

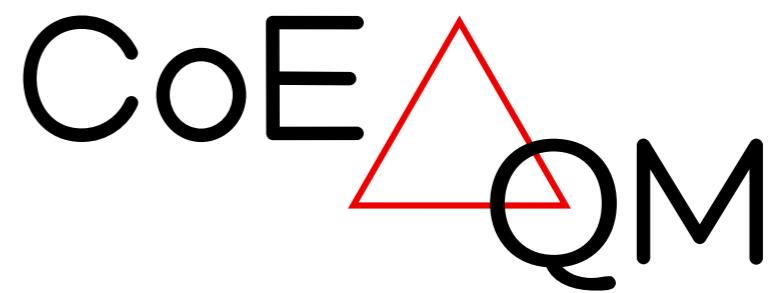


# Understanding the deformed nuclear structure across different energy scales

Pragya Singh

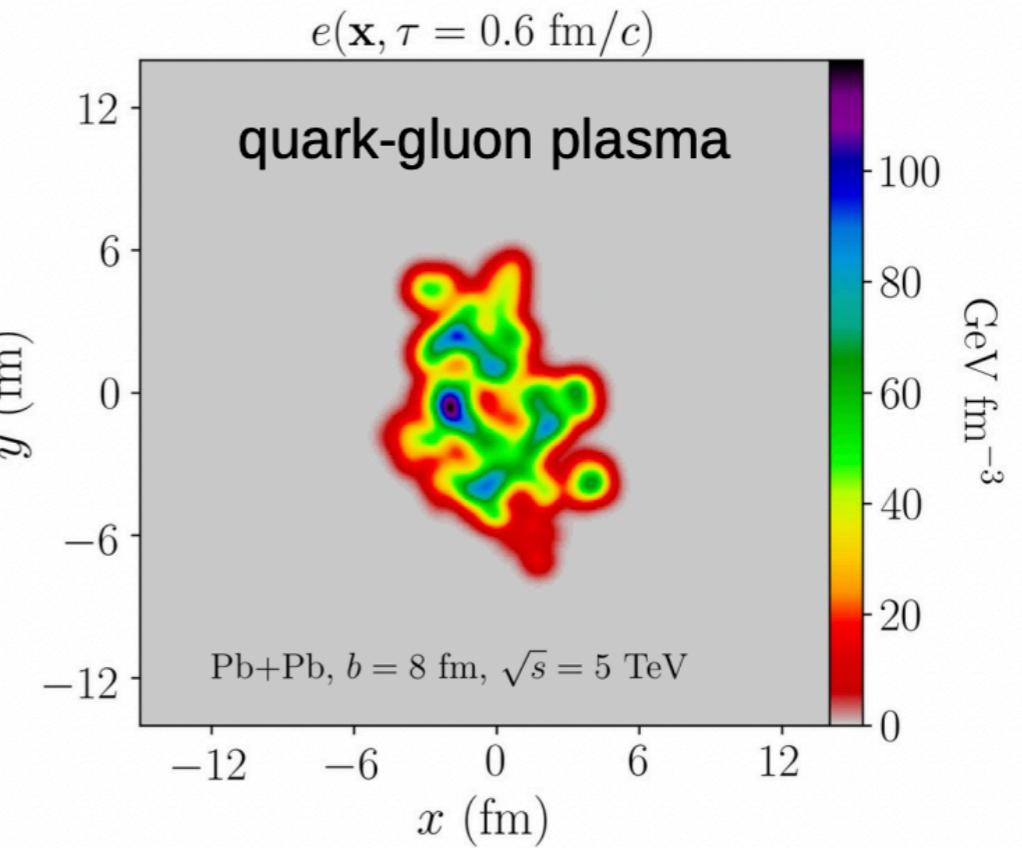
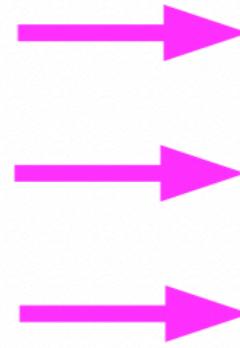
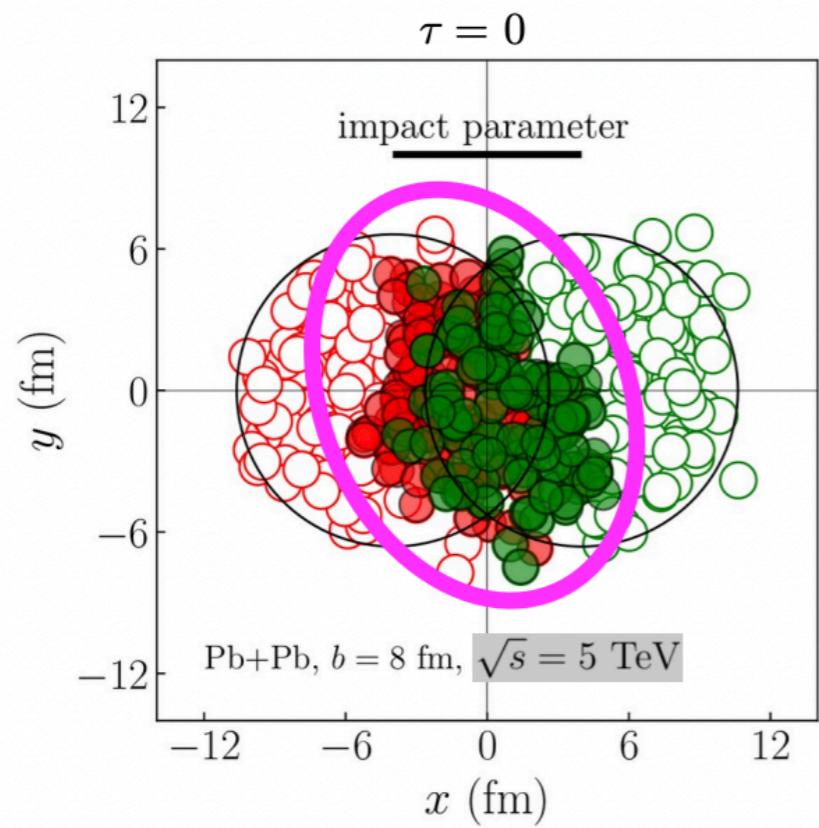
In collaboration with G. Giacalone, B. Schenke, S. Schlichting

University of Jyväskylä, Finland



# Nuclear structure and QGP formation

## Understanding the connection between the two



(Courtesy: G. Giacalone)

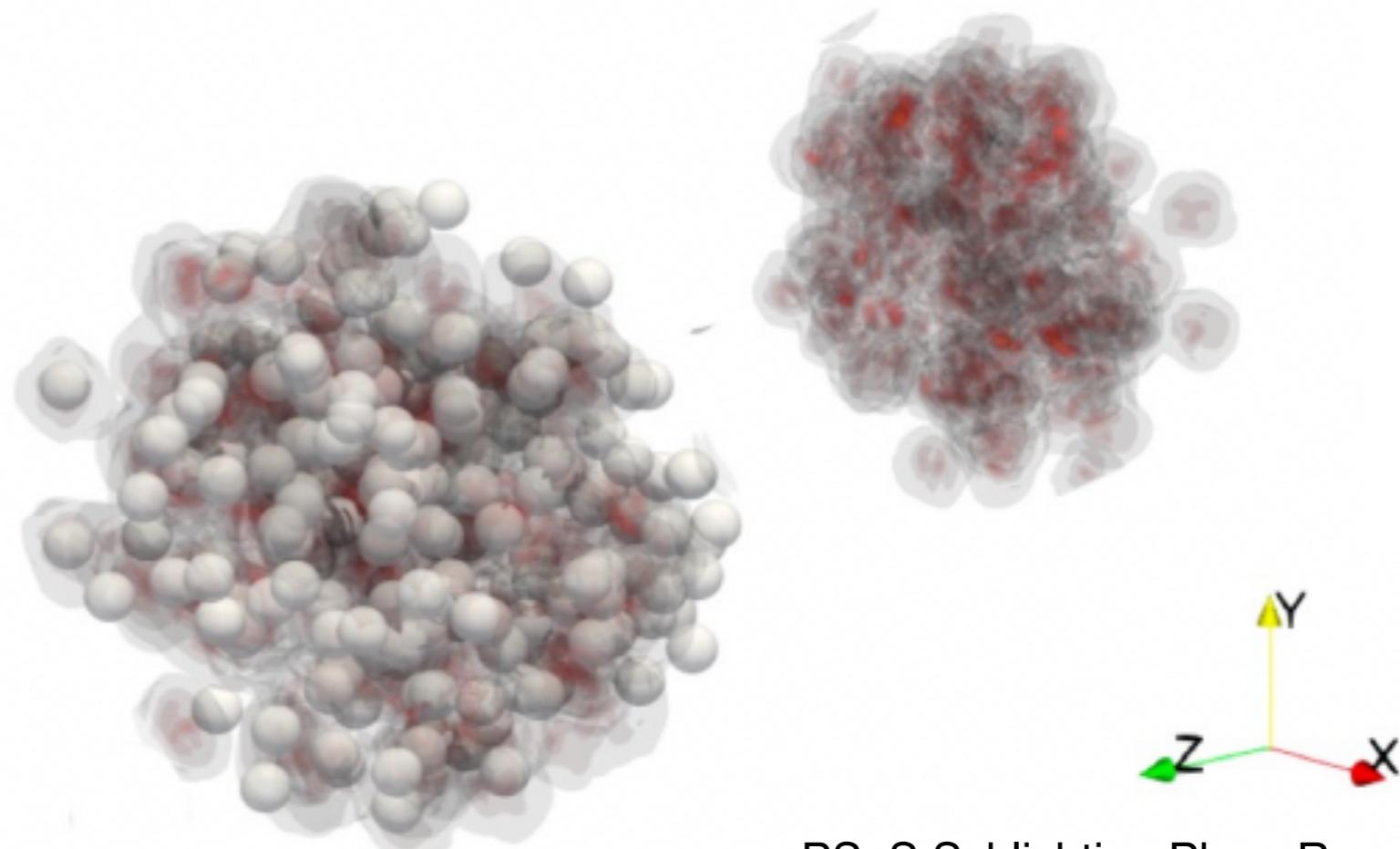
**Correlation between the nucleon density distribution in the colliding nuclei and particle correlation in the final state of nuclear collisions**

G Giacalone arxiv 2305.19843

# Simulating initial state of a nuclear collision

- Sample position of nucleon eg. using Woods-Saxon distribution
- Sample color charges and solve the classical Yang-Mills equation

Jumping to the final step ⏲



PS, S Schlichting Phys. Rev. D 103, 014003

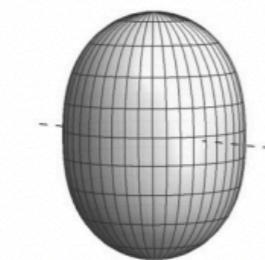
# Nucleon position & low-energy nuclear physics

## 1. Generalised Wood Saxon distribution

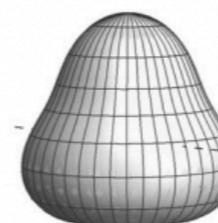
G. Giacalone's Talk  
on Wednesday

$$\rho(r, \Theta, \Phi) \propto \frac{1}{1 + \exp([r - R(\Theta, \Phi)] / a)}$$

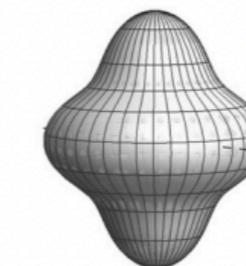
$$R(\Theta, \Phi) = R_0 \left[ 1 + \beta_2 \left( \cos \gamma Y_{20}(\Theta) + \sin \gamma Y_{22}(\Theta, \Phi) \right) + \beta_3 Y_{30}(\Theta) + \beta_4 Y_{40}(\Theta) \right]$$



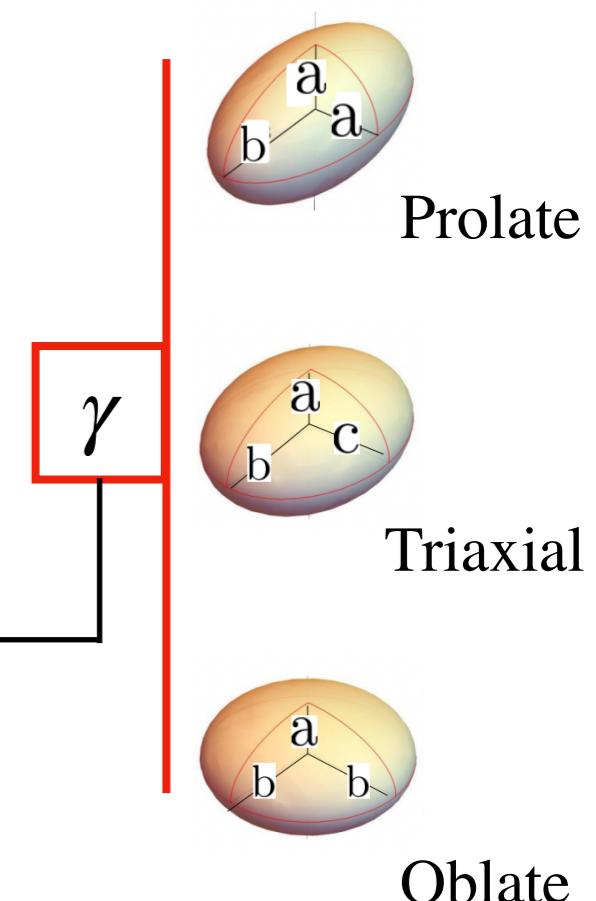
Quadrupole



Octupole



Hexadecapole



## 2. Ab-initio nucleus structure which contains the information of spatial correlations.

Phys Rev Lett.107.072501, R Roth, J Langhammer, A Calci, S Binder, and P Navrátil

Eur. Phys. J. A 58, 64 (2022), M. Frosini, T. Duguet, J.-P. Ebran, B. Bally, H. Hergert, T.R. Rodriguez, R. Roth, J. M. Yao, V. Som`a1, ...

# RHIC results and expectations from low energy

arXiv > nucl-th > arXiv:2302.13617

## Evidence of Hexadecapole deformation in $^{238}U$ at the RHIC

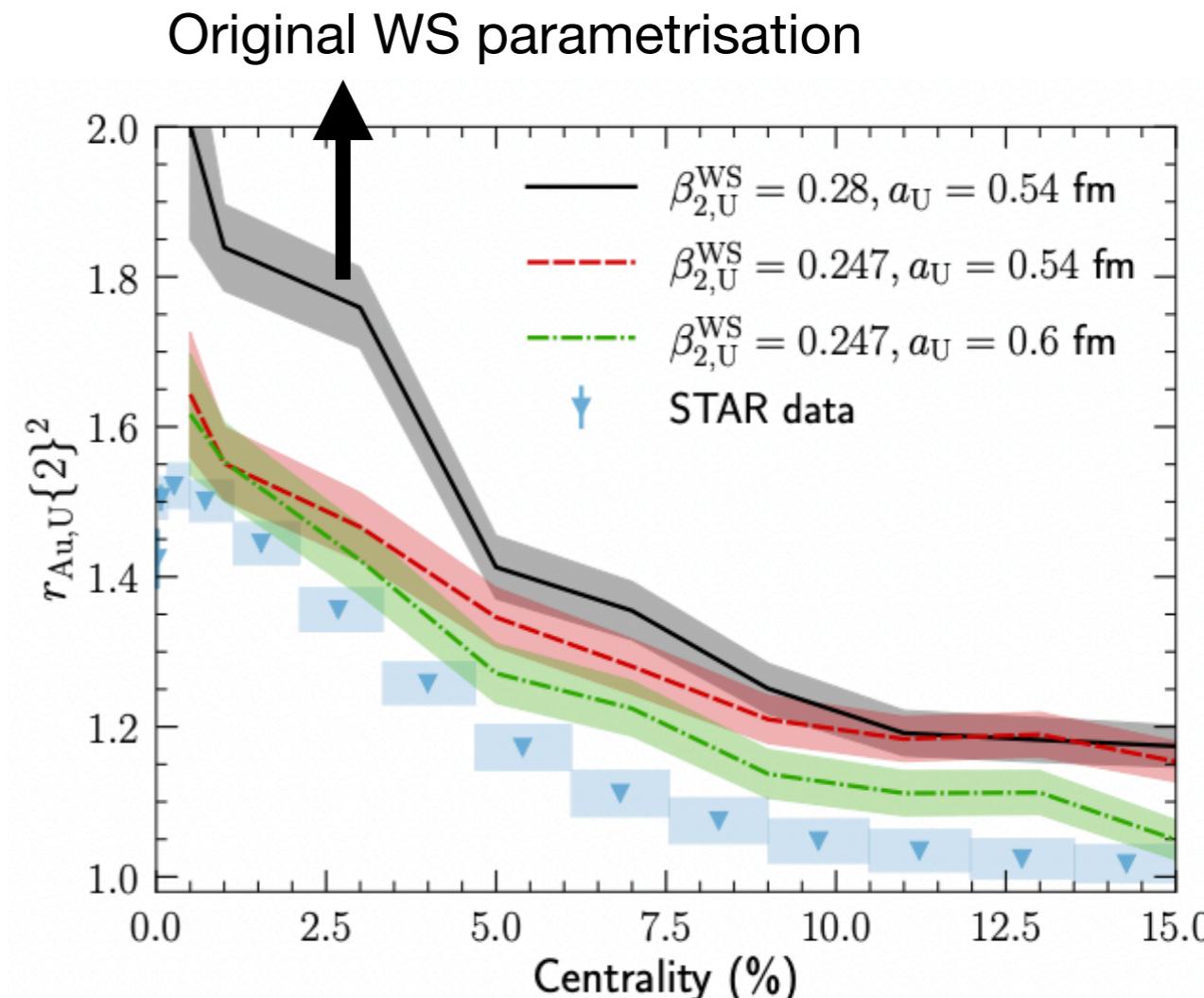
"We show that correcting for such effects in the implementation of nuclear deformations in hydrodynamic simulations restores agreement with **BNL RHIC data**. This brings **consistency to the results of nuclear experiments** across energy scales, and demonstrates the impact of the hexadecapole deformation of  $^{238}U$  on high-energy collisions."

$$r_{\text{Au},\text{U}}\{2\}^2 \equiv \frac{\langle v_2^2 \rangle_{\text{U+U}}}{\langle v_2^2 \rangle_{\text{Au+Au}}}$$

$$\beta_2 = \beta_2^{\text{WS}} + \mathcal{O}[a] + \mathcal{O}[(\beta_2^{\text{WS}})^2] + \underline{\mathcal{O}[\beta_4^{\text{WS}} \beta_2^{\text{WS}}]}$$

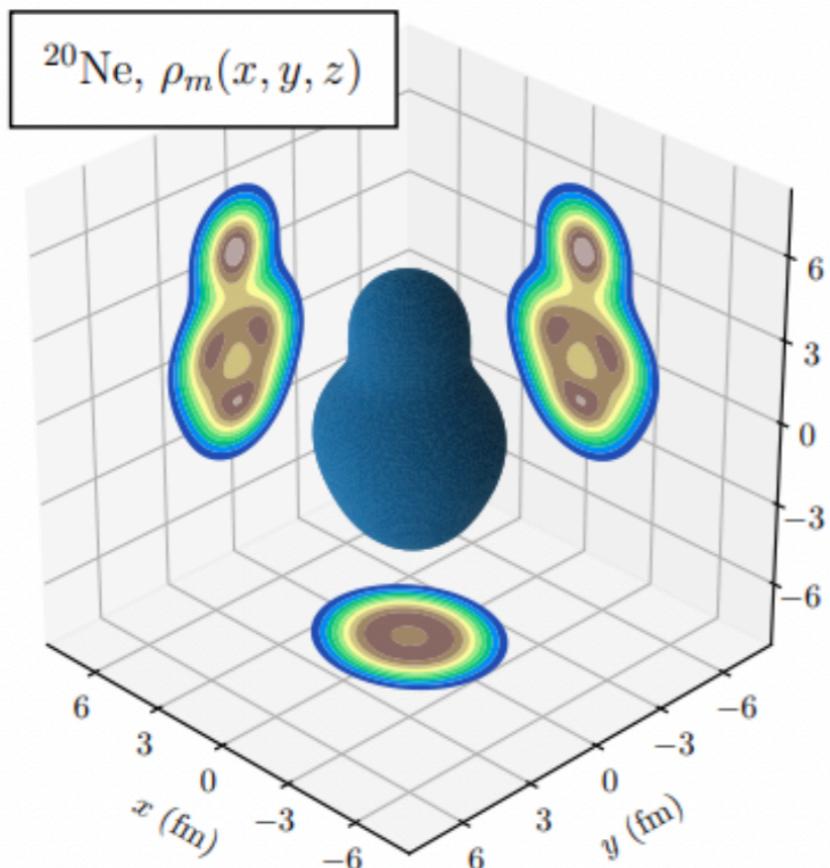
*One of the few examples ...*

W Ryssens, G Giacalone, B Schenke, C Shen  
Phys. Rev. Lett. 130, 212302 (2023)



# Transitioning between the energy ranges of RHIC and LHC

## Ingredients needed

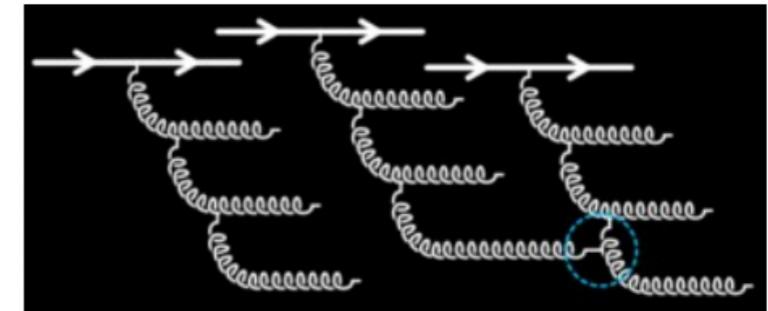


**JIMWLK (here)**

(Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner)

**BK equations**

(Balitsky, Kovchegov)



As we go towards high energy, gluons split and recombine

**Nuclear structure input  
(preferred) or WS  
parametrisation**

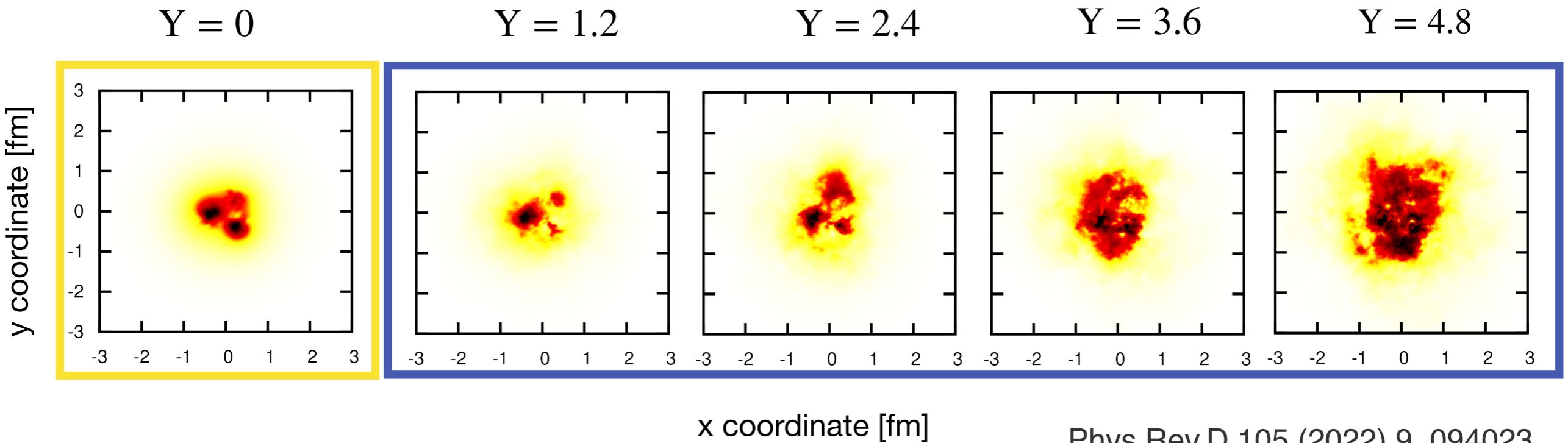
**Energy evolution scheme**

# JIMWLK evolution of proton

Rapidity evolution of Wilson line  $V_{x_\perp}(Y)$

$$V_{x_\perp}(Y + dY) = \exp \left\{ -i \frac{\sqrt{\alpha_s dY}}{\pi} \int_{z_\perp} [K_{x_\perp - z_\perp}] \cdot (V_{z_\perp} \xi_{z_\perp} V_{z_\perp}^\dagger) \right\} V_{x_\perp}(Y) \exp \left\{ i \frac{\sqrt{\alpha_s dY}}{\pi} \int_{z_\perp} [K_{x_\perp - z_\perp}] \cdot \xi_{z_\perp} \right\}$$

T. Lappi and H. Mantysaari, Eur. Phys. J. C 73, 2307 (2013)



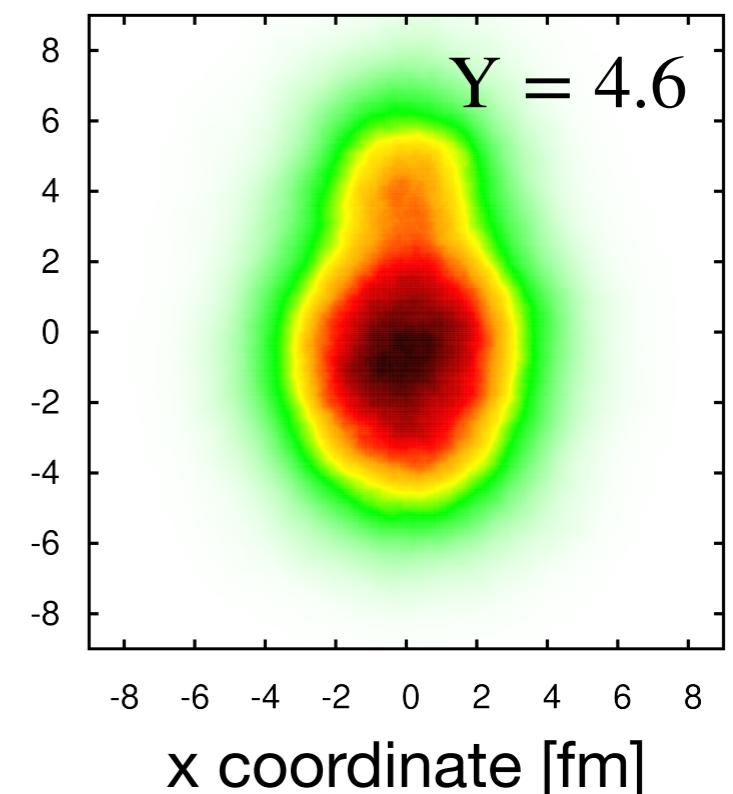
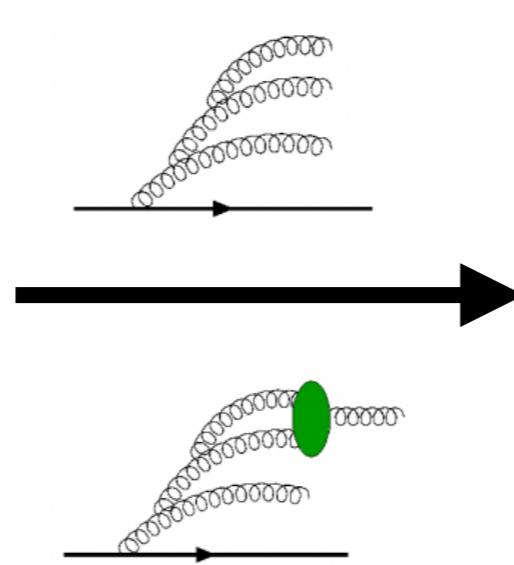
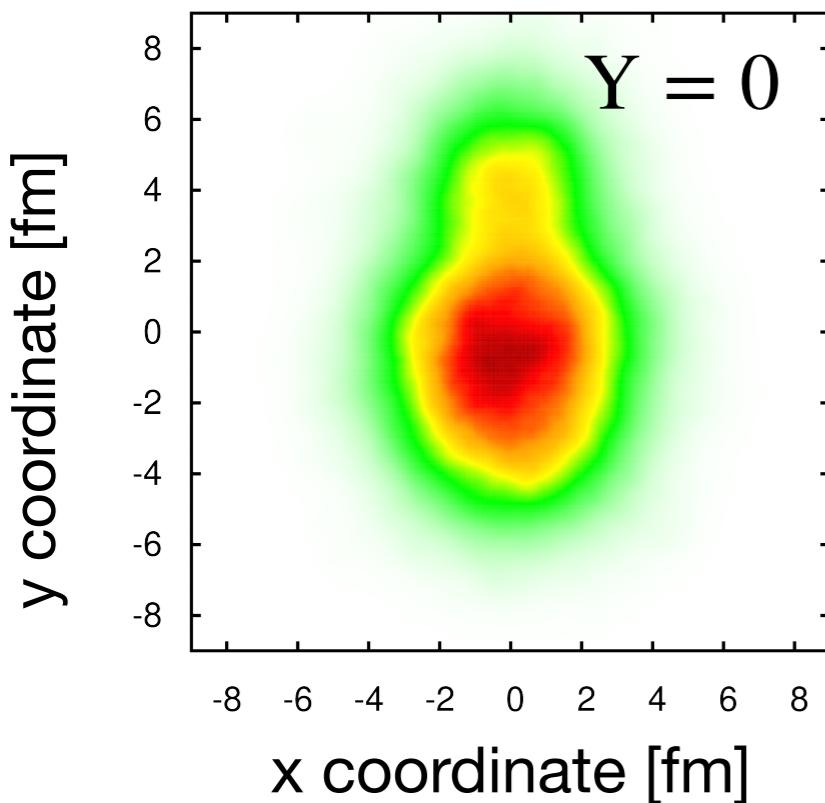
Phys.Rev.D 105 (2022) 9, 094023  
B. Schenke, S. Schlichting and PS

**Slow smoothening of geometric profile with decreasing x**

# Effect of JIMWLK evolution on $^{20}Ne$

Nucleon position obtained using the Projected Generator Coordinate Method (PGCM)

Eur. Phys. J. A 58, 64 (2022), M. Frosini, T. Duguet, J.-P. Ebran, B. Bally, H. Hergert, T.R. Rodriguez, R. Roth, J. M. Yao, V. Somal



$$\sqrt{s} = 70 \text{ GeV}$$

$$\sqrt{s} = 7000 \text{ GeV}$$

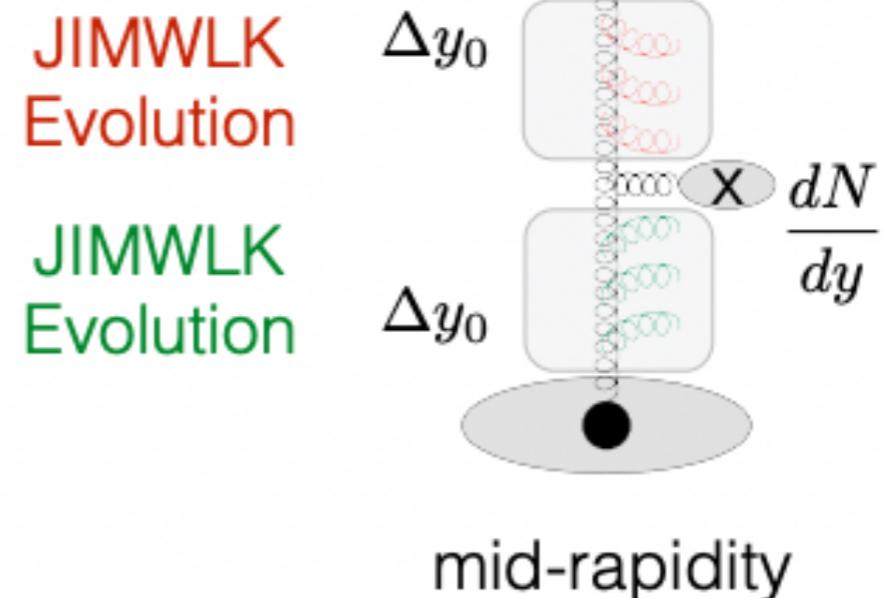
**Small-x evolution smears the bowling pin shape**

# Computing observables at mid-rapidity

## IP Glasma Model (JIMWLK + Classical Yang-Mills equation )

B Schenke, S Schlichting  
Phys.Rev.C 94 (2016) 4, 044907

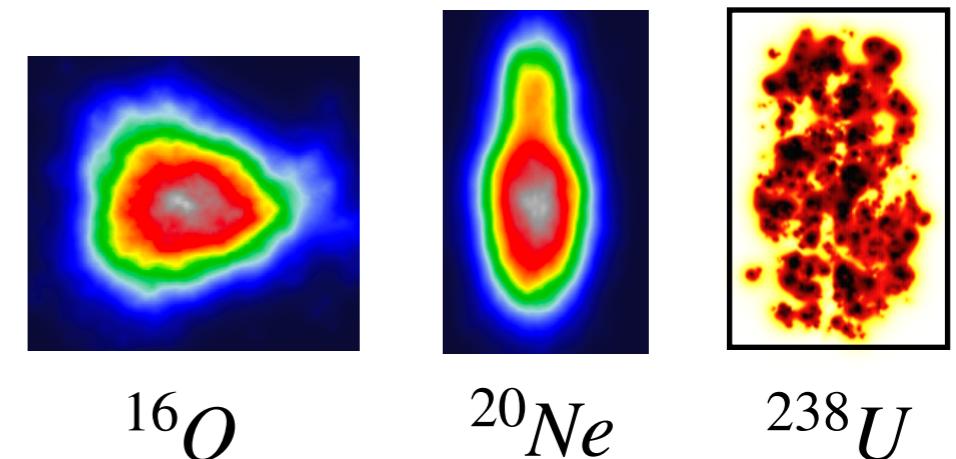
- Series of independent 2+1D CYM simulations from evolved configurations of nuclei.
- Use energy momentum tensor to compute **eccentricity**  $\epsilon_n$  and **anisotropic energy flow**  $\epsilon_p$



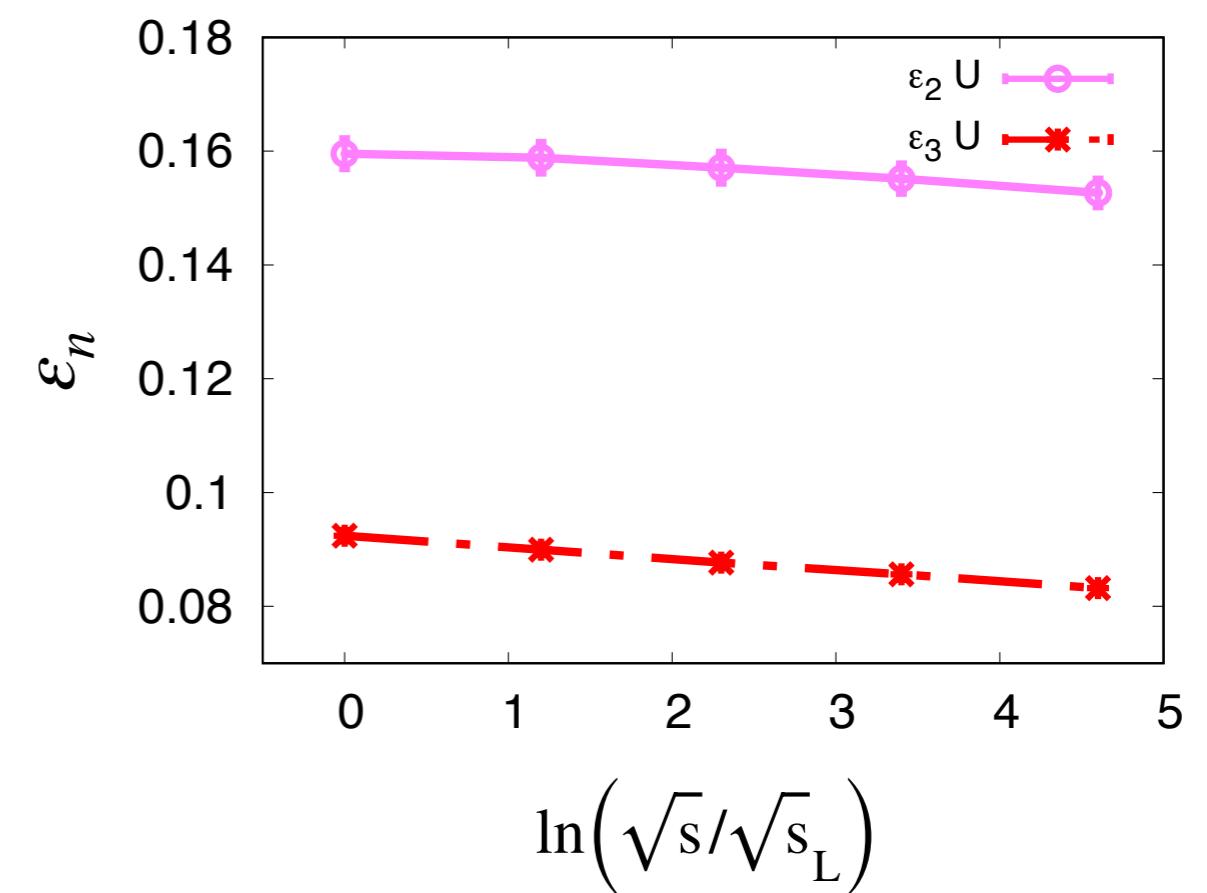
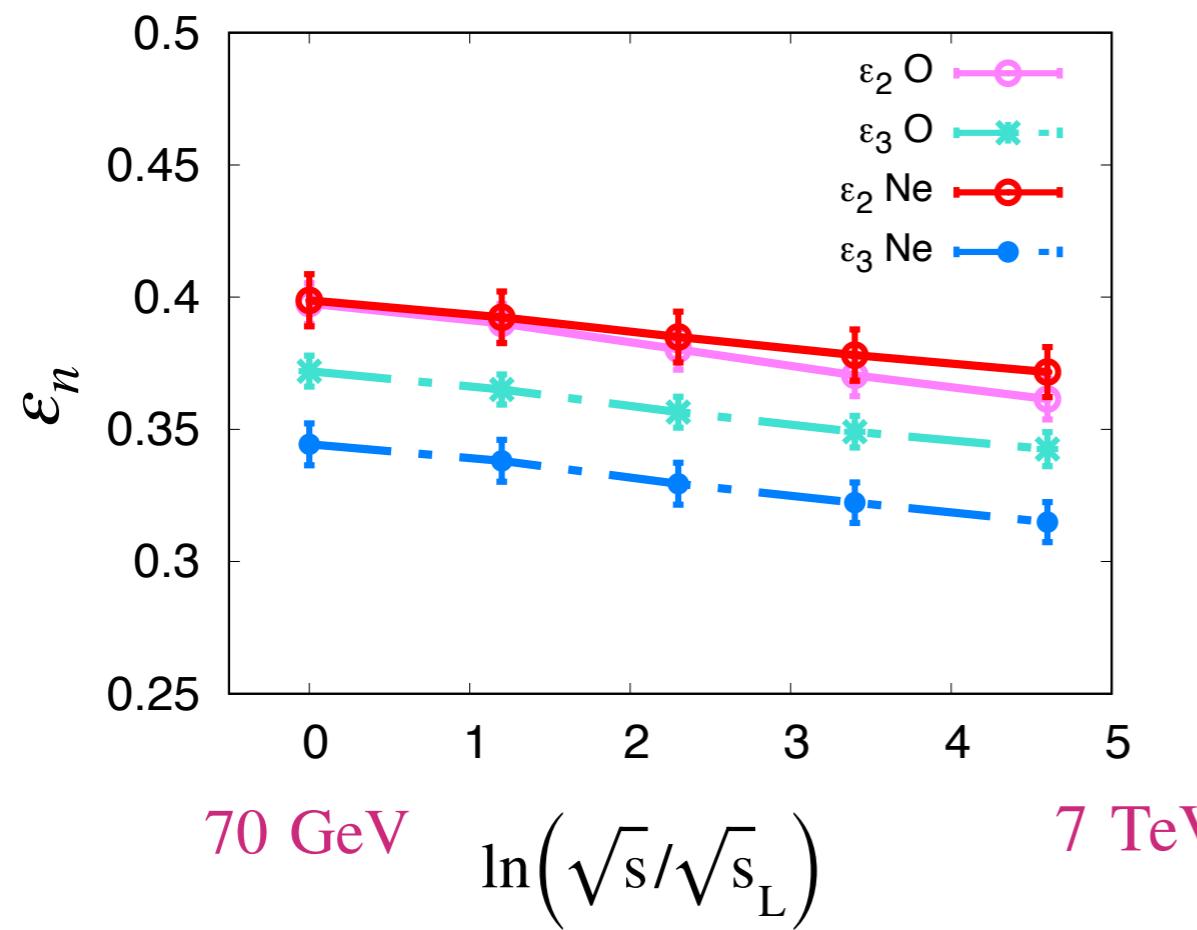
$$\epsilon_n(y) = \frac{\int d^2\mathbf{r}_\perp T^{\tau\tau}(y, \mathbf{r}_\perp) |\mathbf{r}_\perp|^n e^{in\phi_{\mathbf{r}_\perp}}}{\int d^2\mathbf{r}_\perp T^{\tau\tau}(y, \mathbf{r}_\perp) |\mathbf{r}_\perp|^n},$$

# Eccentricities for O, Ne and U for collisions at b=0

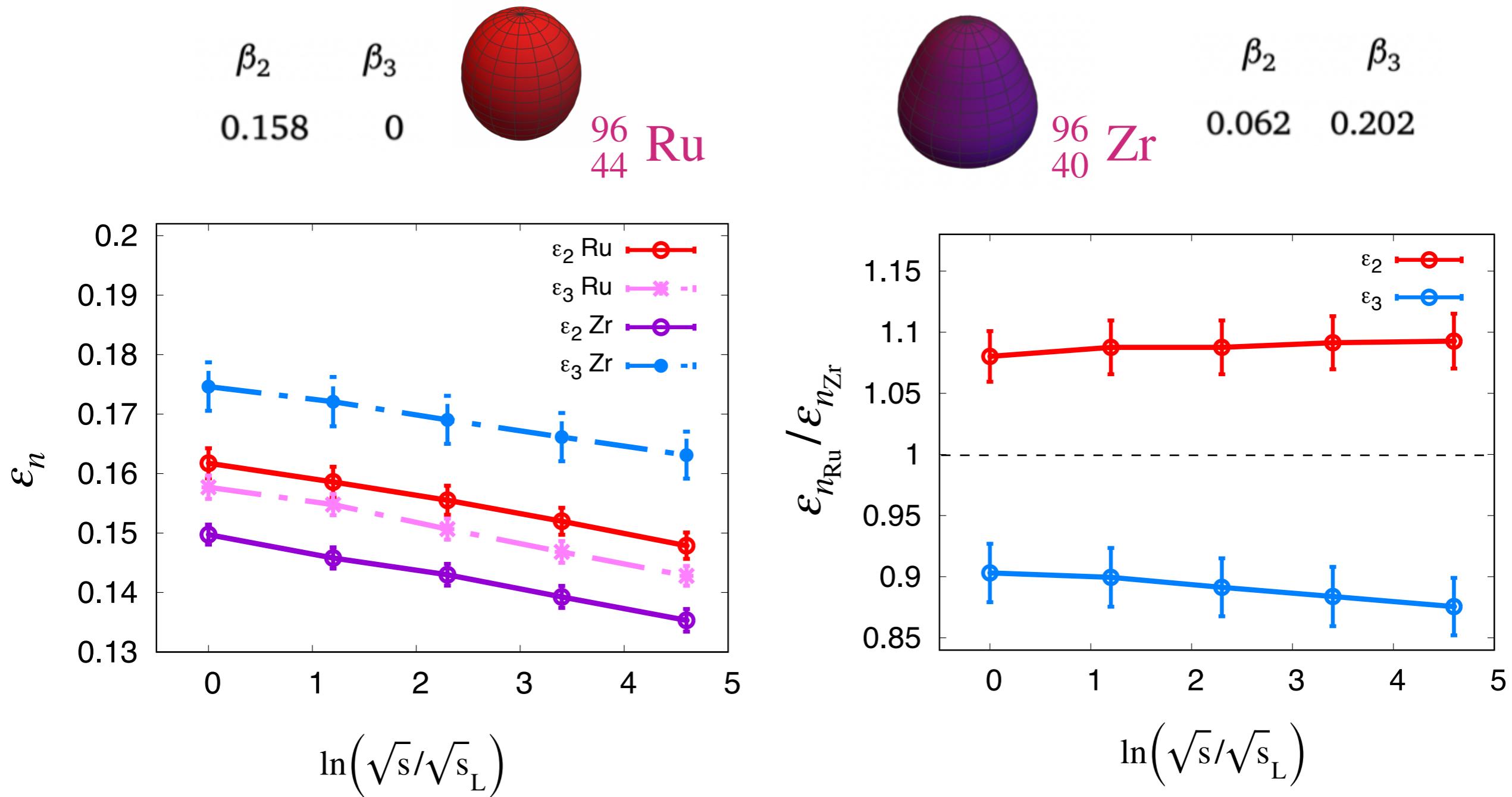
Nucleus	$\varepsilon_2   \sqrt{s}_H / \sqrt{s}_L$	$\varepsilon_3   \sqrt{s}_H / \sqrt{s}_L$
Oxygen	0.91	0.92
Neon	0.93	0.91
Uranium	0.96	0.90



$$\sqrt{s}_L = 70 \text{ GeV} \quad \sqrt{s}_H = 7000 \text{ GeV}$$



# Eccentricities for Isobars for collisions at $b=0$

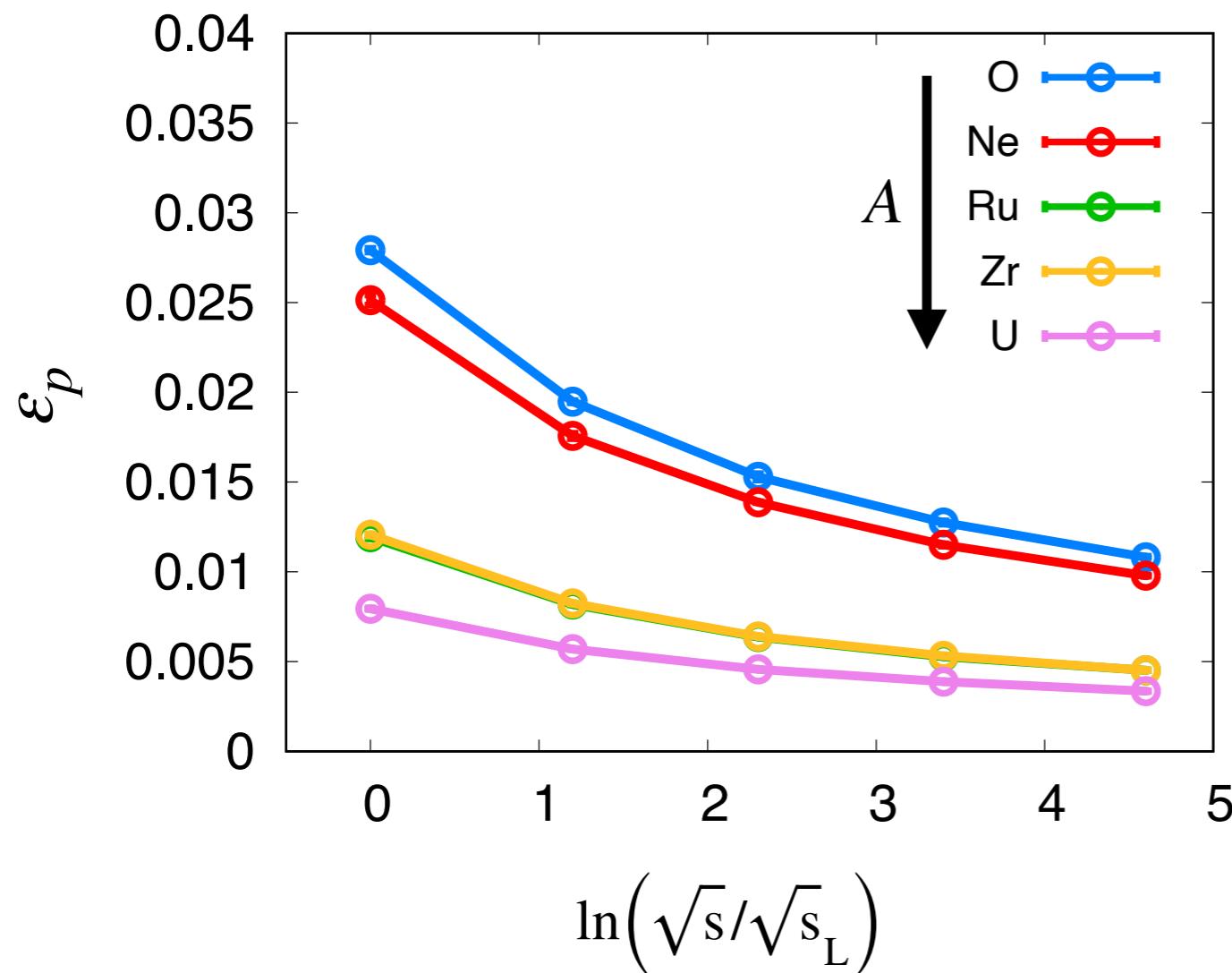


**Ratio different from unity is mainly due to nuclear structure.**

See also: S Bhatta, C Zhang, J Jia, arxiv 2301.01294

# Anisotropic energy flow at $\tau = 0.2$ fm

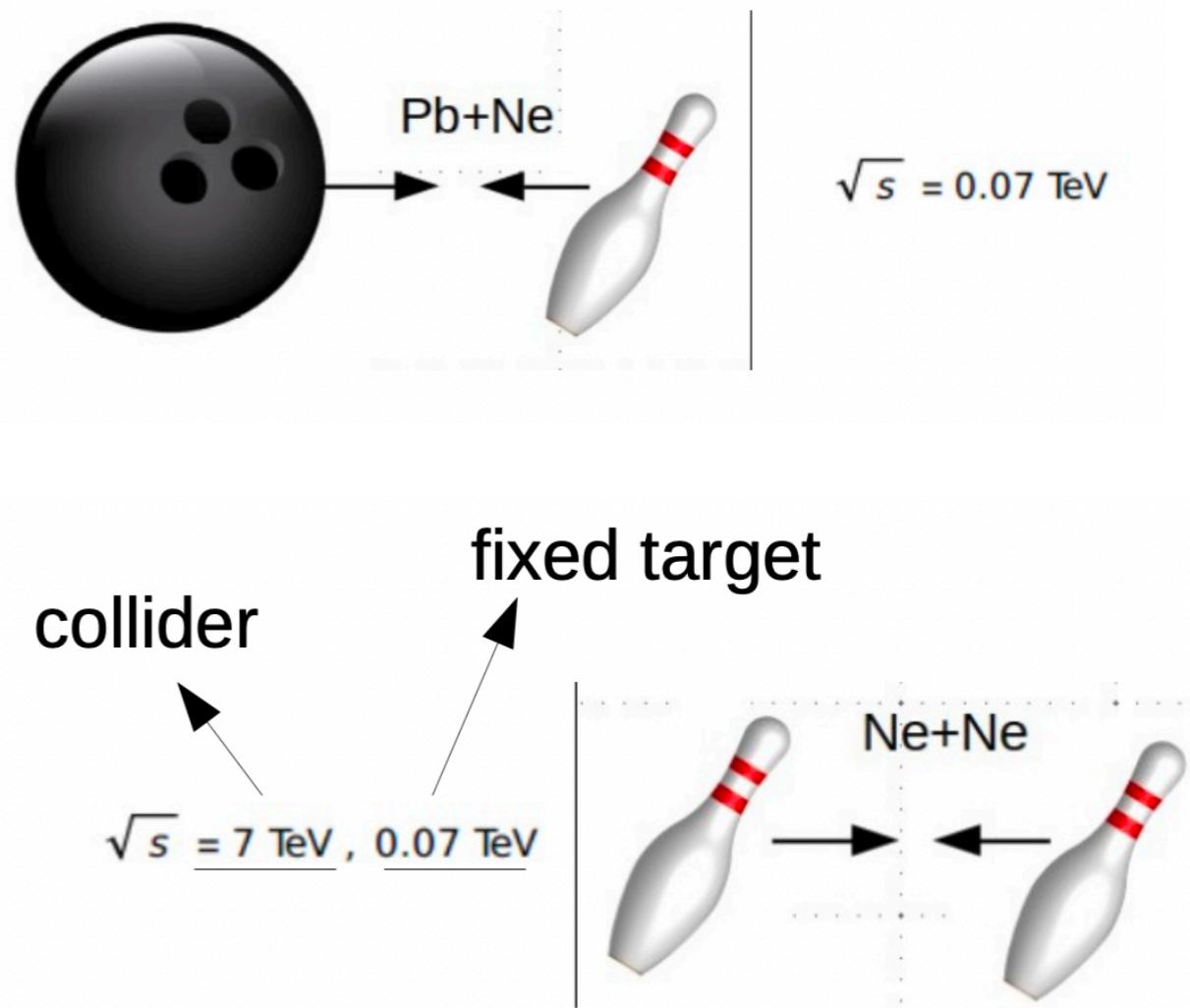
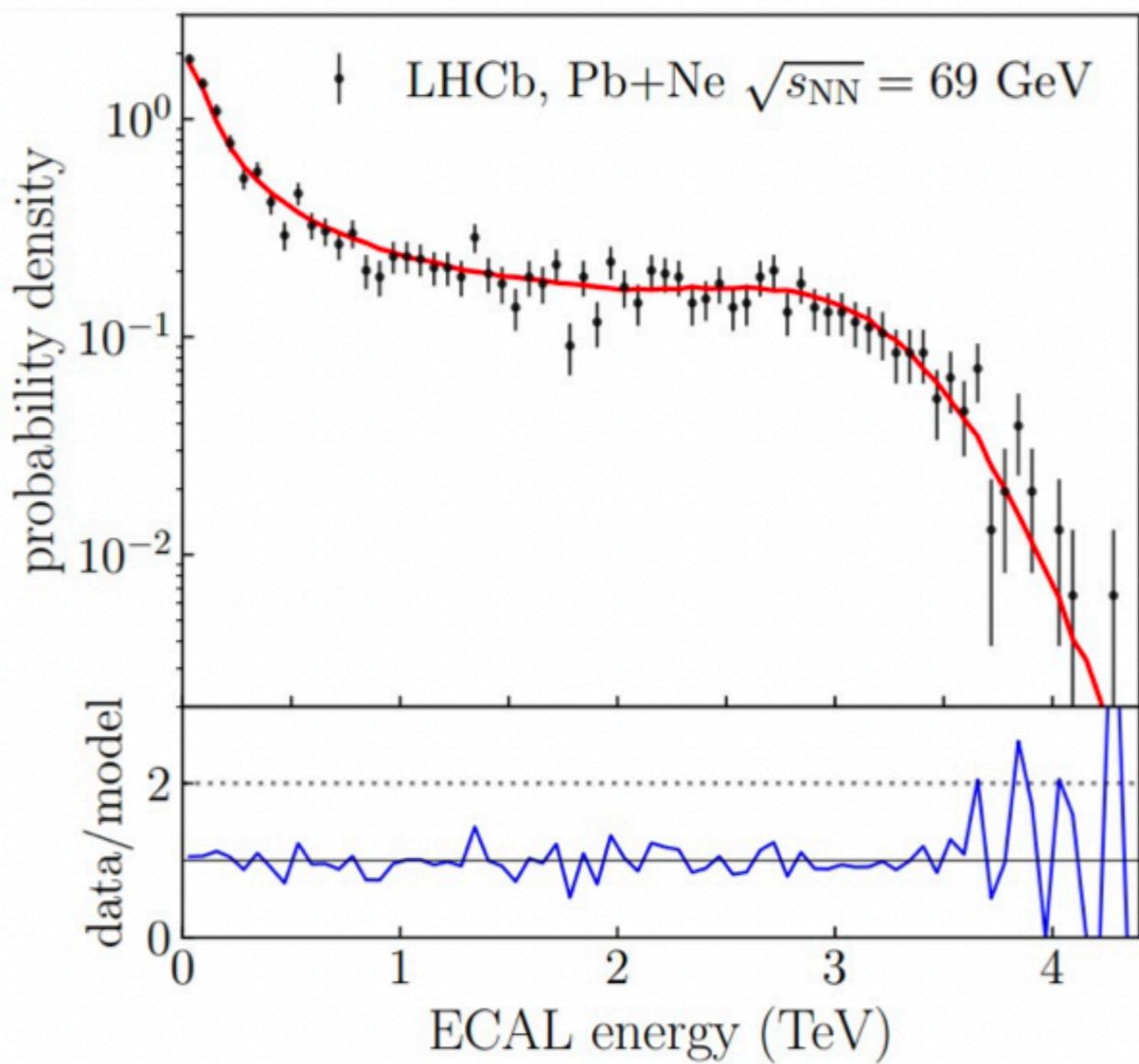
$$\varepsilon_p(y) = \frac{\int d^2\mathbf{r}_\perp T^{xx}(y, \mathbf{r}_\perp) - T^{yy}(y, \mathbf{r}_\perp) + 2iT^{xy}(y, \mathbf{r}_\perp)}{\int d^2\mathbf{r}_\perp T^{xx}(y, \mathbf{r}_\perp) + T^{yy}(y, \mathbf{r}_\perp)}$$



- Ratio unity for the isobars (Zr and Ru)
- Primordial source of anisotropy not affected by the geometry of the collisions
- Decorrelation with rapidity would be quick

Phys.Rev.D 105 (2022) 9, 094023  
B. Schenke, S. Schlichting and PS

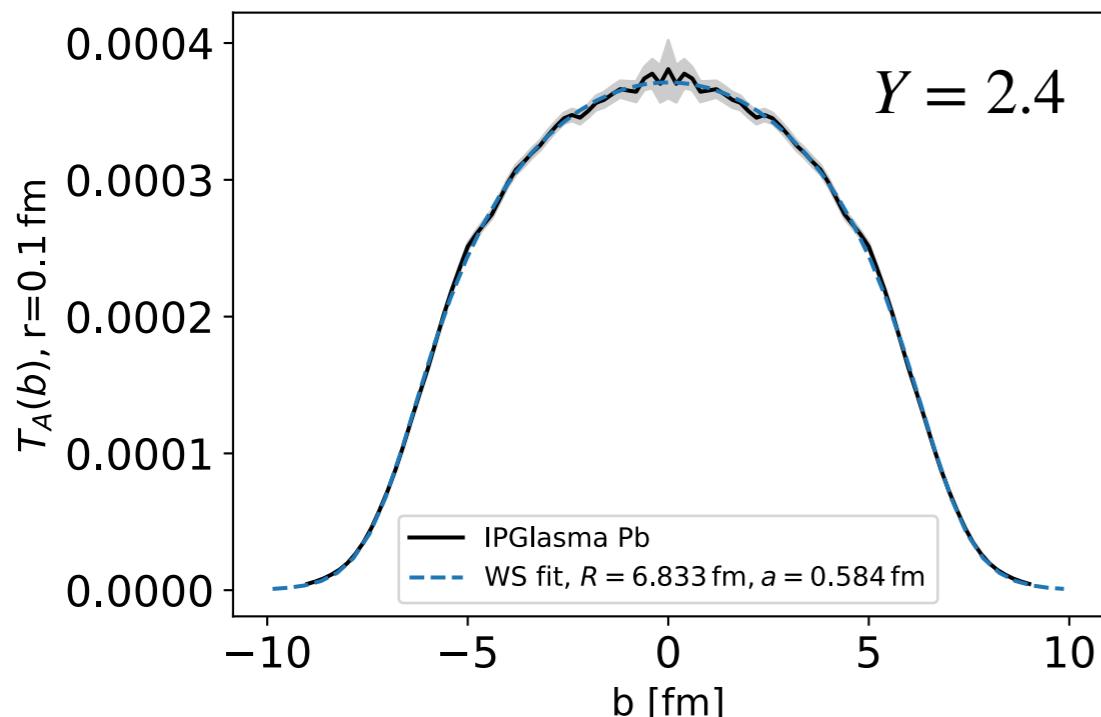
**IMPORTANT: Effects of JIMWLK evolution could be amenable to experimental verifications via synergy with the SMOG system of LHCb detector**



[LHCb Collaboration, JINST 17 (2022) 05, P05009]

# Conclusion & Outlook

- JIMWLK evolution leads to smoothening of profile and growth in impact parameter space
- Strong geometric effect in small systems (OO and NeNe)
- Ratio of eccentricities differs from unity for isobars.



- Centrality based study for  $^{20}Ne$  and  $^{16}O$  to further understand the phenomenon.
- Determination of nuclear structure parameters within high-energy framework.

Ongoing work: H Mäntysaari and PS

Thank you 

# **BACKUP**

# JIMWLK evolution

## Rapidity evolution of Wilson line $V_{x_\perp}(Y)$

$$V_{x_\perp}(Y + dY) = \exp \left\{ -i \frac{\sqrt{\alpha_s dY}}{\pi} \int_{z_\perp} K_{x_\perp - z_\perp} \cdot (V_{z_\perp} \xi_{z_\perp} V_{z_\perp}^\dagger) \right\} V_{x_\perp}(Y) \exp \left\{ i \frac{\sqrt{\alpha_s dY}}{\pi} \int_{z_\perp} K_{x_\perp - z_\perp} \cdot \xi_{z_\perp} \right\}$$

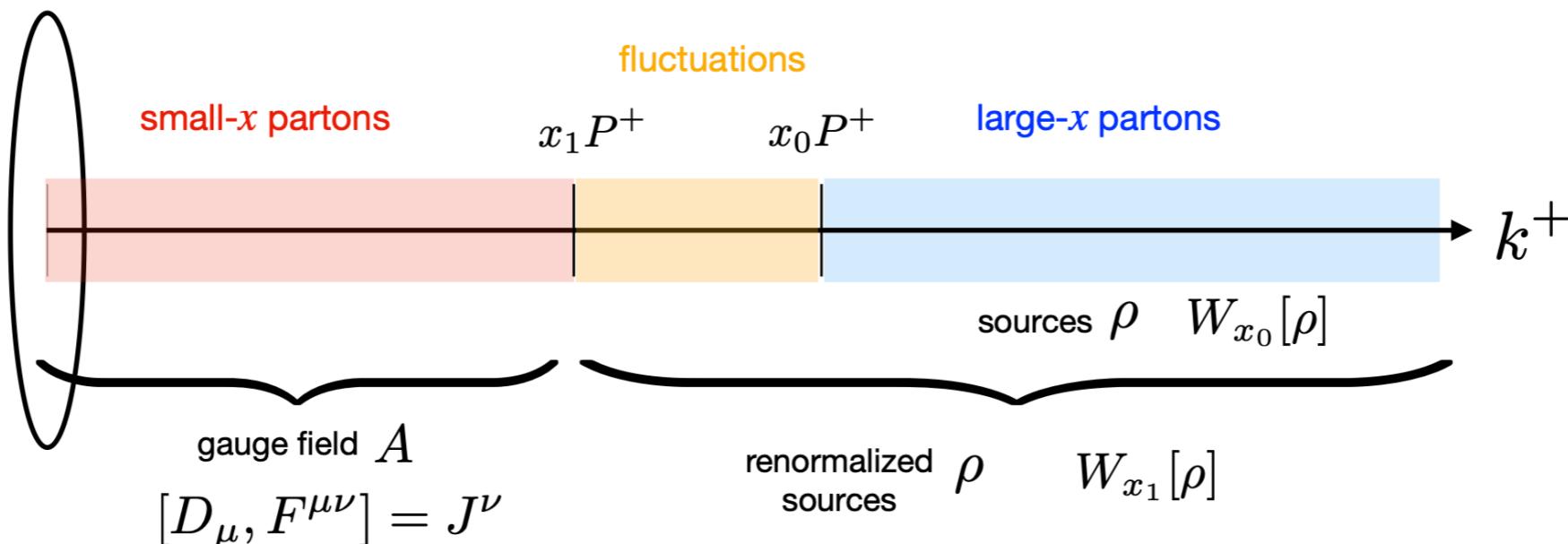
H. Weigert, Nucl. Phys. A 703, 823 (2002),  
 T. Lappi and H. Mantysaari, Eur. Phys. J. C 73, 2307 (2013)

$\xi$  is Gaussian noise with zero average

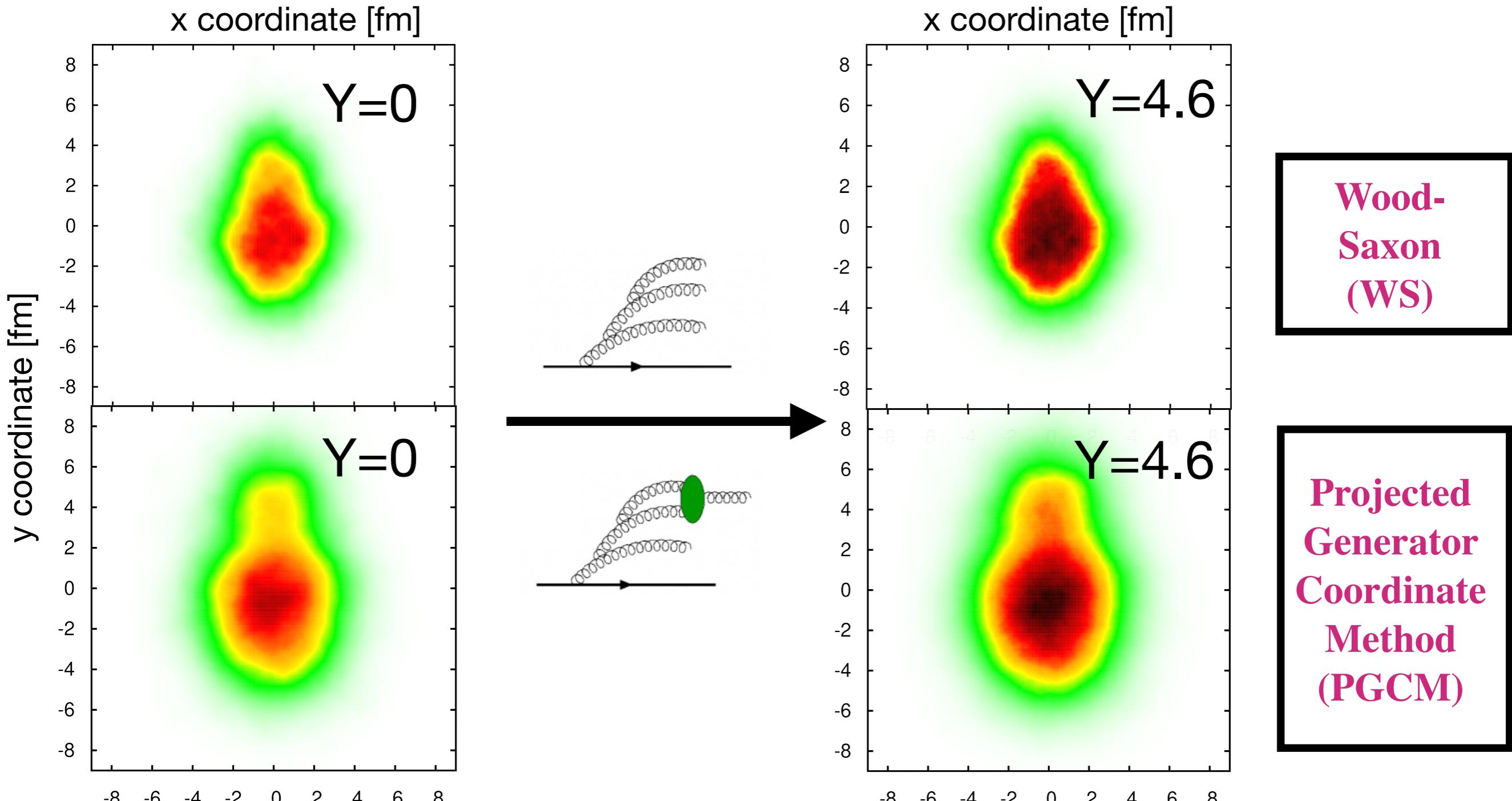
The JIMWLK Kernel is modified to avoid infrared tails:

$$\mathbf{K}_r^{(\text{mod})} = m|\mathbf{r}| K_1(m|\mathbf{r}|) \mathbf{K}_r$$

B. Schenke, S. Schlichting Phys.Lett.B 739 (2014) 313-319



# Effect of JIMWLK evolution on $^{20}Ne$

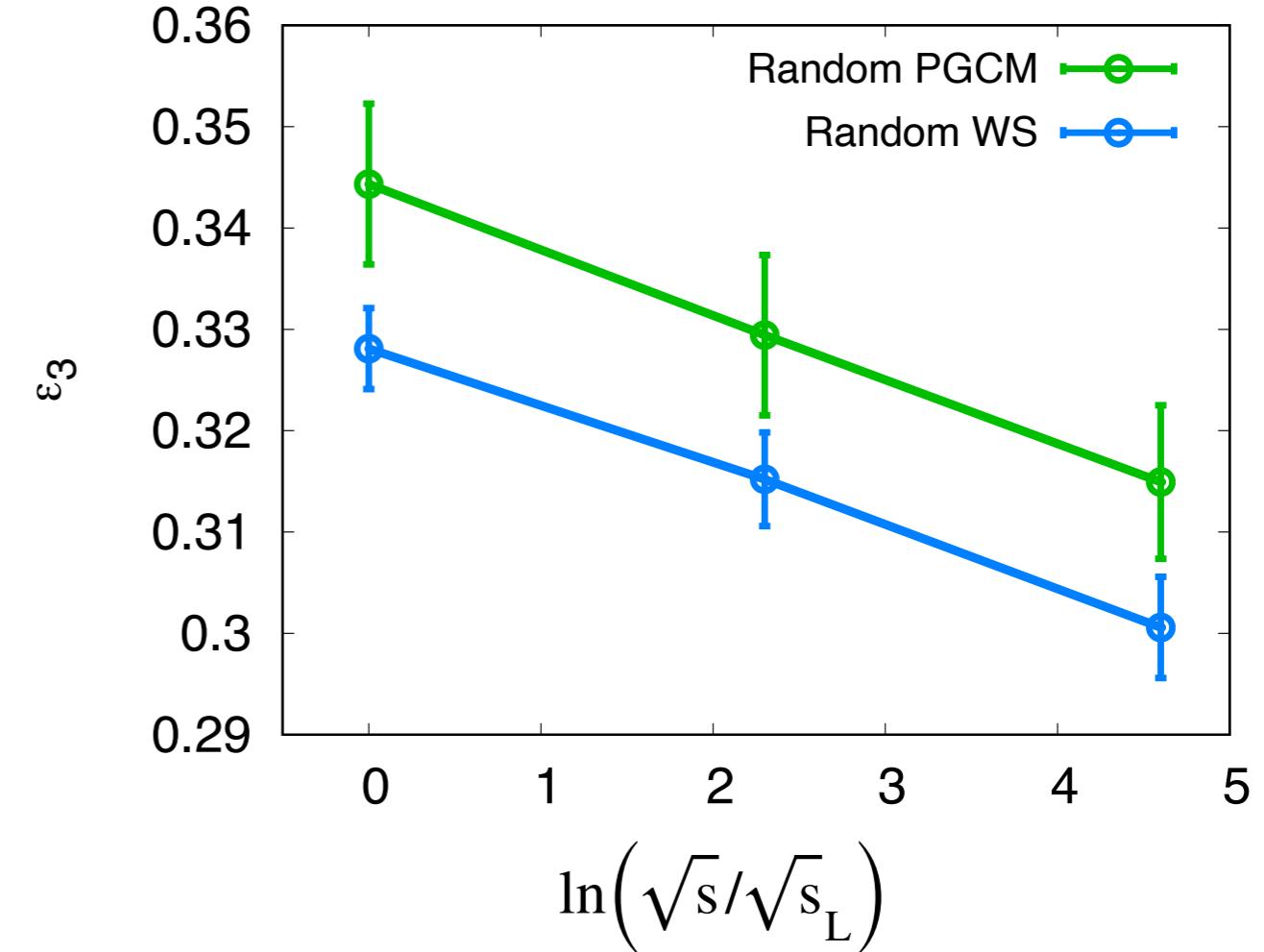
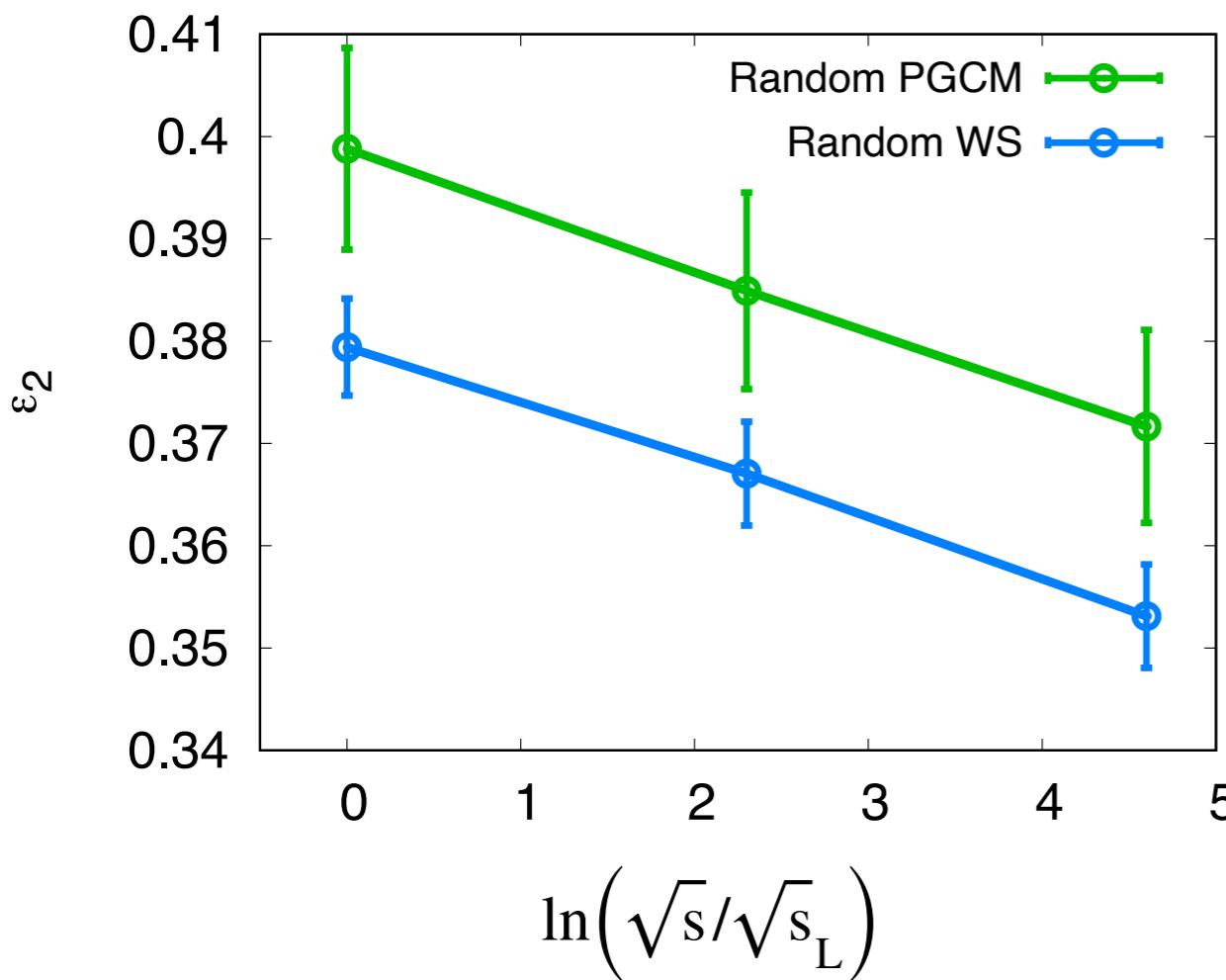


Wood-Saxon (WS)

Projected Generator Coordinate Method (PGCM)

Small-x evolution smear the bowling pin shape

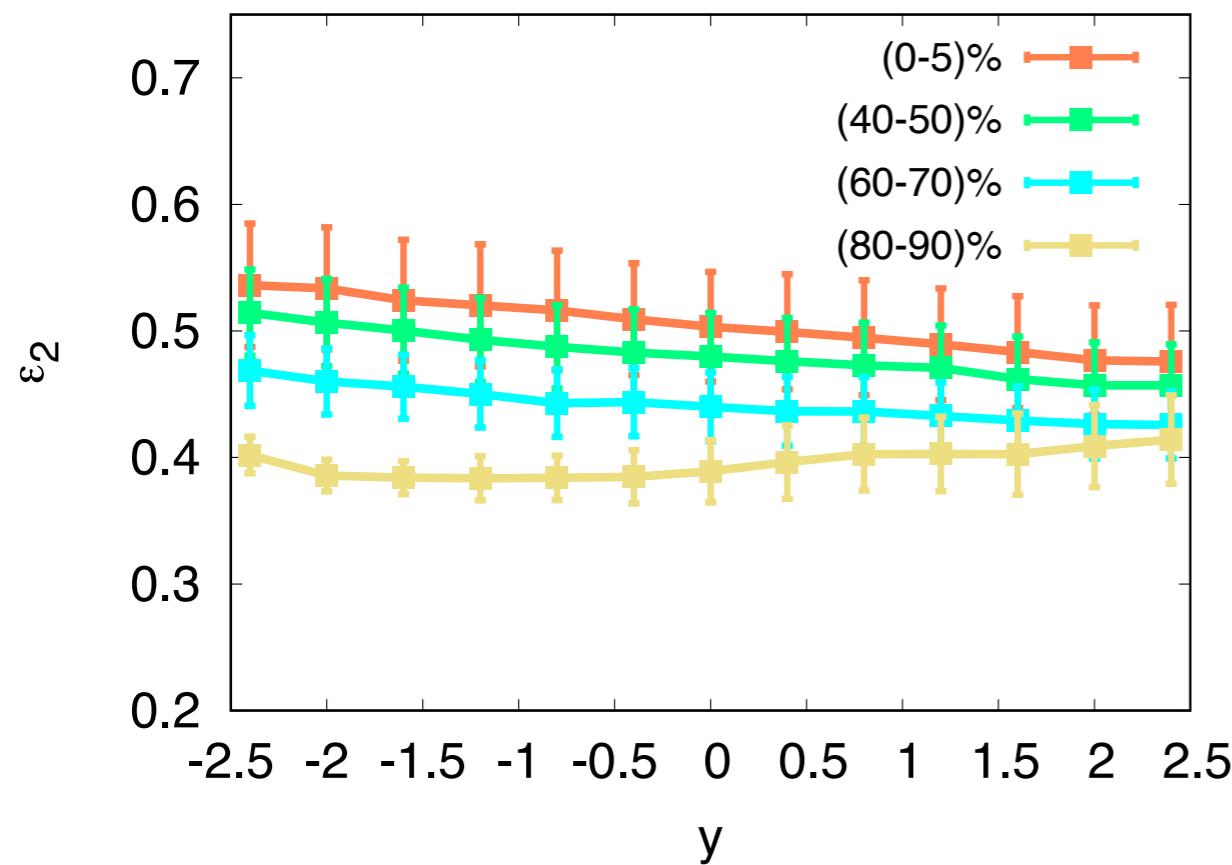
# Eccentricities for $^{20}\text{Ne}$ for collisions at $b=0$



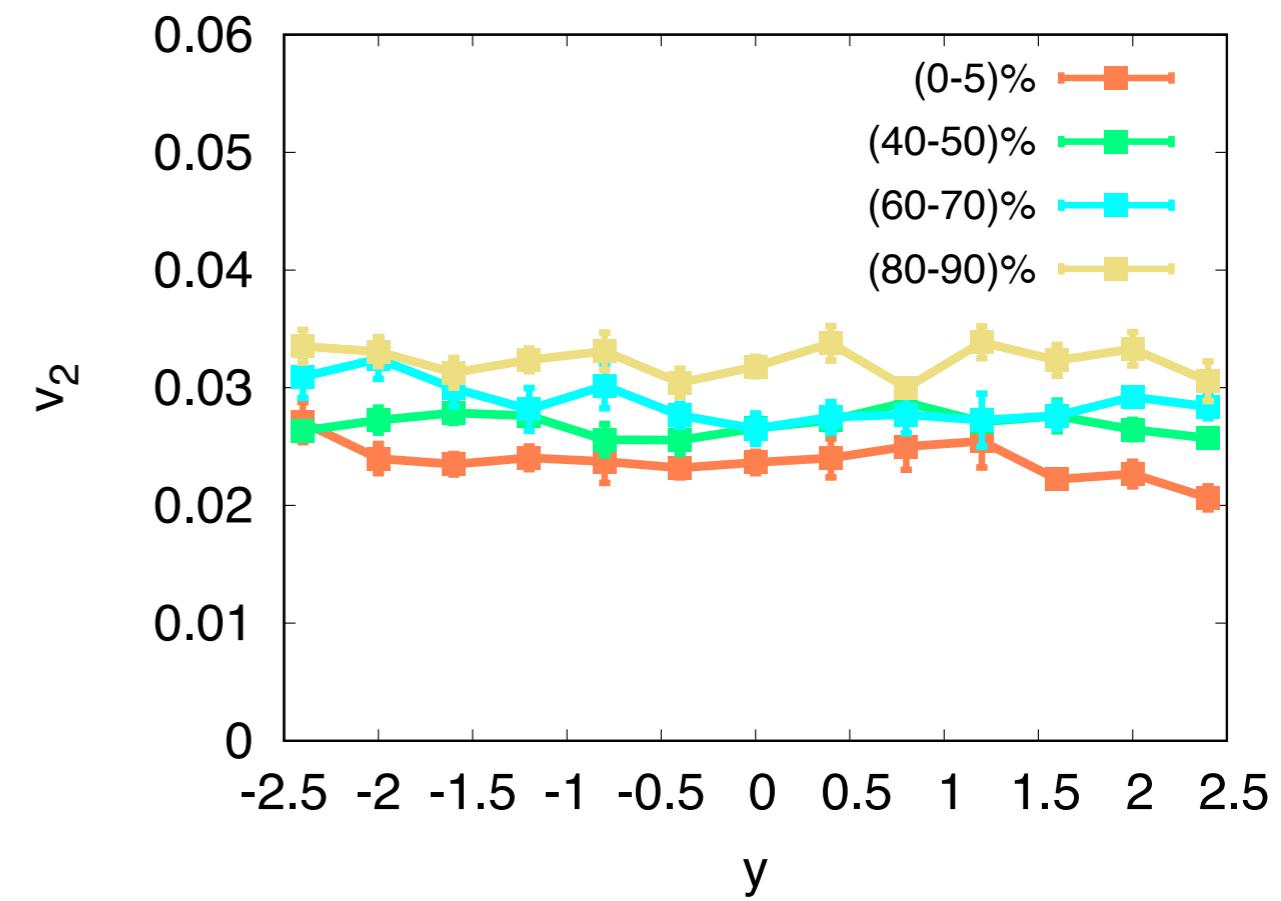
As anticipated, one way to achieve this is moving away from simple shape parametrizations to generate the initial conditions for hydrodynamic simulations, sampling instead nucleon distributions directly provided by nuclear theory. Unfortunately, this does not reduce the model dependency of such analysis: predictions for the shape of nuclei may vary widely across calculations. A truly model-independent way to construct initial conditions for hydrodynamic simulations based on experimental information on nuclear multipole moments seems impossible.

**Sizeable difference coming from nucleon sampling scheme**

## Event geometry

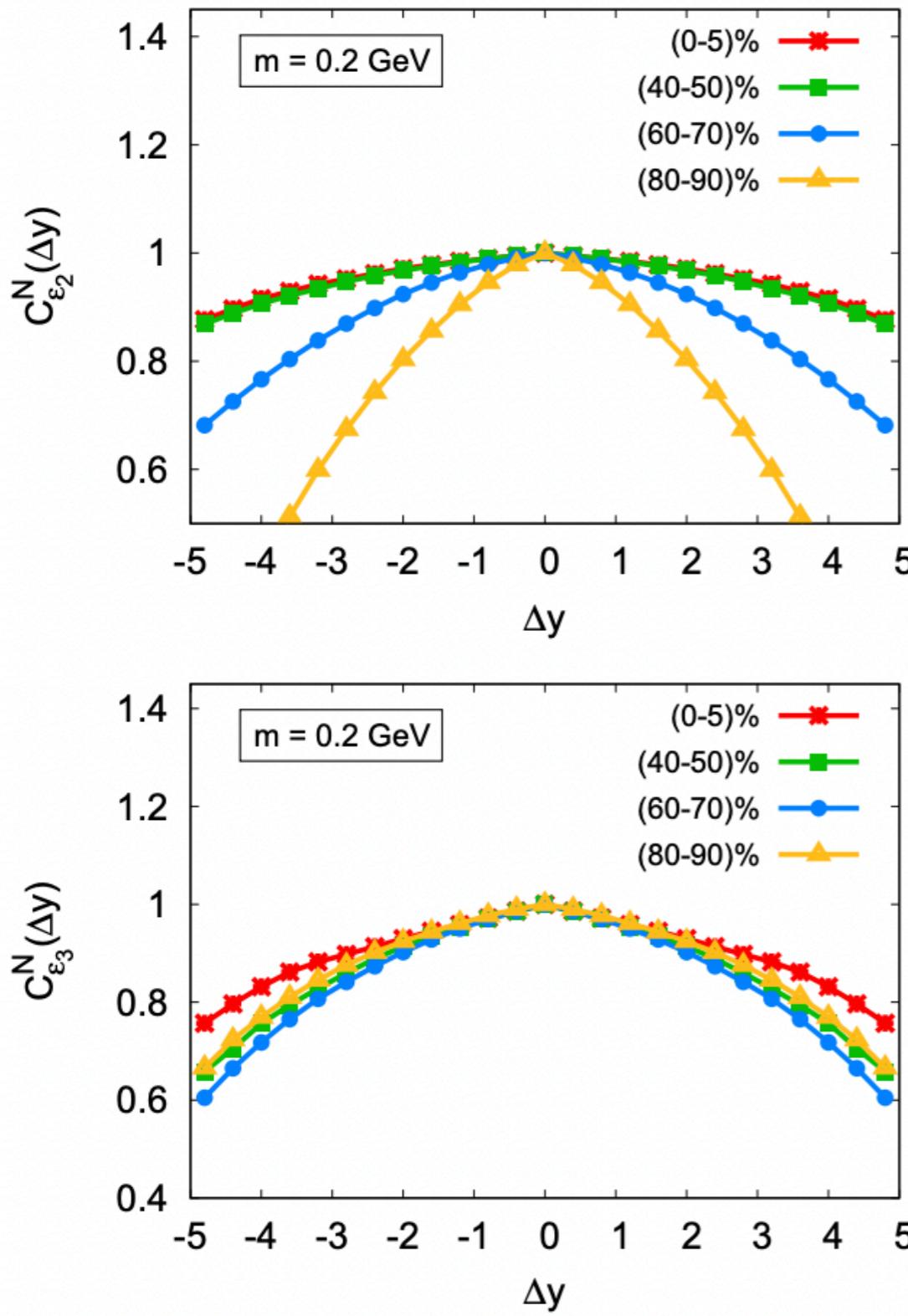


## IS momentum anisotropy

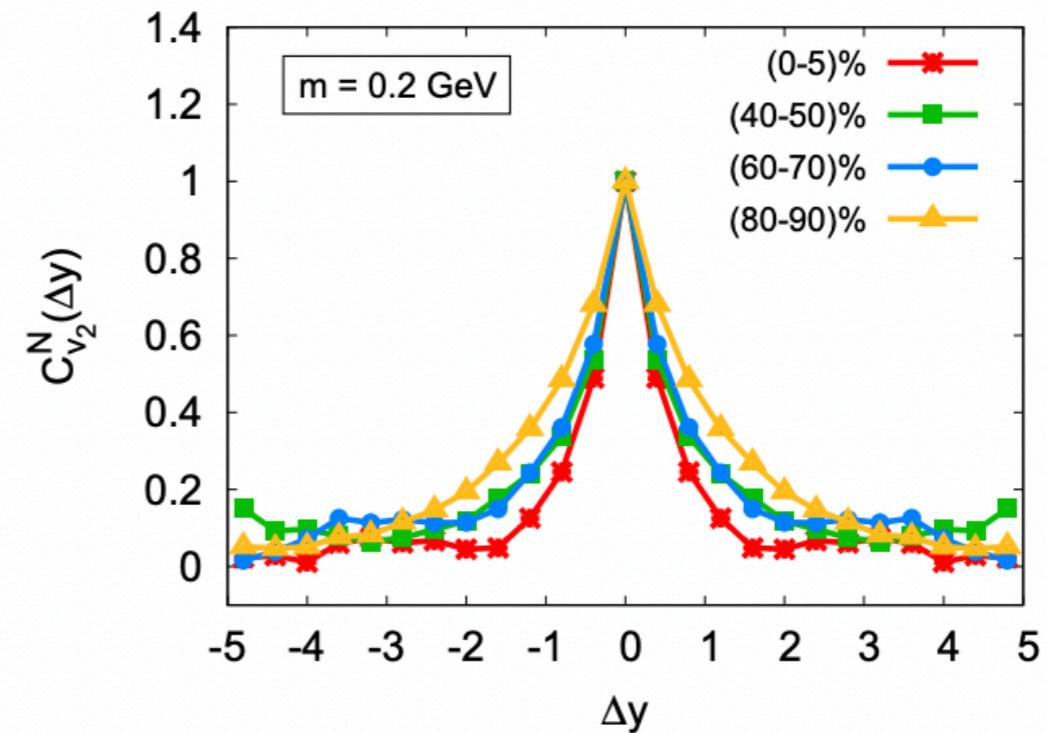


- Opposite trends in centrality in  $\varepsilon_2$  and initial state  $v_2$
- Initial state  $v_2$  largely independent of rapidity in all centrality bins.

# Decorrelation of event geometry and momentum anisotropy



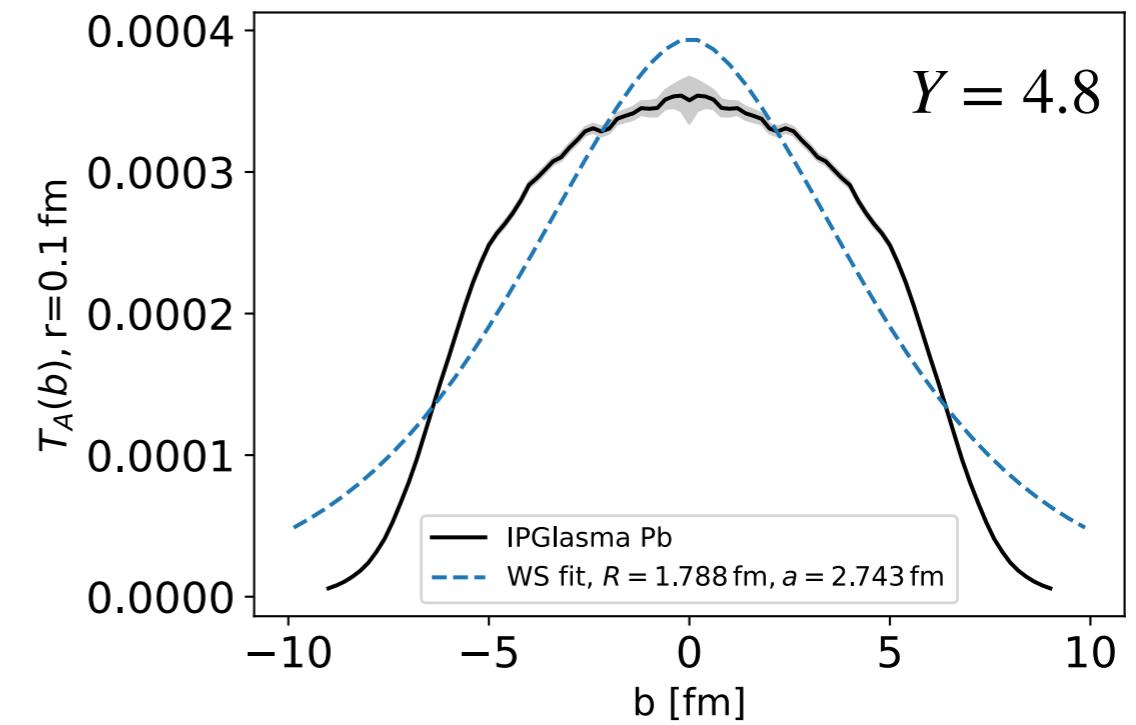
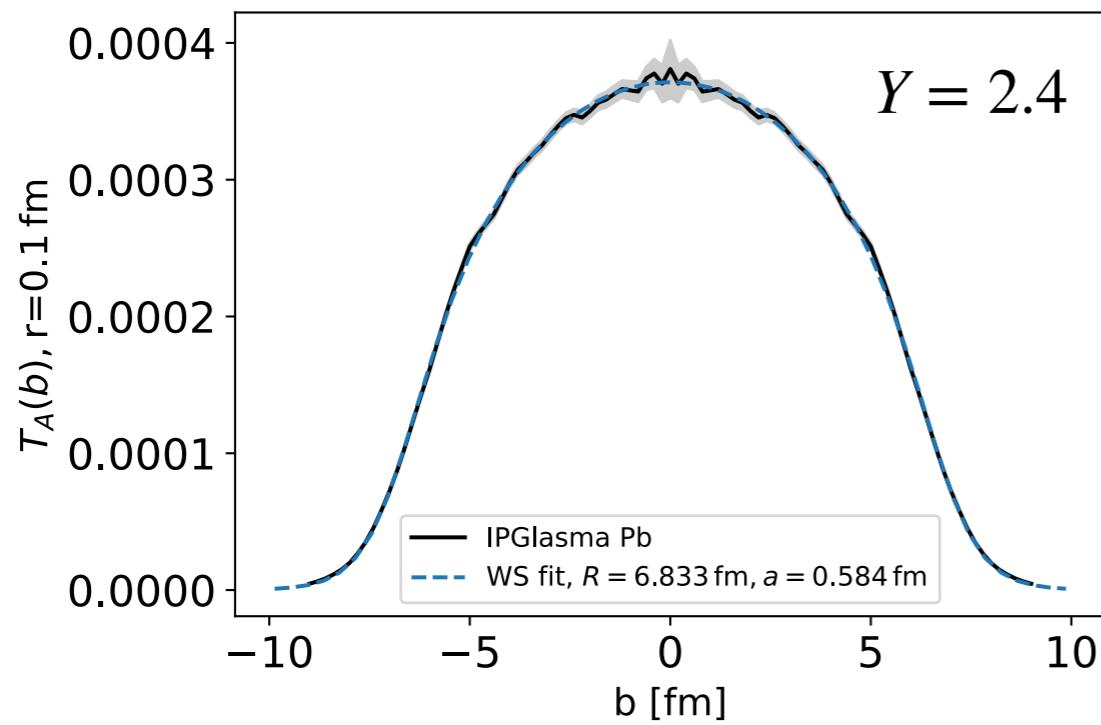
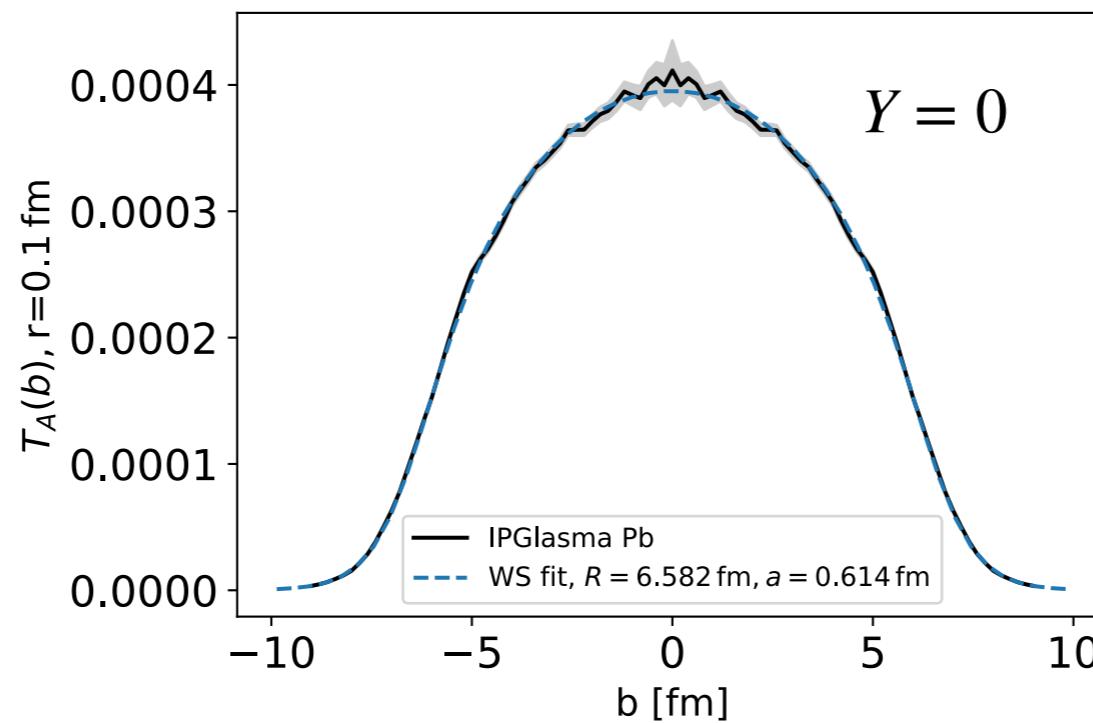
$$C_{\mathcal{O}}^N(y_1, y_2) = \frac{\langle \text{Re}(\mathcal{O}(y_1)\mathcal{O}^*(y_2)) \rangle}{\sqrt{\langle |\mathcal{O}(y_1)|^2 \rangle \langle |\mathcal{O}(y_2)|^2 \rangle}}.$$



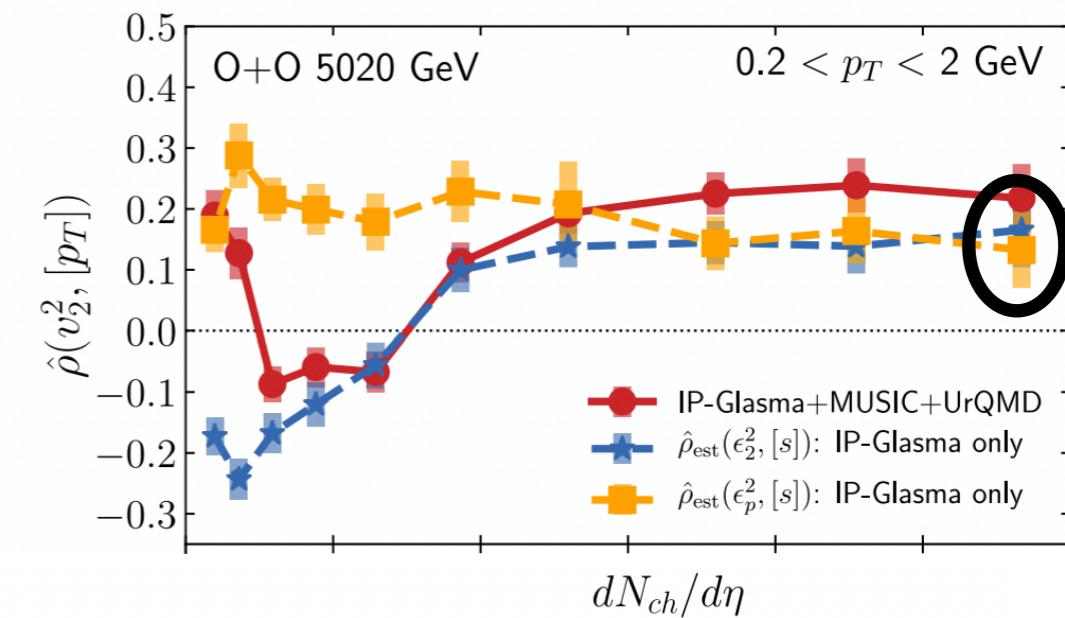
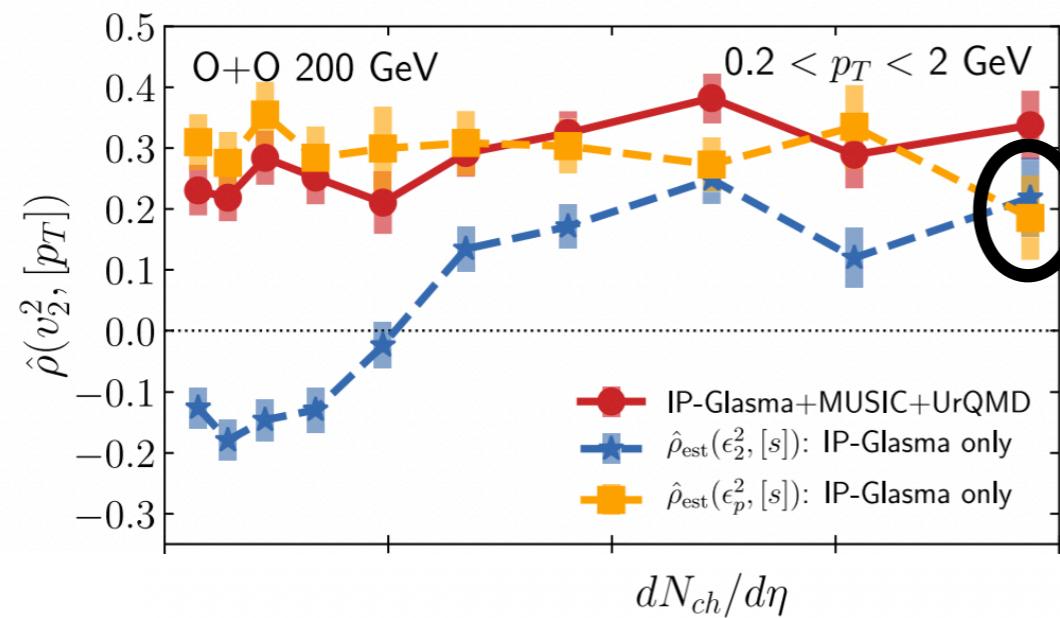
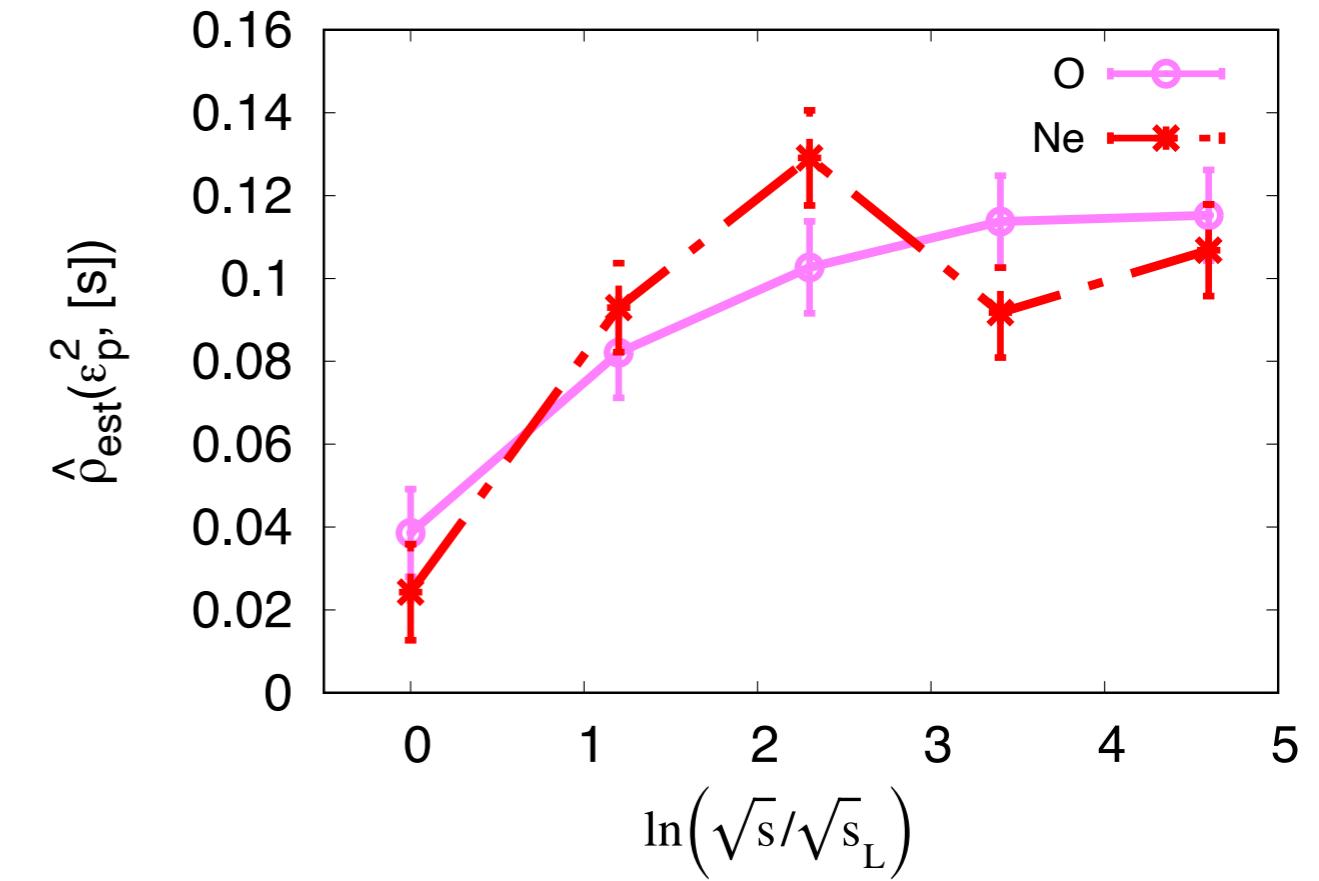
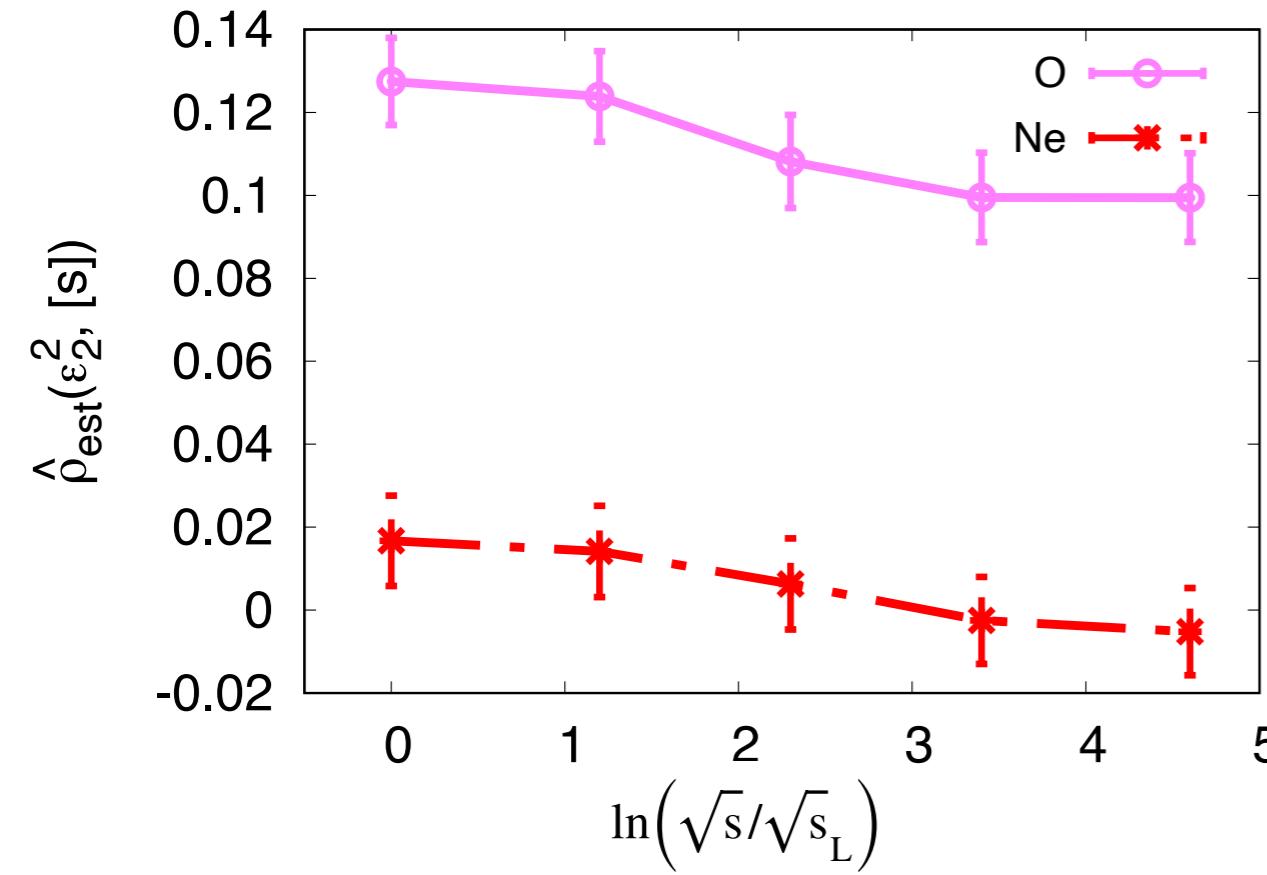
**Event geometry is correlated across large rapidity intervals whereas initial momentum correlations are relatively short ranged in rapidity.**

# Effect of JIMWLK evolution on the profile function

Ongoing work: H Mäntysaari and PS

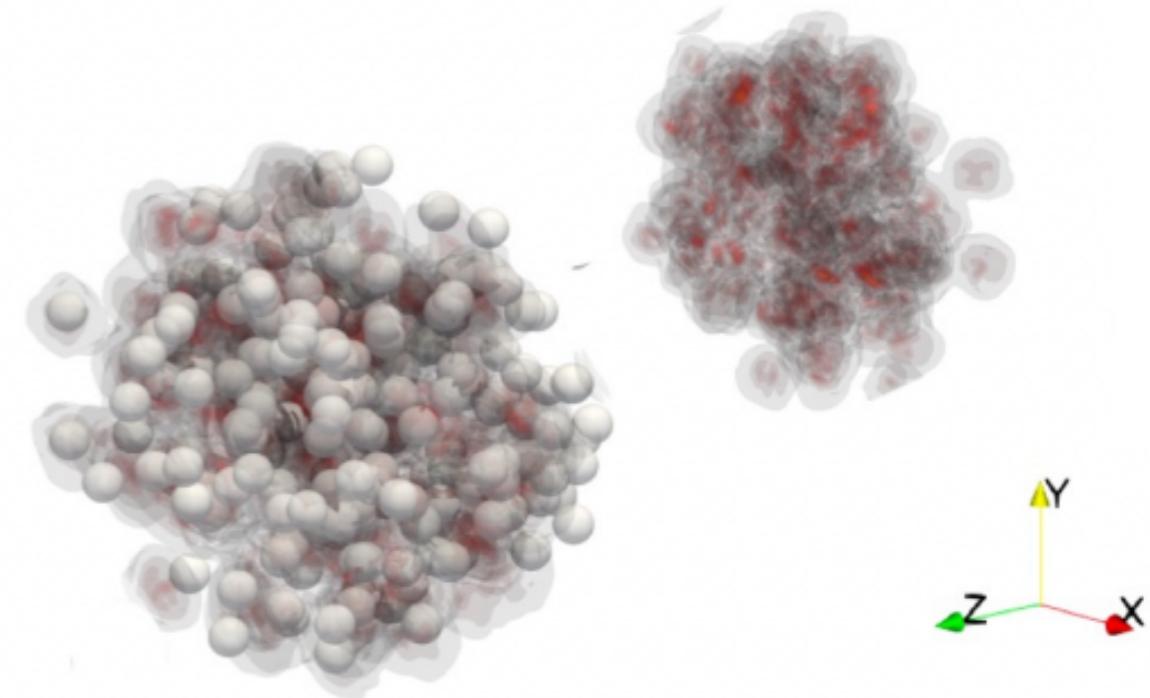


# Rho estimator for small systems



# Simulating initial state of a nuclear collision

- Sample position of nucleon eg. using Woods-Saxon distribution
- IP-Sat provides  $Q_s^2(x, \mathbf{b}_\perp)$  for each nucleon. Color charge density squared  $g^2\mu^2 \propto Q_s^2$
- Superposition of  $g^2\mu^2(\mathbf{x}_\perp)$  in each nucleus to obtain  $g^2\mu_1^2(\mathbf{x}_\perp)$  and  $g^2\mu_2^2(\mathbf{x}_\perp)$
- Set color charge density and solve classical Yang-Mills equation



PS, S Schlichting Phys. Rev. D 103, 014003