3D Glasma Initial state from small-x evolution

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Based on: B. Schenke, S. Schlichting
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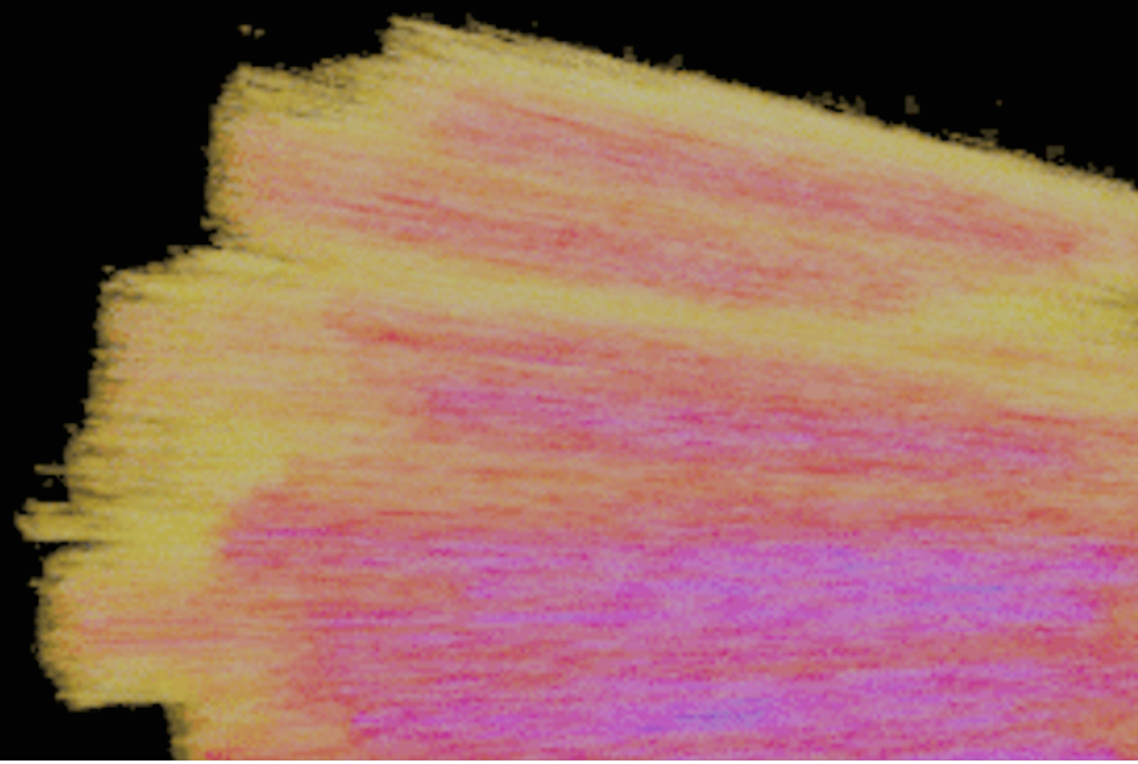

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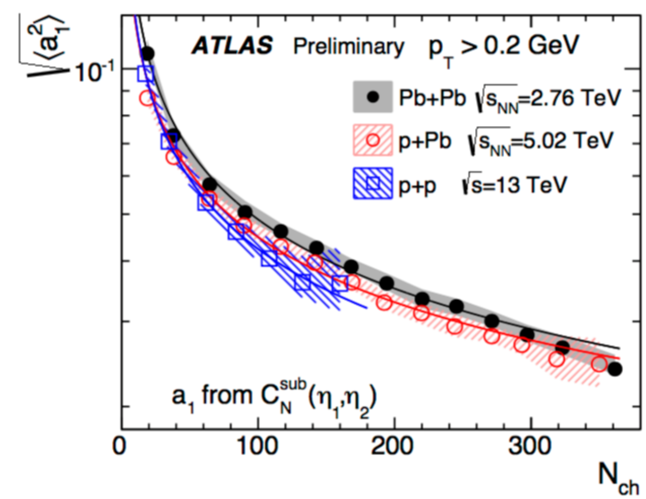
Motivation

ATLAS-CONF-2015-051



Experiment:

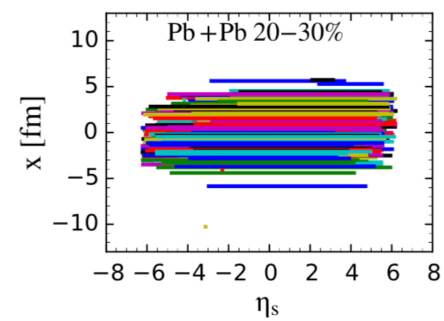
Exciting new insights into 3-D dynamics

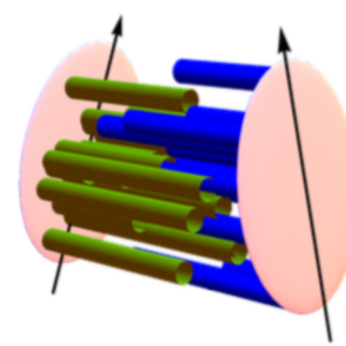
long. multiplicity & geometry fluctuations,
p+p, p+A, A+A, …

Theory:

Variety of models developed involving different degrees of freedom

hadrons, strings, const. quarks,…



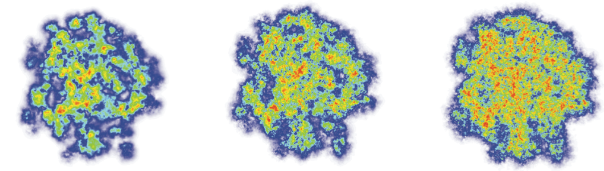


Bozek, Broniowski, PLB 752, 206 (2016),
Pang, Petersen, Qin, Roy, Wang, EPJ A52, 97 (2016),
Monnai, Schenke, PLB 752, 317 (2016),

…

Initial state in high-energy collisions

Energy deposition in high-energy collisions dominated by small-x gluons



-> Color-Glass Condensate effective field theory

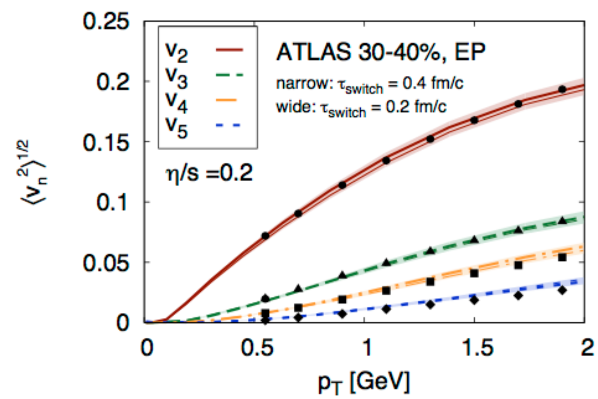
McLerran, Venugopalan PRD49 (1994) 2233-2241, Kovner, McLerran, Weigert D52 (1995) 6231-6237, …

Based on input from DIS fits IP-Glasma model provides successful microscopic description of transverse properties of initial state

event-by-event eccentricities, multiplicity distributions, …

Schenke, Tribedy, Venugopalan, PRC 86 (2012) 034908, PRL 108 (2012) 252301, …

Gale, Jeon, Schenke, Tribedy, Venugopalan, PRL 110 (2013) no.1, 012302



Gale, Jeon, Schenke, Tribedy, Venugopalan PRL 110 (2013) no.1, 012302

-> Extend to 3-D to explore long. dynamics at high-energies

Color-Glass Condensate description

Nucleon structure at small x characterized by correlation functions of light like Wilson lines $V_x = \mathcal{P}\, e^{-ig \int dx^- A^+}$

Based on high-energy factorization single inclusive observables e.g. $\left.\frac{dN}{dy}\right|_{y_{\rm obs}}$ can be calculated to leading log. (LL) accuracy as an average over color charge distributions inside projectile and target

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

$$\left.\frac{dN}{dy}\right|_{y_{\rm obs}} = \int [DU][DV]\ \mathcal{W}^{p}_{y_{\rm obs}-y_{\rm p}}[U]\mathcal{W}^{t}_{y_{\rm obs}-y_{\rm t}}[U]\ \frac{dN}{dy}[U,V]$$

rapidity separation
between projectile and measured rapidity

rapidity separation
between target and measured rapidity

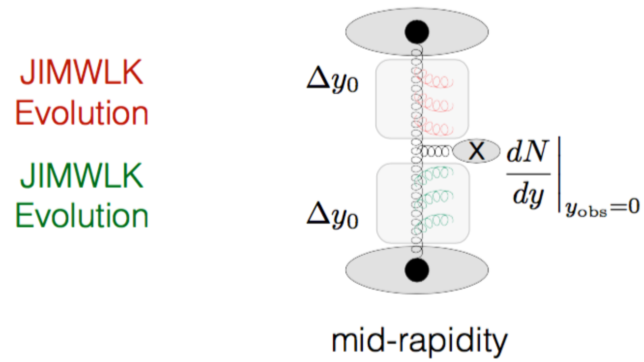
Evolution of weight-functionals $\mathcal{W}_{\Delta y}$ with the rapidity separation Δy is described by JIMWLK evolution equation

High-energy factorization above proven for single inclusive observables, and un-equal rapidity correlations with rapidity separation $y^1_{\rm obs} - y^2_{\rm obs} \ll 1/\alpha_s$ but breaks down when $y^1_{\rm obs} - y^2_{\rm obs} \sim 1/\alpha_s$

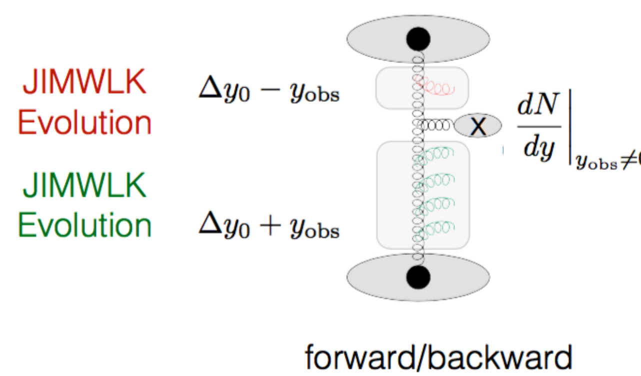
3D-Glasma Initial state

Practical description:

1) Generate configuration of Wilson lines U,V at initial rapidity separation y_{Init} based on IP-Sat



2) Evolve Wilson lines U,V from initial rapidity y_{Init} to all rapidities y_{obs} of interest ($y_{obs} > y_{Init}$)



3) Compute observables at all rapidities of interest by solving class. Yang-Mills equations

Small-x evolution — formalism

Stochastic formulation of (LL) JIMWLK evolution

Blaizot,Iancu,Weigert NPA713, 441 (2003), Lappi,Mäntysaari EPJ C73, 2307 (2013)

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

provides an efficient way to study on an event-by-event basis

Even though NLL effects are know to be important to e.g. slow down evolution of DIS structure functions, we stay at LL accuracy and use α_s as a free parameter to adjust evolution speed

Since we are interested in impact parameter dependence, need to introduce infrared regulator to suppress gluon radiation at large distance scales

Kovner, Wiedemann, PRD 66 (2002) 051502

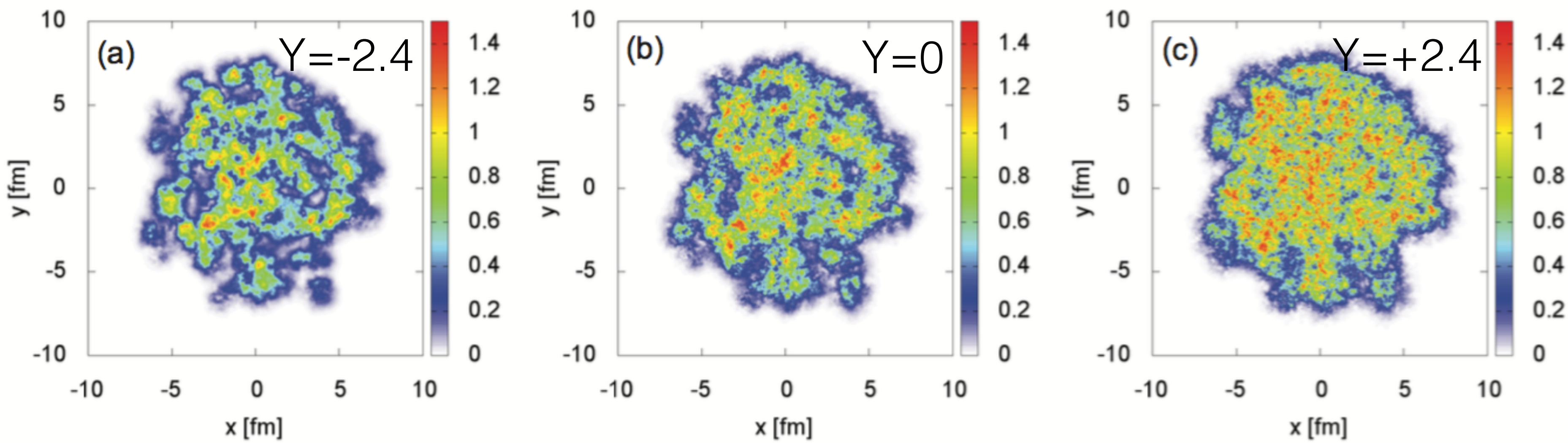
$$\mathbf{K}_{\mathbf{r}}^{(\mathrm{mod})} = m|\mathbf{r}|\; K_1(m|\mathbf{r}|)\; \mathbf{K}_{\mathbf{r}}$$

-> Need to check sensitivity of results to infrared regulator $m \sim \Lambda_{QCD}$

Small-x evolution — results

IP-Sat
(initial condition)

JIMWLK evolution →
α_s=0.3 | m=0.4 GeV



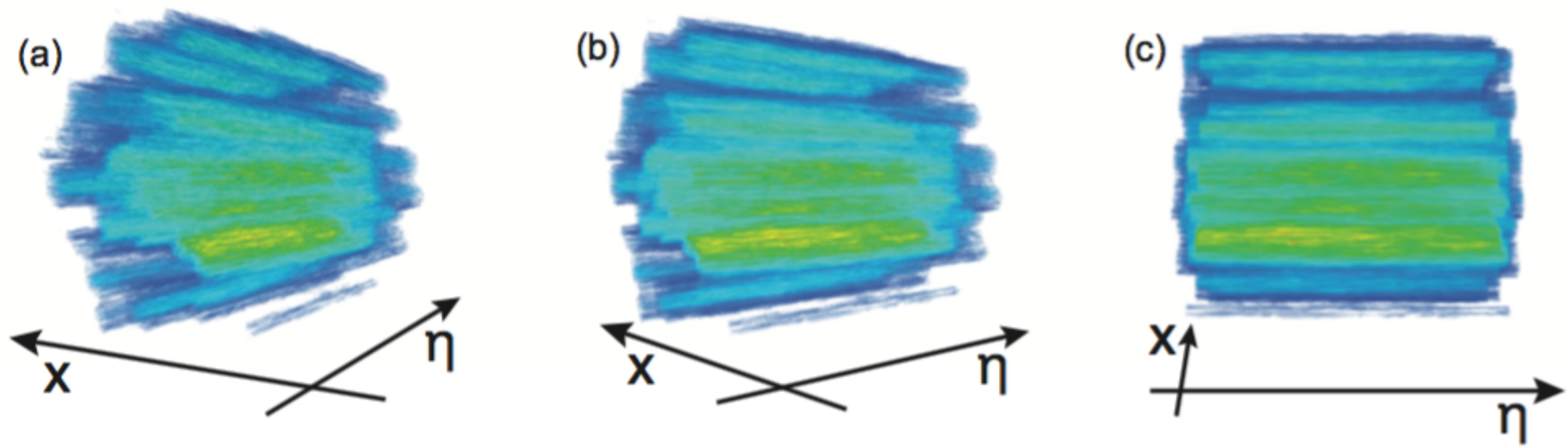
Small scale fluctuations develop and become finer and finer as characterized by the growth of $Q_s(Y)$

Smoothening of geometric profile and growth in impact parameter space (‘Gribov diffusion’)

(c.f. SS, Schenke PLB 739 (2014) 313-319)

3-D Glasma Initial state

Contour plots of initial state energy density ($T^{\tau\tau}$) in a single 2.76 TeV Pb+Pb event (b=0)



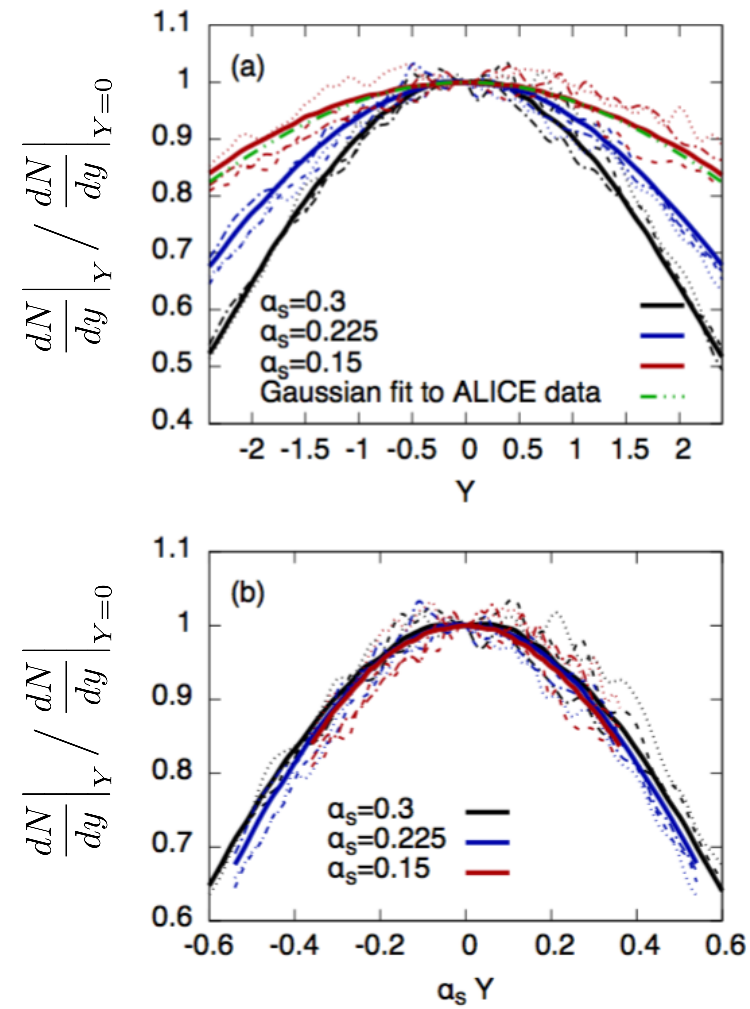
α_s=0.3 | m=0.4 GeV | τ=0.2 fm/c

Energy deposition dominated by approx. boost-invariant flux tubes with characteristic transverse size of nucleon

Short & long range fluctuations (η & x), center of mass shifts (η)

Comparison to 2.76 TeV Pb+Pb data

So far all comparison based on initial state only (no hydro), for central 2.76 TeV Pb+Pb (b=0)



Multiplicity:

Event averaged multiplicity distribution dN/dy shows good agreement with ALICE data for small value of $\alpha_s = 0.15$

Evolution speed of dipole gluon distribution for same value of $\alpha_s = 0.15$

$$\frac{d\ \ln Q_s^2}{dY} = 0.28 - 0.3$$

consistent with extractions from DIS structure functions.

Long. multiplicity fluctuations

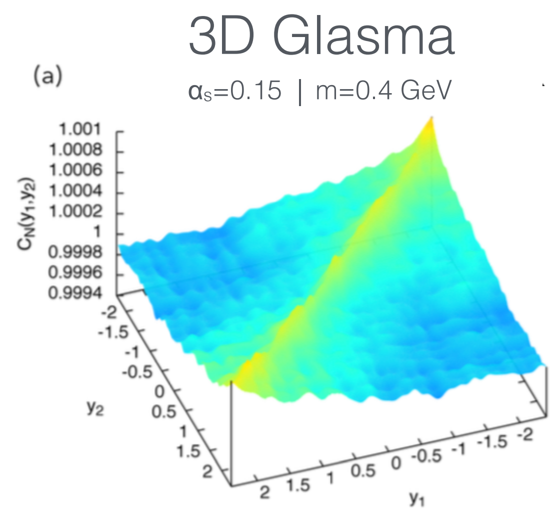
Characterized by correlation function

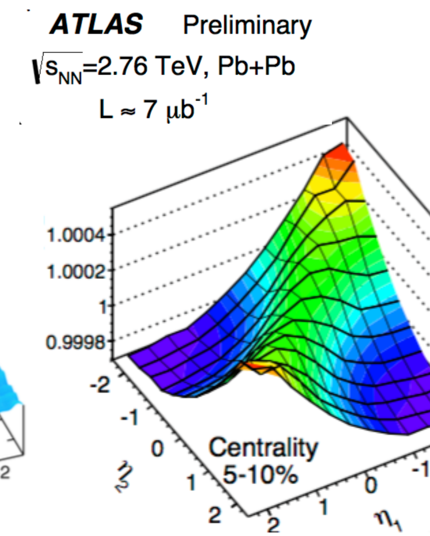
$$C(Y_1, Y_2) = \left\langle \frac{dN}{dY_1} \frac{dN}{dY_2} \right\rangle \Big/ \left\langle \frac{dN}{dY_1} \right\rangle \left\langle \frac{dN}{dY_2} \right\rangle$$

subject to norm. condition

Similar structure to ATLAS measurement

ATLAS-CONF-2015-020



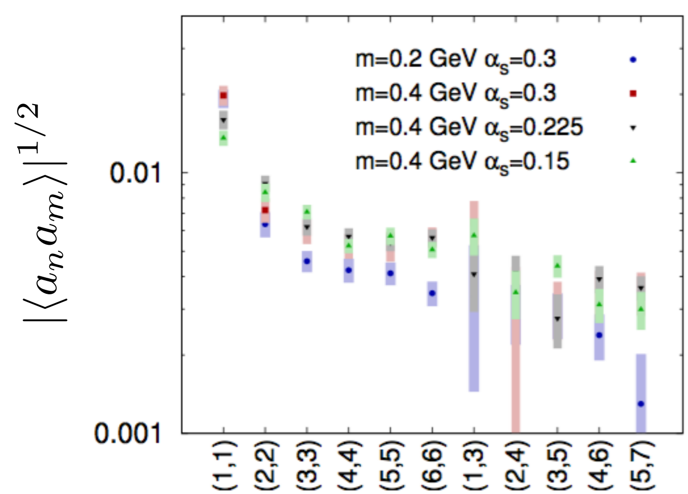


Decomposition in Legendre polynomials

Bzdak, Teaney, PRC 87, 024906 (2013)

$$\frac{dN}{dY} \propto 1 + \sum_n a_n T_n(Y)$$

shows dominance of $\langle a_1 a_1 \rangle$ forward/ backward asymmetry



Dominant effect from Q_s fluctuations at initial rapidity scale

c.f. Bzdak, Dusling PRC C93 (2016) no.3, 031901, PRC 94 (2016) 044918

De-correlation of transverse geometry

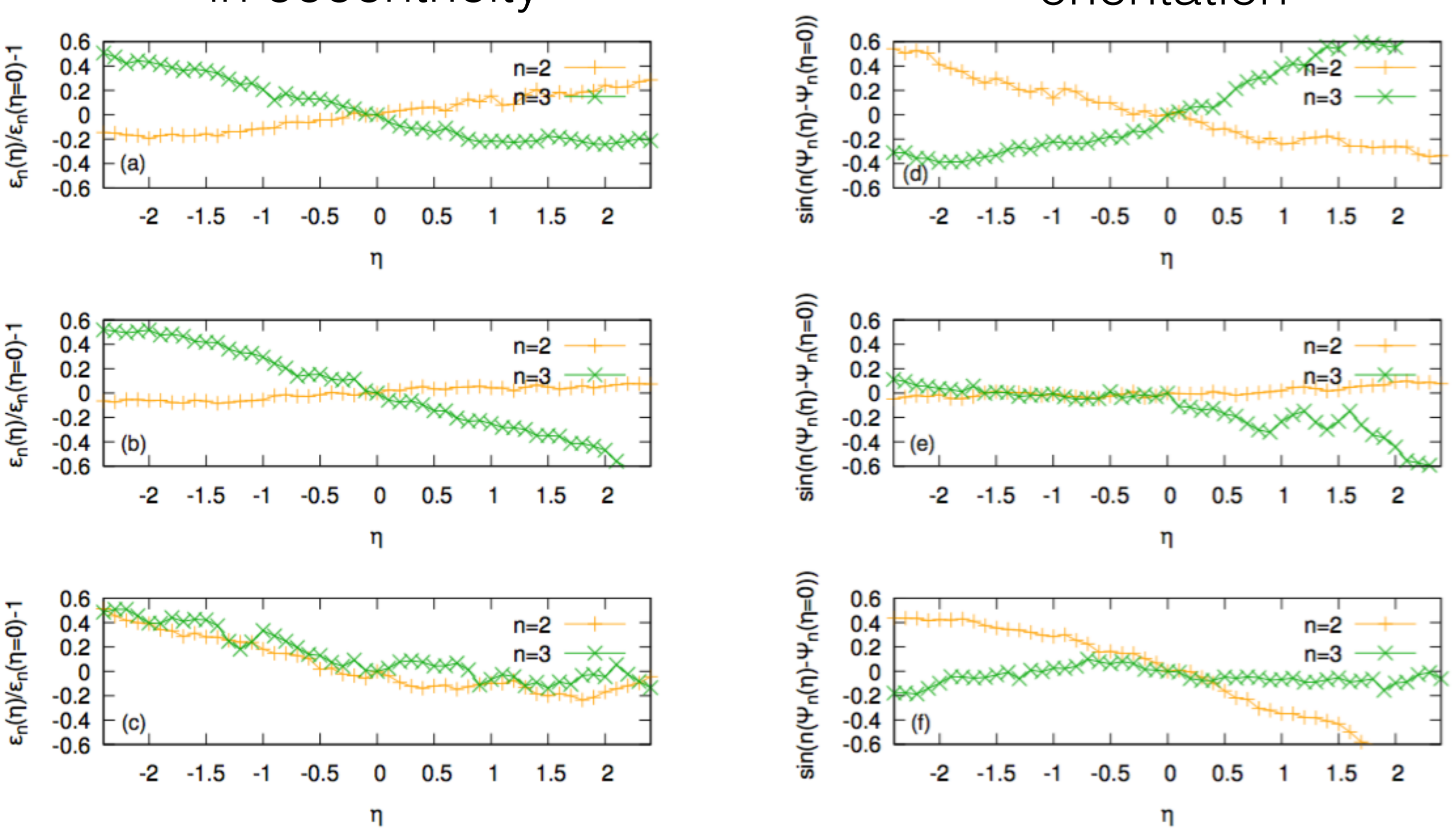
Characterize in terms of initial state eccentricity $|\boldsymbol{\varepsilon}_n|$ and eccentricity plane Ψ_n

relative change in eccentricity | change in event-plane orientation

Event 1

Event 2

Event 3



α_s=0.3 | m=0.4 GeV

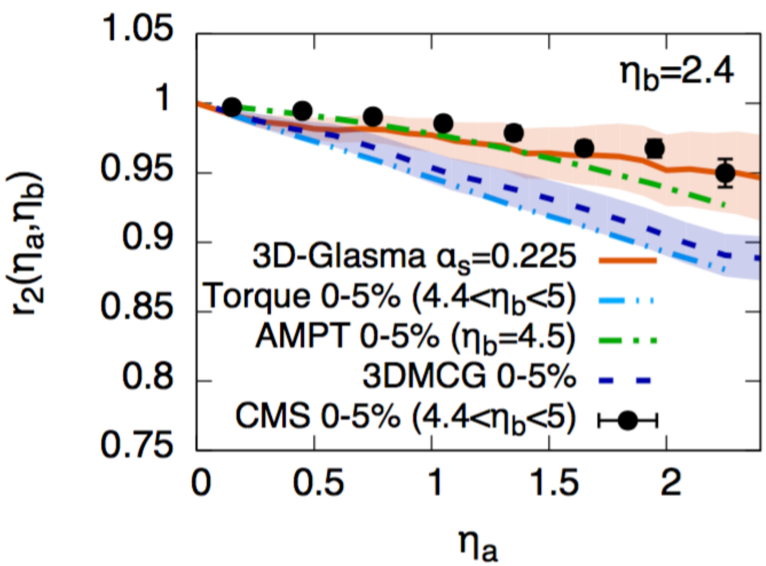
De-correlation of transverse geometry

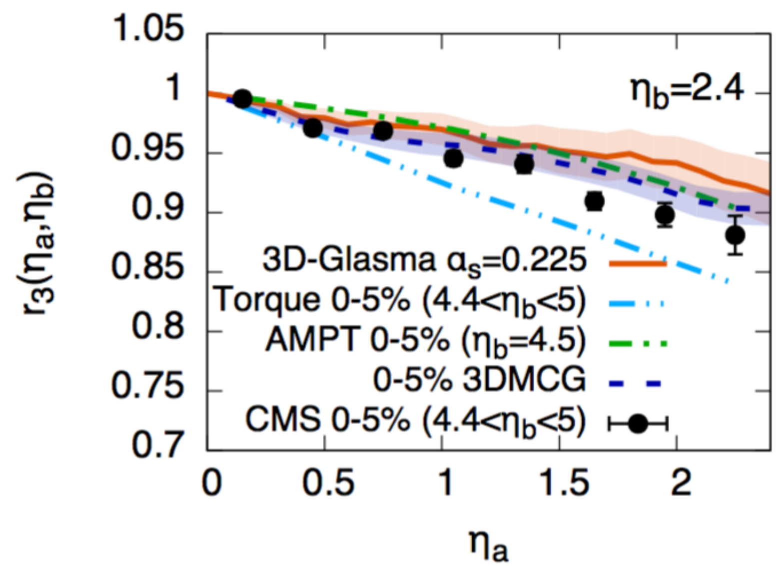
Characterize overall de-correlation by forward/backward ratio

CMS Collaboration PRC 92, 034911 (2015)

$$r_n(\eta_a, \eta_b) = \frac{\langle \mathrm{Re}[\boldsymbol{\epsilon}_n(-\eta_a) \cdot \boldsymbol{\epsilon}_n^*(\eta_b)] \rangle}{\langle \mathrm{Re}[\boldsymbol{\epsilon}_n(\eta_a) \cdot \boldsymbol{\epsilon}_n^*(\eta_b)] \rangle}$$

using initial state $\boldsymbol{\varepsilon}_n$ instead of $\mathbf{Q}_n$





Simultaneous description of r_2,r_3 in central events (0-5%) provides a challenge in various models

(Torque model) Bozek, Broniowski, PLB 752, 206 (2016), (AMPT) Pang, Petersen, Qin, Roy, Wang, EPJ A52, 97 (2016), (3DMCG) Monnai, Schenke, PLB 752, 317 (2016)

Conclusions & Outlook

Developed event-by-event description of 3-D initial state based on high-energy factorization

longitudinal structure is determined by JIMWLK evolution

First applications to initial state in central Pb+Pb collisions shows promising results

avg. multiplicity, multiplicity & geometric fluctuations

Can be extended towards comprehensive study of different collisions systems (p+p,p+p/A)

include running coupling, event selection,, …

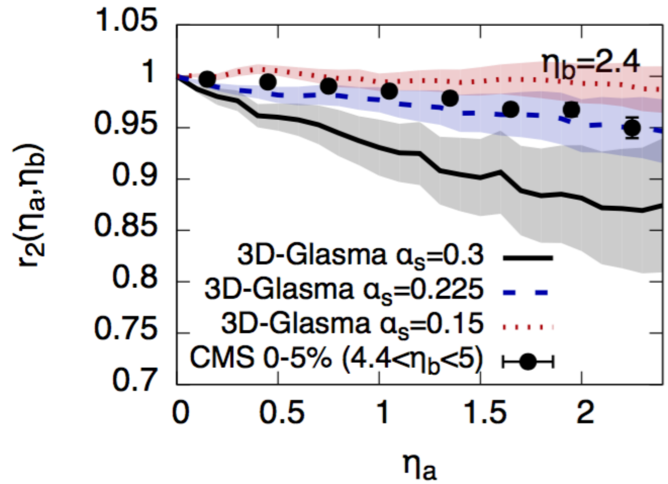
Develop parametric models based on microscopic insights

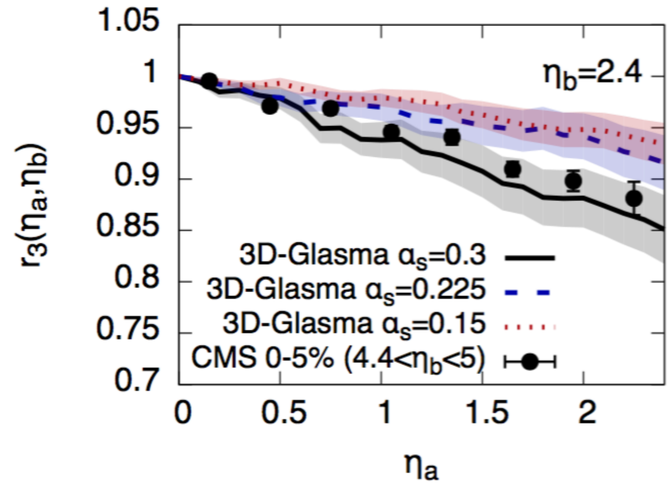
c.f. Bzdak, Dusling PRC C93 (2016) no.3, 031901, PRC 94 (2016) 044918

Backup

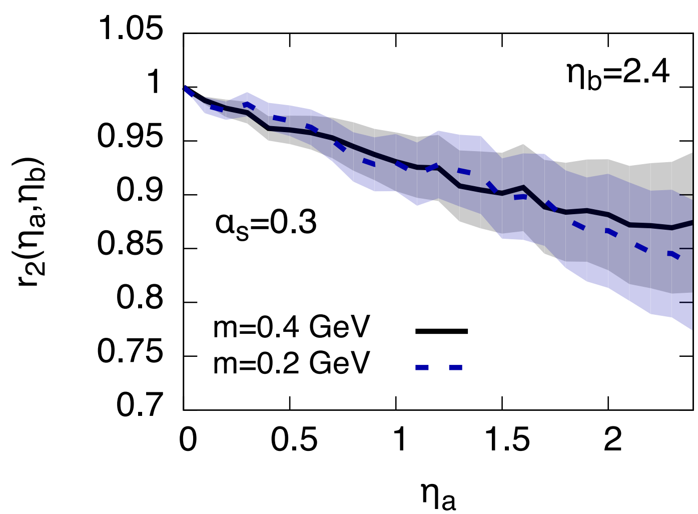
De-correlation of transverse geometry

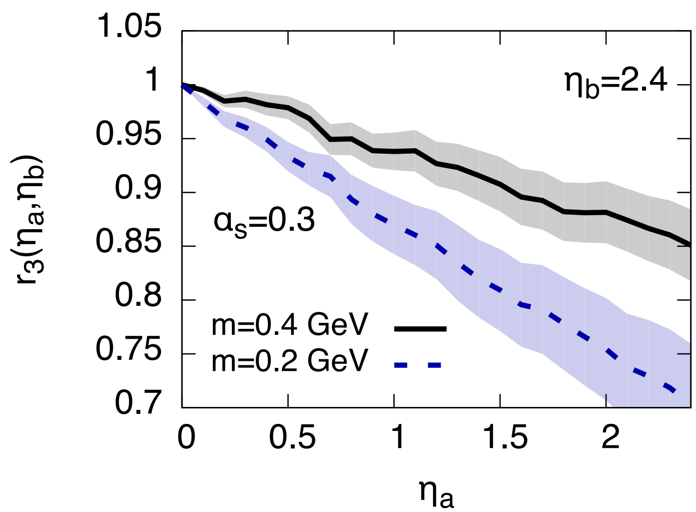
Dependence on coupling constant





Dependence on IR regulator





De-correlation of transverse geometry

Eccentricity change Event plane de-correlation