The role of longitudinal correlations and fluctuations

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Outline

1. 1D multiplicity correlation along the longitudinal direction
2. 2D di-hadron correlation and near side ridge
3. Decorrelation of event plane/anisotropic flow along η
4. Longitudinal fluctuations in CGC model
5. Conclusion

Definition

Longitudinal:

- Space-time rapidity $\eta_s = \frac{1}{2}\ln\frac{t+z}{t-z}$ at initial state
- Rapidity $Y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$ and pseudo-rapidity $\eta = \frac{1}{2}\ln\frac{p+p_z}{p-p_z}$ of final charged hadrons

Fluctuation: deviation of one variable from its event average.

$$\delta f = f - \langle f \rangle \tag{1}$$

Correlation: the extent to which two or more variables fluctuate together.

$$C_{12} = \langle \delta f_1 \delta f_2 \rangle = \langle (f_1 - \langle f_1 \rangle)(f_2 - \langle f_2 \rangle) \rangle = \langle f_1 f_2 \rangle - \langle f_1 \rangle \langle f_2 \rangle \tag{2}$$

Normalized correlation function:

$$C_{12} = \langle f_1 f_2 \rangle / \langle f_1 \rangle \langle f_2 \rangle \tag{3}$$

Longitudinal fluctuations and multiplicity correlation

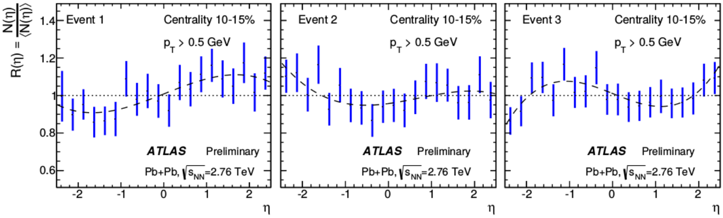


Figure: The longitudinal fluctuations of charged multiplicity in 3 typical events from ATLAS-CONF-2015-020

Two particle correlation function in pseudo-rapidity is,

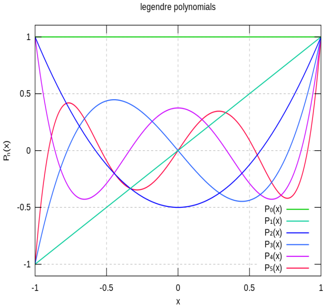
$$C(\eta_1, \eta_2) = \frac{\langle N(\eta_1)N(\eta_2)\rangle}{\langle N(\eta_1)\rangle\langle N(\eta_2)\rangle} \equiv < R(\eta_1)R(\eta_2) >, \qquad R(\eta) \equiv N(\eta)/\langle N(\eta)\rangle \tag{4}$$

where $N(\eta) \equiv dN/d\eta$.

Study the longitudinal structure by two particle rapidity correlation

In practice, $\langle dN/d\eta \rangle$ are different for different centrality classes. The corrected two particle correlation function can be decomposed into orthogonal polynomials,

$$C_N(\eta_1, \eta_2) = 1 + \sum_{n,m=1}^{\infty} a_{n,m} \frac{T_n(\eta_1)T_m(\eta_2) + T_n(\eta_2)T_m(\eta_1)}{2} \tag{5}$$



where $T_n(\eta) \equiv \sqrt{n + \frac{1}{2}} P_n(\eta/Y)$.

$$P_0(x) = 1 \tag{6}$$

$$P_1(x) = x \tag{7}$$

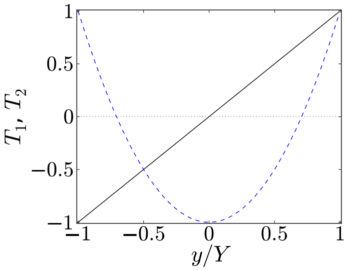
$$P_2(x) = (3x^2 - 1)/2 \tag{8}$$

$$P_3(x) = (5x^3 - 3x)/2 \tag{9}$$

see Broniowski, Wojciech and Jiang Yong, Jia's talk, A. Bzdak and D. Teaney, PRC 87 (2013) 024906, J.Jia,S.Radhakrishnan,M.Zhou,arXiv:1506.03496, ATLAS-CONF-2015-051 and ATLAS-CONF-2015-020 for details.

The physical meaning of $a_{n,m}$

A. Bzdak and D. Teaney, PRC 87 (2013) 024906



- $a_{1,1}$ describes the forward-backward asymmetry.
- $a_{2,2}$ describes the enhancement of forward-backward multiplicity correlation STAR PRL.103,172301(2009).
- The meanings of high order $a_{n,m}$ are still unclear.

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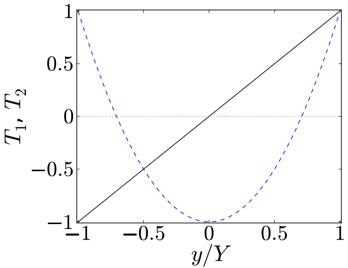

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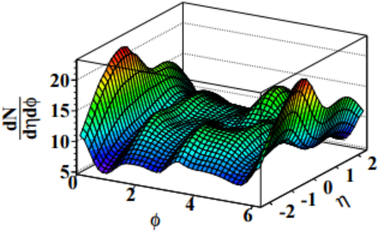
Recent EBE hydrodynamics by Akihiko Monnai and Bjorn Schenke, PLB752 (2016) 317-321 and Piotr Bozek et.el, PRC92 (2015) no.5, 054913 show that pure hydro underestimated $a_{n,m}$. While Piotr Bozek et.el show that $60 - 70\%$ of the $a_{n,m}$ come from non-flow effect. So n-particle rapidity correlation is suggested recently to eliminate (n-1)-particle non-flow correlations.

$$\langle a_i a_k a_m \rangle_3 = \int dy_1 dy_2 dy_3 \frac{C_3(y_1, y_2, y_3) T_i(y_1) T_k(y_2) T_m(y_3)}{\rho(y_1)\rho(y_2)\rho(y_3)} \quad (10)$$

Adam Bzdak and Piotr Bozek, PRC93 (2016) no.2, 024903

2D fluctuations from EBE hydro with AMPT initial conditions

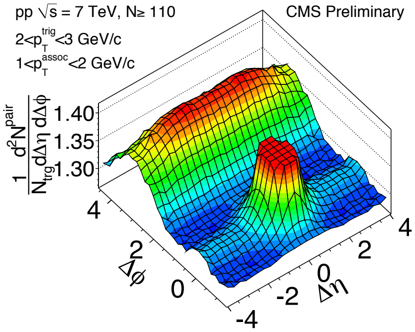


L.G. Pang, Q. Wang, X.N. Wang, PRC.89.064910.

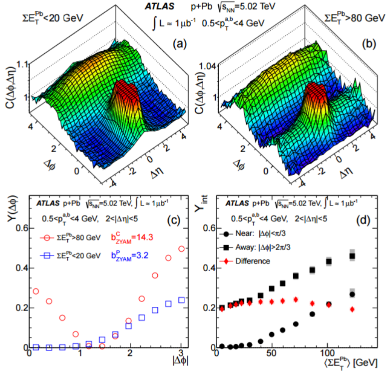
- Calculate the di-hadron correlation as functions of $\Delta\eta$ and $\Delta\phi$.
- Expect that the event plane/anisotropic flow are different at different rapidities.

Di-hadron correlation in P+P and P+A collisions

CMS Collaboration, 1009.4122.

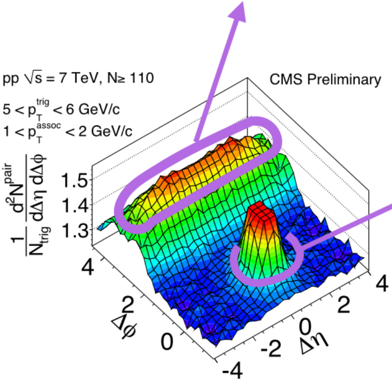


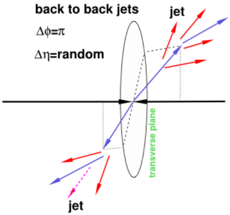
ATLAS Collaboration, 1212.5198v3



Di-hadron correlation from pQCD

Away side ridge from back-to-back jets

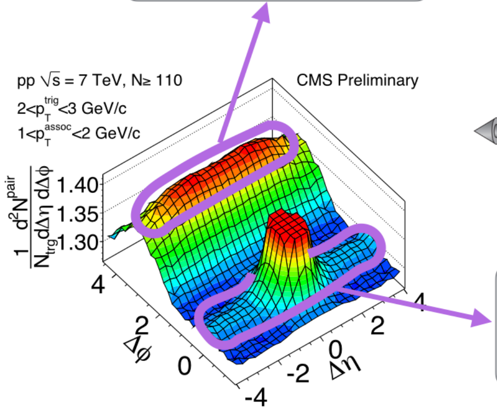


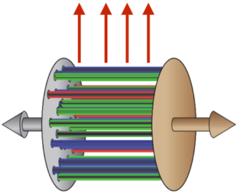


Near side peak from same side jet

Di-hadron correlation from color flux tube/glasma

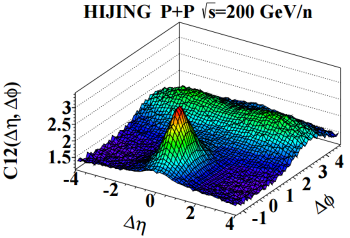
Away side ridge from back-to-back jets + flow (or boosted flux tube)

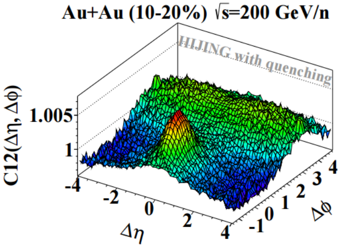




Near side ridge is associated with color flux tube

Color flux tube + isotropic fragmentation does not generate near side ridge

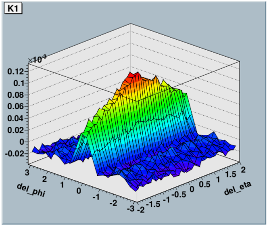




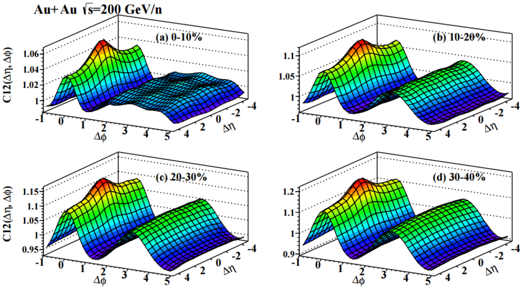
L.G.Pang, Q.Wang, X.N.Wang, PRC89 (2014) no.6, 064910

- Near side peak from minijets and short strings.
- Away side ridge from back-to-back jet pairs.
- Isotropic fragmentation of string + free streaming does not generate near side ridge.

Color flux tube + collective motion (flow) leads to near side ridge



EBE-hydro from EPOS initial condition, K. Werner, Iu. Karpenko, T. Pierog, M. Bleicher, K. Mikhailov, PRC82 (2010) 044904

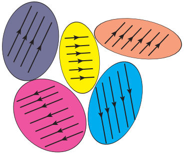


EBE-hydro from HIJING/AMPT initial condition, L.G.Pang, Q.Wang, X.N.Wang, PRC89 (2014) no.6, 064910

- Particles from the same color flux tube need to be boosted to the same direction such that particles with large pseudo-rapidity gap ($\Delta\eta$) fluctuate together.

Other explanations for near side ridge structure

Partons scattering off (boost invariant) color electric domains.



T. Lappi, B. Schenke, S. Schlichting, and R. Venugopalan

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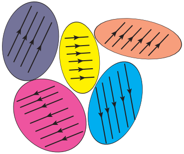

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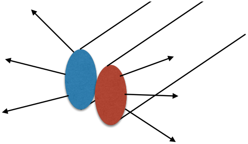
String-string interactions + subsequent string fragmentation



Feofilov's poster

V.A.Abramovskii, Pisma Zh. Eksp. Teor. Fiz. 47. No6. 281-283 (1988)

I.Altsybeev, AIP Conf.Proc.1701(2016)

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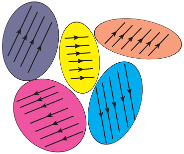

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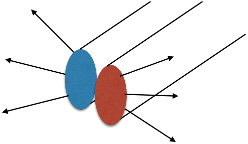
Medium(Color flux tube) kicked by (back-to-back) jets.

Cheuk-Yin Wong, PRC76. 054908

Cheuk-Yin Wong, PRC78. 064905

Cheuk-Yin Wong, PRC84. 024981

String-string interactions + subsequent string fragmentation



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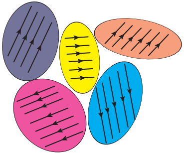

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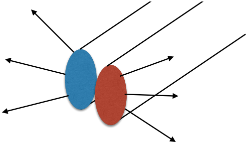

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IP-Glasma + Lund string fragmentation

see Prithwish Tribedy's talk on May 25th

Constraints from the newest LHC exp. data

Maxime Guilbaud's talk and Brian Cole's talk on May 23rd.

- None-vanishing $v_2\{2\},\ v_2\{4\},\ v_2\{6\}$ in p+p collisions.
- The mass ordering of the v_2 in p+p collisions.
- Ridge in low multiplicity p+p event.

Remarks:

- Strong evidence for collective flow.
- Question: can mass ordering and $v_2\{m\}$ pin down some explanations?
- Another constraint: the momentum distribution of the ridge particles
  - Lund string fragmentation .vs. Cooper-Frye particlization.

The longitudinal structure that is responsible for 'ridge'

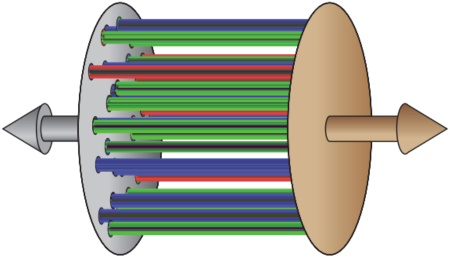


Figure: Fig from: Annu. Rev. Nucl. Part. Sci. 2010. 60:46389, by Francois Gelis,Edmond Iancu, Jamal Jalilian-Marian, and Raju Venugopalan

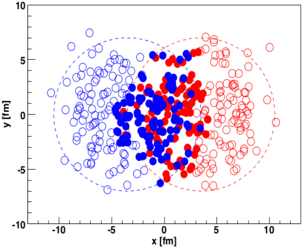
- Color flux tube (glasma):color electric field, color magnetic field

The longitudinal entropy deposition

$$\rho(\eta, x, y) = f_{+}(\eta)N_{+}(x, y) + f_{-}(\eta)N_{-}(x, y)$$

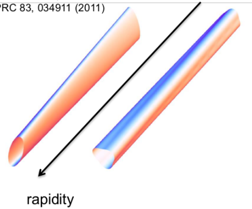
Adil and Gyulassy PRC 72.034907 (2005)

Gluon density is twisted because of the asymmetric distribution of forward and backward going participants.

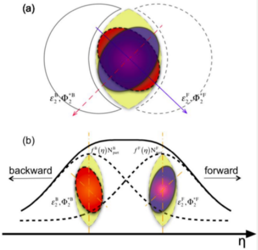


Hydrodynamics , torqued fireball

P Bozek et al,
PRC 83, 034911 (2011)



Transport



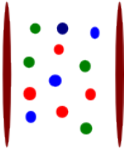
J Jia et al,
PRC 90, 034915 (2014)

Model the longitudinal fluctuations and entropy deposition

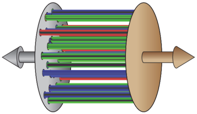
(a)

(b)

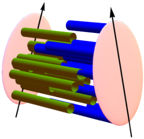
(c)



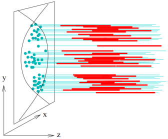
(d)



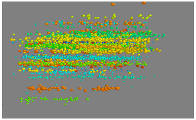
Usual CGC: (a).



Torqued fireball model: (b), (c)

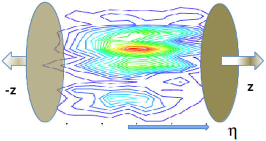


EPOS: (c)

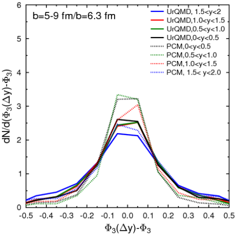


HIJING, AMPT, UrQMD: (c), (d)

Effect of longitudinal fluctuations



H. Petersen, et al.
PRC84 (2011) 054908



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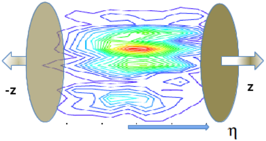

L.G. Pang et al. PRC86 (2012) 024911

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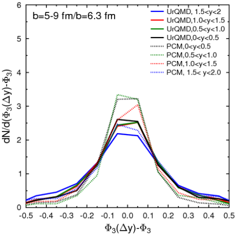

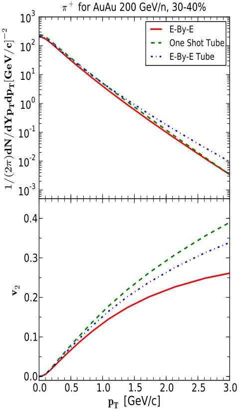

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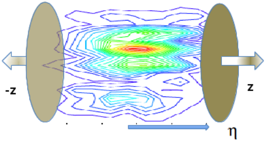

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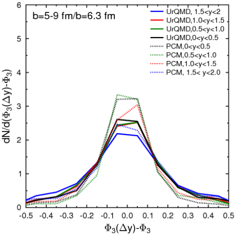

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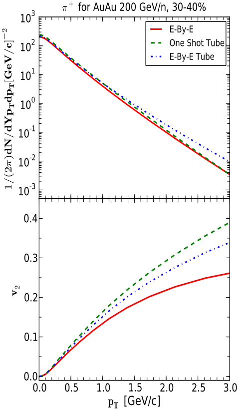
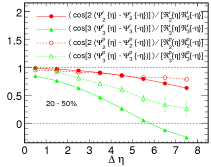
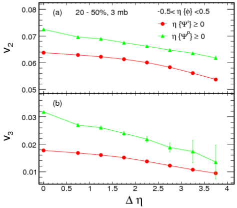


K. Xiao et al. PRC87 (2013) 1, 011901





Decorrelations with big $\Delta\eta$ gap

Piotr Bozek's method

$$\cos(k\Delta_{FB}) = \frac{< \exp\left(ik(\phi_F - \phi_B)\right) >}{\sqrt{< \exp\left(ik(\phi_{F1} - \phi_{F2})\right) >< \exp\left(ik(\phi_{B1} - \phi_{B2})\right) >}} \tag{11}$$

Kai Xiao's method

$$r_n(\Delta\eta = 2\eta_a) =< \cos\left(\Psi_n(-\eta_a) - \Psi_n(\eta_a)\right) > /(R_n(\eta_a)R_n(-\eta_a)) \tag{12}$$

- R_n is the resolution factor to remove the effect of finite multiplicity.

Our method based on Qn vector (LongGang, Pang et.al PRC91 (2015)4, 044904)

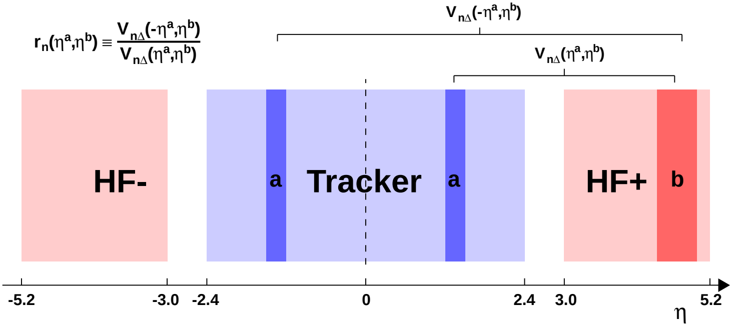
$$\mathbf{Q}_n = \frac{1}{N}\sum_{j=1}^{N} \exp(in\phi_j) = V_n \exp\left(in\Psi_n\right) \tag{13}$$

where $\phi_j = \arctan(p_y/p_x)$.

$$r_n(\Delta\eta = 2\eta_a) = \frac{< \mathbf{Q}_n(\eta_a)\mathbf{Q}_n^*(-\eta_a) >}{\sqrt{< \mathbf{Q}_n^2(\eta_a) >< \mathbf{Q}_n^2(-\eta_a) >}} \tag{14}$$

- This method captures both anisotropic fluctuations and event plane angle fluctuations.

CMS methods, PRC 92 (2015) 034911

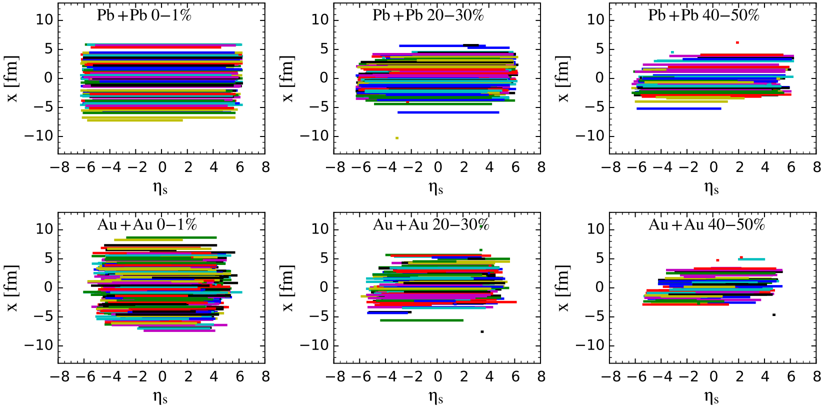


$$r_n(\Delta\eta = 2\eta_a) = \frac{< \mathbf{Q}_n(-\eta_a)\mathbf{Q}_n^*(\eta_b) >}{< \mathbf{Q}_n(\eta_a)\mathbf{Q}_n^*(\eta_b) >} \tag{15}$$

- If η_b is far away from η_a, no short range correlation.

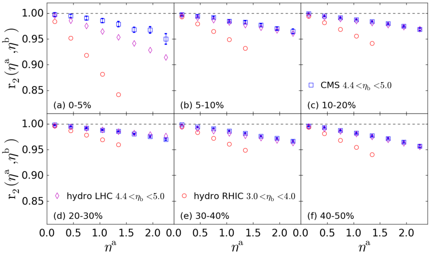
String length fluctuations

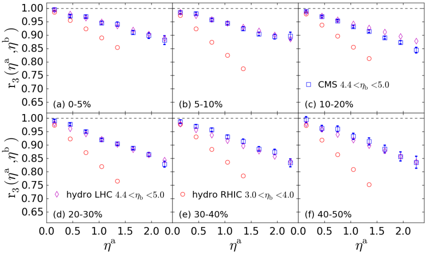
The initial condition for (3+1)D hydrodynamics is given by HIJING/AMPT model. Where the length of soft strings is sensitive to beam energy and centrality.



L.G.Pang, H.Petersen, G.Y.Qin, V.Roy, X.N.Wang, Eur.Phys.J. A52 (2016) no.4, 97

Decorrelation of nth order anisotropic flows

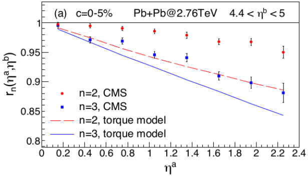


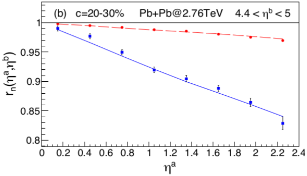


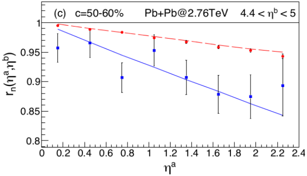
L.G.Pang, H.Petersen, G.Y.Qin, V.Roy, X.N.Wang, Eur.Phys.J. A52 (2016) no.4, 97

- EBE hydro match CMS measurements for r_2 except $0-5\%$ most central collisions.
- r_3 match experimental data for all centralities.
- Much stronger decorrelation at RHIC energy.

Pb+Pb collisions from torqued fireball model





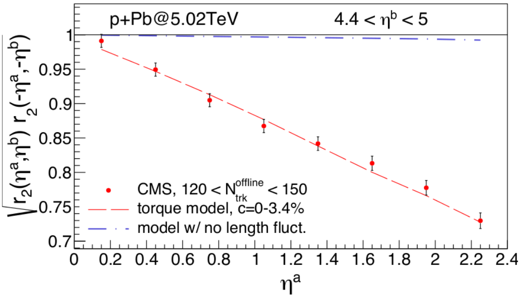


fluctuations improve description of r_2 in Pb-Pb
except for r_2 in central collisions

P.Bozek, W.Broniowski, J.Moreira, A.Olszewski, arXiv: 1011.3354, 1503.07425, 1506.04362

- String length fluctuations improved r_2 in A+A collisions.
- r_2 and r_3 are underestimated too in most central collisions.

p+Pb collisions from torqued fireball model

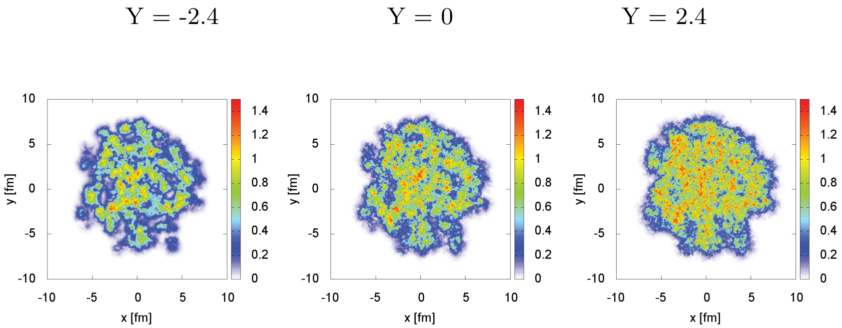


P.Bozek, W.Broniowski, J.Moreira, A.Olszewski, arXiv: 1011.3354, 1503.07425, 1506.04362

- String length fluctuations are crucially important for p+Pb collisions.

Longitudinal fluctuations in 3D-Glasma

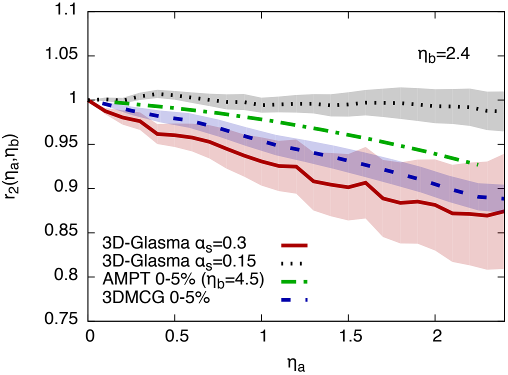
Gluon fields in one nucleus from JIMWLK



Bjorn Schenke and Soren Schlichting, arXiv:1605.07158

- The typical transverse length scale changes with rapidity.
- The global geometry clearly remains correlated over the entire rapidity range.

Longitudinal decorrelation in 3D-Glasma



Bjorn Schenke and Soren Schlichting, arXiv:1605.07158

- With smaller α_s, 3D-Glasma may solve the most central puzzle.

Conclusion

Two particle multiplicity correlation

- Is used to study the forward-backward asymmetry.
- Understanding high order $a_{n,m}$

Di-hadron correlation

- Near side ridge in p+p favors color flux tube/glasma + collective flow.
- Initial stage interaction: tube scatters with (1) partons, (2) tubes, (3) high momentum jets
- Mass ordering and $v_2\{m\}$ are important to find out the right physics for near side ridge in p+p.

Event-plane/anisotropic flow decorrelation along the longitudinal direction

- Asks for string length fluctuations in color flux tube models.
- Has strong centrality and beam energy dependence.
- Color flux tube .vs. Glasma and the importance of valence quarks.