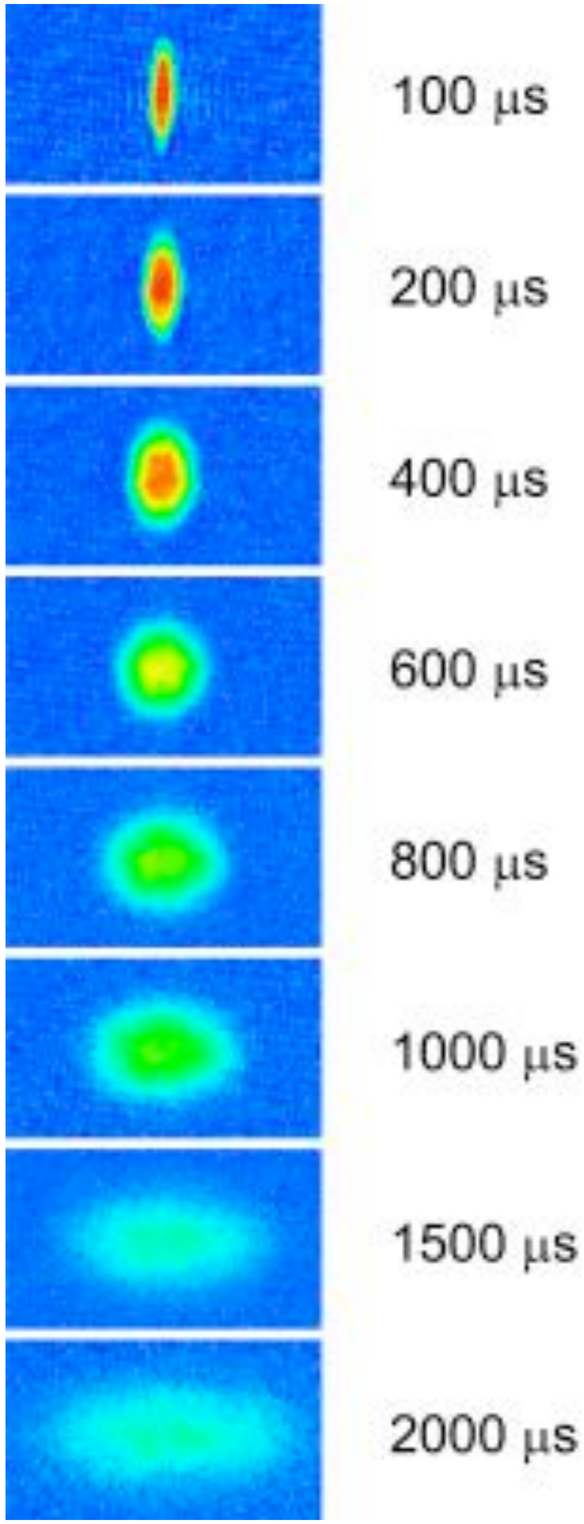


Current status (Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV):

arXiv:1301.2826

$$(\eta/s)_{\mathrm{QGP}} \approx 0.2 = 2.5 \times \frac{1}{4\pi} \qquad \text{(20\% stat. err., 50\% syst. err.)}$$

Universal aspects of the underlying physics

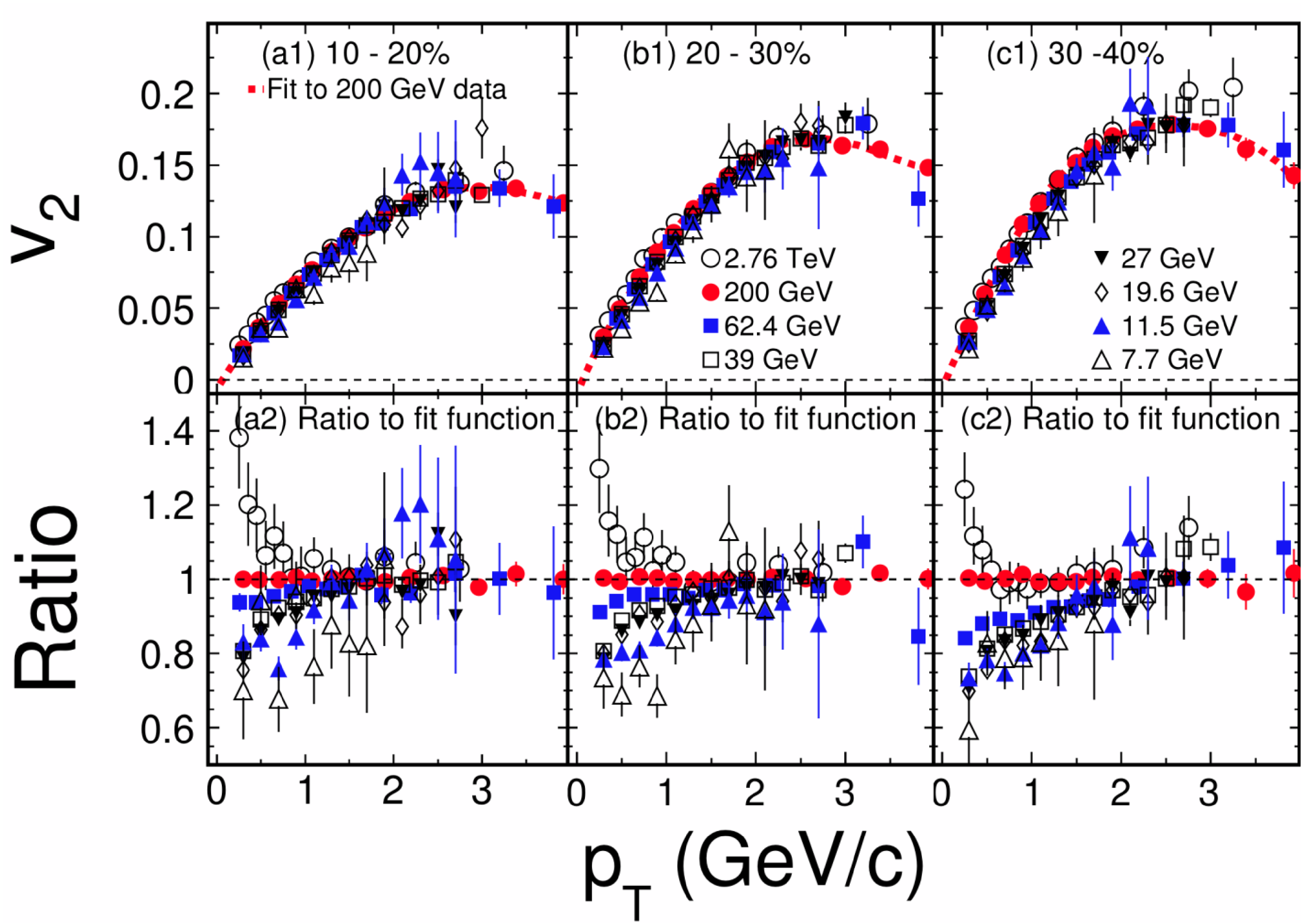


- Strongly-interacting degenerate gas of fermionic ^{6}Li atoms at 0.1 μK
- Cigar-shaped cloud initially trapped by a laser field
- Anisotropic expansion upon abruptly turning off the trap: Elliptic flow!
- η/s can be extracted: $(\eta/s)_{^6\mathrm{Li\,gas}} \approx 0.4 = 5 \times \frac{1}{4\pi}$
  [PhD thesis Chenglin Cao]

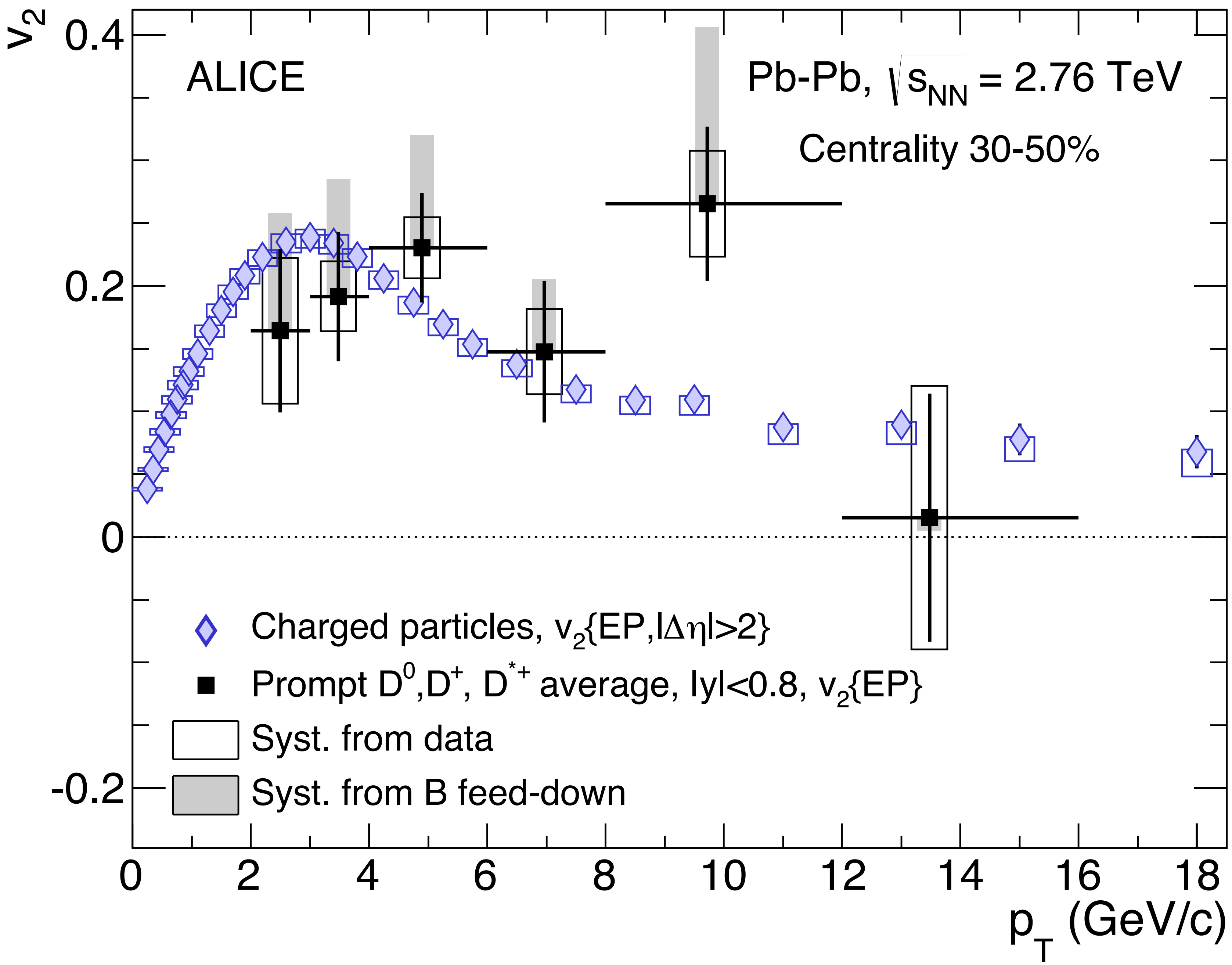
The ultimate goal is to unveil the universal physical laws governing seemingly different physical systems (with temperature scales differing by 19 order of magnitude)

John Thomas, https://www.physics.ncsu.edu/jet/research/stronginter/index.html

$v_2(p_T)$ appears to be rather independent of $\sqrt{s_{NN}}$



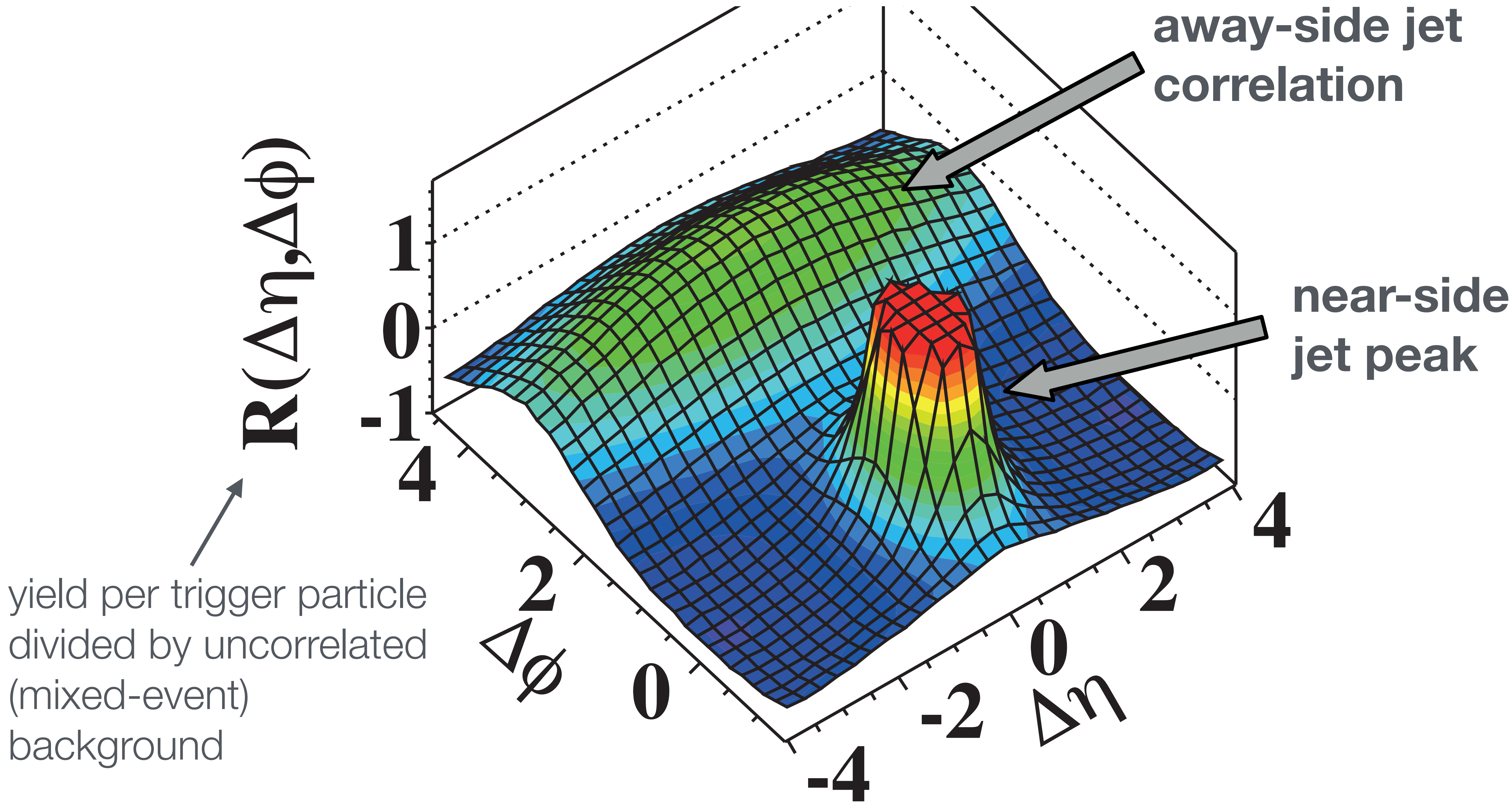
D meson v_2 in Pb-Pb: Heavy quarks seem to flow, too!



Given their large mass, it is not obvious that charm quarks take part in the collective expansion of the medium

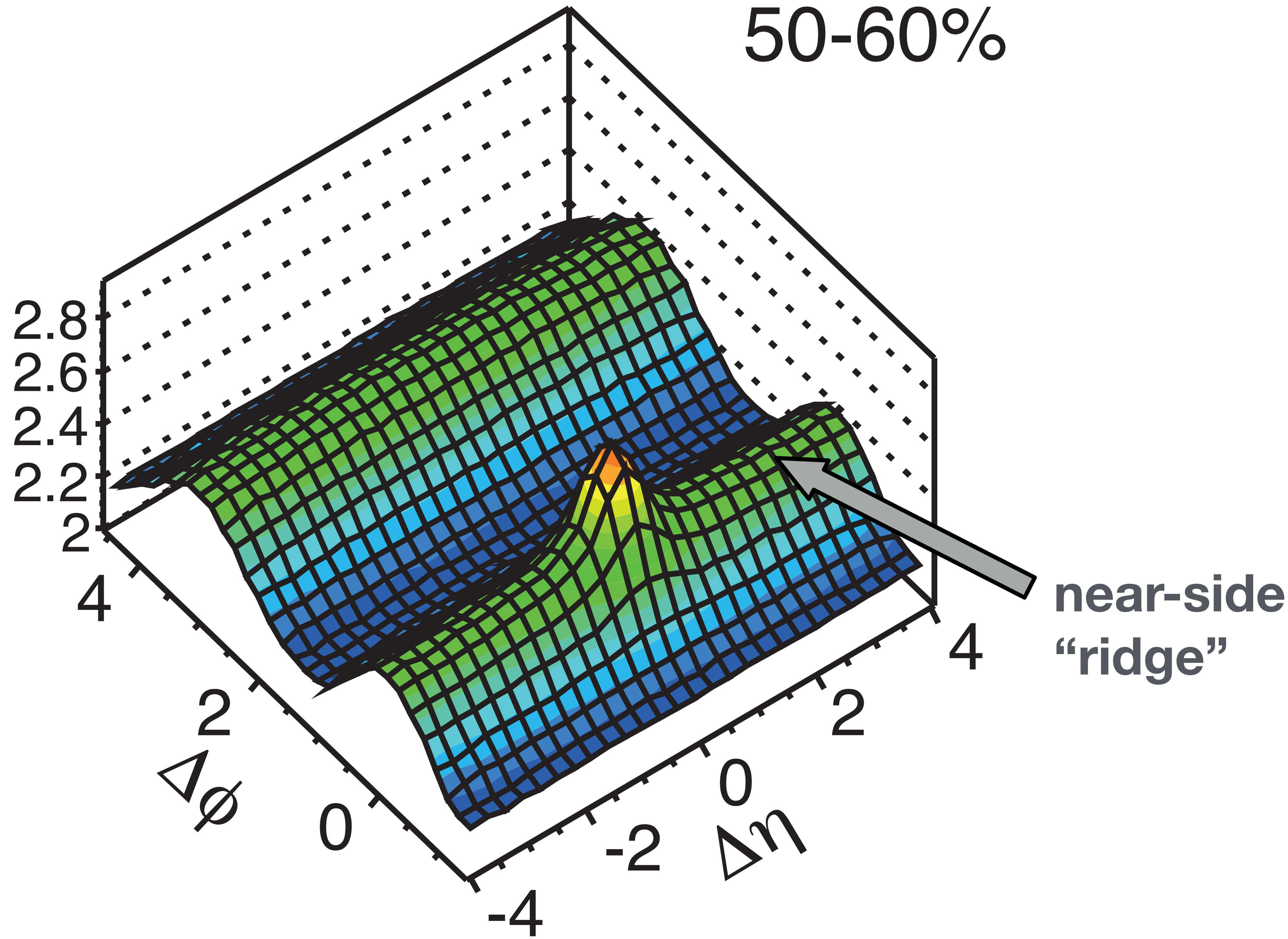
Collectivity in small systems: 2-particle correlation in pp at $\sqrt{s}$ = 7 TeV

CMS MinBias, 1.0GeV/c < p_T < 3.0GeV/c



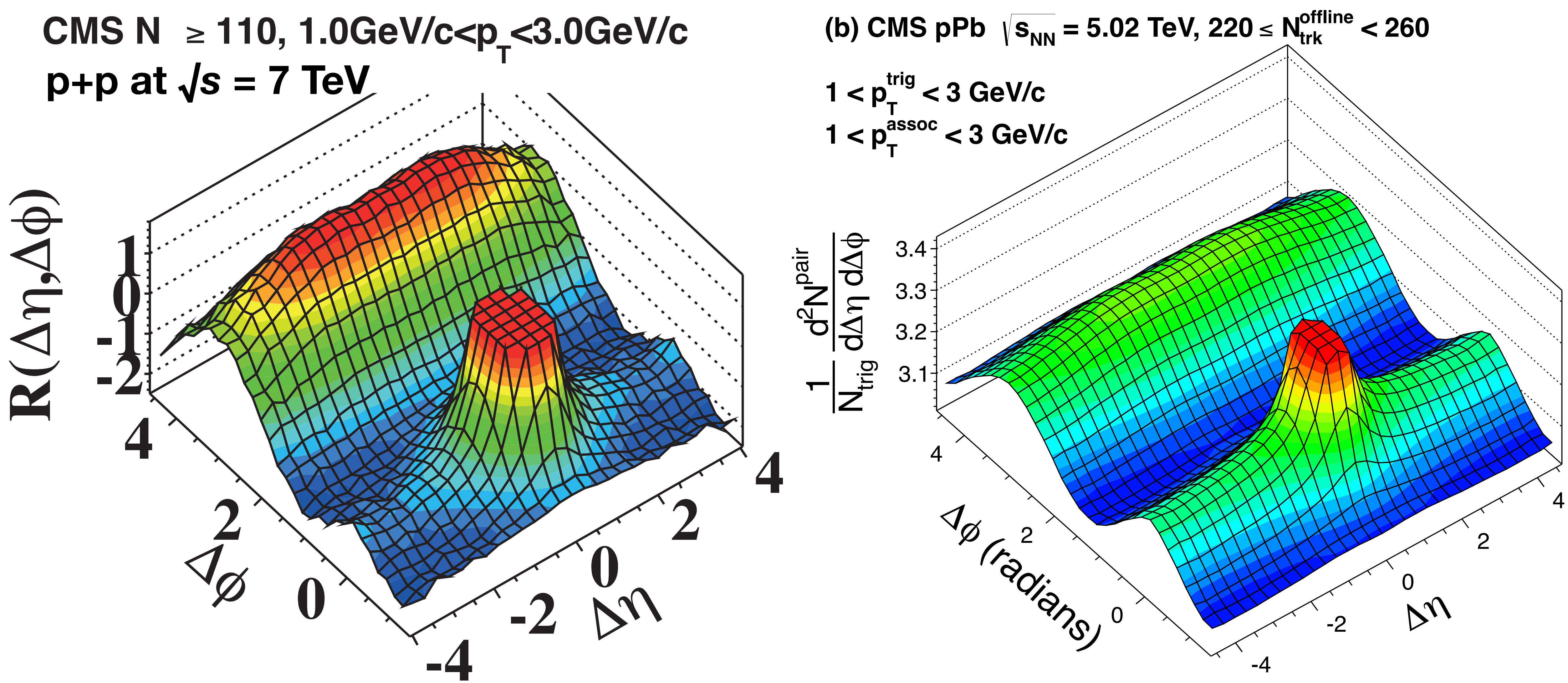
No indication for collective effects in minimum bias pp collisions at 7 TeV

Collectivity in small systems: Two-particle correlations in Pb-Pb collisions



collective flow + jet correlations

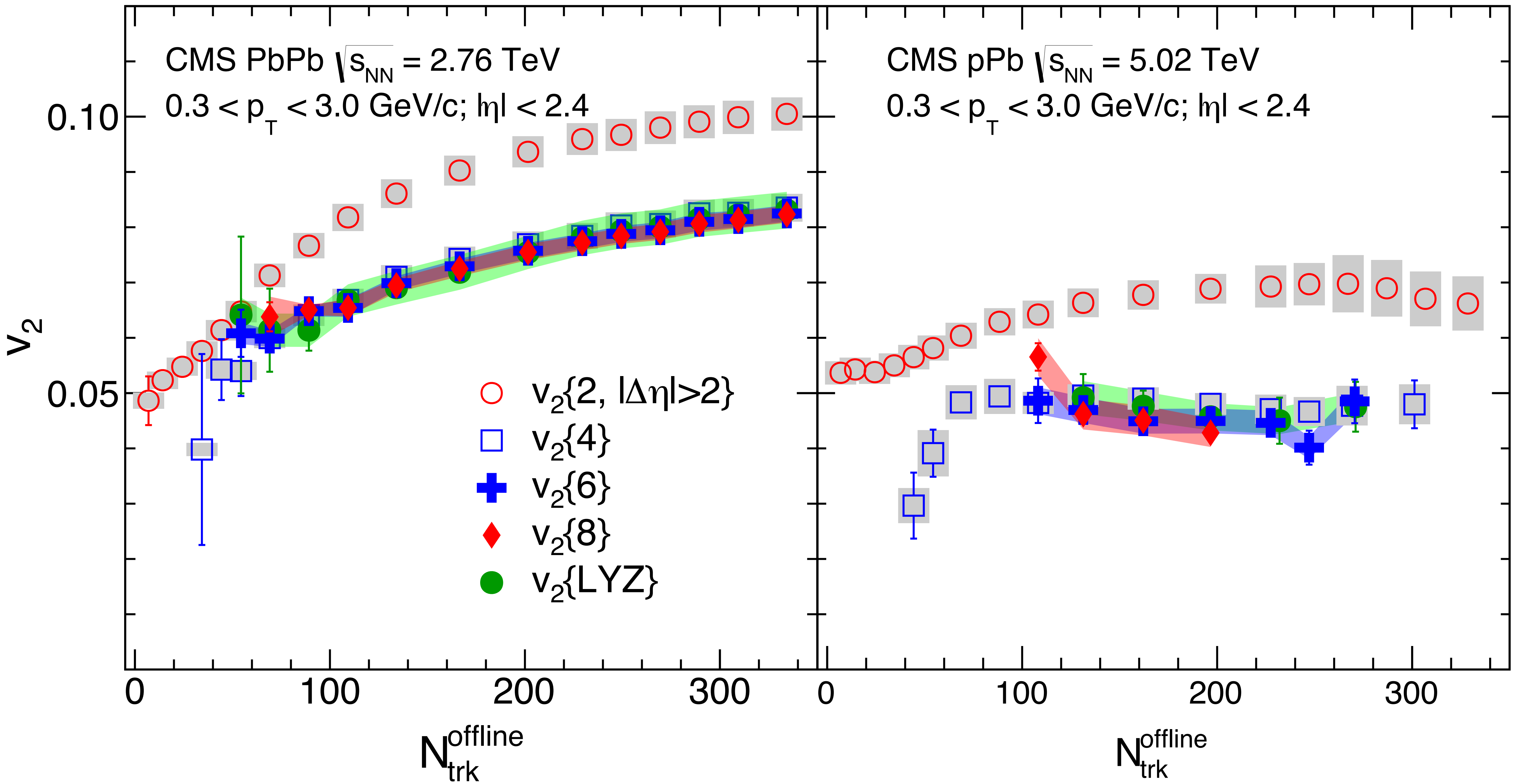
Collectivity in small systems: Two-particle correlations in high-multiplicity pp and p-Pb



Flow-like two-particle correlation become visible in high-multiplicity pp and p-Pb collisions at the LHC

Comparison of v_2 in Pb-Pb and p-Pb for the same track multiplicity

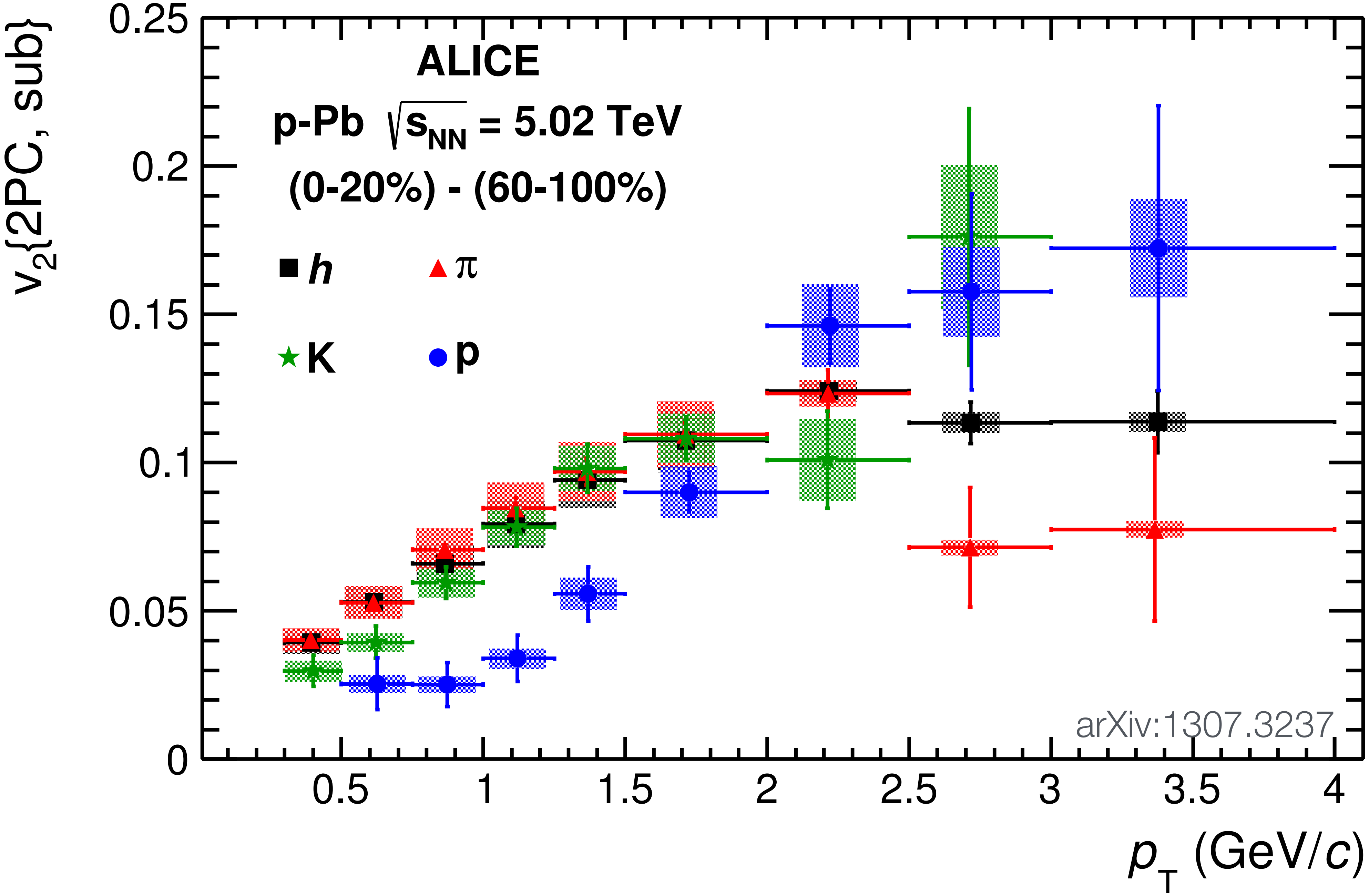
CMS, arXiv:1502.05382v2



- $v_2\{8\}$ measured: v_2 in p-Pb is a genuine multi-particle effect
- v_2 in p-Pb only slightly smaller than in p-Pb

Collectivity in small systems: Mass ordering in p-Pb collisions

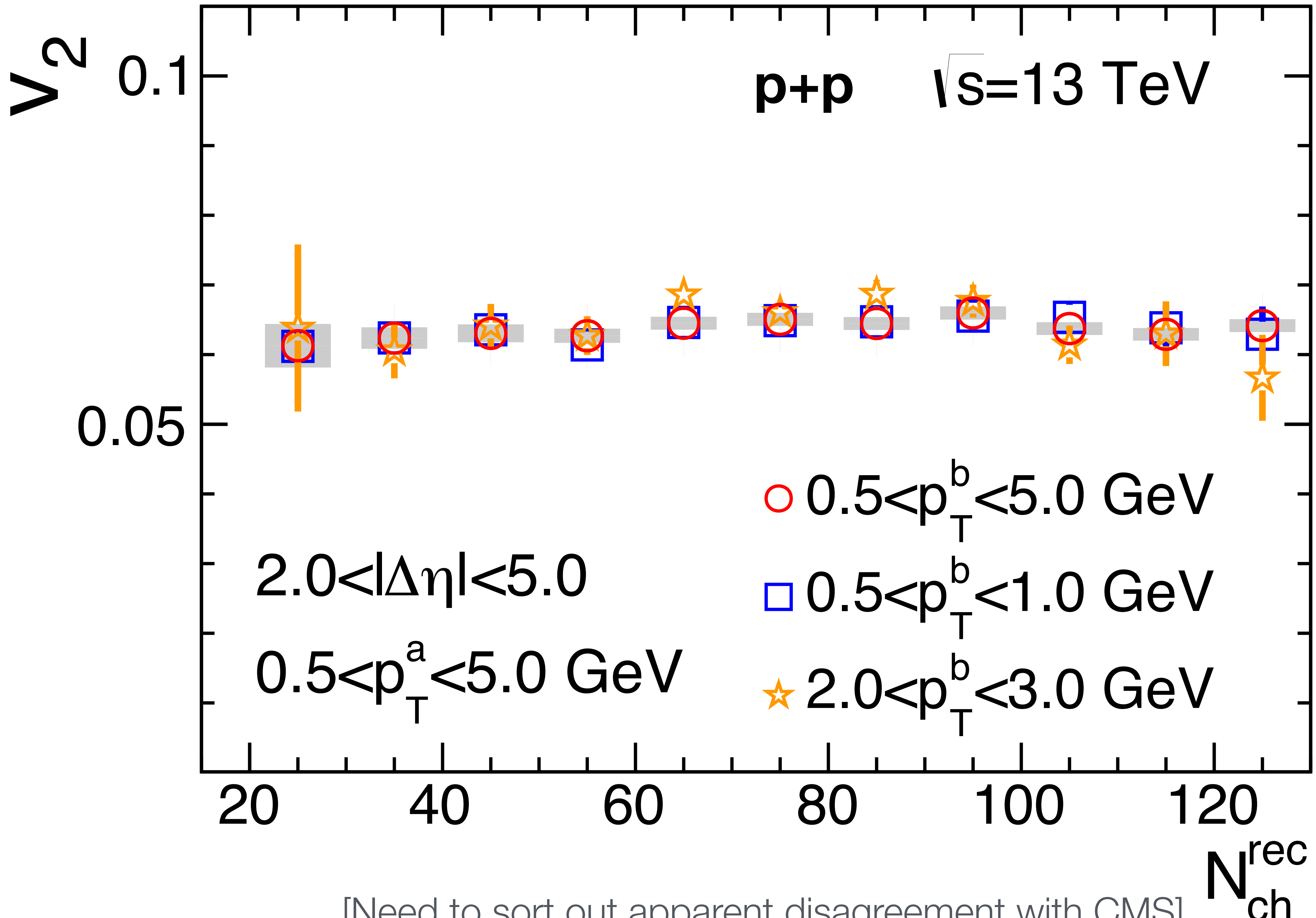
v_2 from fit of two-particle correlation, jet-like correlation removed by taking the difference between central and peripheral p-Pb collisions



Consistent with hydrodynamic expansion of the medium als in p-Pb

Elliptic flow not only in high multiplicity pp collisions?

ATLAS, 1509.04776



[Need to sort out apparent disagreement with CMS]

Summary/questions space-time evolution

- Hydrodynamic models provide an economic description of many observables (spectra, flow)
- Shear viscosity / entropy density ratio in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV from comparing hydrodynamic models to data:

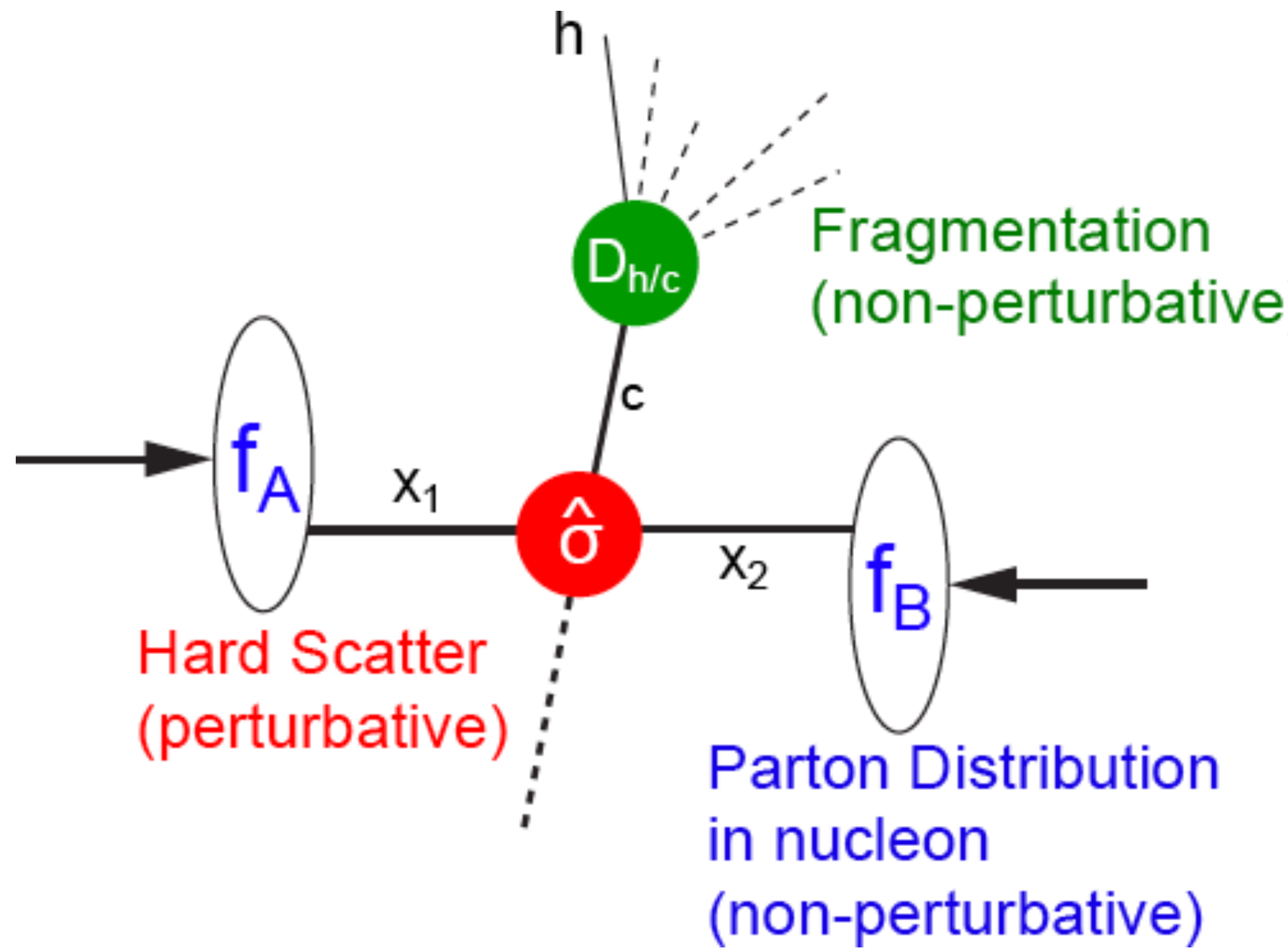
$$(\eta/s)_{\mathrm{QGP}} \approx 0.2 = 2.5 \times \left.\frac{\eta}{s}\right|_{\mathrm{min,KSS}} = 2.5 \times \frac{1}{4\pi}$$

- Appropriate theoretical treatment of thermalization and matching to hydrodynamics?
  - Strong coupling or weak coupling approach?
  - Weak coupling: Applicable at asymptotic energies, but still useful at current $\sqrt{s_{NN}}$
  - Strong coupling (string/gauge theory duality), see e.g. arXiv:1501.04952: Fast thermalization of the order of $1/T$, but too much stopping?
- Can hydrodynamics provide a self-consistent description of collective effects in small system (pp, p-Pb)?

6. Jet quenching

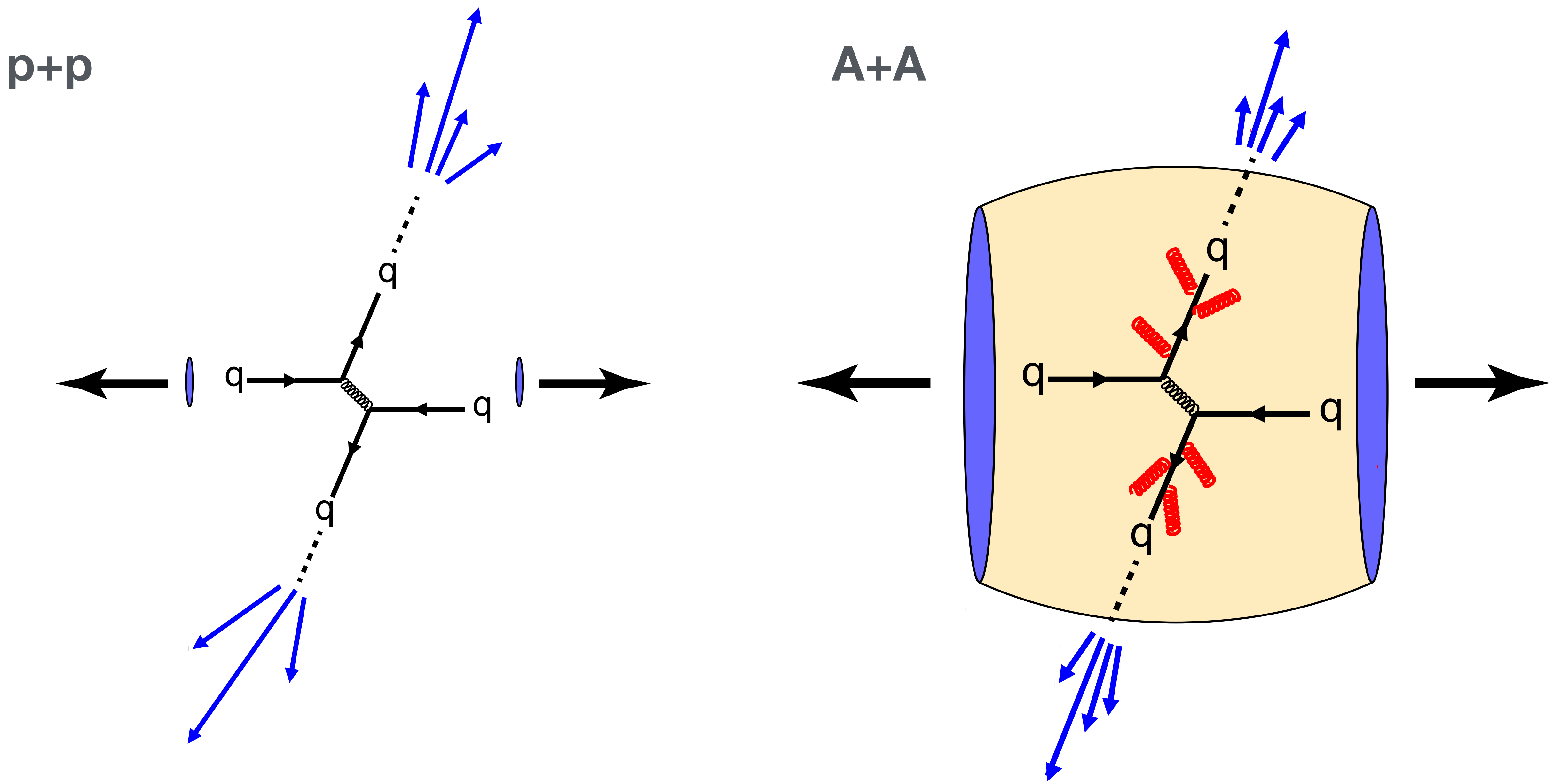
Theoretical description of High-p_T particle production: Perturbative QCD

- Scattering of pointlike partons described by QCD perturbation theory (pQCD)
- Soft processes described by universal, phenomenological functions
  - Parton distribution function from deep inelastic scattering
  - Fragmentation functions from e^+e^- collisions
- Particle production dominated by hard scattering for $p_T \gtrsim 3$ GeV/c
  - However, 99% or so of all particle from soft processes



$$d\sigma = \sum_{a,b,c} f_a \otimes f_b \otimes d\hat{\sigma}^c_{ab} \otimes D_c^{Hadron}$$

Jet quenching in heavy-ion collisions



A-A collision: shower evolution in the medium, energy loss of the leading parton

Jet quenching history

Energy Loss of Energetic Partons in Quark-Gluon Plasma: Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

FERMILAB-Pub-82/59-THY
August, 1982

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

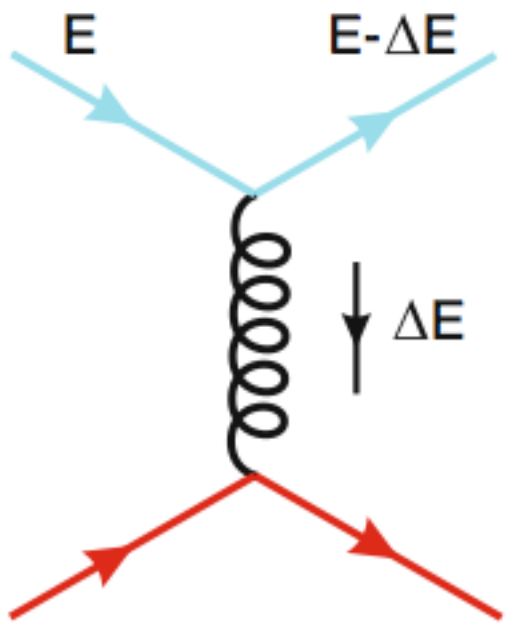
Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

It is now believed that radiative energy loss (gluon bremsstrahlung) is more important than elastic scattering

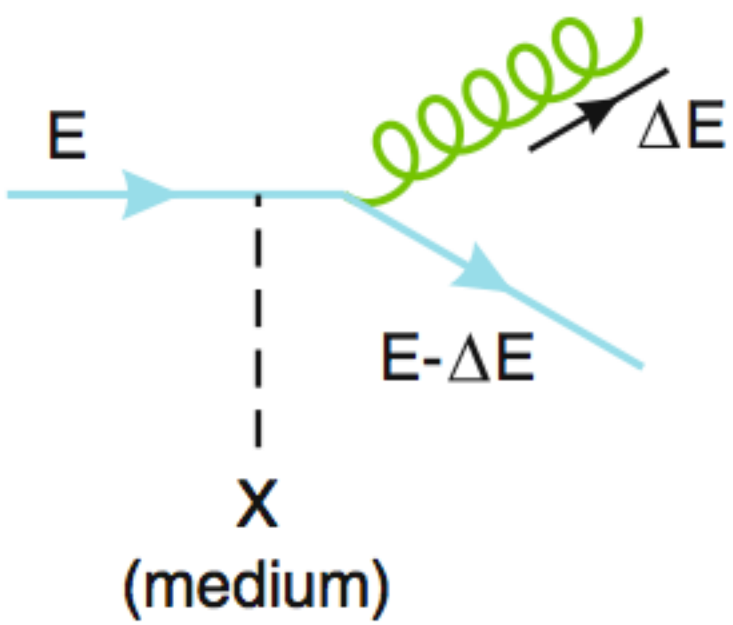
Collisional vs. radiative parton energy loss

Collisional energy loss:



- Elastic scatterings with medium constituents
- Dominates at low parton momenta

Radiative energy loss:



- Inelastic scatterings within the medium
- Dominates at higher momenta

Basics of radiative parton energy loss (1)

- Energy loss E in a static medium of length L for a parton energy $E \to \infty$:

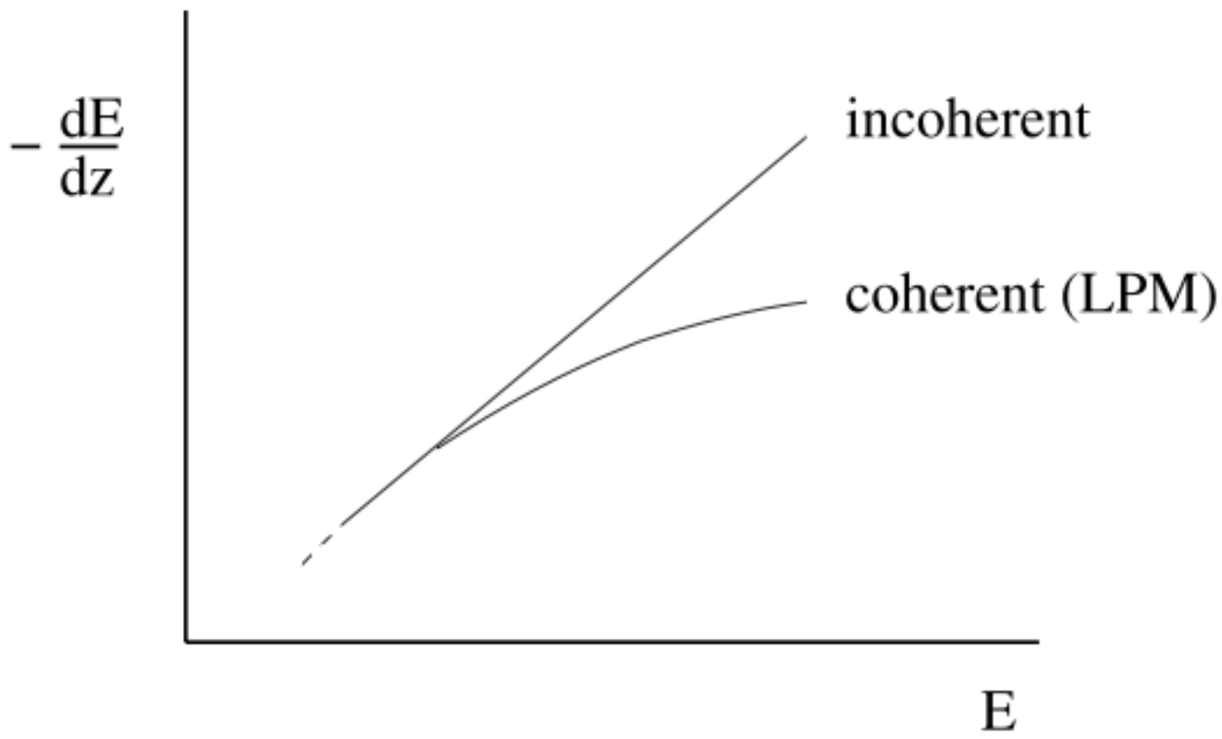
$$\Delta E \propto \alpha_s C_F \hat{q} L^2 \qquad \hat{q} = \frac{\mu^2}{\lambda} \qquad C_F = \begin{cases} 3 & \text{for gluon jets} \\ 4/3 & \text{for quark jets} \end{cases}$$

μ^2 : typical momentum transfer from medium to parton per collision

λ : mean free path length in the medium

BDMPS result, Nucl. Phys. B 483, 291, 1997

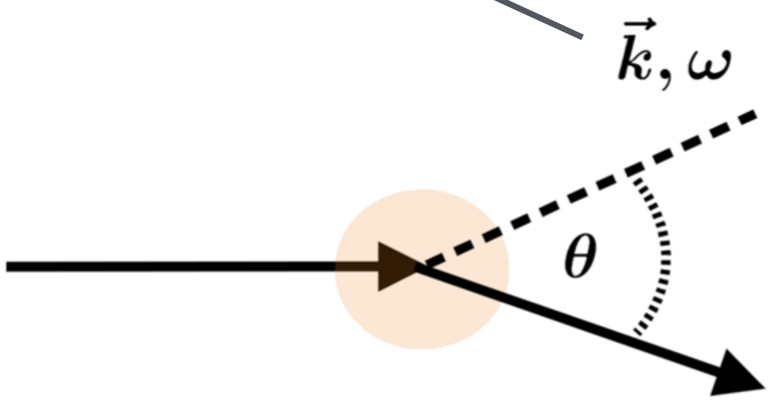
- Landau-Pomeranchuk-Migdal (LPM) effect
  - Parton scatters coherently off many medium constituents: destructive interference
  - Reduces radiative energy loss



Basics of radiative parton energy loss (2)

Formation time (or length) of a radiated gluon:
(“time for the fast parton to get rid of its virtuality”)

$$z_{\mathrm{coh}} = t_{\mathrm{coh}} \simeq \frac{\omega}{k_T^2} \simeq \frac{1}{\omega \theta^2}$$



The gluon acquires additional transverse momentum if it scatters with medium constituents within its formation time (or formation length z_c):

$$k_T^2 \simeq \hat{q} z_{\mathrm{coh}} = \frac{\mu^2}{\lambda} z_{\mathrm{coh}}$$

This results in a medium-modified formation length: $z_{\mathrm{coh}} \simeq \frac{\omega}{k_T^2} \simeq \sqrt{\frac{\omega}{\hat{q}}}$

$\lambda < z_{\mathrm{coh}}$: Coherent scattering with destructive interference

$\lambda > z_{\mathrm{coh}}$: incoherent multiple scattering

Basics of radiative parton energy loss (3)

1. Incoherent regime (mean free path $\lambda > z_{coh}$):

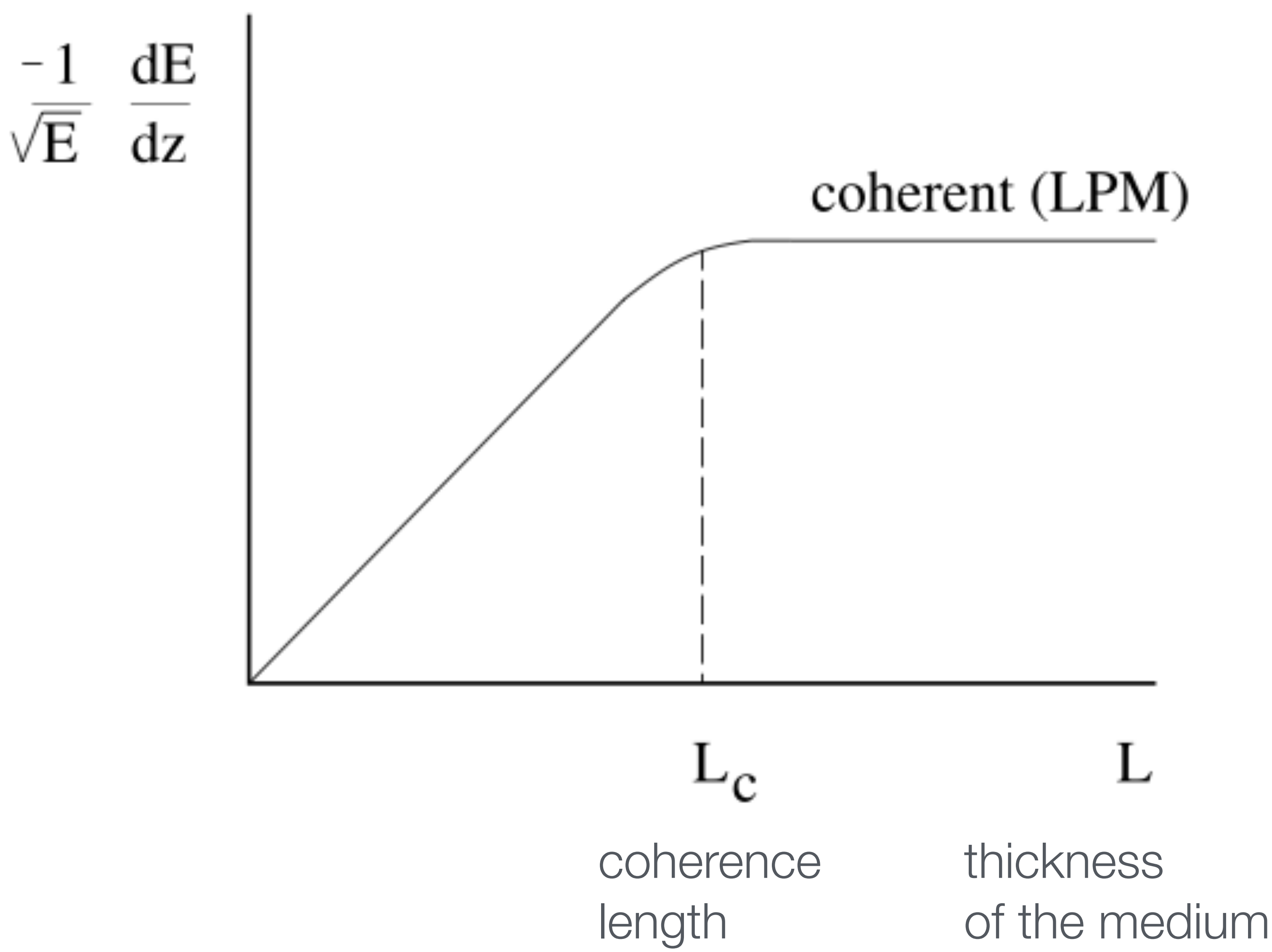
$$-\frac{dE}{dz} \simeq \frac{3\alpha_s}{\pi} \frac{E}{\lambda}$$

2. Coherent regime ($\lambda < z_{coh}$) with medium thickness $L > z_{coh}$ (saturated LPM regime)

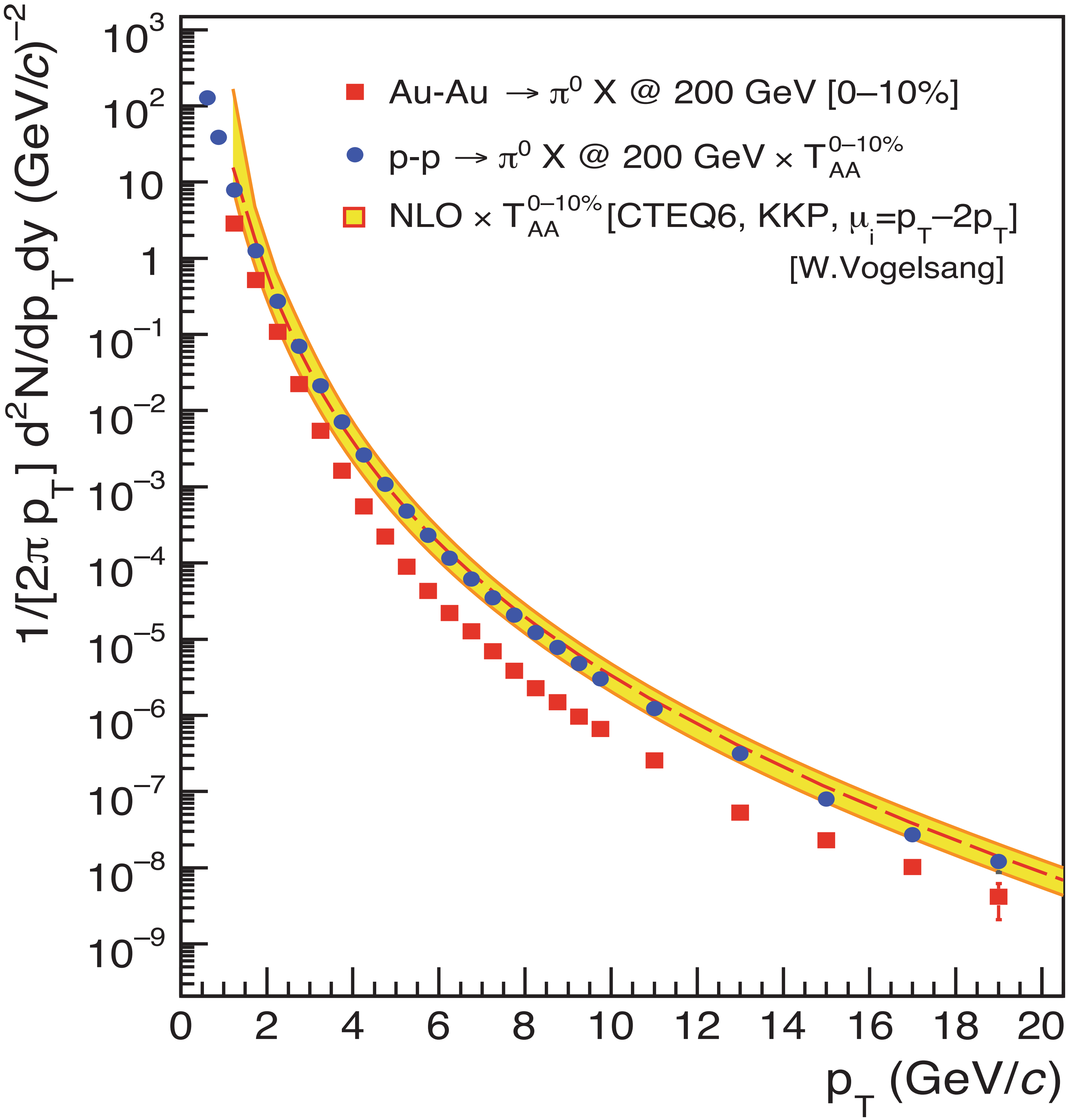
$$-\frac{dE}{dz} \simeq \frac{3\alpha_s}{\pi} \sqrt{\frac{E}{\hat{q}}}$$

3. Coherent regime ($\lambda < z_{coh}$) with $L < z_{coh}$

$$-\frac{dE}{dz} \simeq \frac{3\alpha_s}{\pi} \hat{q} L$$



N_{coll}-scaled π^0 yields in pp compared to Au-Au



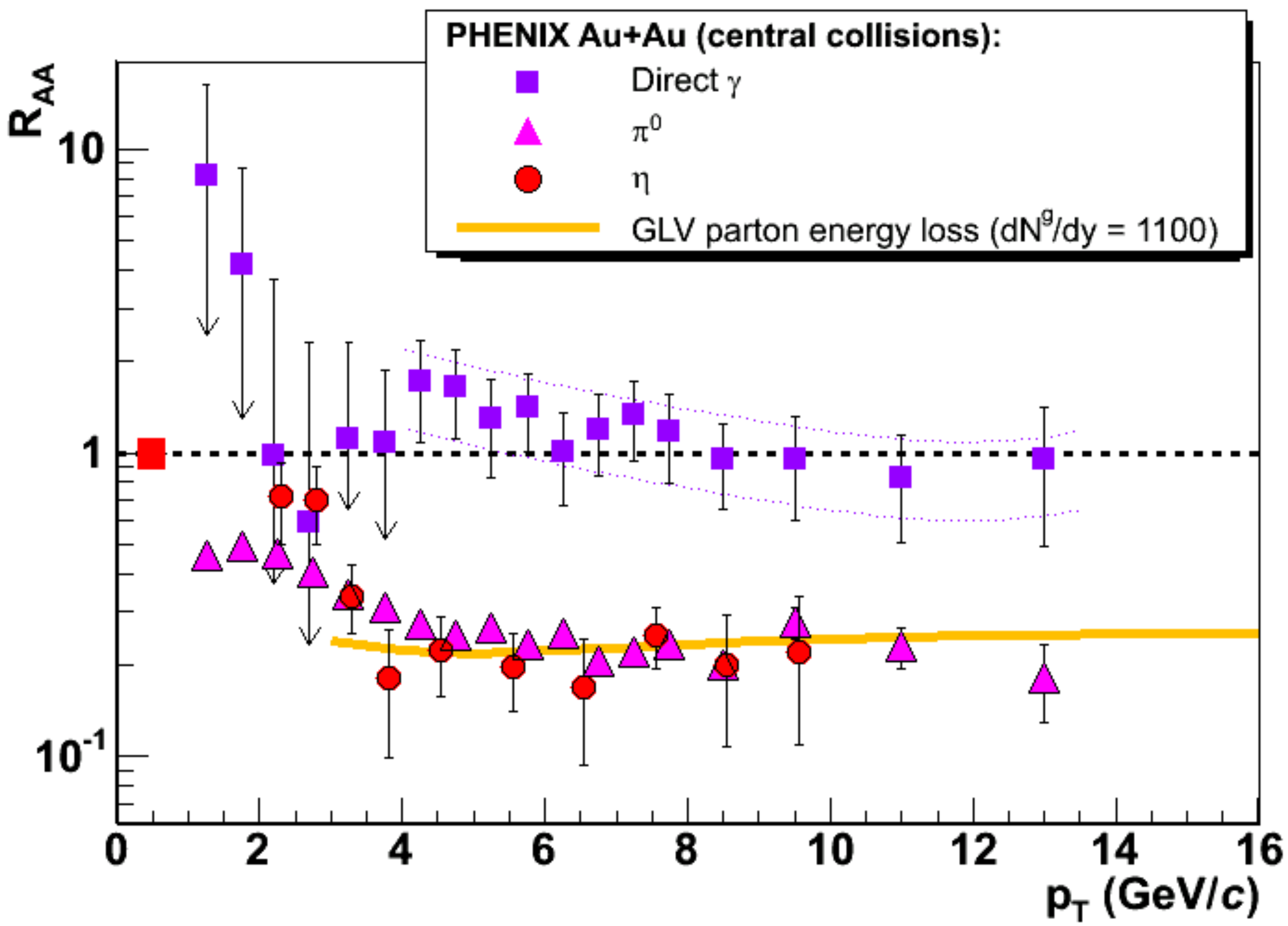
$T_{AA} = \langle N_{\mathrm{coll}} \rangle / \sigma_{\mathrm{inel}}^{\mathrm{NN}}$

"increase in parton luminosity" per collision when going from pp to AA"

Without a medium, hadron yields for $p_T \gtrsim$ 2-3 GeV are expected to scale with N_{coll}

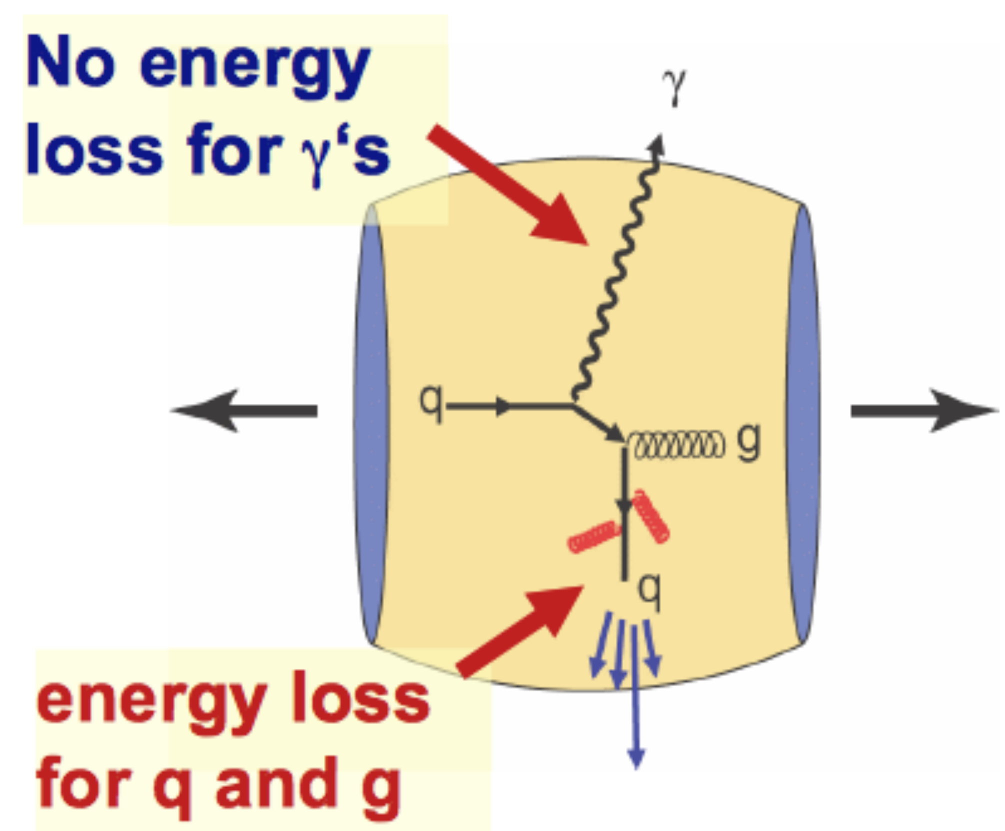
Observation:
Clear suppression w.r.t. N_{coll} scaling

Discovery of Jet Quenching at RHIC (ca. 2000 - 2003)



$$R_{AB} = \frac{dN/dp_T|_{A+B}}{\langle T_{AB}\rangle \times d\sigma_{inv}/dp_T|_{p+p}},$$

$$\text{where} \quad \langle T_{AB}\rangle = \langle N_{coll}\rangle / \sigma_{inel}^{NN}$$

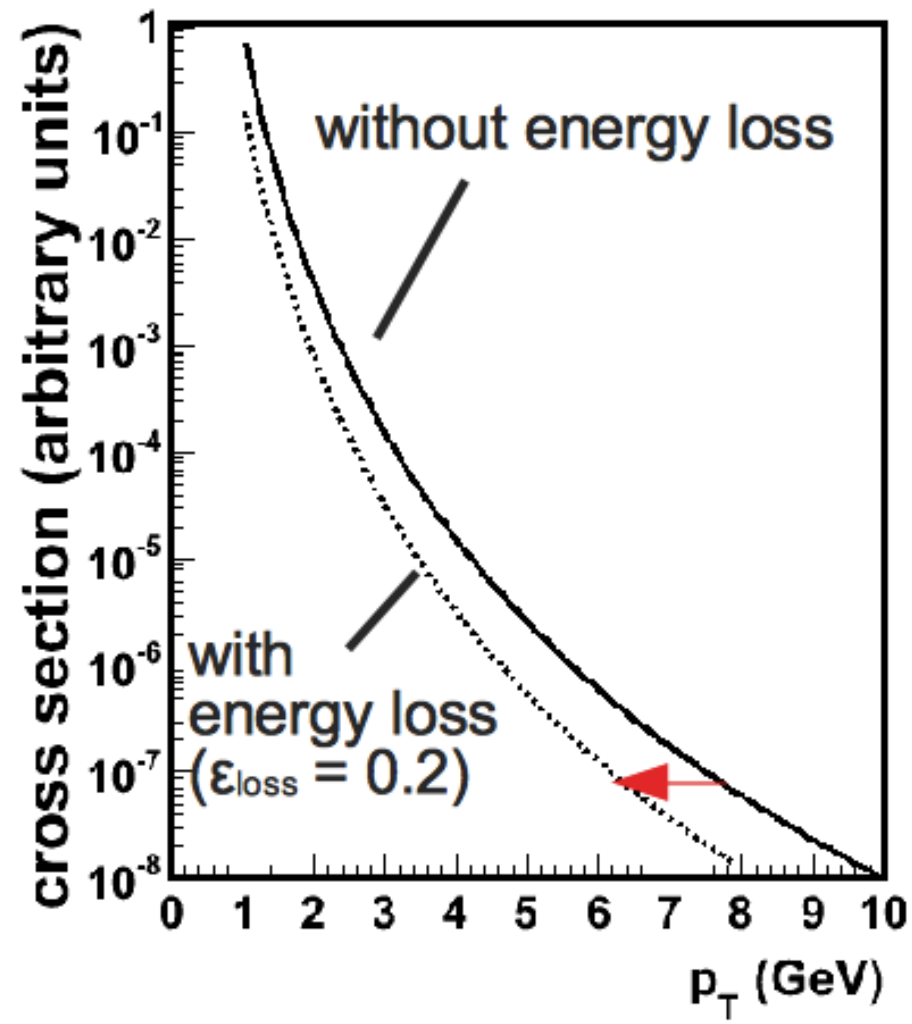


- Hadrons are suppressed, direct photons are not
- Evidence for parton energy loss

A simple explanation for the rather flat R_{AA} at RHIC: a Constant fractional parton energy loss

π^0 spectrum without energy loss: $\frac{1}{p_T}\frac{dN}{dp_T} \propto \frac{1}{p_T^n}$

π^0 spectra at RHIC energy ($\sqrt{s_{NN}}$ = 200 GeV) described with $n \approx 8$



Constant fractional energy loss:

$$\varepsilon_{\text{loss}} := -\frac{\Delta p_T}{p_T} \text{ , i.e., } p_T' = (1 - \varepsilon_{\text{loss}}) p_T$$

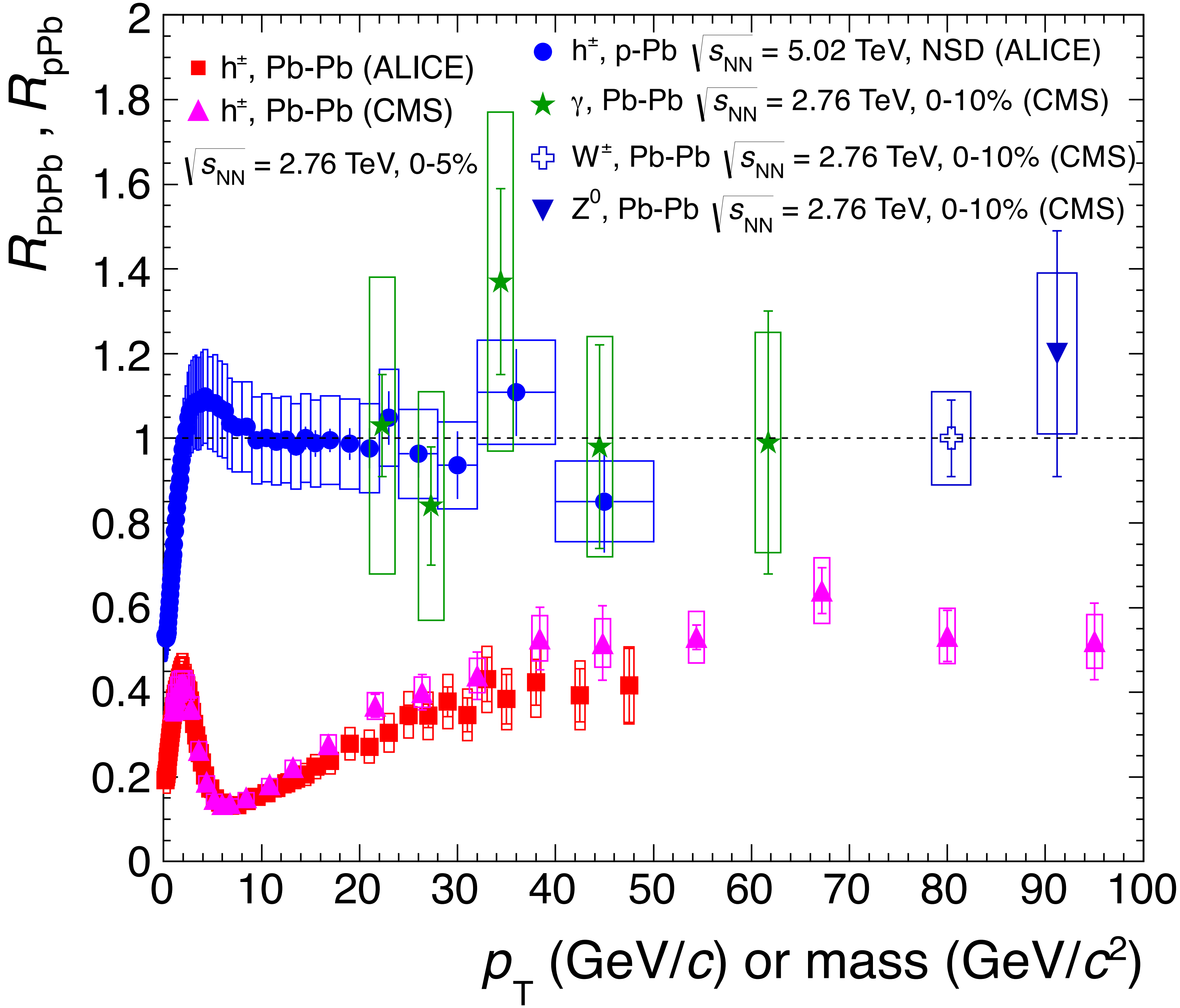
Resulting R_{AA}:

$$R_{AA} = (1 - \varepsilon_{\text{loss}})^{n-2} \quad \Rightarrow \quad \varepsilon_{\text{loss}} = 1 - R_{AA}^{1/(n-2)} \approx 0.2 \text{ for } R_{AA} \approx 0.25$$

R_{AA} depends on the parton energy loss and the shape of the p_T spectrum

In this simplistic model the constant $R_{AA} \approx 0.25$ implies a constant fractional energy loss of about 20% in central Au+Au collisions at 200 GeV

Single-particle R_{AA} in Pb-Pb at the LHC: Qualitatively similar observation as for RHIC energies



- No suppression for γ, W^{+-}, Z^0 in Pb-Pb
- No suppression of hadrons in p-Pb
- Strong suppression of hadrons in Pb-Pb

Medium properties from charged hadron $R_{AA}(p_T)$

- Fit of various models to $R_{AA}(p_T)$ at RHIC and the LHC
- Jet transport parameter loss for radiative energy loss at the highest temperatures reached (for E_{parton} = 10 GeV, QGP thermalization at τ_0 = 0.6 fm/c):

$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC,} \\ 3.7 \pm 1.4 & \text{at LHC,} \end{cases}$$

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV}^2/\mathrm{fm} \ \text{at} \ \begin{array}{l} \mathrm{T{=}370\ MeV,} \\ \mathrm{T{=}470\ MeV,} \end{array}$$

Jet Coll., Phys.Rev. C90 (2014) 014909

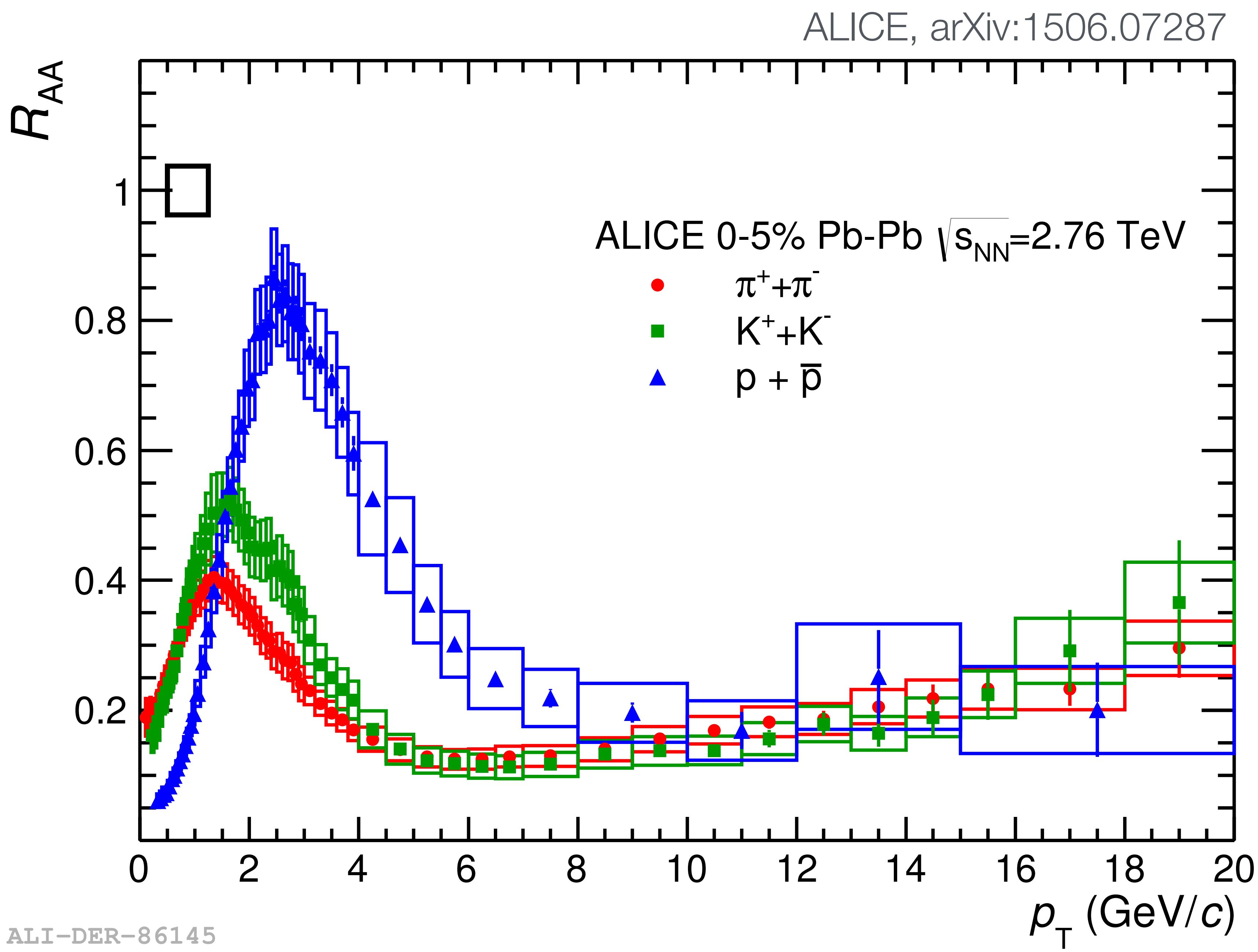
- Result relies on standard hydro description of the medium evolution
- Conjectured relation to η/s:

$$\frac{T^3}{\hat{q}} = K \frac{\eta}{s}$$

weakly-coupled QGP: $K \approx 1$
strongly-coupled QGP: $K \ll 1$

Majumder, Müller, Wang, PRL, 99 (2007) 192301

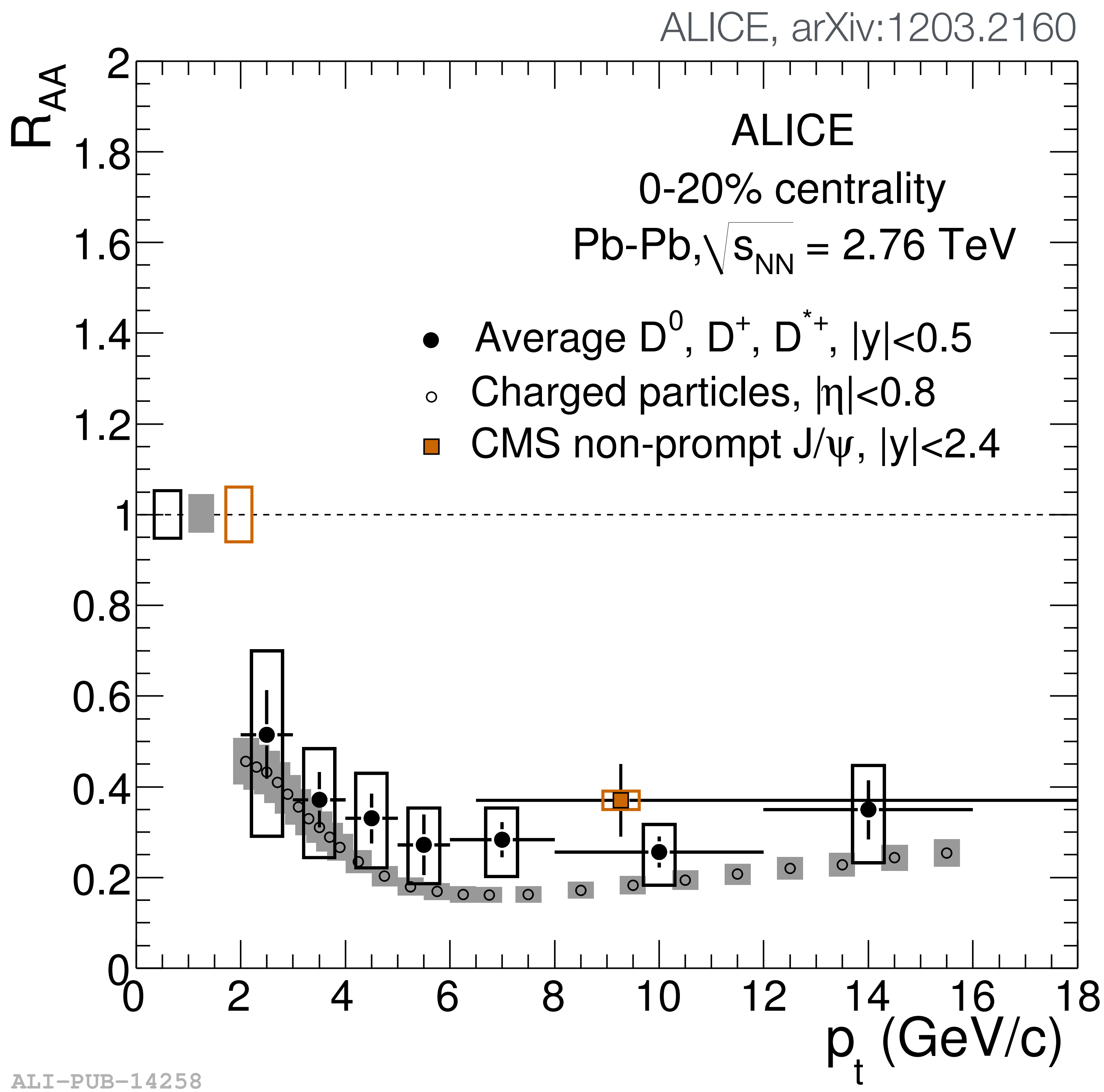
π, K, p R_{AA}: Suppression independent of hadron species for $p_T \gtrsim 8$ GeV/c



- $R_{AA}(p) > R_{AA}(K) \approx R_{AA}(\pi)$ for $3 < p_T < 8$ GeV/c
- Similar p, K and π R_{AA} for $p_T > 8$ GeV/c

Leading-parton energy loss followed by fragmentation in QCD vacuum (as in pp) for $p_{T,hadron} > 8$ GeV/c?

D meson R_{AA}: Charm quark energy loss similar to quark and gluon energy loss

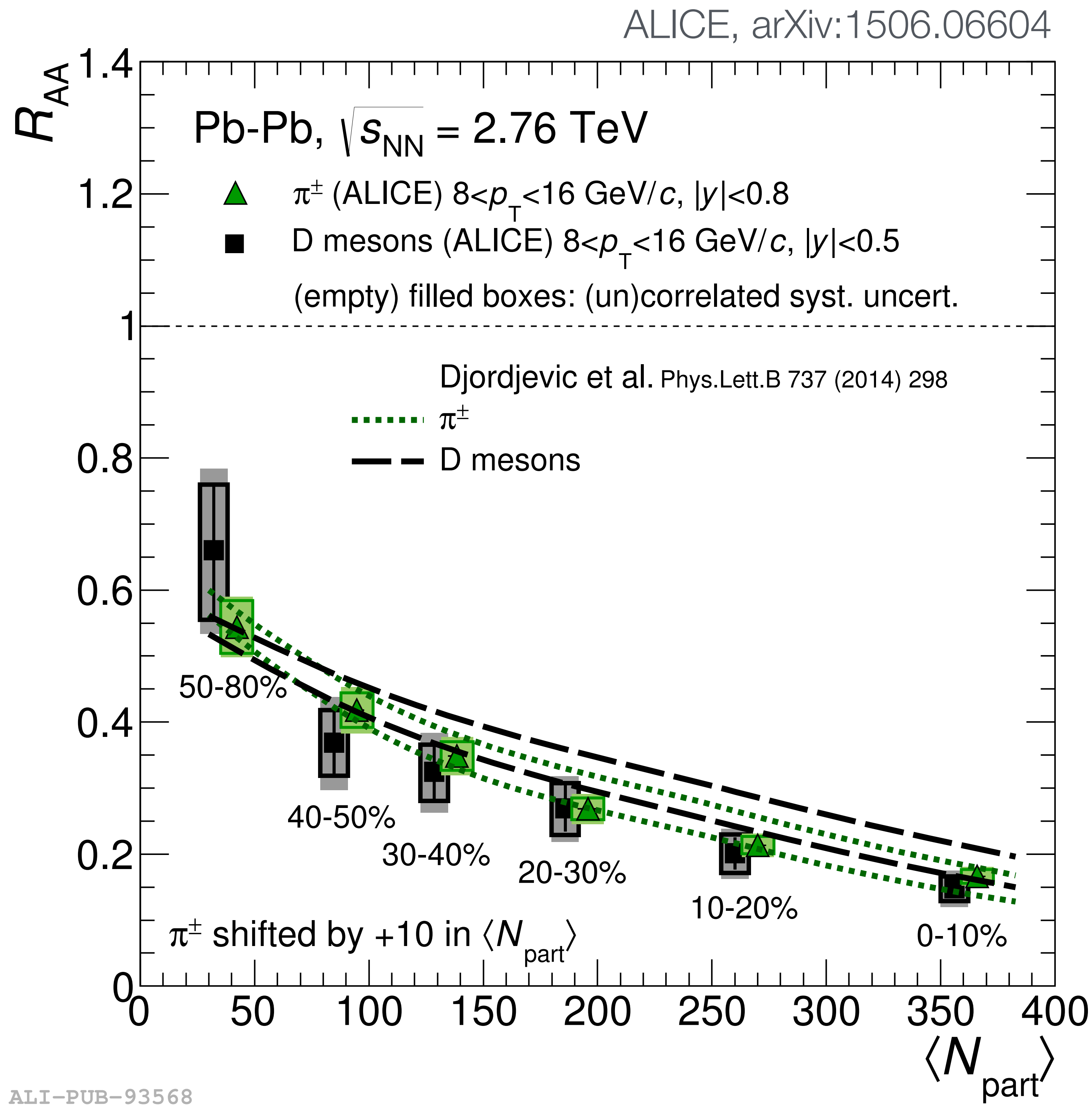


$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

color factor **dead cone effect** (gluon emission suppressed at forward angles for slow quarks)

- Strong suppression also for D mesons (which cannot be explained by shadowing)
- Suppression of D mesons and pions (surprisingly?) similar
  - Pions mainly from gluons
  - Dead cone effect for c and b
- Still hint for expected hierarchy?
  - However, need to carefully consider also the steepness of the initial parton spectra

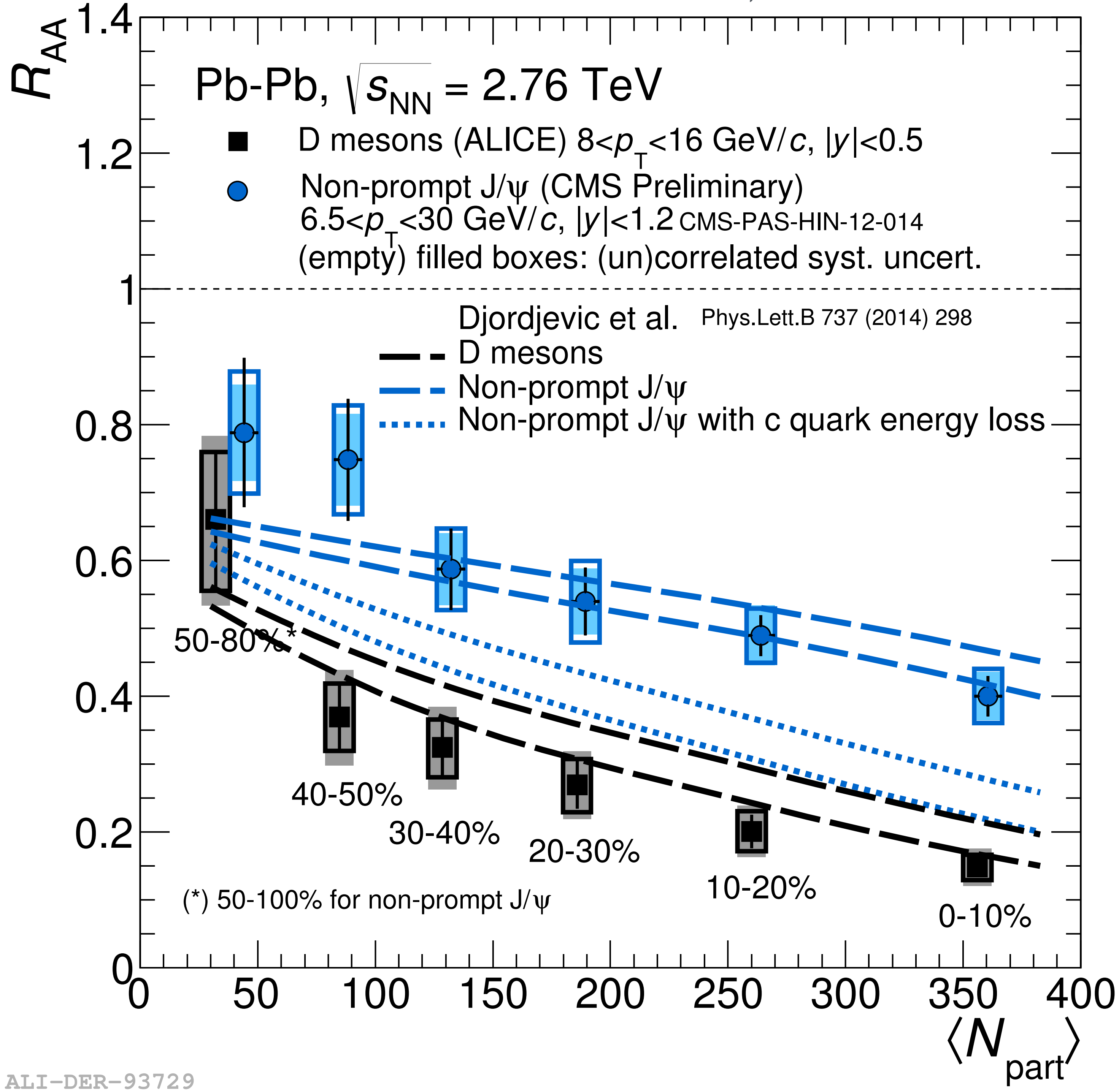
Centrality dependence of R_{AA} for pions and D mesons



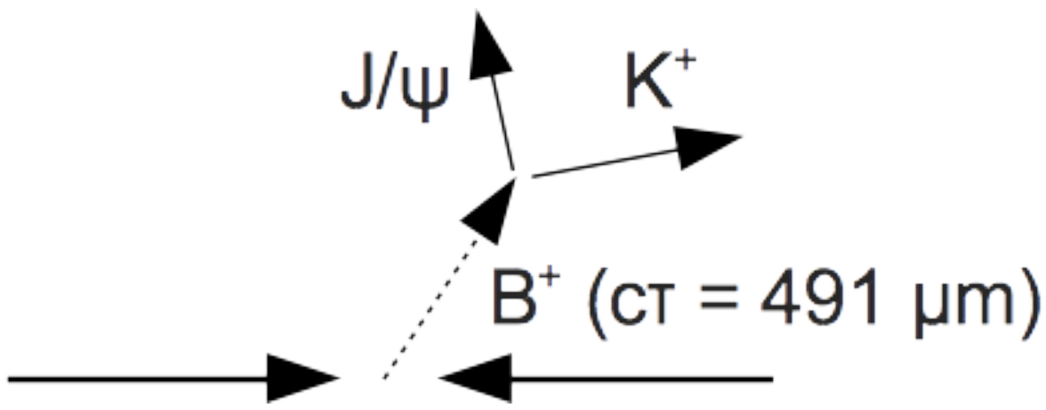
- N_{part} dependence similar for pions and D mesons
- Actually expected in parton energy loss calculation

Evidence for smaller energy loss for b quarks than for c quarks

ALICE, arXiv:1506.06604

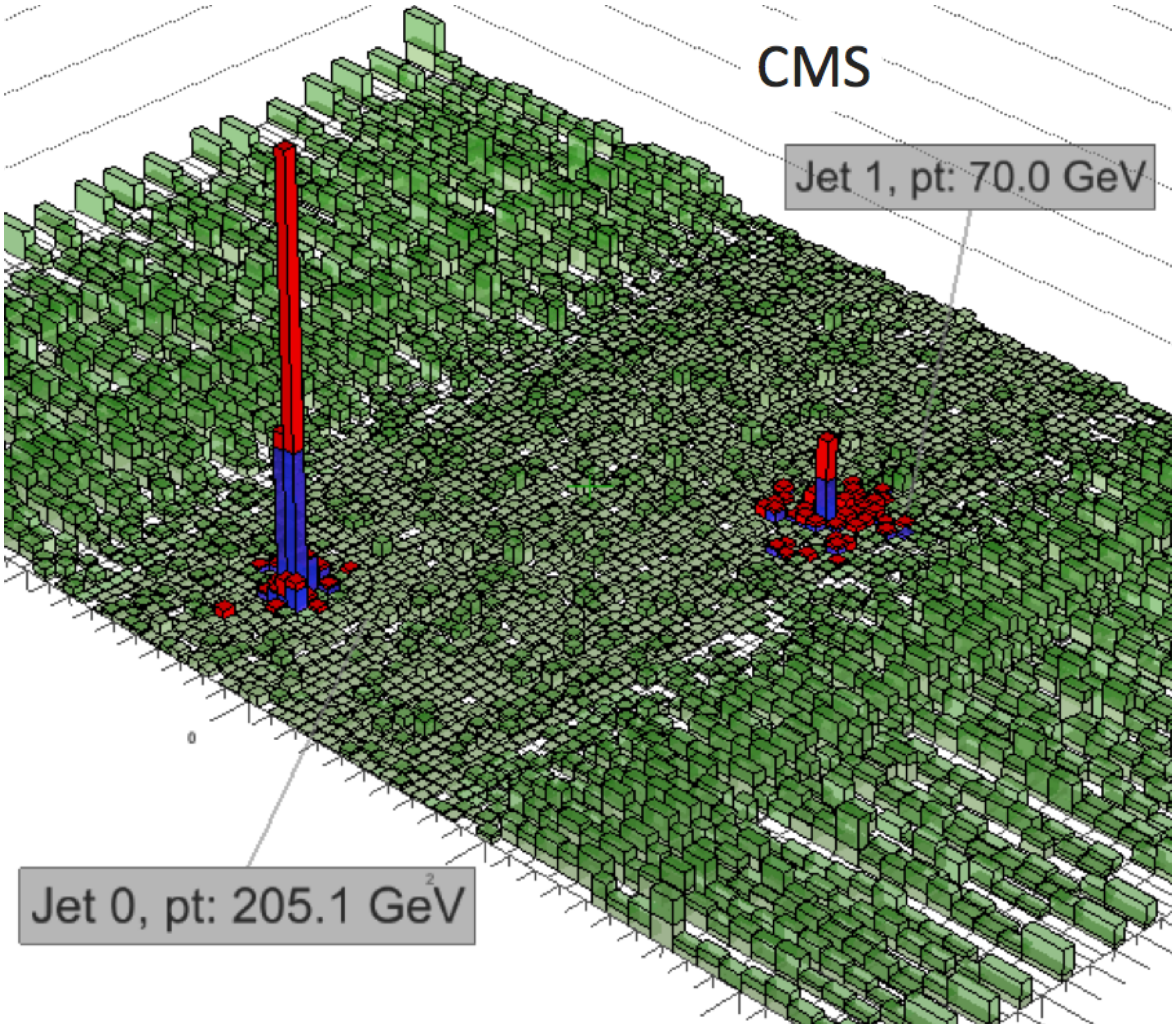


b quark energy loss via non-prompt J/ψ:



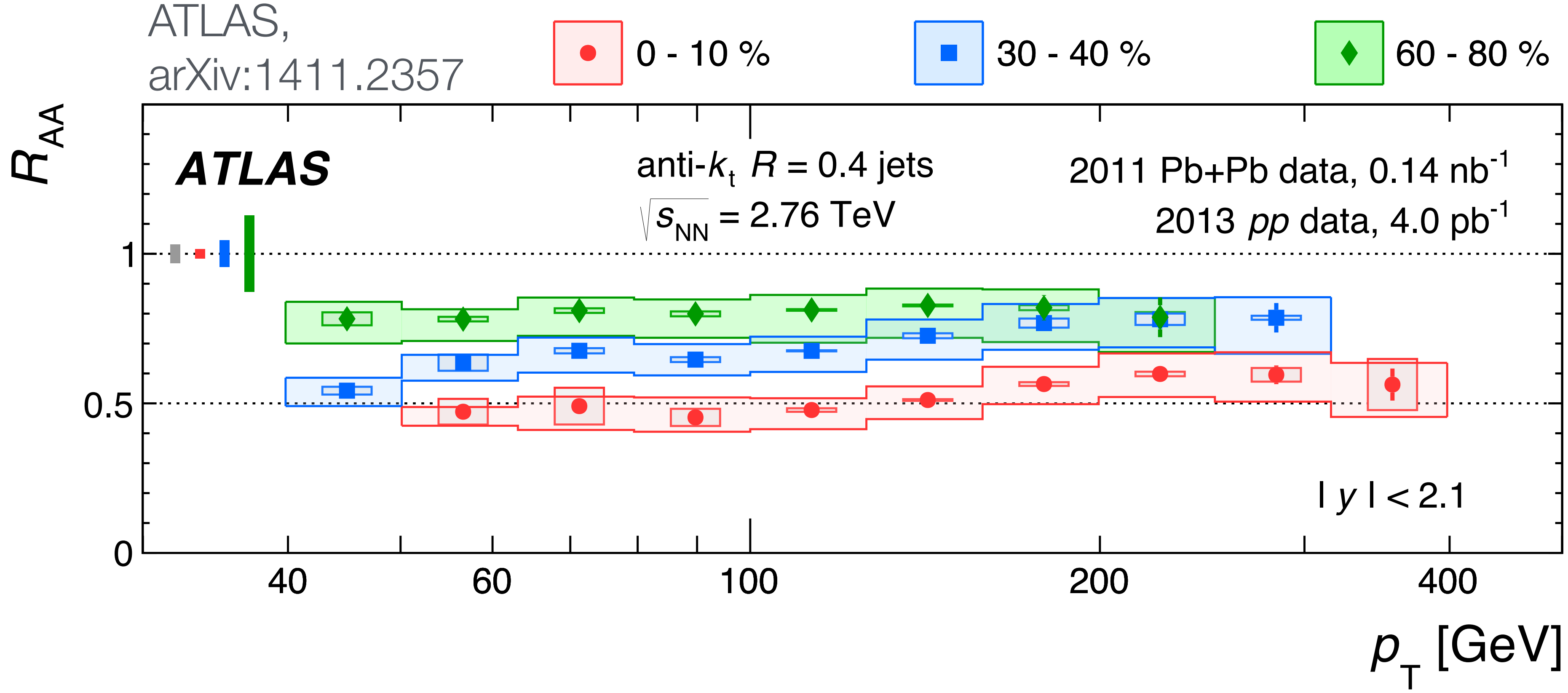
Evidence for the expected energy loss hierarchy between c and b quarks

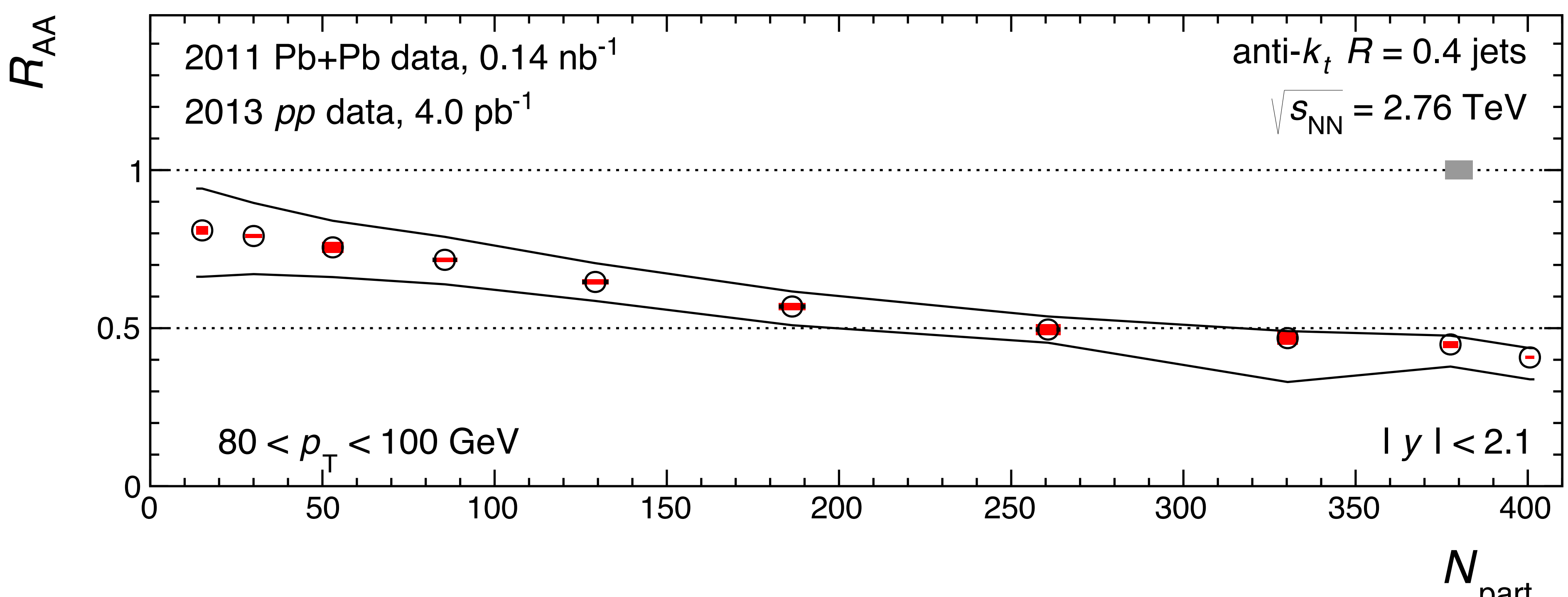
Studying jet quenching with jets: Large dijet energy asymmetries in Pb-Pb



Jet suppression in Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV: $R_{AA} \approx 0.5$ in central collisions

ATLAS, arXiv:1411.2357





Interestingly, there is not much of a p_T dependence of the jet suppression

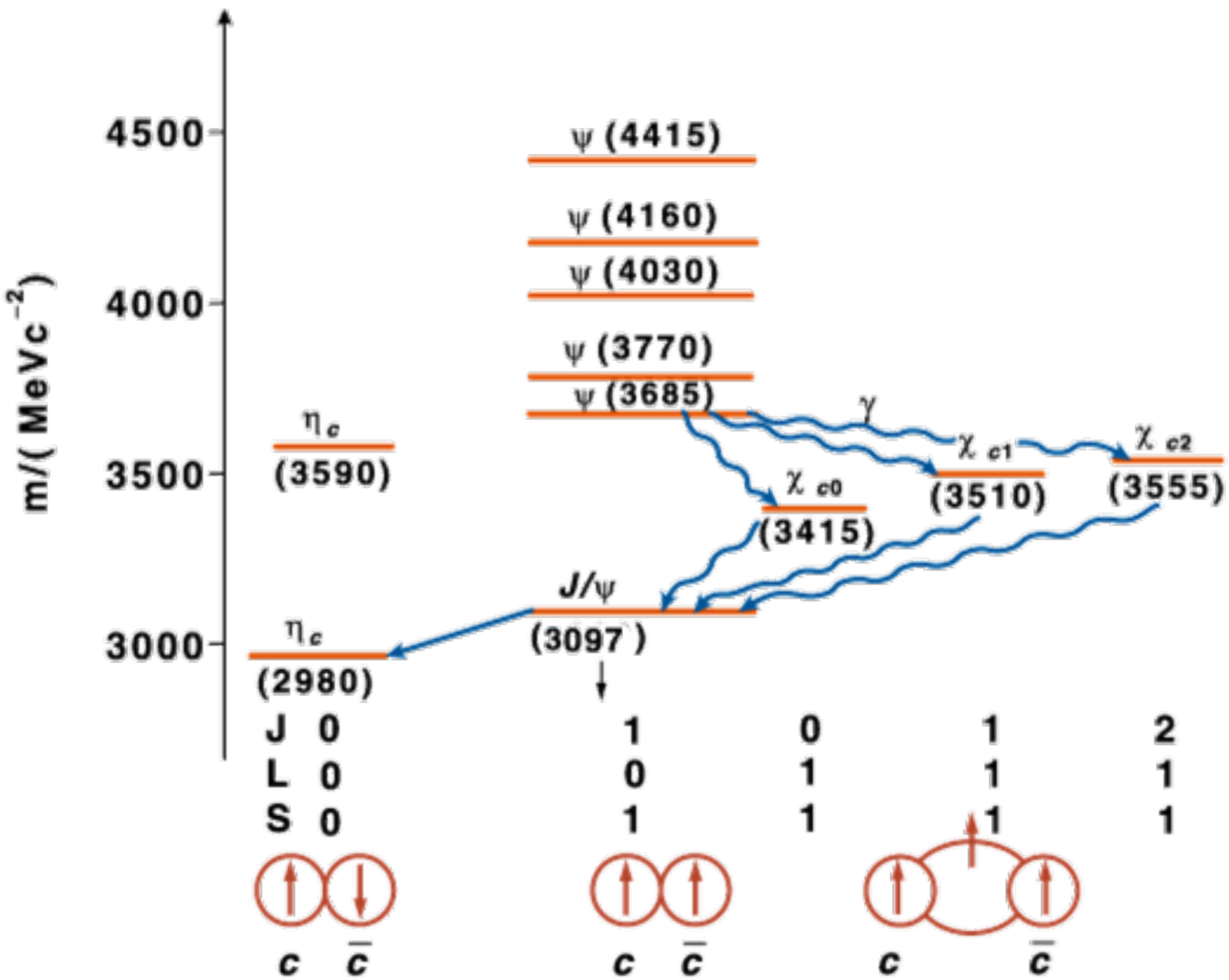
Summary/questions jet quenching

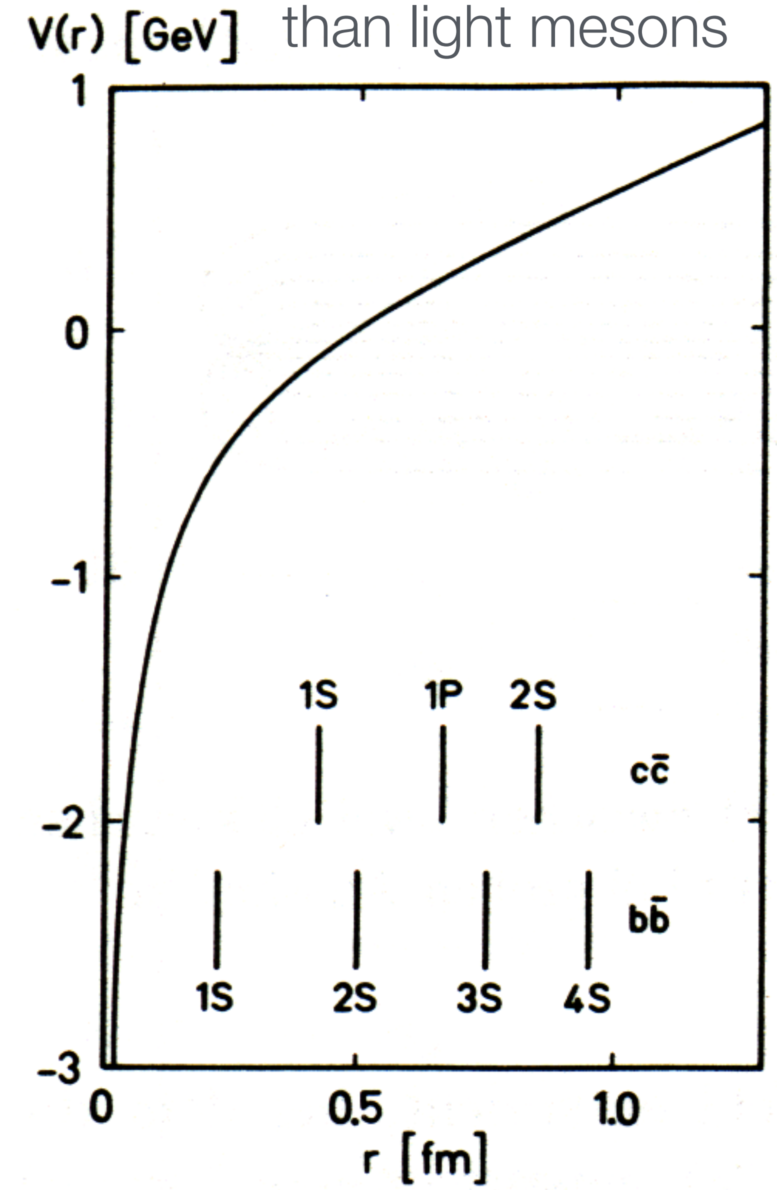
- Collisional and radiative parton energy loss
  - Radiative energy loss expected to be dominant for light quarks
- Evidence for expected quark mass dependence of the energy loss
- QCD inspired models are capable of reproducing many features seen in the data
  - Medium properties can be constrained
- What's next?
  - First generation of models focussed on leading-particle energy loss ("medium-modified fragmentation function")
  - Need to describe full parton shower evolution in the medium
  - Can one eventually describe parton energy loss based on first principles?
  - Can one connect heavy-quark energy loss to string theory via the gauge/gravity duality?

7. Charmonium and bottomonium

Charmonium and bottomium

Quarkonia: tightly bound, smaller radius than light mesons





- Non-relativistic treatment for heavy quarks ($m_c \approx 1.3$ GeV, $m_b \approx 4.7$ GeV)
- Charmonium and bottomium states reproduced by solving Schrödinger equation using Cornell potential:

$$V(r) = -\frac{\alpha}{r} + \sigma r$$

$\sigma \approx 1$ GeV/fm, $\alpha \approx \pi/12$

Debye screening in the QGP

- Matsui, Satz (Phys. Lett. B 178 (1986)):
  - Potential between two heavy quarks is modified in the QGP, preventing initially produced charm anticharm quarks to form a J/ψ
  - J/ψ suppression is a QGP signal

- Simple parameterization of the screened potential ("Debye screening")

$$V(r, T) = -\frac{\alpha}{r} e^{-\mu r} + \sigma r \frac{1 - e^{-\mu r}}{\mu r}$$

screening radius depends on temperature:

$$r_D = 1/\mu \quad \text{(Debye mass: } \mu\text{)}$$

$$\mu = \mu(T) \propto g(T) T$$

- Basic idea: heavy-quark bound state melts in the QGP if $r_{Q\bar{Q}} \gtrsim r_D$

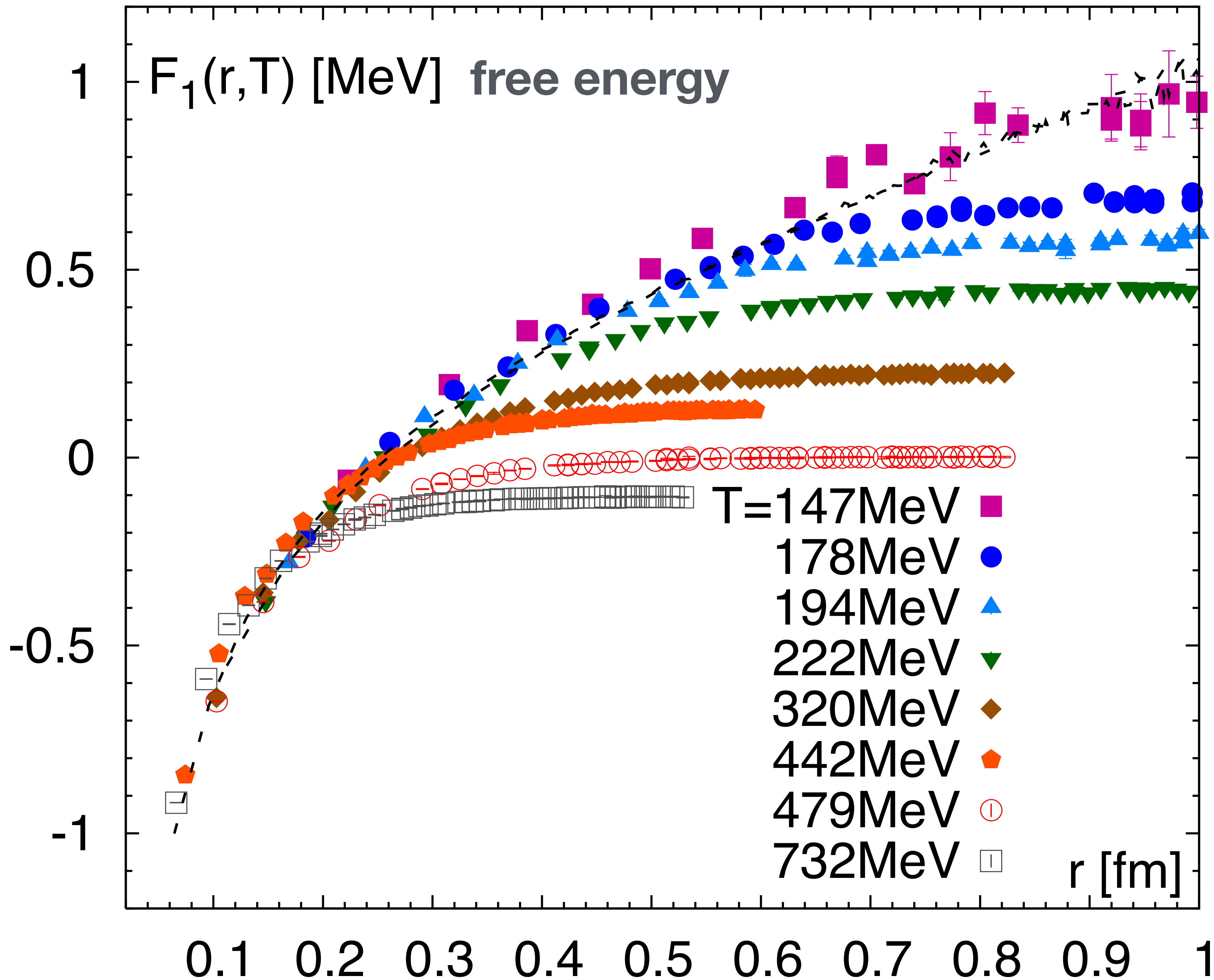
- There is a dissociation temperate T_d for each state ("sequential melting"):

Can the different T_d's serve as a QGP thermometer?

State	$J/\psi(1S)$	$\chi_c(1P)$	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
T_d/T_c	2.0	1.2	1.1	> 4.0	1.8	1.6	1.2	1.2

Heavy quark potential for different temperatures from lattice QCD

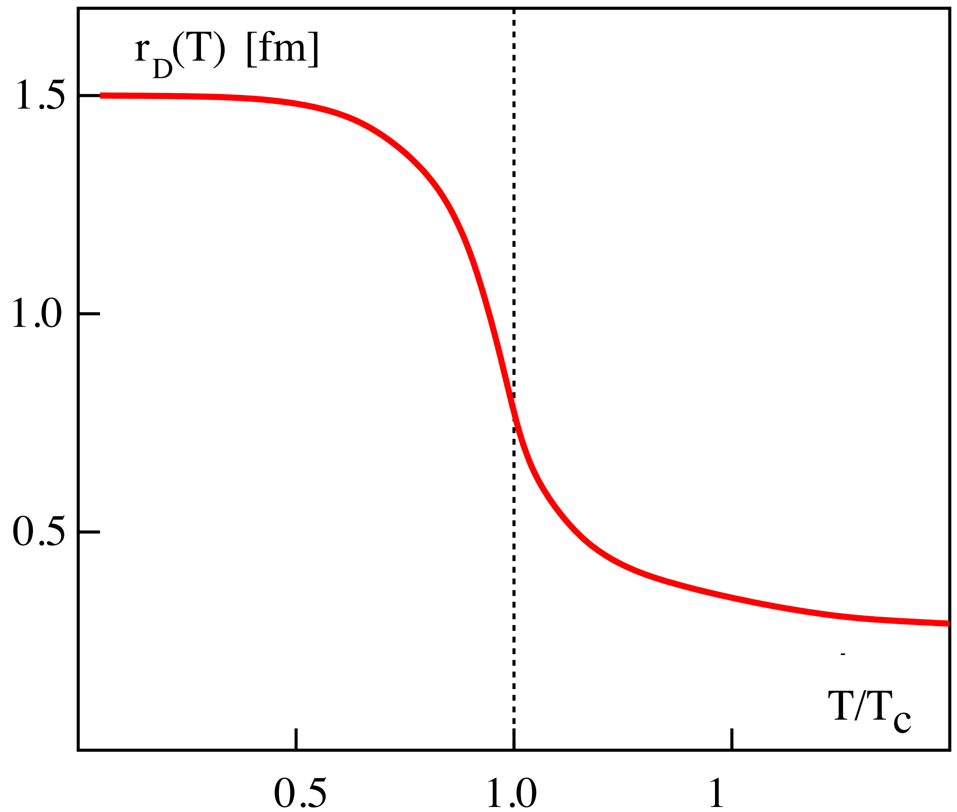
arXiv:1302.2180v1



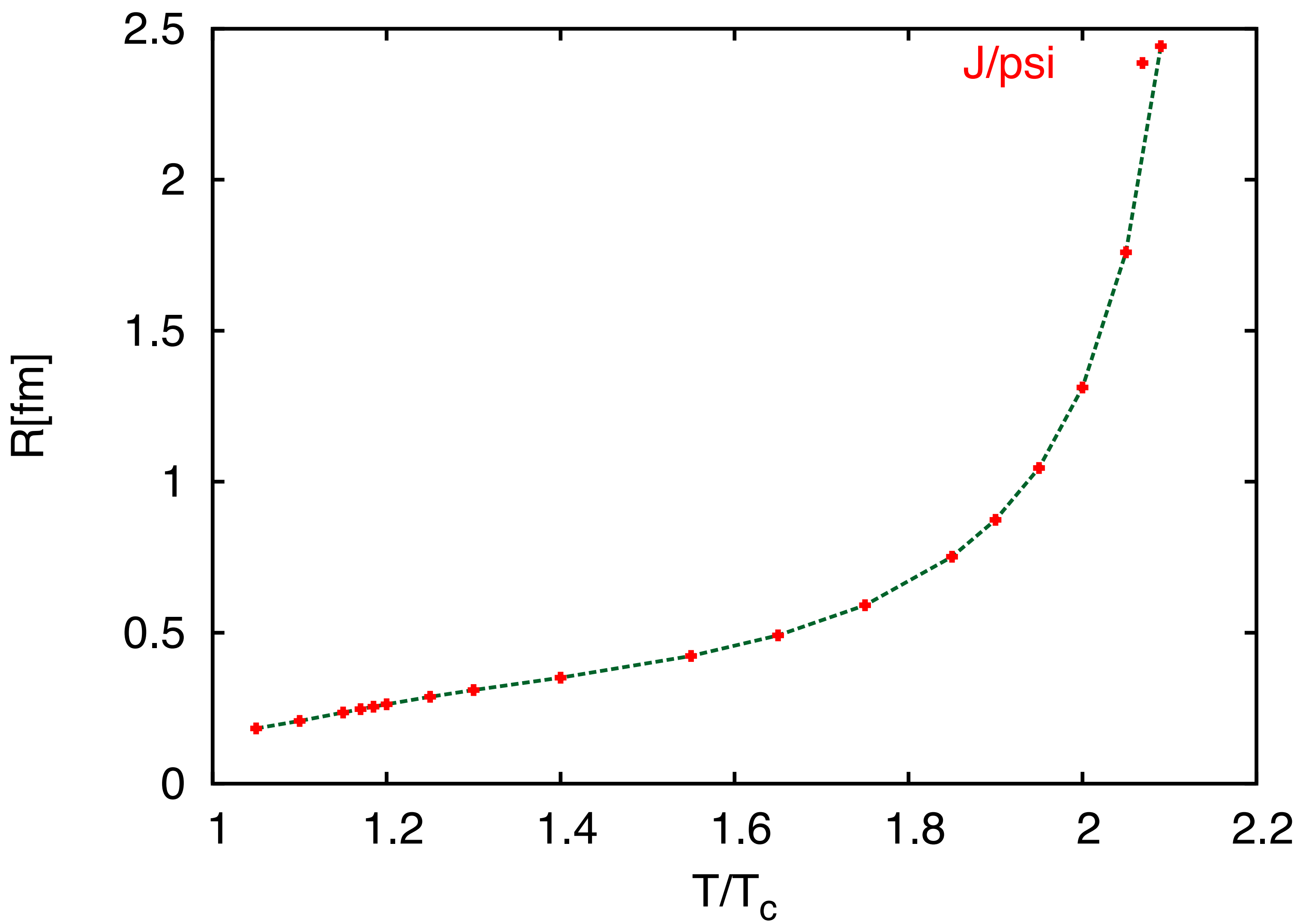
Interaction range and J/ψ radius in the medium as a function of the temperature

H. Satz, hep-ph/0512217

Interaction range vs *T*



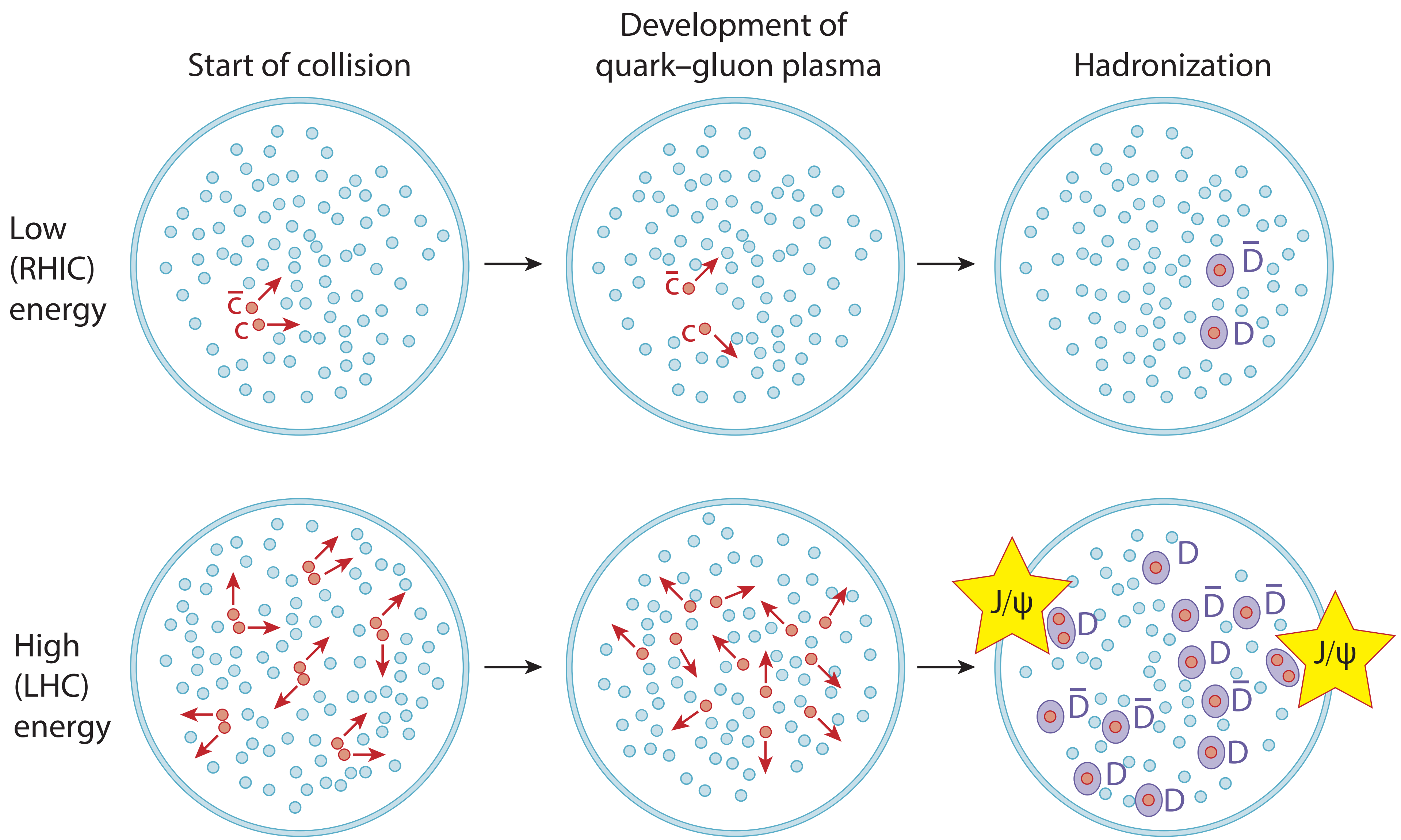
J/ψ radius vs. *T*



- J/ψ radius becomes larger with increasing *T*
- No bound state anymore for $T \gtrsim 2\ T_c$

A new twist:
J/ψ might form again from deconfined charm quarks

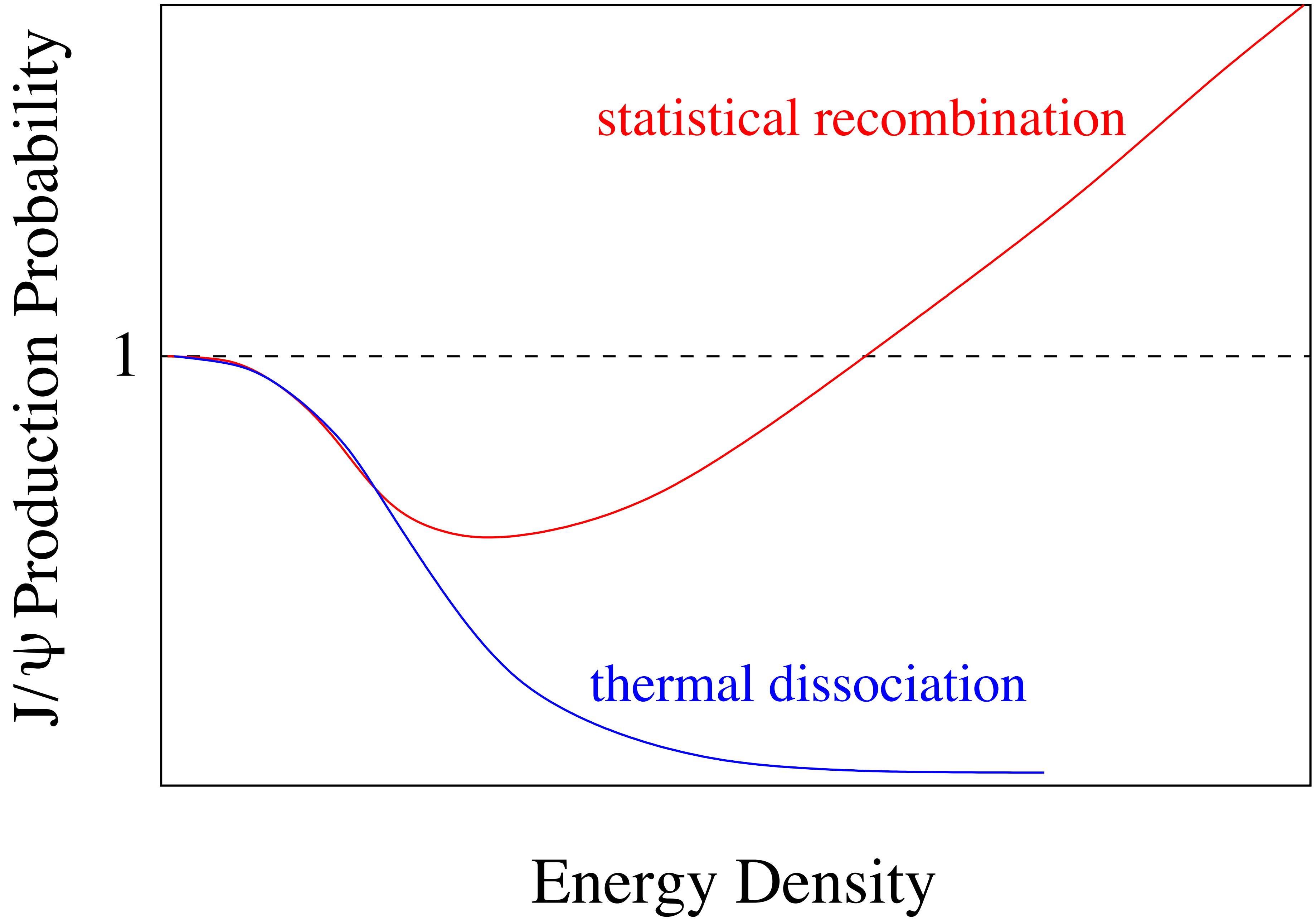
Braun-Munzinger, Stachel, Nature 448 (2007) 302



- Requires large number of initially produced c cbar pairs: $N_{J/\psi} \propto N_{c\bar{c}}^2$
- Expect J/ψ suppression at SPS, RHIC and J/ψ enhancement at high energies

Expected J/ψ signal with or without statistical recombination of charm quarks

Kluberg, Satz, 0901.3831



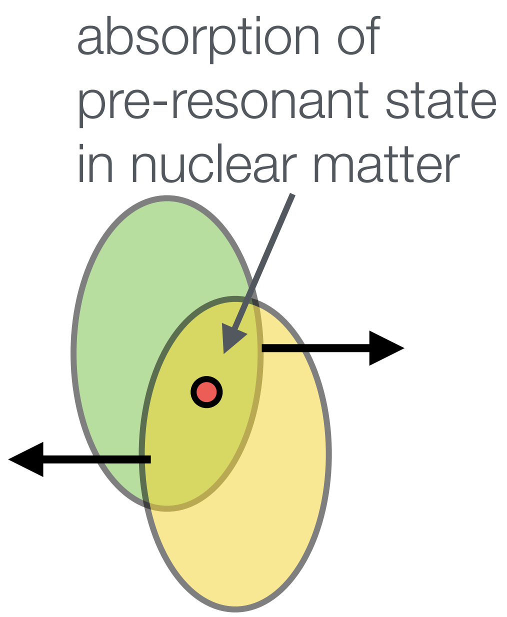
Time scales

Collision time: $t_{\text{coll}} = 2R/\gamma_{cm}$ (RHIC: $0.1\,\text{fm}/c$, LHC: $5 \cdot 10^{-3}\,\text{fm}/c$)

Charm pair formation: $\tau_{c\bar{c}} = \dfrac{1}{2m_c} \approx 0.08\,\text{fm}/c$

QGP formation: $\tau_{\text{QGP,SPS}} \approx 1\,\text{fm}/c,\ \tau_{\text{QGP,SPS}} < 0.5\,\text{fm}/c,\ \tau_{\text{QGP,LHC}} < 0.1\,\text{fm}/c$

Hadron formation time: $\tau_{\text{hadron}} \approx 1\,\text{fm}/c$



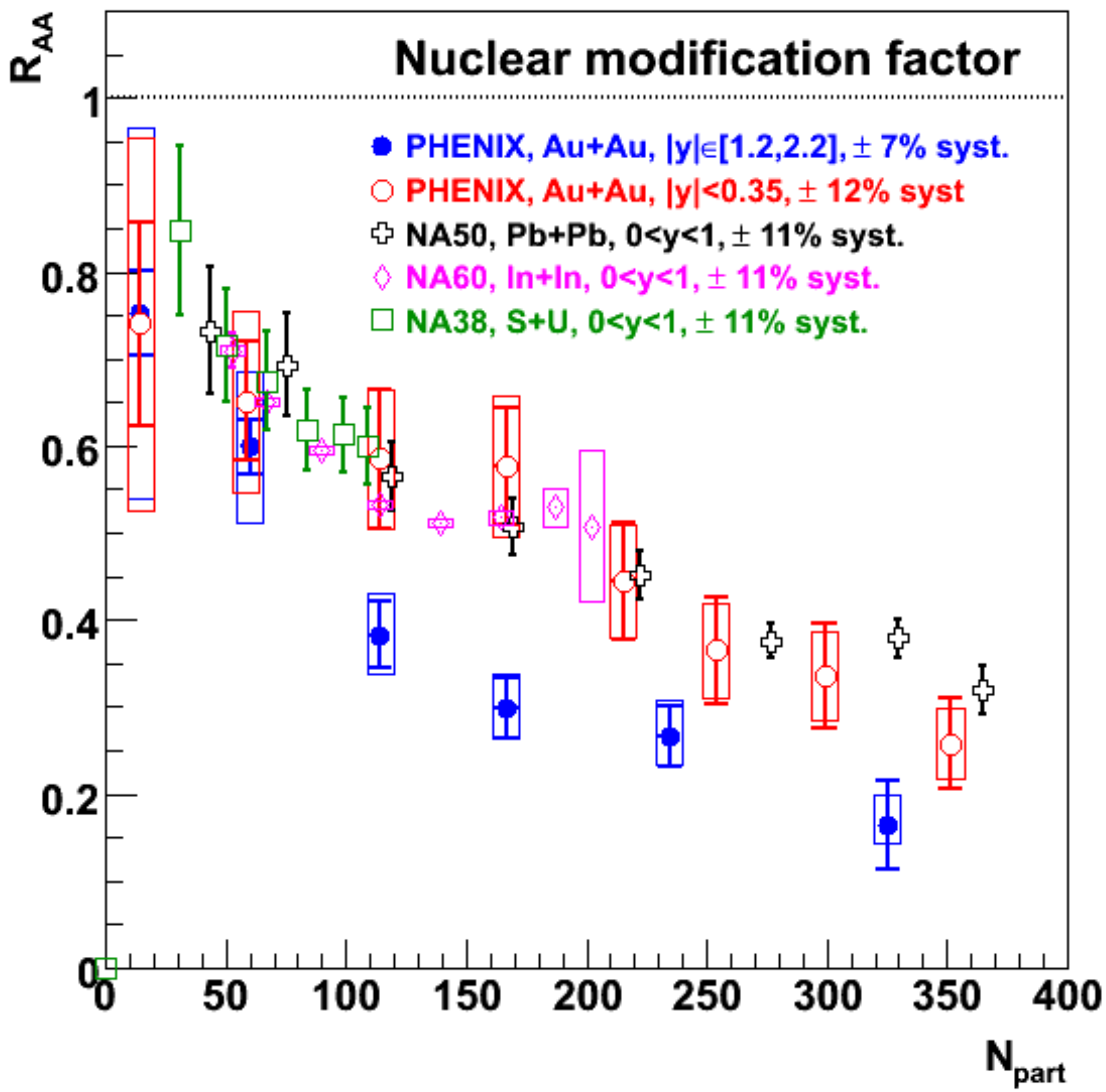
CERN SPS energies and below: $t_{\text{coll}} \simeq \tau_{\text{QGP}} \simeq \tau_{\text{hadron}}$
→ pre-resonant state can be absorbed in cold nuclear matter

Separation of scales at the LHC (and also RHIC):

$$t_{\text{coll}} \ll \tau_{\text{QGP}} < \tau_{\text{hadron}}$$

Interpretation of the J/ψ signal easier at the LHC (and at RHIC) as absorption in cold nuclear matter should not be irrelevant

J/ψ suppression at the CERN SPS and at RHIC



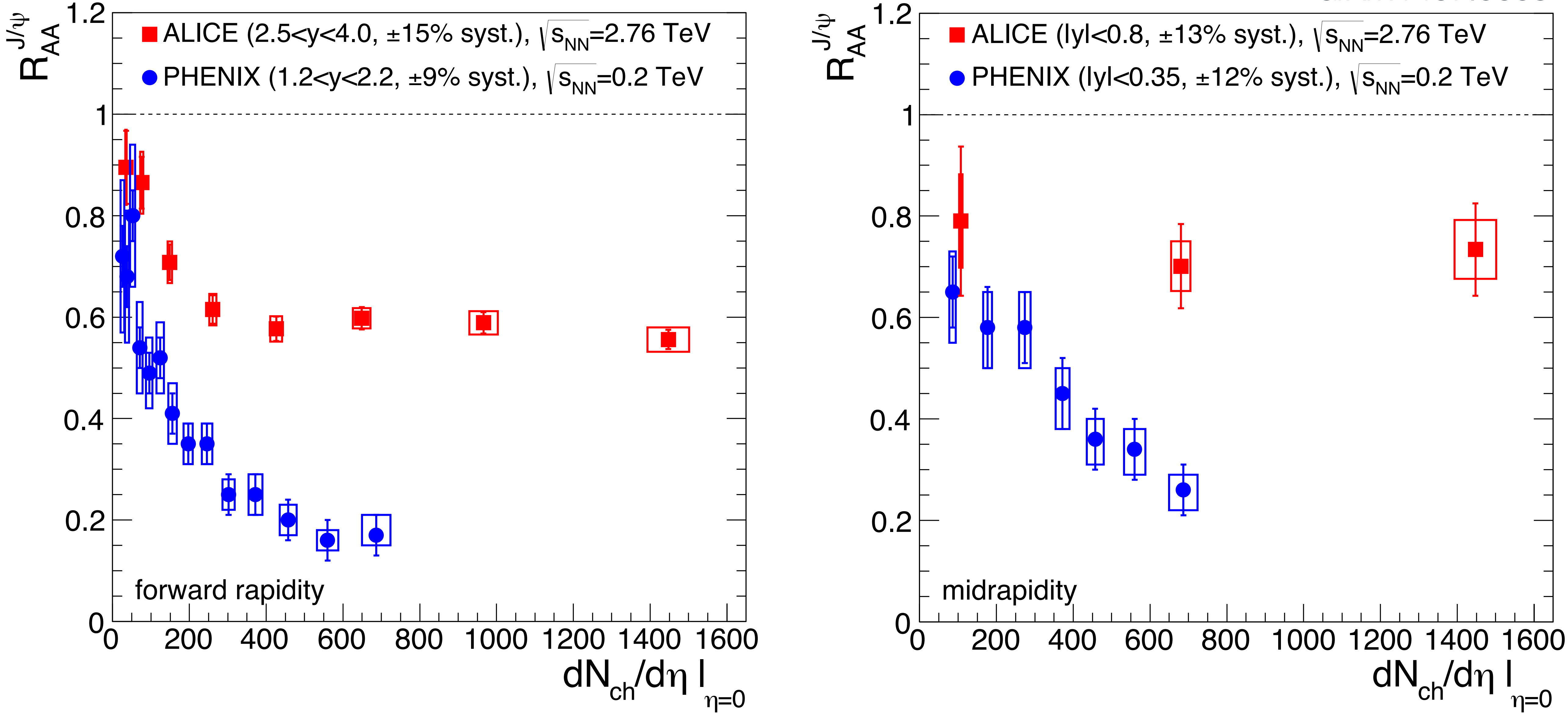
- Same suppression at midrapidity at the CERN SPS and at RHIC, in spite of larger energy density at RHIC
- RHIC: suppression large at forward rapidity, in spite of larger energy density at mid-rapidity
- Not easy to explain in pure dissociation picture

$$R_{AB} = \frac{\mathrm{d}N/\mathrm{d}p_T|_{\mathrm{A+B}}}{\langle T_{\mathrm{AB}}\rangle \times \mathrm{d}\sigma_{\mathrm{inv}}/\mathrm{d}p_{\mathrm{T}}|_{\mathrm{p+p}}},$$

where $\langle T_{\mathrm{AB}}\rangle = \langle N_{\mathrm{coll}}\rangle / \sigma_{\mathrm{inel}}^{\mathrm{NN}}$

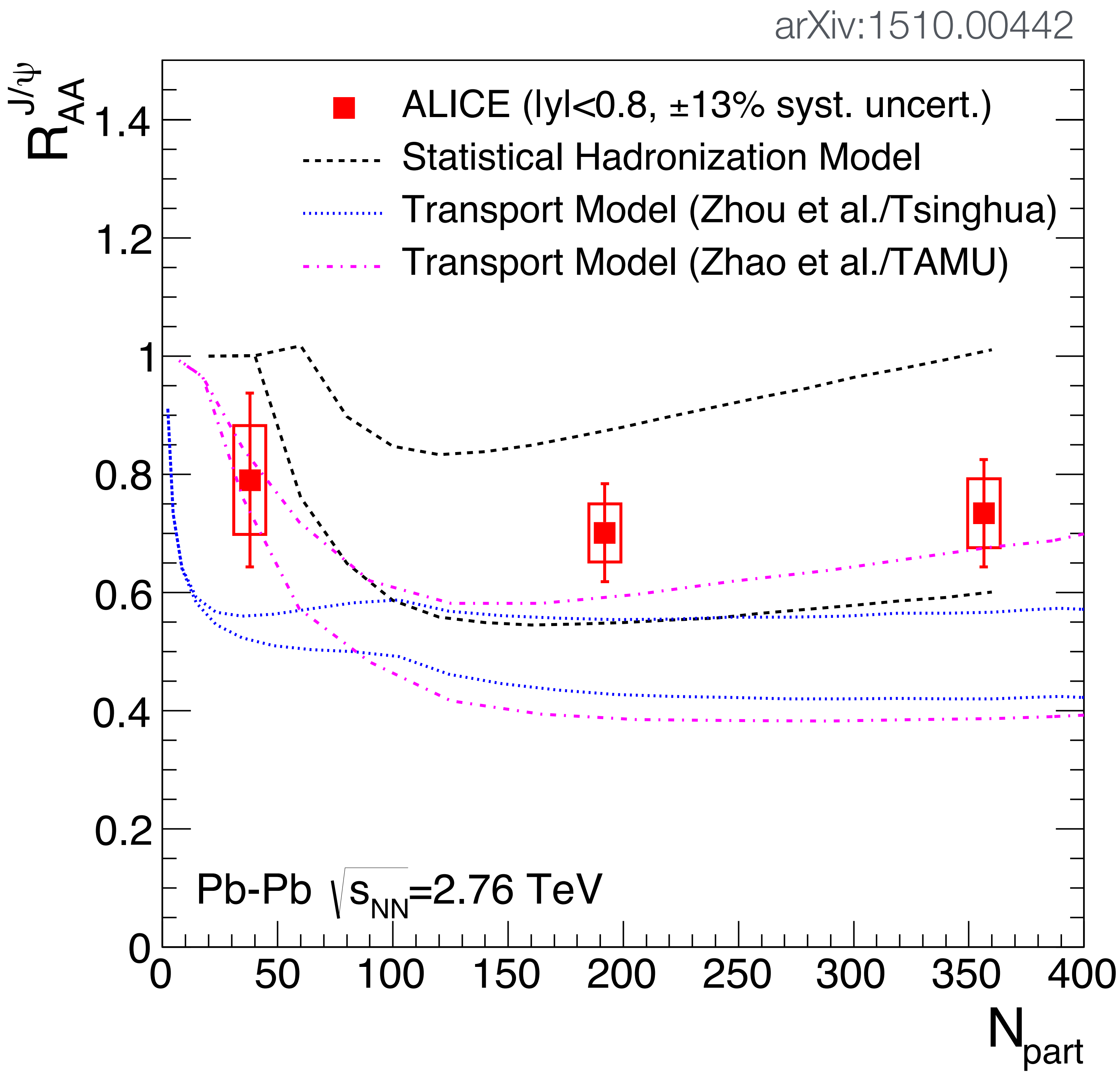
J/ψ suppression at RHIC and the LHC

arXiv:1407.5003



Much less suppression at the LHC in spite of larger energy density

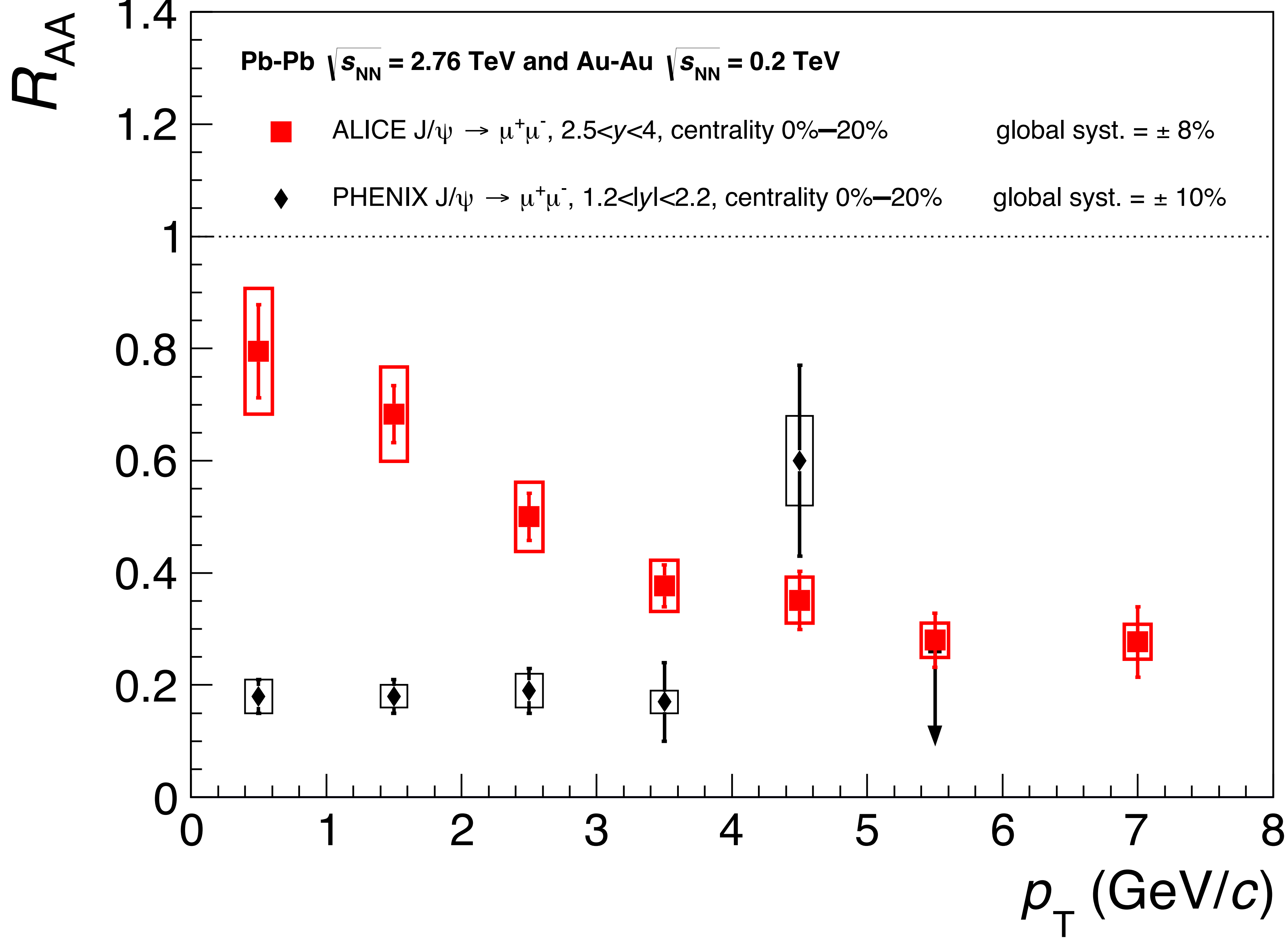
J/ψ R_{AA} at the LHC is reproduced by models based on the regeneration mechanism



- Two different approaches
  - Statistical hadronization at the phase boundary
  - Kinetic recombination of charm and anti-charm quarks in the QGP (hep-ph/0007323)
- Important model input: number of initial charm quark pairs

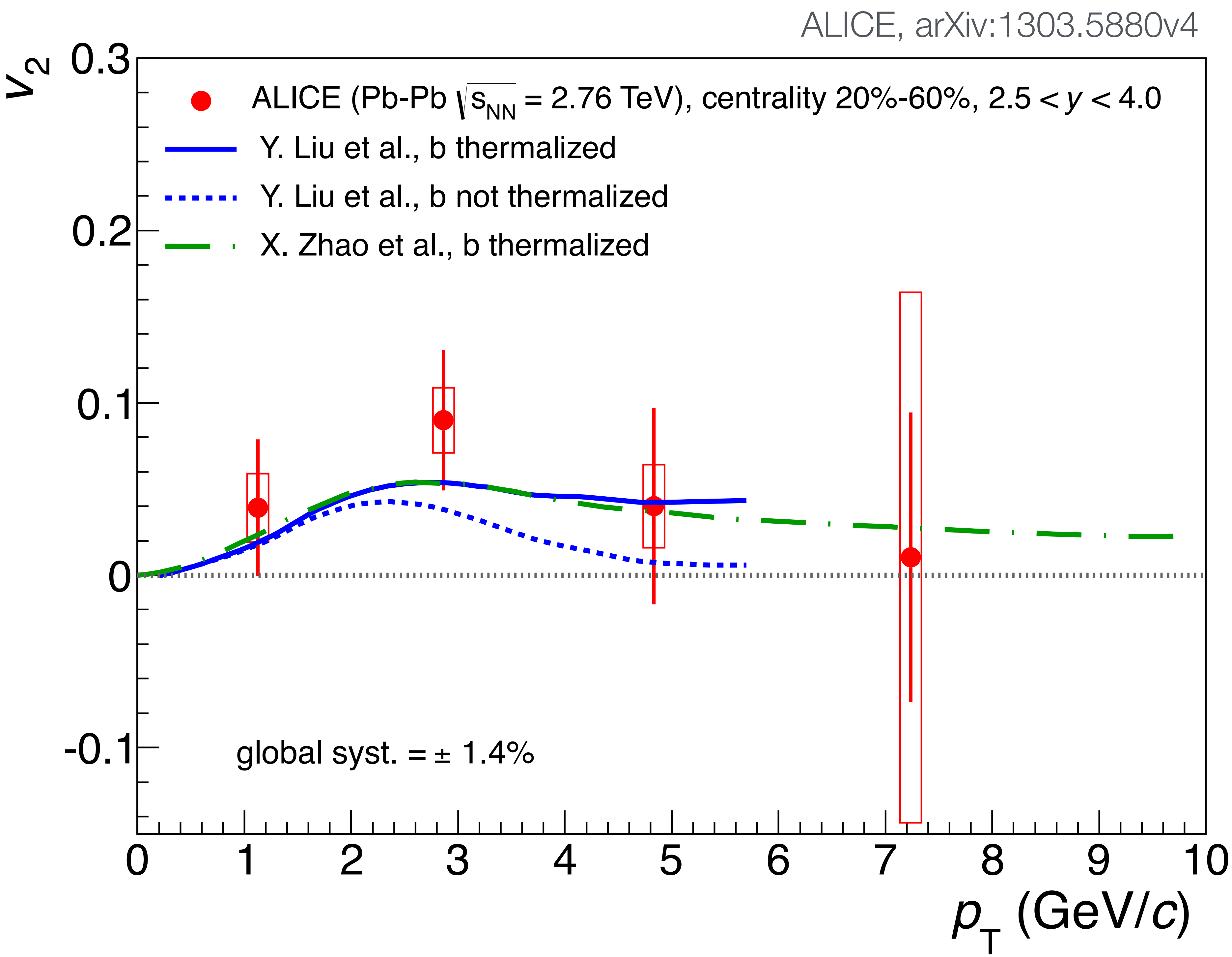
J/ψ R_{AA} vs p_T at RHIC and the LHC (0-20%)

ALICE, arXiv:1510.00442



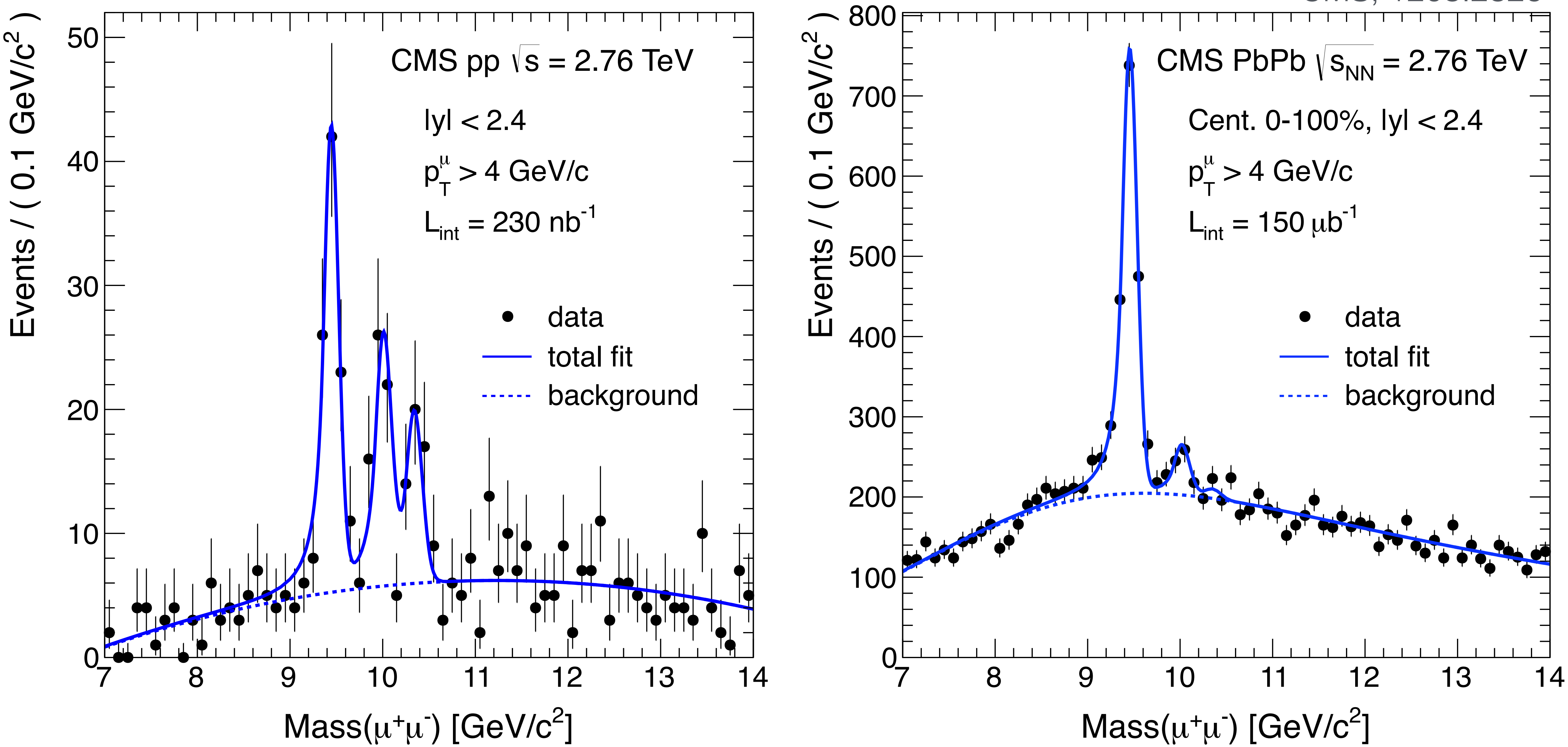
Much less suppression at low p_T, consistent with regeneration picture

J/ψ seems to flow, too — Support for thermalization of charm quarks in the QGP



Υ at the LHC:
Υ(2s) and Υ(3s) more suppressed in Pb-Pb than Υ(1s)

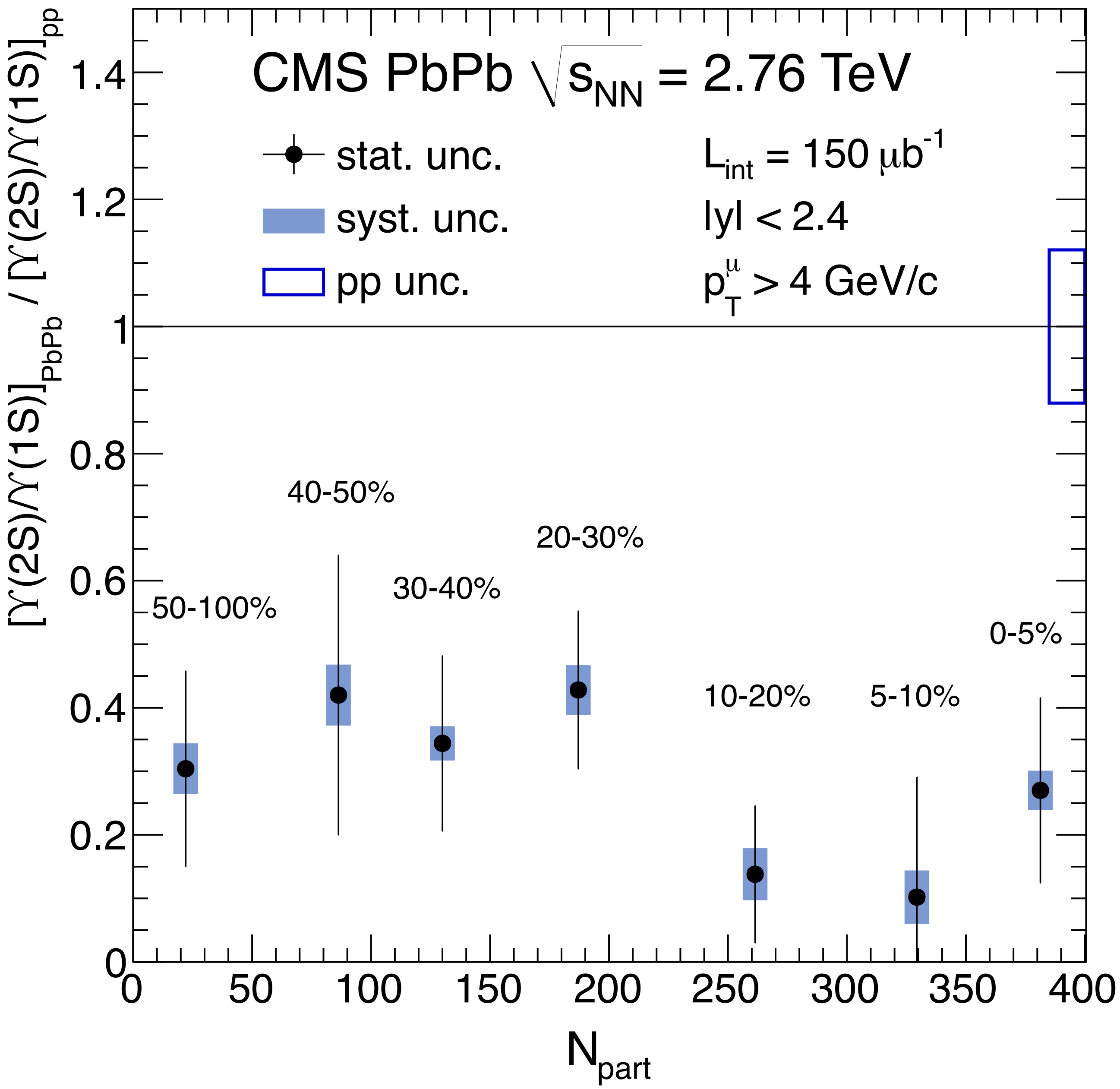
CMS, 1208.2826

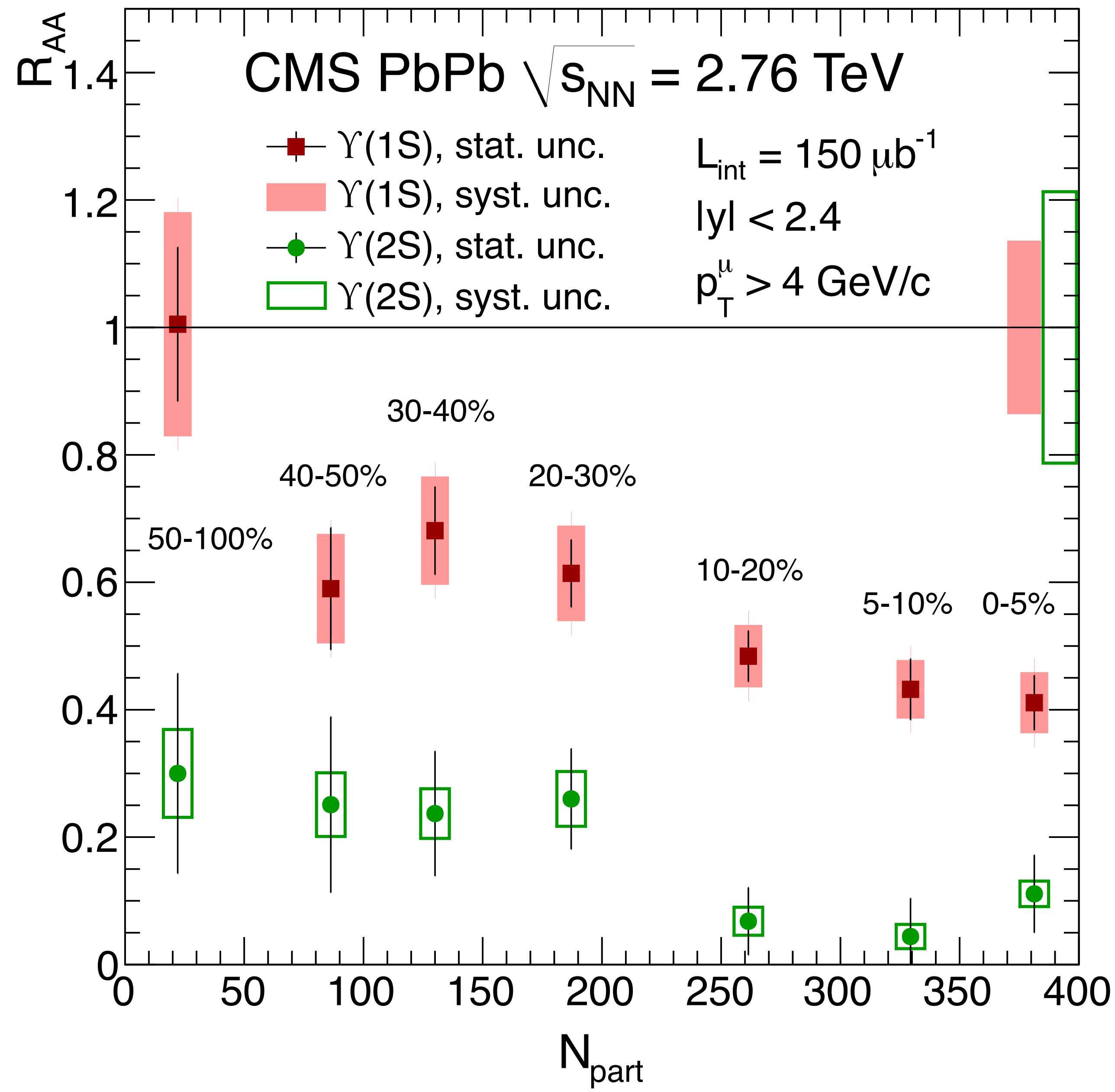


Qualitatively consistent with sequential melting for the Υ states

Υ at the LHC: R_{AA} vs N_{part}

CMS, arXiv:1208.2826





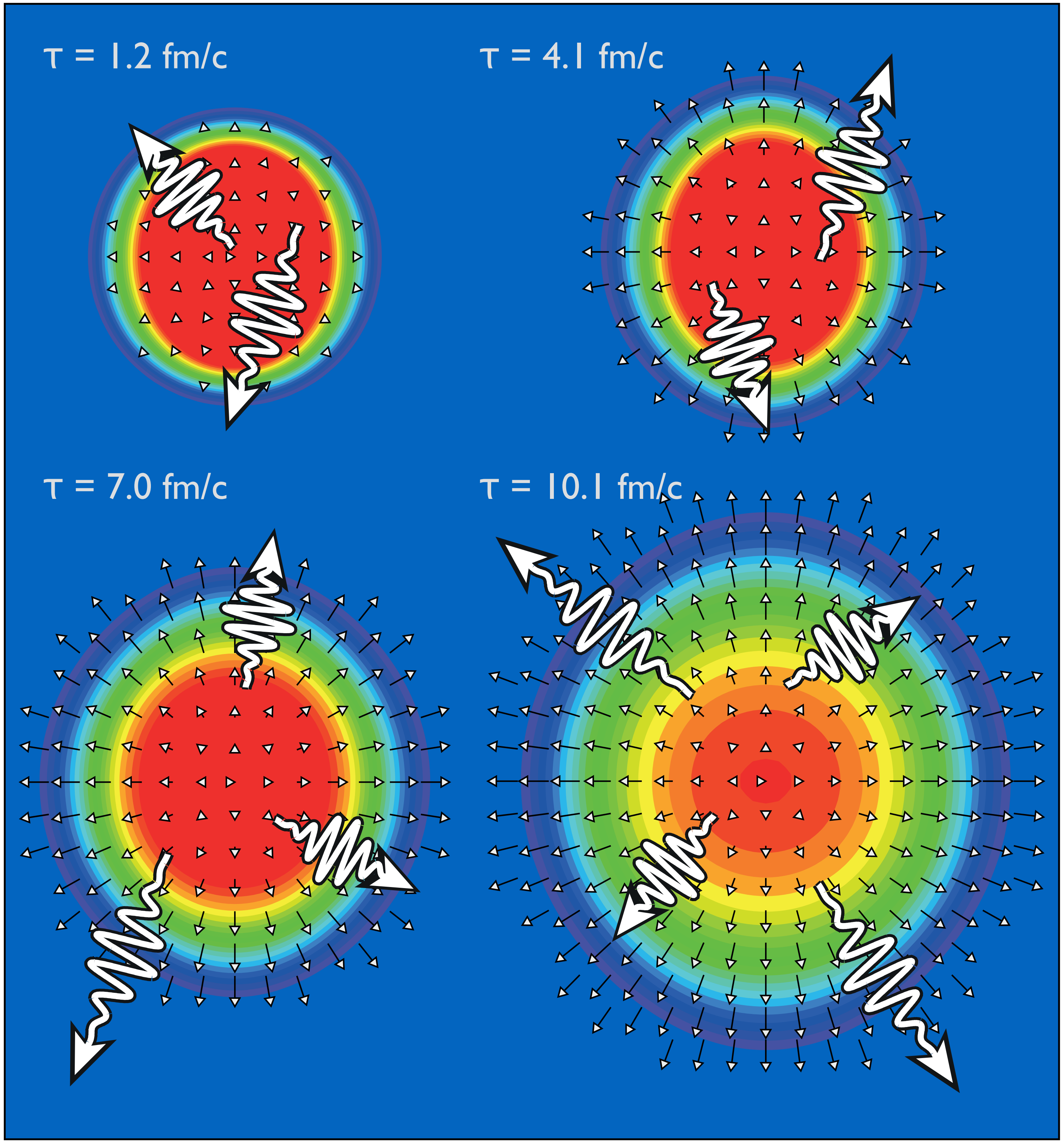
Υ(1S) appears to be suppressed stronger than one would expect from the Υ(2S) and Υ(3S) suppression alone (feeddown)

Summary/questions quarkonia

- Two main effects discussed in A-A collisions
  - Suppression due to color screening in the QGP
  - Regeneration of quarkonia for sufficiently large numbers of deconfined c quarks
- $\sqrt{s_{NN}}$ dependence of J/ψ production consistent with regeneration picture (at RHIC and, more pronounced, at the LHC)
  - However, need stronger constraints on initial number of charm quarks from hard scattering
- What is the appropriate description of the J/ψ regeneration?
- Does the melting scenario hold for Υ production at the LHC?
- Can yields of Υ states serve as a QGP thermometer?

8. Thermal photons and lepton pairs

The role of direct photons in heavy-ion physics



- Escape medium unscathed
- Produced over the entire duration of the collision (unlike low-p_T hadrons)
  - Test of space-time evolution, in particular of the hydro paradigm
- Experimental access to initial QGP temperature (?)

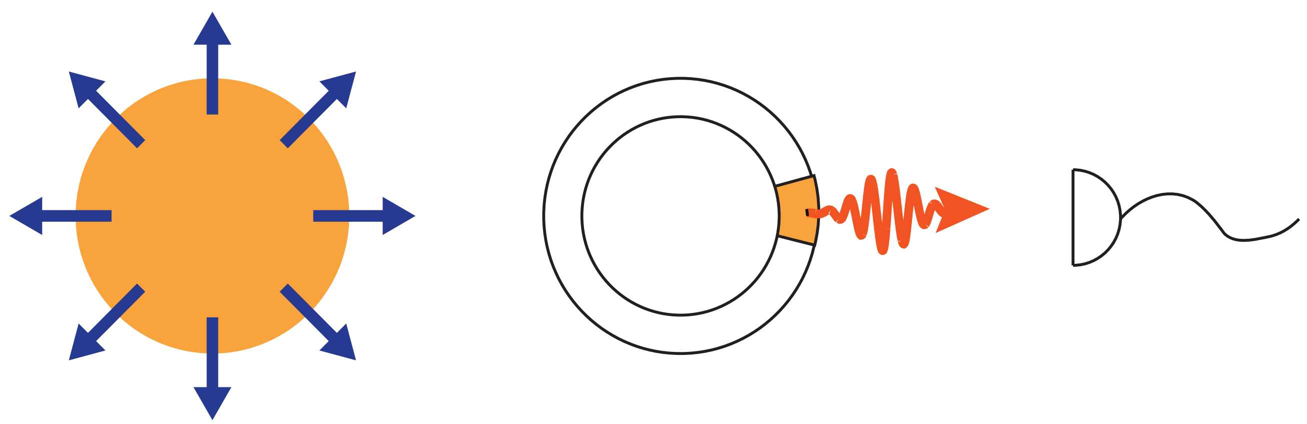
QGP photon rate r_γ (lowest order):

$$E_\gamma \frac{dr_\gamma}{d^3p} \propto \alpha\alpha_s T^2 e^{-E_\gamma/T} \log \frac{E_\gamma T}{k_c^2}$$

Total emission rate:

$$r_\gamma \propto T^4$$

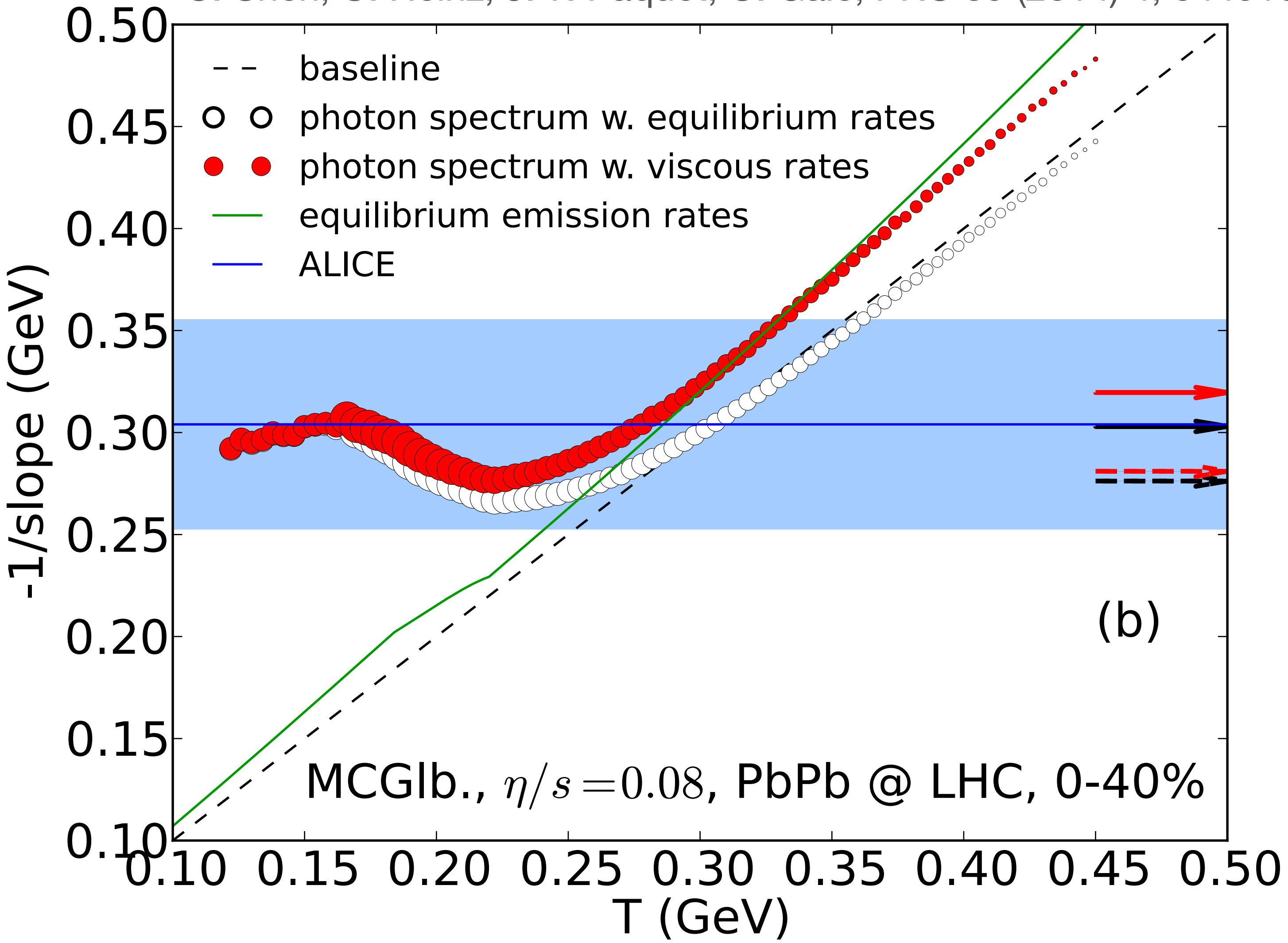
A complication for the temperature measurement: Blueshift due to radial flow



$$E_\gamma \frac{d^3 N_\gamma}{d^3 p_\gamma} \propto e^{-E_\gamma / T_{\text{eff}}}$$

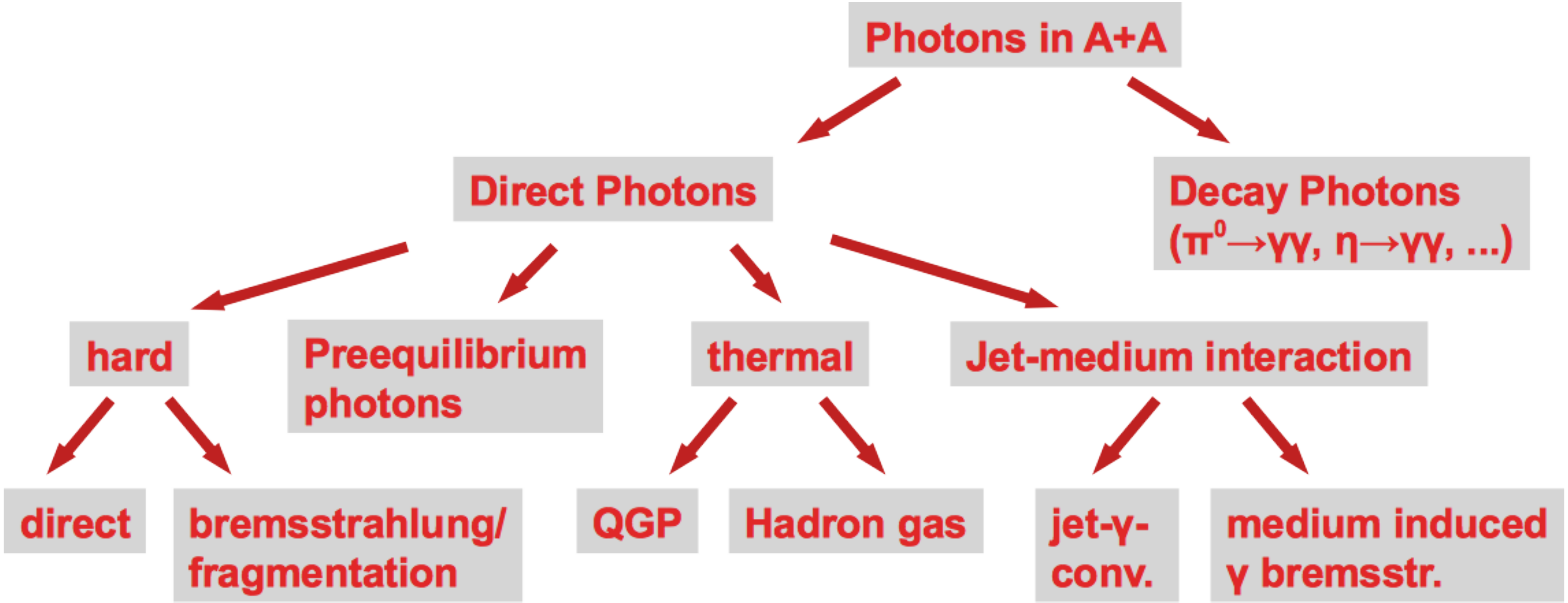
$$T_{\text{eff}} = \underbrace{\sqrt{\frac{1+\beta_{\text{flow}}}{1-\beta_{\text{flow}}}}}_{2 \text{ for } \beta_{\text{flow}}=0.6} \times T$$

C. Shen, U. Heinz, J.-F. Paquet, C. Gale, PRC 89 (2014) 4, 044910



- Large blueshift at late times when $T \approx$ 150 - 200 MeV
- Extraction of initial temperature from data requires comparison to (hydro) model

Known and expected photon sources in heavy-ion collisions

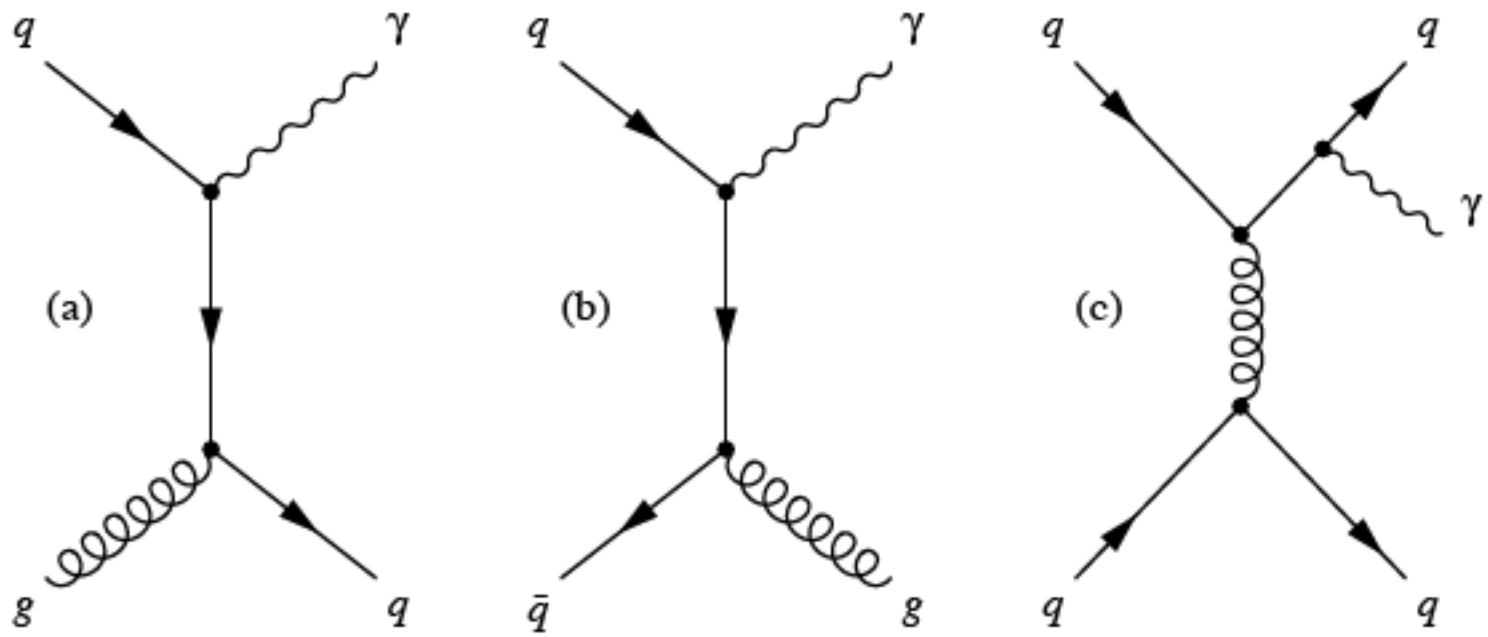


$$\gamma_{\text{direct}} := \gamma_{\text{incl}} - \gamma_{\text{decay}}$$

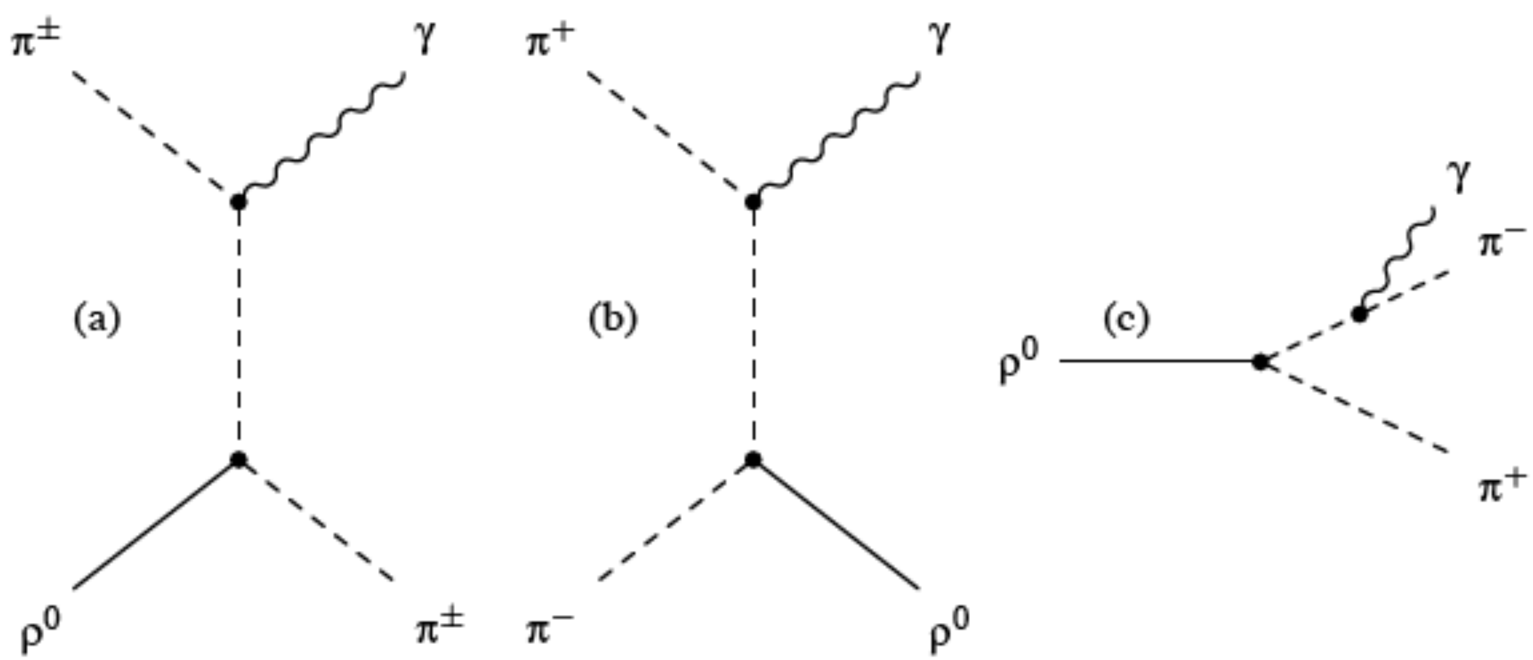
Small signal (O(10)% or smaller) at low p_T ($1 < p_T < 3$ GeV/c), where thermal photon from the QGP are expected

Feynman diagrams

QGP:



Hadron gas:



The Statistical Subtraction Method

- Idea: Cancellation of uncertainties common to photon and π^0 measurement

$$\gamma_{\mathrm{direct}} = \gamma_{\mathrm{incl}} - \gamma_{\mathrm{decay}} = \left(1 - \frac{1}{R_\gamma}\right) \cdot \gamma_{\mathrm{incl}}$$

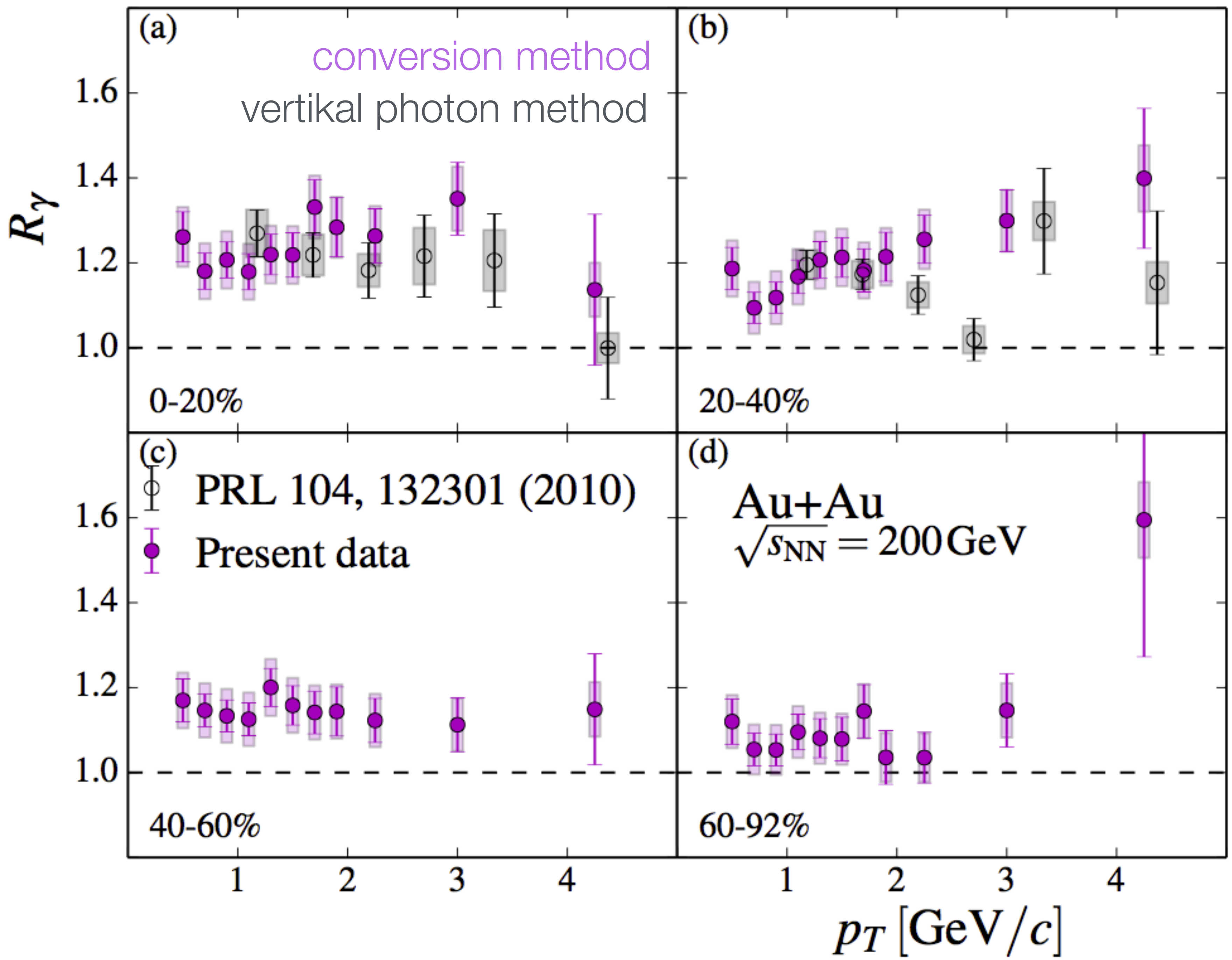
$$R_\gamma = \frac{\gamma_{\mathrm{incl}}}{\gamma_{\mathrm{decay}}} \equiv \boxed{\frac{\gamma_{\mathrm{incl}}}{\pi^0_{\mathrm{param}}}} \Big/ \boxed{\frac{\gamma_{\mathrm{decay}}}{\pi^0_{\mathrm{param}}}}$$

measured   decay photon calculation

- Which uncertainties cancel (partially)?
  - Calorimeter: global energy scale, energy non-linearity
  - Photon conversions: conversion probability, photon selection
- Method pioneered by WA80/98 at the CERN SPS
  - WA98 made the first direct-photon measurement in A-A
  - Interpretation at SPS energies difficult (initial state effect or QGP photons?)

Direct photon excess in Au-Au at $\sqrt{s_{NN}}$ = 200 GeV

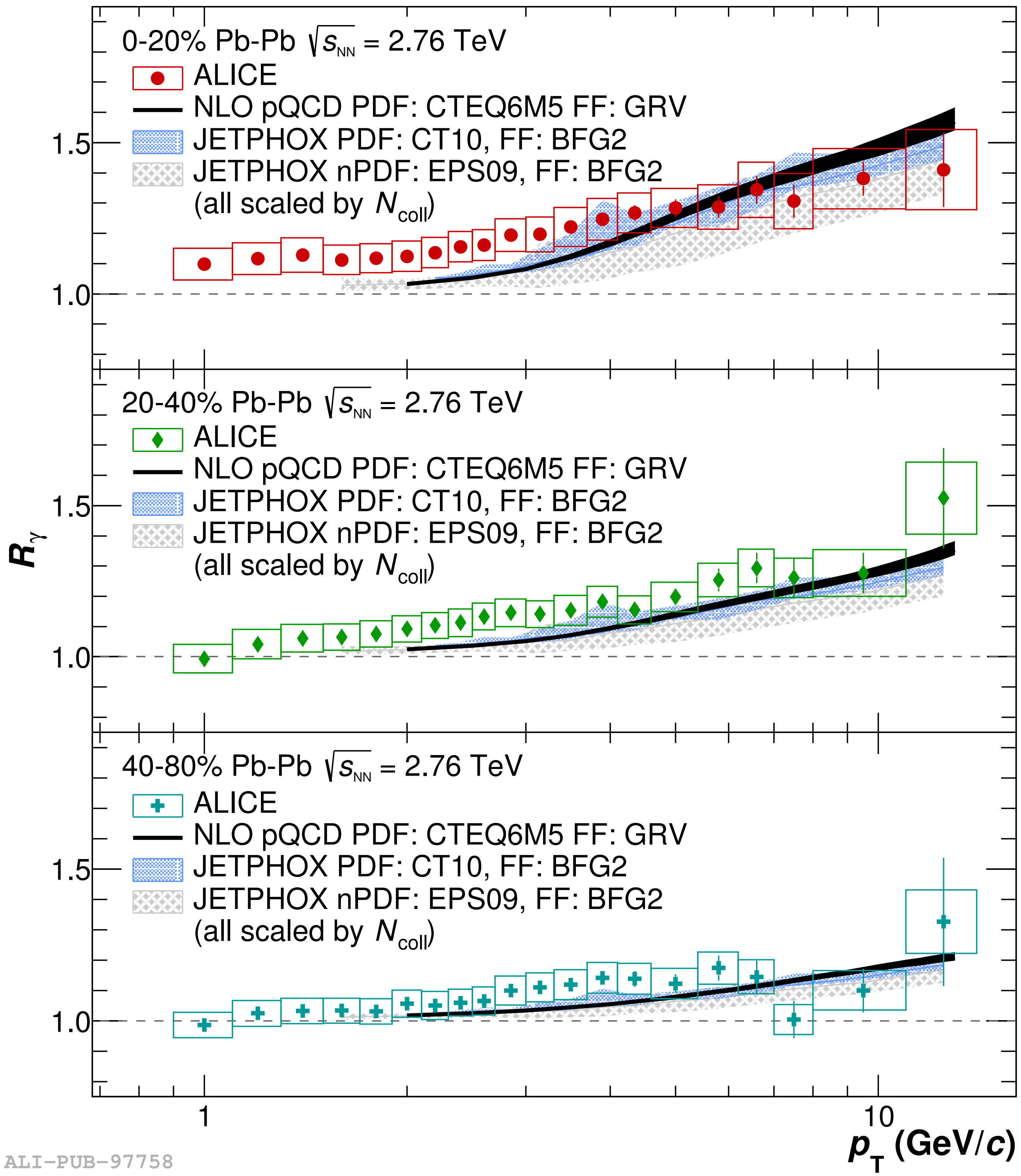
PHENIX, arXiv:1405.3940



$$R_\gamma = \frac{\gamma_{\mathrm{incl}}}{\gamma_{\mathrm{decay}}}$$

- Two experimental techniques
  - Virtual photons ($\gamma^* \to e^+e^-$), extrapolated to $m_{\gamma^*} = 0$
  - Photon conversion combined with π^0 tagging using e.m. calorimeter
- 20-25% excess in

Direct photon excess in Pb-Pb at the LHC



$$R_\gamma^{\mathrm{pQCD}} = 1 + N_{\mathrm{coll}} \frac{\gamma_{\mathrm{pQCD}}}{\gamma_{\mathrm{decay}}}$$

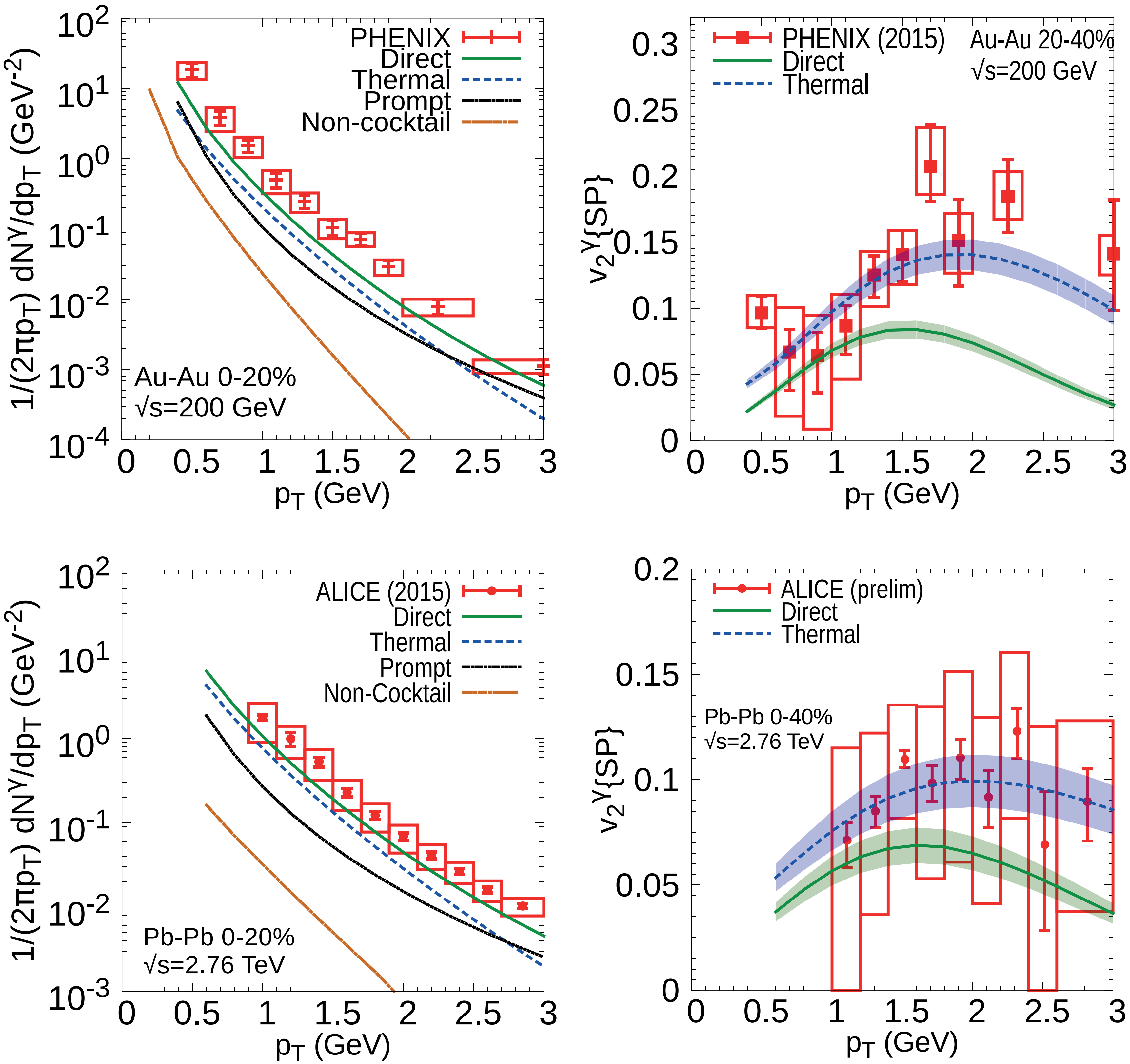
calculated based measured π^0 spectrum

- pQCD agrees with data for $p_T \gtrsim 5$ GeV/c
- Evidence for an additional photon source at lower p_T

ALICE, Physics Letters B 754 (2016) 235

The direct photon puzzle

Plots: Paquet et al., arXiv:1509.06738

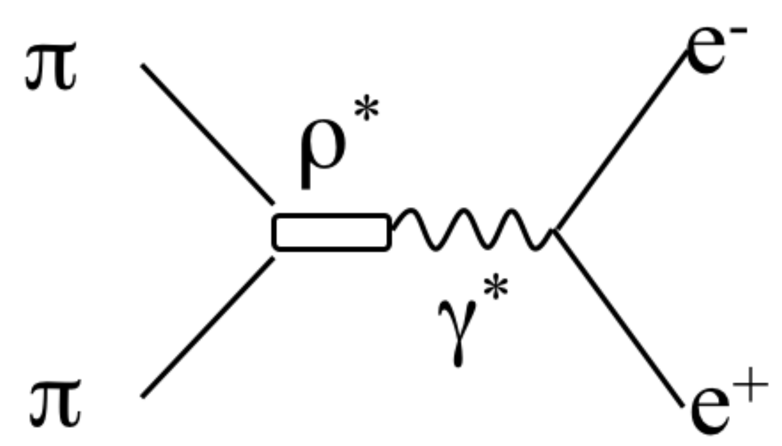


- Au-Au at RHIC
  - Models fail to describe direct photon data
- Puzzle has two parts
  - Yields
  - v_2
- Pb-Pb at the LHC
  - Similar trends
  - However, no puzzle with current uncertainties

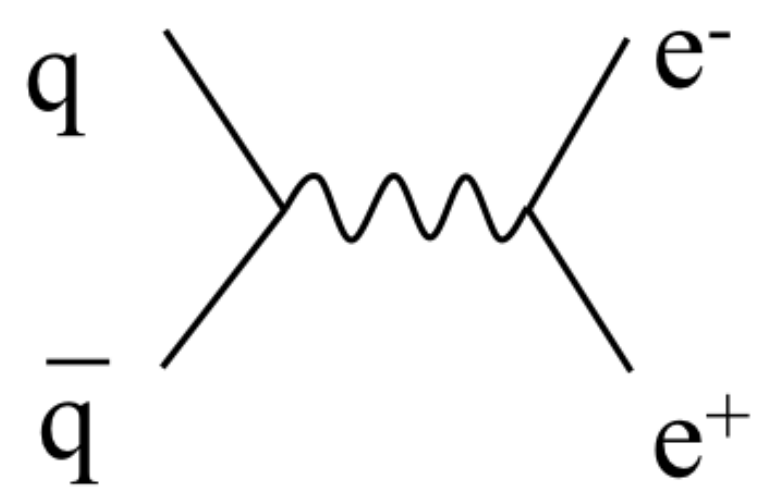
Dileptons: Motivation

- Like photons, negligible final state interaction
- Search for in-medium modifications of vector mesons (M_{ee} < 1 GeV)
  - ρ can decay in the medium ($\tau_{\rho,\mathrm{vacuum}} \approx 1.3$ fm/c < medium lifetime)
  - Broadening of the ρ in the medium, relation to chiral symmetry restoration?
- Thermal radiation from the QGP and access to early temperature? (M_{ee} > 1 GeV)
- Constrains space-time evolution
- Pioneering measurements by CERES at the CERN SPS
  - Di-electron excess for m_{ee} > 200 MeV
  - Hints towards modified ρ meson in dense medium

hadron gas



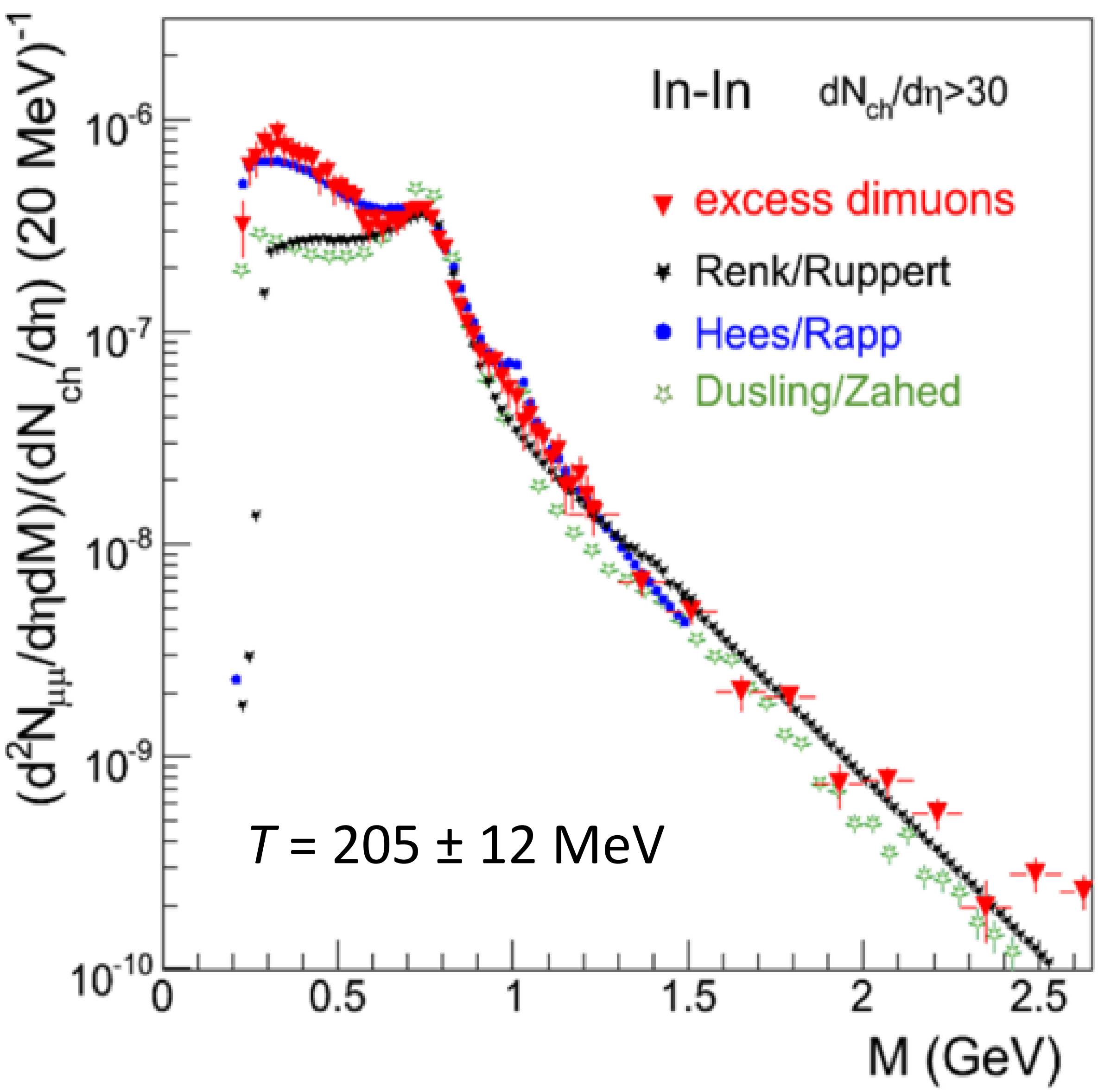
quark-gluon plasma



QGP temperature via dimuons at SPS energies?

NA60,
Eur. Phys. J. C 61 (2009) 711
Eur. Phys. J. C 59 (2009) 607

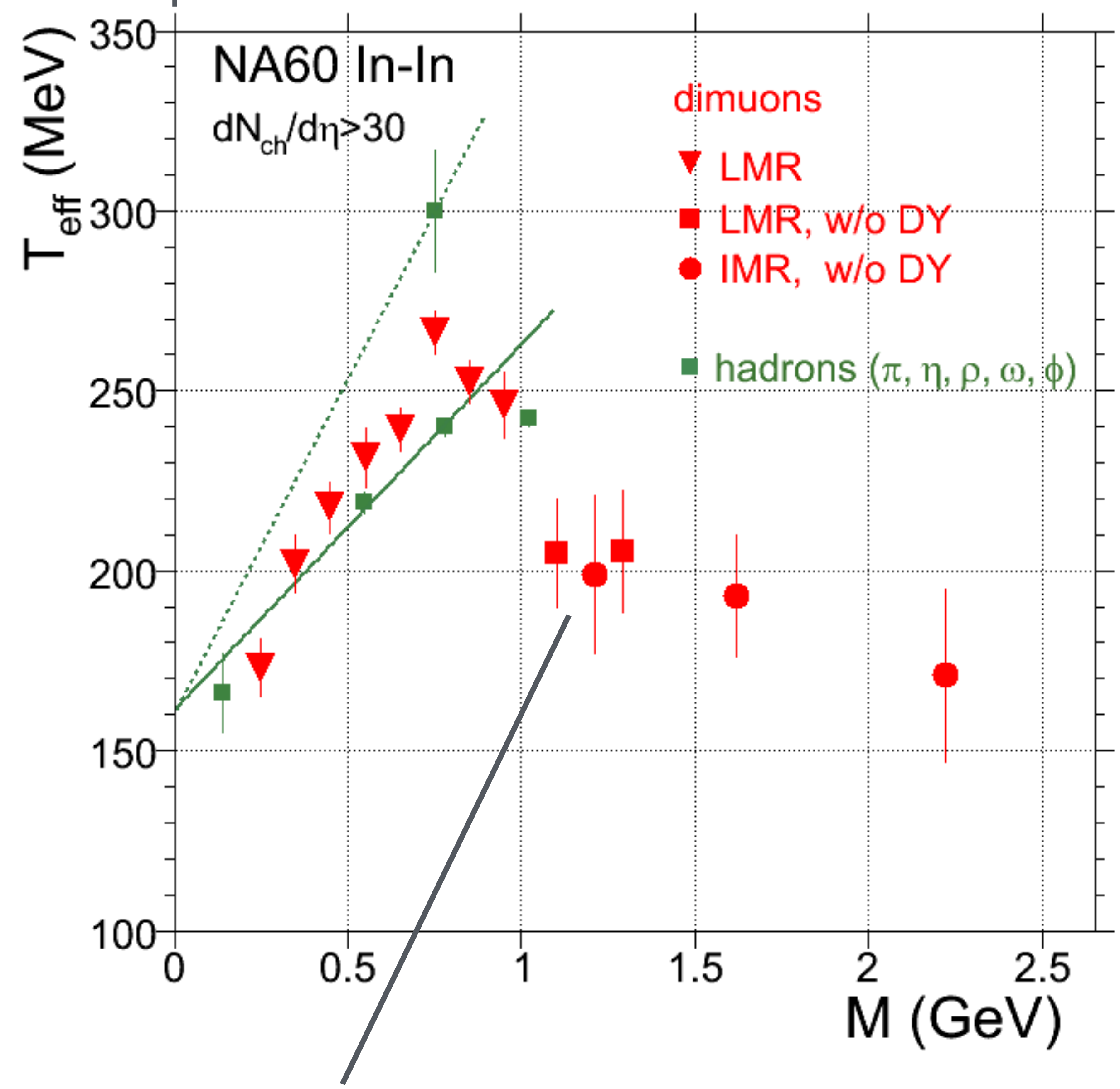
Temperature via dimuon mass spectrum: unaffected by radial flow



$$dN/dM \propto M^{3/2} \times \exp(-M/T)$$

for $M > 1$ GeV

Slope of dimuon m_T spectra: Hadron gas + flow for $M < 1$ GeV, non-flowing partonic source for $M > 1$ GeV?



$T_{eff} \approx 200$ MeV for $M > 1$ GeV consistent with slope of mass spectrum!

Summary/questions thermal photons and dileptons

- Direct photon puzzle
  - Measured yield and v_2 above state-of-the-art hydrodynamic calculations at RHIC (while these models nicely fit hadronic observables)
  - Similar trend at the LHC, but no puzzle with current uncertainties
- Where is our understanding incomplete?
  - QGP and hadron gas photon rates incorrect?
  - Modeling of the space-time evolution?
  - Strong pre-equilibirium photon production and flow?
  - Exotic new photon sources?
  - …
  - Something on the experimental side?
- Di-electrons and di-muons
  - Point to modifications of the ρ meson width in a hadron gas
  - Di-muons at the CERN SPS seem to indicate $T_{QGP} \approx 200$ MeV

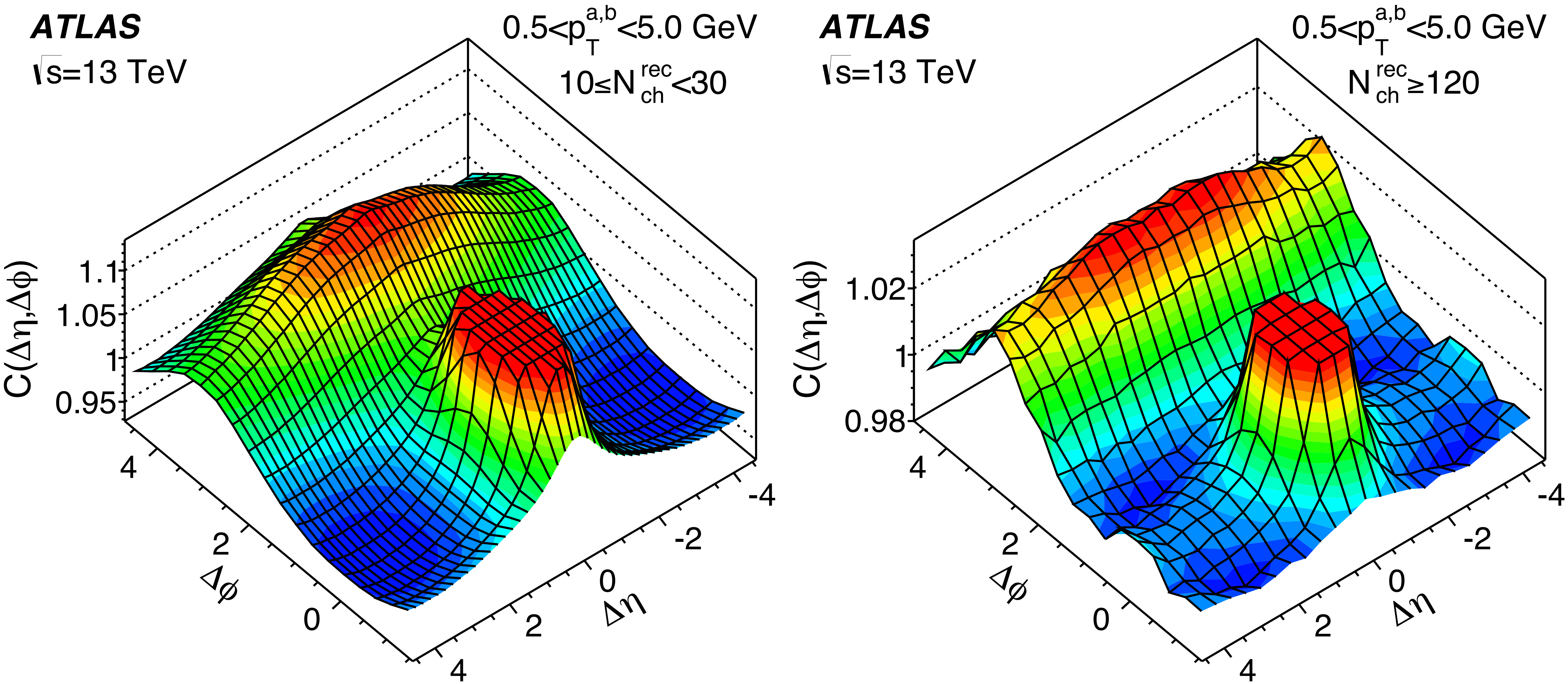
Final remarks

- QGP formation in heavy-ion collisions considered to by established
  - Hydro models with strongly-coupled thermalized partonic phase (i.e., a QGP phase) nicely describe a wealth of data
  - Self-consistent description on a hadronic level conceptually difficult
- Next steps
  - Characterize the medium in more detail
    - In particular: Establish connections between observables and quantities calculated from first QCD principle (example: q-hat from lattice QCD)
  - Establish QCD phase diagram
  - Establish/disprove QGP formation in small systems (e.g., pp)
- Connect to other physical systems (e.g. ultra-cold atoms) to better understand universal aspects of the underlying physics

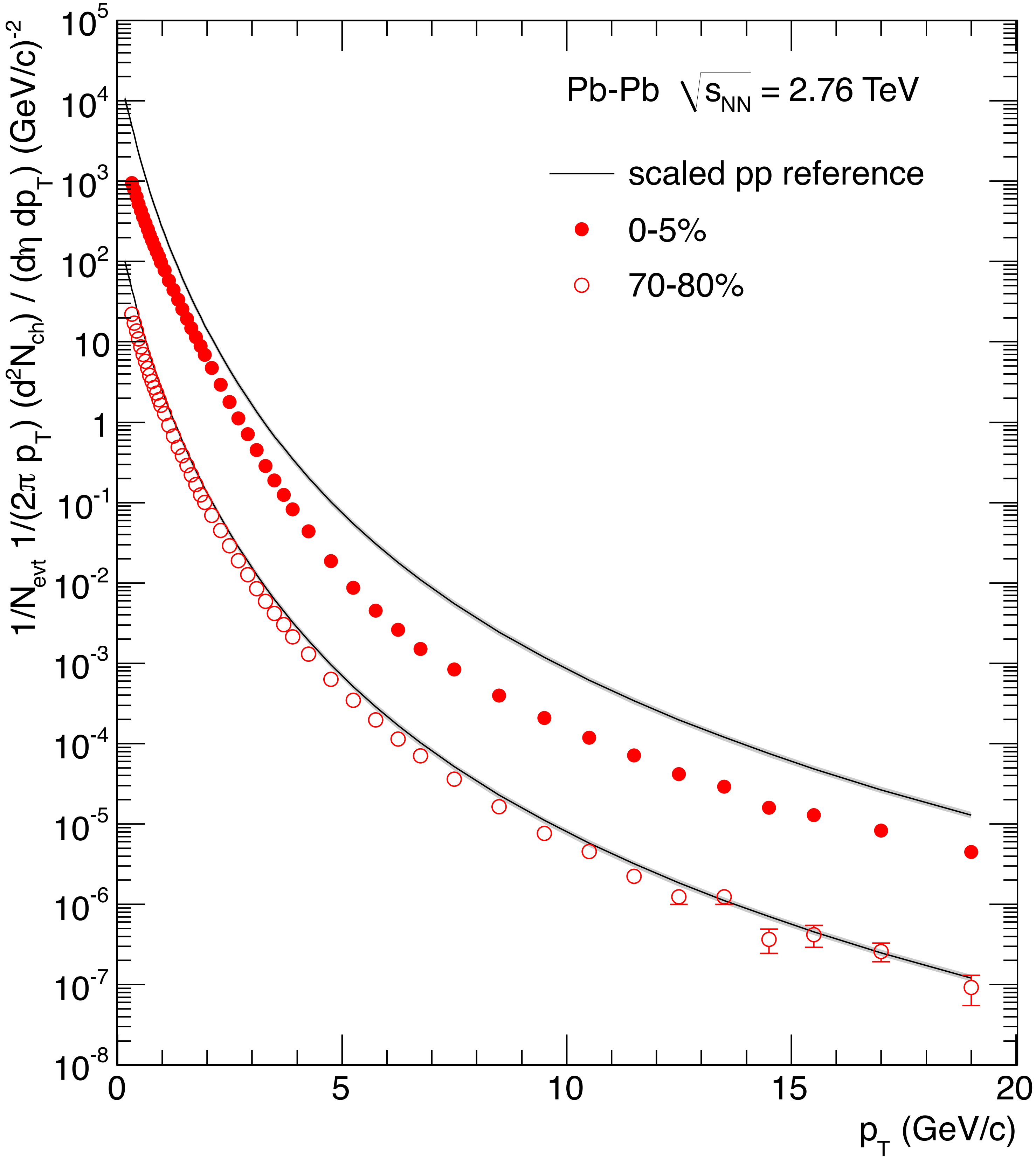
Extra slides

Two-Particle correlations in pp collisions

ATLAS, 1509.04776



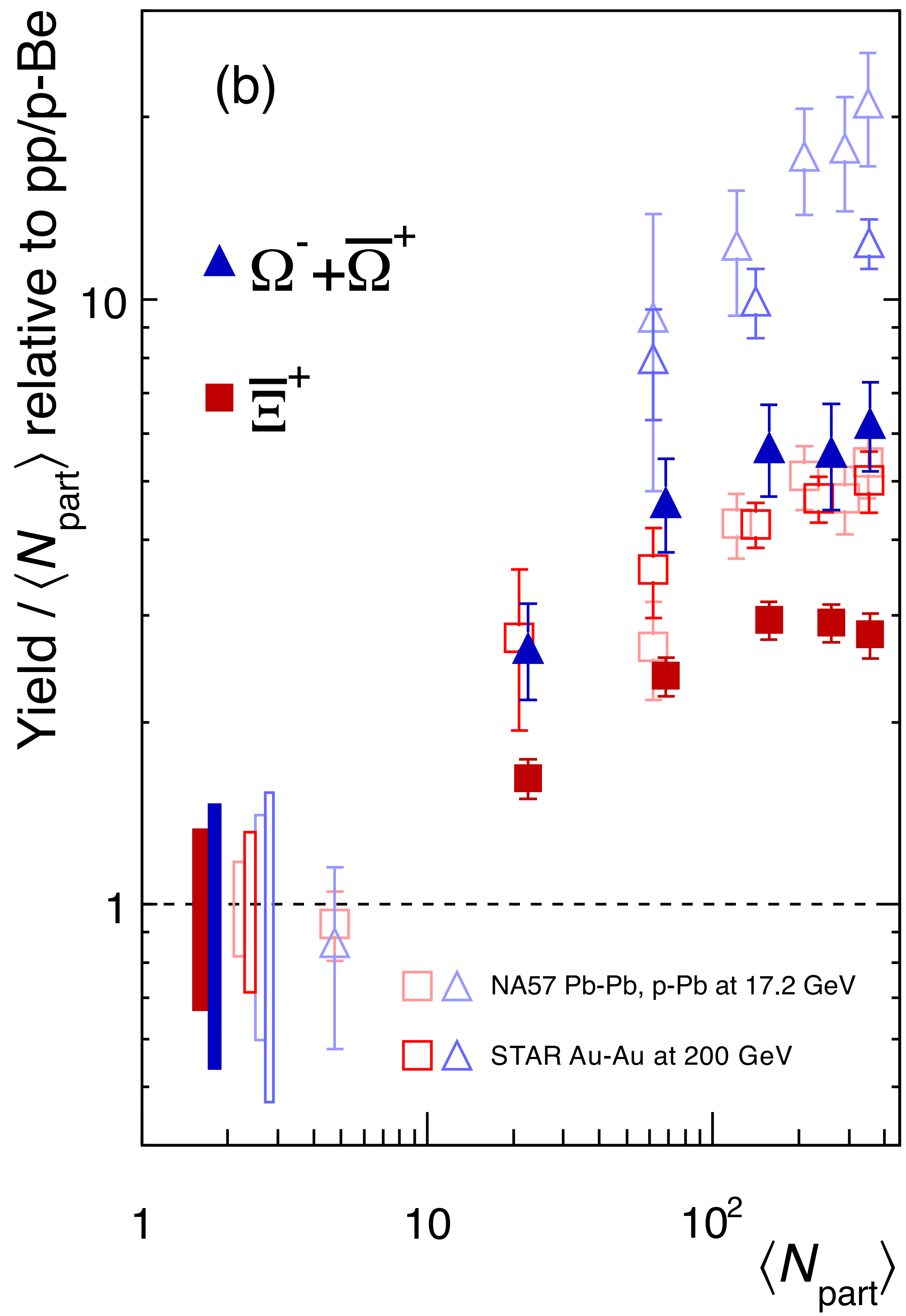
Charged hadron p_T spectra in pp and Pb-Pb at the LHC



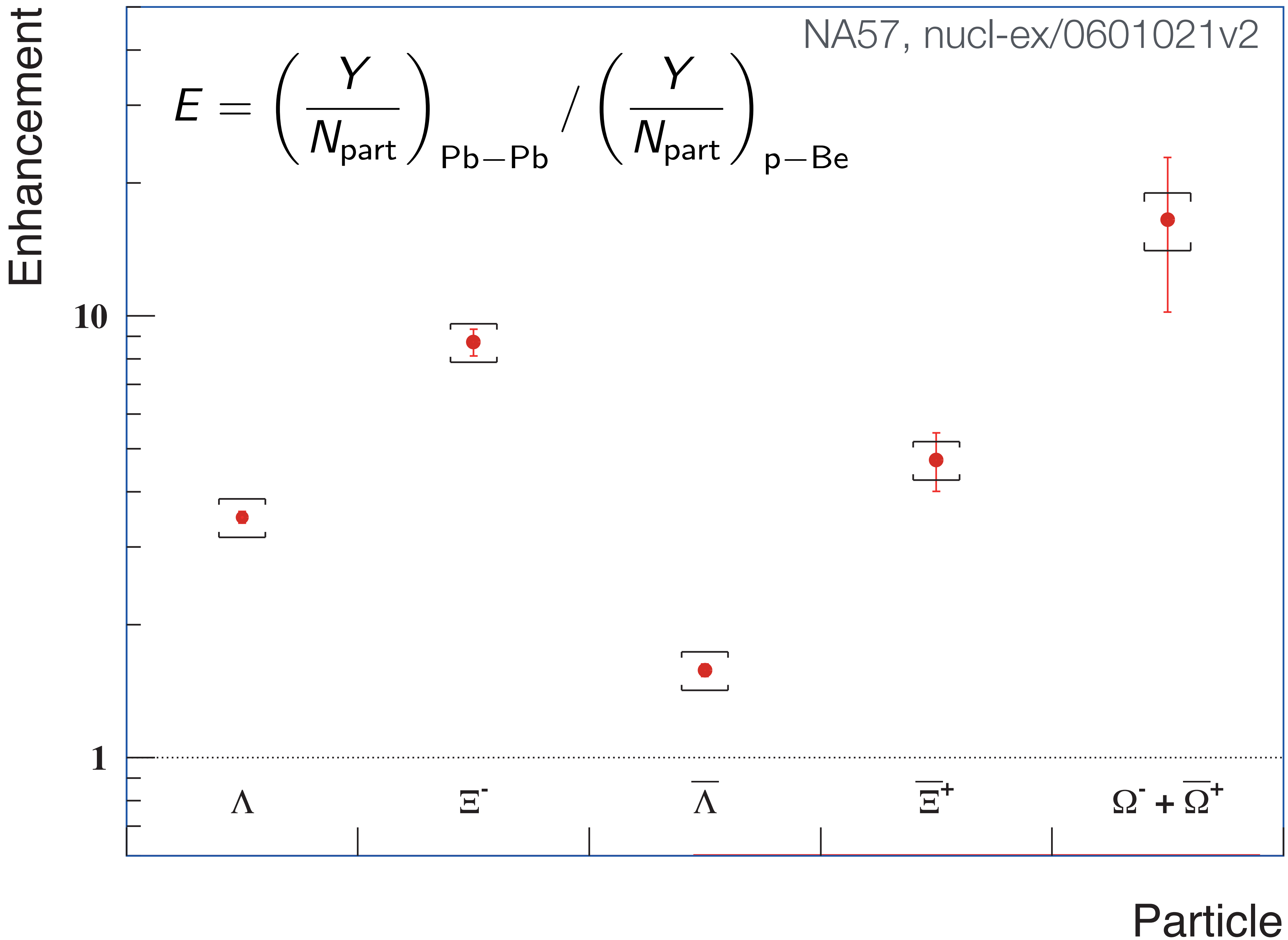
arXiv:1012.1004

Strangeness enhancement: Centrality dependence

ALICE, arXiv:1307.5543v3



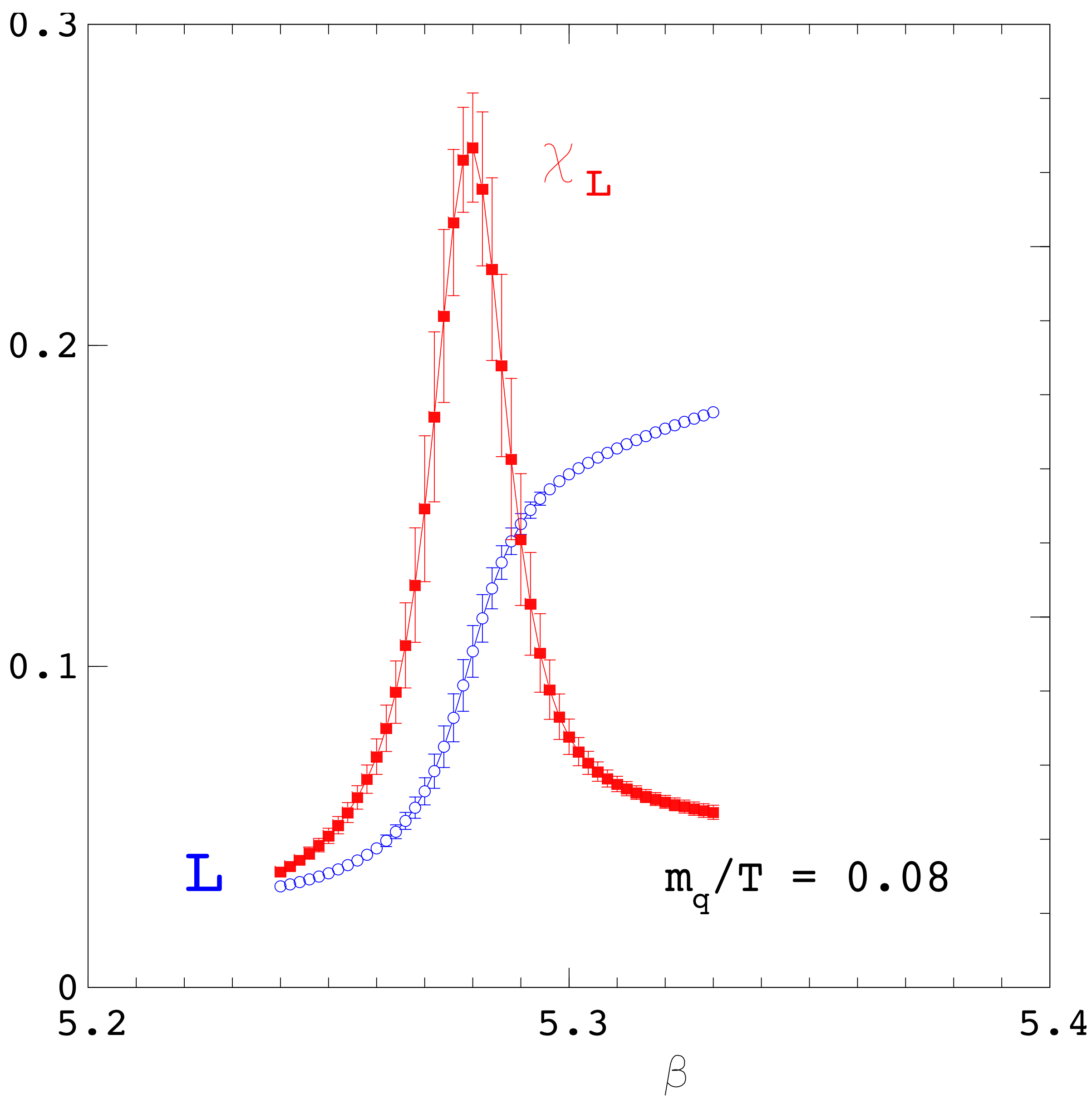
Data on Strangeness Enhancement



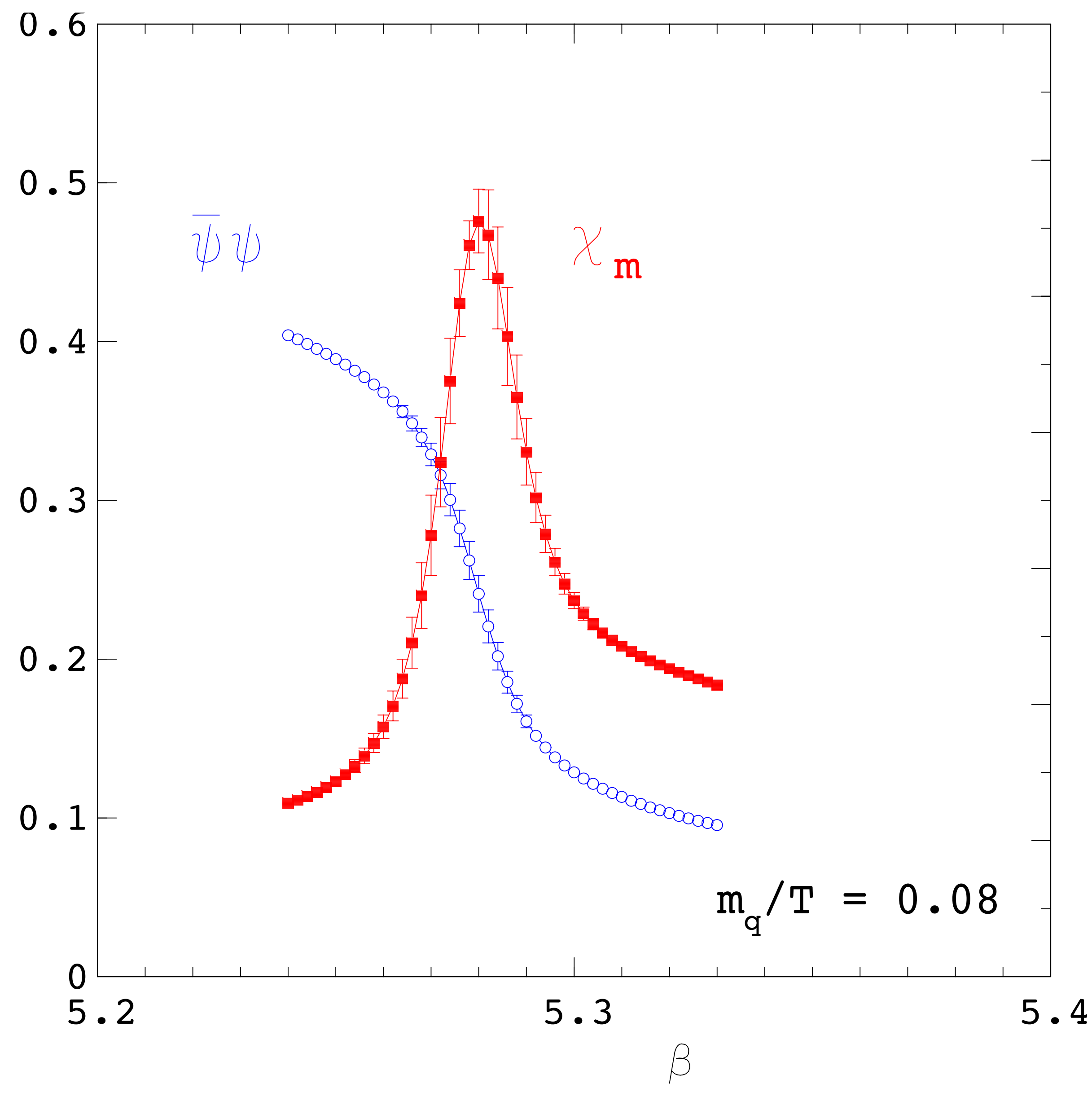
Similar enhancement in Pb-Pb using p-Pb or p-Be as reference

Deconfinement and chiral transition on the lattice

figures taken from hep-ph/0509068v1

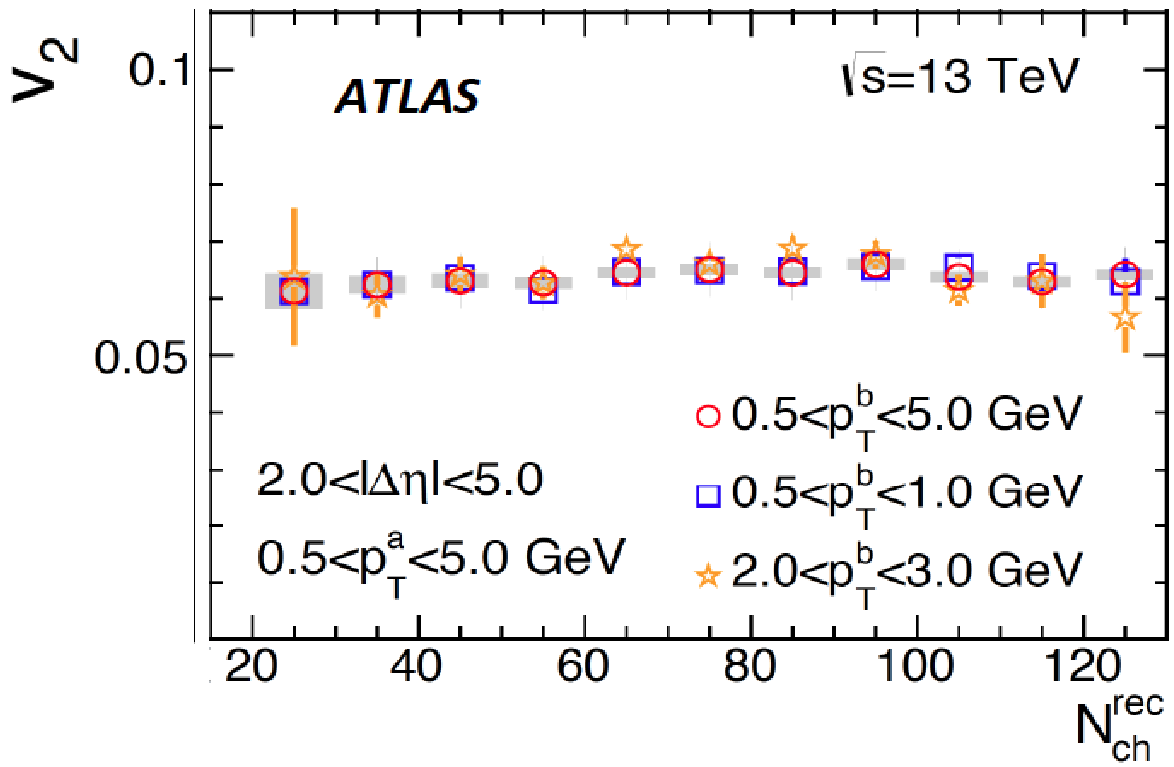


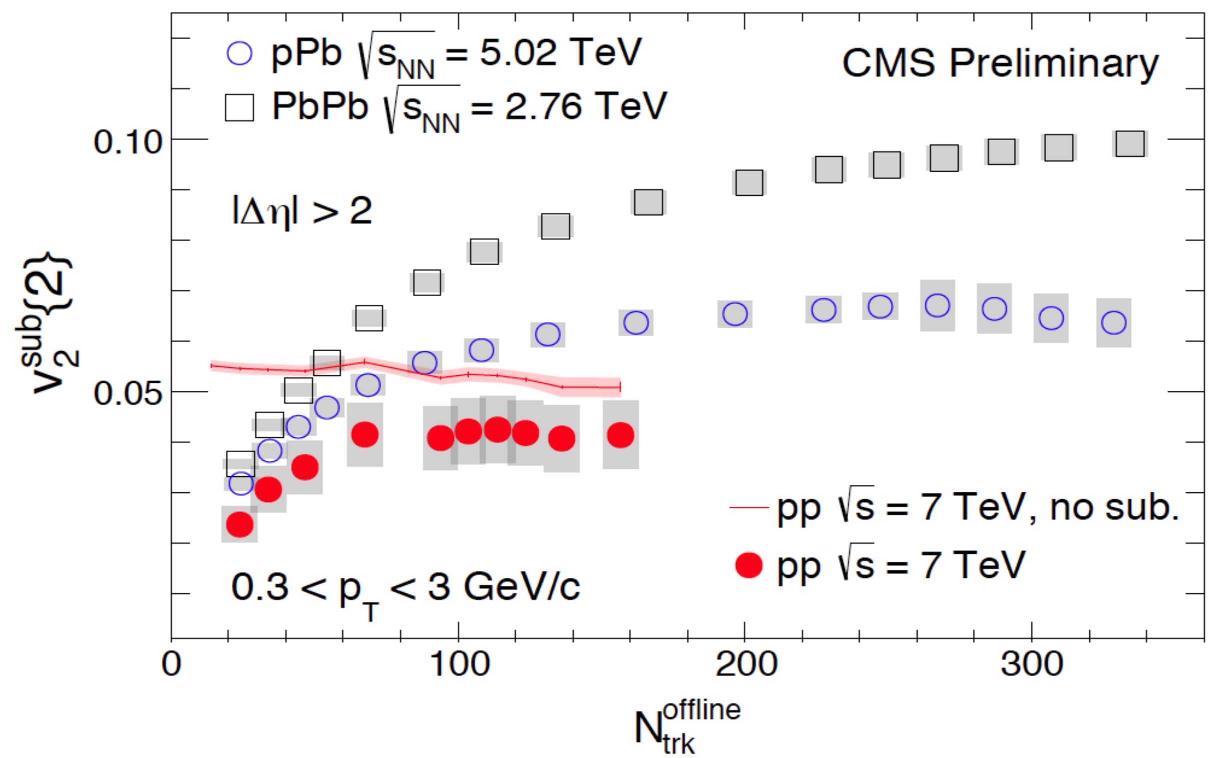
Polyakov loop



chiral condensate

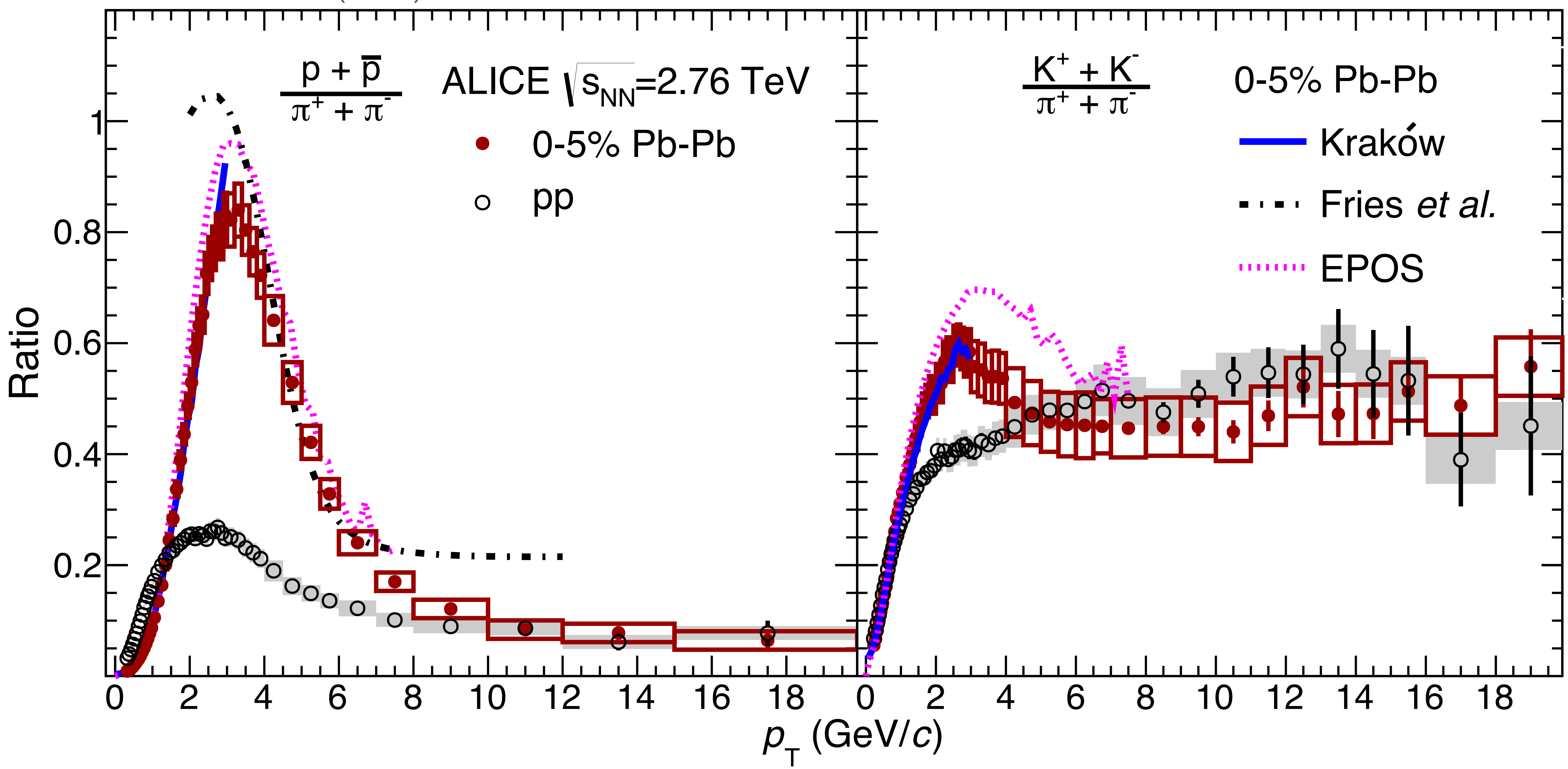
v_2 in pp collisions: CMS vs ATLAS





p/π and K/π Ratios vs. p_T in pp and Pb-Pb

ALICE, PLB 736 (2014) 196



Strong increase of p/π ratio at $p_T \approx 3$ GeV/c in Pb-Pb: due to radial flow alone?