U.S. DEPARTMENT OF ENERGY | Office of Science

Brookhaven National Laboratory

COLLECTIVITY IN ULTRA-PERIPHERAL COLLISIONS AND e+A

Diffraction and Low-x

BJÖRN SCHENKE, BROOKHAVEN NATIONAL LABORATORY

DIFFRACTION AND LOW-X 2024, PALERMO, SICILY

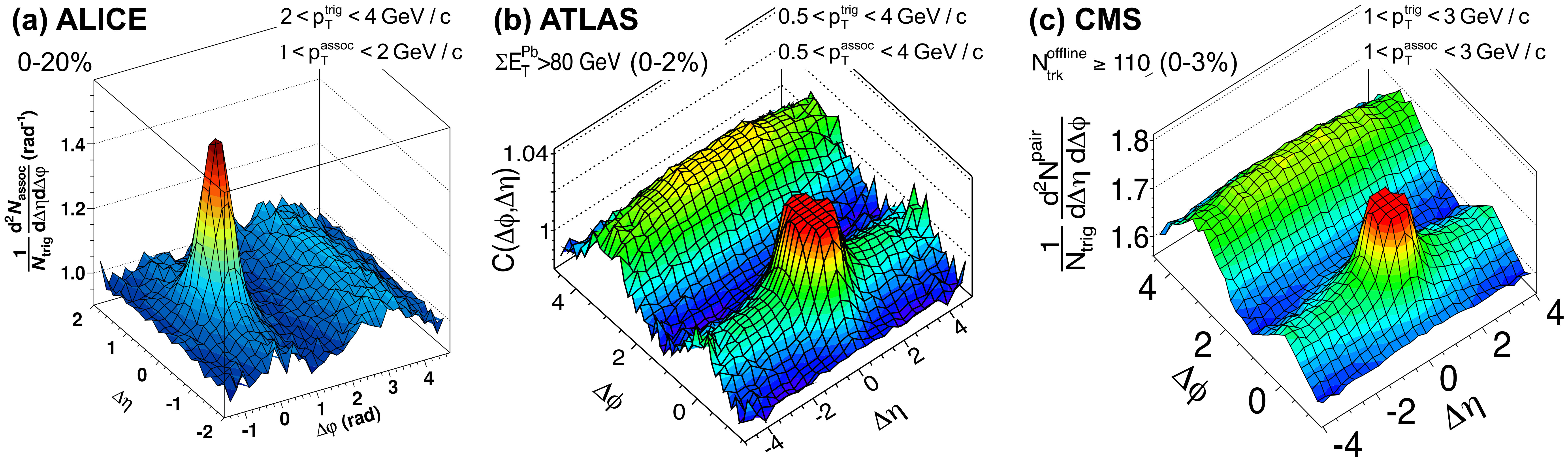
SEPTEMBER 12, 2024

COLLECTIVITY IN SMALL SYSTEMS

Collectivity: “More is different” - Macroscopic volumes of matter manifest qualitatively new phenomena

In heavy ion collisions (and smaller systems) that includes long range rapidity correlations with characteristic azimuthal angle dependencies

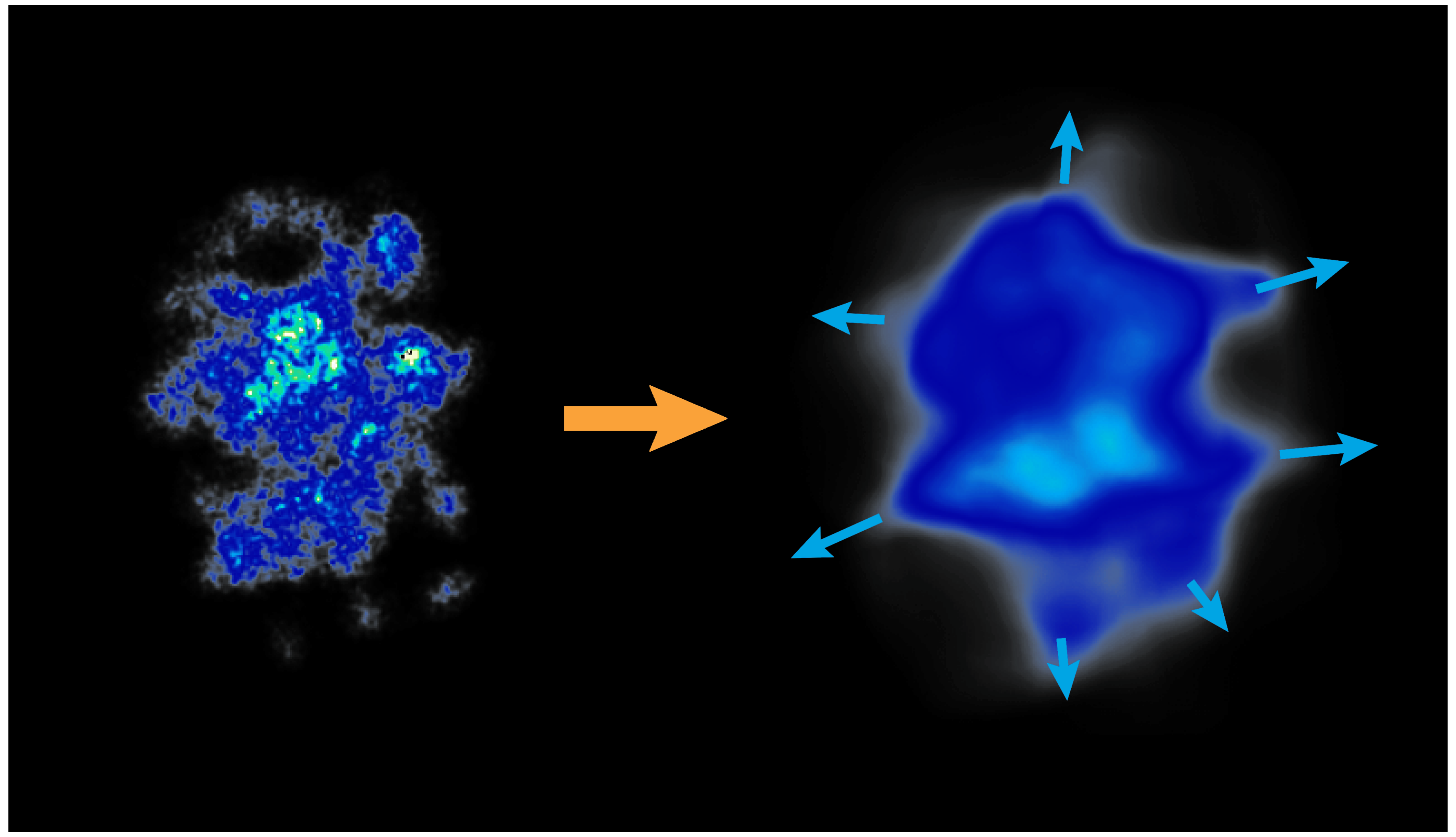
pPb $\sqrt{s_{NN}}$ = 5.02 TeV at the LHC



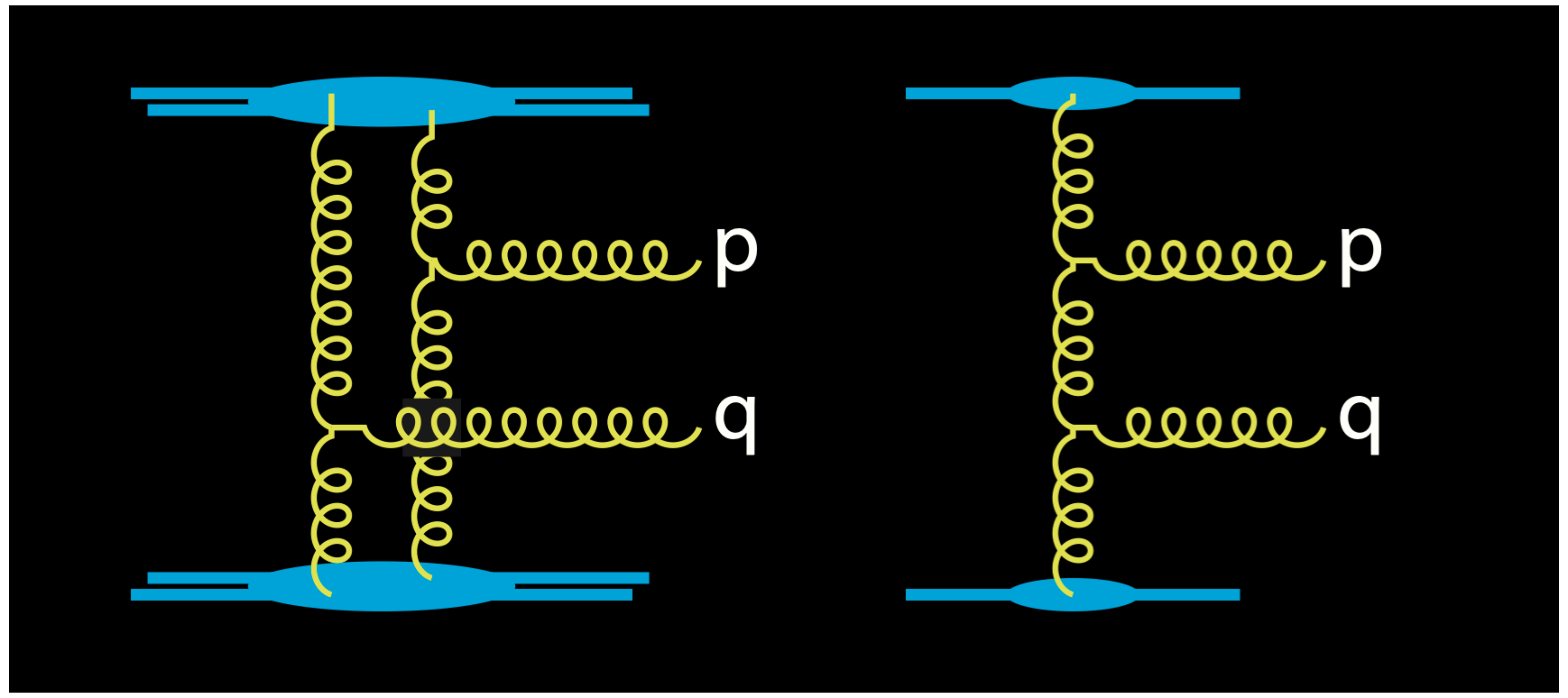
2-PARTICLE CORRELATIONS AS FUNCTION OF RAPIDITY AND ANGULAR DIFFERENCES: $\Delta\eta$ AND $\Delta\phi$

ORIGINS OF COLLECTIVITY

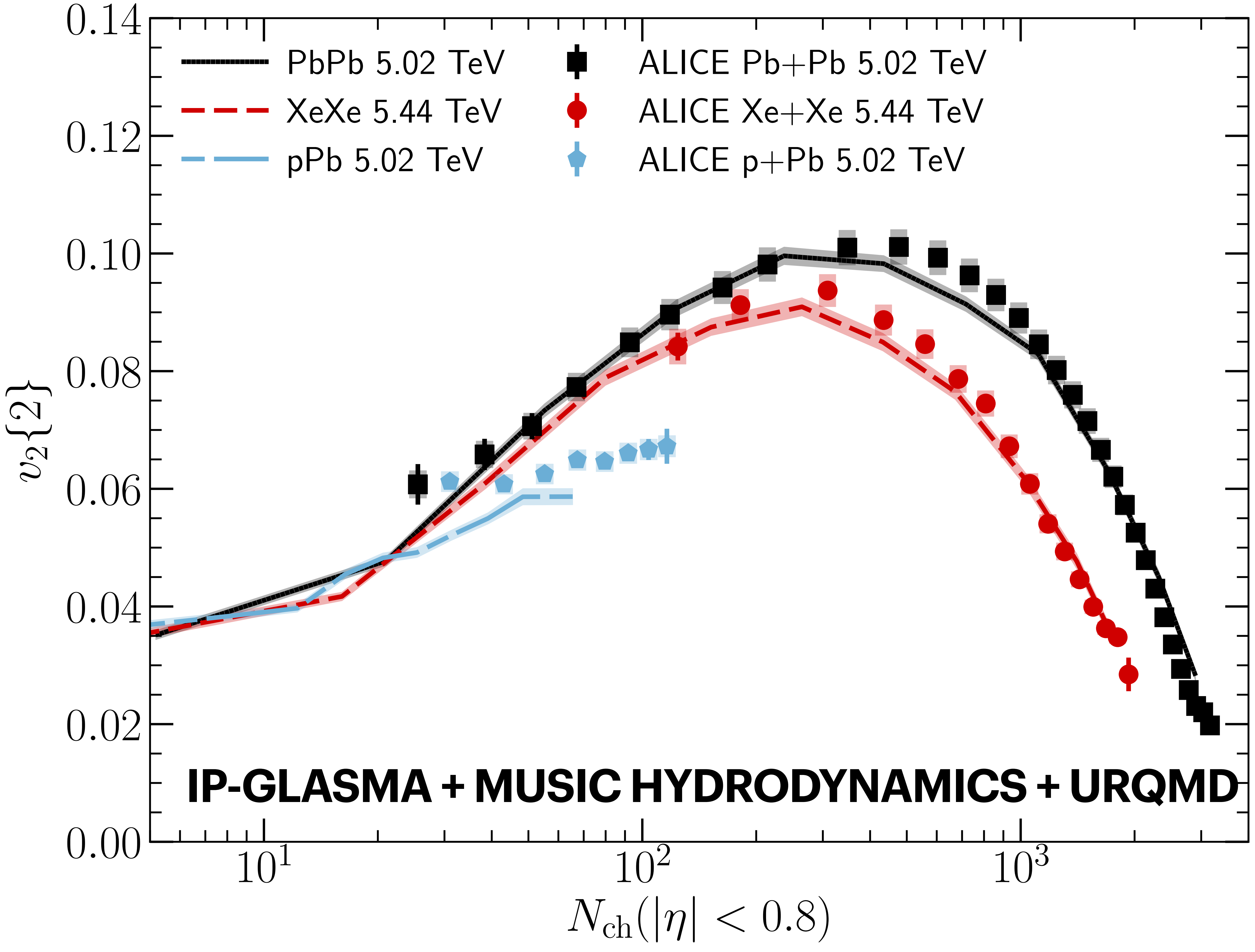
1) Final state effects:
Particles acquire momentum space correlations via final state interactions (conversion of spatial structure into momentum correlations e.g. via hydrodynamic flow)



2) Initial state correlations:
Particles are produced with their momentum space correlations present



COLLECTIVITY IN SMALL SYSTEMS



IP-GLASMA + MUSIC HYDRODYNAMICS + URQMD

COEFFICIENT OF THE $\cos(2\phi)$ MODULATION

NUMBER OF PRODUCED PARTICLES

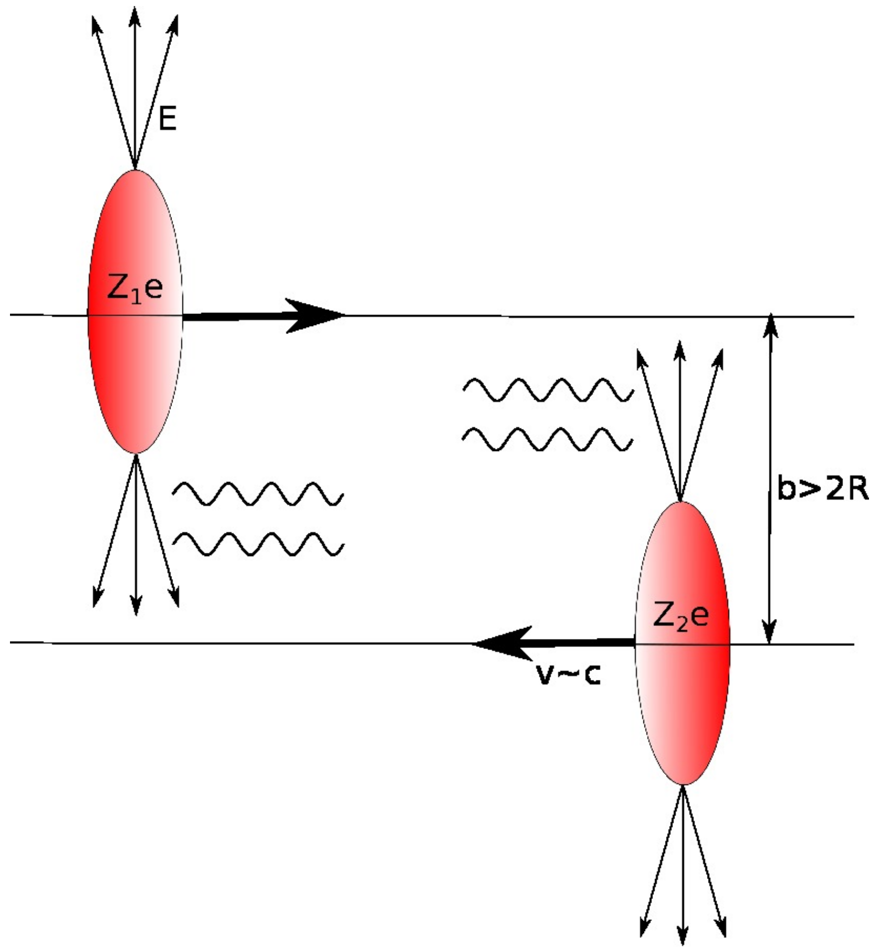
Anisotropic flow in heavy ion collisions is driven by final state response to the initial geometry

There is evidence that the same is true in high multiplicity small systems

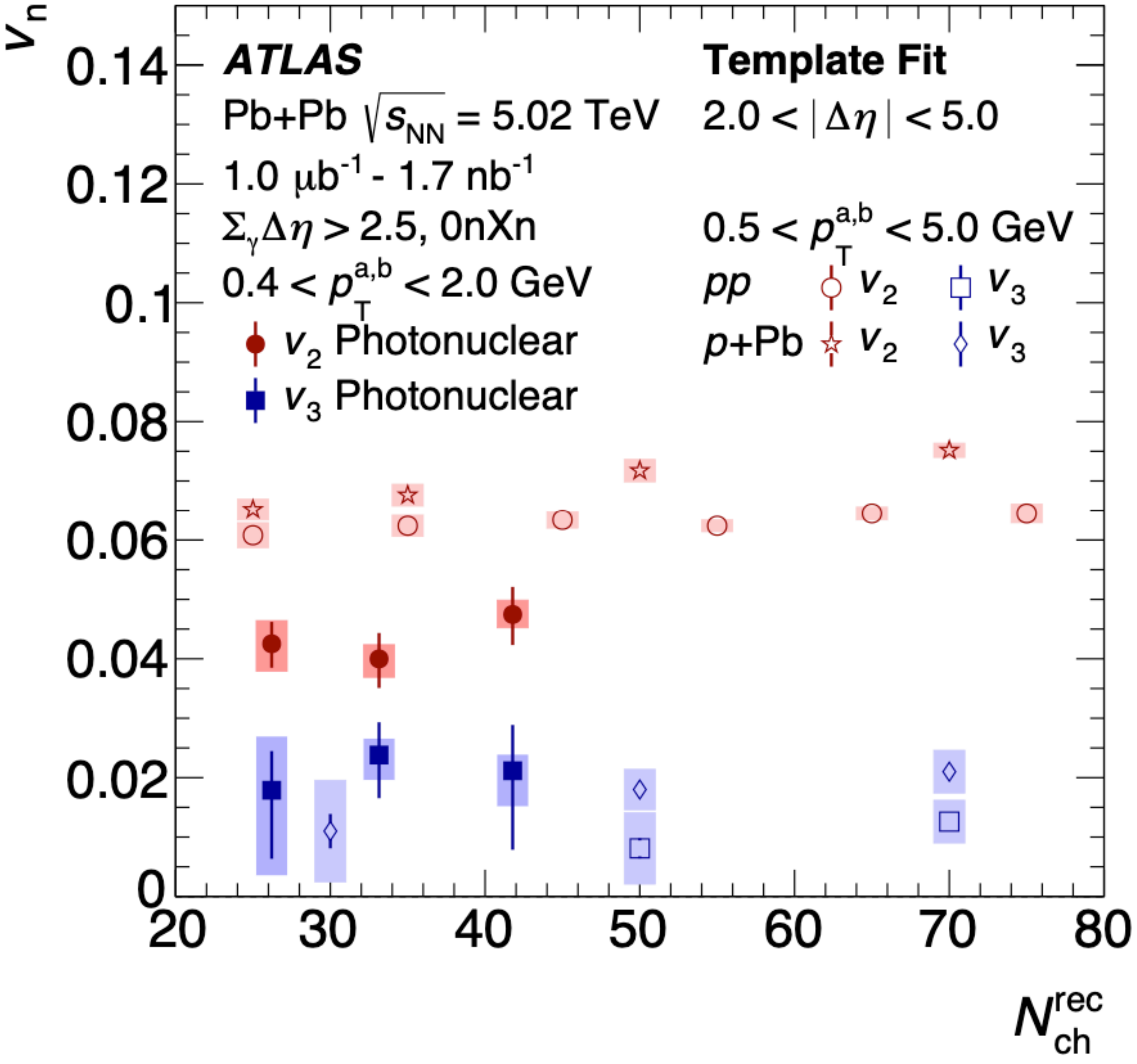
B. Schenke, C. Shen, P. Tribedy, Phys.Rev.C 102 (2020) 044905
ALICE Collaboration, Phys.Rev.Lett. 123 (2019) 142301

ULTRAPERIPHERAL COLLISIONS

ATLAS Collaboration, Phys. Rev. C 104, 014903 (2021)

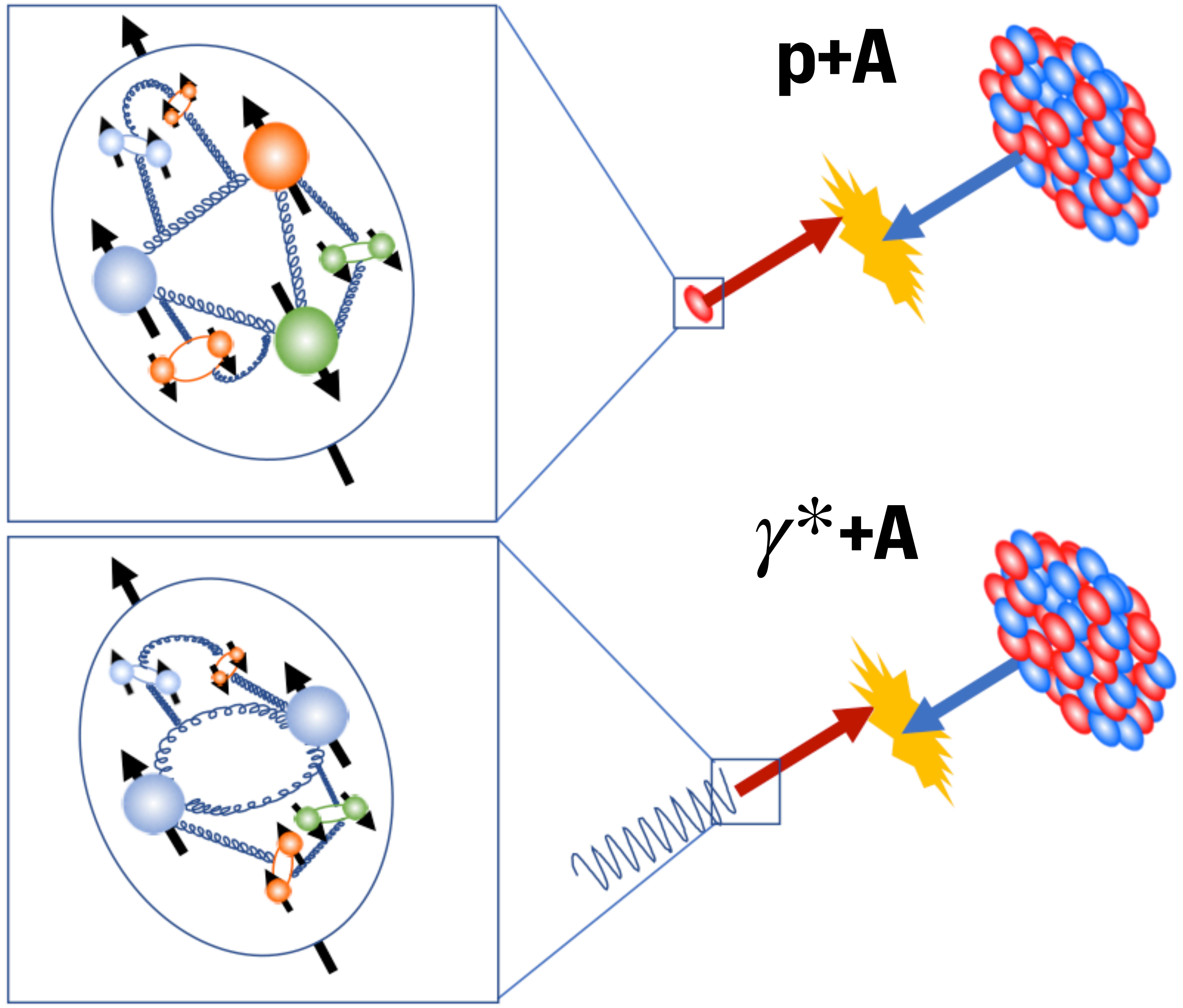


- Long range two-particle correlations were observed in photo-nuclear processes in Pb+Pb UPCs at LHC
- Magnitudes of v_n comparable to those in p+Pb collisions



MODELING THE INCOMING PHOTON

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



Photon: $$|\gamma\rangle = |\gamma_0\rangle + \sum_{m,n} |mq\bar{q} + ng\rangle + \sum_{\rho,\omega,\ldots} |V\rangle + \ldots$$

dominates at large x

dominates at small x and high Q^2

dominates at small x and low Q^2

In high multiplicity events, due to the rare fluctuation with sufficiently long lifetime, the incoming low-Q^2 virtual photon can be viewed as a vector meson with a large number of collinear partons

CGC CALCULATION

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

Compute azimuthal angular correlation in $\gamma^* + A$ collisions by treating the virtual photon as a hadron with a lifetime longer than the time of interaction

Distribution of partons inside the photon: $w(x, b_\perp, k_\perp) = f_{p/\gamma}(x)\frac{1}{\pi^2}e^{-b_\perp^2/B_p - k_\perp^2/\Delta^2}$

B_p: spread of partons in transverse coordinate space

Δ: typical transverse momentum of the parton

Use dilute-dense picture:

- Much higher parton density in the target (Pb) than in the projectile (γ^*)
- Multiple scattering of projectile partons with the dense target gluon fields: Wilson line $U(x_\perp)$ in the eikonal approximation

CGC CALCULATION

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

Production of two initially un-correlated quarks in the dense gluon background:

$$\frac{dN}{d^2k_{1\perp}d^2k_{2\perp}} = \int_{b_1,b_2,r_1,r_2} e^{i(k_1r_1+k_2r_2)}w_1w_2 \left\langle D\left(b_1+\frac{r_1}{2}, b_1-\frac{r_1}{2}\right) D\left(b_2+\frac{r_2}{2}, b_2-\frac{r_2}{2}\right)\right\rangle$$

$\langle\cdots\rangle$: average over dense gluon fields

quark position in the complex conjugate amplitude

where $D(x_\perp, y_\perp) = \frac{1}{N_c}\mathrm{Tr}[U(x_\perp)U^\dagger(y_\perp)]$

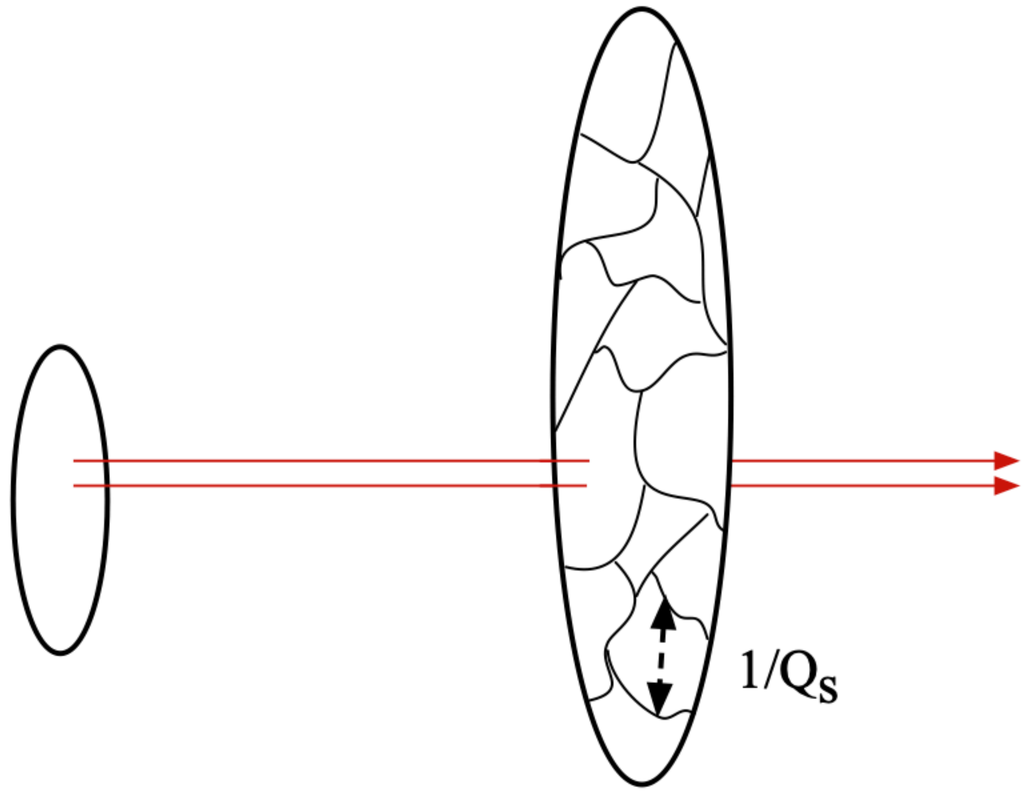
quark position in the amplitude

technically, this is good for forward direction, where the quarks are going

CGC CALCULATION

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

Correlation appears as the higher order N_c corrections in the resulting background average of two dipole amplitudes:



$$\left\langle D\left(b_1+\frac{r_1}{2}, b_1-\frac{r_1}{2}\right) D\left(b_2+\frac{r_2}{2}, b_2-\frac{r_2}{2}\right)\right\rangle\Bigg|_{\text{up to }\frac{1}{\mathrm{N_c^2}}} = e^{-\frac{Q_s^2}{4}(r_1^2+r_2^2)}\left[1+\frac{1}{N_c^2}\underbrace{Q(r_1,b_1,r_2,b_2)}_{\text{quadrupole}}\right]$$

Compute Q in GBW approximation.

ELLIPTIC ANISOTROPY FROM CGC

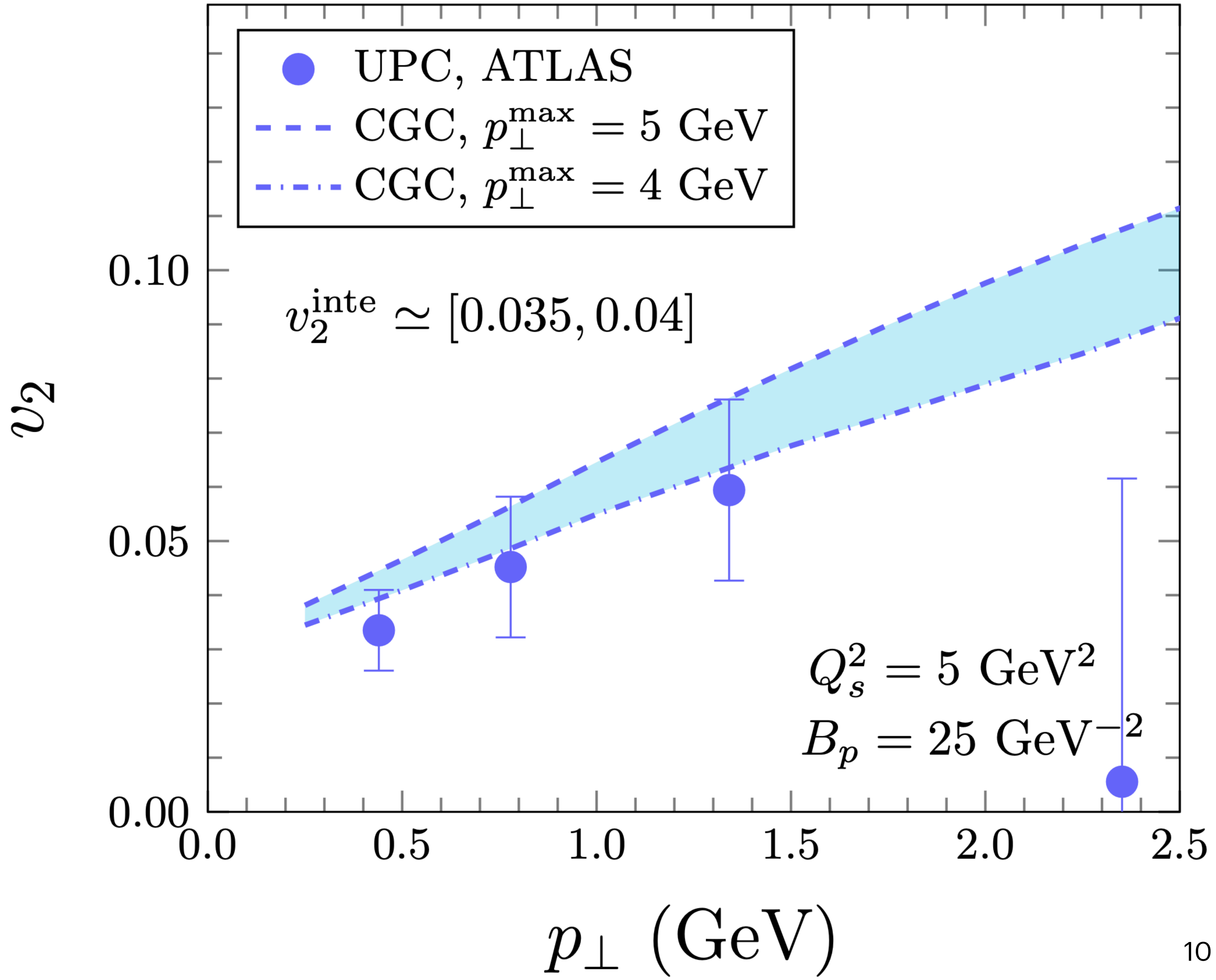
Y. Shi, L. Wang, S. Y. Wei, B. W. Xiao and L. Zheng, Phys. Rev. D 103, 054017 (2021)

Multiparticle spectra and correlations in high energy $\gamma^* + A$ collisions can be obtained from the Fourier transform of above dipole amplitudes as in p+A

UPC: Q ~30 MeV $\ll \Lambda_{\mathrm{QCD}}$

However, the extent of the QCD fluctuation usually does not exceed the size $1/\Lambda_{\mathrm{QCD}}$ due to color confinement, so $B_p = 25\,\mathrm{GeV}^{-2}$

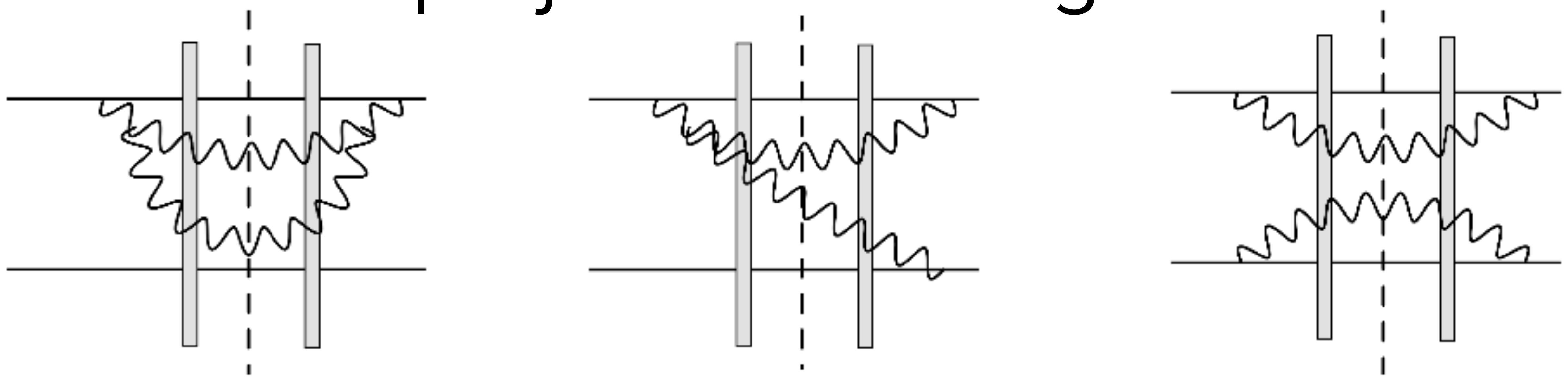
$$w(x, b_\perp, k_\perp) = f_{p/\gamma}(x)\frac{1}{\pi^2}e^{-b_\perp^2/B_p - k_\perp^2/\Delta^2}$$



CGC UPDATE: “A MORE REALISTIC CALCULATION”

H. Duan, A. Kovner, V. V. Skokov, JHEP 12 (2022) 077

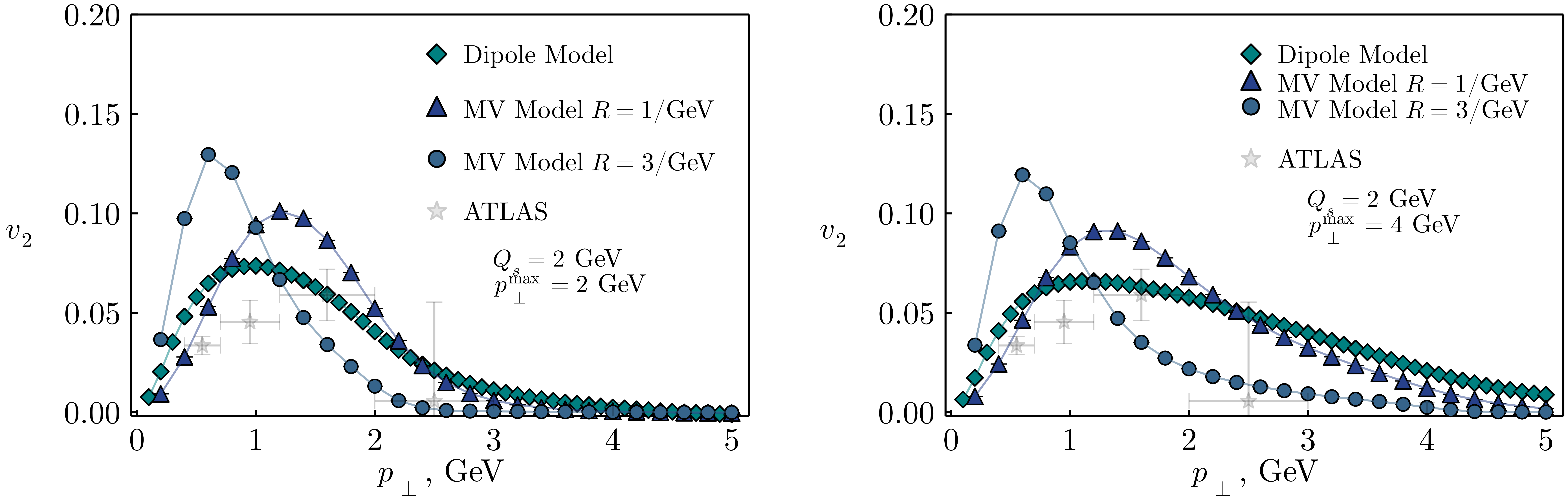
- Previous study considered forward (projectile going) production
- Measurement is done at mid-rapidity
- This new calculation dresses valence partons in the projectile: Accounts for correlations in projectile and target



- Address uncertainty from wave function of the nearly real photon by studying two models: dilute quark-antiquark dipole approximation and the vector meson
- Cannot go to the large N_c limit as correlations of interest are N_c suppressed. Instead, use factorized dipole approximation (FDA) that works when $Q_s^2 S_\perp \gg 1$

NUMERICAL RESULTS

H. Duan, A. Kovner, V. V. Skokov, JHEP 12 (2022) 077



- Additional correlations from Bose enhancement in the projectile, HBT effect
- Previous calculation’s v_2 keeps rising with p_T. Here, turnover comes from the dominance of a narrow gluon HBT peak. This also leads to p_T-bin dependence

MOMENTUM BIN DEPENDENCE

H. Duan, A. Kovner, V. V. Skokov, JHEP 12 (2022) 077

- CGC results lead to fast decorrelation in p_T, i.e., v_2 drops quickly when p_T of the trigger differs from p_T of the associate particle

  Experiment defines $v_n(p_T^a) = v_{n,n}(p_T^a, p_T^b)/\sqrt{v_{n,n}(p_T^b, p_T^b)}$ where $v_{n,n}$ are Fourier coefficients in the expansion of the two-particle distribution

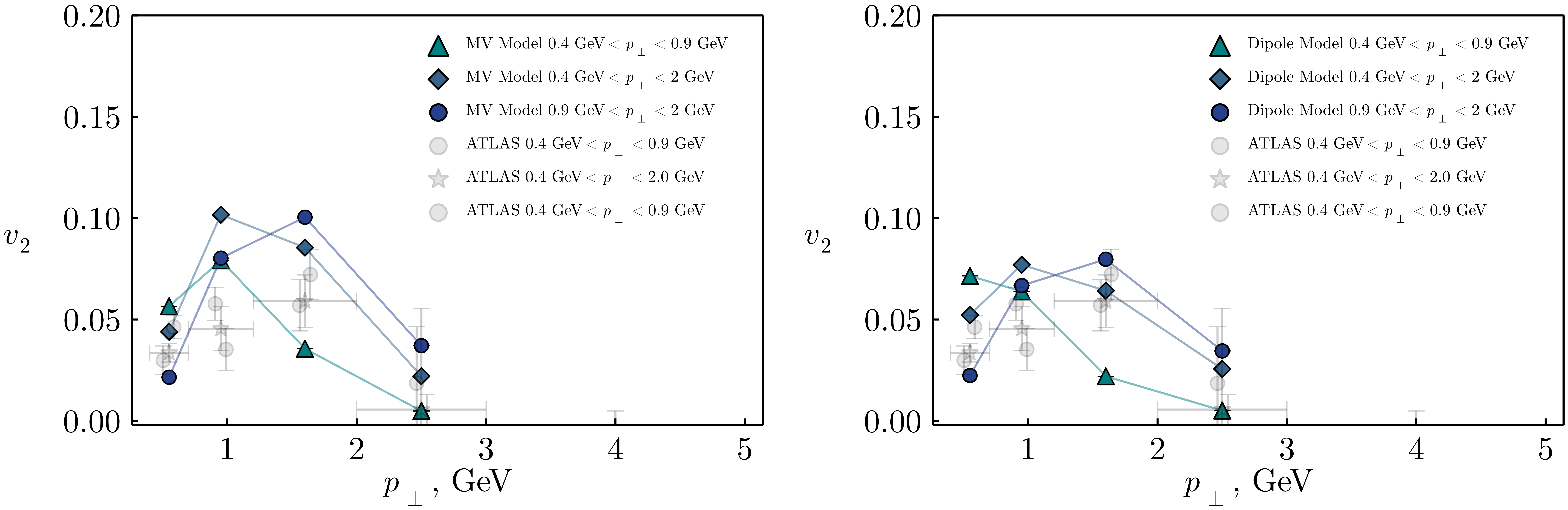
$$\frac{dN}{d\vec{q}_1^2 d\vec{q}_2^2} \propto 1 + 2\sum_n v_{n,n} \cos(n\Delta\phi)$$

- When binning both particle like in the experiment, that fast decorrelation is smeared out

- Different in the final state picture, as we will see

BINNING BOTH TRIGGER AND ASSOCIATE PARTICLE

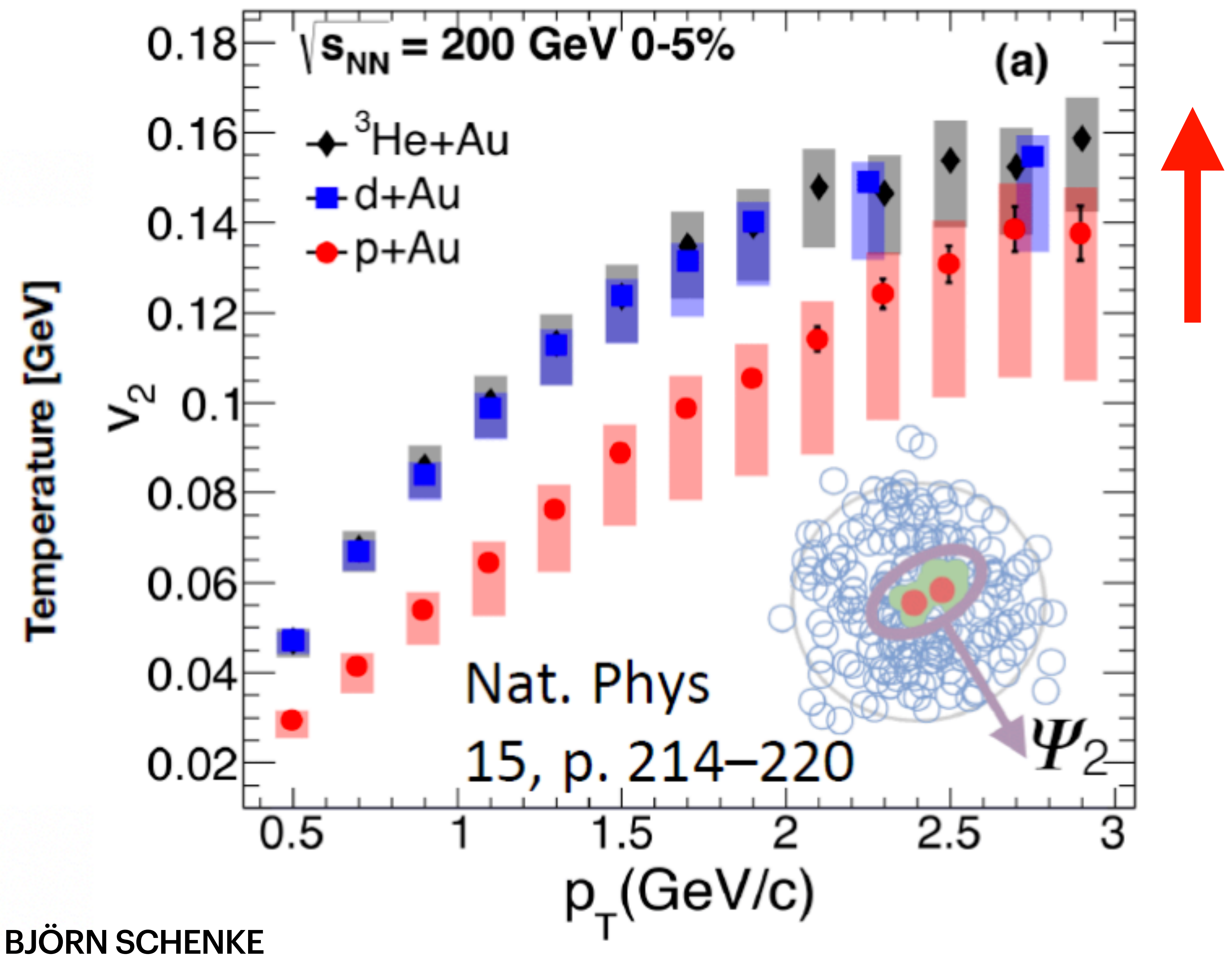
H. Duan, A. Kovner, V. V. Skokov, JHEP 12 (2022) 077

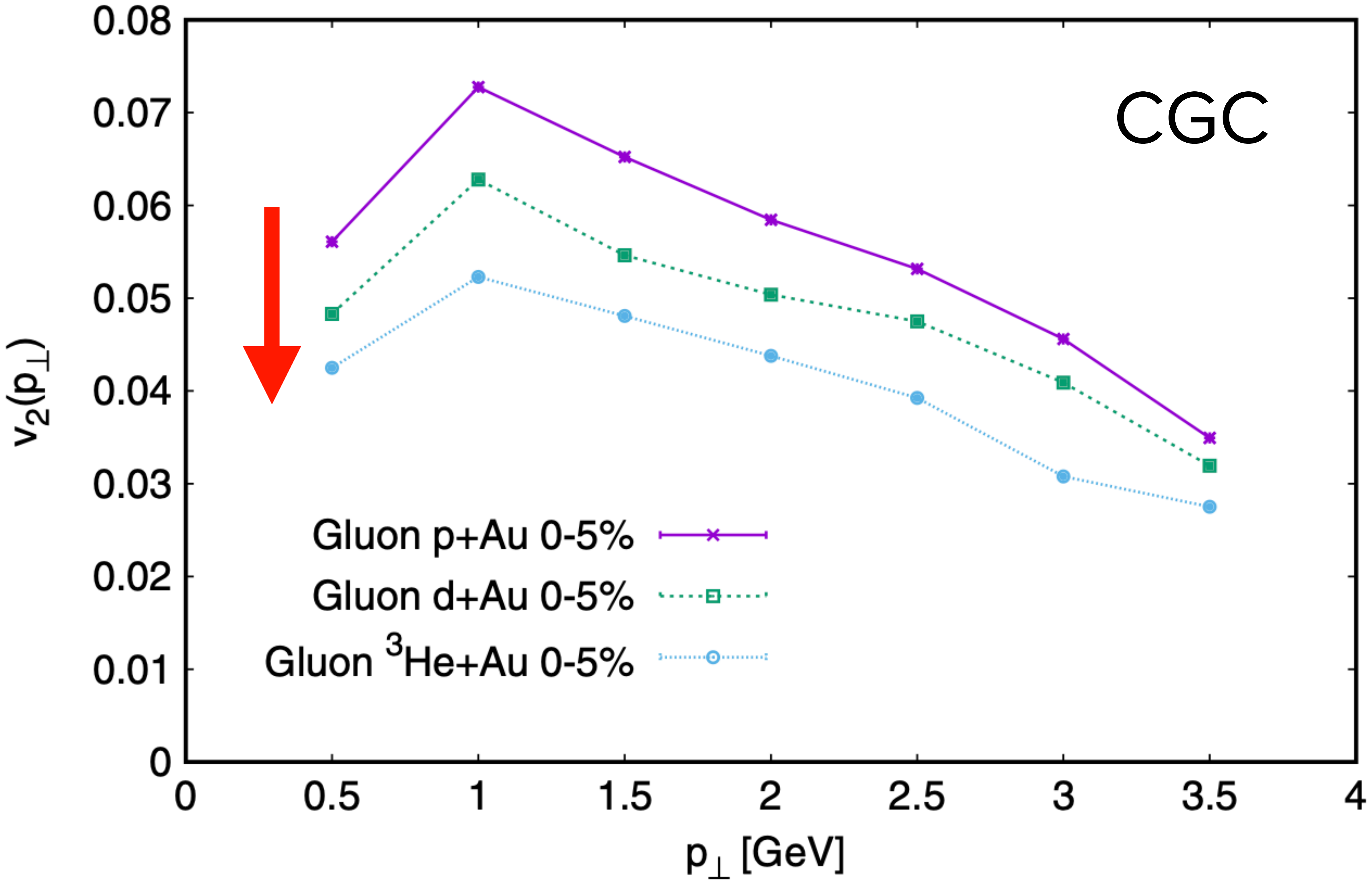


POTENTIAL PROBLEMS

PHENIX Collaboration, Nature Phys. 15, no.3, 214-220 (2019)
B. Schenke, S. Schlichting, R. Venugopalan, Phys.Lett.B 747 (2015) 76-82, 1502.01331
M. Mace, V. V. Skokov, P. Tribedy, R. Venugopalan, Phys. Rev. Lett. 121, 052301 (2018), PRL123, 039901(E) (2019)

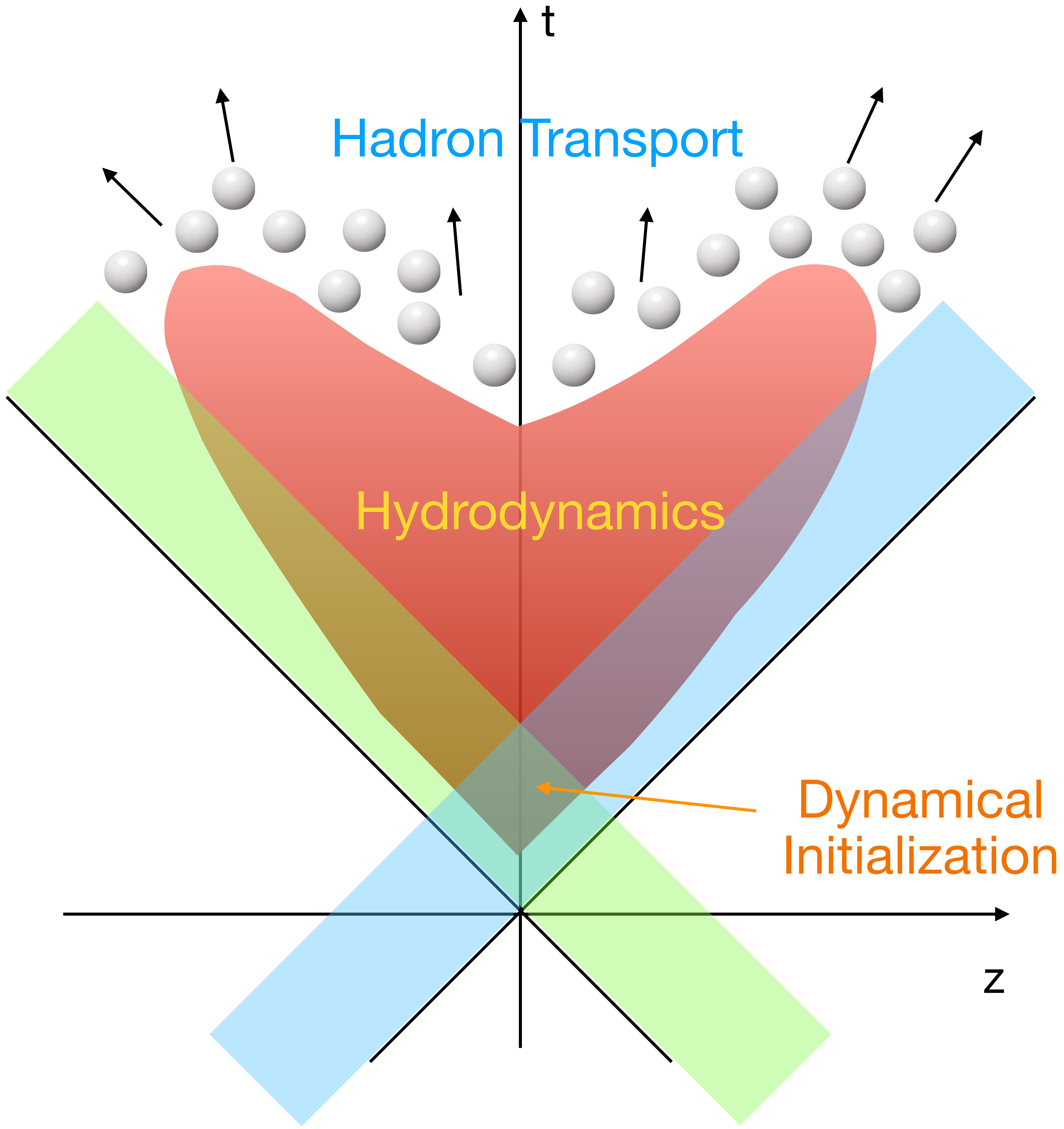
Initial state momentum anisotropy from the Color Glass Condensate cannot get all systematics right (here the system dependence at RHIC):



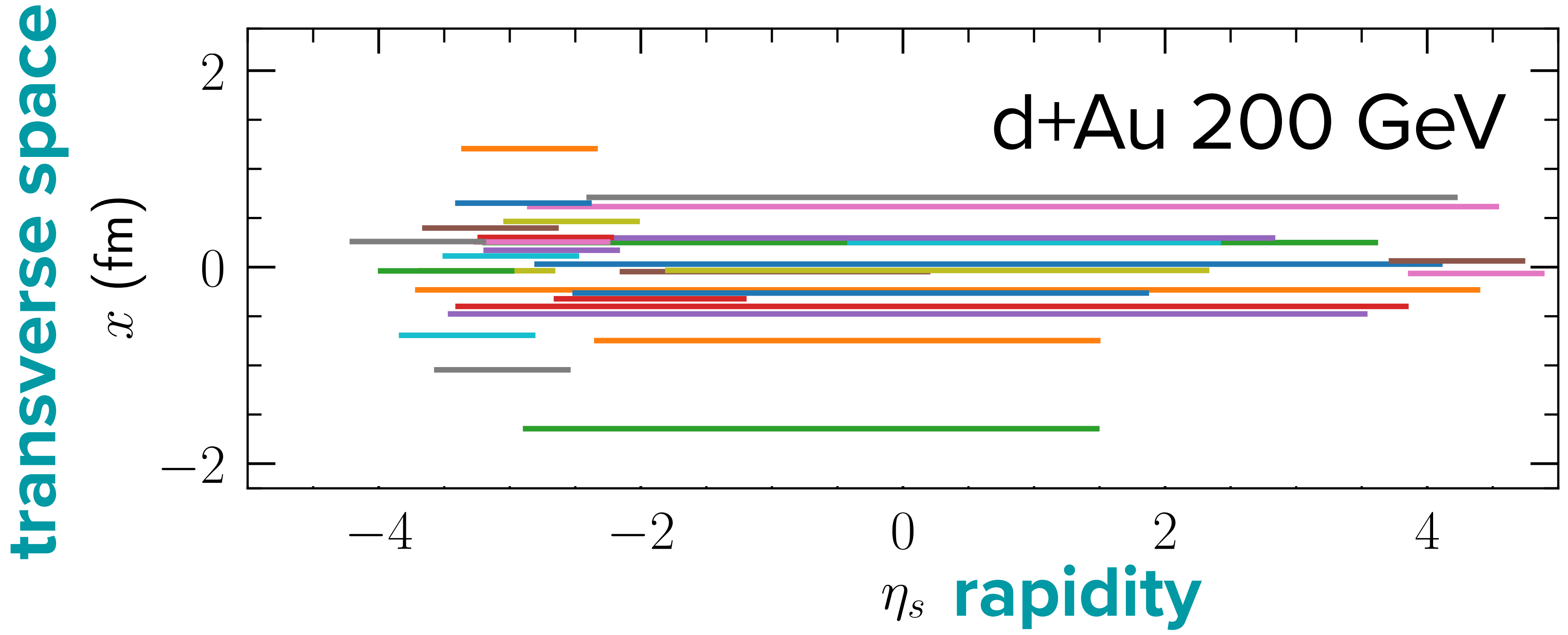


FINAL STATE DESCRIPTION

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

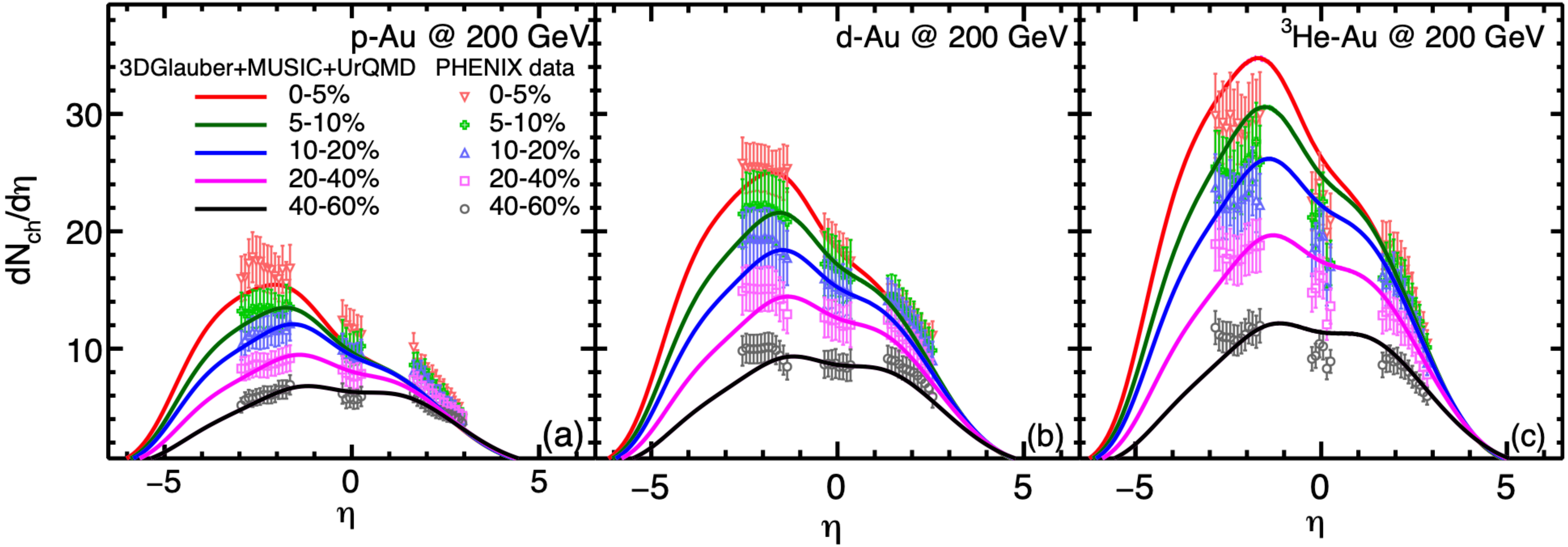


- Simulate small systems dynamically with 3+1D hydrodynamics
- Initialize using MC-Glauber + string deceleration model with source terms in hydro
- Provides fluctuating transverse+longitudinal geometry



SMALL SYSTEMS SCAN AT RHIC

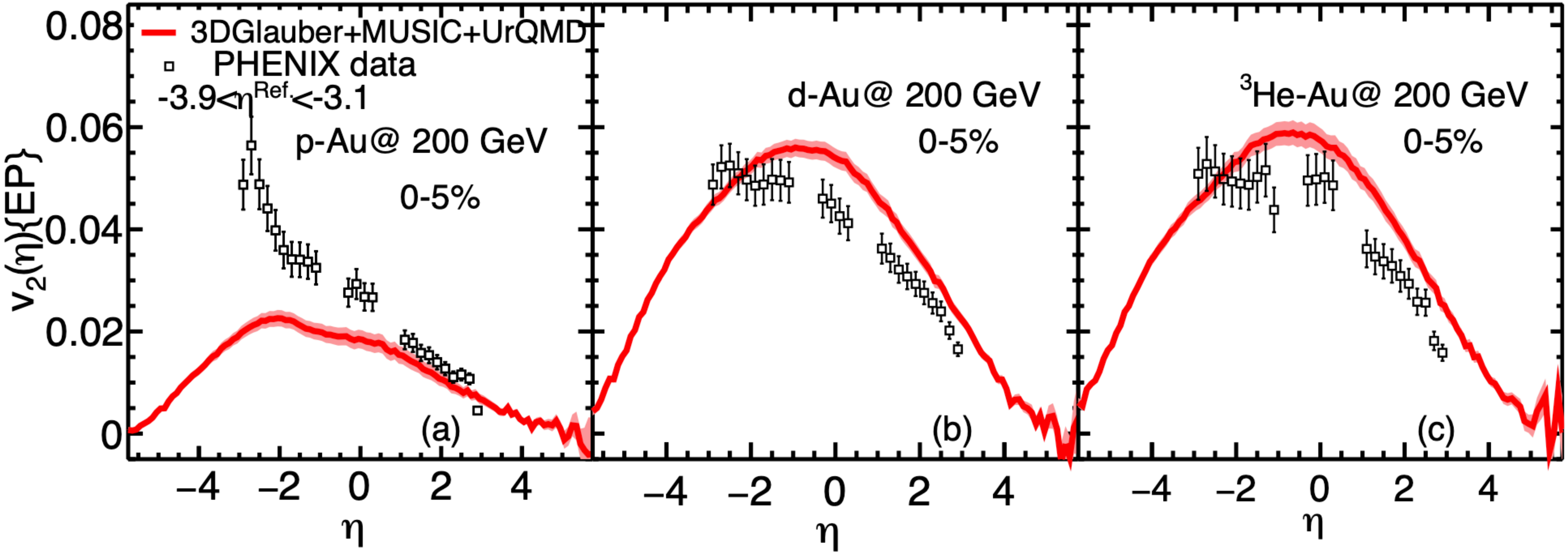
W. Zhao, S. Ryu, C. Shen and B. Schenke, Phys.Rev.C 107 (2023) 1, 014904



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

ANISOTROPIC FLOW VS RAPIDITY

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

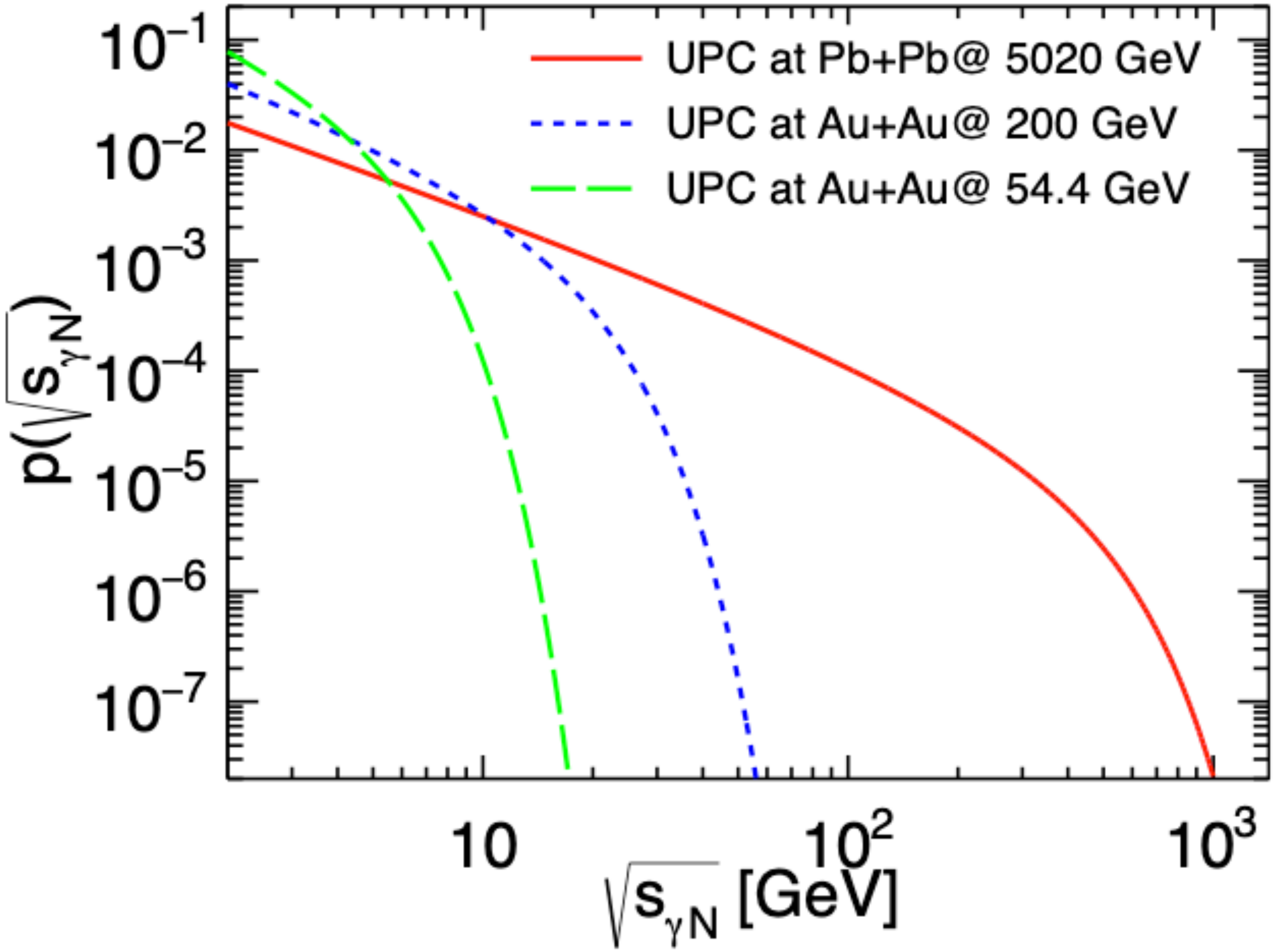


- Pseudo-rapidity dependence of $v_2\{EP\}$ reproduced in d+Au and ³He+Au
- The elliptic flow in $\eta < 1$ in p+Au collisions is underestimated because of the strong longitudinal flow decorrelation in our model + potential non-flow

INITIAL STATE FOR γ^* + Pb

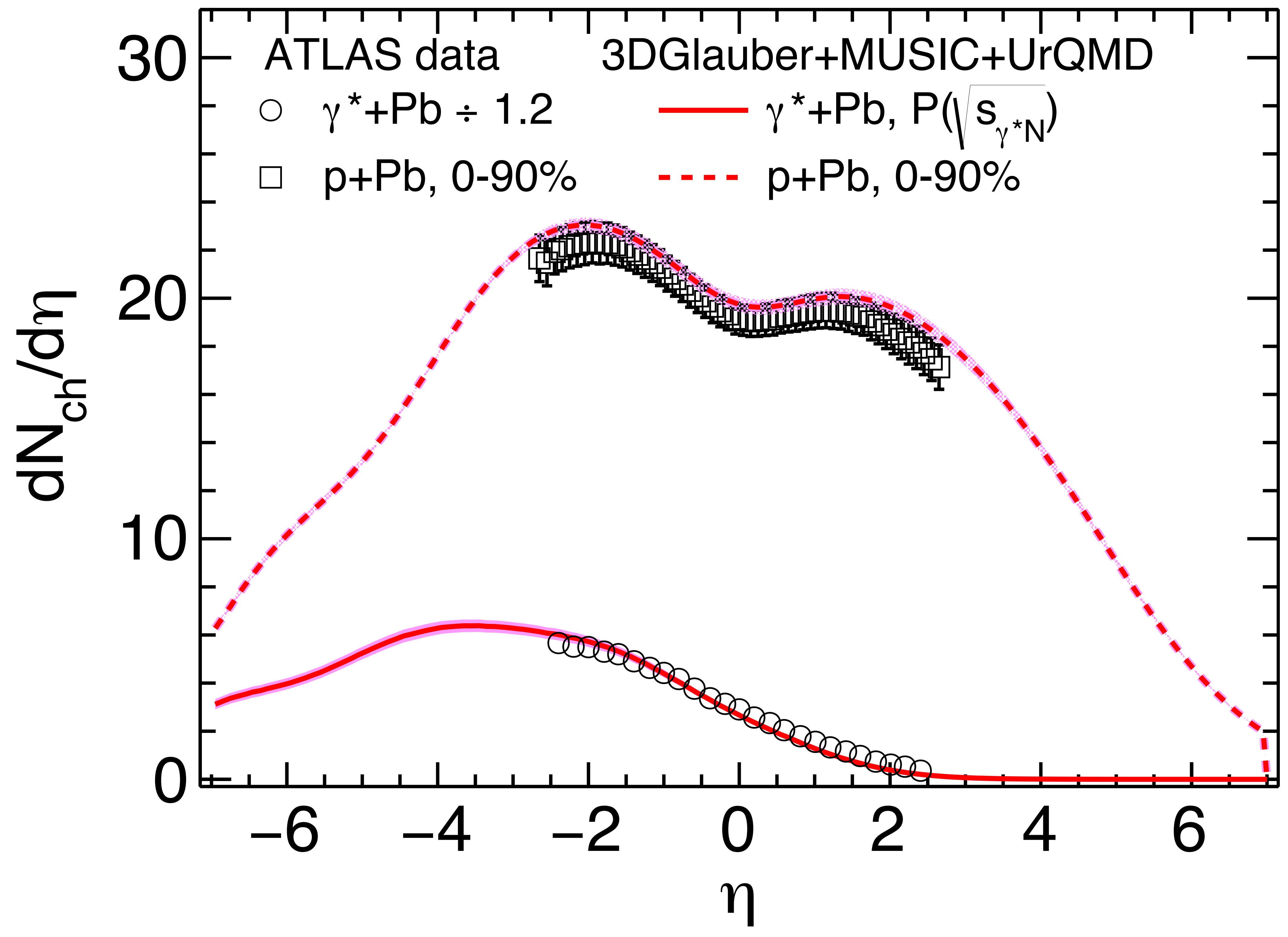
W. Zhao, C. Shen and B. Schenke, Phys.Rev.Lett. 129 (2022) 25, 252302

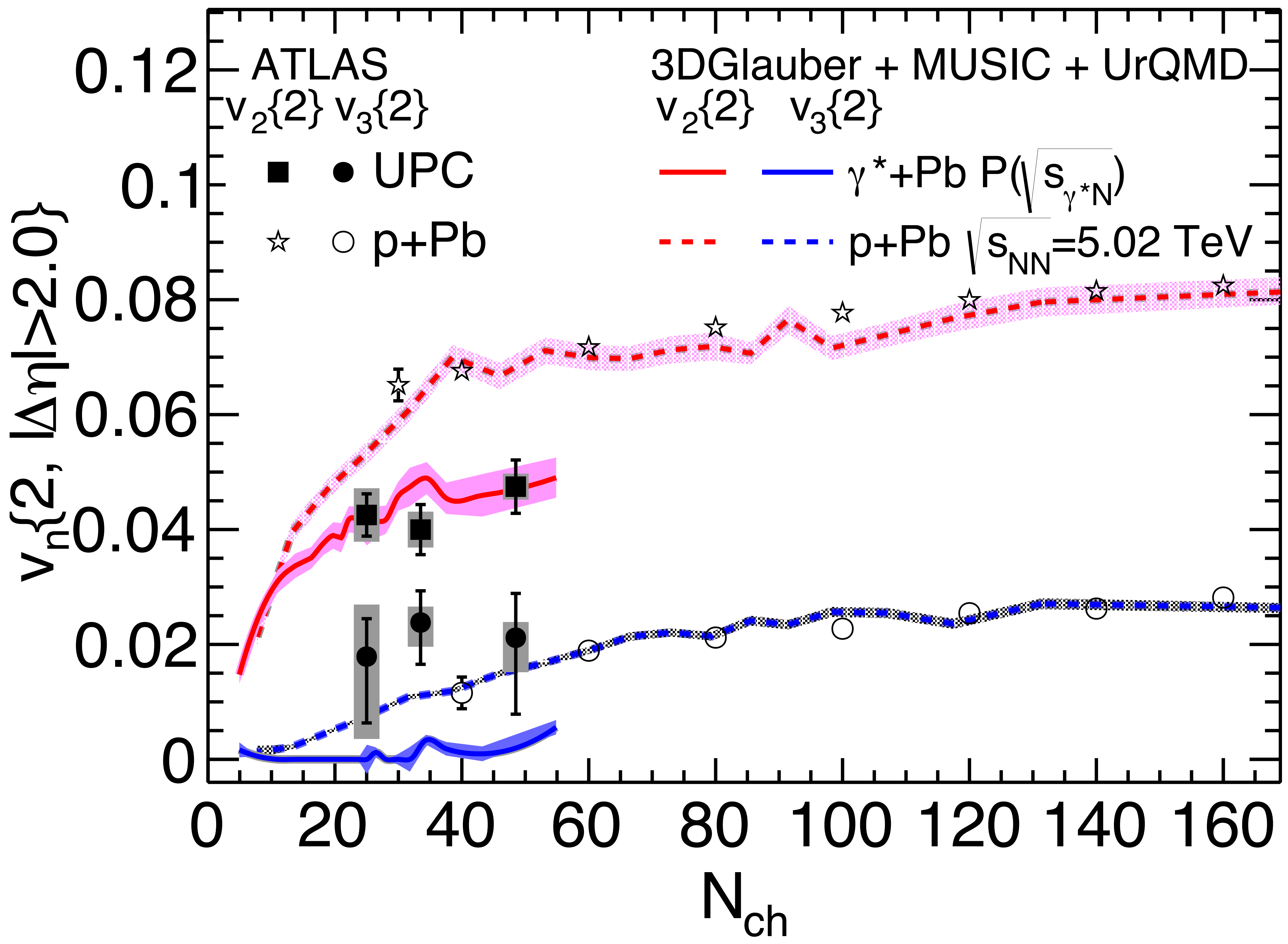
- Same model as used in collision systems discussed so far
- Virtual photon described as a vector meson: two quarks plus soft cloud
- Energy of the incoming quasi-real photon fluctuates event by event
- Leads to fluctuations of $\sqrt{s_{\gamma^* N}}$ and the center of mass rapidity



PARTICLE PRODUCTION AND FLOW IN p+A AND γ^*+A

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



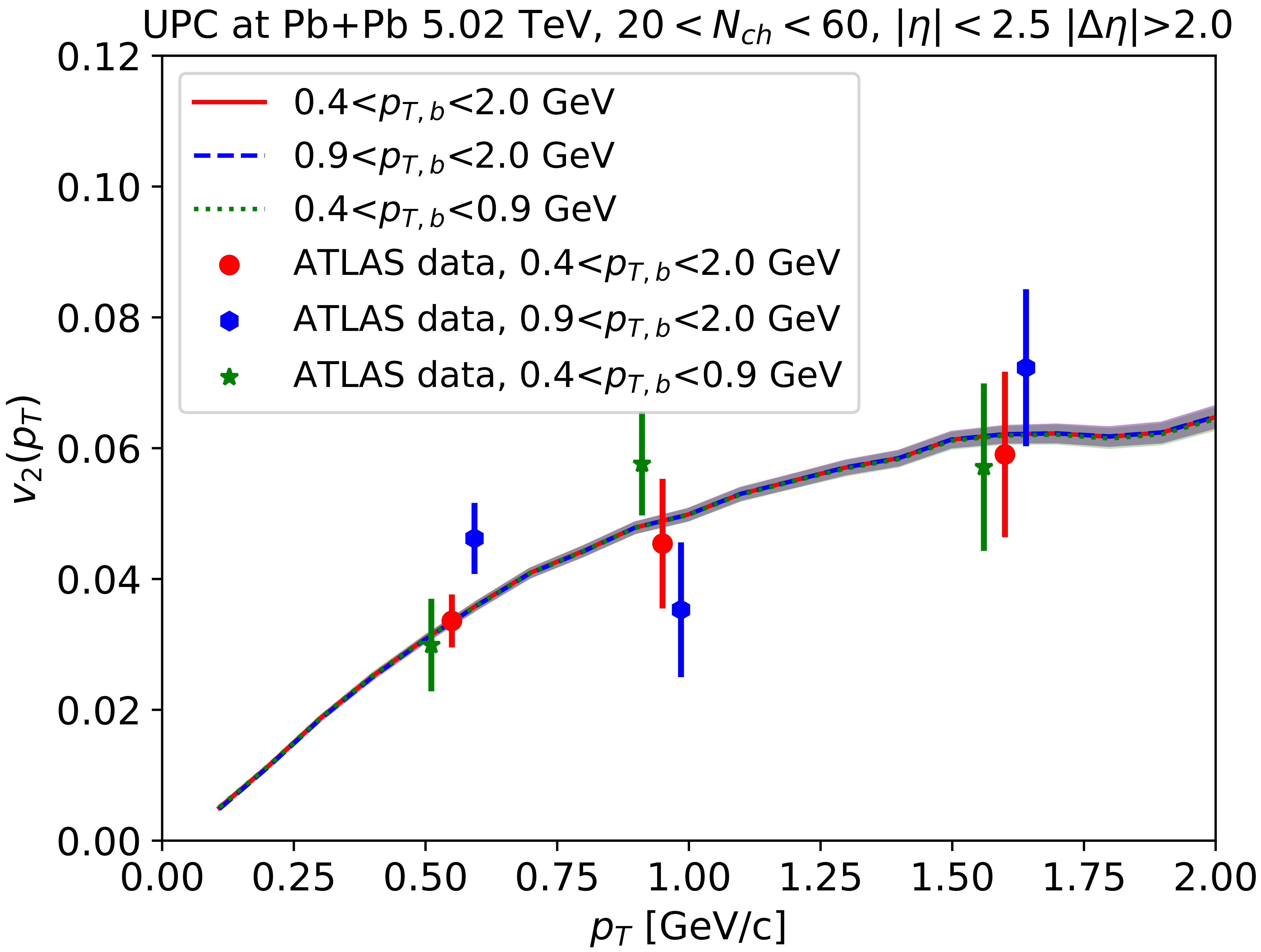


- Shapes of $dN_{ch}/d\eta$ reproduced for p+Pb and γ^*+Pb collisions
- Elliptic flow difference between p+Pb and γ^*+Pb collisions reproduced - driven by different amount of longitudinal flow decorrelation

Experimental data: ATLAS Collaboration, Phys. Rev. C 104, 014903 (2021)

(DE)CORRELATION IN p_T

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



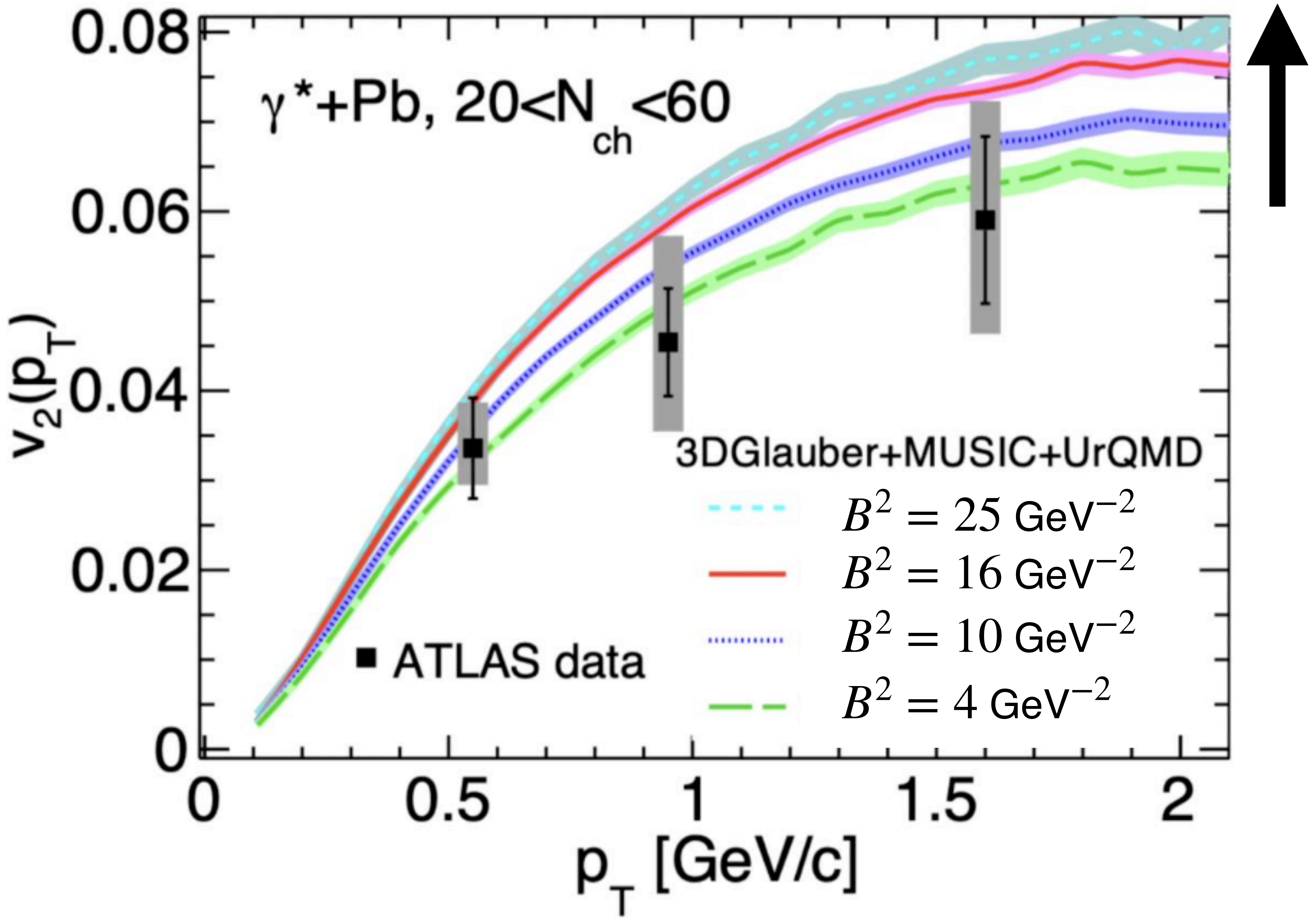
As expected from factorization in hydrodynamics (two-particle azimuthal harmonic $v_{2,2}$ is $\sim$ a product of single particle azimuthal anisotropies)

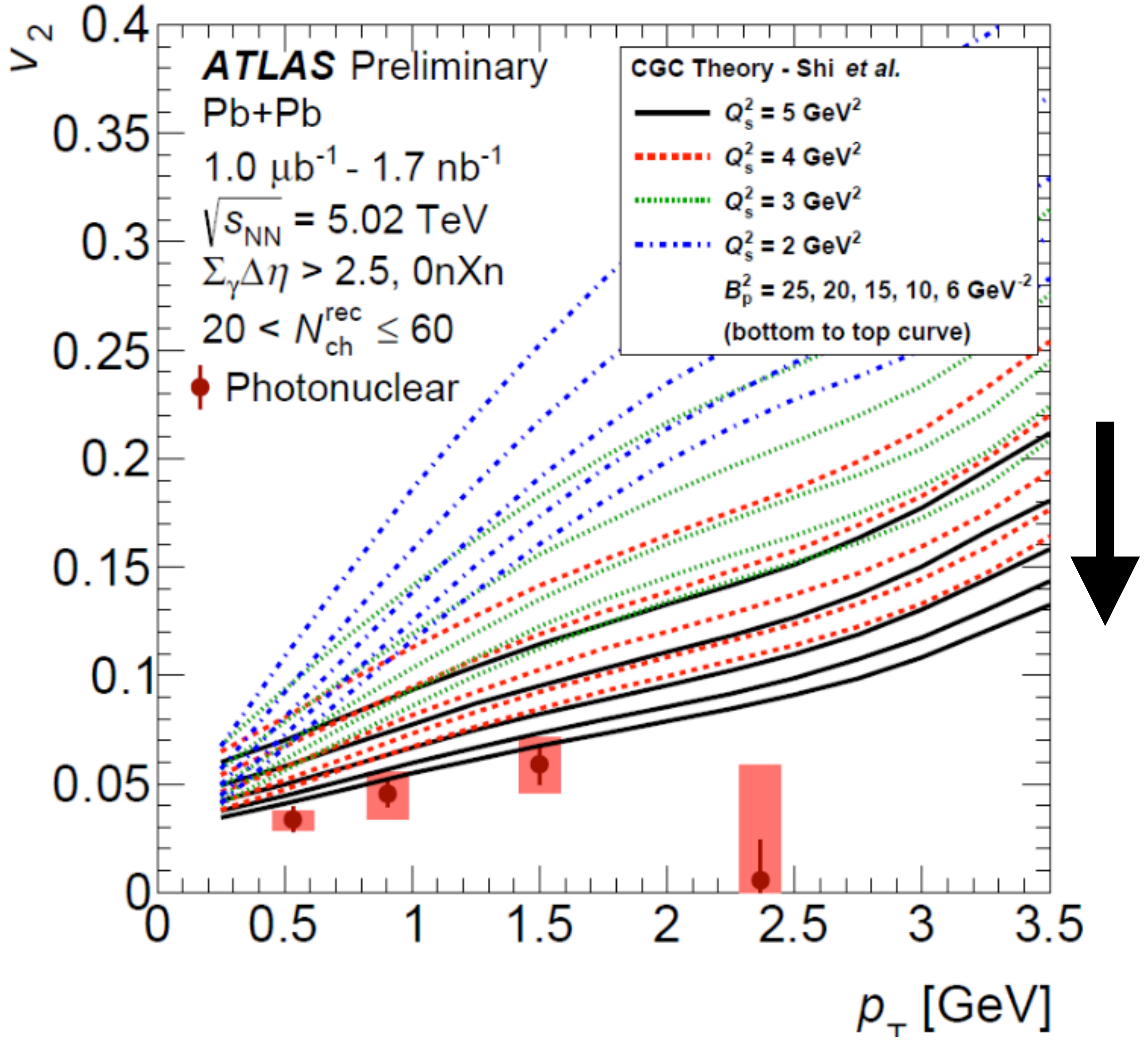
no significant dependence on the p_T range of the reference particles

Experimental data: ATLAS Collaboration, Phys. Rev. C 104, 014903 (2021)

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 $\propto B^2$
$(\sim 1/Q^2)$

- 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 color domains $v_2 \propto 1/B^2$

SUMMARY

- Light ion collisions and even γ+ion collisions show signs of collectivity
- Both initial state correlations and final state effects could contribute
- Described by a) Color Glass Condensate and b) Hydrodynamics
- CGC alone has trouble describing systematics in other small systems
- Final state models are challenged by how small the system is (applicability of hydrodynamics)
- Q^2 dependence at the EIC will shed more light on origin of signals

BACKUP

FACTORIZED DIPOLE APPROXIMATION

H. Duan, A. Kovner, V. V. Skokov, JHEP 12 (2022) 077

- Find leading contributions: area $S_\perp$enhanced contributions $Q_s^2 S_\perp \gg 1$
  A. Kovner, A. Rezaeian, Phys.Rev.D 96 (2017) 7, 074018
- If $\langle U_{ab}\rangle \neq 0$ an integral like the one on the right could maximally go as $S_\perp^4$
- But for dense target $\langle U_{ab}\rangle = 0$ and one needs non-zero contributions from $\langle U_{\vec{x}}^{ab} U_{\vec{y}}^{cd}\rangle$, which is the case for the smallest color singlets
- $\langle U_{\vec{x}}^{ab} U_{\vec{y}}^{cd}\rangle$ for $|\vec{x}-\vec{y}| > Q_s^{-1}$ is negligible due to color neutralization
- This reduces the largest power of $S_\perp$ to $S_\perp^2$
- If singlet state has more than 2 partons, one loses another power of $S_\perp$ for each

$$\int \prod_{i=1}^{4} d^2\boldsymbol{x}_i f(\boldsymbol{x}_1,\dots,\boldsymbol{x}_4)\langle \mathrm{tr}[U_{\boldsymbol{x}_1}U_{\boldsymbol{x}_2}U_{\boldsymbol{x}_3}U_{\boldsymbol{x}_4}]\rangle$$

$$= \int \prod_{i=1}^{4} d^2\boldsymbol{x}_i f(\boldsymbol{x}_1,\dots,\boldsymbol{x}_4)\Big[\langle U^{ab}_{\boldsymbol{x}_1}U^{bc}_{\boldsymbol{x}_2}\rangle\langle U^{cd}_{\boldsymbol{x}_3}U^{da}_{\boldsymbol{x}_4}\rangle$$

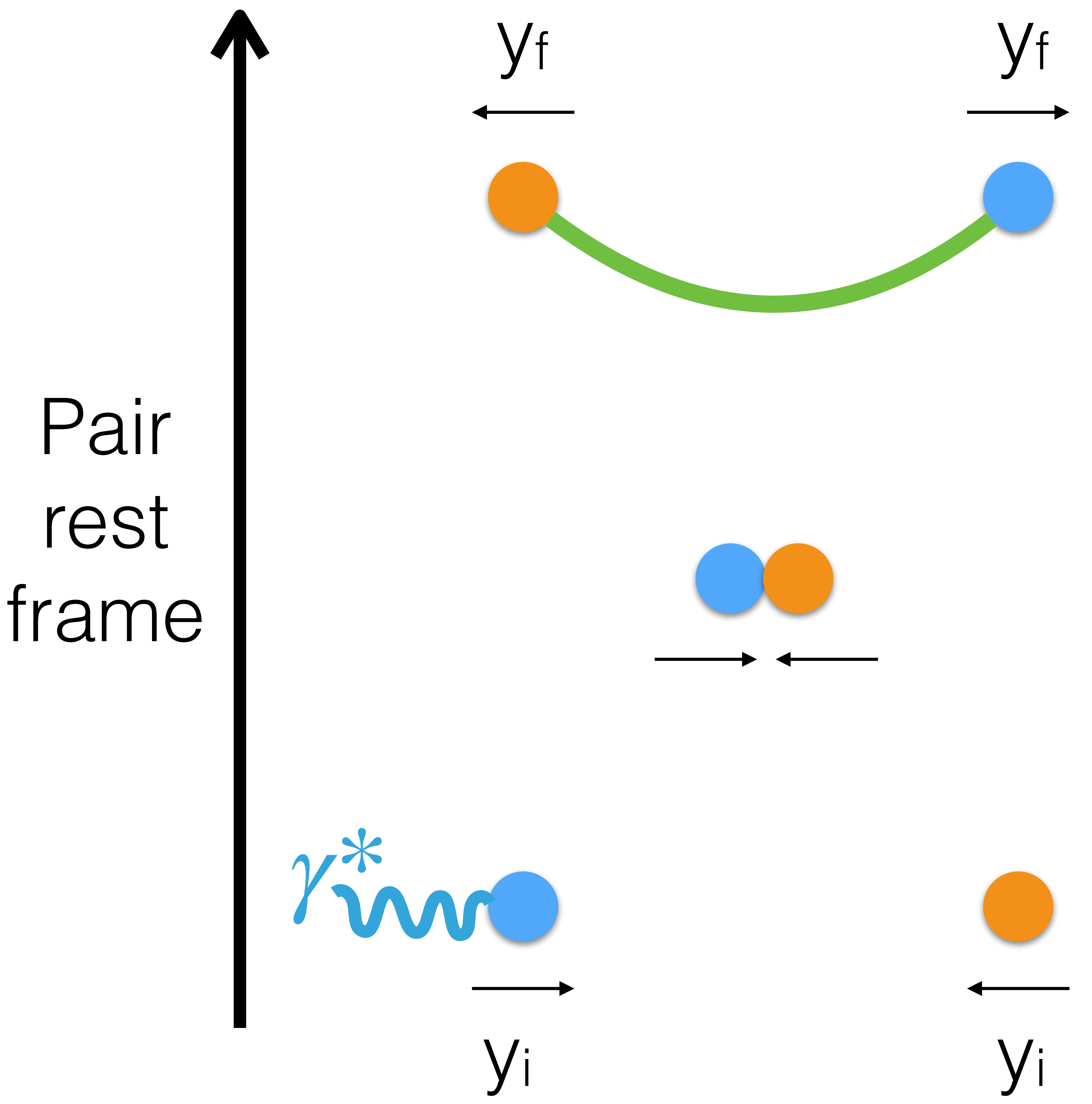
$$+\langle U^{da}_{\boldsymbol{x}_4}U^{ab}_{\boldsymbol{x}_1}\rangle\langle U^{bc}_{\boldsymbol{x}_2}U^{cd}_{\boldsymbol{x}_3}\rangle+\langle U^{ab}_{\boldsymbol{x}_1}U^{cd}_{\boldsymbol{x}_3}\rangle\langle U^{bc}_{\boldsymbol{x}_2}U^{da}_{\boldsymbol{x}_4}\rangle\Big]+\mathcal{O}(S_\perp)$$

- So, the leading result can be expressed just using dipoles:

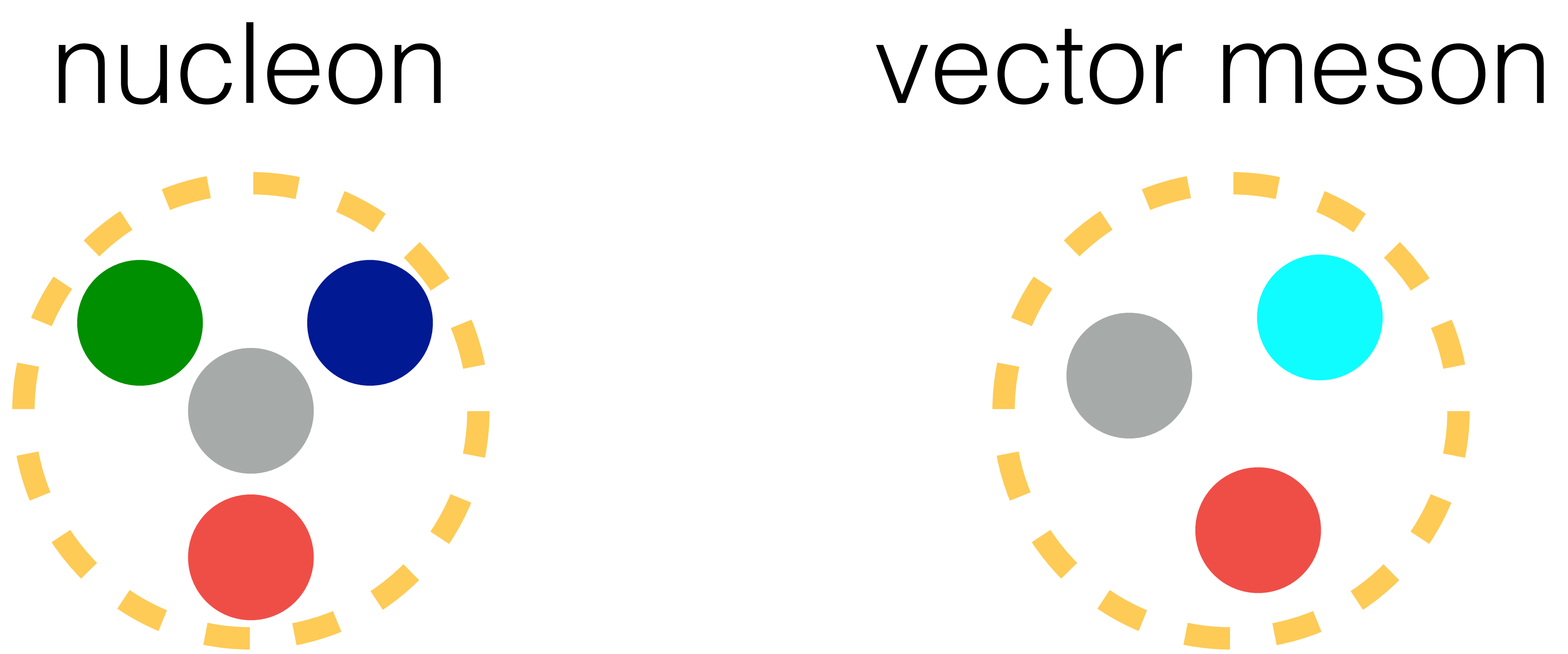
$$\langle U_{\vec{x}}^{ab} U_{\vec{y}}^{cd}\rangle = \frac{1}{N_c^2-1}\delta_{ab}\delta_{cd}D(\vec{x},\vec{y})$$

INITIAL STATE FOR γ^* + Pb

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



- Same model as used in collision systems discussed so far
- Virtual photon described as a vector meson: two quarks plus soft cloud



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:

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

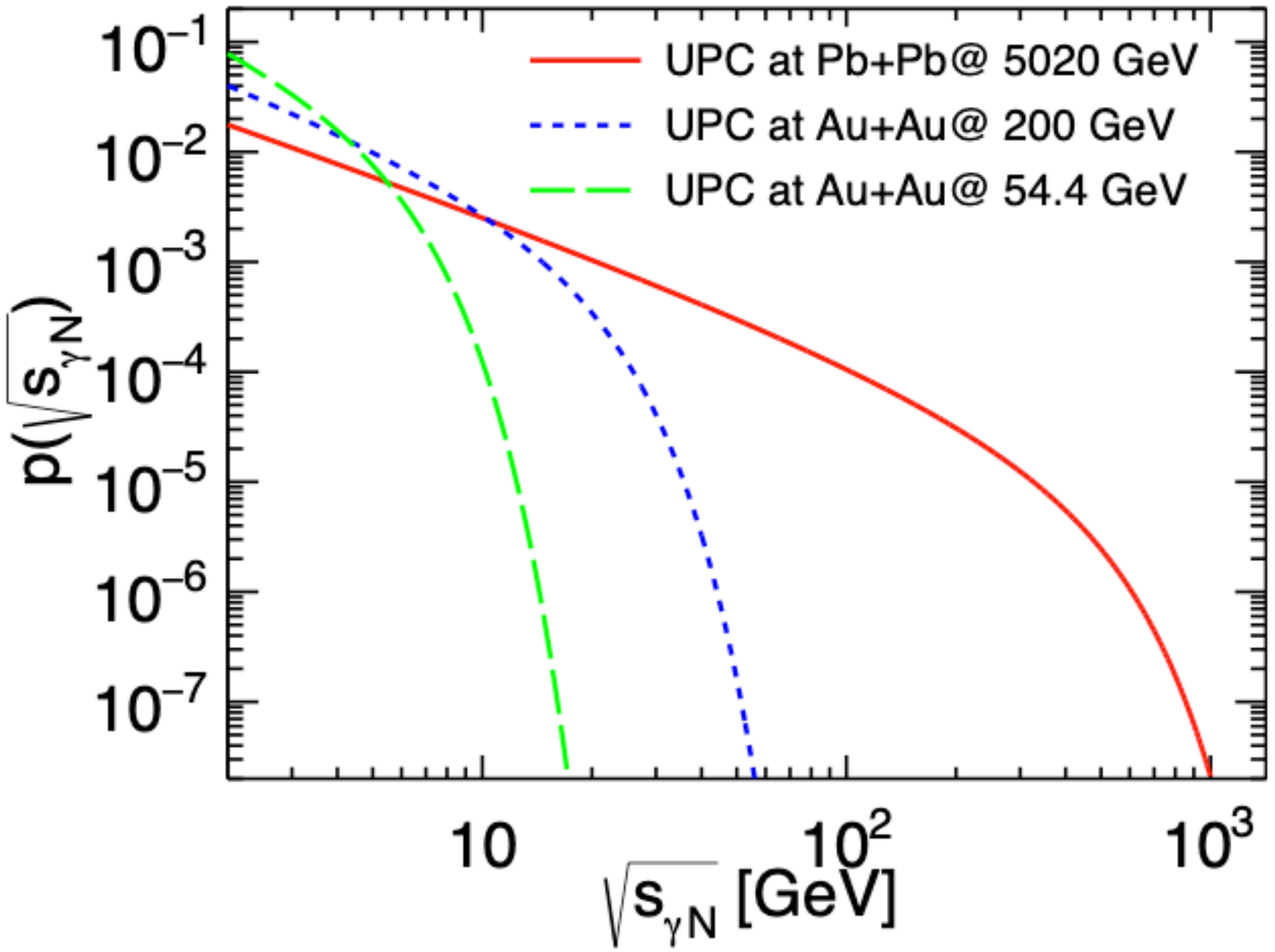
$w_R^{AA} = 2k_\gamma R_A/\gamma_L$ with $\gamma_L = \sqrt{s_{\rm NN}}/(2m_N)$

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

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

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

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



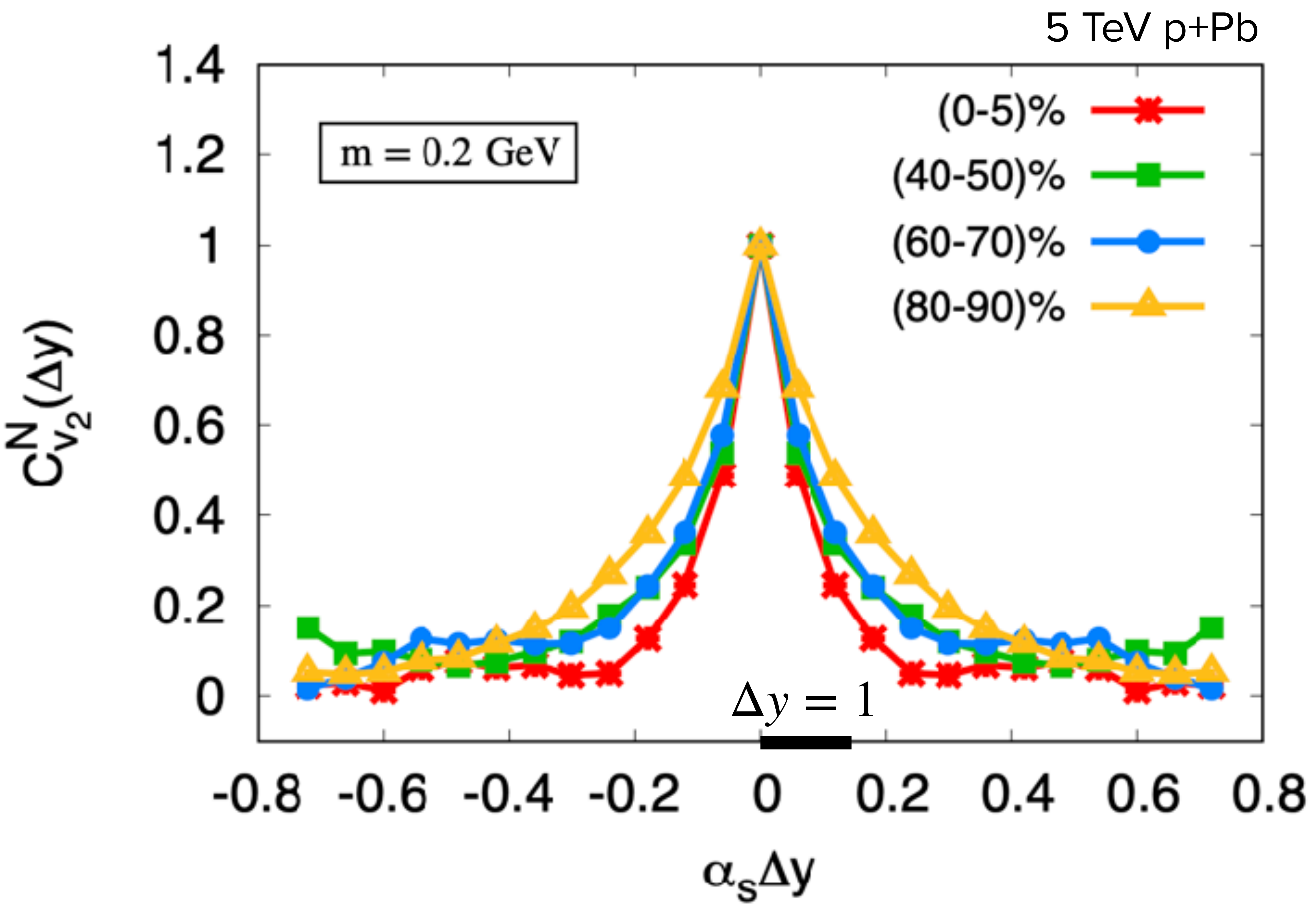
RAPIDITY DEPENDENCE OF INITIAL ANISOTROPY

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

CGC based IP-Glasma
+ rapidity evolution (JIMWLK)

$$C^N_{\mathcal{O}}(\eta_1,\eta_2) = \frac{\left\langle \mathrm{Re}\left(\mathcal{O}(\eta_1)\mathcal{O}^*(\eta_2)\right)\right\rangle}{\sqrt{\langle|\mathcal{O}(\eta_1)|^2\rangle\langle|\mathcal{O}(\eta_2)|^2\rangle}}$$

Initial momentum anisotropy
decorrelates quickly
with rapidity difference



further evidence: Observed Baryon/meson v_2 grouping and splitting (see You Zhou's talk)

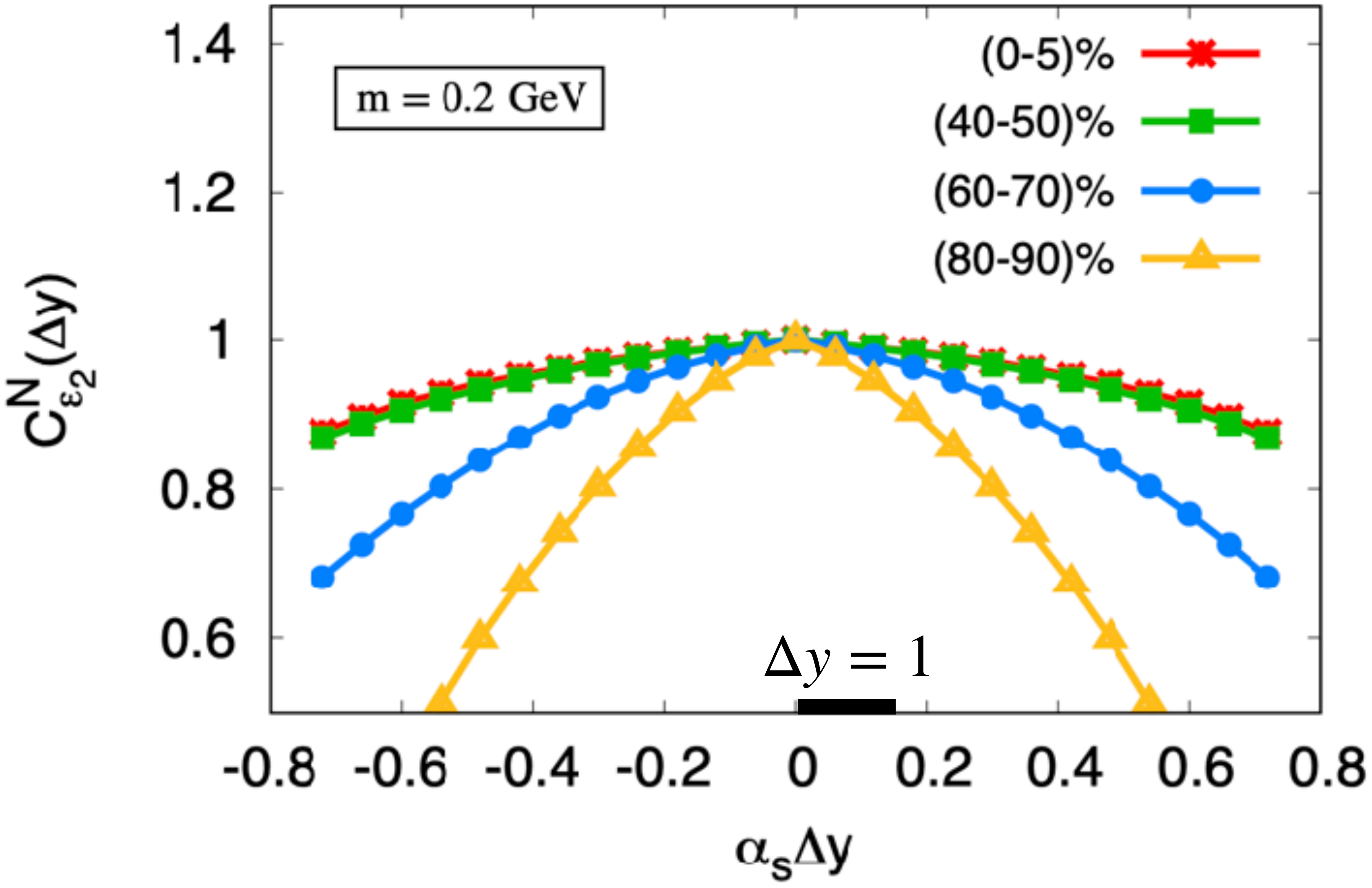
→ Strong final state interactions needed to describe data

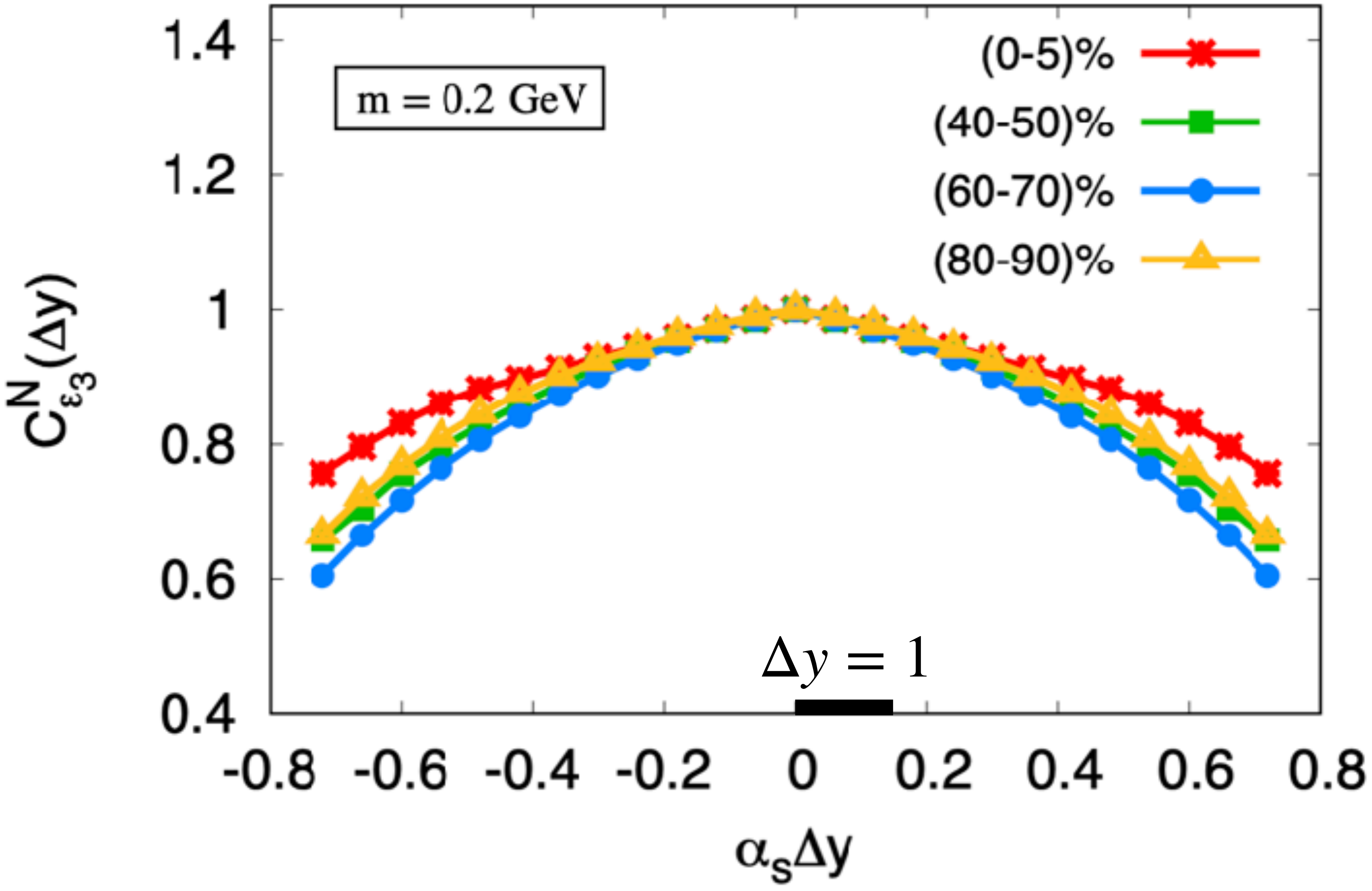
RAPIDITY DEPENDENCE OF GEOMETRY

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

The geometry, quantified here with ε_2 and ε_3, decorrelates slowly

5 TeV p+Pb



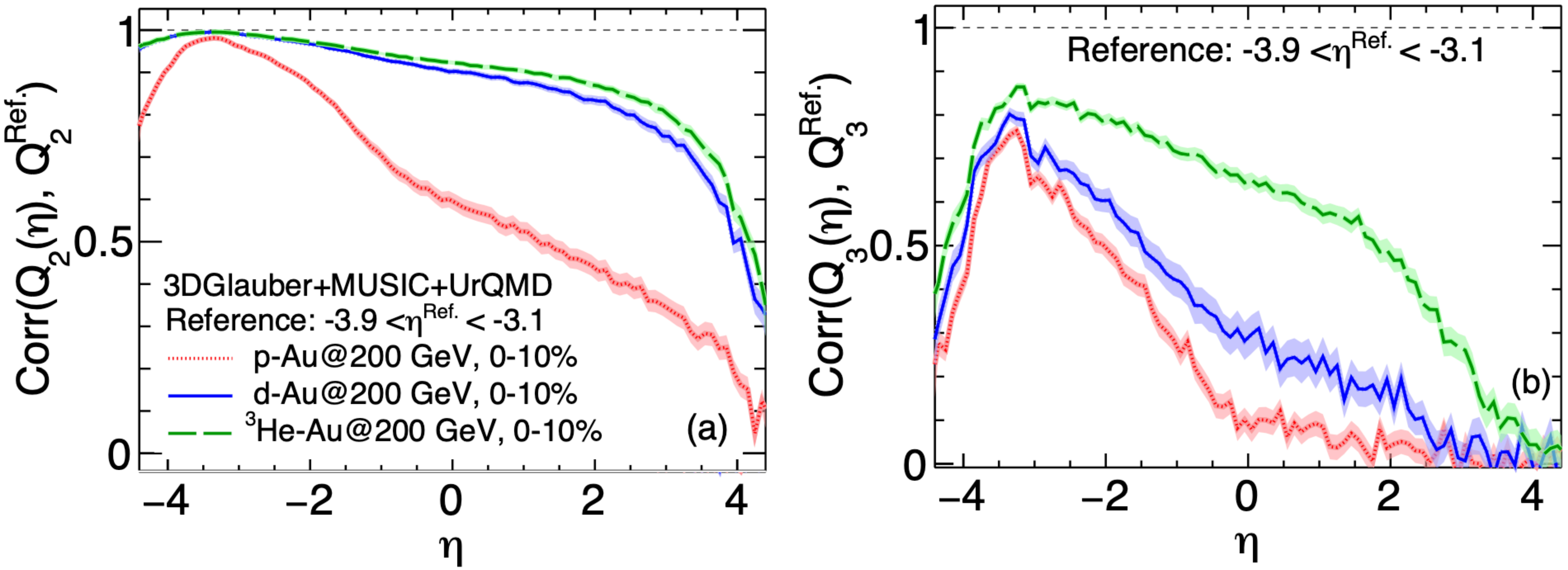


$$C^N_{\mathcal{O}}(\eta_1, \eta_2) = \frac{\left\langle \mathrm{Re}\left(\mathcal{O}(\eta_1)\mathcal{O}^*(\eta_2)\right) \right\rangle}{\sqrt{\langle |\mathcal{O}(\eta_1)|^2 \rangle \langle |\mathcal{O}(\eta_2)|^2 \rangle}}$$

but rapidity dependence is not insignificant

FLOW VECTOR DECORRELATION

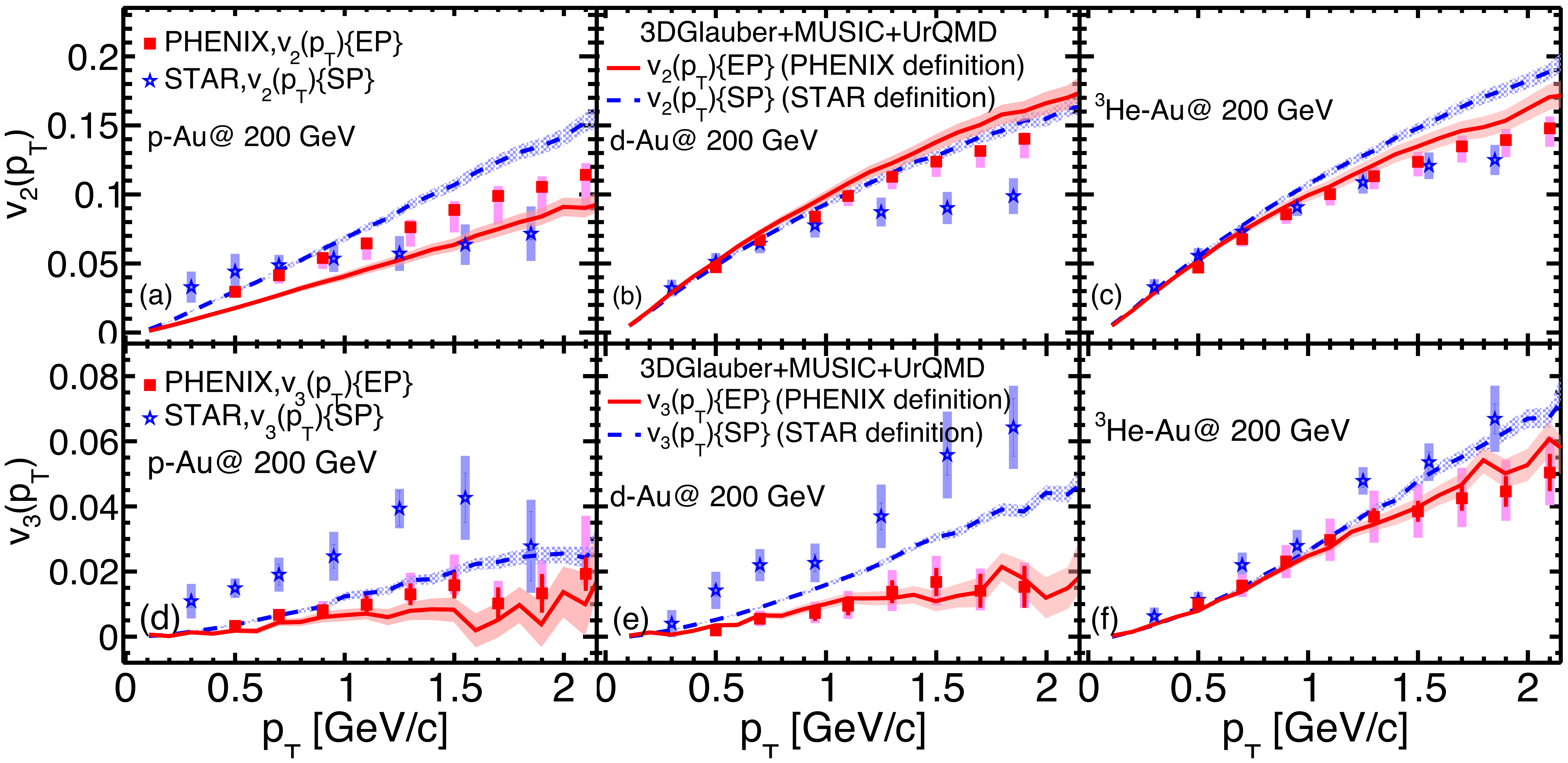
W. Zhao, S. Ryu, C. Shen and B. Schenke, Phys.Rev.C 107 (2023) 1, 014904



- Elliptic flow vectors in (d, ^{3}He)+Au are strongly correlated over wide range in η
- 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

DIFFERENT RAPIDITY BINS, DIFFERENT RESULTS

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



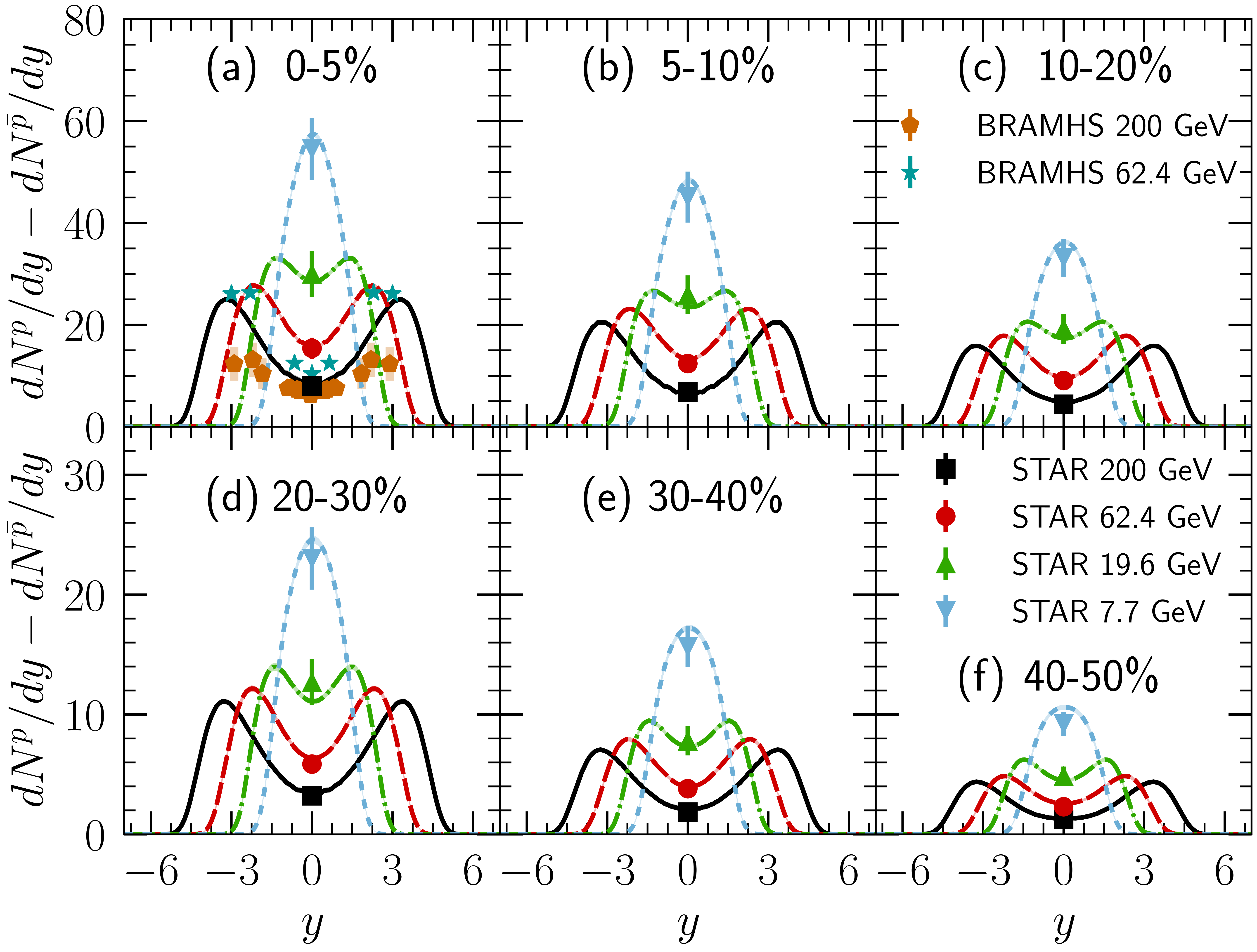
PHENIX:
(p, d)+Au: $\eta_1 \in [-3.9, -3.1]$,
$\eta_2 \in [-0.35, 0.35]$
^{3}He+Au: $\eta_1 \in [-3, -1]$,
$\eta_2 \in [-0.35, 0.35]$

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

- Tune to ^{3}He+Au; PHENIX $v_n(p_T)$ in (d, ^{3}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

NET-PROTON PRODUCTION

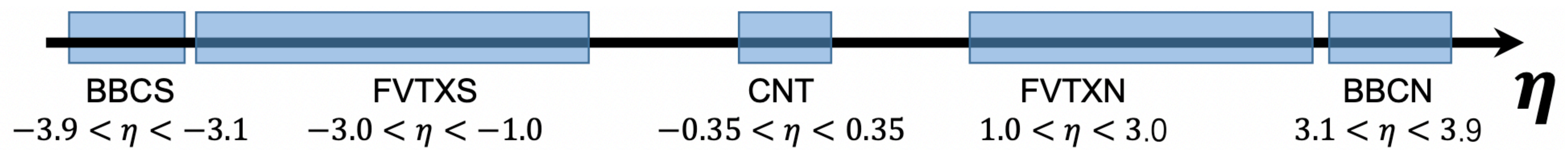
C. Shen and B. Schenke, Phys. Rev. C 105, 064905 (2022)



- 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



BBCS $-3.9 < \eta < -3.1$

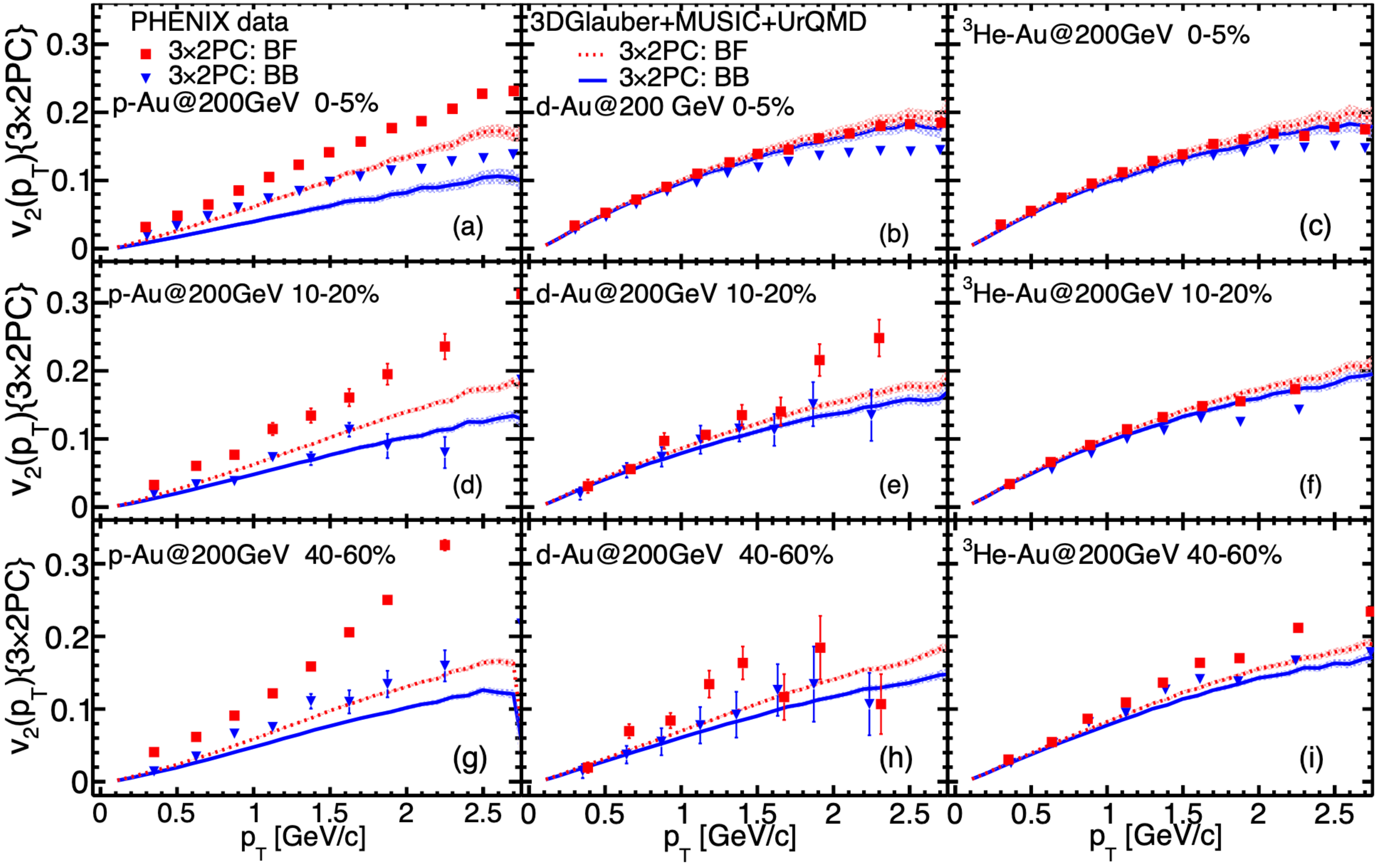
FVTXS $-3.0 < \eta < -1.0$

CNT $-0.35 < \eta < 0.35$

FVTXN $1.0 < \eta < 3.0$

BBCN $3.1 < \eta < 3.9$

η



$3 \times 2PC$

$$C_n^{AB} = \langle Q_{nA} Q_{nB}^* \rangle ,$$

$$c_n^{AC}(p_T) = \langle Q_{nA} q_{nC}^*(p_T) \rangle ,$$

$$c_n^{BC}(p_T) = \langle Q_{nB} q_{nC}^*(p_T) \rangle .$$

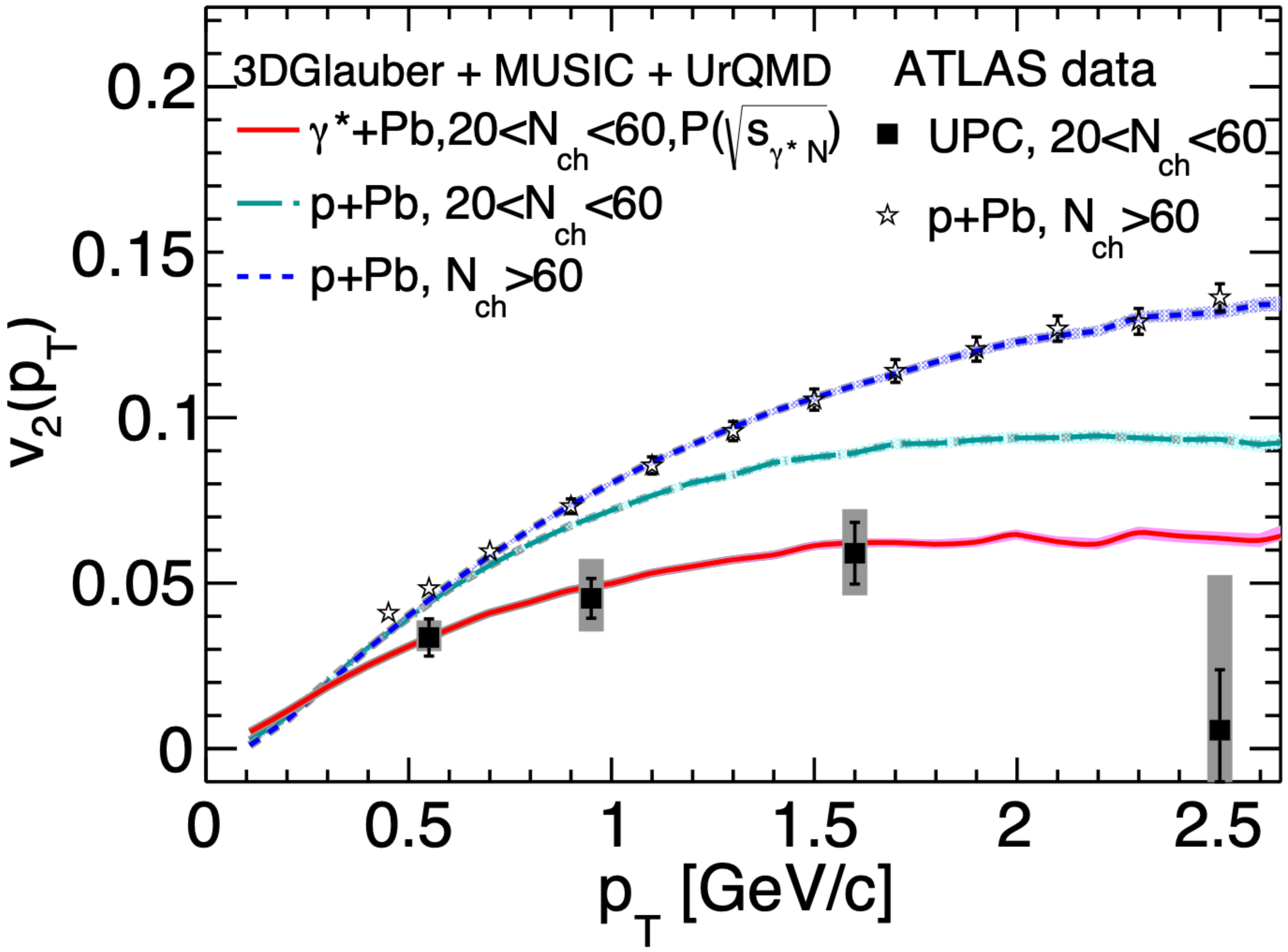
$$v_n^C(p_T) = \sqrt{\frac{c_n^{AC}(p_T) c_n^{BC}(p_T)}{C_n^{AB}}} .$$

BB: BBCS-FVTXS-CNT

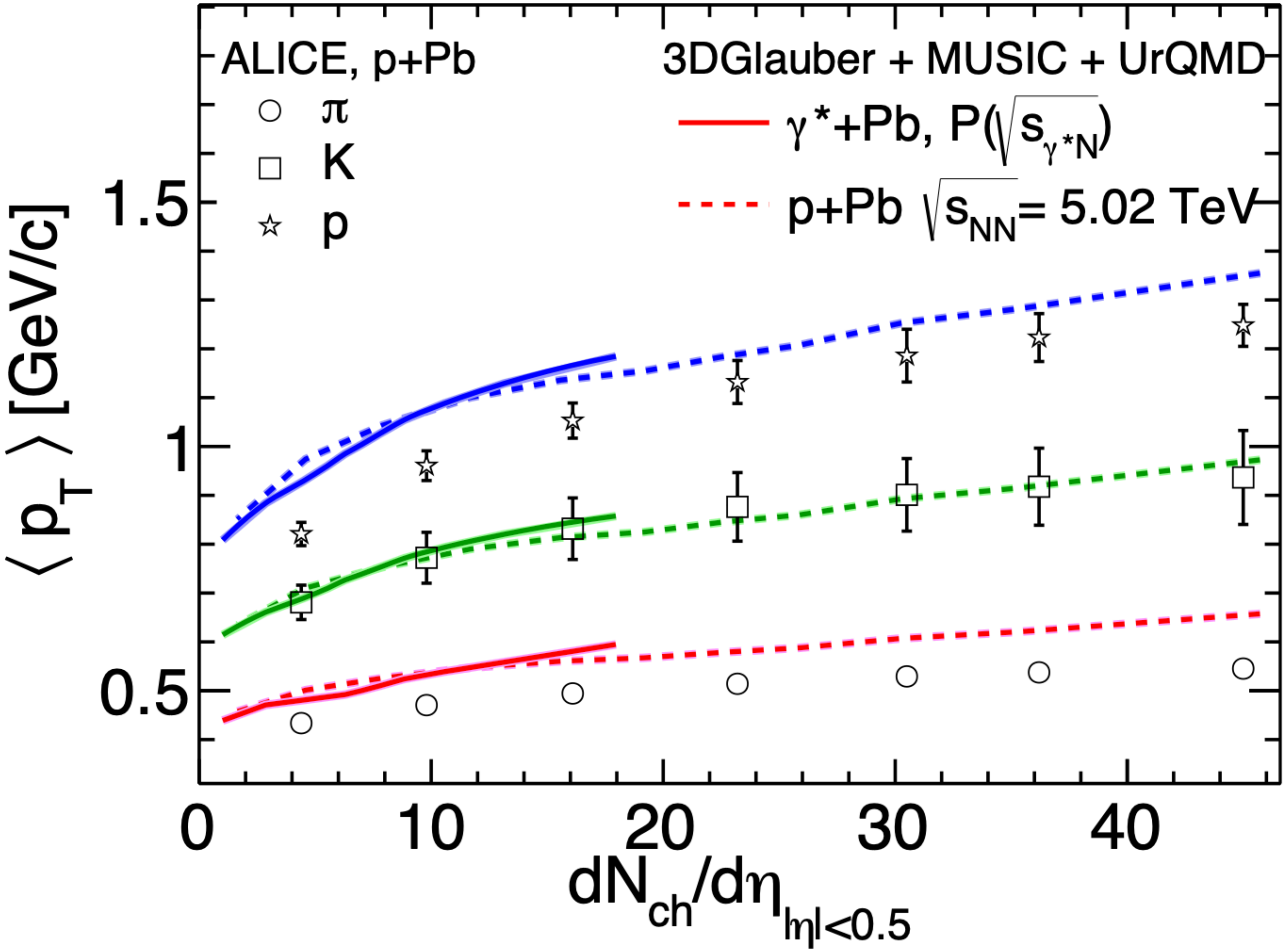
BF: FVTXS-CNT-FVTXT

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