The role of the glasma and hydrodynamics for azimuthal anisotropies in nuclear collisions

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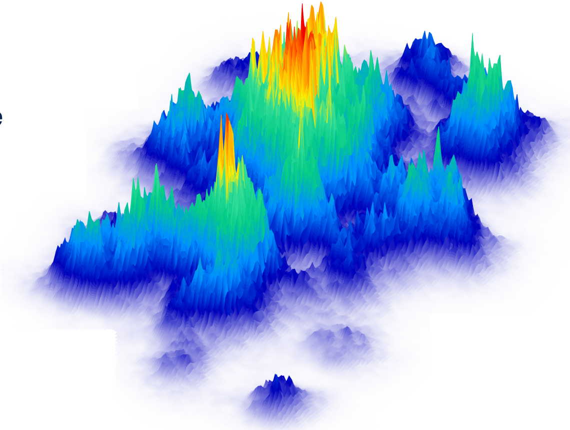

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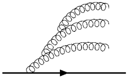
Brief outline

- Gluon saturation and initial glasma state (IP-Glasma model)
- Flow and fluctuations in heavy-ion collisions
- Multiplicity in pp and pA collisions
- Azimuthal anisotropy in pA and dA collisions

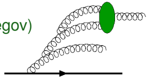
Introduction: Gluon saturation

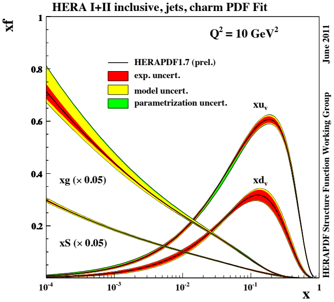
Towards higher energy / smaller x: gluons split, number increases:

BFKL (Balitsky,Fadin,Kuraev,Lipatov) equation describes x-evolution
but violates unitarity: cross-sections grow without bound



JIMWLK (Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner) and BK (Balitsky, Kovchegov)
equations include non-linear evolution $\rightarrow$ saturation





$\mathbf{p}_T \lesssim$ saturation scale $Q_s(x)$:

- strong saturated fields $A_\mu \sim 1/g$
- occupation numbers $\sim 1/\alpha_s$
- $\Rightarrow$ classical field approximation

McLerran and Venugopalan, Phys.Rev. D49 (1994) 2233-2241

Evolution equations determine $Q_s(x)$

x = longitudinal momentum fraction of partons in a hadron or nucleus

Saturation model for the color charge density

Energy and impact parameter b dependence of $Q_s(x, \mathbf{b})$ can be modeled in the IP-Sat model Kowalski, Teaney, Phys.Rev. D68 (2003) 114005

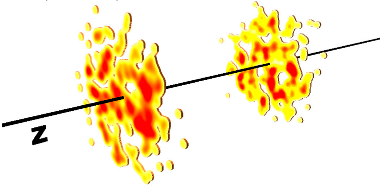
Parametrize cross sections for DIS on protons and fit to HERA diffractive data $\rightarrow Q_s(x, \mathbf{b})$

For a nucleus sample nucleon positions and add all T_p

$$\frac{\mathrm{d}\sigma^{\mathrm{p}}_{\mathrm{dip}}}{\mathrm{d}^2\mathbf{x}_\perp}(\mathbf{r}_\perp, x, \mathbf{x}_\perp) = 2\,\mathcal{N}(\mathbf{r}_\perp, x, \mathbf{x}_\perp) = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c}\mathbf{r}_\perp{}^2\alpha_s(Q^2)xg(x, Q^2)\sum_{i=1}^{A} T_p(\mathbf{x}_\perp - \mathbf{x}_T^i)\right)\right]$$

then determine $Q_s(x, \mathbf{x}_\perp)$ ($\mathcal{N}(1/Q_s(x, \mathbf{x}_\perp), x, \mathbf{x}_\perp) = 1 - e^{-1/2}$)

Color charge density $g\mu(x, \mathbf{x}_\perp)$ is proportional to $Q_s(x, \mathbf{x}_\perp)$



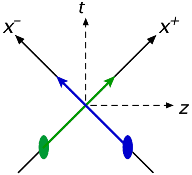
IP-Glasma: Color charges and gluon fields

Sample color charges ρ^a from local Gaussian for each nucleus

$$\langle \rho^a(\mathbf{x}_\perp)\rho^b(\mathbf{y}_\perp)\rangle = \delta^{ab}\delta^2(\mathbf{x}_\perp - \mathbf{y}_\perp)g^2\mu^2(\mathbf{x}_\perp)$$

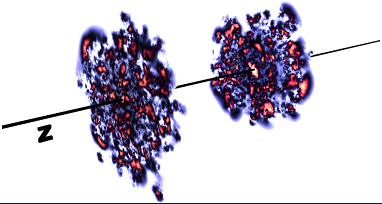
Color charges determine incoming color currents:

$$J_1^\nu = \delta^{\mu +}\rho_1(x^-, \mathbf{x}_\perp)$$
$$[D_\mu, F^{\mu\nu}] = J_1^\nu$$



$$J_2^\nu = \delta^{\mu -}\rho_2(x^+, \mathbf{x}_\perp)$$
$$[D_\mu, F^{\mu\nu}] = J_2^\nu$$

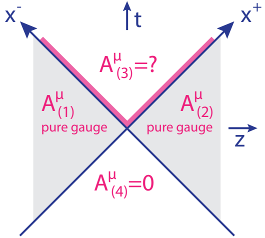
Solve Yang-Mills equations for the gauge fields $A^+(x^-, \mathbf{x}_\perp) = -\frac{g\rho(x^-, \mathbf{x}_\perp)}{\nabla_\perp^2 + m^2}$



Wilson line correlator shows degree of fluctuations in the gluon fields:
Fluctuation scale: $1/Q_s$

IP-Glasma: Gauge fields after the collision

Initial condition on the lightcone:



Configuration in Schwinger gauge $A^\tau = 0$

Solution:

Kovner, McLerran, Weigert, Phys. Rev. D52, 3809 (1995)

$$A^i_{(3)}|_{\tau=0} = A^i_{(1)} + A^i_{(2)}$$

$$A^\eta_{(3)}|_{\tau=0} = \frac{ig}{2}[A^i_{(1)}, A^i_{(2)}]$$

We solve for the gauge fields numerically

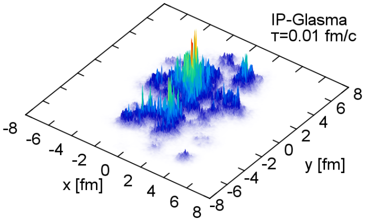
Krasnitz, Venugopalan, Nucl.Phys. B557 (1999) 237

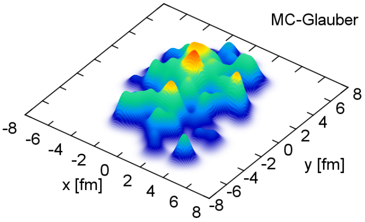
Time evolution follows Yang-Mills equations

Energy density B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett. 108, 252301 (2012)

Compute energy density in the fields at $\tau = 0$
and later times with CYM evolution

for comparison:





arbitrary units
same nucleon positions in both events, impact parameter b=4 fm

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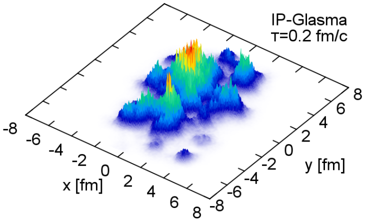

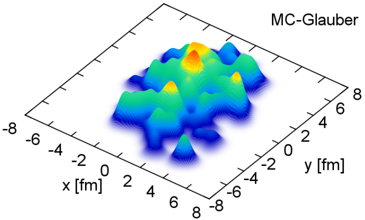

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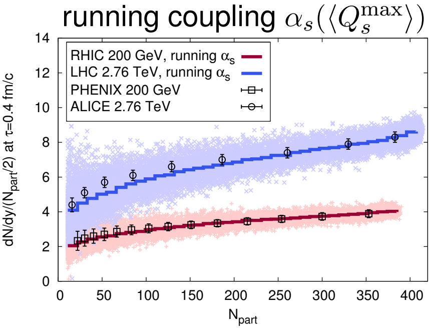
same nucleon positions in both events, impact parameter b=4 fm

Multiplicity
B.Schenke, P.Tribedy, R.Venugopalan, Phys. Rev. C86, 034908 (2012)

dN_g/dy in transverse Coulomb gauge $\partial_i A^i = 0$
N_{part} from MC-Glauber with $\sigma_{NN} = 42\,\text{mb}$ and $64\,\text{mb}$ respectively

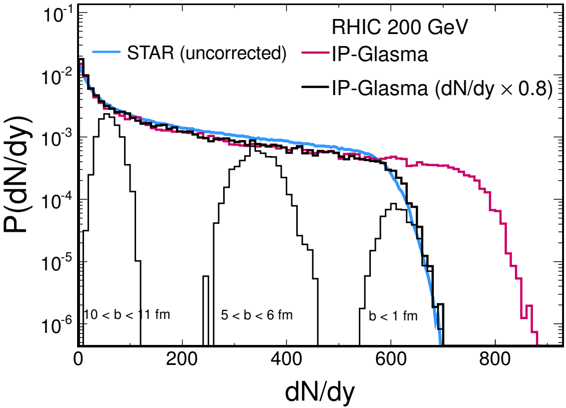


Experimental data: PHENIX, Phys.Rev.C71 034908 (2004) and ALICE, Phys.Rev.Lett. 106, 032301 (2011)

Normalized to RHIC data

Multiplicity B.Schenke, P.Tribedy, R.Venugopalan, Phys. Rev. C86, 034908 (2012)

Experimental data: STAR, Phys. Rev. C79, 034909 (2009)

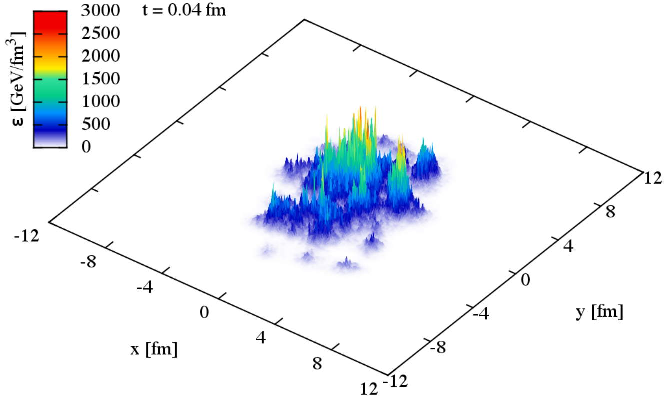


IP-Glasma model gives a convolution of negative binomial distributions

No need to put them in by hand

Yang-Mills + viscous fluid-dynamic evolution

Energy density and initial flow velocity from $u_\mu T^{\mu\nu}_{\rm YM} = \varepsilon u^\nu$ as input for fluid-dynamic simulation



Yang-Mills evolution

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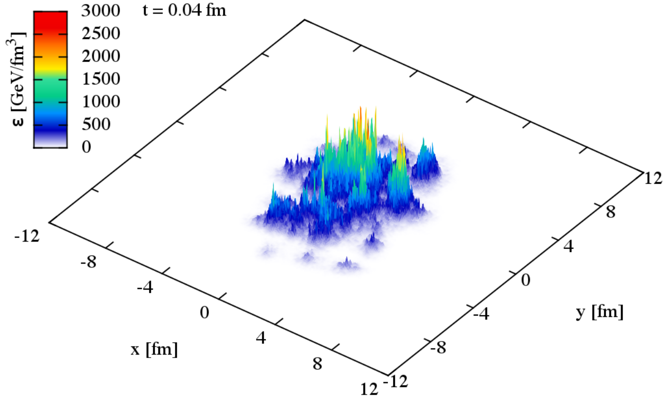

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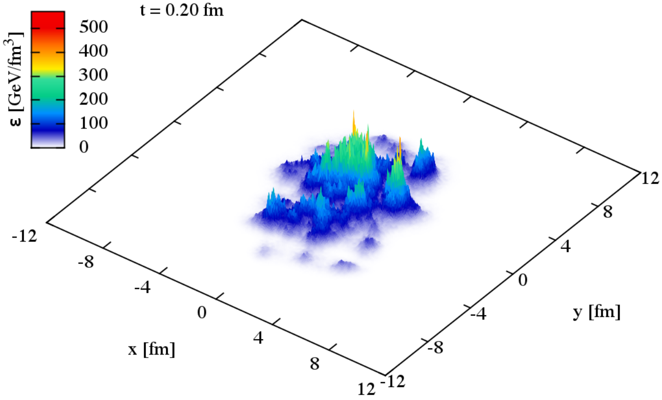
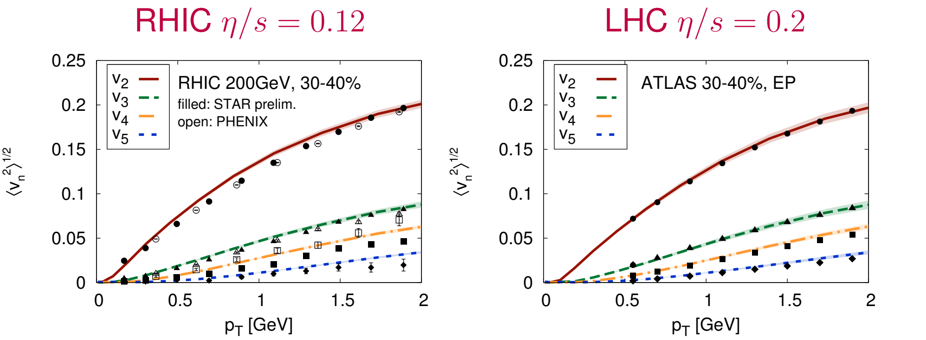


Viscous fluid-dynamic evolution: MUSIC Schenke, Jeon, Gale, Phys.Rev.Lett.106, 042301 (2011)

Viscous flow at RHIC and LHC

C. Gale, S. Jeon, B.Schenke, P.Tribedy, R.Venugopalan, PRL110, 012302 (2013)



Lower effective η/s at RHIC than at LHC needed to describe data

Hints at increasing η/s with increasing temperature

Analysis at more energies can be used to gain information on $(\eta/s)(T)$

Experimental data:

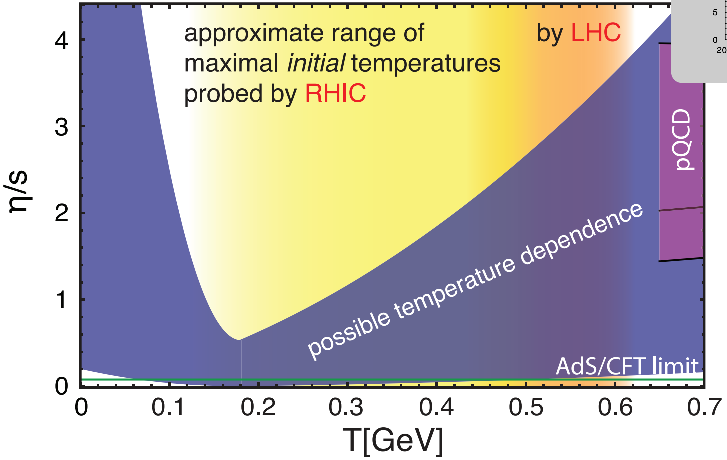
A. Adare et al. (PHENIX Collaboration), Phys.Rev.Lett. 107, 252301 (2011)

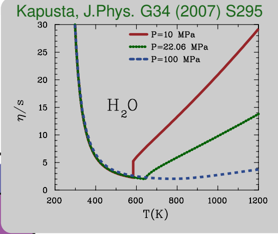
Y. Pandit (STAR Collaboration), Quark Matter 2012, (2012)

ATLAS collaboration, Phys. Rev. C 86, 014907 (2012)

Learning about QCD

Example: extraction of $(\eta/s)(T)$



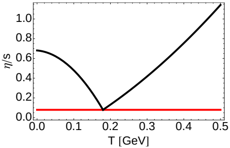


Temperature dependent η/s

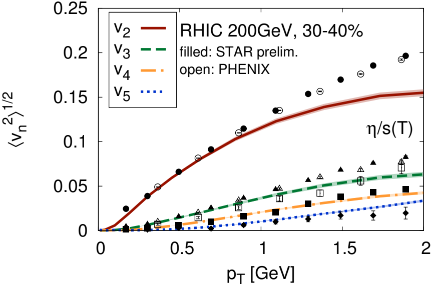
C. Gale, S. Jeon, B.Schenke, P.Tribedy, R.Venugopalan, PRL110, 012302 (2013)

Use $\eta/s(T)$ as in Niemi et al., Phys.Rev.Lett. 106 (2011) 212302

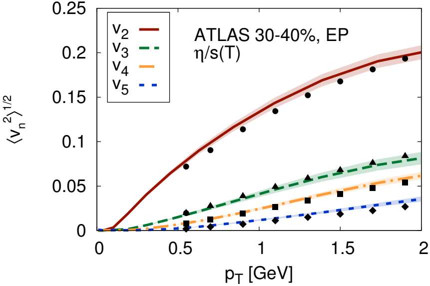
Experimental data: A. Adare et al. (PHENIX), Phys.Rev.Lett. 107, 252301 (2011)
Y. Pandit (STAR), Quark Matter 2012, (2012)
ATLAS collaboration, Phys. Rev. C 86, 014907 (2012)



RHIC



LHC



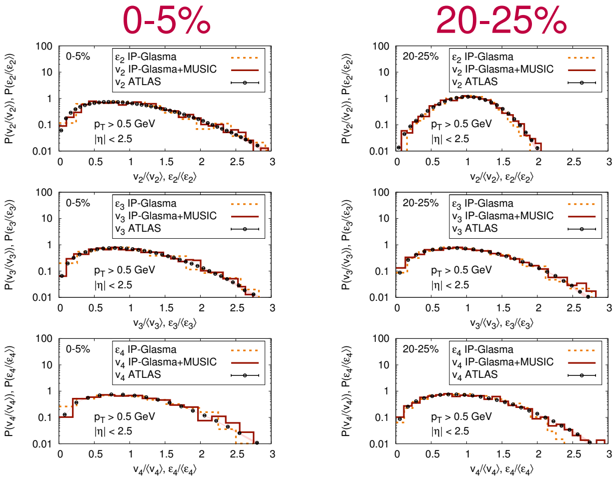
One $(\eta/s)(T)$ will be able to describe both RHIC and LHC data
Used parametrization not yet perfect: no surprise
More detailed study needed - include different RHIC energies and LHC

Event-by-event distributions of v_n

Experimenatal data:

ATLAS collaboration: J. Jia, S. Mohapatra, arXiv:1304.1471

ATLAS collaboration, arXiv:1305.2942

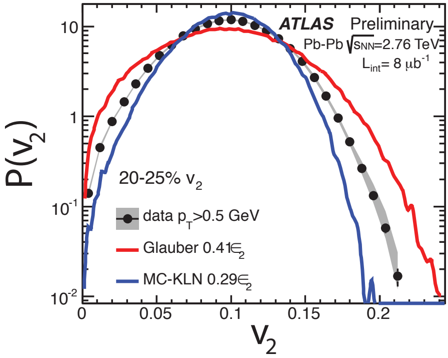


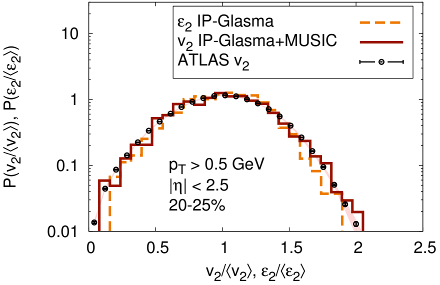
C. Gale, S. Jeon, B.Schenke, P.Tribedy, R.Venugopalan, PRL110, 012302 (2013)

C. Gale, S. Jeon, B.Schenke, P.Tribedy, R.Venugopalan, Nucl.Phys.A904-905 409c-412c (2013)

Event-by-event distributions of v_n - other models

Showing eccentricity distributions (yellow on the right)

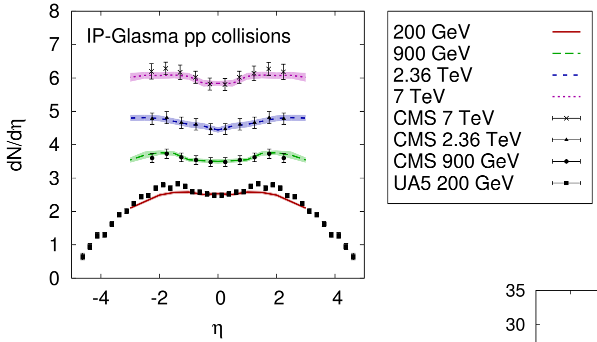




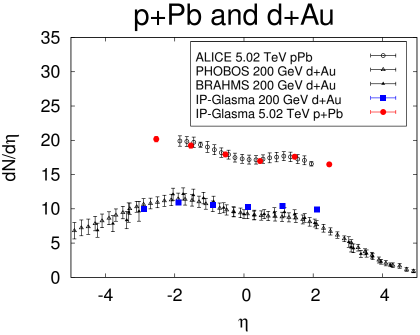
Event-by-event distributions can distinguish between different initial state models $\rightarrow$ see Harri Niemi's talk

Experimental data: ATLAS collaboration, arXiv:1305.2942

Establish a baseline for pp and pA/dA collisions



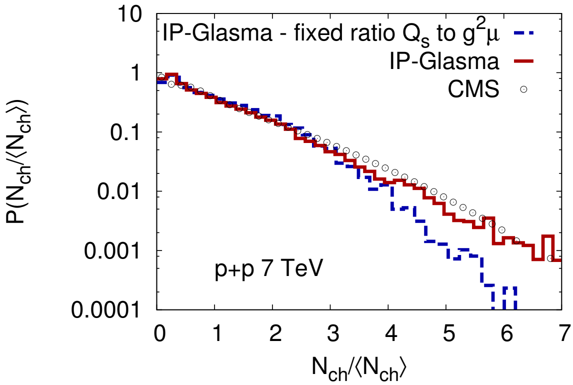
Schenke, Tribedy, Venugopalan
in preparation



Note: Normalization depends on scale used in the running coupling.
Using the produced gluon k_T, energy dependence is too weak.
Need to include normalization $\propto \ln\sqrt{s}$ to account for this

η-dependence then comes from IP-Sat

Multiplicity distributions in pp

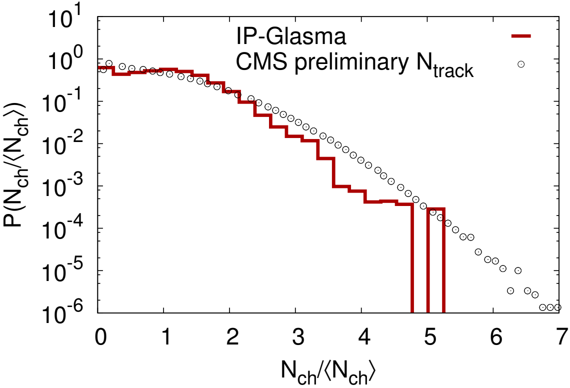


Schenke, Tribedy, Venugopalan
in preparation

Fluctuation of Q_s needed to describe the multiplicity distribution in p+p

Result in red includes a smearing of Q_s by 9% around its mean

Multiplicity distributions in pPb



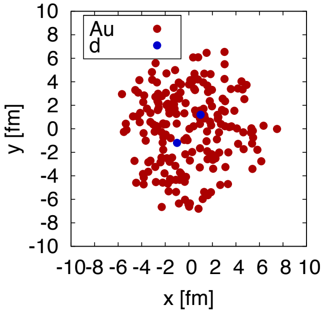
note: comparing to uncorrected data

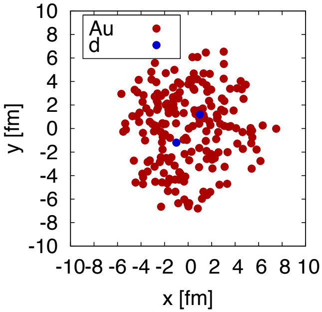
Schenke, Tribedy, Venugopalan, in preparation

d+Au collisions

IP-Glasma results differ significantly from a typical MC-Glauber model:

Energy density for the same nucleon positions:





In MC-Glauber all nucleons that are barely 'touched' contribute fully to the energy density

an MC-Glauber implementation is used in e.g. P. Bozek, Phys.Rev. C85 (2012) 014911

d+Au collisions

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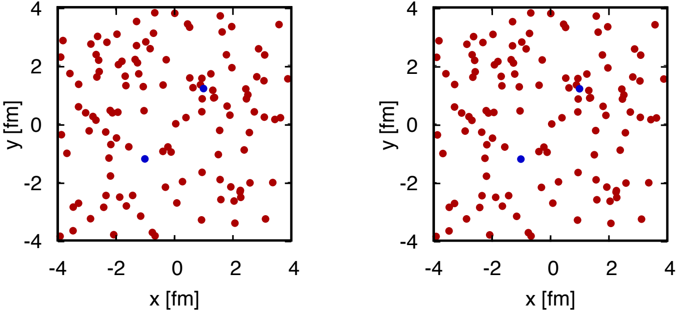

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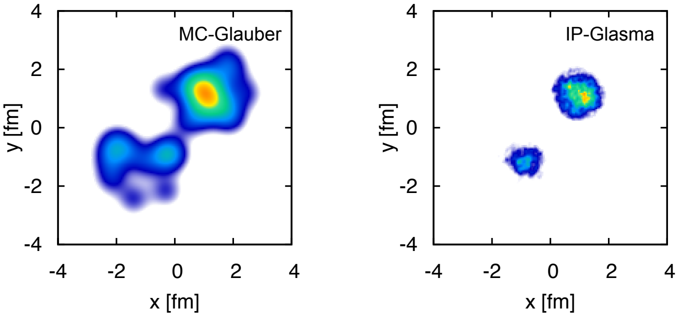

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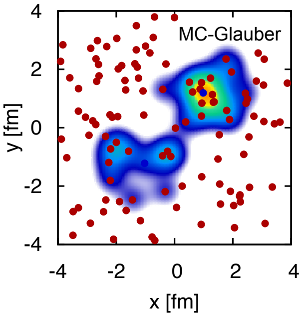

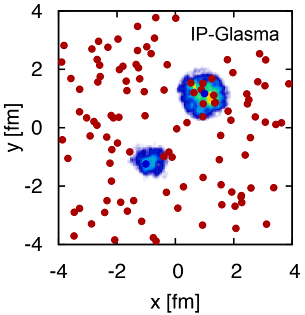

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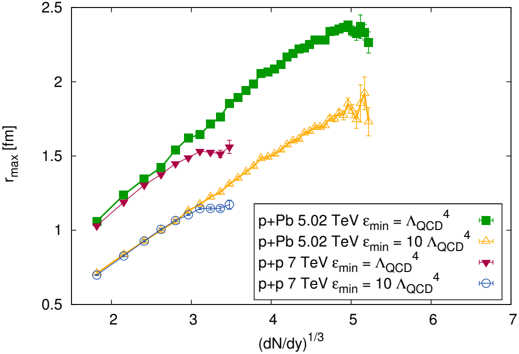
p+A collisions Bzdak, Schenke, Tribedy, Venugopalan, Phys.Rev.C87, 064906 (2013)

System size in p+p and p+Pb in the IP-Glasma model



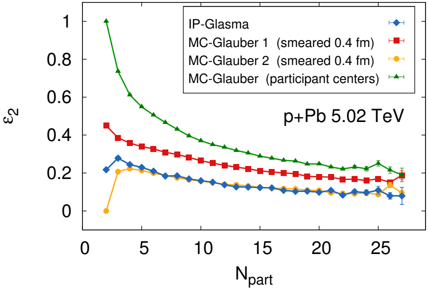
Radius defined by where energy density reaches $\Lambda_{\rm QCD}^4$ or $10\Lambda_{\rm QCD}^4$

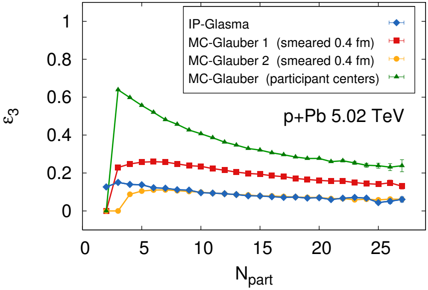
Radius scales with $(dN_g/dy)^{1/3}$ for low dN_g/dy

p+Pb collisions A. Bzdak, B. Schenke, P. Tribedy, R. Venugopalan, Phys.Rev.C87, 064906 (2013)

Eccentricities from different models can differ significantly

MC-Glauber 1 MC-Glauber 2

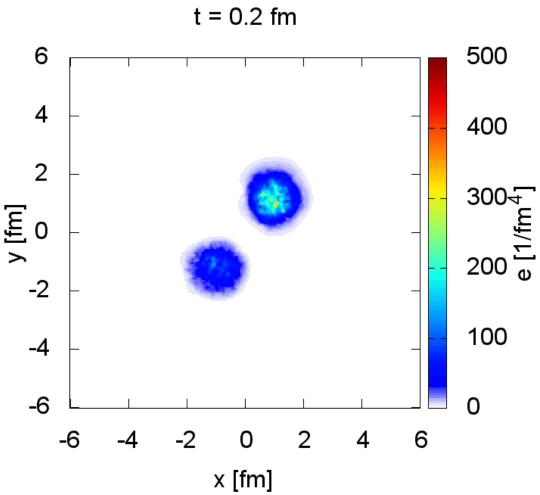




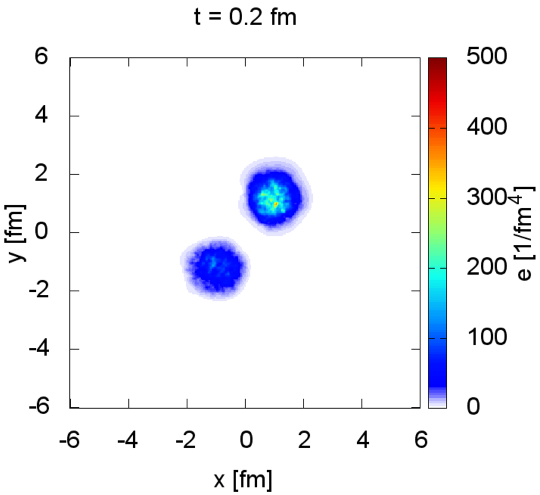
MC-Glauber 1: smeared energy density deposited around center of wounded nucleons

MC-Glauber 2: smeared energy density deposited around binary collision position

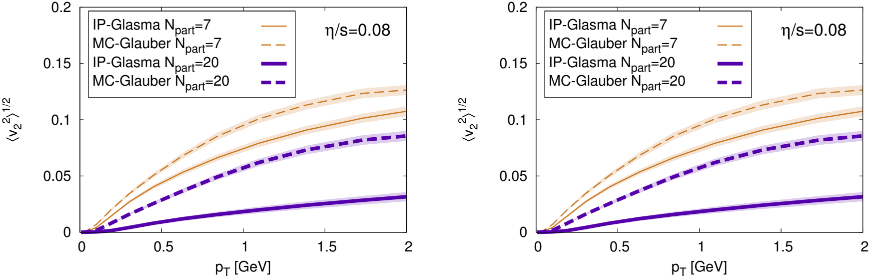
Hydro-evolution in d+Au



Hydro-evolution in d+Au

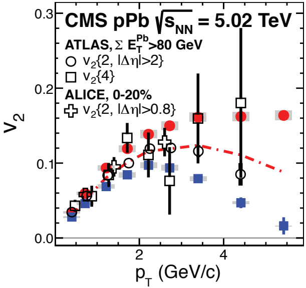


Transverse momentum dependent flow in p+Pb



Flow generated by hydrodynamics alone is much smaller than experimental results when using IP-Glasma initial conditions and $\eta/s = 0.08$

A. Bzdak, B. Schenke, P. Tribedy, R. Venugopalan, Phys.Rev.C87, 064906 (2013)



How much $v_2(\mathrm{2PC})$ comes from the initial state?

Compute two-particle correlations from the initial glasma state:

- compute dN_g/dyd^2k_T from the Fourier transformed glasma fields
- compute the correlation

$$\frac{S(k_1,k_2,\Delta\phi)}{B(k_1,k_2,\Delta\phi)} = \frac{\left\langle\left\langle \frac{d^2N}{d^2k_T}(k_1,\phi_1)\frac{d^2N}{d^2k_T}(k_2,\phi_1+\Delta\phi)\right\rangle\right\rangle_{\phi_1}}{\left\langle\left\langle \frac{d^2N}{d^2k_T}(k_1,\phi_1)\right\rangle\left\langle\frac{d^2N}{d^2k_T}(k_2,\phi_1+\Delta\phi)\right\rangle\right\rangle_{\phi_1}}$$

  which is $\propto \frac{1}{N_{\mathrm{trig}}}\frac{dN^{\mathrm{pair}}}{k_1k_2dk_1dk_2d\Delta\phi}$

- Fourier expand

$$\frac{1}{N_{\mathrm{trig}}}\frac{dN}{d\Delta\phi} = \frac{N_{\mathrm{assoc}}}{2\pi}\left[1+\sum_n 2V_{n\Delta}\cos(n\Delta\phi)\right]$$

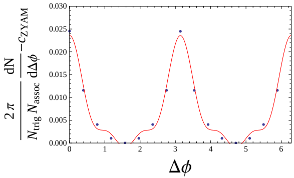
- Finally define

$$v_n(\mathrm{2PC})(p_T) = \frac{V_{n\Delta}(p_T,p_T^{\mathrm{ref}})}{\sqrt{V_{n\Delta}(p_T^{\mathrm{ref}},p_T^{\mathrm{ref}})}}$$

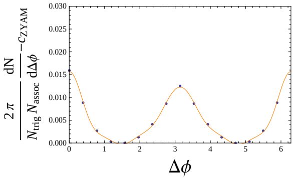
Correlation functions

with Fourier-fits

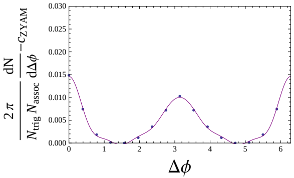
initial state



$\tau = 0.5\,\mathrm{fm}$



$\tau = 1\,\mathrm{fm}$



Near-side and away-side peaks are the same initially (no v_3)
... differ after rescattering in the evolution (introduces v_3)

todo: include additional correlations through JIMWLK evolution

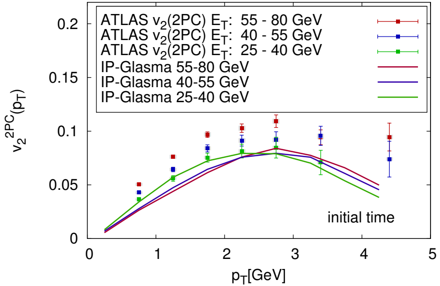
Schenke, Venugopalan, preliminary

How much $v_2(2\mathrm{PC})$ comes from the initial state?

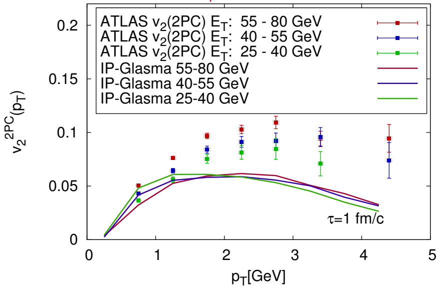
$0.5\,\mathrm{GeV} < p_T^{\mathrm{ref}} < 4\,\mathrm{GeV}$

Schenke, Venugopalan, preliminary

initial state



after $1\,\mathrm{fm}/c$ CYM evolution



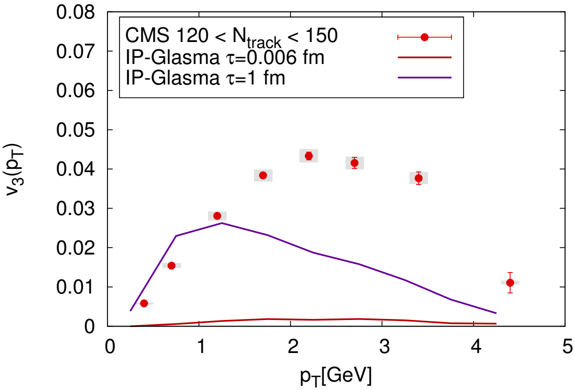
$v_2\{4\}$ in progress. Need lots of statistics.

no hydro

Is there an initial $v_3(2\mathrm{PC})$?

$$0.3\,\mathrm{GeV} < p_T^{\mathrm{ref}} < 3\,\mathrm{GeV}$$

Schenke, Venugopalan, preliminary



No initial v_3! But significant build-up in Yang-Mills evolution.

Summary and conclusions

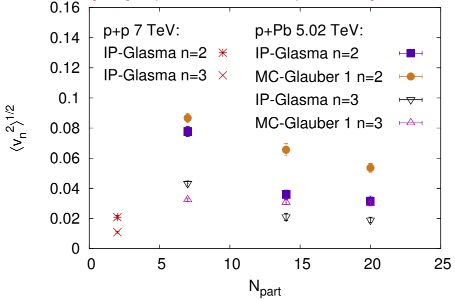
- IP-Glasma model + hydrodynamics very succesful in describing higher flow harmonics in heavy-ion collisions
- Effective shear viscosity at RHIC smaller than at LHC
- Can reasonably reproduce multiplicity distributions in pp, pA, AA
- In small systems like p+Pb, initial shape and system size is very sensitive to model assumptions
- Hydro needs very small η/s in p+Pb to get close to the observed v_n - with IP-Glasma initial conditions it will not get there
- Significant initial v_2 from 2-particle correlations in the glasma
- No initial v_3, but built-up during Yang-Mills evolution

BACKUP

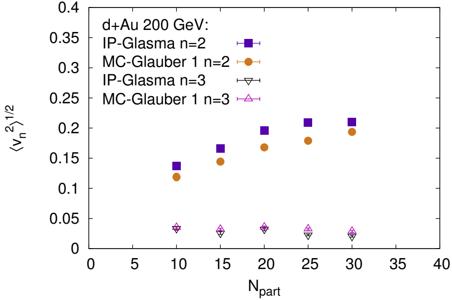
Flow in p+p, p+Pb and d+Au collisions

Only qualitative scaling between flow and eccentricities

p+p (at $b = 0\,\mathrm{fm}$) and p+Pb



d+Au



p+Pb: Ellipitc flow decreases with N_{part}

d+Au: Elliptic flow increases with N_{part}

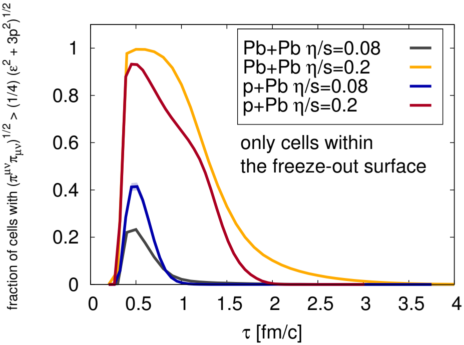
p+p: Elliptic flow small, but not as small as expected from eccentricity

Need sophisticated centrality selection to compare with experiments

A. Bzdak, B. Schenke, P. Tribedy, R. Venugopalan, Phys.Rev.C87, 064906 (2013)

p+A collisions - is viscous hydro valid?

Initial $\pi_0^{\mu\nu} = 0$, $b = 0$ fm, IP-Glasma. Cells within f.o. surface that have $> 25\%$ viscous correction in p+Pb and Pb+Pb:

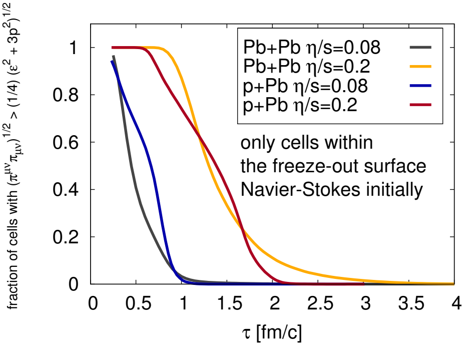


Important: Lifetime in Pb+Pb is about 6 times longer than in p+Pb

Also see Dumitru, Molnar, Nara, Phys.Rev. C76 (2007) 024910

p+A collisions - is viscous hydro valid?

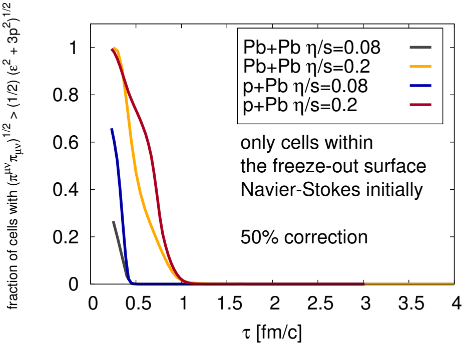
same with Navier-Stokes $\pi_0^{\mu\nu}$, count cells within f.o. surface that have more than a 25% viscous correction in p+Pb and Pb+Pb:



Important: Lifetime in Pb+Pb is about 6 times longer than in p+Pb

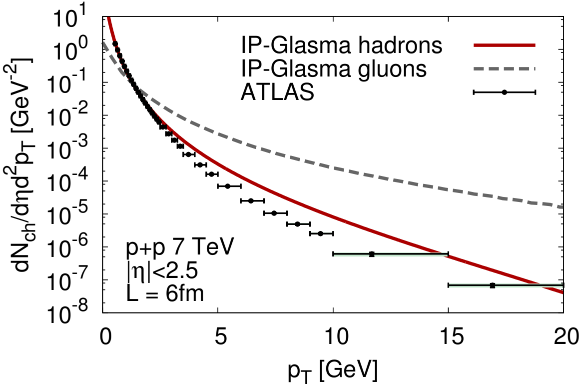
p+A collisions - is viscous hydro valid?

Initial Navier-Stokes $\pi_0^{\mu\nu}$, count cells within f.o. surface that have more than a 50% viscous correction in p+Pb and Pb+Pb:



Important: Lifetime in Pb+Pb is about 6 times longer than in p+Pb

p_T distribution in pp



Charged hadrons from KKP fragmentation Kniehl, Kramer, Potter, NPB582 (2000) 514

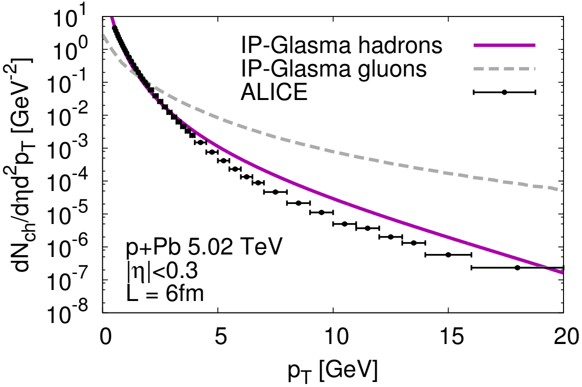
As expected, spectra are too hard as in the MV model

We do not include an anomalous dimension γ

Schenke, Tribedy, Venugopalan, in preparation

Experimental data: ATLAS Collaboration, New J.Phys. 13, 053033 (2011), arXiv:1012.5104

p_T distribution in pPb



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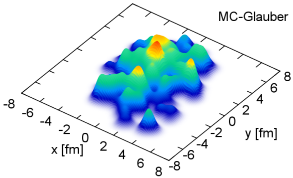
Schenke, Tribedy, Venugopalan, in preparation

Experimental data: ALICE Collaboration, Phys.Rev.Lett. 110, 082302 (2013), arXiv:1210.4520

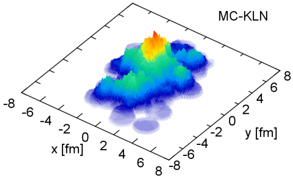
Existing initial state models

There are several models of fluctuating initial conditions in HICs
Most commonly used with fluid-dynamic simulations:
Both include geometric fluctuations of nucleons in nucleus

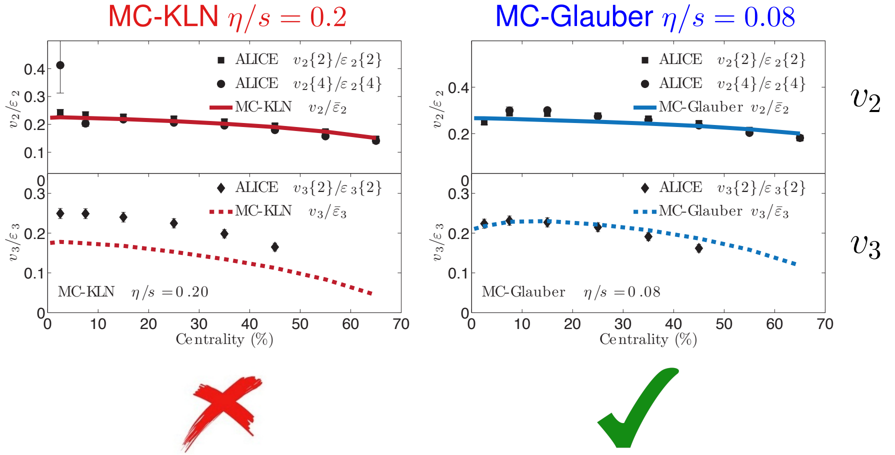
- MC-Glauber model
  Participants determined from nucleon-nucleon cross-section
  Gaussian energy density assigned to each wounded nucleon



- MC-KLN model
  Saturation based model (we'll get to that)
  Initial energy density from convolution of the two gluon distribution functions
  Drescher, Nara, Phys.Rev. C75 (2007) 034905



Testing initial state models with higher harmonics

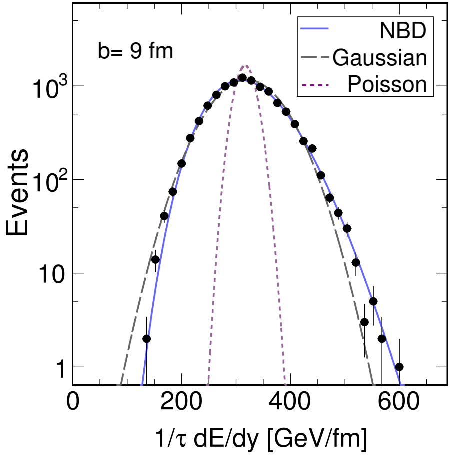


Z. Qiu, C. Shen, U. Heinz, Phys.Lett. B707 (2012) 151-155

Negative binomial fluctuations

B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett.108, 252301 (2012)

Fluctuations in the total energy per unit rapidity produce negative binomial distribution (NBD).



$$P(n) = \frac{\Gamma(k+n)}{\Gamma(k)\Gamma(n+1)} \frac{\bar{n}^n k^k}{(\bar{n}+k)^{n+k}}$$

Good, since multiplicity in pp collisions can be described well with NBD.

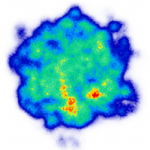
In AA, convolution of NBDs at all impact parameters describes data well too.

P. Tribedy and R. Venugopalan
Nucl.Phys. A850 (2011) 136-156

MC-KLN does not do that - these fluctuations need to be put in by hand.

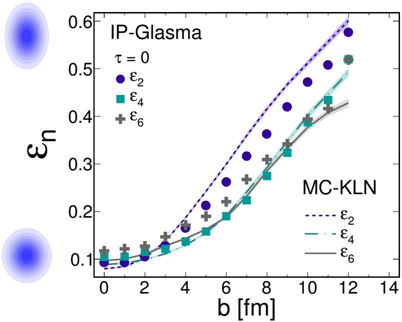
see Dumitru and Nara arXiv:1201.6382

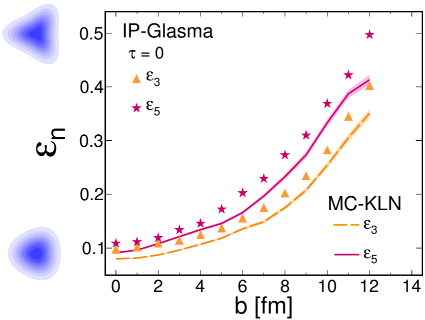
Eccentricities B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.C86, 034908 (2012)



Characterize the initial distribution
by its ellipticity, triangularity, etc...

$$\varepsilon_n = \sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2} / \langle r^n \rangle$$





- ε_n larger in Glasma model for odd n
- ε_n smaller in Glasma model for $n = 2$ (for $b > 3\,\mathrm{fm}$)
  about equal for $n = 4$, larger for $n = 6$