Collective phenomena in small and large hadronic collisions

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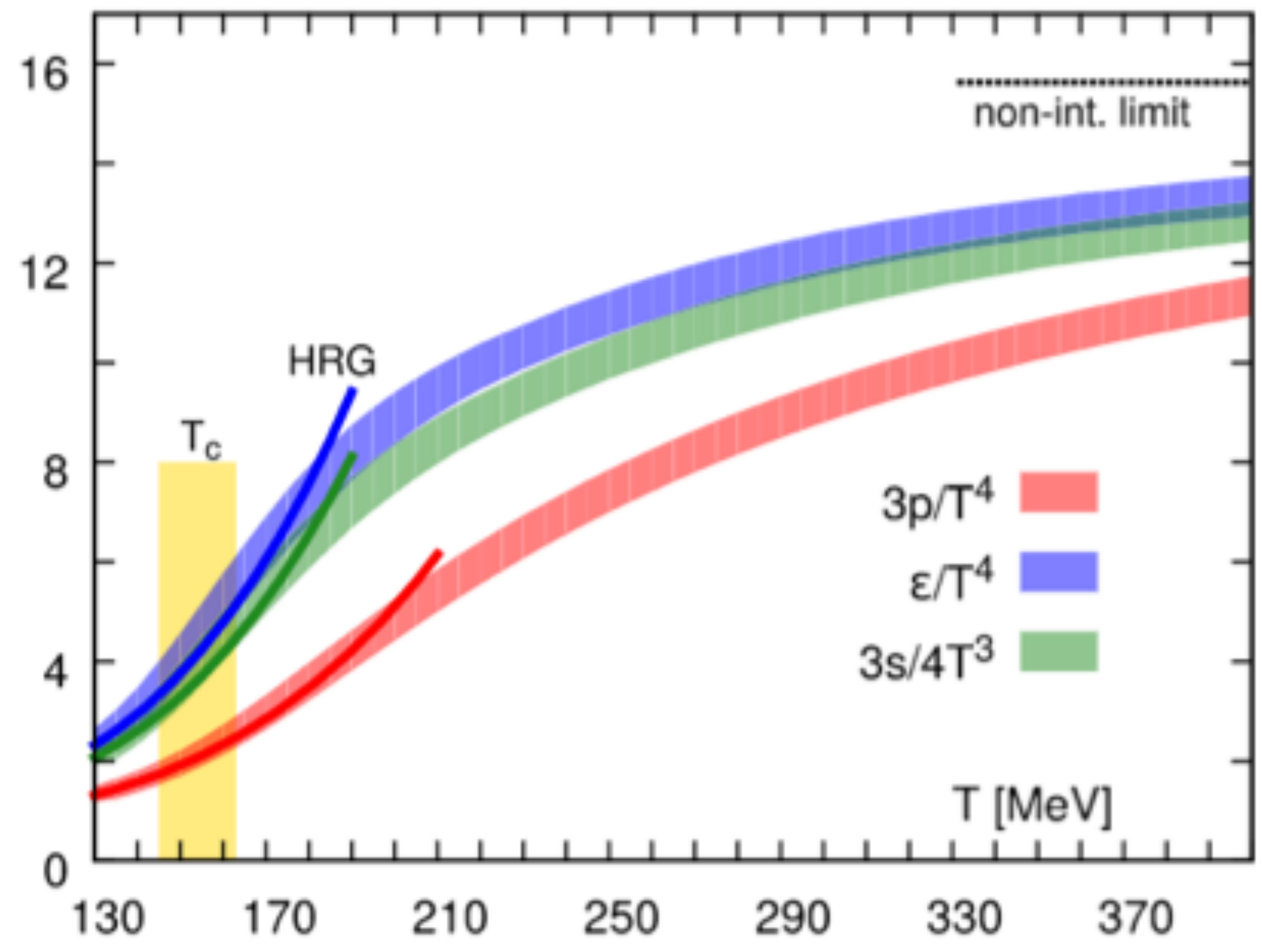
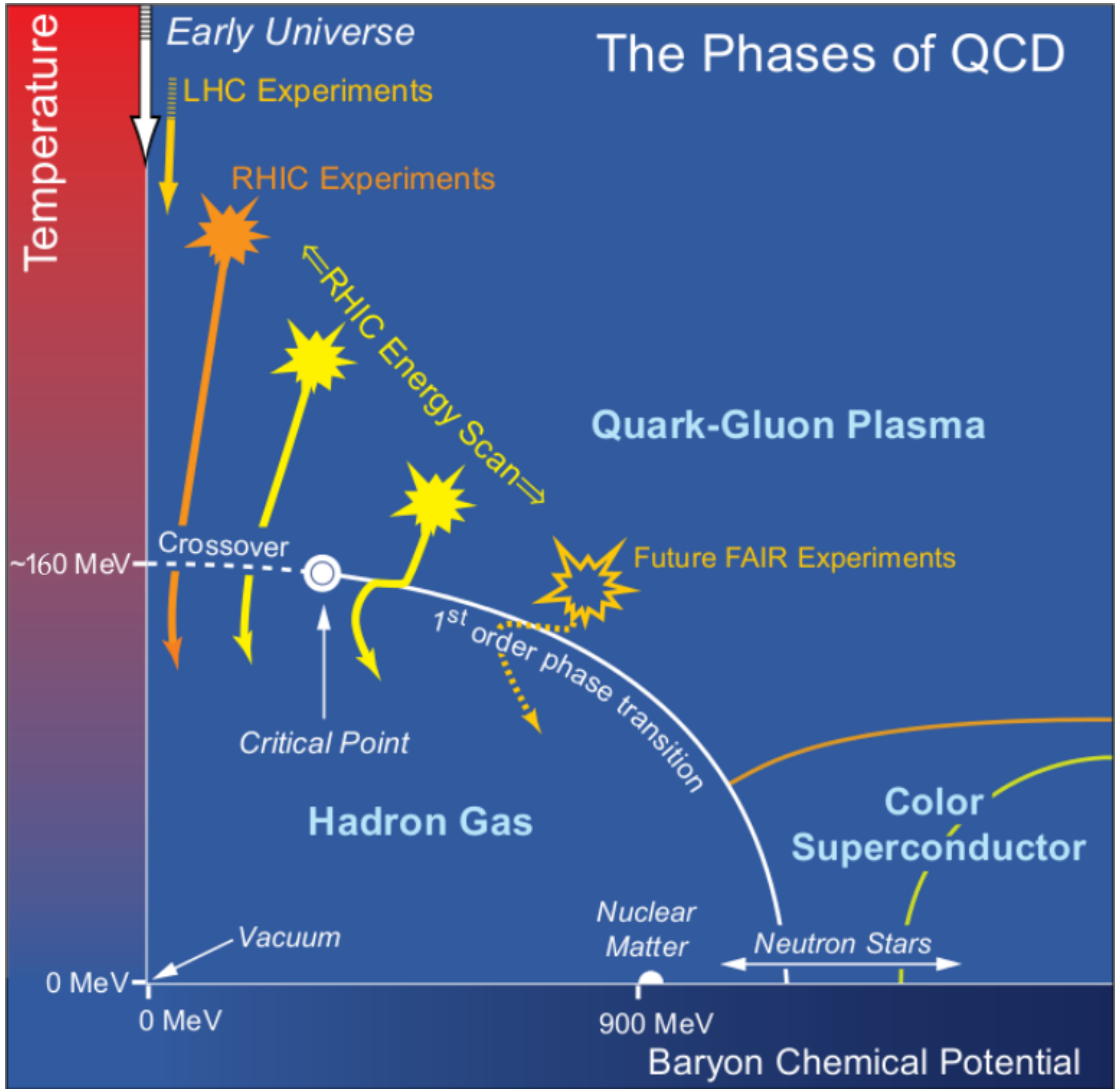
Lund University

EMMI RRTF Open Symposium, 18 March 2024

- At high temperatures and densities, quarks and gluons are no longer confined into hadrons but behave quasi-freely
  - Quark-Gluon Plasma (QGP)

[PRD 90 094503 (2014)]

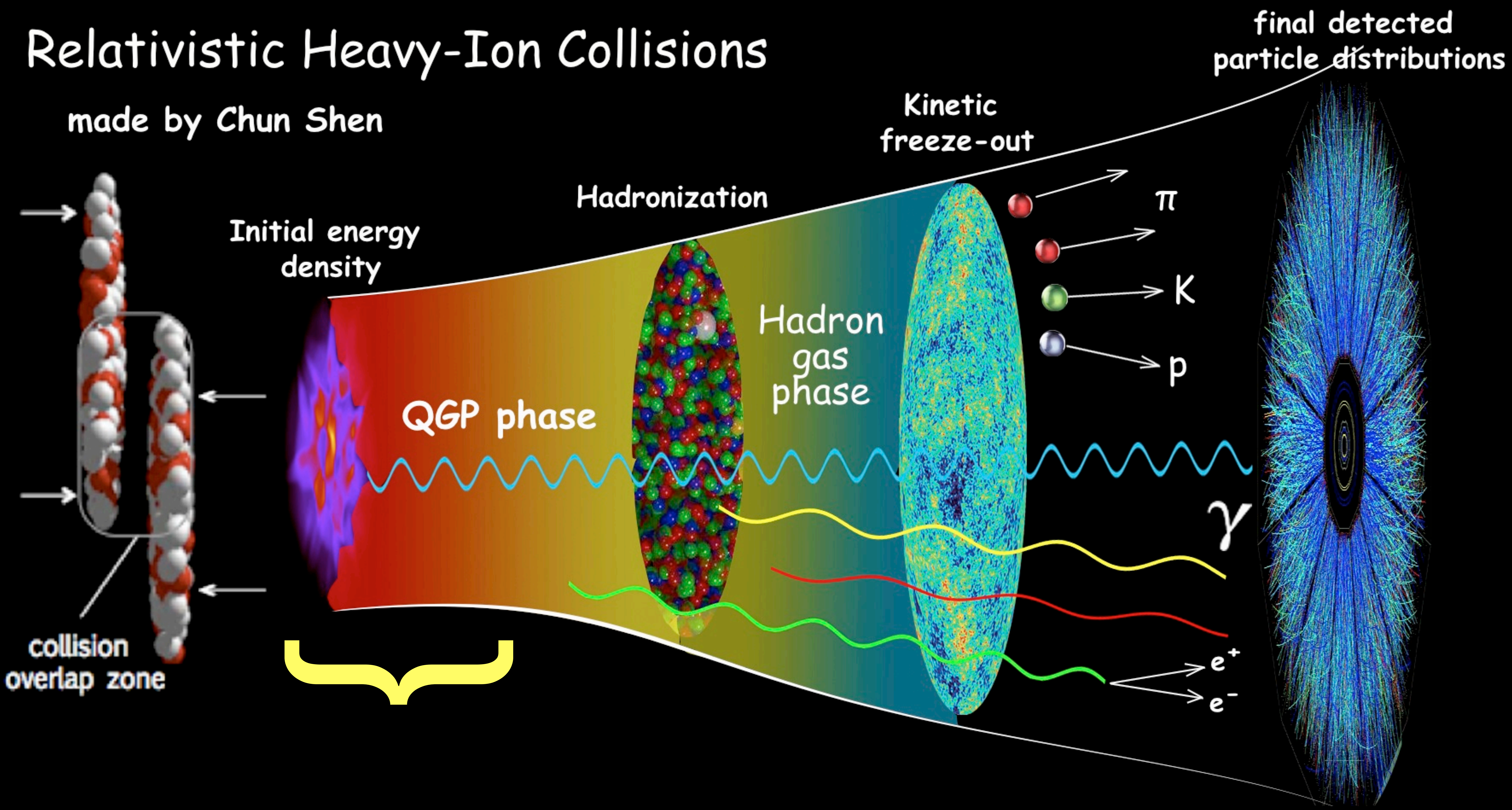




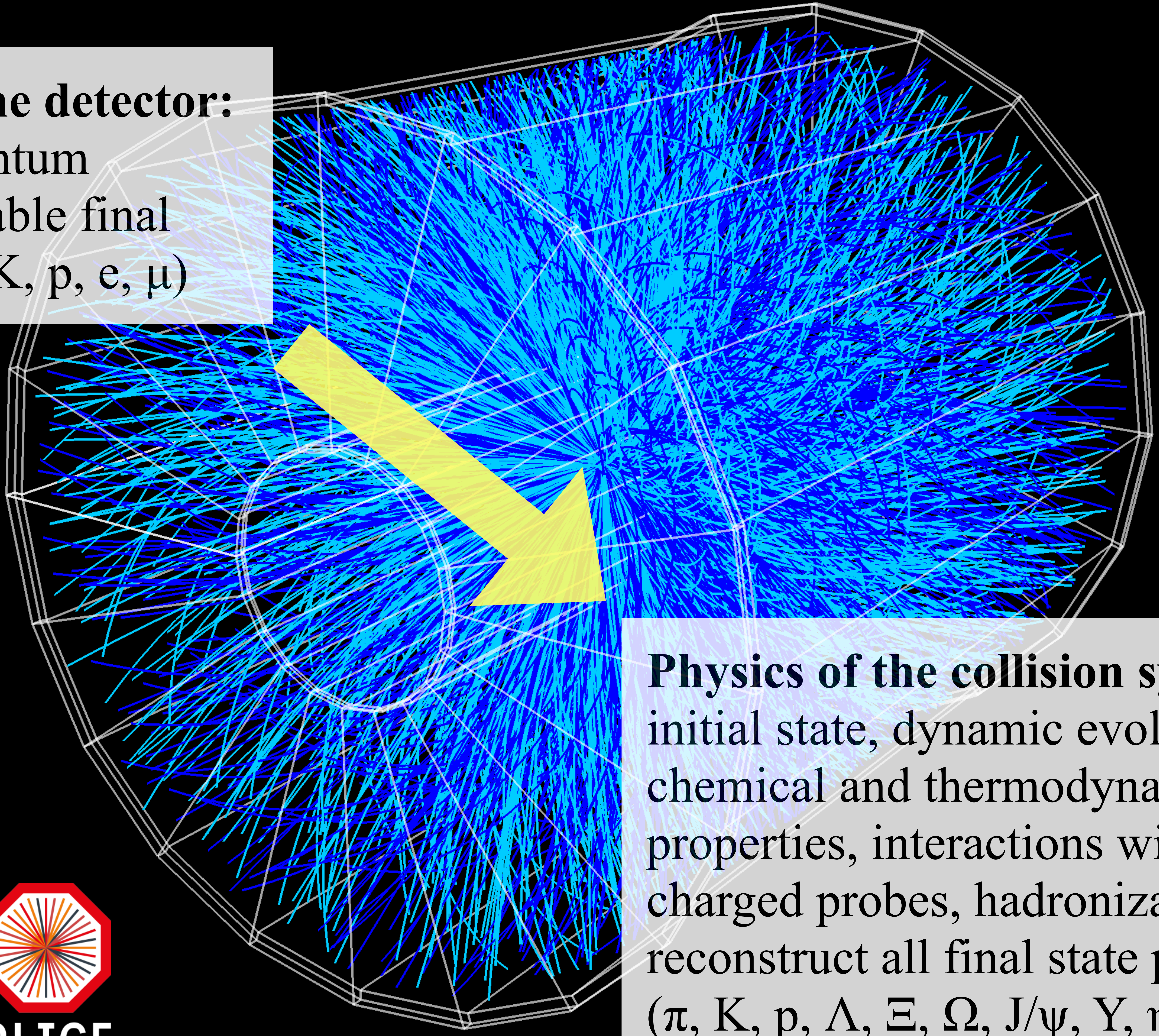
Relativistic Heavy-Ion Collisions
made by Chun Shen
final detected particle distributions
Kinetic freeze-out
Hadronization
Initial energy density
Hadron gas phase
QGP phase
π
K
p
γ
e+
e−
collision overlap zone
pre-equilibrium dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

Relativistic Heavy-Ion Collisions

made by Chun Shen



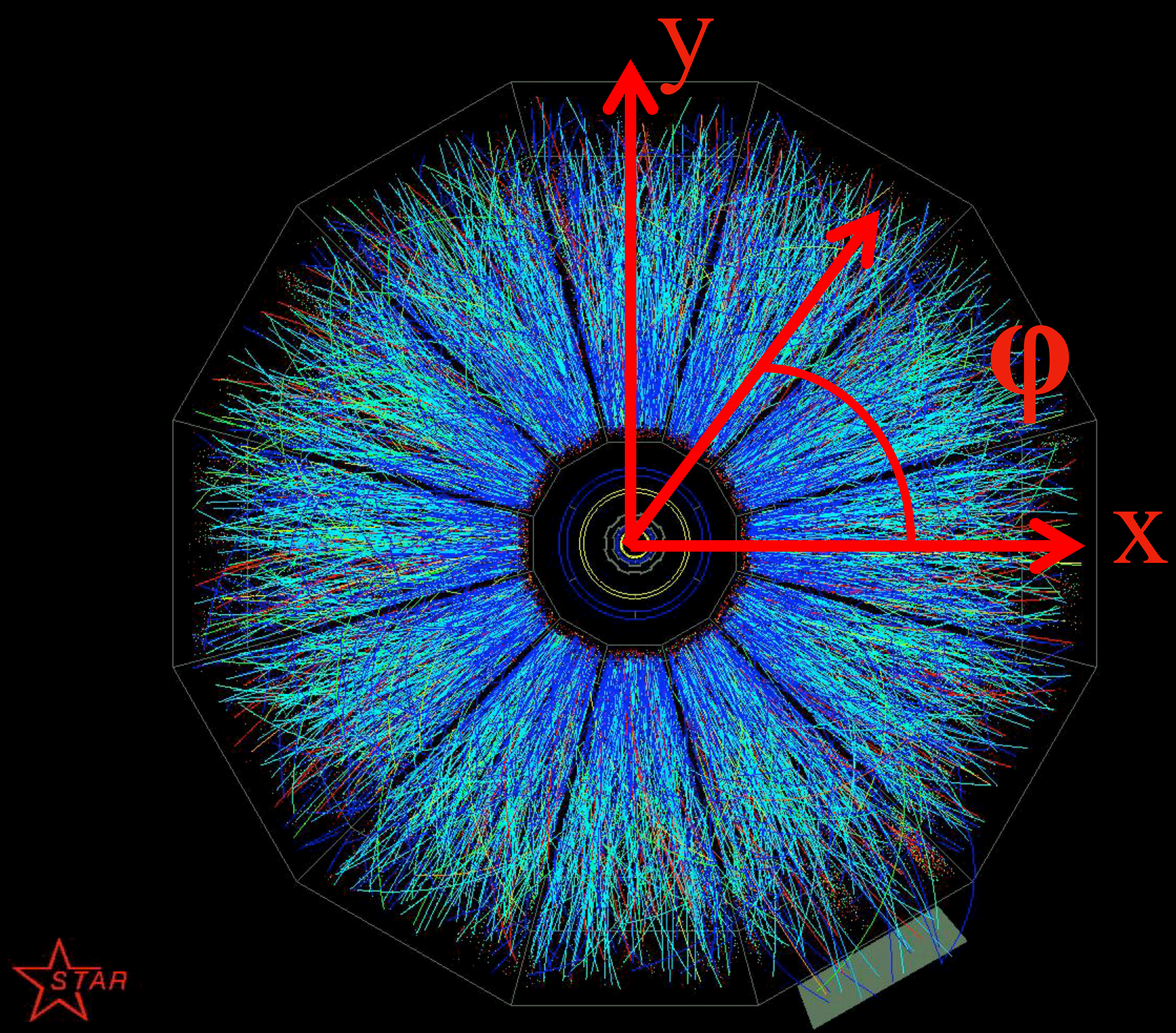
Observables in the detector: spatial and momentum distributions of stable final state particles (π, K, p, e, μ)

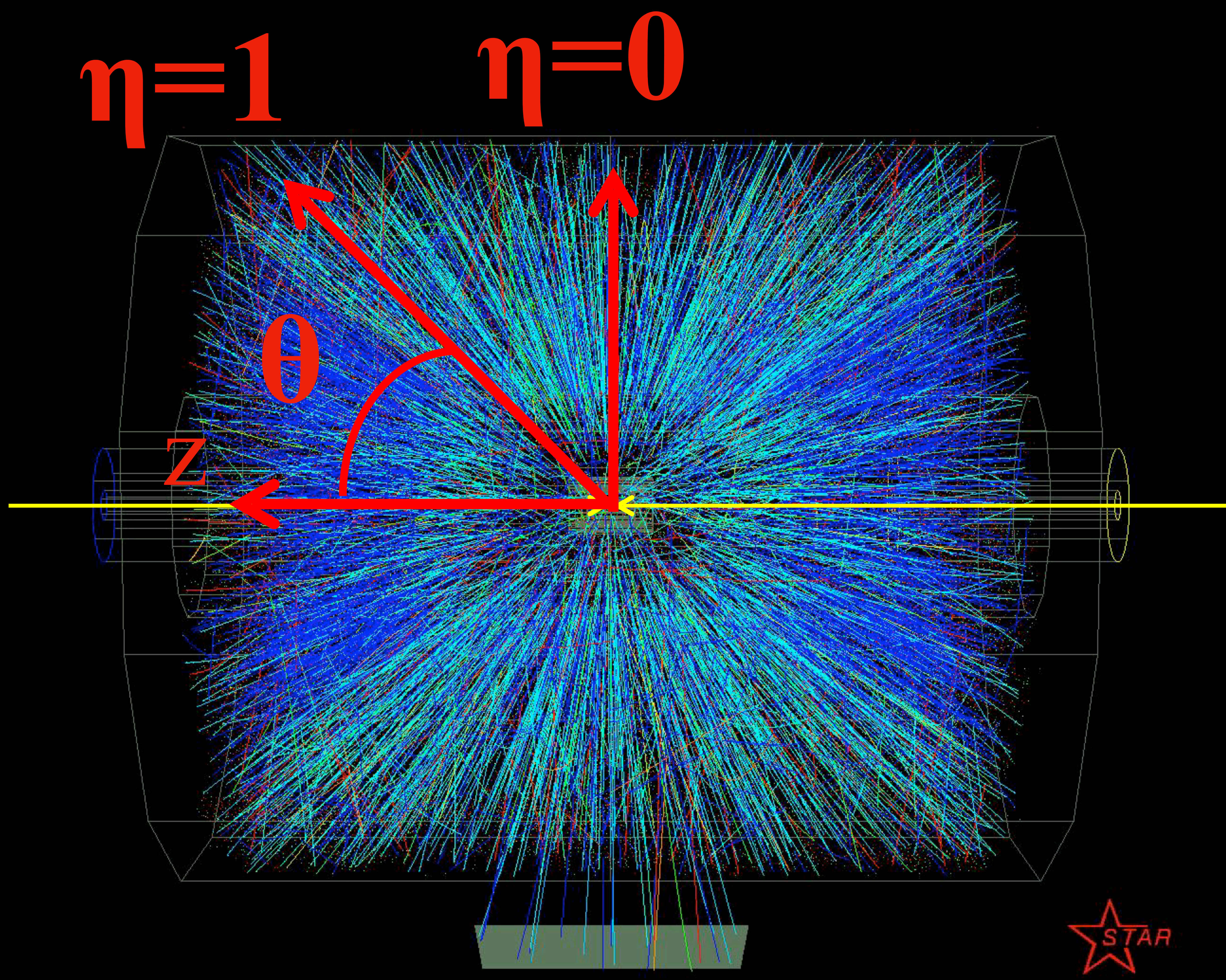


Physics of the collision system: initial state, dynamic evolution, chemical and thermodynamic properties, interactions with charged probes, hadronization, reconstruct all final state particles (π, K, p, Λ, Ξ, Ω, J/ψ, Y, η, ρ, γ, e, μ,…)

ALICE

Coordinate systems (φ, η)



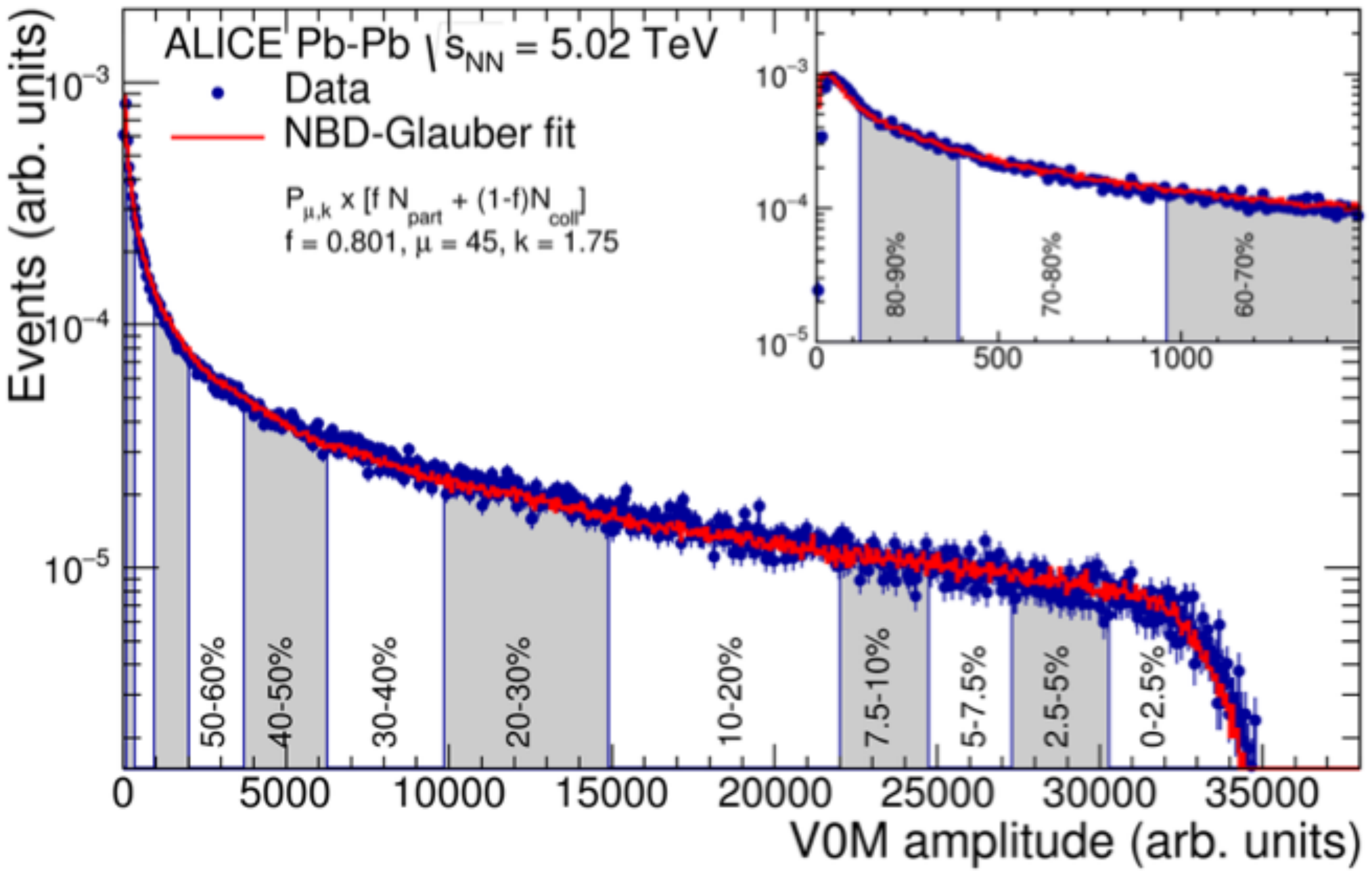


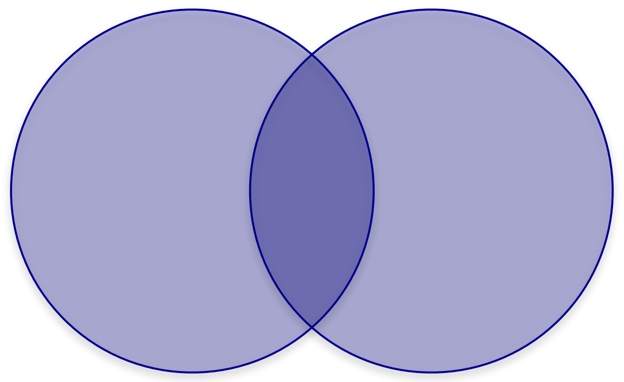
Geometry of a heavy-ion collision

- **Central** (head-on) **collision**
  → smaller impact parameter
  → larger overlap region
  → more particles produced

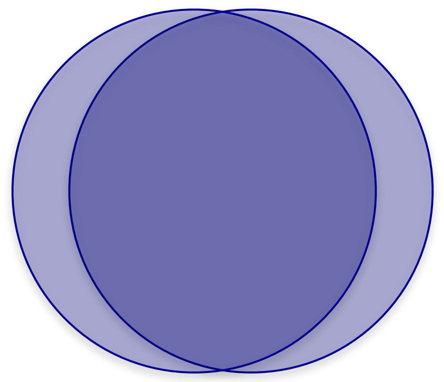
- **Peripheral** (glancing) **collision**
  → larger impact parameter
  → smaller overlap region
  → fewer particles produced

- Centrality is usually quoted as a percentage of the cross-section





70-90%, “peripheral”

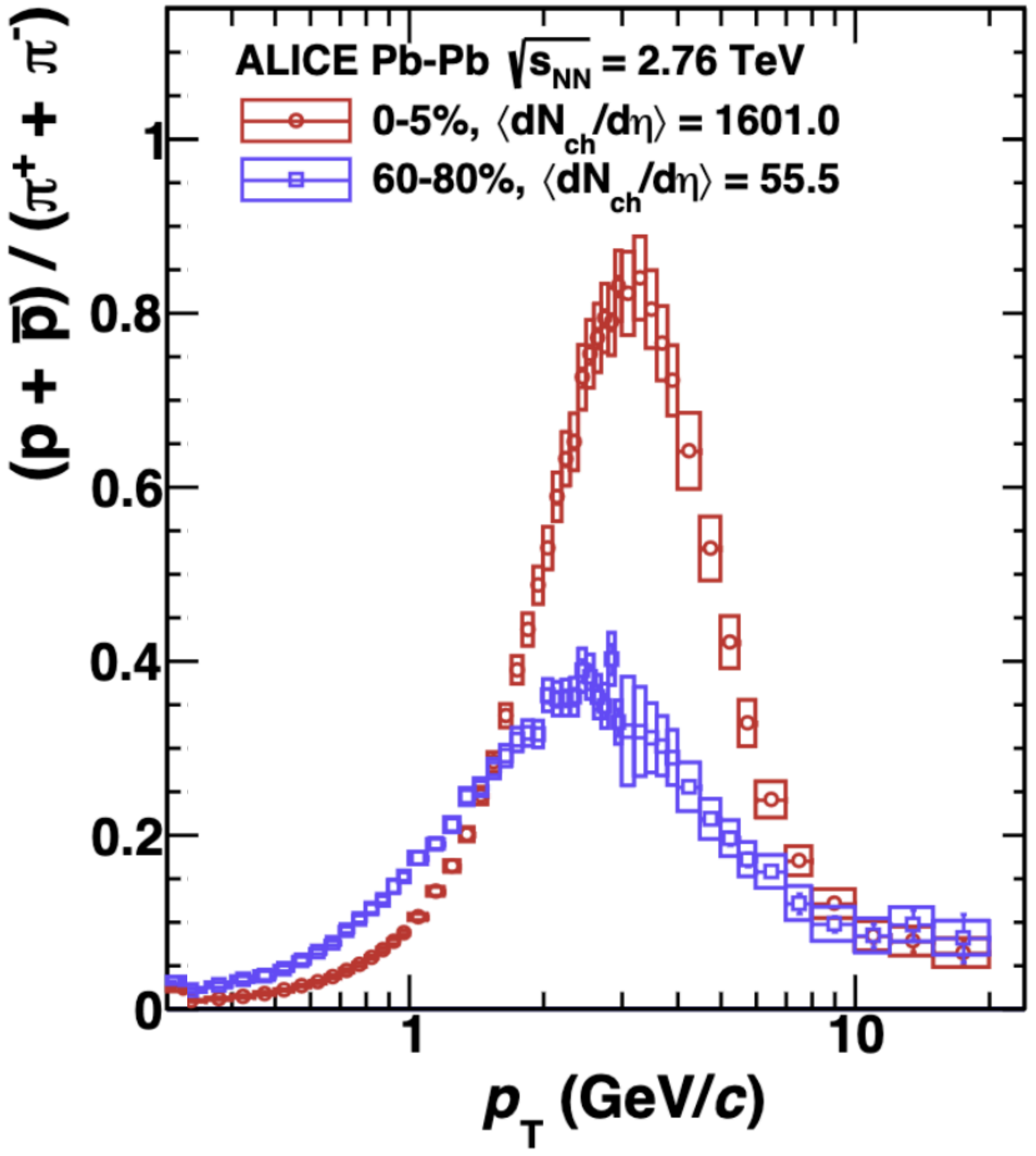


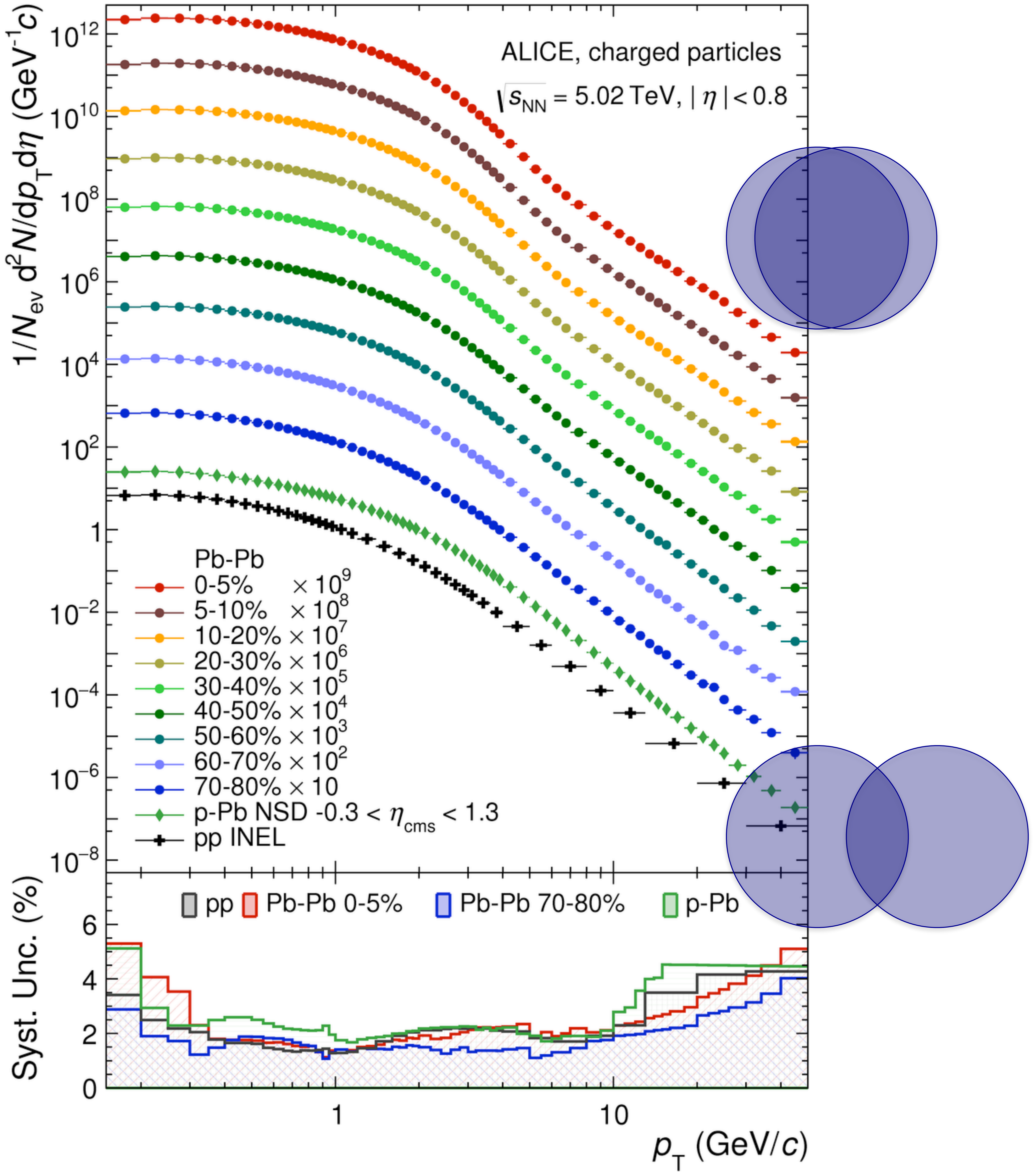
0-5%, “central”

- Centrality determination by counting number of final-state particles (“**multiplicity**”) or energy deposition in a region of phase space *independent* from the measurement, to avoid biases/autocorrelations in the results

Isotropic expansion of the fireball

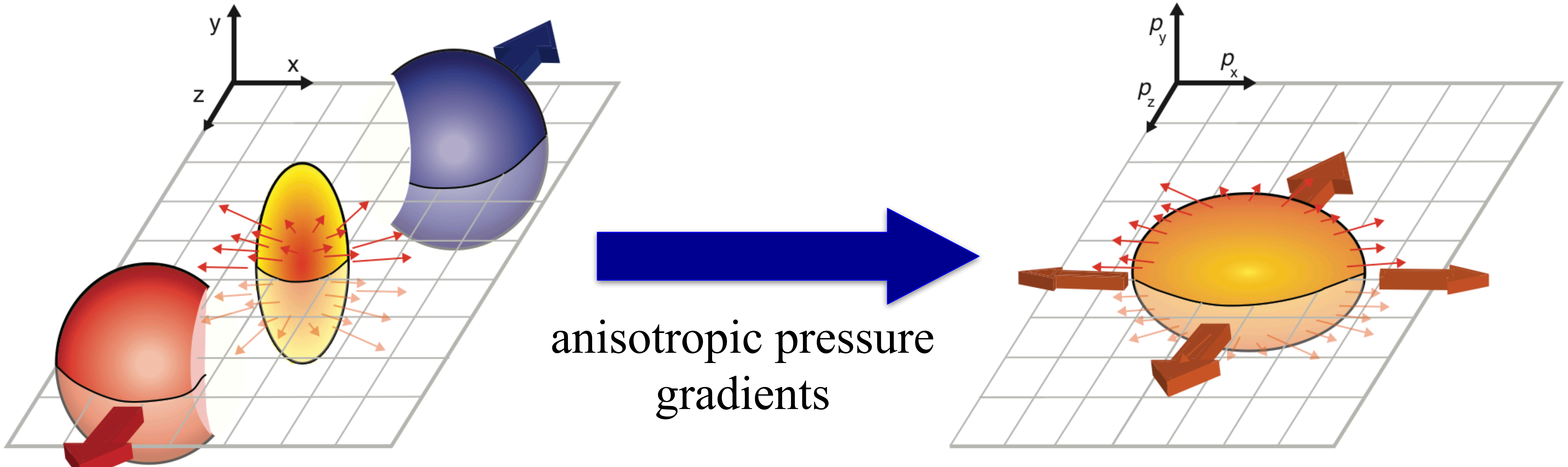
- Pressure gradients build up in the fireball
- Particles boosted in the radial direction
  → "radial flow"
  → higher mean p_T
- Velocity boost leads to enhancement in ratio of protons (heavy) to pions (light)





ALICE, JHEP 11 (2018) 013,
arxiv: 1802.09145 [nucl-ex]

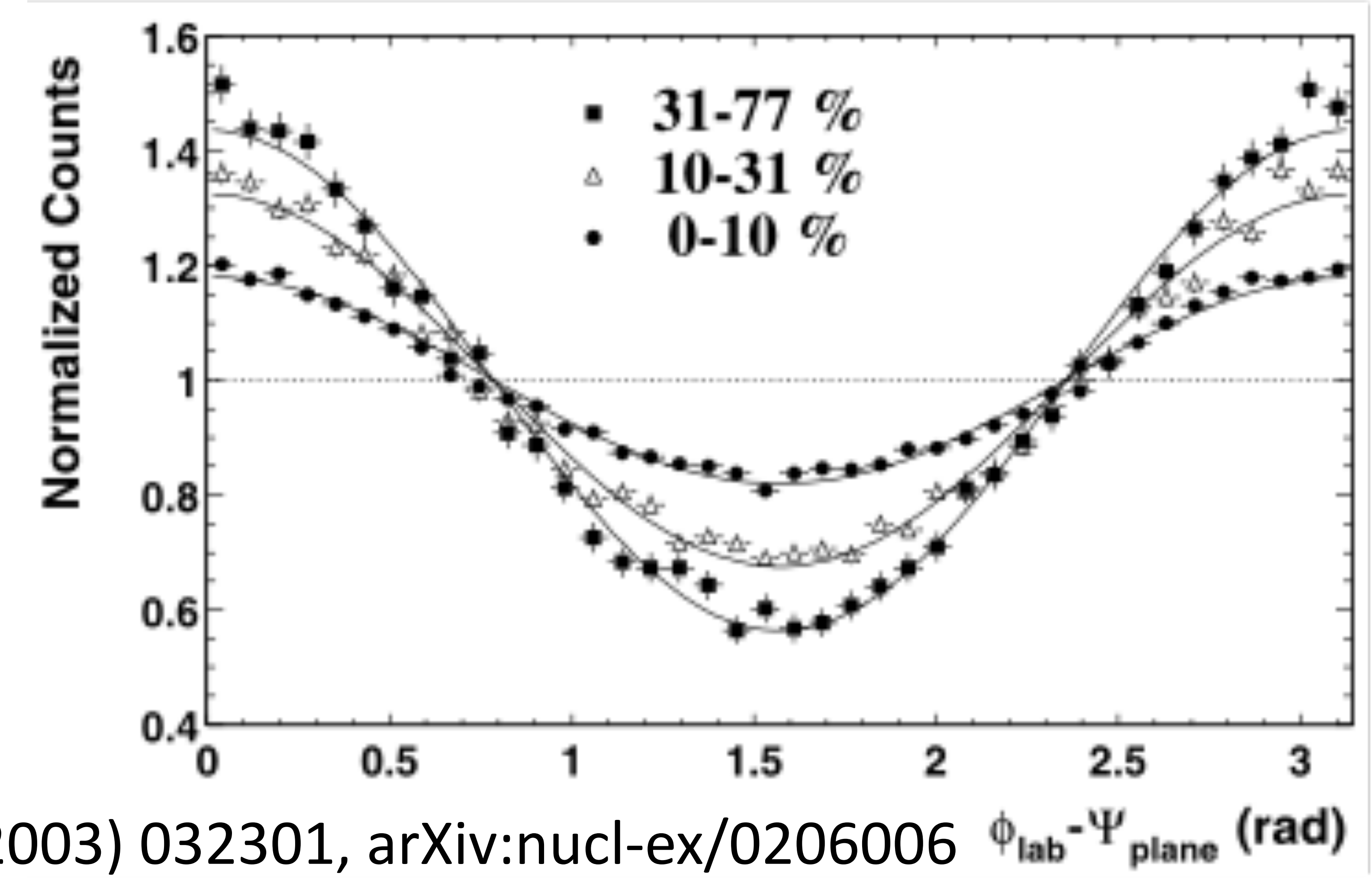
Anisotropic expansion



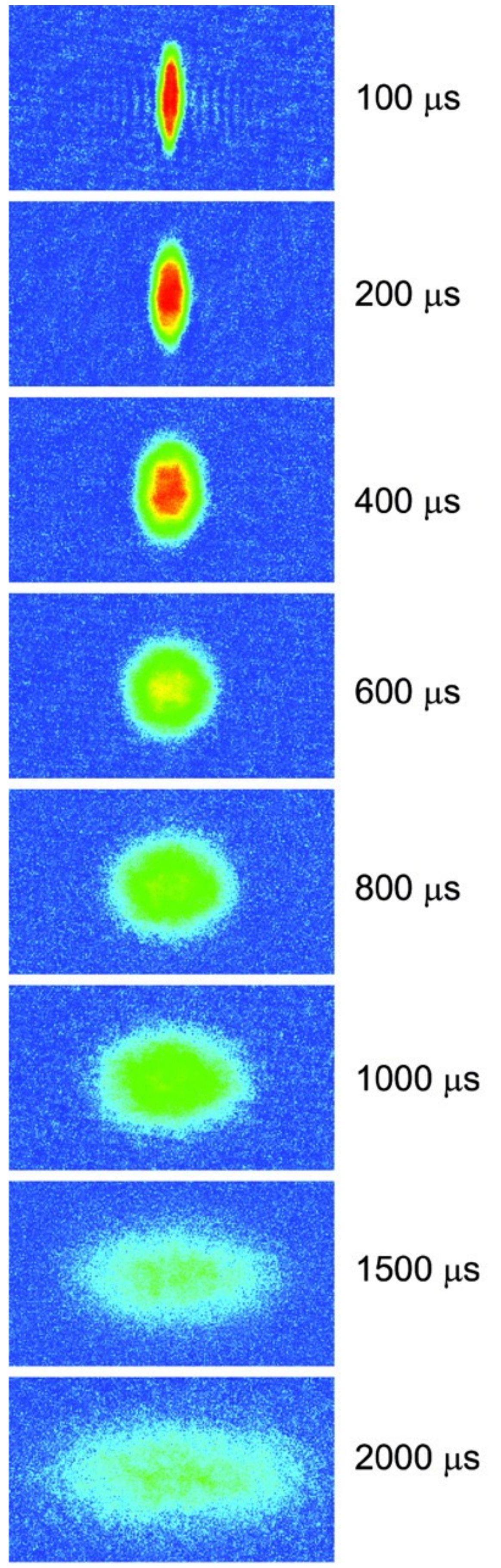
position-space anisotropy

momentum-space anisotropy

- Stronger in-plane pressure gradients, velocity field → particles boosted in-plane more than out-of-plane
- Particles correlated with a "global" symmetry plane



STAR, PRL 90 (2003) 032301, arXiv:nucl-ex/0206006



Elliptic Flow in Ultracold Lithium

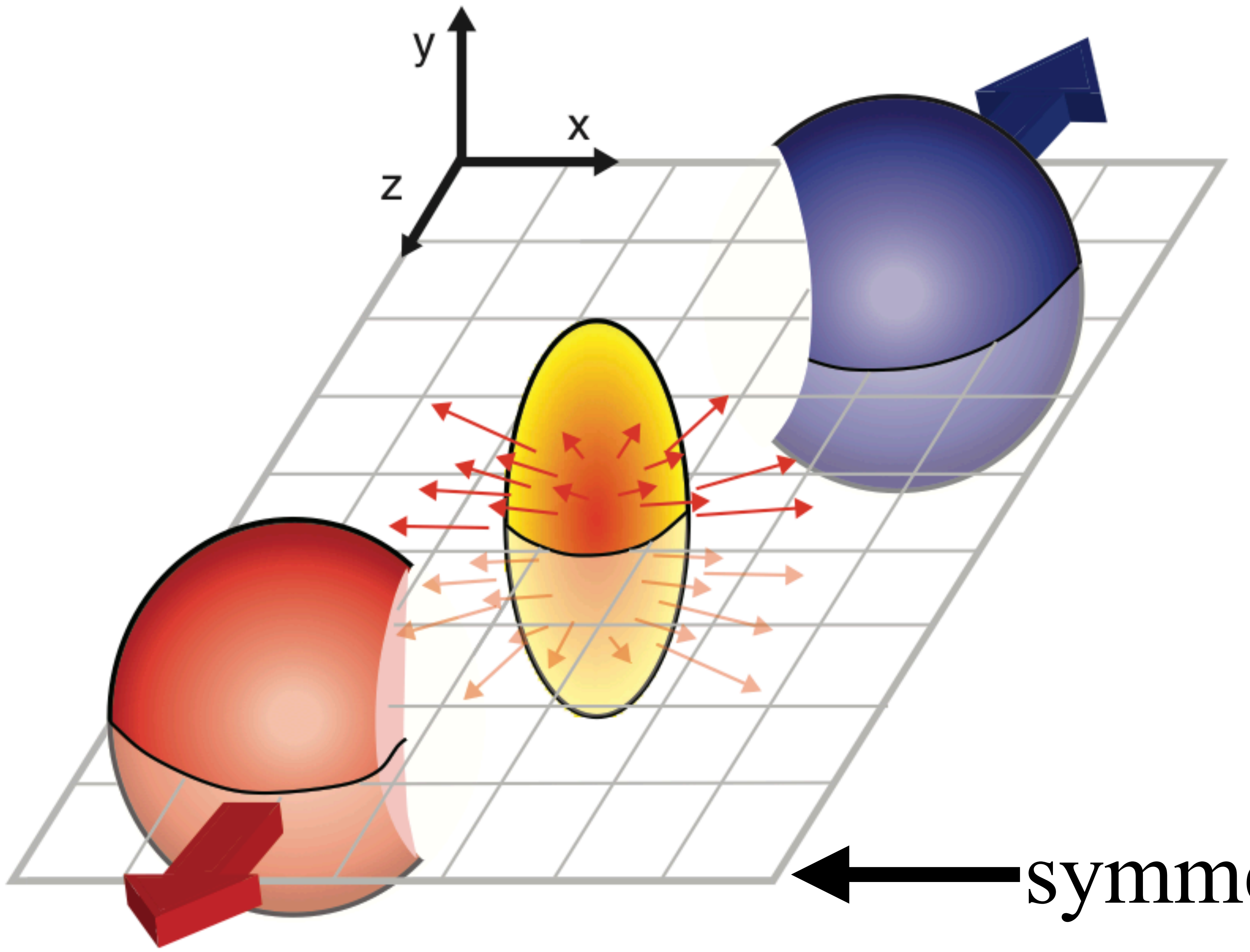
K.M. O'Hara et al., Science, 13 Dec 2002: 2179-2182

Anisotropic flow coefficients

- Particle distribution described by a Fourier cosine series

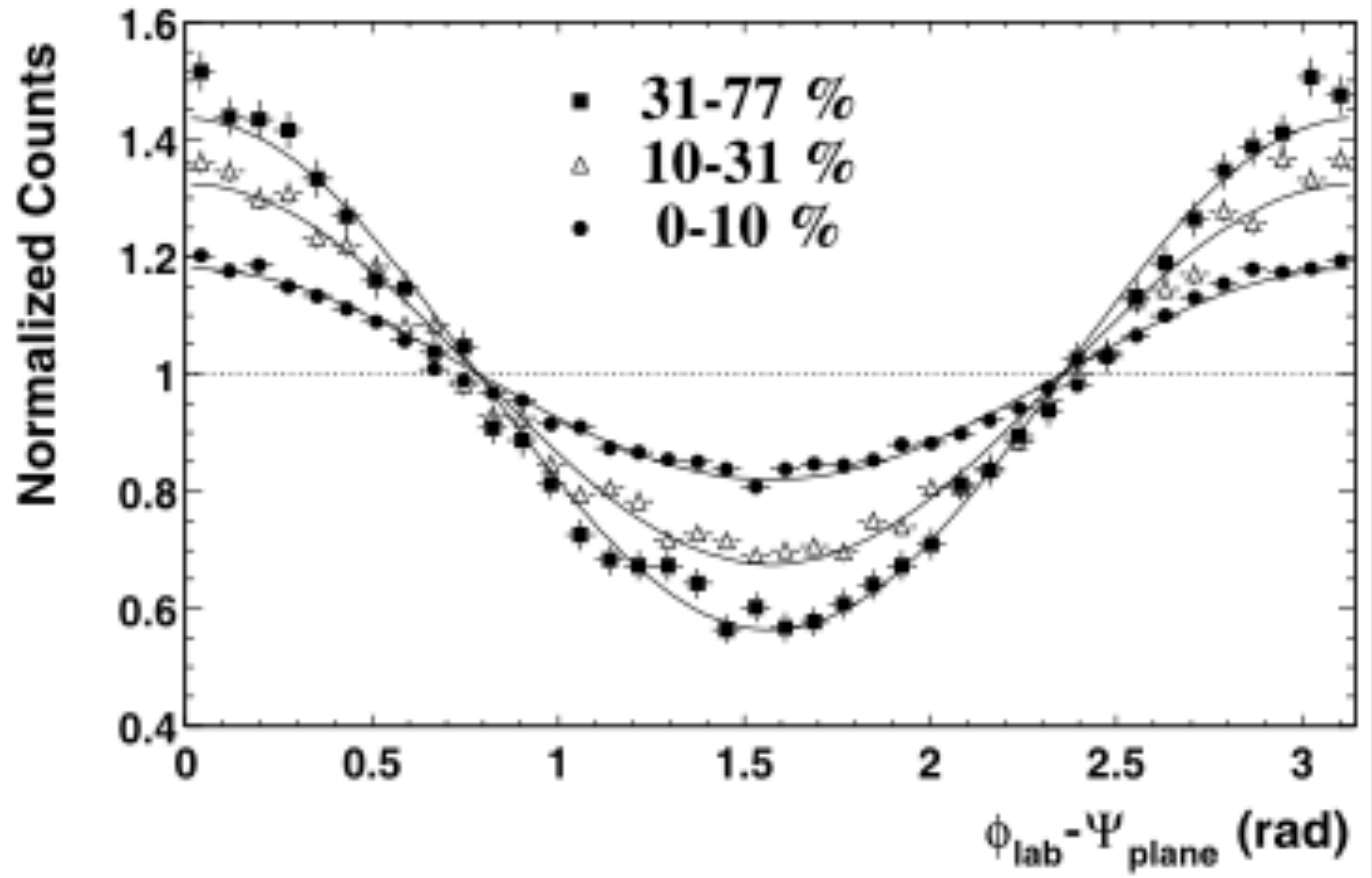
$$dN/d\varphi \sim 1 + 2v_2\cos(2(\varphi-\Psi_2))$$

- $v_2 \rightarrow$ "elliptic flow"

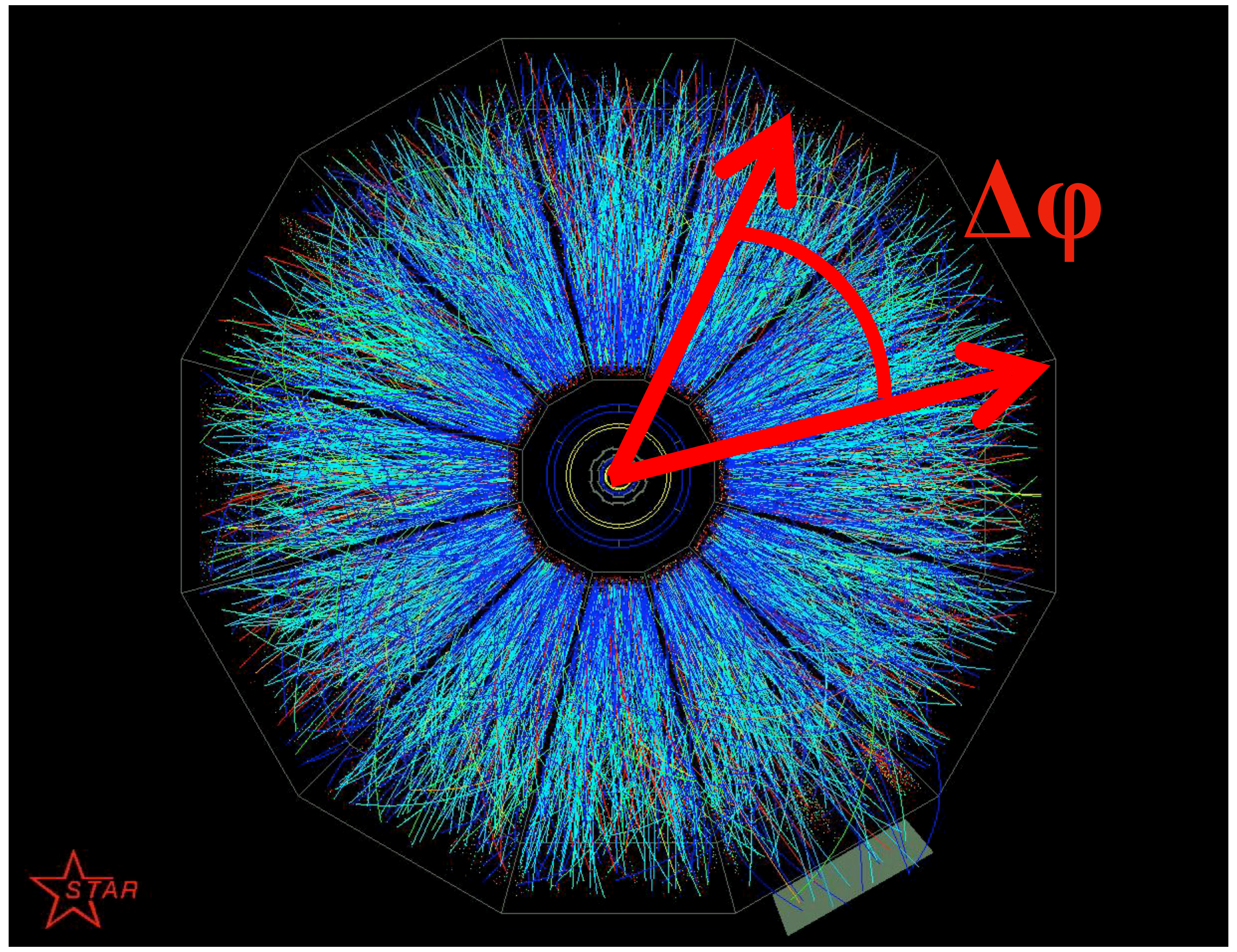


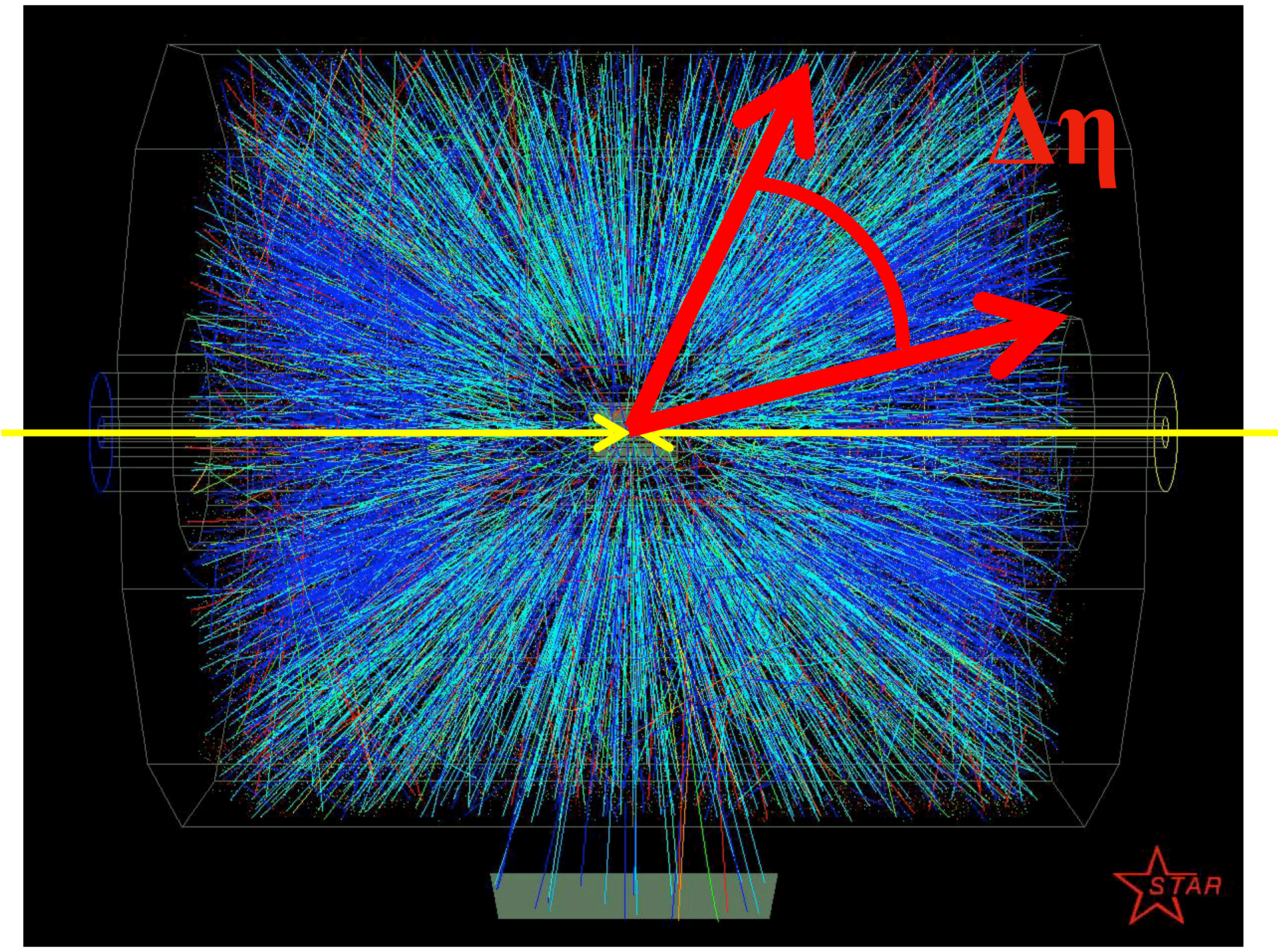
symmetry plane $\Psi_{RP} \simeq \Psi_2$

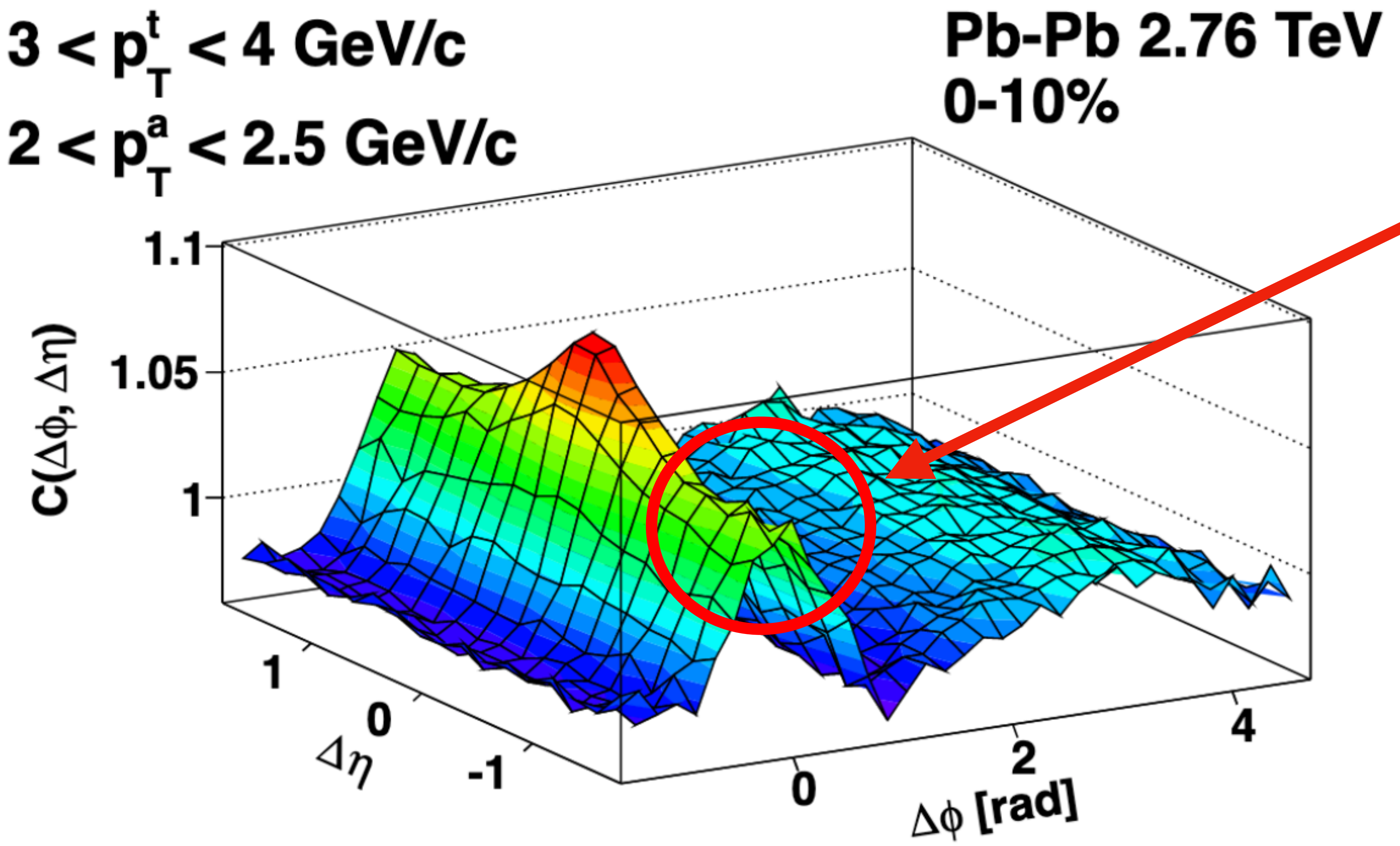
STAR, PRL 90 (2003) 032301, arXiv:nucl-ex/0206006



Two-particle correlations







- Long-range correlations (localized in Δφ, extended in Δη) → collectivity
- Two-particle (Δφ) distribution described by Fourier series with coefficients v_n^2

$$dN/d\varphi \sim 1 + 2v_2^2\cos(2\Delta\varphi)$$

ALICE, PLB 708 (2012) 249, arXiv:1109.2501 [nucl-ex]

Anisotropic flow coefficients

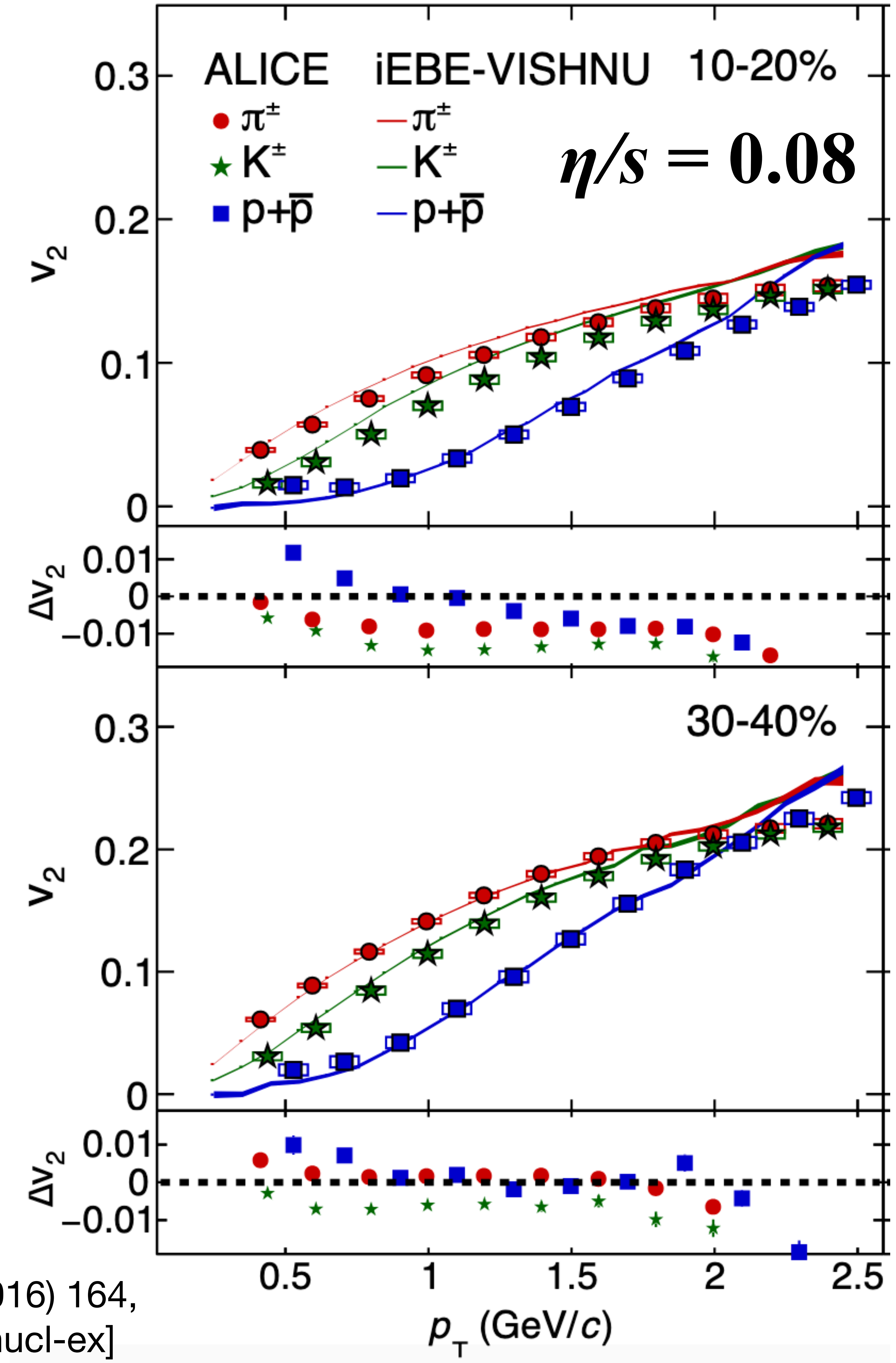
- Particle distribution described by a Fourier cosine series

$$dN/d\varphi \sim 1 + 2v_2\cos(2(\varphi-\Psi_2))$$

- v_2 → "elliptic flow"

- Measurements of v_2 are described very well by hydrodynamic models → QGP behaves as a liquid!

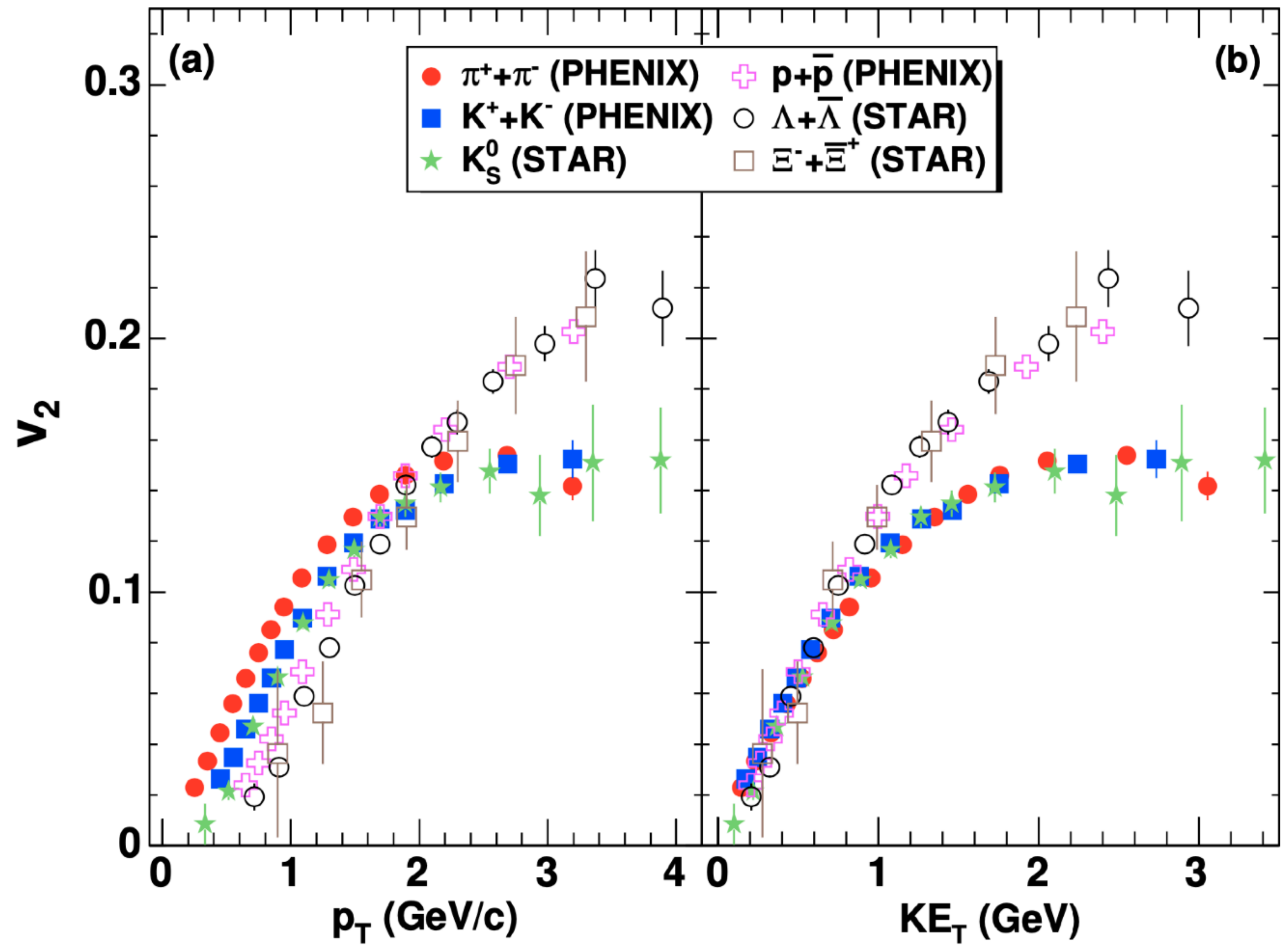
- Viscosity (η/s) is near quantum lower bound → QGP is the "perfect liquid"



ALICE, JHEP 09 (2016) 164,
arXiv:1606.06057 [nucl-ex]

What is flowing?

- The RHIC story: when scaled by the number of quarks (NCQ), the flow of different particle species converges on a common curve → flow at the *parton* level
- The LHC story: NCQ scaling broken on the level of 10-20%, it's mostly a mass effect → interesting case is the φ meson (2 quarks, but mass similar to the proton), follows the proton at low p_T and follows the mesons at higher p_T



PHENIX, Phys. Rev. Lett 98 (2007) 162301, arXiv: nucl-ex/0608033

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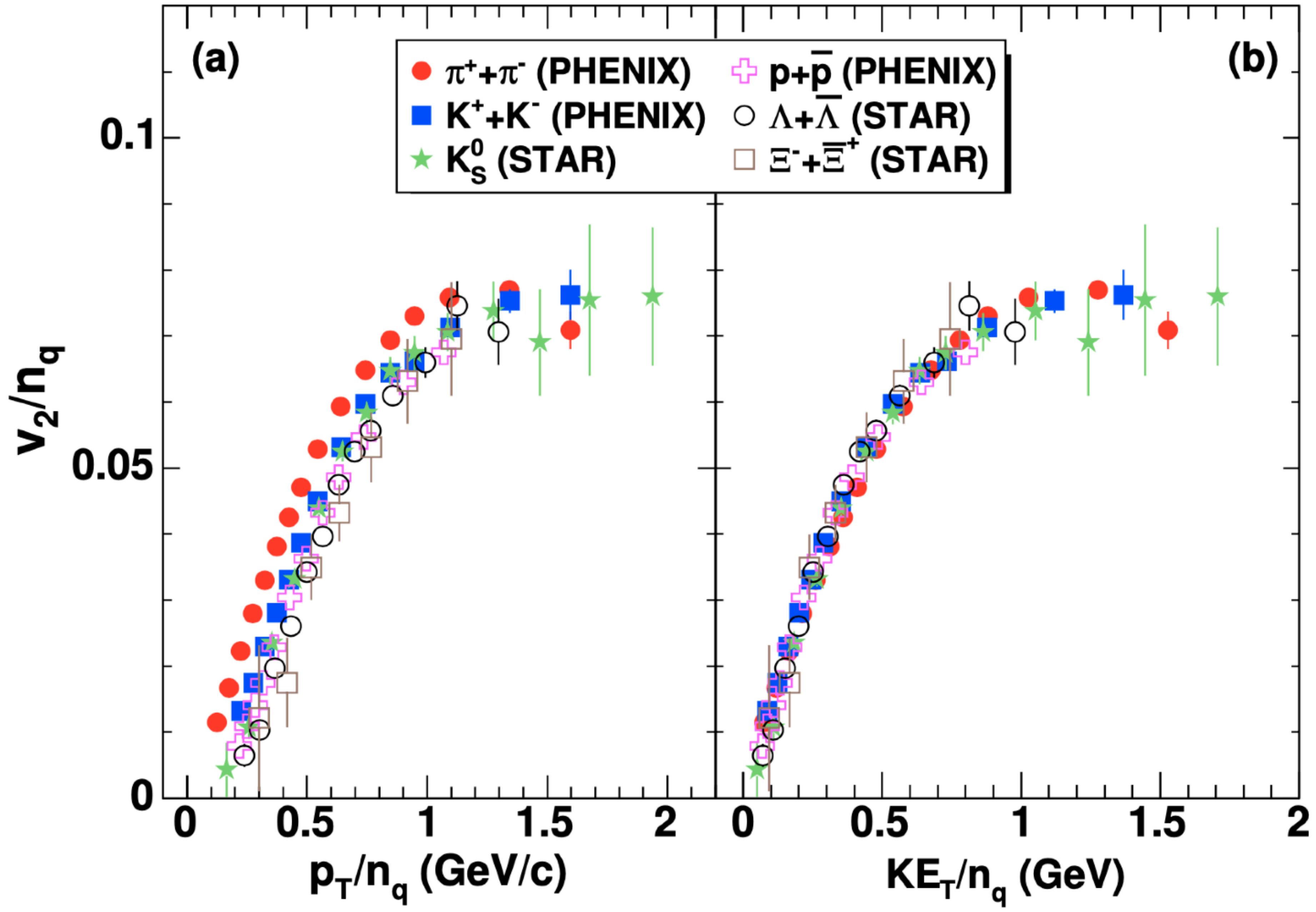
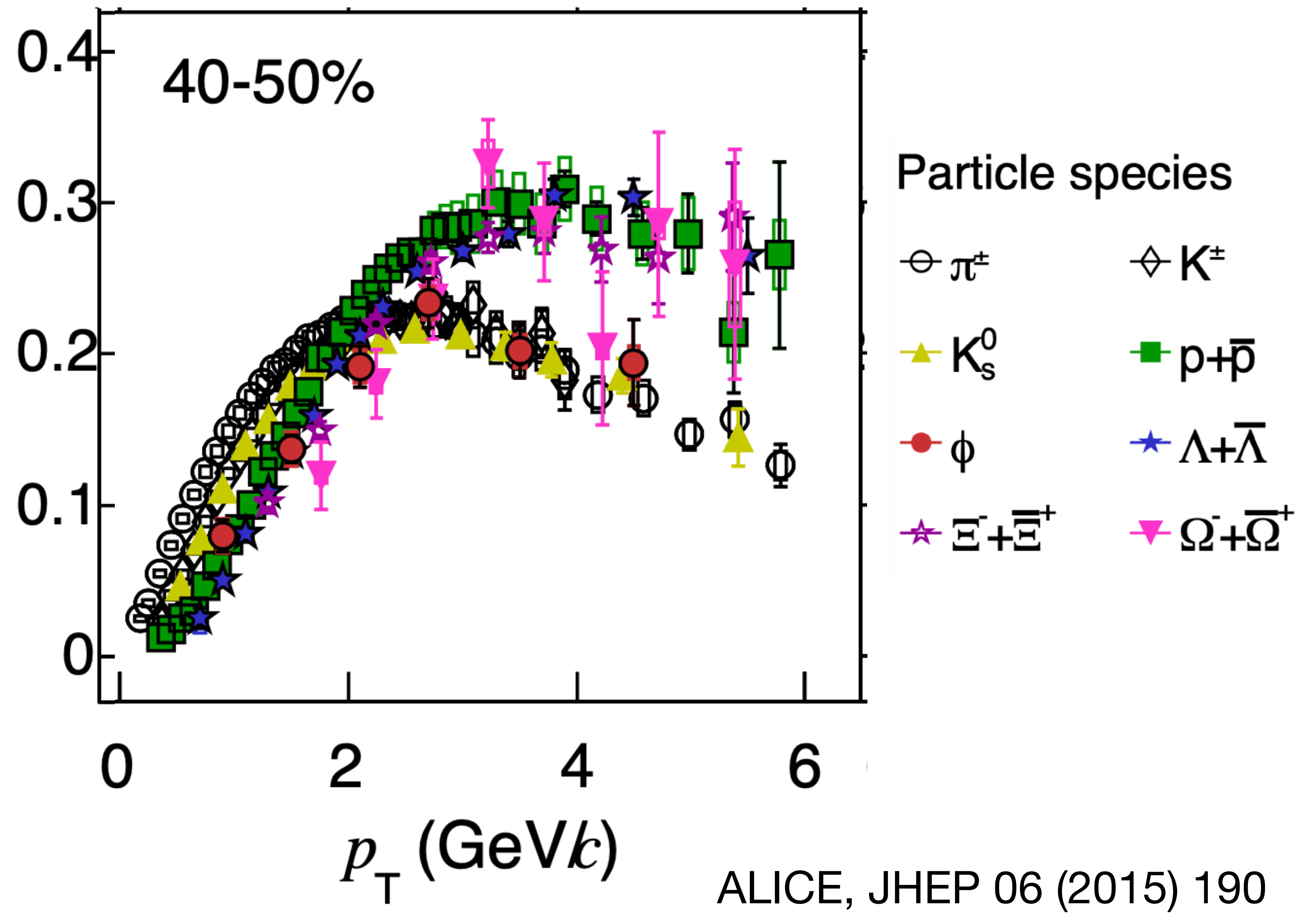


PHENIX, Phys. Rev. Lett 98 (2007) 162301, arXiv: nucl-ex/0608033

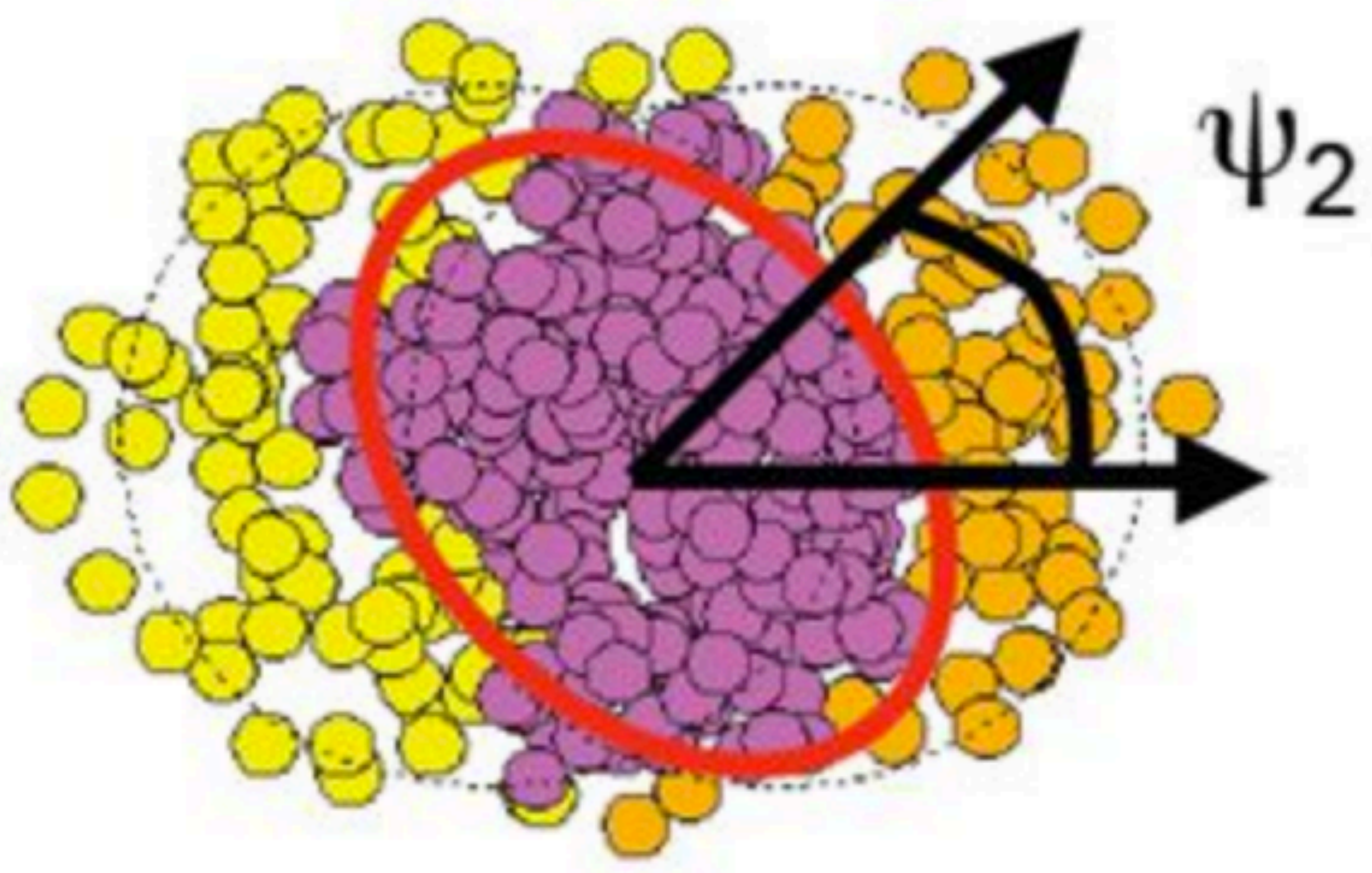


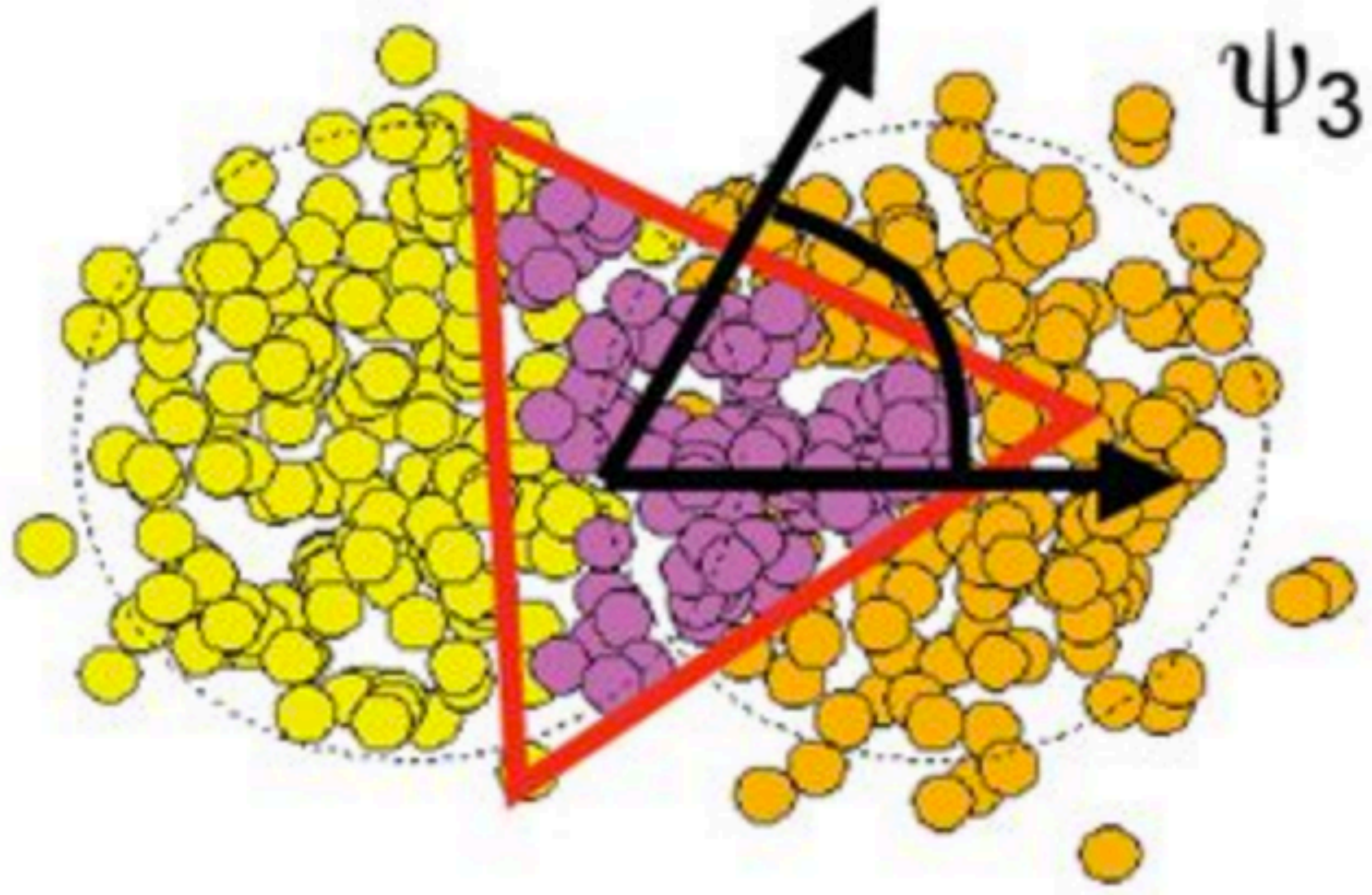
ALICE, JHEP 06 (2015) 190
arXiv: 1405.4632 [nucl-ex]

Higher-order flow coefficients

- Due to event-by-event fluctuations of the positions of nucleons, overlap region is not perfectly symmetric
  → development of triangular flow v_3, quadrangular flow v_4,…
  with respect to higher-order symmetry planes Ψ_3, Ψ_4,…
- v_n coefficients sensitive to **geometry** and **fluctuations**
- Hydrodynamic response suggests that

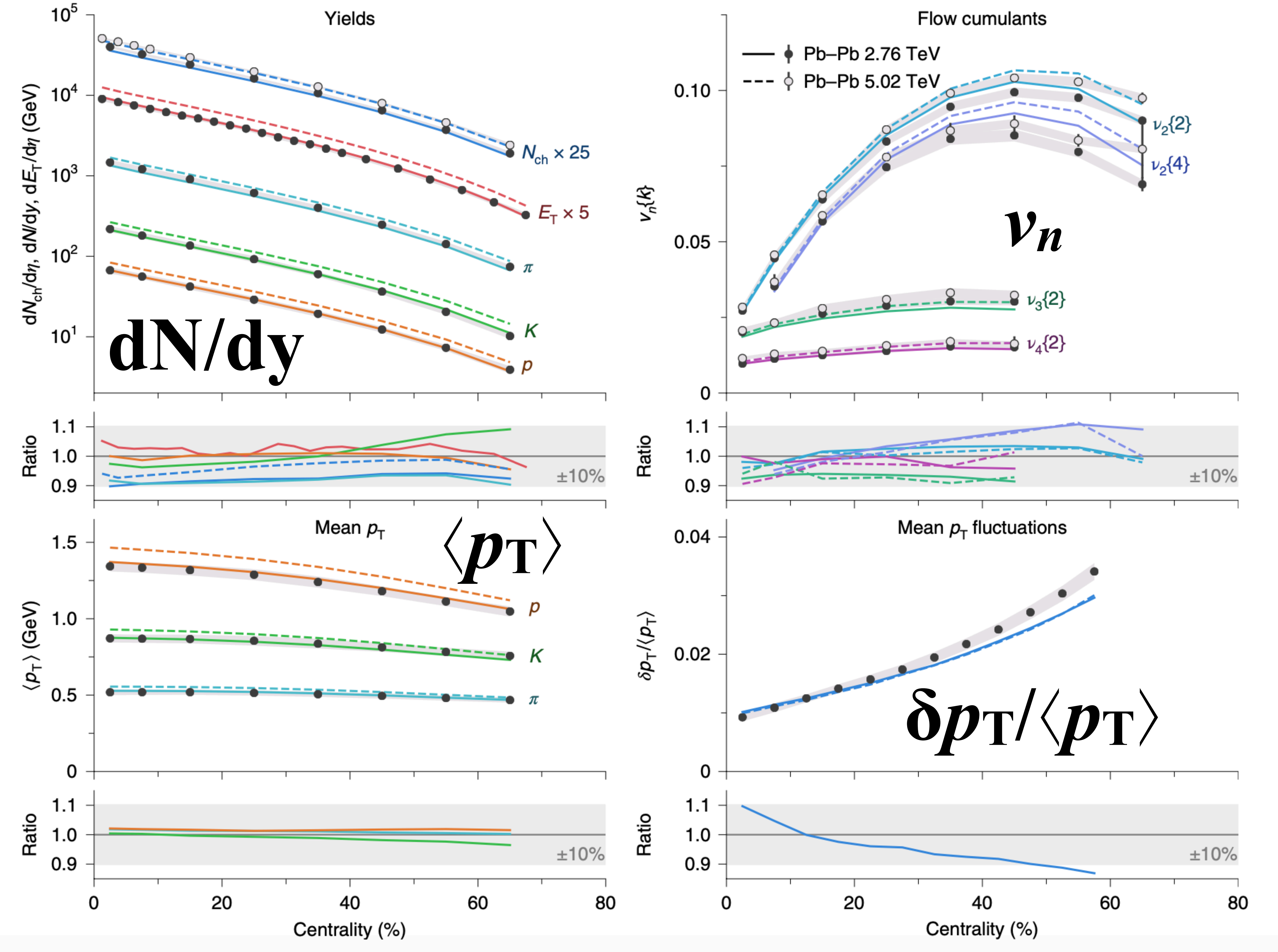
$$v_n \propto \varepsilon_n$$





Extracting QGP properties with flow

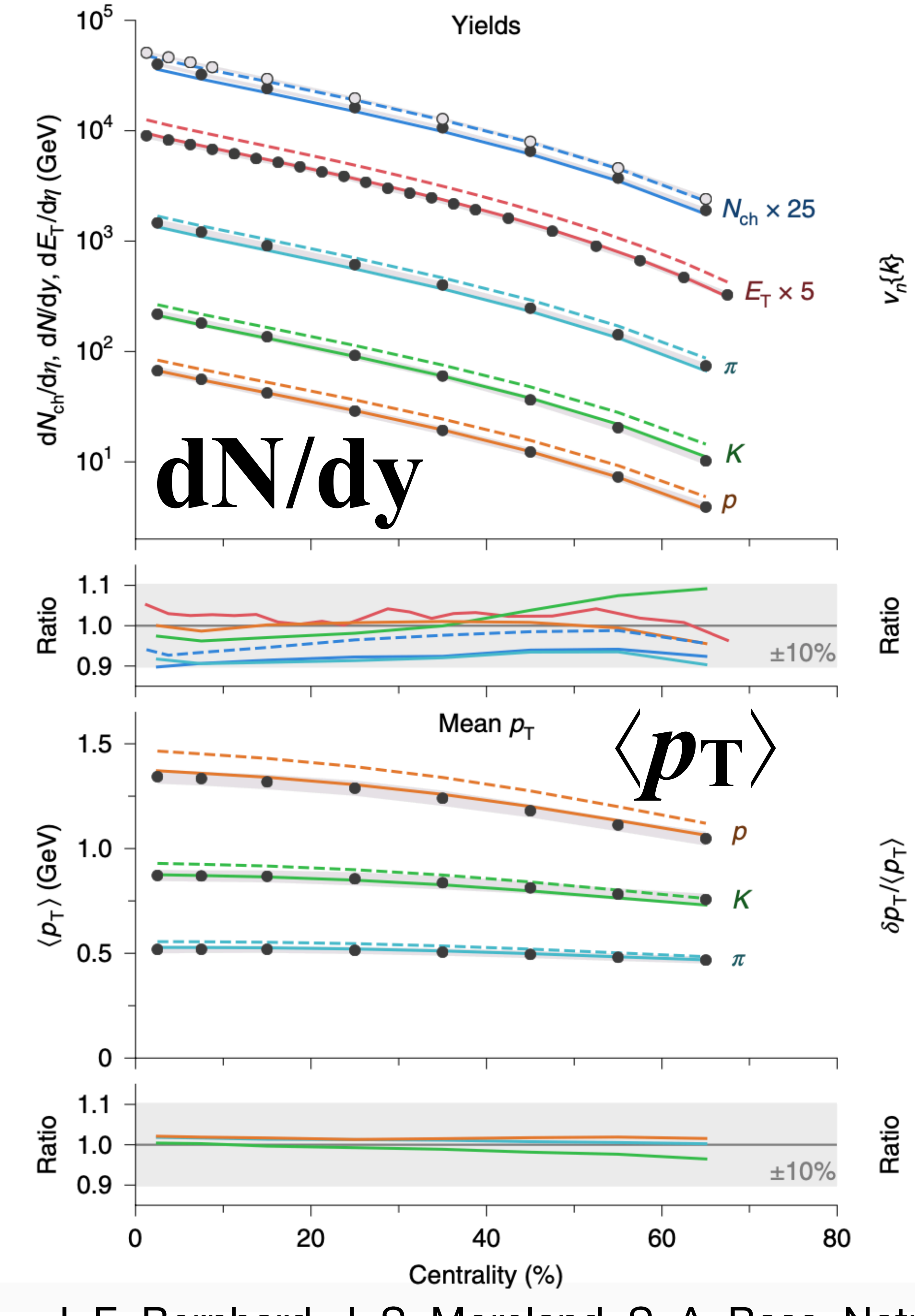
- Bayesian analysis of particle yields, mean p_T, v_2, v_3, v_4 measured by ALICE

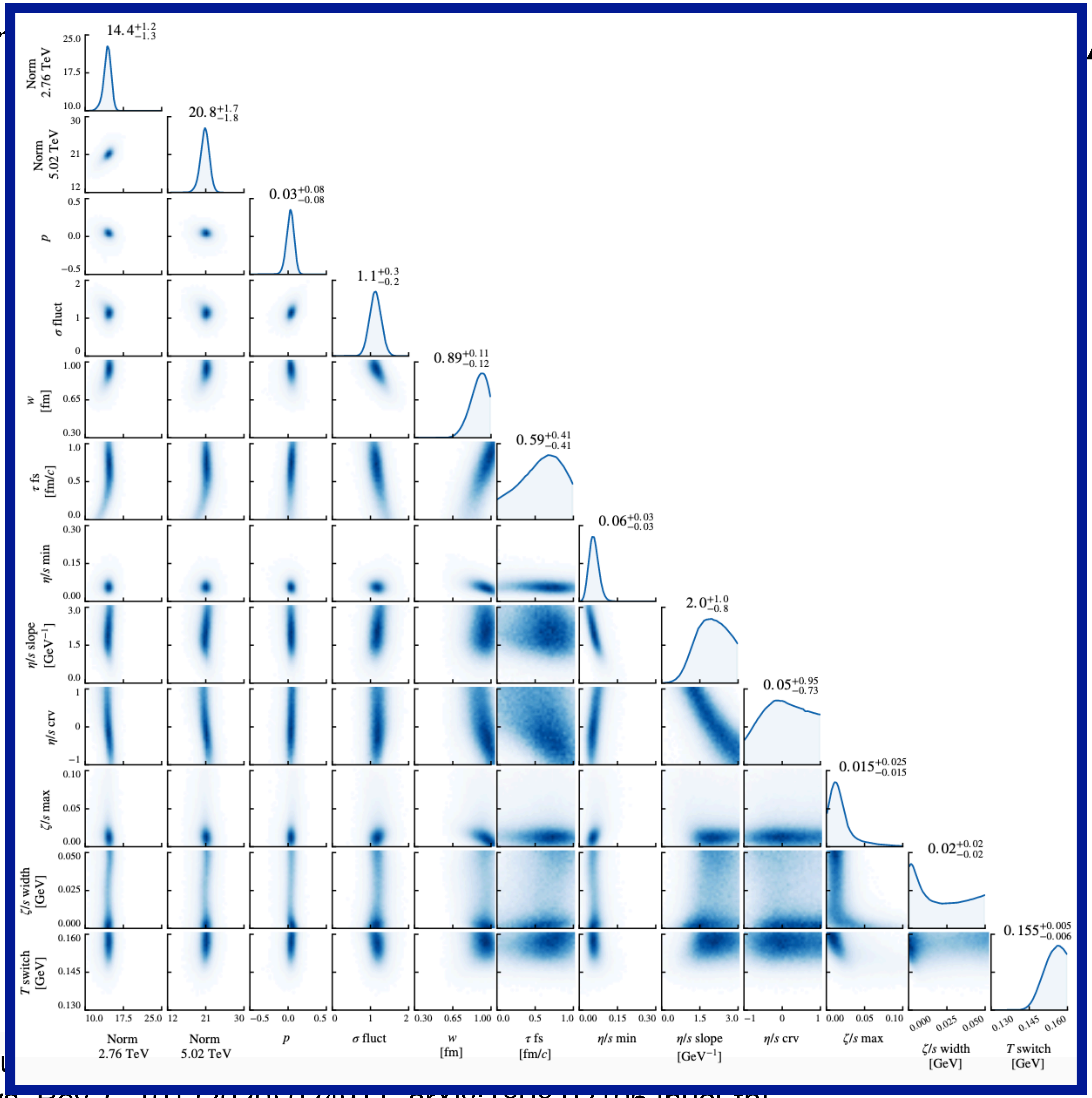


J. E. Bernhard, J. S. Moreland, S. A. Bass, Nature Physics 15 (2019) 1113
J. S. Moreland, J. E. Bernhard, S. A. Bass, Phys. Rev. C 101 (2020) 024911, arXiv:1808.02106 [nucl-th]

Extracting QGP properties with flow

- Bayesian analysis of par… ALICE





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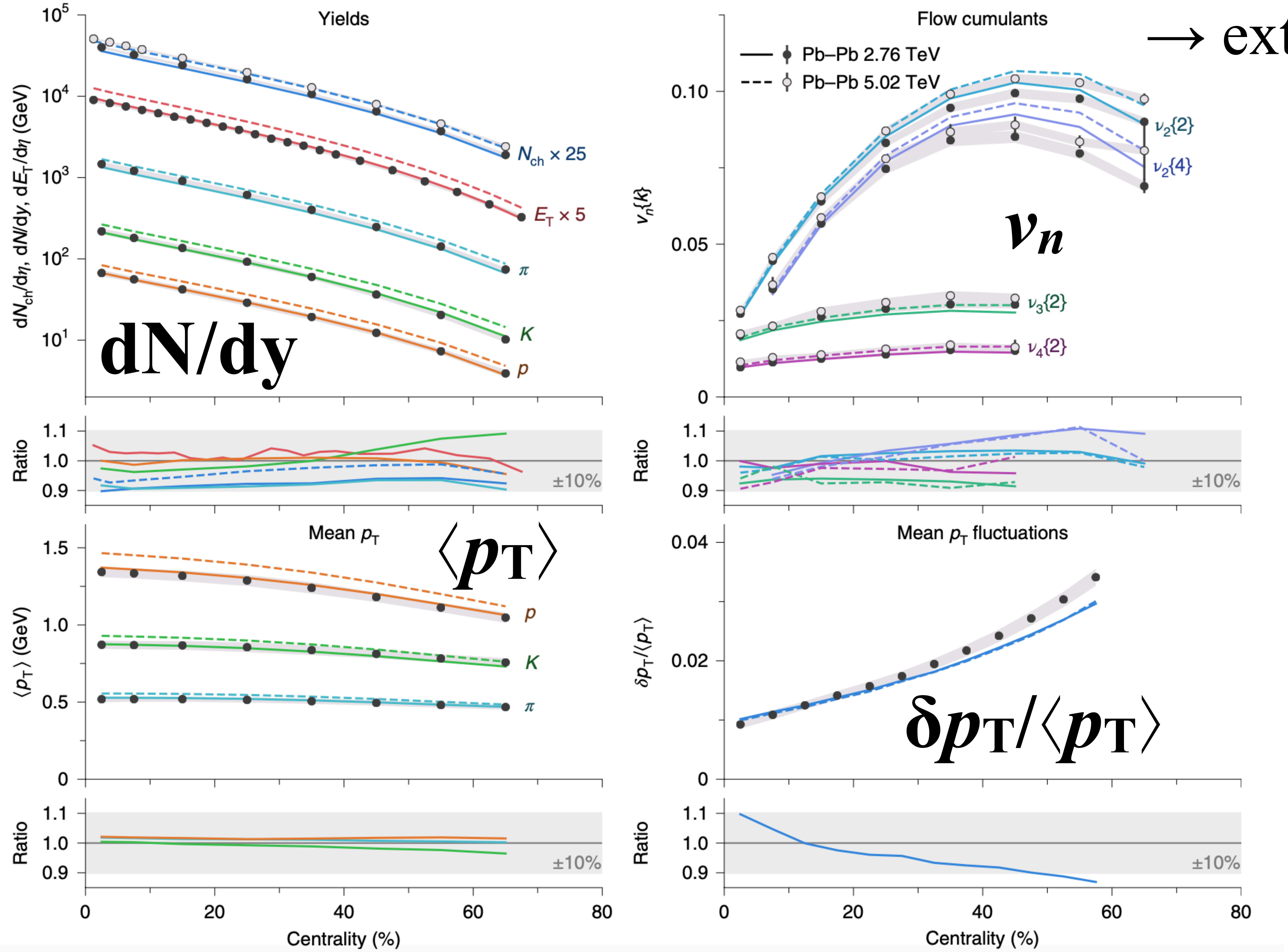
Extracting QGP properties with flow

- Bayesian analysis of particle yields, mean p_T, v_2, v_3, v_4 measured by ALICE

  → extract shear and bulk viscosity $\eta/s(T)$, $\zeta/s(T)$



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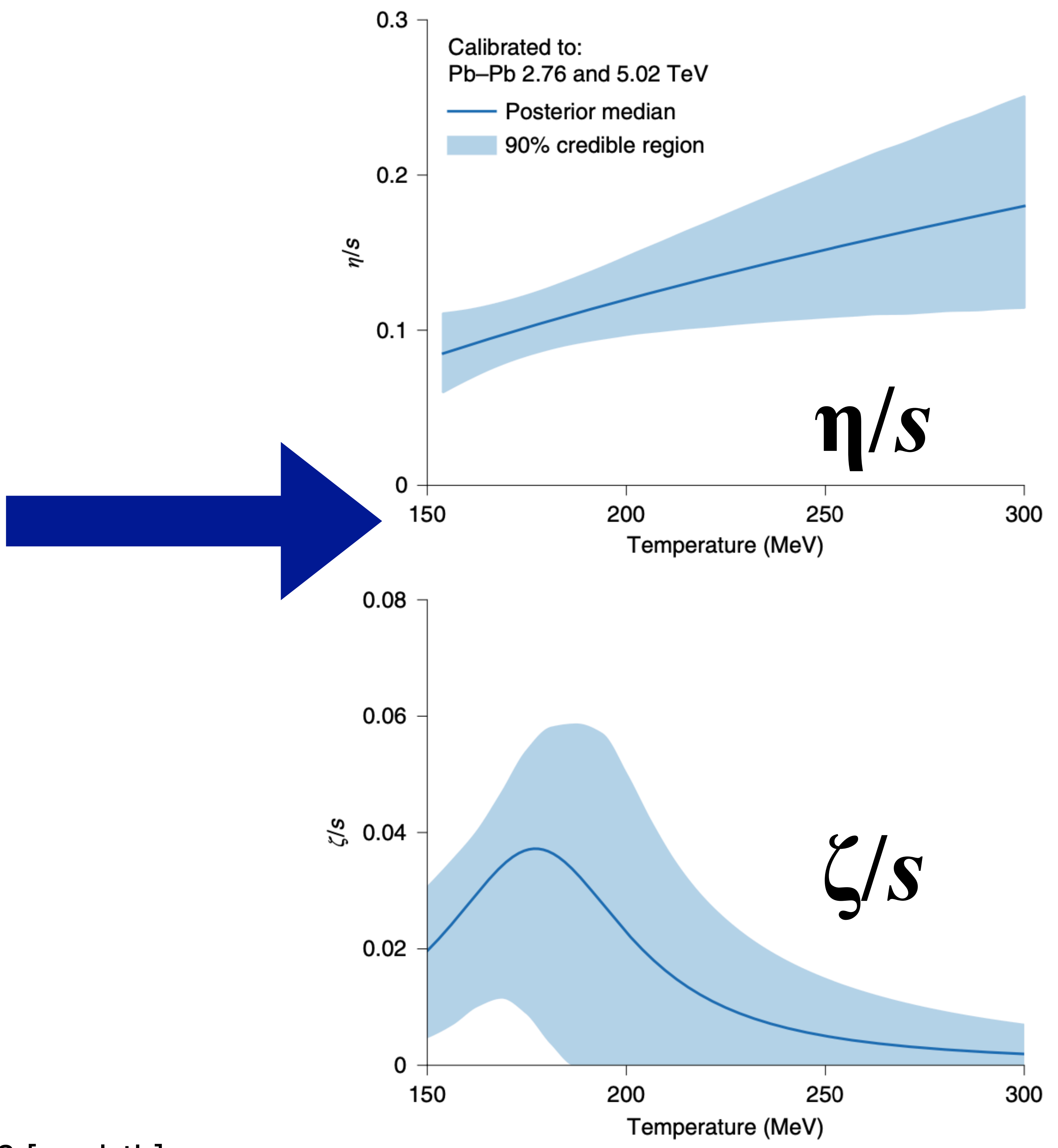
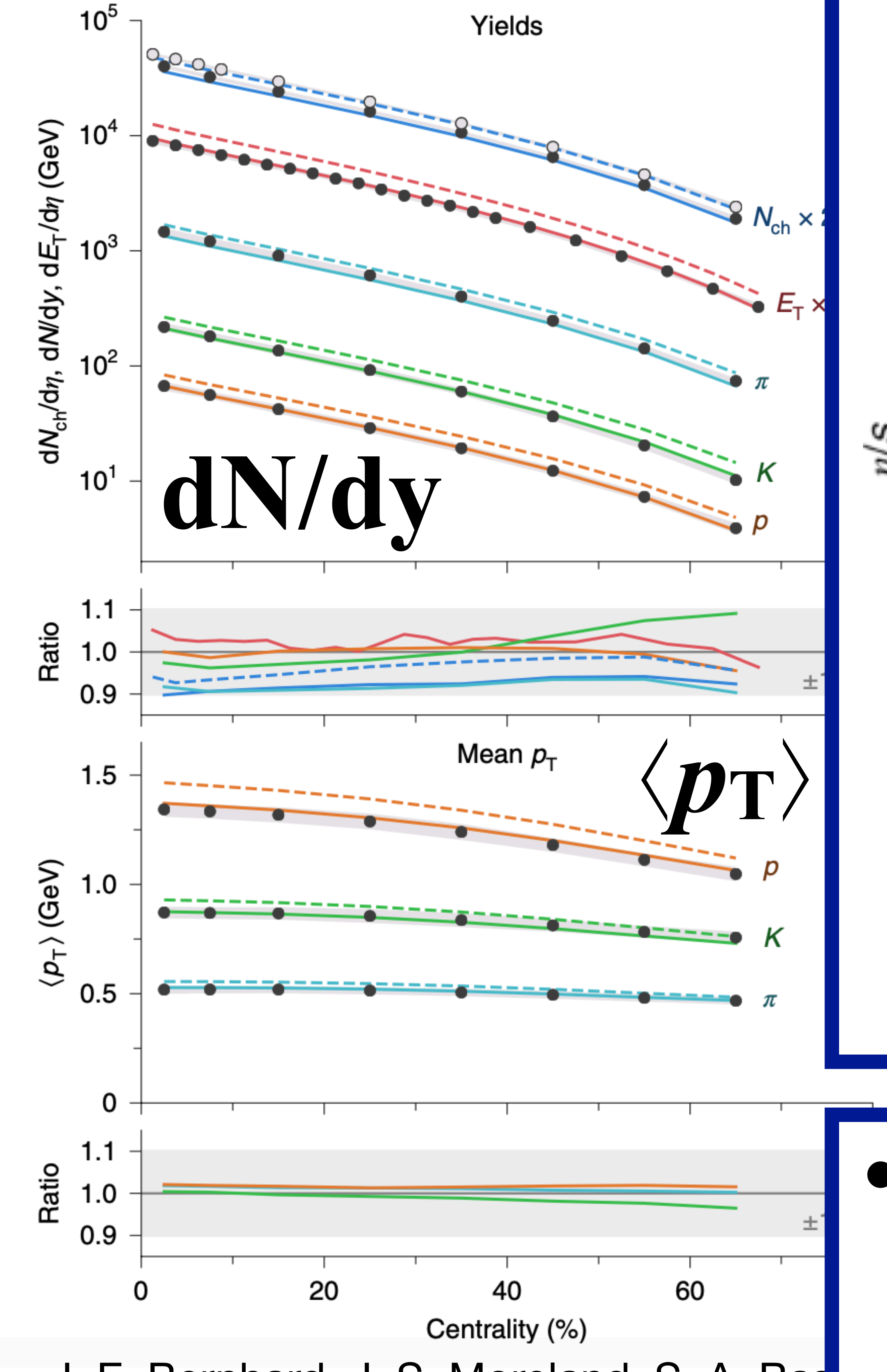
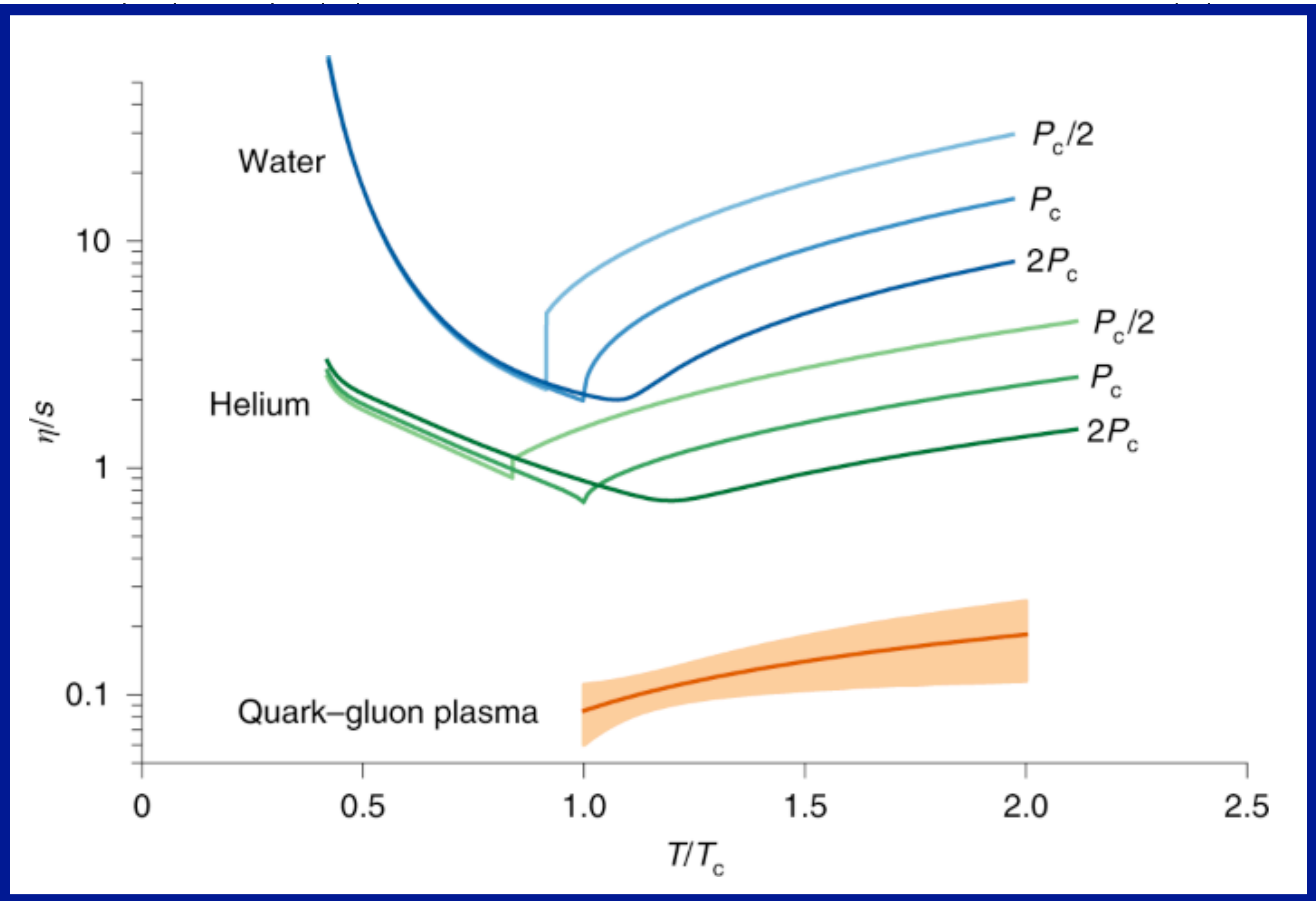
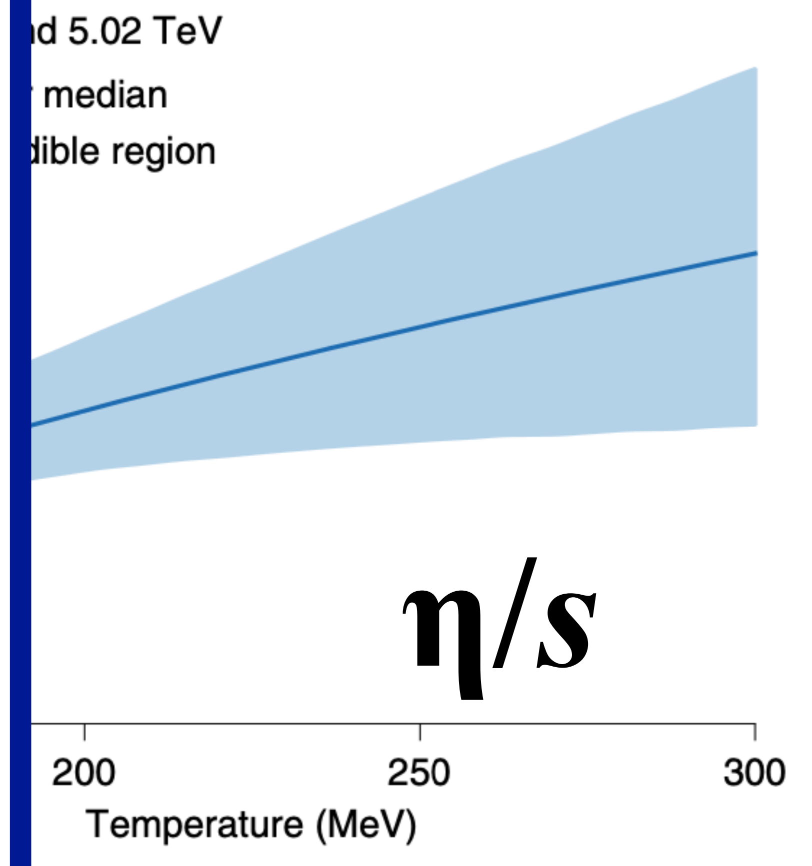


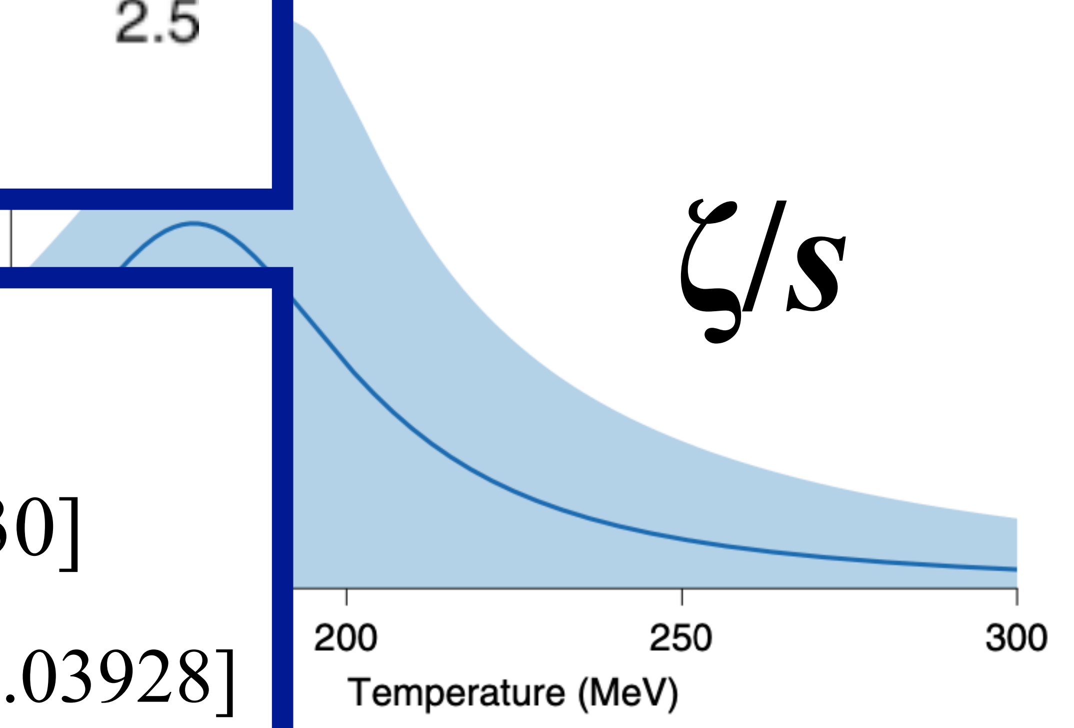
Extracting QGP properties with flow

- Bayesian analysis of ... ALICE ... viscosity η/s(T), ζ/s(T)









J. E. Bernhard, J. S. Moreland, S. A. Bas...
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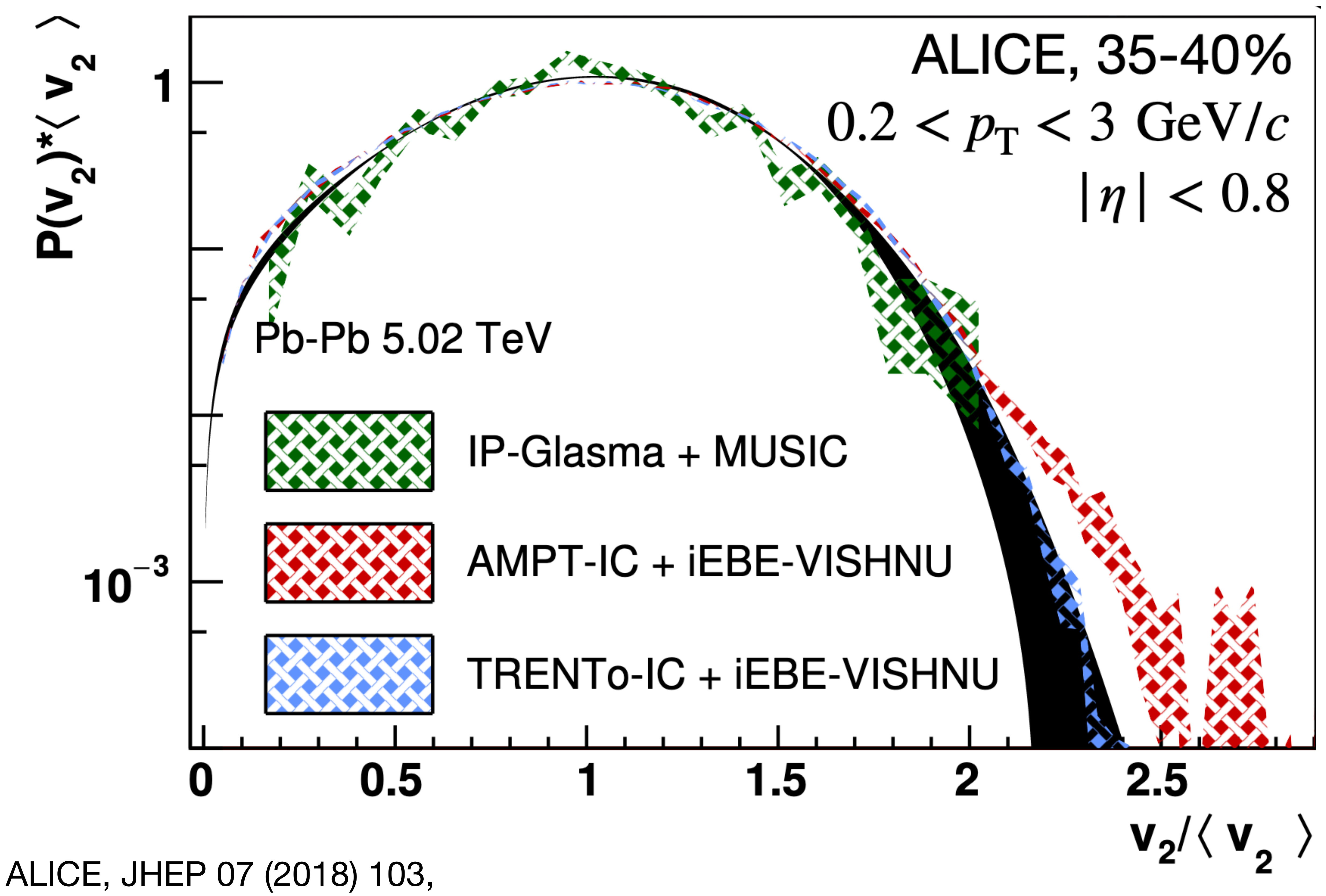
- Similar analyses performed using Trajectum [PRL 126 (2021) 202301, arXiv:2010.15130] and JETSCAPE [PRL 126 (2021) 242301, arXiv:2010.03928]

Higher-order flow observables and measurements

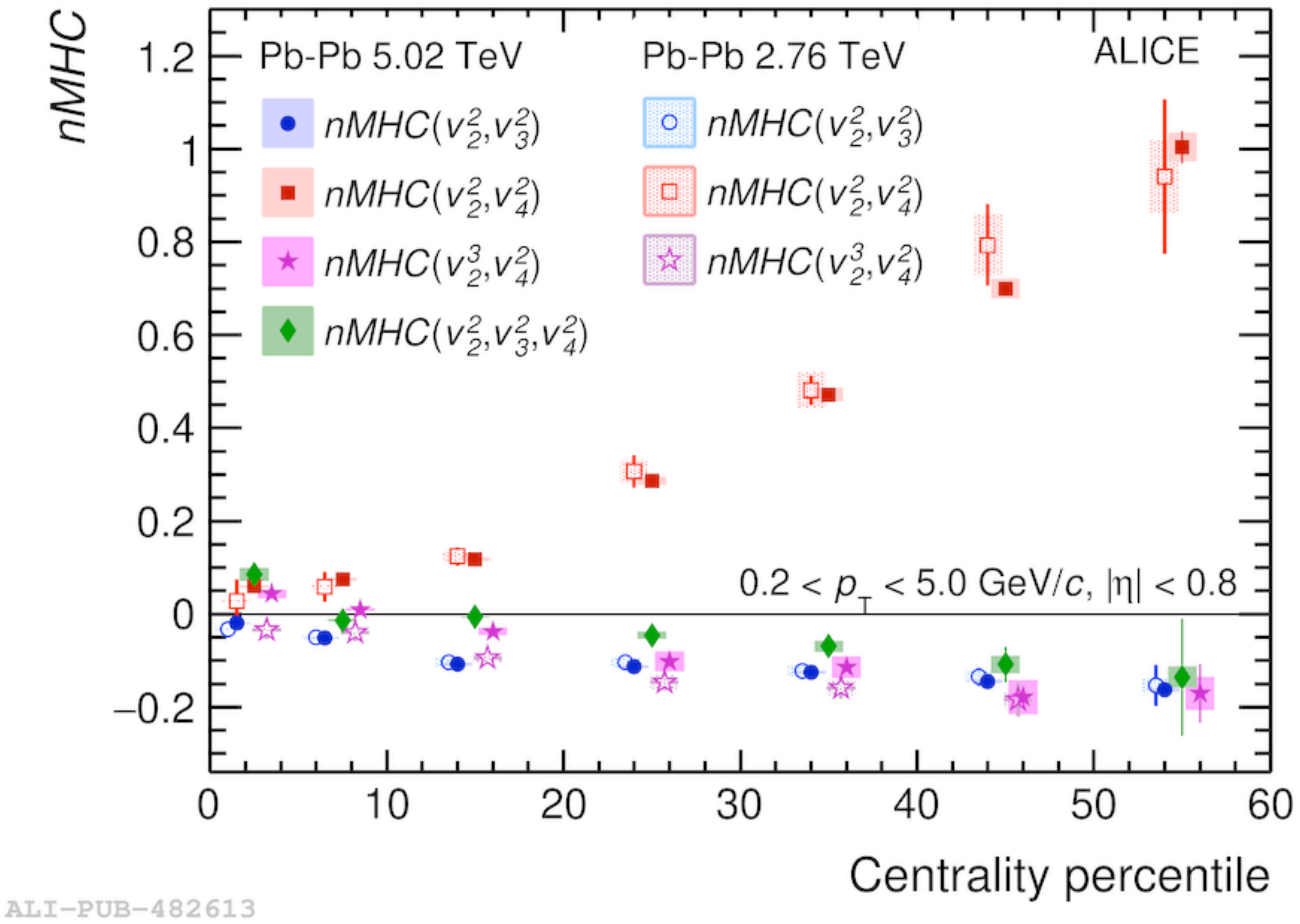
- Differential flow with respect to momentum, particle species, collision energy, pseudorapidity (decorrelation)
- Event-by-event fluctuations of flow



ALICE, JHEP 07 (2018) 103,
arXiv:1804.02944 [nucl-ex]

Higher-order flow observables and measurements

- Differential flow with respect to momentum, particle species, collision energy, pseudorapidity (decorrelation)
- Event-by-event fluctuations of flow
- Linear and non-linear flow components beyond $v_n \propto \varepsilon_n$
- Correlations between flow harmonics



ALICE, PLB 818 (2021) 136354, arXiv:2102.12180 [nucl-ex]

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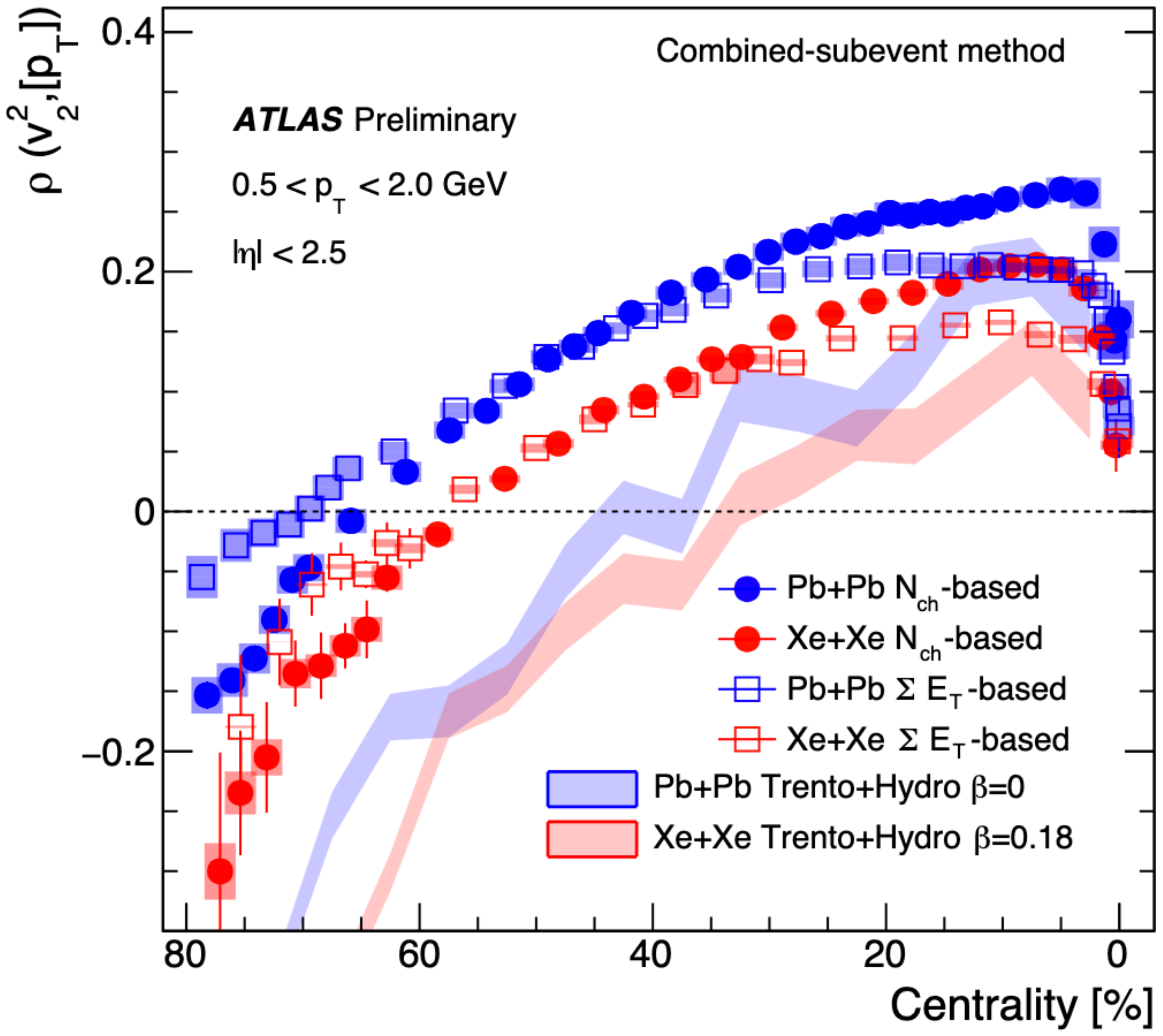
- Event-by-event fluctuations of flow

- Linear and non-linear flow components beyond $v_n \propto \varepsilon_n$

- Correlations between flow harmonics including radial flow

ATLAS-CONF-2021-001



$$\rho\left(v_n^2, \langle p_T \rangle\right) = \frac{cov\left(v_n^2, \langle p_T \rangle\right)}{\sqrt{var\left(v_n^2\right)}\sqrt{var\left(\langle p_T \rangle\right)}}$$

Higher-order flow observables and measurements

- Differential flow with respect to momentum, particle species, collision energy, pseudorapidity (decorrelation)
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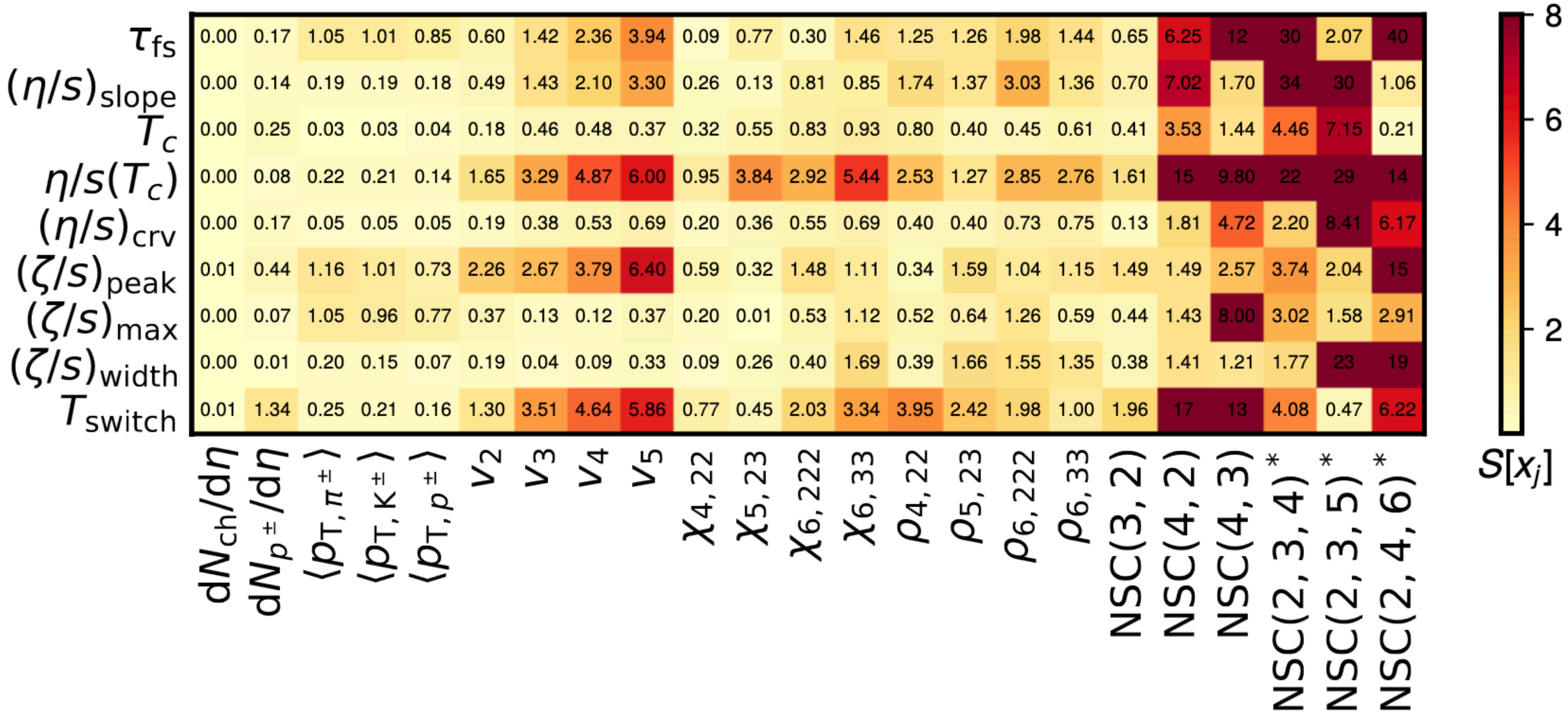


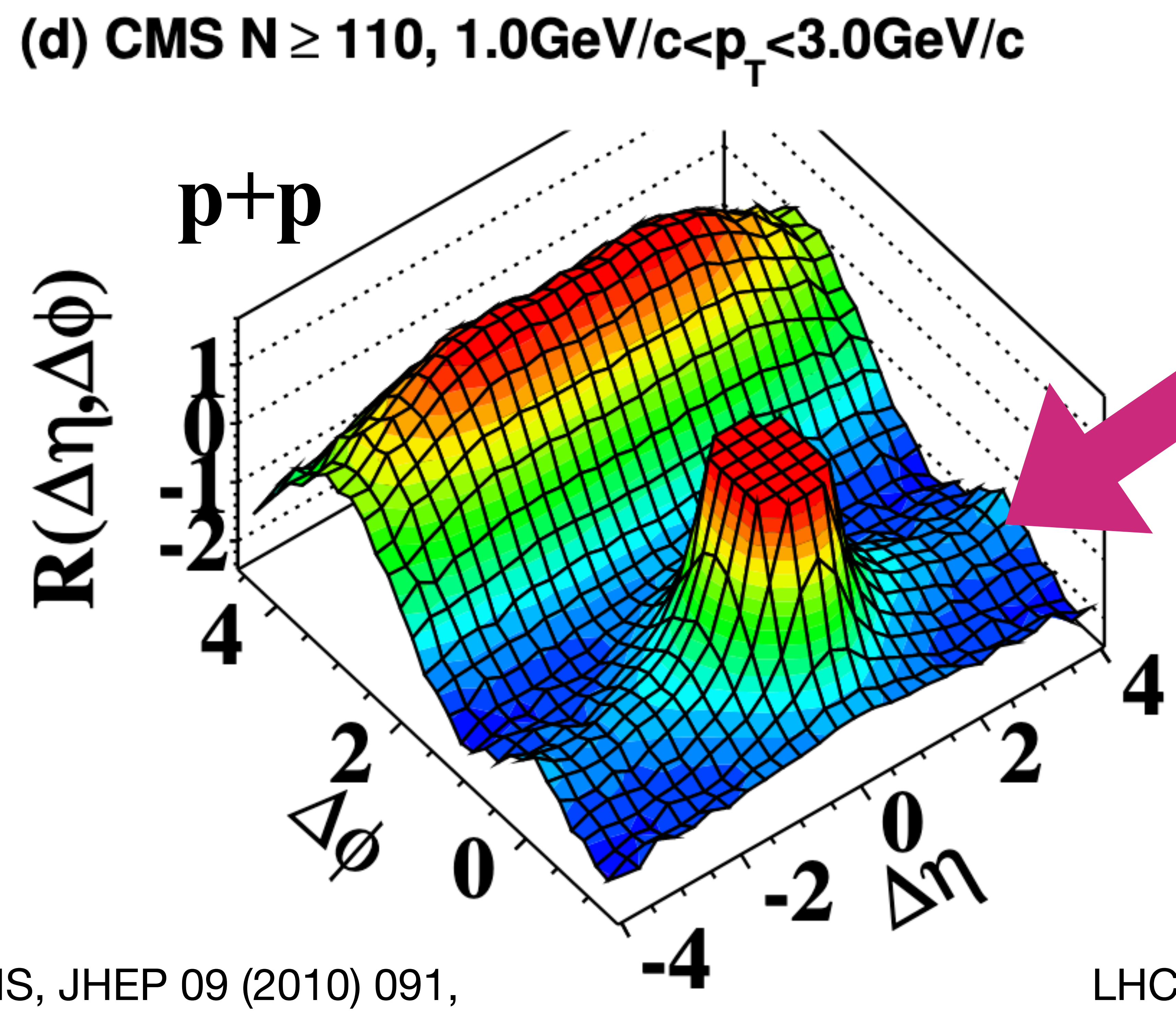
- These higher-order observables are very sensitive to properties of the QGP!

J.E. Parkkila, A. Onnerstad, S. F. Taghavi, C. Mordasini, A. Bilandzic, D.J. Kim, arXiv: 2111.08145 [hep-ph]

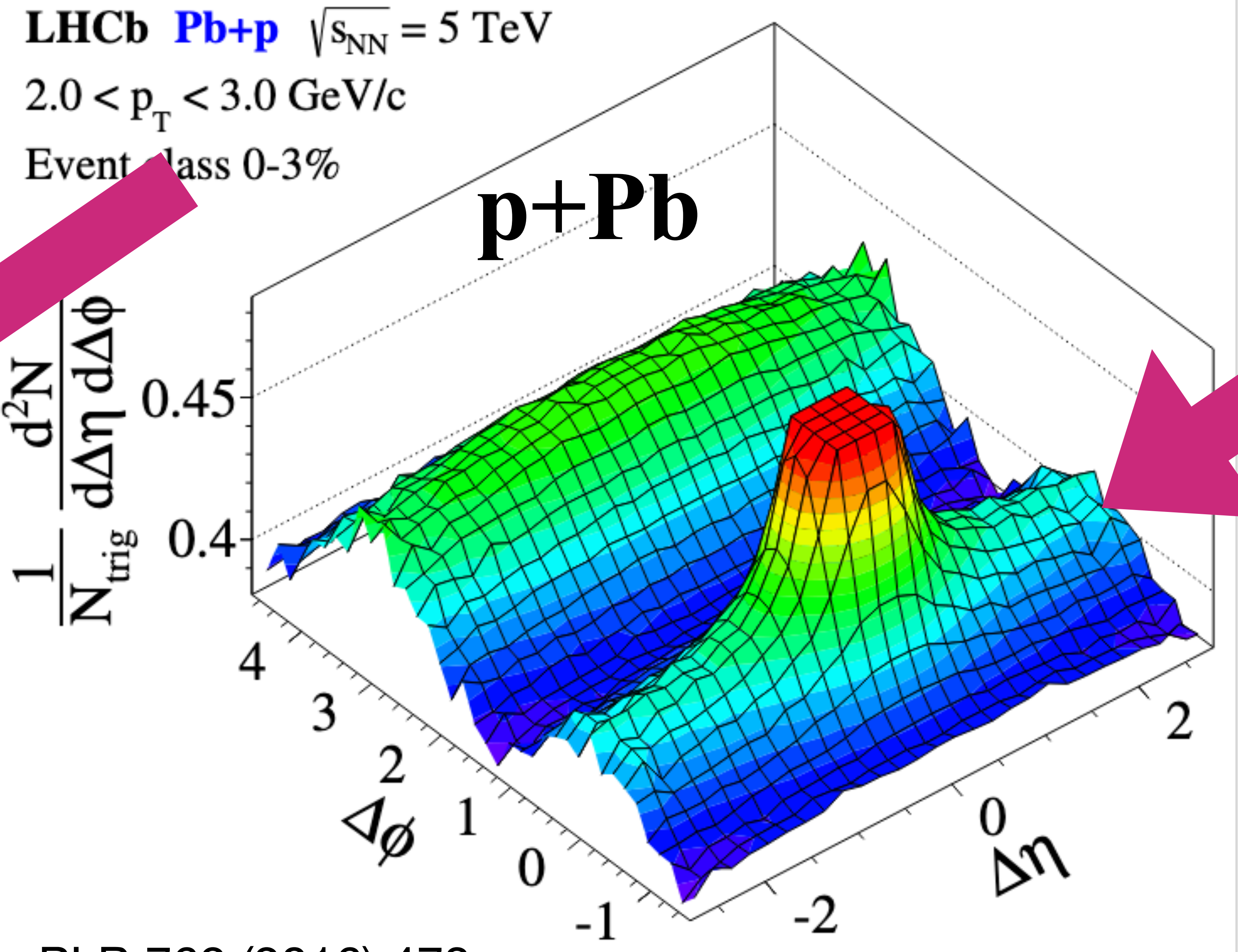

pp
13 TeV
p-Pb
5.02 TeV
Xe-Xe
5.44 TeV
Pb-Pb
5.02 TeV
p → ← p
p → ← Pb
Pb → ← Pb
dilute system, few interactions
dense system
many interactions
low multiplicity
high multiplicity

Collective behavior in small systems

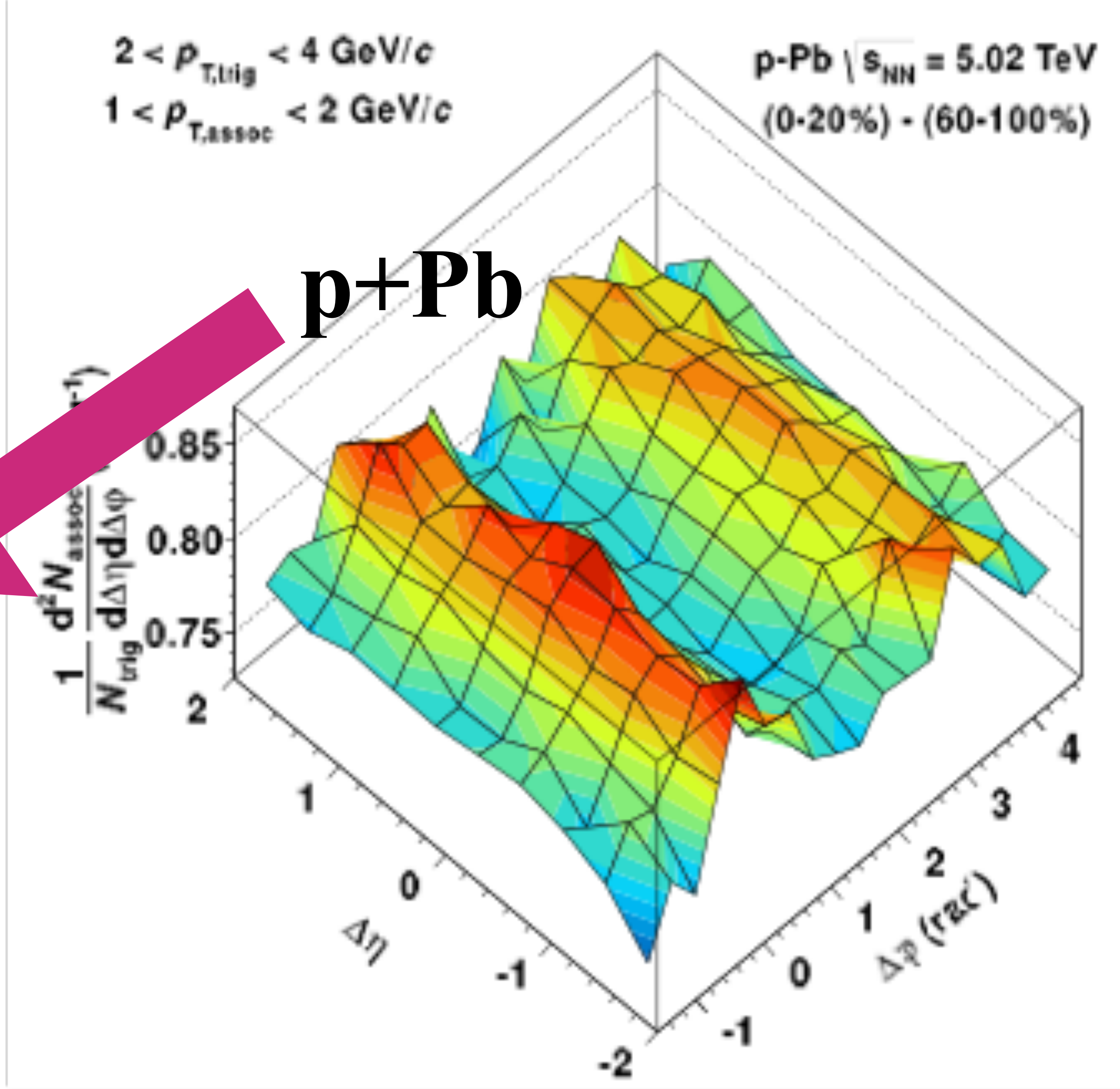
- Flow-like (v_n) signals observed in high-multiplicity p+p and p+Pb collisions as well!



CMS, JHEP 09 (2010) 091,
arXiv: 1009.4122 [hep-ex]



LHCb, PLB 762 (2016) 473,
arXiv:1512.00439 [nucl-ex]

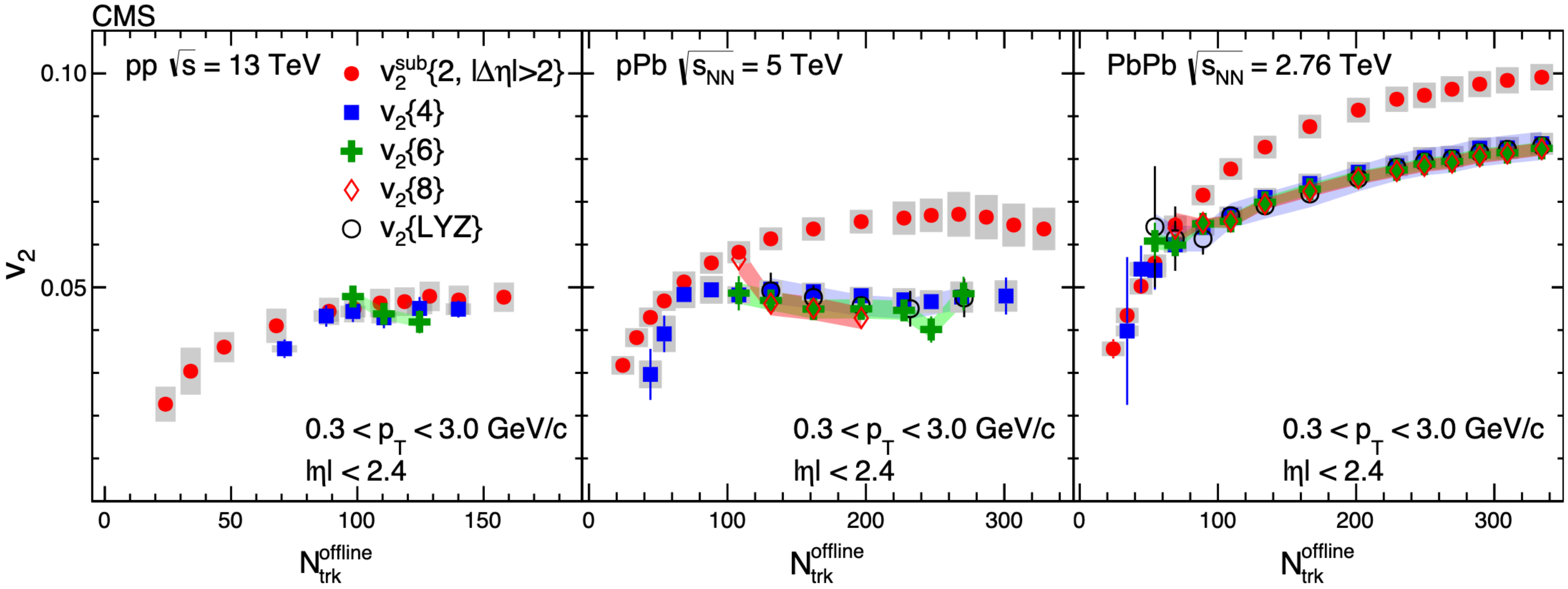


ALICE, PLB 719 (2013) 29,
arXiv: 1212.2001 [nucl-ex]

Surprise!

But is it collective…?

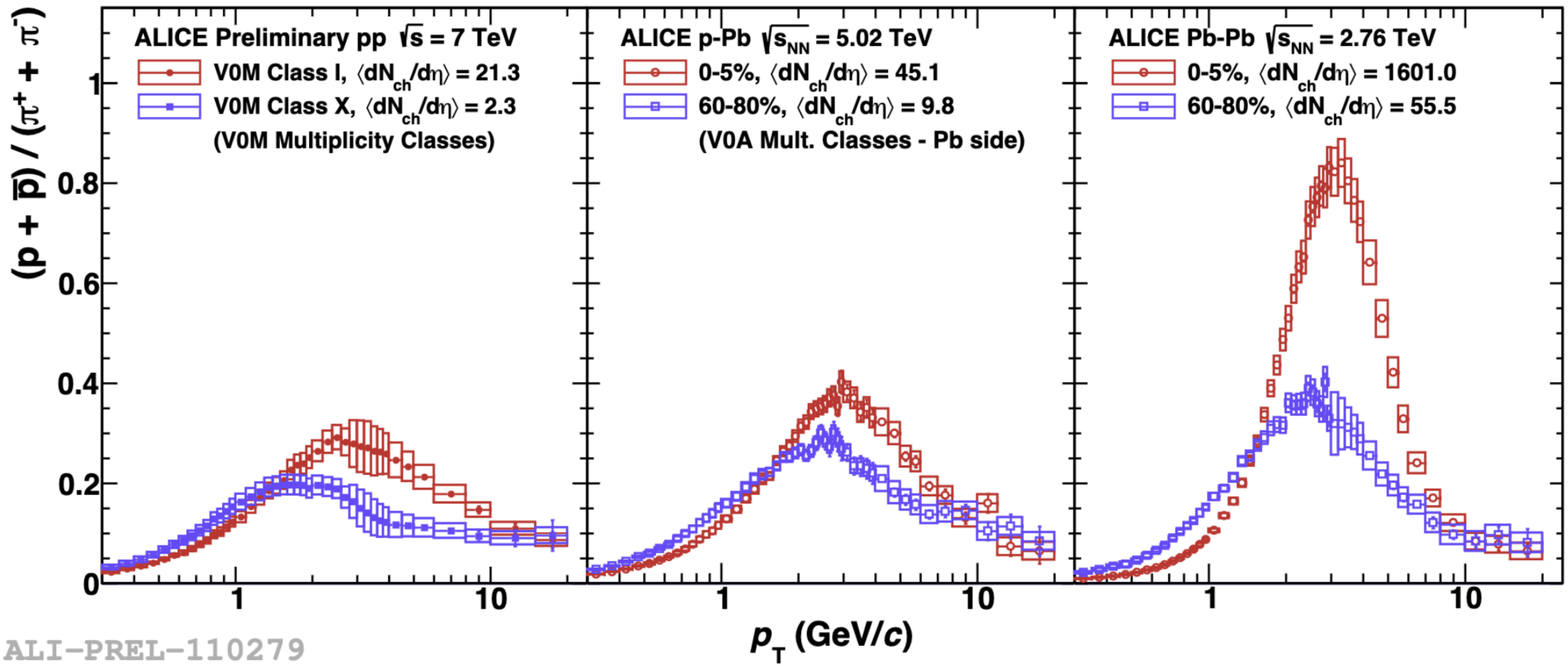
- Collectivity: momentum **correlations** among **many particles** which are **widely separated** (e.g. in pseudorapidity)
- Multi-particle cumulants used to measure non-zero v_2



CMS, PLB 765 (2017) 193, arXiv: 1606.06198 [nucl-ex]

- Remember! Collectivity (an observation) does not imply hydrodynamics (an interpretation)

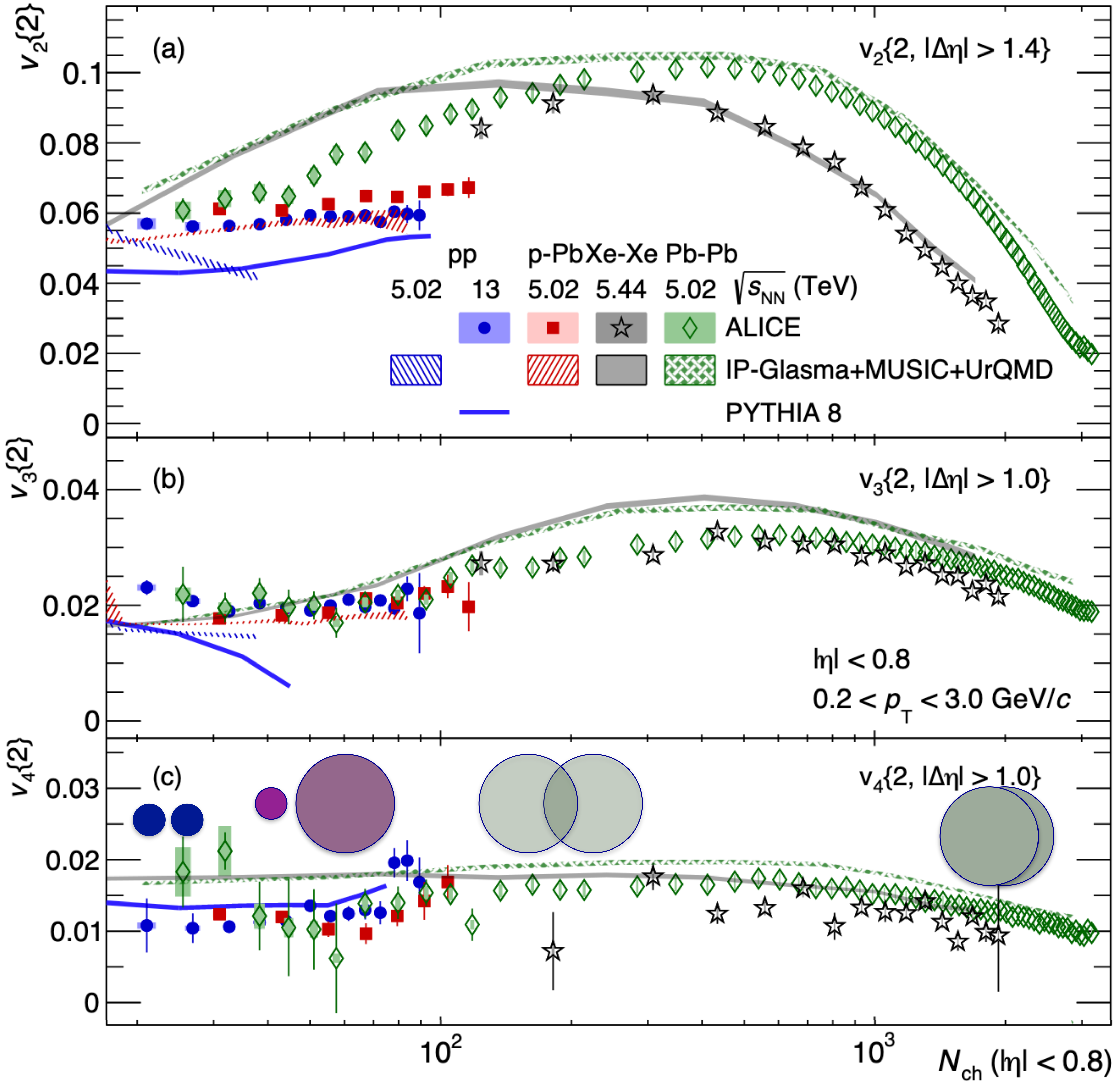
Isotropic flow



- Increase in baryon-to-meson ratio indicates presence of radial boost in p+p, p+Pb, Pb+Pb

Anisotropic flow v_n

- Non-zero v_n coefficients measured across all multiplicities in p+p, p+Pb, Xe+Xe, and Pb+Pb systems
- No clear “turn-off” or “turn-on” of collectivity
- Is this hydrodynamic flow?
  Is there a geometry in small systems? Or is it just fluctuations?
  Are there enough parton-parton interactions to produce this collective effect (e.g. translate the initial anisotropy to the final state)?



ALICE, PRL 123 (2019) 142301, arXiv: 1903.01790 [nucl-ex]

The role of initial geometry

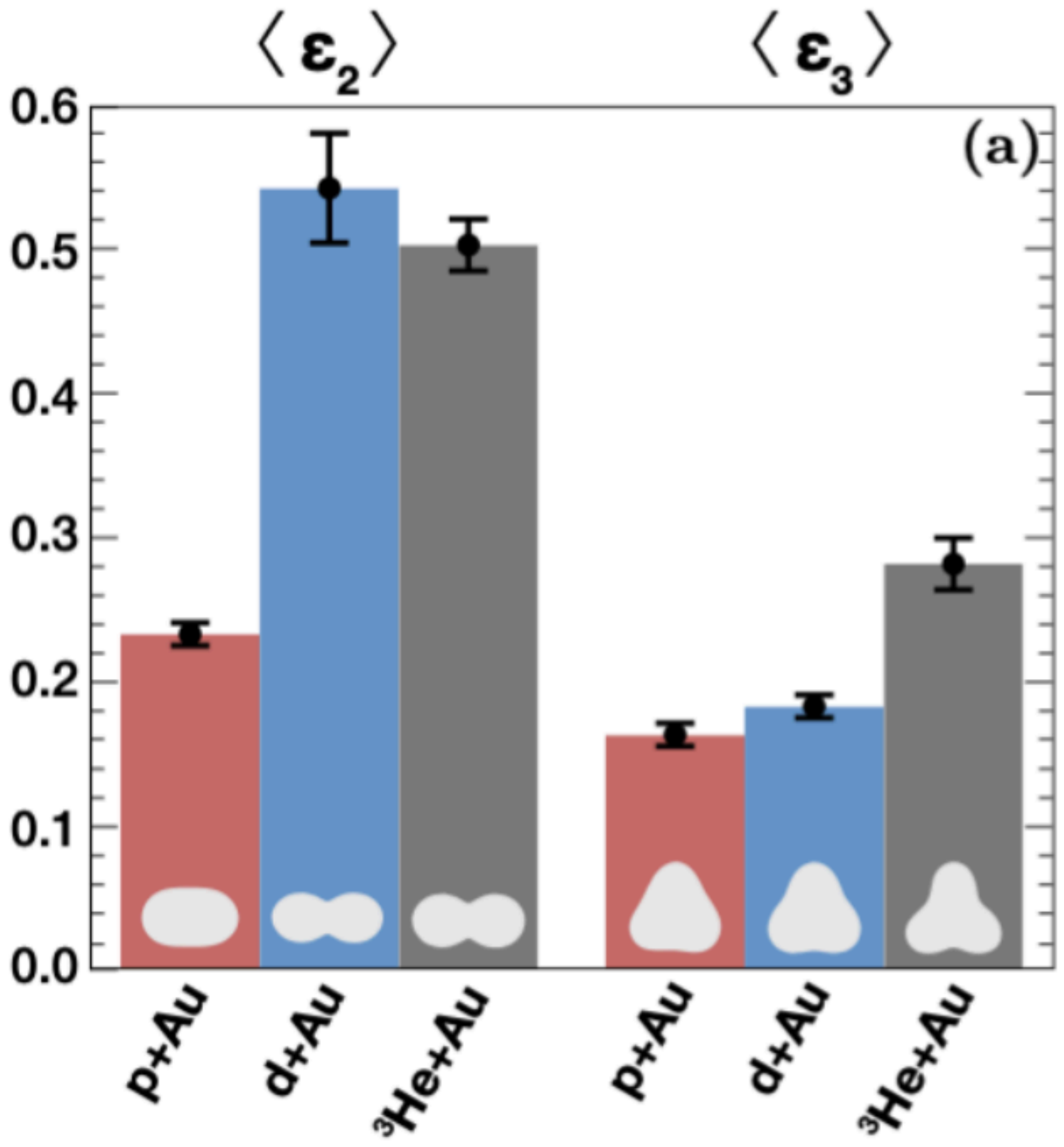
- v_2 measured in spherical (p+Au), ellipsoidal (d+Au), and triangular (^{3}He+Au) systems

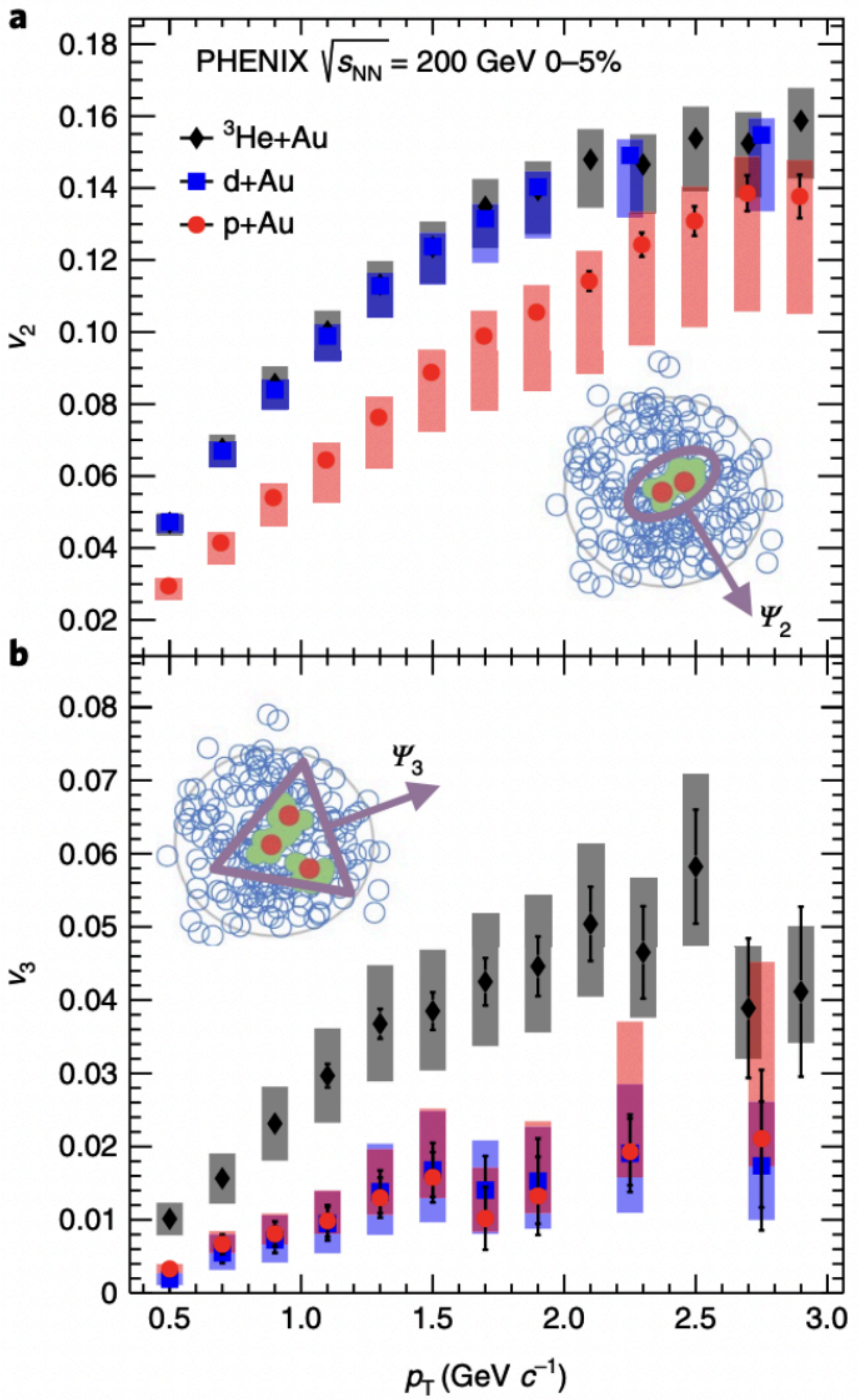
- Hydrodynamics predicts translation from initial state eccentricity to final state anisotropy $v_n \propto \varepsilon_n$

- Measurements consistent with hydro expectation

$$v_2^{\text{p+Au}} < v_2^{\text{d+Au}} \approx v_2^{^3He+Au}$$

$$v_3^{\text{p+Au}} \approx v_3^{\text{d+Au}} < v_3^{^3He+Au}$$





PHENIX, Nature Physics 15 (2019) 214

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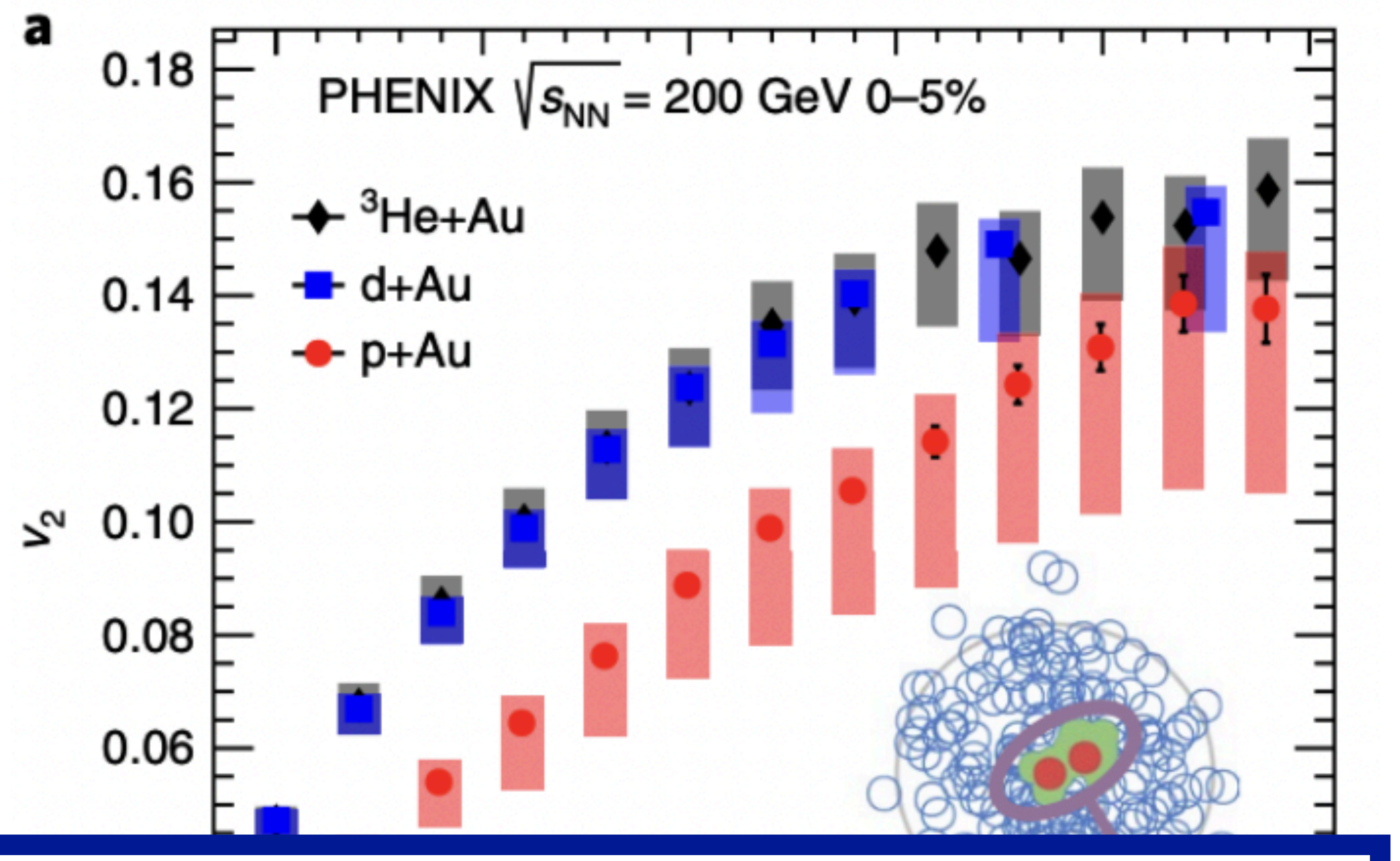
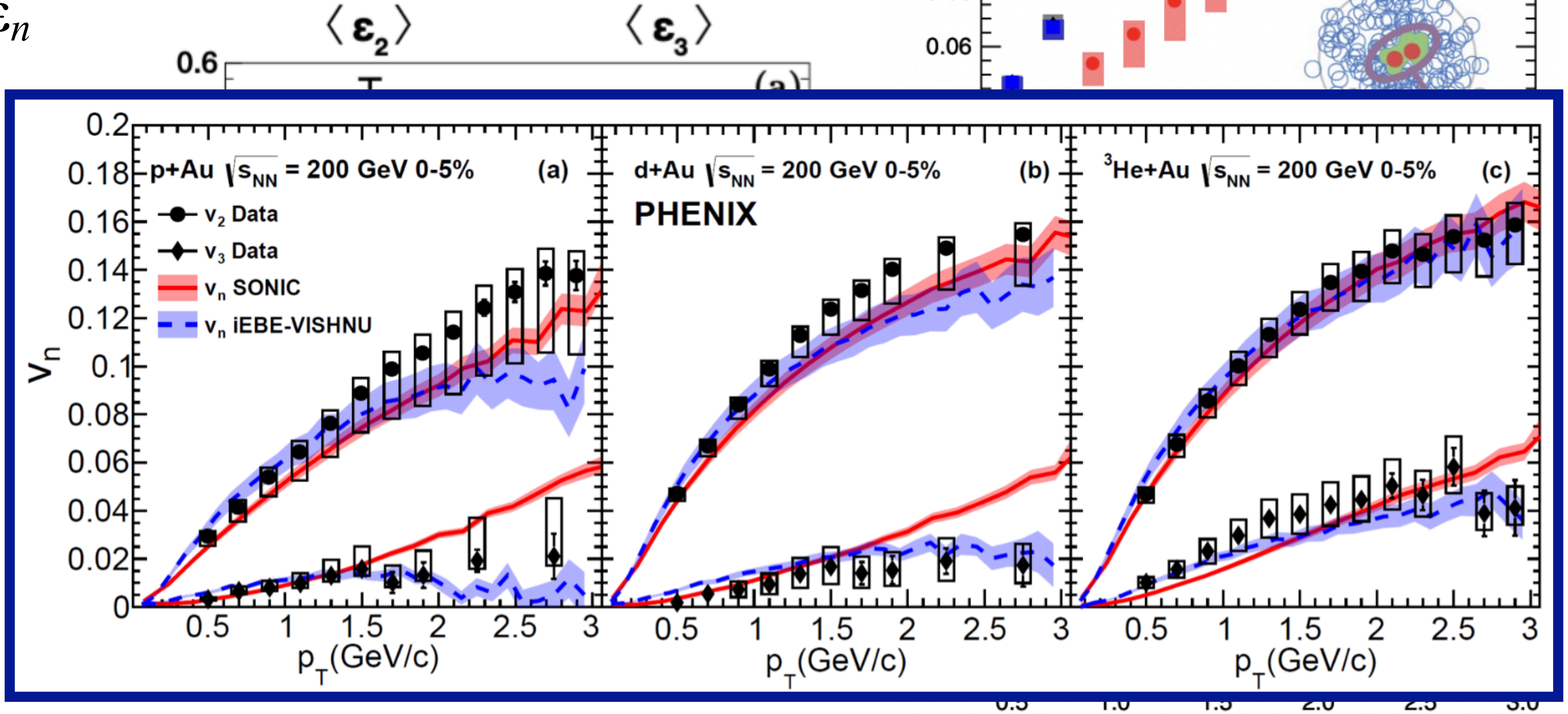
$$v_3^{p+Au} \approx v_3^{d+Au} < v_3^{^3He+Au}$$

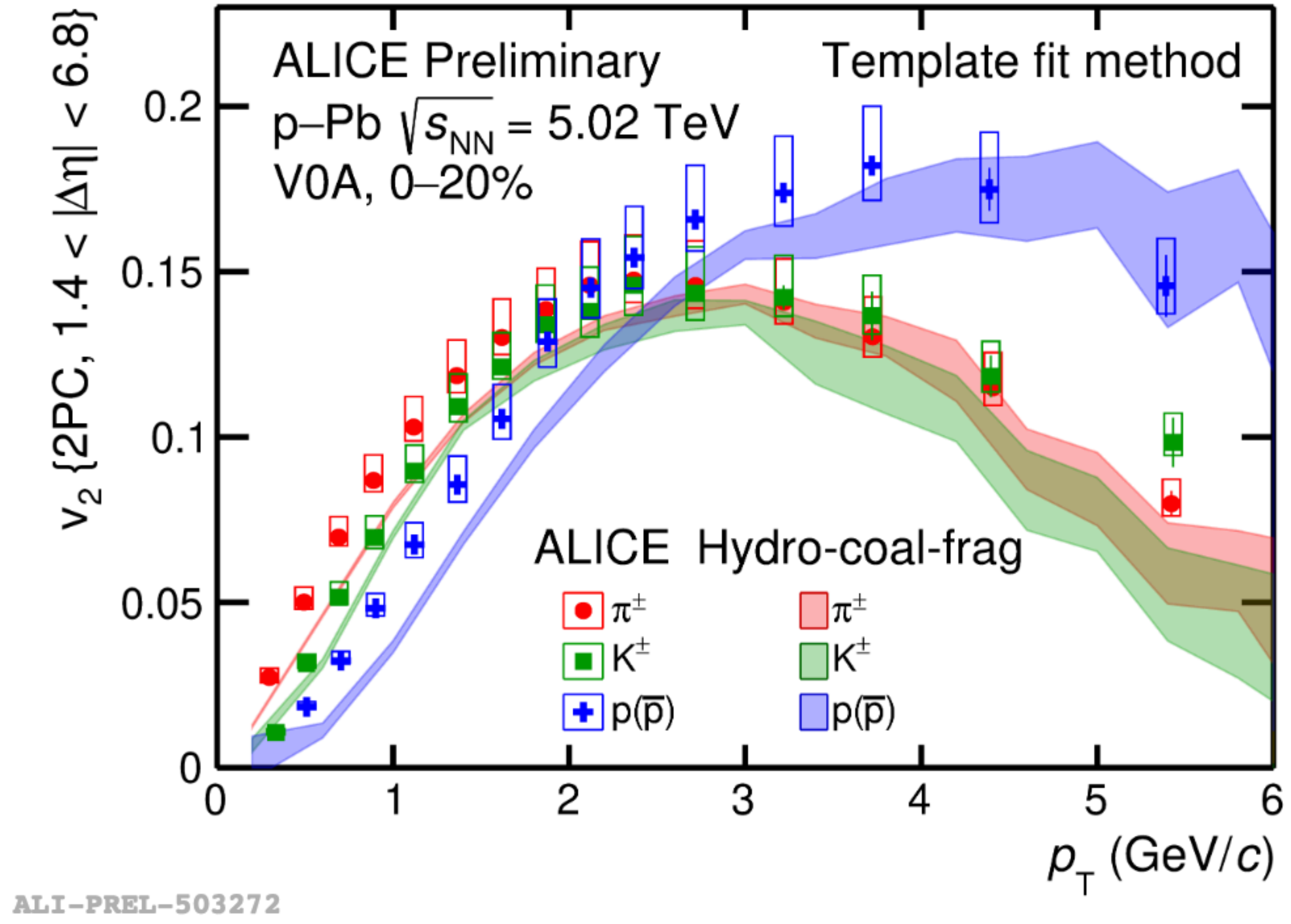




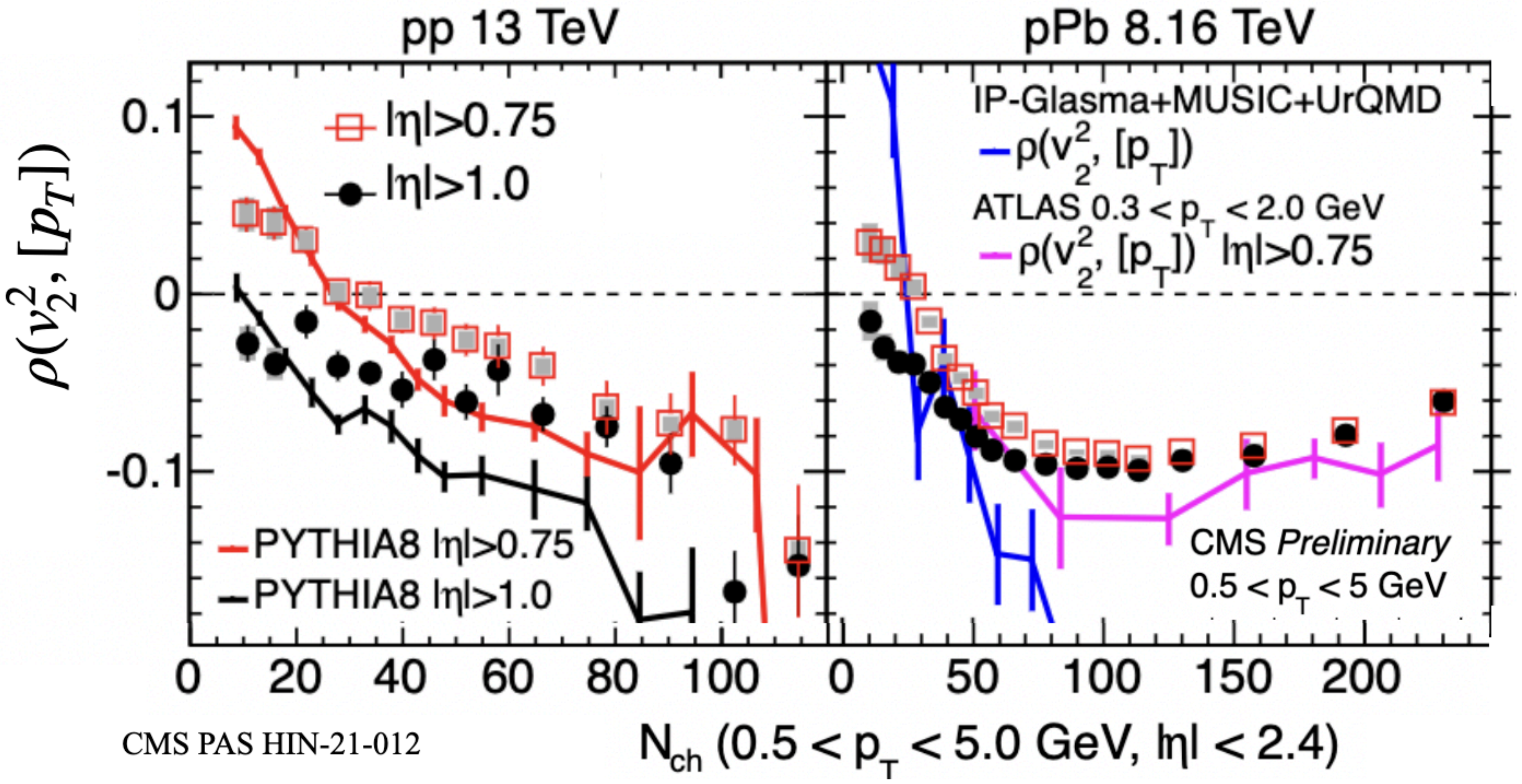
PHENIX, Nature Physics 15 (2019) 214

Digging deeper into small-system v_n

- Identified-particle v_2 shows similar mass ordering and baryon-meson splitting in p+Pb as in Pb+Pb



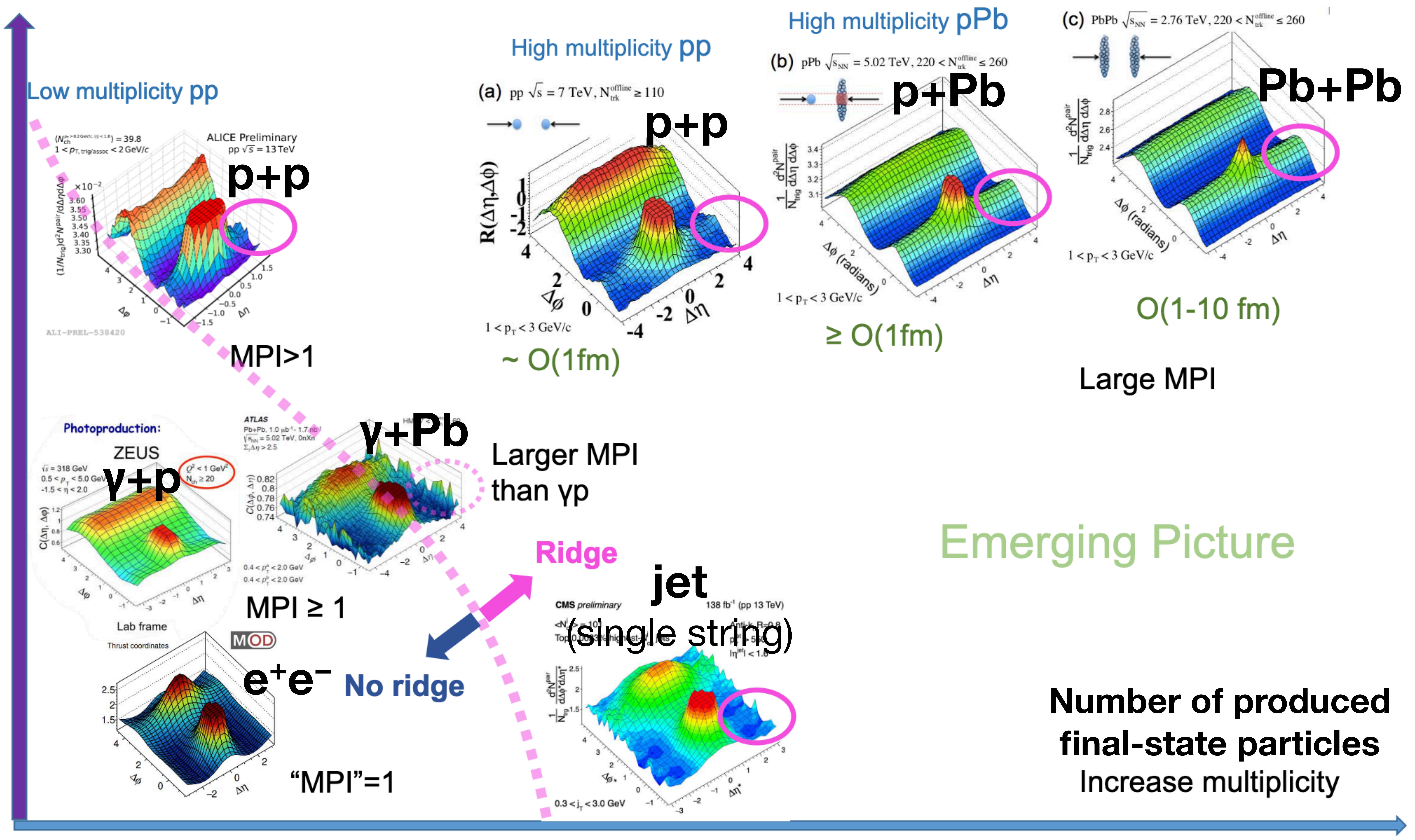
- Measurements of higher-order correlations and fluctuations are ongoing
- Can be extremely sensitive to kinematic selections and non-flow removal!



πάντα ῥεῖ: Everything flows, or does it?

Increase the MPI

Number of parton-parton interactions



Number of produced final-state particles

Increase multiplicity

Image from Yen-Jie Lee's talk at Initial Stages 2023

Open questions

- How does initial state energy deposition (geometry) transfer into final-state anisotropic particle distribution? Is hydrodynamics the explanation in large systems? Can we develop a microscopic description?

- What is the origin of anisotropic flow in small systems? Is hydrodynamics the answer?

- How many scatterings or interactions does it take to generate flow, equilibrate, thermalize?

- Is there a medium produced in small systems? What are its properties?

- What is the interplay between momentum scales (hard and soft probes)? Is there jet quenching in small systems?

Transverse size vs multiplicity

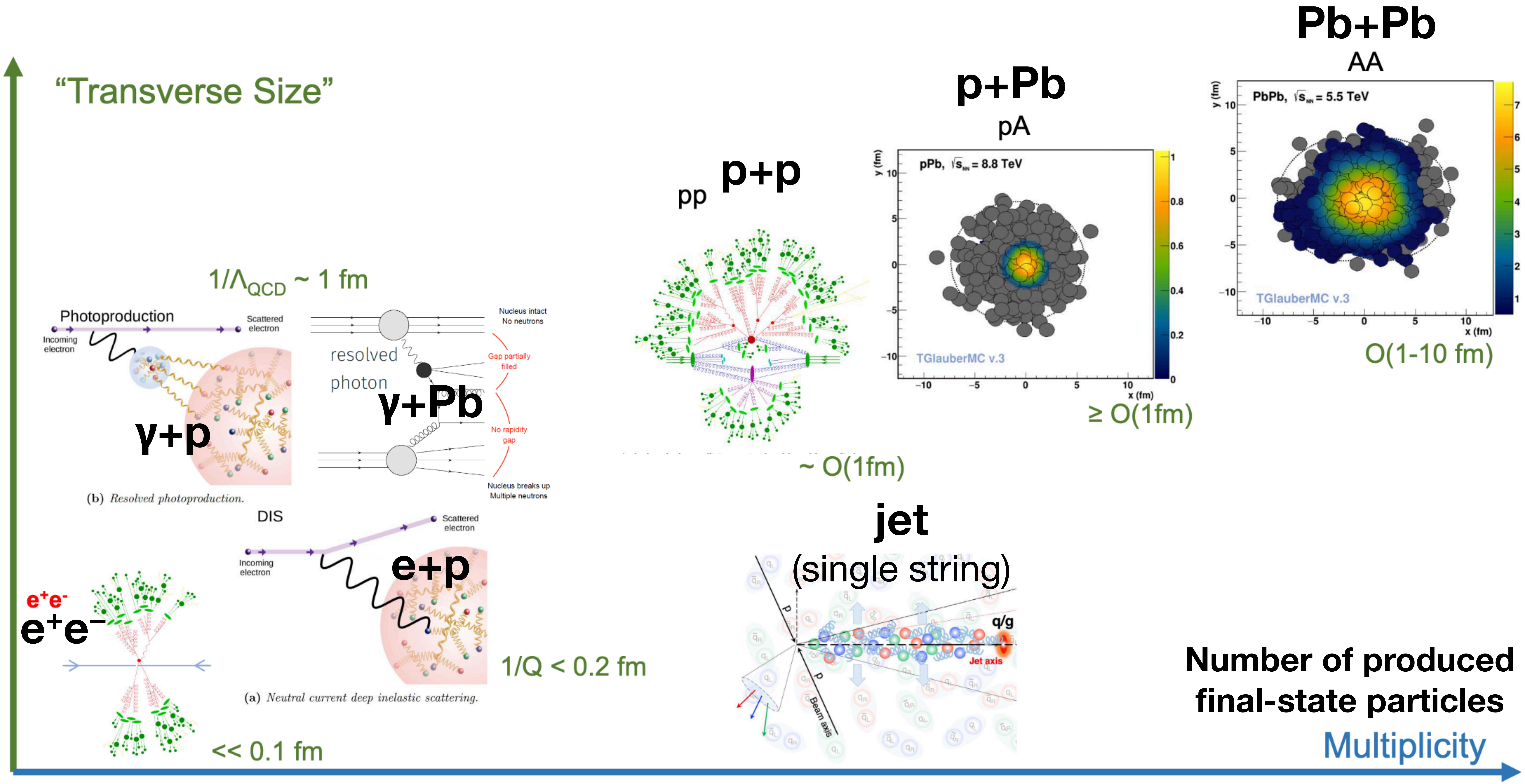


Image from Yen-Jie Lee's talk at Initial Stages 2023

Multi-particle correlations in small systems

- Are these correlations a true "collective" (many-particle) effect, or just between few (~2) particles?

- Measure multi-particle cumulants
  Example: four-particle cumulants

$$c_2\{4\} = \langle\langle \cos 2(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)\rangle\rangle$$ ← four-particle correlation

$$- \langle\langle \cos 2(\varphi_1 - \varphi_3)\rangle\rangle \langle\langle \cos 2(\varphi_2 - \varphi_4)\rangle\rangle$$

$$- \langle\langle \cos 2(\varphi_1 - \varphi_4)\rangle\rangle \langle\langle \cos 2(\varphi_2 - \varphi_3)\rangle\rangle$$

← subtract two-particle correlations

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

- Similarly for six-particle, eight-particle cumulants