Characterizing the initial conditions of heavy-ion collisions with correlation of mean transverse momentum and anisotropic flow

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November 15th -16th

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THE VELUX FOUNDATIONS

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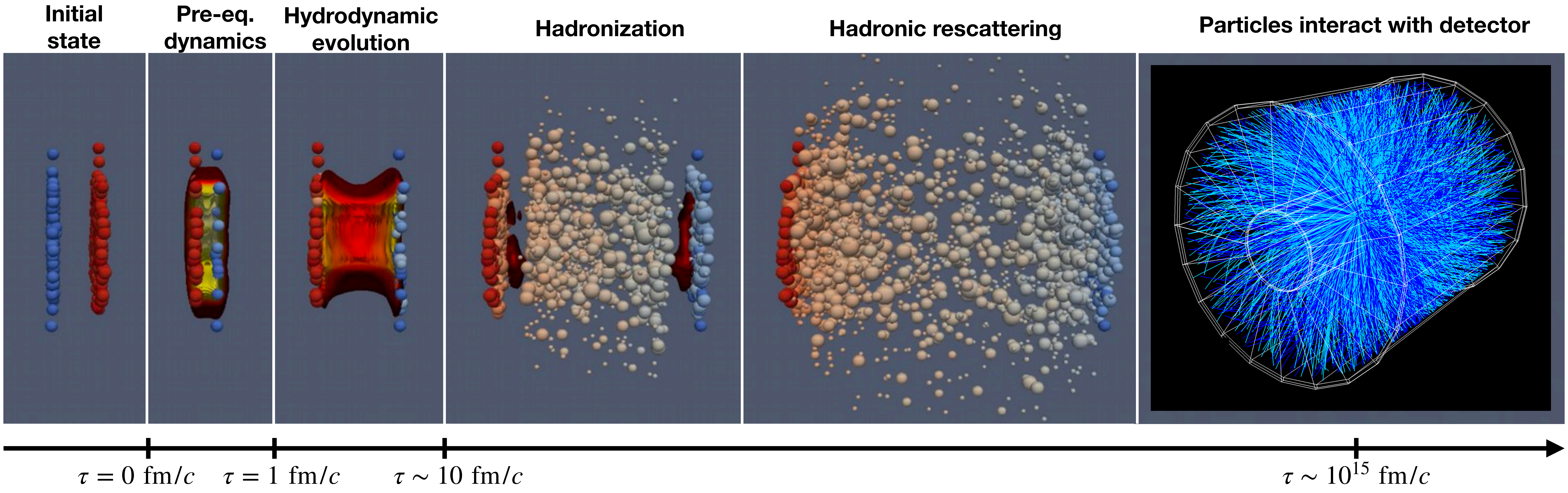
Heavy-ion collisions

The main goal of heavy-ion collisions is to extract information about the quark-gluon plasma (QGP)



MADAI collaboration, Hannah Petersen and Jonah Bernhard

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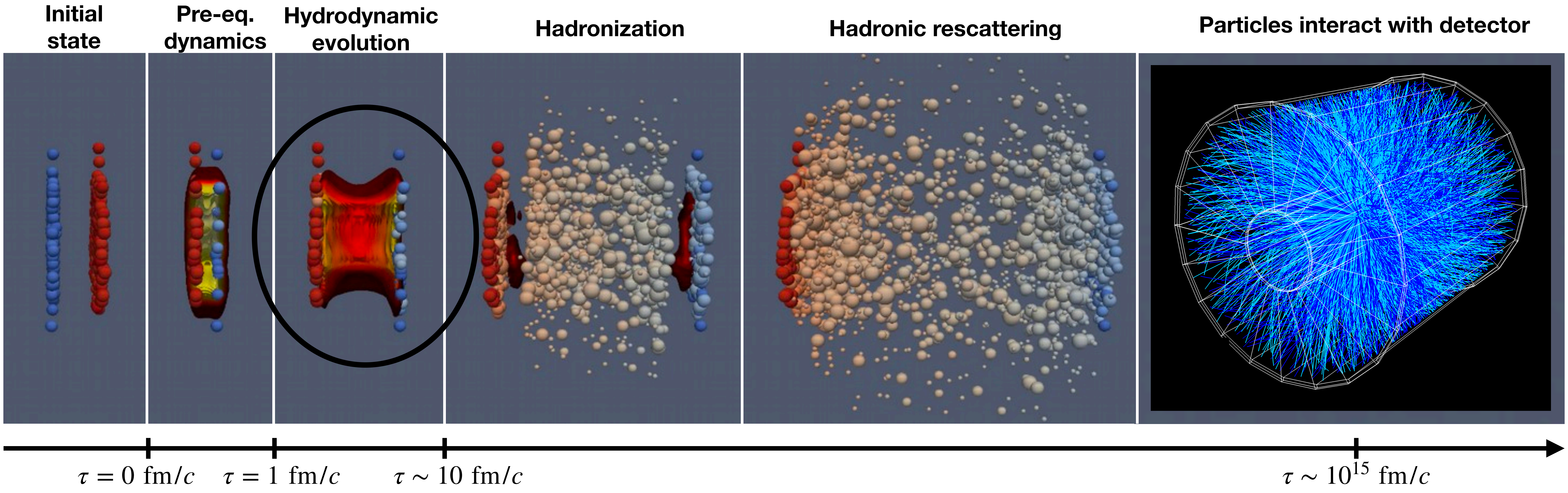


How do we probe the system with information from the final state?

Anisotropic flow: v_n

Mean transverse momentum: $[p_{\mathrm{T}}]$

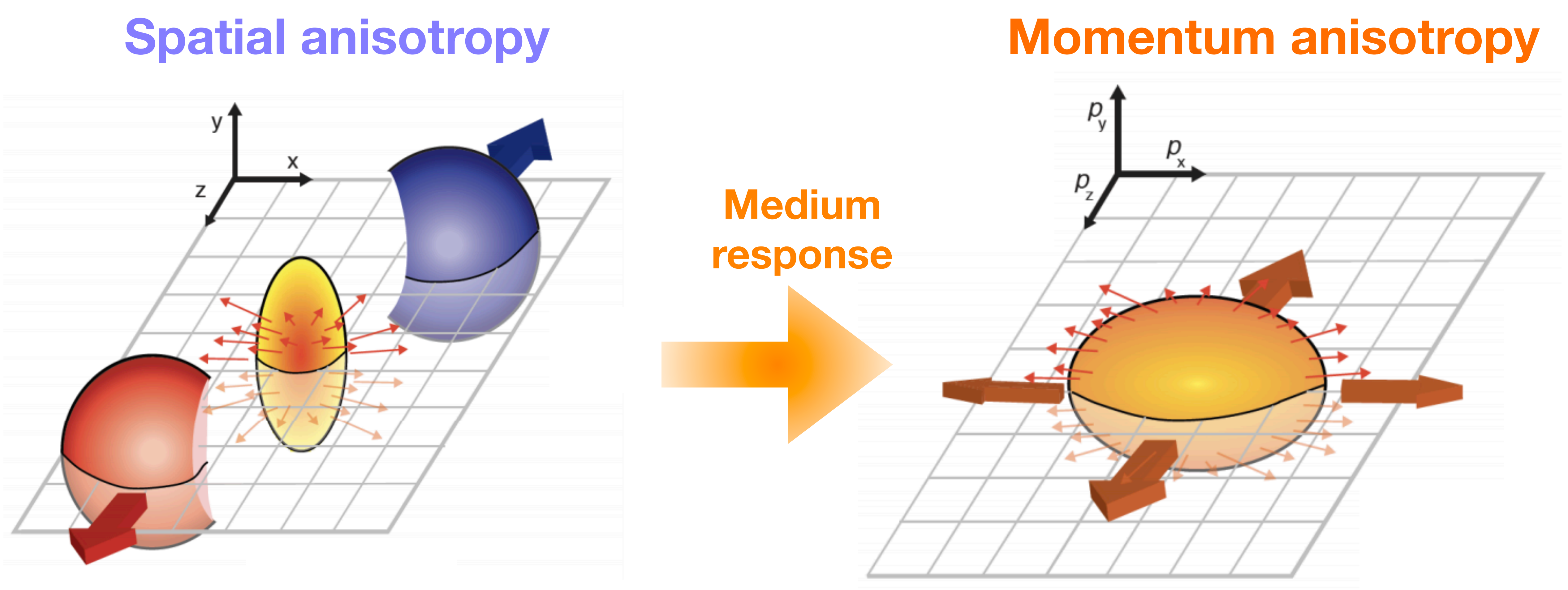
MADAI collaboration, Hannah Petersen and Jonah Bernhard

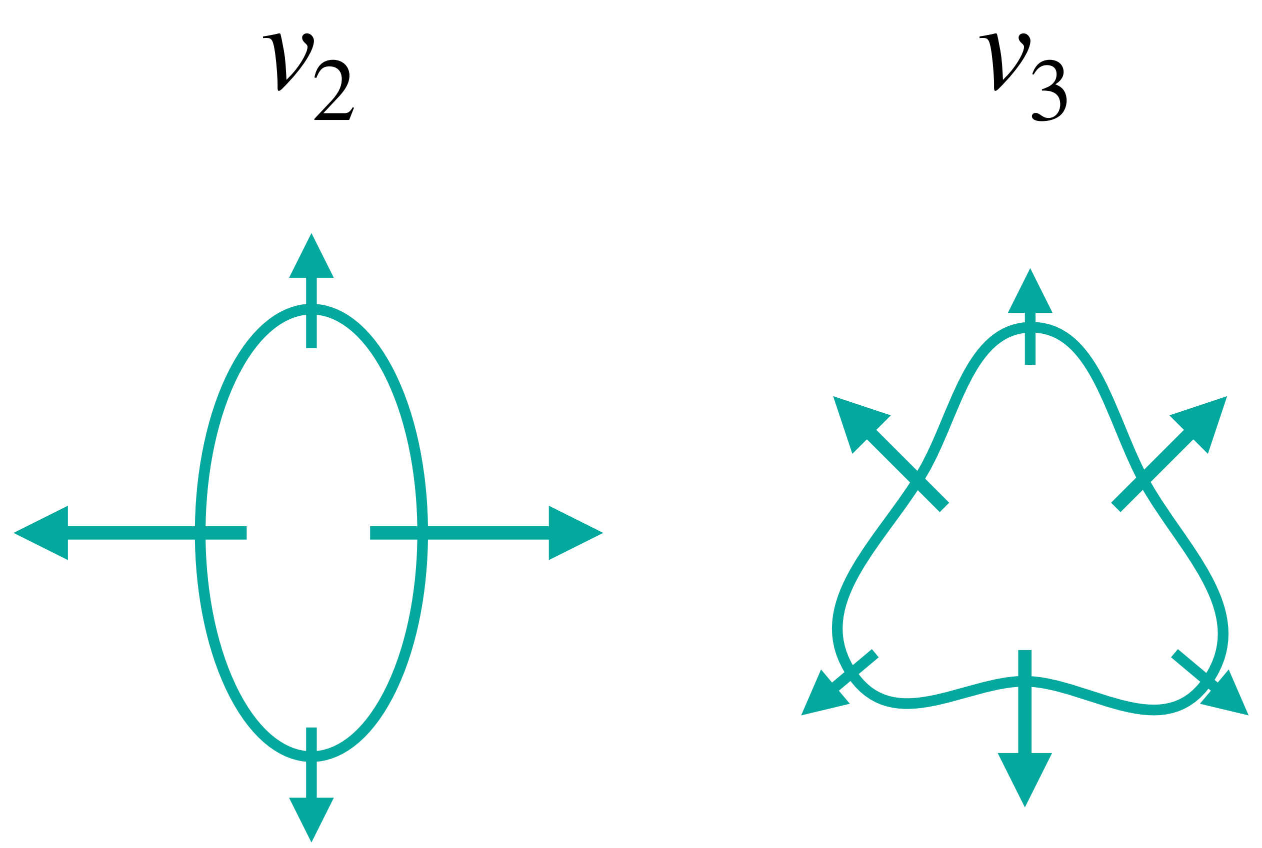
Key observables in heavy-ion collisions

Anisotropic flow, v_n, reflect the **initial shape**

$$P(\varphi) = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi_n)\right]$$

Flow coefficients **Symmetry plane angle**





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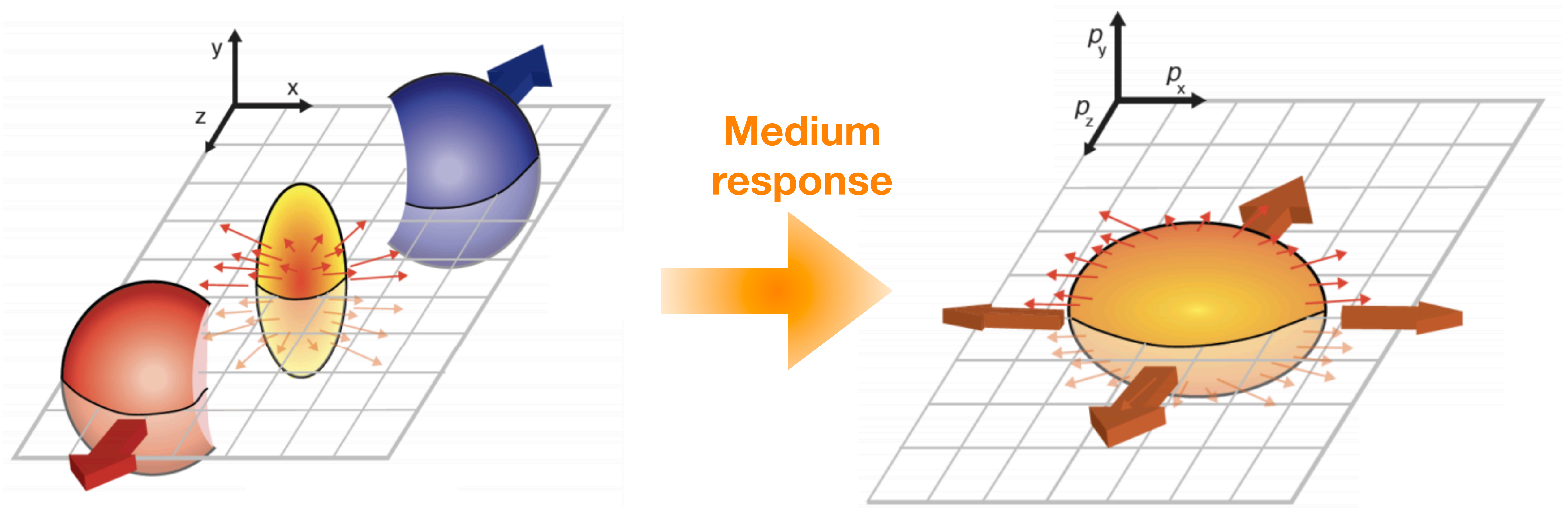
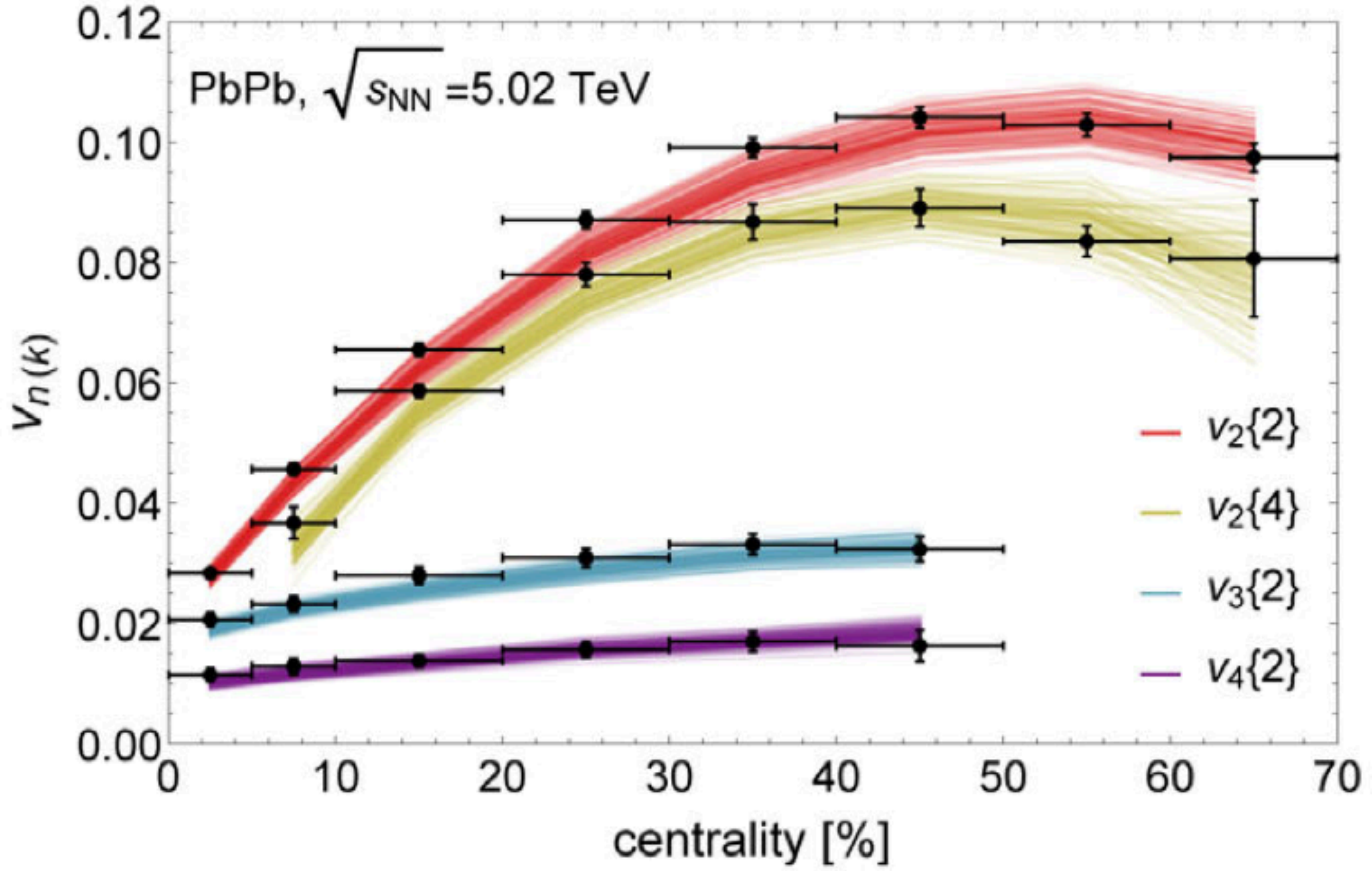
Spatial anisotropy

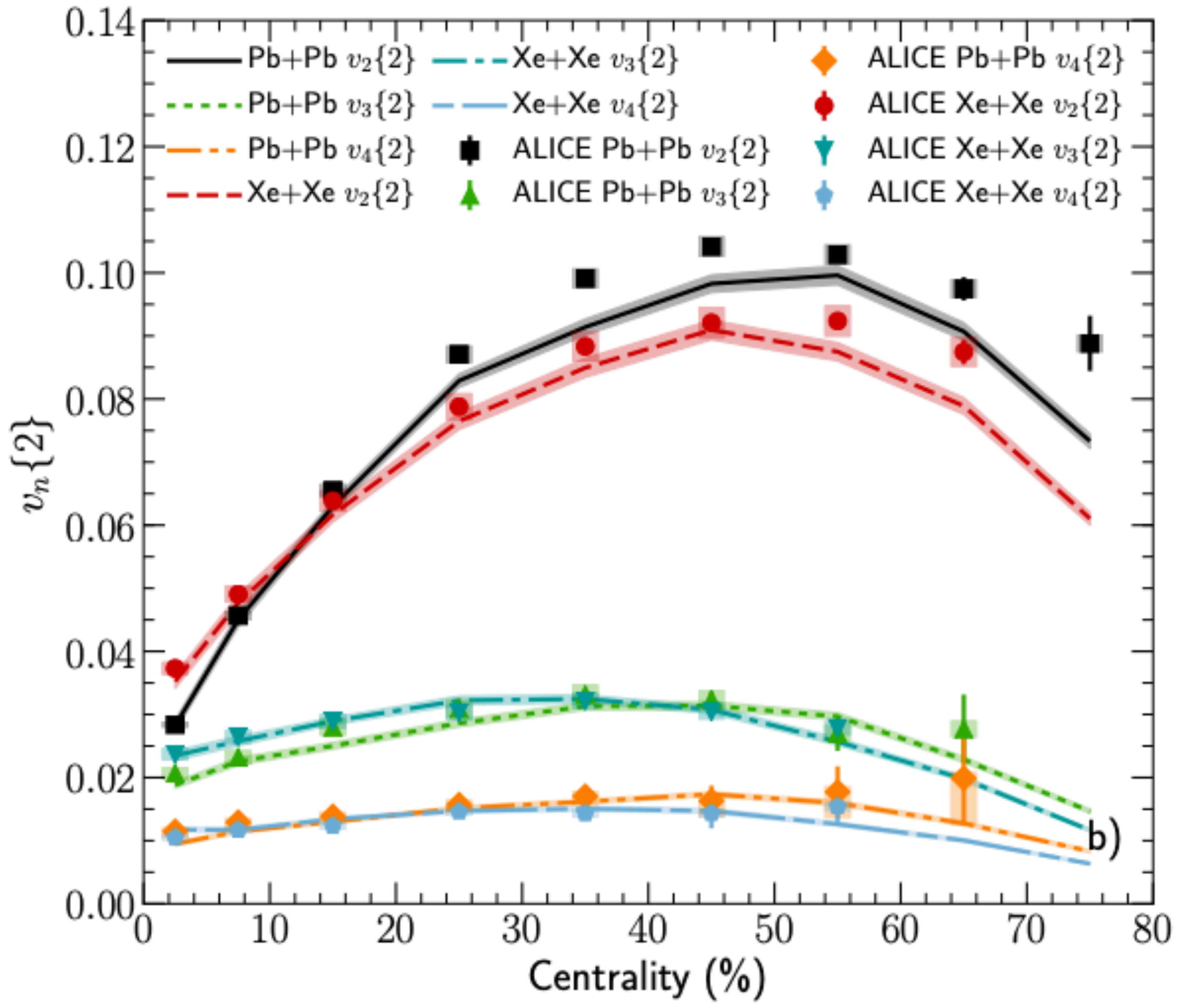
Momentum anisotropy



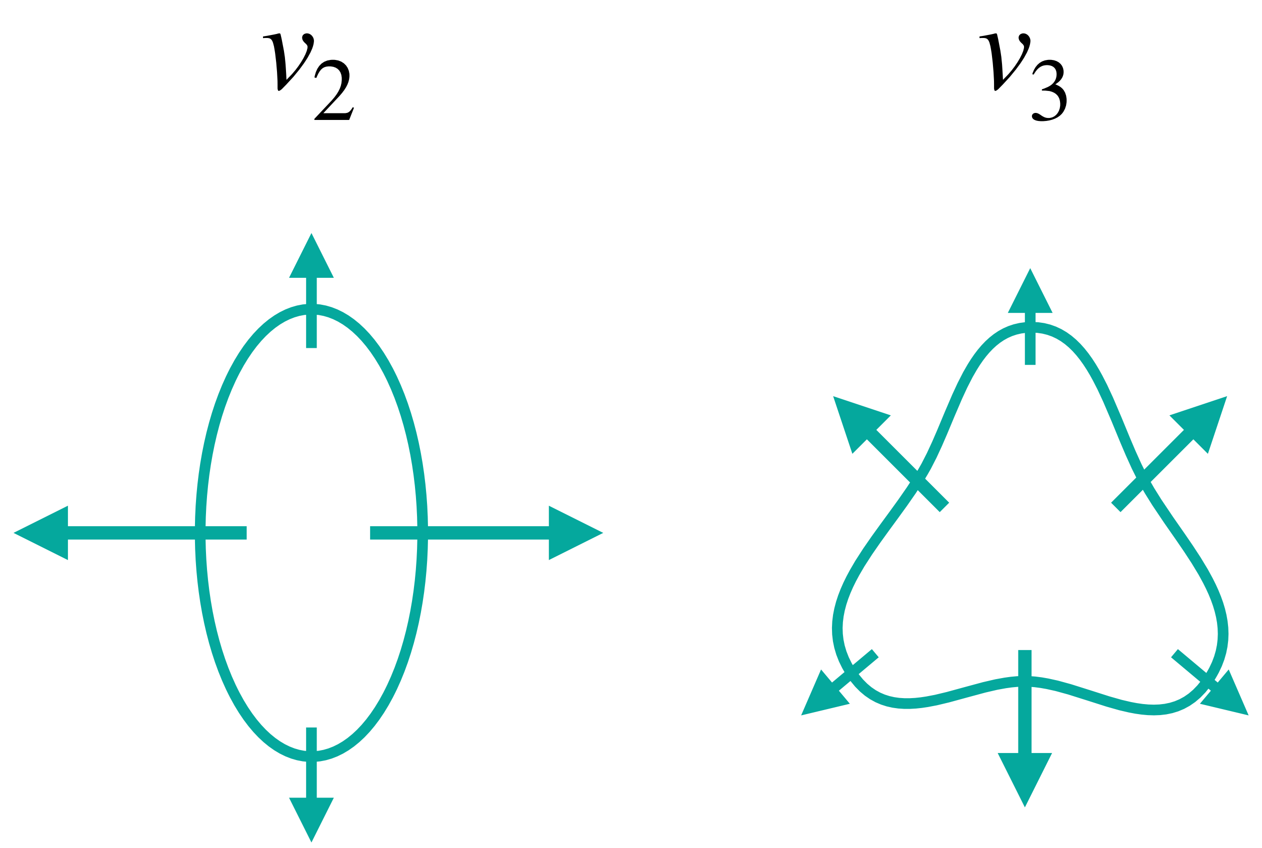
State-of-the art understanding of QGP



Trajectum



IP-Glasma



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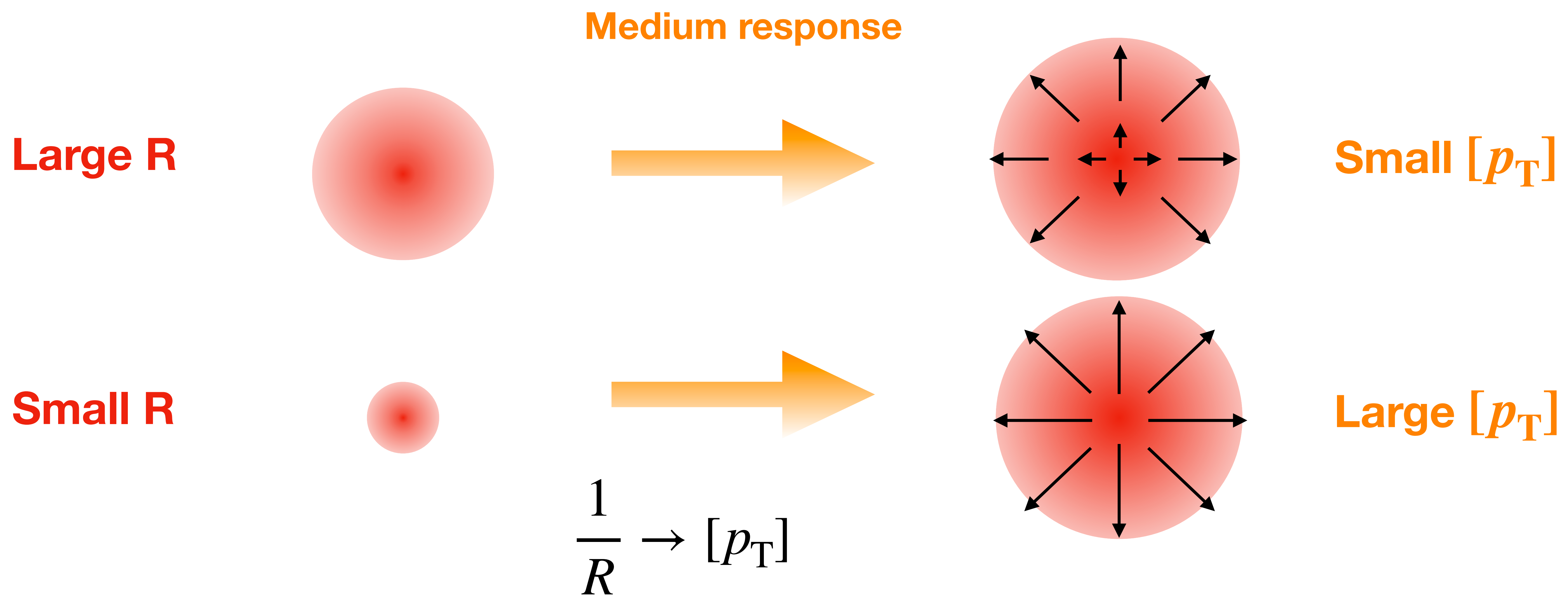

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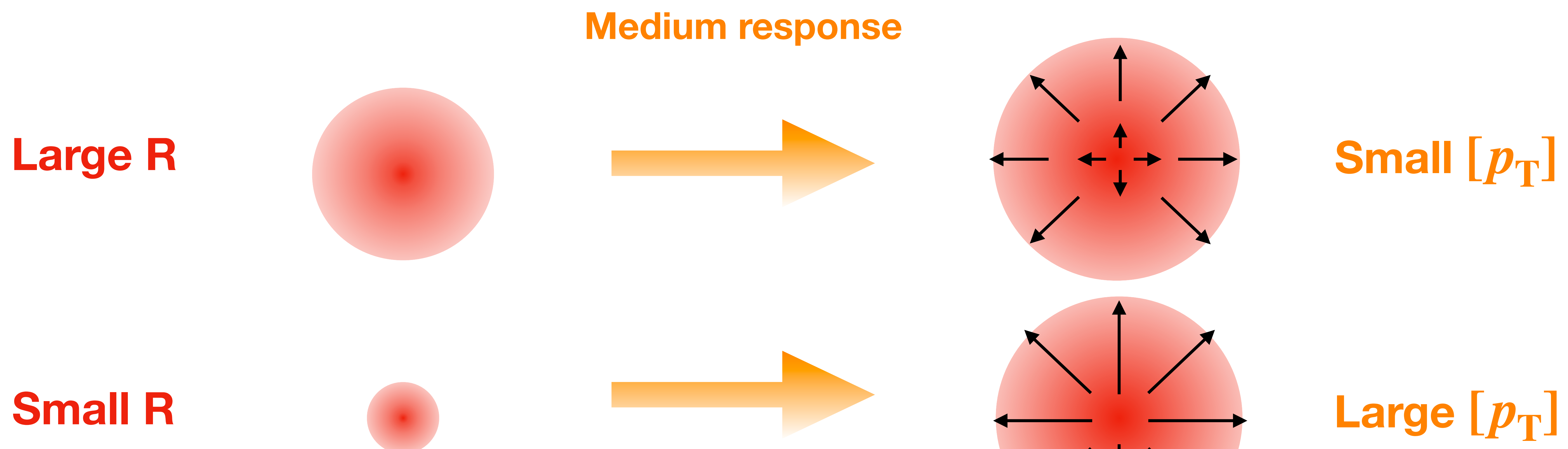
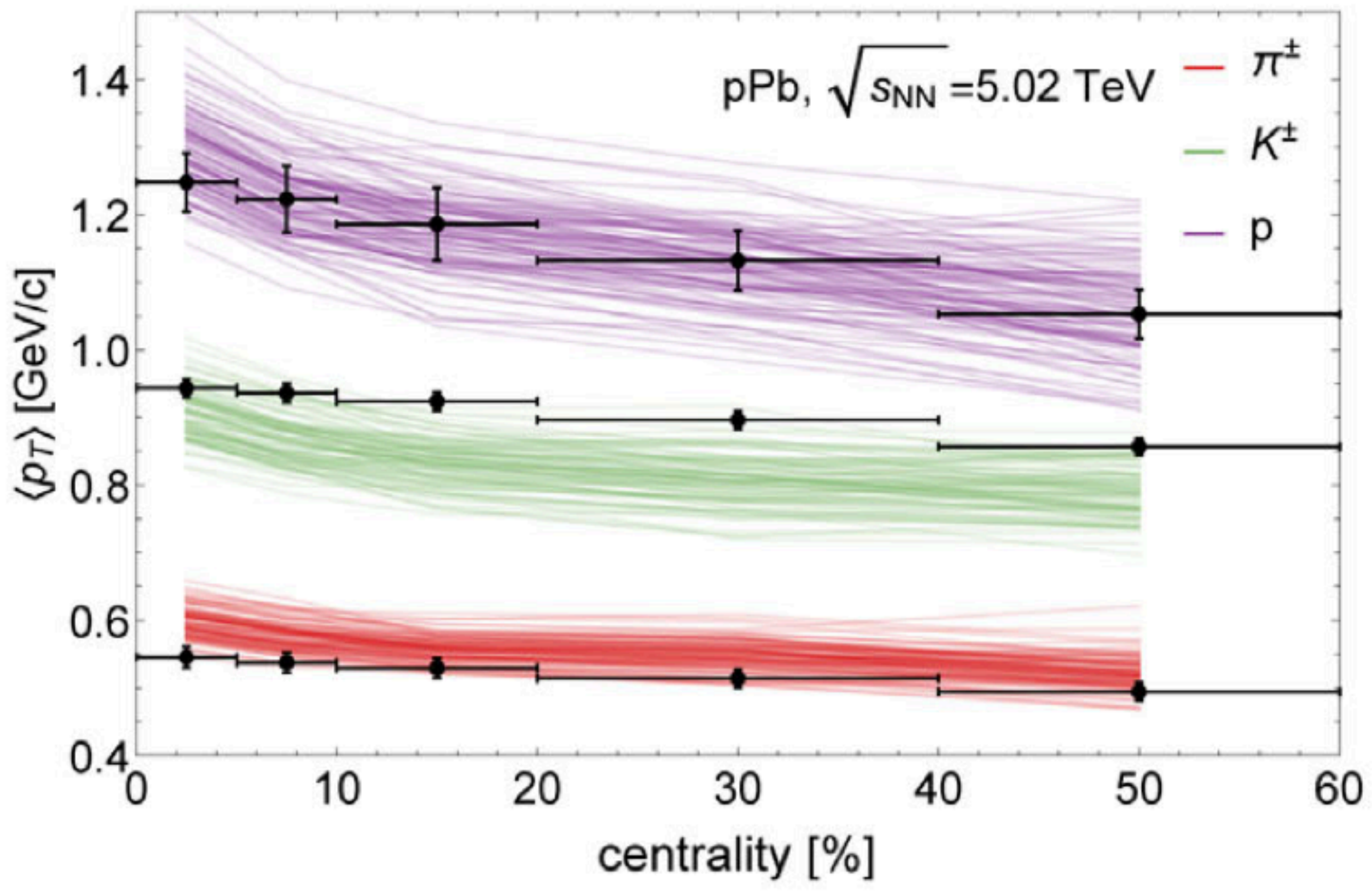


$$\frac{1}{R} \rightarrow [p_{\mathrm{T}}]$$



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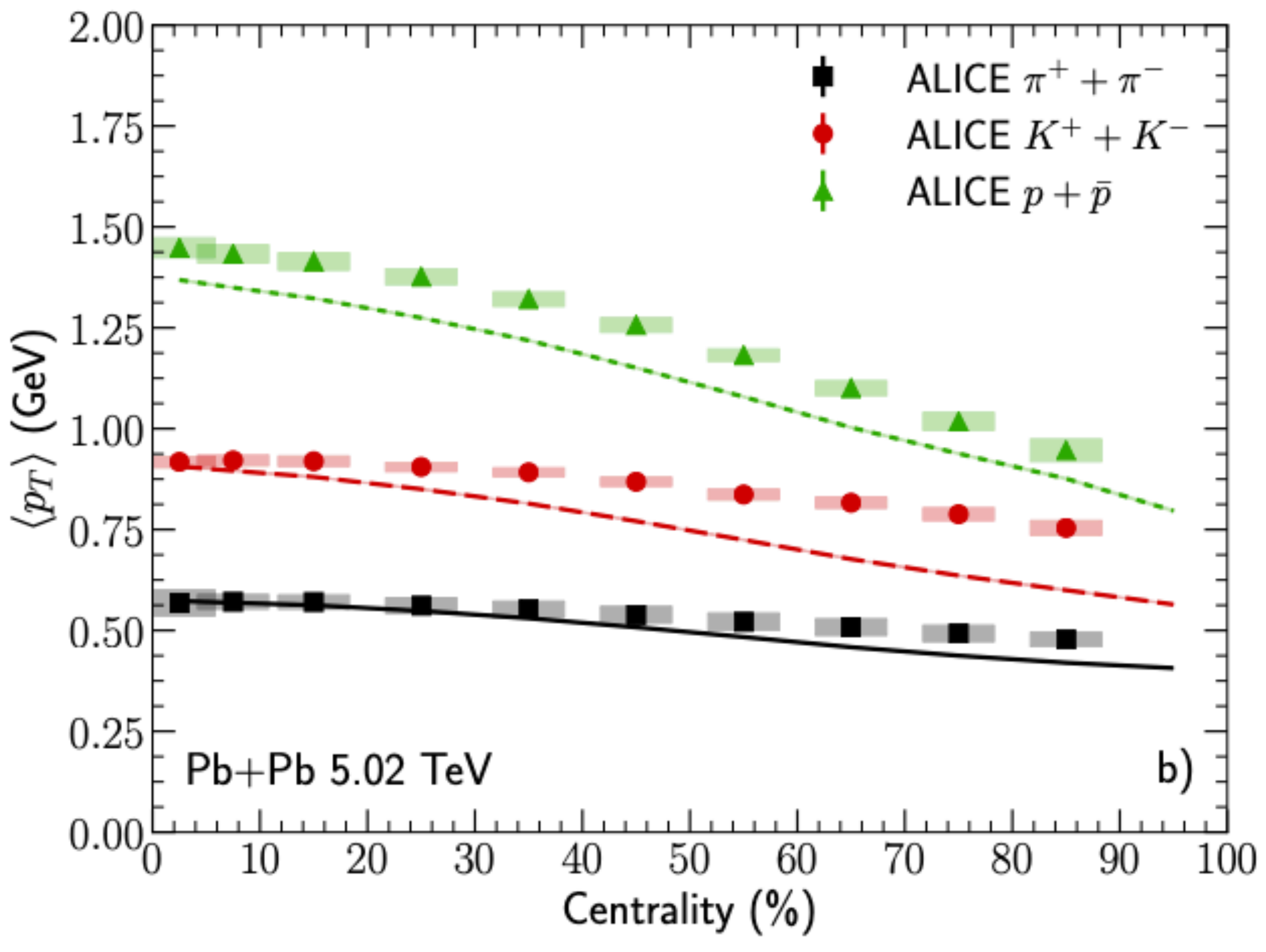


IP-Glasma

Current understanding of initial conditions

State-of-the-art models

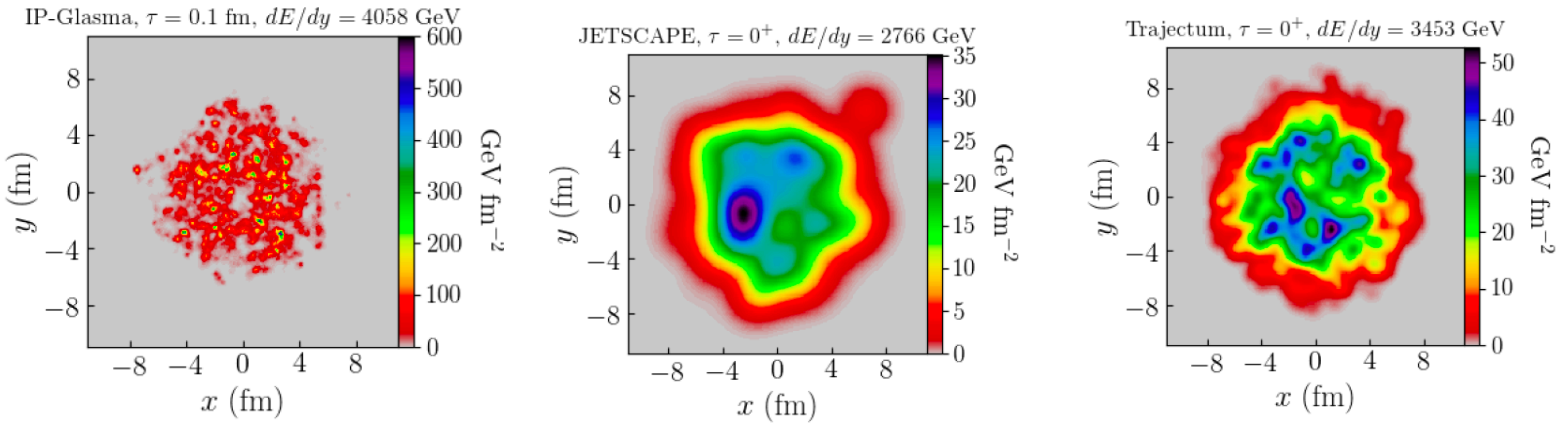
IP-Glasma initial conditions

B. Schenke et al., PRC 102, 044905 (2020)

T_RENTo initial conditions used for Bayesian analyses

J.E. Bernhard et al., Nature Physics, 15, 1113 (2019)
G. Nijs et al., PRL 126, 202301 (2021)
JETSCAPE, PRL 126, 242301 (2021)

IP-Glasma | **JETSCAPE** | **Trajectum**



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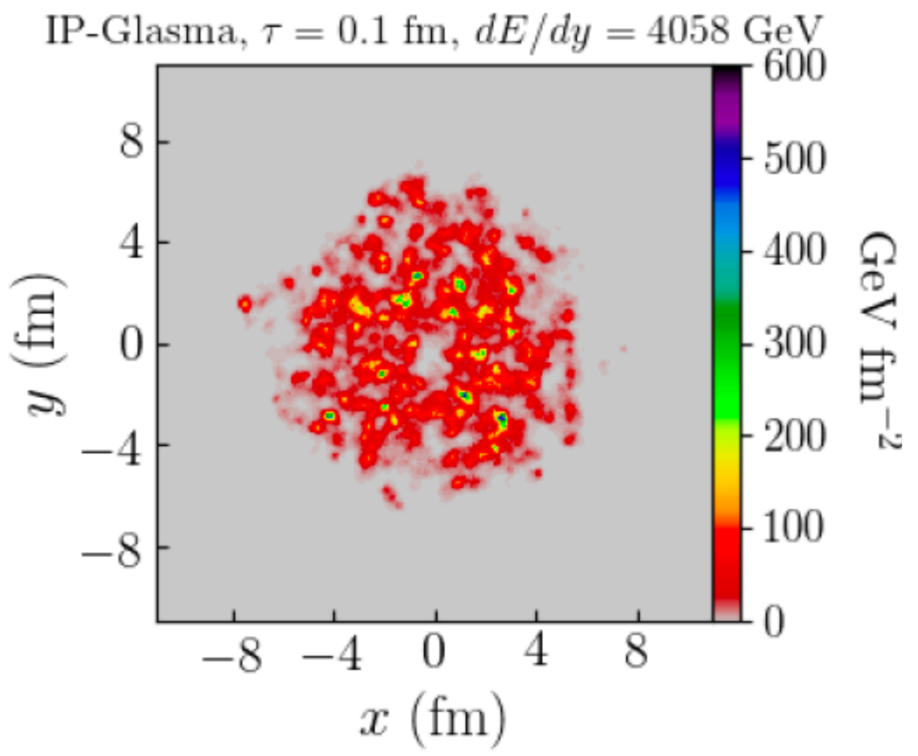
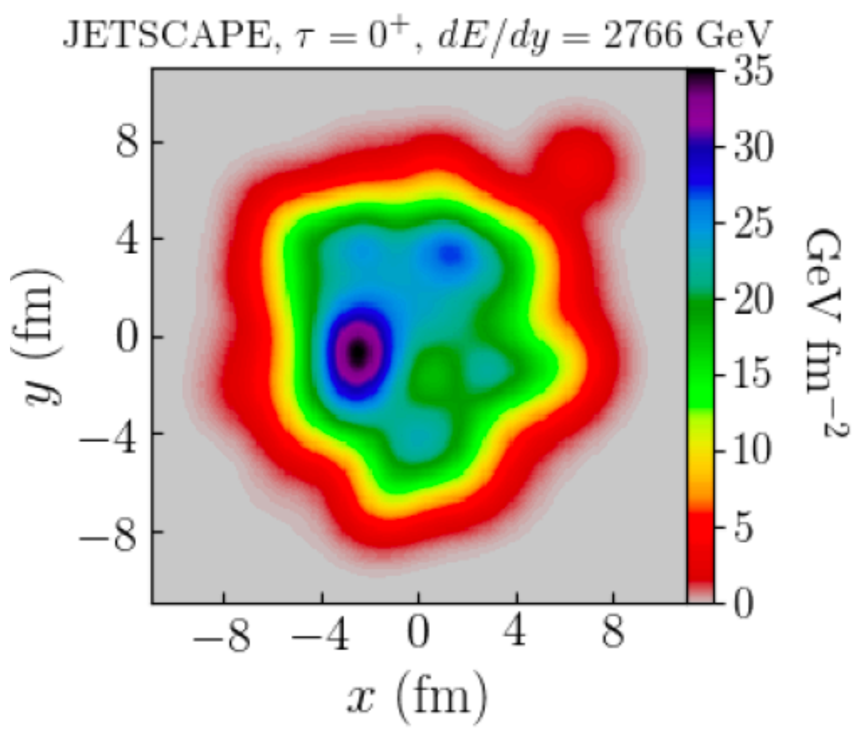


JETSCAPE



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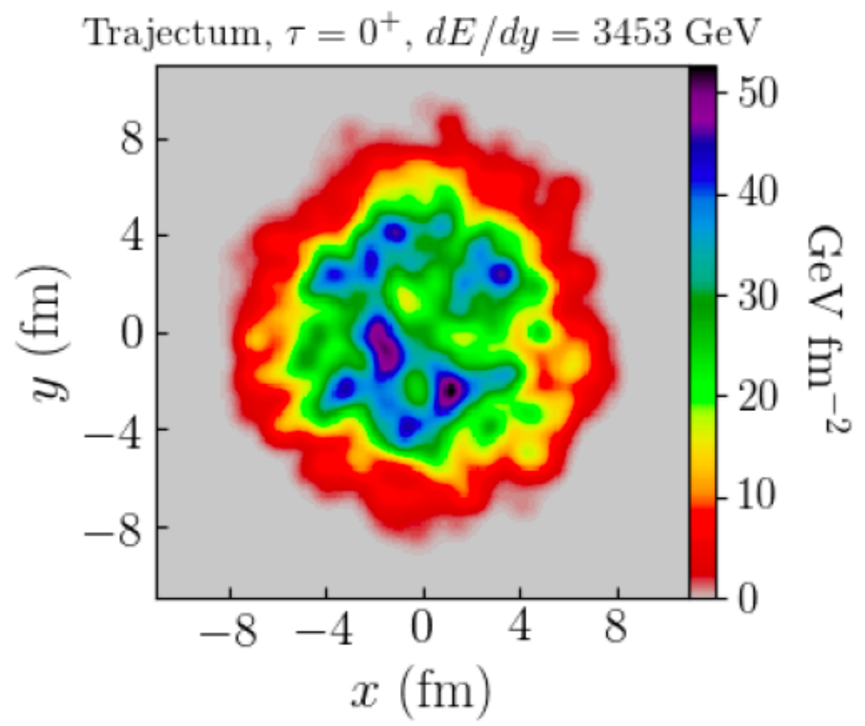
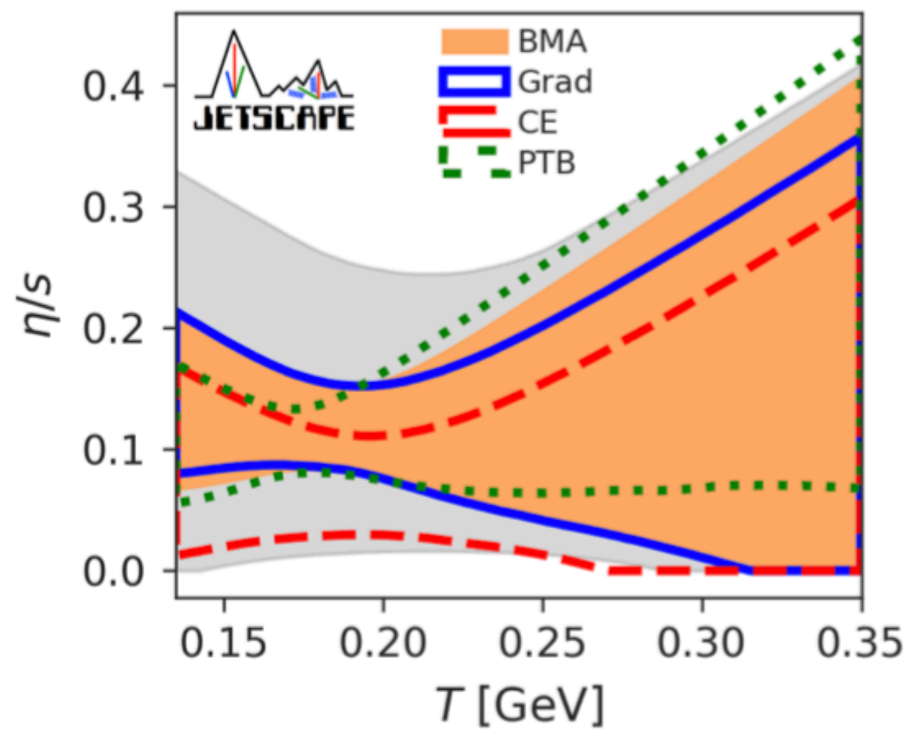
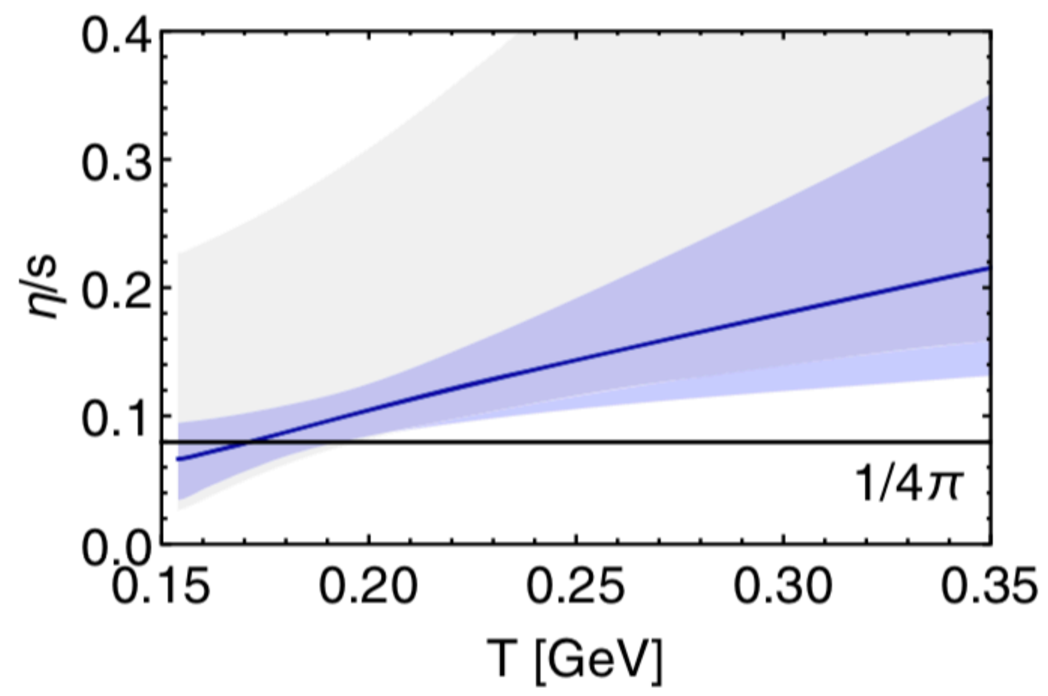


Constant
$\eta/s = 0.12$





Poor knowledge of the initial conditions

→ **Large uncertainty in extracted transport properties**

Transverse momentum-flow correlations

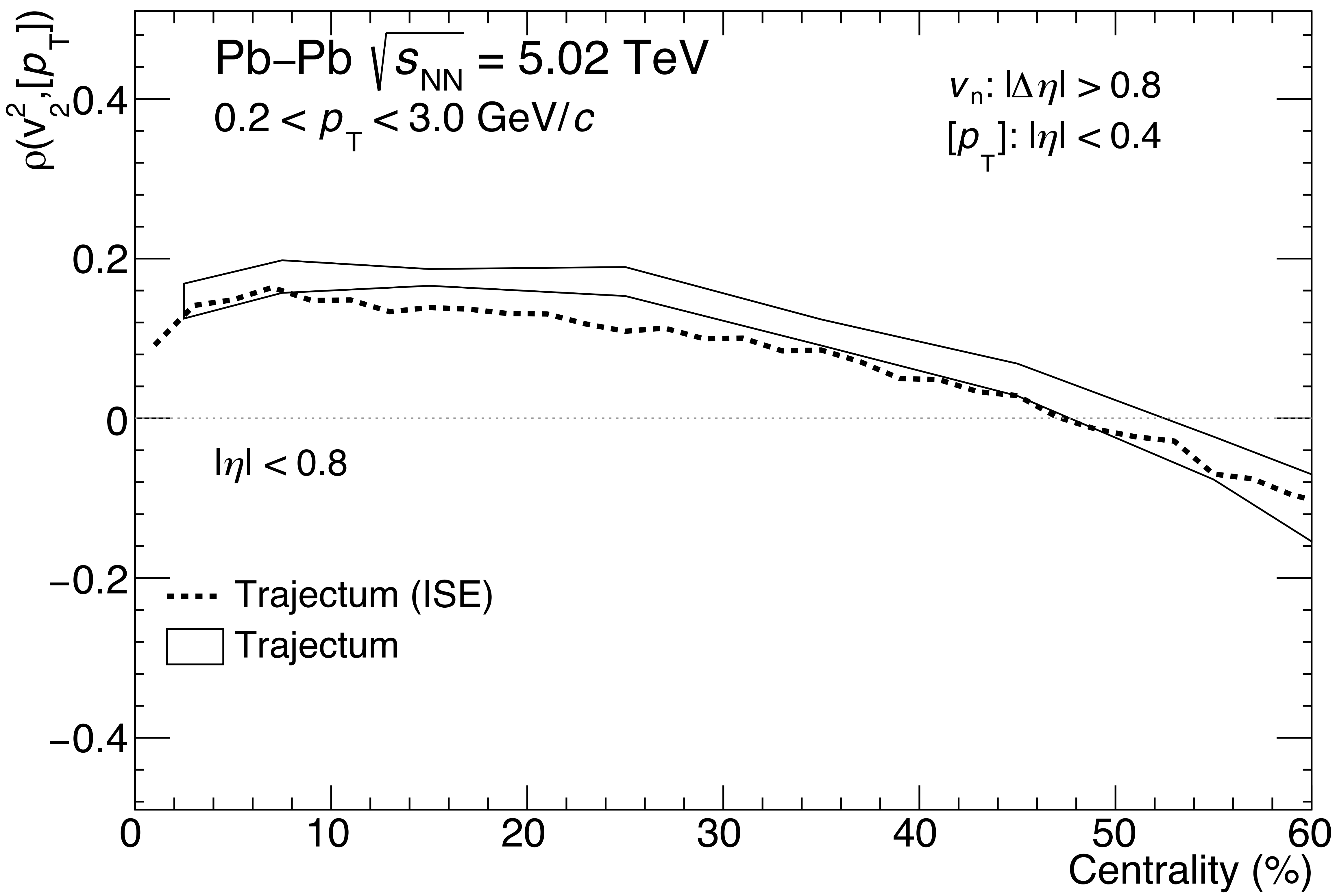
Correlation of v_n^2 with $[p_\mathrm{T}]$

$$\rho(v_n^2,[p_\mathrm{T}]) = \frac{\mathrm{cov}(v_n^2,[p_\mathrm{T}])}{\sqrt{var(p_\mathrm{T})}\sqrt{\mathrm{var}(v_2^2)}}$$

P. Bozek, PRC 93, 044908 (2016)

Initial state = final state

Confirmed by TRAJECTUM



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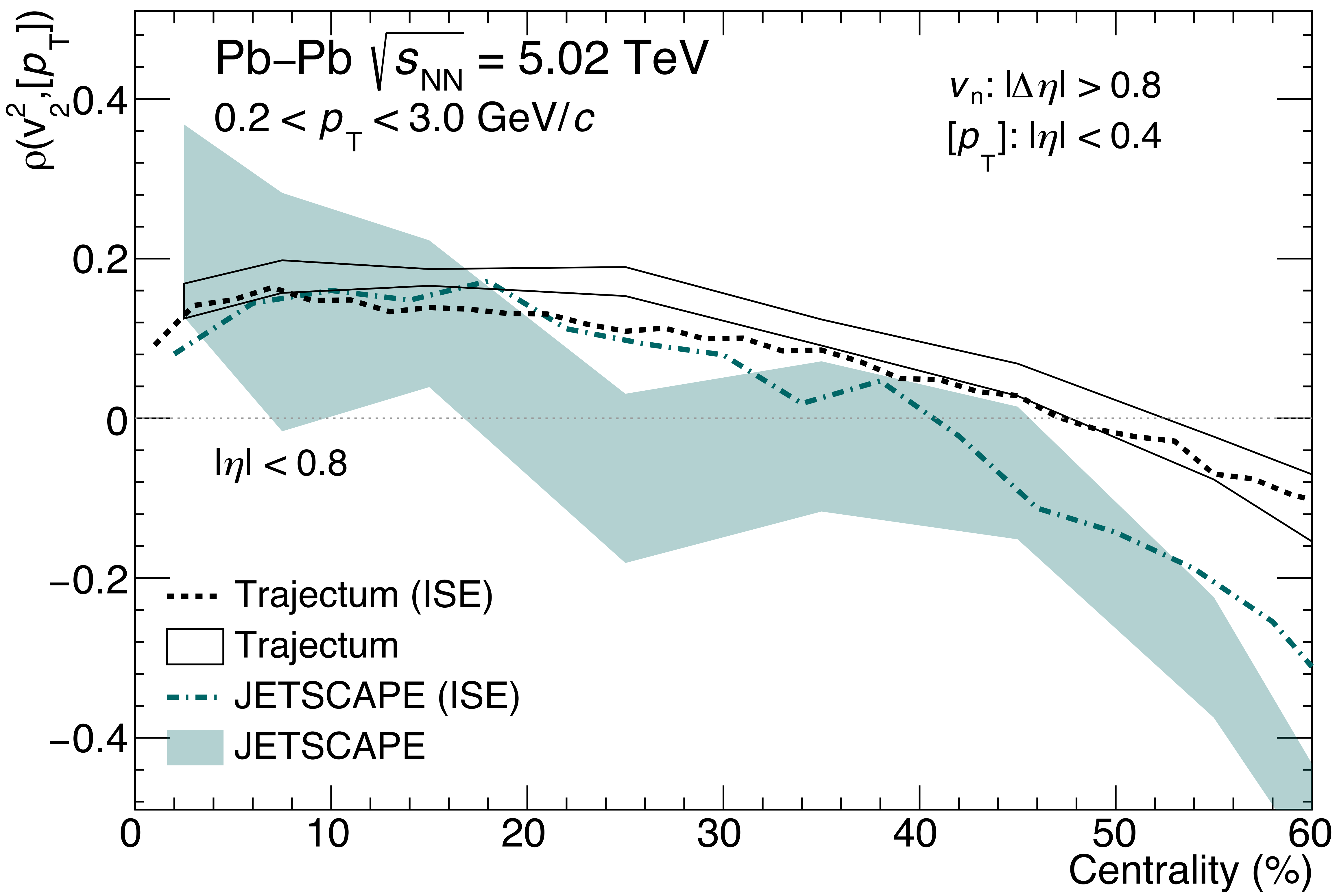

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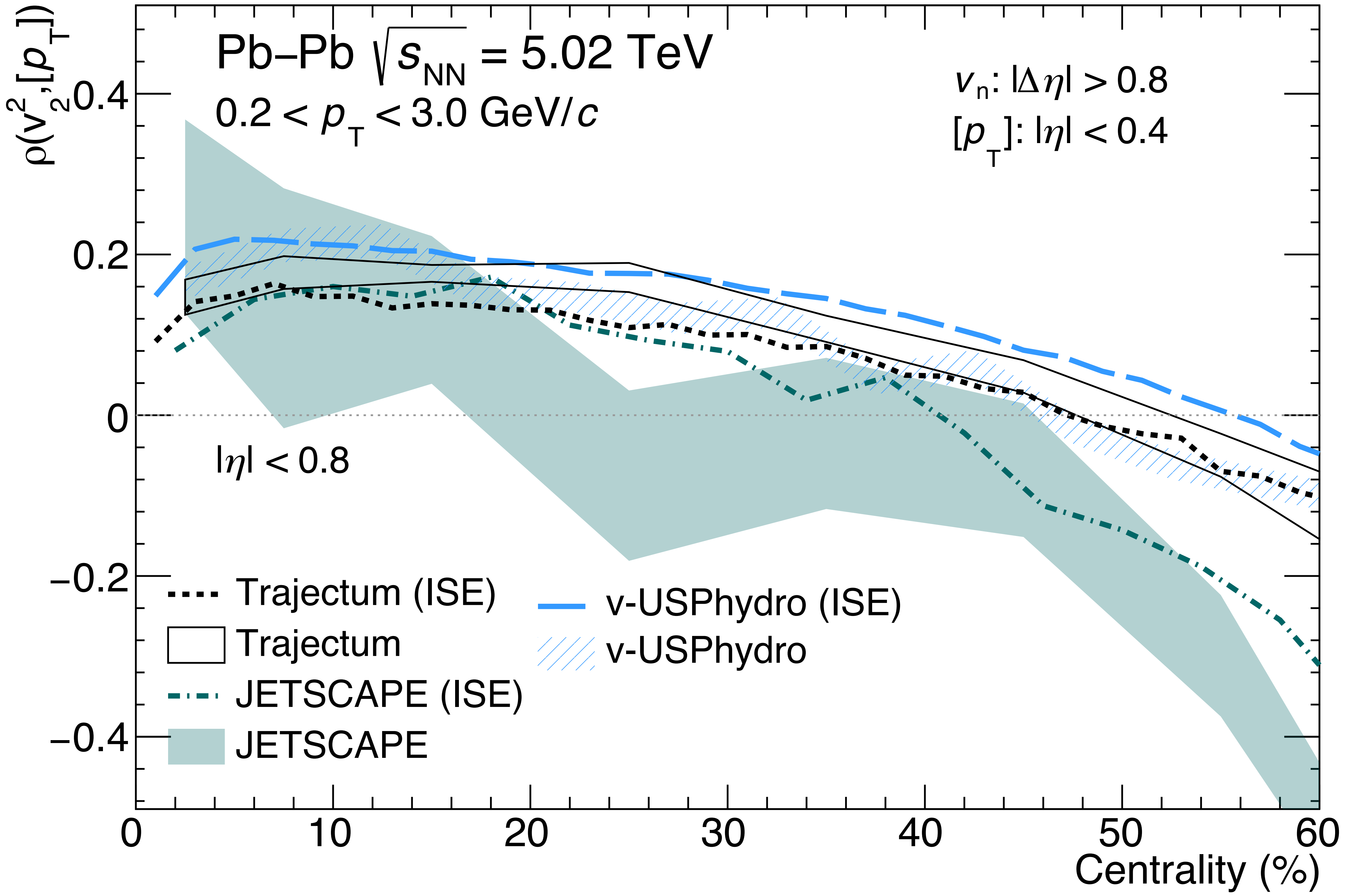

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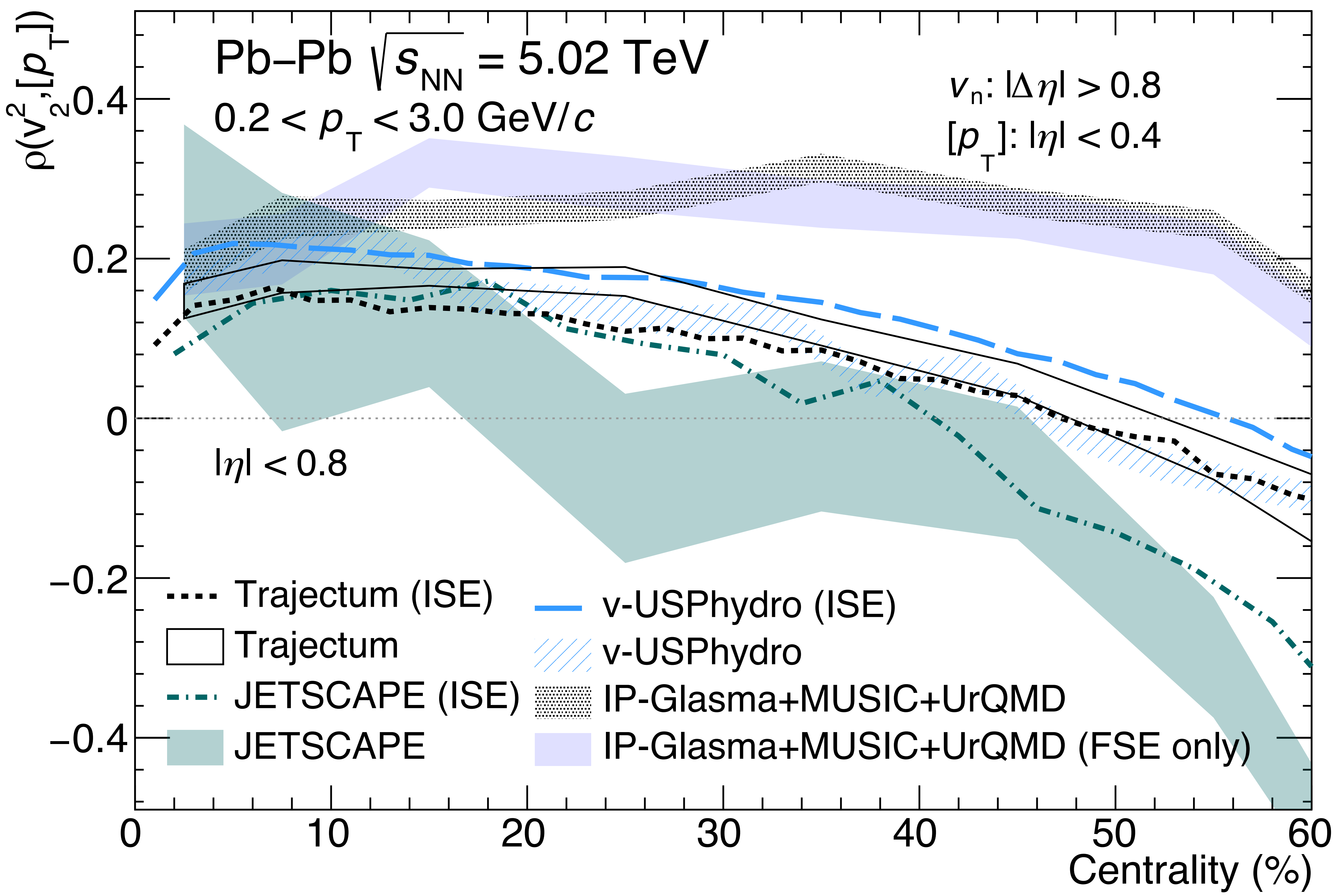

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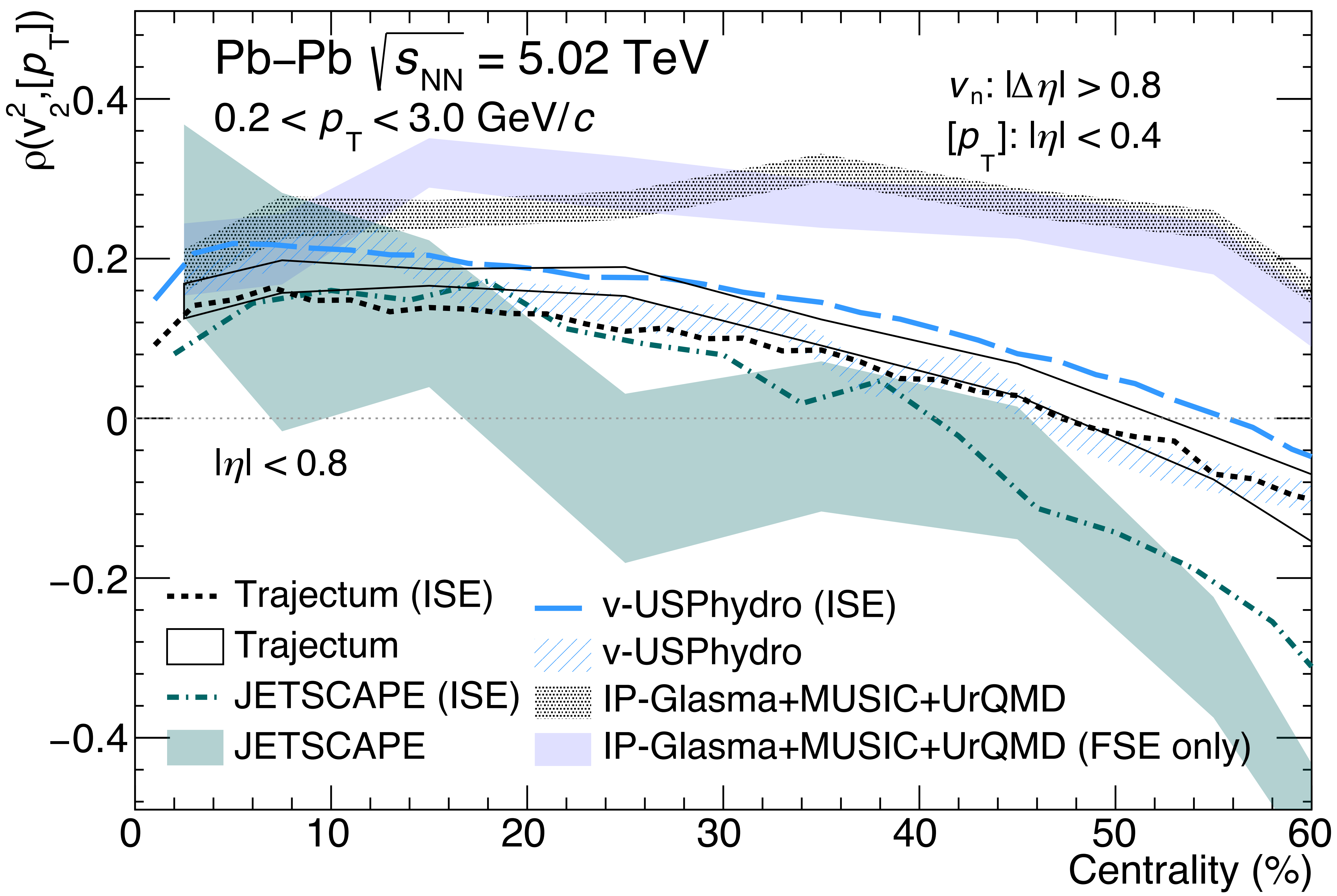
Agreement between initial state estimations and final state calculations → **ρ directly reflects information from the initial state!**



Nuclear deformation

Sensitive to nuclear deformation in central collisions

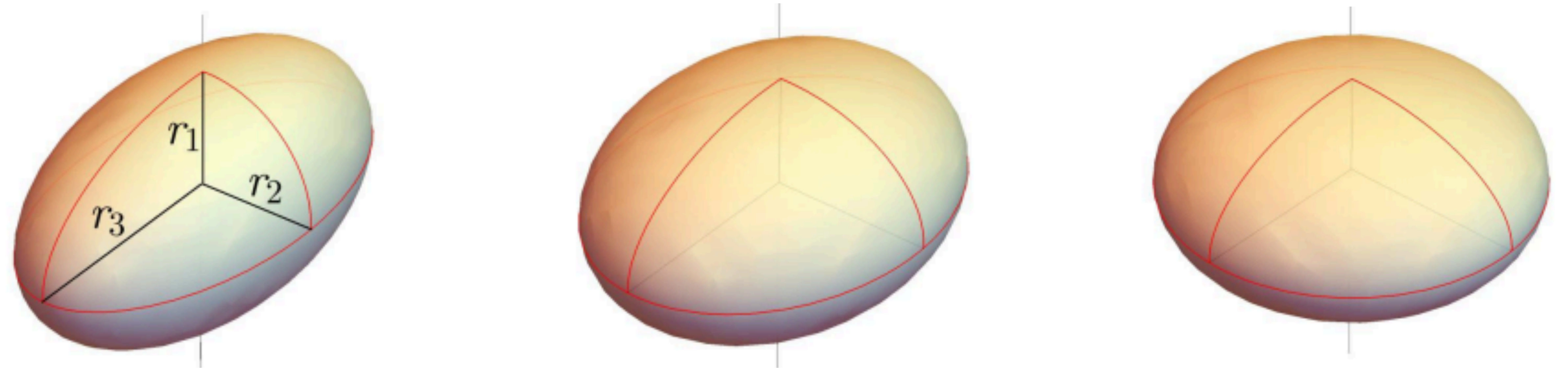
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1 + e^{[r - R(\theta,\phi)/a]}}$$

$$R(\theta,\phi) = R_0\left(1 + \beta_2\left[\cos\gamma Y_{2,0}(\theta,\phi) + \sin\gamma Y_{2,2}(\theta,\phi)\right]\right)$$

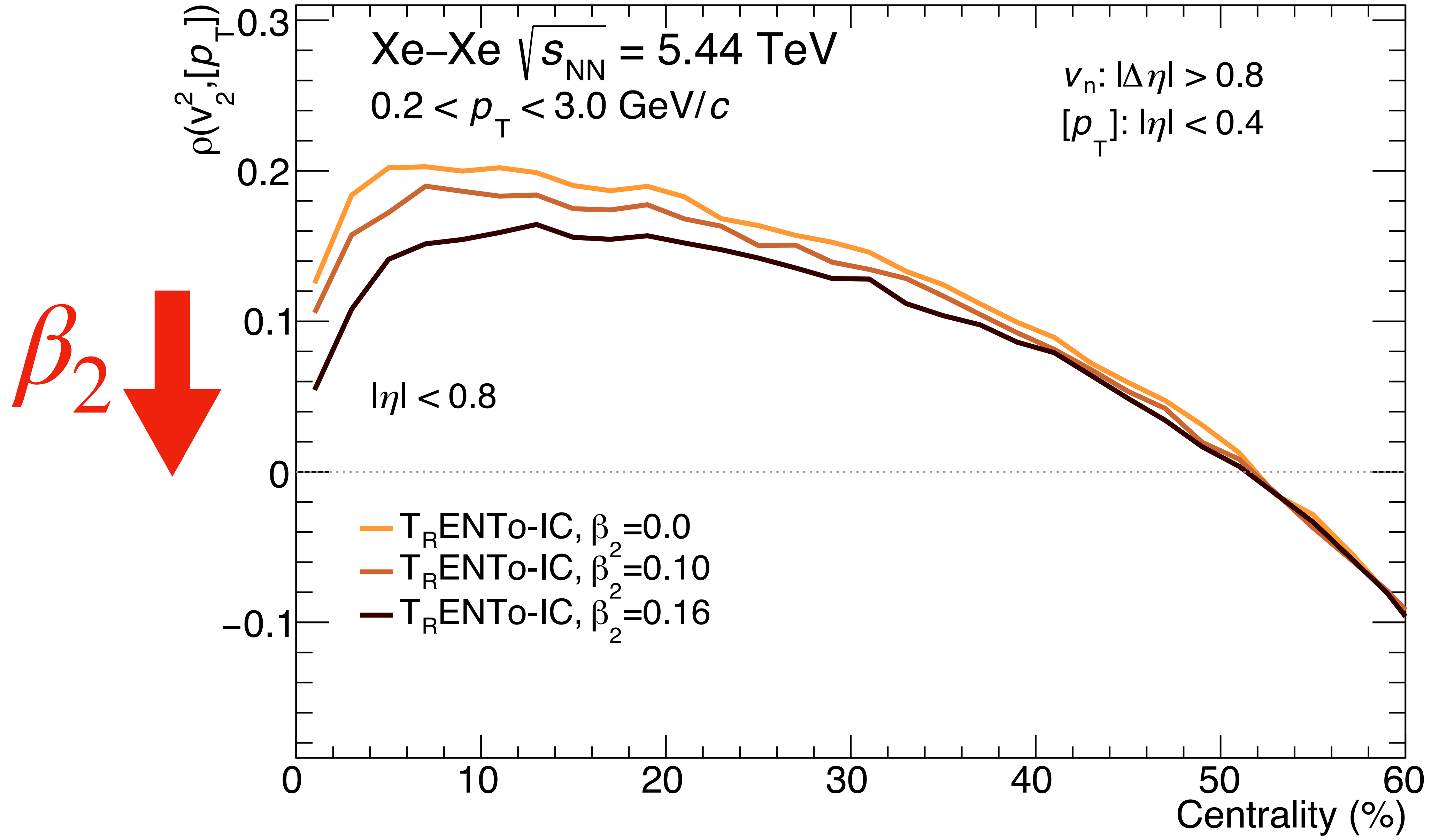
Quadropole deformation parameter β_2

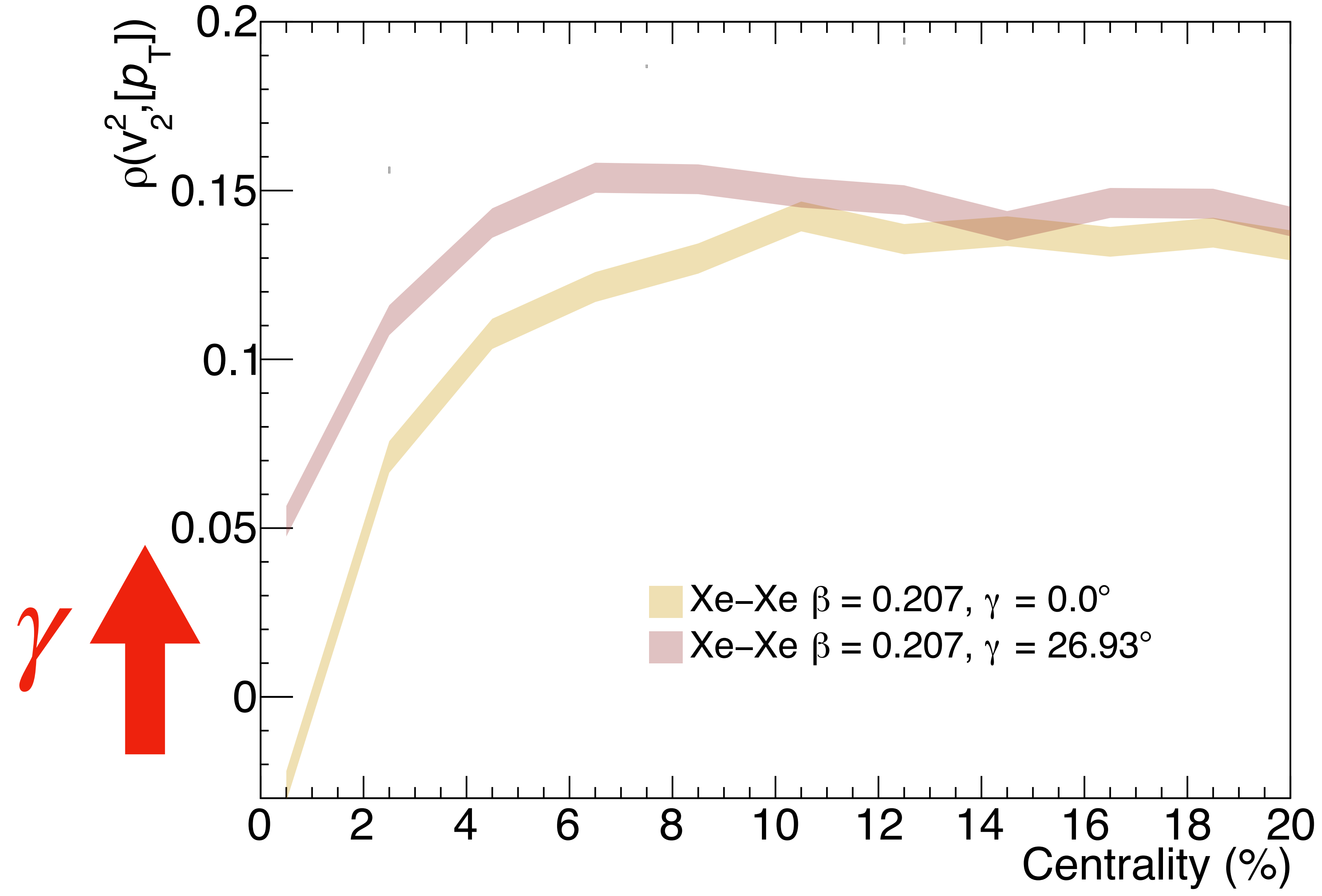
Triaxiality parameter γ

Prolate **Triaxial** **Oblate**



$r_1 = r_2 < r_3$ $r_1 \neq r_2 \neq r_3$ $r_1 < r_2 = r_3$



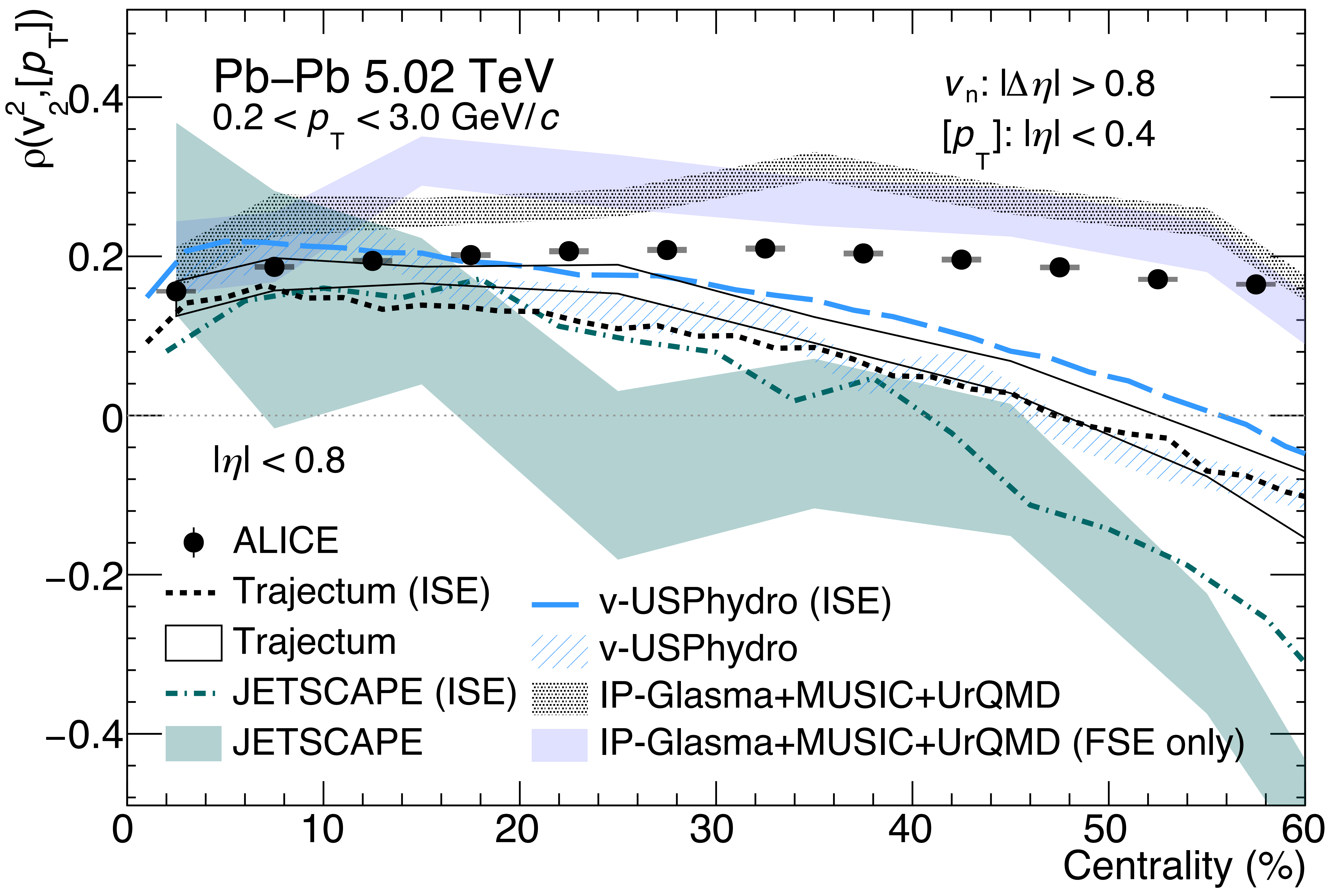


Correlations of v_2 and $[p_T]$

$\rho(v_2^2, [p_T])$ positive with weak centrality dependence

→ Correlation of initial eccentricity and size

ALICE Collaboration, Phys. Lett. B 834, 137393 (2022)



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Model comparison

Centrality dependence of $\rho(v_2^2, [p_\mathrm{T}])$ captured by IP-Glasma + MUSIC + UrQMD

Models based on Bayesian analysis **fail** to describe the trend of the data

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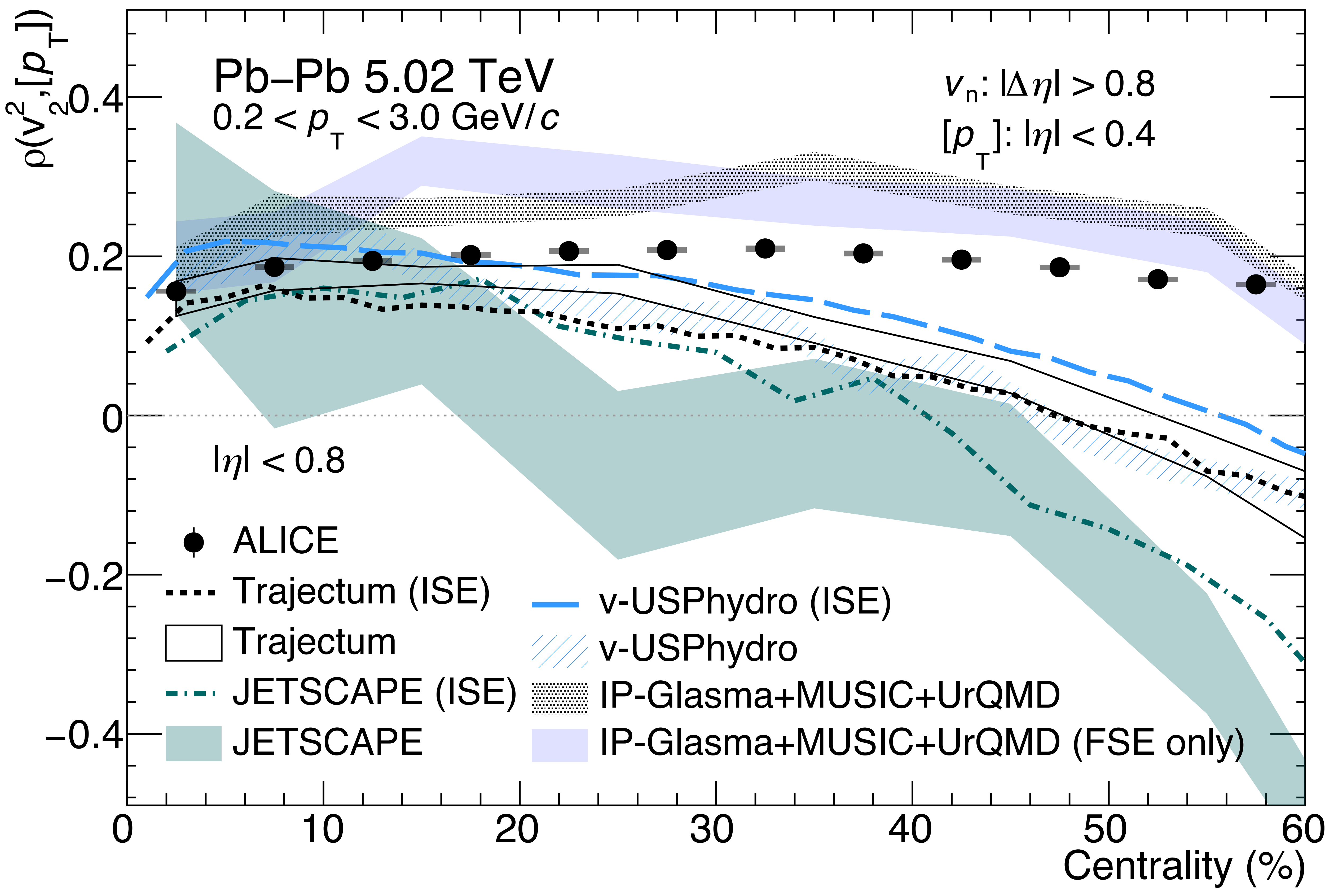

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<u>What drives the difference between the models?</u>

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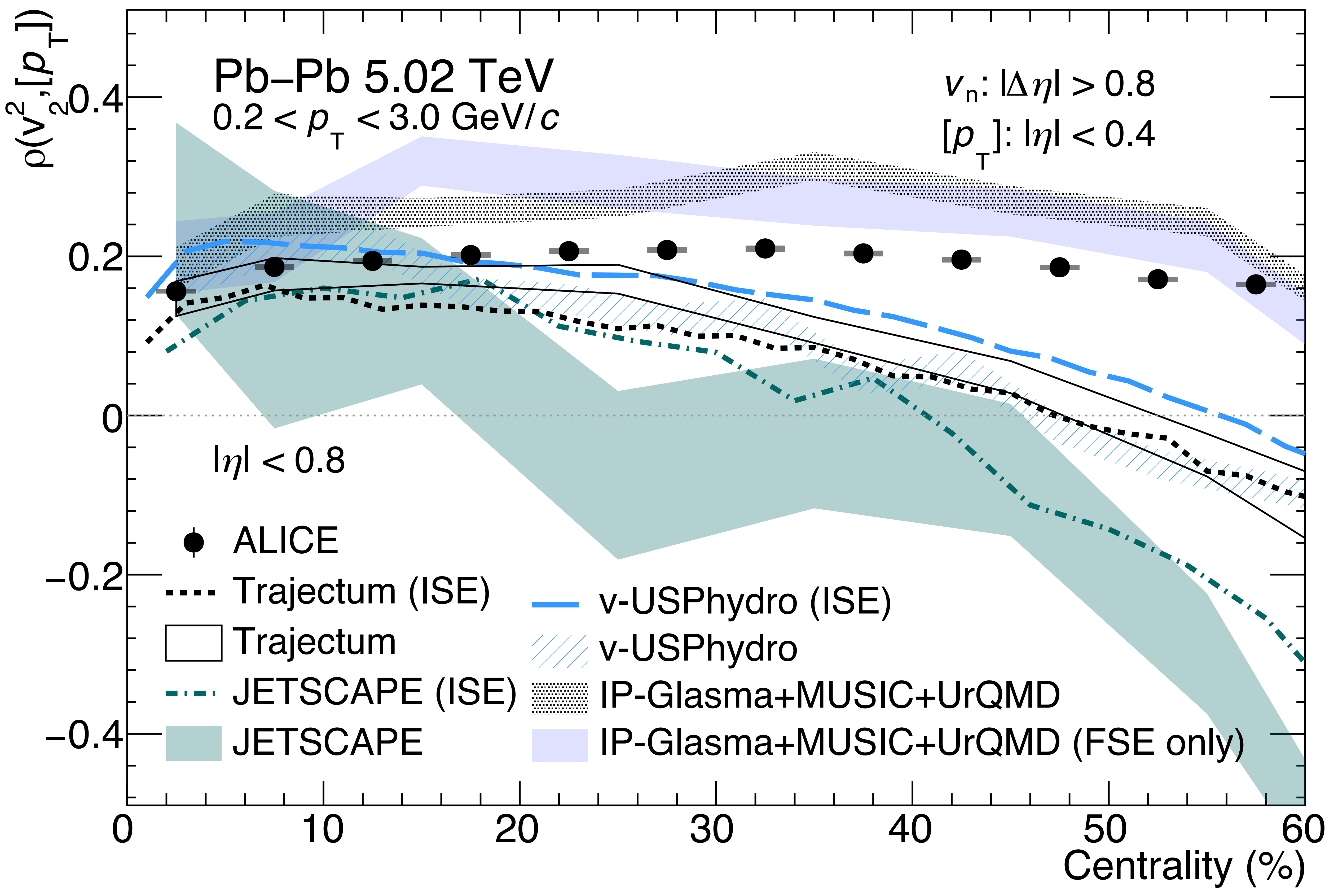

Correlations of v_3 and $[p_\mathrm{T}]$

$\rho(v_3^2, [p_\mathrm{T}])$ positive with modest increase in 50-60% centrality

Weaker correlation of v_3 - $[p_\mathrm{T}]$ compared to v_2 - $[p_\mathrm{T}]$

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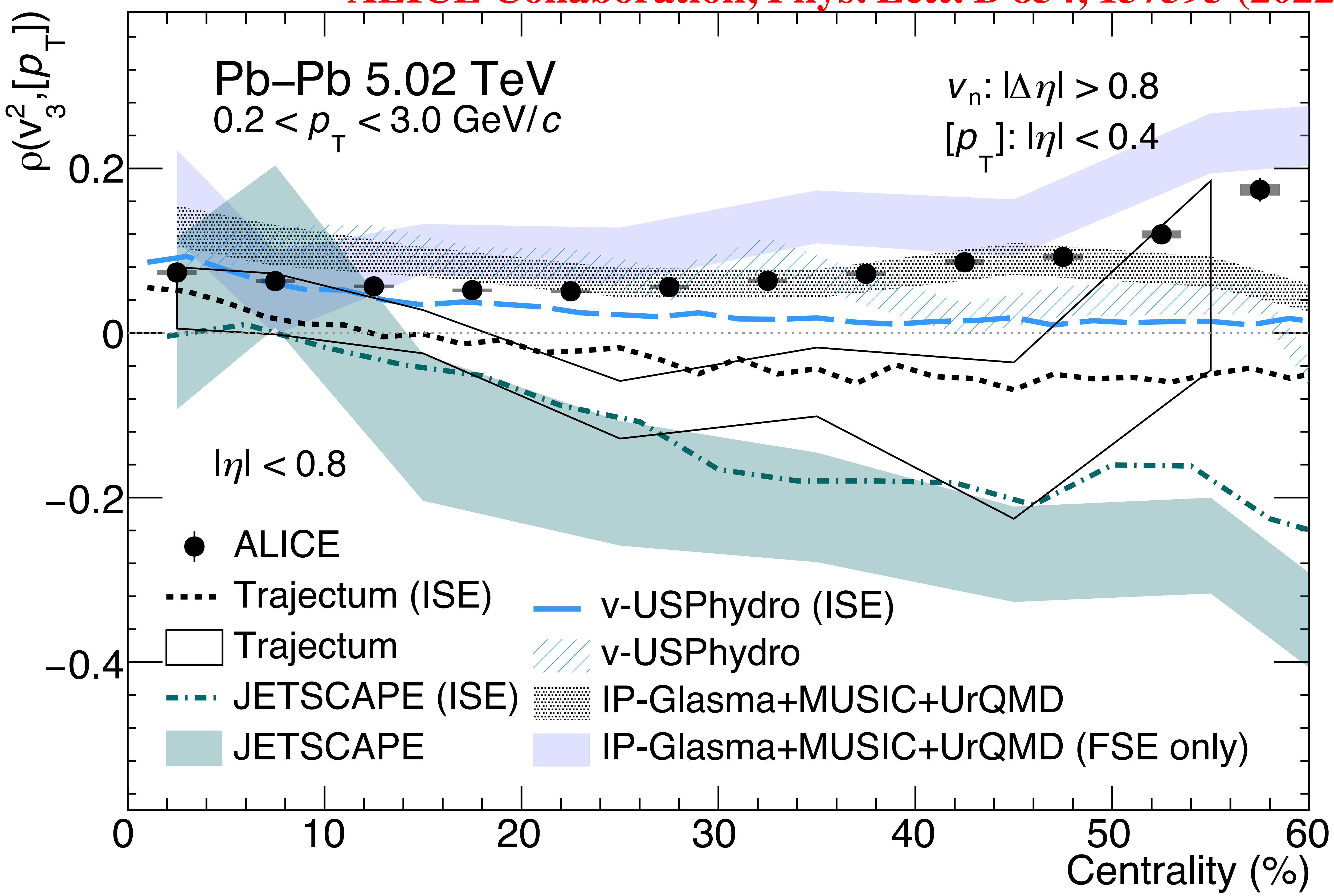

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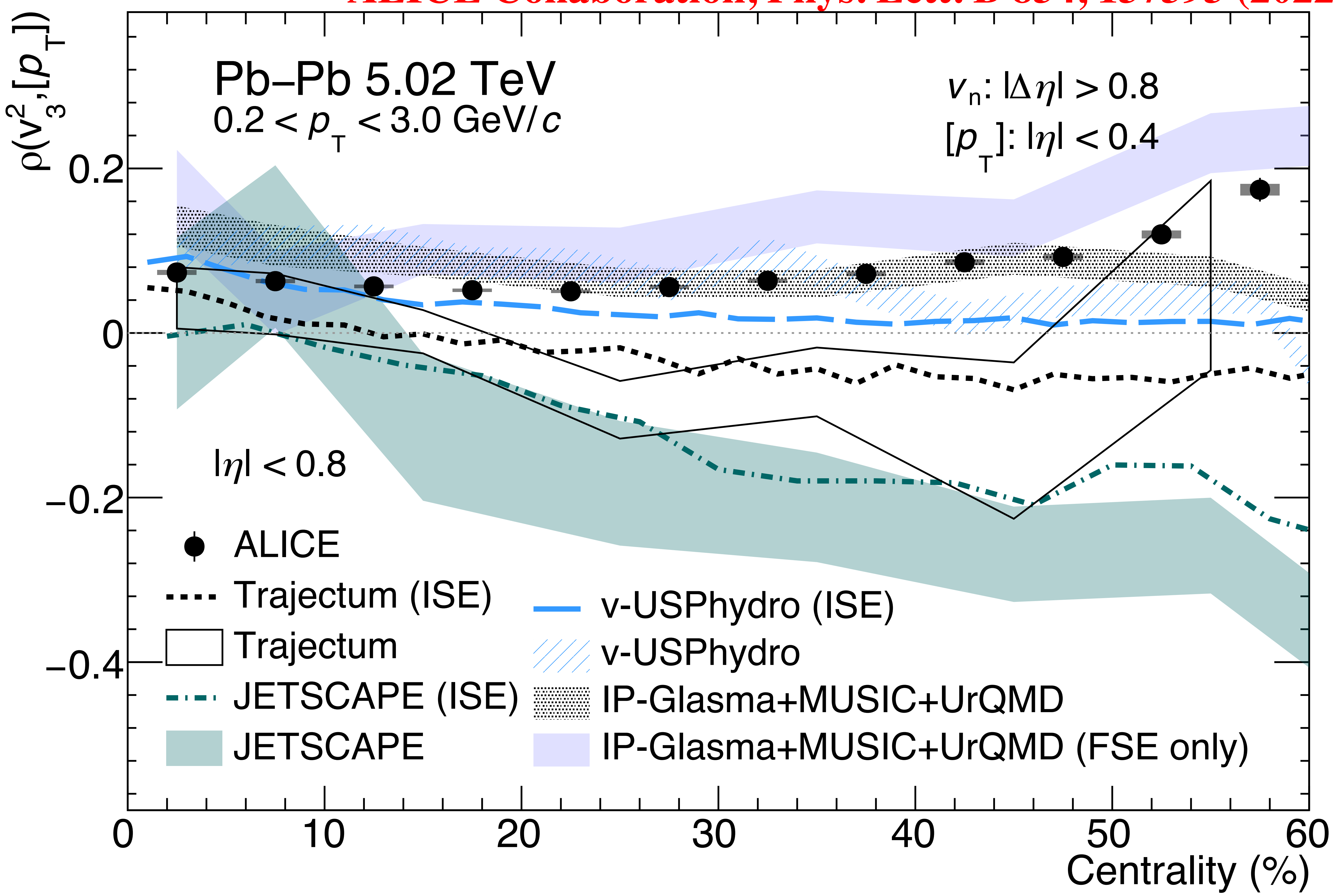
$\rho(v_3^2, [p_\mathrm{T}])$ trend also captured by IP-Glasma + MUSIC + UrQMD

Models based on Bayesian analysis show entirely the **wrong sign** of the correlation

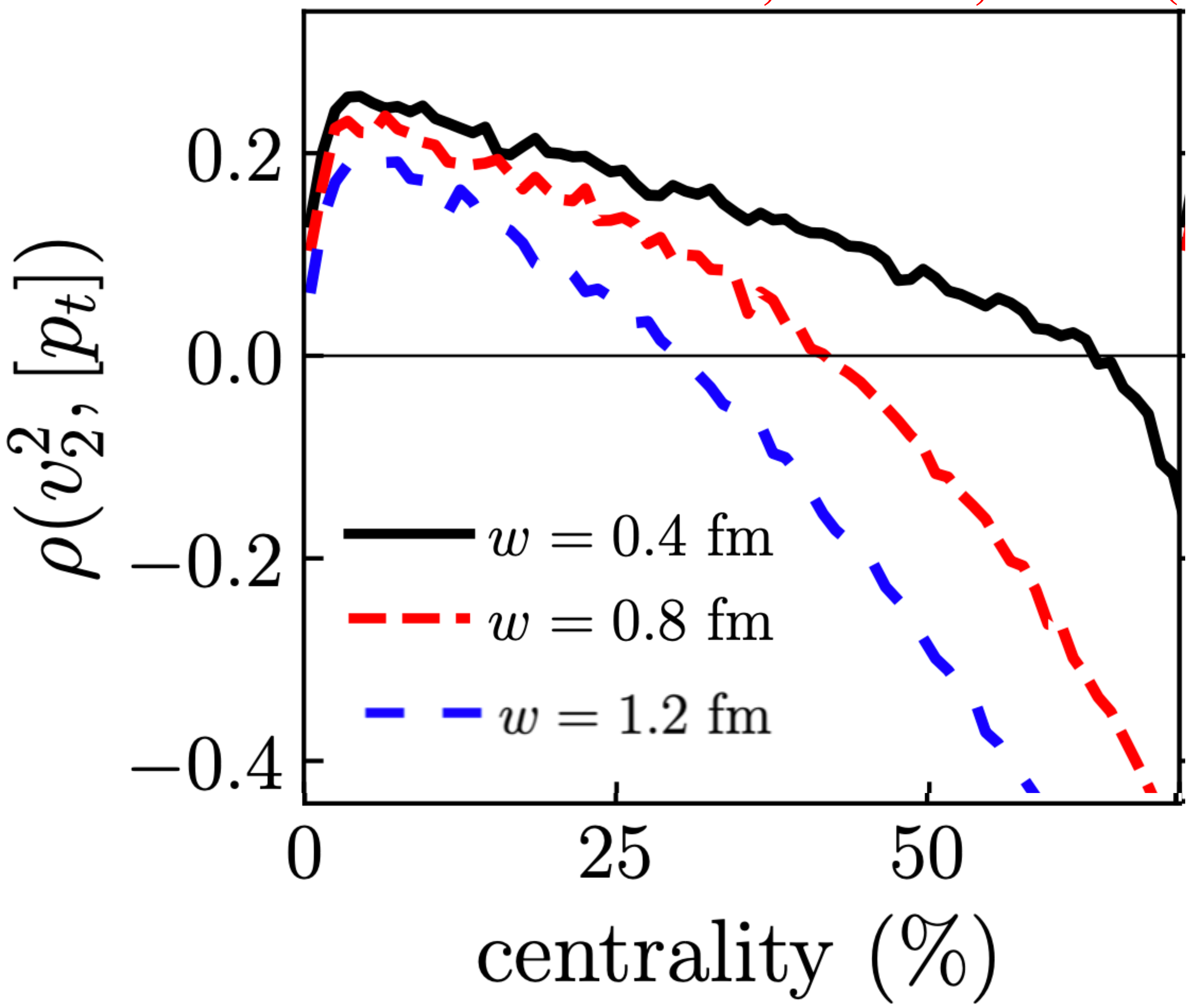
What drives the difference between the models?

ALICE Collaboration, Phys. Lett. B 834, 137393 (2022)



Constraining the nucleon width

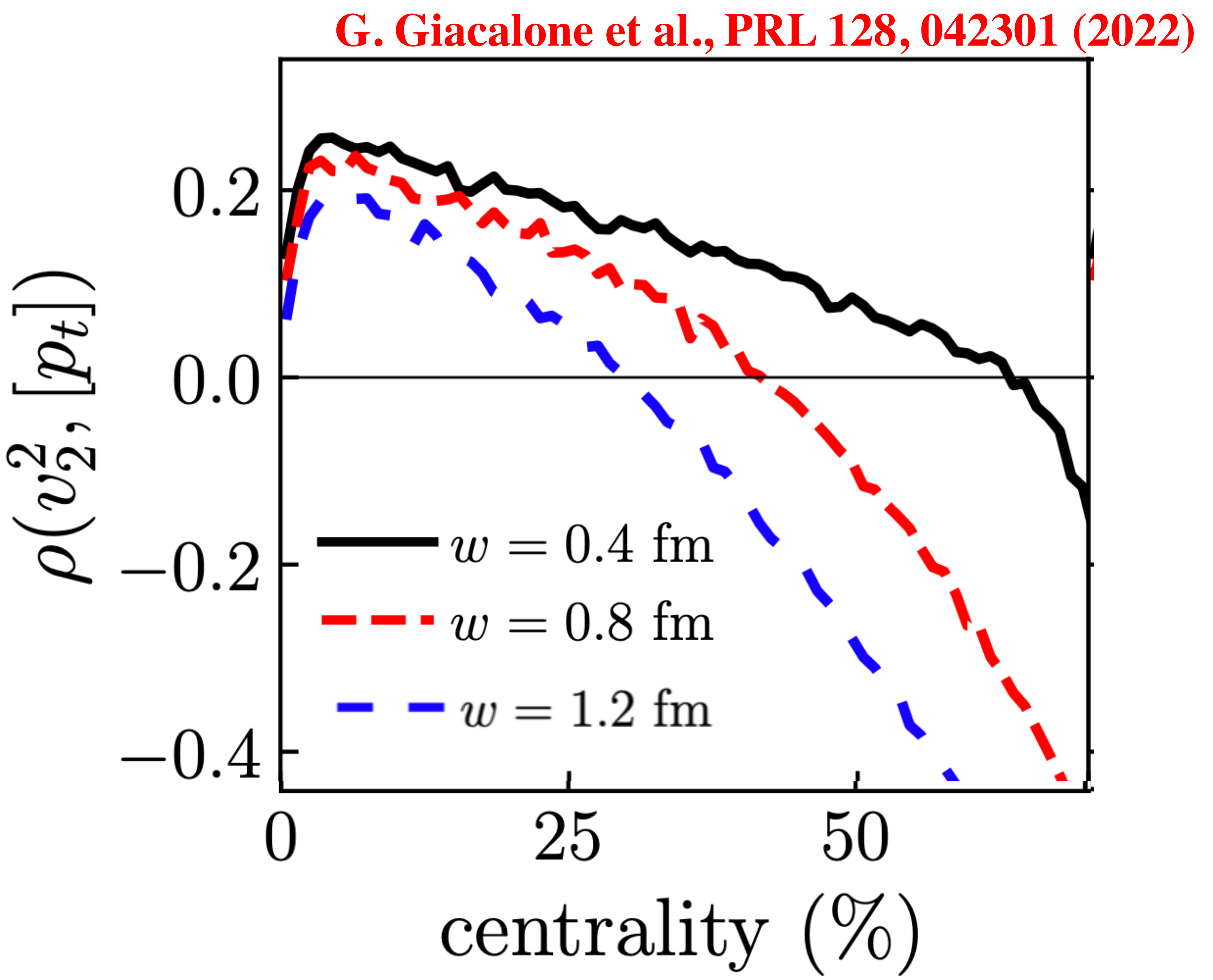
G. Giacalone et al., PRL 128, 042301 (2022)

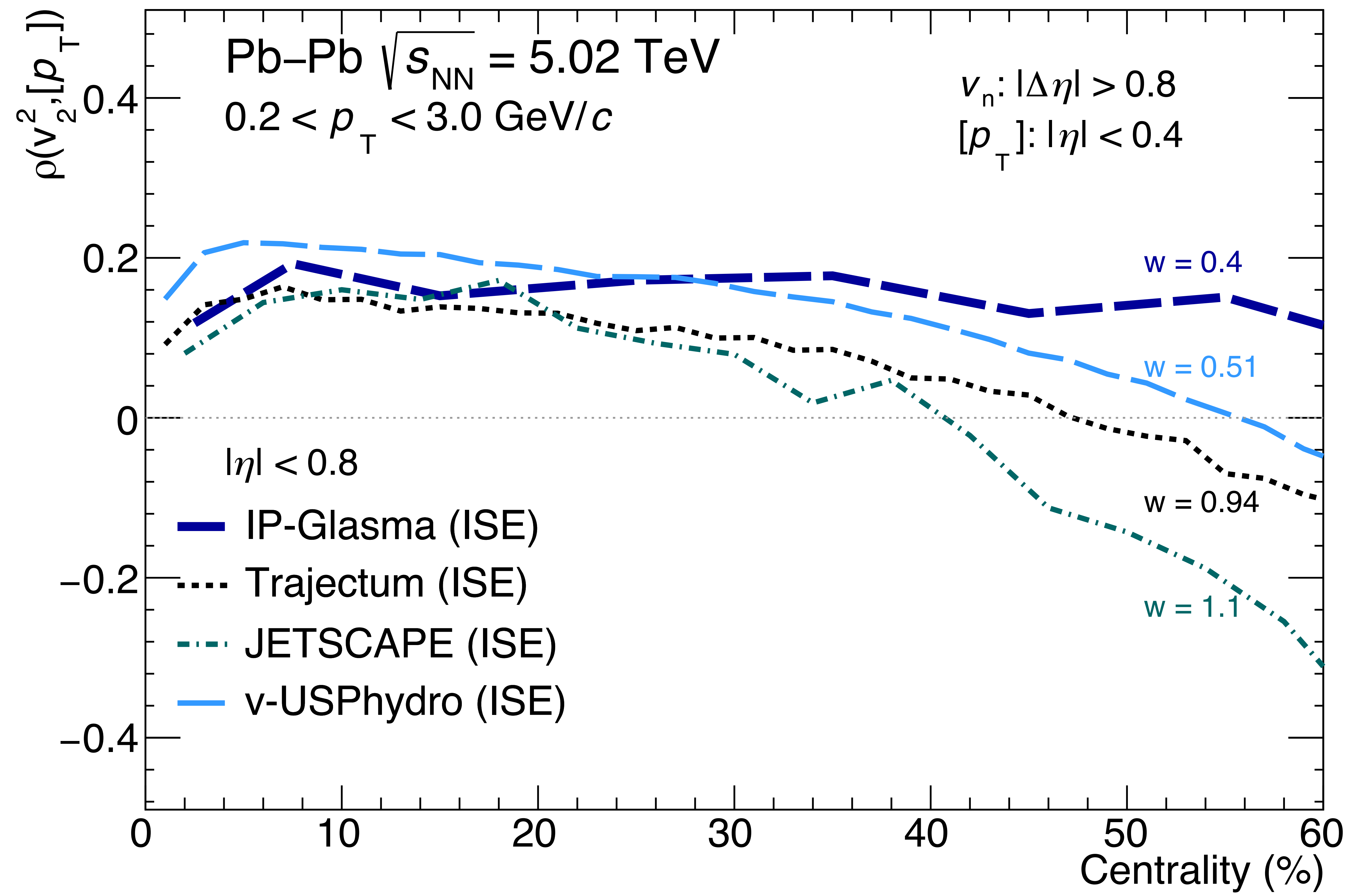


The nucleon width, *w*, has been shown to greatly affect ρ

Small width needed to keep $\rho(v_2^2, [p_T])$ positive

Constraining the nucleon width





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Constraining the nucleon width

Recent state-of-the-art Bayesian analyses

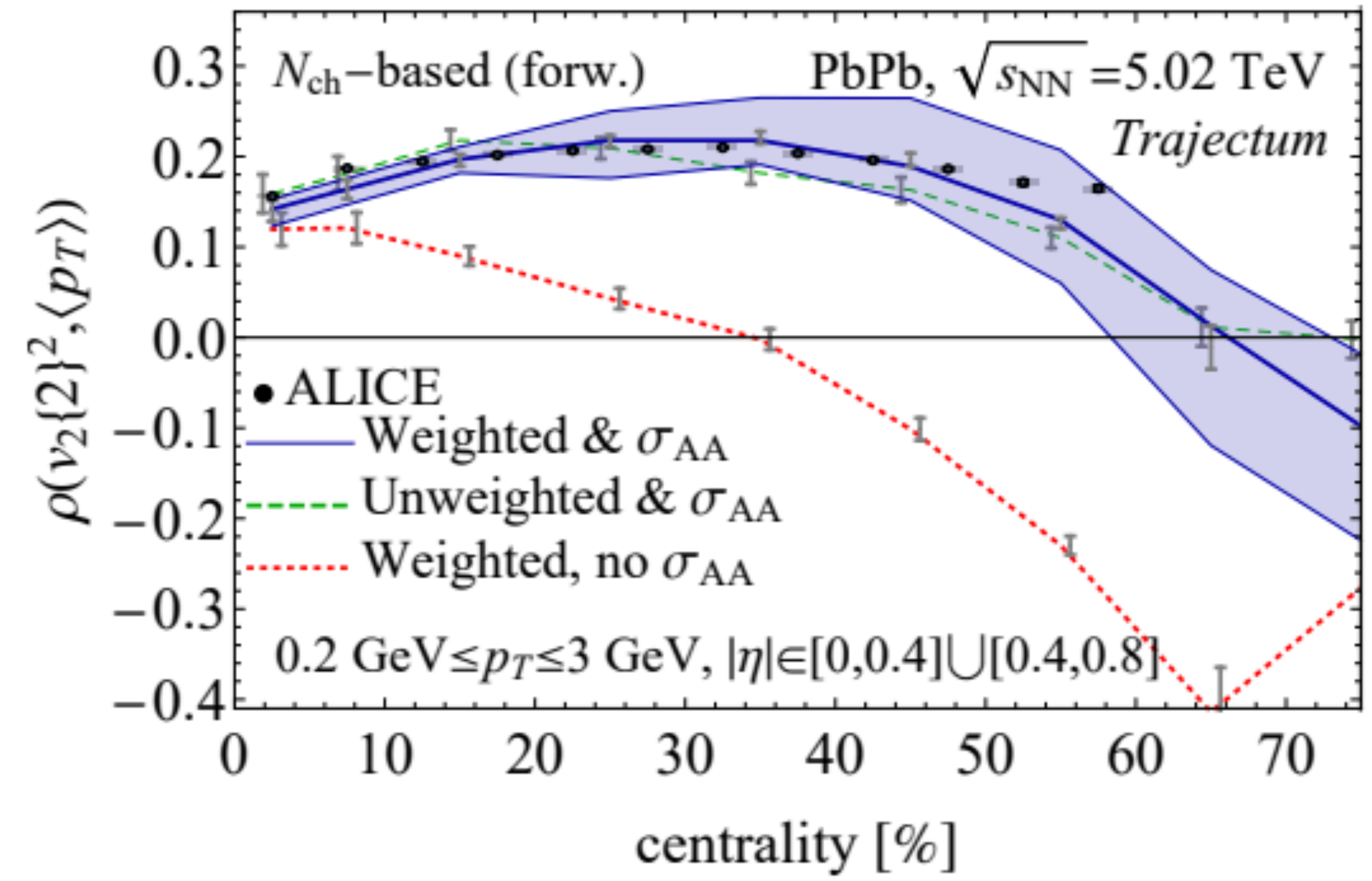
→ *Large nucleon width, $w > 0.8$ fm*

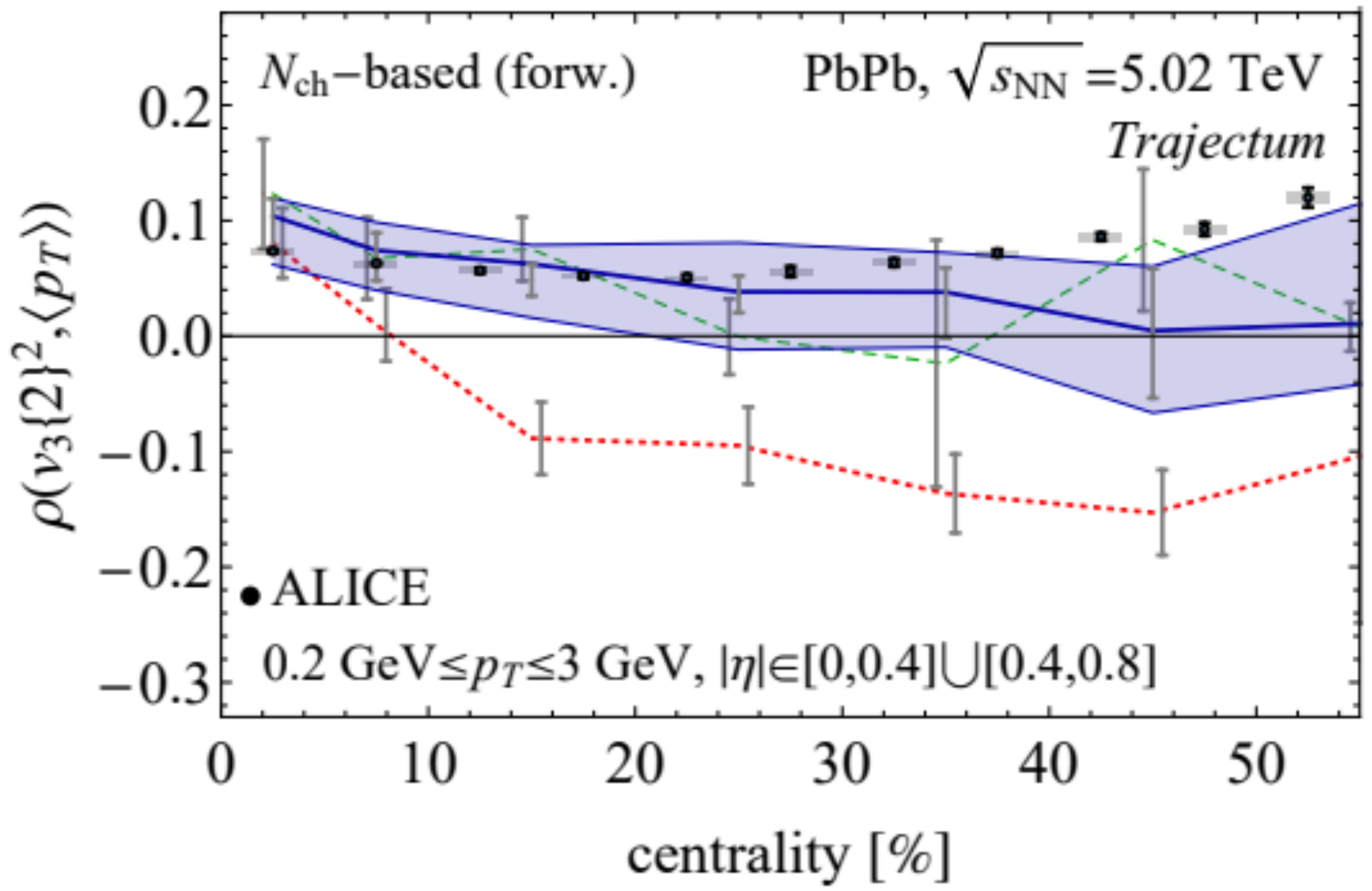
Constrain Bayesian analysis with σ_{AA} measurements

→ *Nucleon width of 0.62 fm (IP-Glasma: 0.4 fm)*

→ *Use ρ measurements for validation of model*

G. Nijs and W. Van der Schee, arXiv:2206.13522





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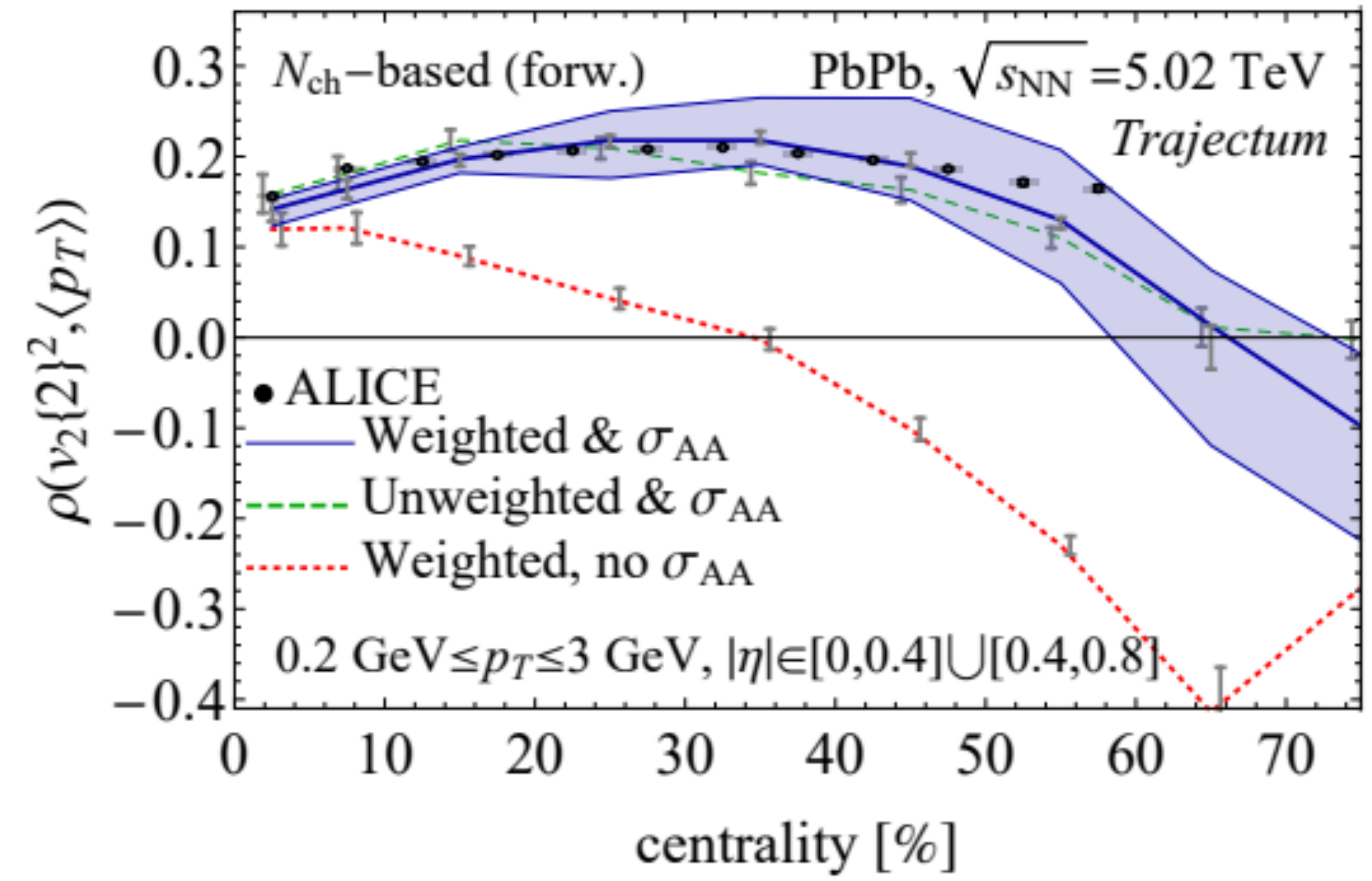
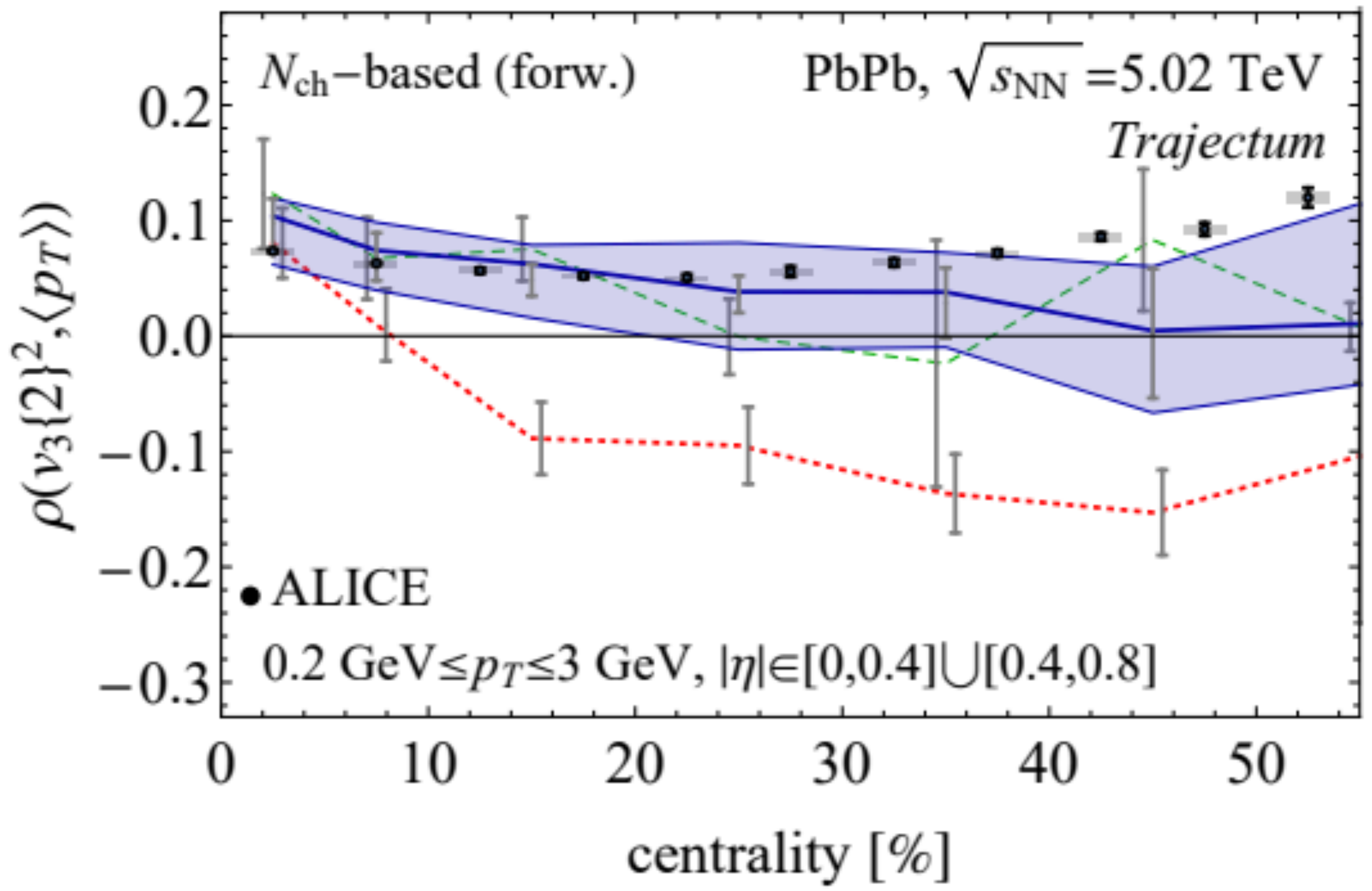
The ALICE measurements serve as important constraint on the nucleon spatial profile

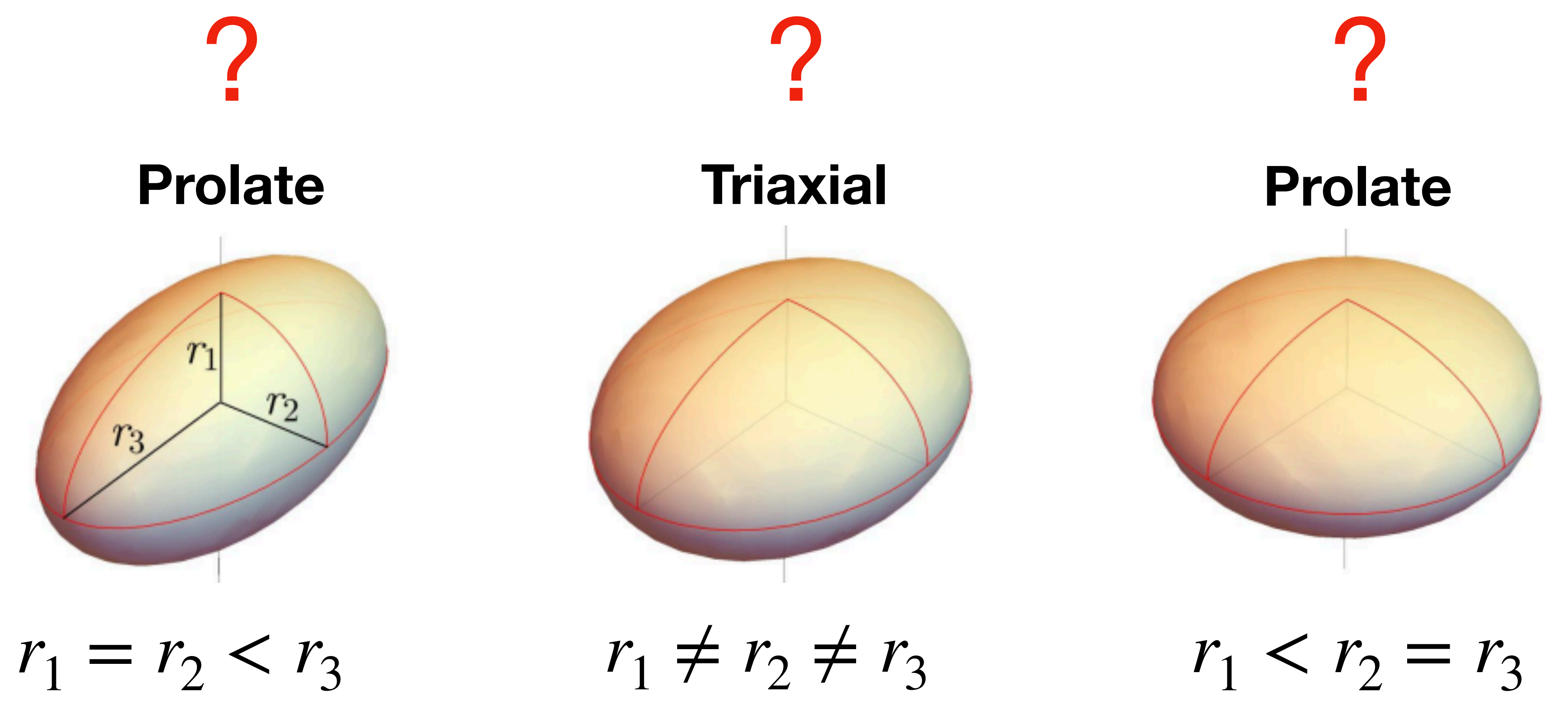




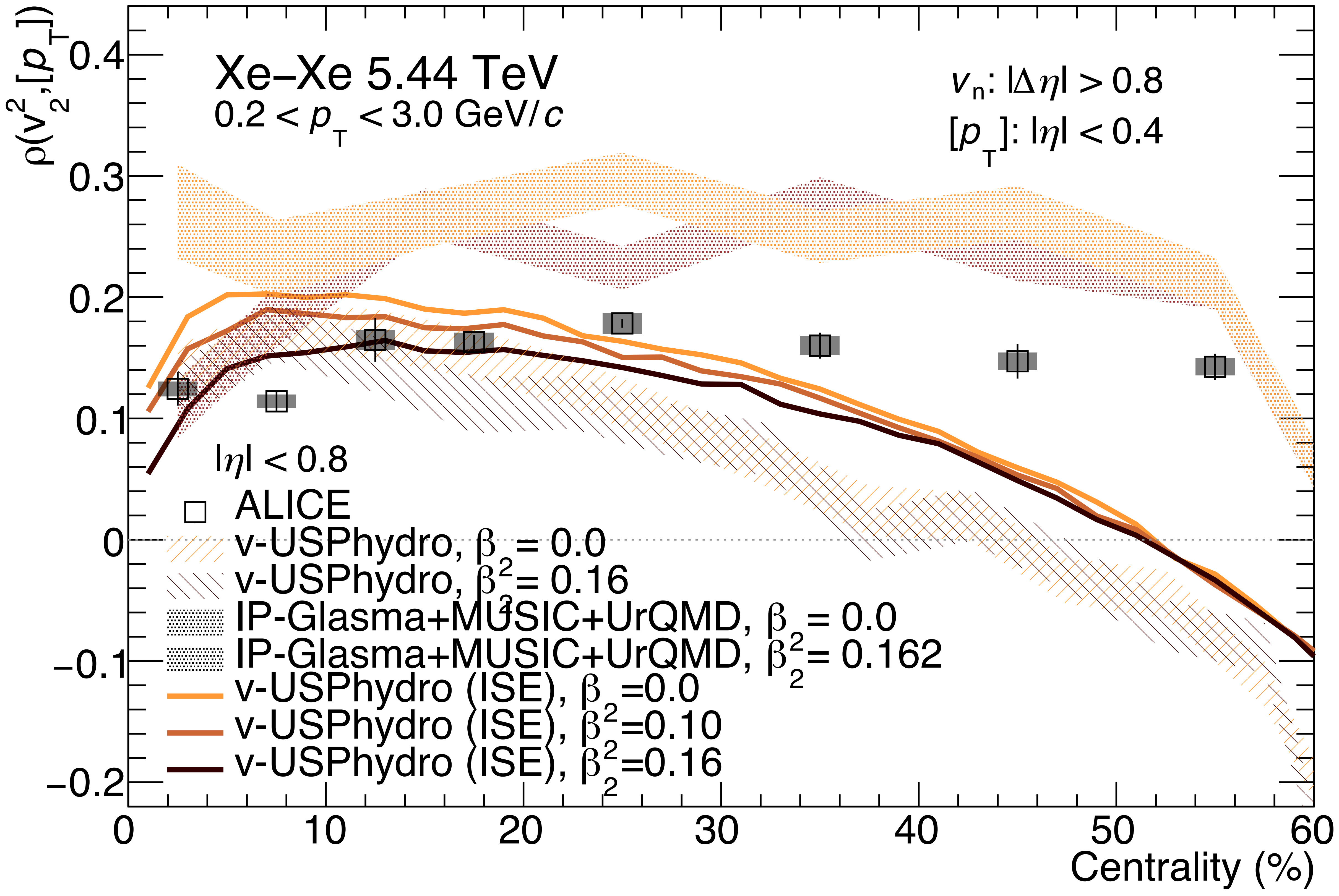
Nuclear deformation in Xe-Xe

$\rho(v_2^2, [p_\mathrm{T}])$ has strong sensitivity to deformation parameter β_2 in central collisions

Insufficient data to distinguish between β_2 values, $\beta_2 = 0.0$ ruled out by low energy experiments



ALICE Collaboration, Phys. Lett. B 834, 137393 (2022)



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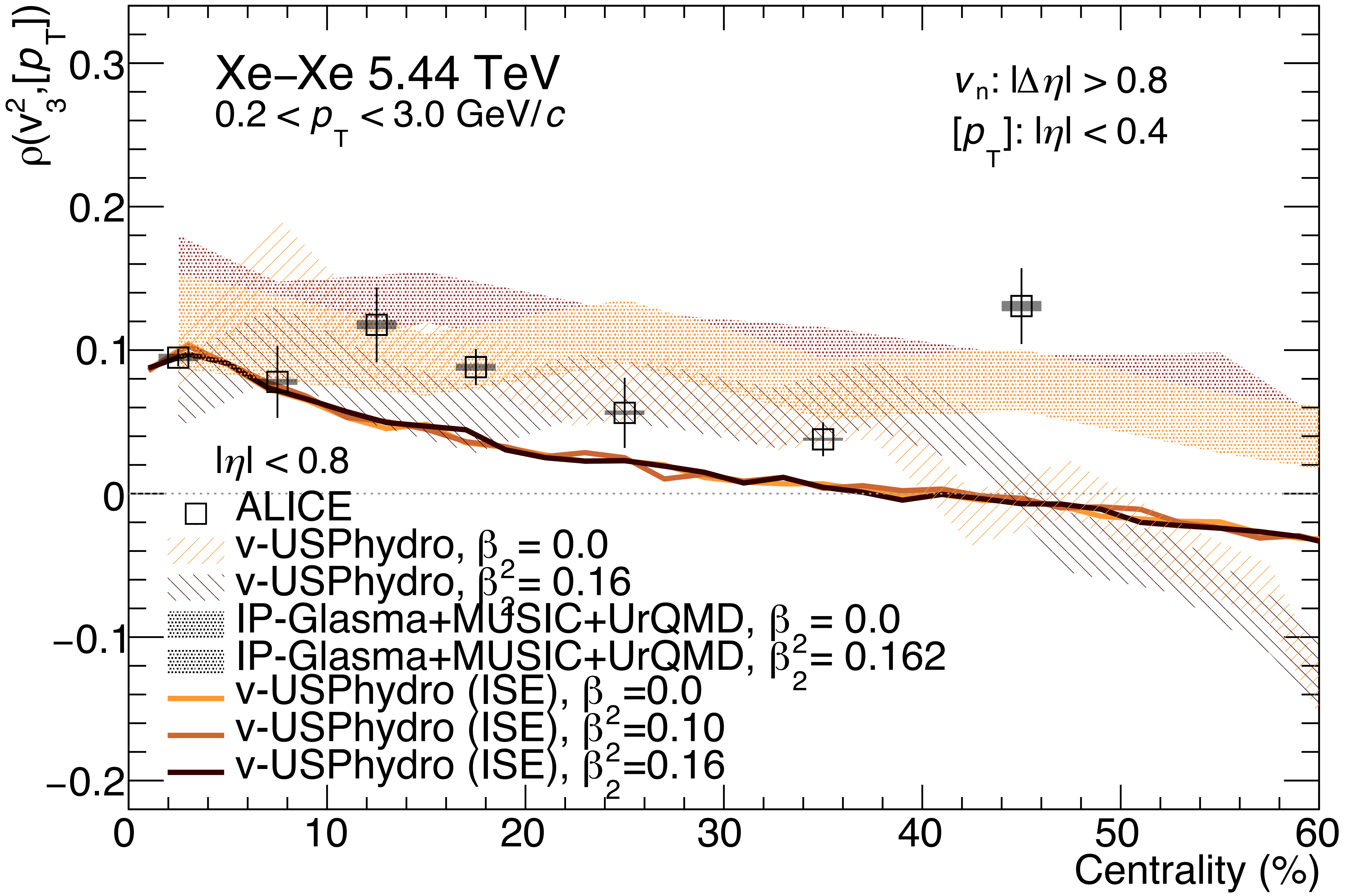
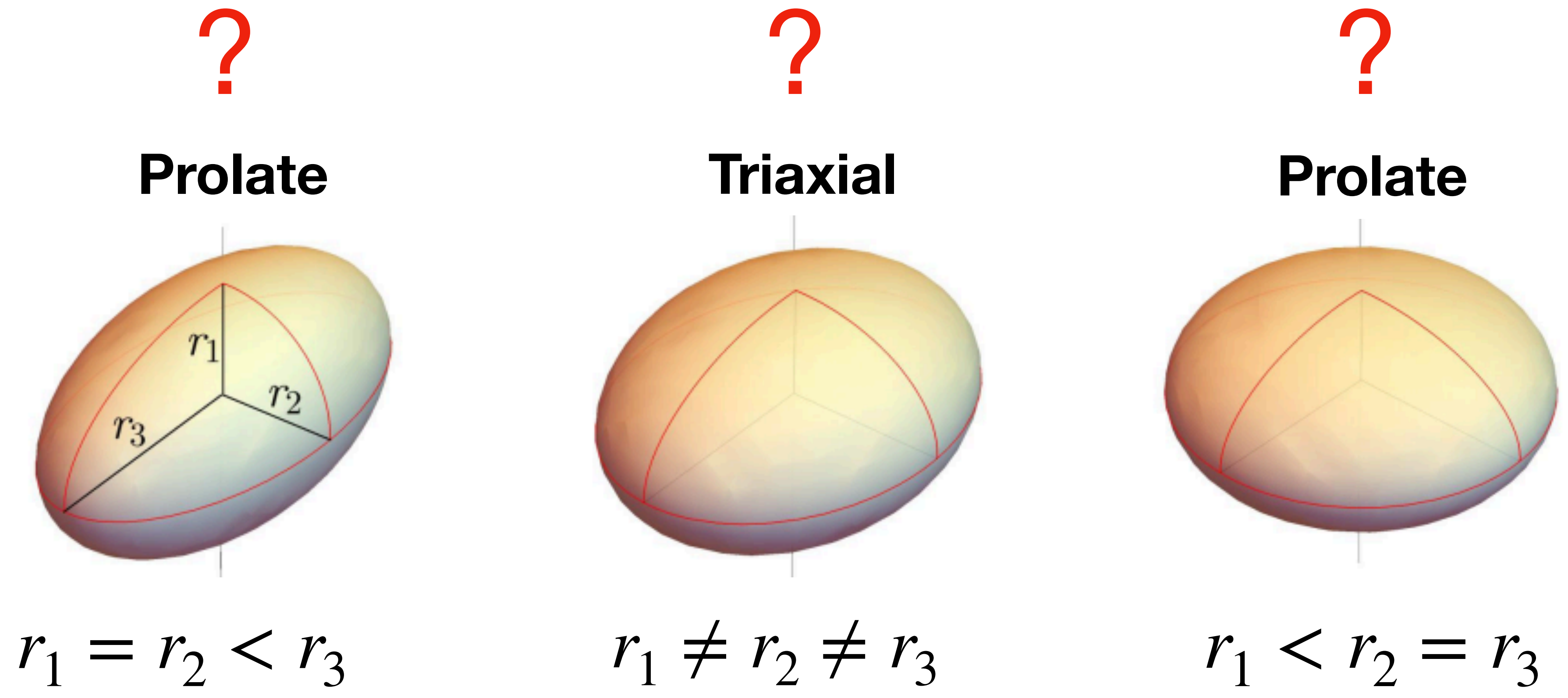
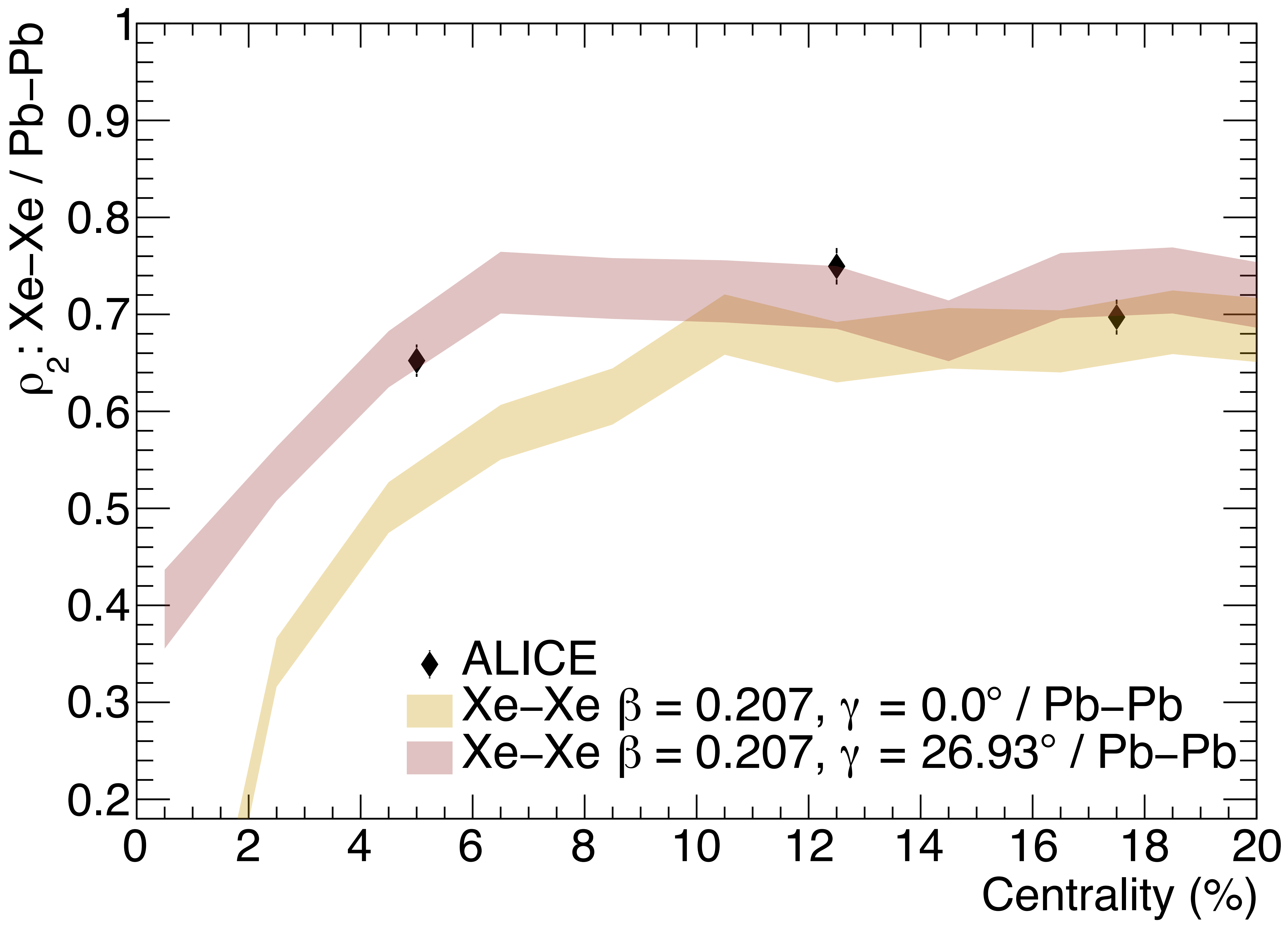


$\rho(v_3^2, [p_\mathrm{T}])$ exhibits no sensitivity to β_2

Fluctuation driven, insensitive to initial geometry



System ratio



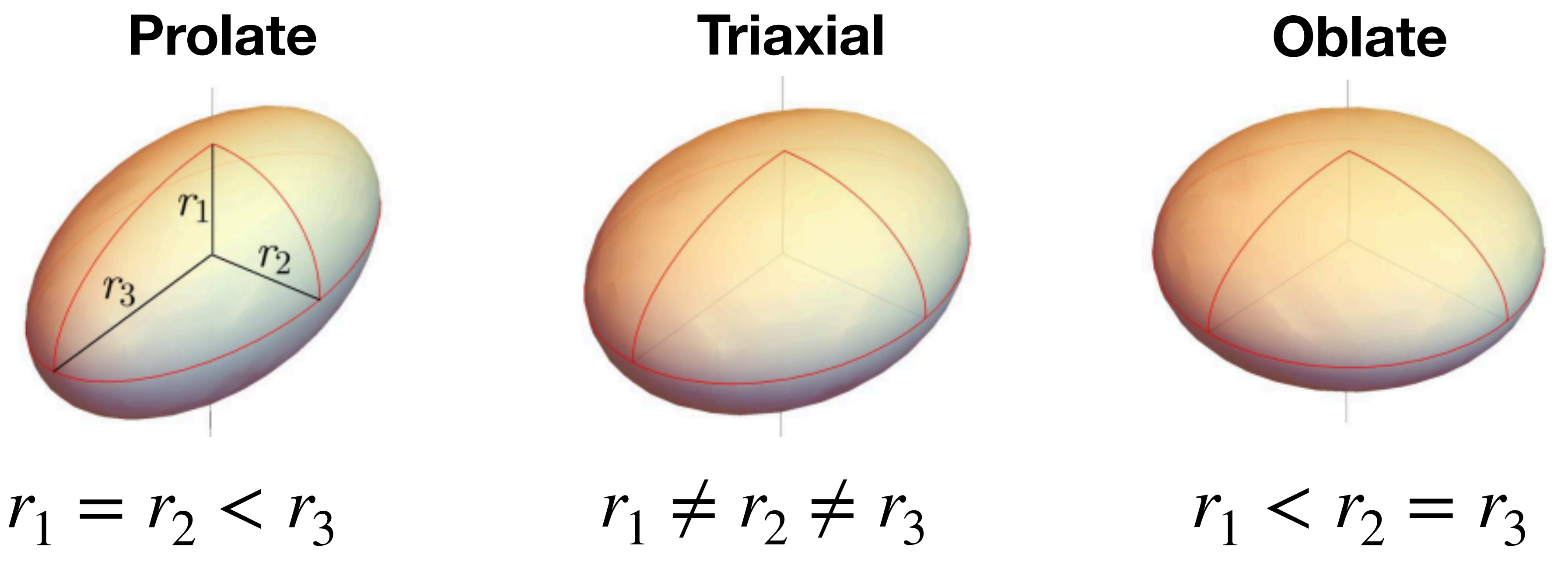
Ratio of Xe-Xe to Pb-Pb removes most systematic effects

Difference due to nuclear structure

Sensitivity to the triaxiality?

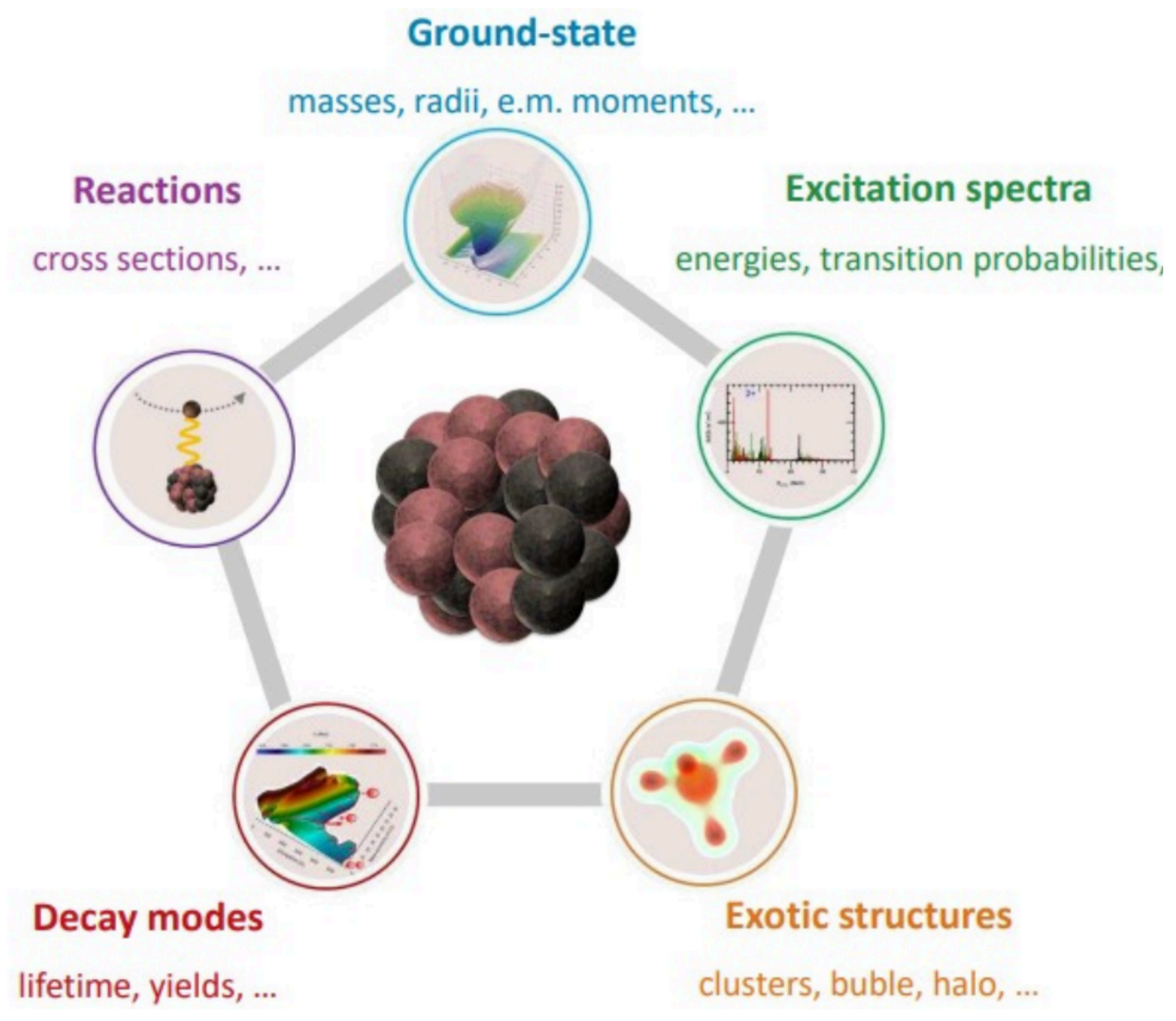
Data suggest **triaxial structure** of Xe^{129}

!



Connection to low-energy nuclear physics

Rich phenomenology in low-energy nuclear physics



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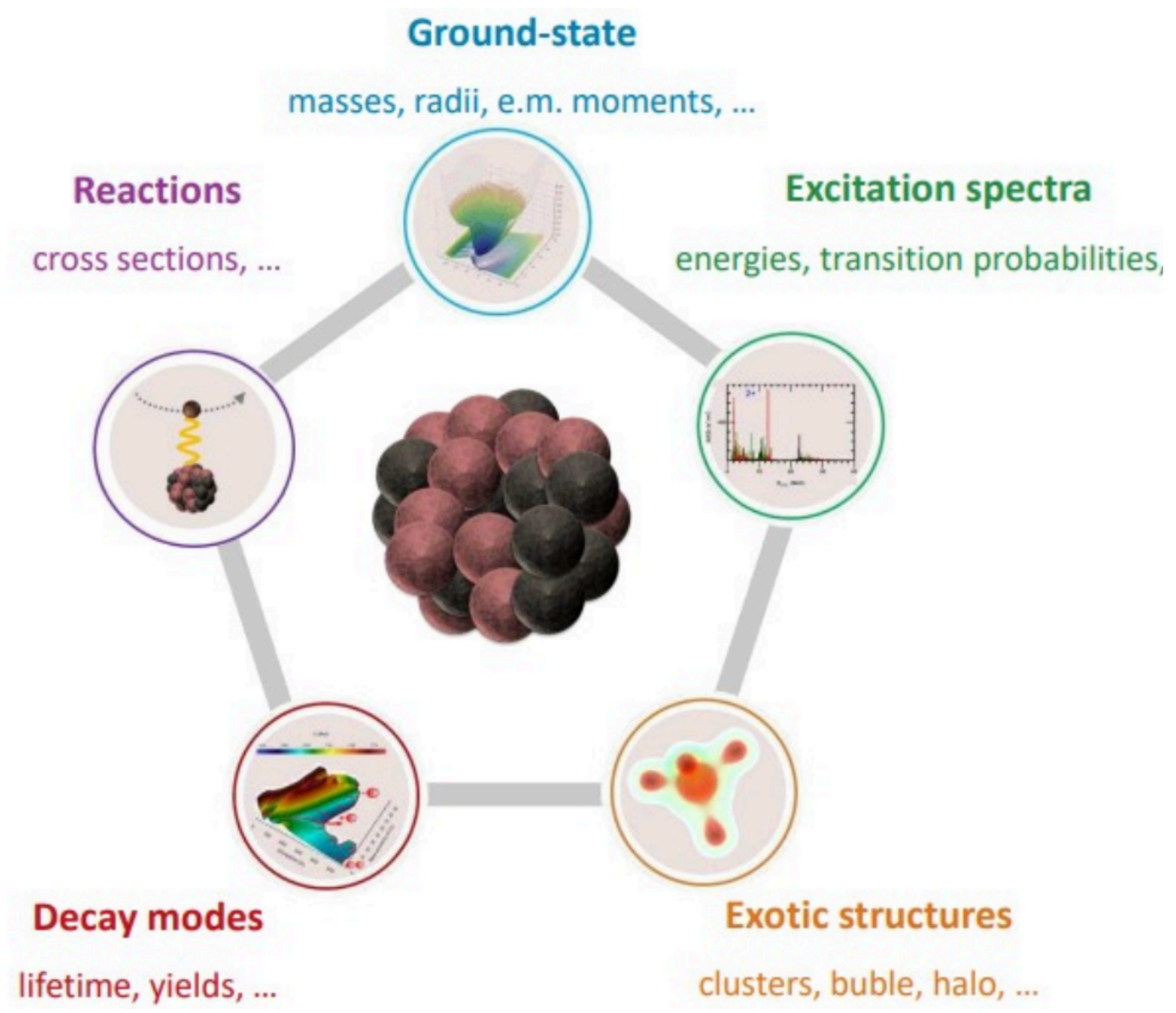
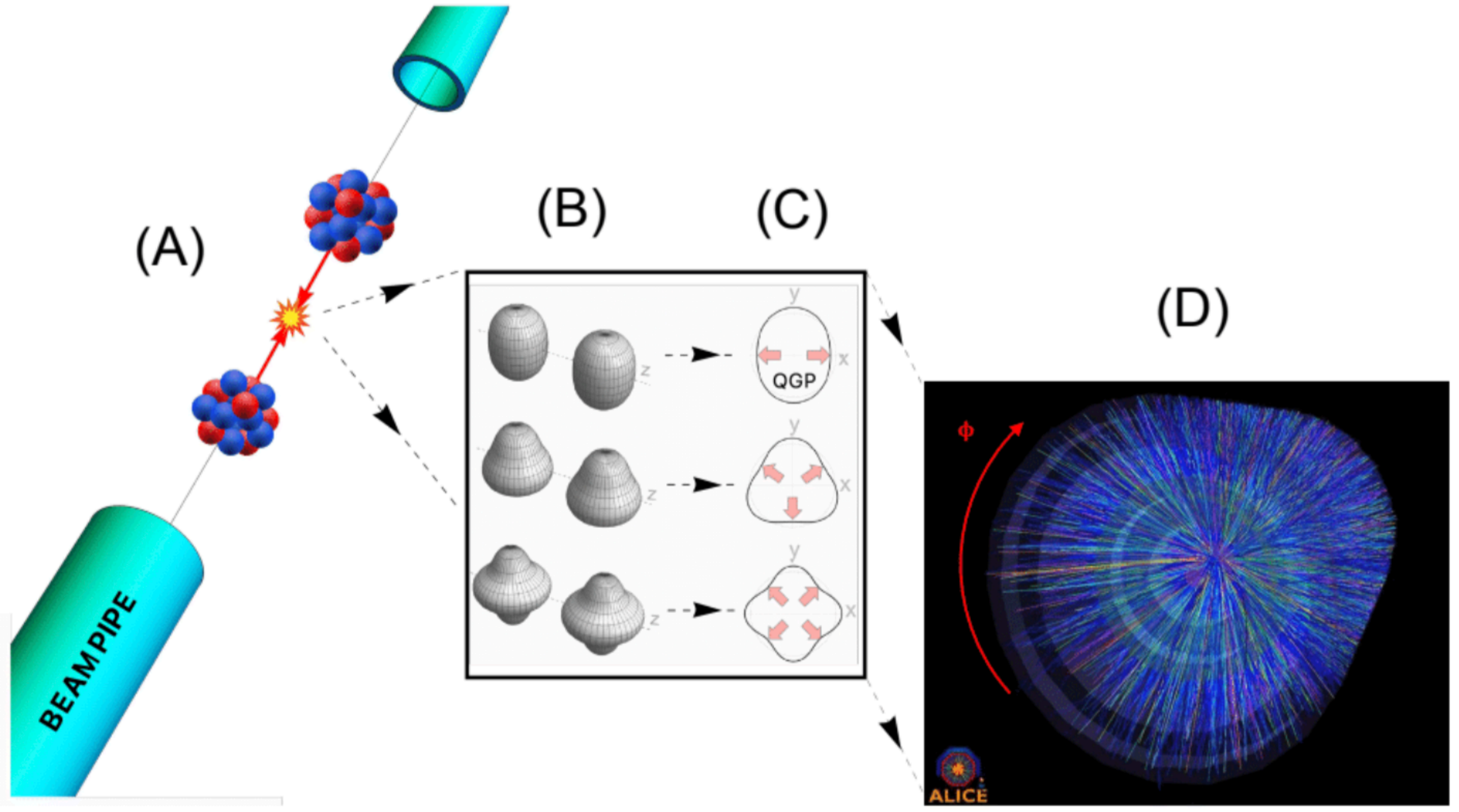
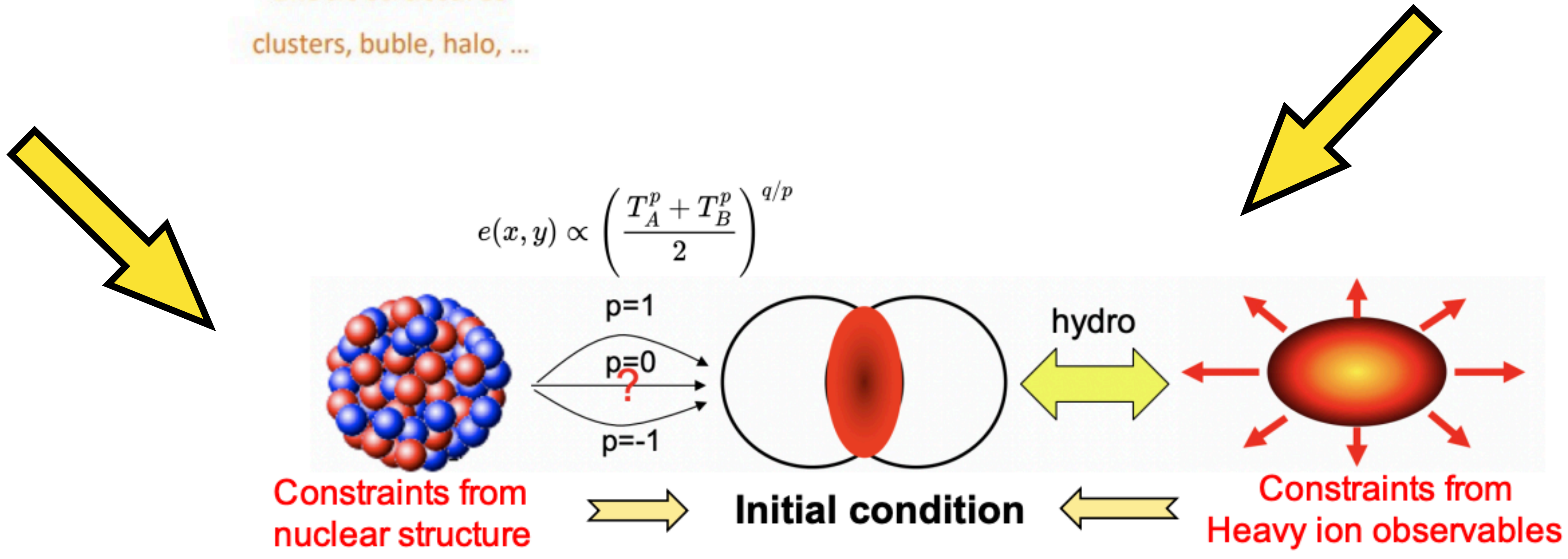
Complementary to heavy-ion physics → Pin down the initial state







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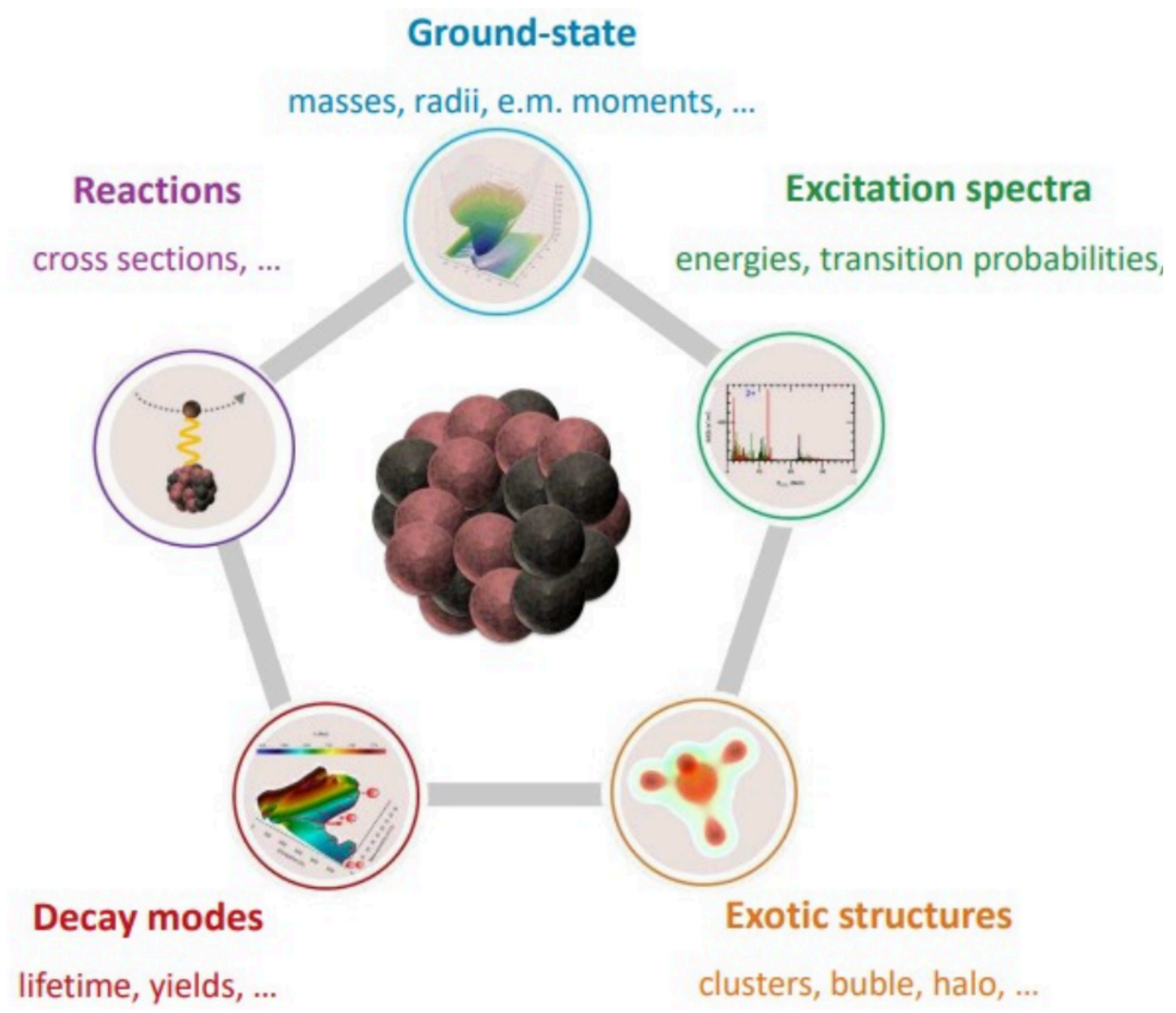
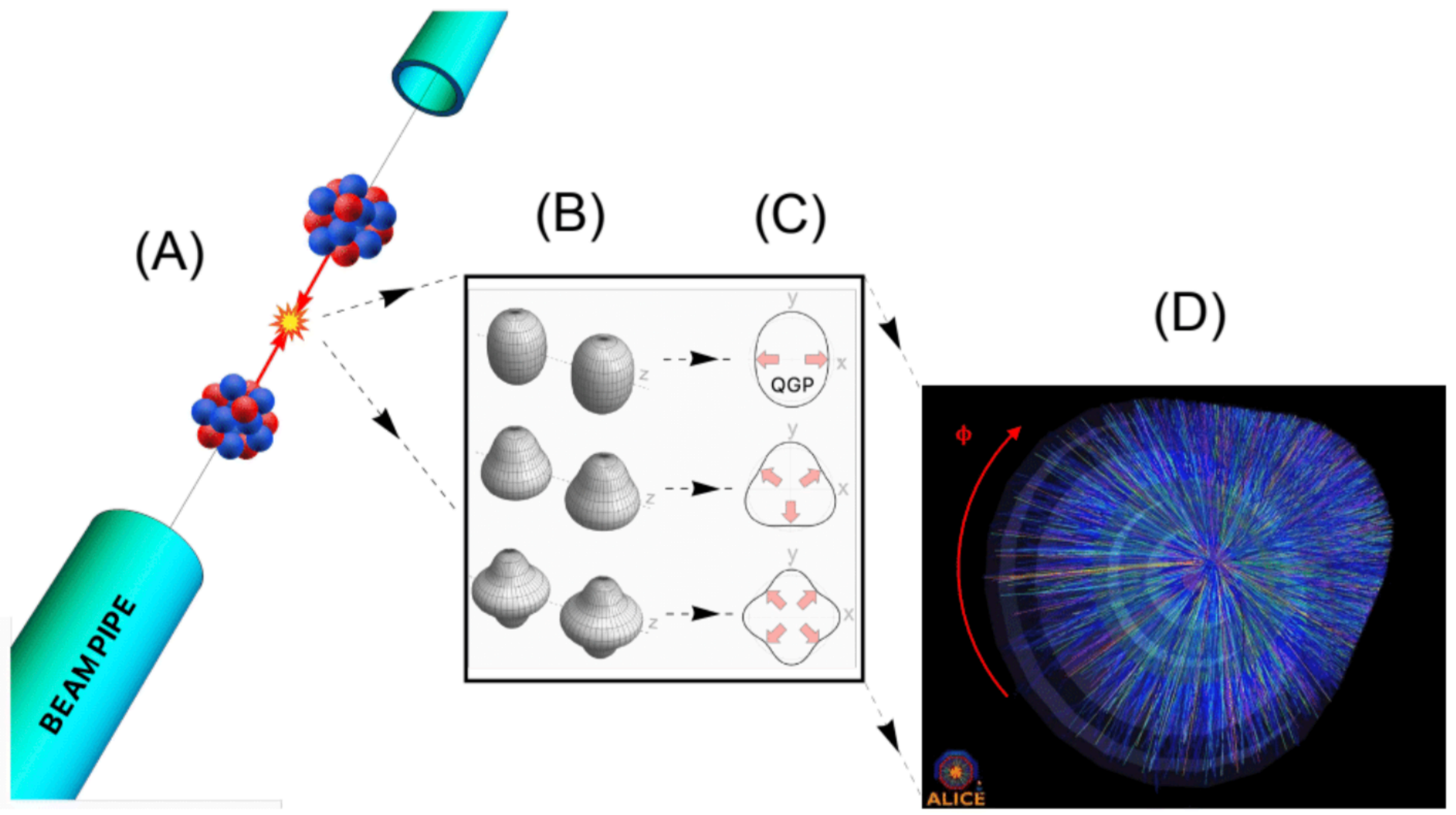
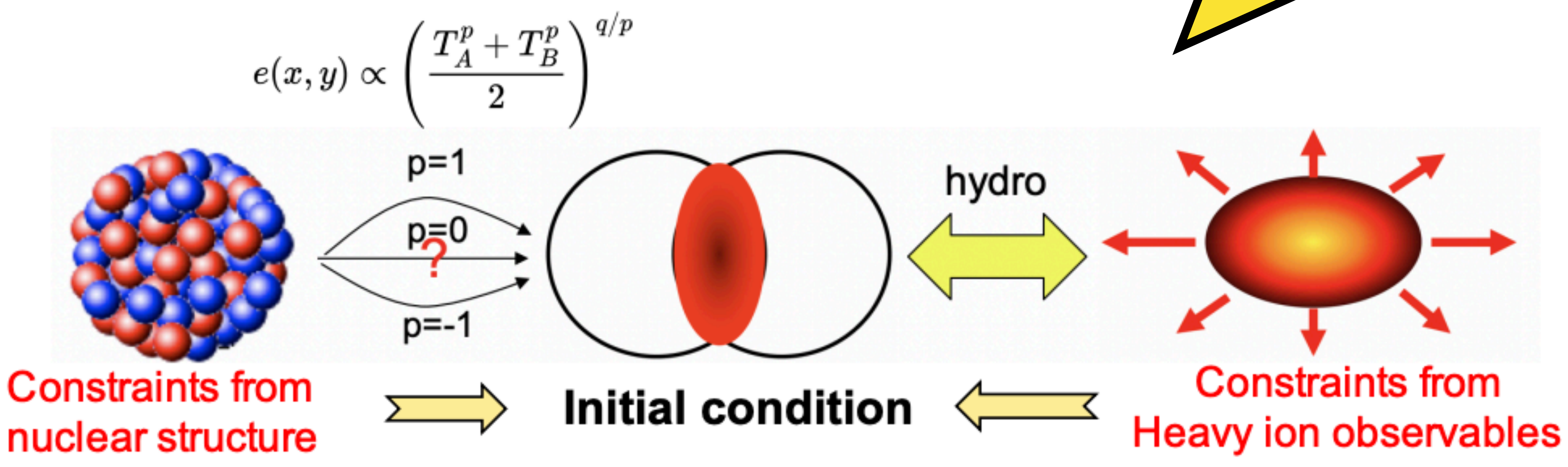
Consistent nuclear structure?

Low energy → High energy

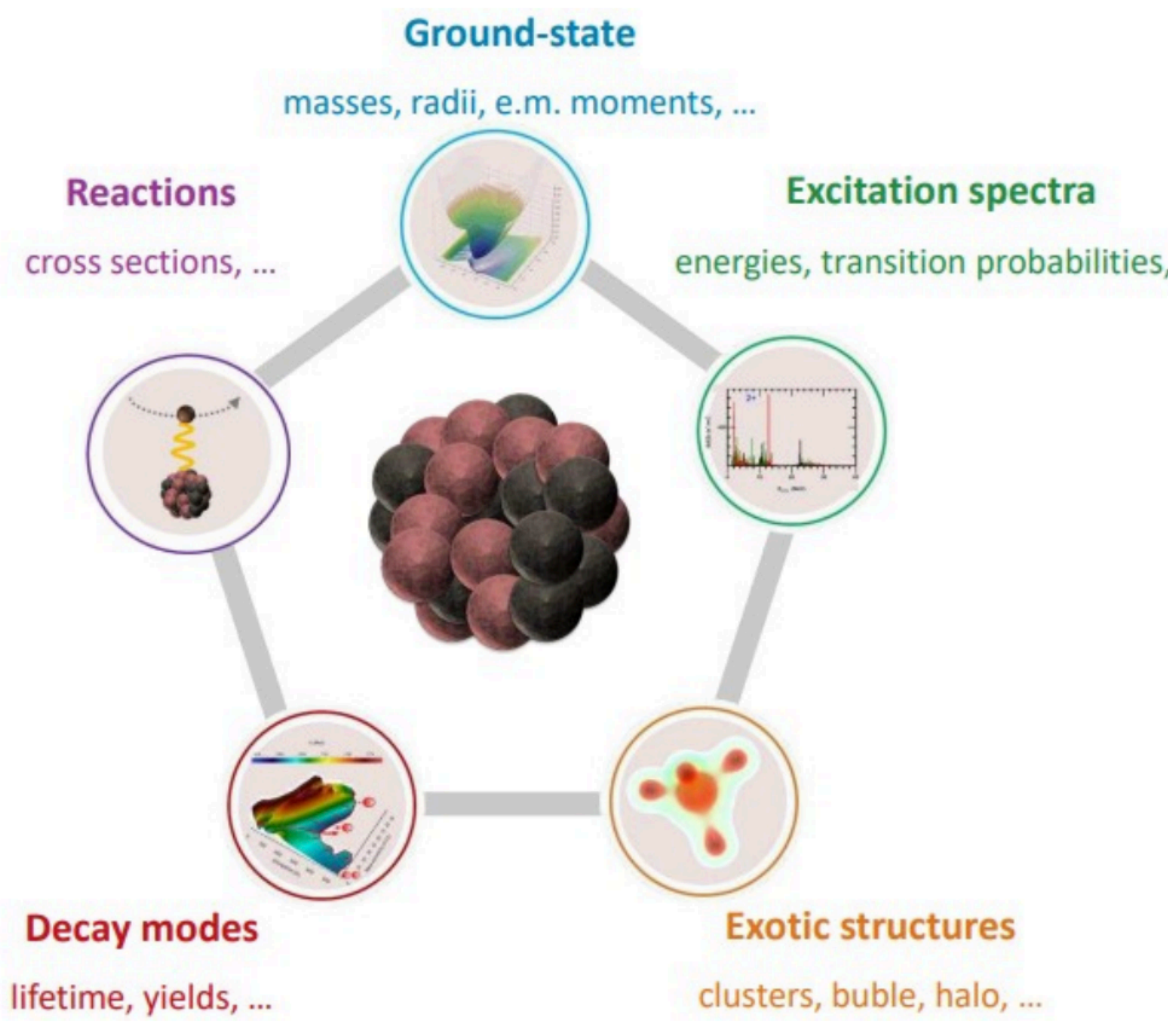




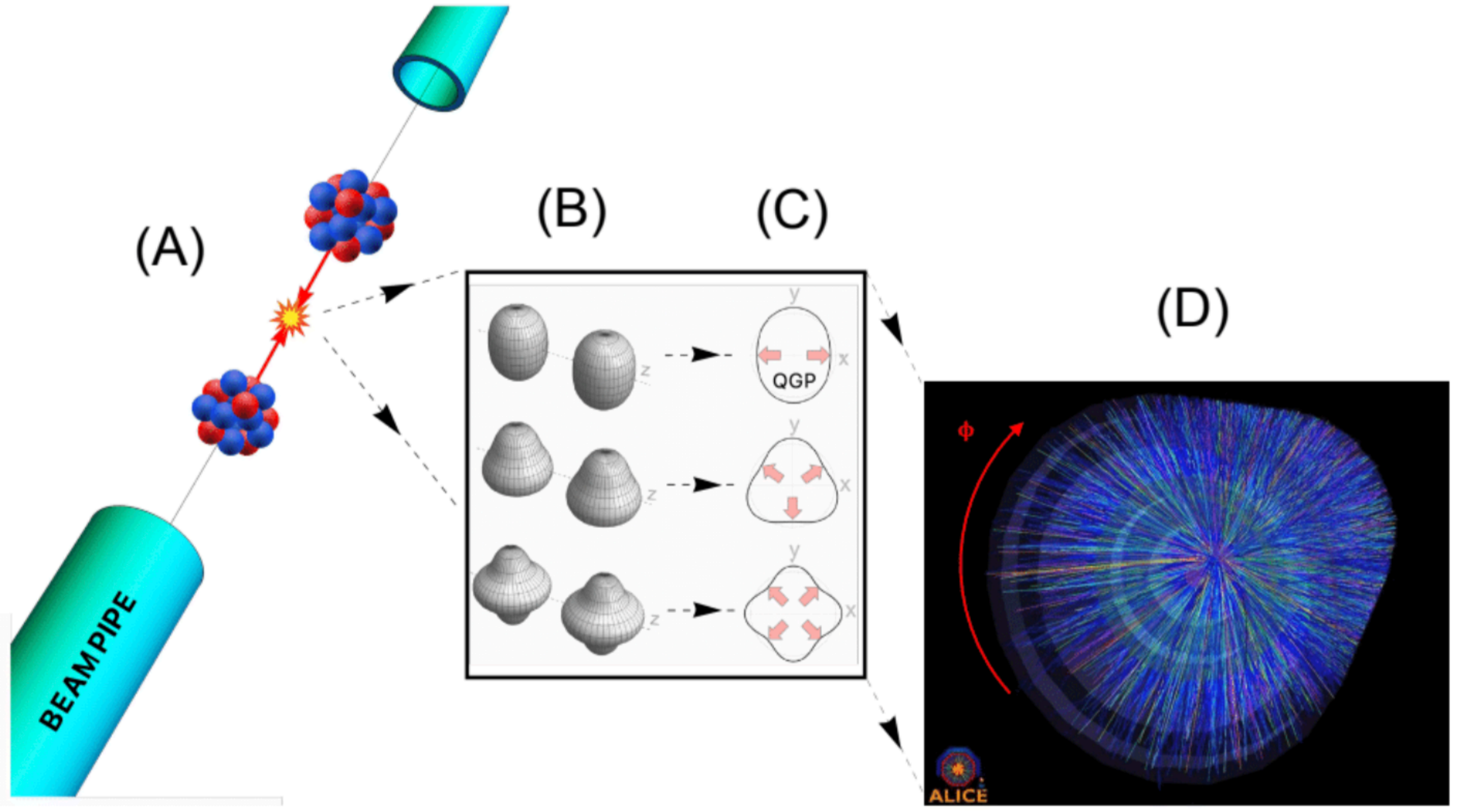


Connection to low-energy nuclear physics

Rich phenomenology in low-energy nuclear physics



Complementary to heavy-ion physics → Pin down the initial state



Consistent nuclear structure?

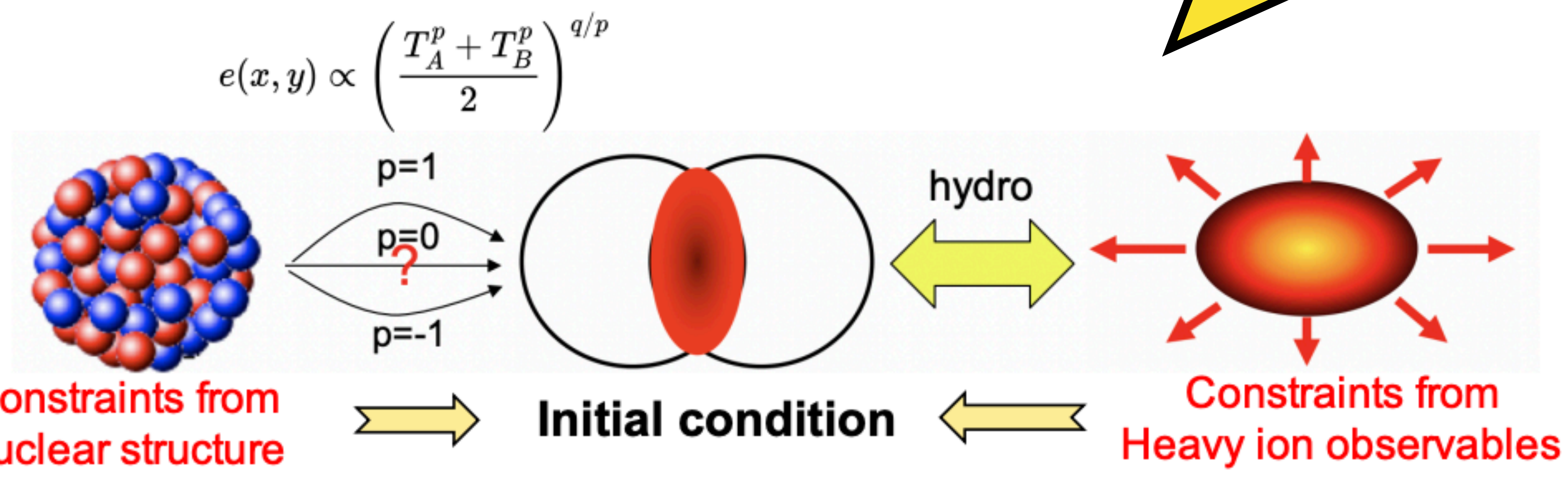
Low energy ➡ High energy

Large potential for exciting physics in heavy-ion runs of new species

Alpha clusters in O-O

Neutron skin Ca^{40} and Ca^{48}

Nuclear structure with isobar runs



Summary

Measurements of $\rho(v_2^2, [p_\mathrm{T}])$ is uniquely sensitive to the initial conditions of the heavy-ion collisions

Crucial constraints on initial state parameters

In particular, the ***nucleon width*** *is important in accurately reproducing the experimental data*

New way to study the nuclear structure at LHC energies

Sensitive to the quadrupole deformation parameter β_2 and triaxial structure γ

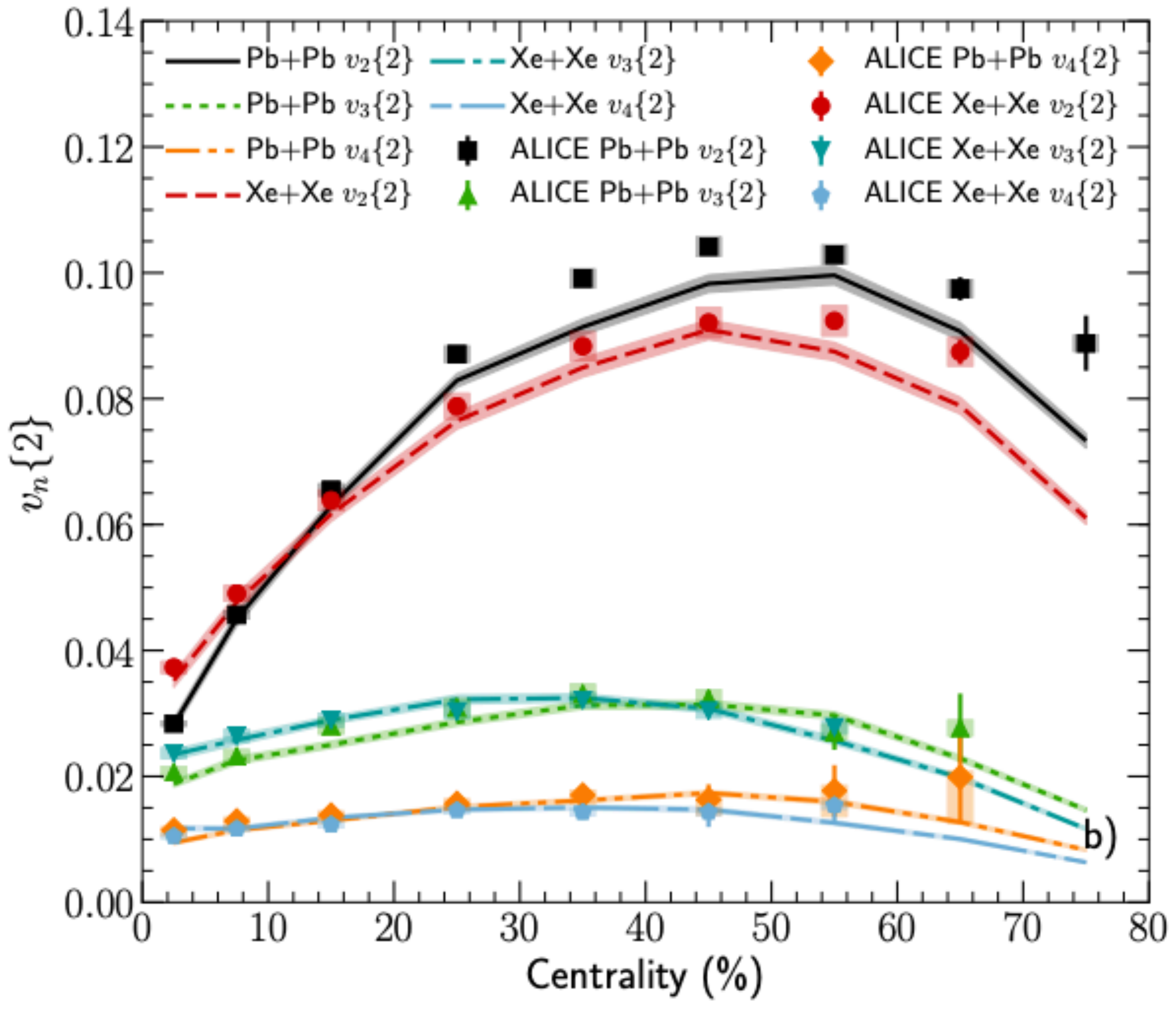
Complement the low-energy nuclear experiments

Back up

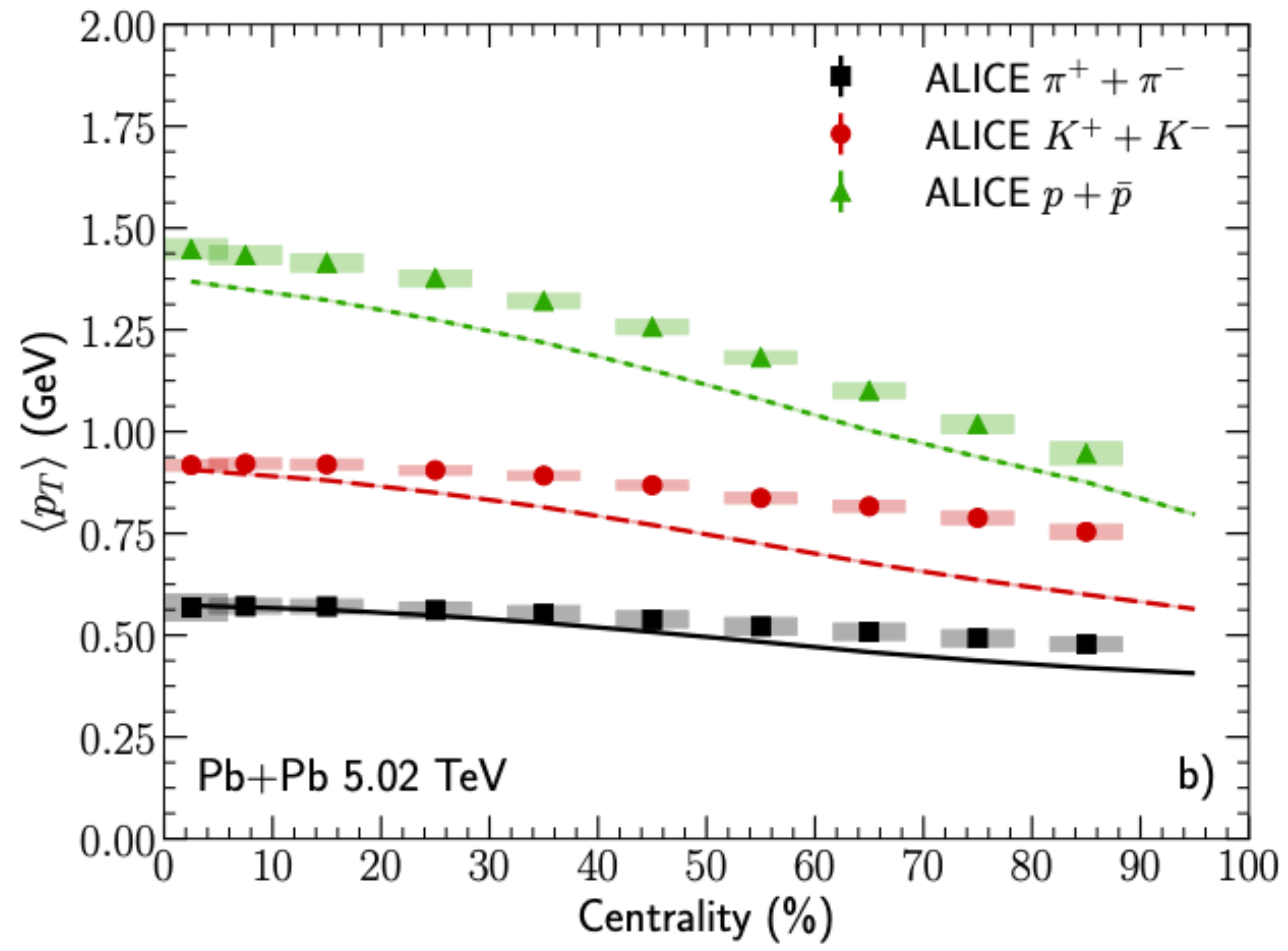
State-of-the-art models

IP-Glasma

- IP-Glasma initial conditions with hydrodynamic evolution (MUSIC) and hadronization (UrQMD)
- IP-Glasma well describes ALICE data with $\eta/s = 0.12$ and temperature dependent ζ/s up to 0.13 at $T = 160$ MeV

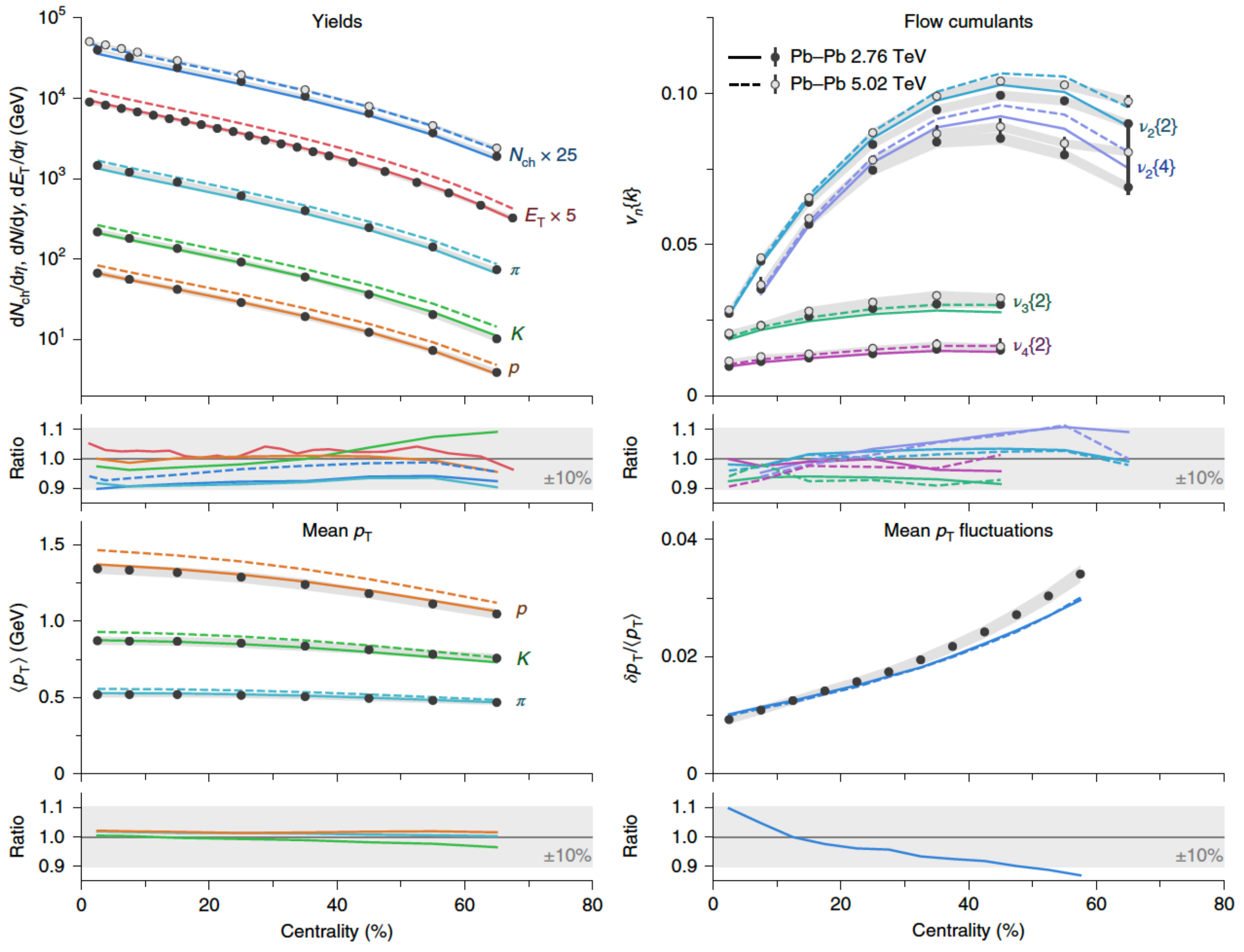


B. Schenke et al., PRC 102, 044905 (2020)

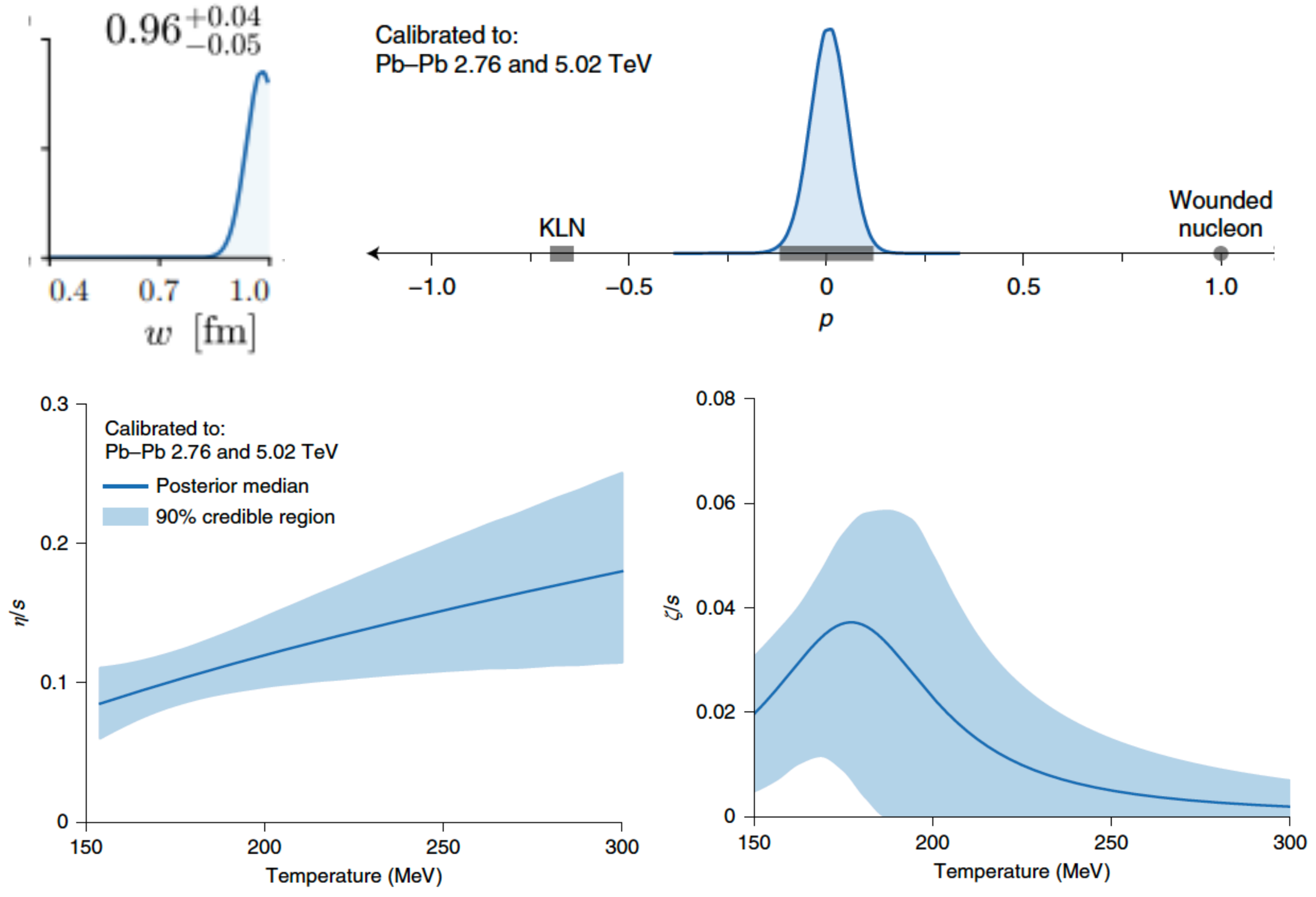


Bayesian analysis

- Based on T_RENTo initial conditions
- Fit experimental data separately to constrain the initial conditions and extract transport coefficients of QGP



J.E. Bernhard et al., Nature Physics, 15, 1113 (2019)

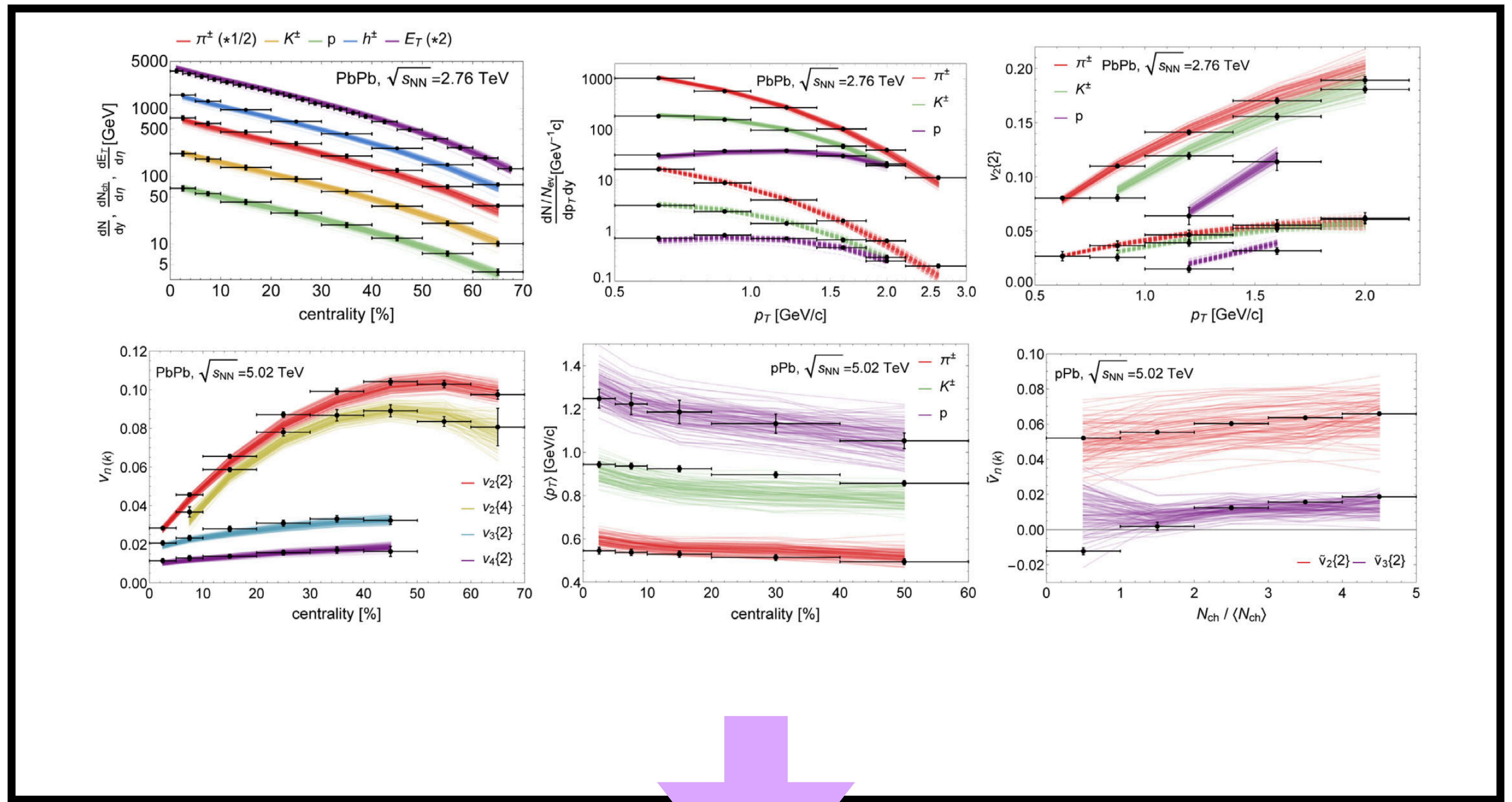


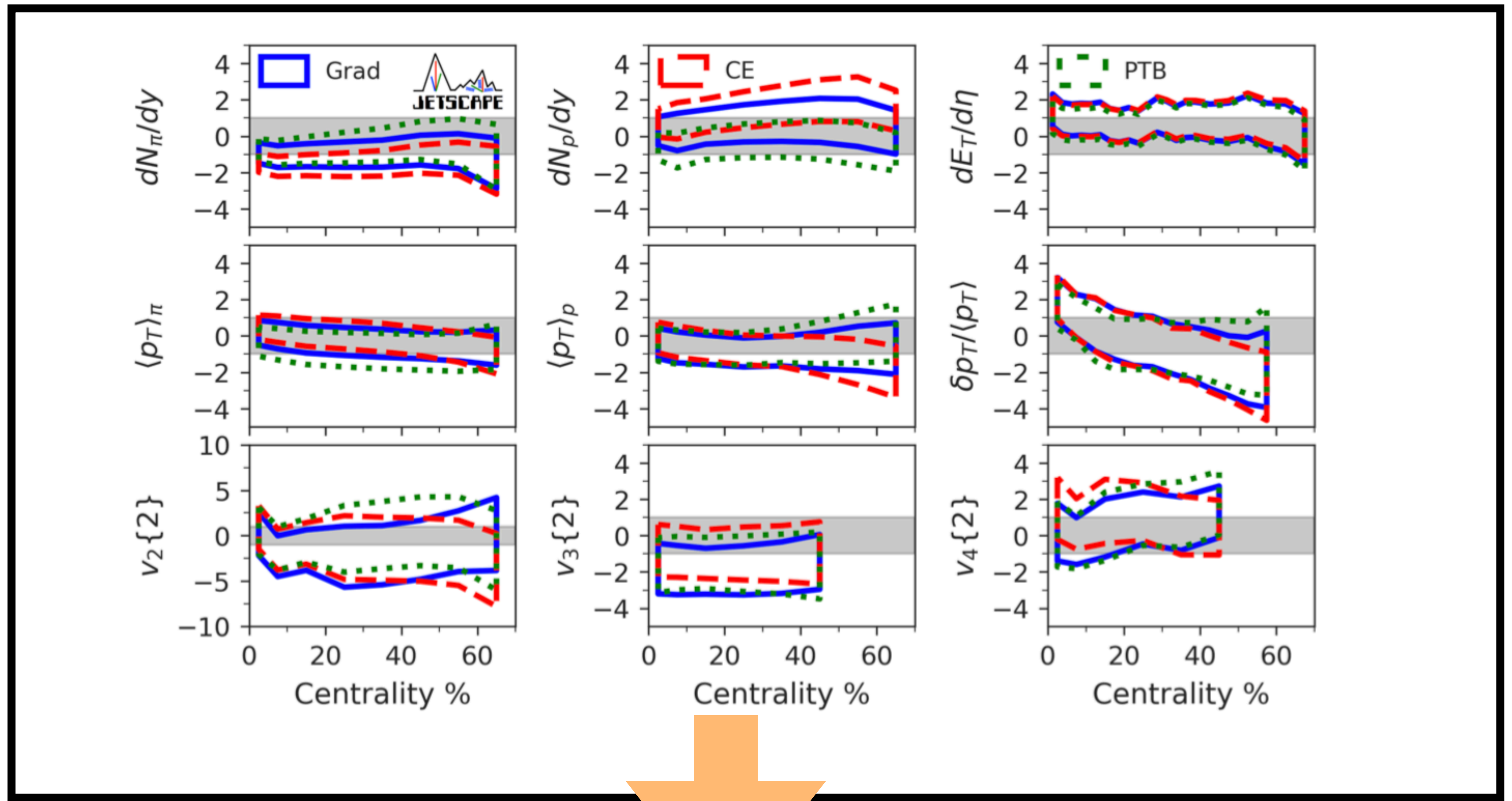
More from Bayesian analysis

Trajectum G. Nijs etc, PRL 126, 202301 (2021)

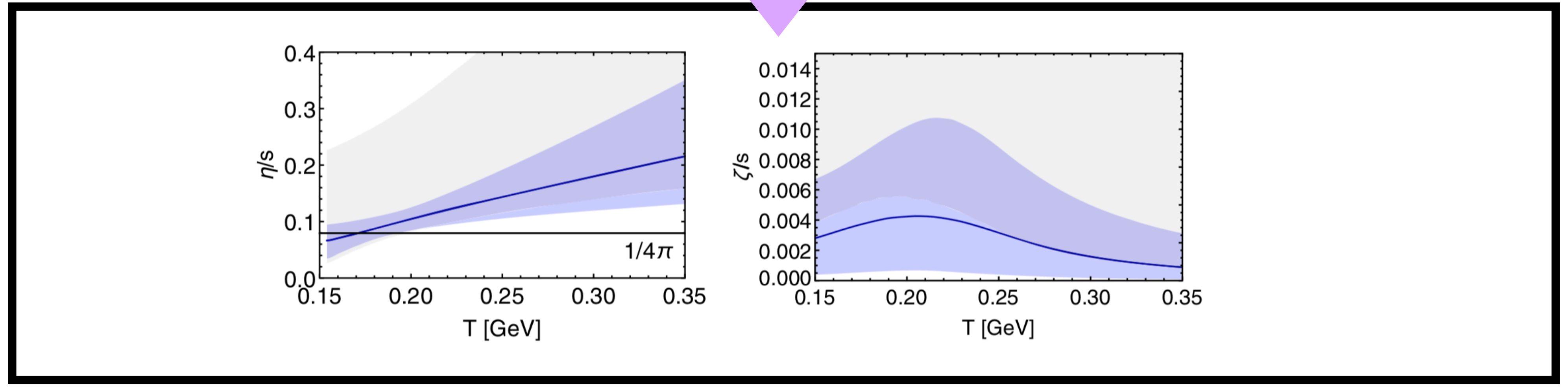
JETSCAPE JETSCAPE, PRL 126, 242301 (2021)

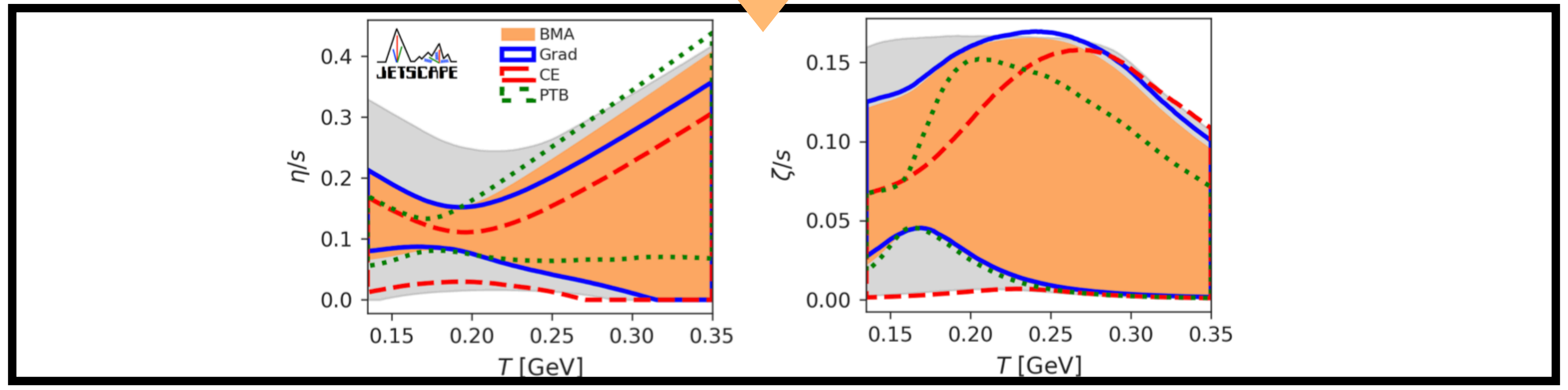
Simultaneous fits to data





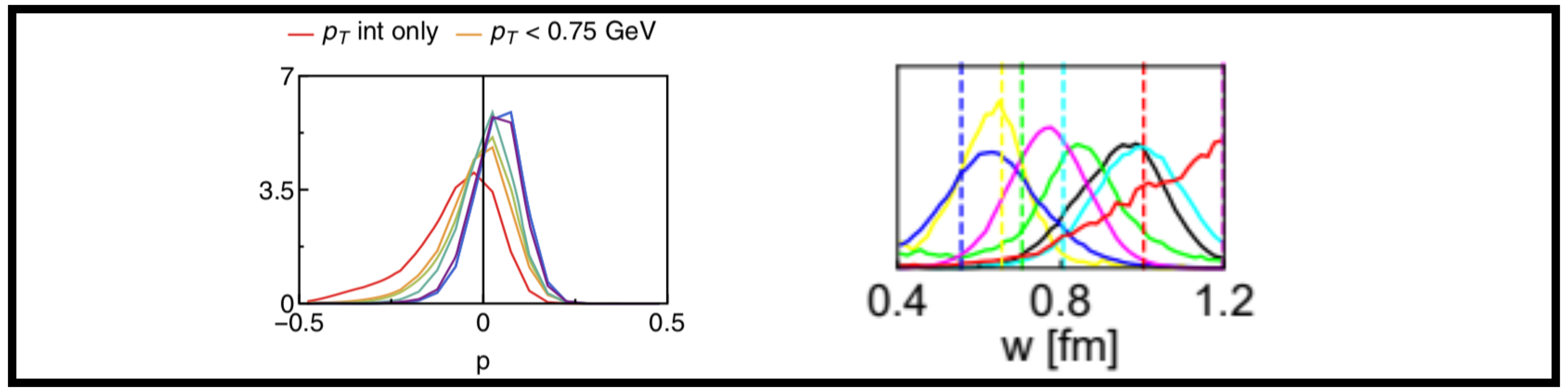
Transport coefficients

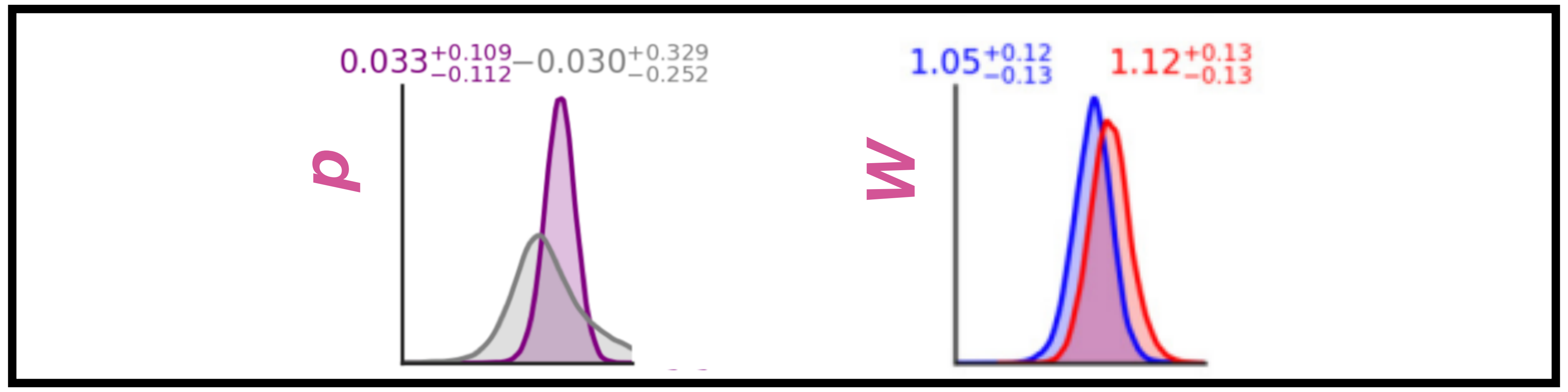




&

Initial conditions





Initial state estimators

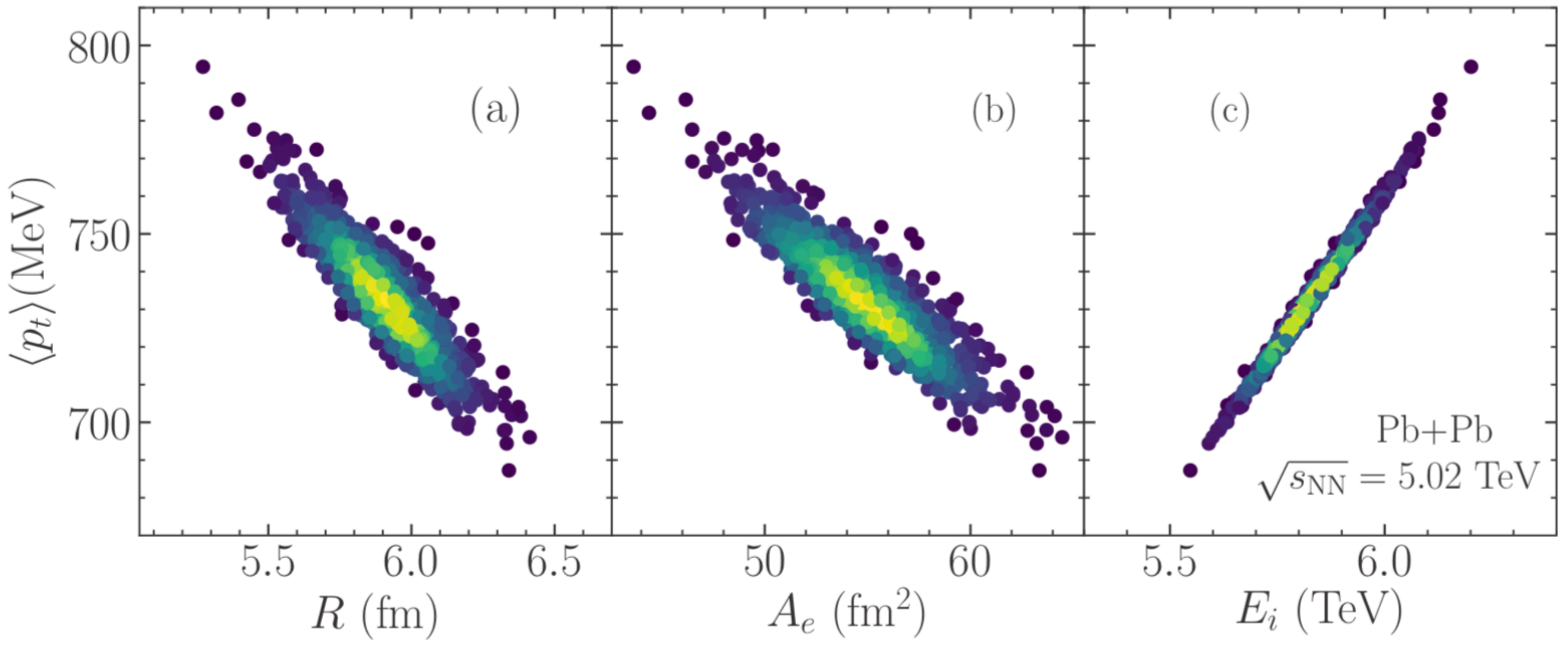
Probing the initial state requires *initial state estimators*

Estimating v_n^2

- In hydrodynamics: proportional to **initial eccentricity** $v_n \propto \kappa_n \epsilon_n$
- Hydrodynamic response to initial geometry

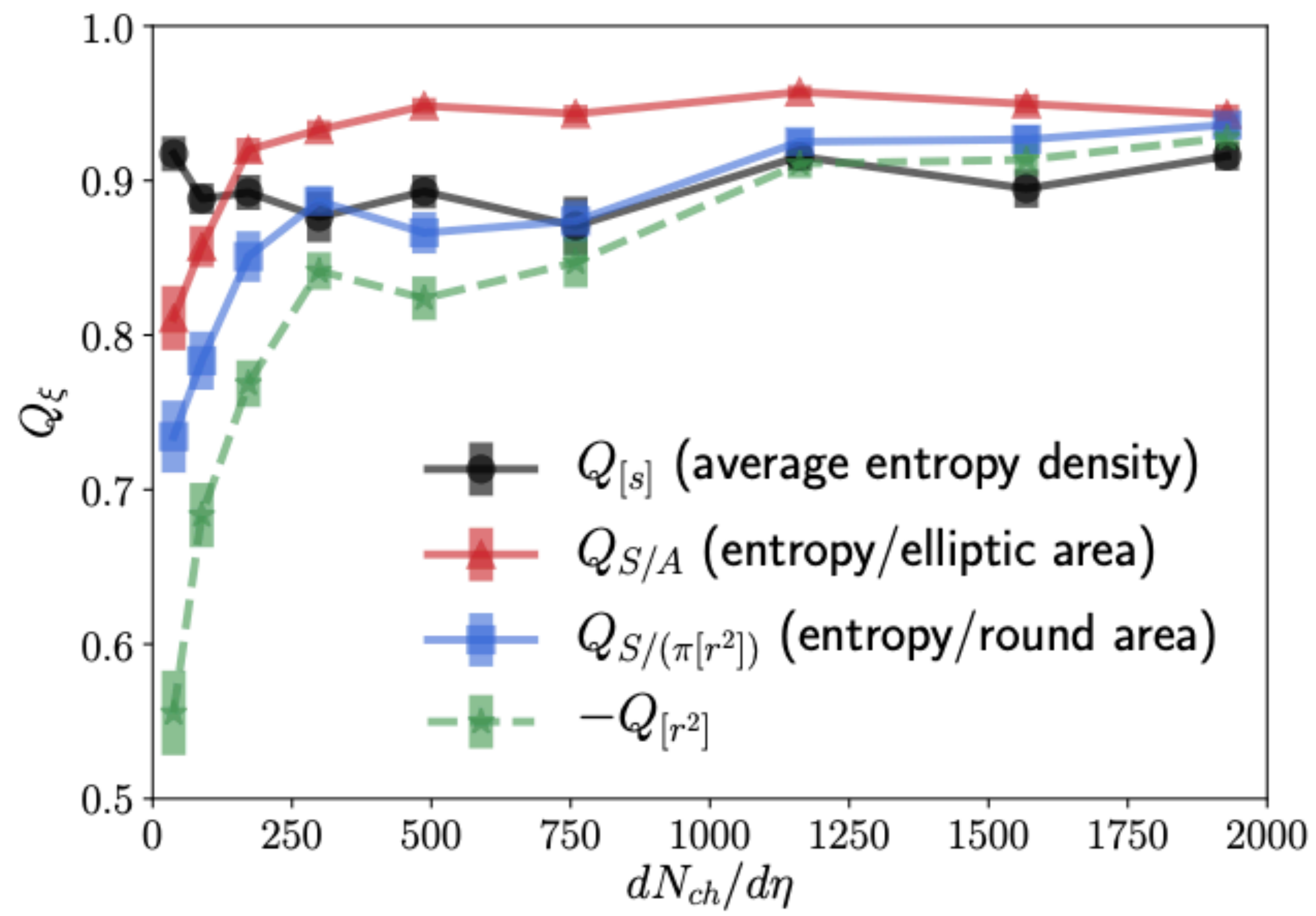
Estimating $[p_T]$

- Inversely related to the size of the system
- Proportional to the **initial energy** of the fluid



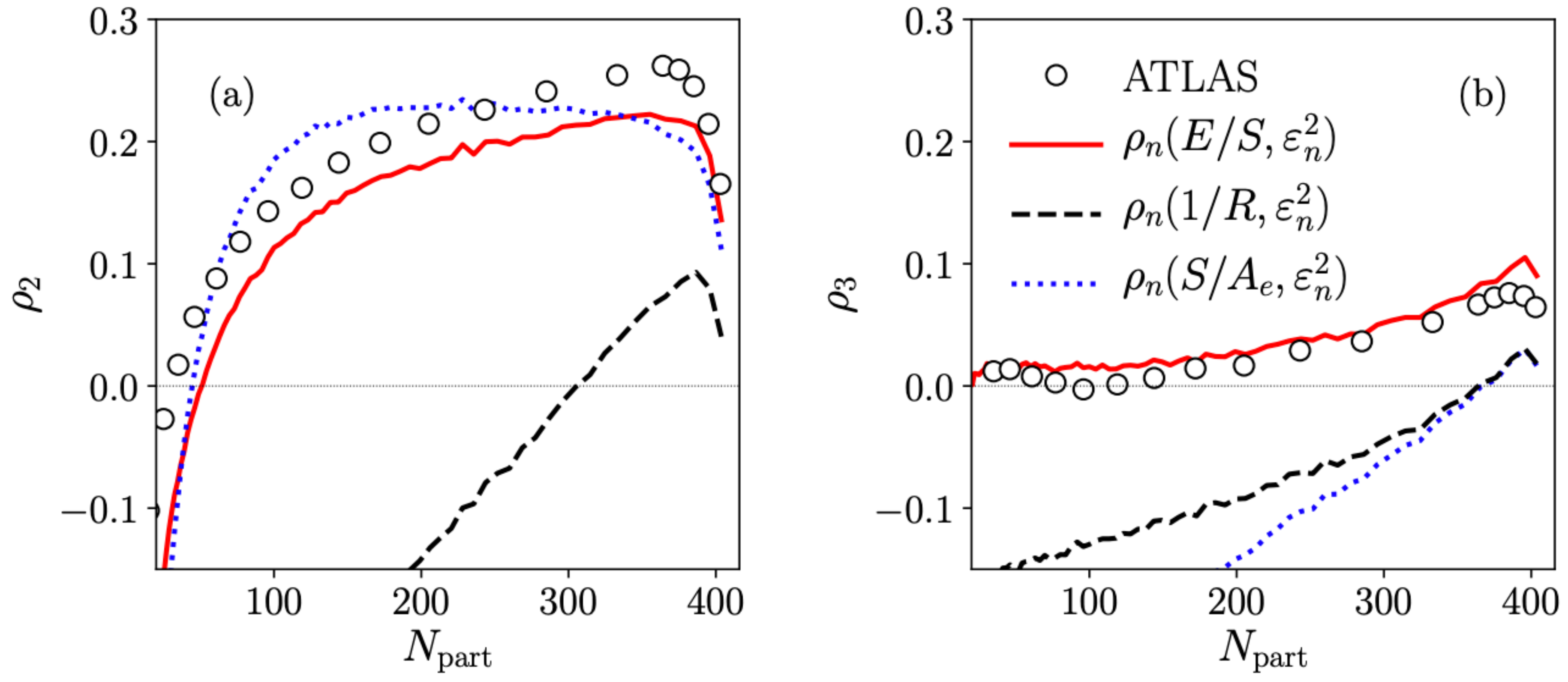
G. Giacalone et al., PRC 103, 024909 (2021)

IP-Glasma: B. Schenke et al., PRC 102, 034905 (2020)



Q values close to 1.0
→ better estimator

T_RENTo: G. Giacalone et al., PRC 103, 024909 (2021)



Use ε_n and E_i/S for the estimation of v_n-$[p_T]$ correlation

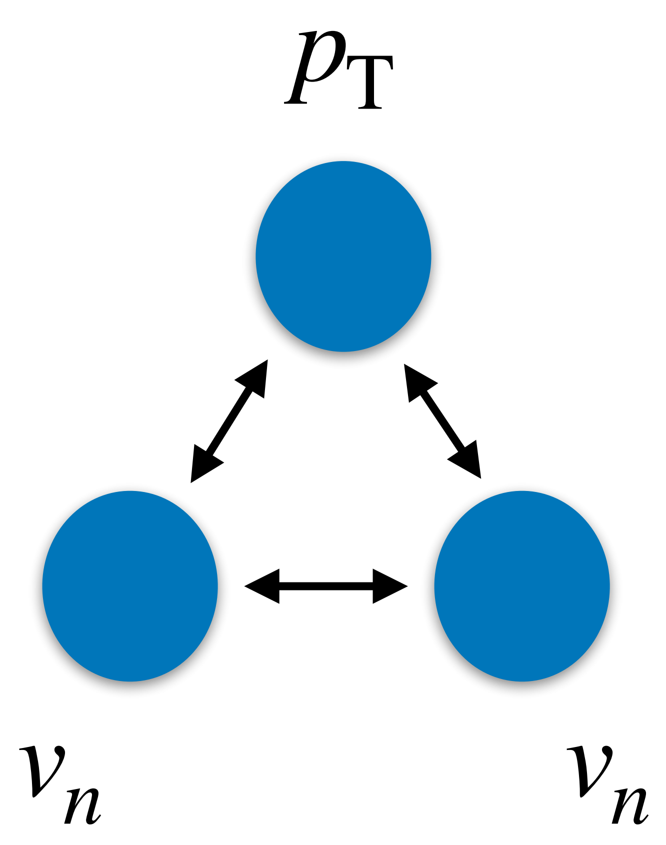
Observable

Correlation of v_n^2 with $[p_\mathrm{T}]$

$$\rho(v_n^2, [p_\mathrm{T}]) = \frac{\mathrm{cov}(v_n^2, [p_\mathrm{T}])}{\sqrt{c_k}\sqrt{\mathrm{var}(v_2^2)}}$$

P. Bozek, PRC 93, 044908 (2016)

Three-particle cumulant



$$\langle\langle 3\rangle\rangle - 3\langle\langle 2\rangle\rangle\langle\langle 1\rangle\rangle + 2\langle\langle 1\rangle\rangle^3$$
$$= \langle\langle v_n^2 \cdot [p_\mathrm{T}]\rangle\rangle - \langle\langle v_n^2\rangle\rangle\langle[p_\mathrm{T}]\rangle$$
$$= \mathrm{cov}(v_n^2, [p_\mathrm{T}])$$

Normalization

Dynamical $[p_\mathrm{T}]$-fluctuations

Particle weight, w, to correct detector inefficiencies

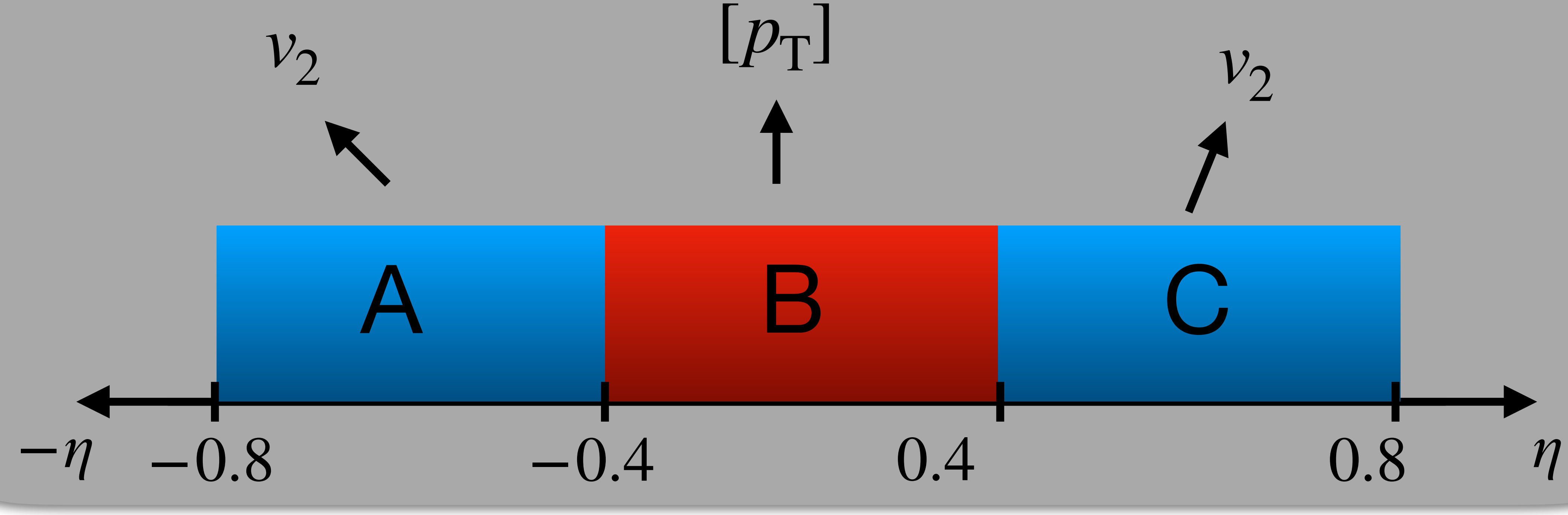
$$c_k = \frac{\sum_{i\neq j} w_i w_j (p_{\mathrm{T,i}} - [p_\mathrm{T}])(p_{\mathrm{T,j}} - [p_\mathrm{T}])}{\sum_{i\neq j} w_i w_j}$$

Dynamical v_n-fluctuations

$$\mathrm{var}(v_n^2) = v_n\{2\}^4 - v_n\{4\}^4$$

Subevents

- Separate v_n and $[p_\mathrm{T}]$ by a gap in pseudorapidity
- Removes autocorrelations



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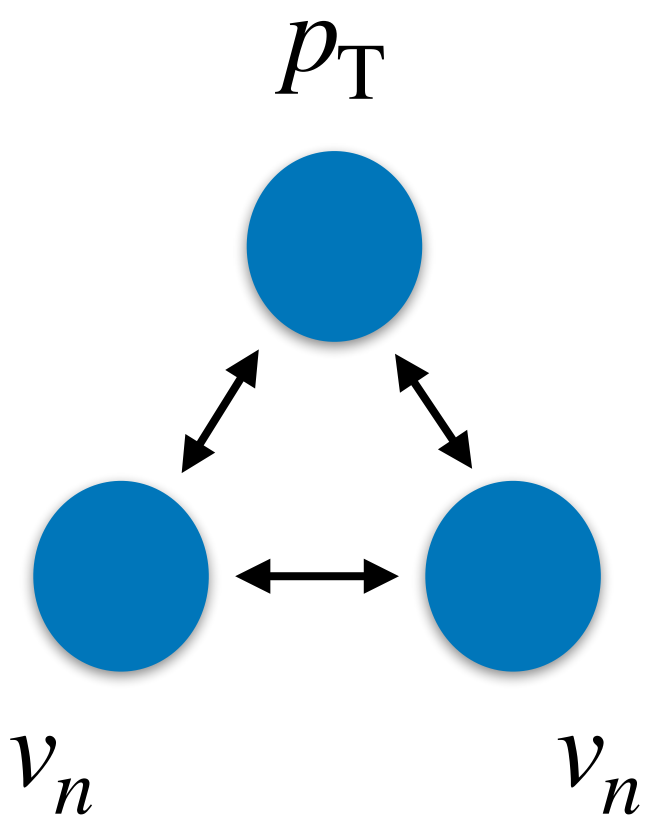

$$\langle\langle 3\rangle\rangle - \cancel{3}\langle\langle 2\rangle\rangle\langle\langle 1\rangle\rangle + \cancel{2\langle\langle 1\rangle\rangle^3}$$
$$= \langle\langle v_n^2 \cdot [p_\mathrm{T}]\rangle\rangle - \langle\langle v_n^2\rangle\rangle\langle[p_\mathrm{T}]\rangle$$
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