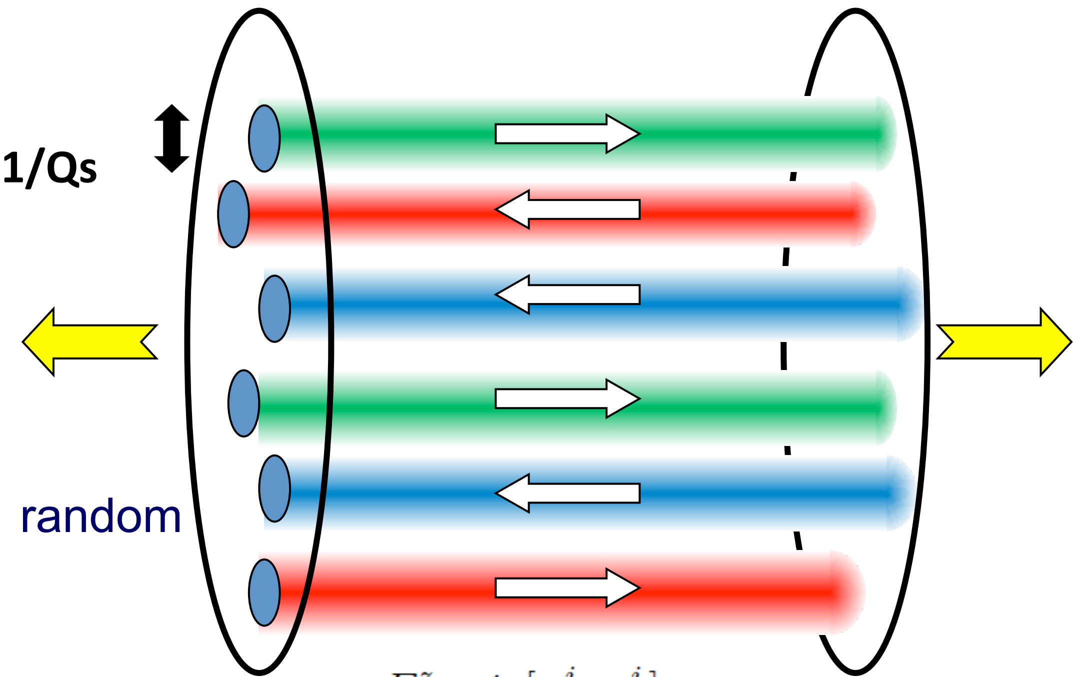
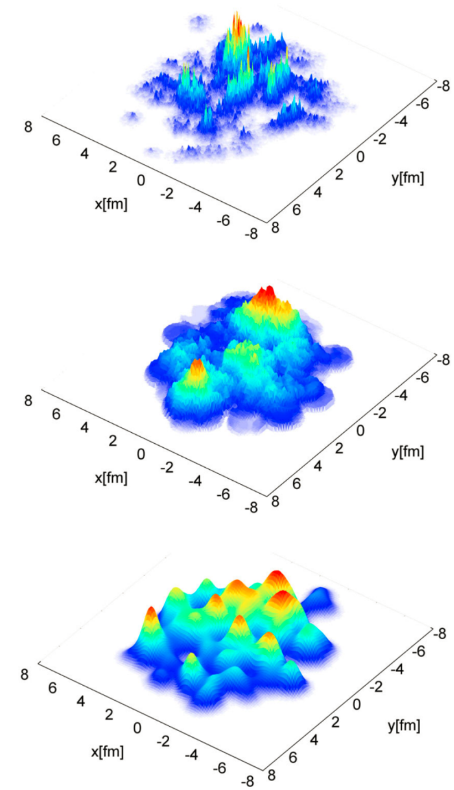
Flow in pA Collisions: Is It Hydrodynamics or Something Else?

Wuhan Quadrangle, CCNU, Wuhan, China, September 2014



$$E^z = ig[\alpha_1^i, \alpha_2^i]$$
$$B^z = ig\epsilon^{ij}[\alpha_1^i, \alpha_2^j].$$

Typical configuration of a single event
just after the collision



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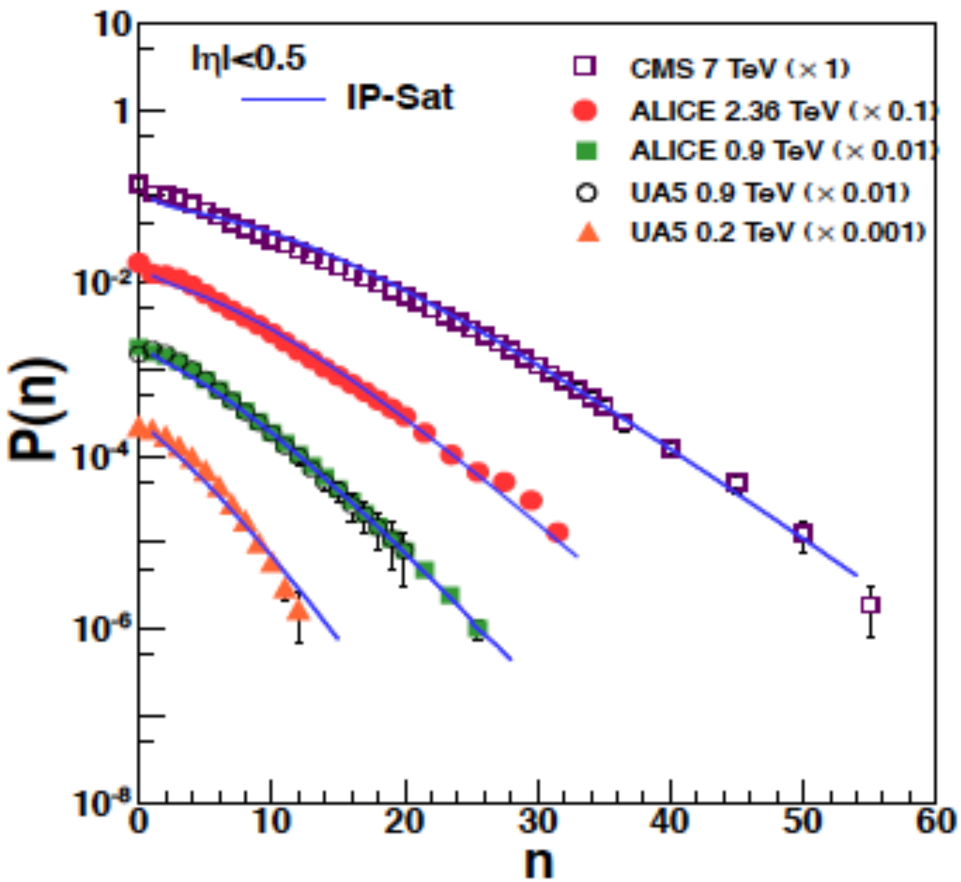
A Sub-Nucleonic description such as the CGC-Glasma is **absolutely necessary** for a well motivated description of pp and pA

Transverse size scales are less than a Fermi
Glauber at the nucleon level is certainly not applicable for pp or high multiplicity pA events



Including fluctuations and better positioning of matter produced makes a big difference:

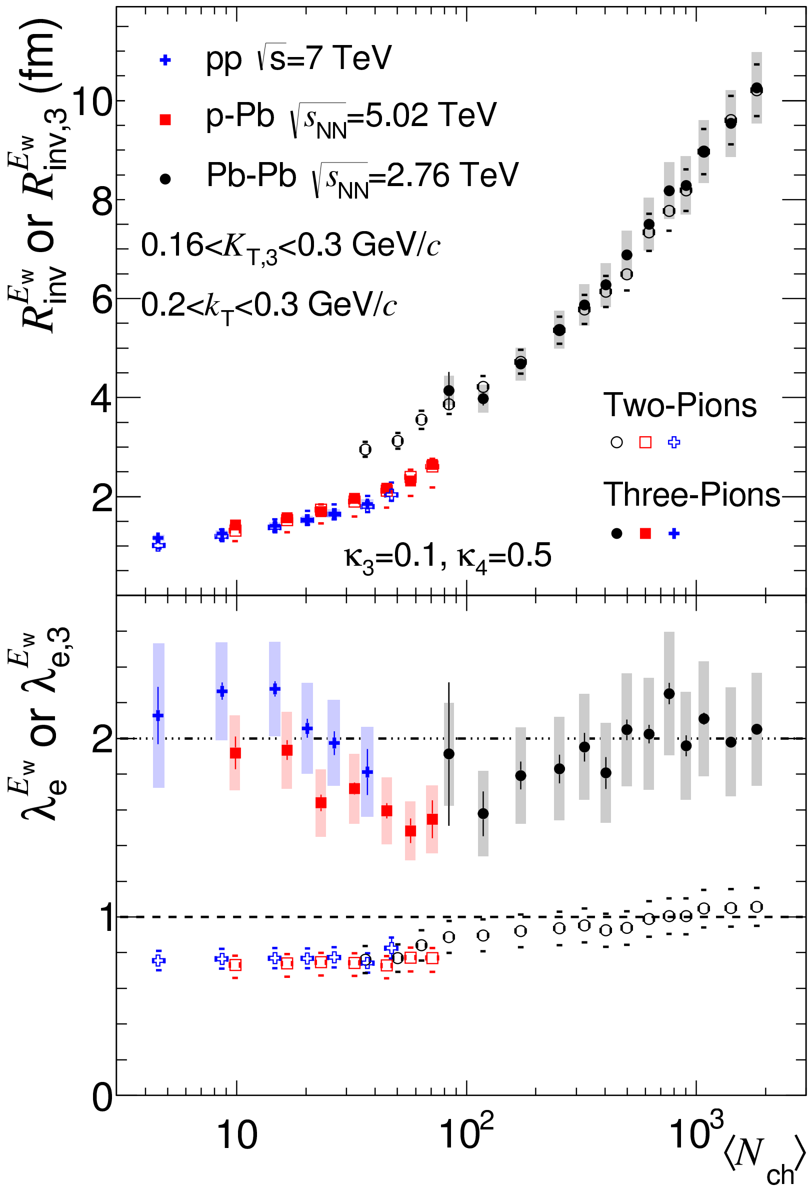
Size of region is

dN/dy ~ 30-50

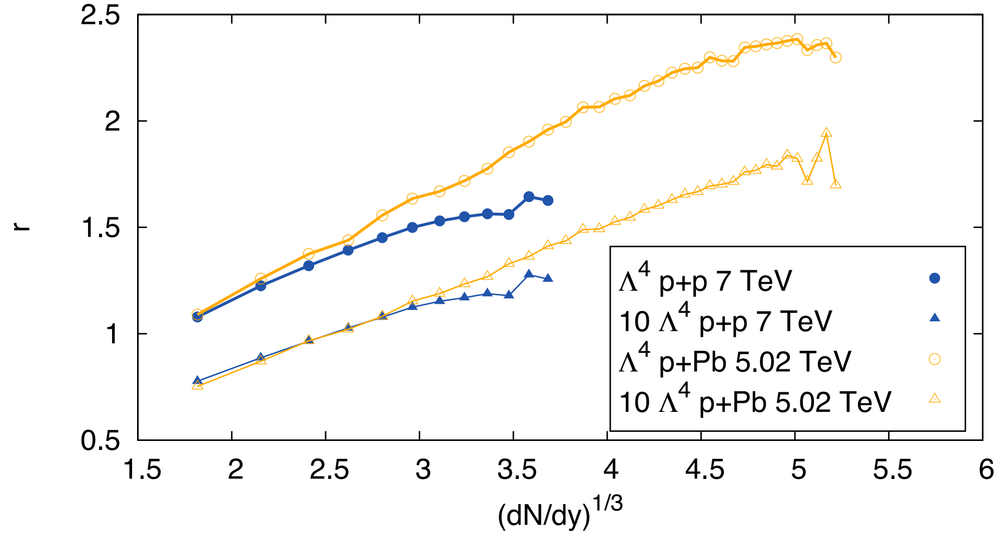
Since the ridge appears in pp collisions, there must be a sub nucleonic component

Schenke, Tribedy, Venugopalan

HBT Radii are of order 1 Fm for pp at largish multiplicities



Bzdak, Schenke, Tribedy, Venugopalan



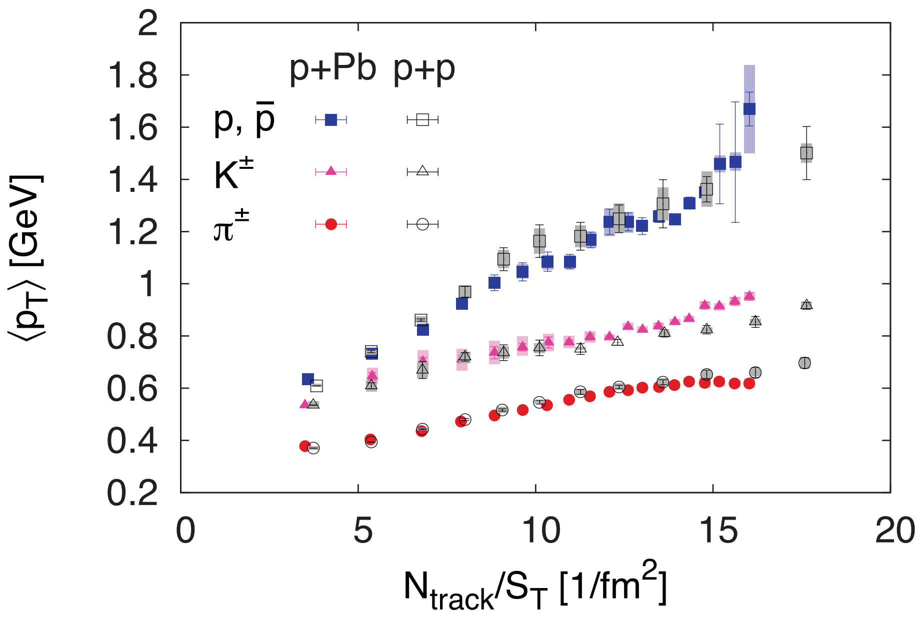
Radii computed in IP Sat Model

CGC Predicted radii in pA would be basically the same as in pp, and different from AA. Verified by Alice results. Would have expected larger radii in pp and pA and radii in AA the same as in pA and pp if hydro was working.

Geometric scaling maps pp data into pA in CMS identified particle data and for unidentified particles in ALICE

If true, low and high multiplicity data are related as well as pp and pA

Praszalowicz, LDM



On the other hand, hydrodynamics predicts flow patterns that would enhance pT distributions of massive particles and would have a similar multiplicity dependence

Problems:

Glasma-CGC description for pA involves two scales and is hard to do

Hydordynamics would need to work in low-ish multiplicity pp and pA collisions, and at largish pT values. Flow is strongest in pp and weakest in AA

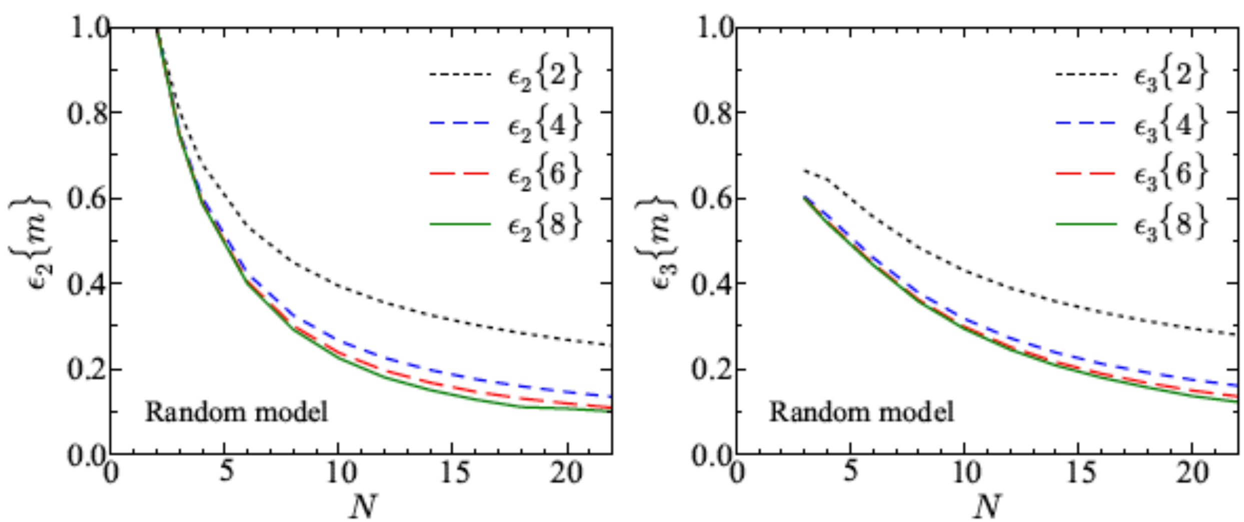
Flow in pA Collisions:

Initial State or Hydrodynamic or Both?

Collaborations with Dumitru and Lappi; with Bzdak and Bozek; With Dumitru, Ho-Ung Yee, Skokov

$$\epsilon_n = \frac{1}{\langle r_T^n \rangle} \int d^2 r_T e^{in\phi} r_T^n \frac{dN}{dy d^2 r_T}$$

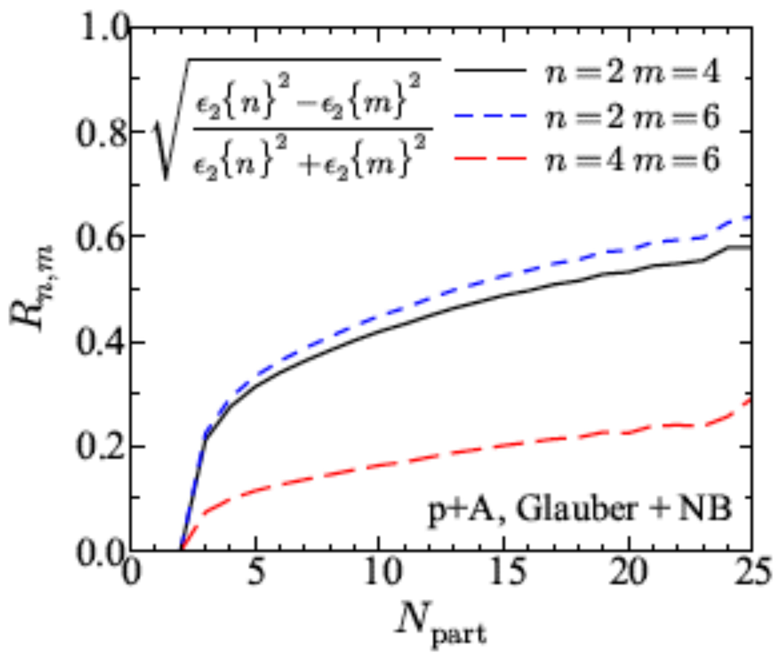
Define m particle cummulents: $\epsilon_n\{m\}$



Similar results for Glauber or Glauber plus Negative Binomial

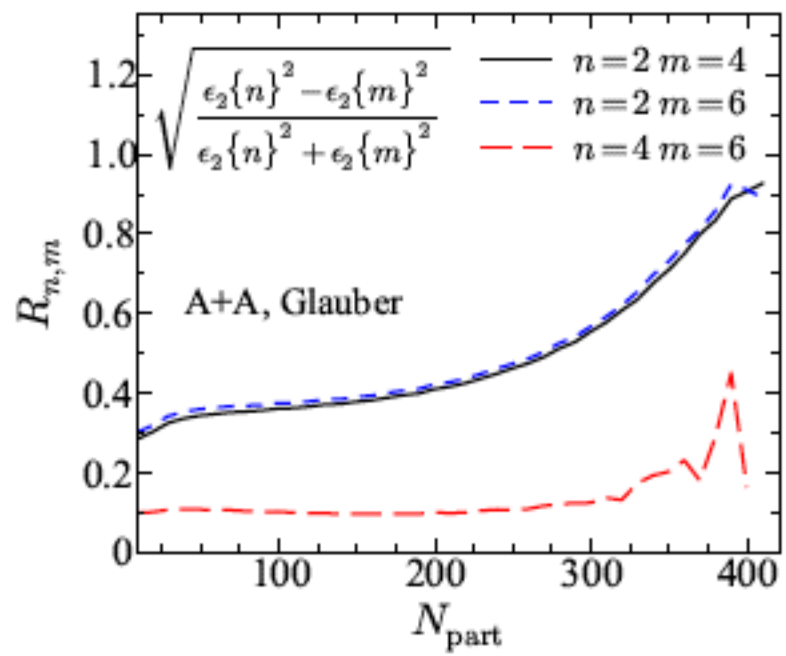
It looks like a nonzero impact parameter, but is not. Entirely fluctuation based: Li Yan and Ollitrault

$$\langle|\epsilon_n|^m\rangle = \frac{\int dz d\bar{z} e^{-(z-z_n)(\bar{z}-\bar{z}_n)/\sigma_n^2}(z\bar{z})^{m/2}}{\int dz d\bar{z} e^{-(z-z_n)(\bar{z}-\bar{z}_n)/\sigma_n^2}}$$

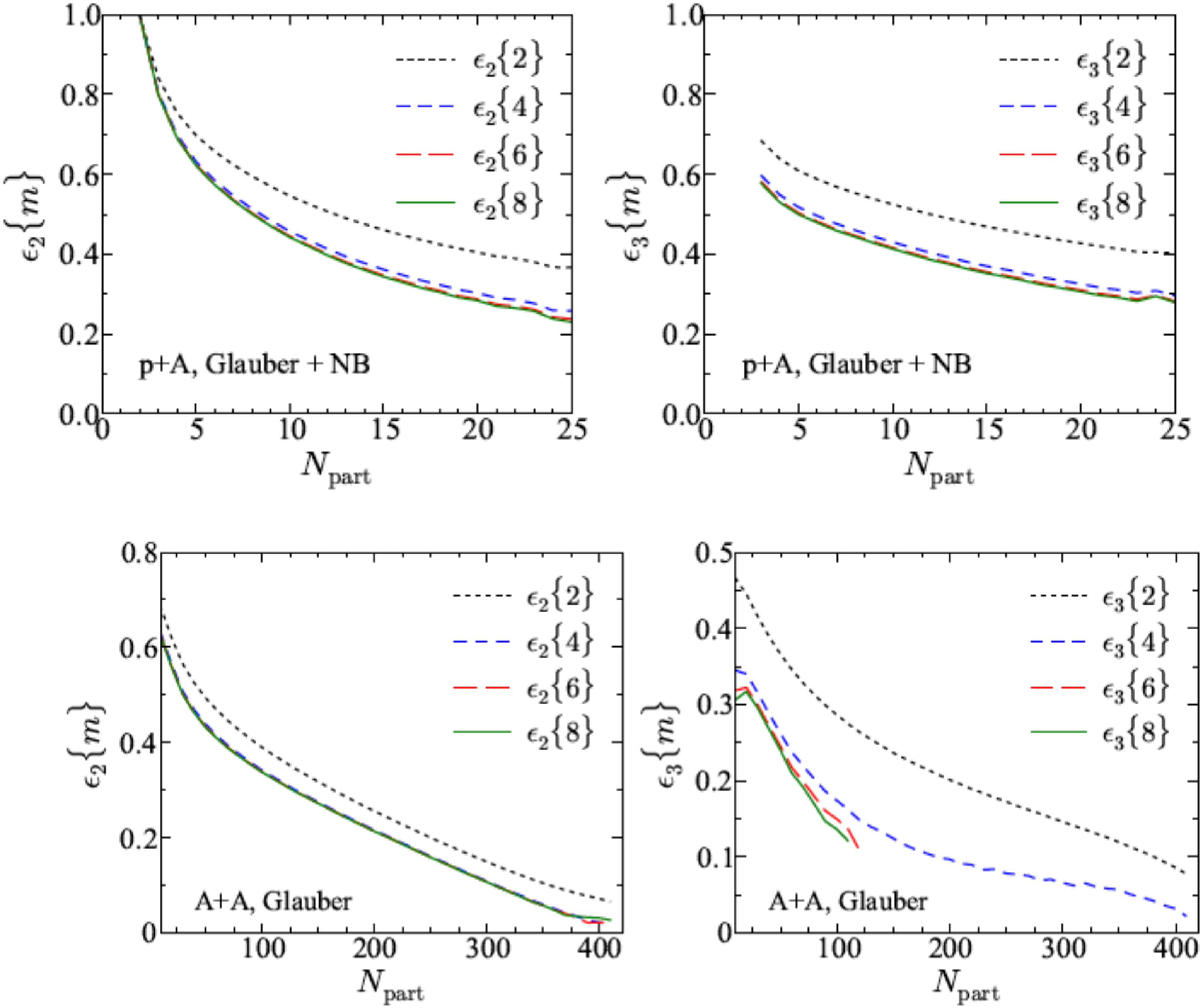


$$\epsilon_n\{2\} = \sqrt{|z_n|^2+\sigma_n^2}$$

$$\epsilon_n\{m\} = |z_n|,$$



Multi-particle flow follows ellipticity in a linear response dynamics:
Hydro, Classical radiation



$\epsilon_2\{2\}$
$\epsilon_2\{4\}$
$\epsilon_2\{6\}$
$\epsilon_2\{8\}$
$\epsilon_2\{m\}$
p+A, Glauber + NB
N_{part}
$\epsilon_3\{2\}$
$\epsilon_3\{4\}$
$\epsilon_3\{6\}$
$\epsilon_3\{8\}$
$\epsilon_3\{m\}$
p+A, Glauber + NB
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A+A, Glauber
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$\epsilon_3\{8\}$
$\epsilon_3\{m\}$
A+A, Glauber
N_{part}

The observed patterns seen in elliptic flow reflects the behaviour of initial eccentricity of the matter distribution. Hydrodynamics for small ellipticities gives v_n proportional to e_n. The patterns seen in ellipticity are then the same as those in flow.

There are a variety of ways to get linear response however. Classical radiation from a source will do this.
Molnar and Huang

In any case, whatever mechanism: There is collective motion of the produced fluid. Collective motions is not the same as hydrodynamics. A laser has collective motion of the produced photons, but it is not a hydrodynamical fluid of photons.

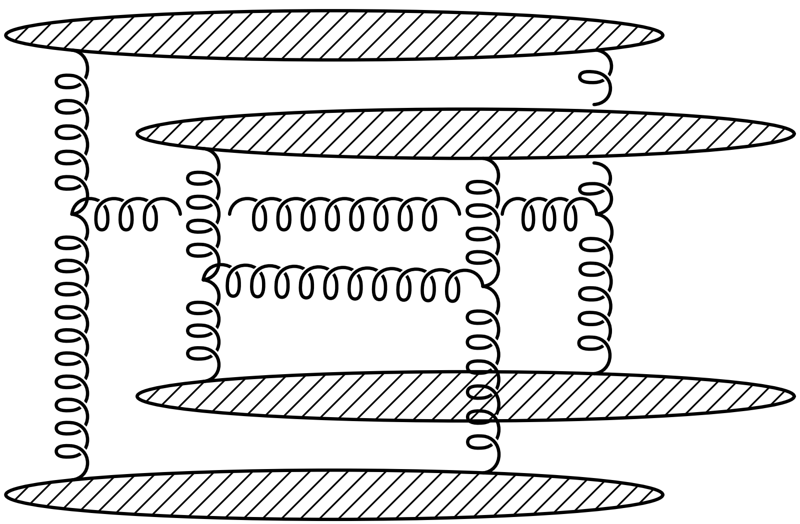
The collective motions is of GREAT INTEREST,
and we must understand it.

Initial State Interpretation: Why Is it attractive?

No evidence of jet media interaction in pA collisions, so why should hydro describe the high p_t particle?

At high p_T, theoretical considerations argue that hydro should not be important. Two particle correlations persist at multiple GeV scale.

Computations which describe flow patterns in AA collision fail to reproduce flow needed to explain correlations seen in pA collisions

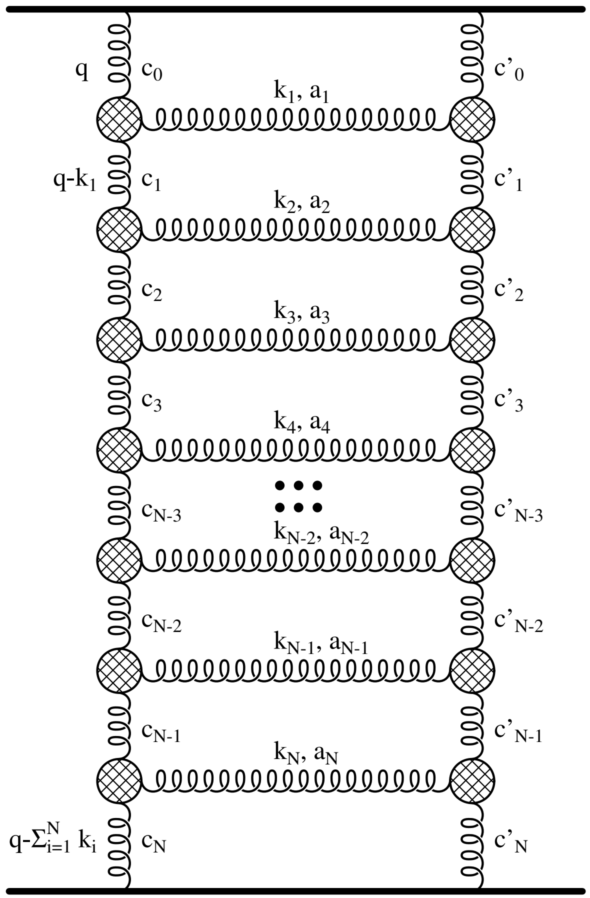


Dumitru, Gelis, McLerran, Venugopalan;
Dusling, Venugopalan

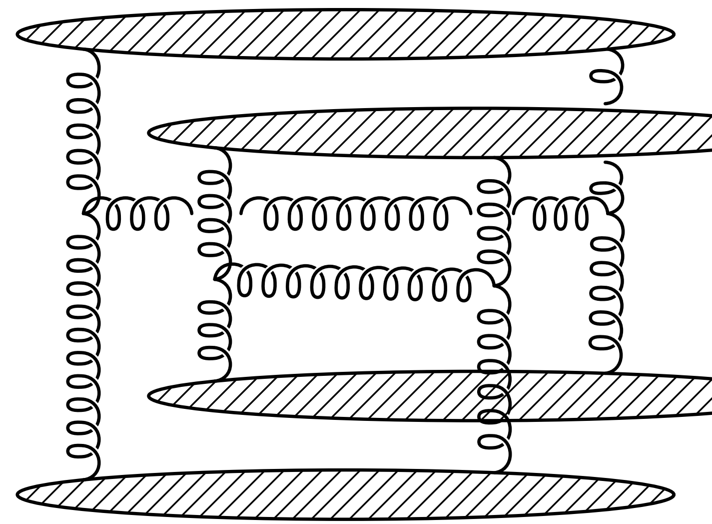
Intrinsic two particle correlation. Will generate v_2[2] and can describe pA and pp data

Odd moments? V_3, v_5?
Multiple particle moments v_2[4], v_2[6]?
Sign and magnitude of v_4[2}?

An example of collective behaviour in an elementary object: The Pomeron



Pomeron correlations are planar and leading order in Nc



Glasma correlations are non-leading in Nc

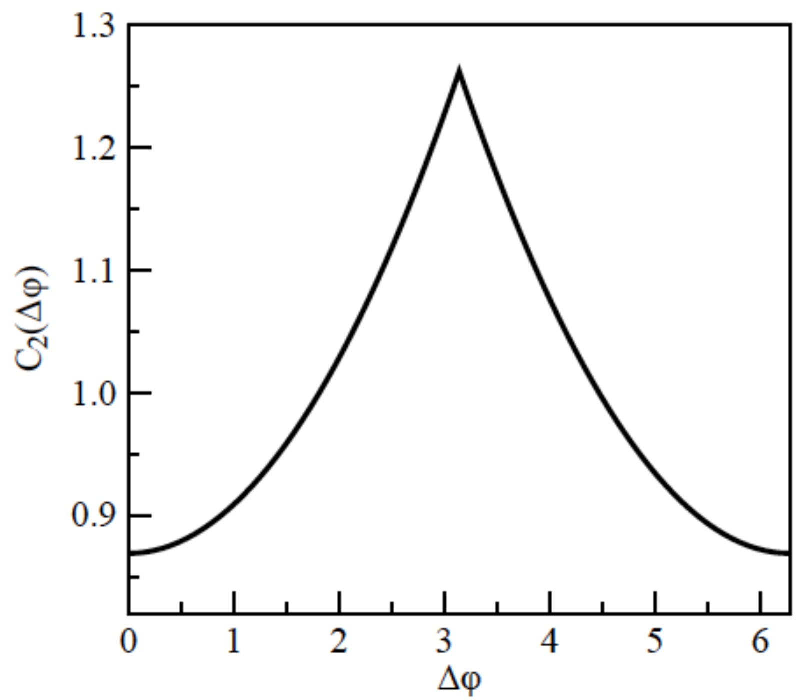
System	Pomeron graph	Glasma graph
Dense-Dense	1	$1/g^4$
Dilute-Dense	g^4	g^4
Dilute-Dilute	g^8	g^{12}

But different dependences on coupling

Multi gluon emission from a Pomeron is highly coherent:

Can compute V_n

$$
\begin{aligned}
v_2[2] &= 0.353553,\\
v_2[4] &= 0.404931,\\
v_2[6] &= 0.40857,\\
v_2[8] &= 0.408991,\\
v_2[10] &= 0.409049,\\
v_2[12] &= 0.409057.
\end{aligned}
$$



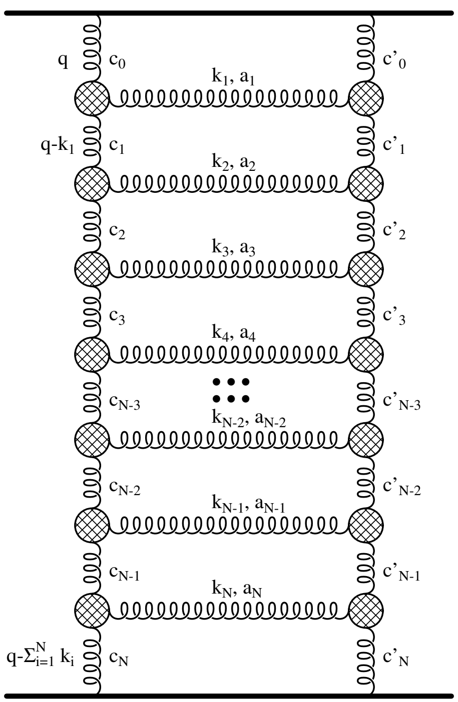
v_4, v_6 are like this but odd v_3, v_5 .. Are imaginary

Angular distribution of two particle correlation is backwards peaked, BUT uniform in rapidity. Momentum conservation would be expected to be peaked in rapidity in the backwards direction, not uniform.

Gyulassy, Biro, Levai and Vitev:
A calculus of correlations?

$$\frac{d^{3N}\sigma}{dy_1 d^2k_1 dy_2 d^2k_2 \cdots dy_N d^2k_N} = f \int d^2q_\perp \frac{1}{q_\perp^2+\mu^2} \frac{1}{\left(\vec{q}_\perp - \sum_{j=1}^{n} \vec{k}_{\perp j}\right)^2 + \mu^2} \prod_{i=1}^{N} \frac{1}{k_{\perp i}^2}$$

Imaginary part of ladder diagram is amplitude squared for multiple gluon bremstrahhlung.

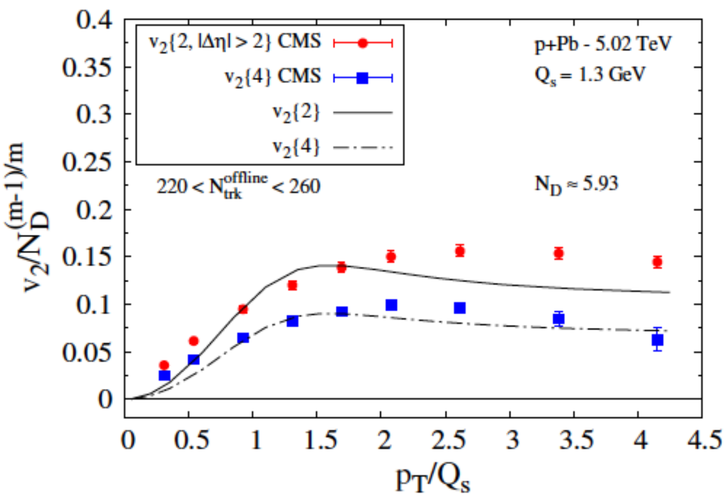


Correlation all the k_i's are correlated with q.

How can we get the q's correlated?

Ask Biro or Levai!

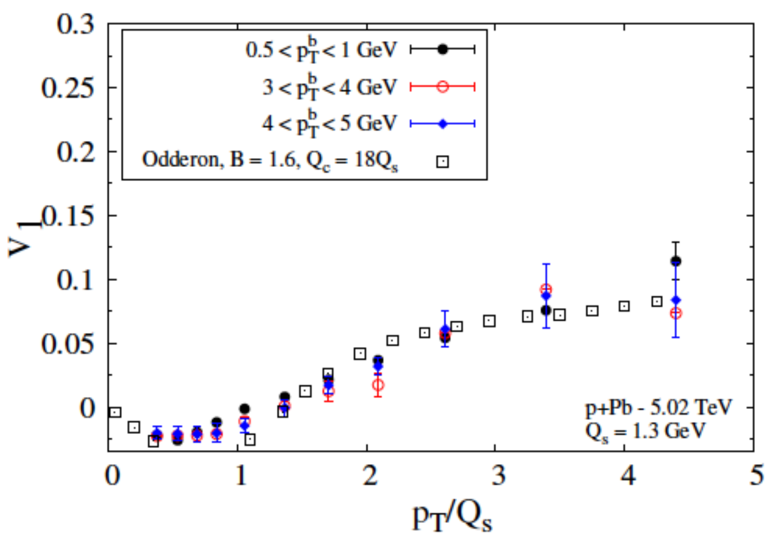
Dumitru and Giannini; Kovner and Lublinsky

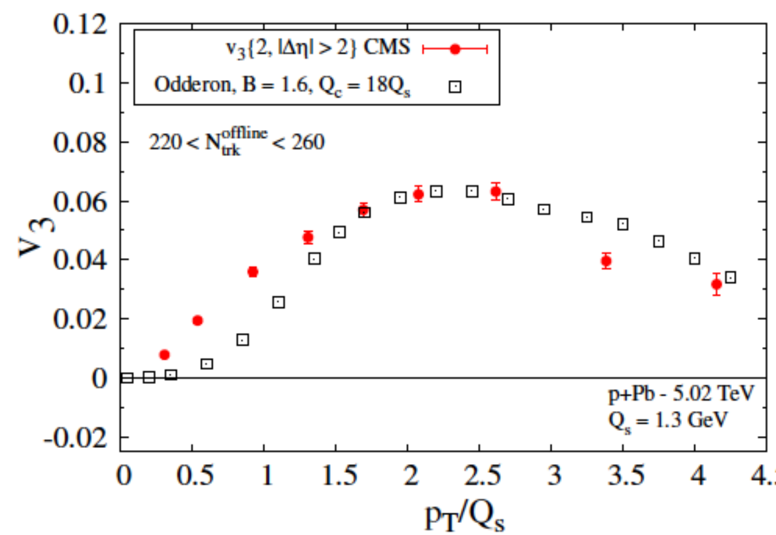


In pA collisions striking domains of electric field in nucleus which generates orientation of gluons. Get good behaviour for v_n[m] Note that always odd moments are hard to get from initial state effects. Possibly needs interferences with final state interactions?

Use dipole model: Even V_n from two gluon exchange and odd from three.

How to generate domain like structure in pA collisions?





In pp and pA, small system size means hydro probably has large viscous correction. Glasma treatment may not suffer from treating viscous effects as an approximation.

CGC+Glasma+Hydro

Estimate limits of validity of various approaches

Determine contribution of various stages of evolution to quantities such as the ridge and photon production

Probably biggest uncertainty will be edge effects and hadronization

Summary:

If we accept that there is saturation, then we must conclude that interactions among the constituents within a single hadron are strong, then for some time in a collision of two hadrons there must also be strong interactions among these constituents. Perhaps in some situations initial state or final state effect may be more important, but both are present and must play important roles.

The scientific issue is how do we properly understand, compute and probe these interactions.