Initial conditions of heavy ion collisions

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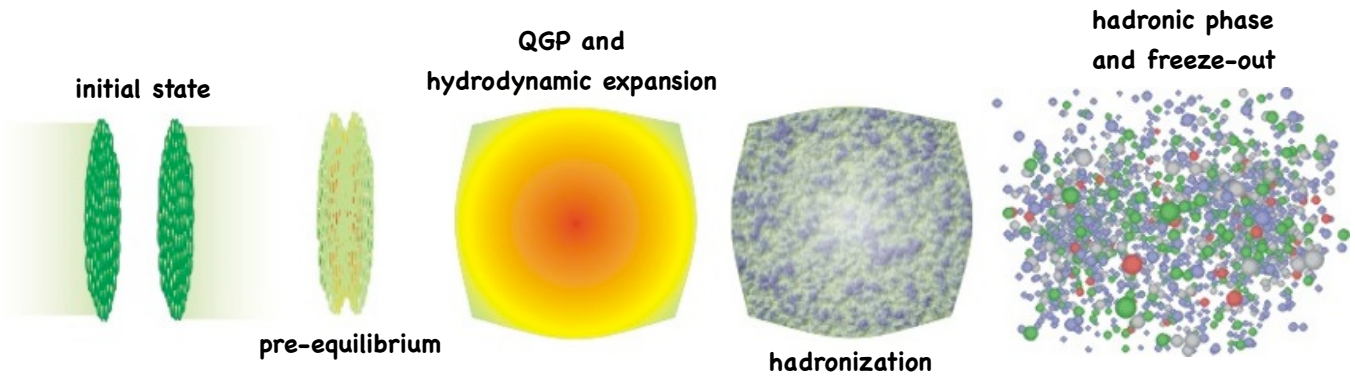
Outline

Initial conditions of heavy ion collisions: their role in quantifying the Properties of the Perfect Liquid

- Different approaches to model the initial stages of HICs
- Constraining initial conditions from global data.
- Open problems, what can we learn for small size systems ?

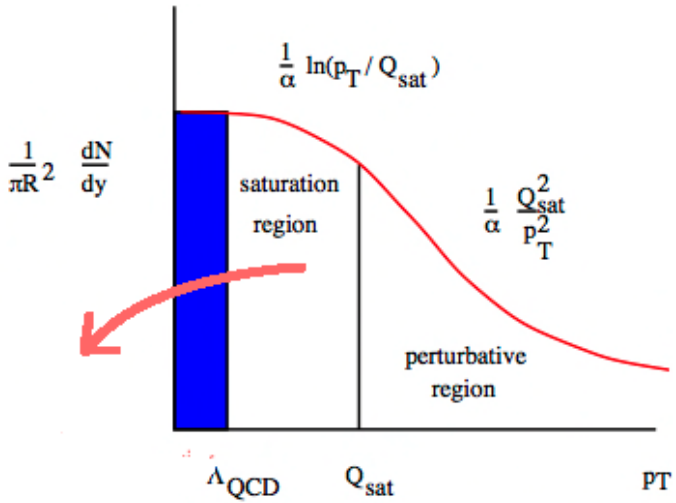
The early stages of heavy ion collisions



Effects of initial stages are inevitable on bulk particle production regardless of any final stage effect.

Initial wave function $\rightarrow$
high occupancy states
below $p_T < Q_{sat}$

These modes will
show collective behaviour



It is essential get an *ab initio* description of the early stage of HICs

Ab initio description of Initial state

Two essential ingredients are:

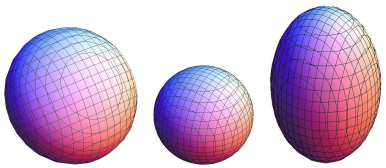
- A good description of initial state geometry and fluctuations.
- An ab initio mechanism of multi-particle production.

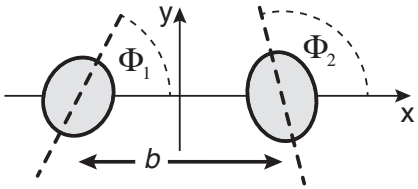
$\rightarrow$ input to viscous hydrodynamic simulation

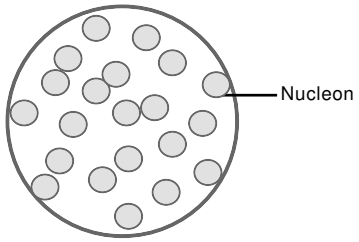
Initial state geometry and fluctuations

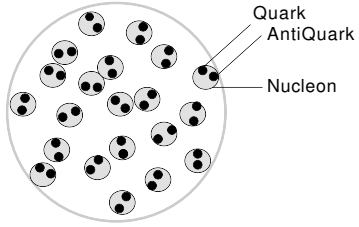
Initial state fluctuations

- Geometric
  - Deformation (prolate, oblate)
  - Collision-geometry ($b, \Theta_{1,2}, \Phi_{1,2}$)
- Dynamical
  - Nucleonic ($\sim 1/\Lambda_{QCD}$)
  - Sub-nucleonic ($\sim 1/Q_S(x, A)$)









In addition a good framework of multi-particle production is needed

MC-Glauber: A simple model of initial condition

Model of multiplicity : Kharzeev, Nardi nucl-th/0012025

$$\frac{dN}{d\eta} = n_{\rm pp}\left(xN_{\rm coll} + (1-x)\frac{N_{\rm part}}{2}\right),$$

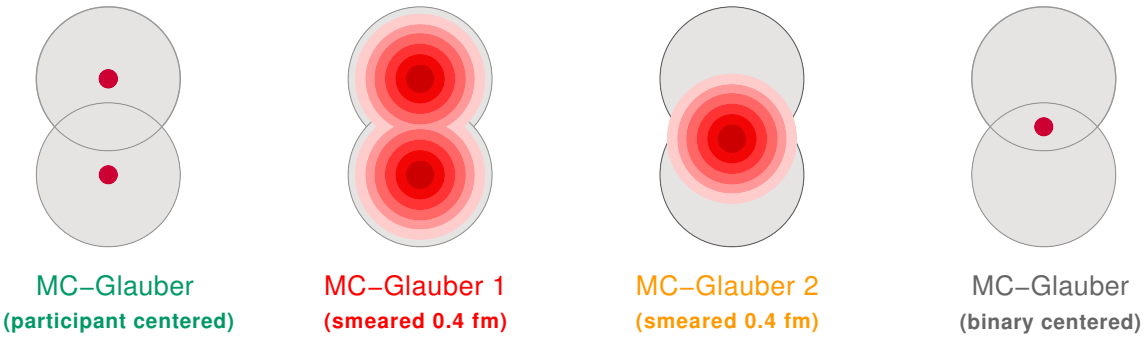
$n_{pp} \rightarrow$ multiplicity in p+p collisions, $x \rightarrow$ "hardness" scale, $N_{\rm coll} \rightarrow$ binary collisions, $N_{\rm part} \rightarrow$ participants.

Intrinsic correlation between the multiplicity and the initial shape.

Multiplicity fluctuation introduced as : $P_n^{NB}(\bar{n}, k) = \frac{\Gamma(k+n)}{\Gamma(k)\Gamma(n+1)} \frac{\bar{n}^n k^k}{(\bar{n}+k)^{n+k}}$

Each n-n collision as identical sources with mean $\bar{n}$ & width $\sim 1/k$

Model of Energy density profile : Bzdak, Schenke, PT,Venugopalan 1304.3403



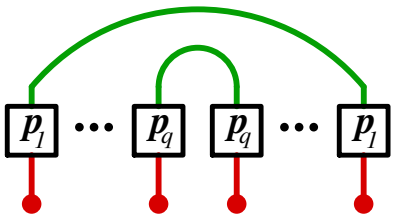
$\rightarrow$ no unique implementation of energy deposition (x, k, $\sigma_0 \rightarrow$ free parameters)

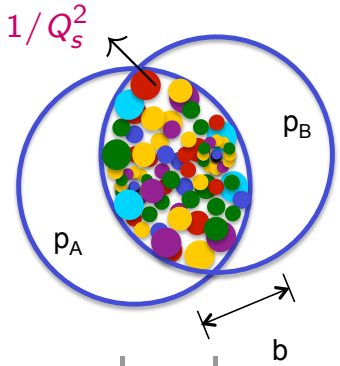
$\rightarrow$ An *ab initio* mechanism of multi-particle production is missing.

Color Glass Condensate : Multi-particle production

Dumitru, Gelis, McLerran, Venugopalan 0804.3858

Correlated multi particle production from disconnected diagrams connected by color averaging.





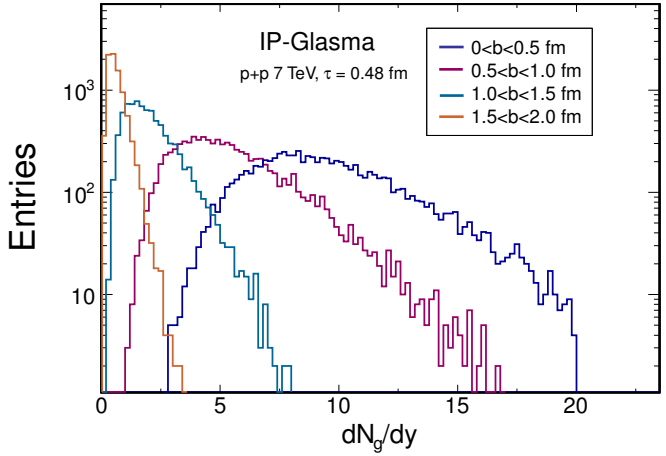
Dusling, Venugopalan 1302.7018

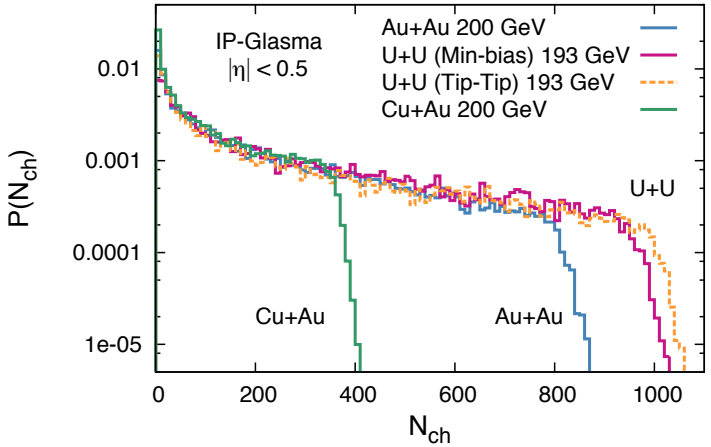
2-particle correlation $\rightarrow$ ridge.
n-particle correlation $\rightarrow$ negative-binomial fluctuation.

Gelis, Lappi, McLerran 0905.3234

Yang-Mills introduces non-local gauge-field correlation over length scale $1/Q_s$ $\rightarrow$ Glasma flux tube picture. $\rightarrow$ Negative Binomial distributions

Schenke, PT, Venugopalan 1403.2232





Are there additional sources of fluctuations ?

CGC initial conditions

Development over past decade :

Kharzeev, Levin, Nardi, hep-ph/0111315, Drescher, Nara 0707.0249

- KLN model, f-KLN, MC-KLN: $k_\perp$-factorization (dilute-dense approximation) with UGDs dependent on $N_{\rm part}$, $((Q_s)(x_\perp)^2 \propto N_{\rm part}(x_\perp))$.

Albacete, Dumitru 1011.5161

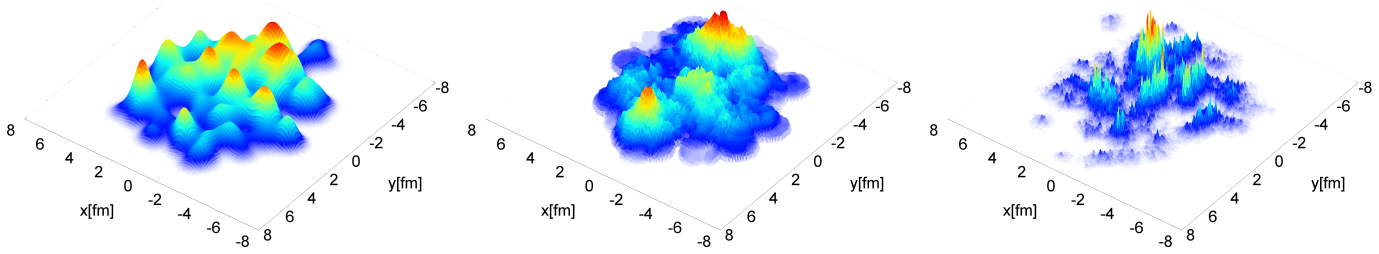
- MC-rcBK: Monte-Carlo implementation of $k_\perp$-factorization with rc-BK UGDs constrained by HERA-data.

Schenke, PT, Venugopalan 1202.6646

- IP-Glasma : IP-Sat initial condition (constrained by HERA data) and solutions of Classical Yang-Mill equations.

Different models of initial conditions.

I.C.	Geometry	$k_T - factorization$	Classical Yang-Mills
framework	2-component model	CGC perturbative	CGC non-perturbative
E-by-E	✓	✓	✓
Sub-nucleonic fluctuation	✗	✗	✓
Time evolution	✗	✗	✓
pre-equilibrium flow	✗	✗	✓
NBD fluctuation	by hand	by hand	✓



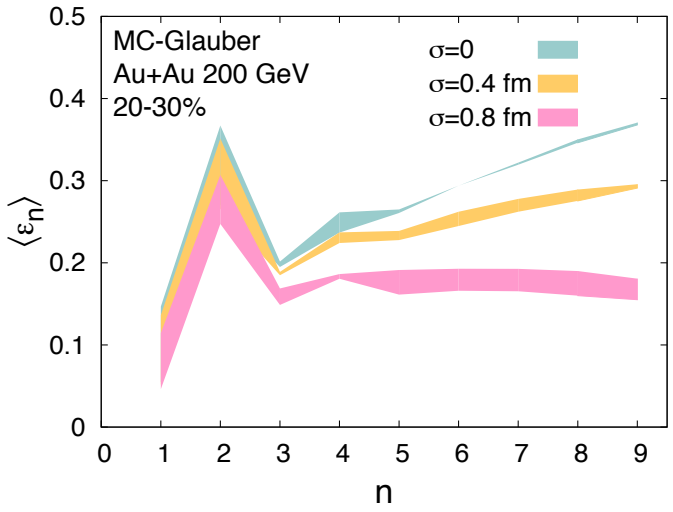
Initial eccentricities in different models

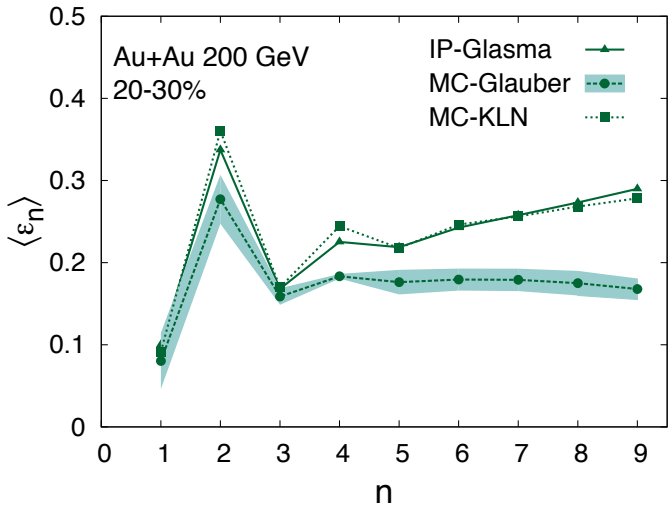
MC-Glauber eccentricities → strong dependence on implementations.

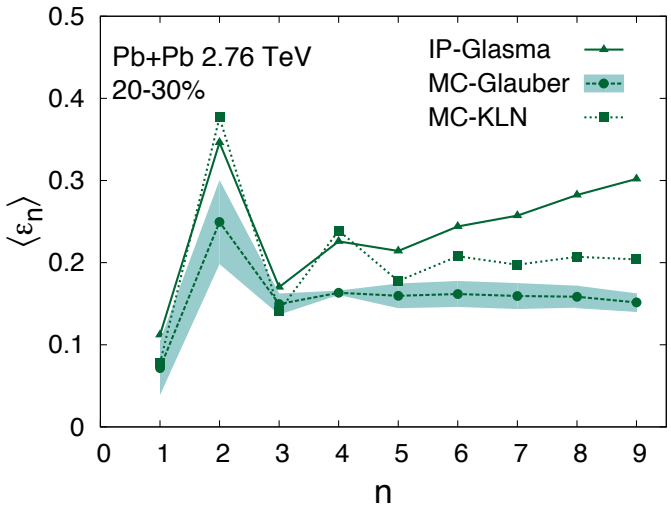
$$\varepsilon_n e^{in\Psi_n^{PP}} = -\frac{\int d^2r\, r^n e^{in\phi}\, \epsilon(r,\phi)}{\int d^2r\, r^n\, \epsilon(r,\phi)}$$

with r^3 weight for $n = 1$

MC-Glauber (Gaussian density profile) band → participant/binary centered





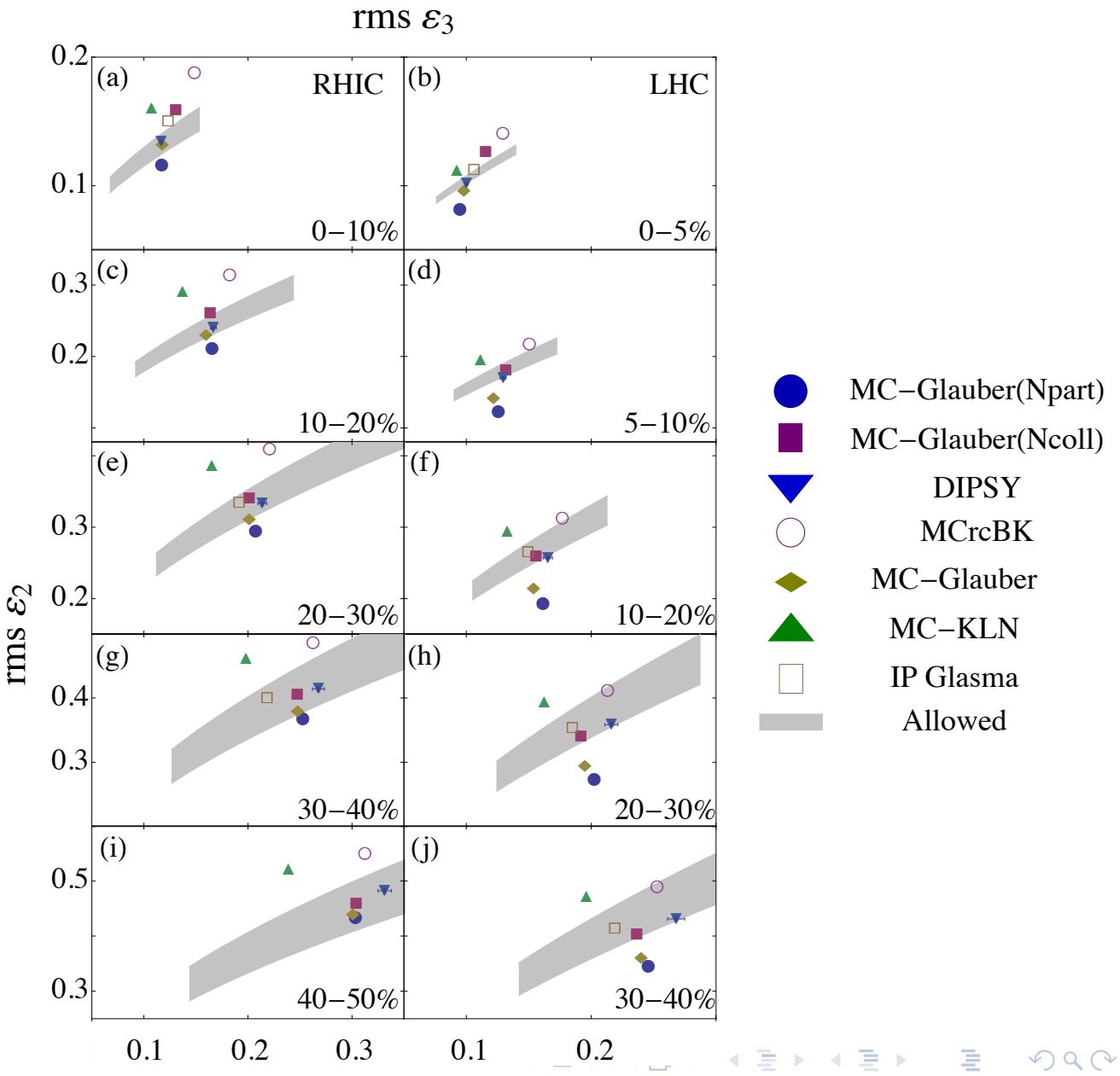


also see Heinz 1304.3634

Constraining different models of initial conditions

Retinskaya, Luzum, Ollitrault 1311.5339

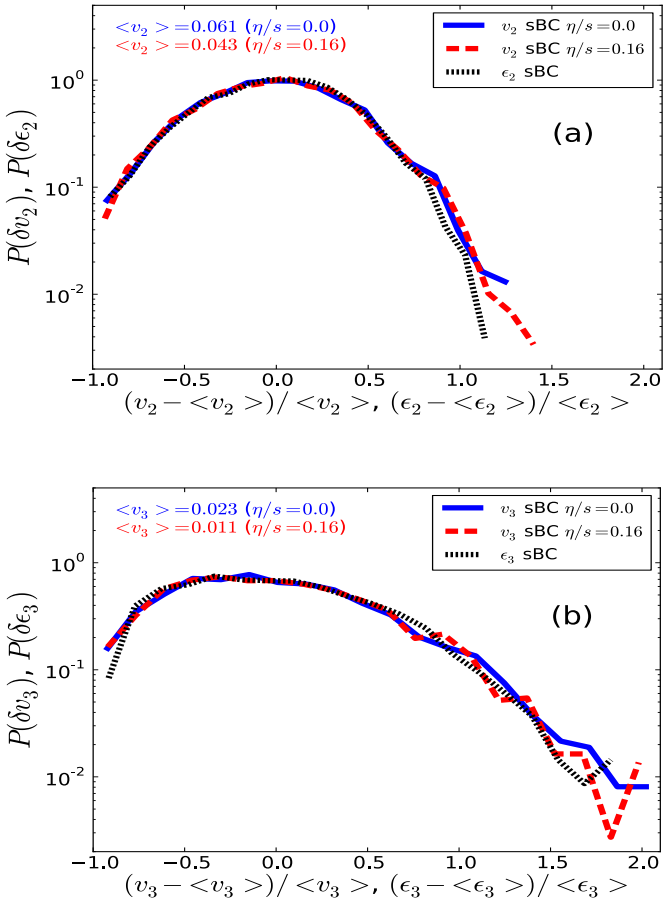
ε_n's are strongly model dependent $\rightarrow$ correlations are better ways to compare.



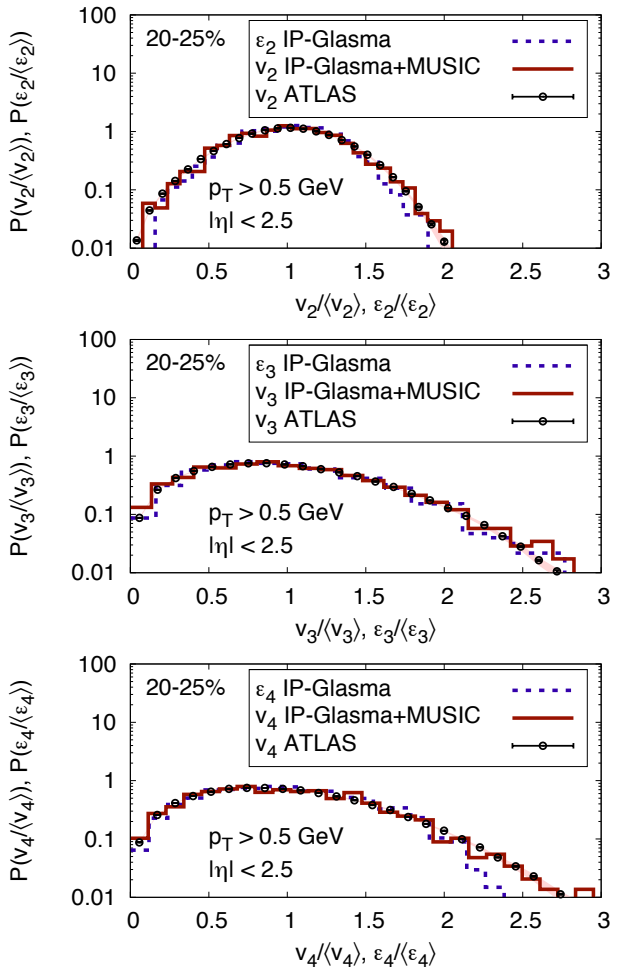
Constraining initial conditions with hydro simulations

Probability distributions of v_n at LHC : weak dependence on η/s

Niemi, Denicol, Holopainen, Huovinen 1212.1008



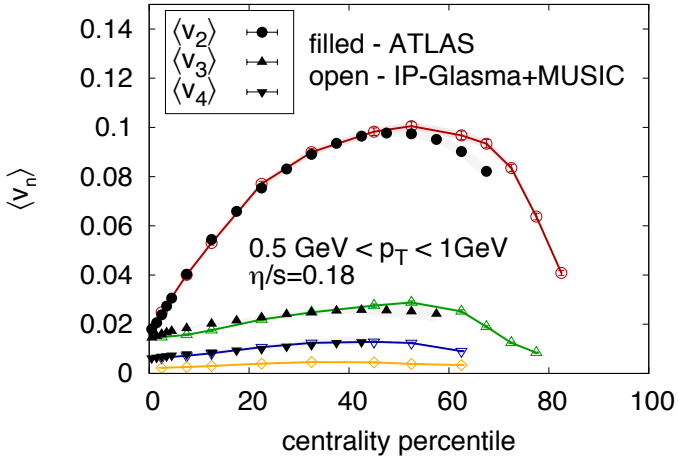
Gale, Jeon, Schenke, PT, Venugopalan 1209.6330



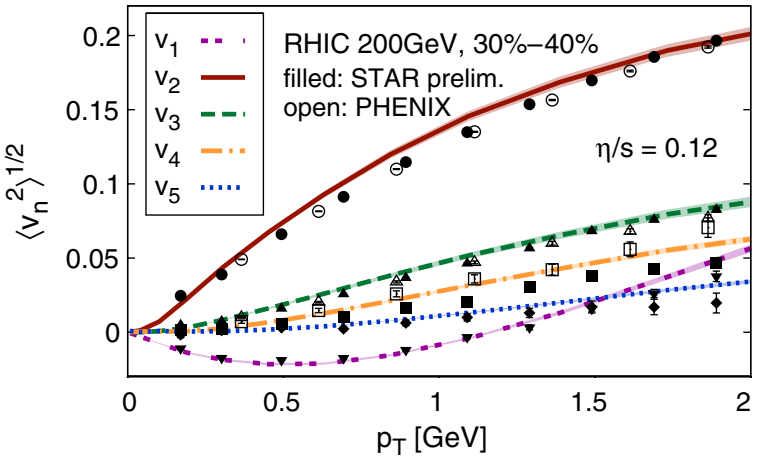
Strong sensitivity to the initial conditions $\rightarrow$ constrain on initial conditions : Similar measurements at RHIC can further constrain these models at low energy.

Global observables at RHIC and LHC

Schenke, Venugopalan 1405.3605



Gale, Jeon, Schenke, PT, Venugopalan 1209.6330



IP-Glasma + MUSIC $\rightarrow$ good description of $P(v_n)$ and $\langle v_n \rangle$ in Pb+Pb and Au+Au $\rightarrow$ higher η/s at LHC($\sim$0.18-0.2) than RHIC ($\sim$0.12).

Ryu, Paquet, Shen, Denicol, Schenke, Jeon, Gale 1502.01675

IP-Glasma + MUSIC + UrQMD (+bulk viscosity)$\rightarrow$ better description of the shape of $p_T - spectra$ $\rightarrow$ reduces shear viscosity by 50% at LHC.

Niemi, Eskola, Paatelainen 1505.02677

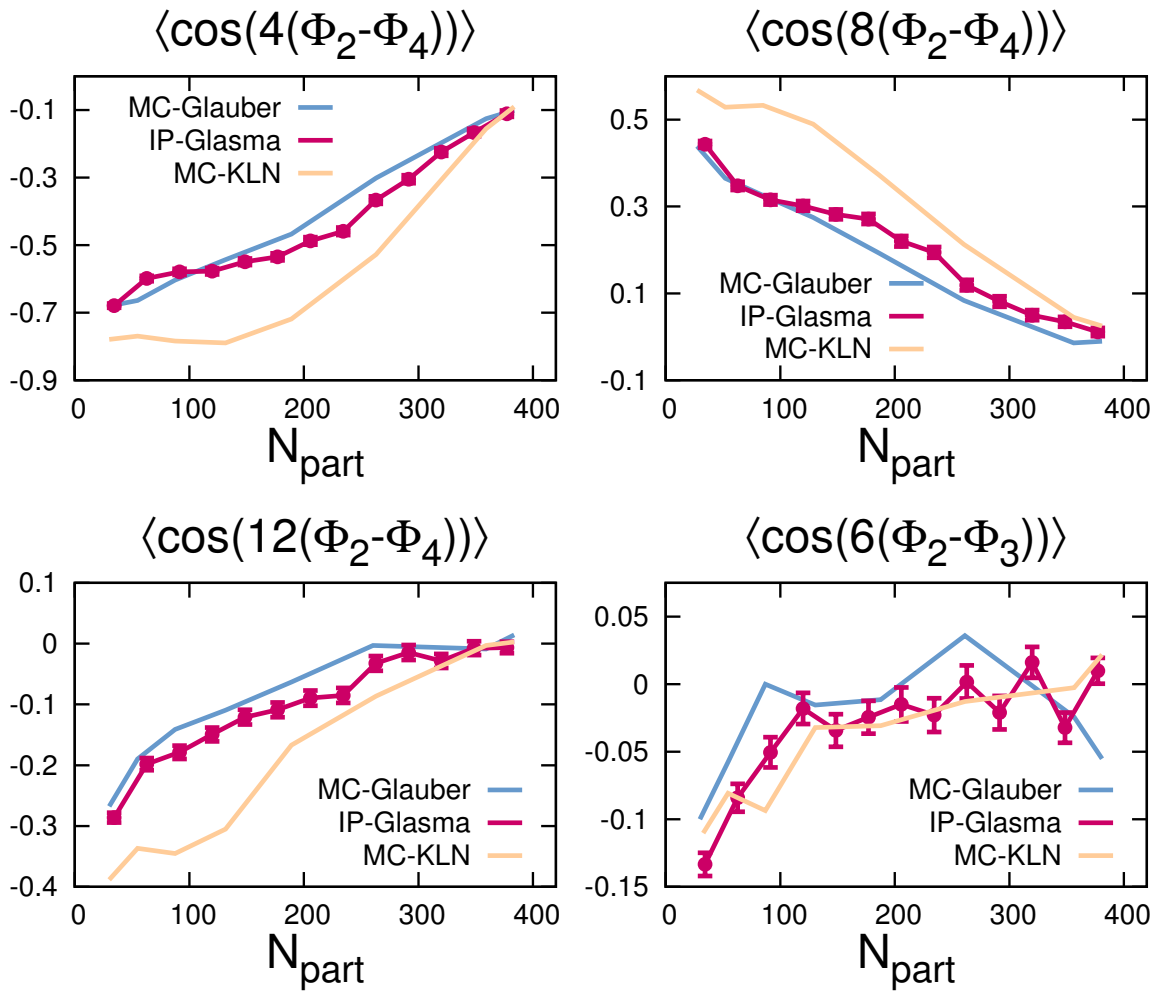
A multi-observable analysis of global data (NLO p-QCD + saturation + hydro ("EKRT")) $\rightarrow$ extract $\eta/s(T)$ at RHIC and LHC.

Participant-plane correlations

Schenke, PT, Venugopalan work in progress

Zhi, Heinz 1104.0650

$$\varepsilon_n e^{in\Phi_n^{PP}} = -\frac{\int d^2r\, r^n e^{in\phi}\, \epsilon(r,\phi)}{\int d^2r\, r^n\, \epsilon(r,\phi)}$$



Φ_{PP} correlations $\rightarrow$ baseline for linear response

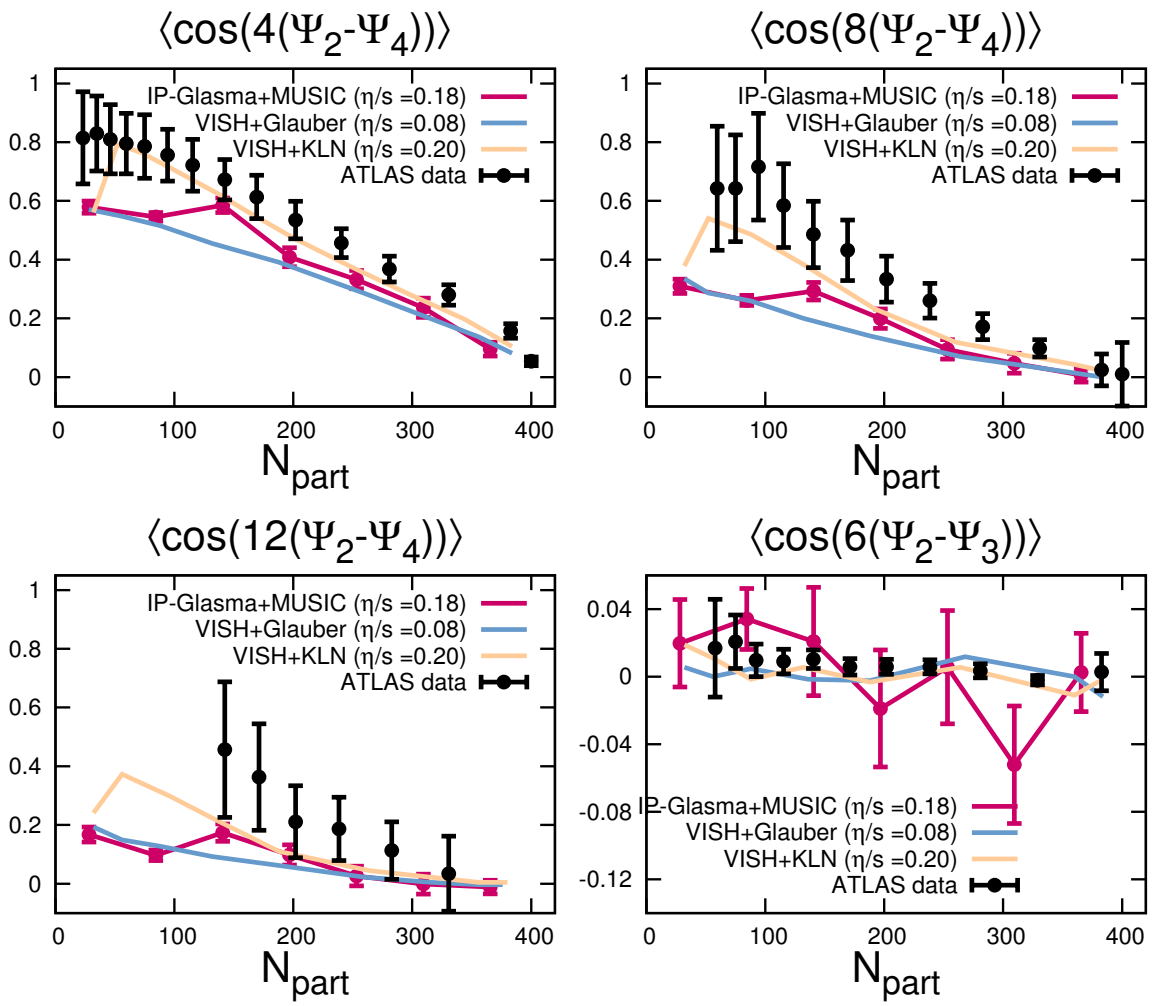
MC-Glauber and KLN results : Qiu, Heinz 1208.1200

Event-plane correlations

Schenke, PT, Venugopalan work in progress

Zhi, Heinz 1104.0650

$$v_n e^{in\Psi_n^{EP}} = \frac{\int \frac{dN}{d^2p_T\, d\eta}\, e^{in\phi}\, d^2p_T}{\int \frac{dN}{d^2p_T\, d\eta}\, d^2p_T}$$

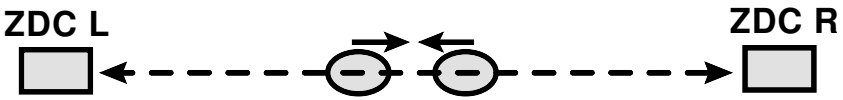


Non-linear coupling between modes → sensitive to η/s → independent constraint

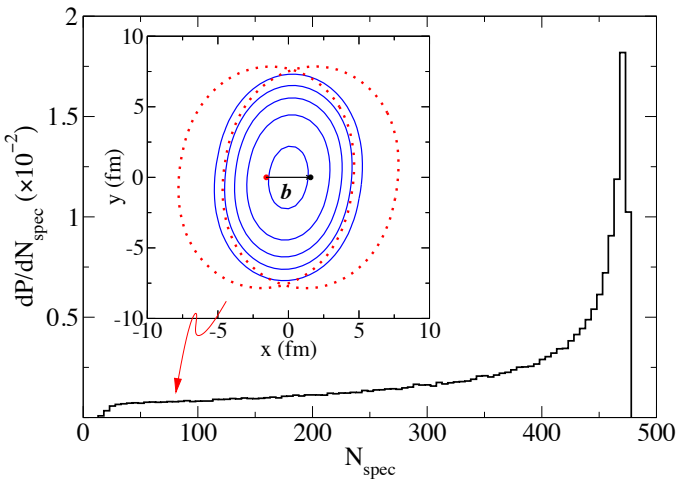
MC-Glauber and KLN results : Qiu, Heinz 1208.1200

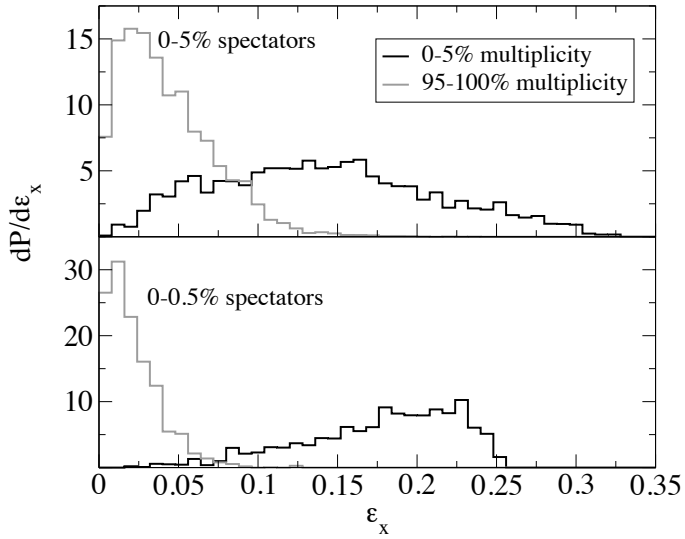
Constraining initial conditions at RHIC

Full overlap events → very low spectators and very high multiplicity. The STAR results → ultra-central $U + U$ and $Au + Au$ collisions.
→ selected using combined cuts on multiplicity and ZDC (spectators)



Heinz and Kuhlman nucl-th/0506088, Goldschmidt, Qiu, Shen, Heinz 1502.00603





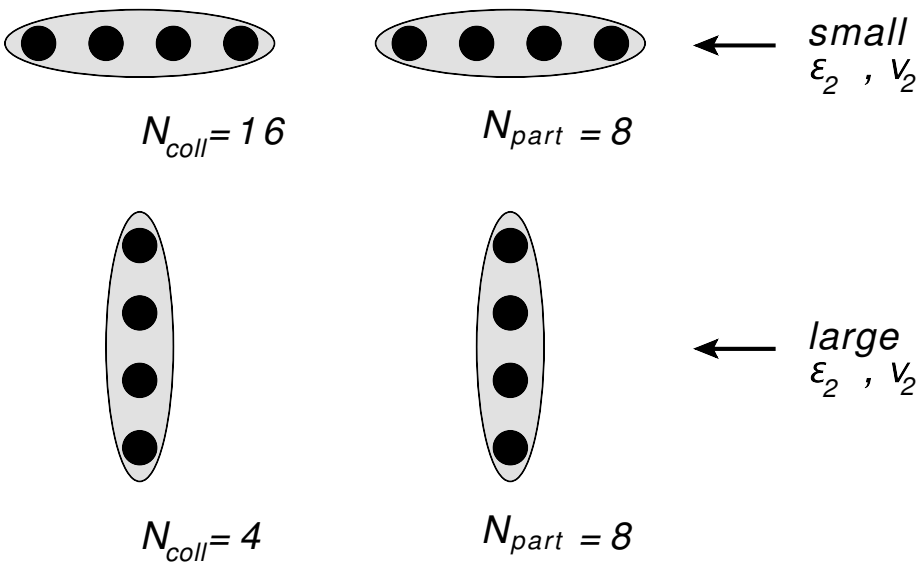
STAR collaboration → study ultra-central (full overlap) events using cuts on neutron numbers → combination of tip-tip or side-side events

Correlation between geometry and multiplicity

A new test of initial conditions in deformed nuclear collisions

Glauber

$dN/d\eta \sim x\, N_{coll} + (1-x)\, N_{part}/2$



Correlation between geometry and multiplicity

A new test of initial conditions in deformed nuclear collisions

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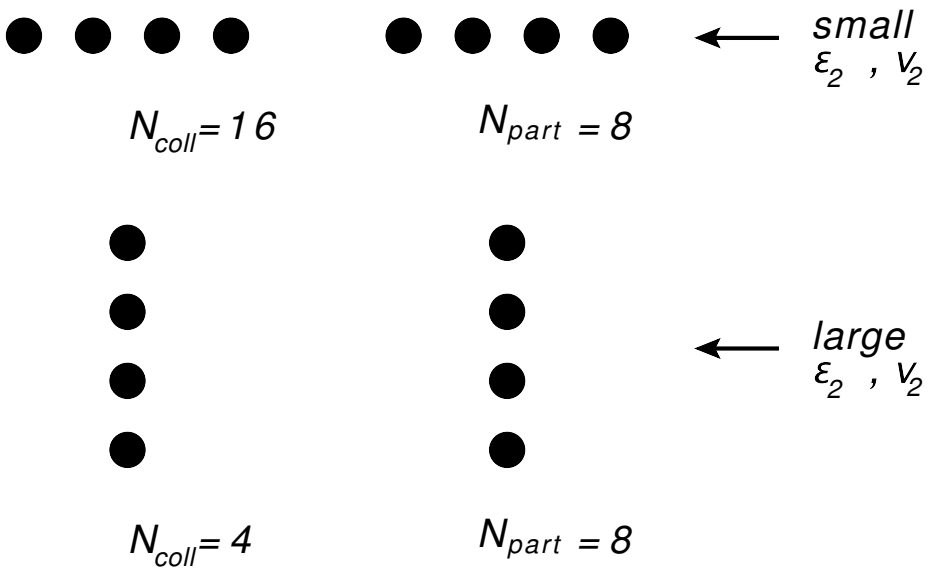


$dN/d\eta \uparrow \varepsilon_2(v_2) \downarrow$
$dN/d\eta \downarrow \varepsilon_2(v_2) \uparrow$

strong correlation

Correlation between geometry and multiplicity

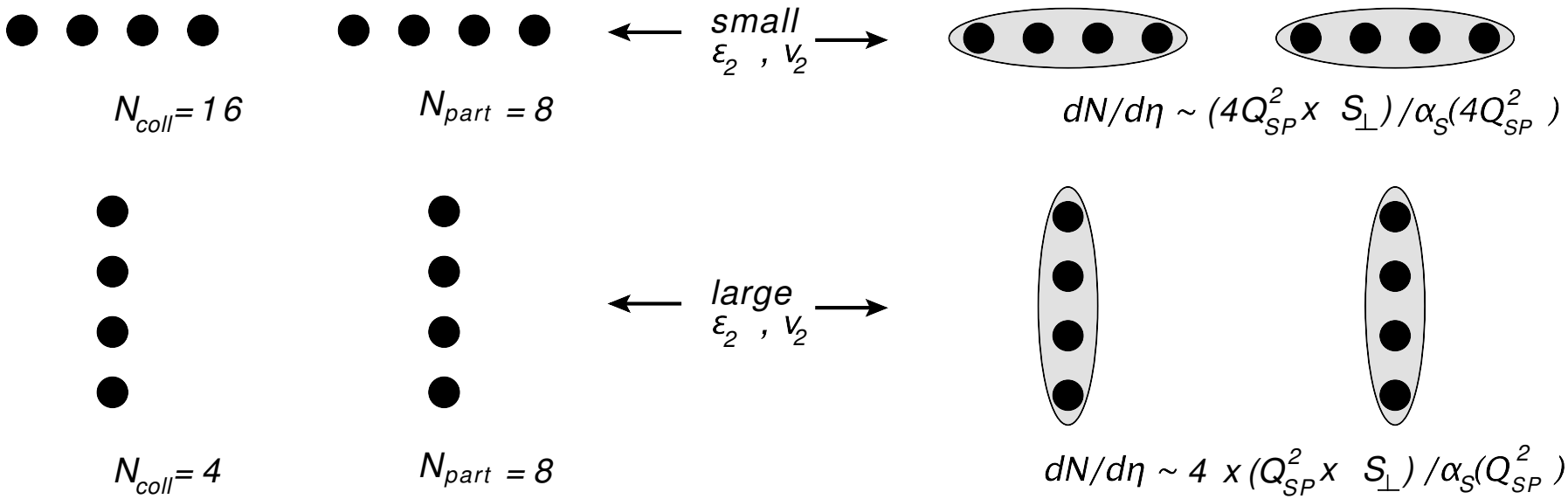
A new test of initial conditions in deformed nuclear collisions

Glauber

$dN/d\eta \sim x\, N_{coll} + (1-x)\, N_{part}/2$

CGC

$dN/d\eta \sim Q^2_{S,min}\, S_\perp / \alpha_S(Q^2_{S,min})$



Correlation between geometry and multiplicity

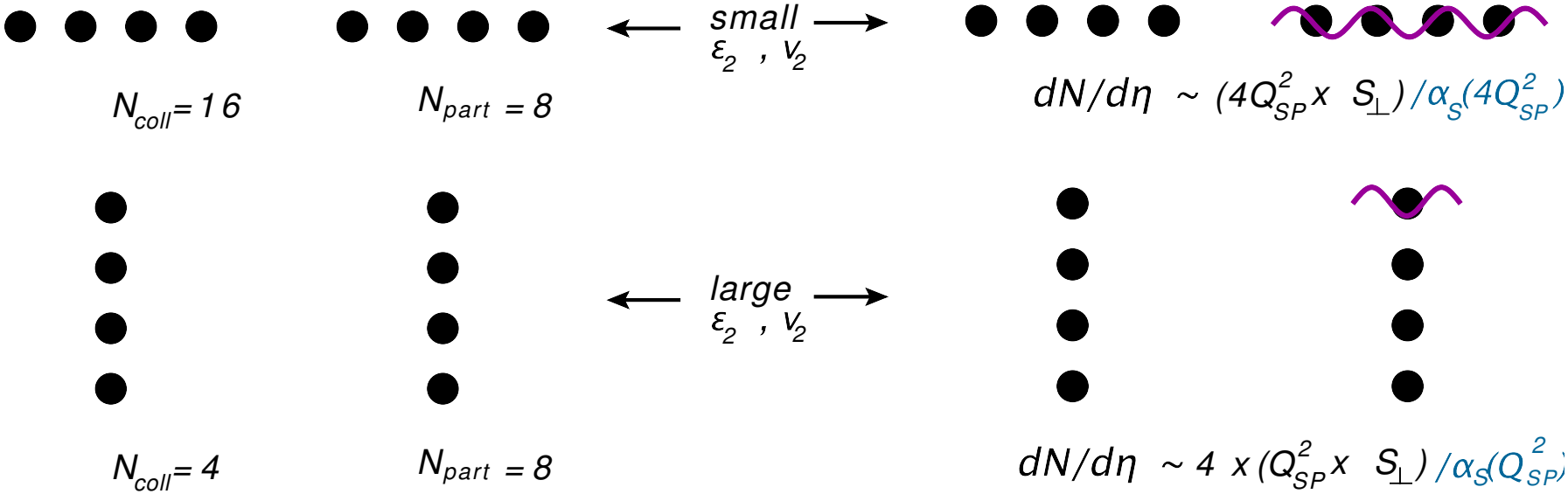
A new test of initial conditions in deformed nuclear collisions

Glauber

$dN/d\eta \sim x\, N_{coll} + (1-x)\, N_{part}/2$

CGC

$dN/d\eta \sim Q^2_{S,min}\, S_\perp / \alpha_S(Q^2_S)$

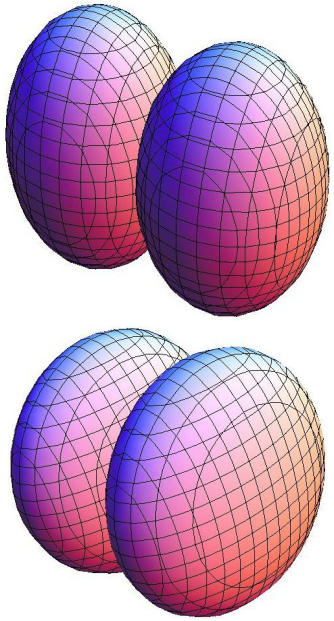


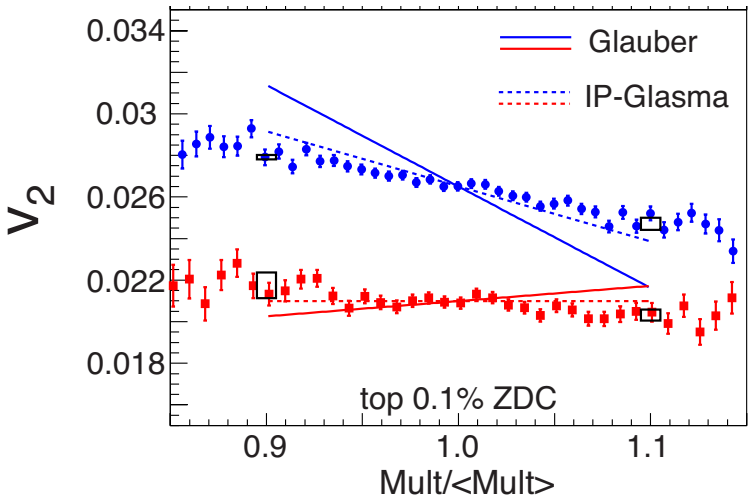
$dN/d\eta \uparrow \varepsilon_2(v_2) \downarrow$
$dN/d\eta \downarrow \varepsilon_2(v_2) \uparrow$
strong correlation (linear)

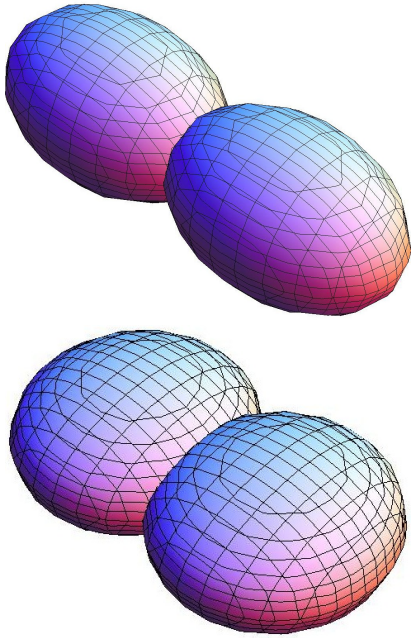
$\sim dN/d\eta\ \varepsilon_2(v_2) \downarrow$
$\sim dN/d\eta\ \varepsilon_2(v_2) \uparrow$
weak correlation (logarithmic)

Correlation between multiplicity and $v_2(\varepsilon_2)$

STAR Collaboration 1505.07812







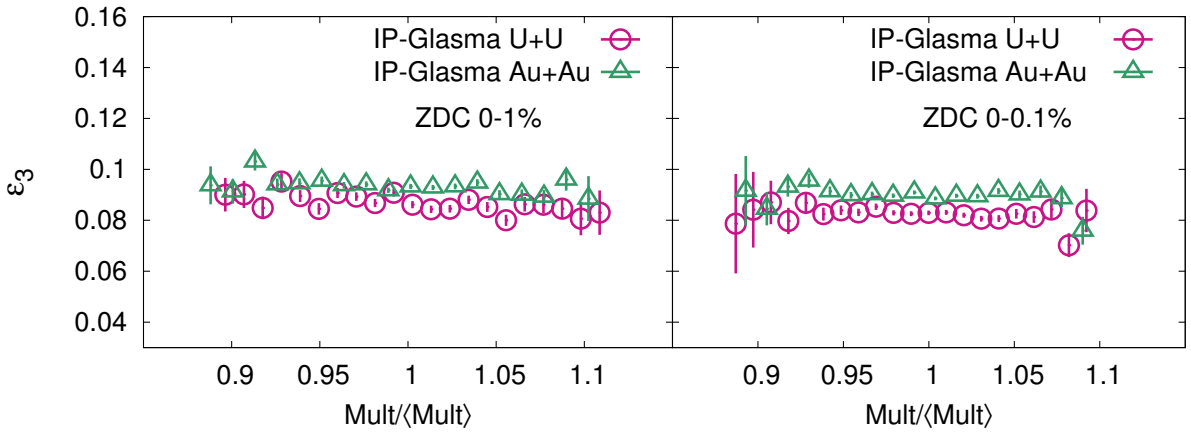
Schenke, PT, Venugopalan 1403.2232

- Stronger correlation in MC-Glauber compared to IP-Glasma
- Opposite slope for ultra-central Au+Au events.

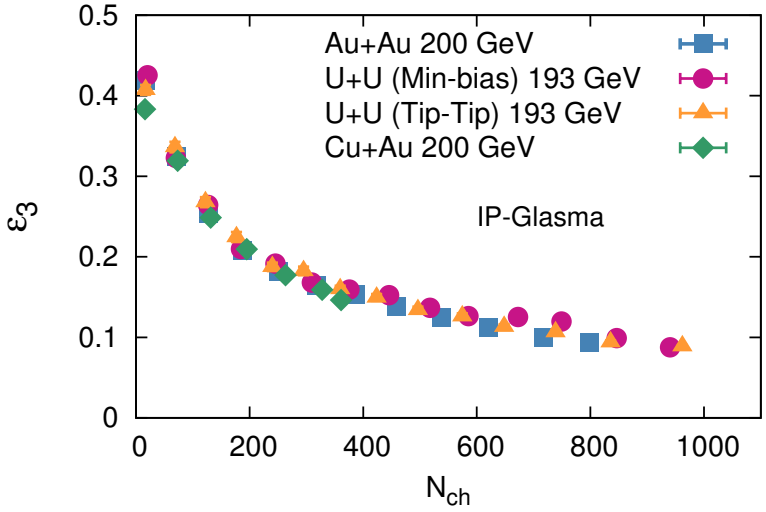
$\rightarrow$ STAR results $\rightarrow$ IP-Glasma results are more consistent with data. $\rightarrow$ can not be explained in conventional two component model + eikonal energy deposition picture.

Moreland, Bernhard, Bass 1412.4708

Correlation between multiplicity and eccentricity ($n > 2$)



Very weak dependence of ε_3 on multiplicity ($y \sim 0$) & system size.

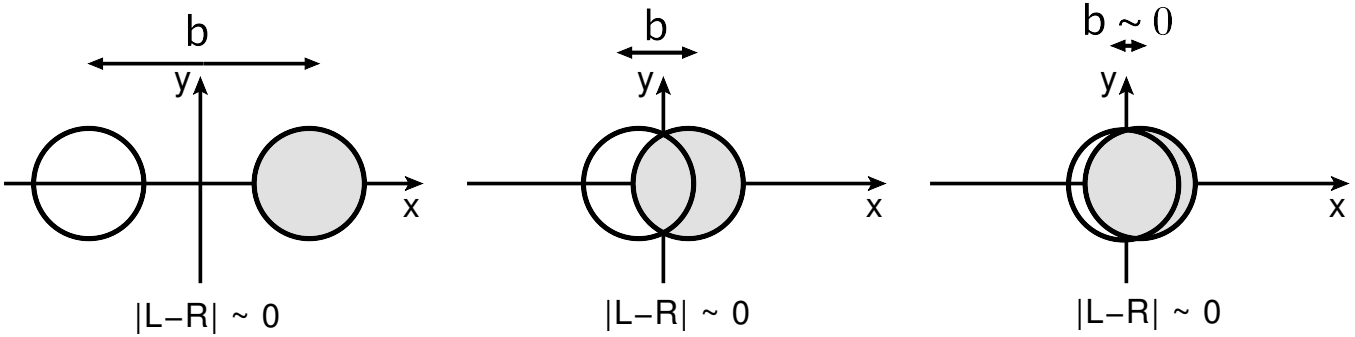


$\rightarrow$ Scaling of v_3 for different systems at RHIC ?

Spectator Asymmetry to constrain initial state

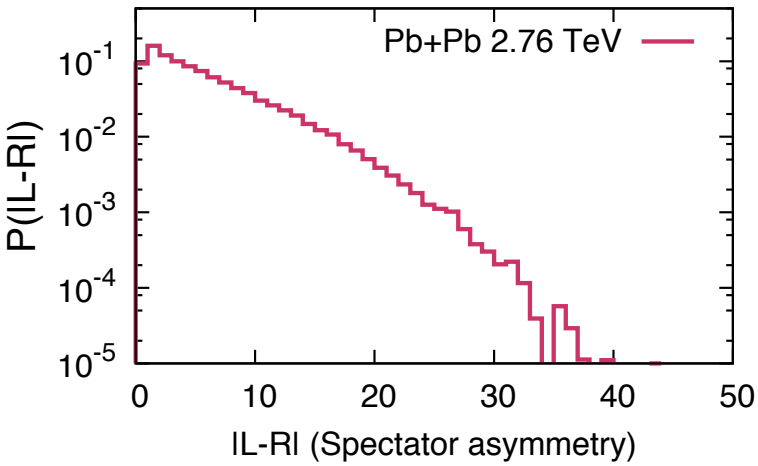
For non-deformed nuclear collisions : Chatterjee, PT 1412.5103

→Sensitive to nucleonic scale fluctuations

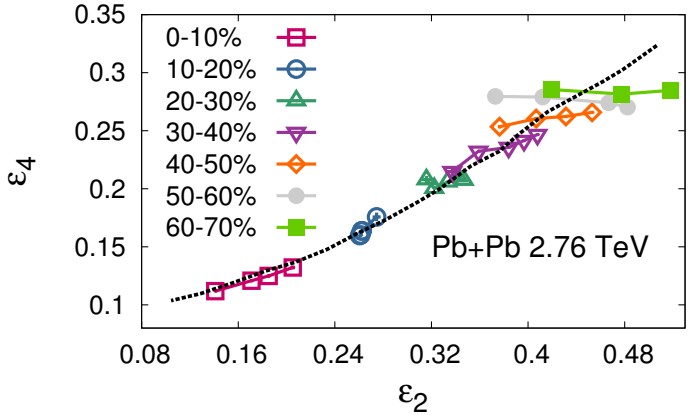


$$\langle \delta N_{\rm part}{}^2 \rangle = |L-R|^2 \;+\; 4\left(\langle LR\rangle - \langle L\rangle\langle R\rangle\right)$$

nucleon position fluctuations geometry/impact parameter



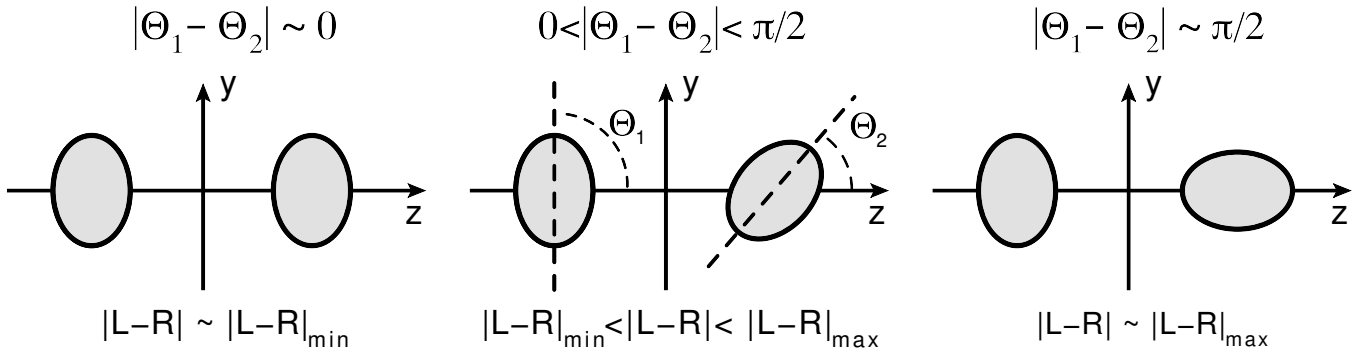
Disentangling ε_4-ε_2

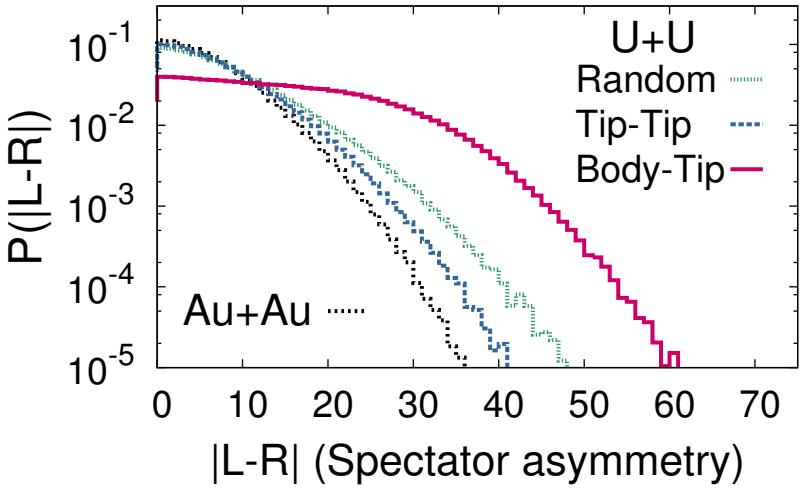


Spectator Asymmetry to constrain initial state

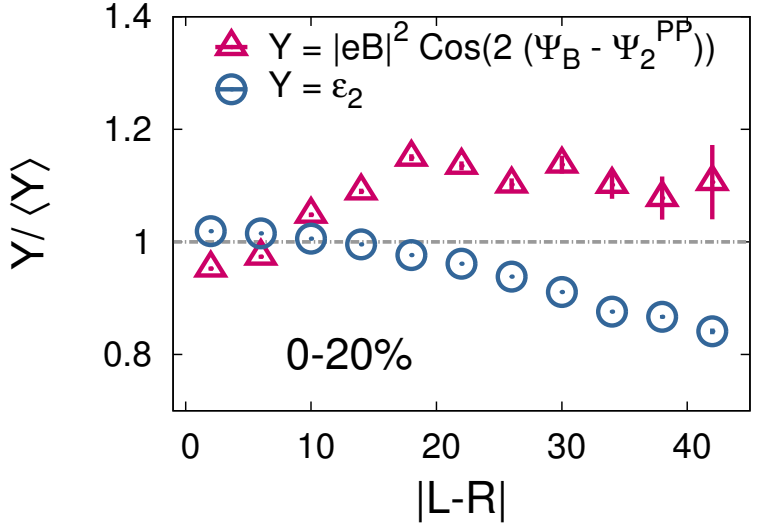
For deformed nuclear collisions : Chatterjee, PT 1412.5103

→Sensitive to azimuthal angle of orientations.





Tuning parameter for transverse geometry.



Open issues

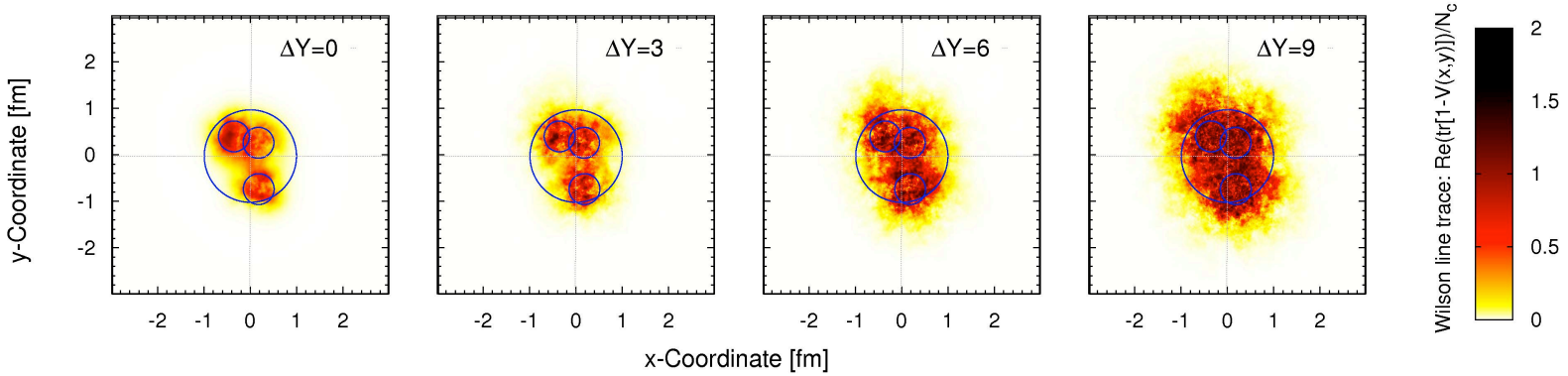
- Imperfect matching of initial conditions to hydro : loss of information/multi-particle correlations.
- Full 3+1 D simulation of initial state.
- *Ab initio* modelling of initial state at lower energy collisions.
- Description of light-heavy ion and heavy ion data using same approach.

Small systems

A dedicated session on Wednesday morning

Schlichting, Schenke 1407.8458

Gaussian color charge distributions (MV type) around valance quark + JIMWLK evolution.



Purely initial state (CYM) evolution → sizeable v_ns in p+A

Schenke, Schlichting and Venugopalan 1502.01331

Azimuthal harmonics from initial color fields in forward proton-nucleus scattering T. Lappi 1501.0550

Breaking of rotational invariance of color fields → higher order angular correlations Dumitru, McLerran, Skokov 1410.4844

Summary

- Understanding the initial stages is essential in the modelling of heavy ion collisions and quantifying the properties of the created medium.
- A framework including initial geometry and different sources of quantum fluctuations and *ab initio* framework of multi-particle production is required to describe the initial dynamics of heavy ion collisions.
- A multi-observable analysis of global data at RHIC and LHC can better constrain the initial state.
- A wide range of future measurements including small systems will further improve our understanding of initial conditions.