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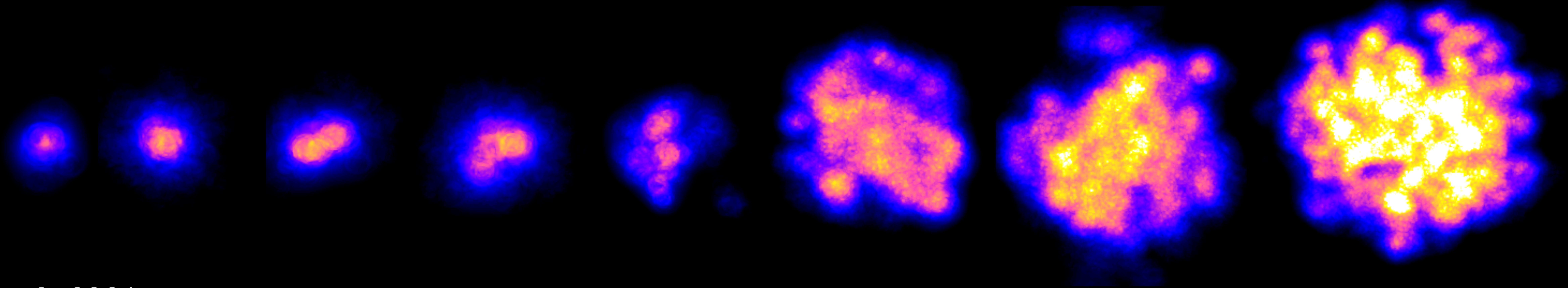
COLLECTIVITY IN SMALL COLLISION SYSTEMS

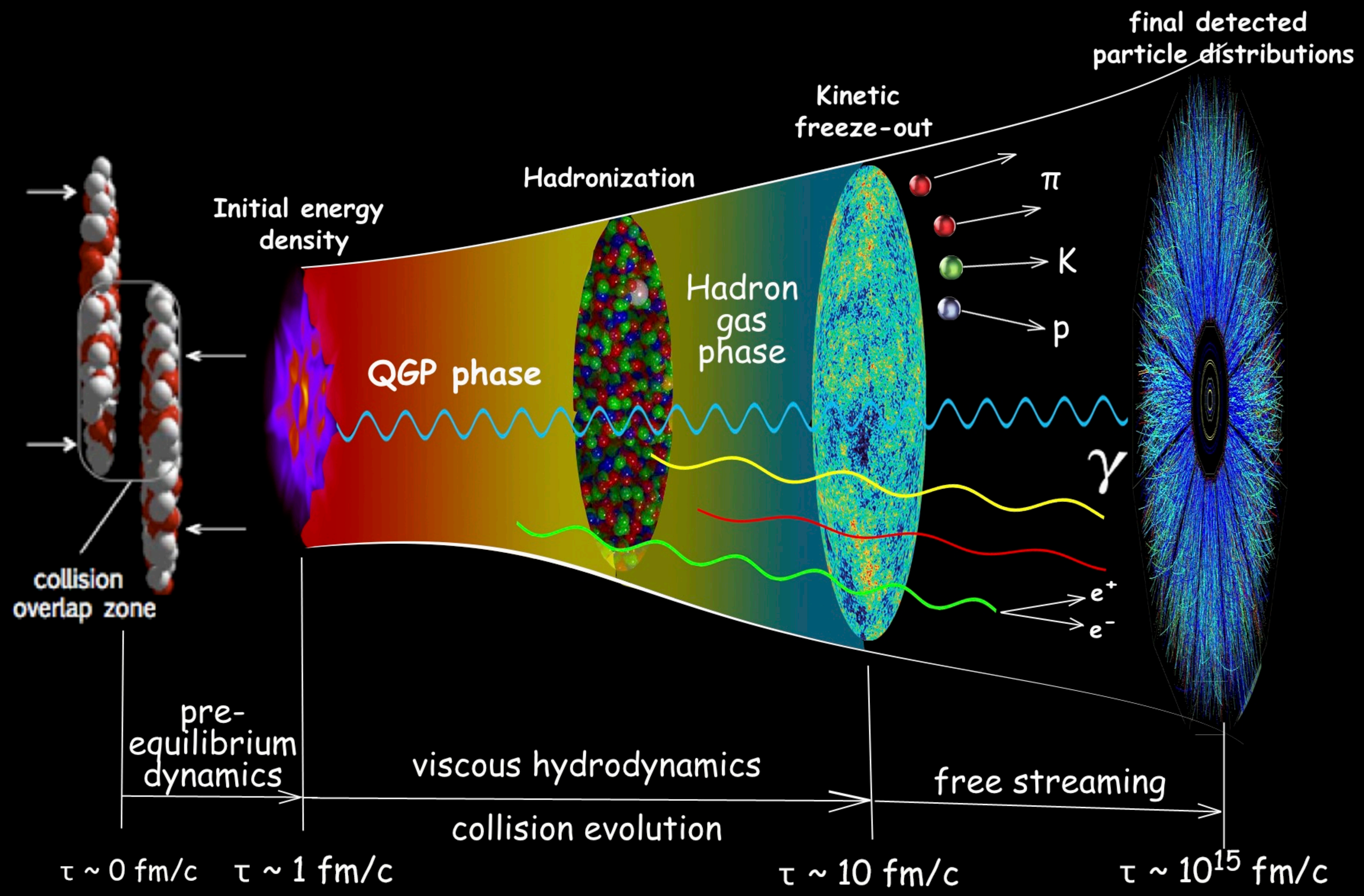
CHUN SHEN



June 9, 2021

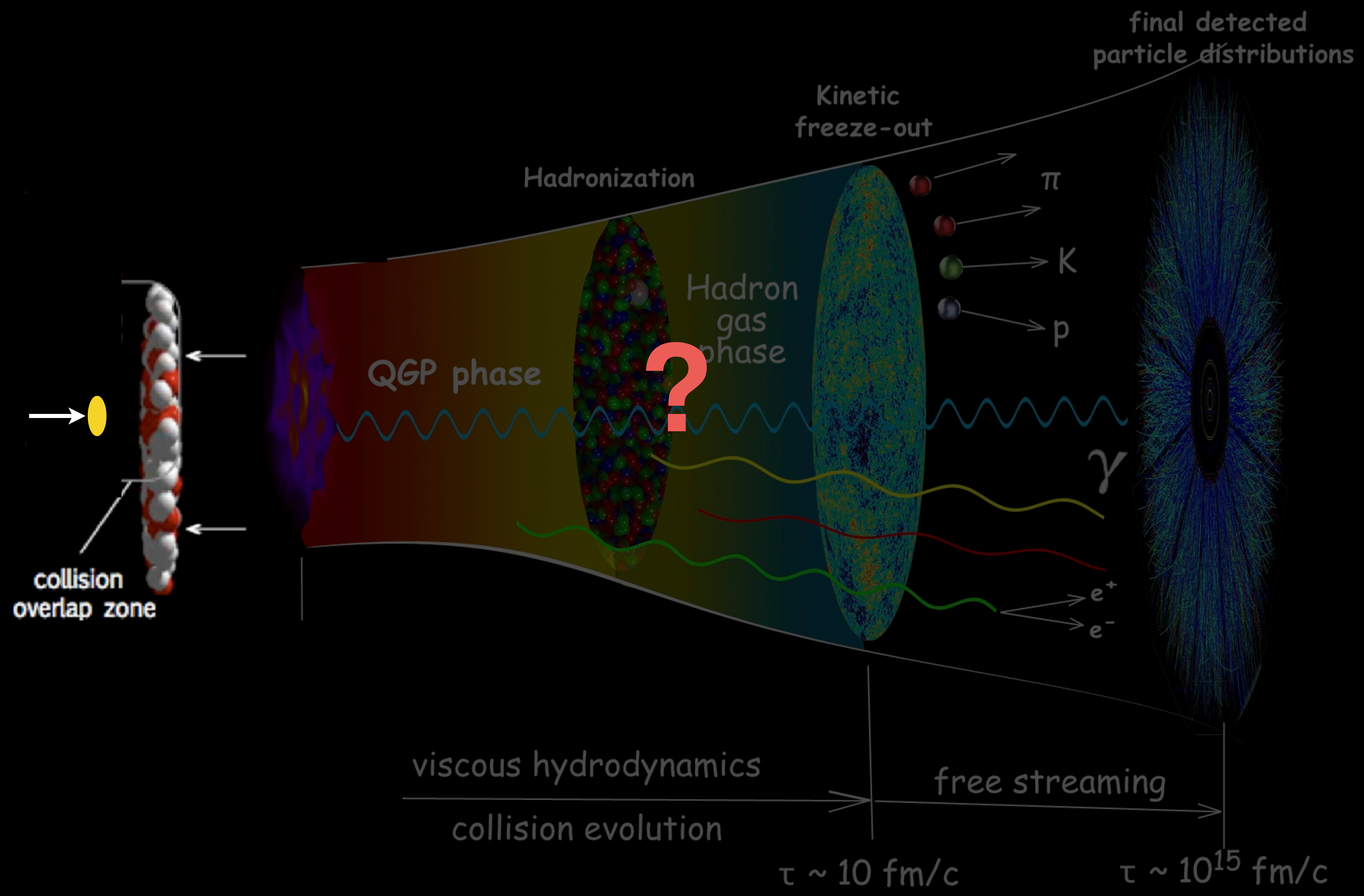
2021 RHIC/AGS Annual User's Meeting

RELATIVISTIC HEAVY-ION COLLISIONS



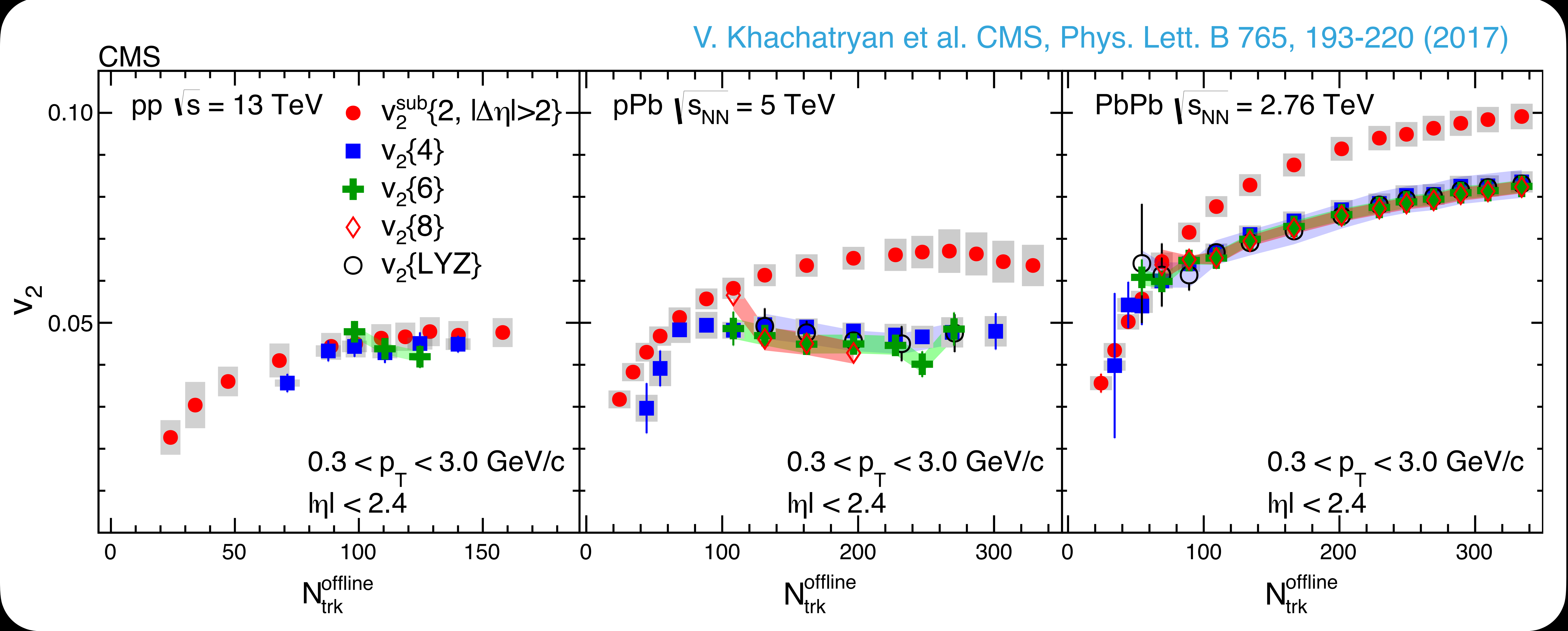
Hybrid modeling with event-by-event fluctuations can describe the complex dynamics of heavy-ion collisions, which is driven by multiple length scales

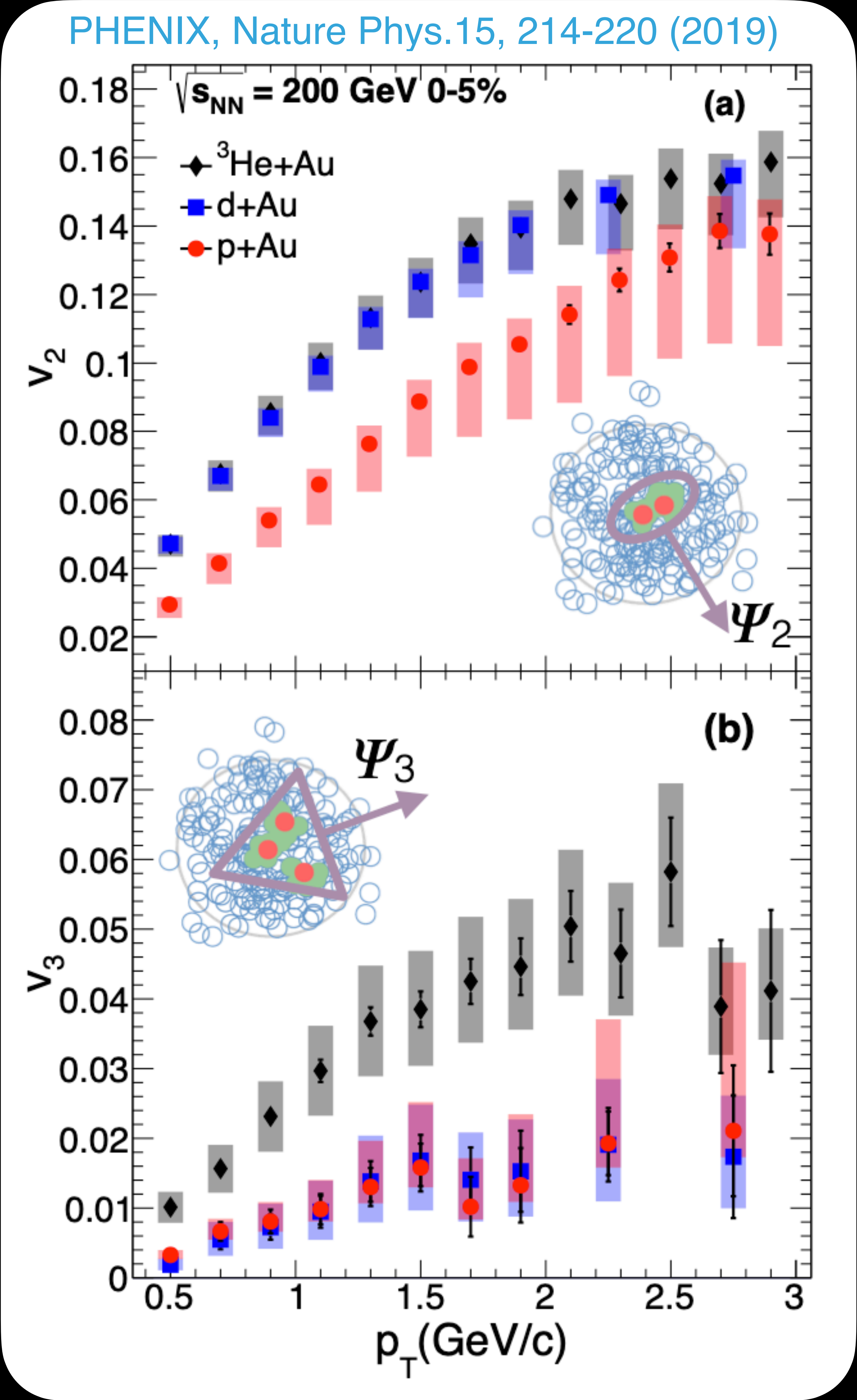
RELATIVISTIC HEAVY-ION COLLISIONS



Extending this hybrid dynamical framework to study collectivity in small collision systems has been driving the frontier theory development for relativistic nuclear collisions

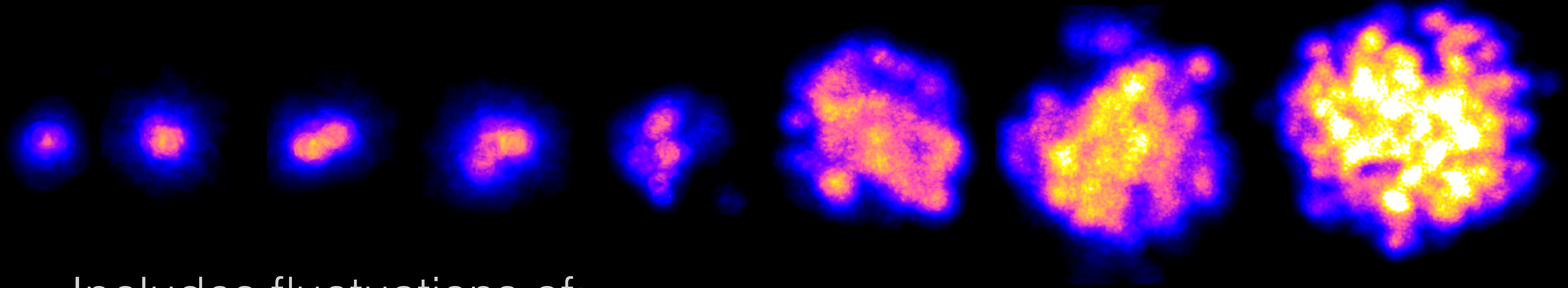
COLLECTIVITY IN SMALL SYSTEMS





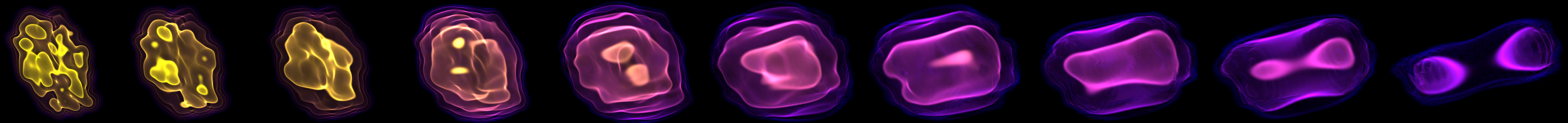
- Collective multi-particle correlations have been observed at RHIC and the LHC
- Anisotropic flow coefficients show strong responses to initial geometry in high multiplicity light-heavy collisions

THE HYBRID THEORETICAL FRAMEWORK



Includes fluctuations of:

Impact parameter, nucleon positions, valence quark positions, color charges



$T^{\mu\nu}$ 0^+ 0.5-1 → τ (fm)

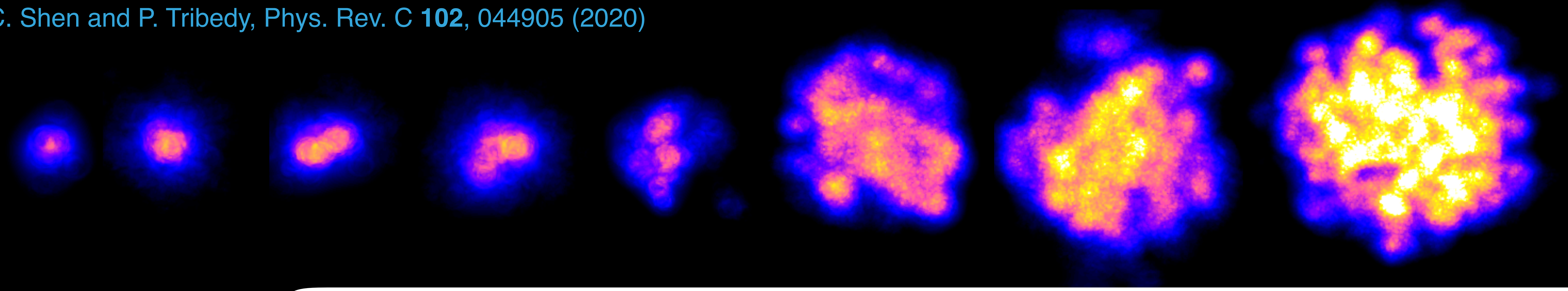
Initial State +
Pre-equilibrium dynamics

Hydrodynamics

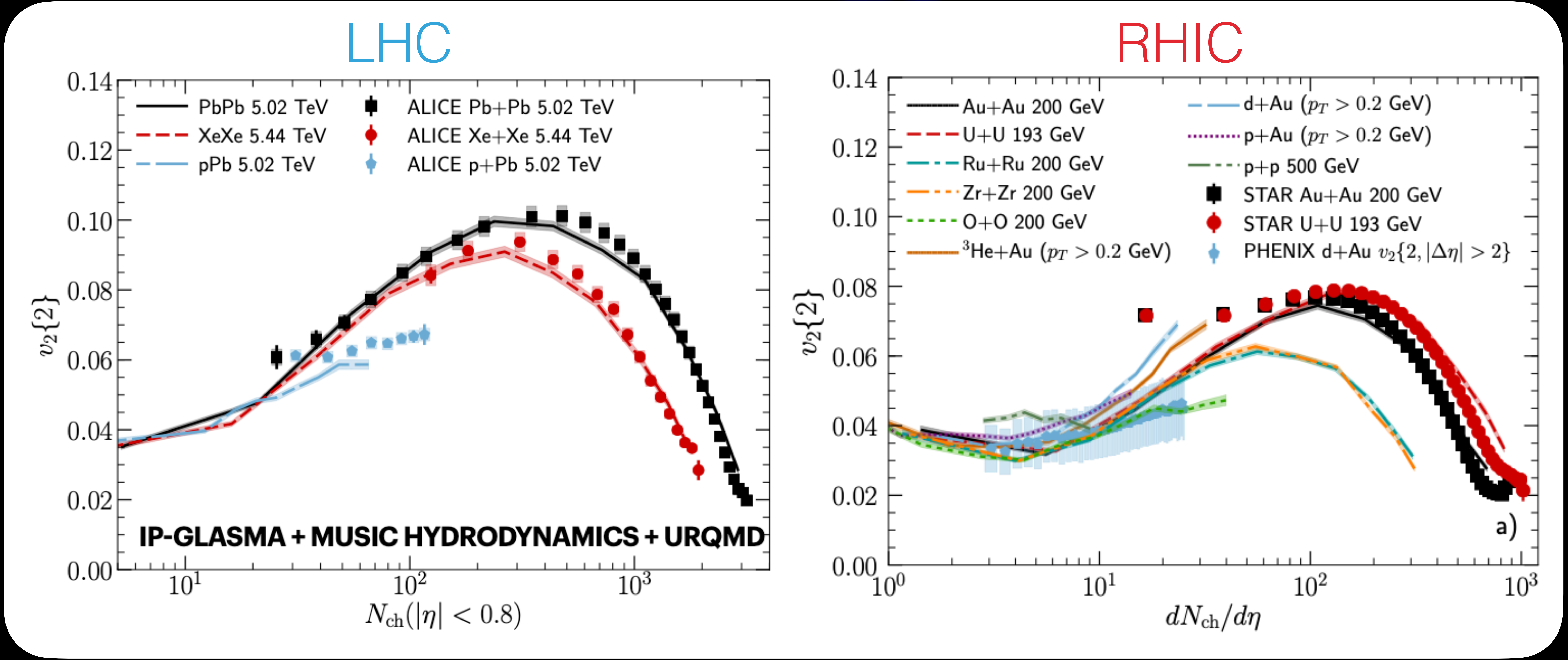
Hadronic Transport

RUNNING THE GAMUT OF HIGH ENERGY NUCLEAR COLLISIONS

B. Schenke, C. Shen and P. Tribedy, Phys. Rev. C **102**, 044905 (2020)

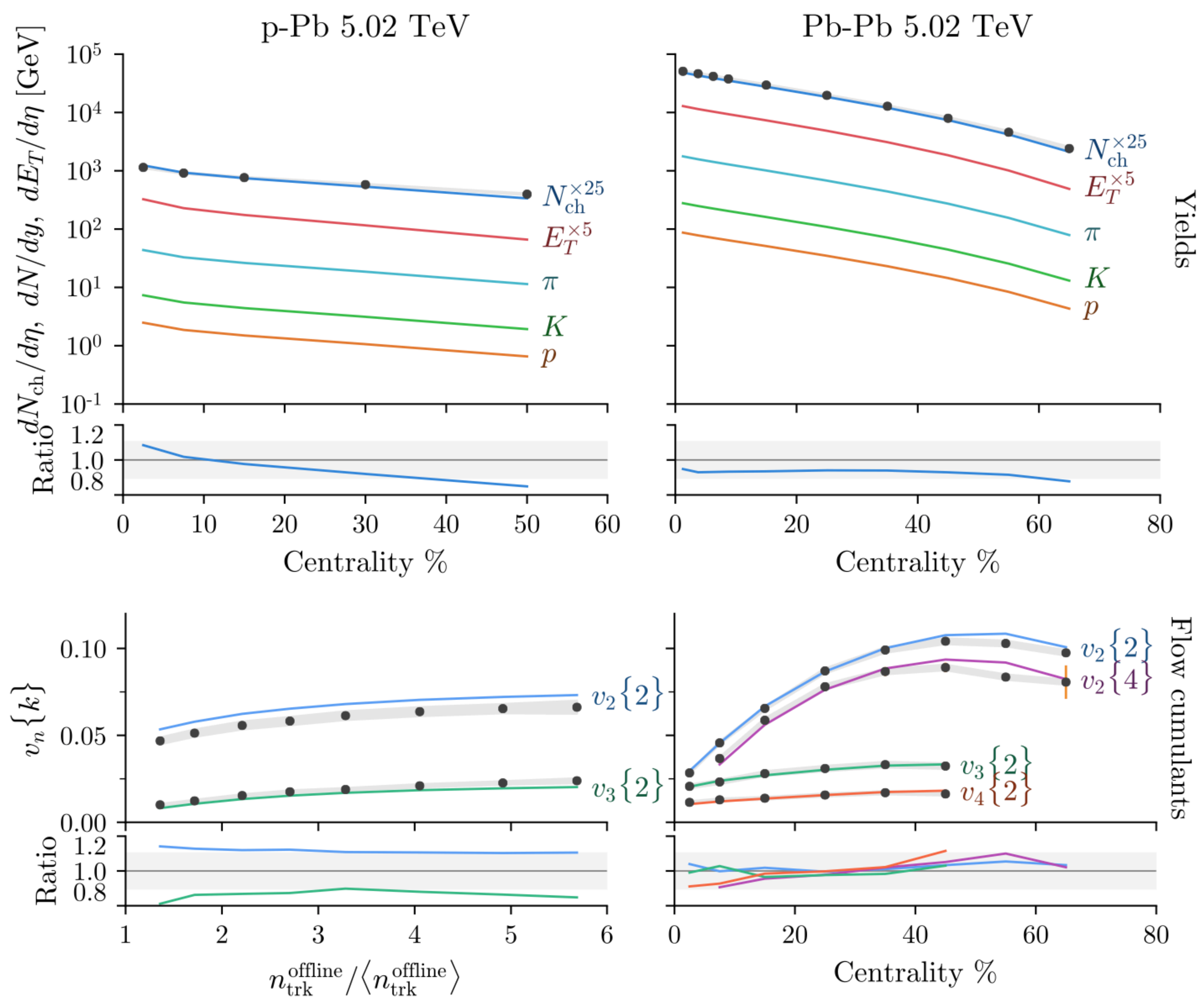


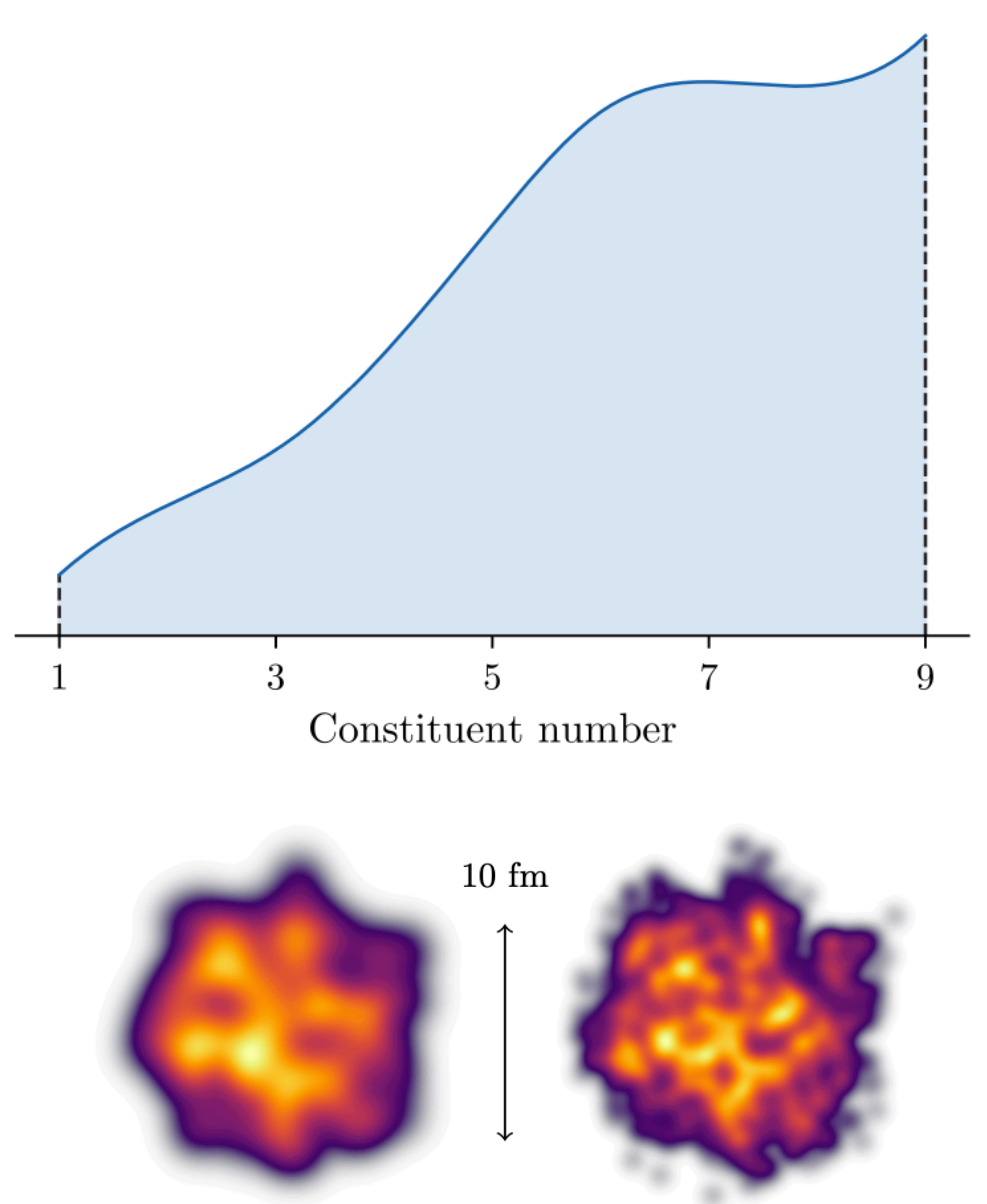
- One single set of model parameters for *ALL* types of collisions at the top RHIC and LHC energies



PROBING SUBNUCLEON SCALE FLUCTUATIONS

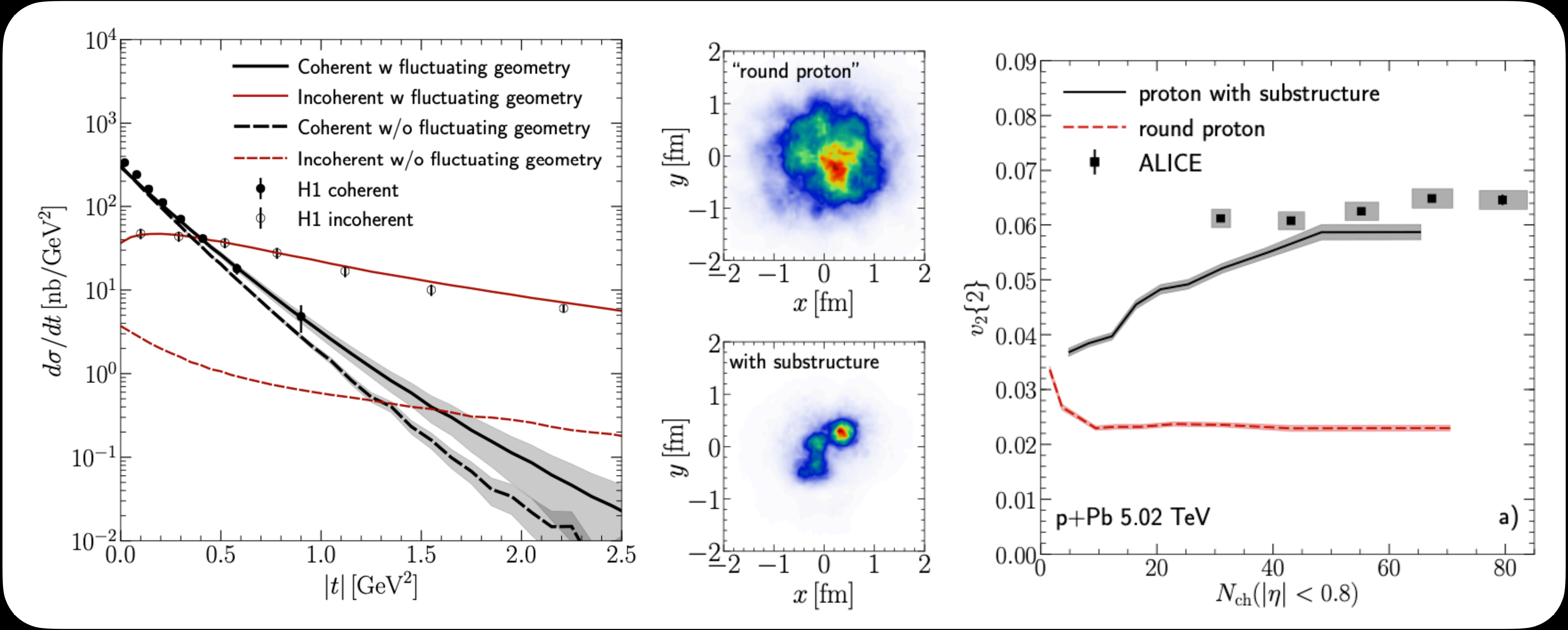
J. S. Moreland, J. E. Bernhard and S. A. Bass, Phys. Rev. C101, 024911 (2020)





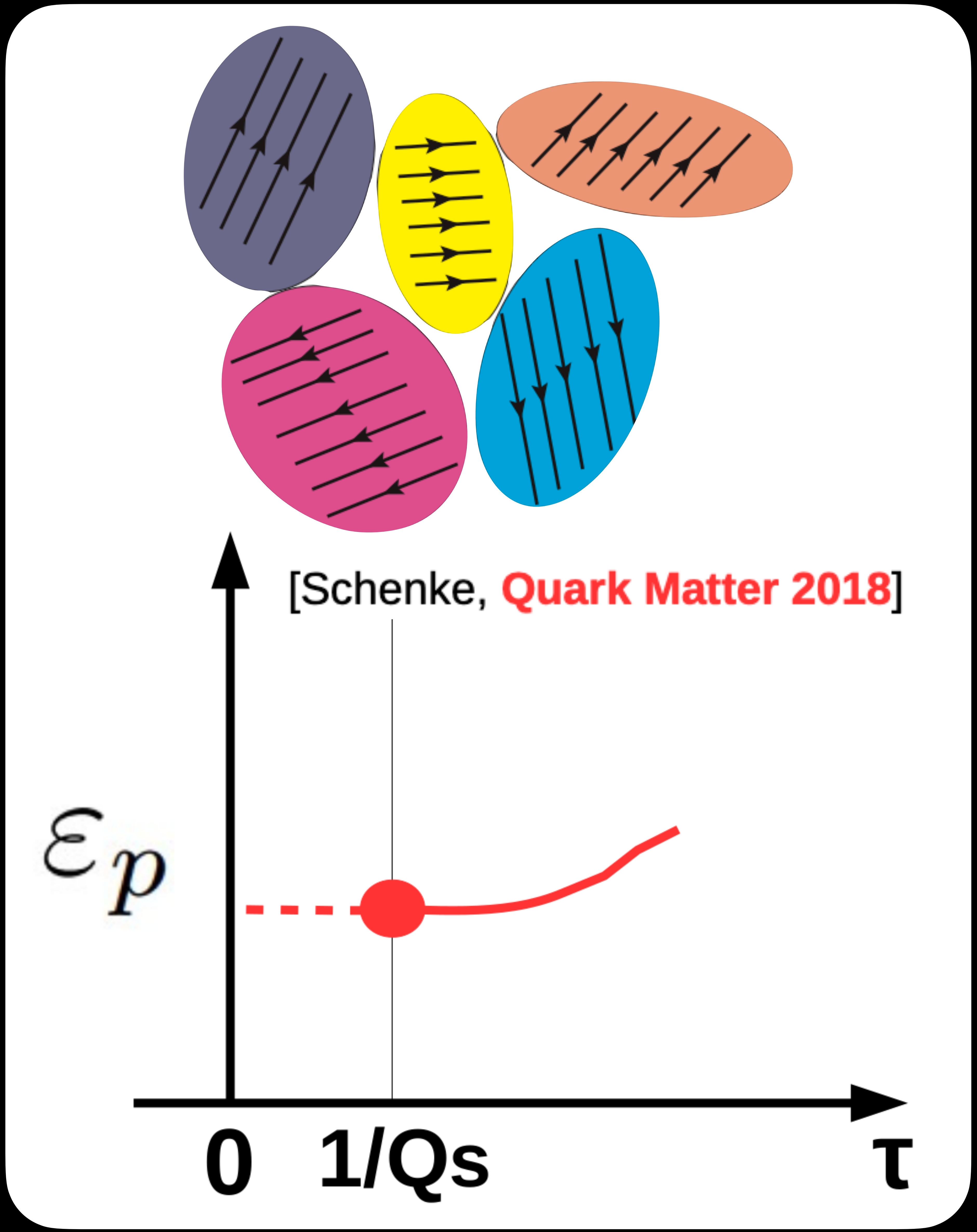
PROBING SUBNUCLEON SCALE FLUCTUATIONS

B. Schenke, arXiv:2102.11189 [nucl-th]



- Subnucleon scale fluctuations are essential for anisotropic flow in p+Pb collisions

BEYOND GEOMETRIC RESPONSE



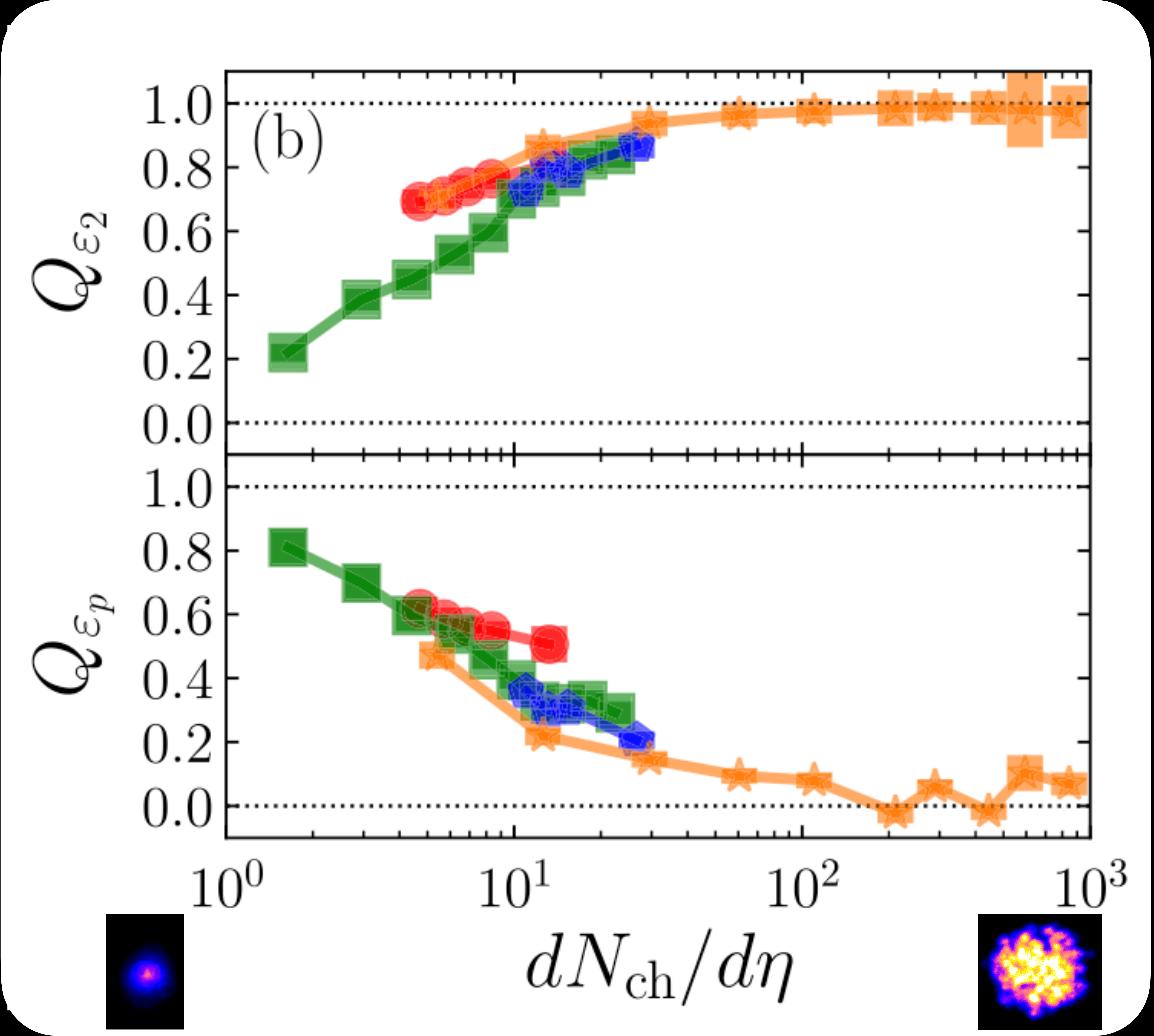
B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

- The Color Glass Condensate (CGC) predicts anisotropic particle productions because of

  1. Local anisotropies in the color fields
  2. Local density gradients
  3. Quantum interference effects

$$\mathscr{E}_p = \varepsilon_p e^{i2\psi_2^p} = \frac{\langle T^{xx} - T^{yy}\rangle + i\langle 2T^{xy}\rangle}{\langle T^{xx} + T^{yy}\rangle}$$

INITIAL STATE ANISOTROPIES VS GEOMETRIC RESPONSE



B. Schenke, C. Shen and P. Tribedy, Phys. Lett. B803, 135322 (2020)

Examine the Pearson correlation between initial state $\mathscr{E}_2$, $\mathscr{E}_p$ and final state V_2 in the model

$$Q_\varepsilon = \frac{Re\{\langle \mathscr{E} V_2^* \rangle\}}{\sqrt{\langle |\mathscr{E}|^2 \rangle \langle |V_2|^2 \rangle}}$$

The elliptic flow in low multiplicity events is more strongly correlated with $\mathscr{E}_p$ than $\mathscr{E}_2$

THE FULL PICTURE — WHICH ONE DOMINATES?

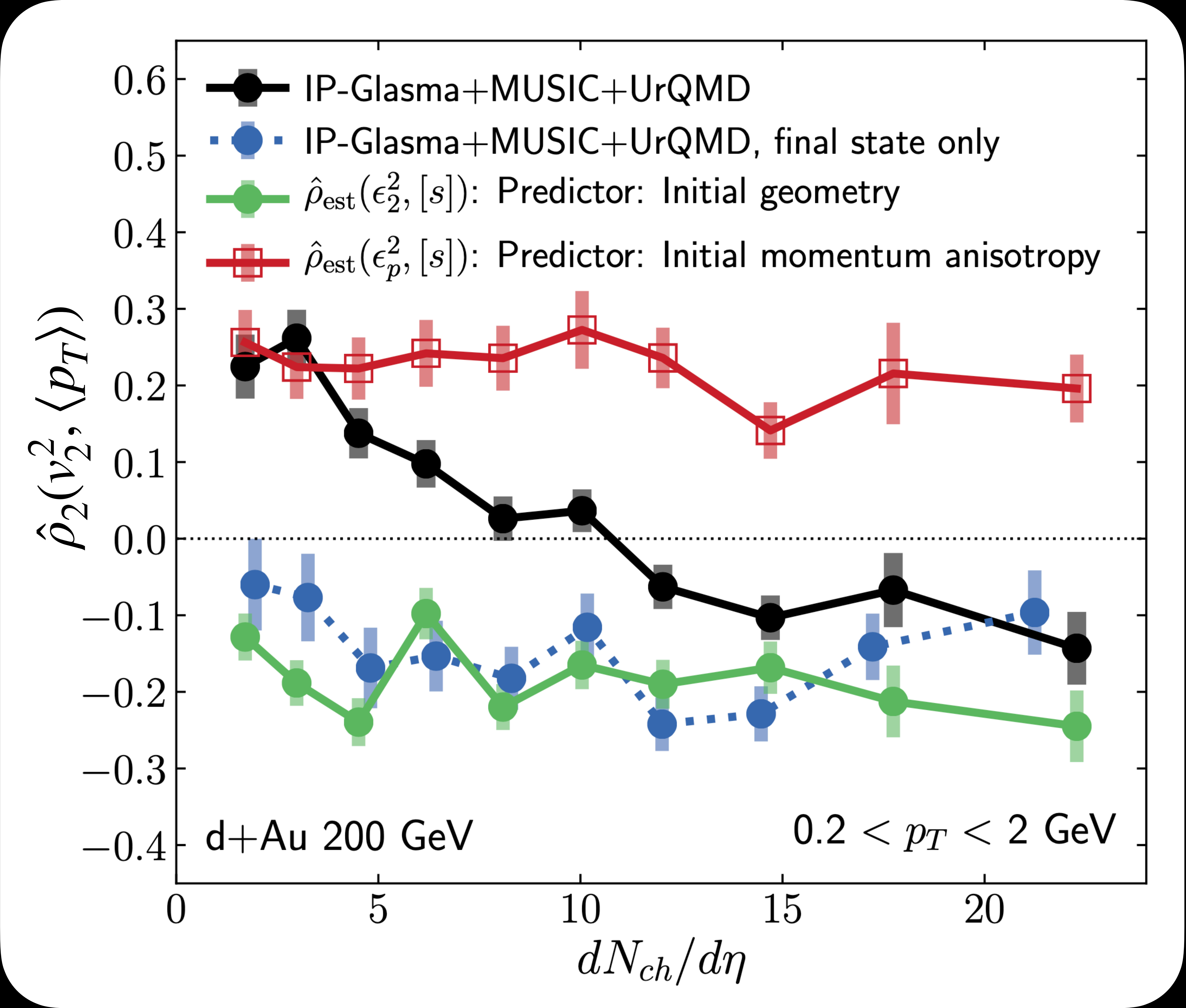
G. Giacalone, B. Schenke and C. Shen, Phys. Rev. Lett. 125, 192301 (2020)

$$\hat{\rho}_2(v_2^2, \langle p_T \rangle) = \frac{\langle \hat{\delta} v_2^2 \hat{\delta} \langle p_T \rangle \rangle}{\sqrt{\langle (\hat{\delta} v_2^2)^2 \rangle \langle (\hat{\delta} \langle p_T \rangle)^2 \rangle}}$$

We predict a sign change of the $\hat{\rho}_2$ correlator with multiplicity in p/d+Au collisions at RHIC and p+Pb collisions at LHC

For $dN^{ch}/d\eta \lesssim 10$, initial state correlation dominates

For $dN^{ch}/d\eta \gtrsim 10$, final state response to geometry dominates



NON-FLOW CONTRIBUTION IN ρ_2

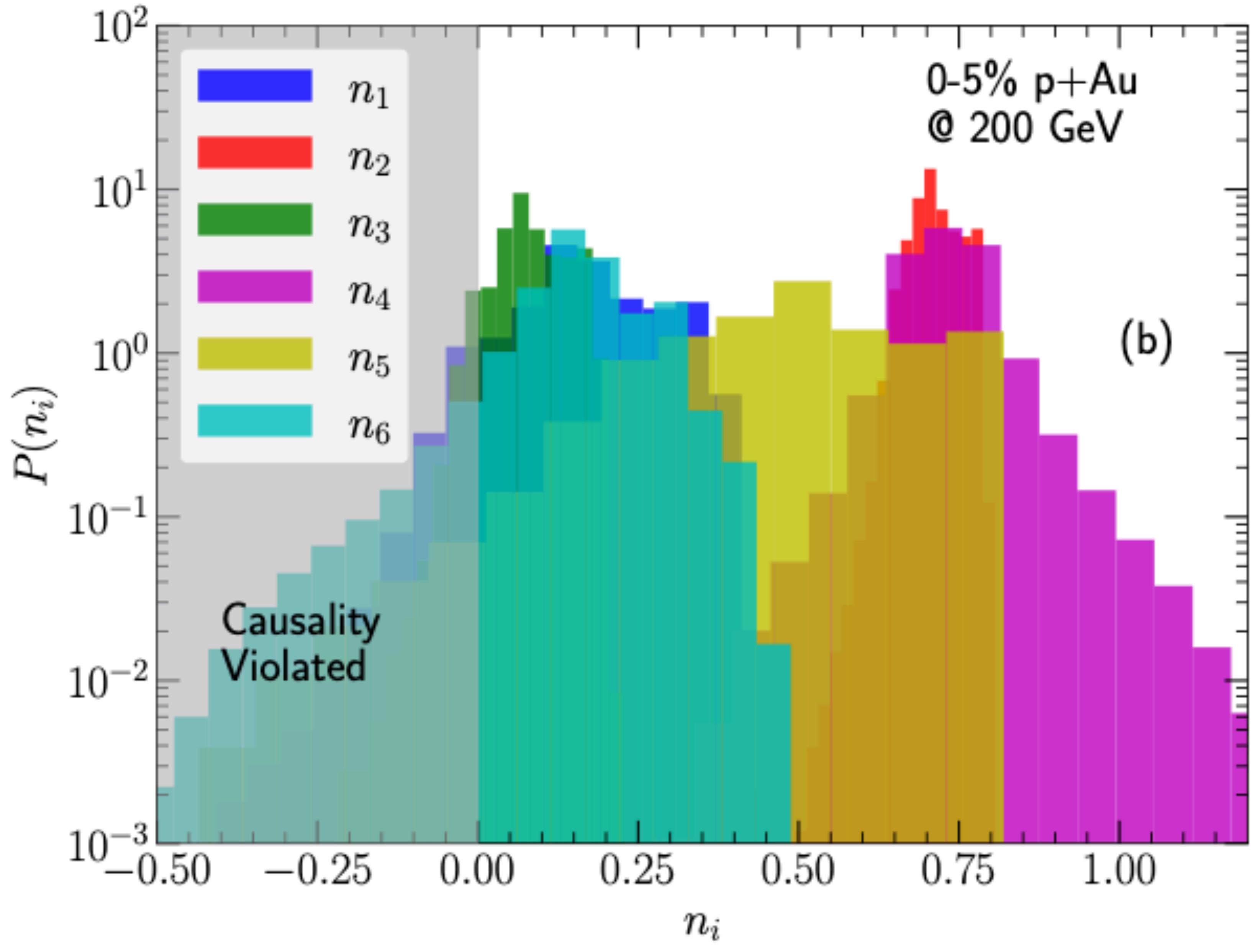
S. H. Lim and J. L. Nagle, arXiv:2103.01348 [nucl-th]

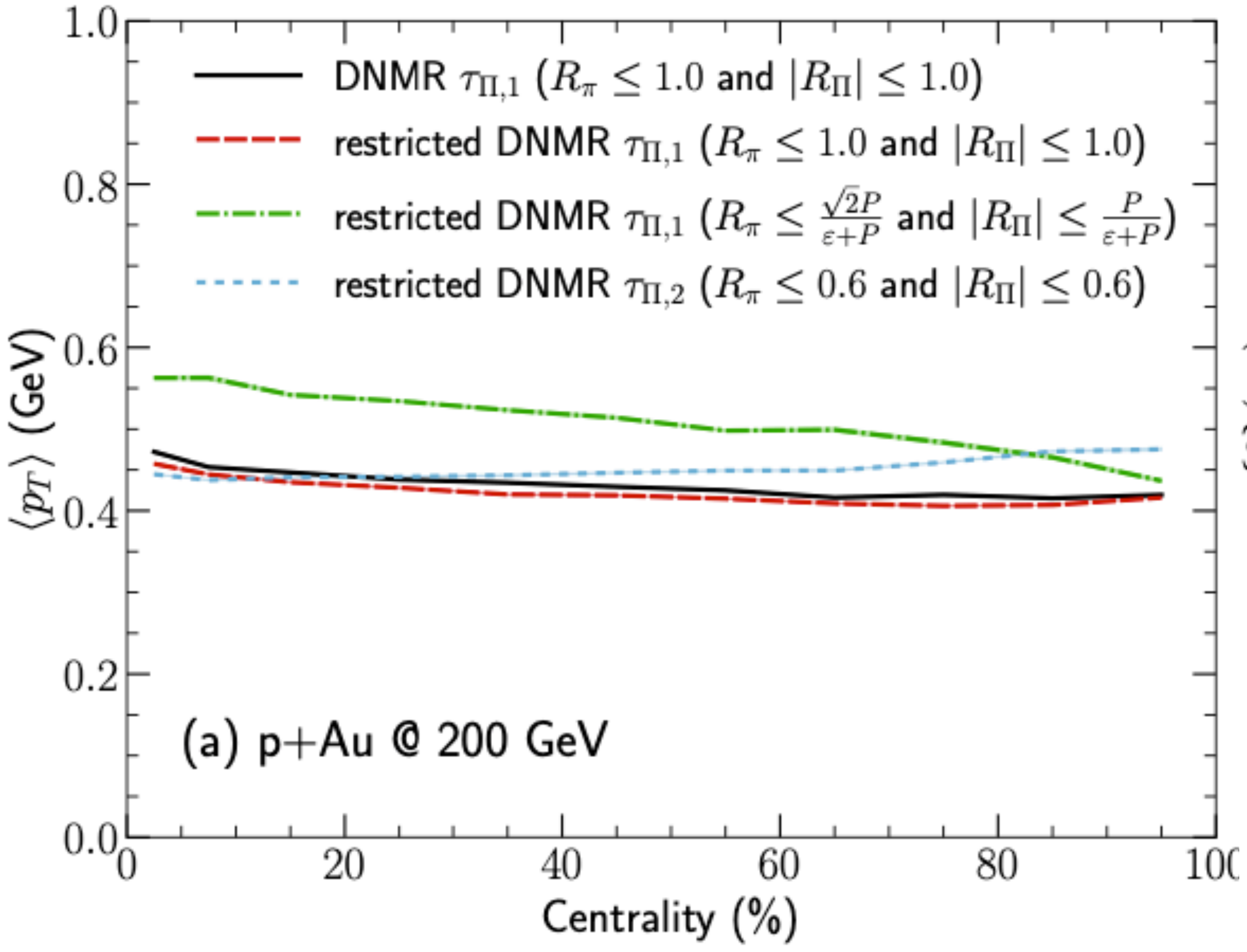
C. Zhang, A. Behera, S. Bhatta and J. Jia, arXiv:2102.05200 [nucl-th]

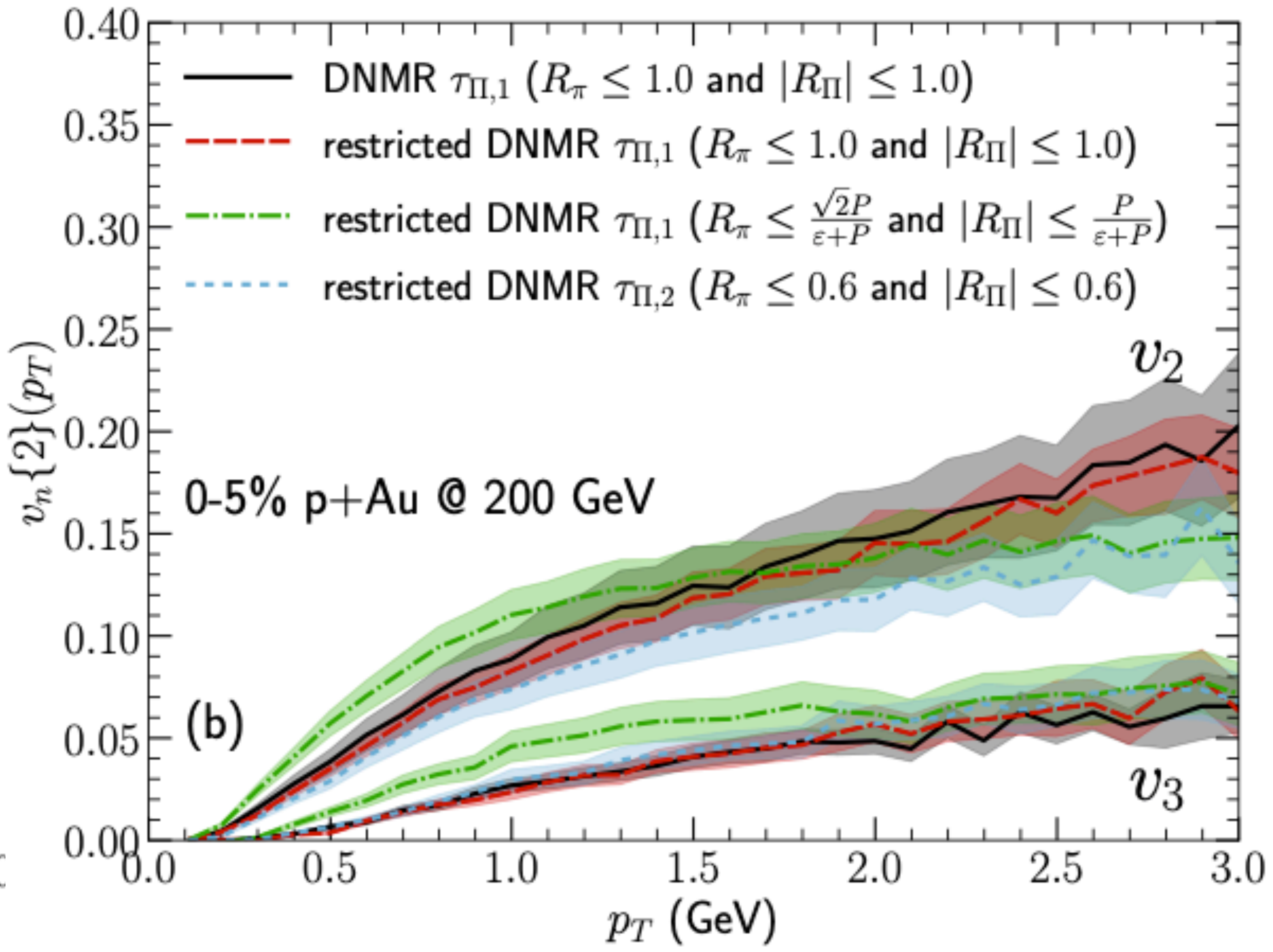
- Non-flow contribution is substantial and challenging to eliminate in the experiments
- Need global comparisons with different kinematics and across multiple collision systems

THEORETICAL UNCERTAINTY IN MODELING SMALL SYSTEMS

C. Chiu and C. Shen, Phys. Rev. C103, 064901 (2021)



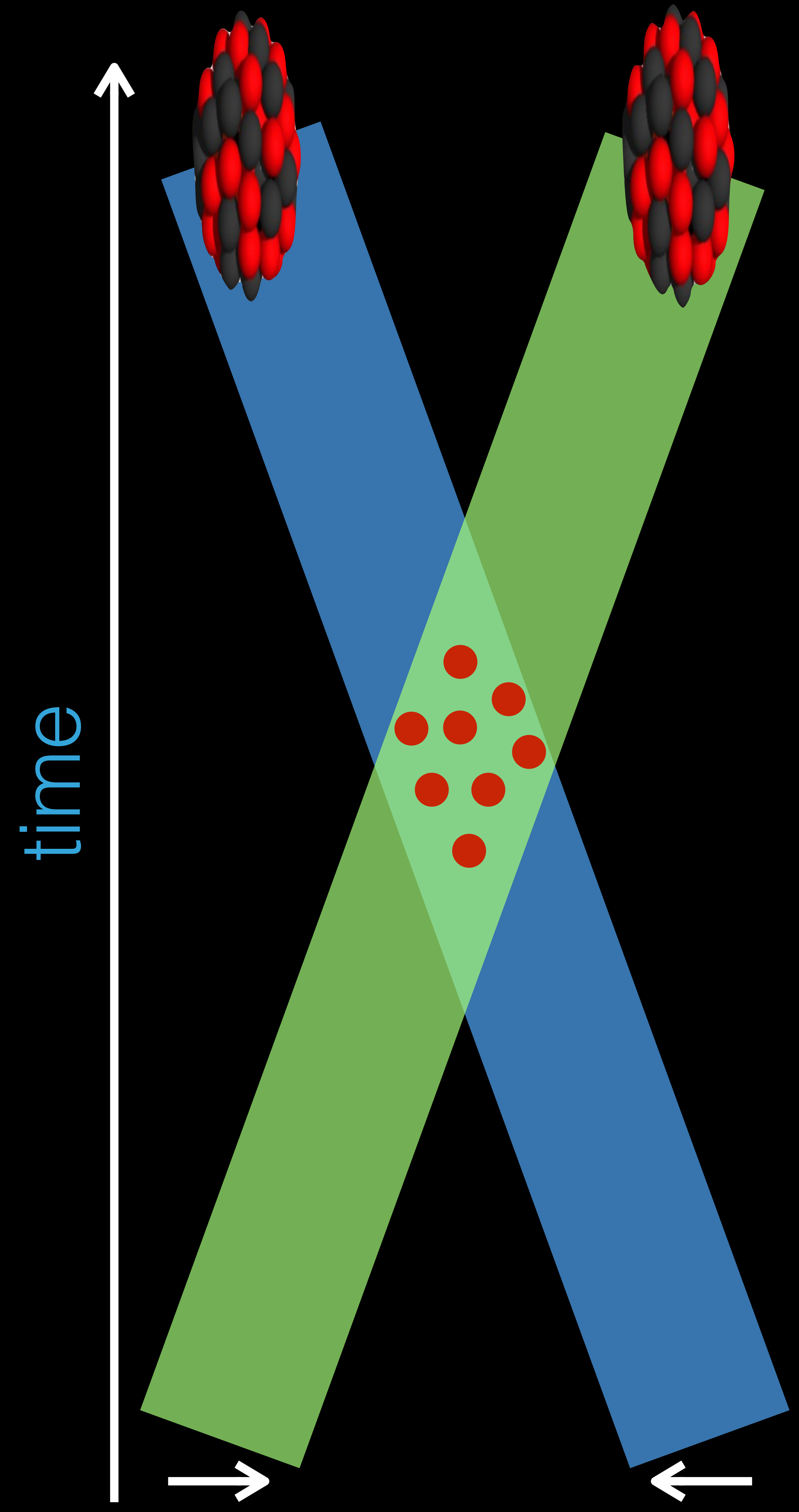


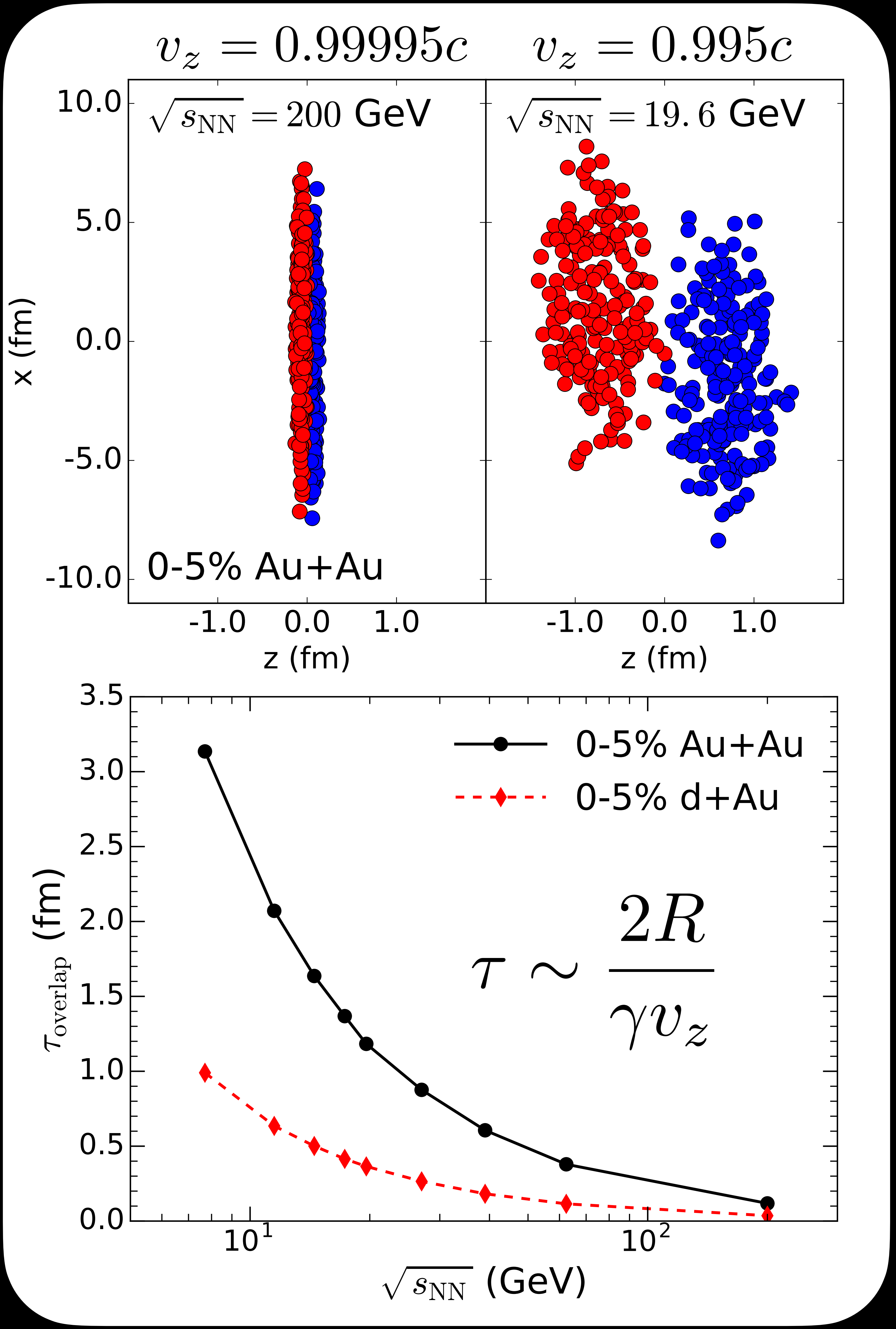


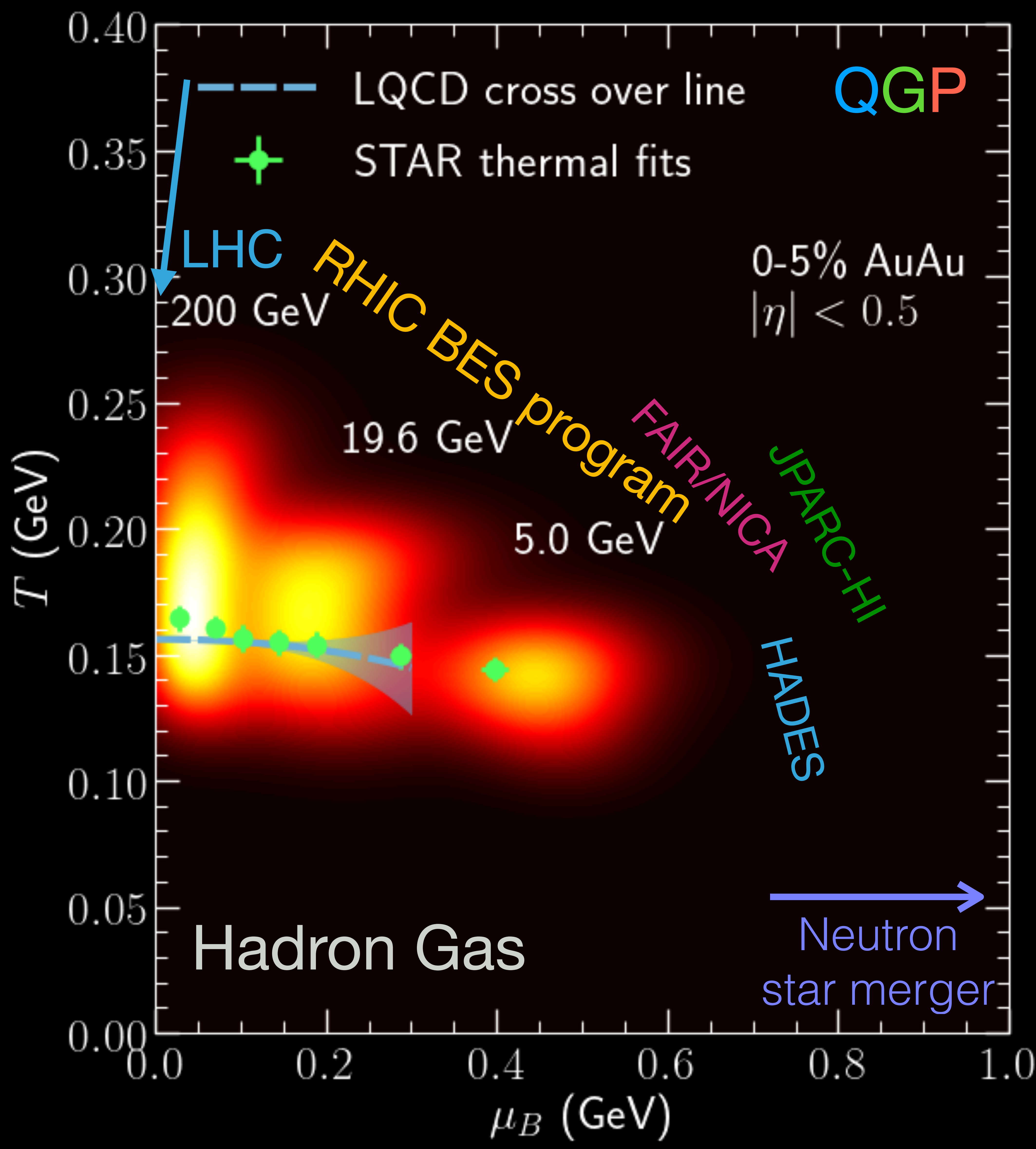
F. Bemfica, M. Disconzi, V. Hoang, J. Noronha and M. Radosz, Phys. Rev. Lett. 126, 222301 (2021)

- There are ~17% fluid cells violating causality in central p+Au collisions
- Regulating these violations results in 20-30% variations in mean p_T and $v_n(p_T)$ in p+Au collisions

GOING TOWARDS FULL 3D DYNAMICS

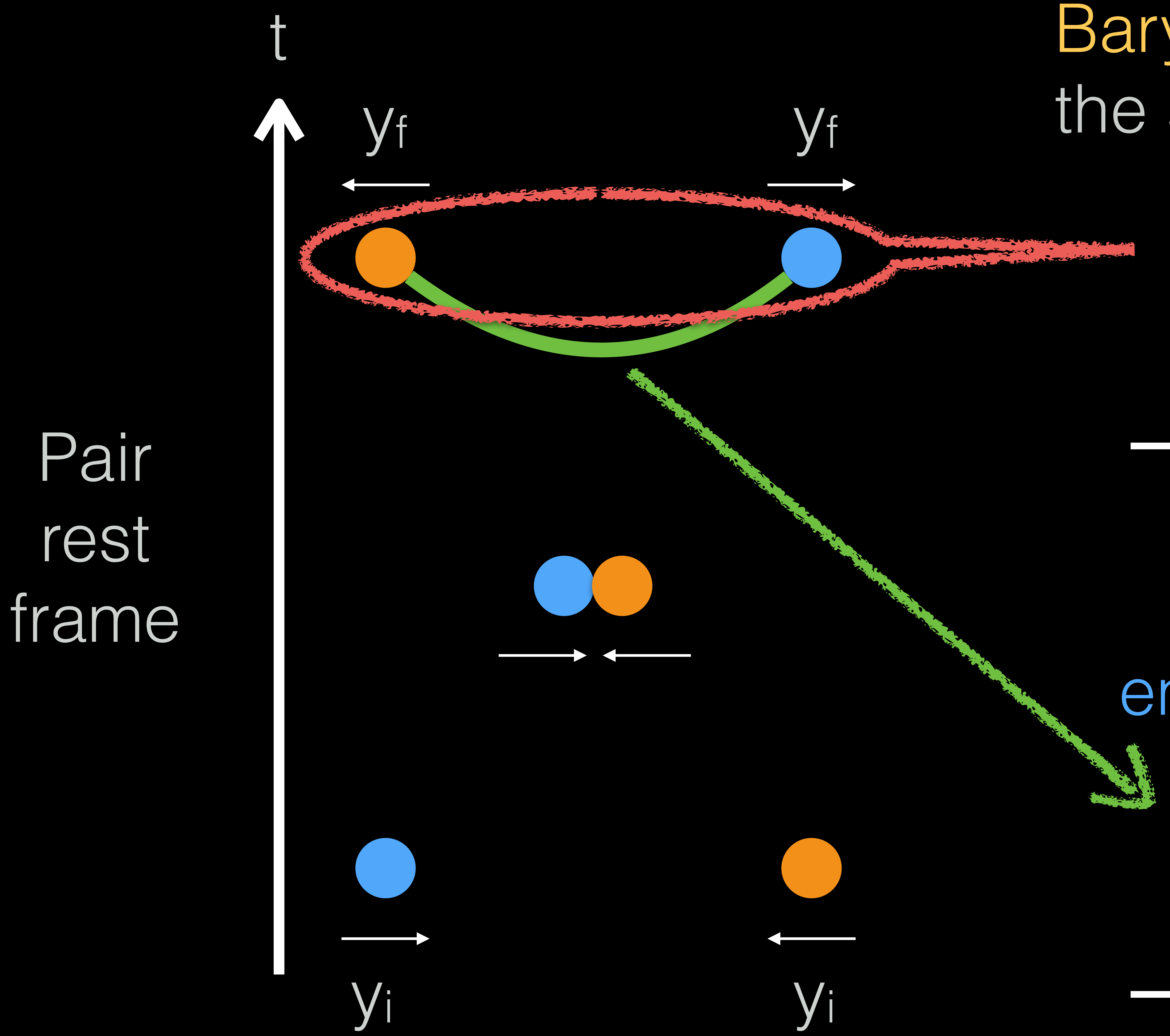






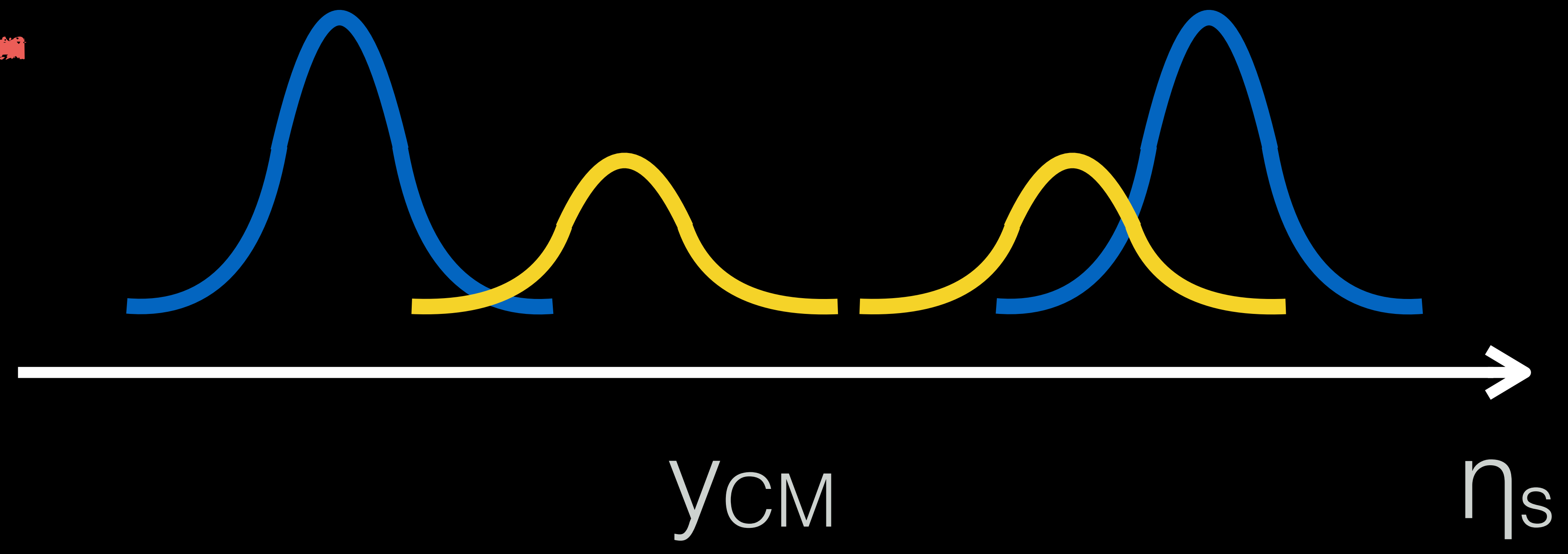
THE 3D MC-GLAUBER + STRING MODEL

C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907



Baryon density are deposited at the string ends or string junctions

D. Kharzeev, Phys. Lett. B 378, 238 (1996)



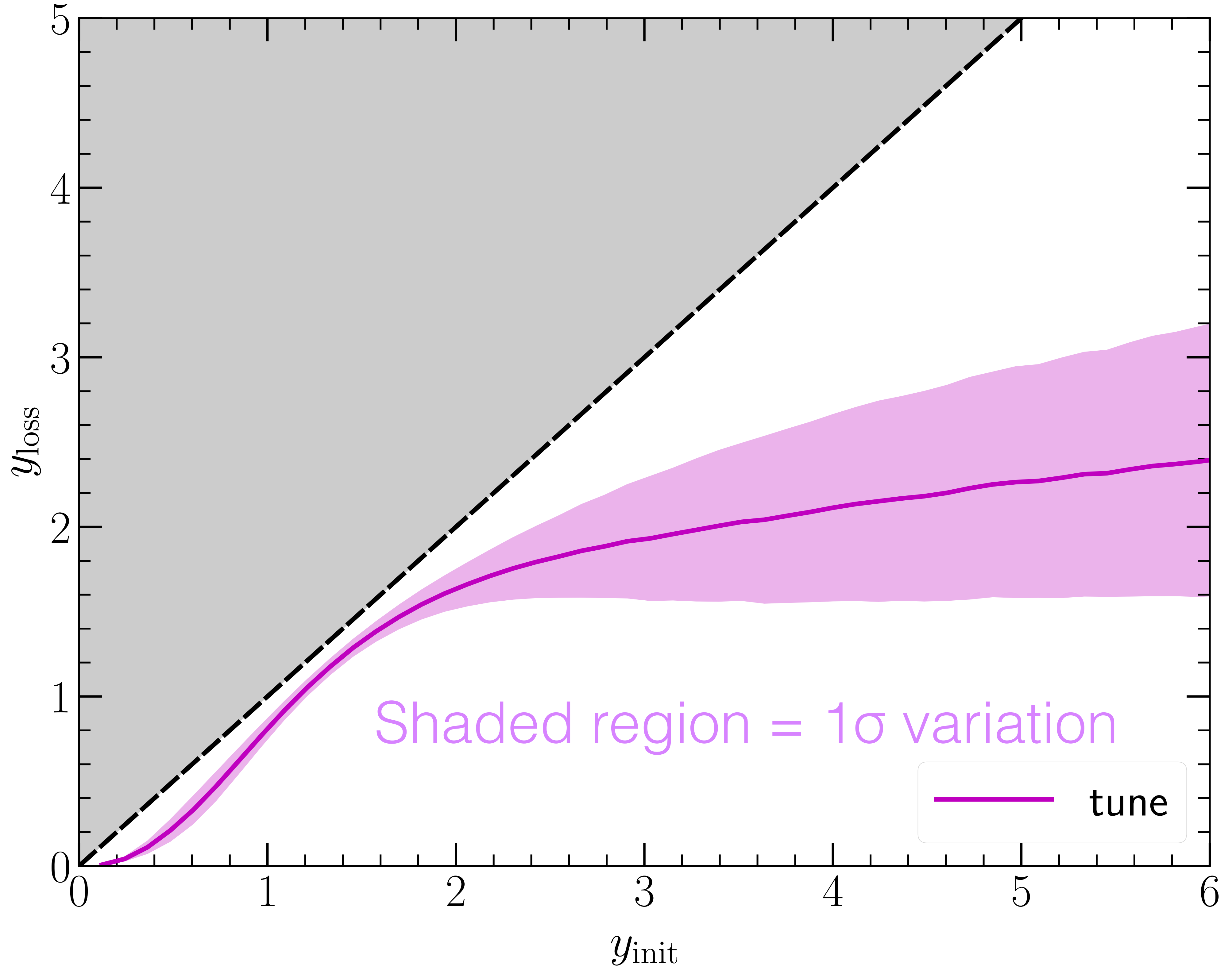
energy density inside the string

Imposed conservation for energy, momentum, and net baryon density

CALIBRATION OF INITIAL ENERGY LOSS

C. Shen and B. Schenke, in preparation

Parameterize the valence quark energy loss



$$\langle y_{\rm loss} \rangle = A y_{\rm init}^{\alpha_2} [\tanh(y_{\rm init})]^{\alpha_1 - \alpha_2}$$

- A: the slope
- At small y: $\langle y_{\rm loss} \rangle \propto y_{\rm init}^{\alpha_1}$
- At large y: $\langle y_{\rm loss} \rangle \propto y_{\rm init}^{\alpha_2}$
- Std of $y_{\rm loss}$ fluctuations: σ_y ($y_{\rm loss} \in [0, y_{\rm init}]$)

3D DESCRIPTION OF SMALL SYSTEMS AT RHIC BES

C. Shen and B. Schenke, in preparation

- Calibrate with minimum bias pp measurements at mid-rapidity and their multiplicity distributions
- Our model overestimate the midrapidity $dN^{\rm ch}/d\eta$ by 10% at 200 GeV

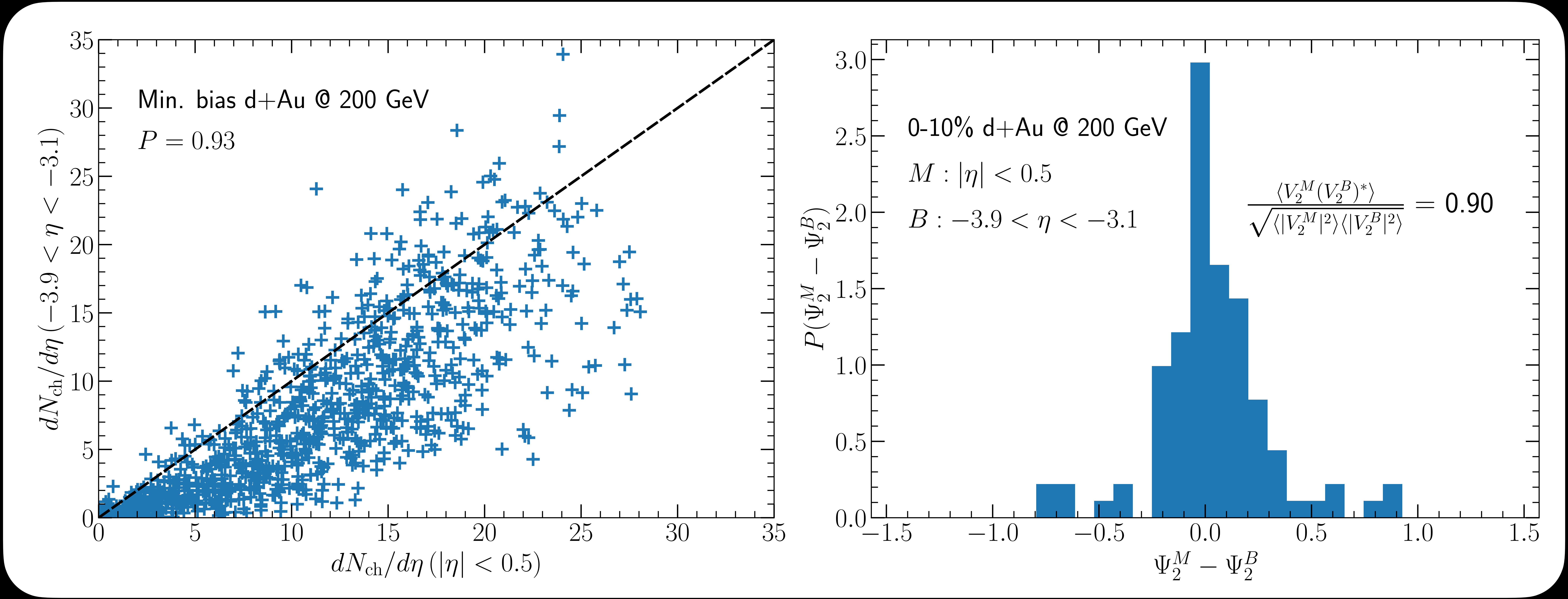
3D DESCRIPTION OF SMALL SYSTEMS AT RHIC BES

C. Shen and B. Schenke, in preparation

- Our model reproduces the STAR multiplicity distribution in the d+Au collisions at 200 GeV
- The predicted charged hadron rapidity distribution agrees well with the PHENIX measurements from central to peripheral collisions
- The role of spectators in the forward rapidity need further investigation at low energies

UNLOCK FORWARD TO CENTRAL CORRELATION

C. Shen and B. Schenke, in preparation



- Decorrelation of particle multiplicity between the PHENIX BBC and the midrapidity region is important for centrality selection
- The event-plane angle at the PHENIX BBC decorrelates with the mid-rapidity elliptic flow vector by 10% in central d+Au collisions

SUMMARY

- Collectivity in small collision systems has been challenging and stimulating major theory and experiment breakthroughs over the past decades
- Subnucleon scale fluctuations are essential for v_n in proton-nucleus collisions
- Peripheral AA, pA, and pp collisions can systematically study the $\hat{\rho}_2(v_2^2, \langle p_T \rangle)$ correlations to reveal initial-state momentum anisotropy
- New development of the 3D framework enables us to quantitatively study particle production and flow correlation in rapidity

Consistent 3D dynamical description of pp, pA, and AA collisions from few GeV to TeV in collision energy