# Longitudinal De-correlation of Anisotropic Flow at RHIC-STAR

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For the STAR Collaboration

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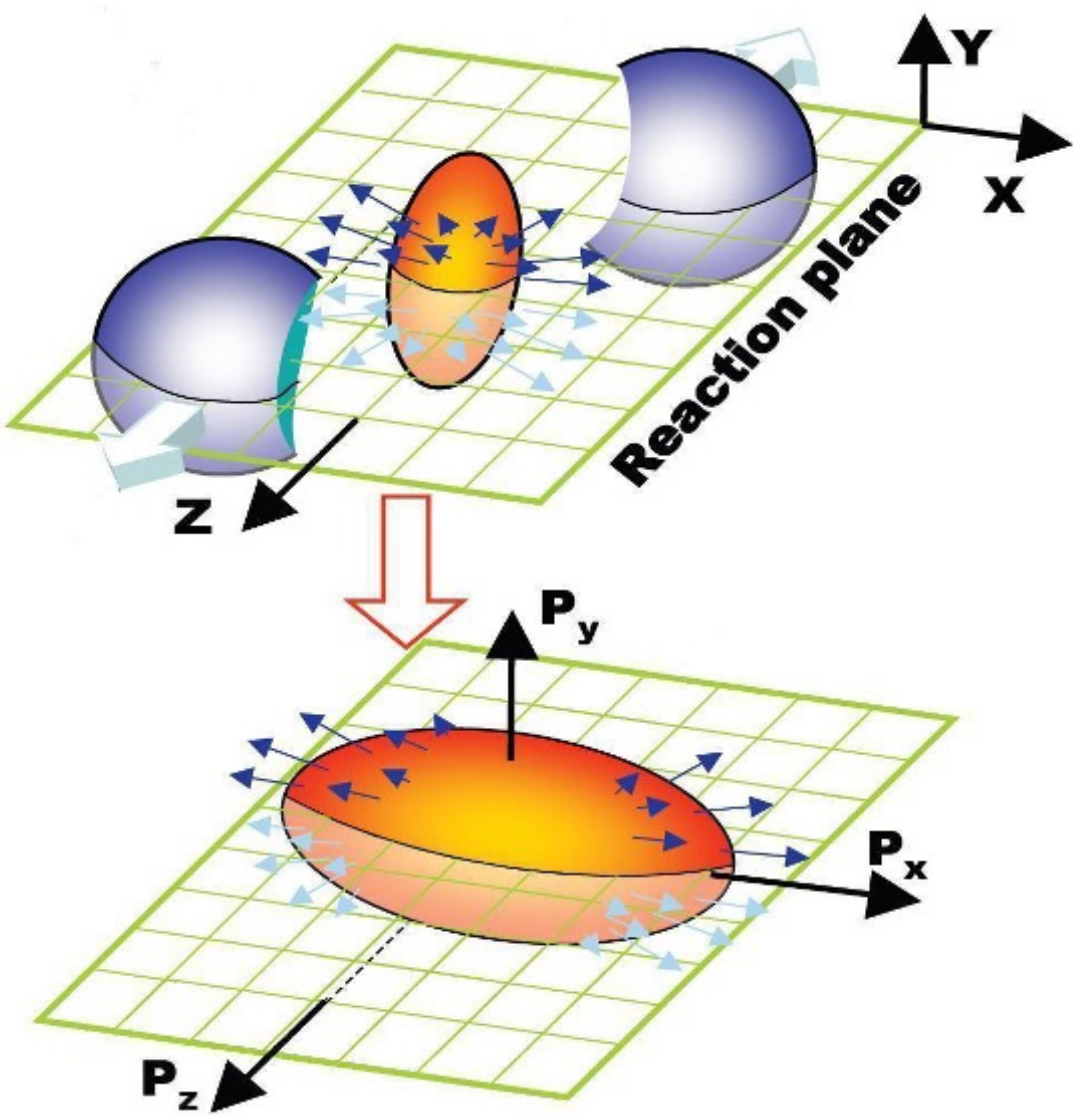
# Anisotropic flow




$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1} v_n cos\{n(\phi - \psi_n)\}$$

S. Voloshin, Y. Zhang
Z. Phys. C70: 665-672,1996

$v_2$: elliptic flow  $v_3$: triangular flow

- Two-particle correlation method (2PC)

$$\frac{dN^{pair}}{d\phi} \propto 1 + 2\sum_{n=1} V_{n\Delta} cos(n\Delta\phi)$$

S. Wang et al.
Phys. Rev. C 44, 1091 (1991).

- Single particle flow:

$$V_{n\Delta} = v_n^a(p_T^a, \eta^a) v_n^b(p_T^b, \eta^b)$$

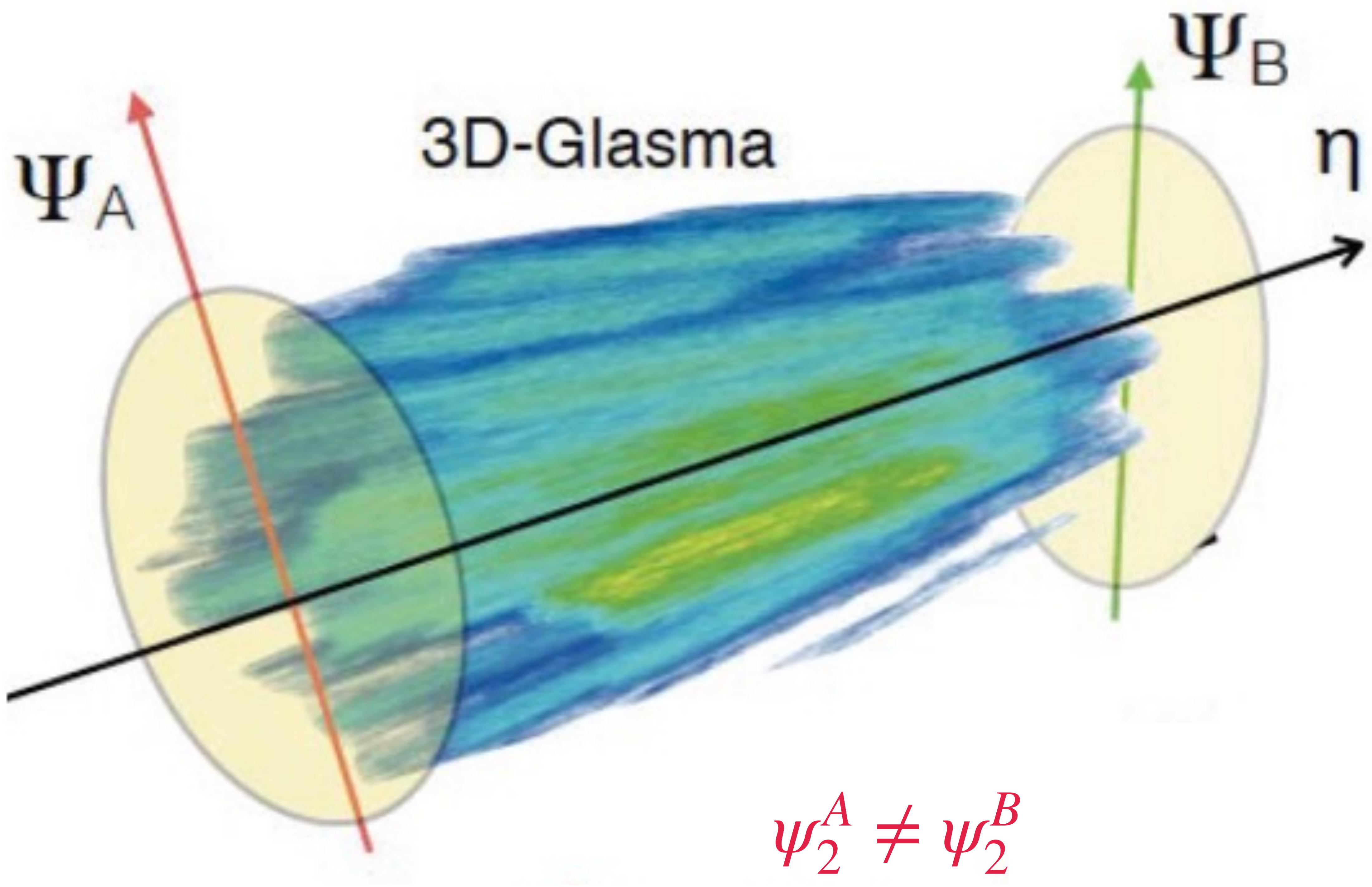
- Event-by-event fluctuation

$$V_{n\Delta} = v_n^a(p_T^a, \eta^a) v_n^b(p_T^b, \eta^b) e^{in(\psi_n^a - \psi_n^b)}$$

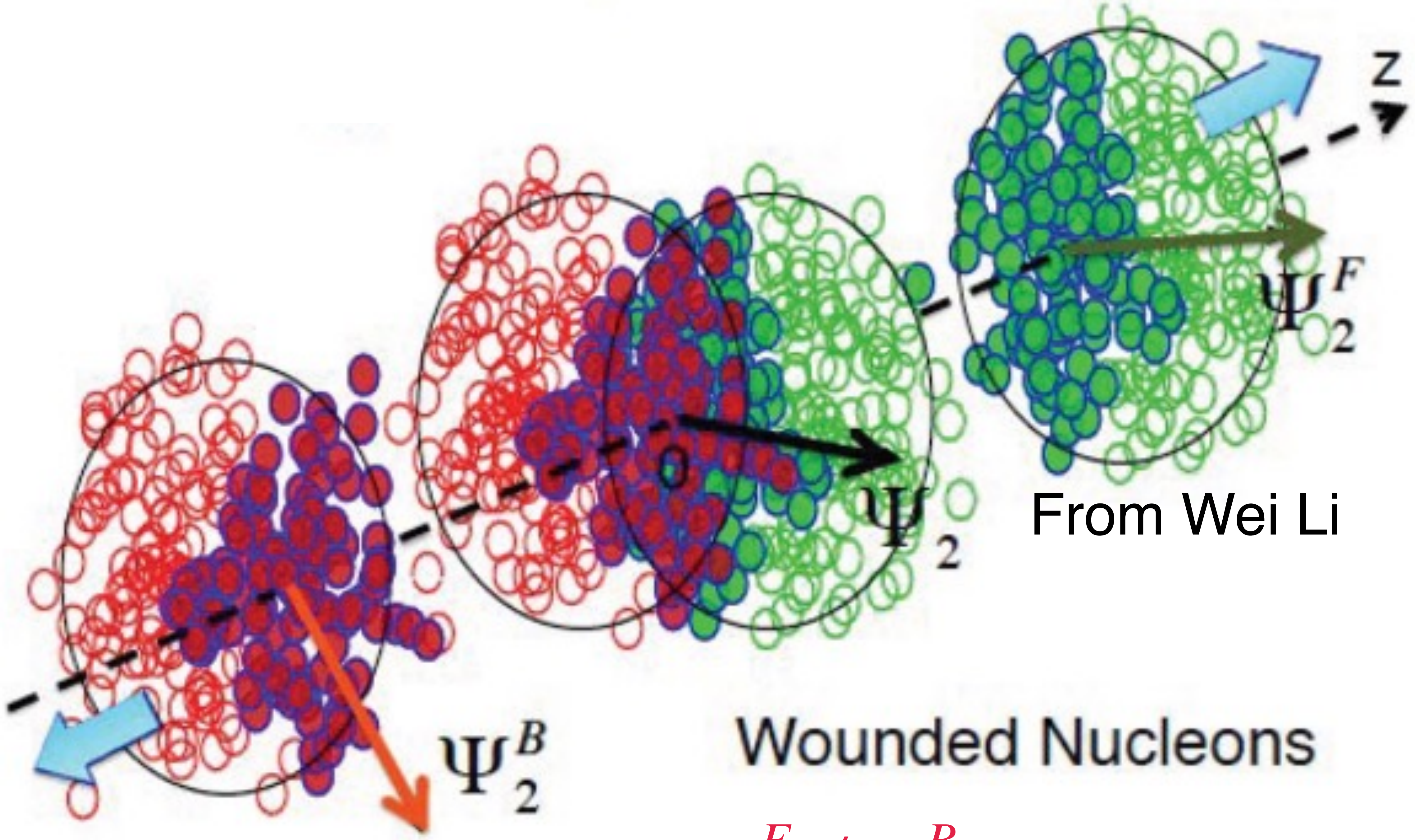
Fernando G. Gardim et al.
Phys. Rev. C. 87. 031901

Piotr Bozek et al.
Phys. Rev. C. 83. 034911

# Longitudinal de-correlation




$\psi_2^A \neq \psi_2^B$




$\psi_2^F \neq \psi_2^B$

Bjorn Schenke, Soren Schlichting
Phys. Rev. C 94 (2016) 4, 044907

Jiangyong Jia, Peng Huo
Phys. Rev. C 90 (2014) 034905

Measurement of de-correlation can probe 3D initial state and dynamical evolution of the QGP

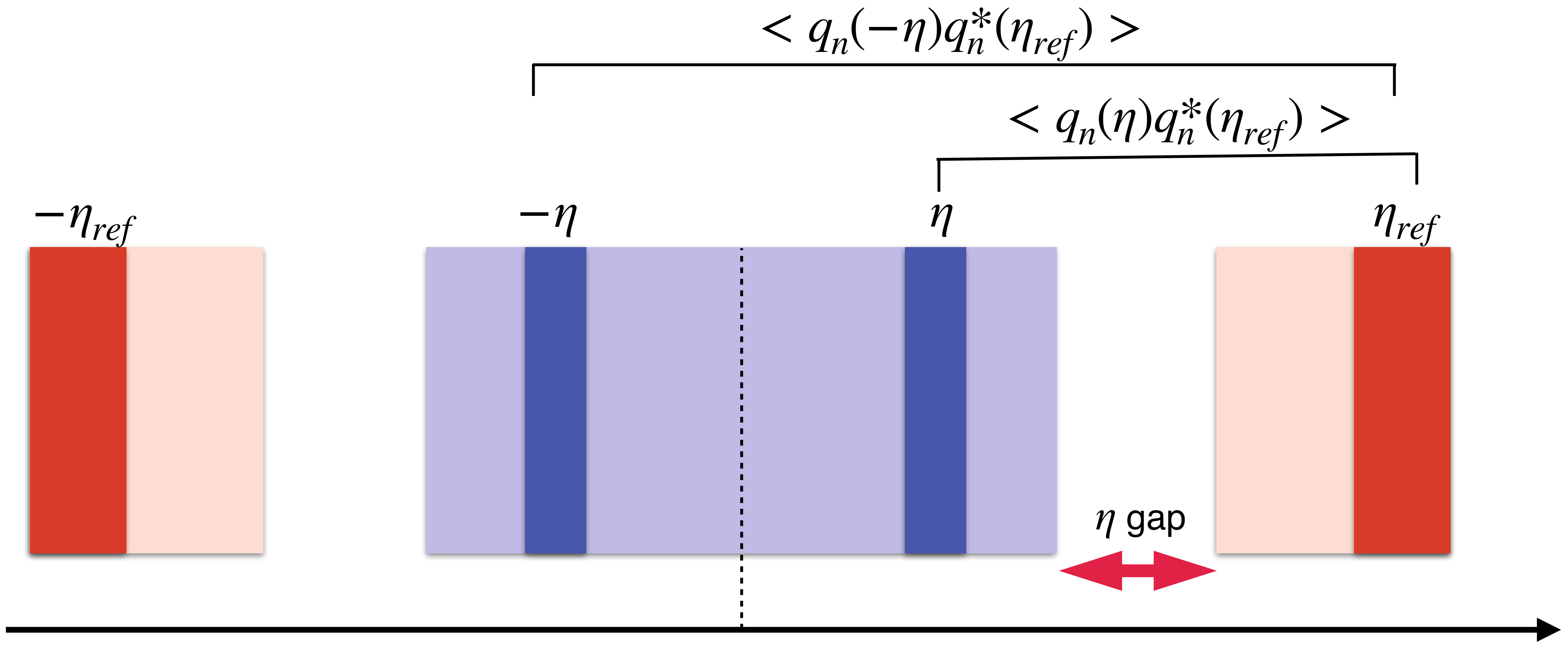
# Measuring de-correlation

- The factorization ratio, $r_n$, is constructed to measure flow de-correlation

$$r_n(\eta) = \frac{< q_n(-\eta)q_n^*(\eta_{ref}) >}{< q_n(+\eta)q_n^*(\eta_{ref}) >} = \frac{< v_n(-\eta)v_n(\eta_{ref})cos\{n[\psi_n(-\eta) - \psi_n(\eta_{ref})]\}) >}{< v_n(+\eta)v_n(\eta_{ref})cos\{n[\psi_n(+\eta) - \psi_n(\eta_{ref})]\}) >}$$

CMS Collaboration
Phys. Rev. C 92 (2015) 034911

- The $r_n(\eta)$ measures relative fluctuation between $-\eta$ and $+\eta$



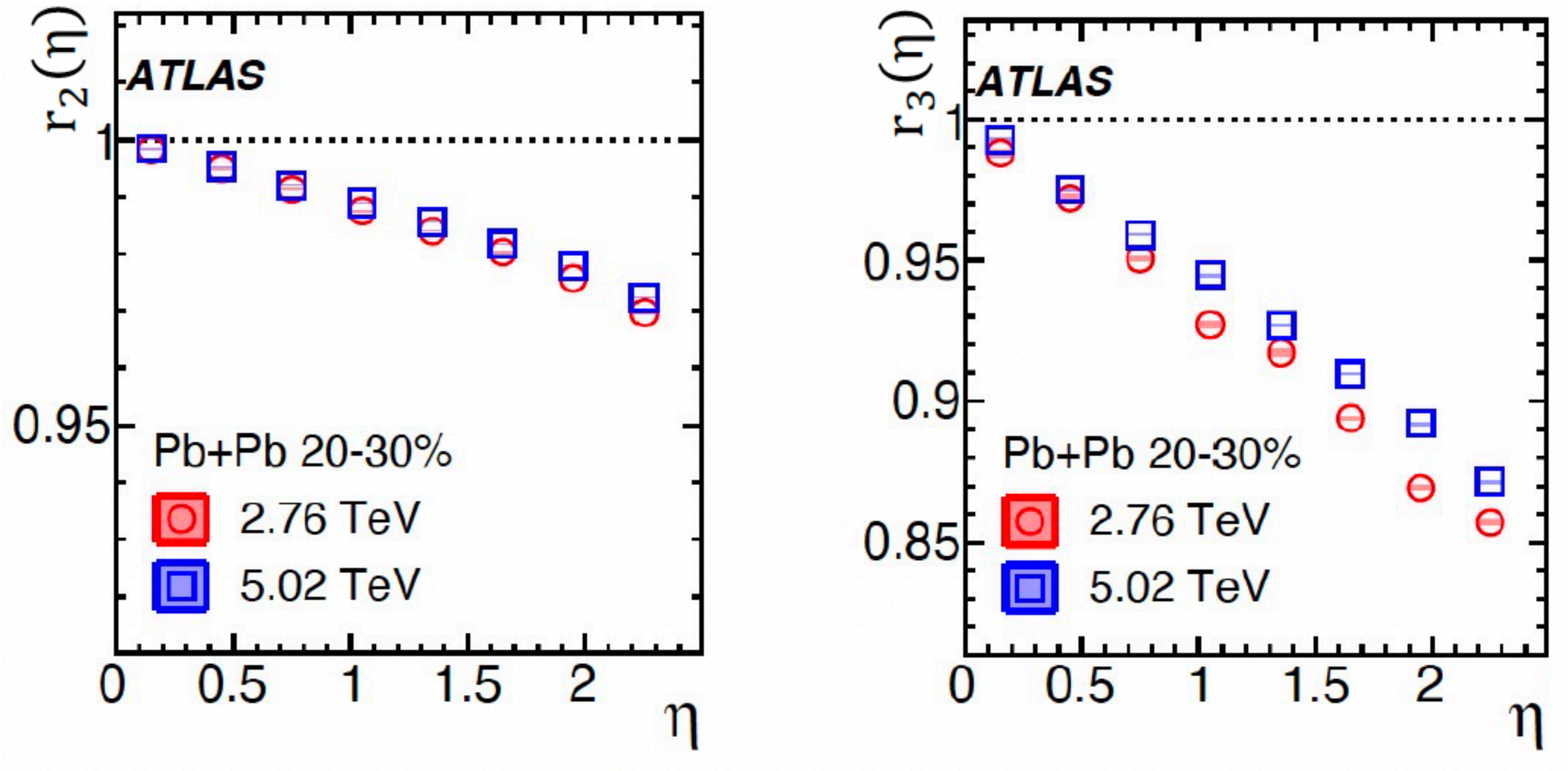

From Maowu Nie

A large $\eta$ gap can avoid short-range correlation

# LHC results

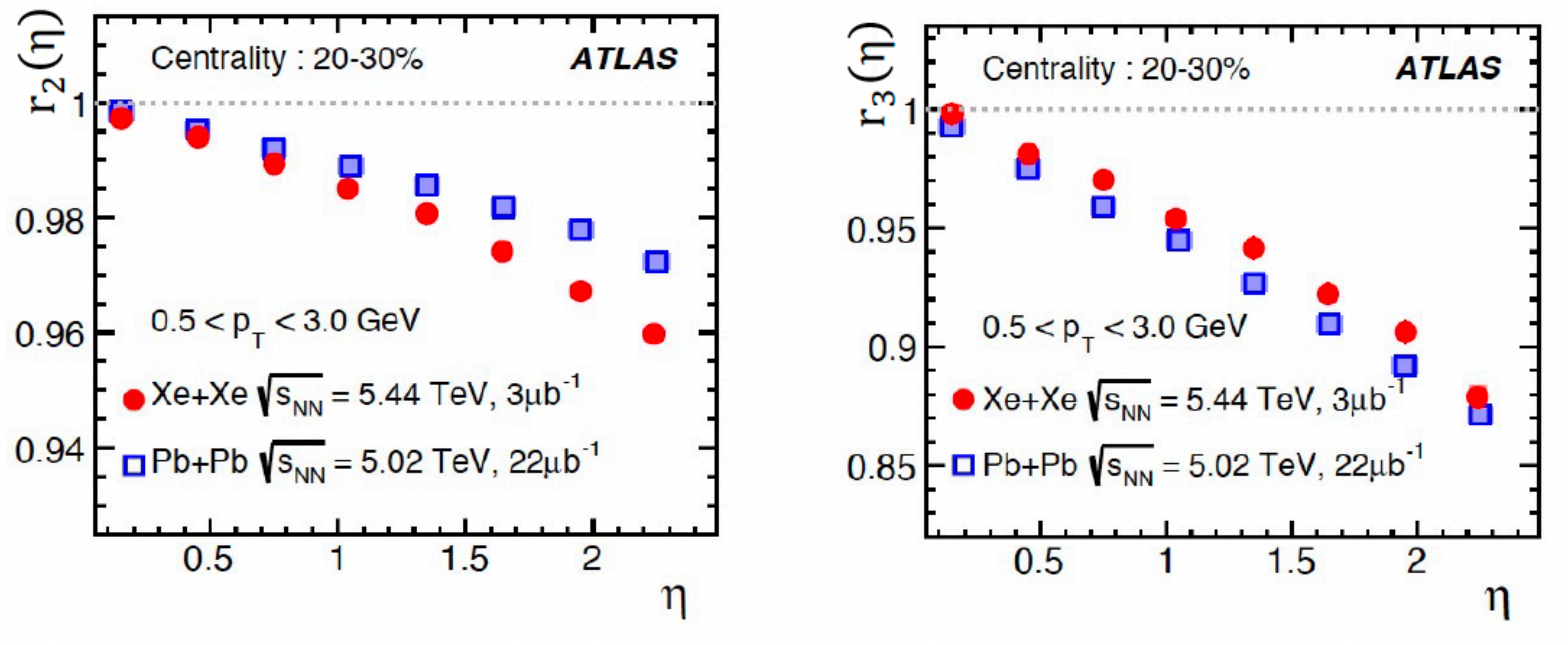
- Energy dependence

ATLAS Collaboration
Eur. Phys. J. C 78 (2018) 2, 142




- System size dependence

ATLAS Collaboration
Phys. Rev. Lett. 126 (2021) 122301

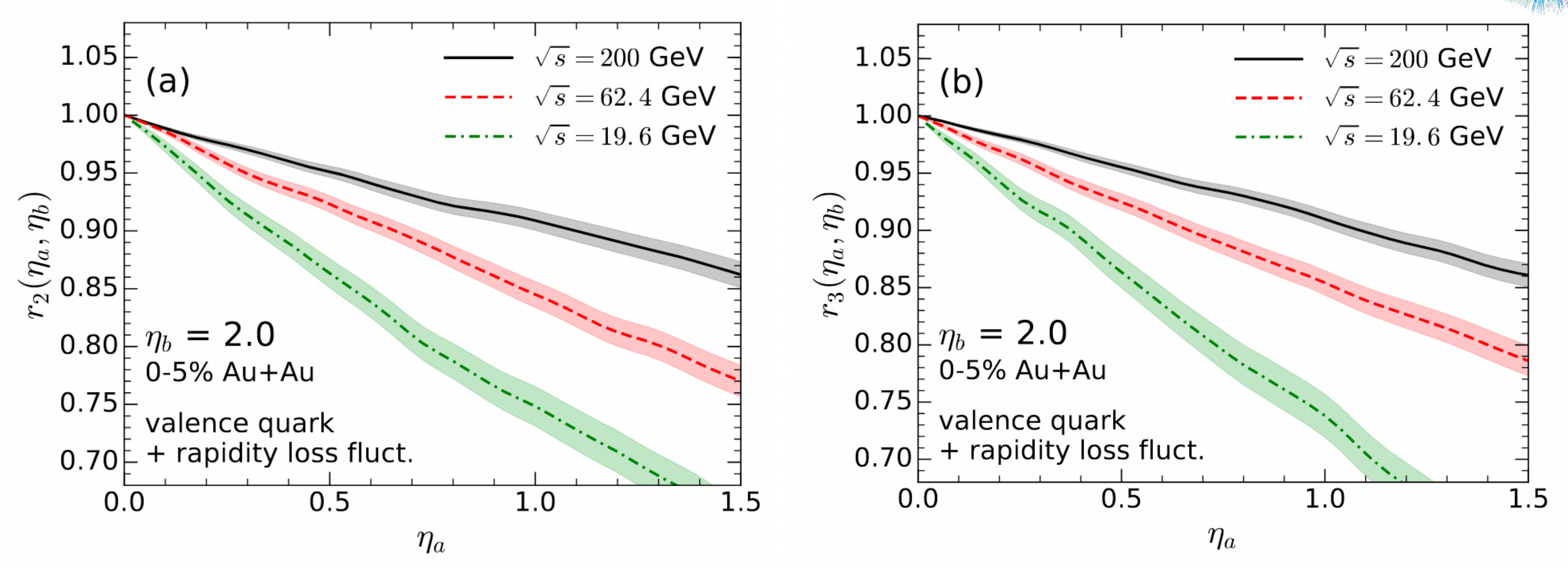



Indication of larger longitudinal de-correlation at lower energy

Smaller system size has larger longitudinal de-correlation

What about at RHIC? → Energy dependence: Beam Energy Scan
System size dependence: various species

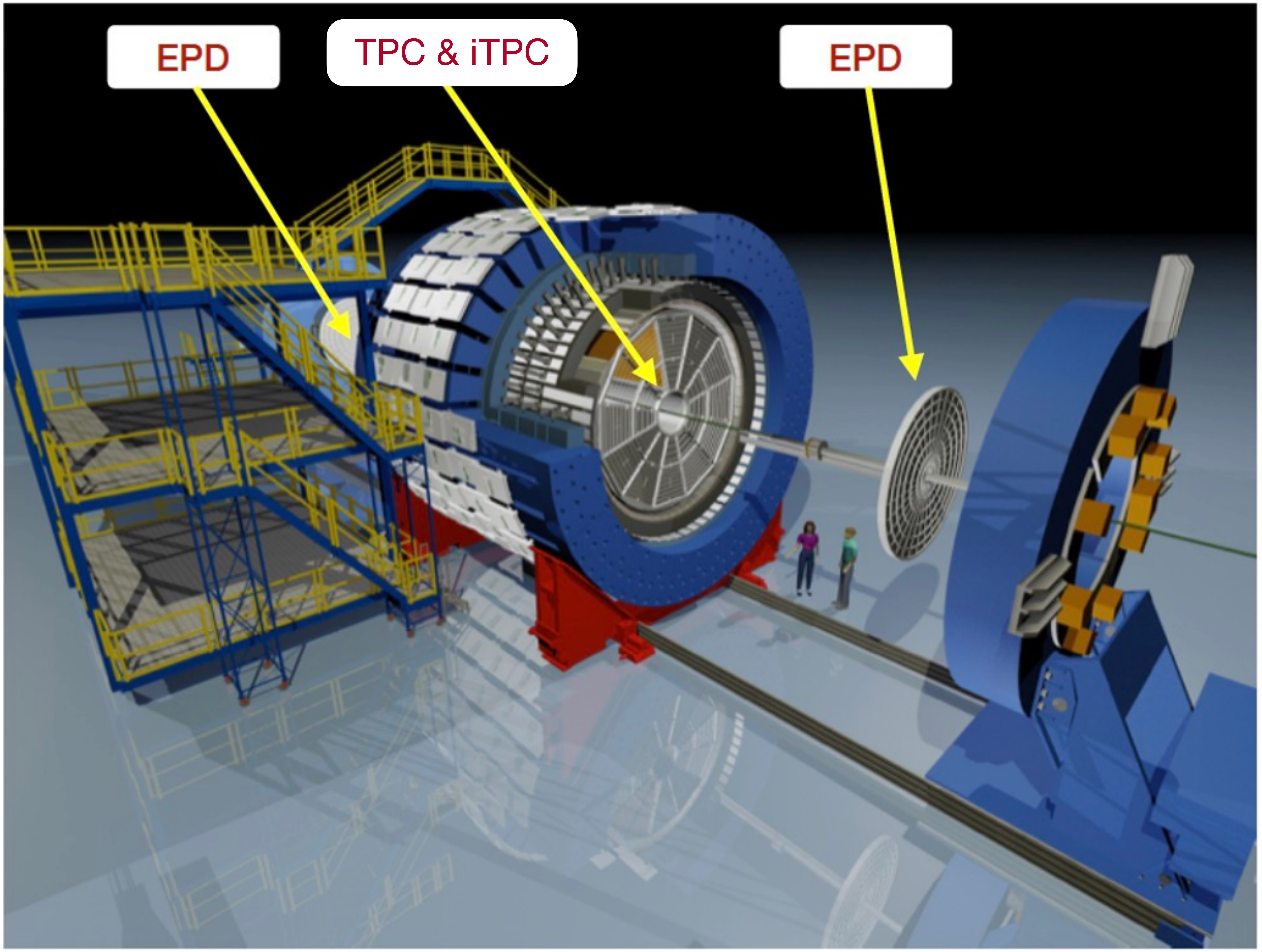
# Dynamical initial state model calculation




The de-correlation effect becomes stronger at lower collision energies

Chun Shen, Bjorn Schenke
Phys. Rev. C 97 (2018) 2, 024907

# The STAR detector and datasets




- Time Projection Chamber

  Full azimuthal coverage

  TPC: $|\eta| < 1.0$

  iTPC: $|\eta| < 1.5$

- Event Plane Detector

  Better event plane resolution

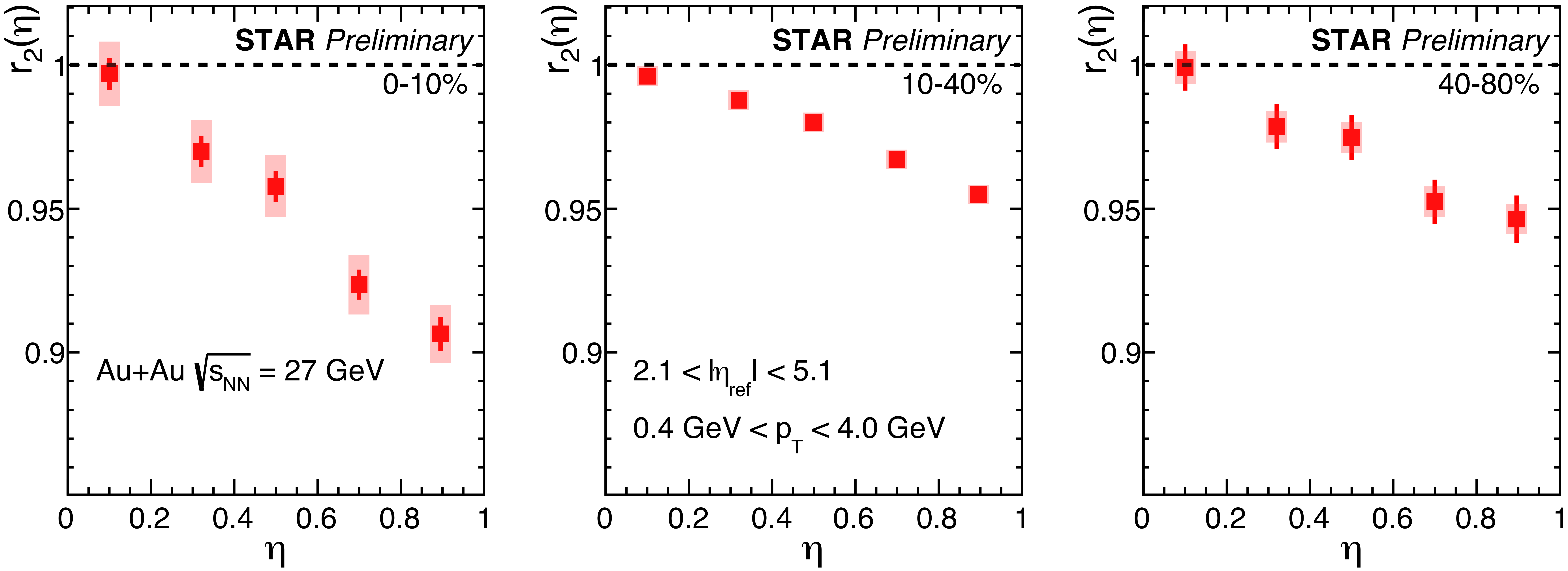
  $2.1 < |\eta| < 5.1$

- Data

  Zr+Zr/Ru+Ru collisions at 200 GeV

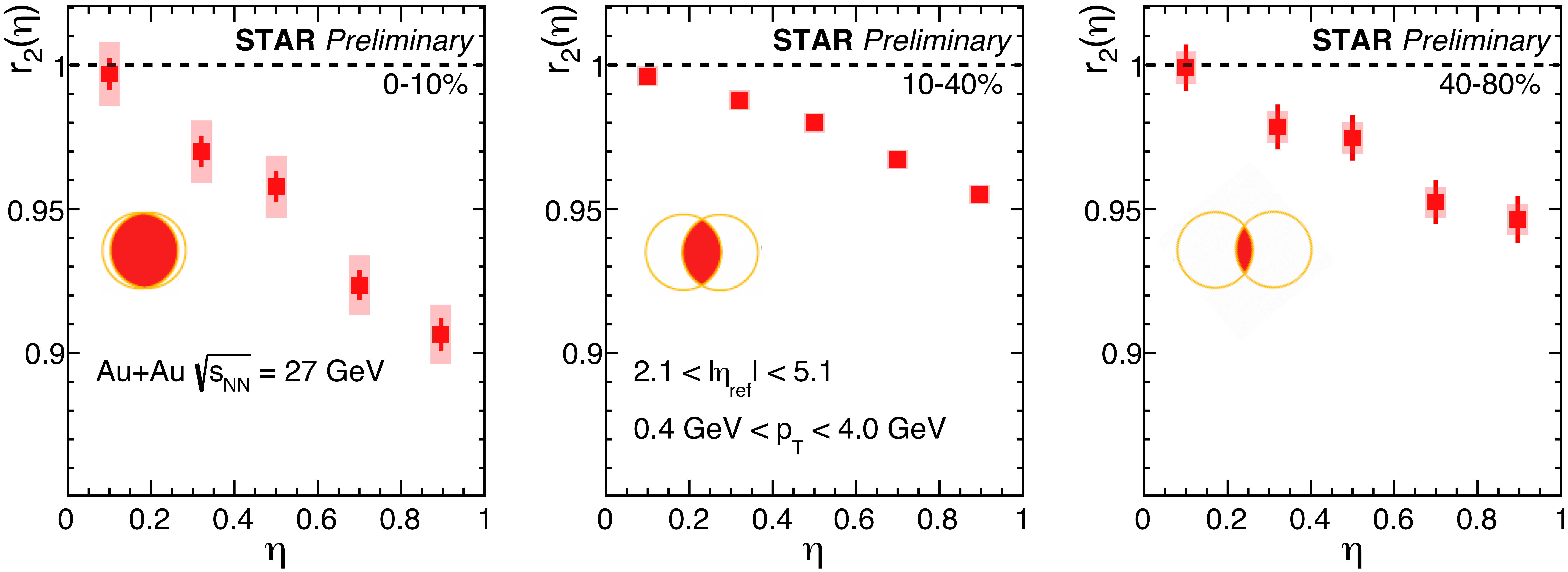
  Au+Au collisions at 19.6, 27, 54.4 GeV

# 2nd order de-correlation in Au+Au at 27 GeV




Significant longitudinal de-correlation at RHIC energy

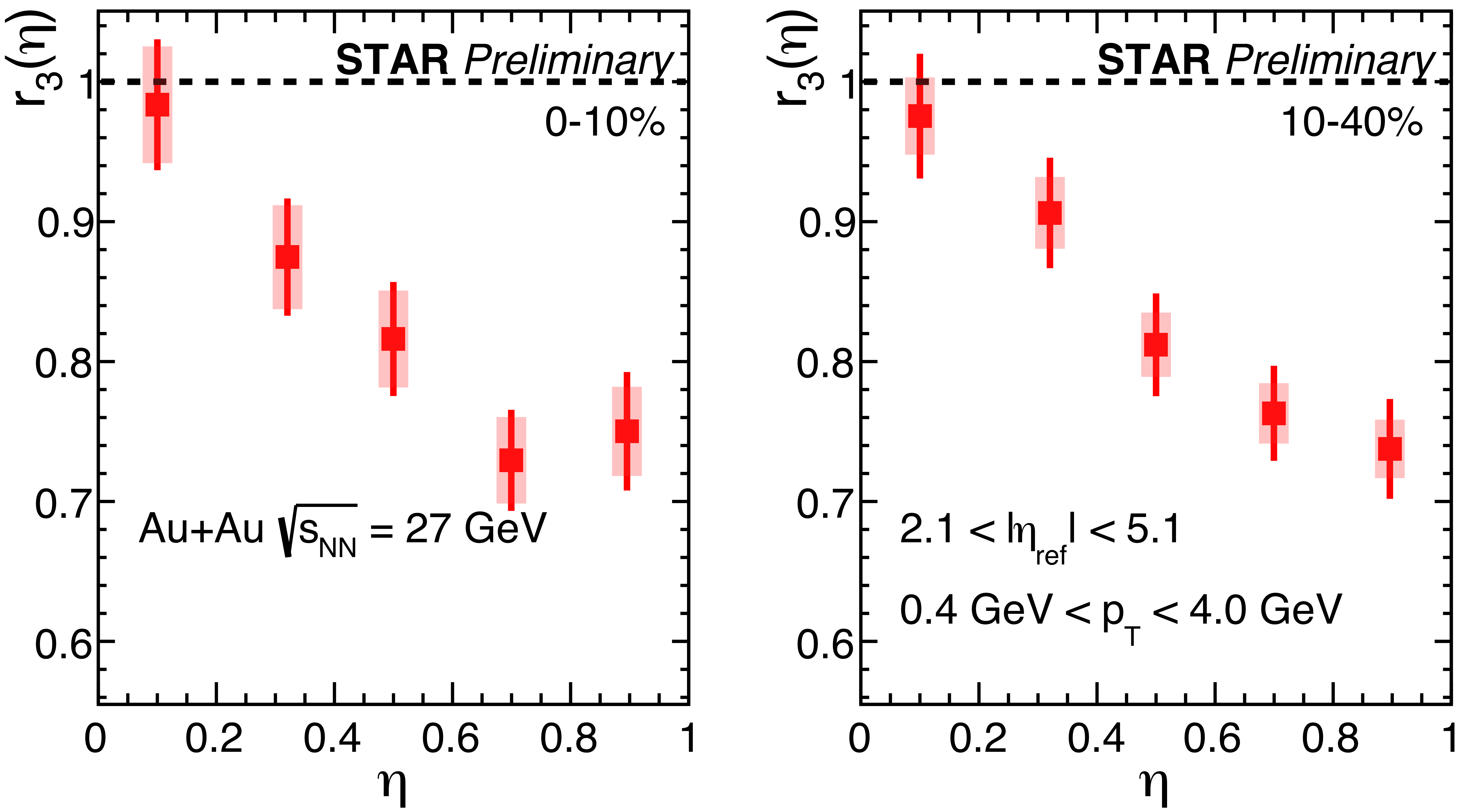
# 2nd order de-correlation in Au+Au at 27 GeV




Significant longitudinal de-correlation at RHIC energy

De-correlation is the strongest in central collisions

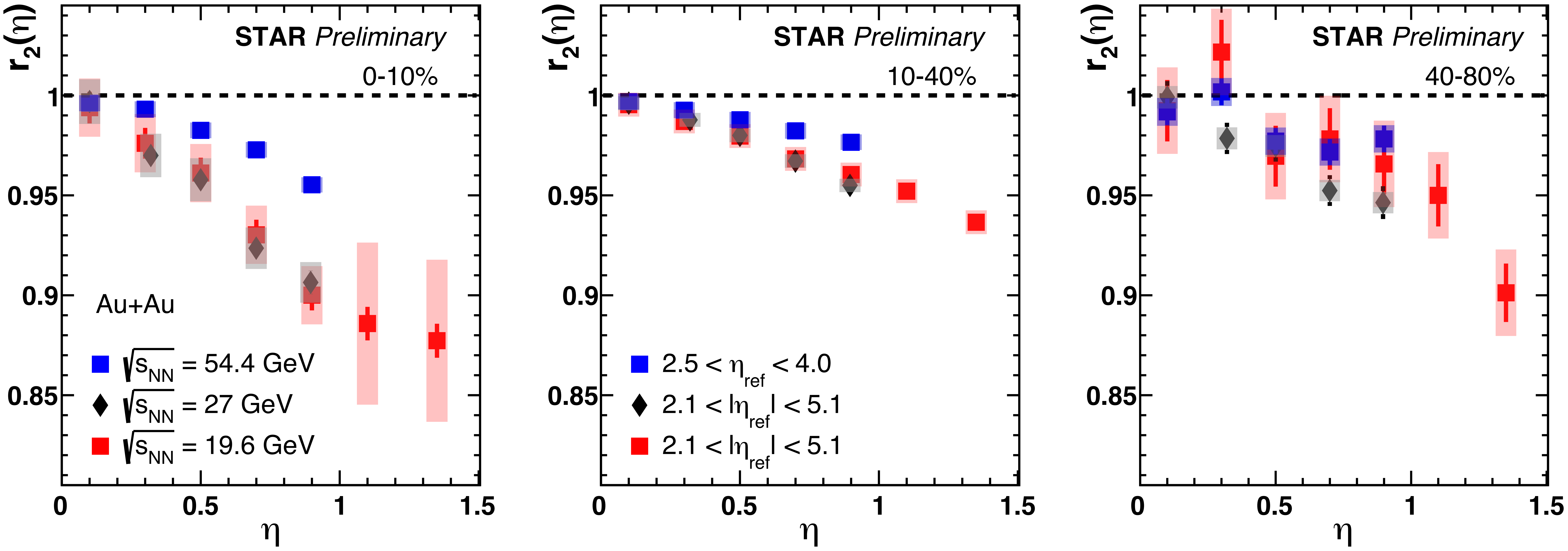
# 3rd order de-correlation in Au+Au at 27 GeV




No obvious centrality dependence

The 3rd order de-correlation is 2-3 times stronger than 2nd order

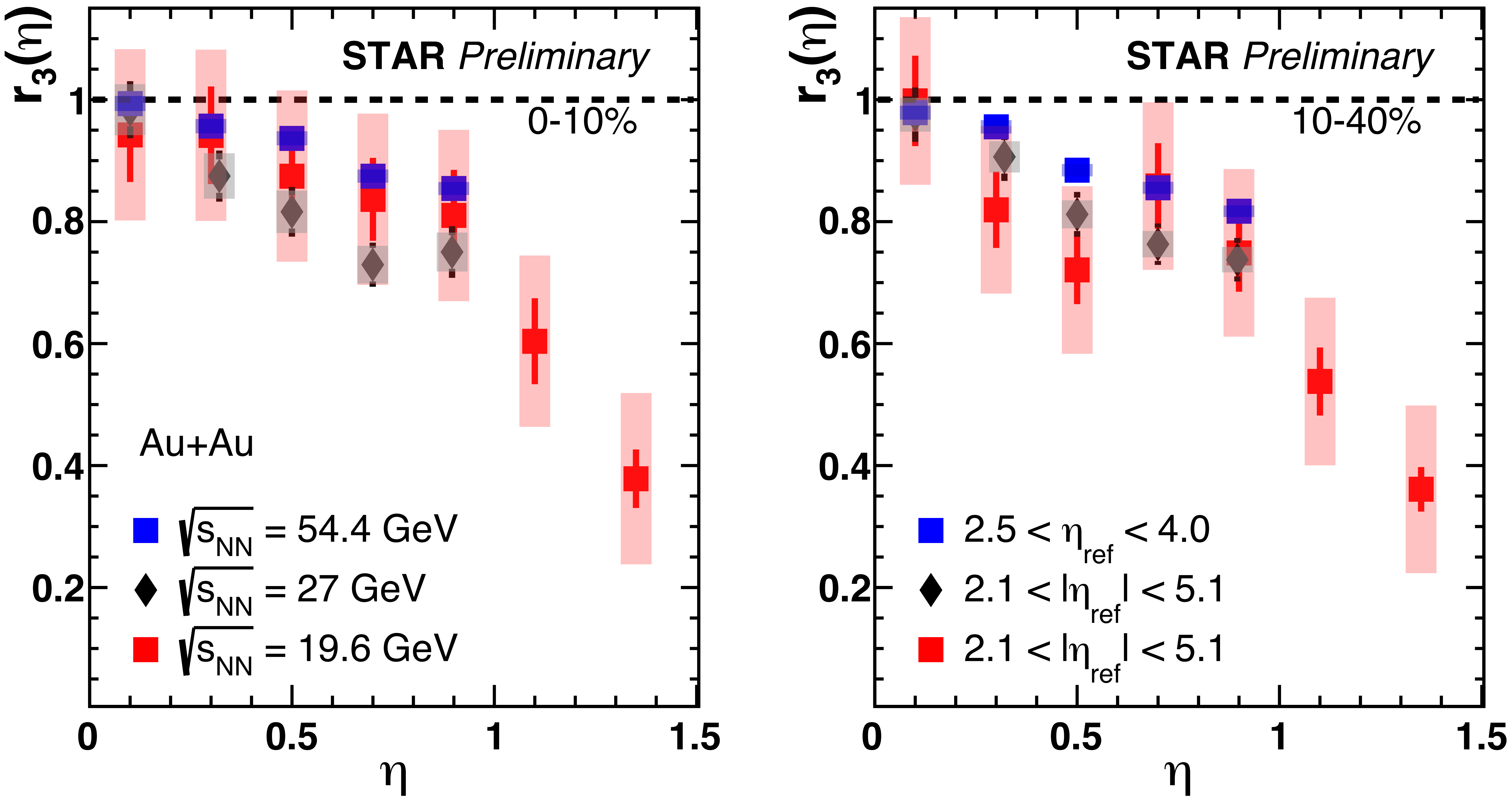
# Collision energy dependence of $r_2$




Clear energy dependence between 54 GeV and 27 GeV

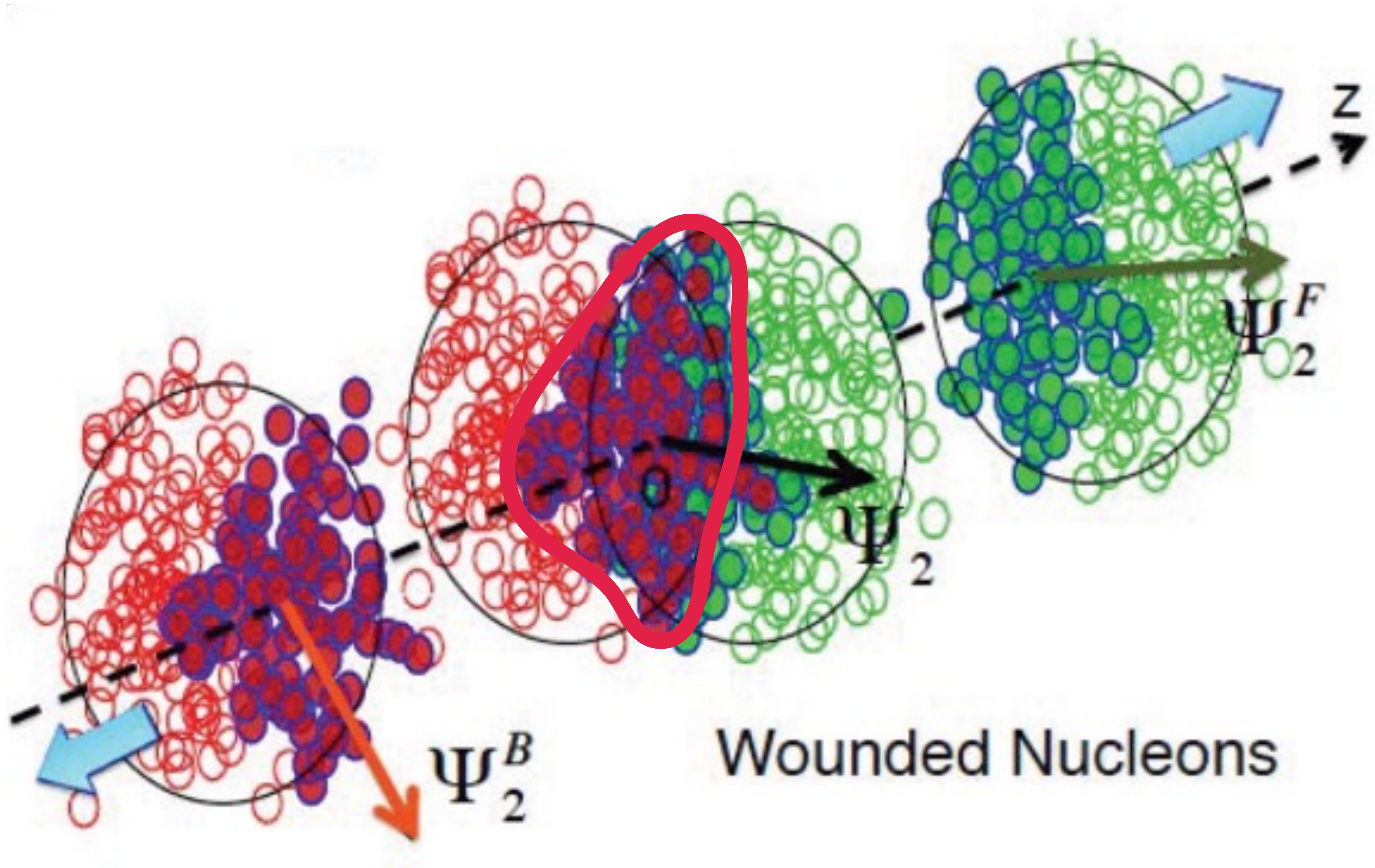
Hint of nonlinear energy dependence?

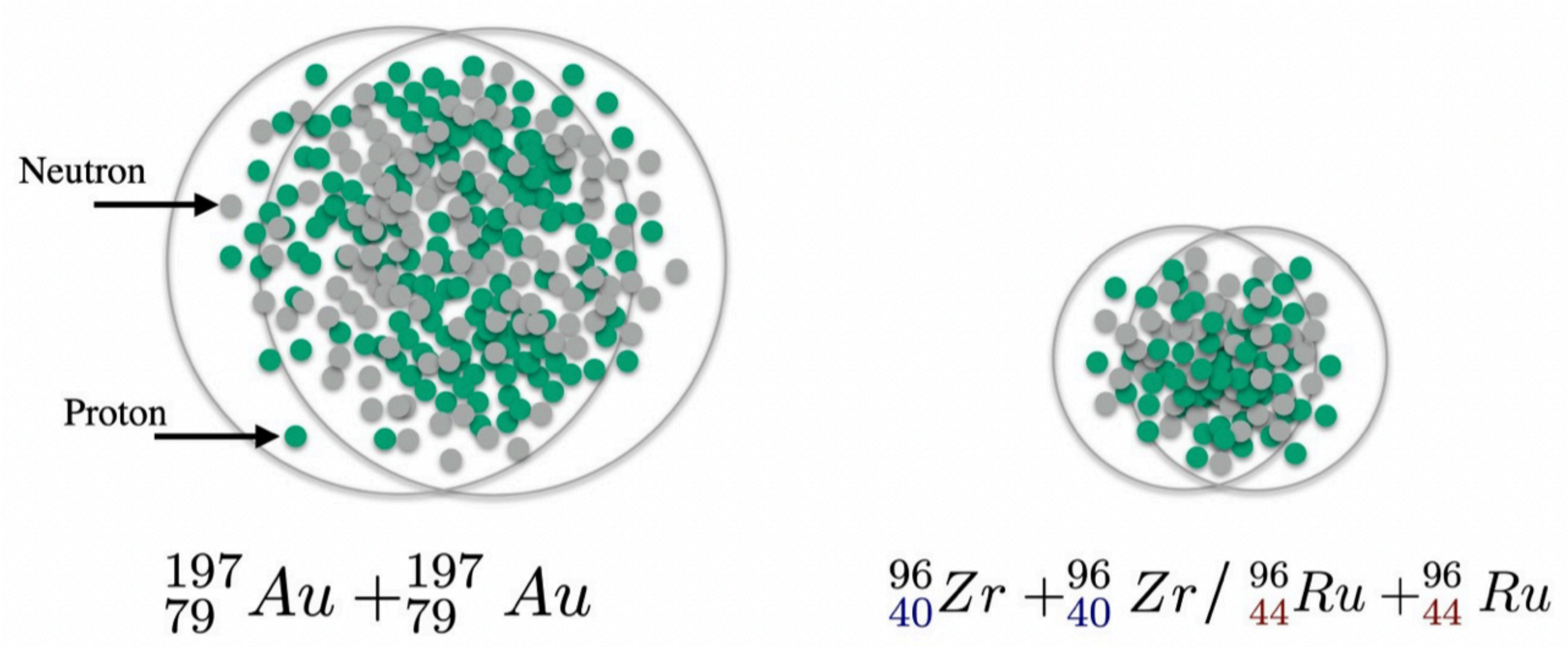
# Collision energy dependence of $r_3$




Clear energy dependence between 54 GeV and 27 GeV

# System size dependence

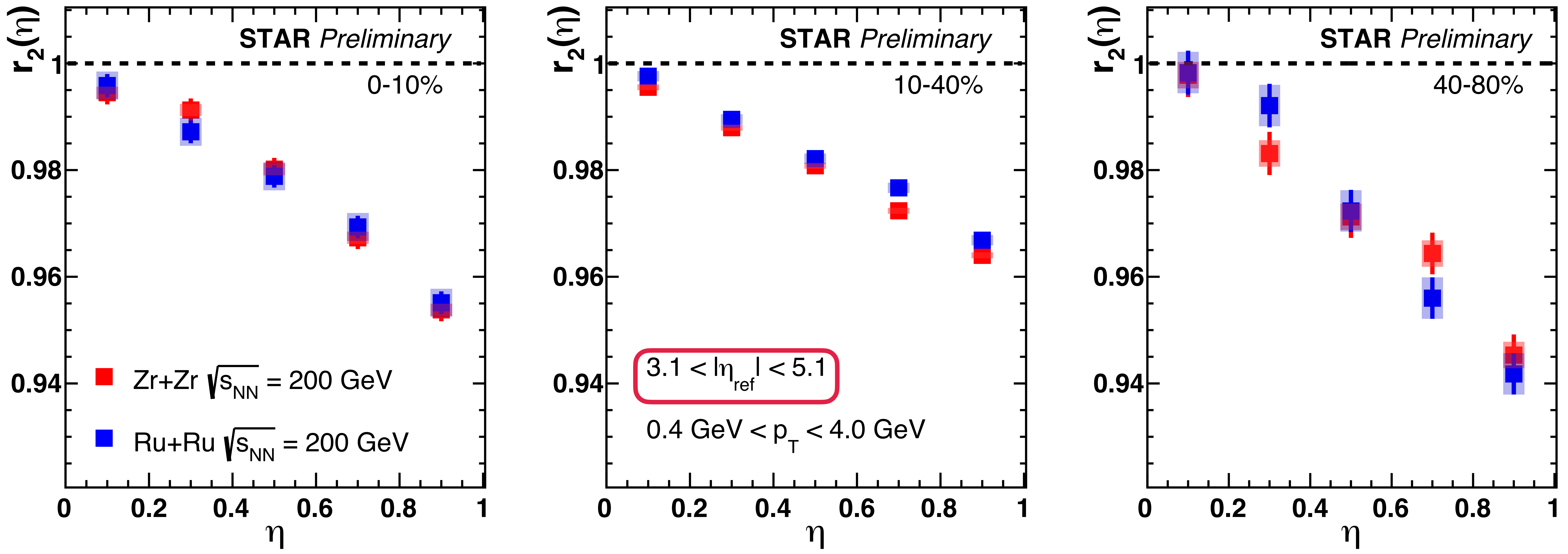



Smaller initial size and shorter evolution time lead to larger different event plane between forward and backward directions

Longitudinal de-correlation in smaller collisions system is expected to be larger

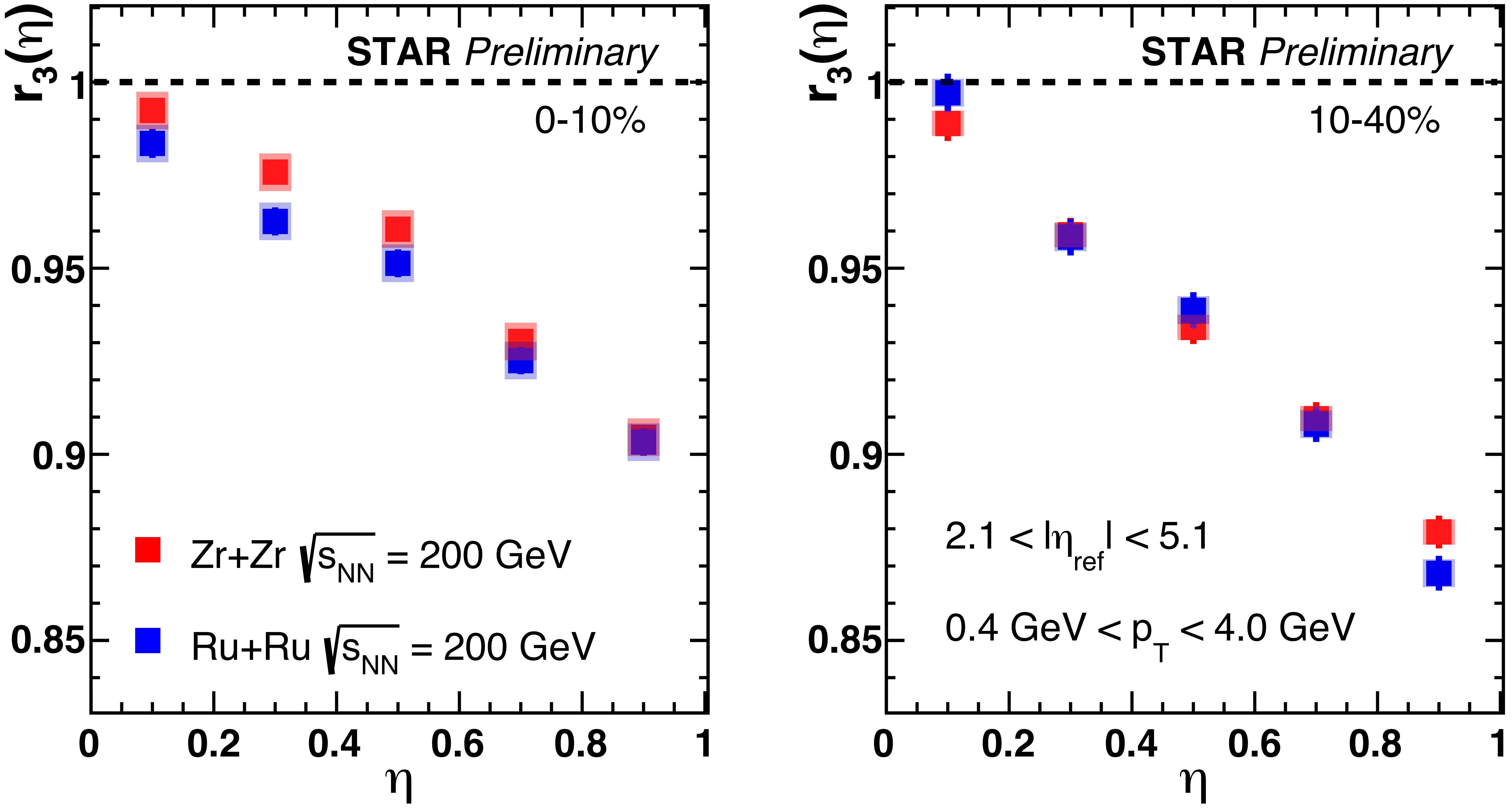
# 2nd order de-correlation in Zr+Zr/Ru+Ru




No obvious difference between Zr+Zr and Ru+Ru collisions within uncertainties

De-correlation is weakest in mid-central collisions

# 3rd order de-correlation in Zr+Zr/Ru+Ru

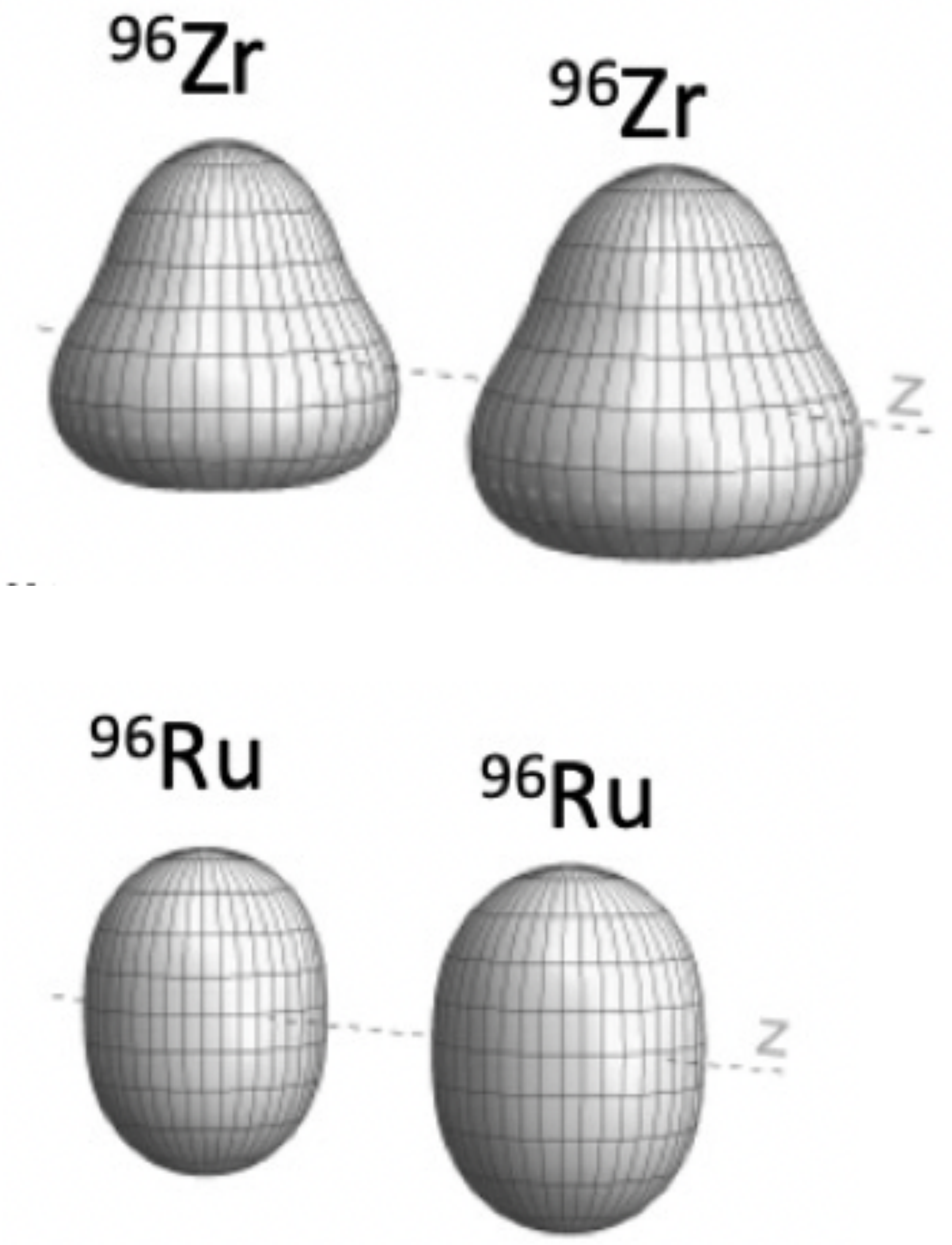



No obvious difference between Zr+Zr and Ru+Ru collisions within uncertainties

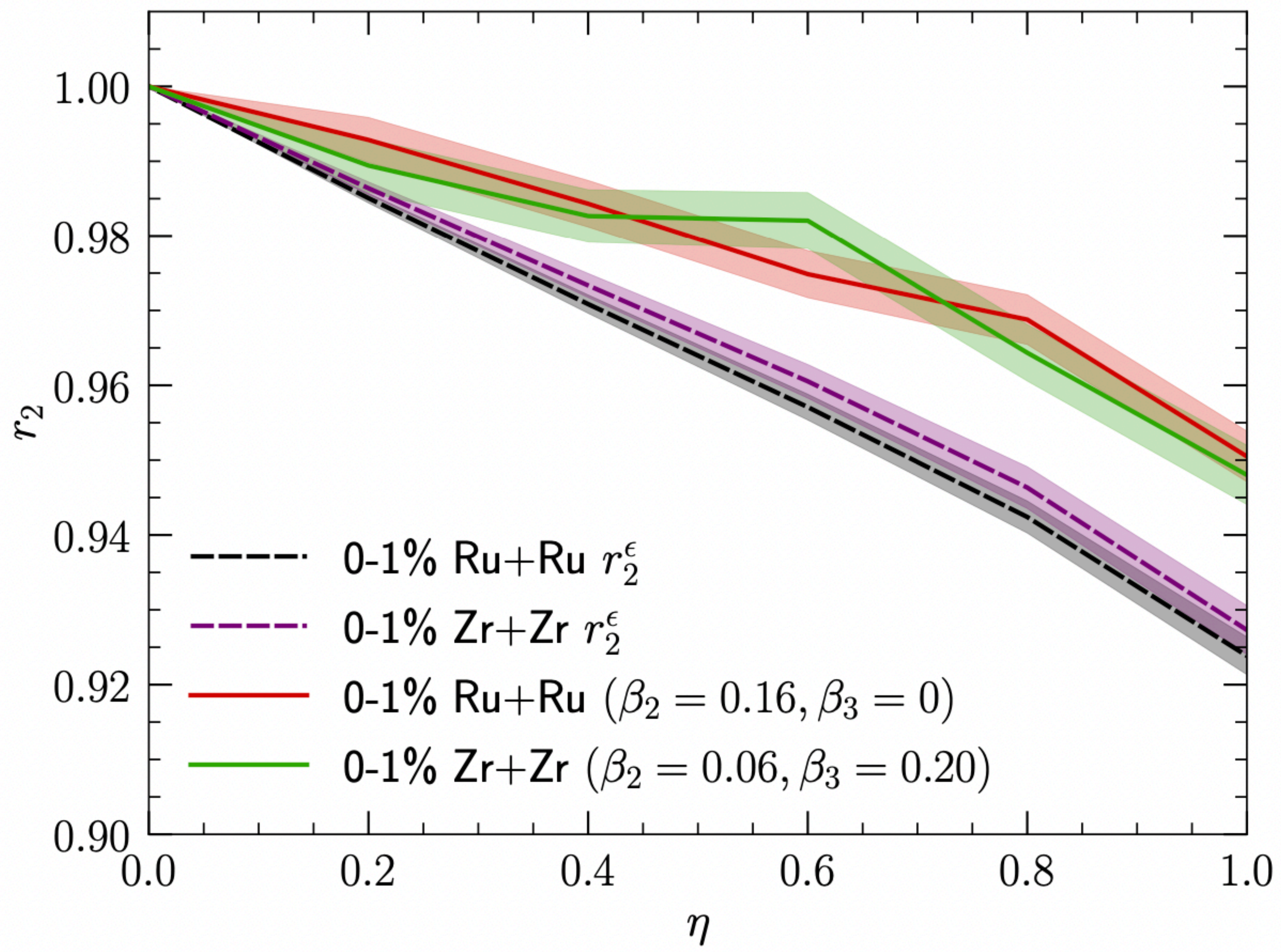
Indication of centrality dependence

The 3rd order de-correlation is 2-3 times stronger than 2nd order

# Nuclear structure effect



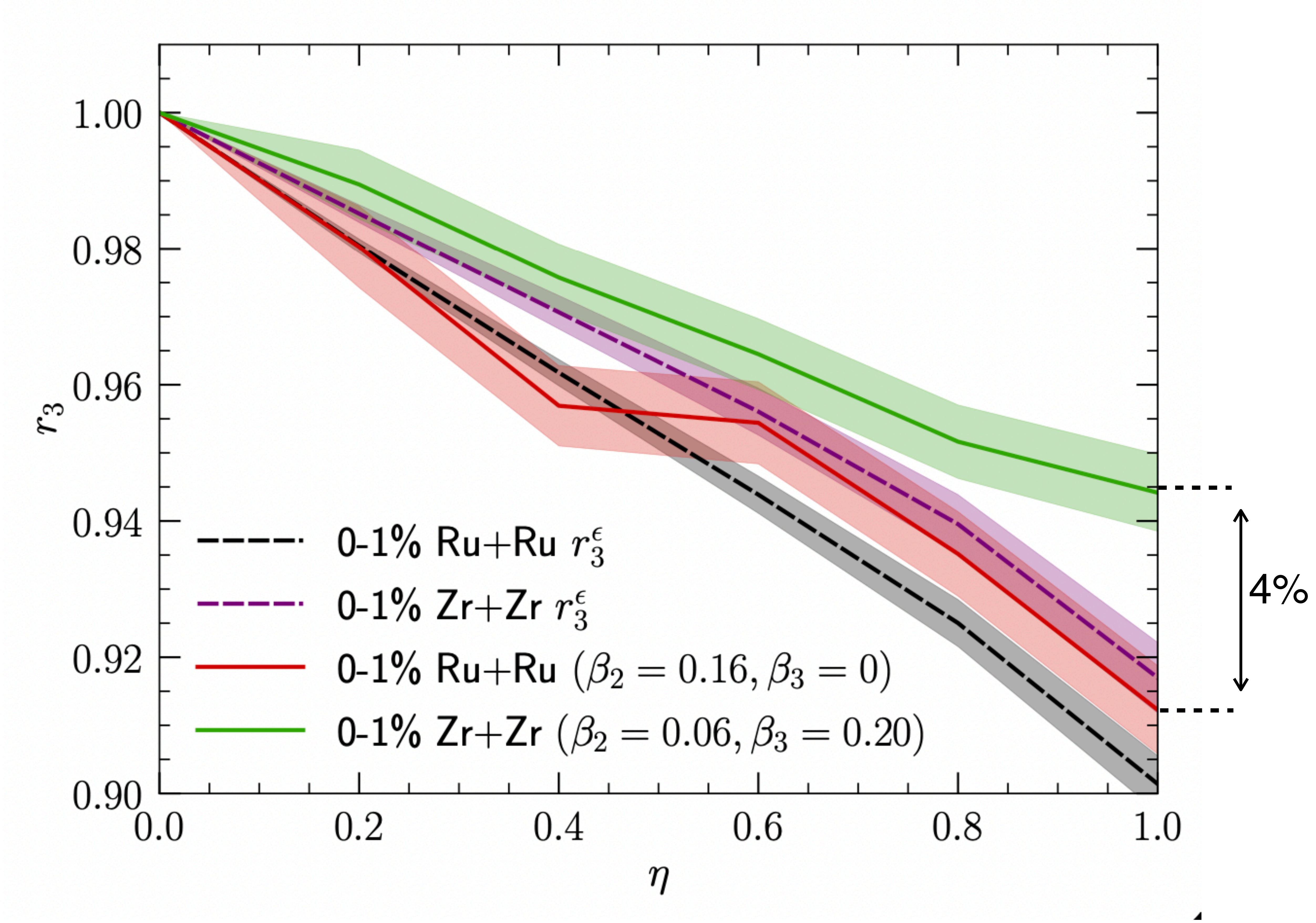

Chunjian Zhang and Jiangyong Jia
Phys. Rev. Lett. 128 (2022) 2, 022301

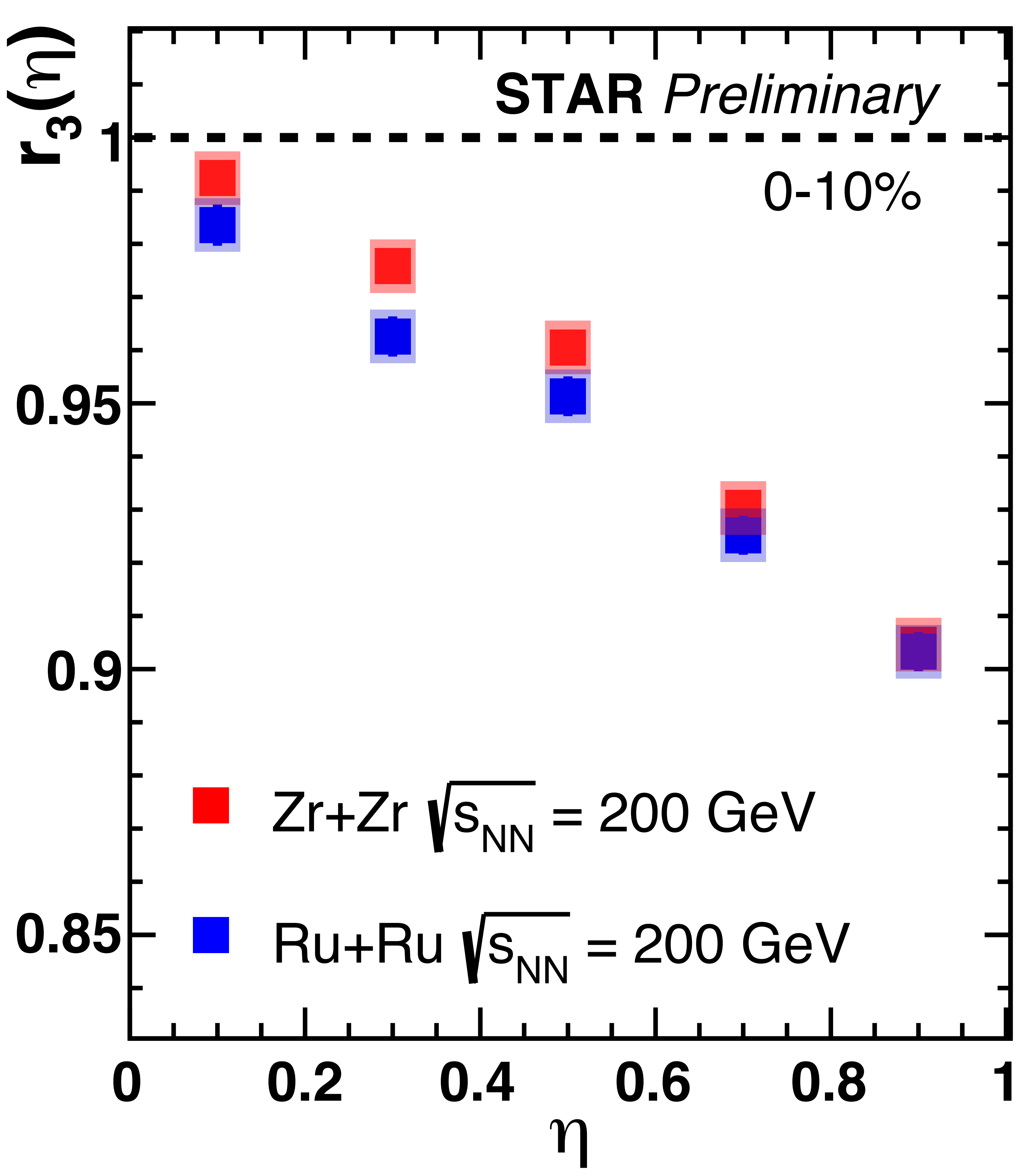



The $\beta_2$ has a very small influence in Zr+Zr and Ru+Ru collisions

From Chun Shen at the INT workshop: Intersection of nuclear structure and high-energy nuclear collisions

# Nuclear structure effect



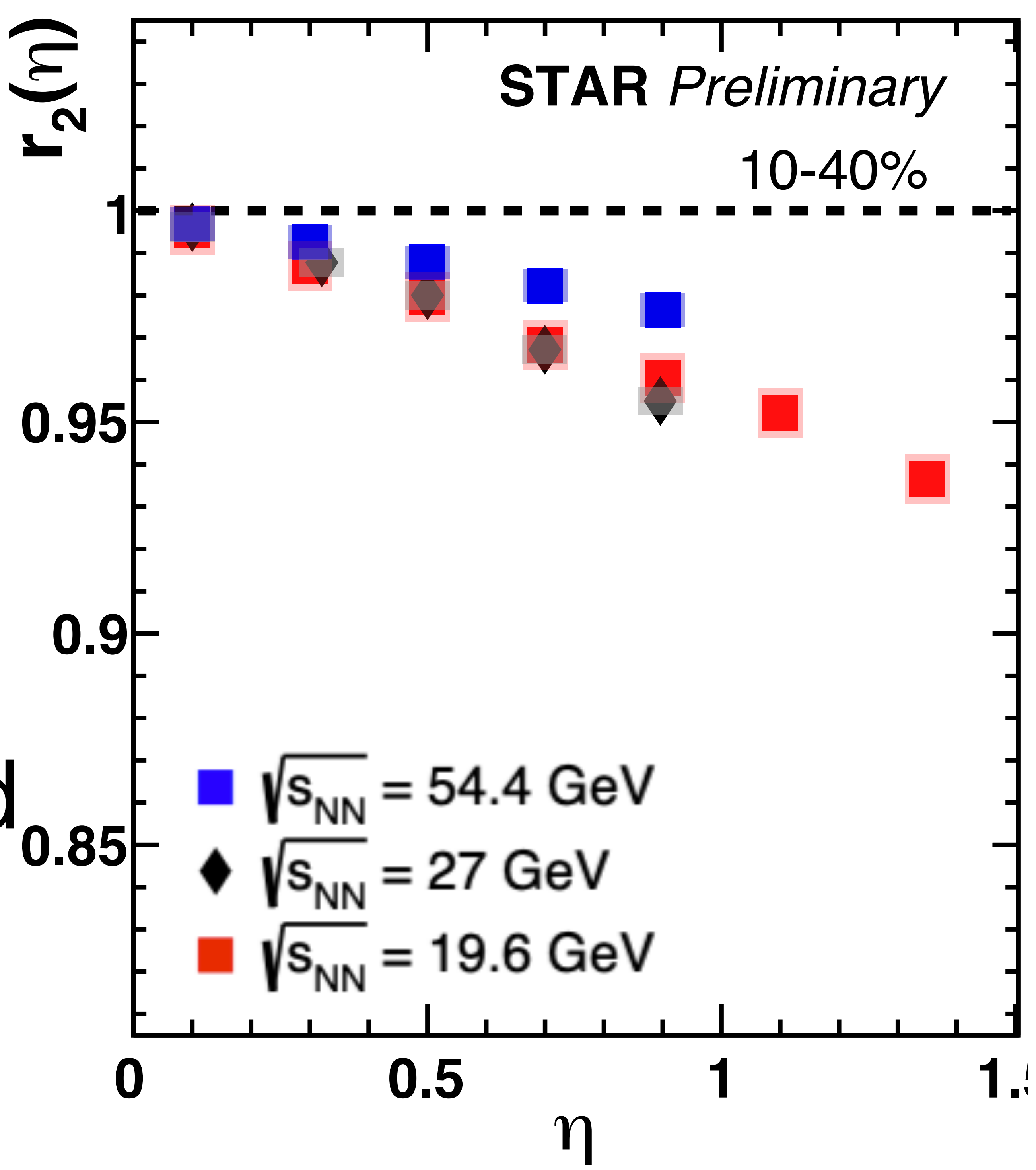



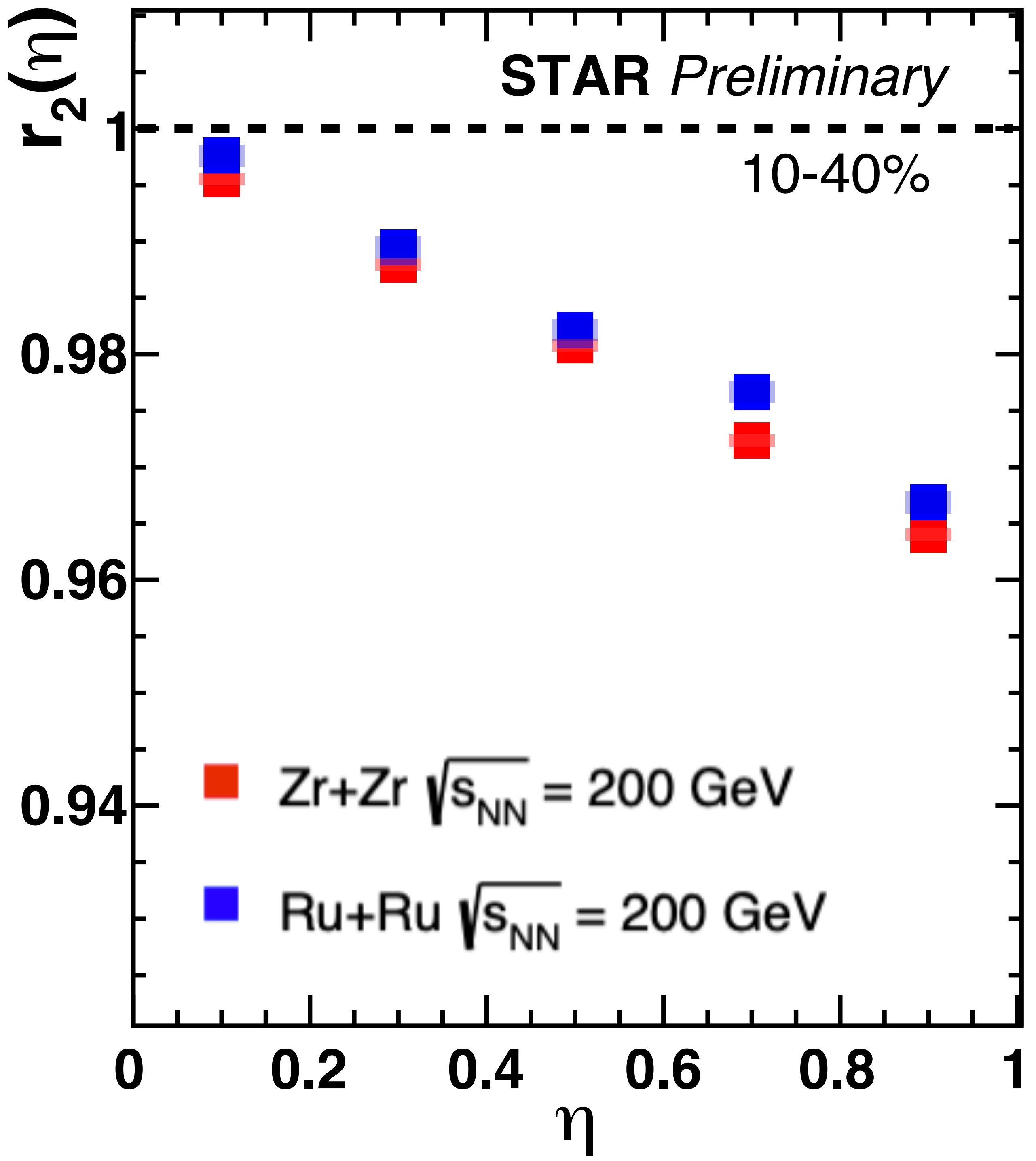

The non-zero $\beta_3$ in Zr+Zr collisions results in a smaller third order de-correlation than Ru+Ru collisions in very central collisions

From Chun Shen at the INT workshop: Intersection of nuclear structure and high-energy nuclear collisions

# Summary

- Longitudinal de-correlation, $r_n(\eta)$ $(n = 2,3)$, in Au+Au collisions at 19.6, 27, 54.4 GeV and in Zr+Zr and Ru+Ru collisions at 200 GeV are measured
  - $r_2(\eta)$ shows centrality dependence
  - $r_3(\eta)$ shows weak centrality dependence
  - Lower collision energies show larger longitudinal de-correlation
  - No obvious difference between Zr+Zr and Ru+Ru collisions




- The results provide new constraints on 3D structure of initial stages and dynamical evolution of the QGP in heavy-ion collisions

# Outlook

- Using STAR BES-II data to study energy dependence precisely
- System size dependence: Au+Au, Zr+Zr/Ru+Ru and O+O collisions

| System | $\sqrt{s_{NN}}$ (GeV) | Events ($10^6$) | Year |
|---|---|---|---|
| Au+Au | 54.4 | 1200 | 2017 |
| Isobar | 200 | 4000 | 2018 |
| Au+Au | 27 | 560 | 2018 |
| Au+Au | 19.6 | 538 | 2019 |
| Au+Au | 14.5 | 325 | 2019 |
| Au+Au | 11.5 | 230 | 2020 |
| Au+Au | 9.2 | 160 | 2020 |
| Au+Au | 7.7 | 100 | 2021 |
| Au+Au | 200 | 138 | 2019 |
| O+O | 200 | 400 | 2021 |
| Au+Au | 200 | 10000 | 2023 |

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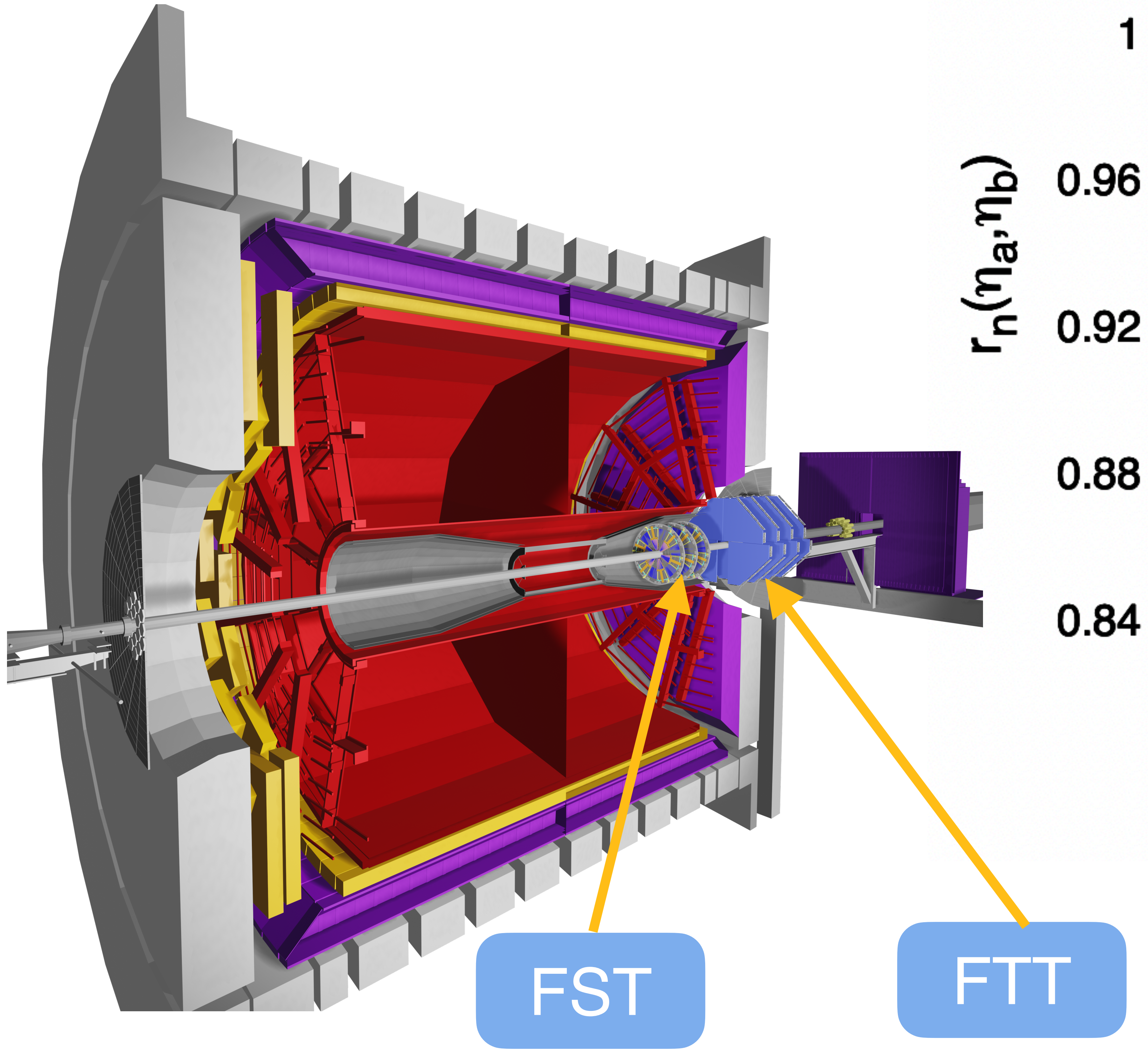
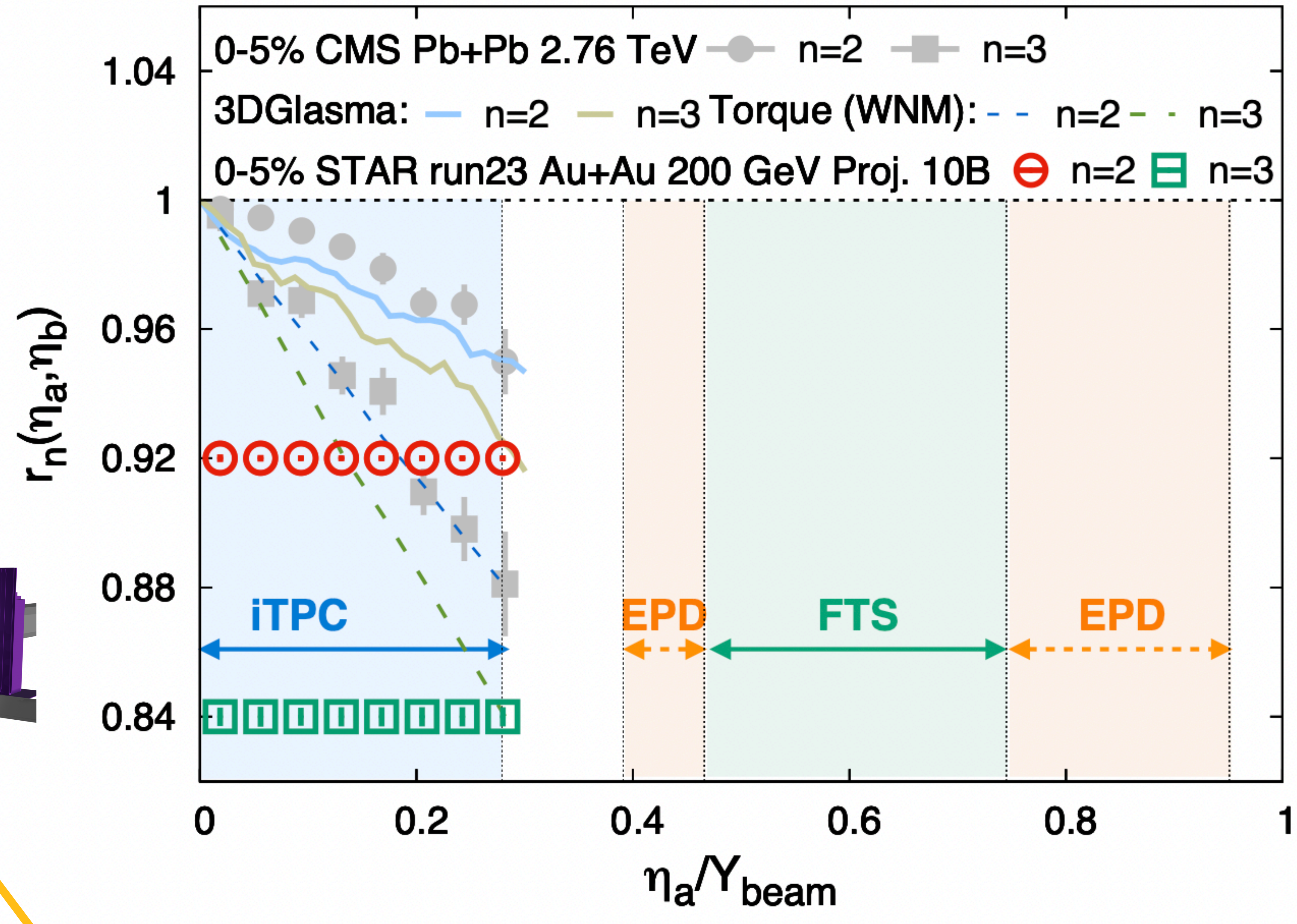
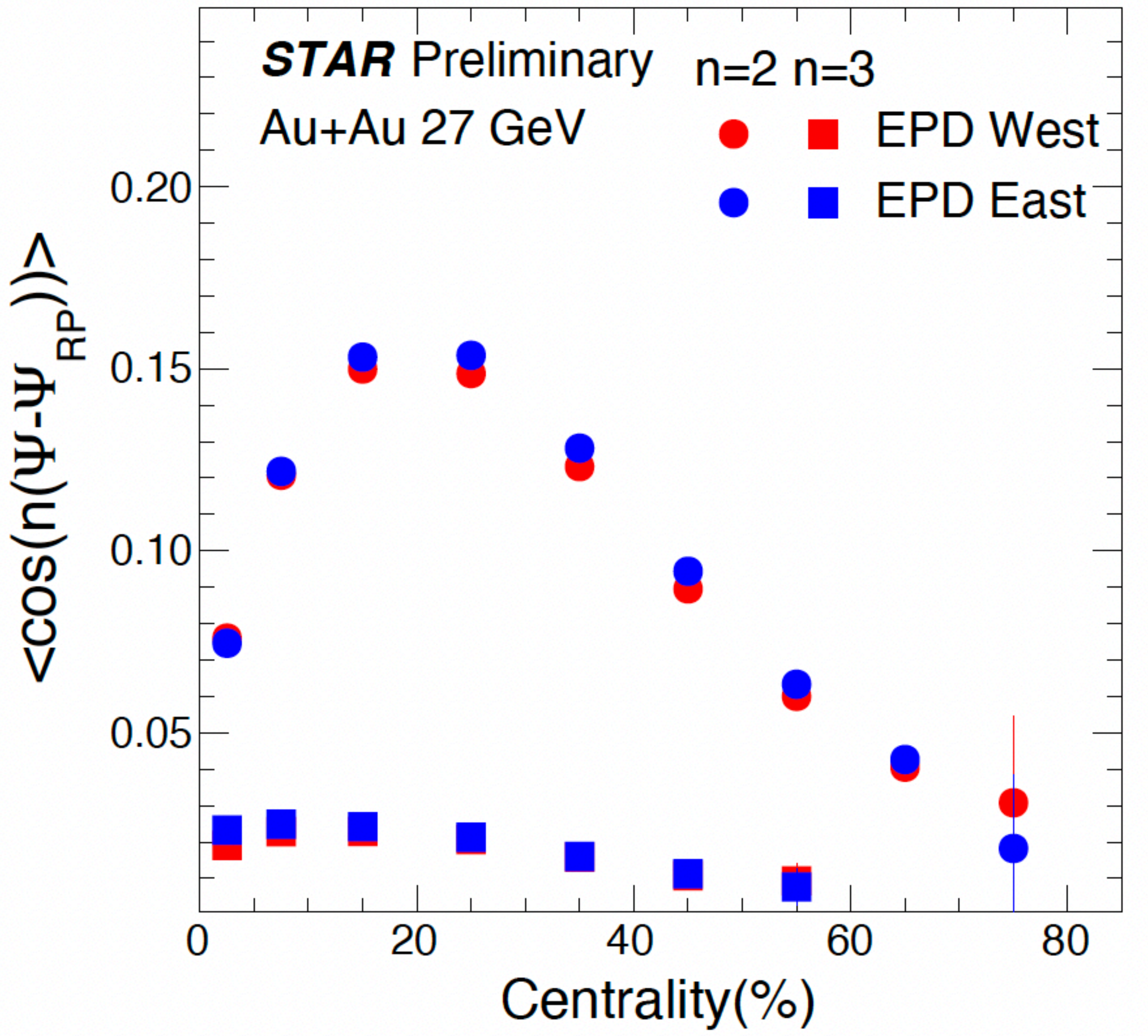
- Forward upgrade ($2.5 < \eta < 4.0$): de-correlation in a larger $\eta$

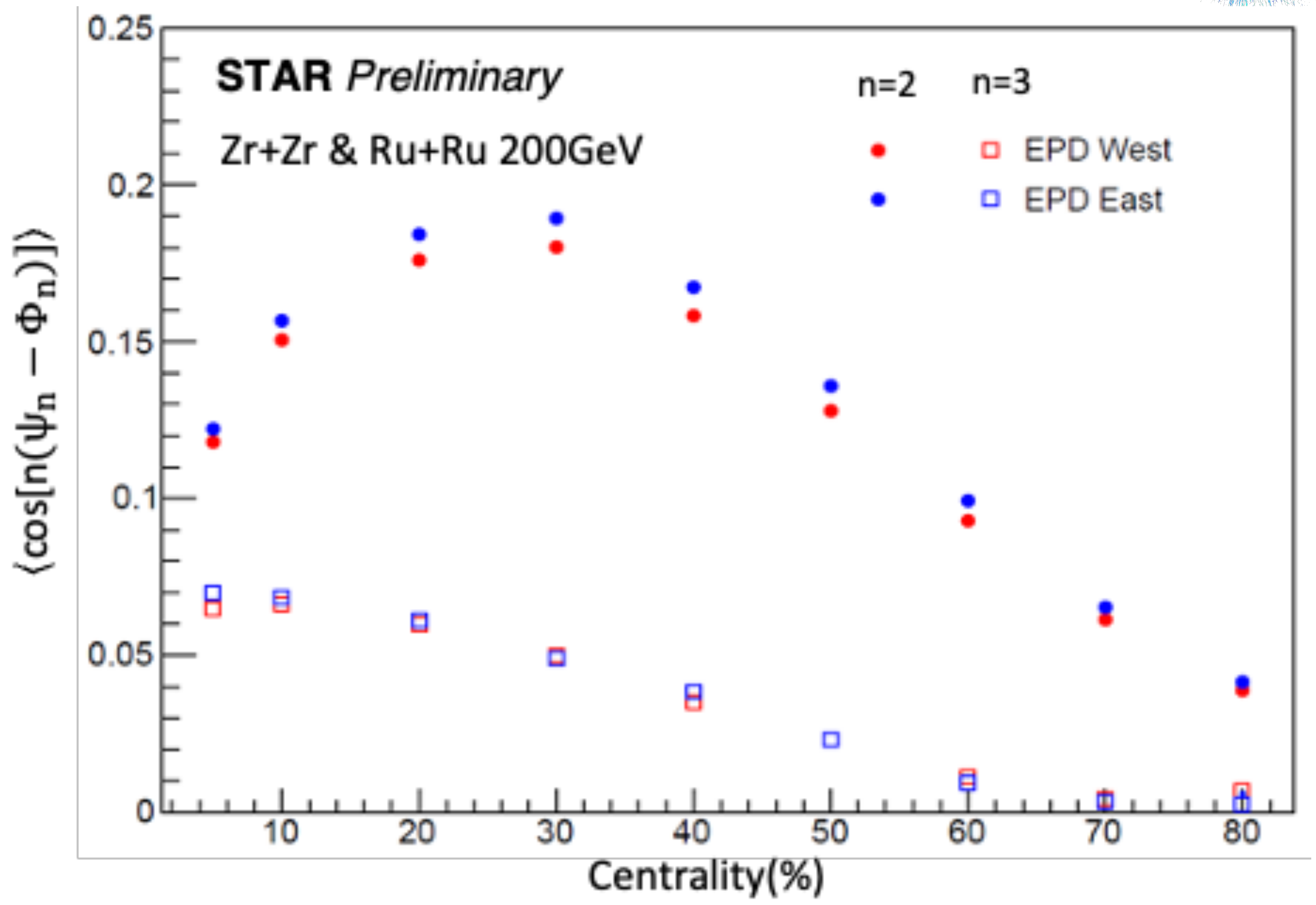


# Backup

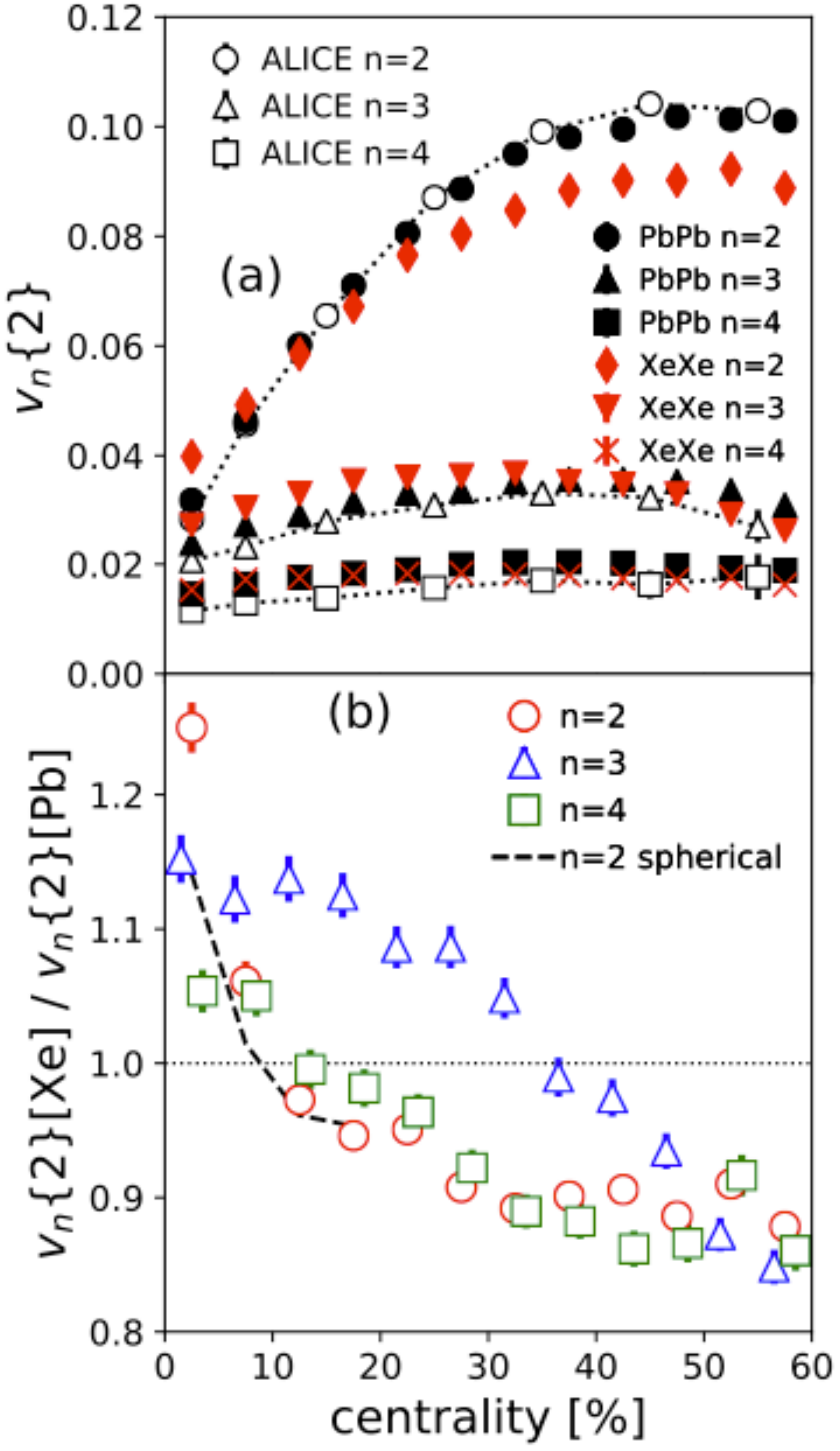
# Resolution



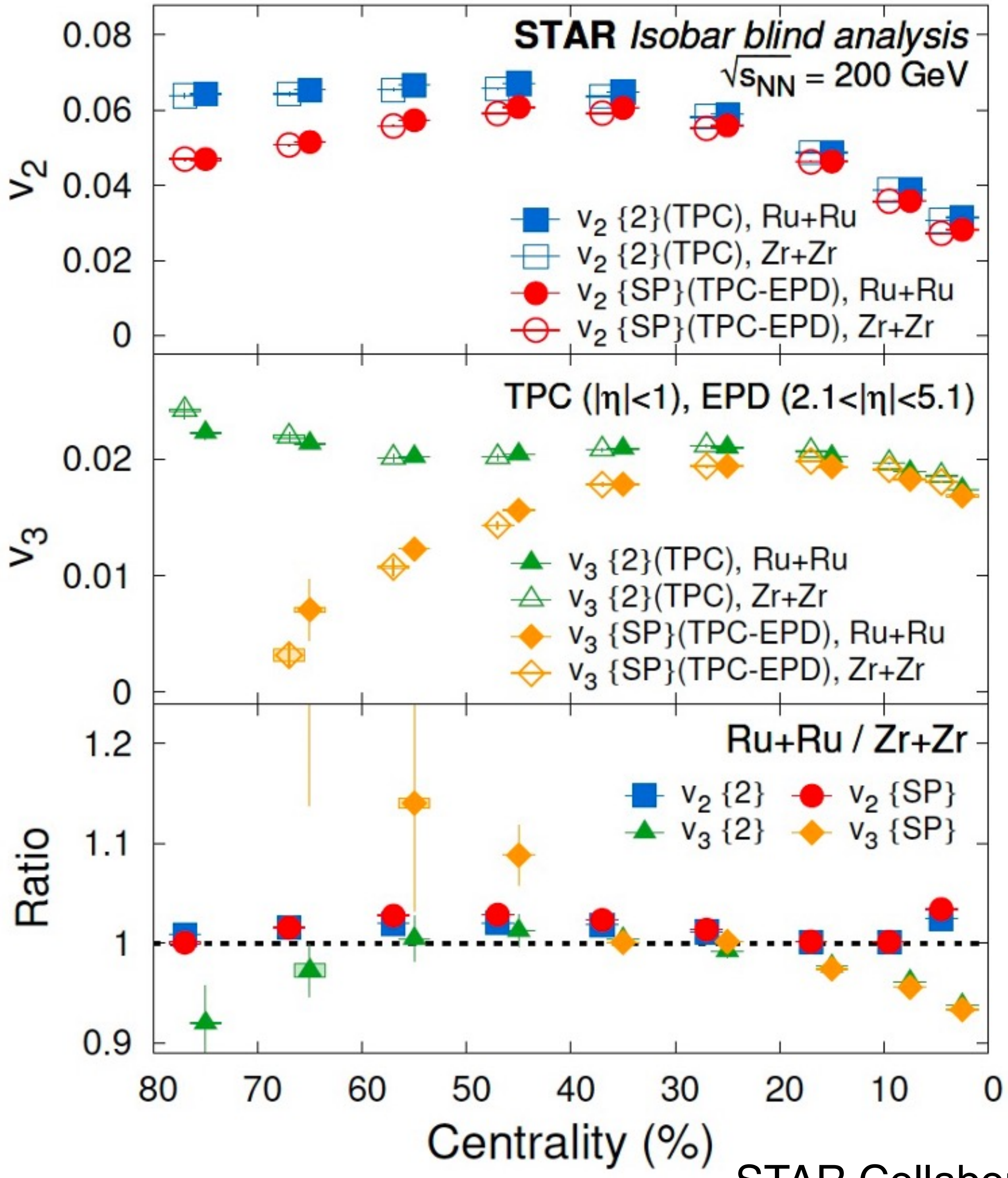




EPD shows consistent results for second and third order event plane resolutions

# Anisotropic flow




Phys. Rev. C 97 (2018) 034904




STAR Collaboration
Phys. Rev. C 105 (2022) 014901