Tracing the emergence of collective phenomenon in small systems

Pragya Singh

Quark Matter 2022 Krakow

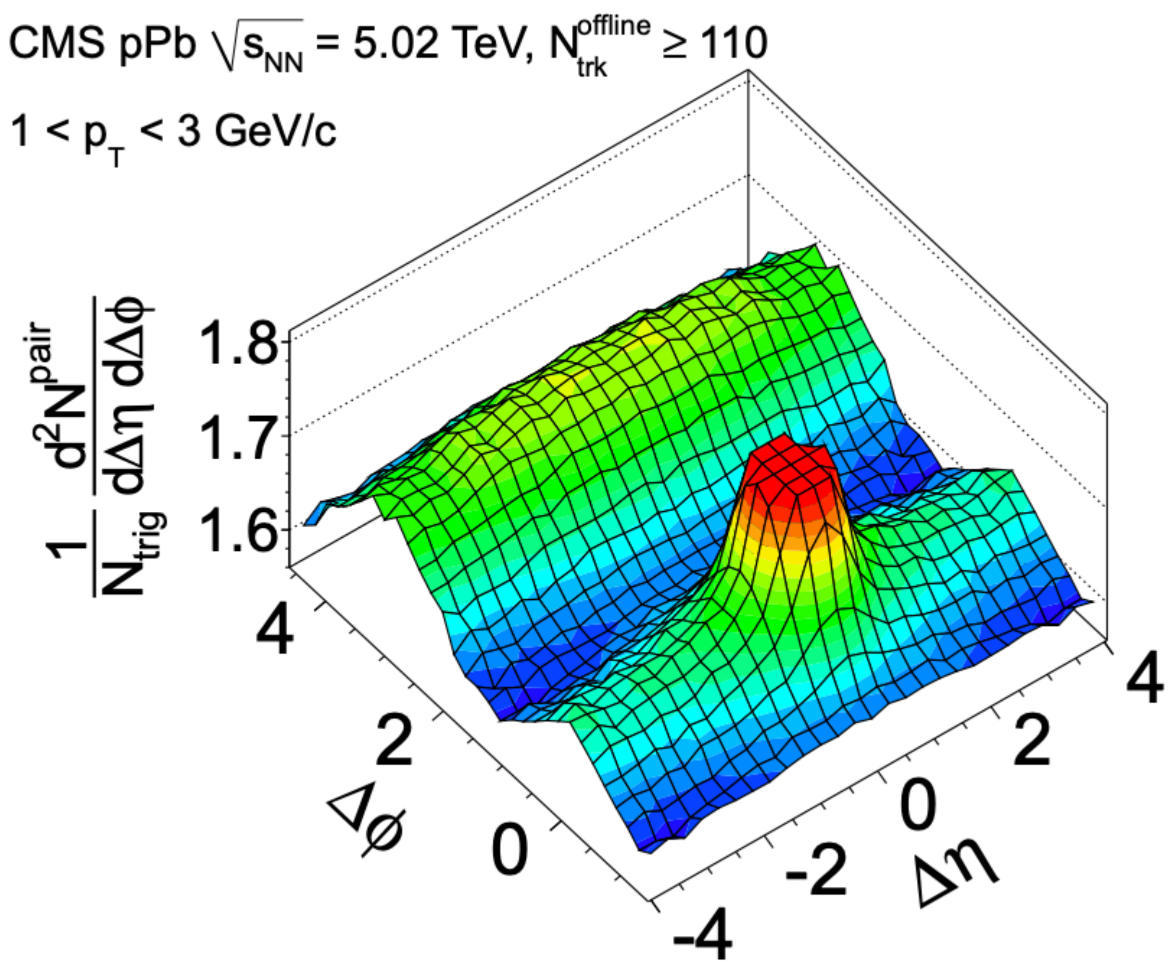
Based on Björn Schenke, Sören Schlichting, PS arXiv:2201.08864

UNIVERSITY OF JYVÄSKYLÄ

UNIVERSITÄT BIELEFELD

CRC-TR 211
Strong-interaction matter under extreme conditions

Two (multi) particle correlations



CMS Collaboration , Phys. Lett. B 718 (2013) 795

Similar results at:

ALICE Collaboration, Phys. Lett. B 719 (2013) 29

ATLAS Collaboration, Phys. Rev. Lett. 110 (2013) 182302

$\Delta\eta$ difference in pseudorapidity

$\Delta\phi$ difference in azimuthal angle

Ridge: Collimate structure ($\Delta\phi$) that is long range in $\Delta\eta$

Ridge in pp and pA collisions similar to AA collisions

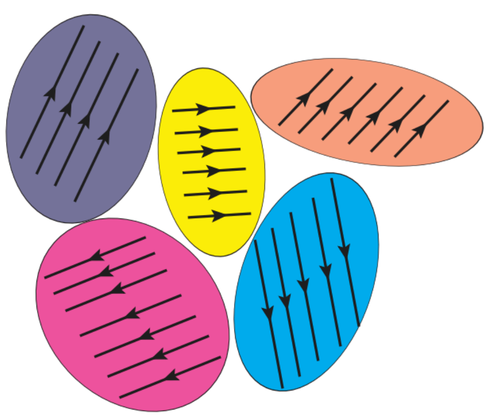
Long-range correlations have only been observed in high multiplicity events at LHC energies in the small system

Interpretation of n-particle correlations in small systems

Different mechanisms have been proposed:

1. Initial state correlations

2. Response to initial geometry



AND / OR

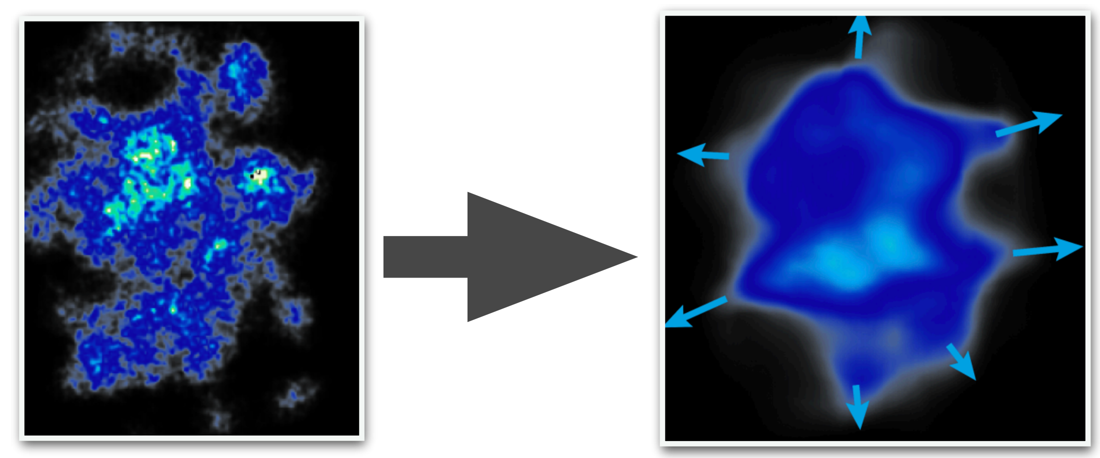


Figure: T Lappi, B Schenke, S Schlichting, R Venugopalan JHEP 1601 (2016) 061
A Dumitru, A Giannini, Nucl. Phys. A933(2014) 212
A Dumitru, V Skokov, Phys Rev. D91 (2015) 074006
A Dumitru, L McLerran, V Skokov, Phys Lett B743 (2015), …

Figure: B Schenke talk SQM 2016
P Bozek, W Broniowski PRC 88 (2013) 014903
J Nagle, R Belmont, S H Lim, B Seidlitz, 2107.07287, …

Other possible explanations:

C Andres, A Moscoso, C Pajares, Phys.Rev.C 90 (2014) 5, 054902, E Shuryak, I Zahed, Phys.Rev.D 89 (2014) 9, 094001, J Bjorken, S Brodsky, A Goldhaber, Phys.Lett.B 726 (2013) 344-346, …

What we do

Explore rapidity dependence of both the mechanisms in p+Pb collisions at $\sqrt{s} = 5.02\ \mathrm{TeV}$

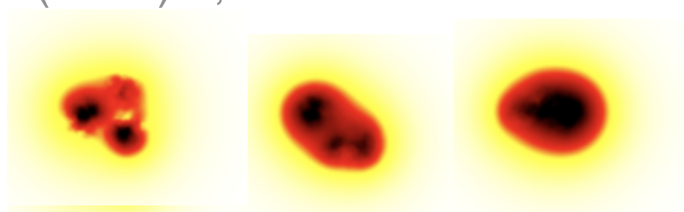
Critical Details:

1. 3D Glasma initial state

   -> Relax the assumption of boost-invariance by using CGC with JIMWLK[1] evolution

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

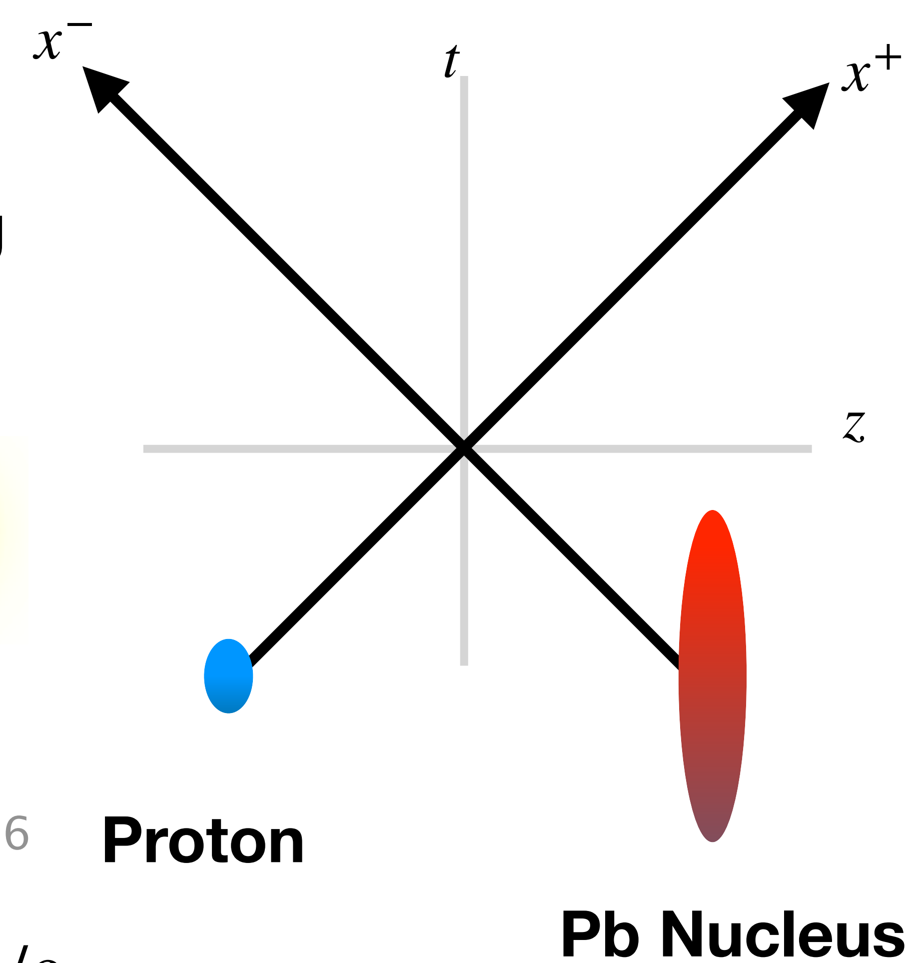
2. Sub-nucleonic fluctuations

   -> Needed to describe the momentum anisotropy in pA collisions

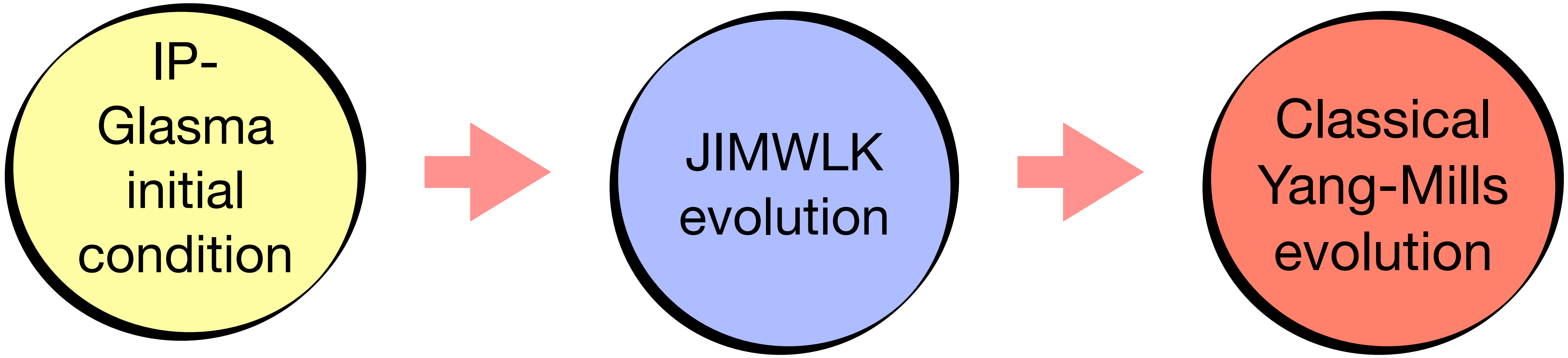
   Phys. Rev. Lett. 113, 102301 (2014), Phys.Lett.B 772 (2017) 681-686

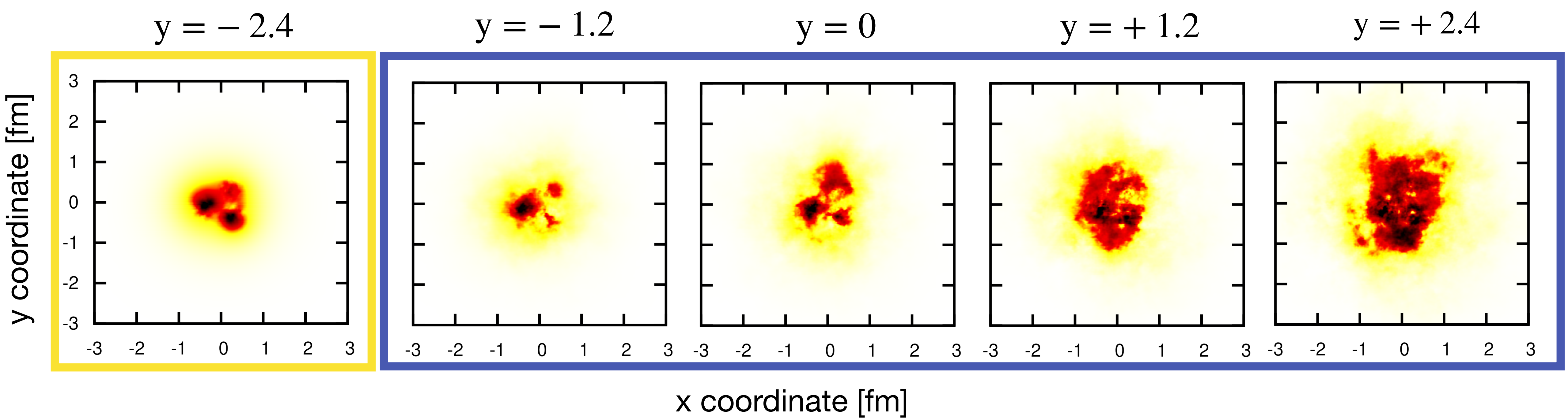
3. Solve classical Yang-Mills equations up to $\tau = 0.2\ \mathrm{fm/c}$ and compute unequal rapidity correlations



[1] Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov and Kovner

3D IP-Glasma





- Size of the proton (quantified by trace of Wilson line) grows with decreasing x.
- Series of independent 2+1D CYM simulations using initial gauge fields

$$A^i_{x_\perp}(\tau = 0^+) = A^i_p(+y_{obs}) + A^i_{Pb}(-y_{obs}); \quad E^\eta_{x_\perp}(\tau = 0^+) = \frac{i}{g}\left[A^i_p(+y_{obs}), A^i_{Pb}(-y_{obs})\right]$$

Refer to B. Schenke, S. Schlichting Phys. Rev. C 94 (2016) 4, 044907 for technical details.

Gluon multiplicity

Standard JIMWLK parameters: $\alpha_s = 0.15 \quad m = 0.2\ \mathrm{GeV}$

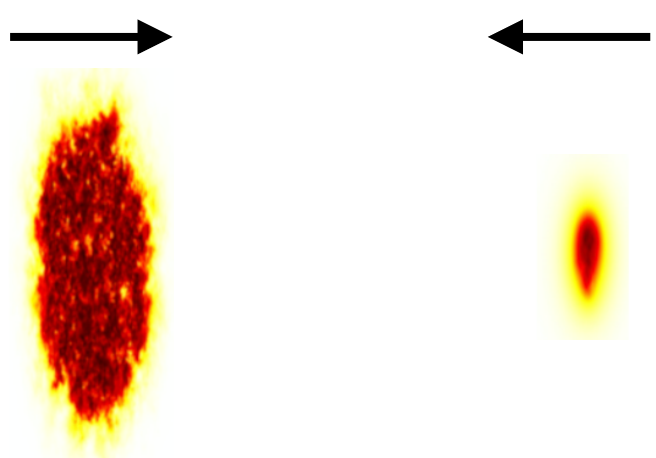
Total number of events

$$N_{\text{events}} = N_{b_\perp} \times N_p \times N_{Pb} = 4096$$

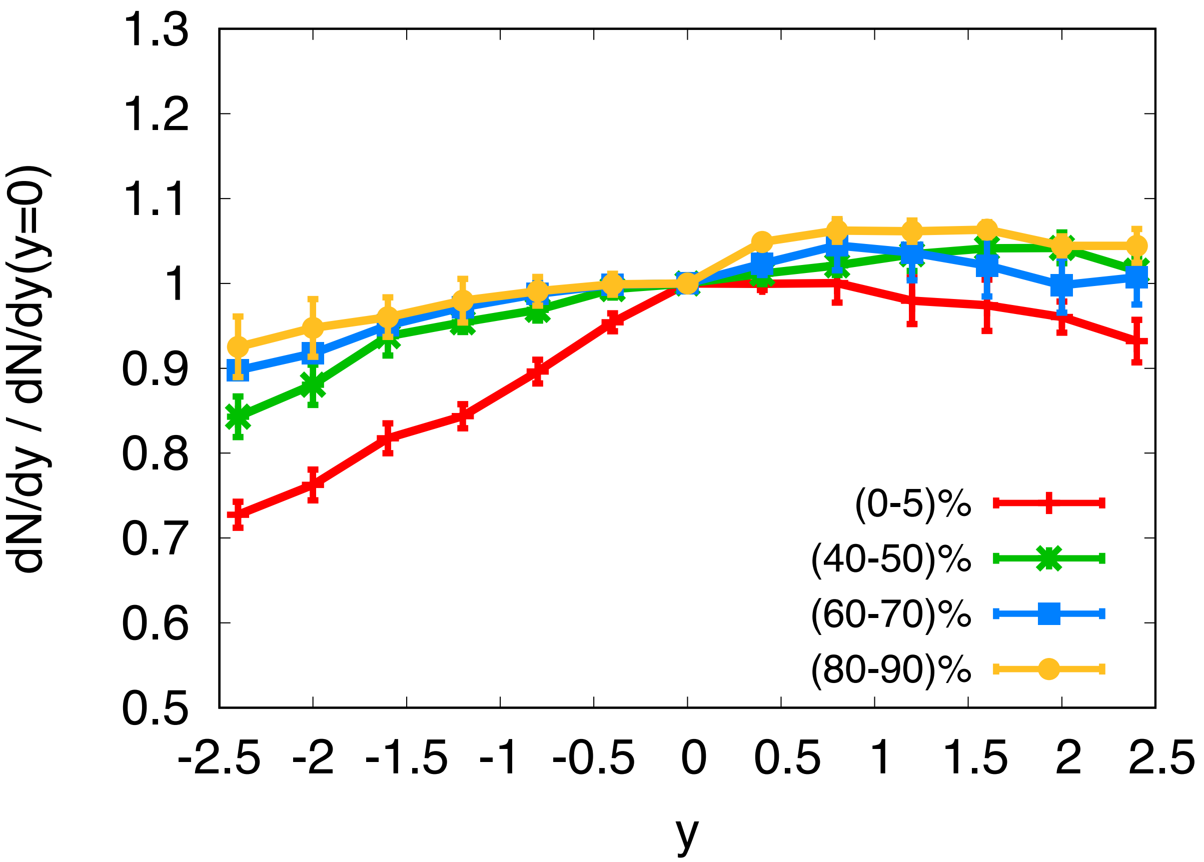
$N_p \equiv$ Number of protons = 32

$N_{Pb} \equiv$ Number of Pb nuclei = 8

$N_{b_\perp} \equiv$ Number of different impact parameters used = 16



Pb nucleus   Proton

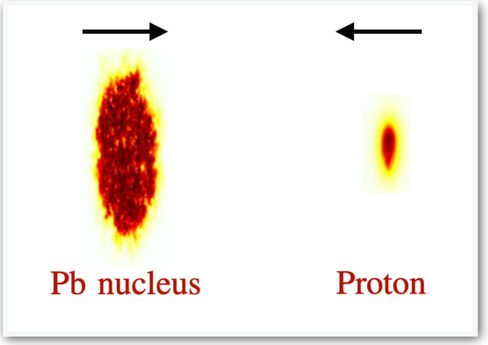


Gluon rapidity distribution

Further insights into low and high multiplicity events

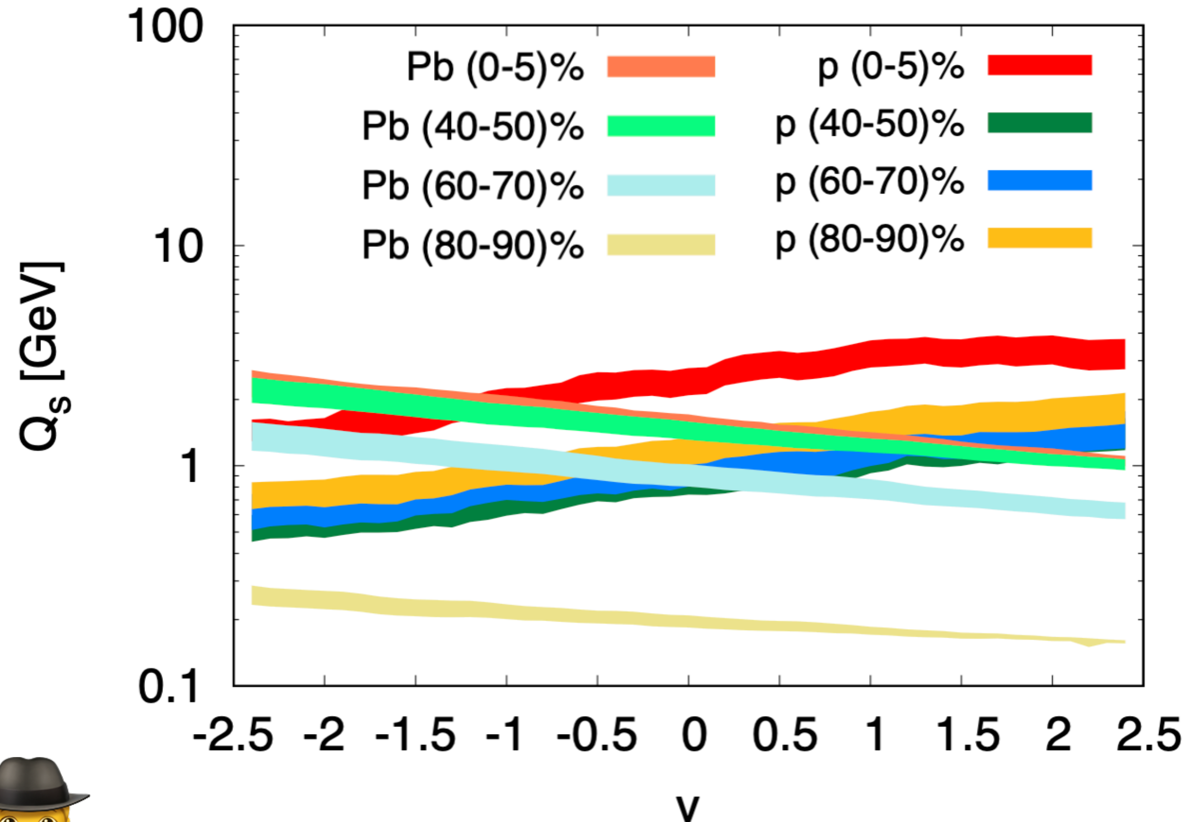
Saturation scale $Q_s^{p/Pb}$ obtained from dipole scattering amplitude

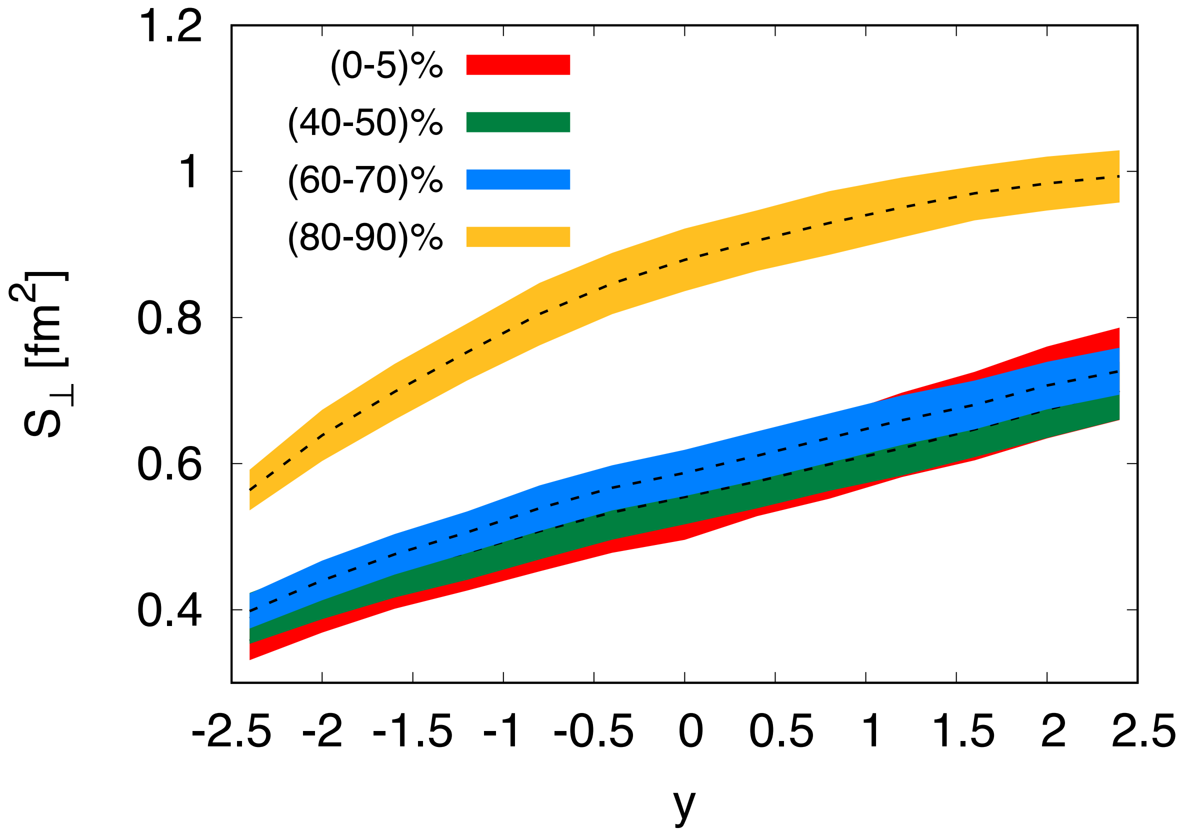
For computation procedure refer to Phys. Lett. B 739 (2014) 313-319



System size

$$S_\perp = \frac{\int d^2x_\perp\, \mathbf{x}_\perp^2 T^{\tau\tau}(x_\perp)}{\int d^2x_\perp T^{\tau\tau}(x_\perp)}$$





- Highest multiplicities result from exotic protons with large Q_s^p .
- Except for most peripheral events, multiplicity driven by change in Q_s values.

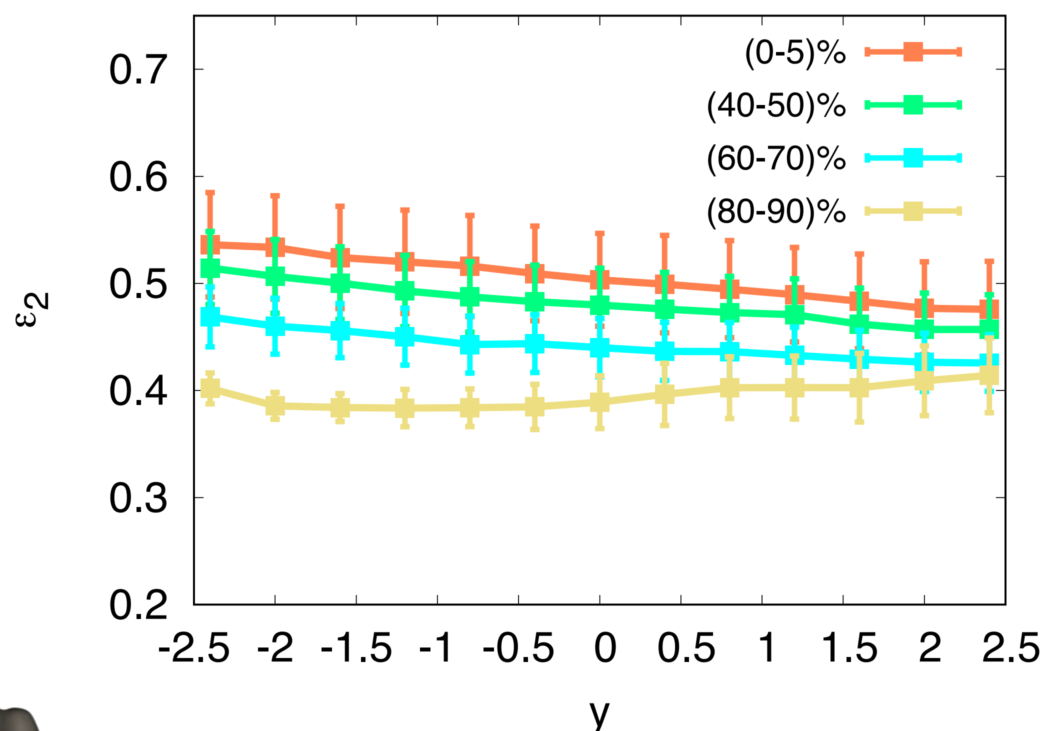
Event geometry & Initial State (IS) momentum anisotropy

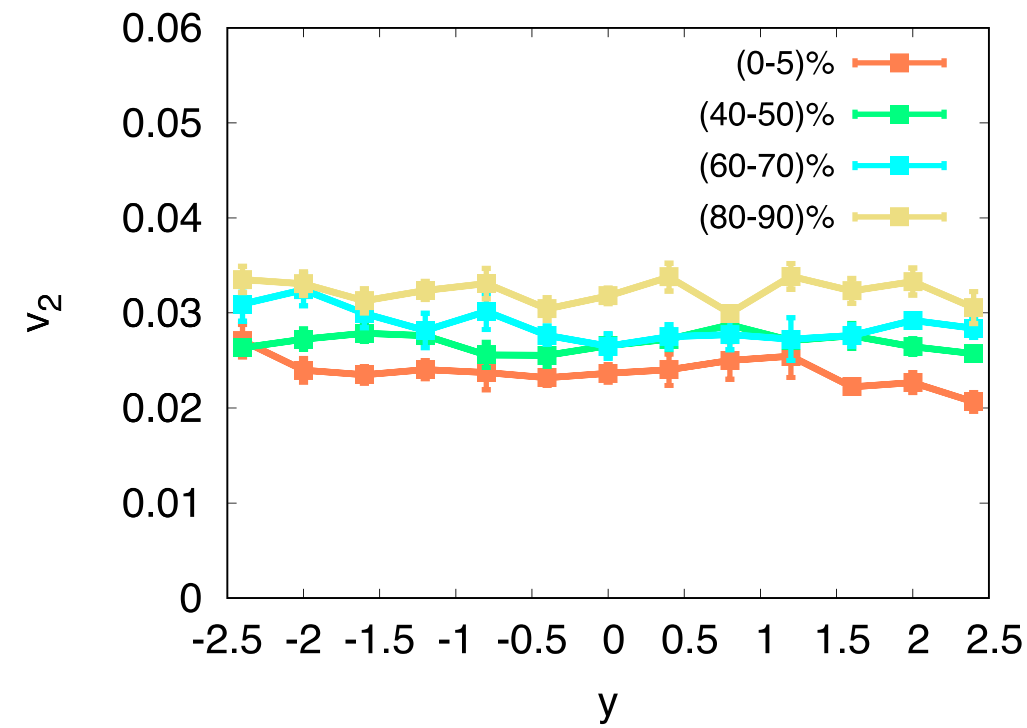
Event geometry

Eccentricities ε_n

IS momentum anisotropy

Anisotropic energy flow ε_p $\equiv$ Azimuthal anisotropy gluon v_2





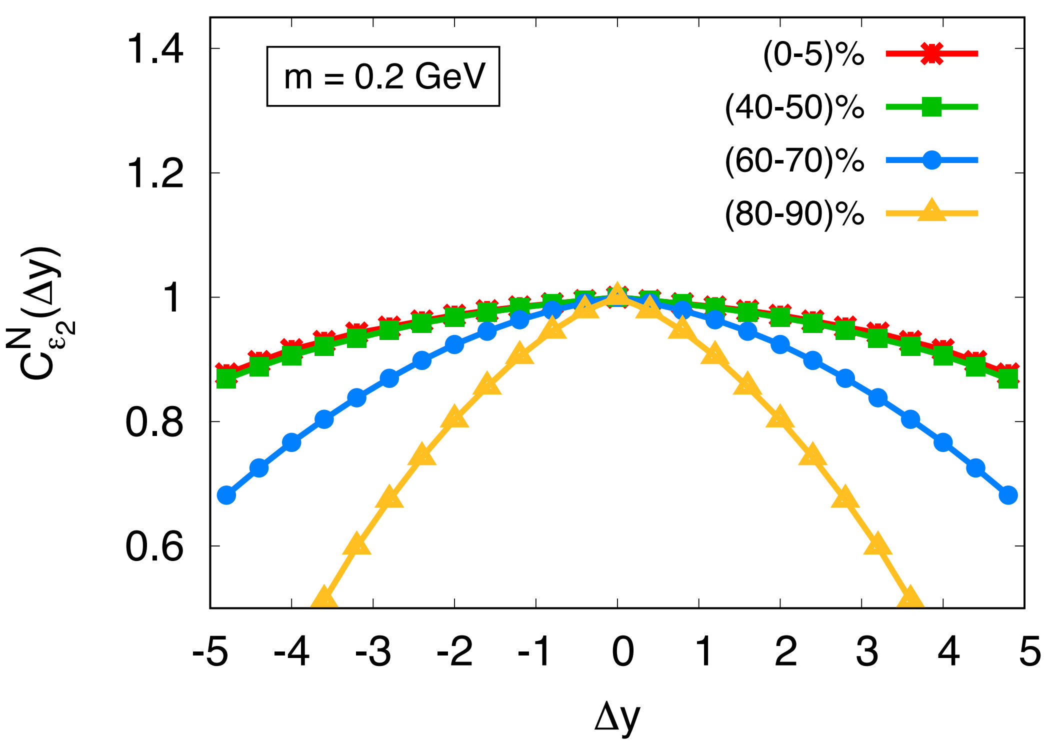
- Opposite trends in centrality in ε_2 and initial state v_2
- Initial state v_2 largely independent of rapidity in all centrality bins.

Event geometry & initial state momentum anisotropy

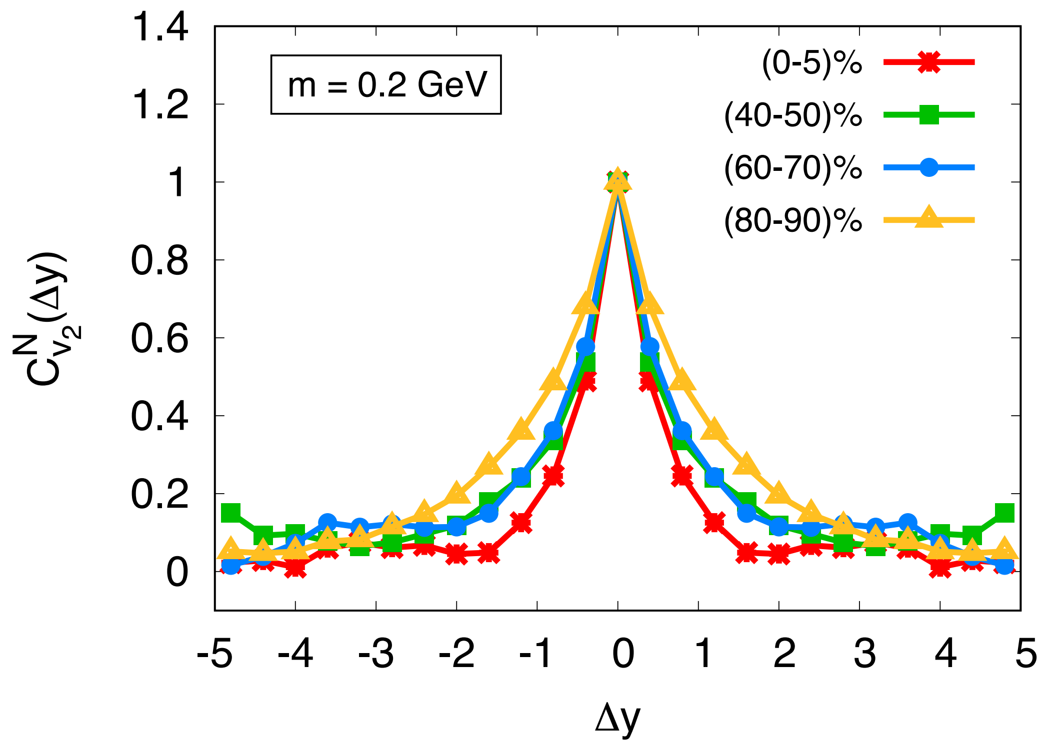
Normalized rapidity correlation function $C^N_{\mathcal{O}}$

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

Event geometry



IS momentum anisotropy



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

Centrality ↑ **Correlation in event geometry** ↓ **Correlation in momentum anisotropy** ↑

How to distinguish the source of anisotropy?

P. Bozek, Phys. Rev. C 93. 044908 (2016), B. Schenke, C. Shen, D. Teaney, Phys. Rev. C 102, 034905 (2020)
G. Giacalone, B. Schenke, C. Shen, Phys. Rev. Lett. 125 (2020) 19, 192301

Use the correlation of mean transverse momentum $[p_T]$ and v_2^2 at fixed multiplicity.

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

where

$$\hat{\delta} O \equiv \delta O - \frac{\langle \delta O \delta N \rangle}{\sigma_N^2} \delta N$$

$$\delta O = O - \langle O \rangle$$

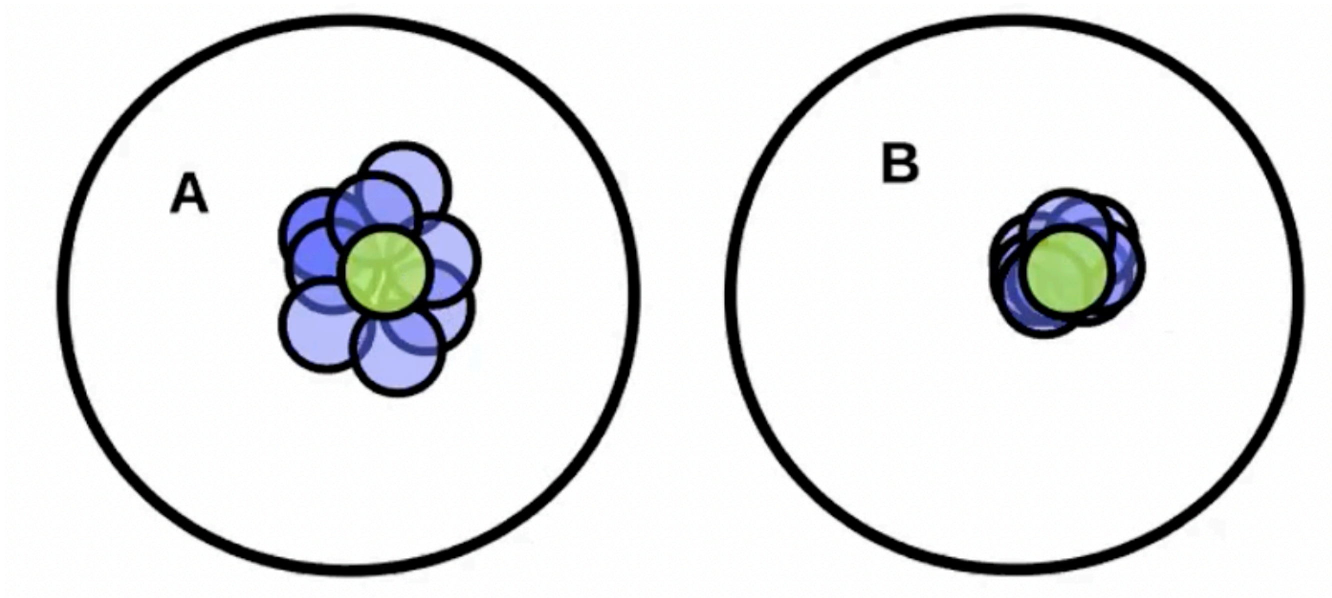
A. Olszewski, W. Broniewski, Phys. Rev. C96, 054903 (2017)

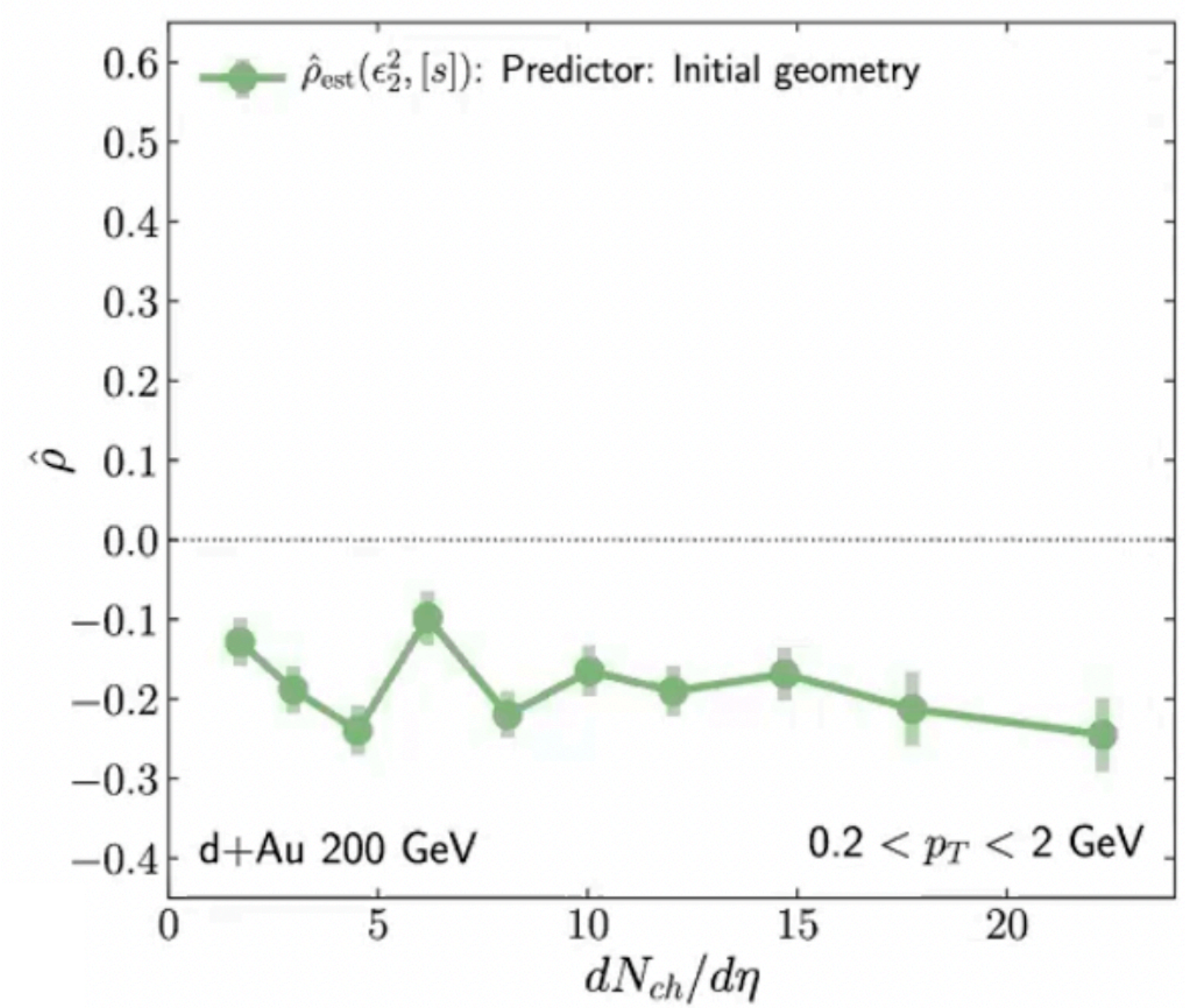
The two origins of v_2 have very distinct predictions for this correlator.

Correlation from geometry

G. Giacalone, B. Schenke, C. Shen, Phys. Rev. Lett. 125 (2020) 19, 192301

Wounded nucleon picture





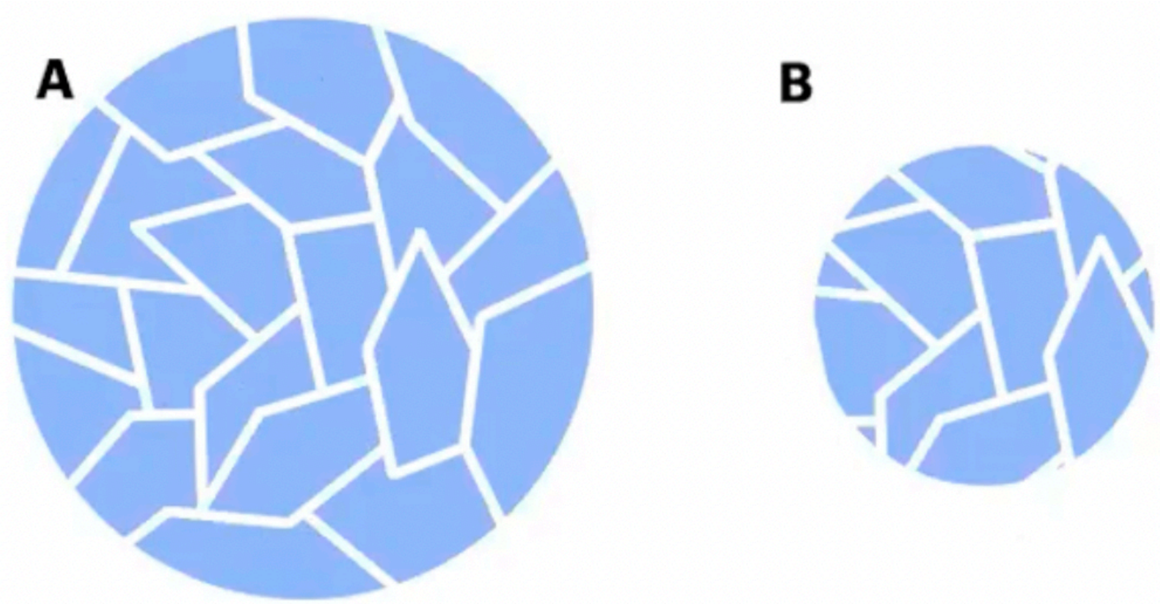
$$R(A) > R(B)$$
$$\langle p_T \rangle(A) < \langle p_T \rangle(B)$$
$$\varepsilon_2(A) > \varepsilon_2(B)$$

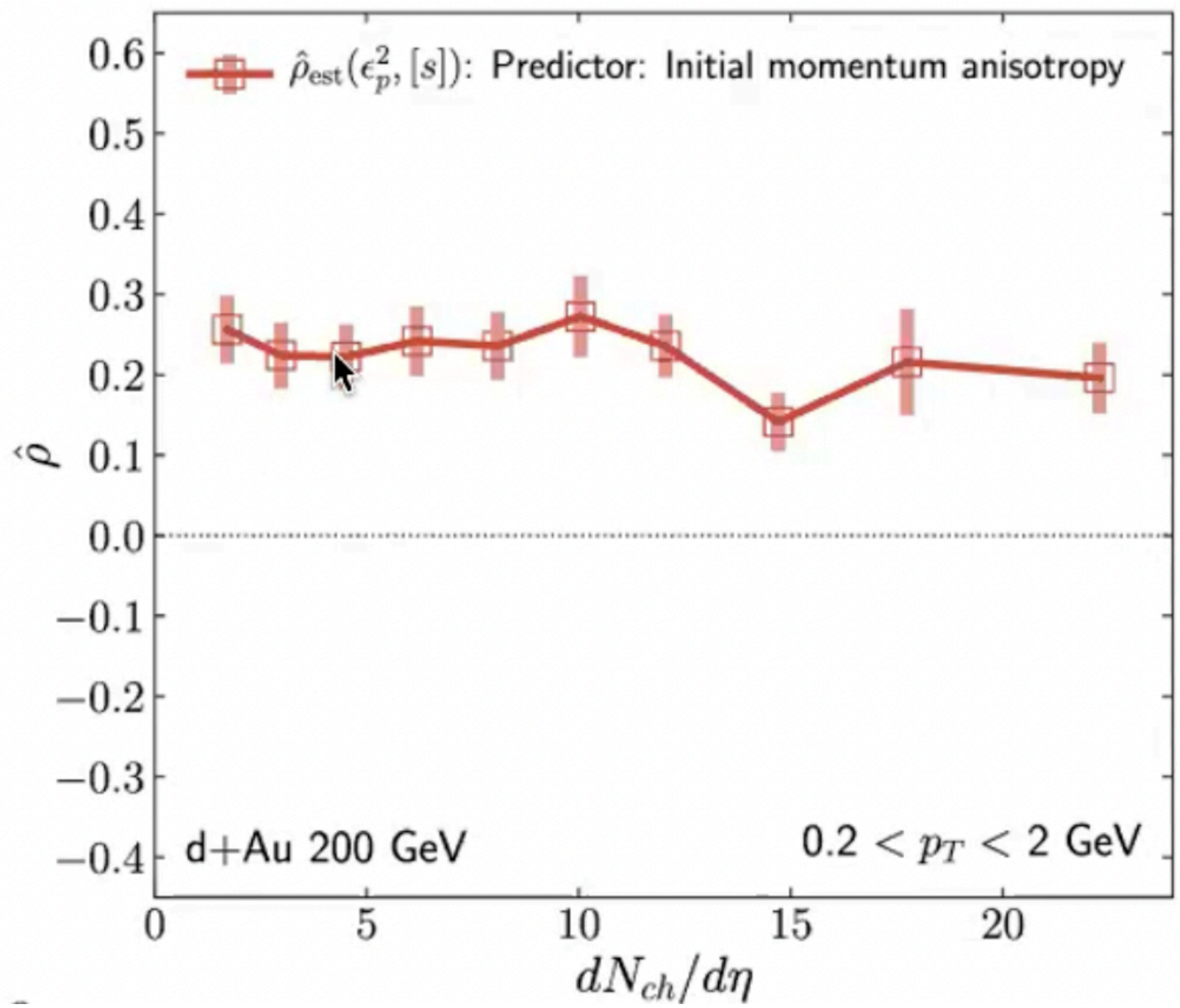
v_2 and $\langle p_T \rangle$ are anti-correlated

Correlation from initial momentum anisotropy

G. Giacalone, B. Schenke, C. Shen, Phys. Rev. Lett. 125 (2020) 19, 192301

Color domain cartoon (particle produced from same domain are correlated)





$$R(A) > R(B)$$

$$\langle p_T \rangle(A) < \langle p_T \rangle(B)$$

$$\varepsilon_p(A) < \varepsilon_p(B)$$

v_2 and $\langle p_T \rangle$ are correlated

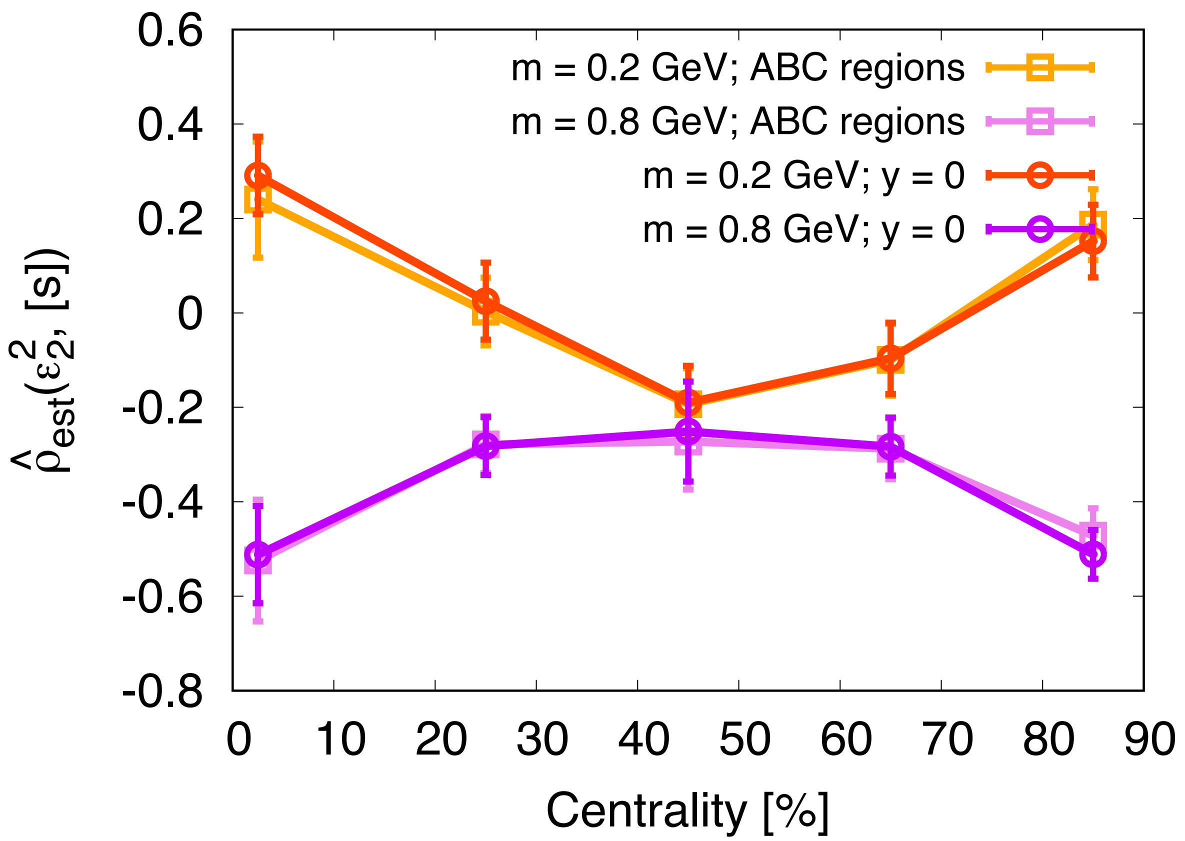
Estimators for correlation between $[p_T]$ and v_2

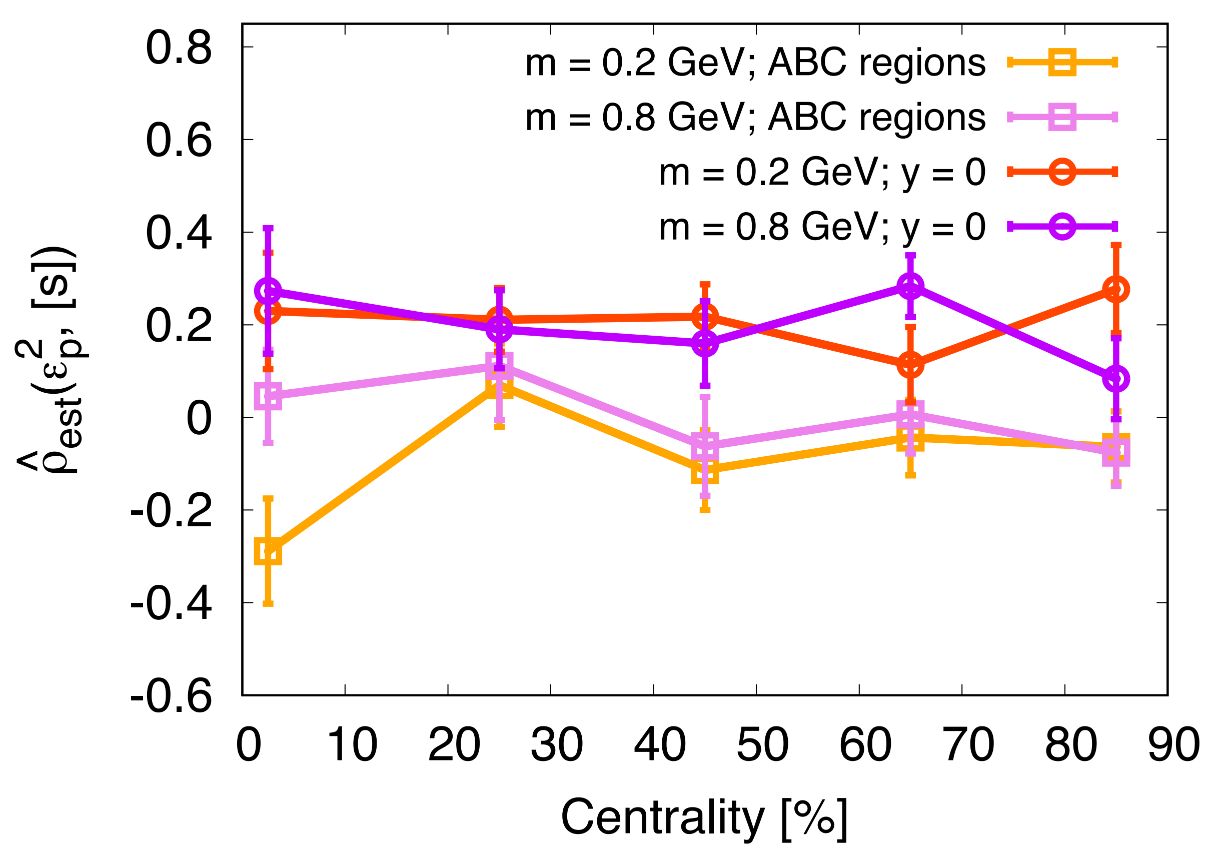
For small systems, we employ the following estimators

$$v_2 \rightarrow \varepsilon_2 \text{ or } \varepsilon_p$$
$$[p_T] \rightarrow [s]$$

B. Schenke, C. Shen and D. Teaney
Phys. Rev. C 102, 034905 (2020)

where $[s] = [e^{3/4}]$ is the average initial entropy density in a given event





ABC: region A with –2.4 < y < –0.8, central region B with |y| < 0.8 and region C with 0.8 < y < 2.4

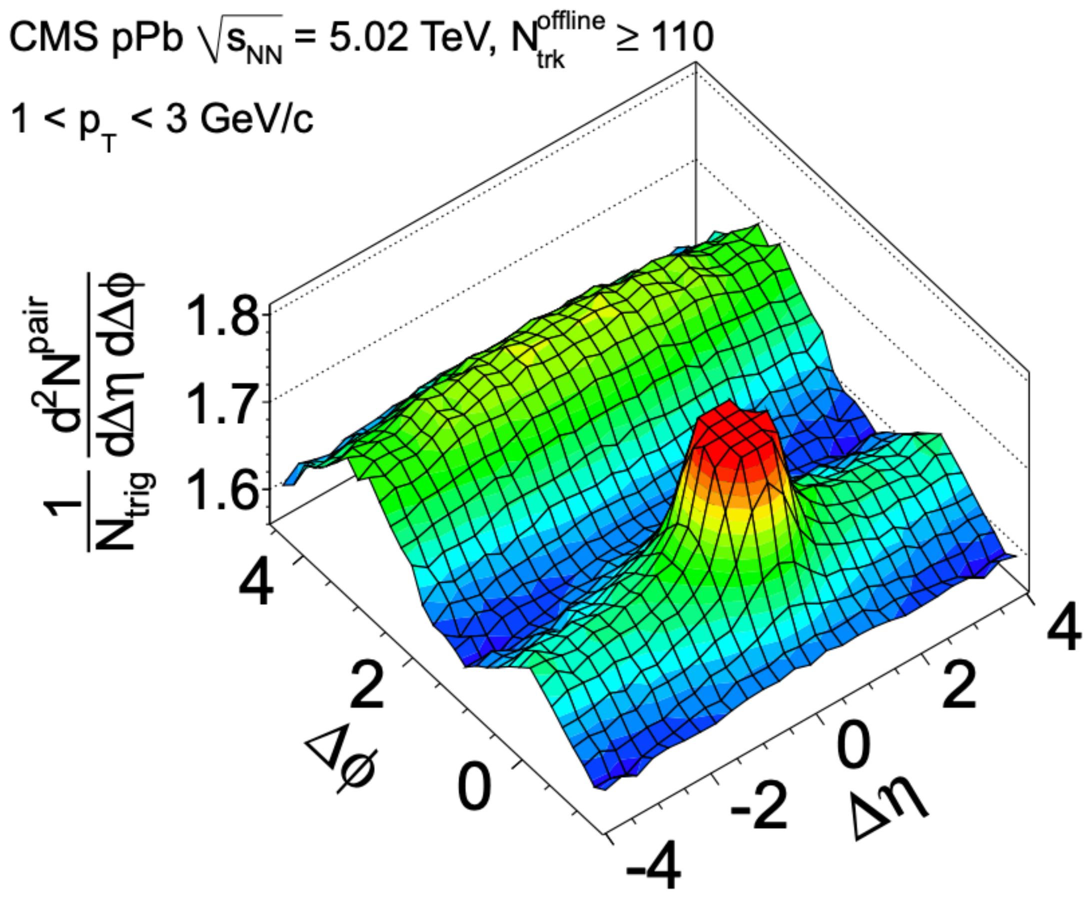
ATLAS Eur. Phys. J. C 79 (2019) 985

Infrared regulators (size) have a strong effect on geometric $\hat{\rho}$ estimator

P. Bozek, H. Mehrabpour Phys. Rev. C 101, 064902 (2020)

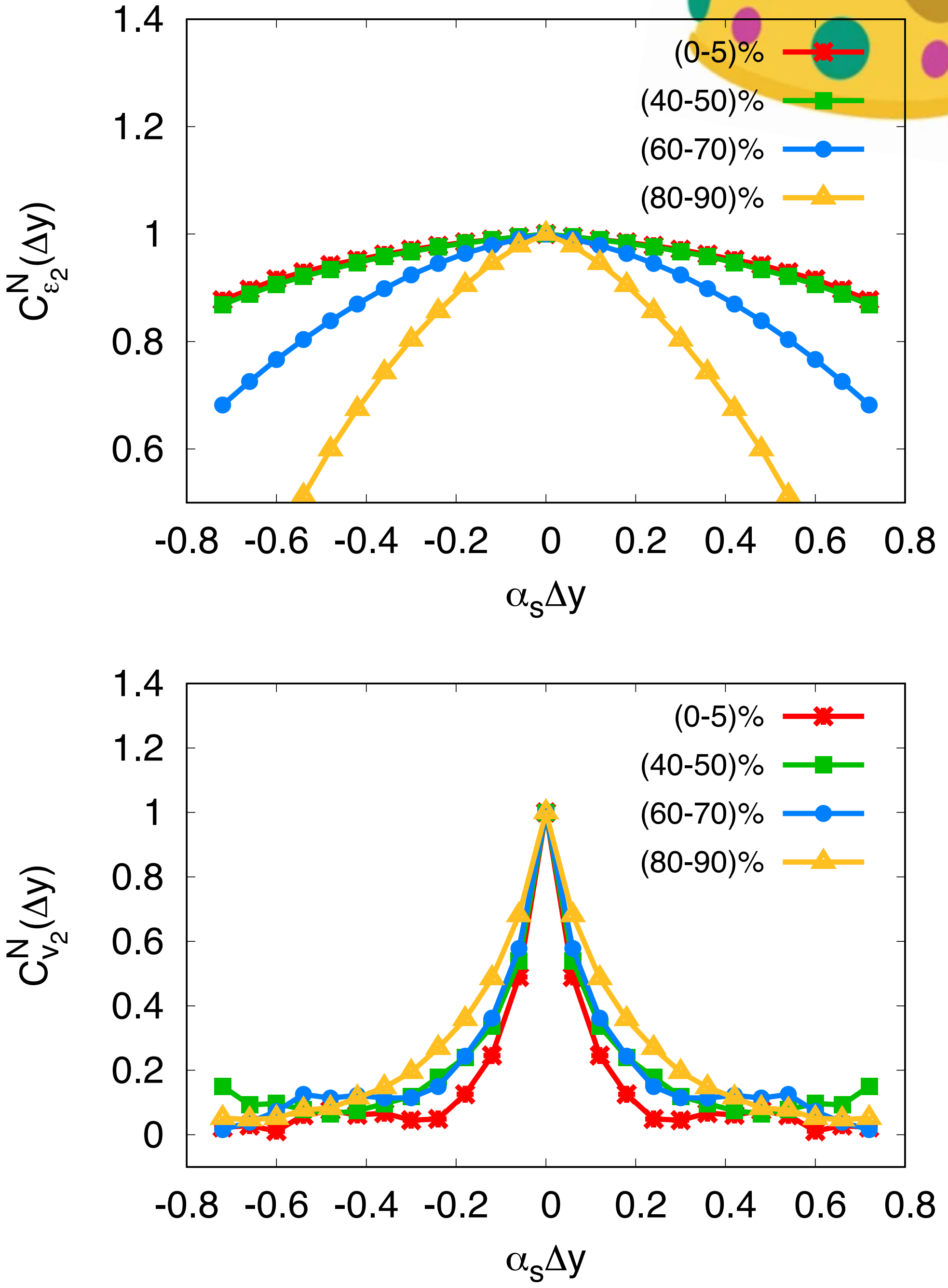
Origin of collectivity in small systems

Experimental observation



Long-range rapidity correlation in high-multiplicity events

Theoretical explanations



Conclusion & Outlook

- Event geometry and initial state anisotropy are the possible explanations of long range azimuthal correlations observed in small systems.
- Investigated the rapidity dependence of the two possible explanations in pPb at $\sqrt{s} = 5.02\ \mathrm{TeV}$ within the 3+1D IP-Glasma model.
- Geometry decorrelates with rapidity (faster for low multiplicity); initial state anisotropy decorrelates more quickly (faster for high multiplicity)
- In the future, couple 3D IP-Glasma with viscous hydrodynamics (e.g. MUSIC)

Thank you

BACK-UP

JIMWLK evolution

Employ JIMWLK small-x evolution to the proton and nucleus

$$V_{\mathbf{x}_\perp}(Y+dY) = \exp\left\{-i\frac{\sqrt{\alpha_s dY}}{\pi}\int_{\mathbf{z}_\perp} K_{\mathbf{x}_\perp-\mathbf{z}_\perp}\cdot\left(V_{\mathbf{z}_\perp}\boldsymbol{\xi}_{\mathbf{z}_\perp}V^\dagger_{\mathbf{z}_\perp}\right)\right\} \times V_{\mathbf{x}_\perp}(Y)\exp\left\{i\frac{\sqrt{\alpha_s dY}}{\pi}\int_{\mathbf{z}_\perp} K_{\mathbf{x}_\perp-\mathbf{z}_\perp}\cdot\boldsymbol{\xi}_{\mathbf{z}_\perp}\right\}$$

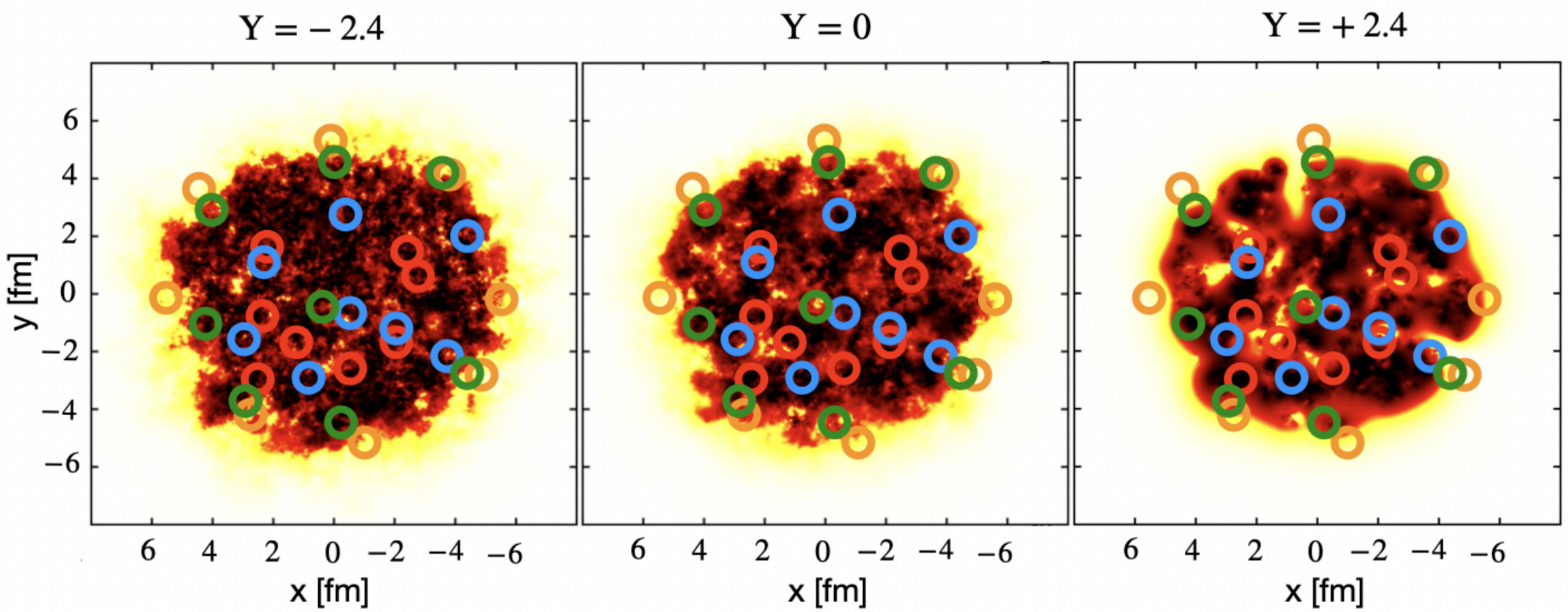
Functional Langevin equation

T. Lappi, H. Mäntysaari Eur. Phys. J. C73 (2013) 2307

IR regularised JIMWLK kernel

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

$$K_{\mathbf{x}_\perp-\mathbf{z}_\perp} = m|\mathbf{x}_\perp-\mathbf{z}_\perp|\,K_1(m|\mathbf{x}_\perp-\mathbf{z}_\perp|)\,\frac{\mathbf{x}_\perp-\mathbf{z}_\perp}{(\mathbf{x}_\perp-\mathbf{z}_\perp)^2}$$



red (0 – 5)%,
blue (40 –50)%,
green (60 —70)%
orange (80 – 90)%.

Circles represent where proton hits in a given event, whose centrality is color coded

Longitudinal structure of high-energy collisions

Incorporate longitudinal structure using 3D IP-Glasma model

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

Based on the high-energy factorisation of inclusive observables

F Gelis, T Lappi, R Venugopalan, PRD 78, 054019 (2008), PRD 78, 054020 (2008), PRD 79, 094017 (2008)

$$\langle \mathcal{O} \rangle = \int [D\rho_p][D\rho_{Pb}] W^{p}_{y_{obs}-y}[\rho_p] W^{Pb}_{y_{obs}+y}[\rho_{Pb}] \mathcal{O}[\rho_p, \rho_{Pb}]$$

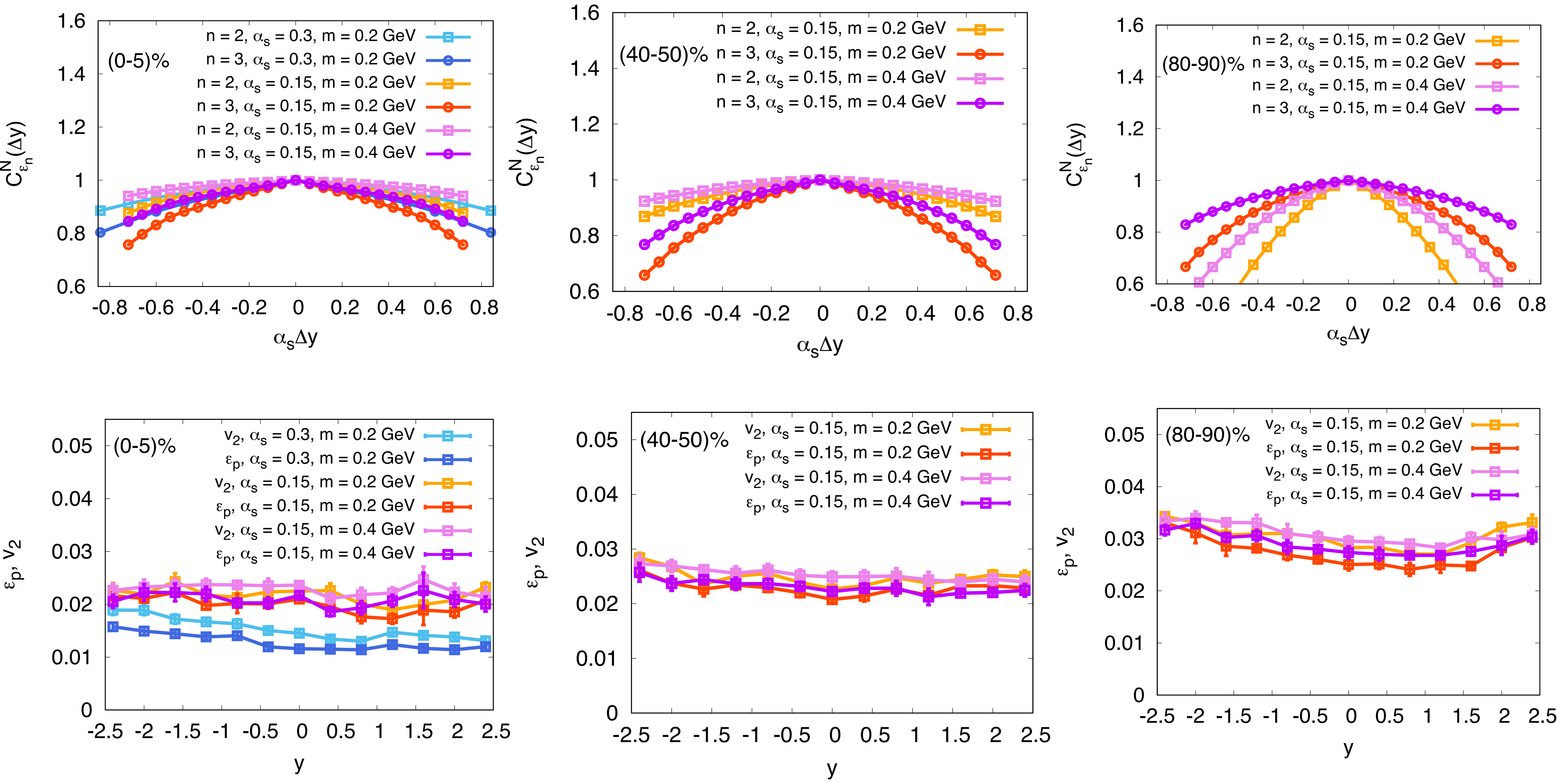
Evolution of weight-functional $W_{\Delta y}$ with rapidity separation Δy provided by JIMWLK evolution equation

J Jalilian-Marian, A Kovner, L McLerran, H Weigert Phys. Rev. D **55**, 5414, Phys. Rev. D **59**, 014014

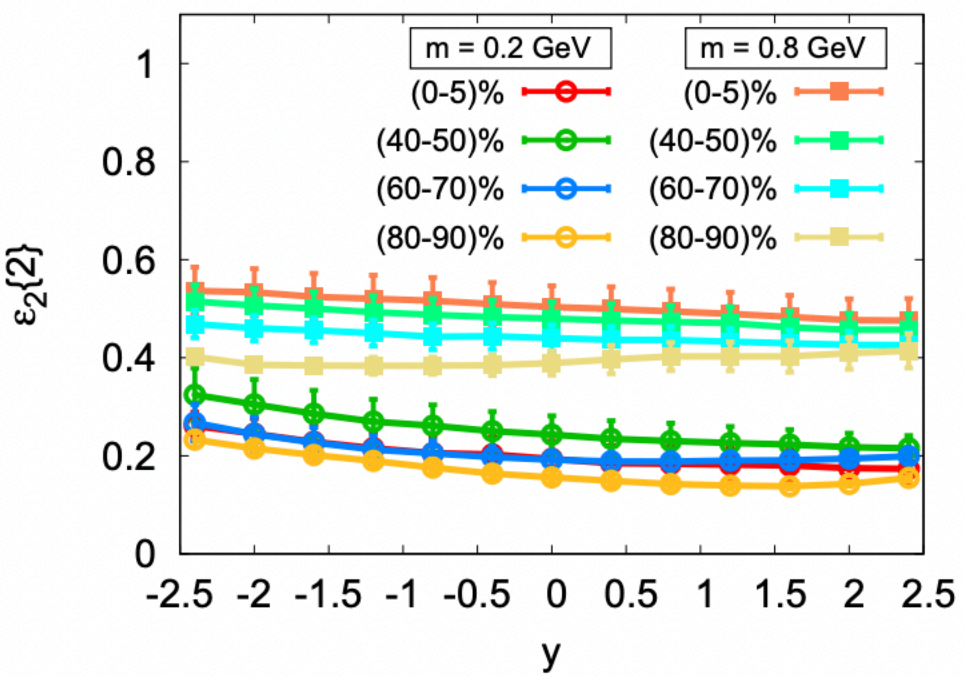
High energy factorisation proven only for inclusive quantities which encompass measurements at a single rapidity

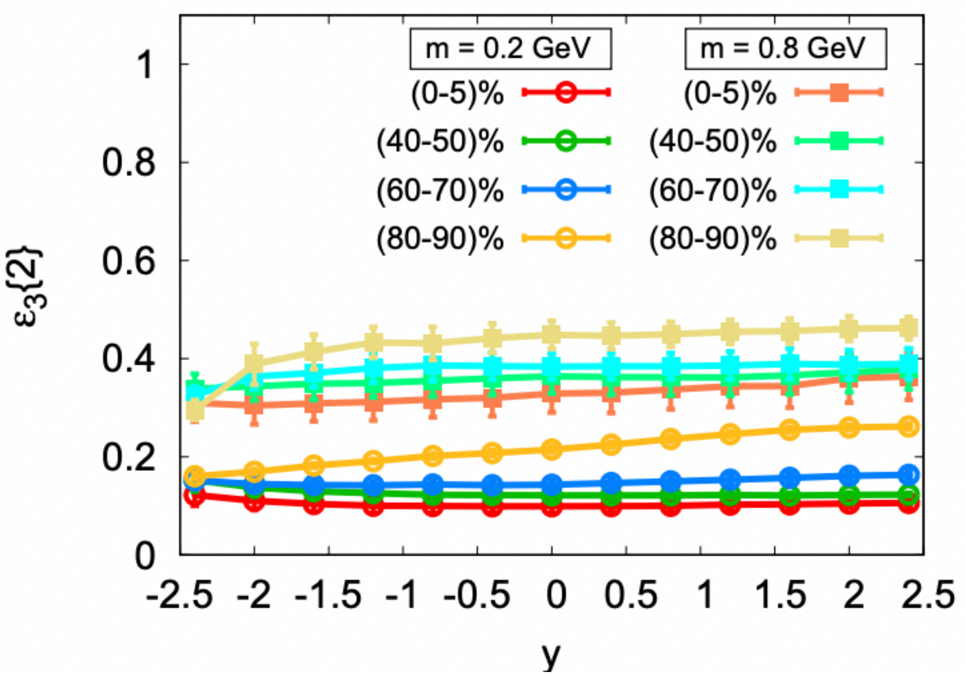
Using same prescription to calculate un-equal rapidity correlation

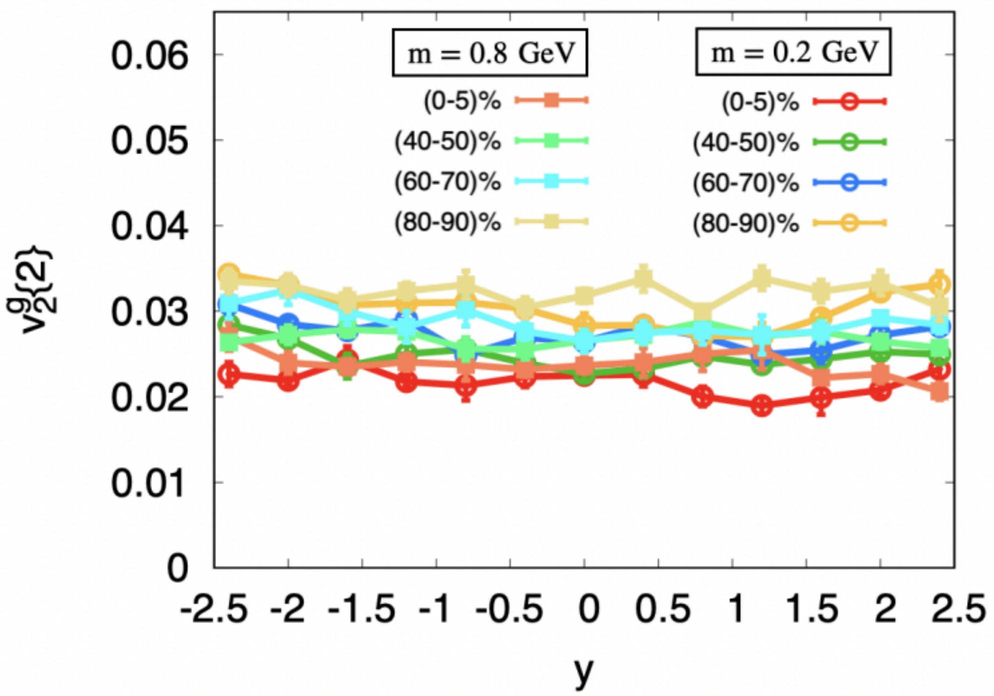
Correlations and e_p and v_2



Event geometry & IS momentum anisotropy







Behaviour in a single event

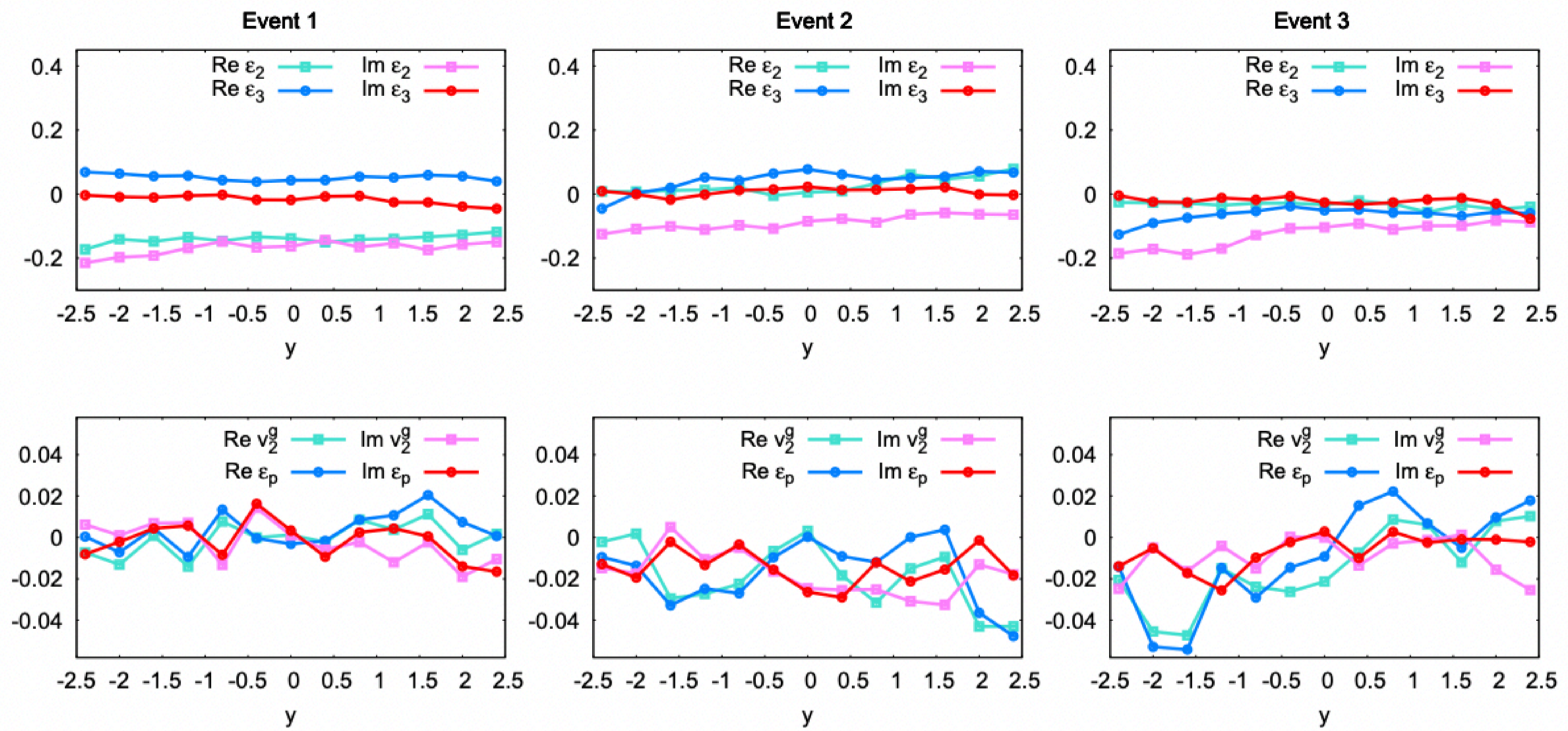


FIG. 11. Rapidity dependence of the real and imaginary parts of the 2[nd] and 3[rd] order spatial eccentricities (top-panel) for three different events in the $(0-5)\%$ centrality class (top-panel). Similar result are given for the azimuthal anisotropy of initial state gluon v_2^g and initial state momentum anisotropy ϵ_p in the bottom panel. Simulation parameters: $\alpha_s = 0.15$ and $m = \tilde{m} = 0.2$ GeV.

Dipole scattering amplitude

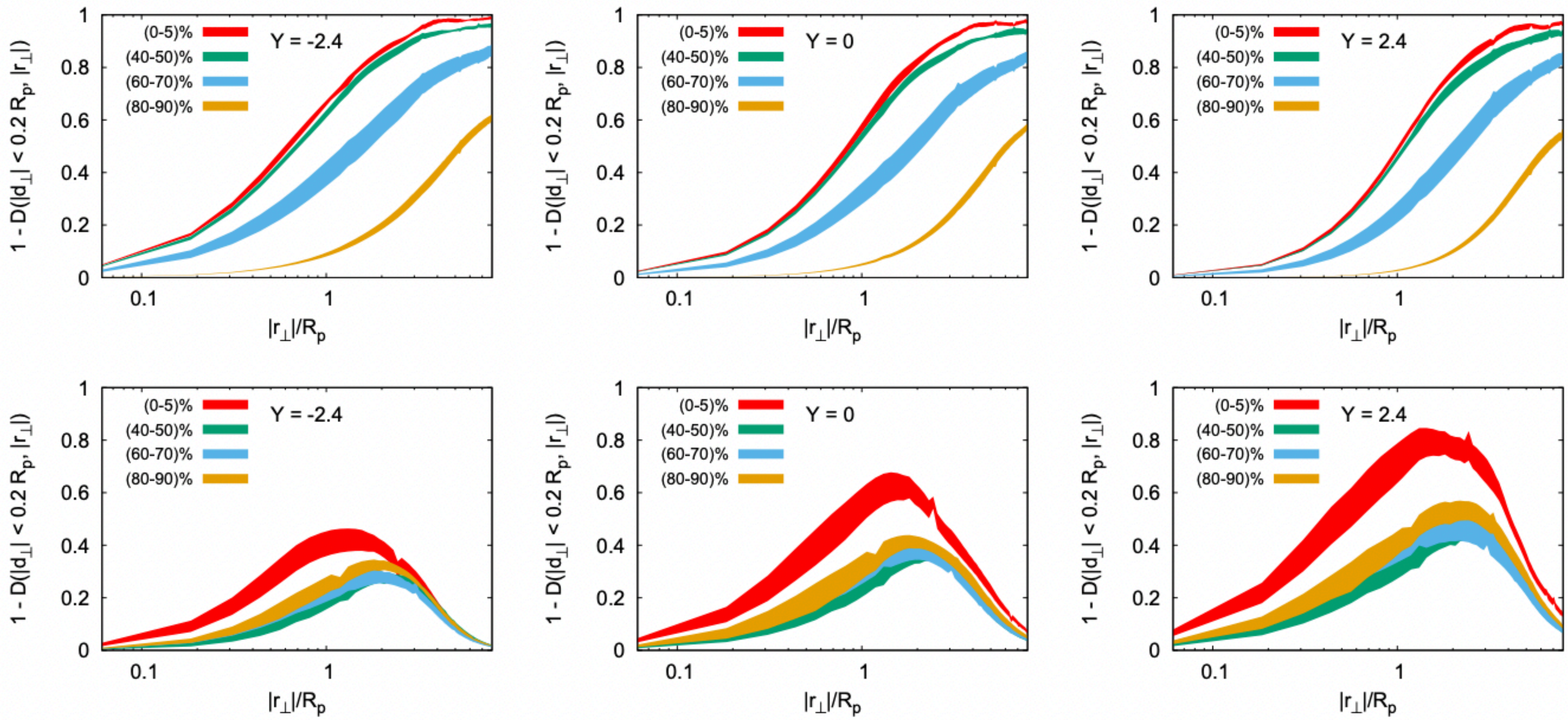


FIG. 13. Dipole scattering amplitudes $1 - D(\mathbf{r}_\perp, |\mathbf{d}_\perp| < 0.2R_p)$ of the lead nucleus (top) and proton (bottom) at three different rapidites $Y = -2.4, 0, +2.4$ as a function of dipole size $|\mathbf{r}_\perp|$ in units of the proton radius R_p.

$$D(|\mathbf{r}_\perp|_c, |\mathbf{d}_\perp| < 0.2R_p) = c$$

The parameterisation $D(\mathbf{r}_\perp) = \exp(-Q_s^2 {\mathbf{r}_\perp}^2/4)$. gives $Q_s = 2/|\mathbf{r}_\perp|_c \log^{1/2}(1/c)$