Probing the nuclear structure with multiparticle correlation in Xe–Xe collisions

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For the ALICE Collaboration

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ALICE

From final state to nuclear structure

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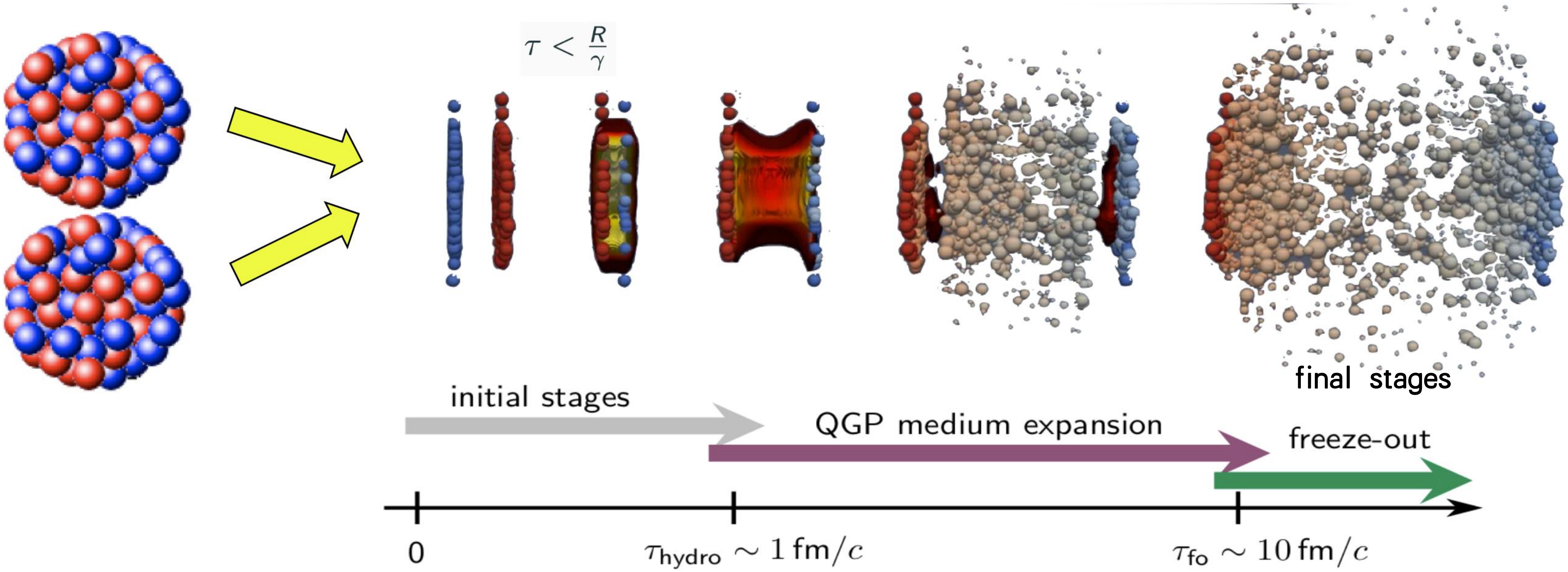

hydro evolution

nuclear structure ⟷ **inital conditions** ⇄ **anisotropic distribution of final-state particles**

probe

From final state to nuclear structure

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nucleon density described by **Woods-Saxon profile**

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{[r-R(\theta,\phi)]/a_0}},$$

$$R(\theta,\phi) = R_0\left(1+\beta_2[\cos\gamma Y_{2,0} + \sin\gamma Y_{2,2}] + \beta_3\sum_{m=-3}^{3}\alpha_{3,m}Y_{3,m} + \beta_4\sum_{m=-4}^{4}\alpha_{4,m}Y_{4,m}\right)$$

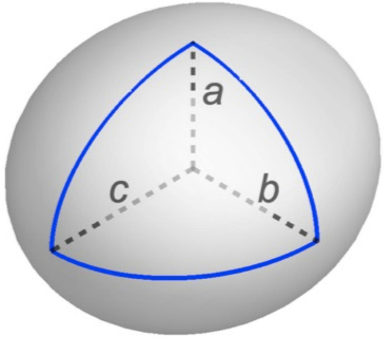
β_2: overall deformation parameter
a_0: diffuseness parameter
γ: triaxiality parameter

We study the structure of ^{129}Xe at the LHC,
as it is predicted to exhibit deformed and triaxial structure ($r_1 \neq r_2 \neq r_3$).

B. Bally et al., Phys.Rev.Lett. 128 (2022) 8, 082301

Stronger effect from deformation

β_2=0.2, γ=30°



$a \neq b \neq c$

J. Jia, Phys.Rev.C 105 (2022) 4, 044905

Observables

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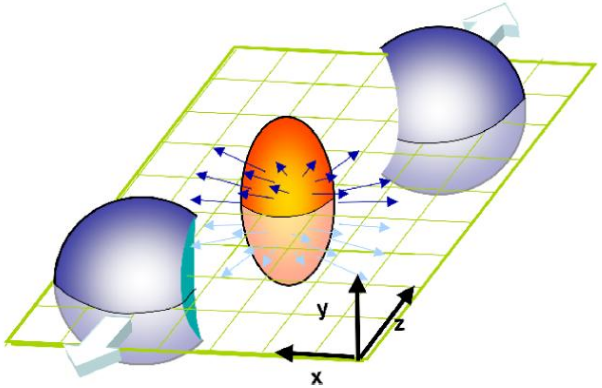
$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi_n)$$



- **flow coefficients with 2- and 4-particle cumulants:** $v_n\{2\}(n = 2,3,4)$, $v_2\{4\}$
- **mean elliptic flow:** $\bar{v}_2 = \sqrt{(v_2\{2\}^2 + v_2\{4\}^2)/2}$
- **elliptic flow fluctuations:** $\sigma_{v_2} = \sqrt{(v_2\{2\}^2 - v_2\{4\}^2)/2}$
- **nonlinear flow modes** ($v_{n,mk}$, $\chi_{n,mk}$, $\rho_{n,mk}$) **(n = 4,5)**
- **normalized symmetric cumulants** (NSC(3,2), NSC(4,2))

add for Gaussian fluctuations and $\sigma_{v_2} \ll \bar{v}_2$

Y. Zhou, Phys.Rev.C 93 (2016) 3, 034909

R. S. Bhalerao et al., Phys. Lett. B742 (2015) 94–98

A. Bilandzic et al., Phys.Rev.C 89 (2014) 6, 064904

Measured for the first time in Xe–Xe collisions

Compared to results in Pb–Pb collisions

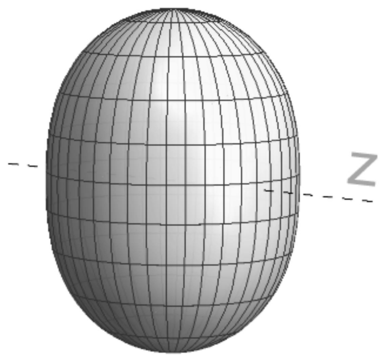
The first systematic study on nuclear structure with various flow observables at the LHC energies!

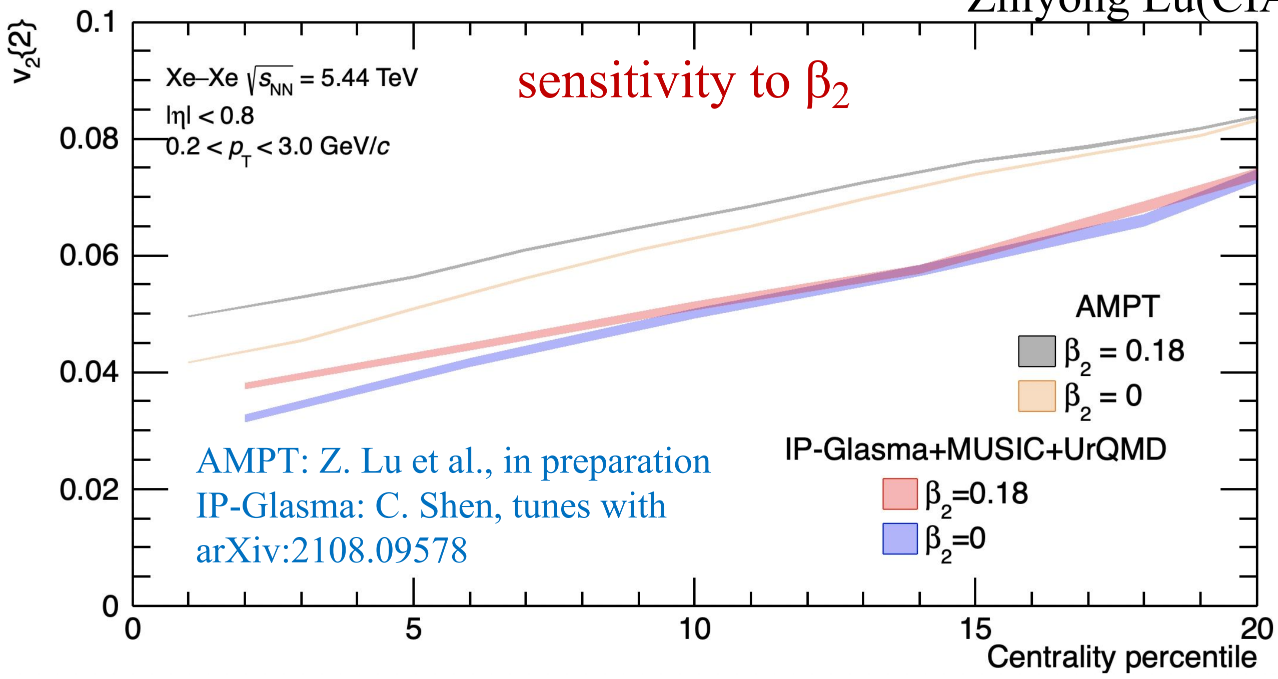
Sensitivity in model

larger β_2

increase initial geometric anisotropy (more elliptical)

$$1+\beta_2 Y_{2,0}(\theta,\phi)$$

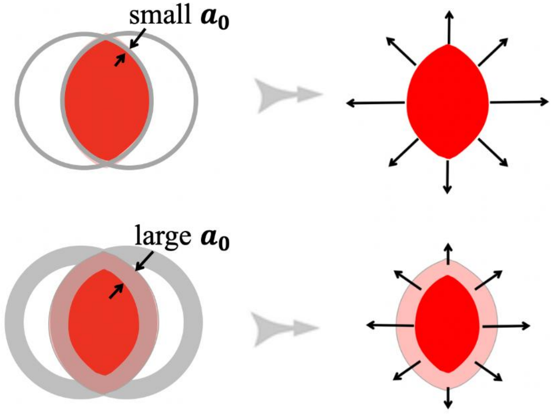


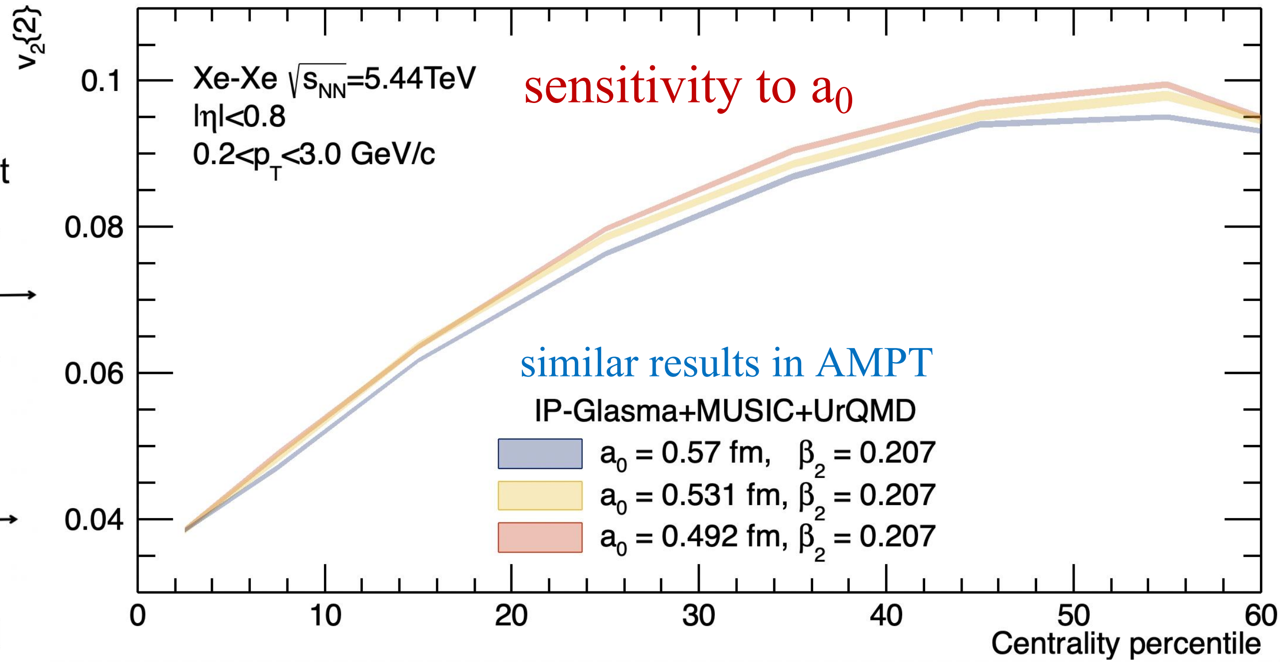


larger a_0

more diffuse and less elliptical

Radial profile:





ALICE detector and data sample

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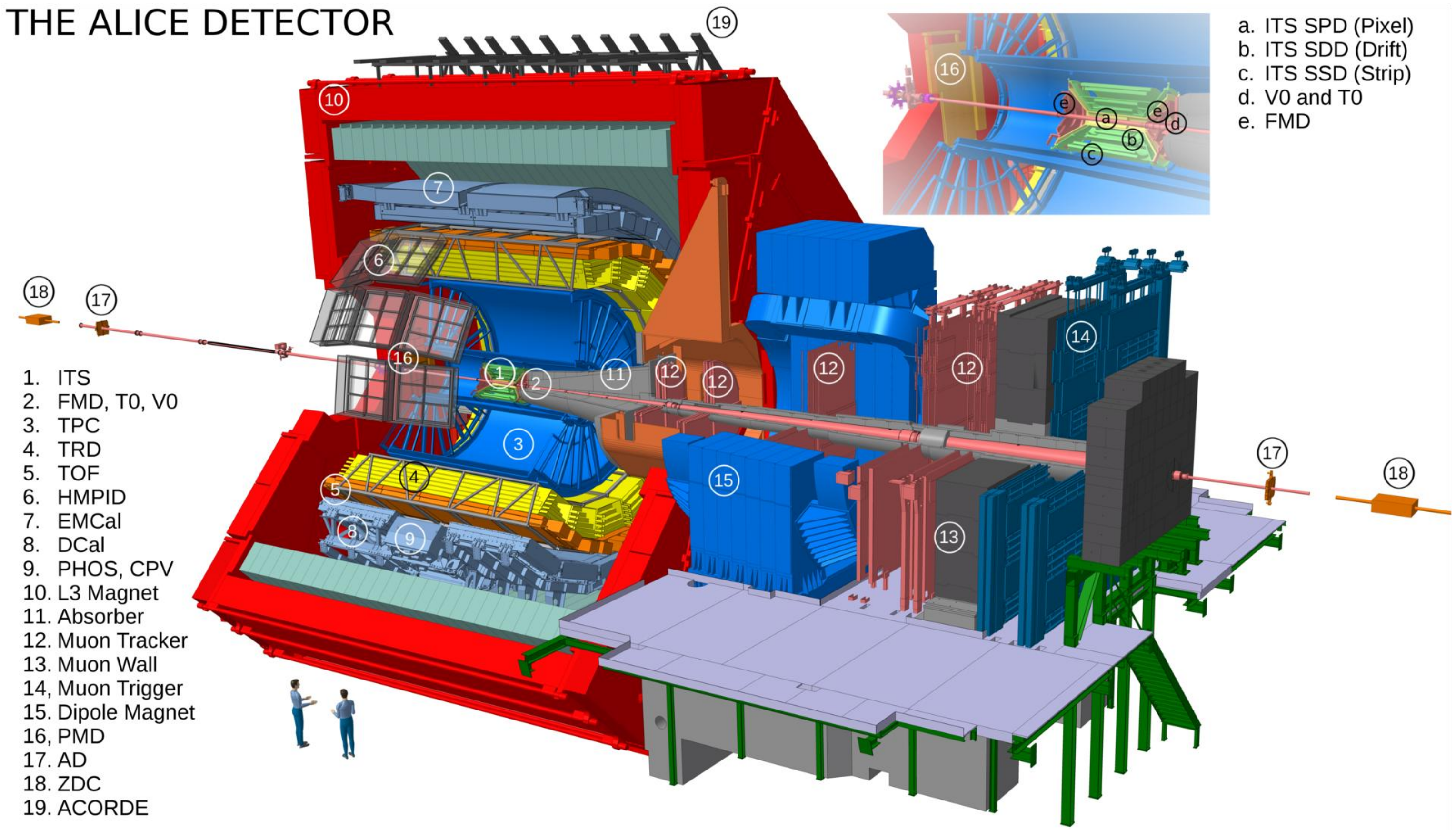
1. Inner Tracking System (ITS)
- Tracking and triggering

2. V0 detector
- Triggering and event
- centrality determination

3. Time Projection Chamber (TPC)
- Tracking



Datasets:
Xe–Xe at 5.44 TeV Run 2
Pb–Pb at 5.02 TeV Run 2

Kinematic region:
$0.2 < p_{\mathrm{T}} < 3.0$ GeV/c
$|\eta| < 0.8$

Results-$v_2\{2\}$

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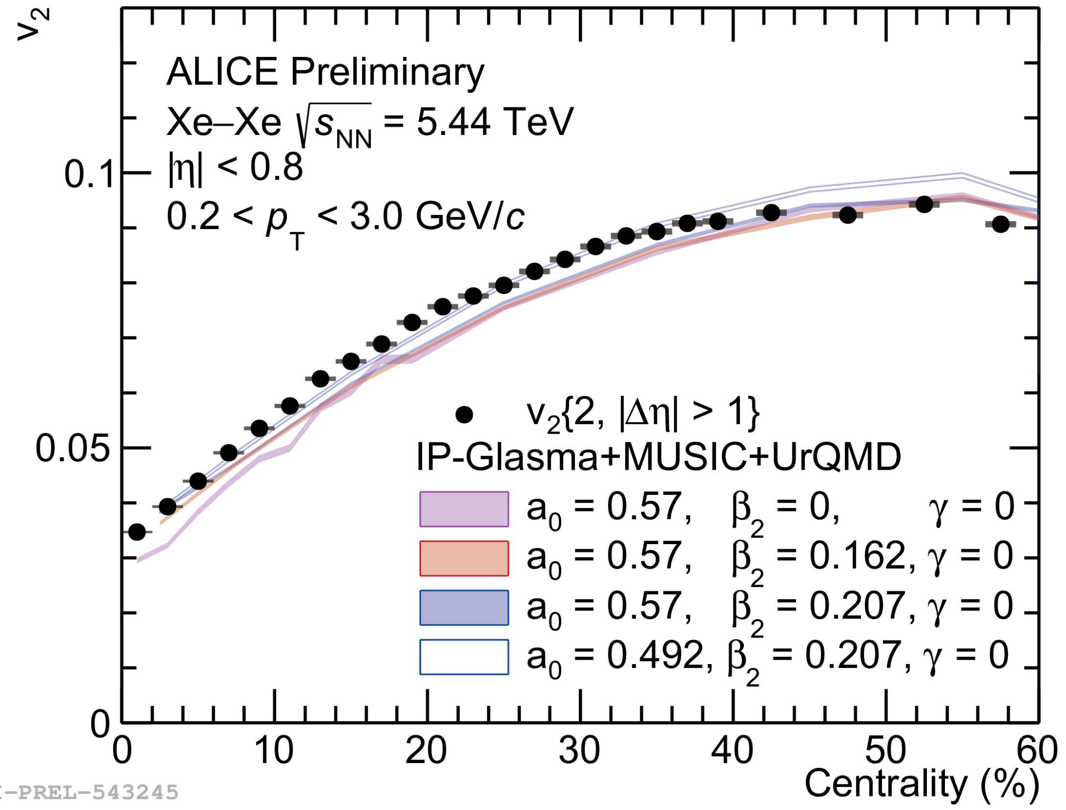

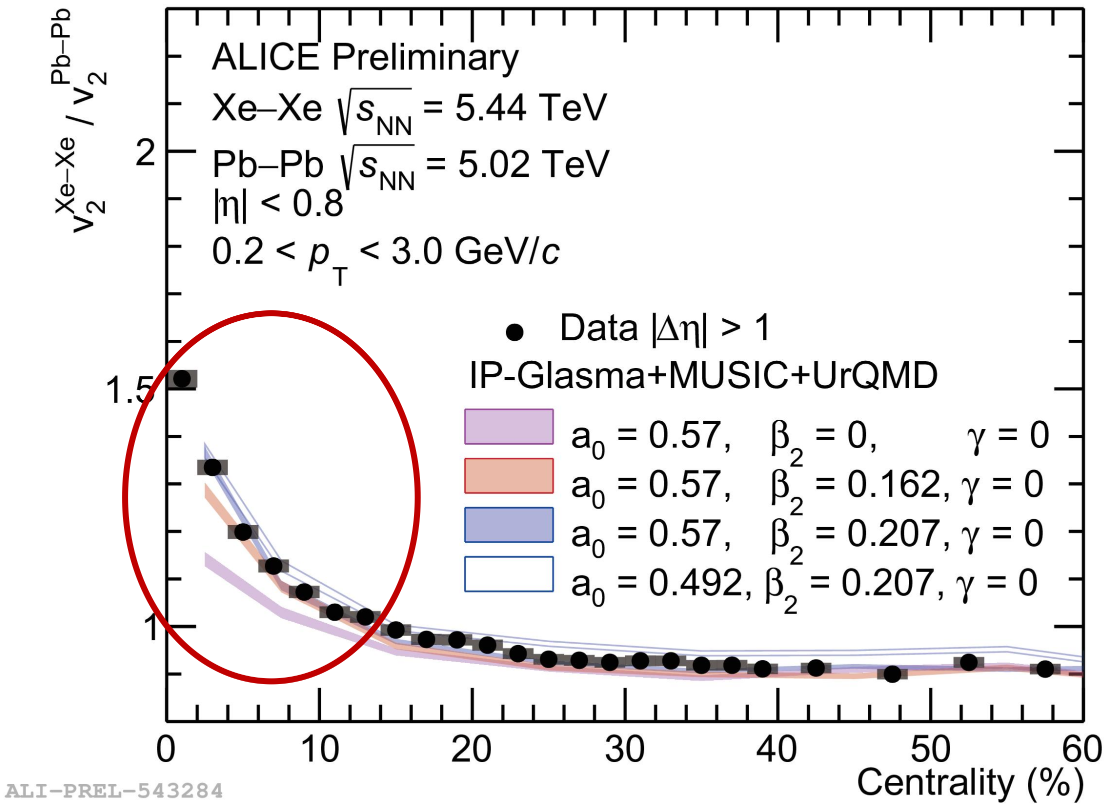

- sensitive to both β_2 and a_0
- ALICE data better described by larger β_2
- agrees with smaller a_0 below 40%, and agrees better with larger a_0 above 40%

- In 0-15%, $v_2\{2\}$(Xe–Xe) >$v_2\{2\}$(Pb–Pb):
  - ^{129}Xe is deformed, while ^{208}Pb is not
  - flow fluctuations in smaller system are stronger (slide 11)

* Results in Pb–Pb collisions are in backup slide 21

Results-$v_3\{2\}, v_4\{2\}$

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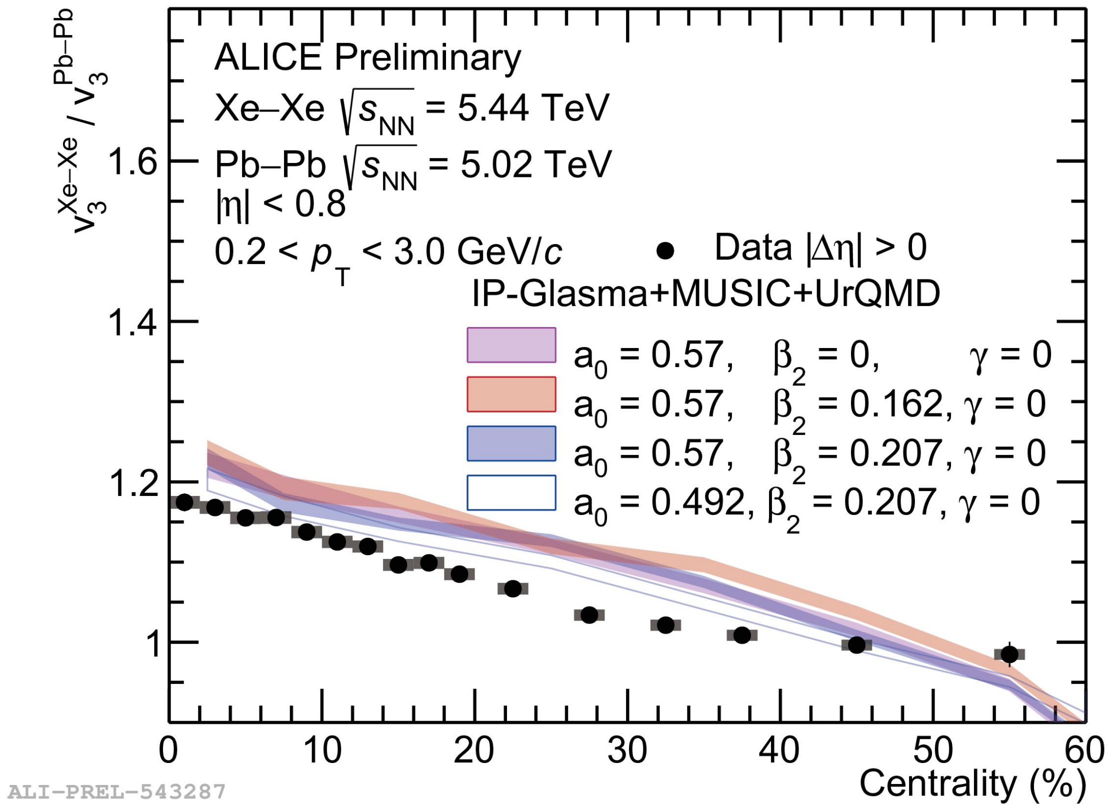

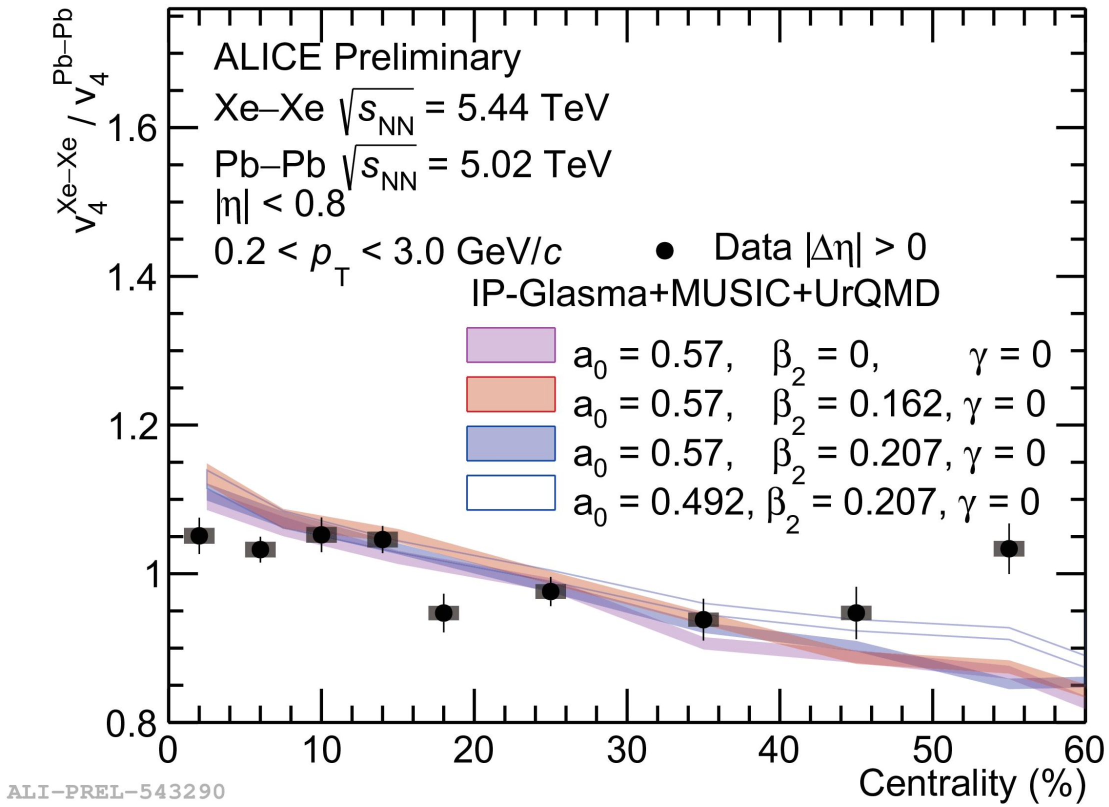

- $v_3\{2\}, v_4\{2\}$ are insensitive to β_2
  - $v_3 \propto \varepsilon_3$ and ε_3 is less affected by β_2
  - v_4 is dominant by linear component in central collisions, which is insensitive to β_2 (see backup slide 34)
- $v_3\{2\}$ is insensitive to a_0, while $v_4\{2\}$ is enhanced by smaller a_0 after 35% centrality (need further confirmation)

Results-$v_2\{4\}$

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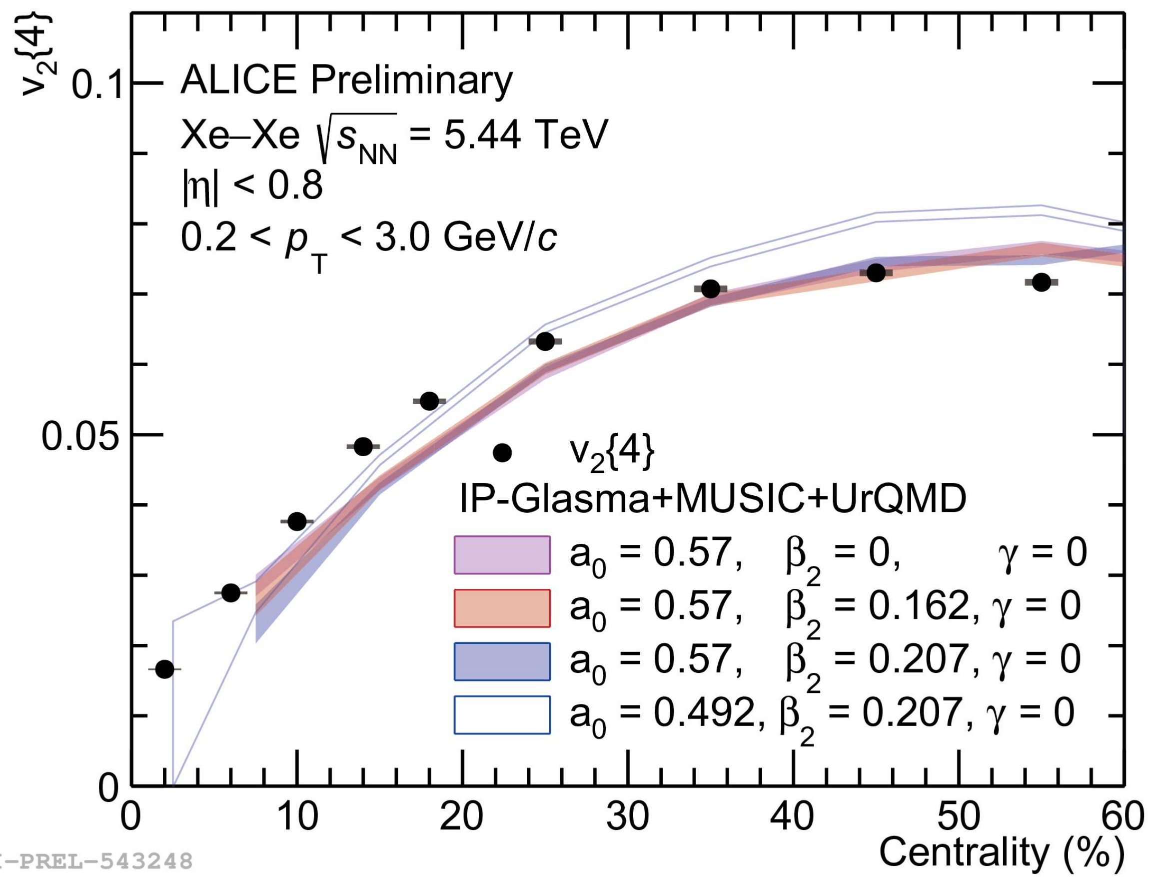

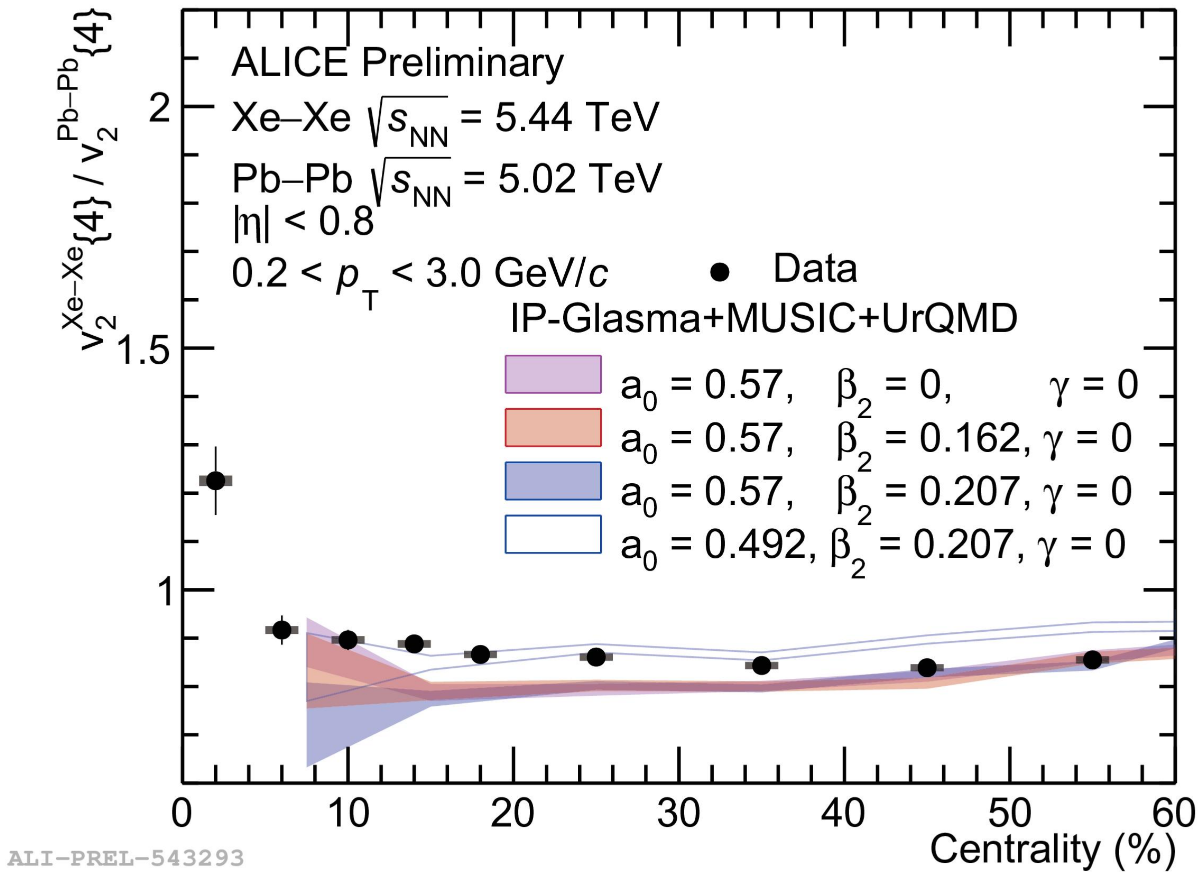

- $v_2\{4\}$ agrees with smaller a_0 below 30% and with larger a_0 above 30%
- may expect $v_2\{4\}$(Xe–Xe) > $v_2\{4\}$(Pb–Pb) in the central region due to the deformation of Xe

* Results in Pb–Pb collisions are in backup slide 22
$v_2\{2\}/v_2\{4\}$ is insensitive to β_2 and a_0 (see backup slide 23)

Results-σ_{v_2}

$\overline{v}_2$, σ_{v_2} are derived from:

$$v_2\{2\}^2 \approx \overline{v}_2^{\,2} + \sigma_{v_2}{}^2; \quad v_2\{4\}^2 = \overline{v}_2^{\,2} - \sigma_{v_2}{}^2$$

similar conclusions in $\overline{v}_2$ as in $v_2\{4\}$ (see backup slide 24)

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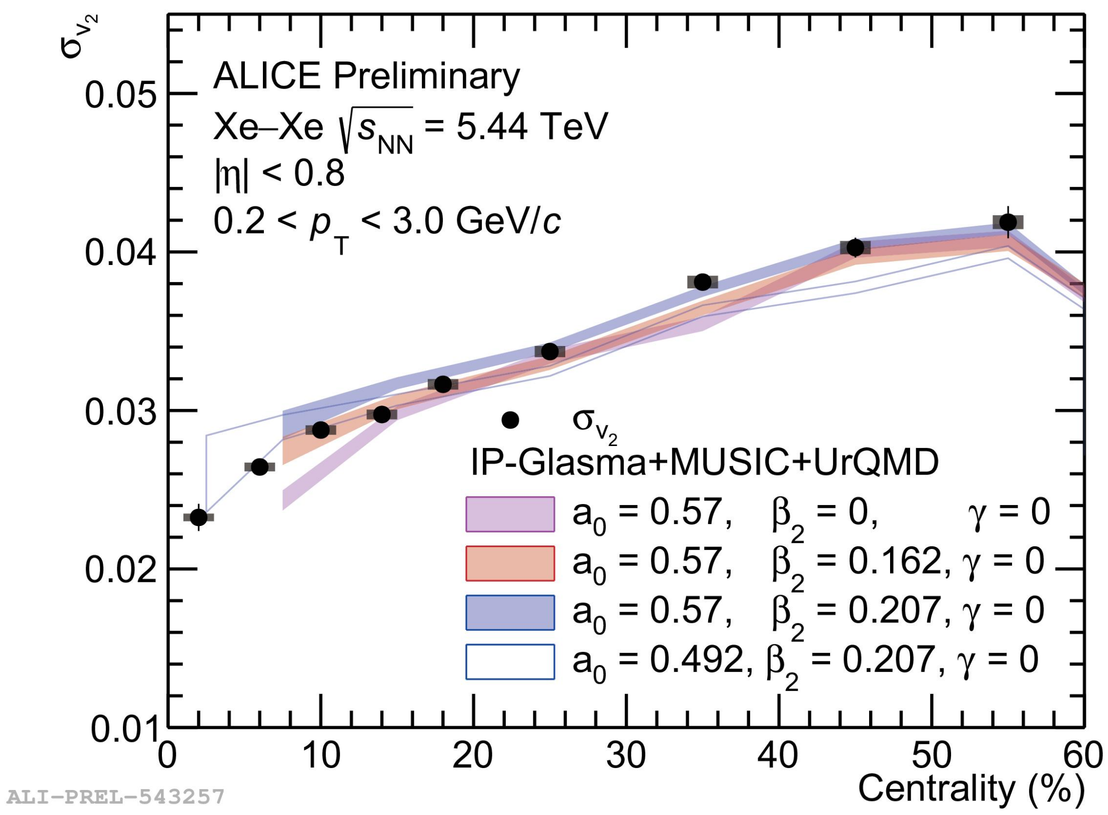
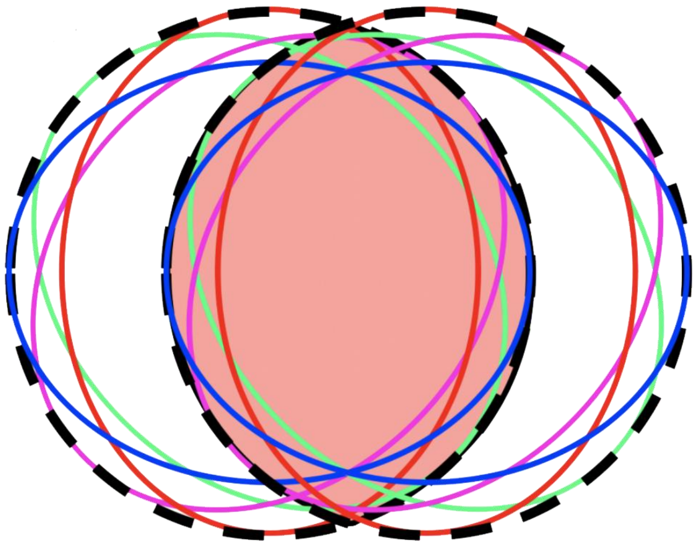


For σ_{v_2}

- insensitive to a_0
- enhanced by β_2 in the central region
- described by a model with β_2=0.162

deformed shape in solid lines



random orientations

↓

fluctuation

↓

σ_{v_2} increases

Results-σ_{v_2}

$\overline{v}_2$, σ_{v_2} are derived from:

$$v_2\{2\}^2 \approx \overline{v}_2^{\,2} + \sigma_{v_2}^{\,2}; \quad v_2\{4\}^2 = \overline{v}_2^{\,2} - \sigma_{v_2}^{\,2}$$

similar conclusions in $\overline{v}_2$ as in $v_2\{4\}$ (see backup slide 24)

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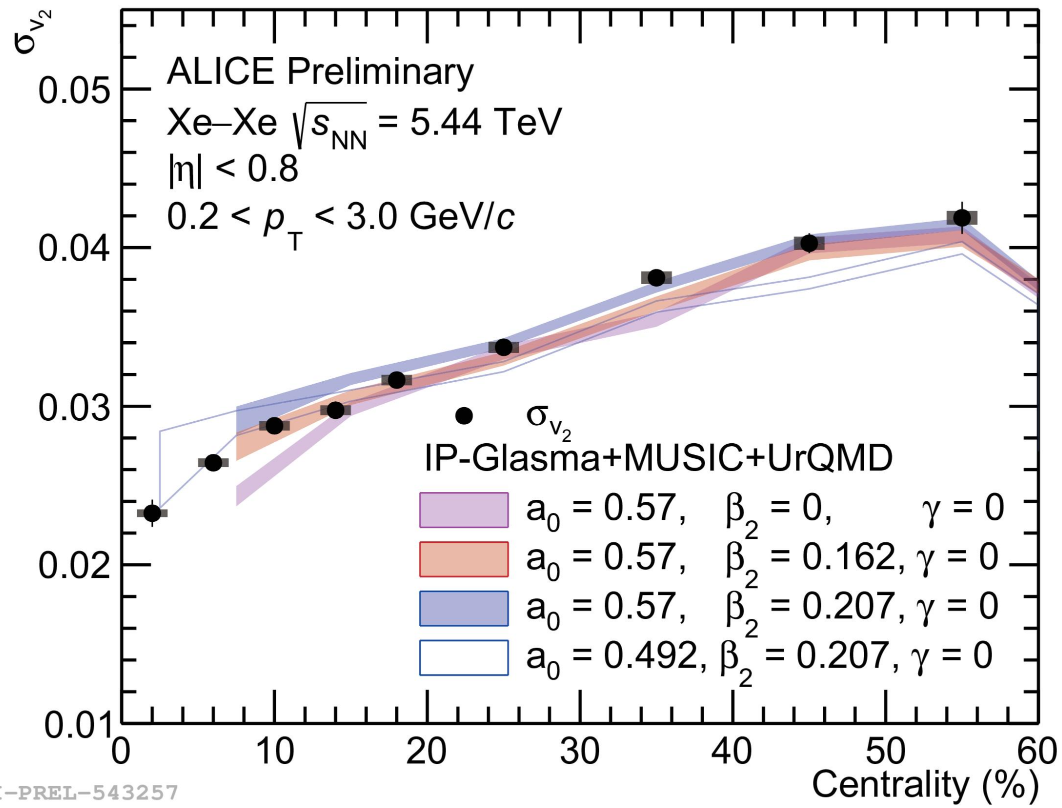

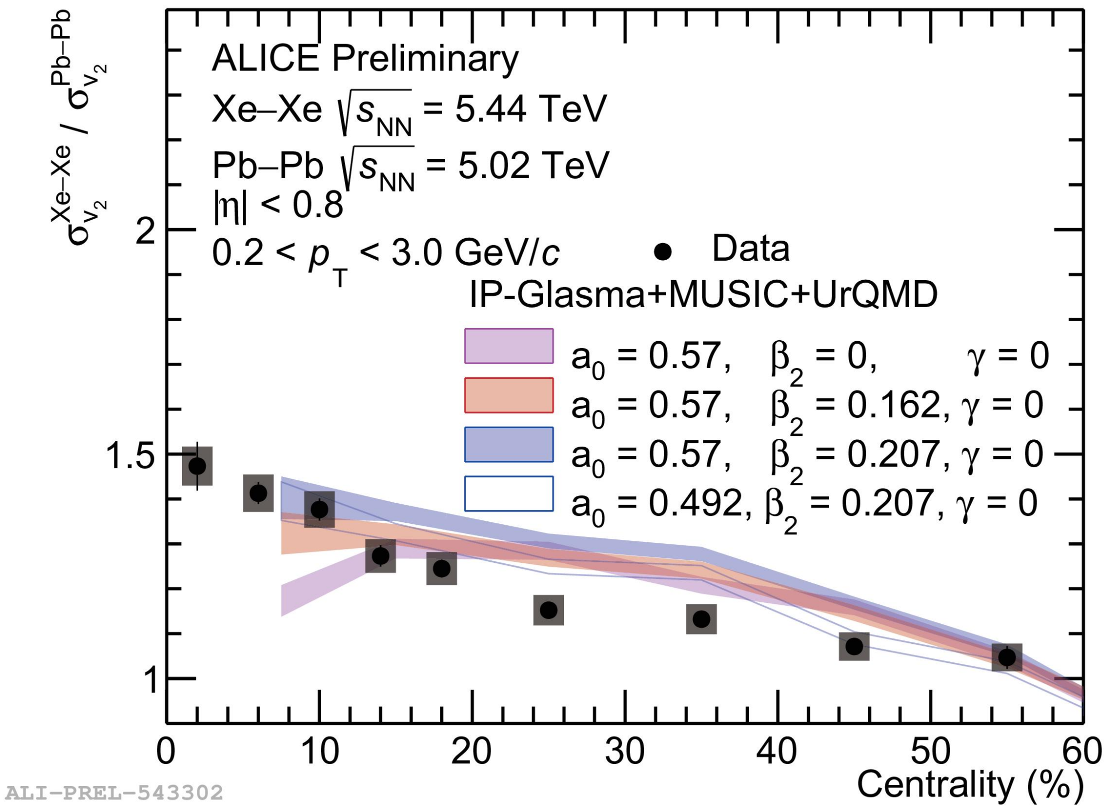

For σ_{v_2}

- insensitive to a_0
- enhanced by β_2 in central region
- described by a model with β_2=0.162

- σ_{v_2}(Xe–Xe)>σ_{v_2}(Pb–Pb) across 0-60% centrality range
- flow fluctuations in smaller system are stronger

* Results in Pb–Pb collisions are in backup slide 25

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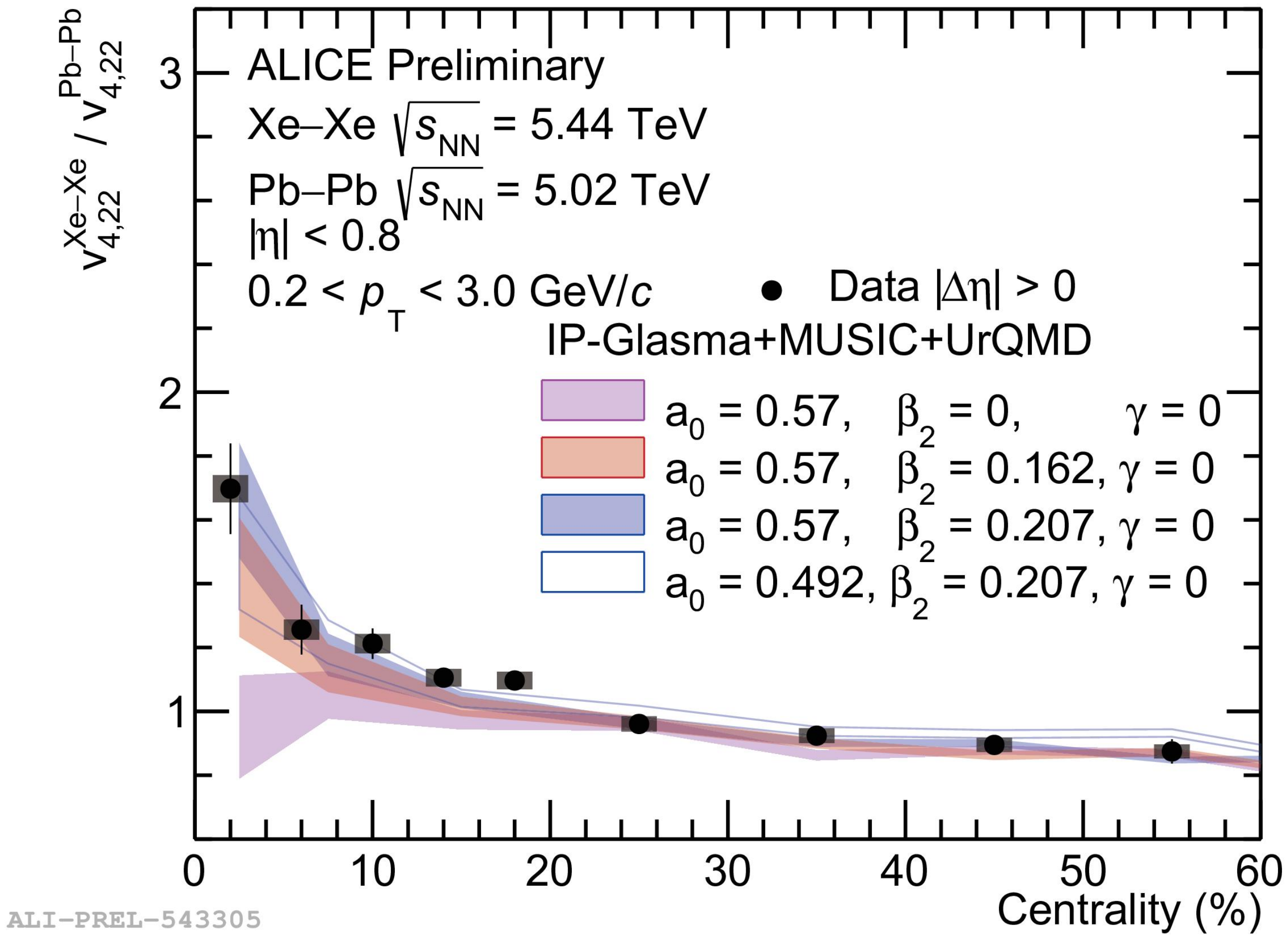
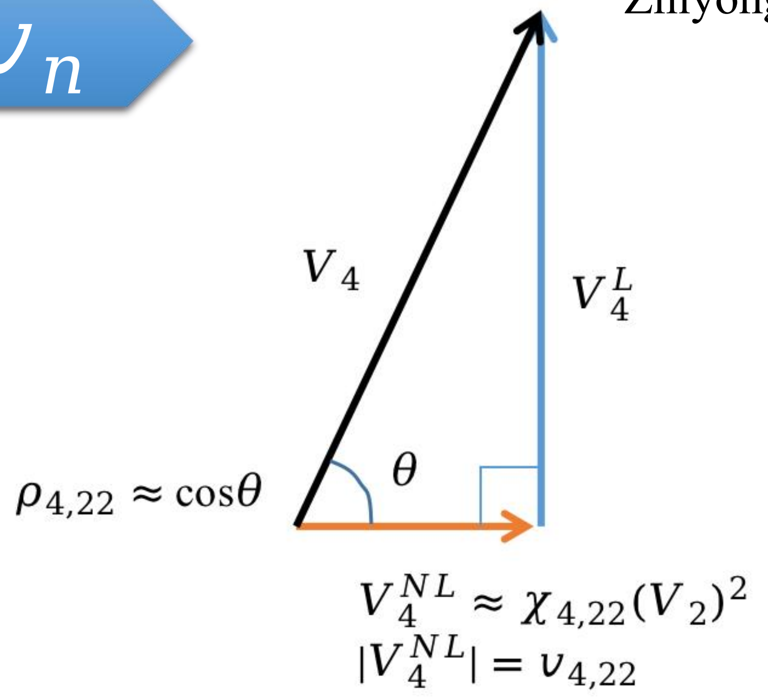
Results-nonlinear component of v_n

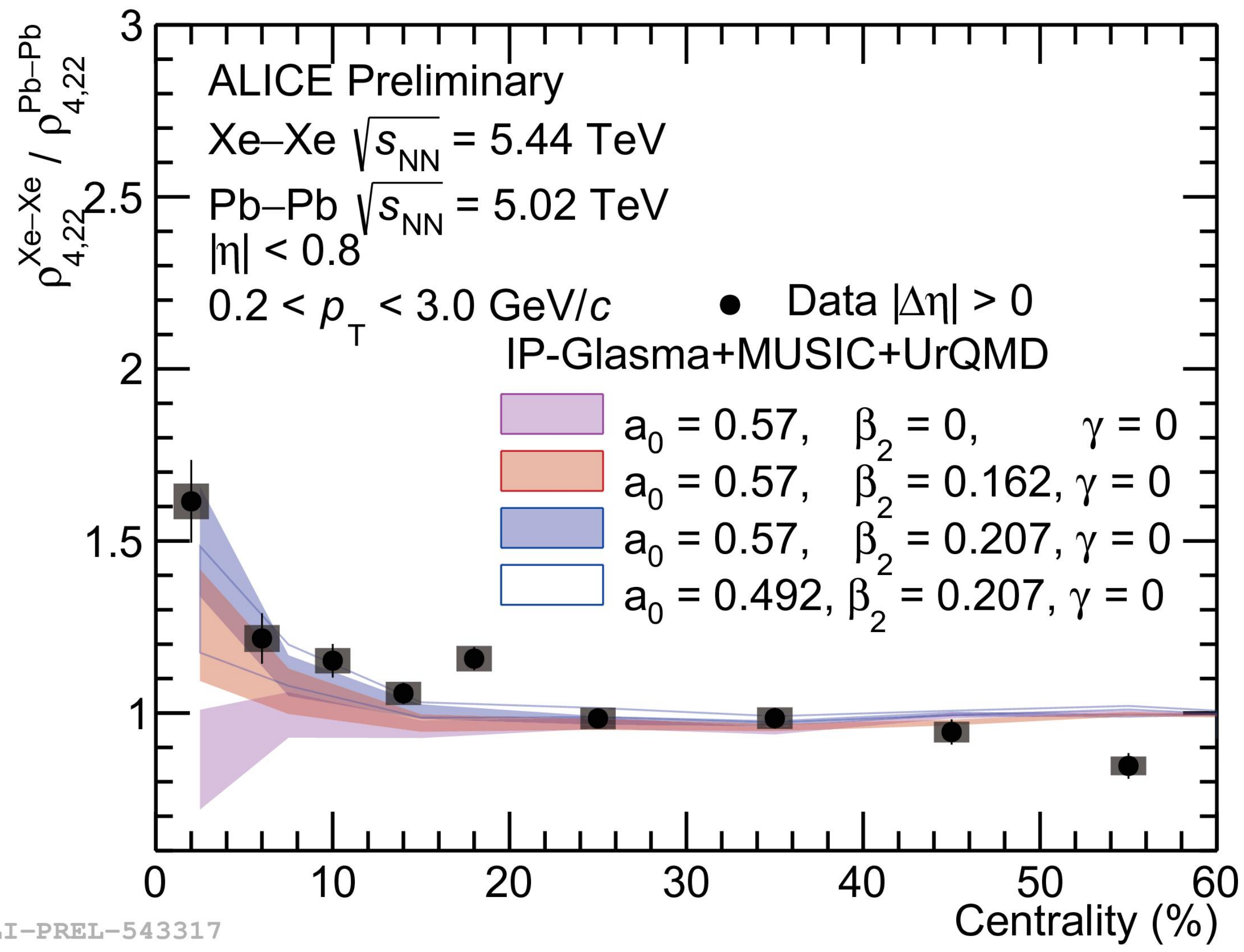


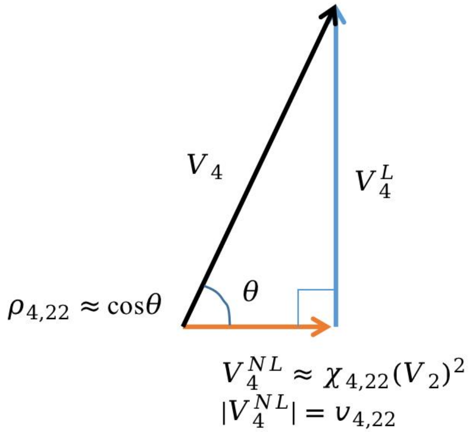


- β_2 enhances $v_{4,22}$, but not $v_4\{2\}$
- probe smaller spatial distribution than $v_4\{2\}$
  → provide stricter constraints
- small difference caused by a_0 in peripheral region

* for individual $v_{4,22}$ in Xe–Xe and Pb–Pb collisions, see backup slide 26
$v_{5,32}$ have similar conclusion but with larger uncertainties, see backup slide 27

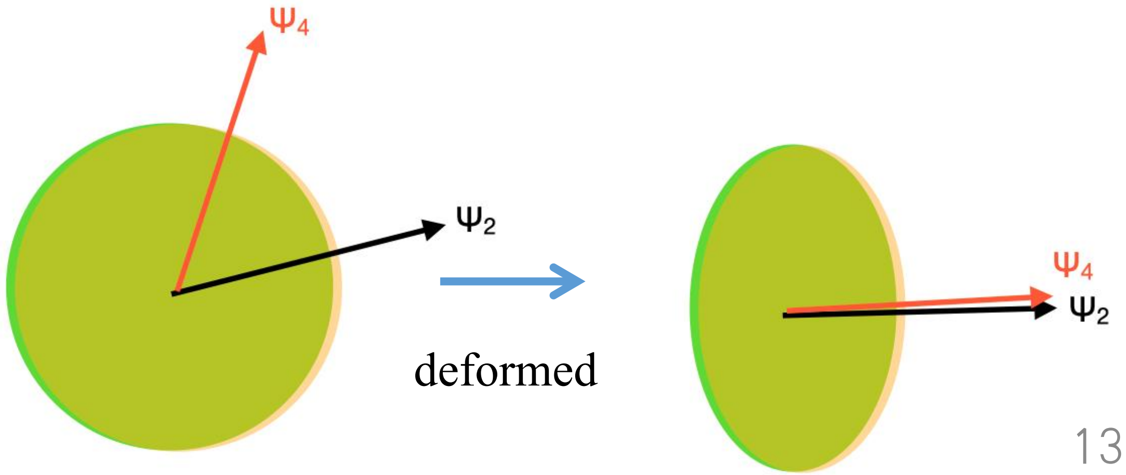
Results-flow symmetry plane correlation $\rho_{n,mk}$



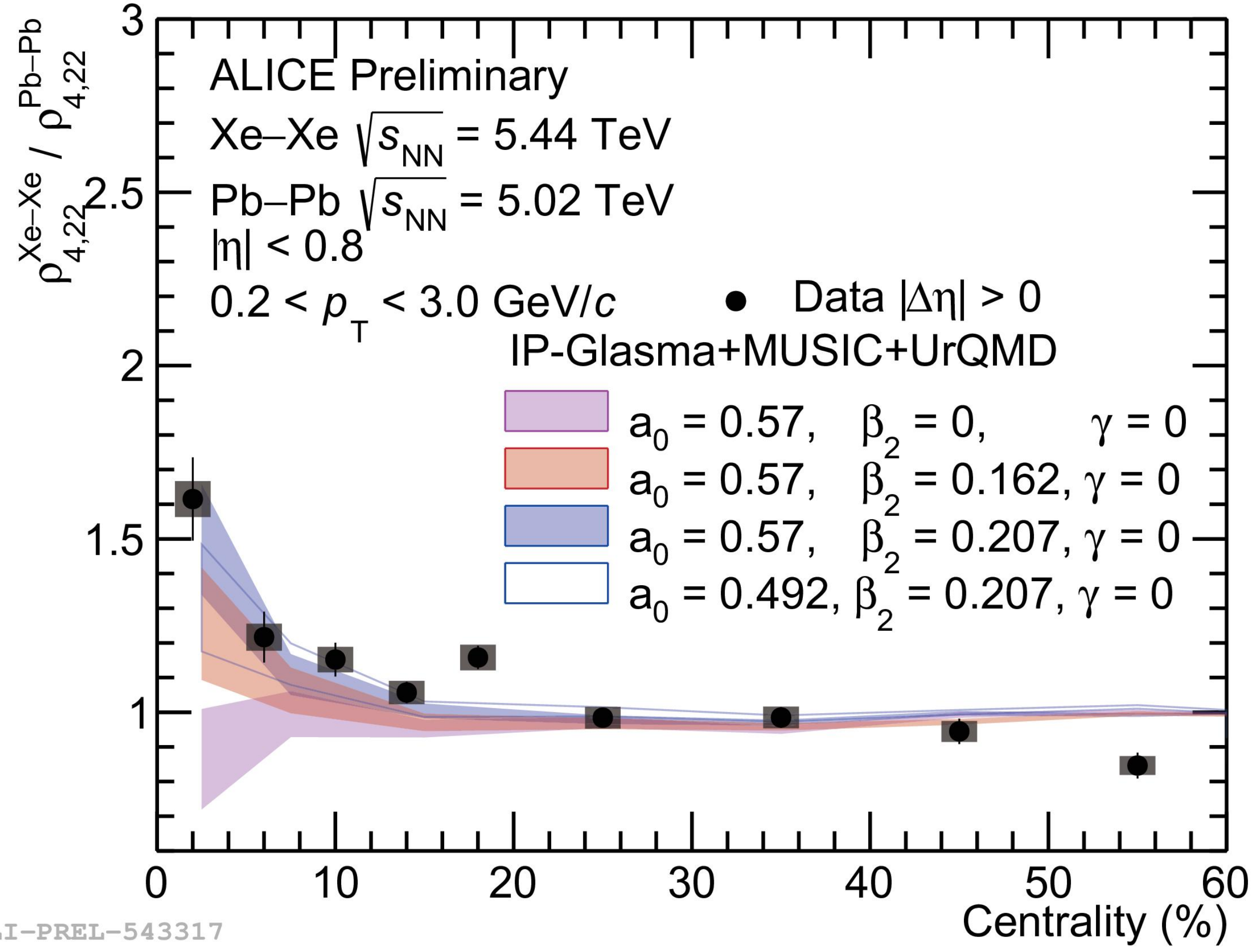


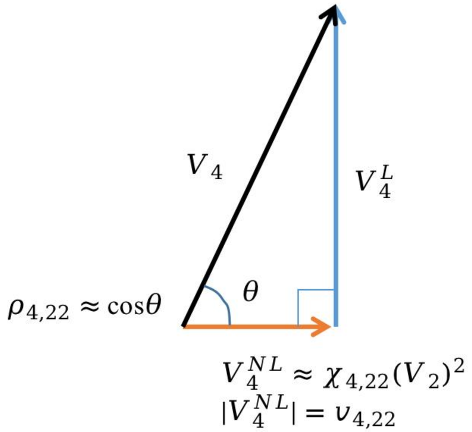
$\rho_{4,22} = v_{4,22}/v_4\{2\}$: the correlation between ψ_4 and ψ_2

- enhanced by β_2 in central region



Results-flow symmetry plane correlation $\rho_{n,mk}$





$\rho_{4,22} = v_{4,22}/v_4\{2\}$: the correlation between ψ_4 and ψ_2

- enhanced by β_2 in central region
- insensitive to a_0
  →sensitivity to a_0 is cancelled by the ratio of $v_{4,22}/v_4\{2\}$

* for individual $\rho_{4,22}$ in Xe–Xe and Pb–Pb collisions, see backup slide 28
$\rho_{5,32}$ is in backup slide 29

Results-nonlinear coefficients $\chi_{n,mk}$

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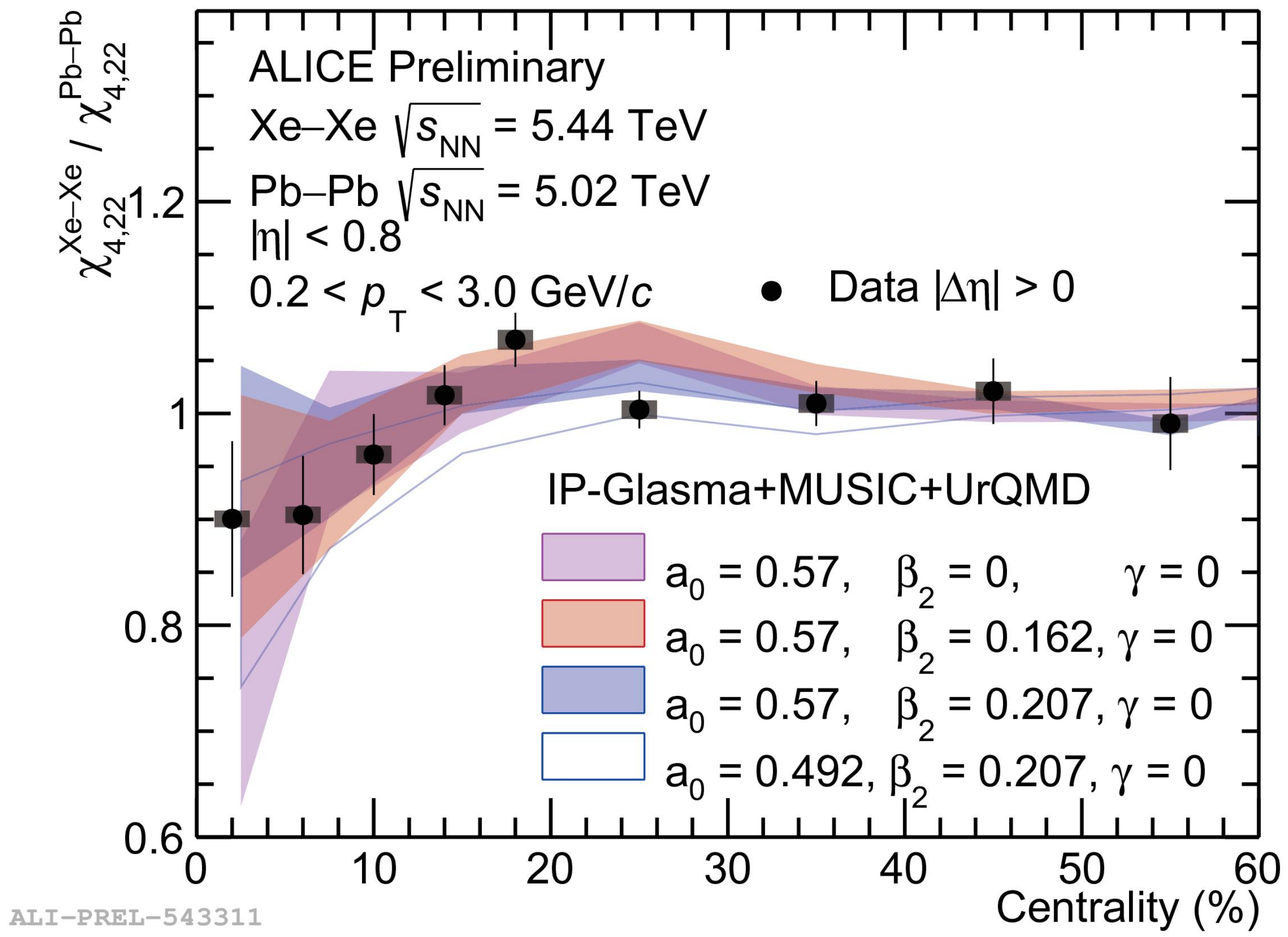

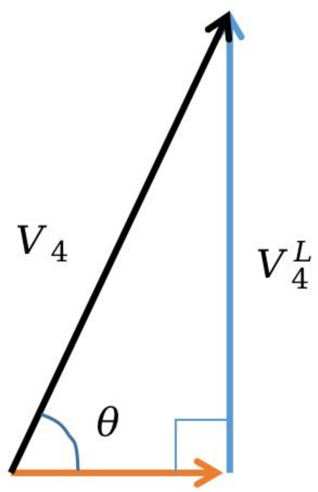

$V_4^{NL} \approx \chi_{4,22}(V_2)^2$

$|V_4^{NL}| = v_{4,22}$

- ratio drops in central collisions
- $\chi_{4,22}$ is independent of deformation effect, while $v_{4,22}$ is sensitive to both β_2 and a_0

↓

the sensitivitites of $v_{4,22}$ are largerly from $(V_2)^2$

* for individual $\chi_{4,22}$ in Xe–Xe and Pb–Pb collisions, see backup slide 30
$\chi_{5,32}$ is in backup slide 31

Results-normalized symmetric cumulants

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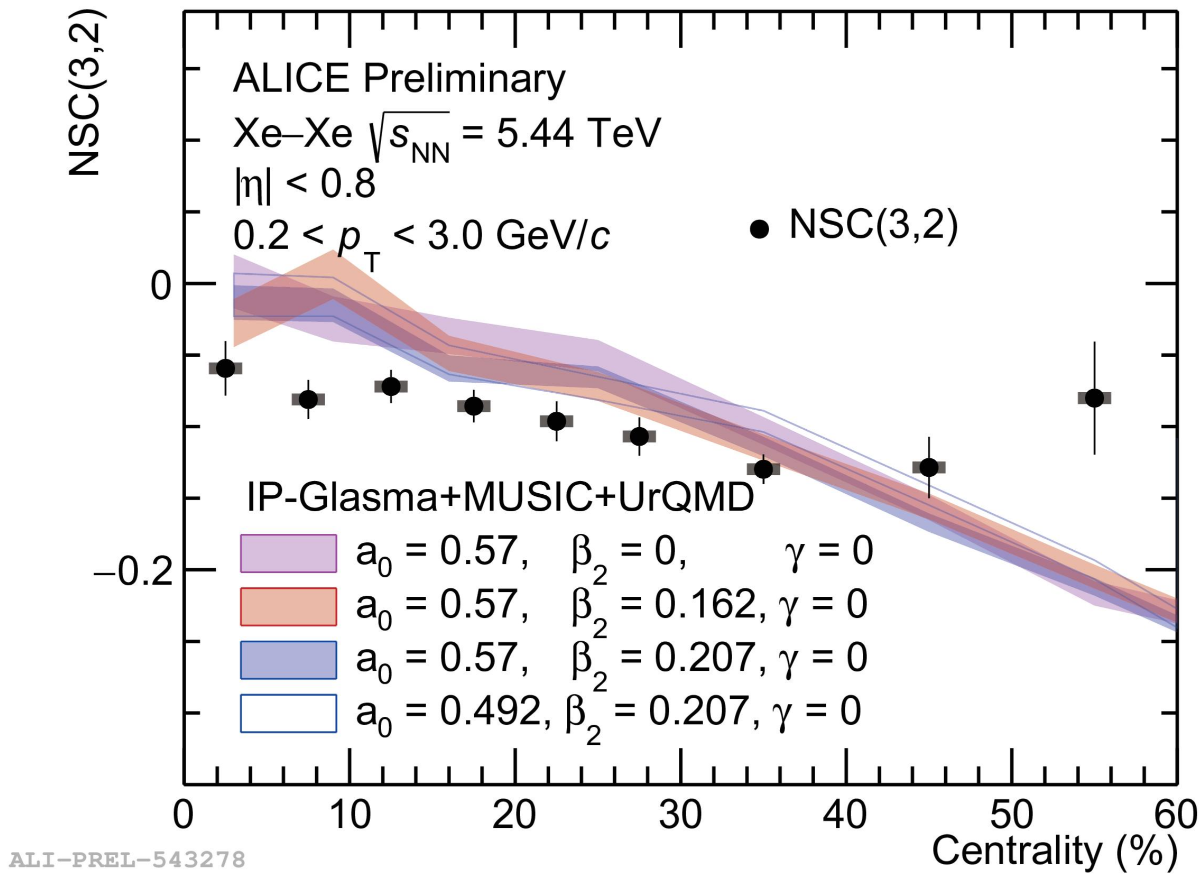

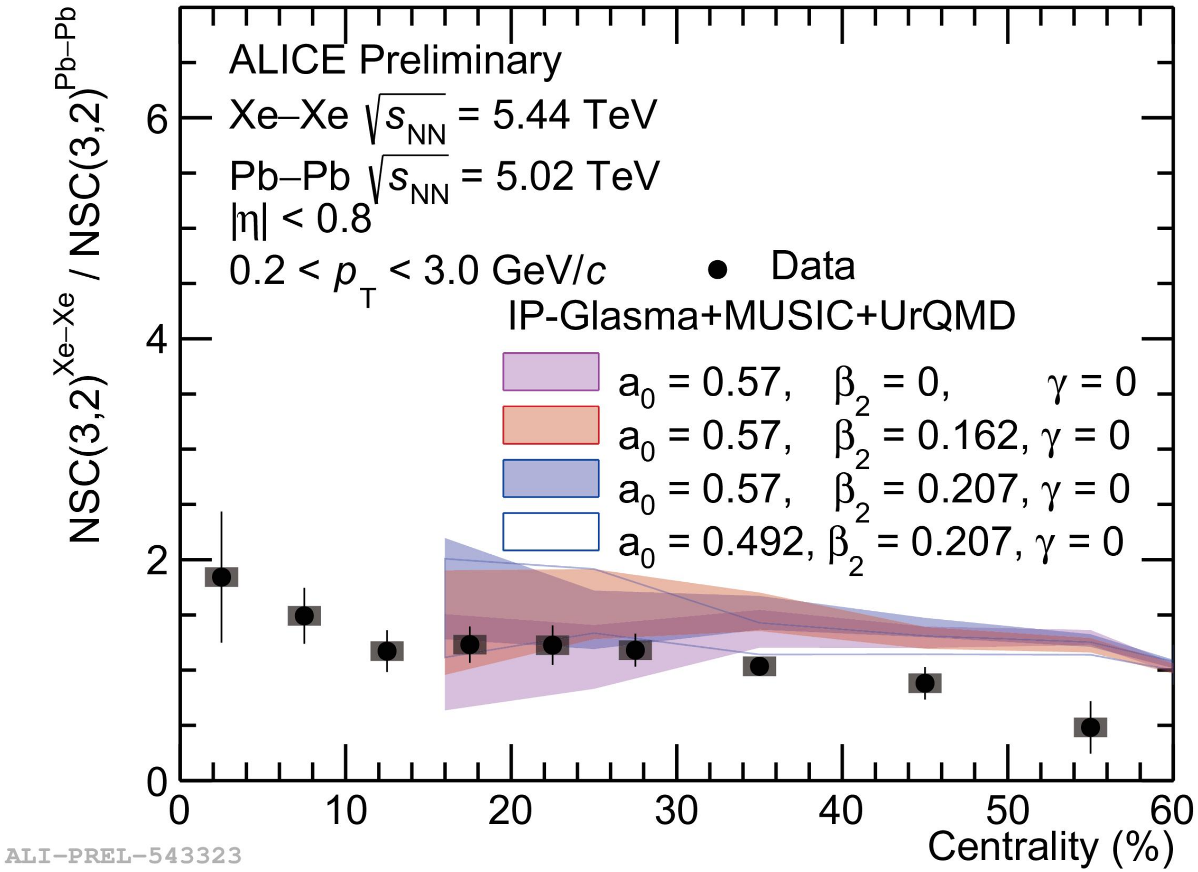

NSC(3,2): the correlation between v_3^2 and v_2^2

- insensitive neither to β_2 nor a_0
- model deviates from the data in central and peripheral region

* NSC(3,2) in Pb–Pb collisions and NSC(4,2) are in slide 32 and 33

Sensitivity to γ

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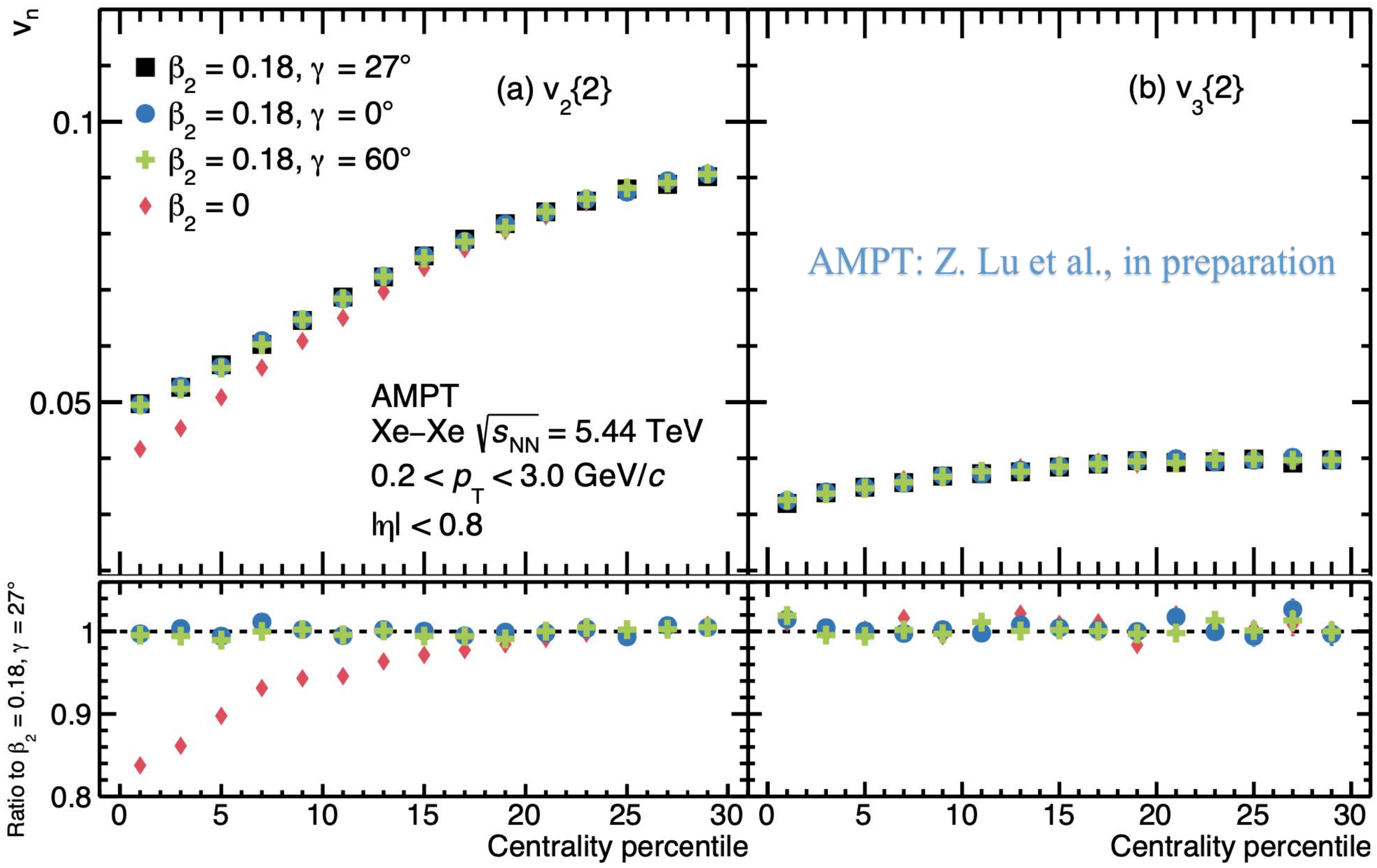

- Discussion on previous slides missed the contribution of γ, which represents the imbalance of the radius
- According to the last AMPT simulations, none of the “standard” flow observables are sensitive to γ
- New observables, i.e., $v_n - p_T$ correlation can probe γ

ALICE, Phys. Lett. B834 (2022) 137393

Summary

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✓ **We present a systematic study on the centrality dependence of various flow observables in Xe–Xe and Pb–Pb collisions**

- $v_2\{2\}, \sigma_{v_2}, v_{4,22}, v_{5,32}, \rho_{4,22}$ in Xe–Xe central collisions are enhanced by nuclear deformation
- $v_2\{2\}, v_2\{4\}, \overline{v}_2, v_4\{2\}, v_{4,22}, v_{5,32}$ are sensitive to a_0

✓ **New experimental measurements at the LHC enable a novel tool to probe the nuclear structure, complementary to the low-energy studies**

Thanks for your attention!

Backup

Final state cancellation

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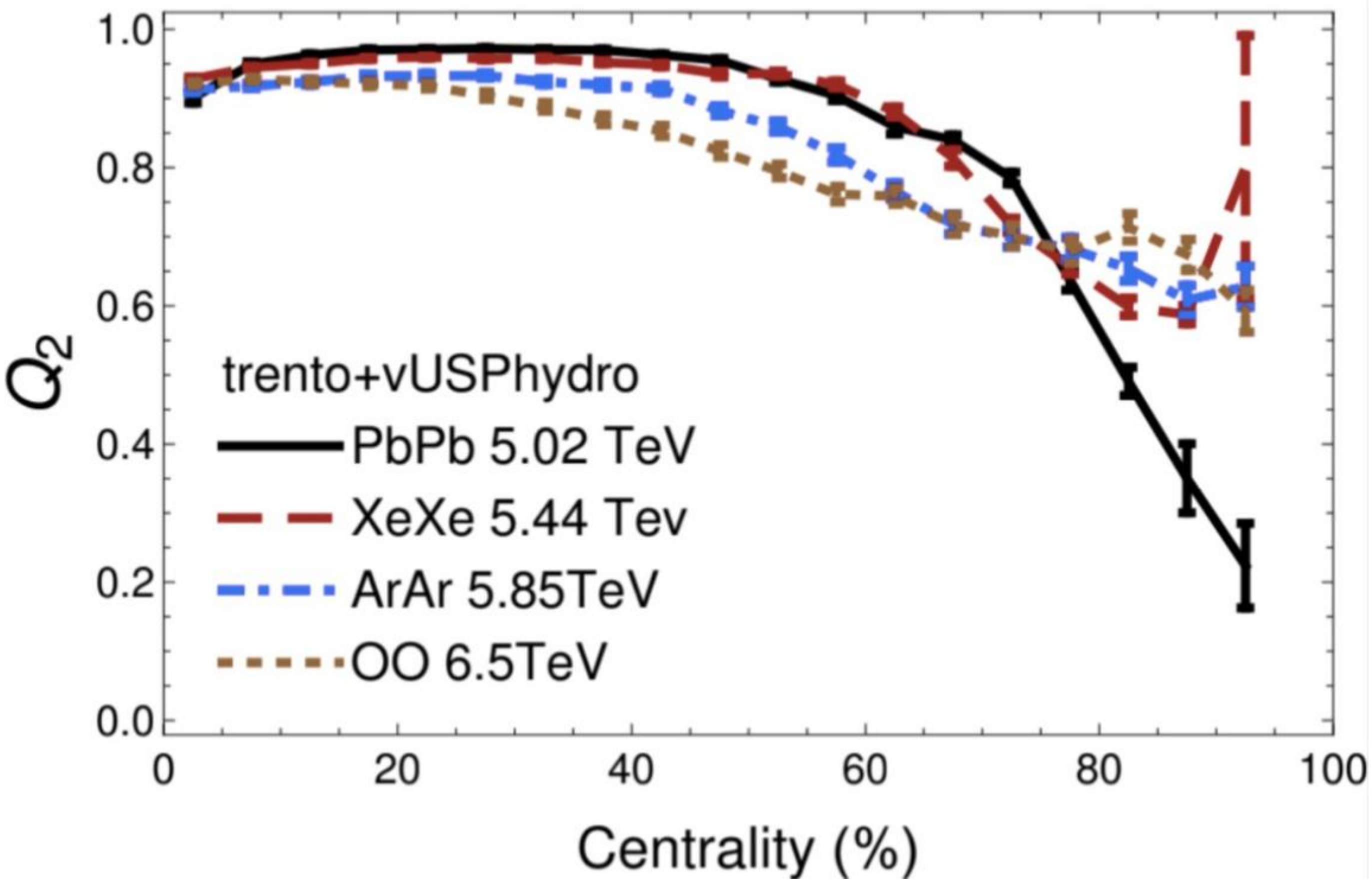
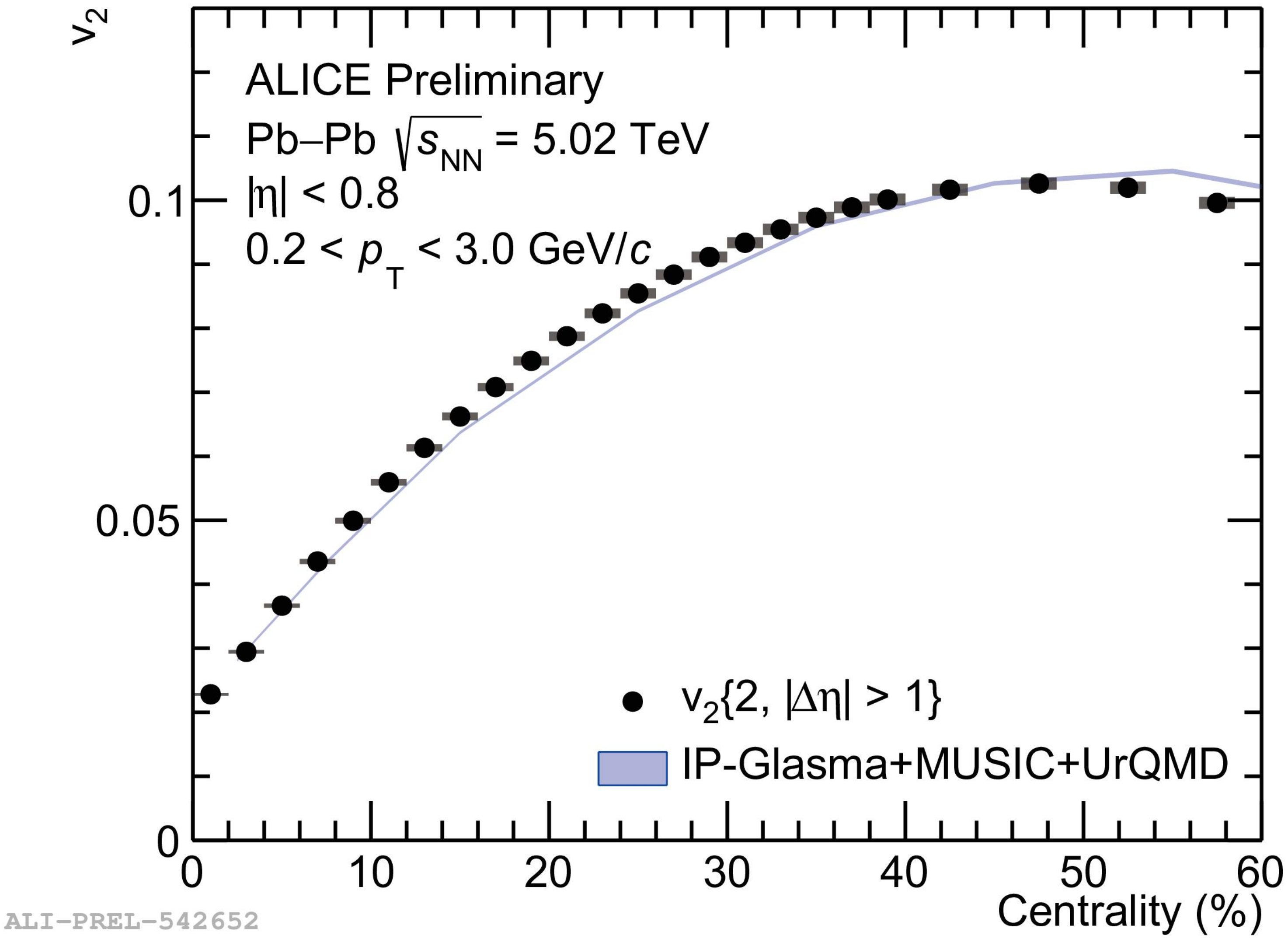
Theorist:

- the cancellation can be seen in the PCC correlation between the initial state and final state
- Basically, the two systems have the same linear correlation between initial and final, which suggests the same final state effects.

$$Q_n = \frac{\langle v_n \varepsilon_n \cos n(\psi_n - \phi_n) \rangle}{\sqrt{\langle v_n^2 \rangle \langle \varepsilon_n^2 \rangle}}$$



Results-$v_2\{2\}$ in Pb–Pb



Results-$v_2\{4\}$ in Pb–Pb

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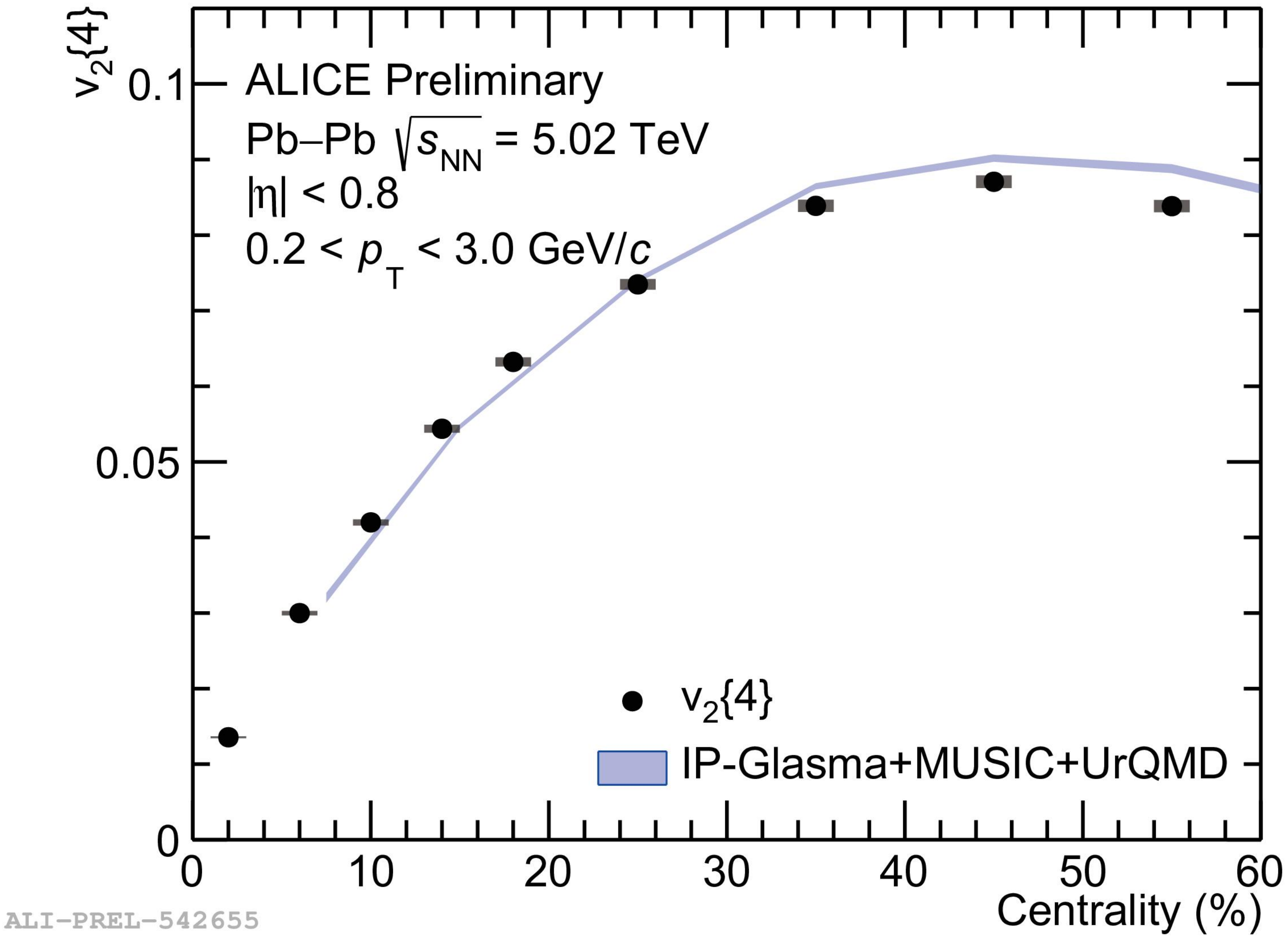

Results-$v_2\{2\}/v_2\{4\}$

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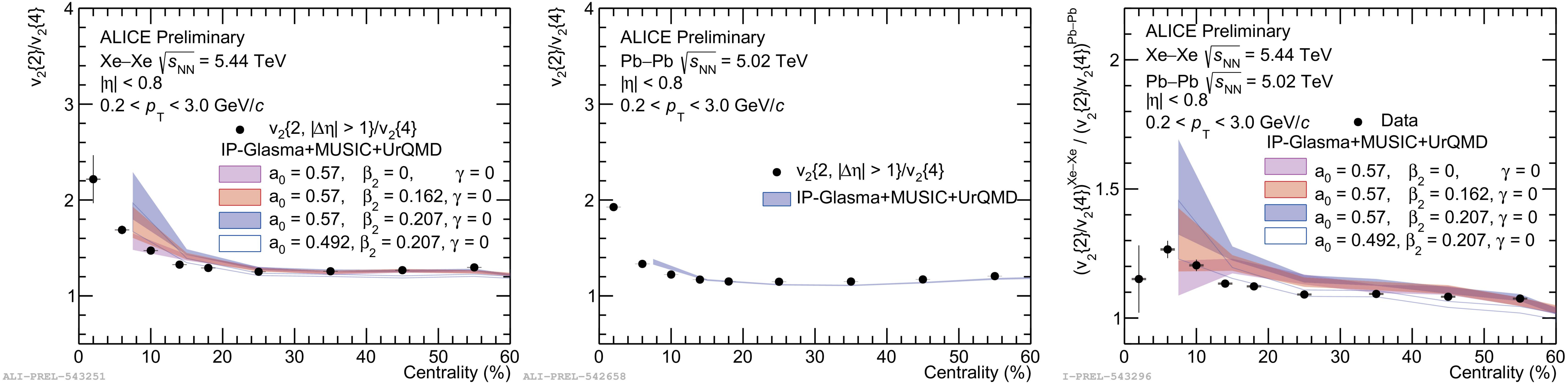

- taking the ratio of $v_2\{2\}/v_2\{4\}$, the sensitivities to β_2 and a_0 are almost cancelled
- $v_2\{2\}$ and $v_2\{4\}$ seems to have similar level of sensitivities

Results-$\overline{v}_2$

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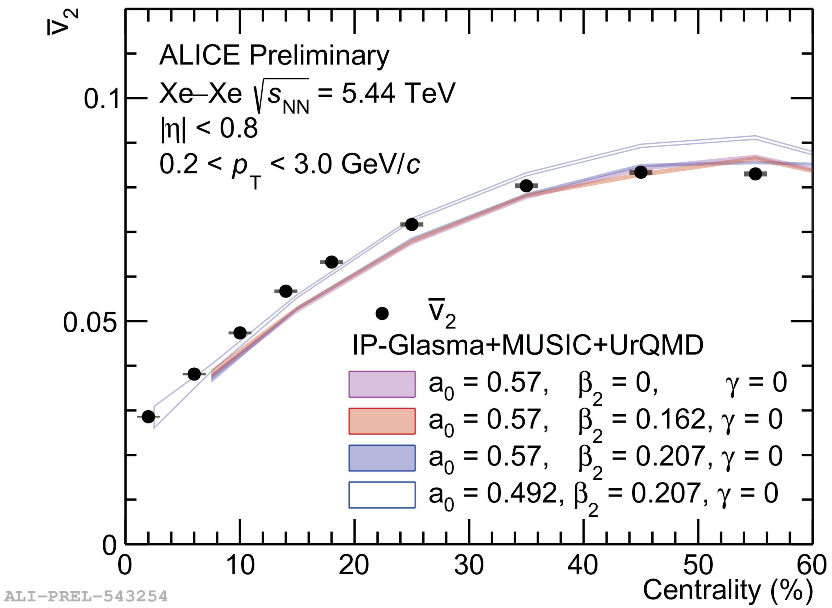

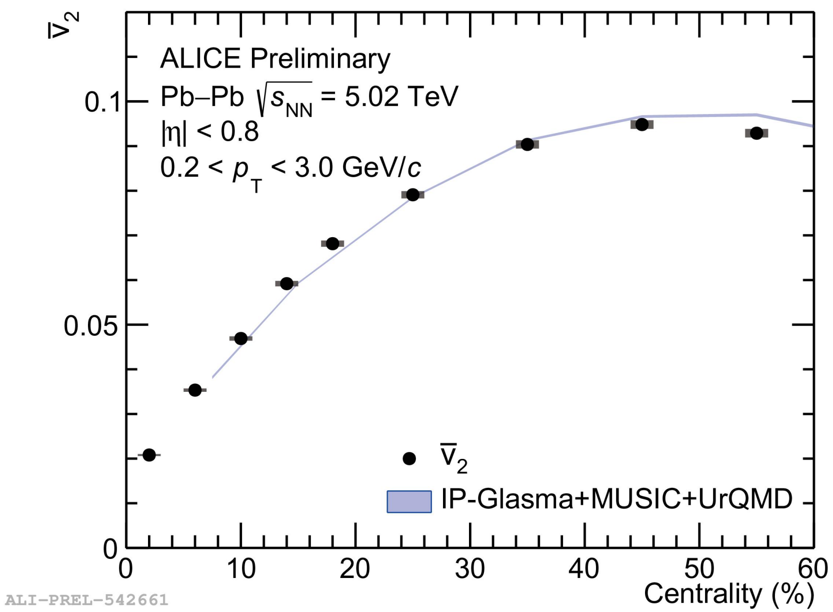

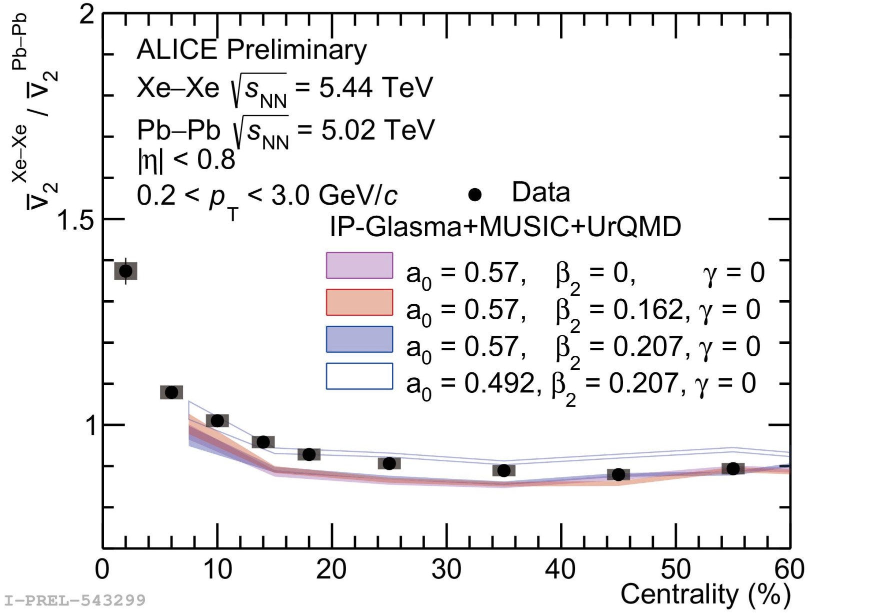

- uncertainties in 0-15% too large
- a_0 have a significant effect above 15%
- described by larger a_0 = 0.57 before 30%, by smaller a_0 above 30%

Results-σ_{v_2}

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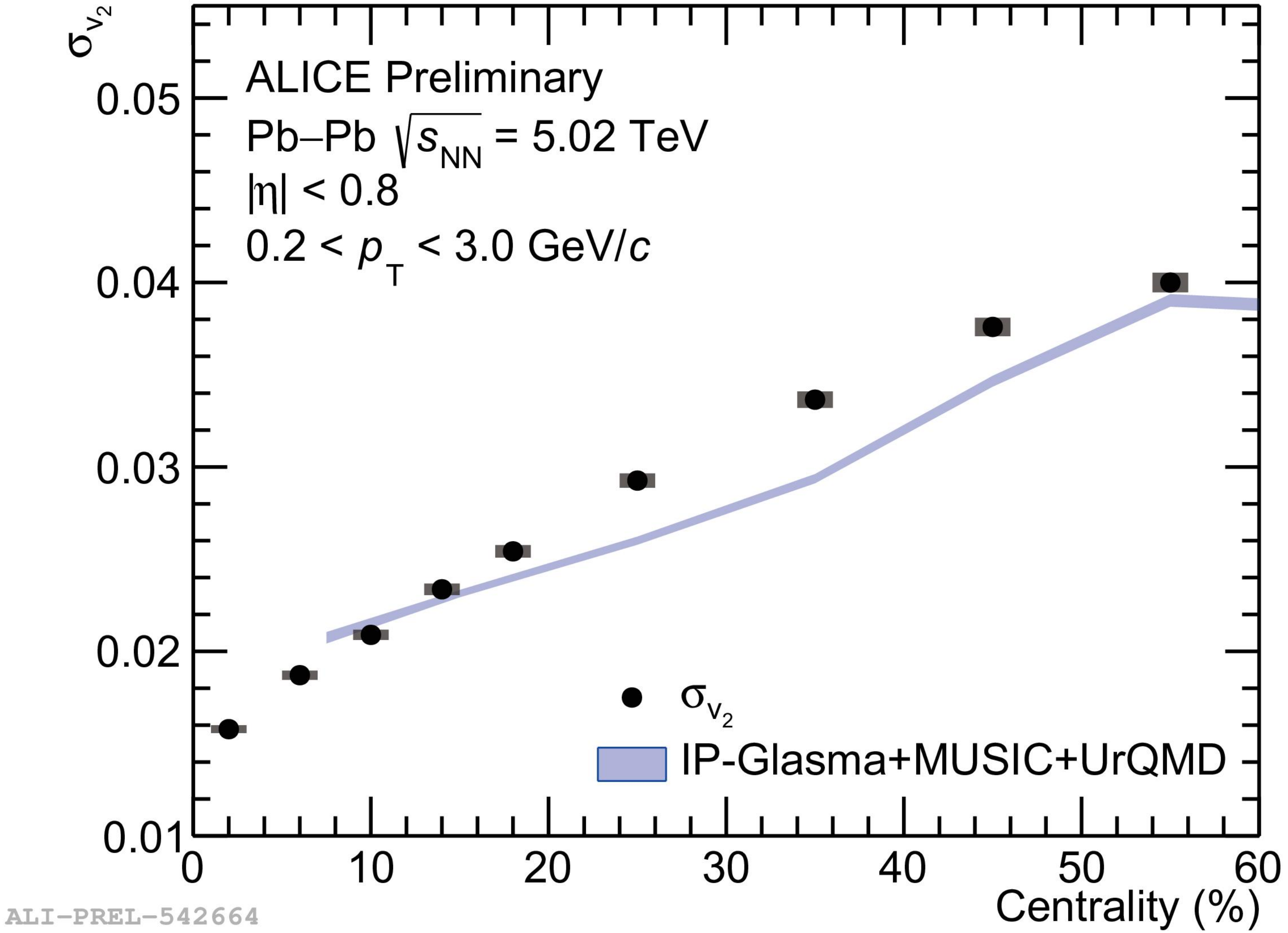

Results-nonlinear component of v_n

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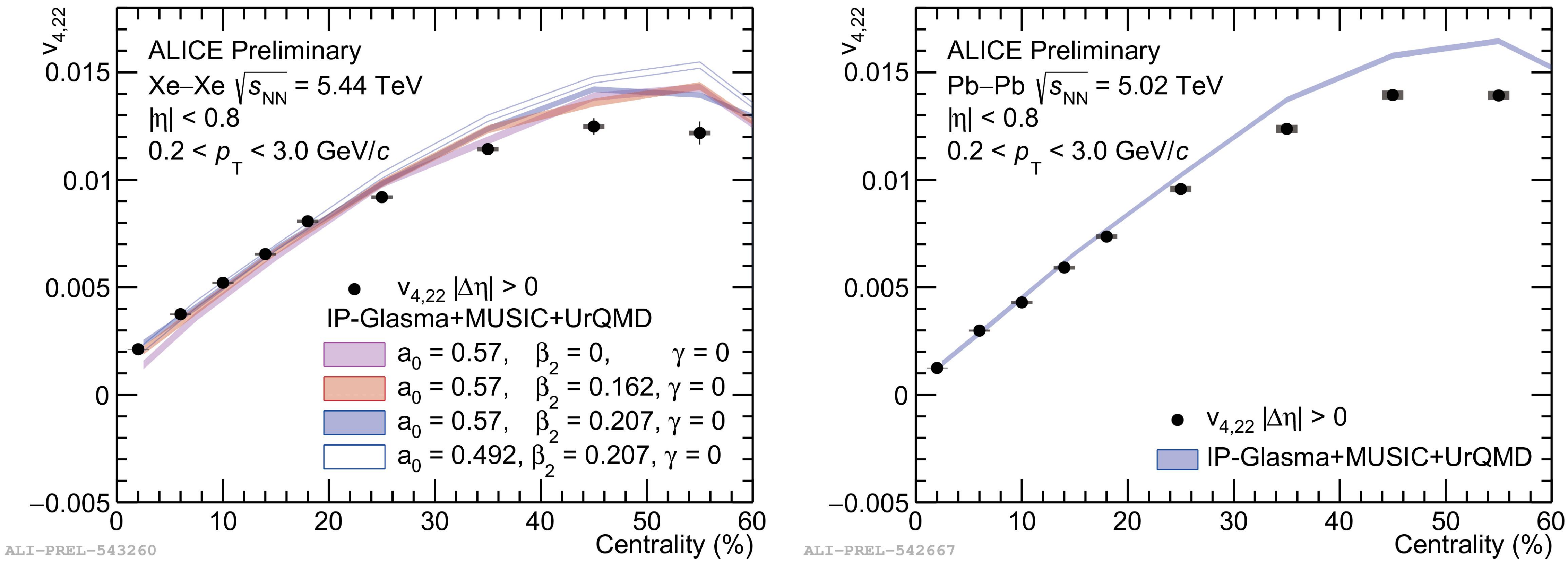
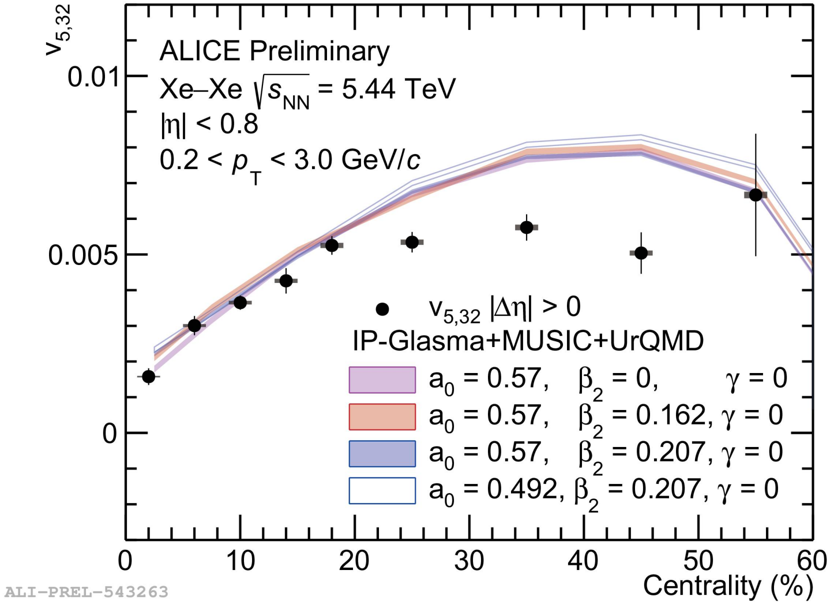
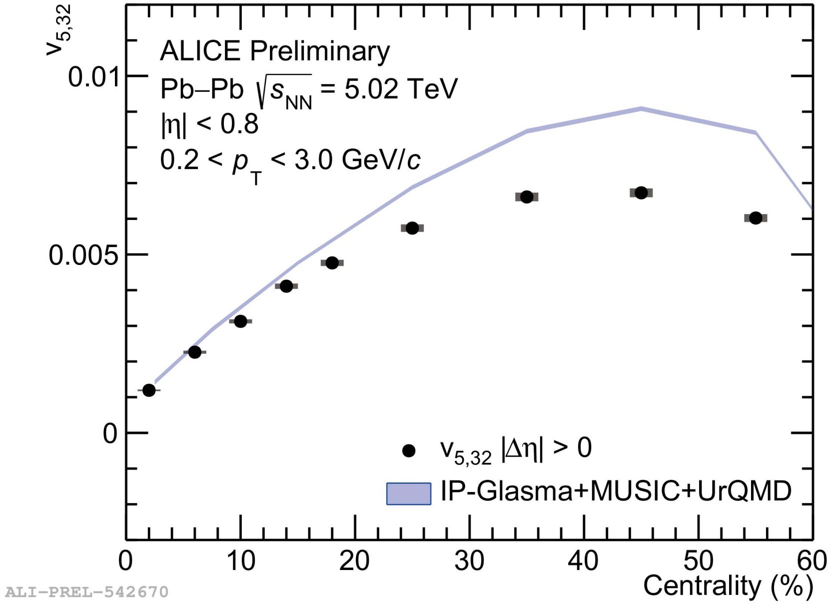
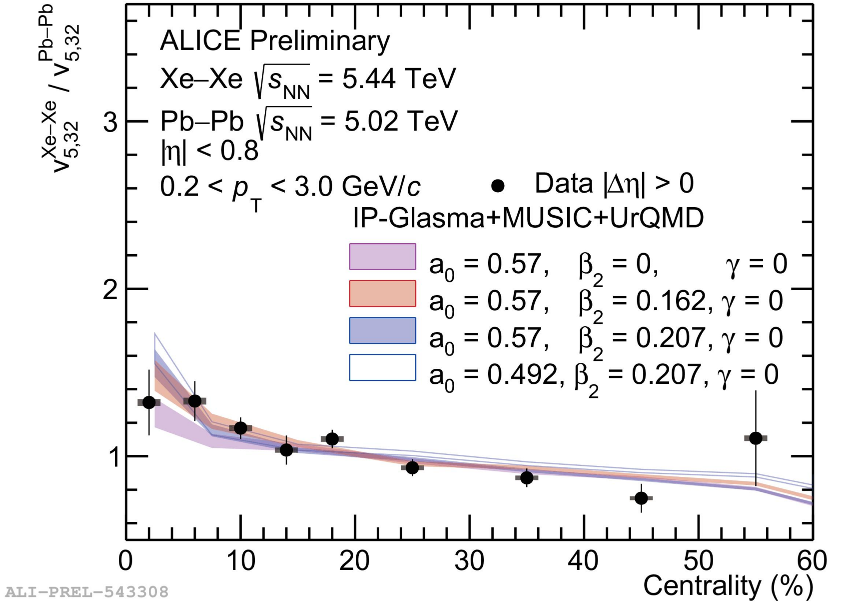


Results-nonlinear component of v_n

Zhiyong Lu(CIAE)





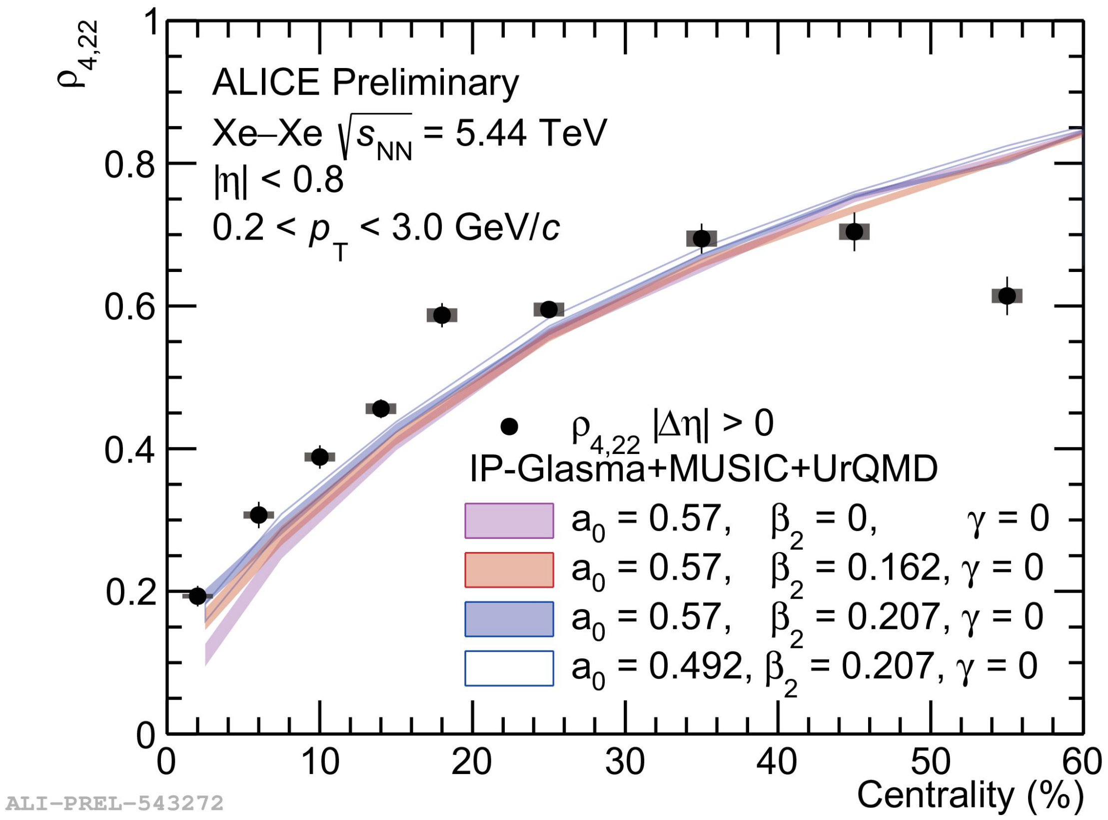


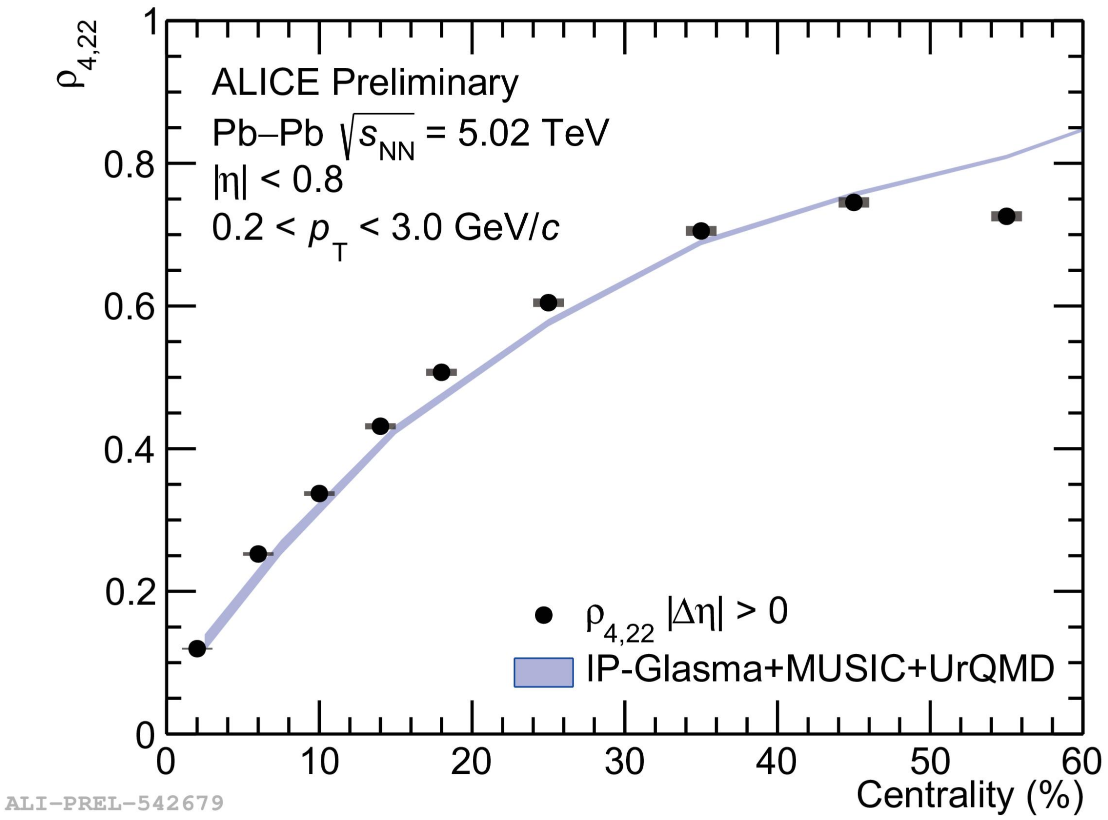
$v_{5,32}$ is the nonlinear response from $\varepsilon_2\varepsilon_3$

- $v_{5,32}$ is sensitive to β_2 in the central region
- small difference caused by a_0 in peripheral region

Results-flow symmetry plane correlation $\rho_{n,mk}$

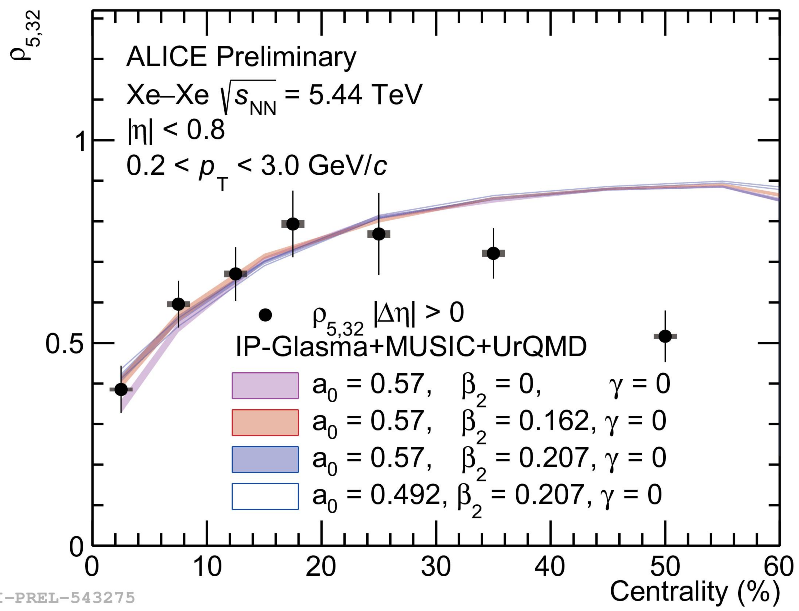
Zhiyong Lu(CIAE)

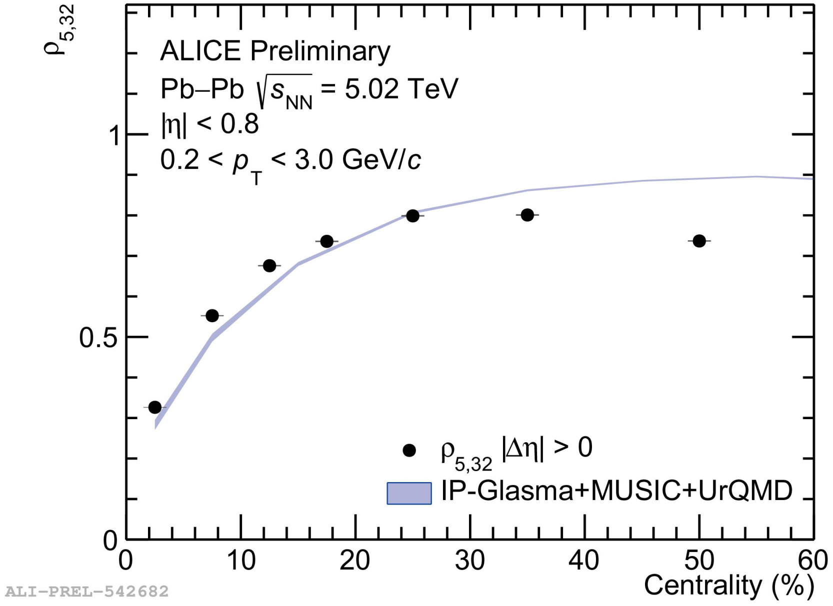


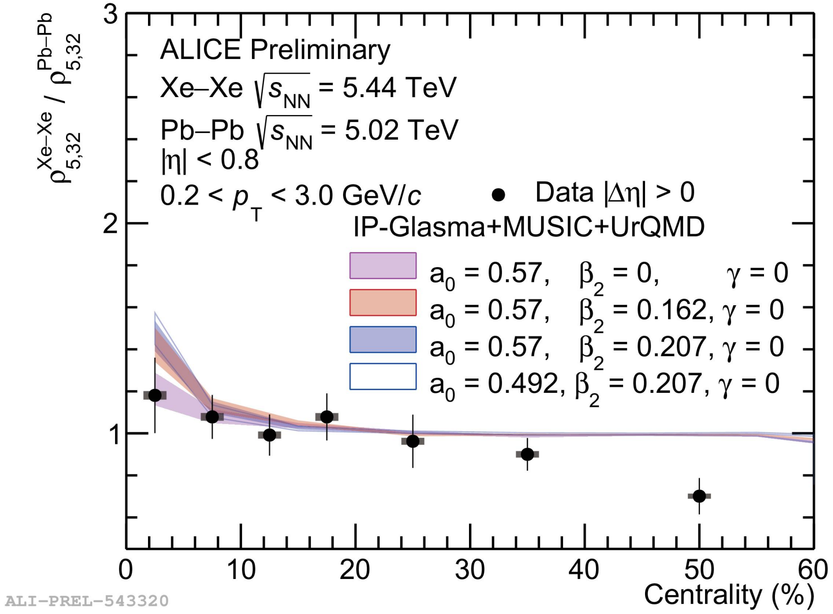


Results-flow symmetry plane correlation $\rho_{n,mk}$

Zhiyong Lu(CIAE)







$\rho_{5,32} = v_{5,32}/v_5\{2\}$

- closer to the model with no deformation but with large uncertainties
- insensitive to a_0

Results-nonlinear coefficients $\chi_{n,mk}$

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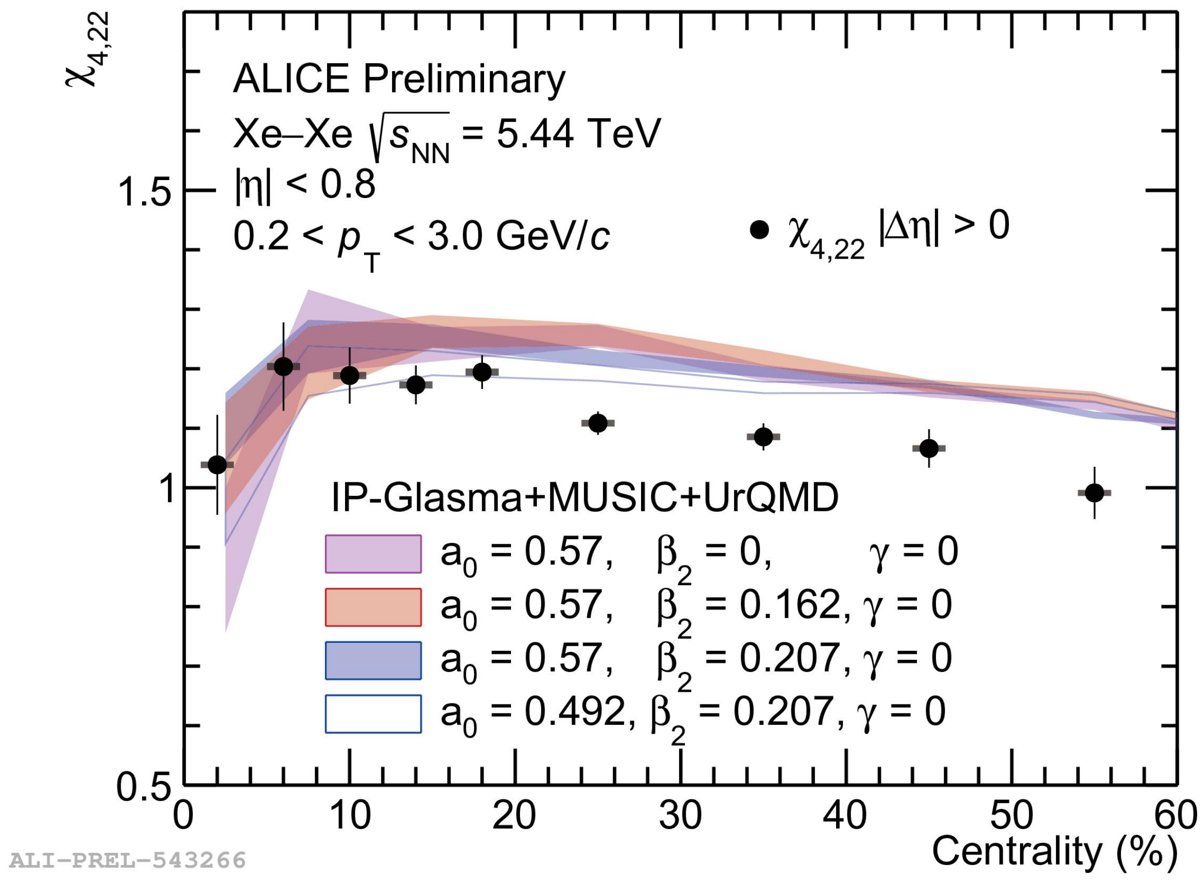
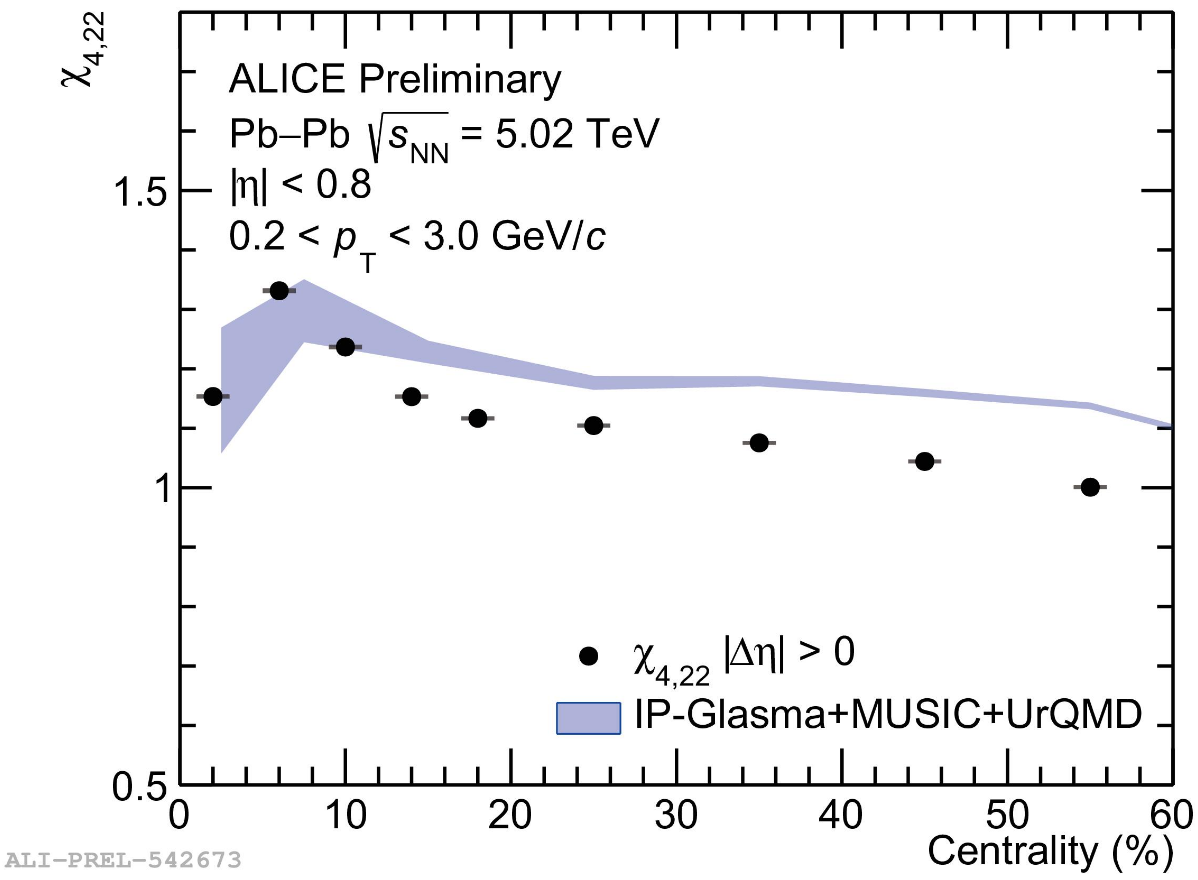
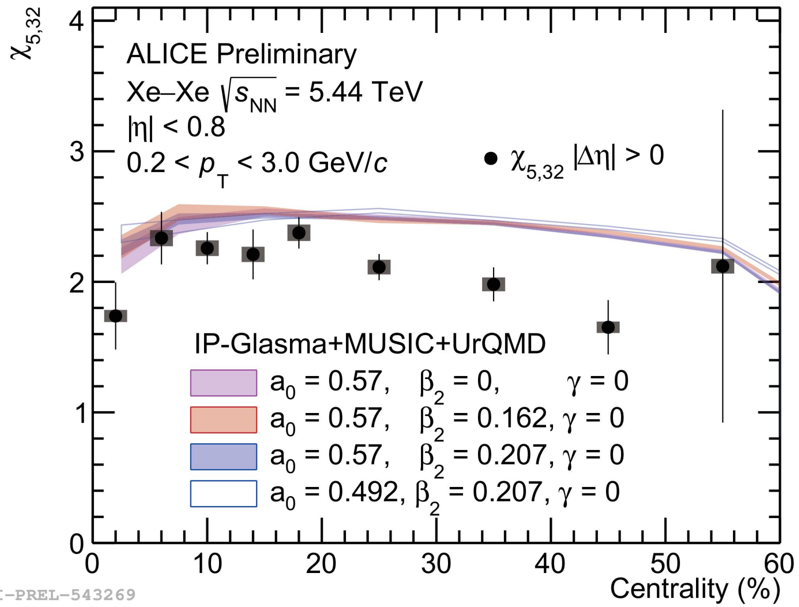
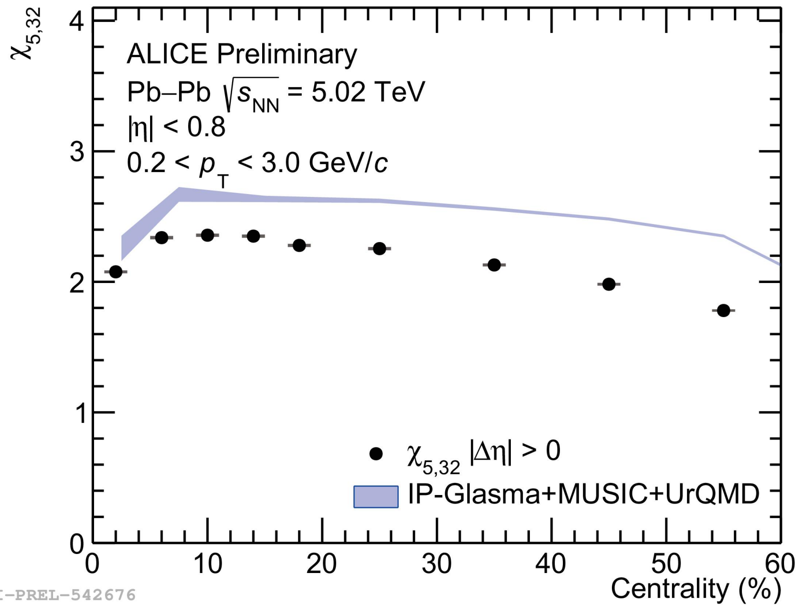
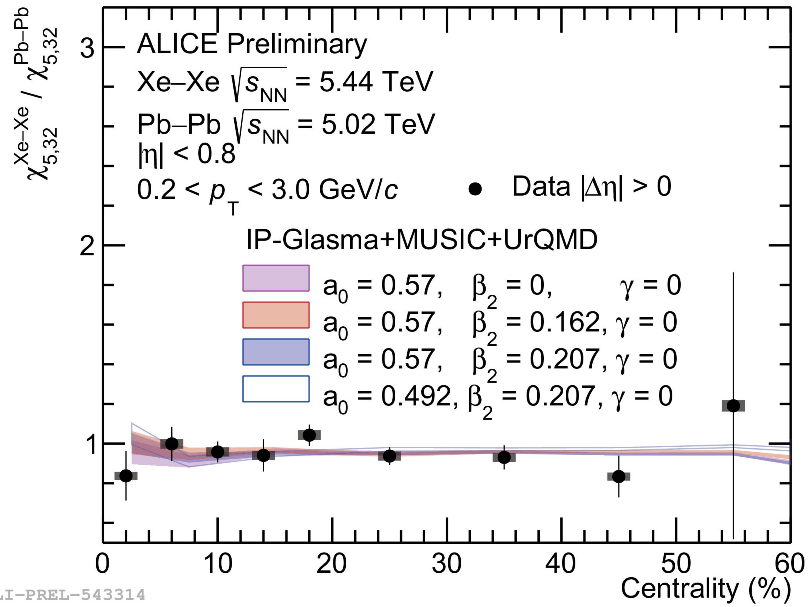




Results-nonlinear coefficients $\chi_{n,mk}$







- $V_5 = V_5^L + V_5^{NL} = V_5^L + \chi_{5,32} V_2 V_3$,
- the sensitivities of $v_{5,32}$ to β_2 and a_0 are largely from $V_2 V_3$
- V_3 is insensitive neither to β_2 nor a_0 → mainly from V_2

Results-normalized symmetric cumulants

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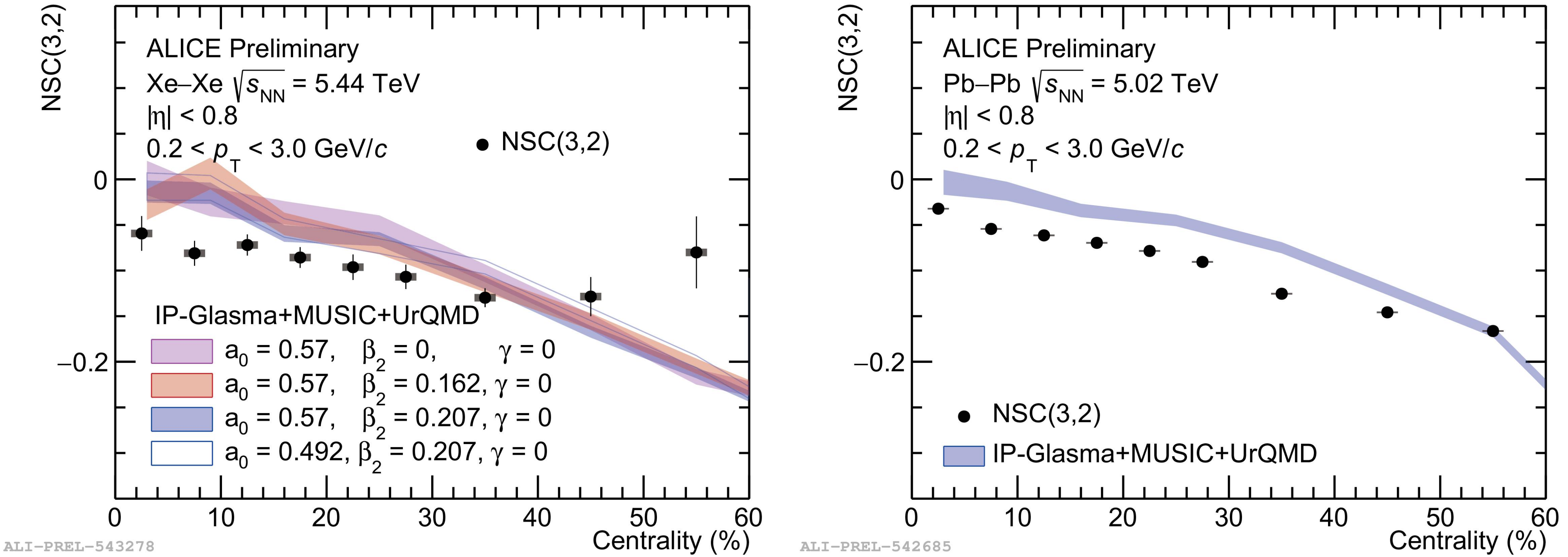

Results-normalized symmetric cumulants

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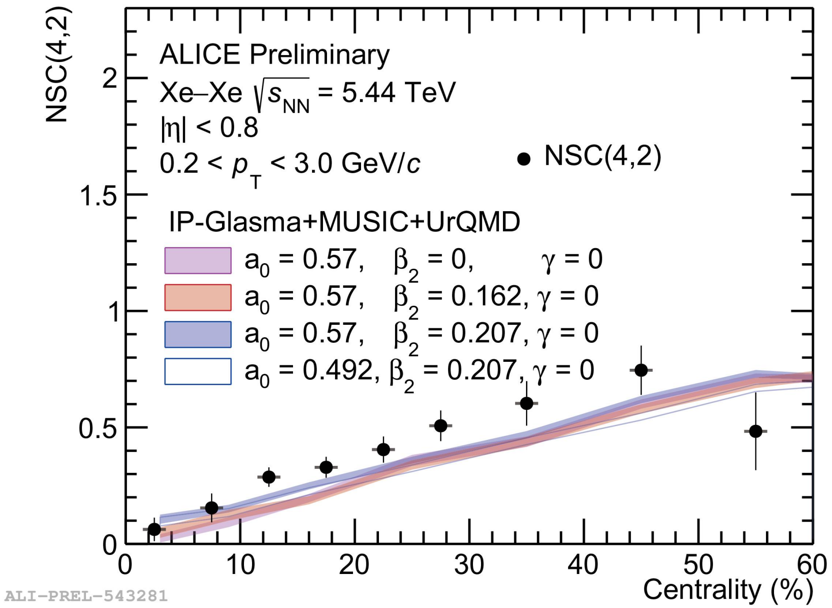

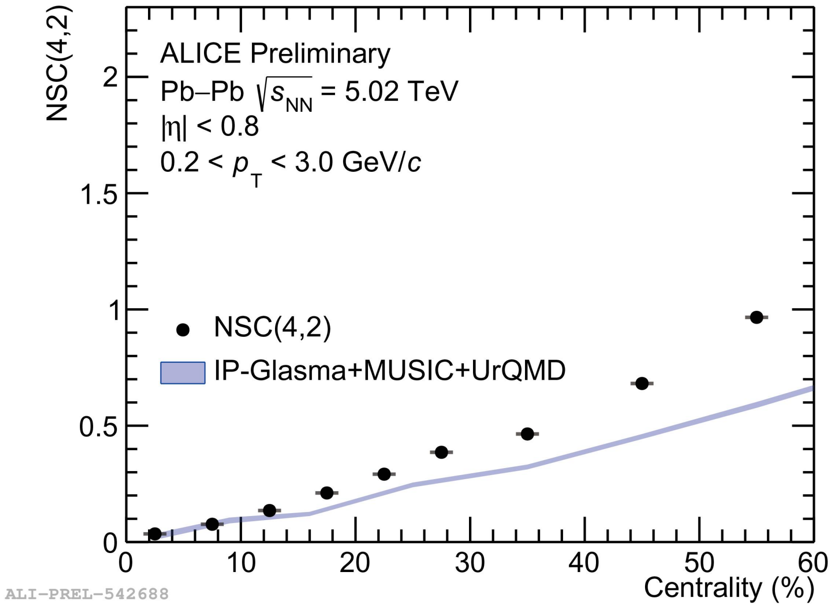

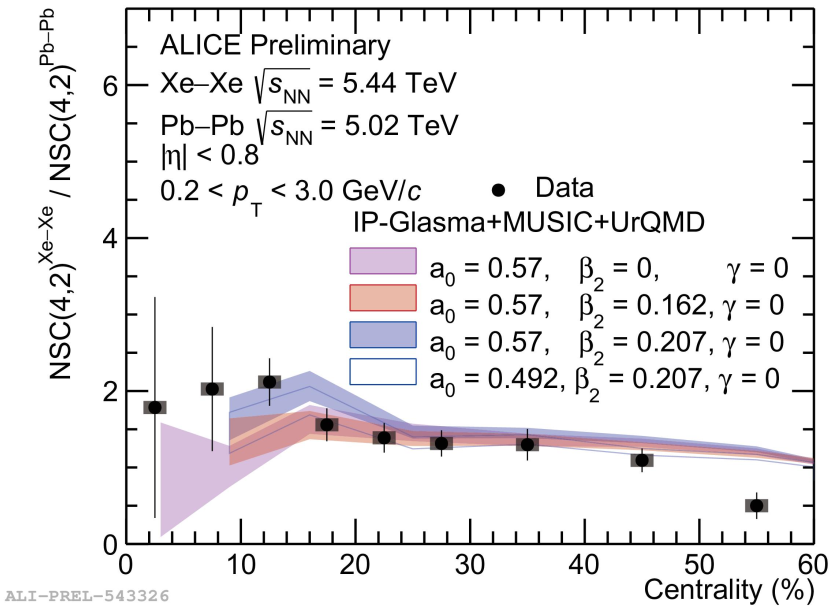

NSC(4,2): the correlation between v_4^2 and v_2^2

- IP-Glasma does not describe the data points
- insensitive neither to β_2 nor a_0

Results-AMPT simulation of $v_{4}, v_{4,22}, v_{4}^{L}$

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