

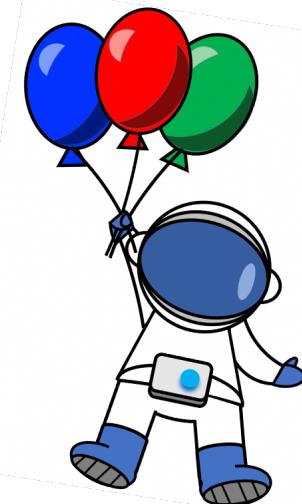


U.S. DEPARTMENT OF  
**ENERGY**

Office of  
Science



# FLOWING TO THE FUTURE: SIMULATING THE TINIEST FLUIDS IN 3+1 DIMENSIONS



**BJÖRN SCHENKE, BROOKHAVEN NATIONAL LABORATORY**  
**with Sangwook Ryu, Chun Shen, and Wenbin Zhao**

**QUARK MATTER 2023**  
**HOUSTON, TEXAS, USA**

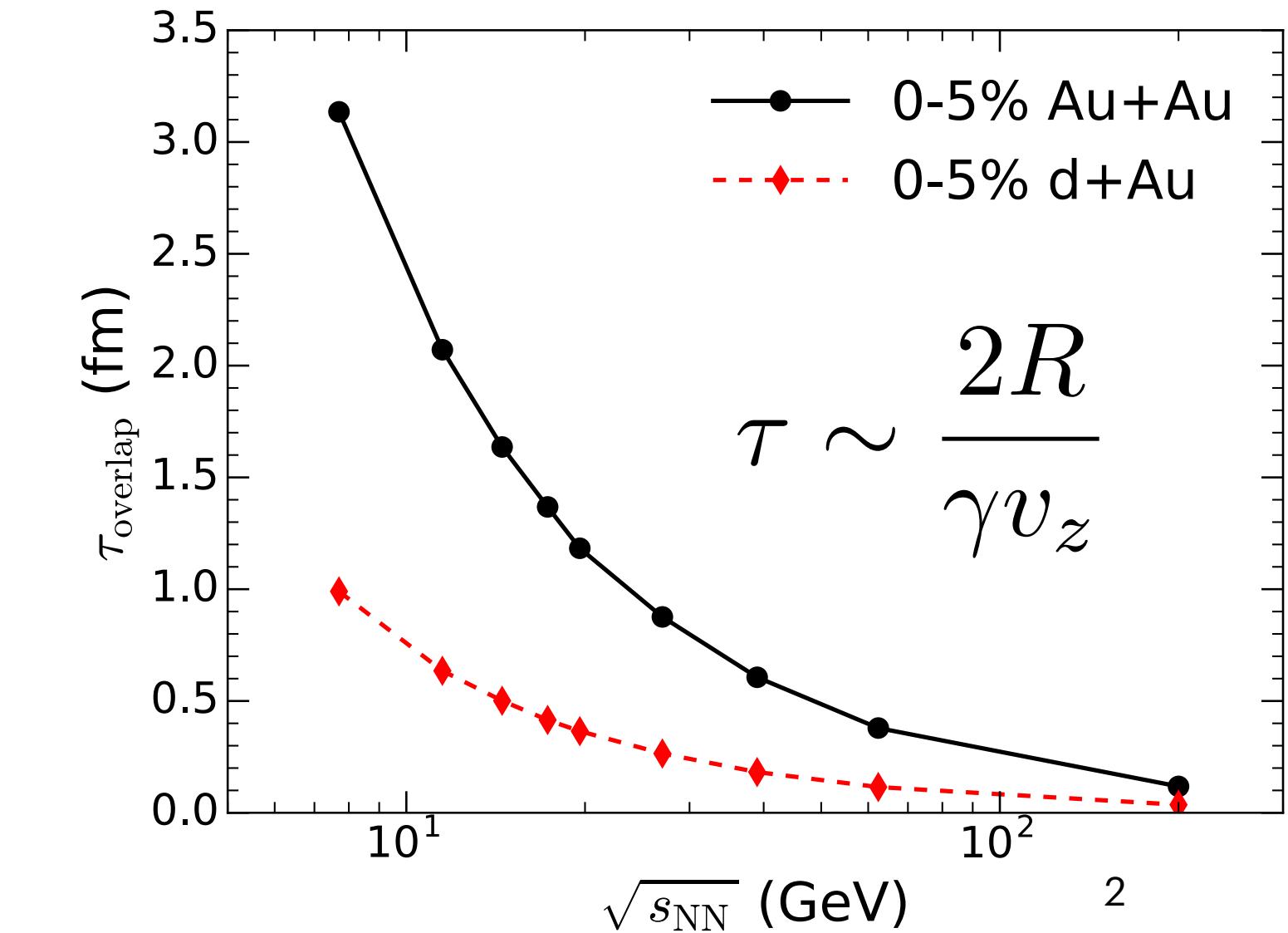
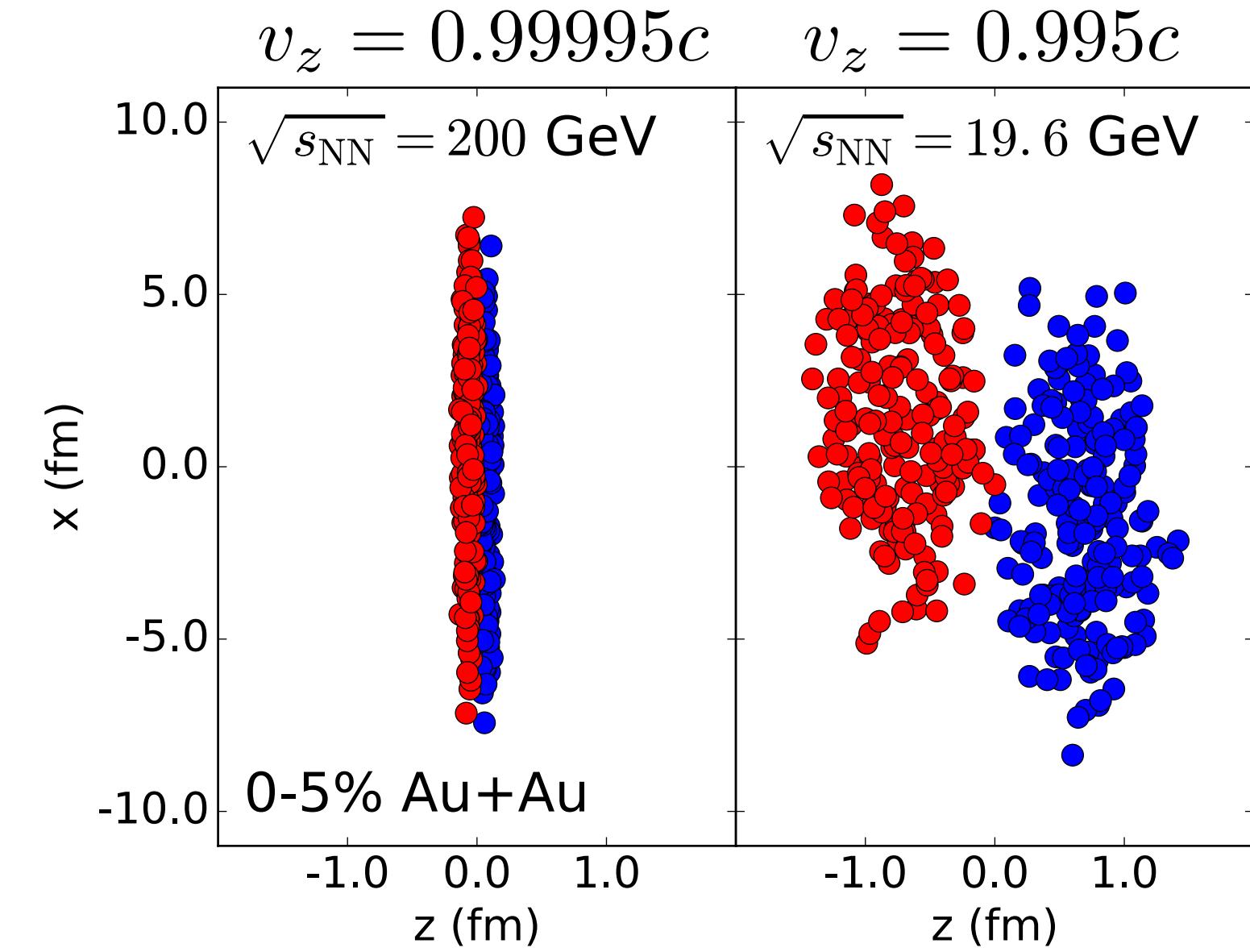
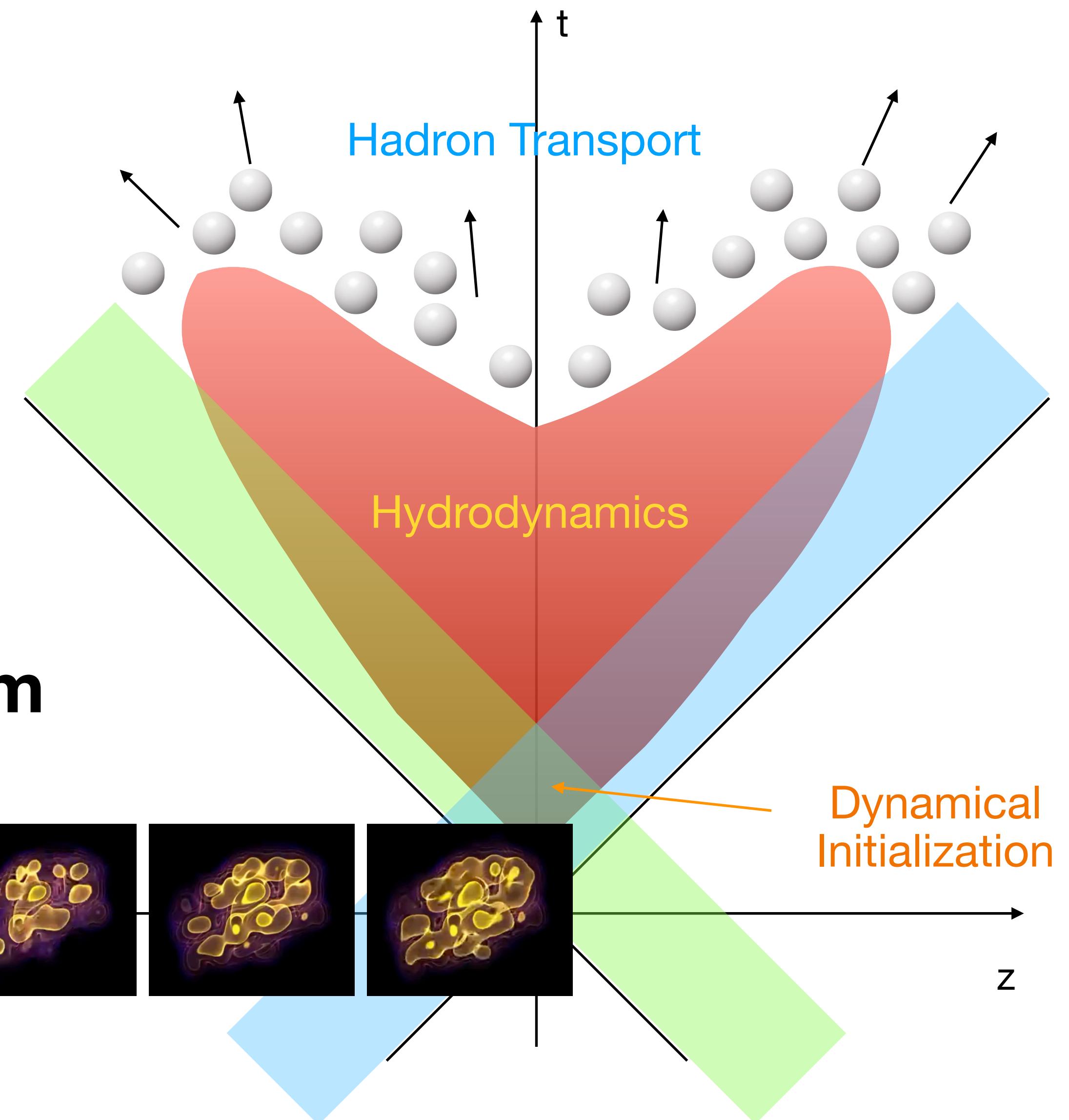
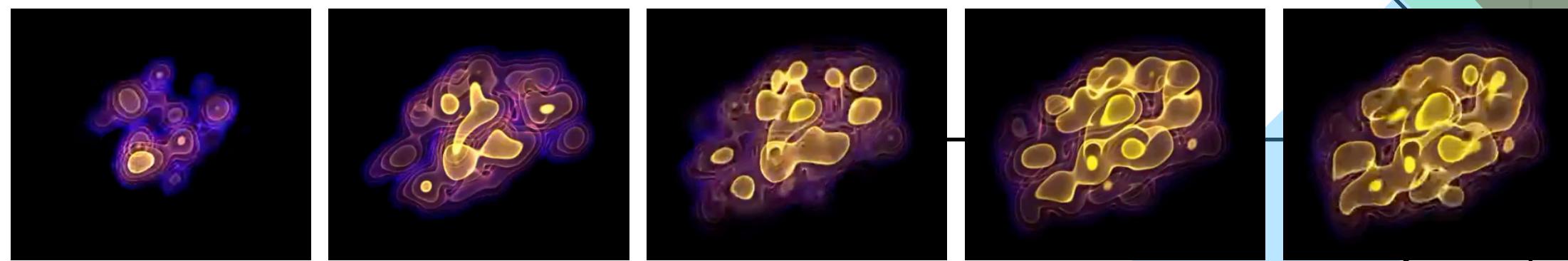
**SEPTEMBER 5 2023**

W. Zhao, S. Ryu, C. Shen and B. Schenke, Phys.Rev.C 107 (2023) 1, 014904  
W. Zhao, C. Shen and B. Schenke, Phys.Rev.Lett. 129 (2022) 25, 252302

# DYNAMIC 3+1D INITIAL STATE

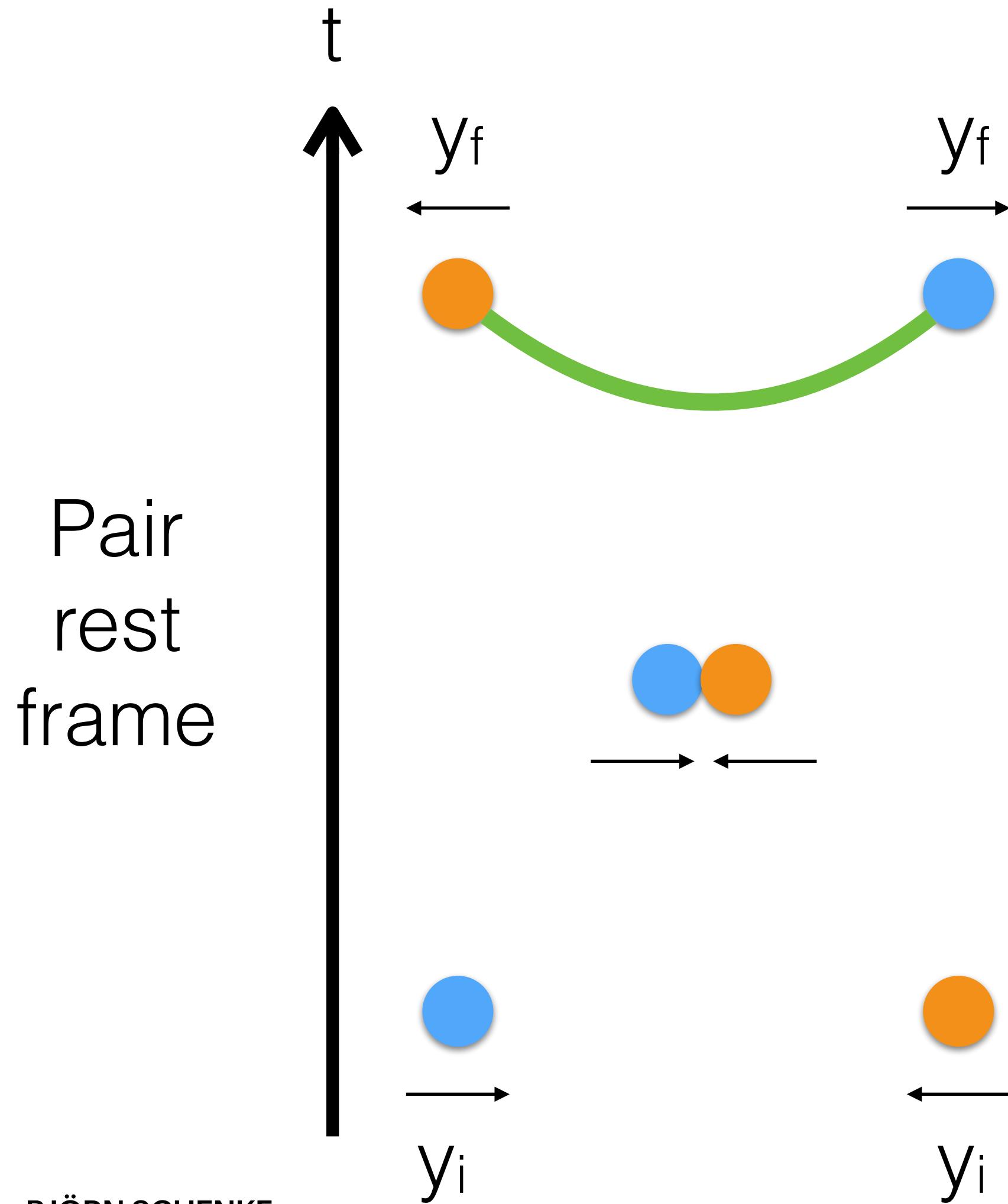
C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907; Phys. Rev. C 105, 064905 (2022)

Dynamical  
string  
deceleration  
model  
feeding into  
hydrodynamics  
via a source term



# 3D MC-GLAUBER + STRING MODEL

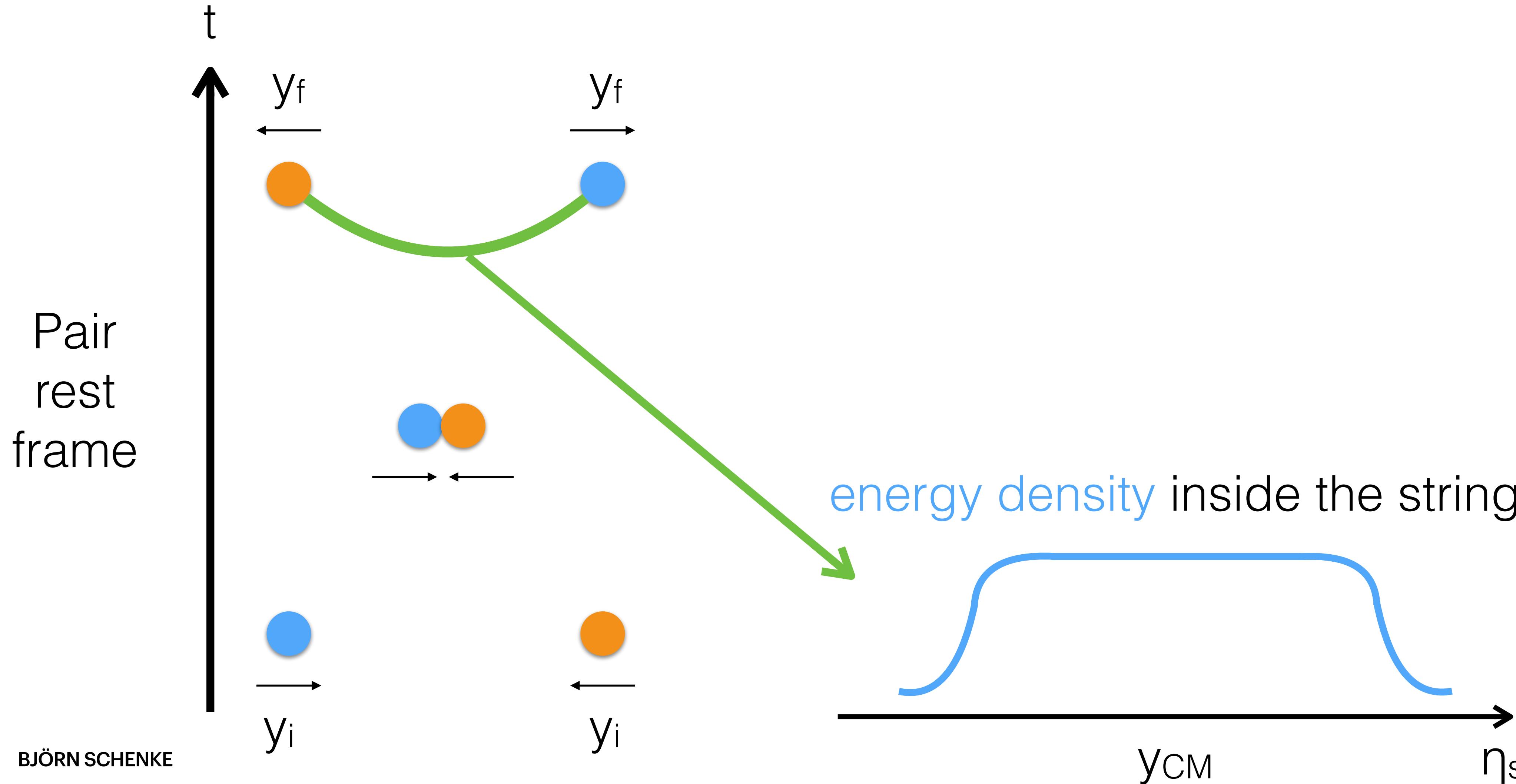
C. Shen and B. Schenke, Phys. Rev. C 97 (2018) 024907; Phys. Rev. C 105, 064905 (2022)



- Transverse collision geometry is determined by MC-Glauber model
- Hot spots associated with valence quarks are sampled from PDF + a soft partonic cloud carrying the rest (small  $x$  partons)
- Hot spots are randomly picked to lose energy during a collision, using a classical string tension  $dp^z/dt = -\sigma$

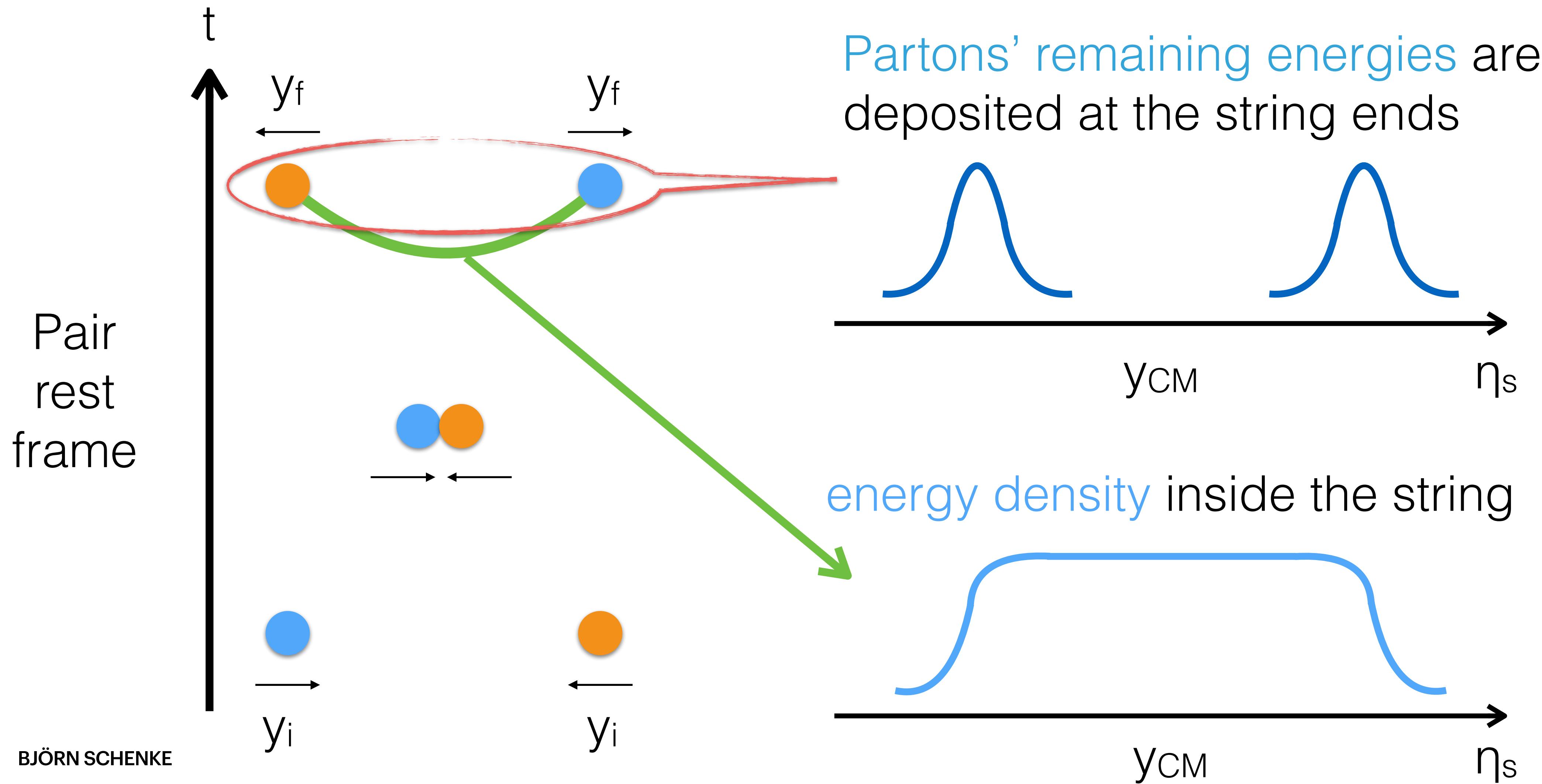
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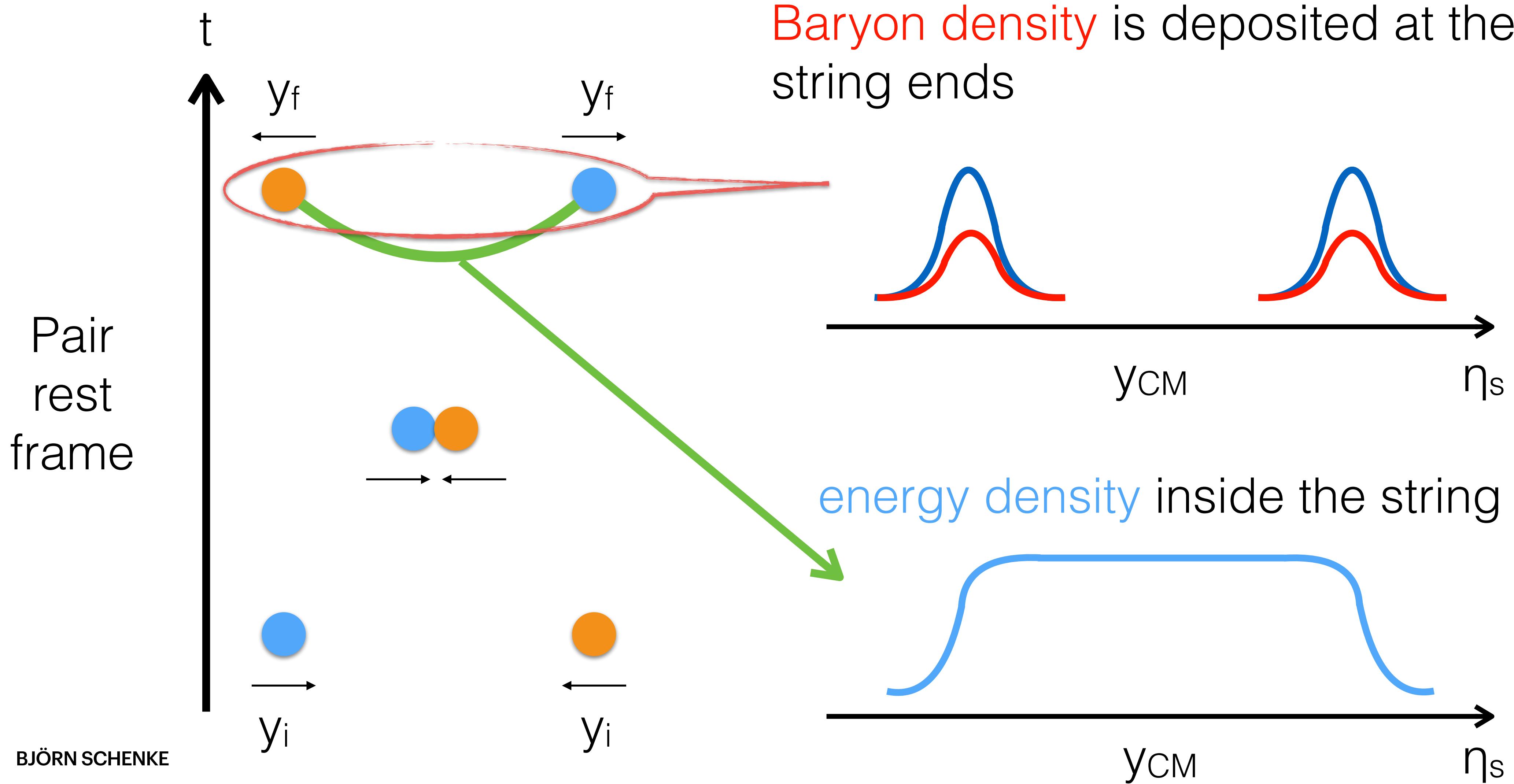
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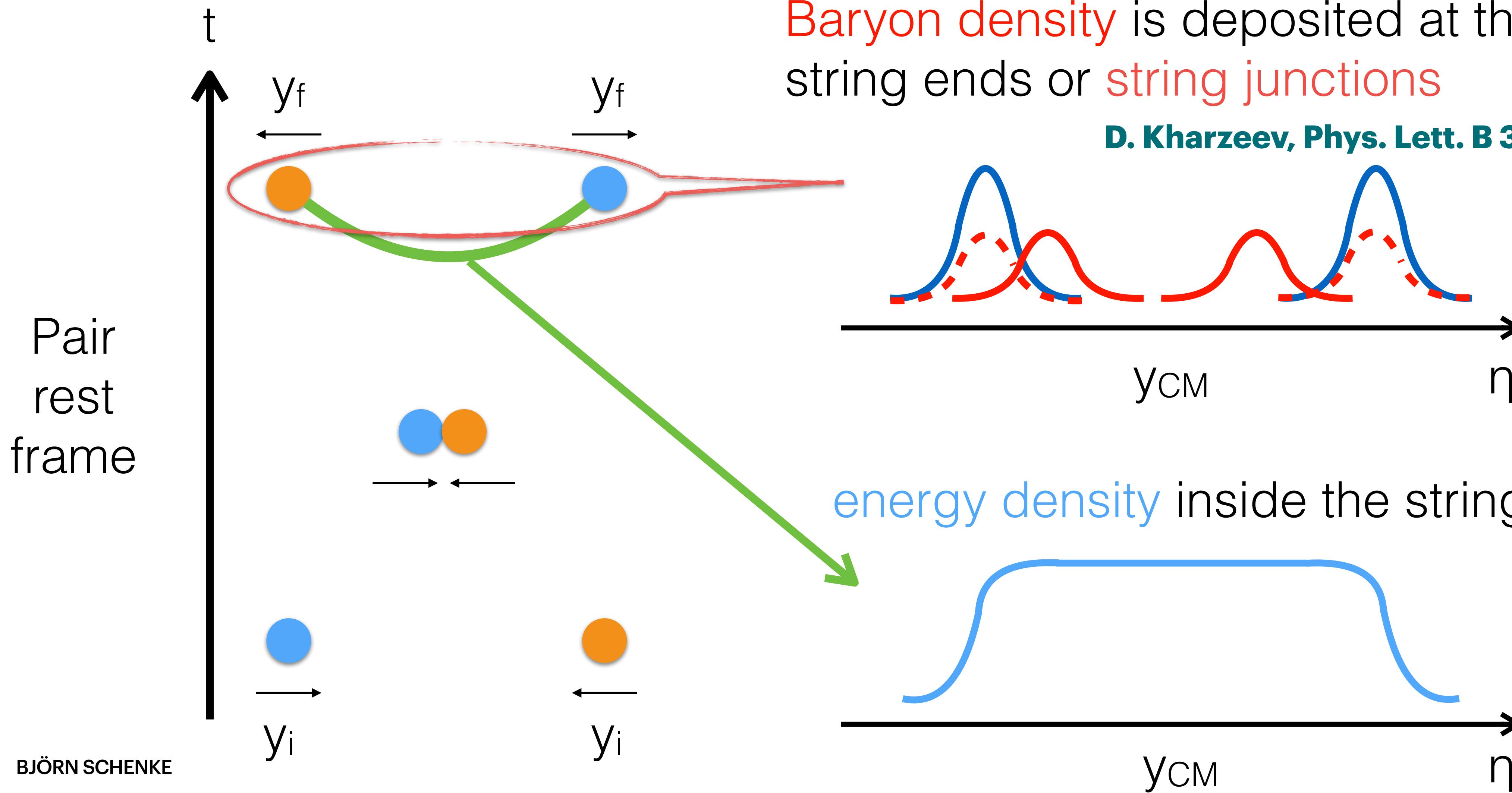
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C. Shen and B. Schenke, Phys. Rev. C 97 (2018) 024907; Phys. Rev. C 105, 064905 (2022)



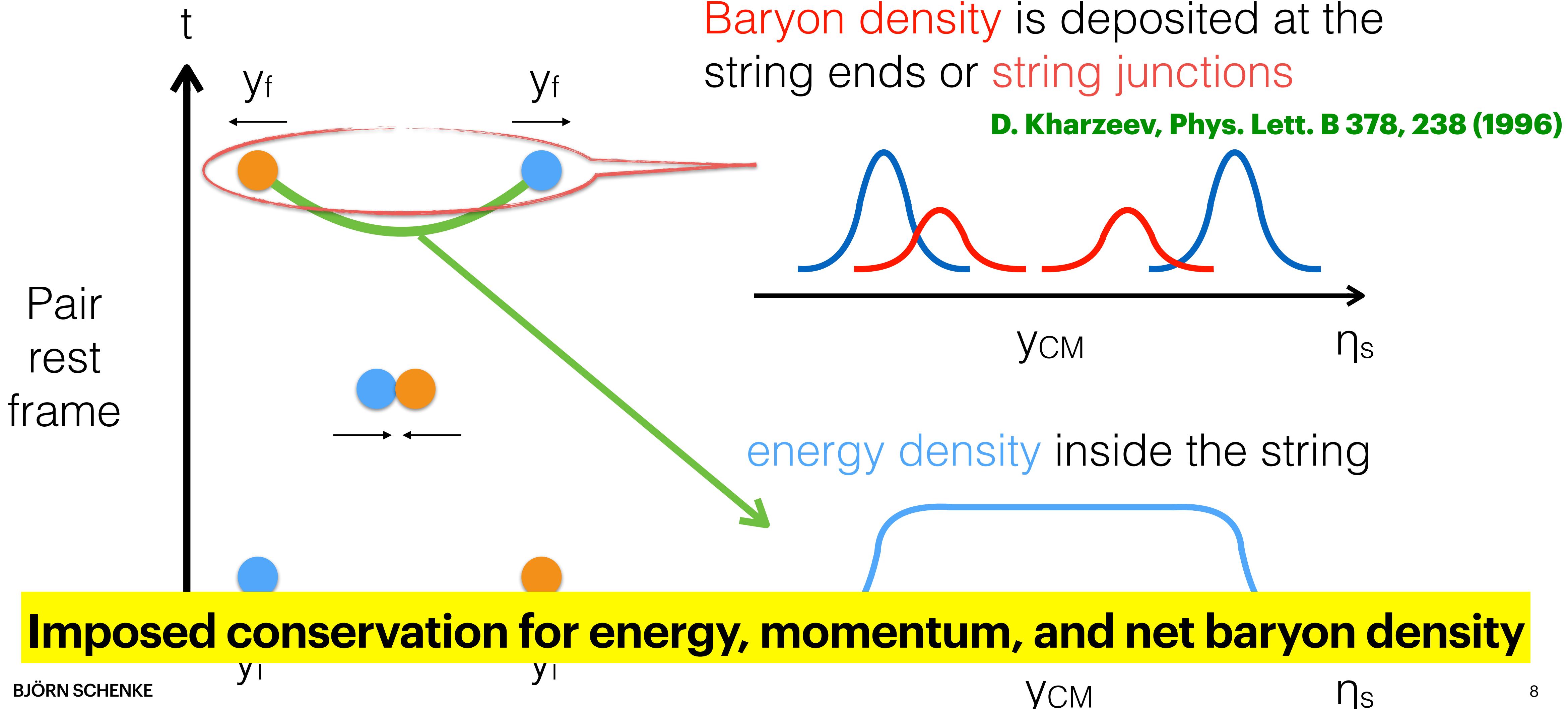
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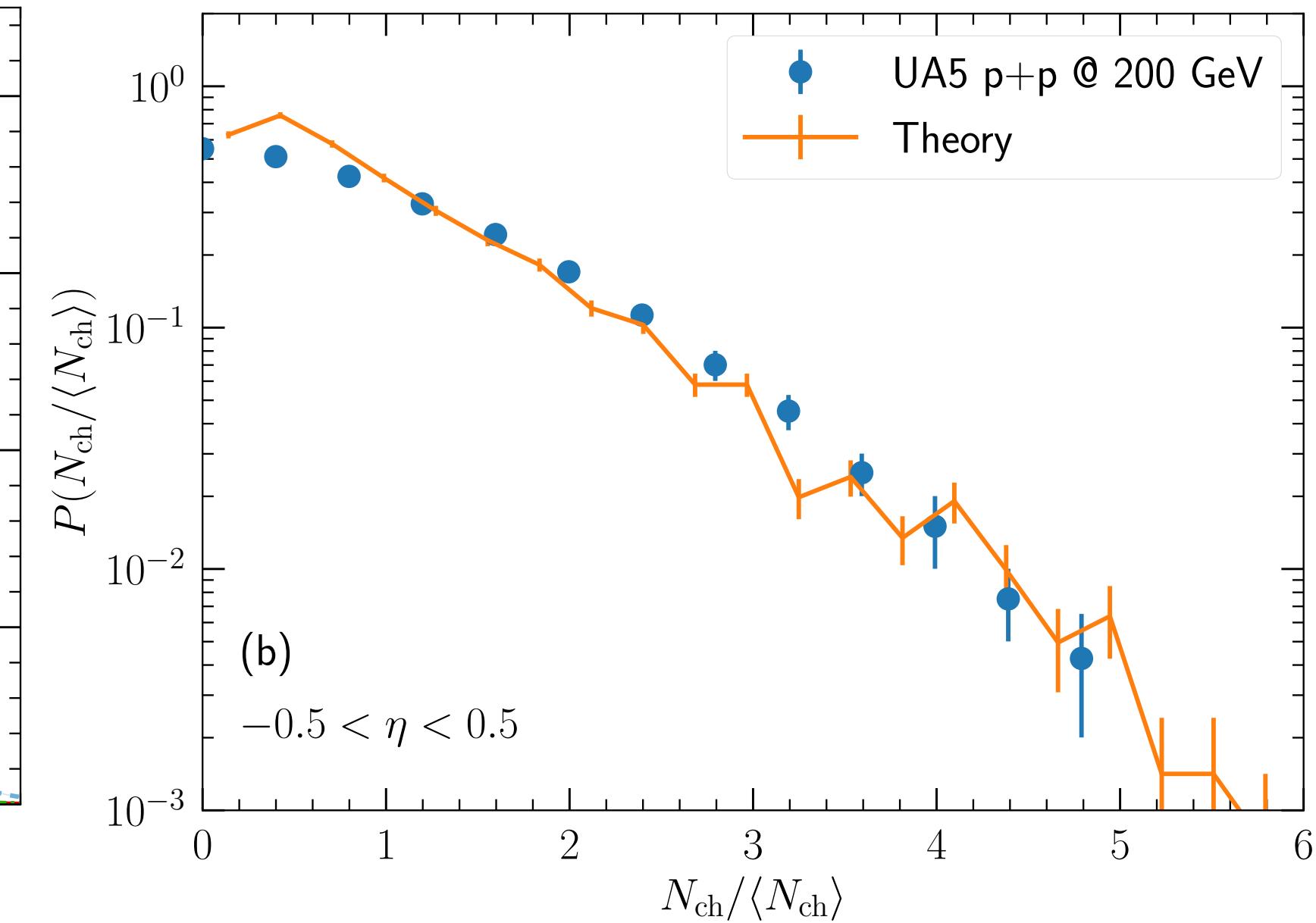
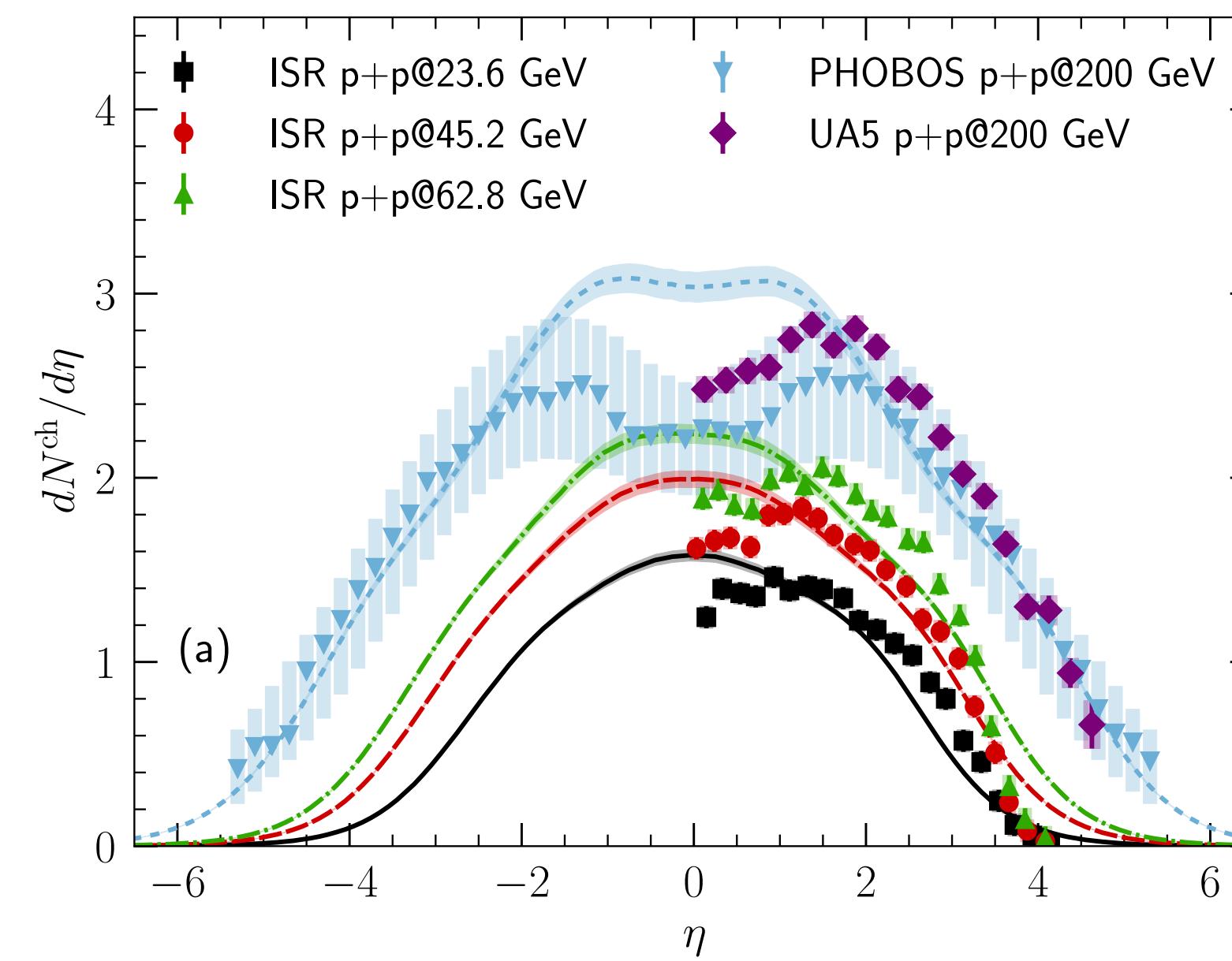
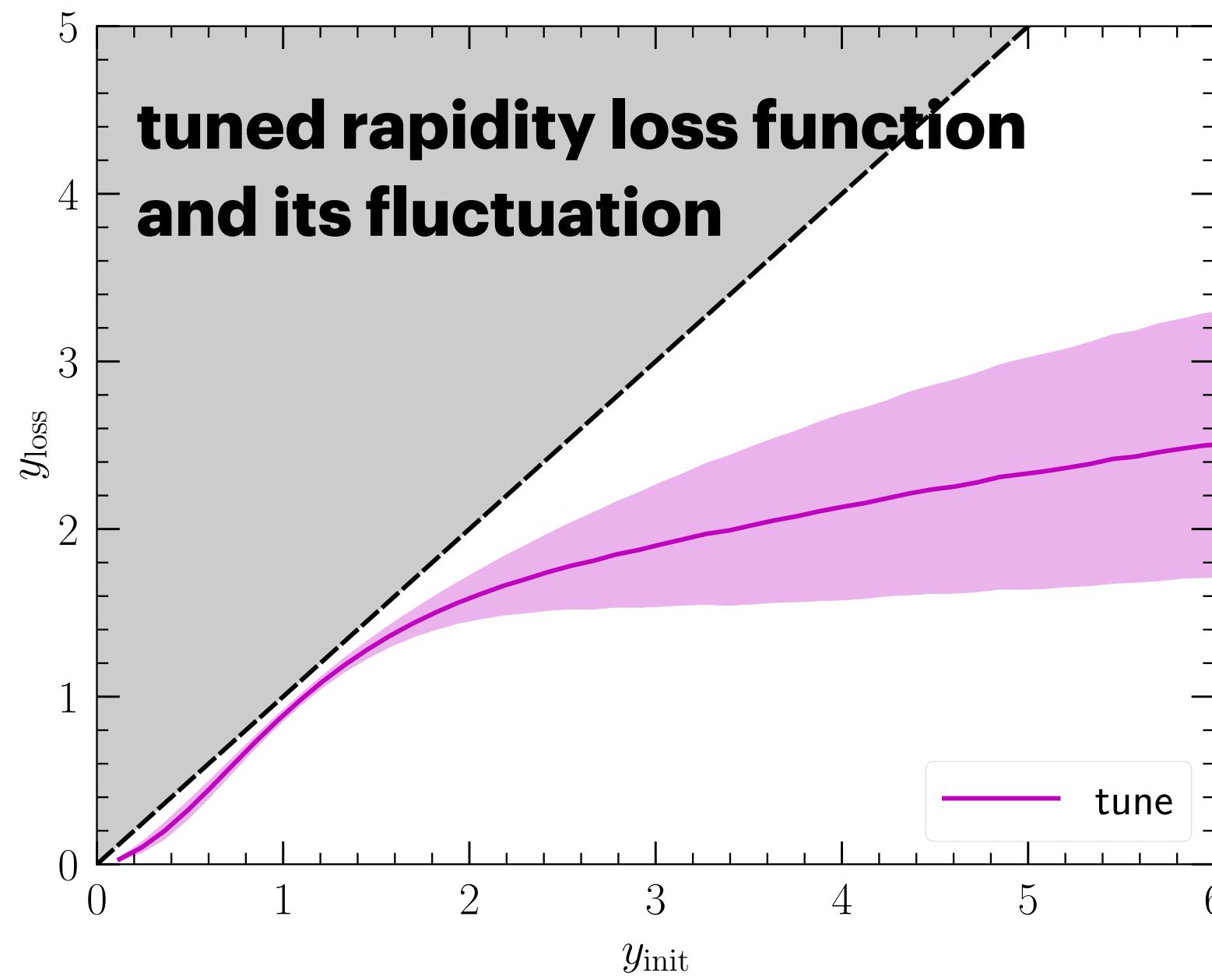
# 3D MC-GLAUBER + STRING MODEL

C. Shen and B. Schenke, Phys. Rev. C 97 (2018) 024907; Phys. Rev. C 105, 064905 (2022)



# CALIBRATION IN p+p COLLISIONS

C. Shen and B. Schenke, Phys. Rev. C 105, 064905 (2022)

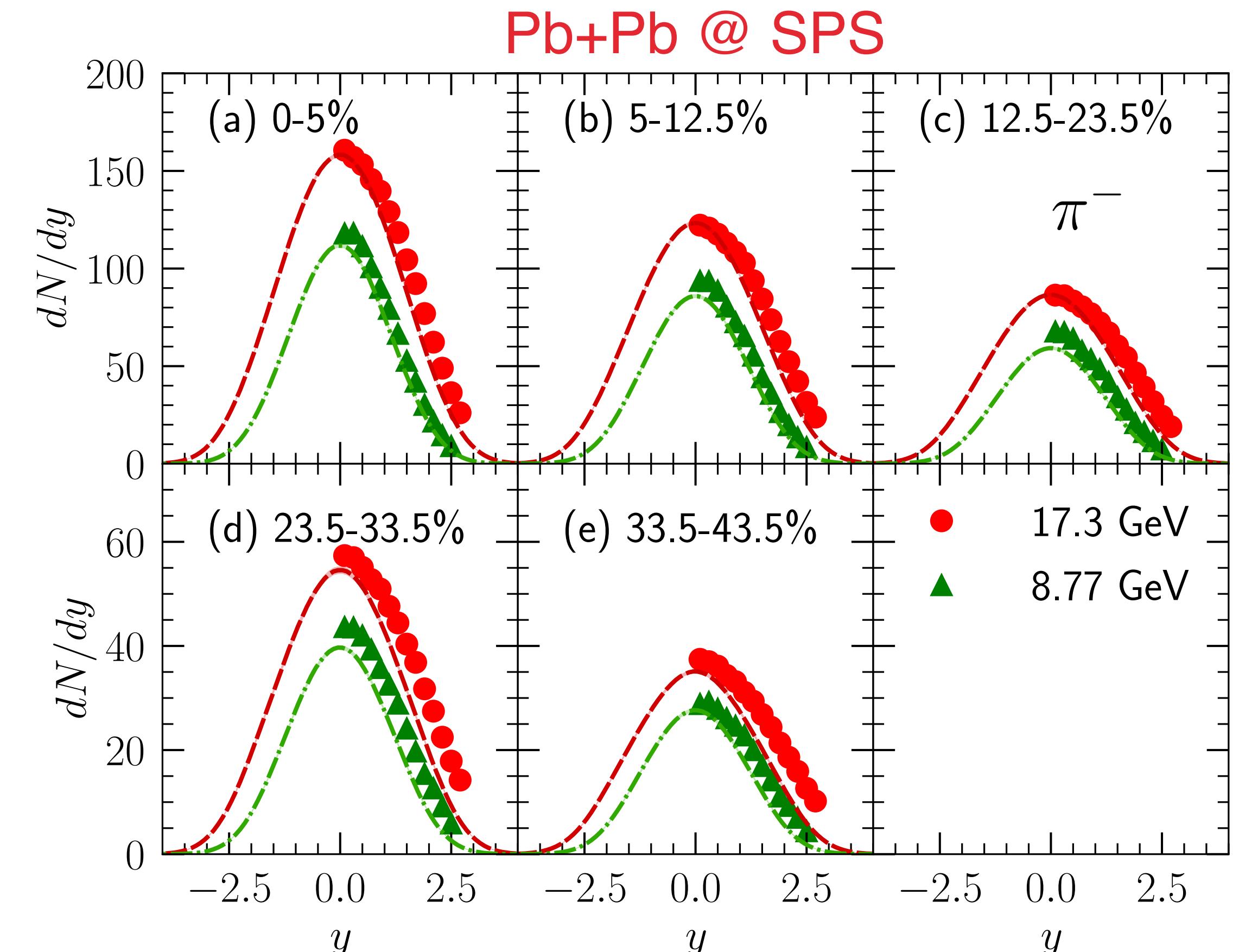
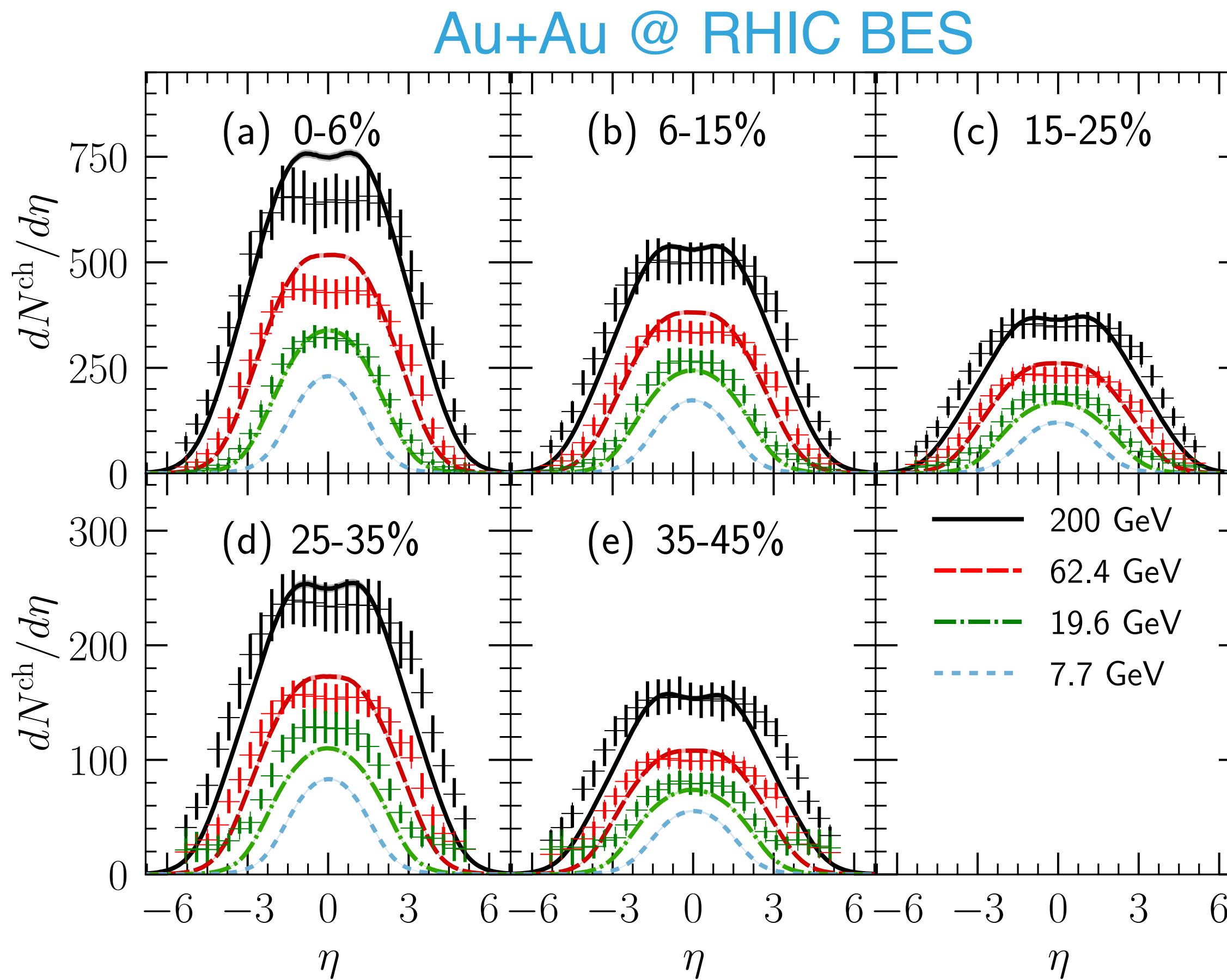


Calibrated with minimum bias p+p measurements at mid-rapidity  
and their multiplicity distributions

also see Chun Shen's talk

# COMPARISON TO A+A DATA

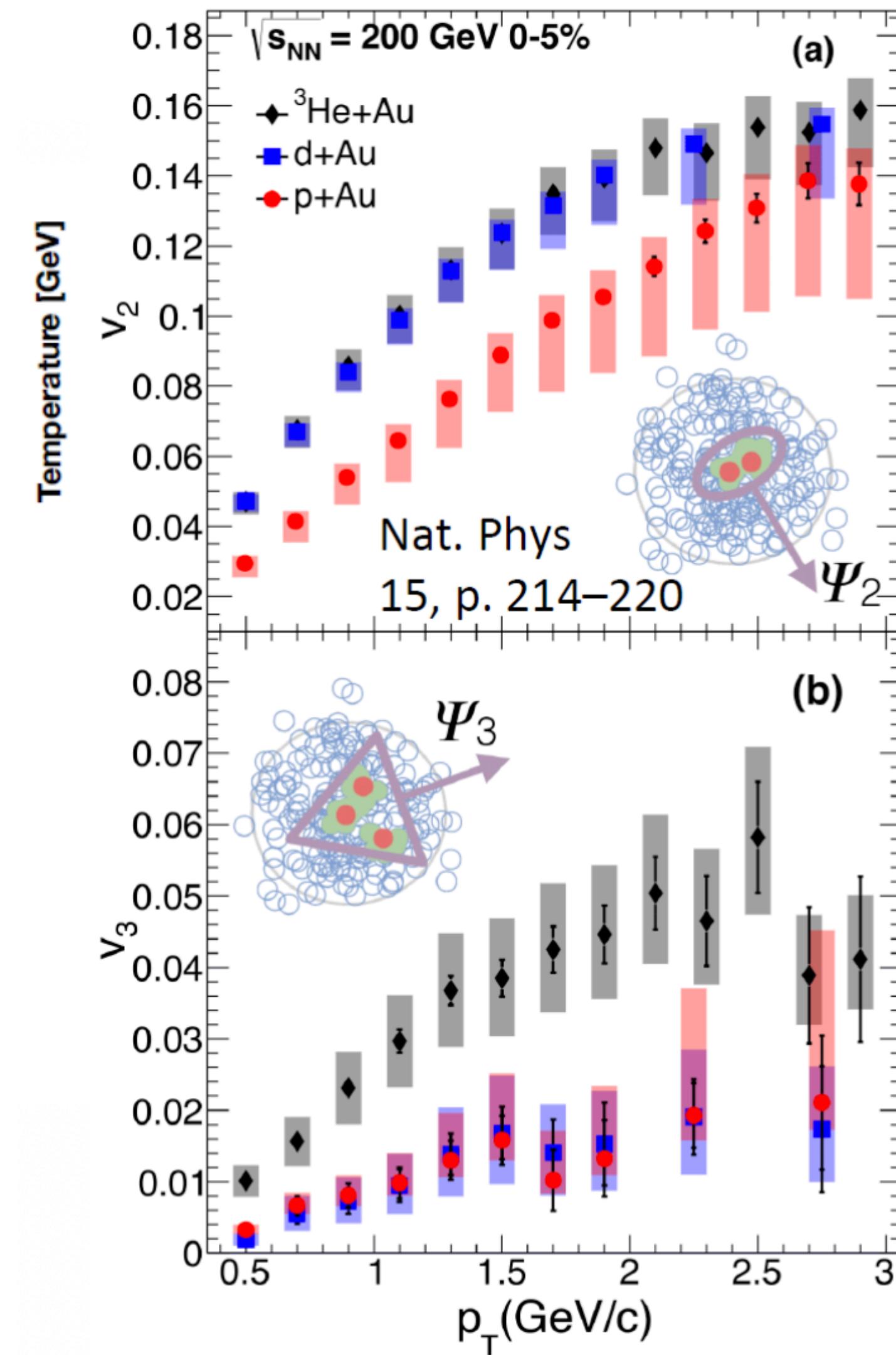
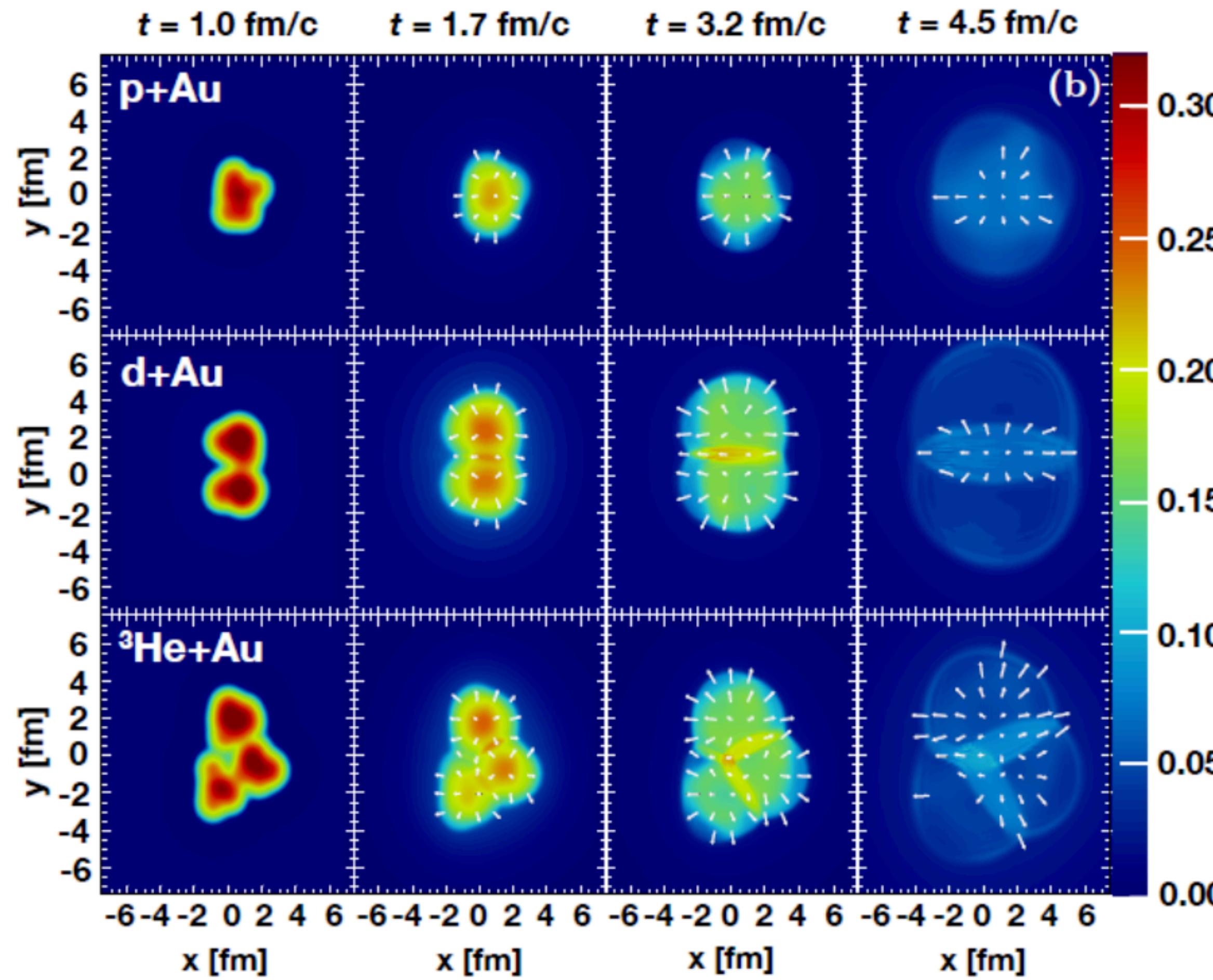
C. Shen and B. Schenke, Phys. Rev. C 105, 064905 (2022)



- Reasonable description of A+A experimental data

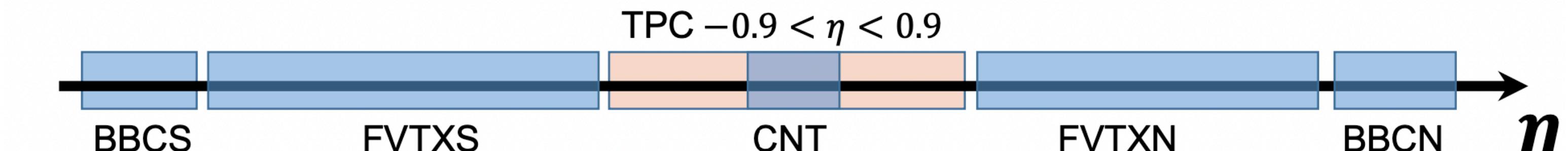
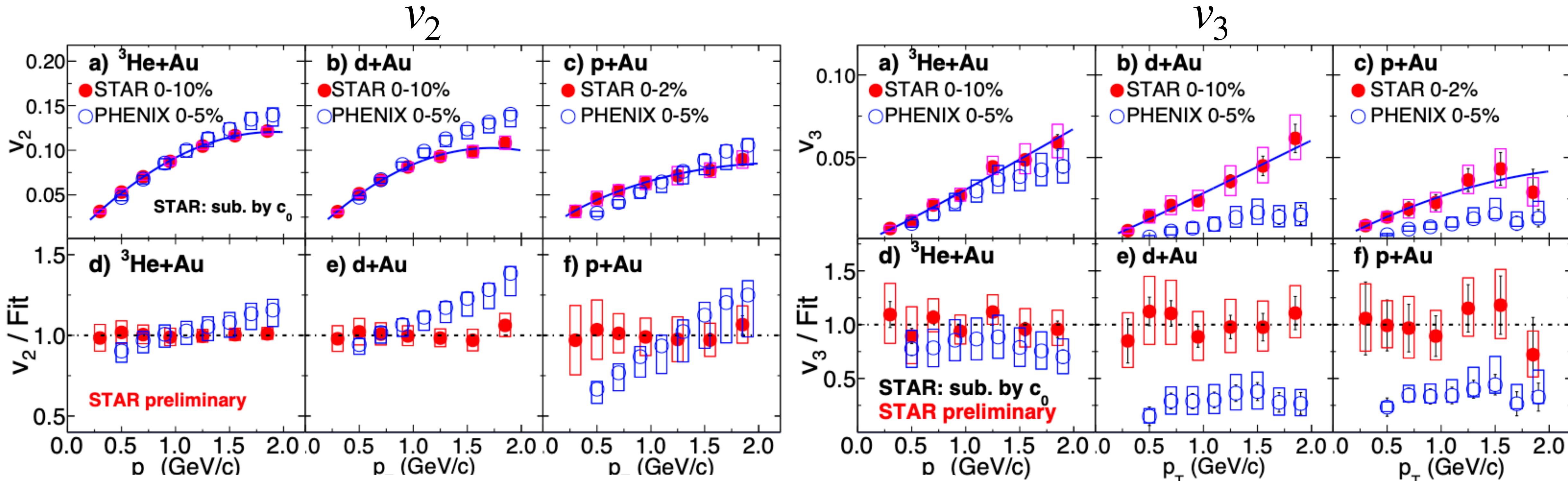
# SMALL SYSTEM SCAN AT RHIC

PHENIX Collaboration, Nature Phys. 15, no.3, 214-220 (2019)



# SMALL SYSTEM SCAN AT RHIC

STAR Collaboration, Phys.Rev.Lett. 130 (2023) 24, 242301

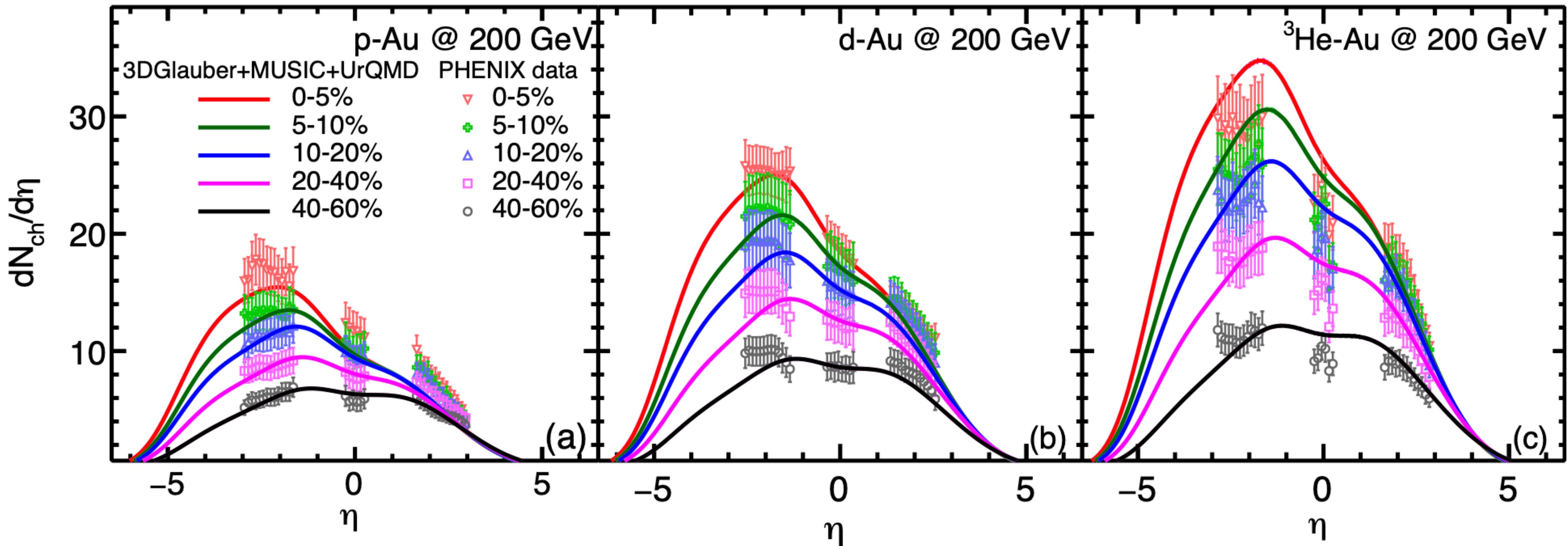


PHENIX: two-particle correlations between BBCS-CNT or FVTXS-CNT.  
STAR: TPC, ( $|\eta| < 0.9$  and  $|\Delta\eta| > 1.0$ )

(3+1)D simulations are essential to understand the difference between PHENIX and STAR measurements

# APPLYING OUR MODEL TO SMALL SYSTEMS

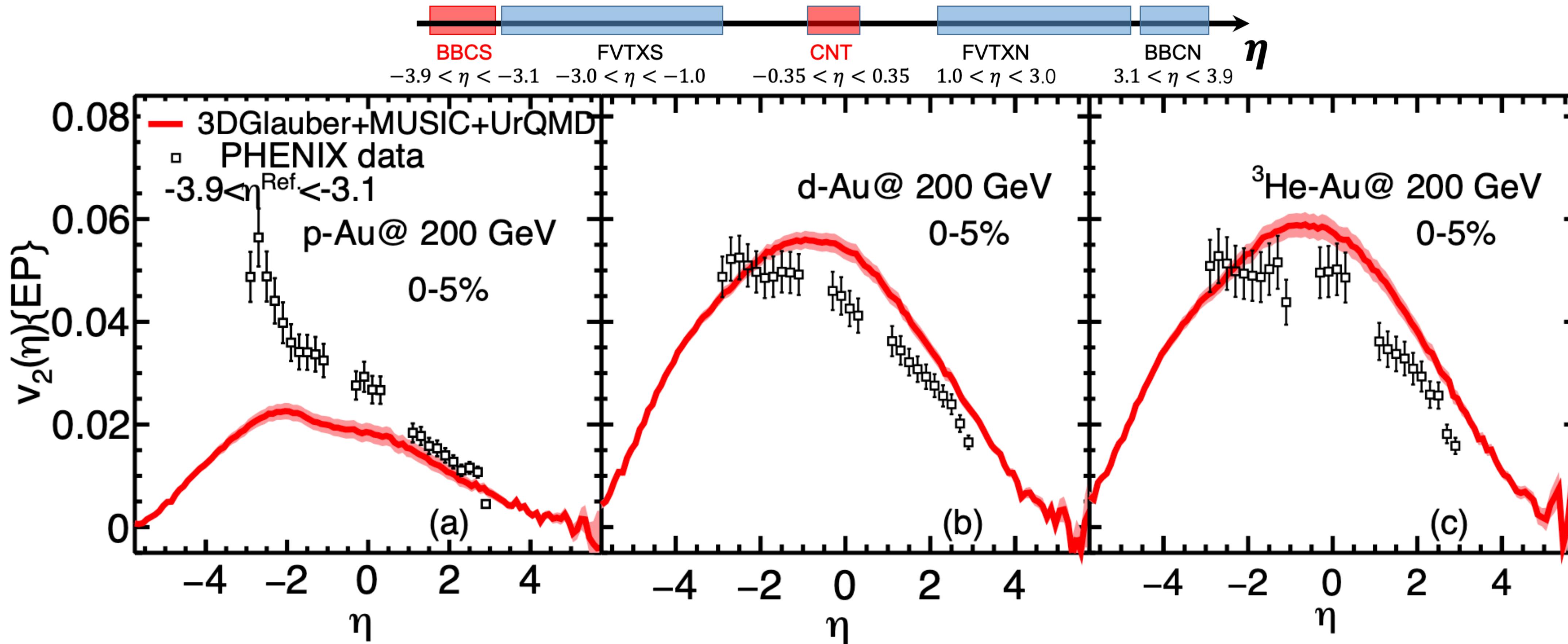
W. Zhao, S. Ryu, C. Shen and B. Schenke, Phys.Rev.C 107 (2023) 1, 014904



The (3+1)D hybrid model captures the rapidity and centrality dependence of  $dN_{ch}/d\eta$  for all asymmetric systems

# ANISOTROPIC FLOW VS RAPIDITY

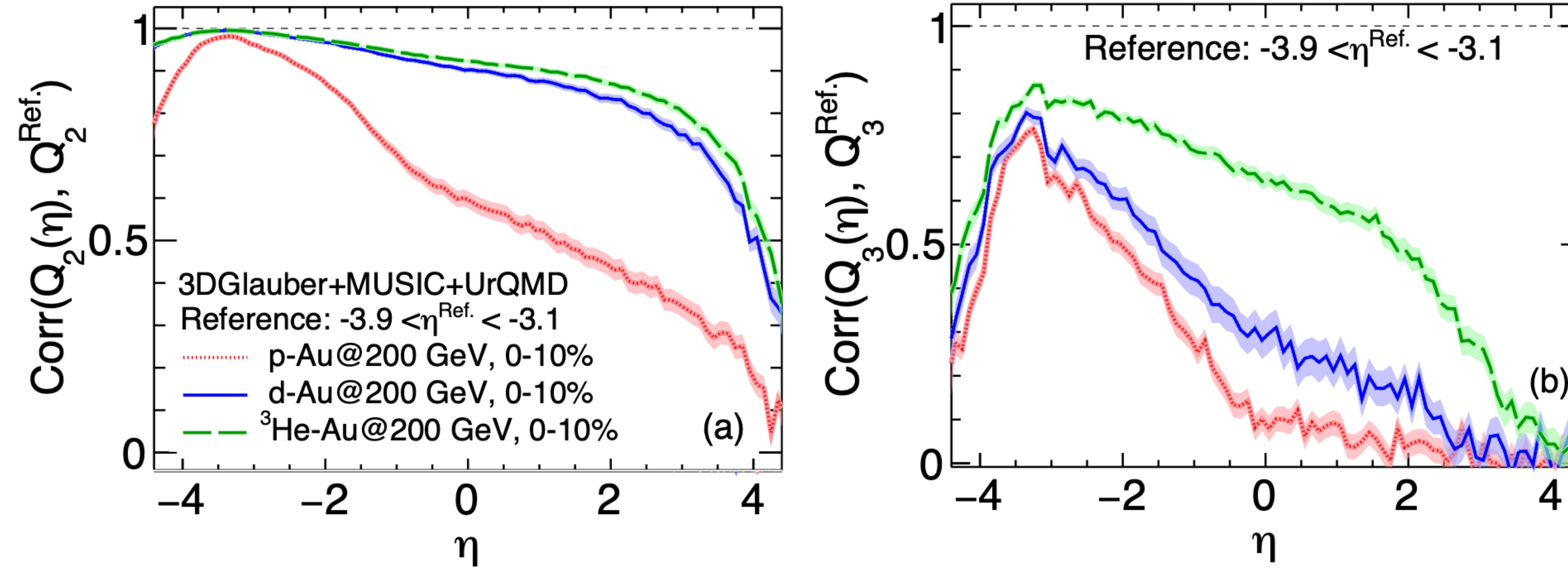
W. Zhao, S. Ryu, C. Shen and B. Schenke, Phys. Rev. C 107 (2023) 1, 014904



- Pseudo-rapidity dependence of  $v_2\{EP\}$  reproduced in d+Au and  $^3\text{He}+\text{Au}$
- The elliptic flow in  $\eta < 1$  in p+Au collisions is underestimated because of the strong longitudinal flow decorrelation in our model + potential non-flow

# FLOW VECTOR DECORRELATION

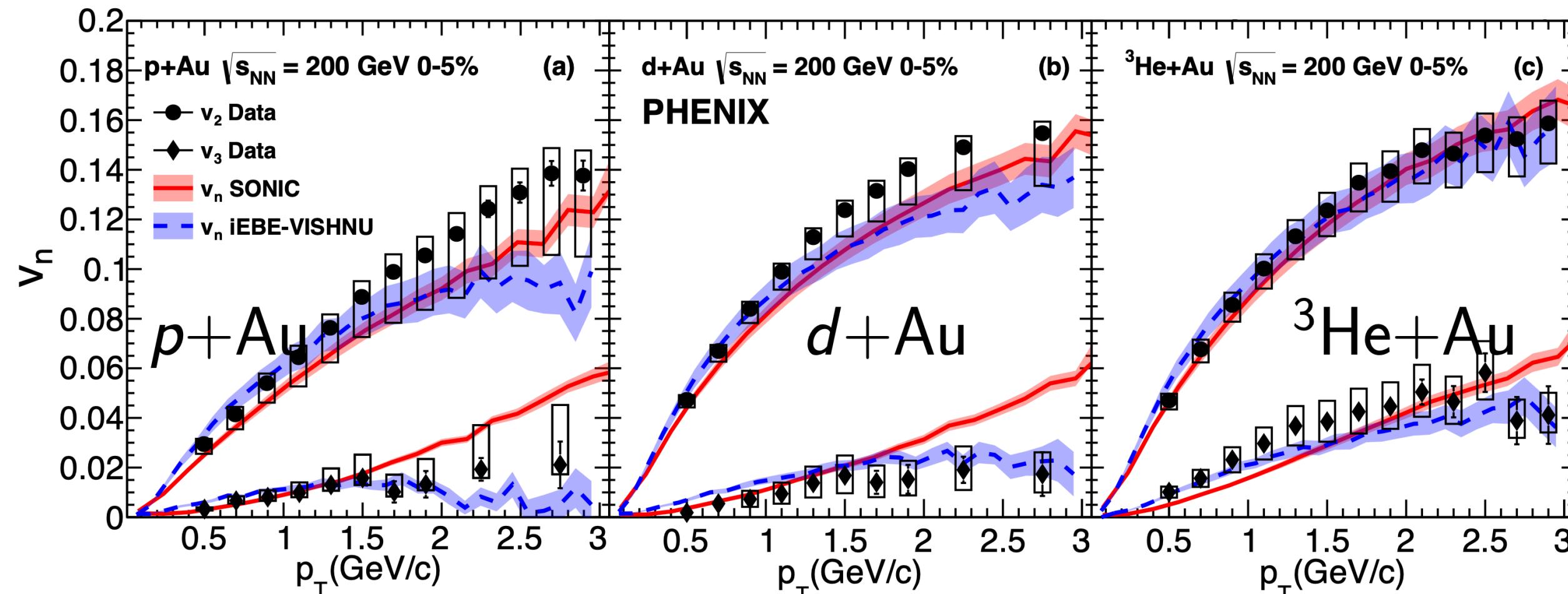
W. Zhao, S. Ryu, C. Shen and B. Schenke, Phys. Rev. C 107 (2023) 1, 014904



- Elliptic flow vectors in ( $d$ ,  ${}^3\text{He}$ )+Au are strongly correlated over wide range in  $\eta$
- Decorrelation is much stronger in the smaller p+Au system
- Decorrelations of  $v_3$  flow vectors are much stronger than  $v_2$ : Hierarchy between  $v_n$  driven by decorrelation in this model, not only the hierarchy of eccentricities

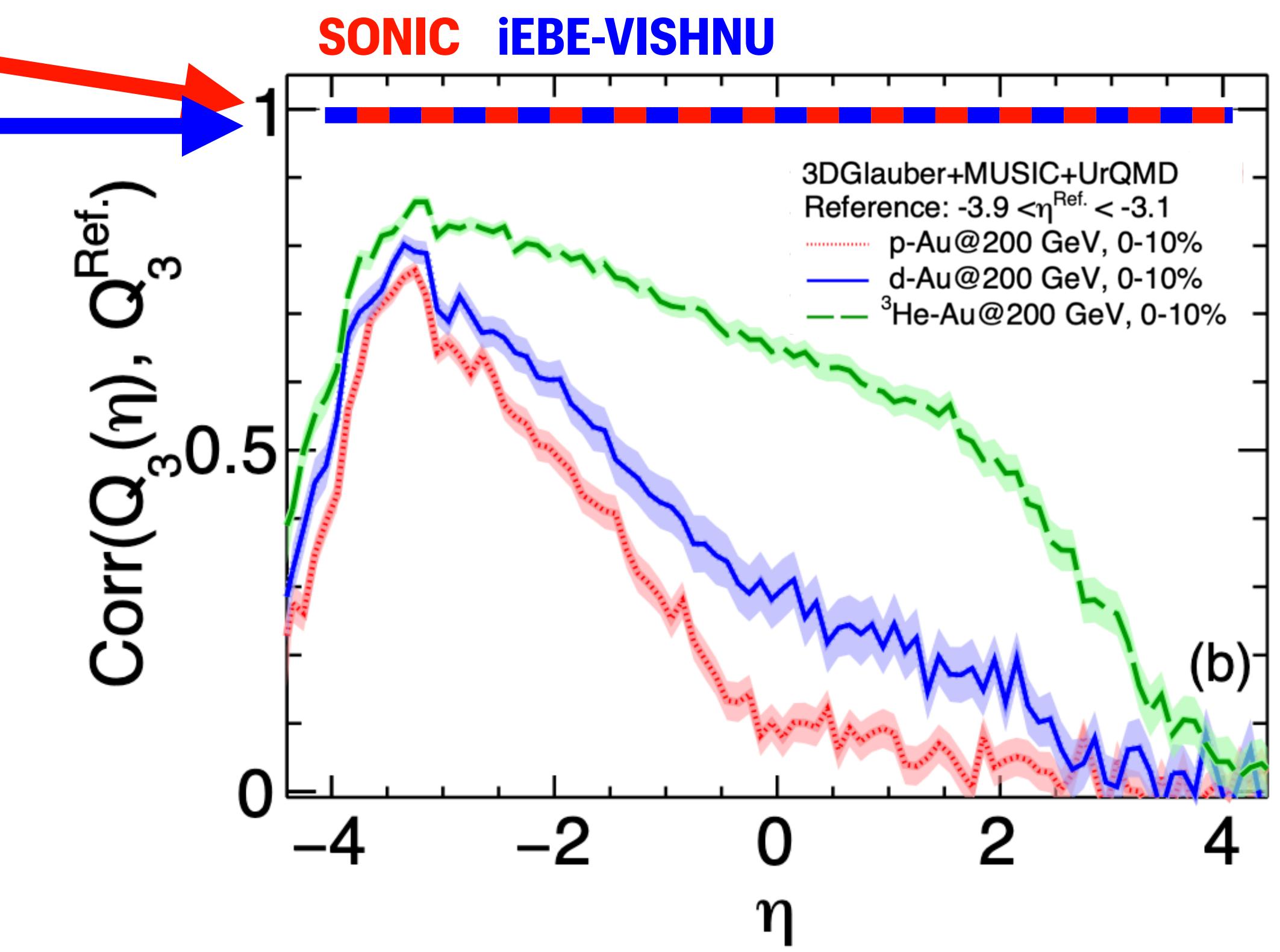
# BIG DEAL?

**W. Zhao, S. Ryu, C. Shen and B. Schenke, Phys.Rev.C 107 (2023) 1, 014904**



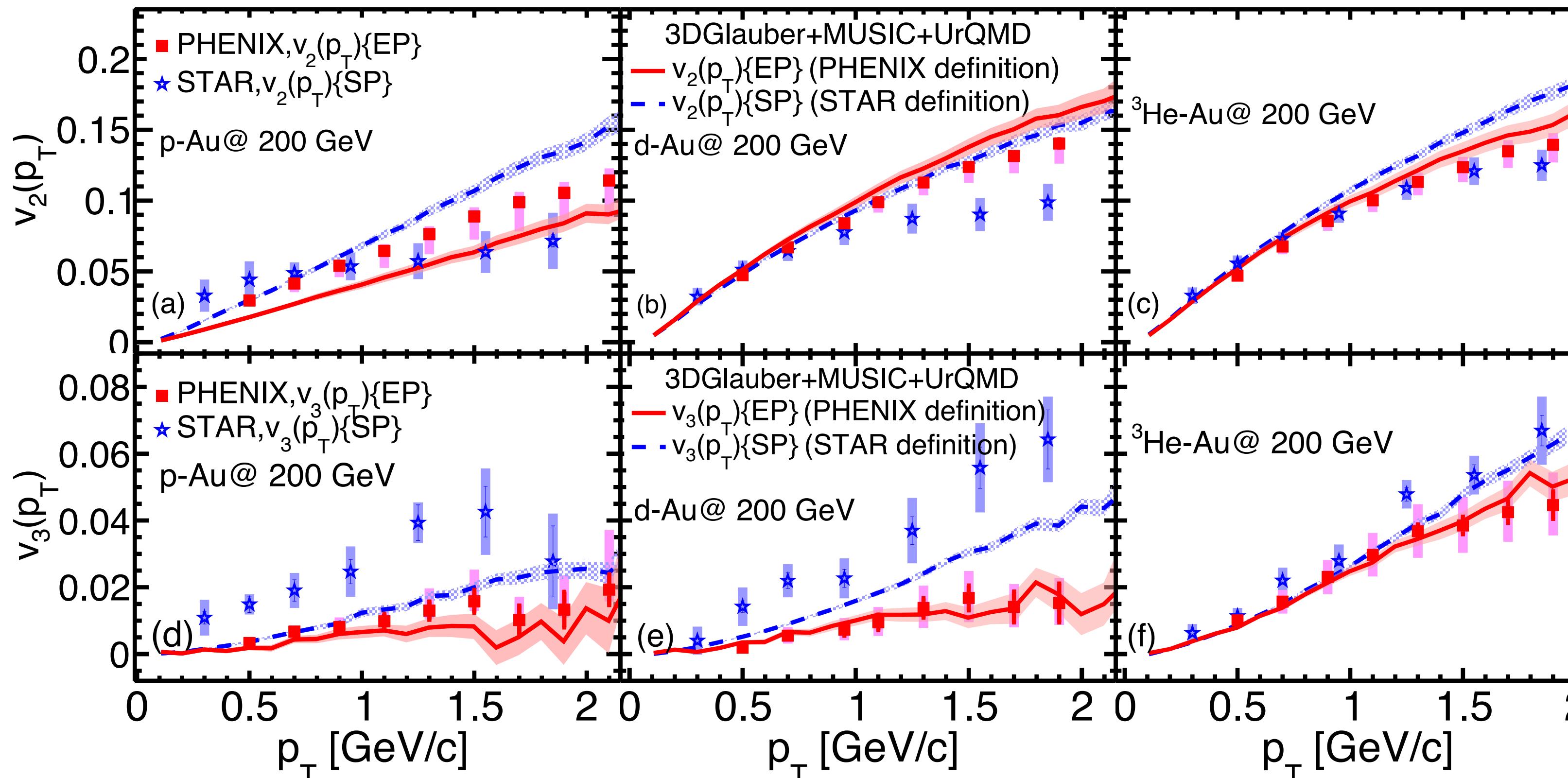
**PHENIX Collaboration, Nature Phys. 15, no.3, 214-220 (2019)**

- Meaningful comparison?
- Assuming boost invariance and ignoring decorrelation can cause errors of an order of magnitude
- Same problem for all boost invariant models



# DIFFERENT RAPIDITY BINS, DIFFERENT RESULTS

**W. Zhao, S. Ryu, C. Shen and B. Schenke, Phys.Rev.C 107 (2023) 1, 014904**



## PHENIX:

(p, d)+Au:  $\eta_1 \in [-3.9, -3.1]$ ,  
 $\eta_2 \in [-0.35, 0.35]$

${}^3\text{He}+\text{Au}$ :  $\eta_1 \in [-3, -1]$ ,  
 $\eta_2 \in [-0.35, 0.35]$

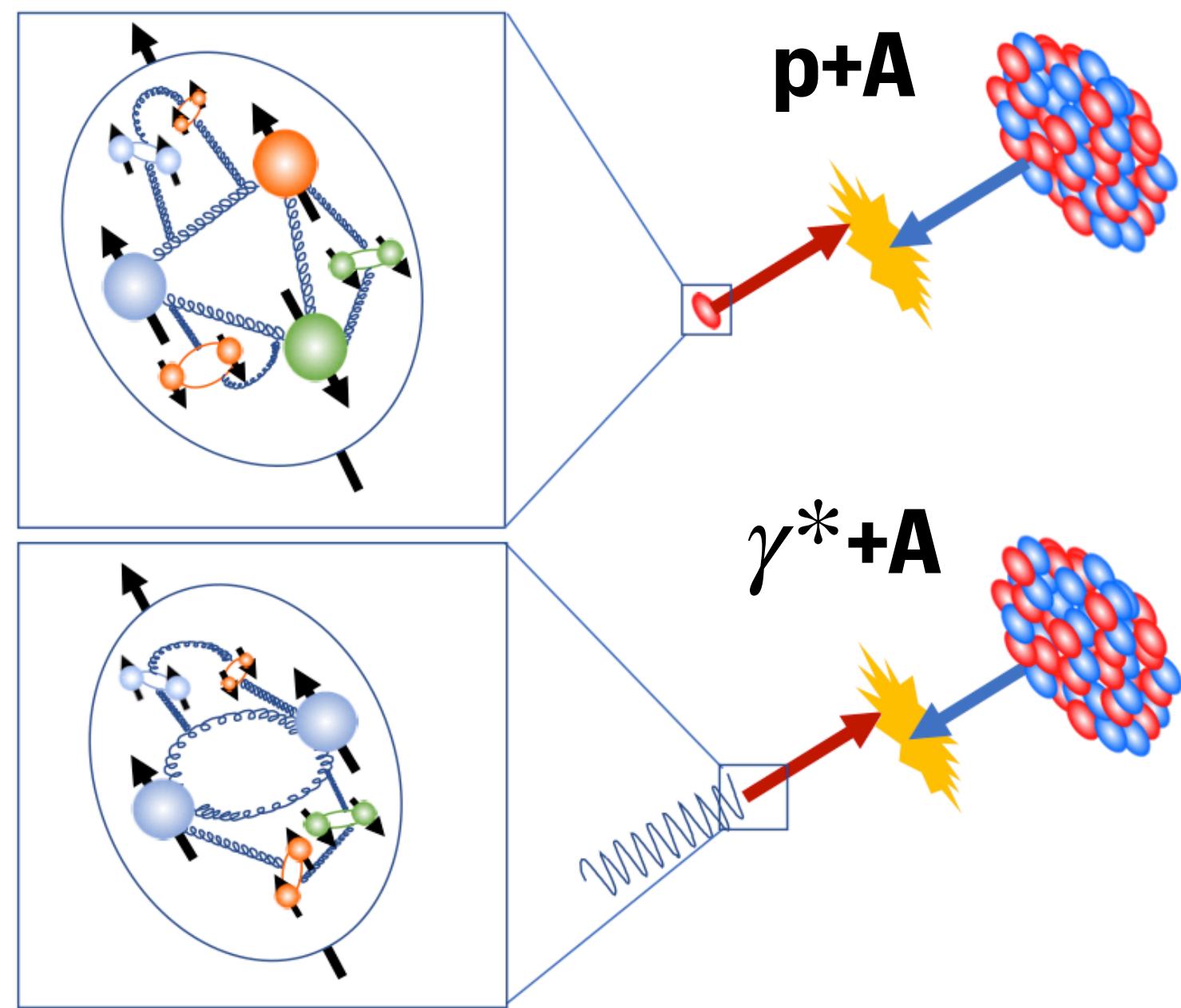
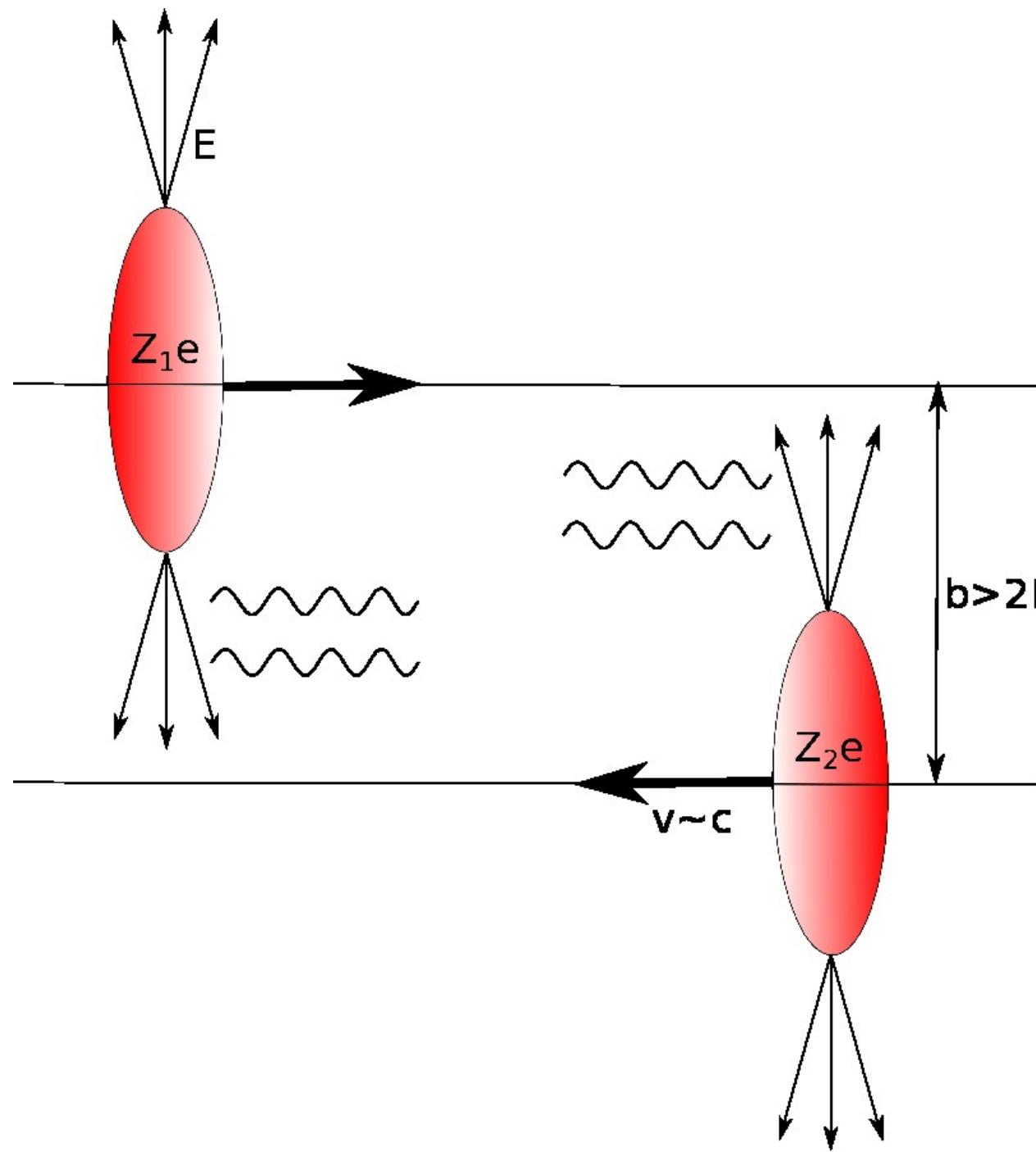
## STAR:

$\eta \in [-0.9, 0.9]$  with  $|\Delta\eta| > 1$

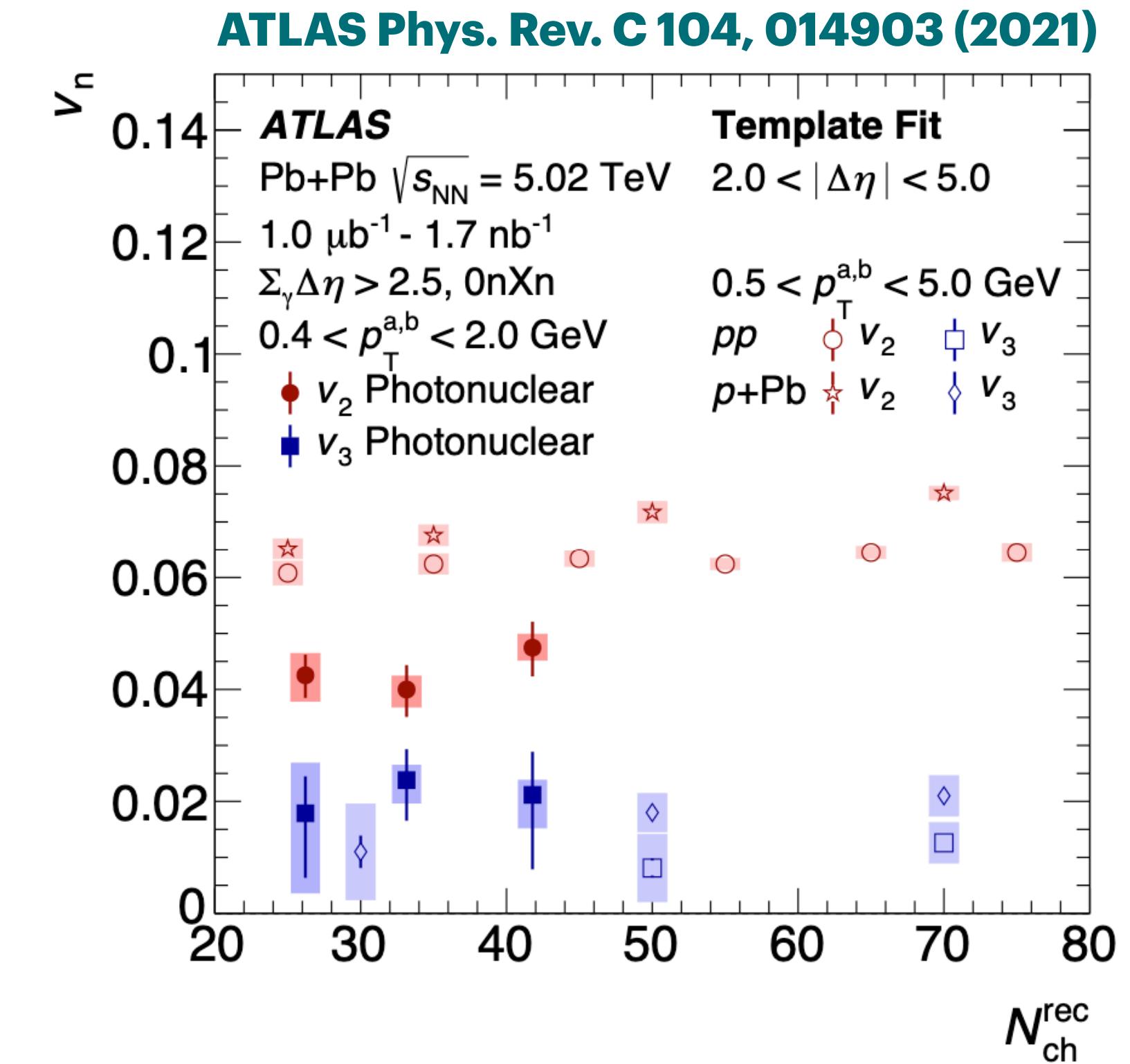
- Tune to  ${}^3\text{He}+\text{Au}$ ; PHENIX  $v_n(p_T)$  in (d,  ${}^3\text{He}$ )+Au collisions well described
- Longitudinal flow decorrelations lead to larger  $v_3(p_T)$  for STAR, explaining ~50% of the difference between the two measurements

# ULTRAPERIPHERAL COLLISIONS

W. Zhao, C. Shen and B. Schenke, Phys.Rev.Lett. 129 (2022) 25, 252302



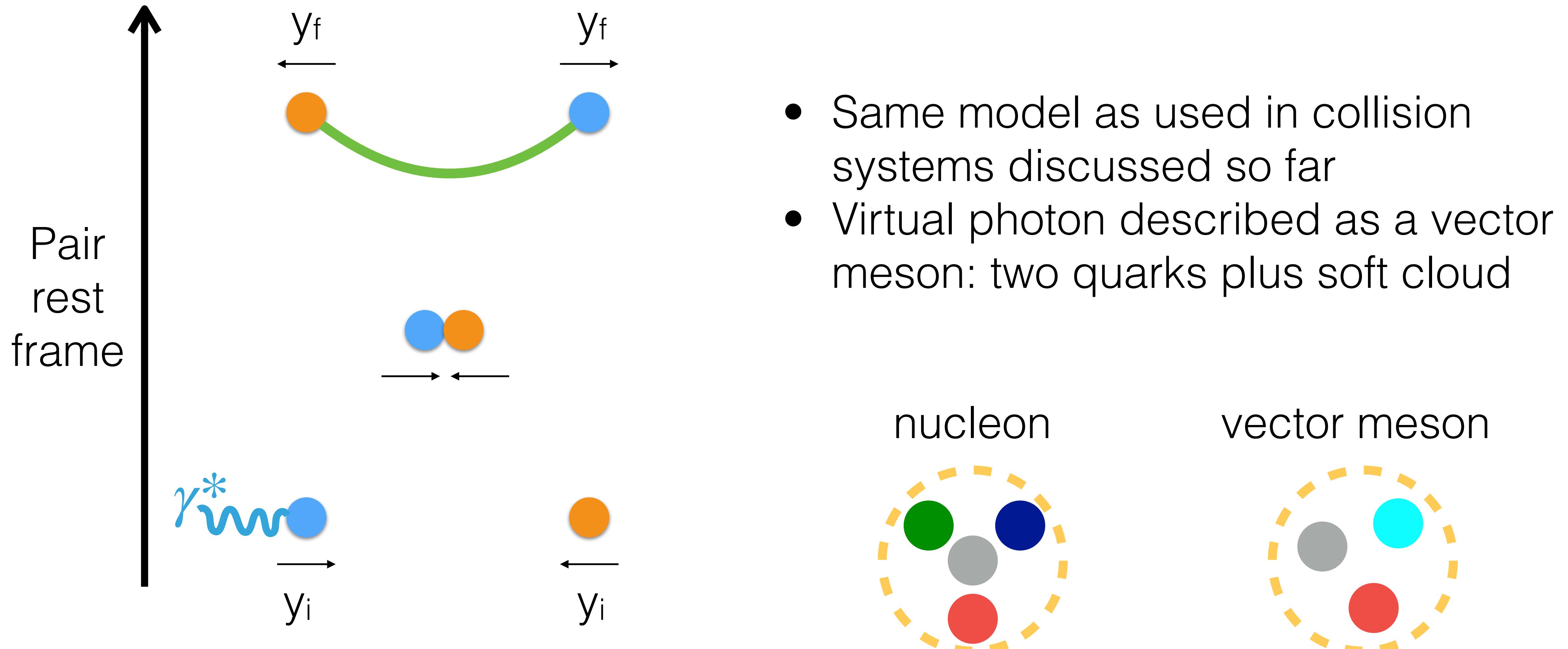
Phys. Rev. D 103, 054017 (2021)



- Long range two-particle correlations were observed in photo-nuclear processes in ultra-peripheral Pb+Pb collisions (UPC) at the LHC
- The magnitudes of  $v_n$  in UPCs are comparable with those in p+Pb collisions

# INITIAL STATE FOR $\gamma^* + \text{Pb}$

W. Zhao, C. Shen and B. Schenke, Phys.Rev.Lett. 129 (2022) 25, 252302



# COLLISION KINMATICS FOR $\gamma^* + \text{Pb}$

**A. J. Baltz et al.** Phys. Rept. 458, 1-171 (2008); **W. Zhao, C. Shen and B. Schenke**, Phys. Rev. Lett. 129 (2022) 25, 252302

- Energy of the incoming quasi-real photon fluctuates event by event:

$$\frac{dN^\gamma}{dk_\gamma} = \frac{2Z^2\alpha}{\pi k_\gamma} \left[ w_R^{AA} K_0(w_R^{AA}) K_1(w_R^{AA}) - \frac{(w_R^{AA})^2}{2} (K_1^2(w_R^{AA}) - K_0^2(w_R^{AA})) \right]$$

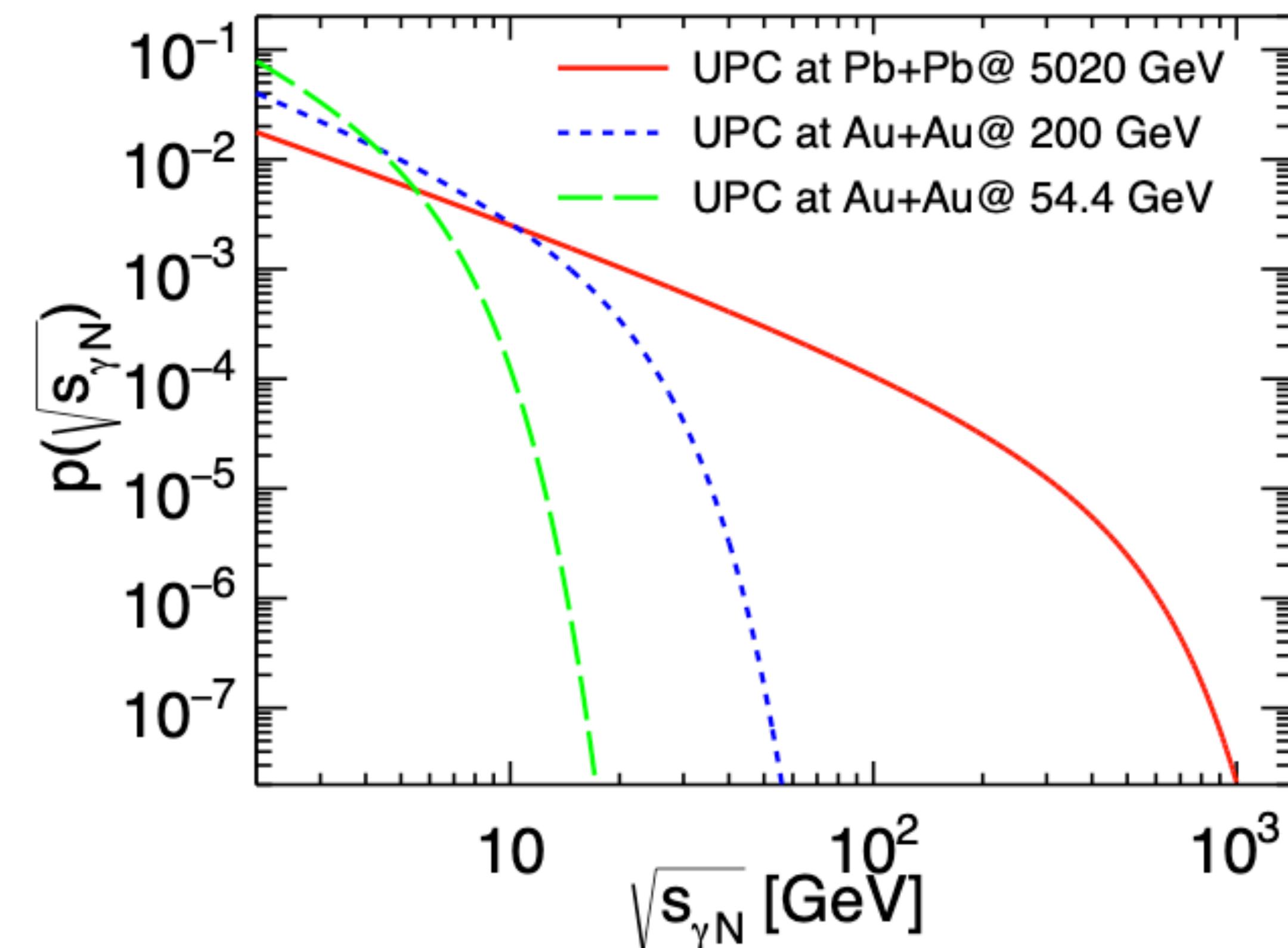
$$w_R^{AA} = 2k_\gamma R_A / \gamma_L \quad \text{with} \quad \gamma_L = \sqrt{s_{\text{NN}}} / (2m_N)$$

- Center of mass collision energy for the  $\gamma^* + A$  system fluctuates

$$\sqrt{s_{\gamma N}} = (2k_\gamma \sqrt{s_{\text{NN}}})^{1/2}$$

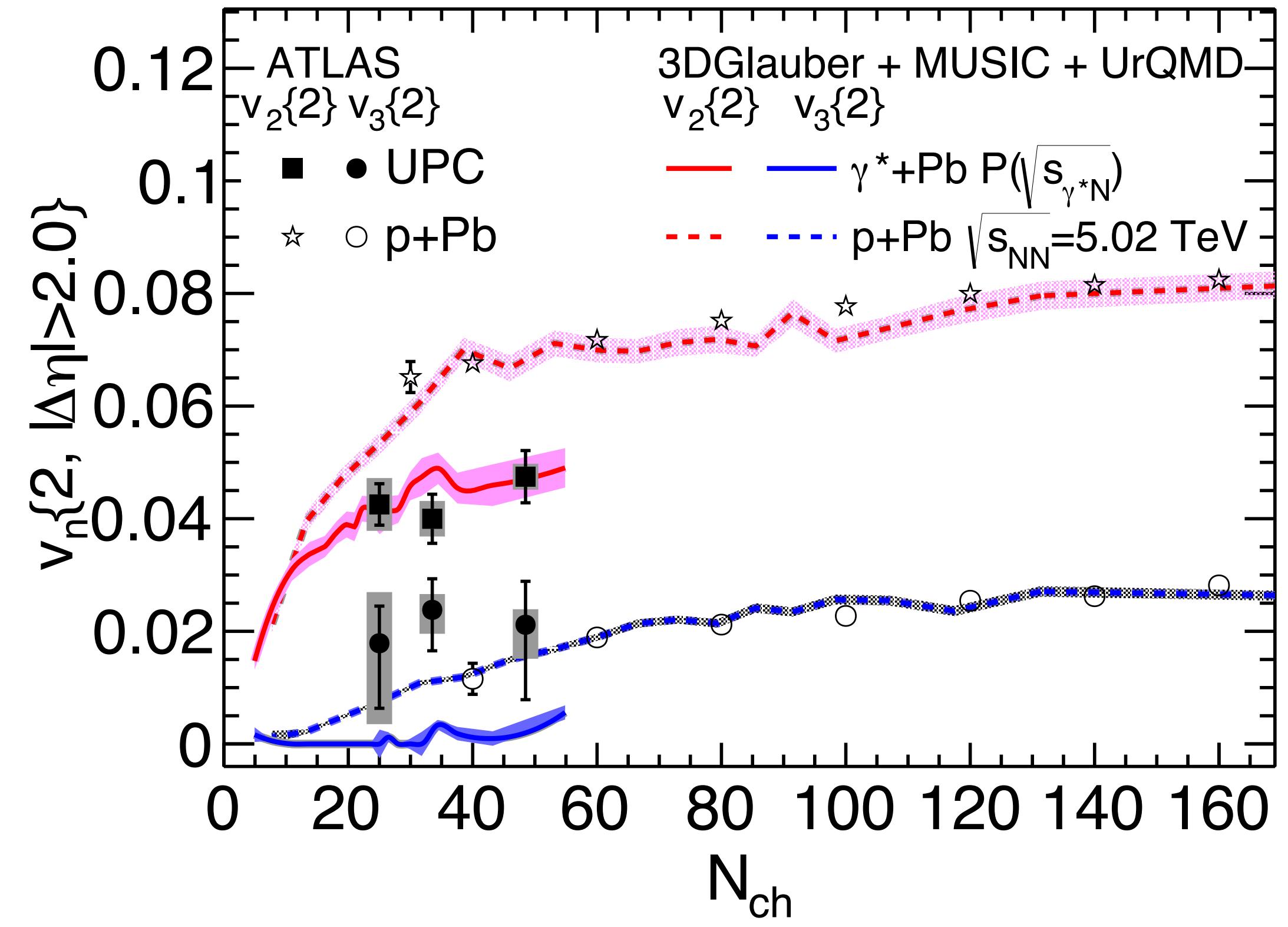
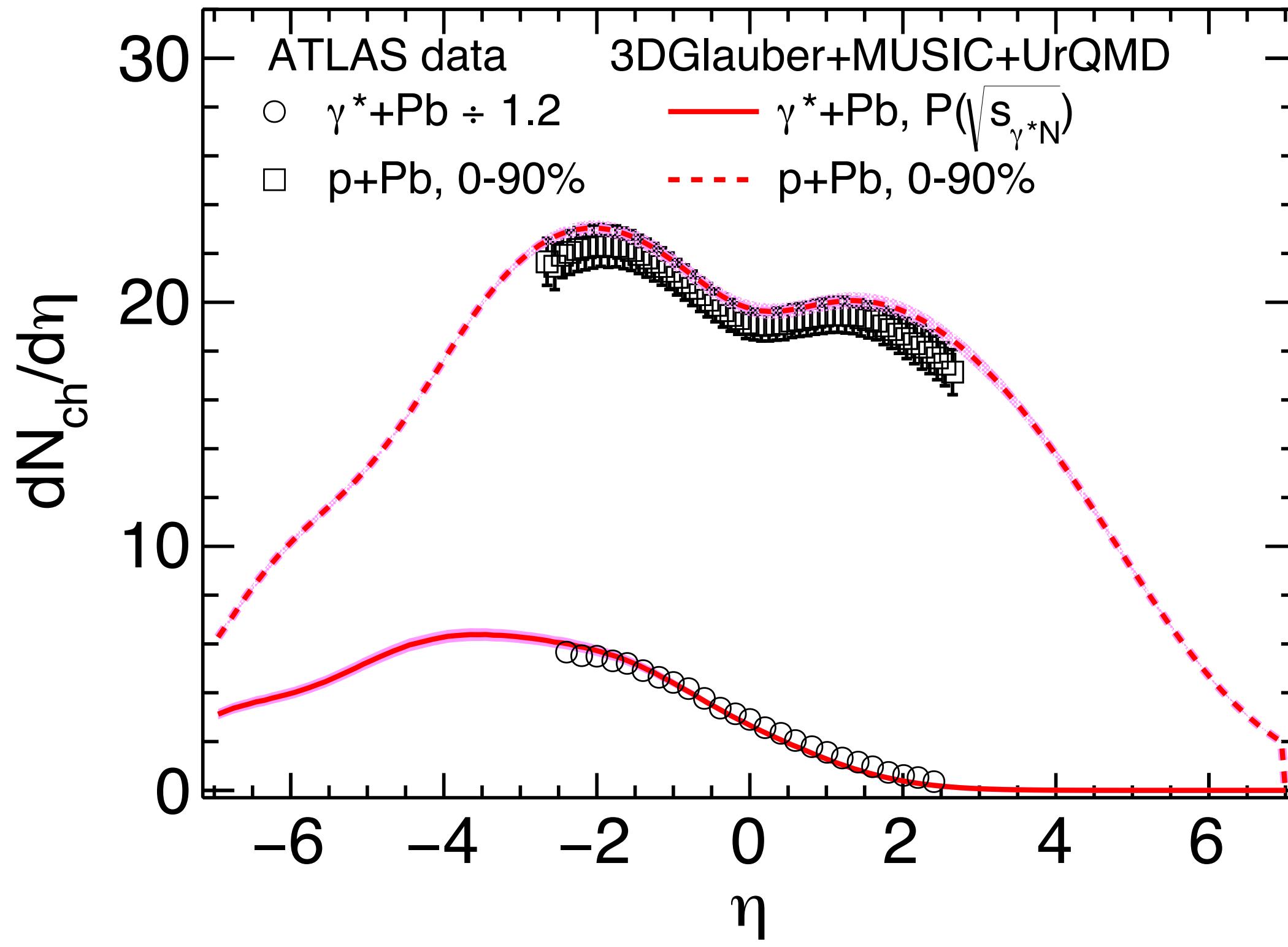
- Center of mass rapidity of  $\gamma^* + A$  collision fluctuates in the lab frame

$$\Delta y = y_{\text{beam}}(\sqrt{s_{\gamma N}}) - y_{\text{beam}}(\sqrt{s_{\text{NN}}})$$



# PARTICLE PRODUCTION AND FLOW IN p+A AND $\gamma^*+A$

W. Zhao, C. Shen and B. Schenke, Phys.Rev.Lett. 129 (2022) 25, 252302

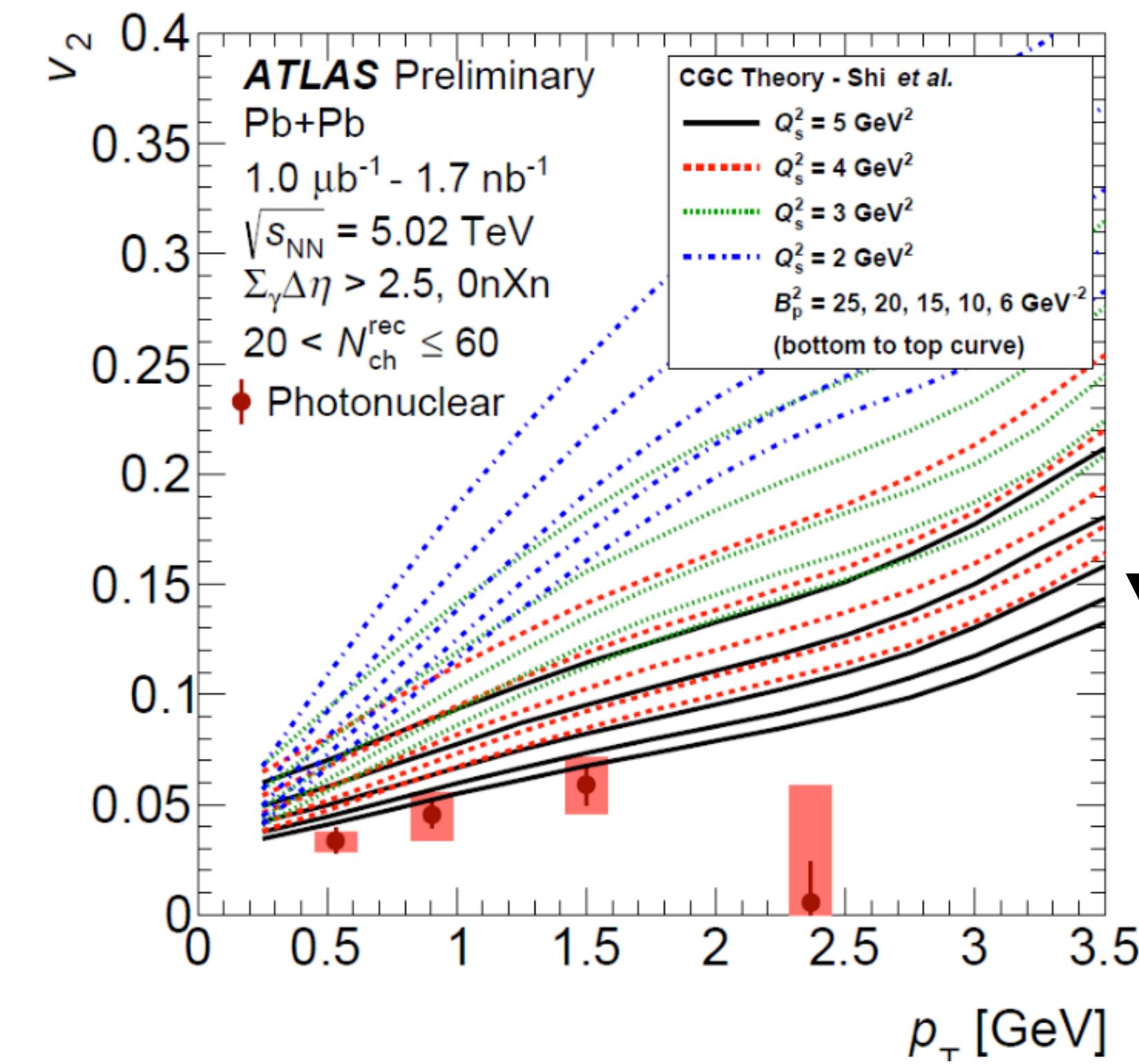
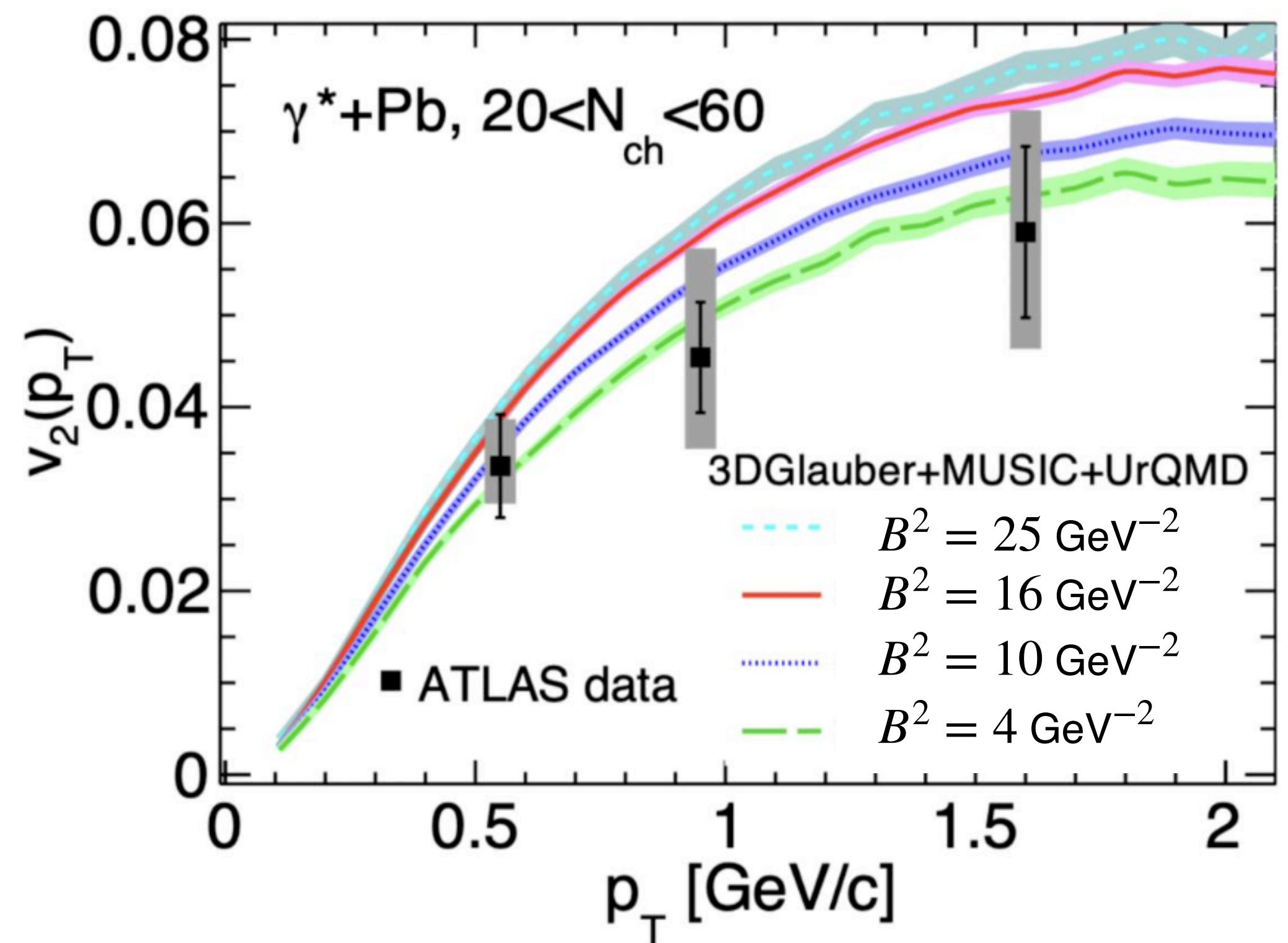


- Shapes of  $dN_{ch}/d\eta$  reproduced for  $p+Pb$  and  $\gamma^*+Pb$  collisions
- Elliptic flow difference between  $p+Pb$  and  $\gamma^*+Pb$  collisions reproduced - driven by different amount of longitudinal flow decorrelation

# DISTINGUISH MODELS IN e+A COLLISIONS AT EIC

W. Zhao, C. Shen and B. Schenke, Phys. Rev. Lett. 129 (2022) 25, 252302

Y. Shi, L. Wang, S. Y. Wei, B. W. Xiao and L. Zheng, Phys. Rev. D 103, 054017 (2021)

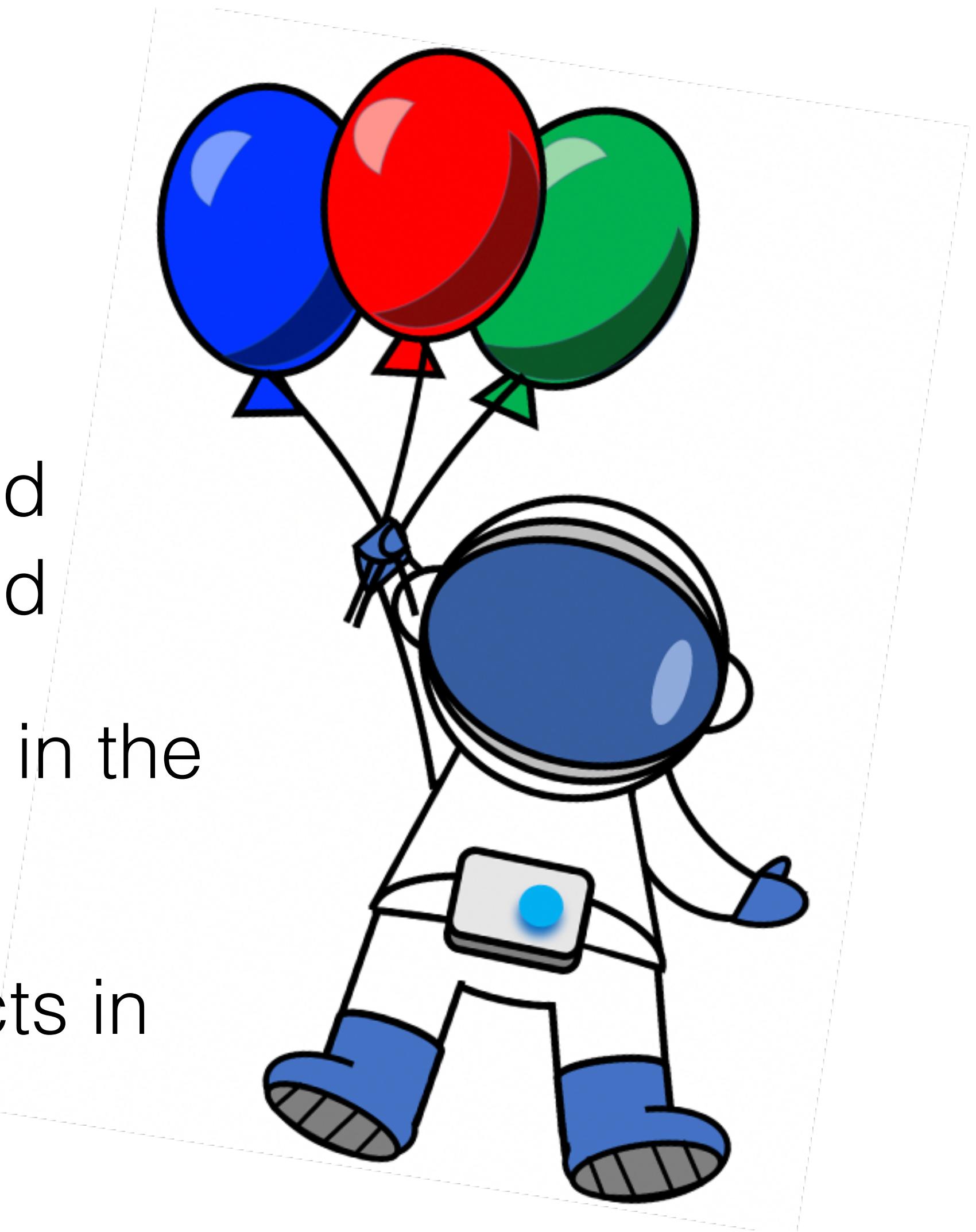


increasing  
transverse size  
 $\propto B^2$

- Hydro: Larger  $B^2$  means larger transverse area for geometry to fluctuate  $v_2 \propto B^2$
- CGC: Larger  $B^2$  leads to a larger number of independent domains  $v_2 \propto 1/B^2$

# SUMMARY

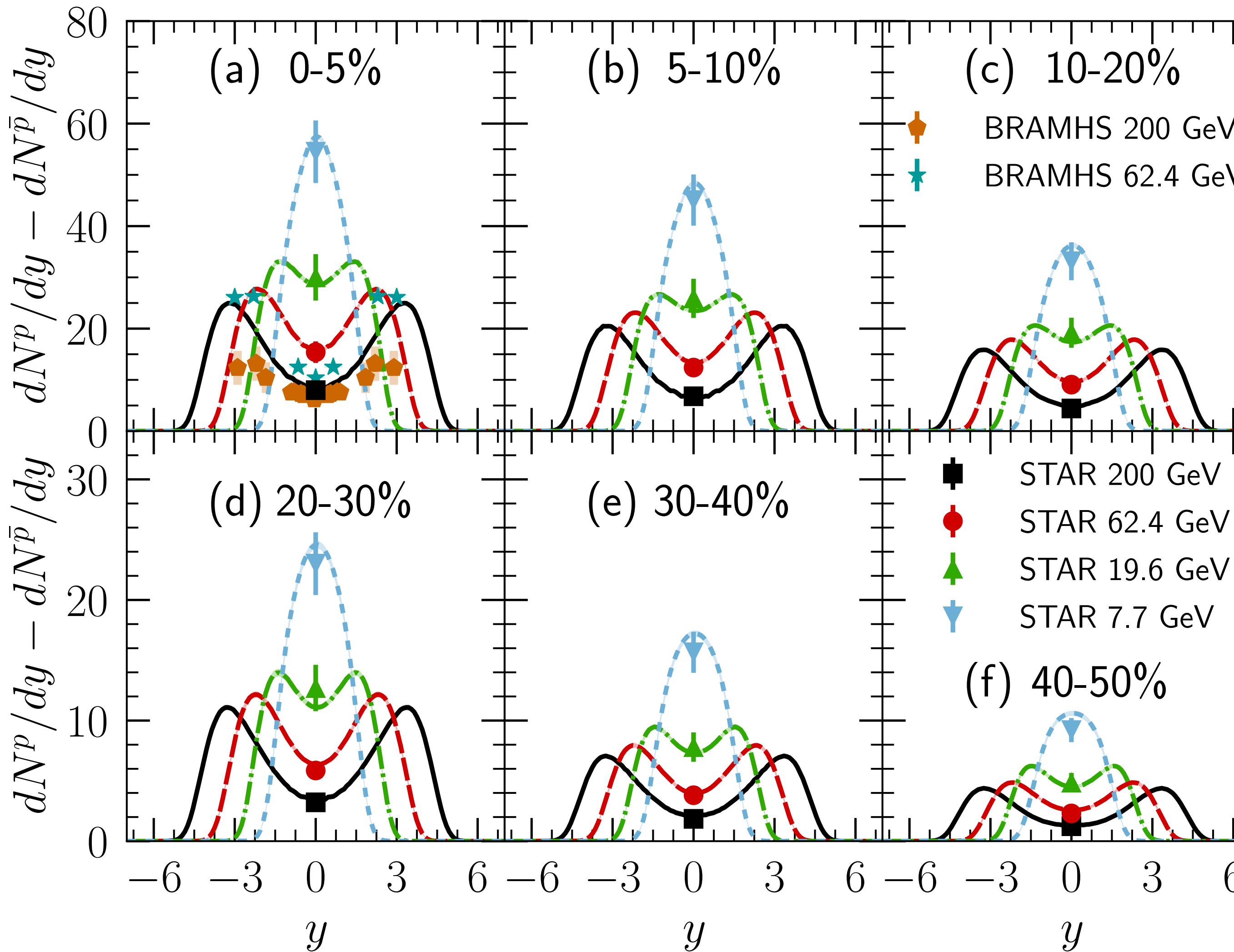
- The longitudinal direction is important:  
Need 3+1D hydrodynamics
- Large part of differences between  $v_n$  from STAR and PHENIX are a result of different rapidity ranges used
- Elliptic flow in photo-nuclear events well described in the same framework as that in p+A collisions
- Flow in the future: Potential to study collective effects in high multiplicity e+A collisions at EIC



# **BACKUP**

# NET-PROTON PRODUCTION

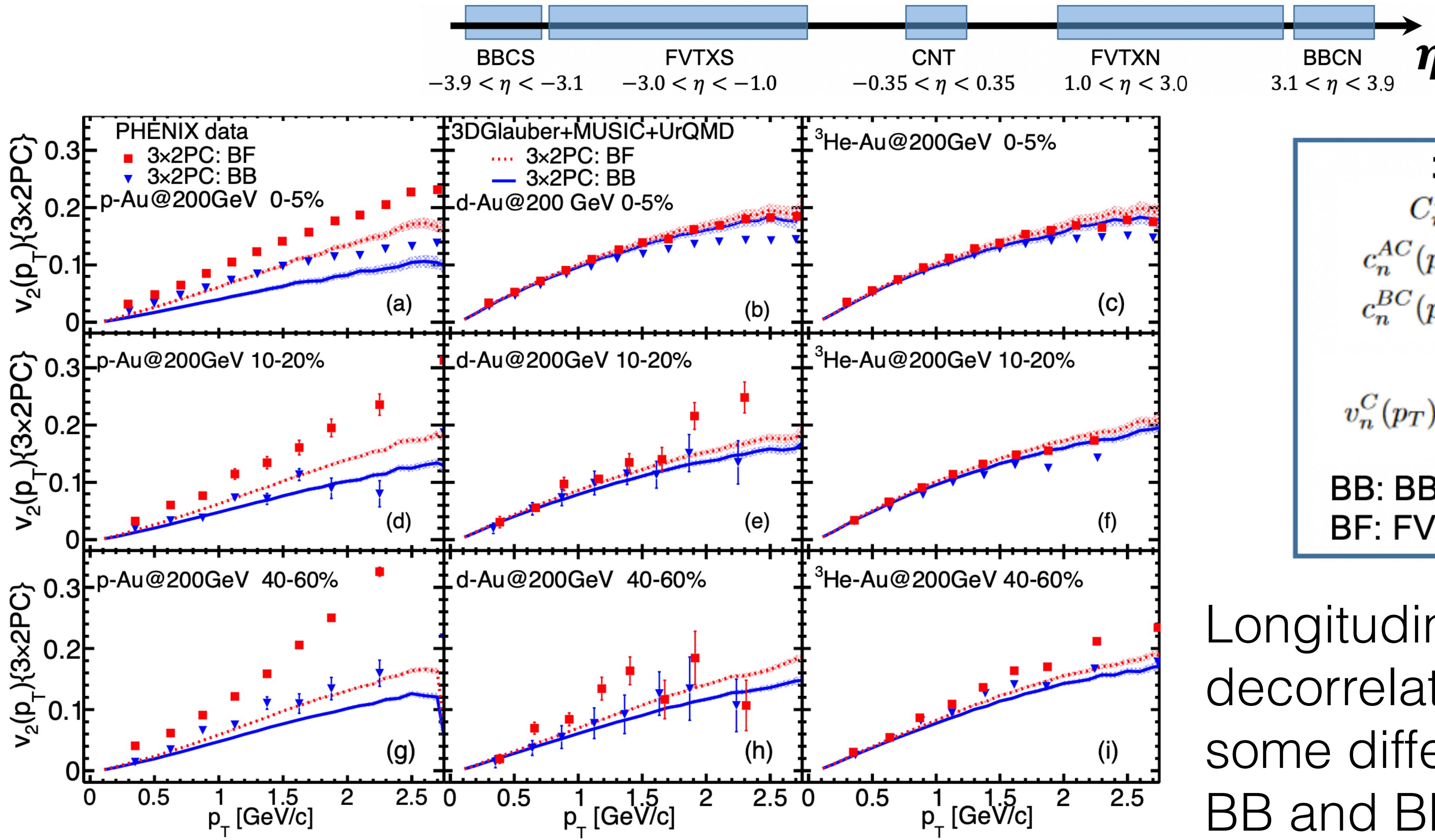
C. Shen and B. Schenke, Phys. Rev. C 105, 064905 (2022)



- Predictions for the net proton rapidity and centrality dependence at RHIC BES energies
- Our results at mid-rapidity are consistent with the STAR measurements
- Measurements of the rapidity dependence can further constrain the distributions of initial baryon charges

# PHENIX 3X2PC STUDY

W. Zhao, S. Ryu, C. Shen and B. Schenke, Phys. Rev. C 107 (2023) 1, 014904



## **3 × 2PC**

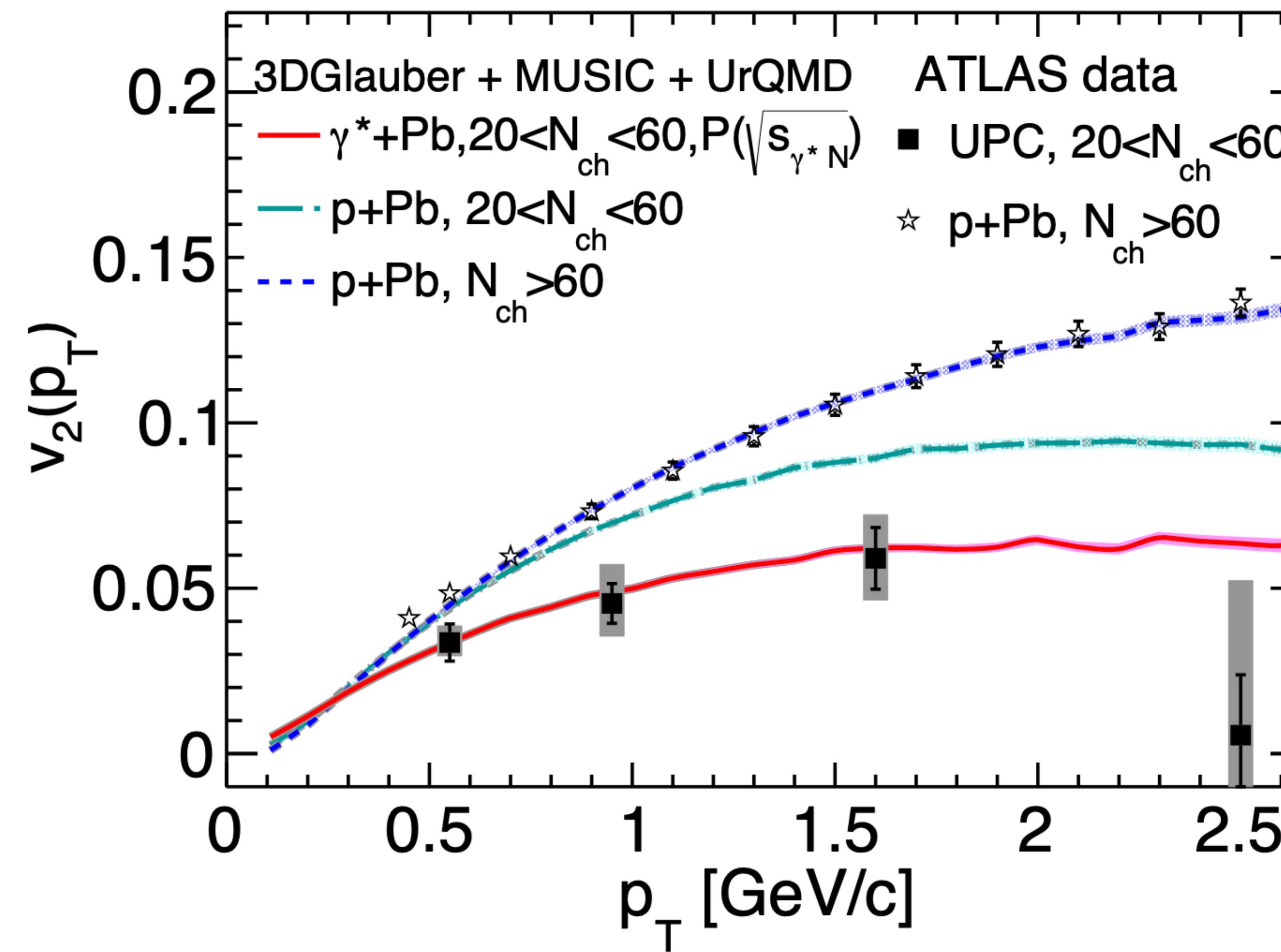
$$C_n^{AB} = \langle Q_{nA} Q_{nB}^* \rangle, \\ c_n^{AC}(p_T) = \langle Q_{nA} q_{nC}^*(p_T) \rangle, \\ c_n^{BC}(p_T) = \langle Q_{nB} q_{nC}^*(p_T) \rangle.$$

$$v_n^C(p_T) = \sqrt{\frac{c_n^{AC}(p_T)c_n^{BC}(p_T)}{C_n^{AB}}}.$$

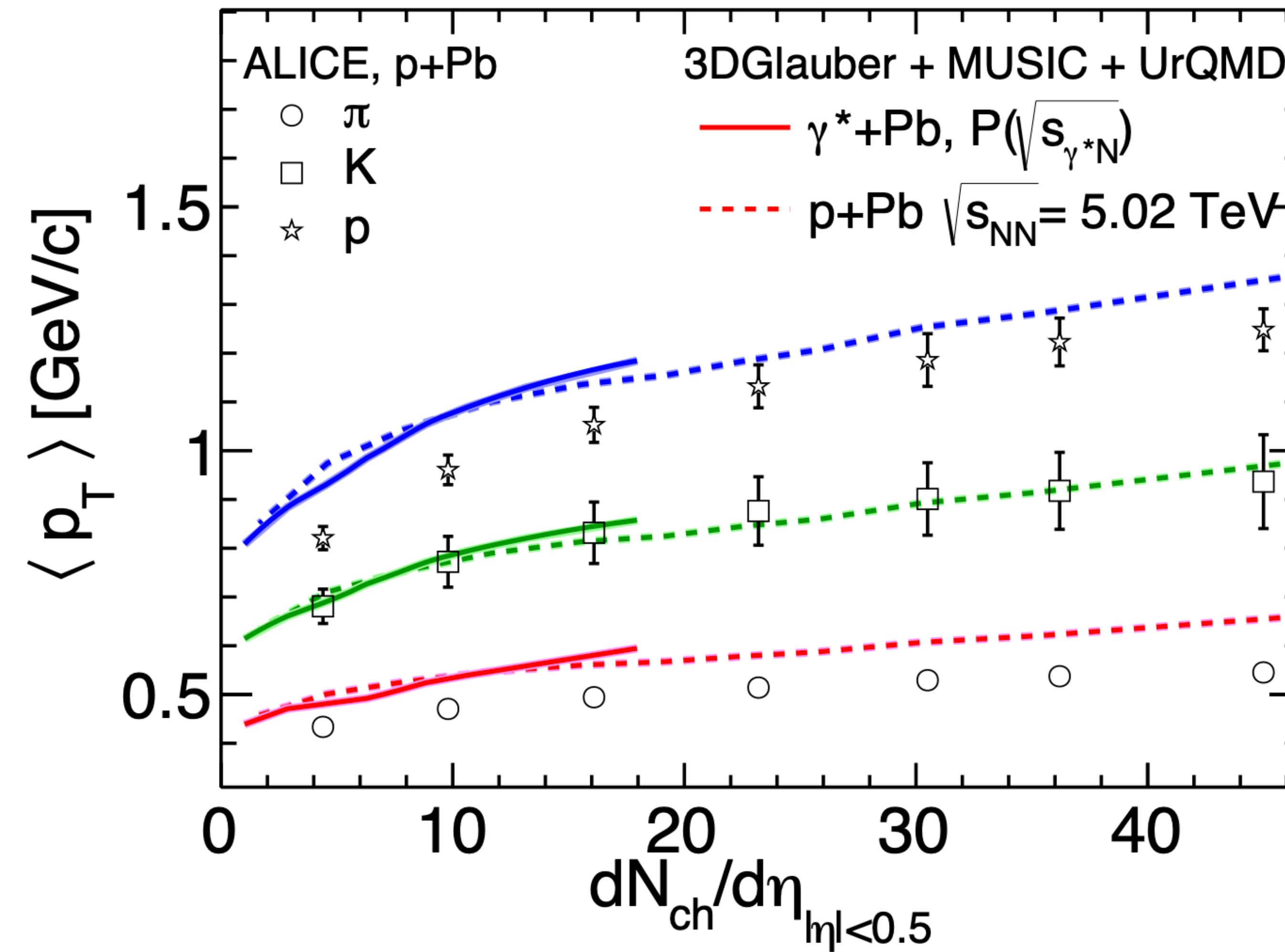
BB: BBCS-FVTXS-CNT  
BF: FVTXS-CNT-FVTXT

Longitudinal flow  
decorrelation reproduces  
some differences between  
BB and BF measurements

# DIFFERENTIAL $v_2$ IN UPC Pb+Pb



# MEAN $p_T$ IN UPC Pb+Pb



# DECORRELATION IN UPC

