Probing extreme QCD through ridge-like correlations in small systems: status and problems

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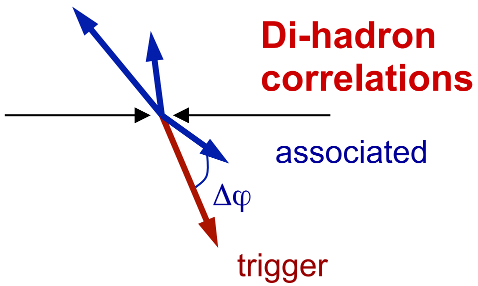
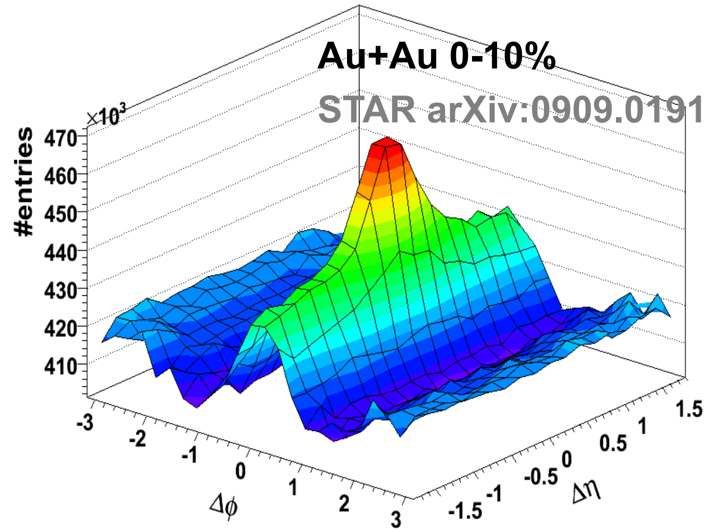
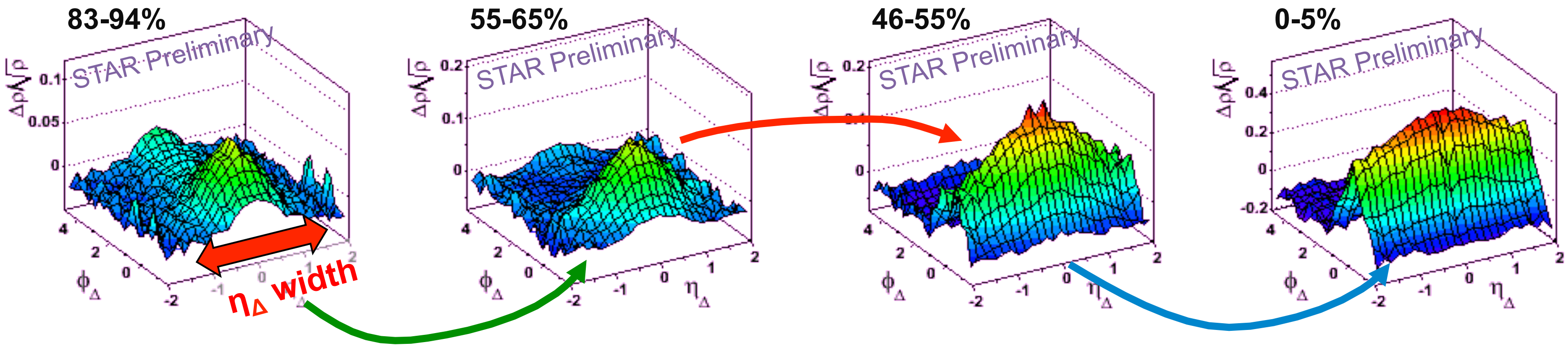
RBRC Saturation Workshop, April 26-28, 2017

The ridge in A+A collisions



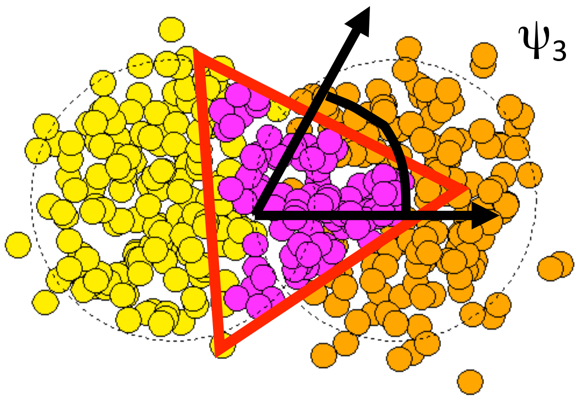


$3 < p_{t,trigger} < 4$ GeV
$p_{t,assoc.} > 2$ GeV

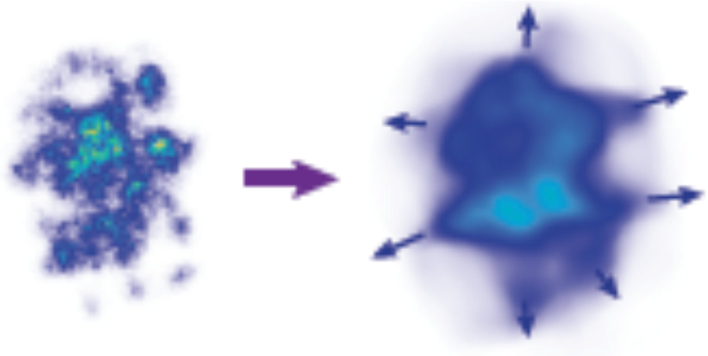


Collimated, long range rapidity correlations:
First seen by RHIC Au+Au experiments: STAR, PHOBOS, PHENIX

The ridge in A+A collisions



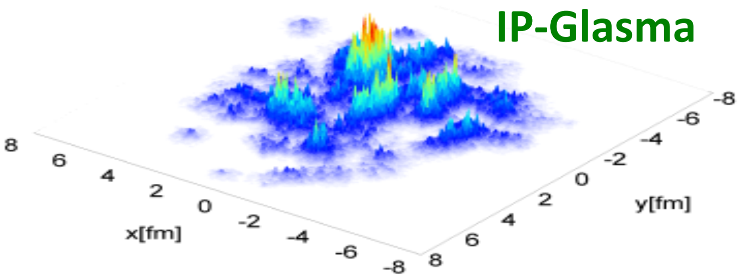
Alver, Roland, PRC81(2010) 054905
Alver, Gombeaud, Luzum, Ollitrault, PRC82 (2010) 03491

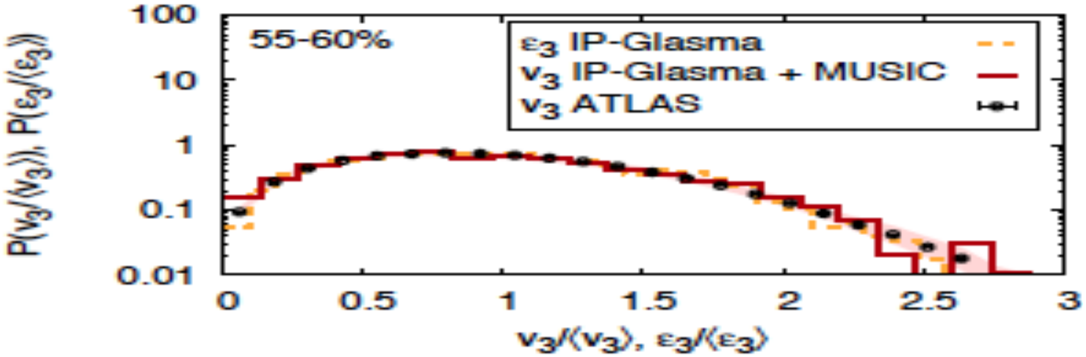


Structure of ridge-correlations can be understood as hydrodynamic flow driven by event-by-event fluctuations in nucleon positions

$$\frac{1}{N_{\rm trig} N_{\rm assoc.}} \frac{d^2N}{d\Delta\Phi} = 1 + V_1\, Cos(\Delta\Phi) + V_2\, Cos(2\Delta\Phi) + \cdots$$

Gale,Jeon,Schenke,Tribedy,Venugopalan, PRL110 (2013) 012302



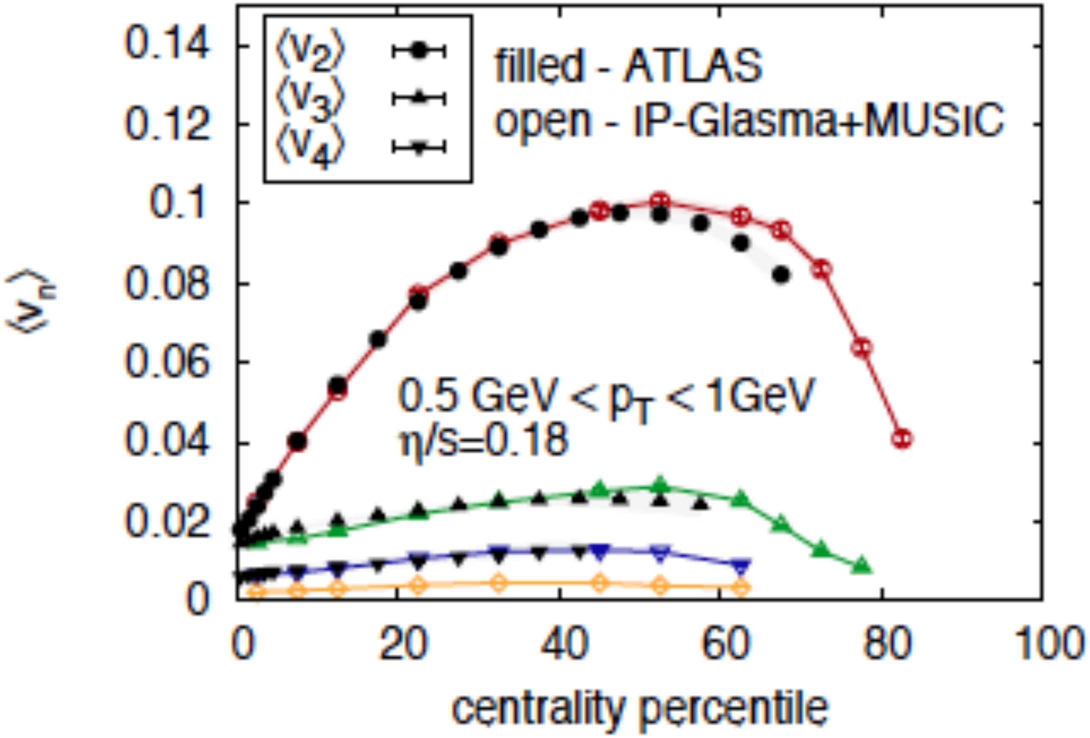


Some evidence of sensitivity of data to sub-nucleon scale fluctuations

What's the smallest sized QGP droplet?

IP-Glasma= initial state
MUSIC=event.by.event. hydro

Schenke, Venugopalan, PRL 113 (2014) 102301



Where does the hydro paradigm break down?

Higher cumulants of elliptic flow

m-particle flow cumulants

$$c_n\{2m\} = \langle\langle e^{in(\phi_1 + \cdots \phi_m - \phi_{m+1} - \cdots \phi_{2m})}\rangle\rangle$$

Borghini,Dinh,Ollitrault, nucl-th/0105040

$$v_n\{2\}^2 \equiv c_n\{2\}\,;\; v_n\{4\}^2 \equiv -c_n\{4\}\,;\; v_n\{6\}^6 \equiv c_n\{6\}/4$$

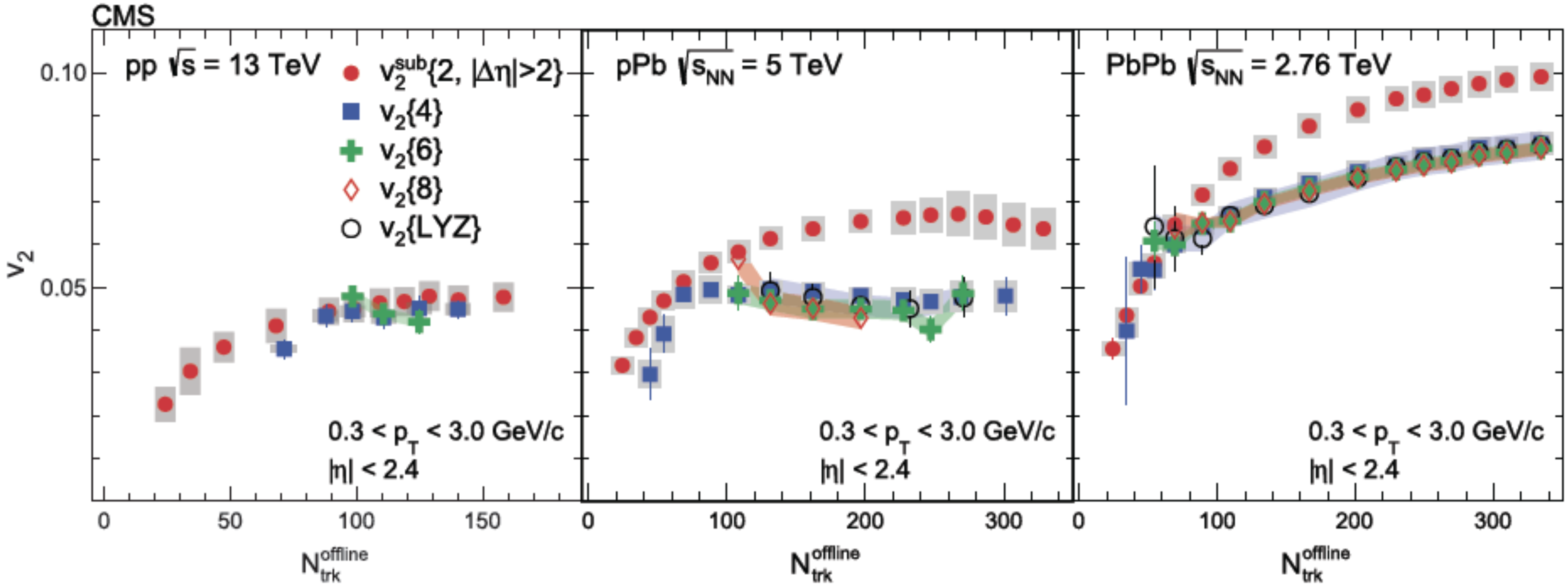
Spatial eccentricities: $$\epsilon_n = \frac{1}{< r_\perp^n >}\int d^2 r_\perp\, e^{in\phi_r}\, r_\perp^n\, \frac{dN}{dy d^2 r_\perp}$$

A number of simple models give $\epsilon_n\{2\} > \epsilon\{4\} = \epsilon\{6\} = \cdots$

Hydro linear response: $v_n\{m\} \approx c_n \varepsilon_n\{m\}$

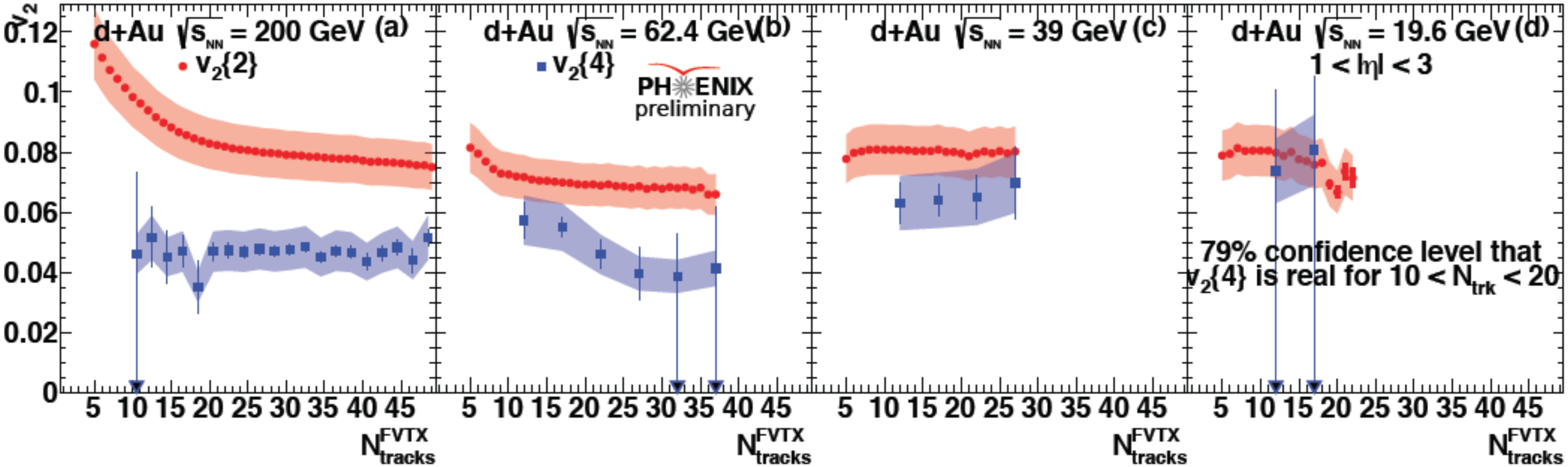
Gardim,Grassi,Luzum,Ollitrault, PRC (2012)024908; Niemi,Denicol,Holopainen,Huovinen, PRC87 (2013)054901
Bzdak,Bozek,McLerran, arXiv:1311.7325, Bzdak, Skokov, arXiv: 1312.7349
Li, Ollitrault, arXiv:1312.6555, Basar,Teaney, arXiv:1312.6770

Collectivity across system size

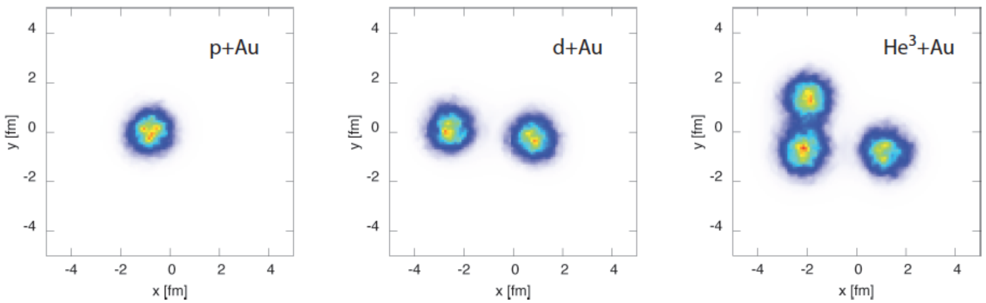


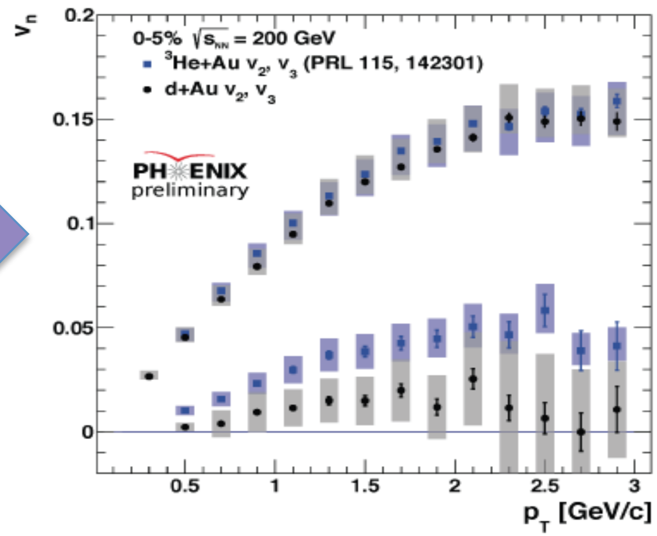
Collectivity across wide energy scales

200 GeV 62.4 GeV 39 GeV 19.6 GeV

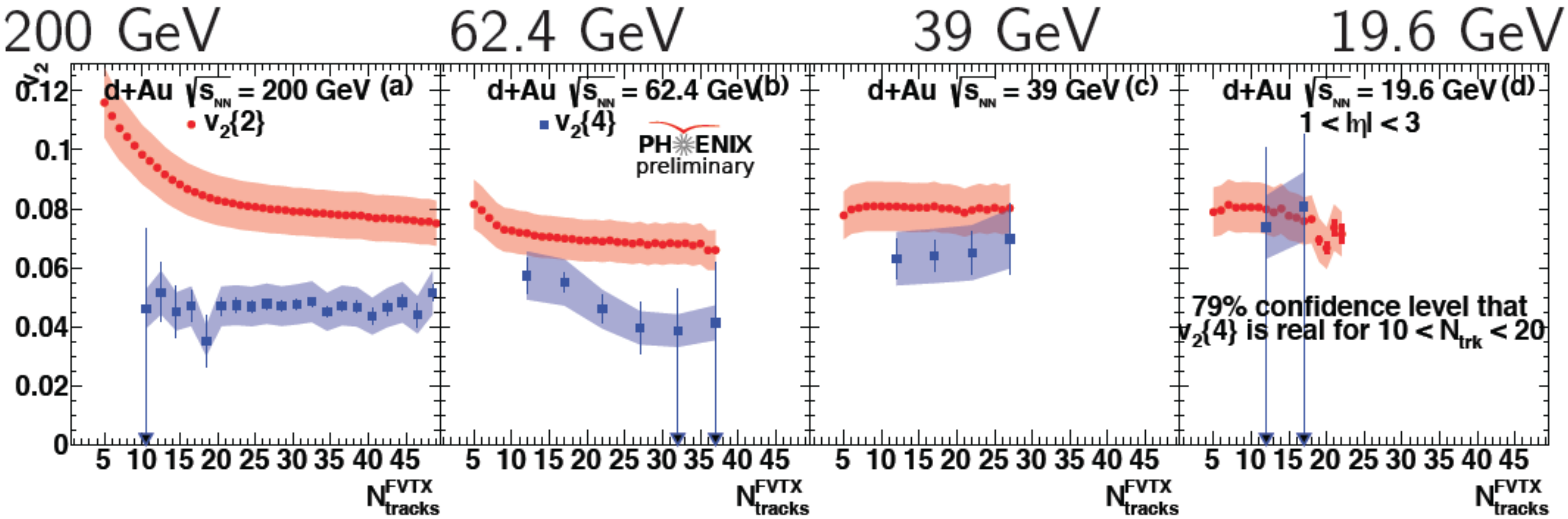


Schenke, RV:1407.7557





Collectivity across wide energy scales



Panta Rhei ?

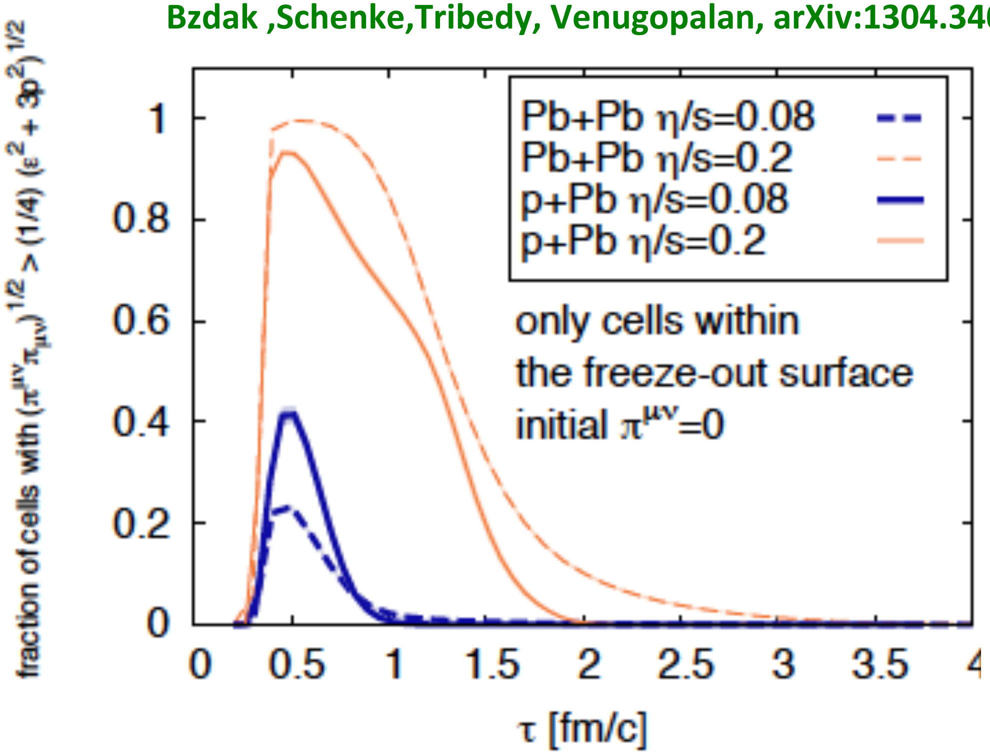
Heraclitus of Ephesus
535-475 BC

Issues with the hydrodynamic paradigm: I

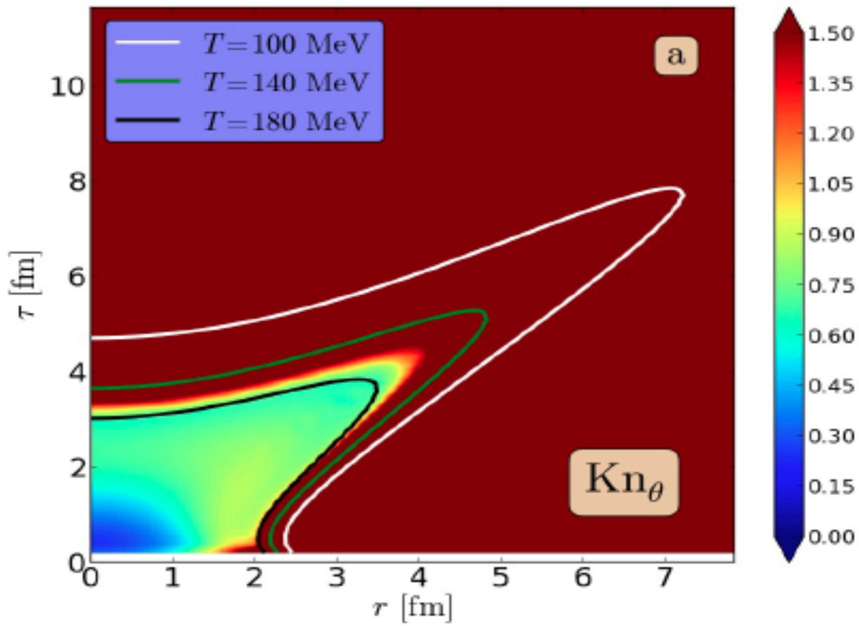
Two frequently used measures: Reynolds # and Knudsen #

$$R^{-1} \propto (\Pi^{\mu\nu}\Pi_{\mu\nu})^{1/2}/(\epsilon^2 + 3P^2)^{1/2} \qquad \mathrm{Kn} = \frac{\tau_\pi}{L} \ ; \ \tau_\pi \propto \frac{\eta}{sT}$$

Bzdak ,Schenke,Tribedy, Venugopalan, arXiv:1304.3403



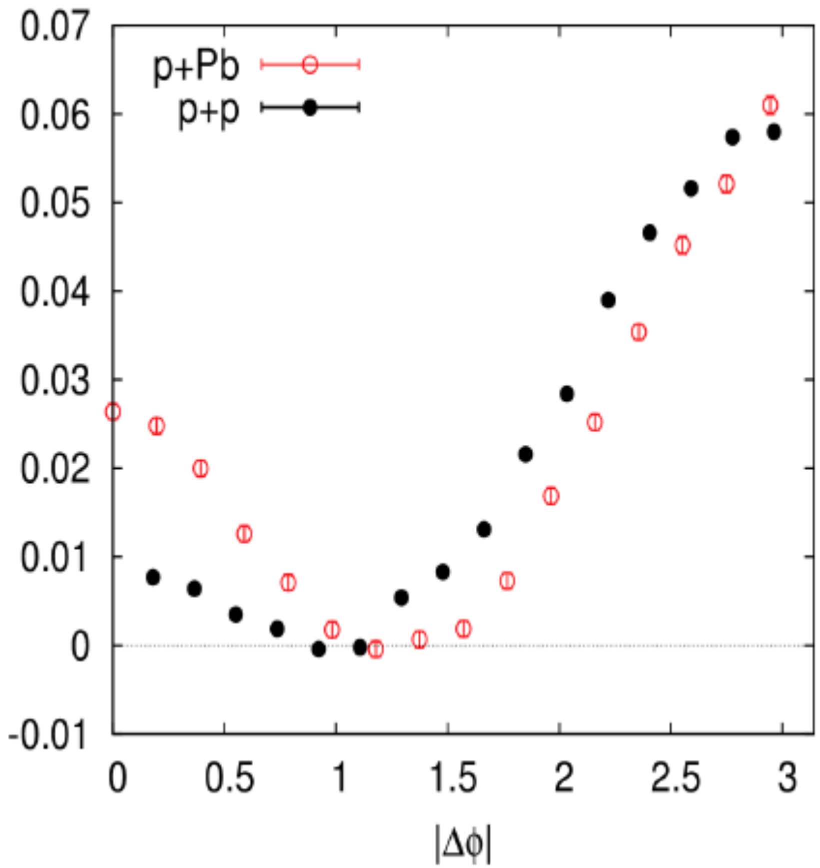
Dumitru,Molnar,Nara,arXiv:0706.2233
Denicol, Niemi, arXiv:1404.7327

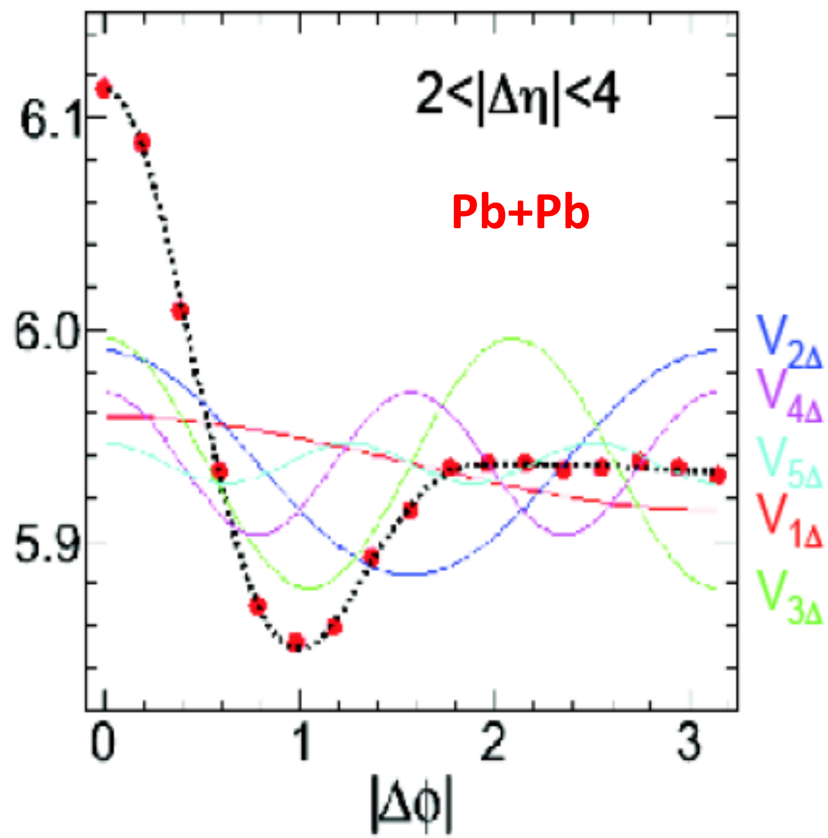


Hydro good for Kn < 0.5, marginal for K < 1 transient regime; K > 1 free streaming

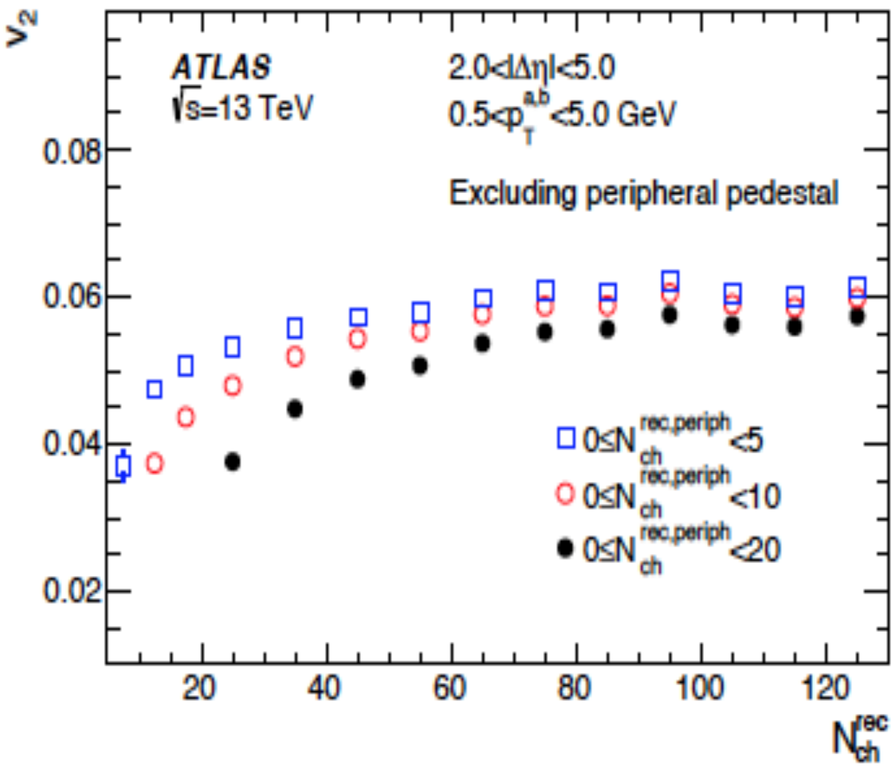
Issues with the hydrodynamic paradigm: II

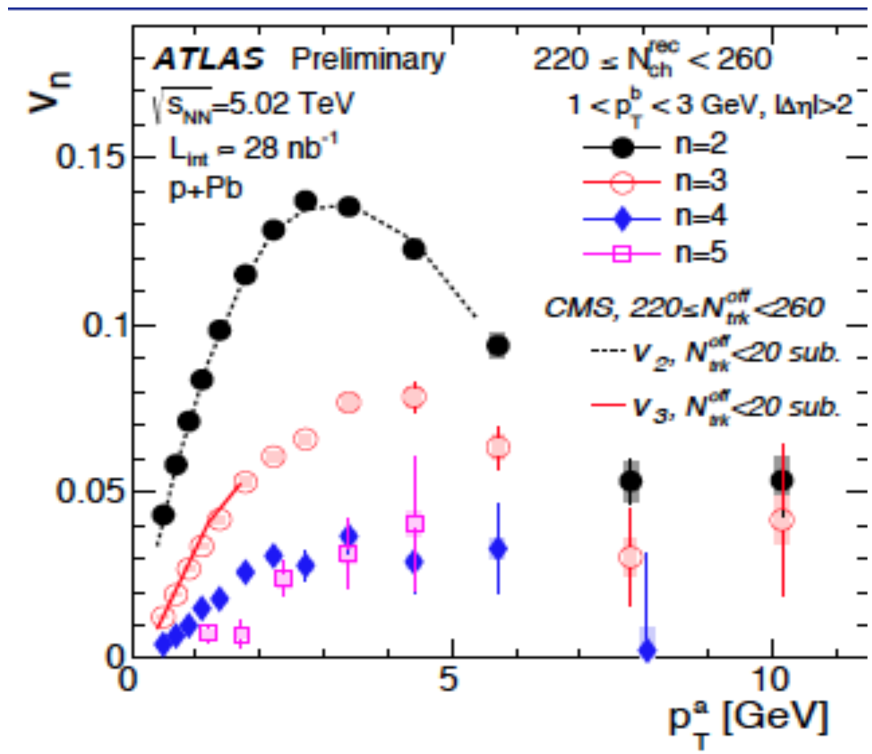
No (mini-) jet quenching seen in the smaller systems





Issues with the hydrodynamic paradigm: III



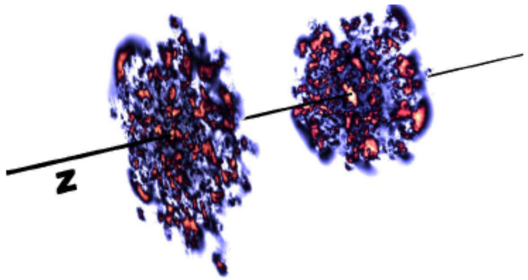


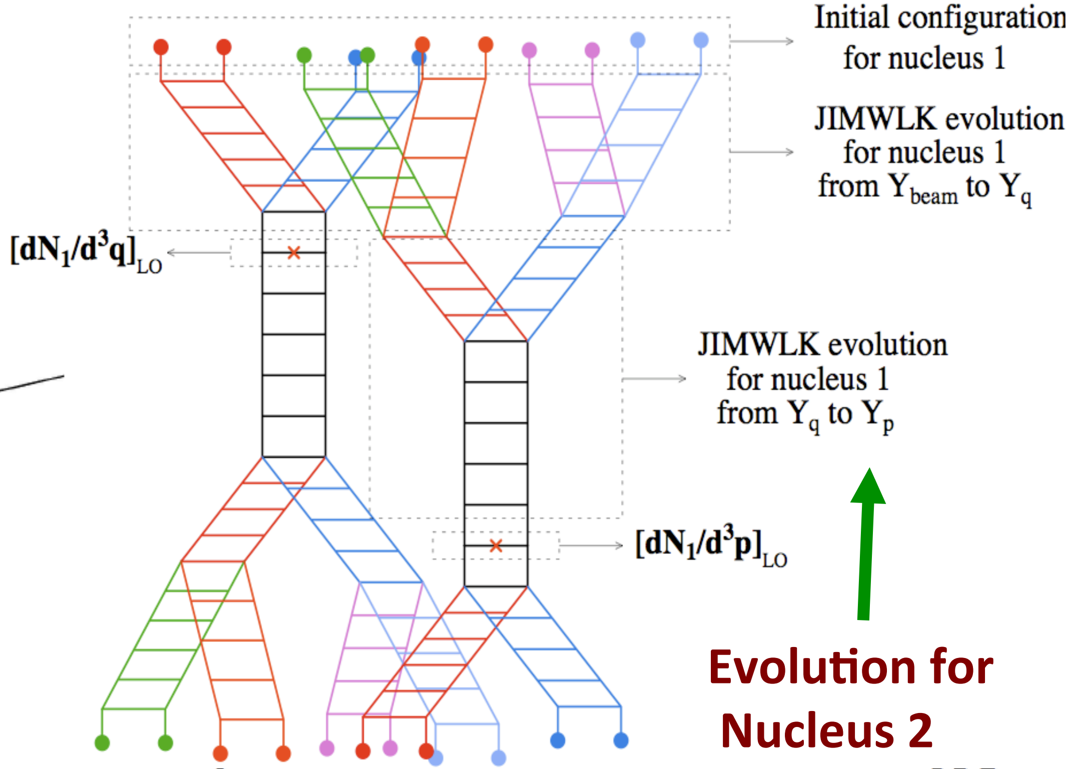
Large anistropies at larger p_T and smaller N_{ch} than one might reconcile with a hydrodynamic description

Can we understand multiparticle correlations in an *ab initio* approach

Two-parton azimuthal correlations in the CGC

Dumitru,Gelis,McLerran,Venugopalan: 0804.3858
Gelis, Lappi, Venugopalan, arXiv: 0807.1306
Dusling,Gelis,Lappi,Venugopalan, arXiv:0911.2720





Evolution for Nucleus 2

$$\langle \frac{dN_2}{d^3p\, d^3q} \rangle_{\rm LLogs} = \int [d\rho_1][d\rho_2] W_{Y_1}[\rho_1]\, W_{Y_2}[\rho_2]\, \frac{dN}{d^3p}\Big|_{\rm LO} \frac{dN}{d^3q}\Big|_{\rm LO}$$

JIMWLK evolution

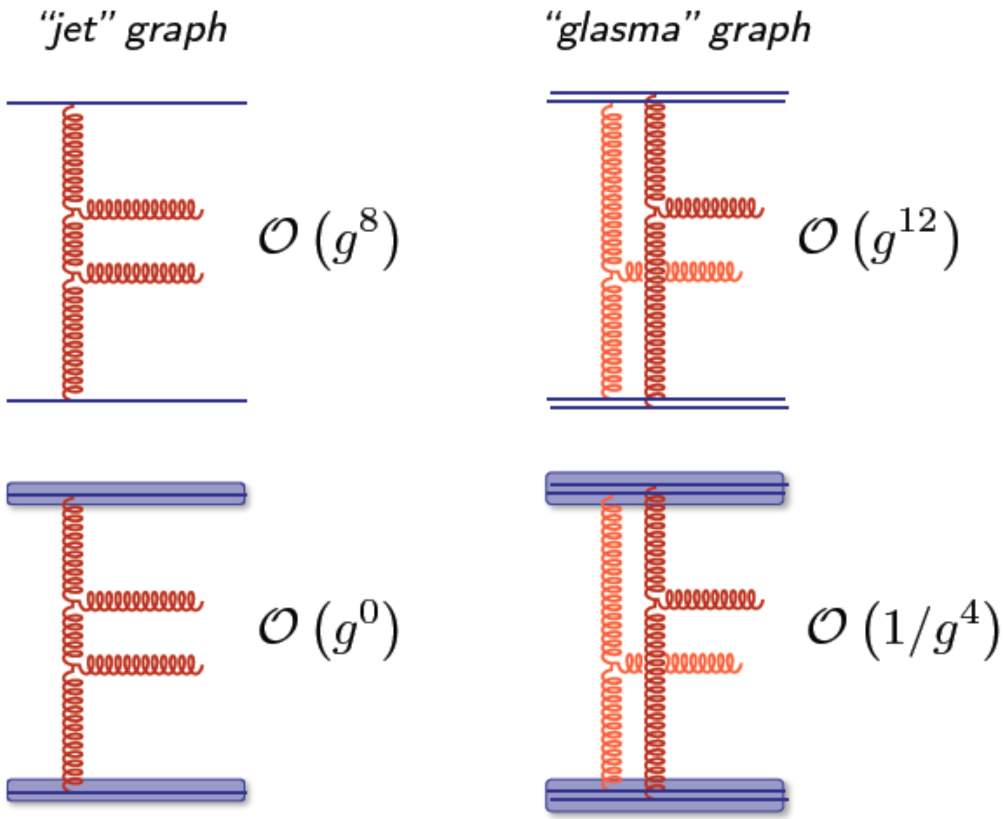
Solution of Yang-Mills for dense-dense systems (as in A+A)

Glasma graph approximation: power counting

Dumitru,Dusling,Gelis,Jalilian-Marian,
Lappi,Venugopalan, PLB697 (2011)21
Dusling,Venugopalan,PRL108 (2012)262001

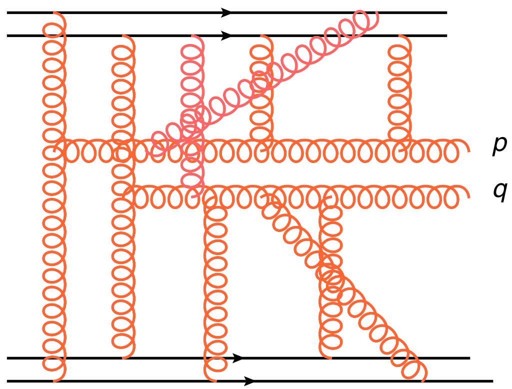
Low color density
(min. bias events)

High color density
("central" events)

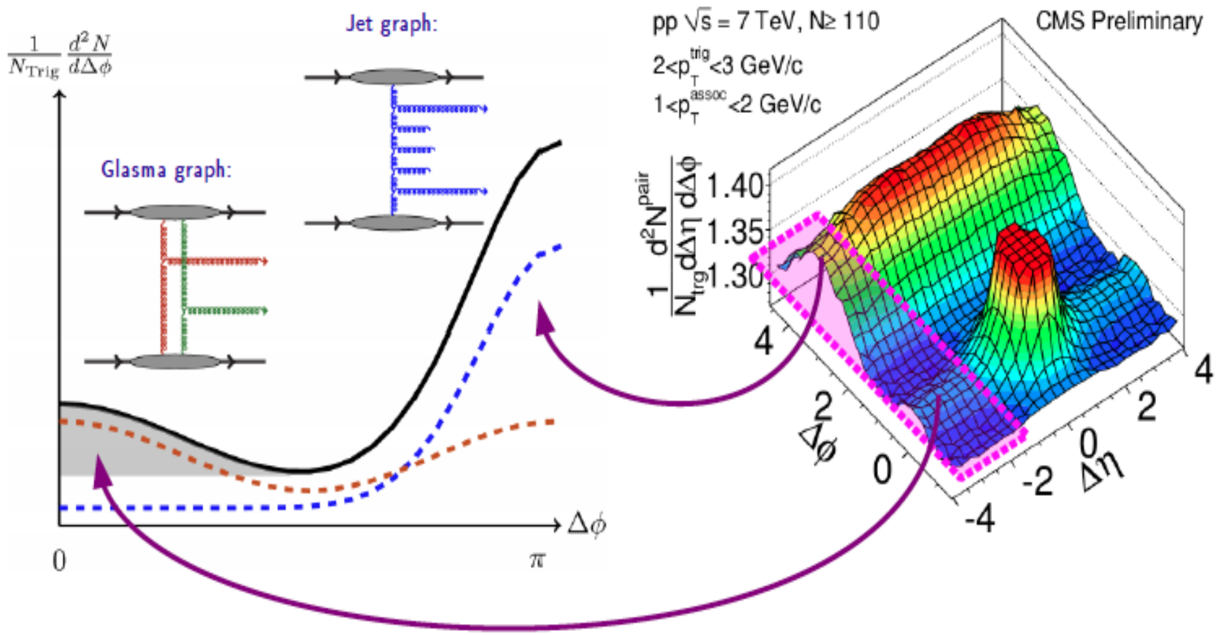


Gluons with k_T ~ Q_S resolve
n ~ $1/g^2$ color sources
Effective coupling: g*n ~ 1/g

Note: neither the Glasma graphs nor the jet graphs include the multiple coherent scatterings resummed by the YM equations…
become important for $p_T < Q_S$



Anatomy of long range collimations



RG evolution of Glasma graphs:

$$C(\mathbf{p},\mathbf{q}) \quad \propto \quad \frac{g^4}{\mathbf{p}_\perp^2\mathbf{q}_\perp^2}\int \mathrm{d}^2\mathbf{k}_{1\perp}\ \Phi^2_{A_1}(y_p,\mathbf{k}_{1\perp})\Phi_{A_2}(y_p,\mathbf{p}_\perp-\mathbf{k}_{1\perp})\Phi_{A_2}(y_q,\mathbf{q}_\perp-\mathbf{k}_{1\perp})$$
$$+ \quad \text{permutations}$$

Dusling,RV, PRD 87, 051502 (R) (2013); PRD87 (2013) 094034
Dusling,Tribedy,RV,PRD93 (2016) 014034

RG evolution of the mini-jets:

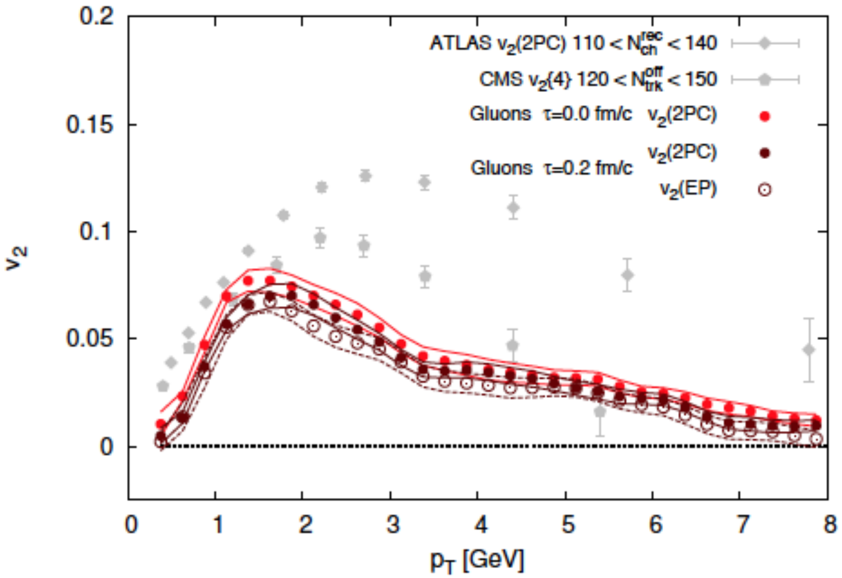
$$C_{\rm dijet}(\mathbf{p},\mathbf{q}) \propto \Phi_A \otimes \Phi_B \otimes G_{\rm BFKL}$$

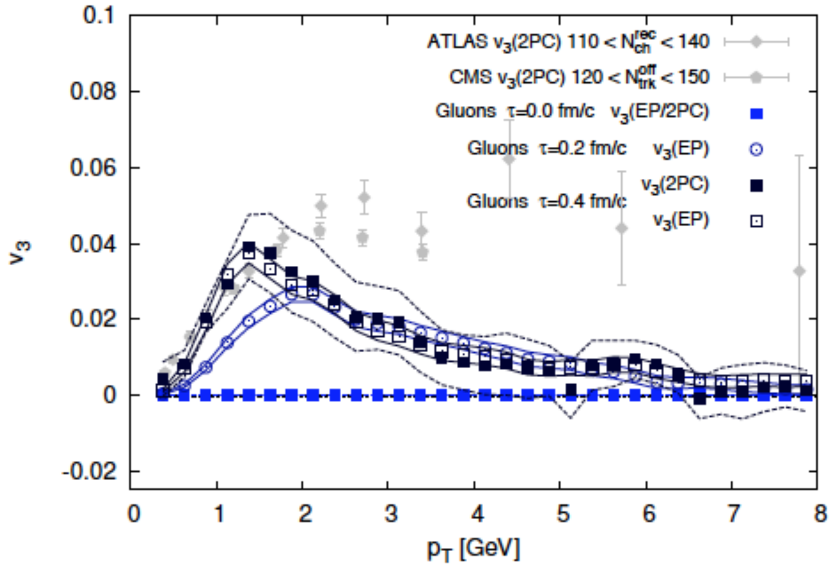
Good agreement with data for $p_T > Q_S$

However no odd harmonics v_3, v_5 in this approximation...

Azimuthal anistropy from Yang-Mills dynamics

Schenke,Schlichting,RV, PLB747(2015)76





See also, Lappi,Srednyak,RV, JHEP1001 (2010)066

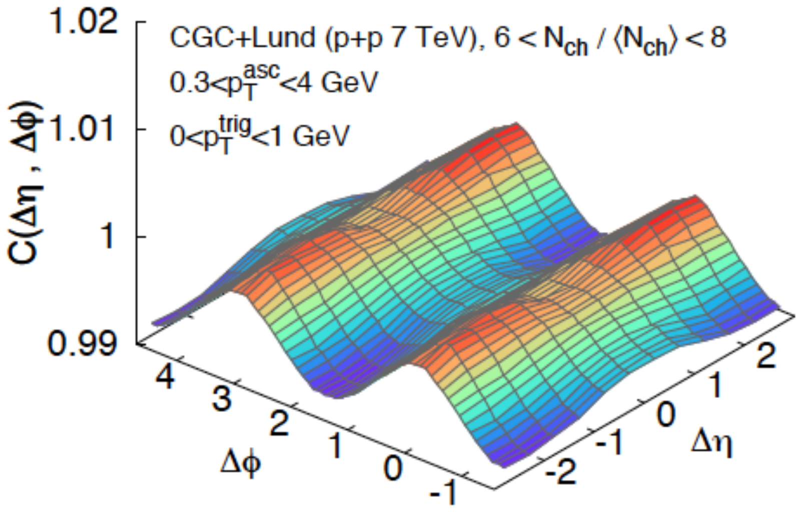
Recent analytical work in dilute-dense approx:
Kovchegov,Wertepny,NPA906 (2013)50
McLerran, Skokov arXiv:1611.09870
Kovner,Lublinsky,Skokov, arXiv:1612.07790

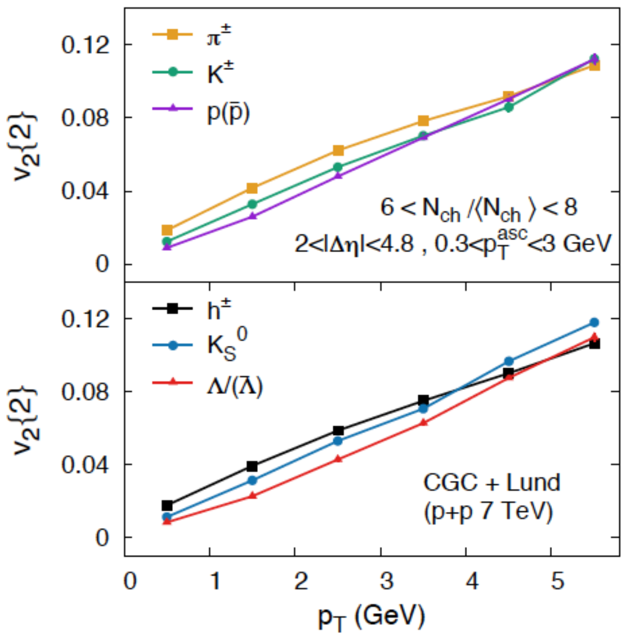
What about 4 and higher particle cumulants from YM dynamics?

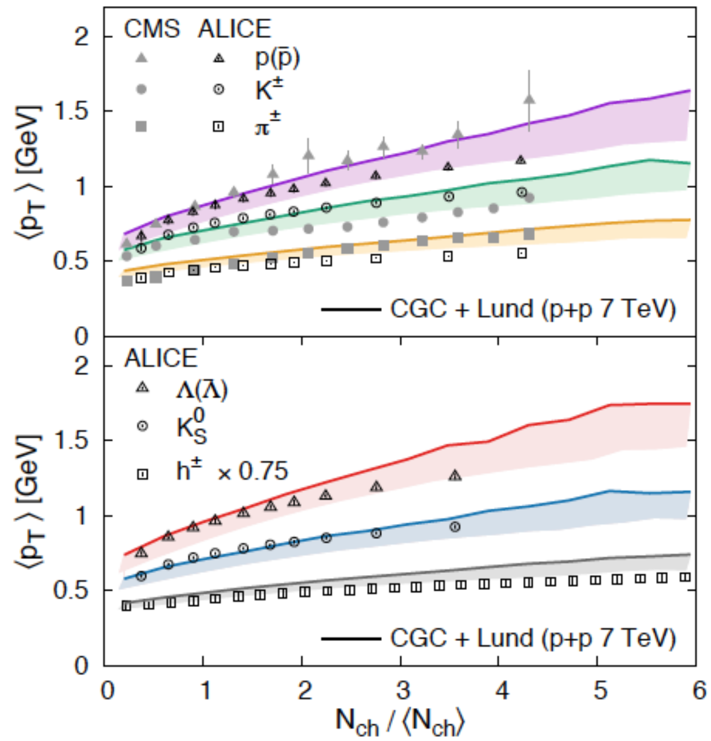
Numerically very challenging to look at rare events – in progress

Schenke,Schlichting,Tribedy,RV

IP-Glasma+Lund fragmentation







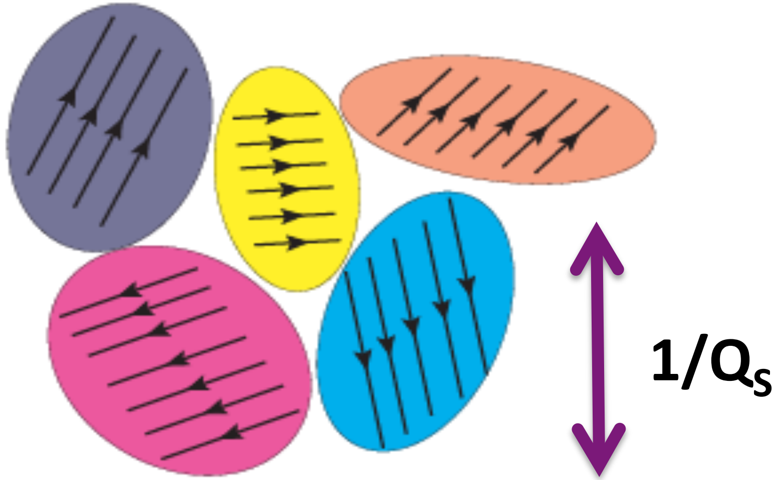
Schenke,Schlichting,Tribedy,RV, PRL117(2016)162301

Pattern of mass splitting of $<p_T>$ and v_2 seen in high multiplicity events is reproduced

Tracing azimuthal initial state correlations

Multi-particle correlations from eikonal scattering of partons off color domains in a nuclear target

Kovner,Lublinsky,arXiv:1012.3398,1109.0347
Dumitru,Gianini, arXiv:1406.5781
Dumitru,Skokov,arXiv:1411.6630,
Dumitru,McLerran,Skokov,arXiv:1410.4844



Explore in simple model:

$$\frac{d^2N}{d^2\mathbf{p}_1 d^2\mathbf{p}_2} = \int d^2\mathbf{b}_1 d^2\mathbf{b}_2 \int \frac{d^2\mathbf{k}_1}{(2\pi)^2}\frac{d^2\mathbf{k}_2}{(2\pi)^2} W(\mathbf{b}_1,\mathbf{k}_1,\mathbf{b}_2,\mathbf{k}_2)$$

$$\times \int d^2\mathbf{r}_1 d^2\mathbf{r}_2\, e^{i(\mathbf{p}_1-\mathbf{k}_1)}\, e^{i(\mathbf{p}_2-\mathbf{k}_2)} \langle D\left(\mathbf{b}_1+\frac{\mathbf{r}_1}{2},\mathbf{b}_1-\frac{\mathbf{r}_1}{2}\right) D\left(\mathbf{b}_2+\frac{\mathbf{r}_2}{2},\mathbf{b}_2-\frac{\mathbf{r}_2}{2}\right)\rangle$$

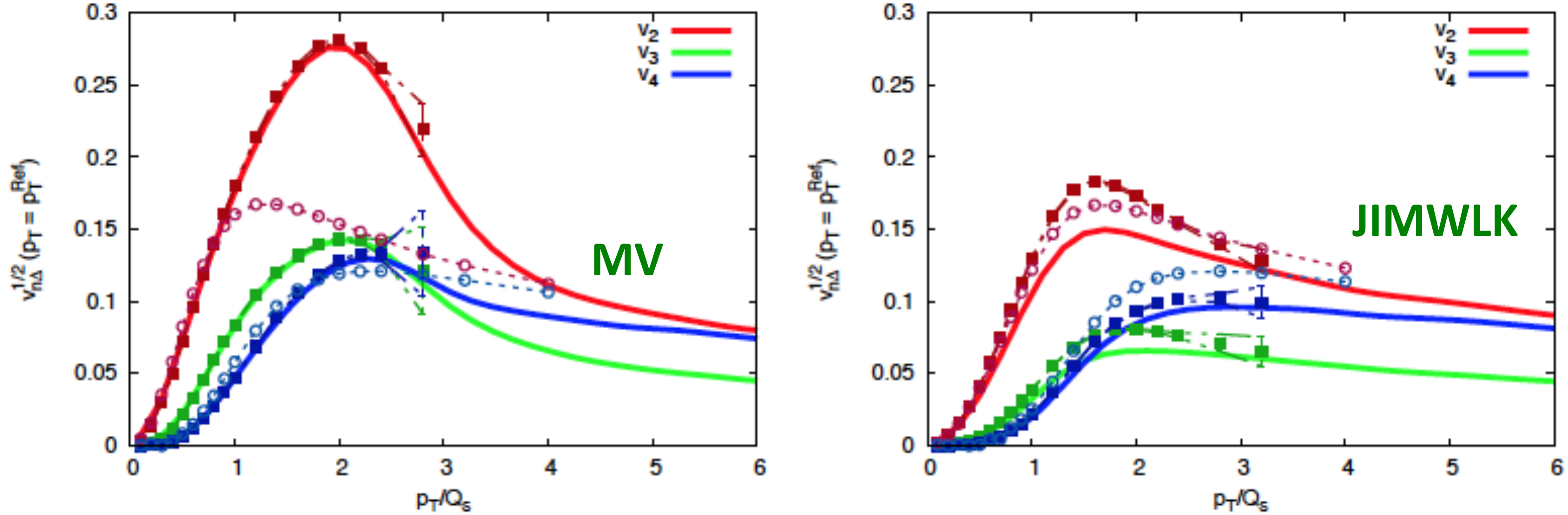
Dipole $D(\mathbf{x},\mathbf{y}) = \frac{1}{N_c}\mathrm{Tr}\left(V(\mathbf{x})V^\dagger(\mathbf{y})\right)$ $\quad V(\mathbf{x}) = P\exp\left(-ig\int dx^+ A^-(\mathbf{x},x^+)\right)$

Ansatz: $W(\mathbf{b}_1,\mathbf{k}_1,\mathbf{b}_2,\mathbf{k}_2) = W(\mathbf{b}_1,\mathbf{k}_1)\, W(\mathbf{b}_2,\mathbf{k}_2)$

$W(\mathbf{b},\mathbf{k}) = \exp\left(-\mathbf{b}^2/B - \mathbf{k}^2 B\right)$ **B=transverse area of projectile**

Tracing azimuthal initial state correlations

Lappi, arXiv:1501.05505
Lappi,Schenke,Schlichting,RV, arXiv:1509.03499



What about 4-particle correlations?

$$\frac{d^m N}{\prod_{i=1}^{m} d^2 \mathbf{p}_{\mathbf{i}\perp}} = \frac{1}{(4\pi^3 B)^m} \prod_{i=1}^{m} \int d^2\mathbf{b}_\mathbf{i} \int d^2\mathbf{r}_\mathbf{i}\; e^{-b_i^2/B}\; e^{-r_i^2/4B} e^{i\mathbf{p}_{\mathbf{i}\perp}\cdot\mathbf{r}_\mathbf{i}} \left\langle \prod_{j=1}^{m} D(\mathbf{b}_\mathbf{j} + \frac{\mathbf{r}_\mathbf{j}}{2}, \mathbf{b}_\mathbf{j} - \frac{\mathbf{r}_\mathbf{j}}{2}) \right\rangle$$

$$\kappa_n\{m\} = \int d^2\mathbf{p}_{1\perp} \ldots d^2\mathbf{p}_{m\perp} \frac{d^m N}{\prod_{k=1}^{m} d^2\mathbf{p}_{k\perp}} \prod_{j=1}^{m/2} \prod_{l=\frac{m}{2}+1}^{m} e^{ni(\phi_j^p - \phi_l^p)}$$

$$c_n\{4\} = \frac{\kappa_n\{4\}}{\kappa_0\{4\}} - 2\left(\frac{\kappa_n\{2\}}{\kappa_0\{2\}}\right)^2$$

First initial state results on $c_n\{4\}$, SC{m,n}
Kevin Dusling's talk at 10:30 am Friday
Dusling,Mace,RV, in preparation

Summary-I

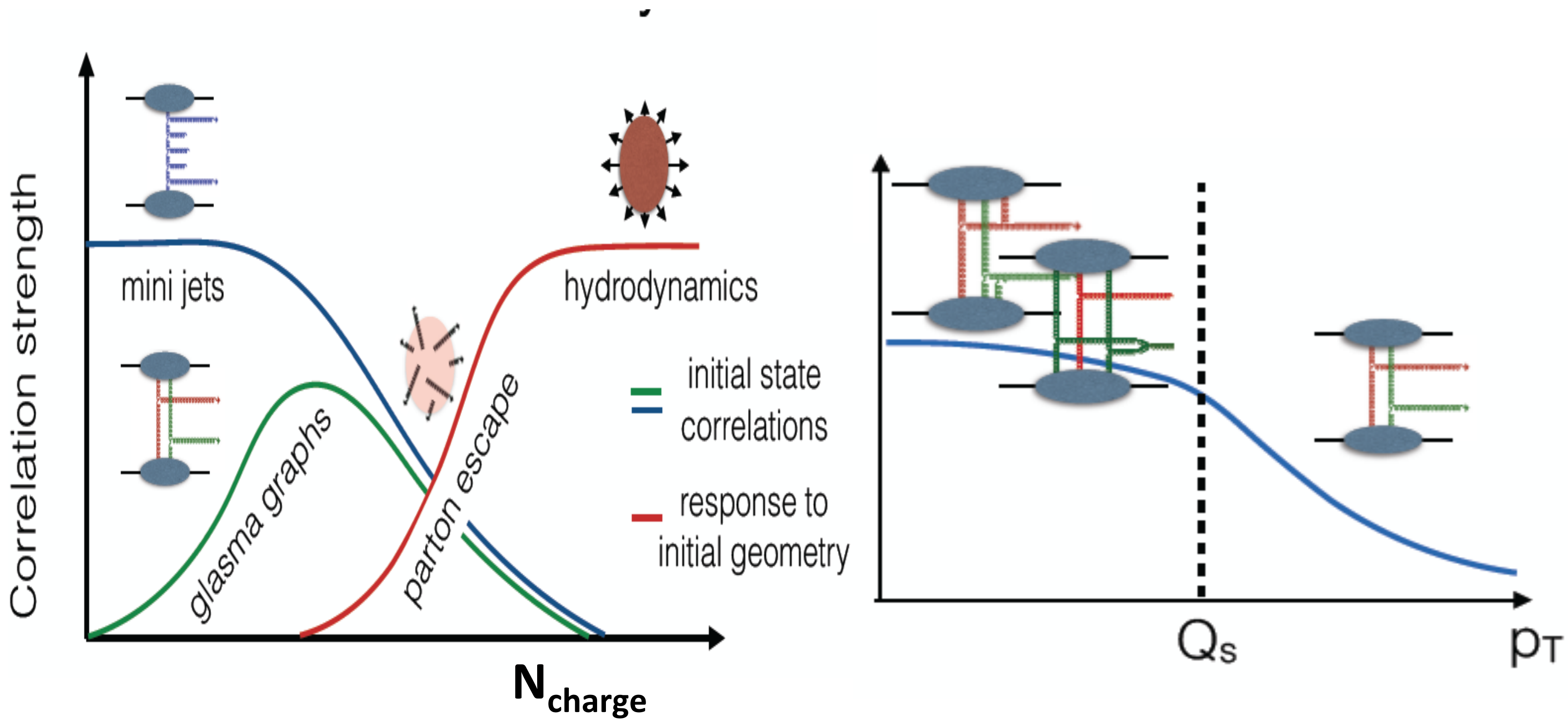
Hydrodynamic paradigm appears to describe
multi-particle correlations even in the smallest systems

There are however puzzling features of the data,
questions about the the validity of hydro, fine tuning of initial conditions (requiring implicitly strong initial state correlations),
··· and explanation of anisotropies for p_T > few GeV

Initial state QCD frameworks now also able to explain many features of the data but systematic treatments are still in their infancy

Despite much progress no satisfactory explanation of the data
-- the problem is still wide open

Summary-II



Event engineering across system sizes, energies, and varieties of probes, offers the exciting possibility of exploring dynamical evolution of strongly correlated quark-gluon matter from high occupancy, out of equilibrium, dynamics… to hydrodynamics

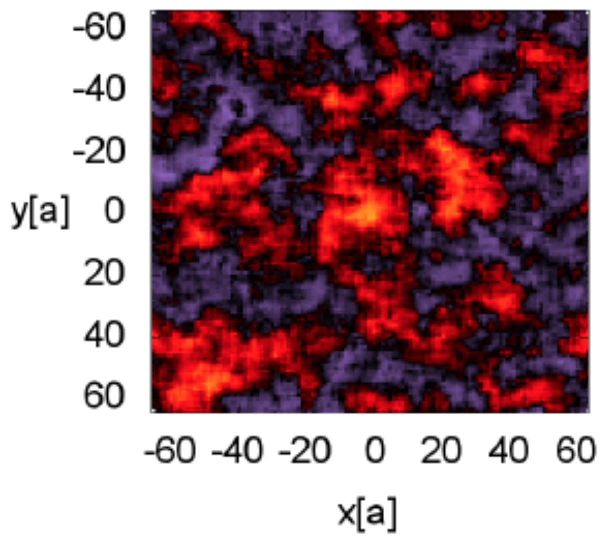
Figiures: S. Schlichting at Quark Matter 2015

Thanks for listening!

Higher cumulants from Glasma domains

Dumitru,McLerran,Skokov, 1410.4844

$$\mathrm{Re}\,\mathrm{Tr}\left(V^\dagger(0,0)V(x,y)\right)/N_c$$



Simple model: express intrinsic higher point correlators as correlators of produced particles with a target field in a color domain, averaged over all orientations of the field.

$$c_2\{2\} = \frac{1}{N_D}\left(\mathcal{A}^2 + \frac{1}{4(N_c^2-1)}\right)$$

$$c_2\{4\} = -\frac{1}{N_D^3}\left(\mathcal{A}^4 - \frac{1}{4(N_c^2-1)^3}\right)$$

"A" term is the correlation induced between projectile particles due to color field orientation of target (more generically, non-Gaussian correlations)

The N_c term is the "connected Glasma graph" (Gaussian correlations)

N_D is # of color domains – few in p+A, several in A+A

Shape matters ?

Schenke,Schlichting, 1407.8458