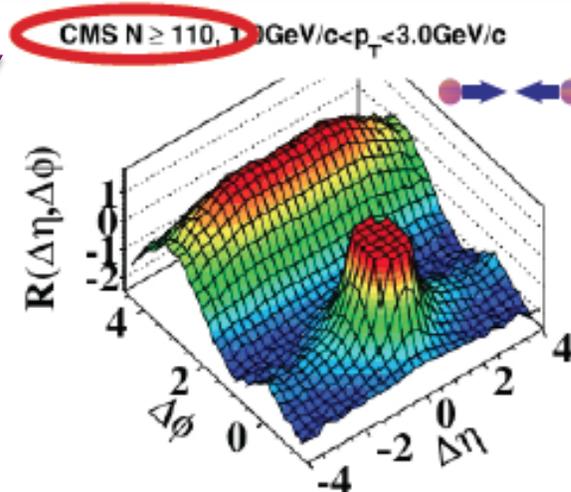
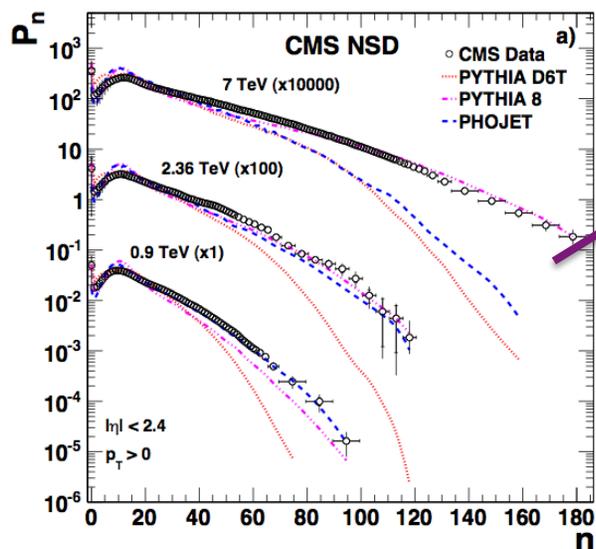


The ridge through colored glass

**Raju Venugopalan
Brookhaven National Laboratory**

Quark Matter 2014, Darmstadt

The ridge Tsunami

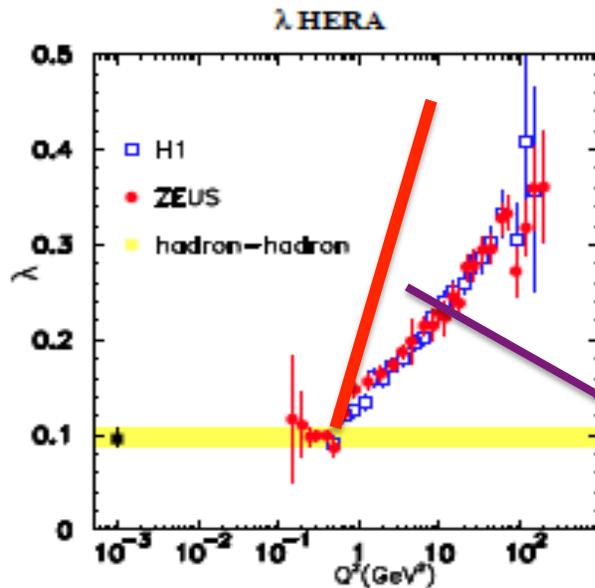
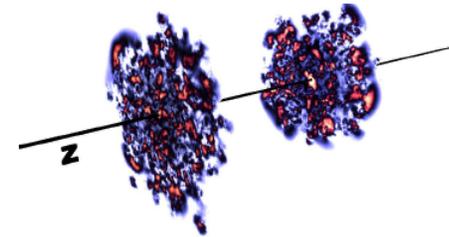


CMS Collaboration (Khachatryan, Vardan et al.)
JHEP 1009 (2010) 091 arXiv:1009.4122 [hep-ex]

- ◆ What is the underlying QCD mechanism of the ridge?
- ◆ How far can we extend the collective flow paradigm to small size systems – and do we see systematic deviations?
- ◆ Is there “spooky quantum mechanics” at work a la photon or spin entanglement ?
- ◆ Are hadronization patterns universal QCD physics or do they reflect thermal abundances ?

High multiplicities + small systems = gluon saturation

What does it take to produce ~ 150 hadrons per 5 units of rapidity in a single p+p event ?



For $\lambda=0.14$, get about 13 gluons produced in 5 units \sim min.bias hadron multiplicity

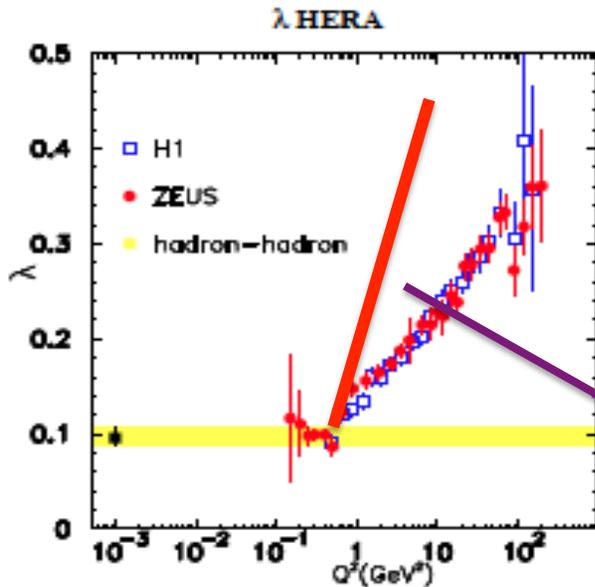
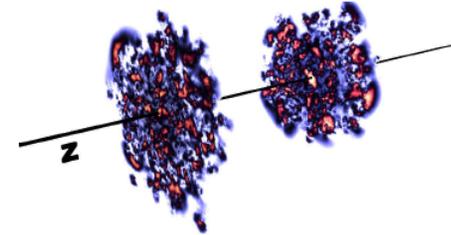
$\lambda=0.3$: ~ 45 gluons in 5 units,

$\lambda=0.4$: ~ 90 gluons in 5 units, in ball park...

Very rapid growth of gluon dist. in such events...

High multiplicities + small systems = gluon saturation

What does it take to produce ~ 150 hadrons per 5 units of rapidity in a single p+p event ?



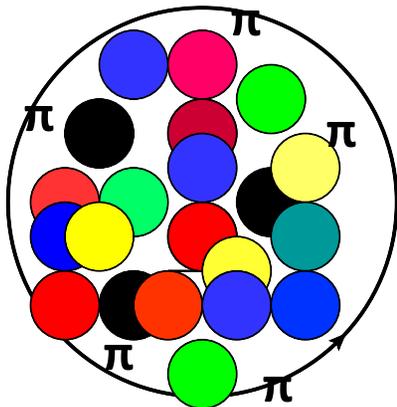
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Very rapid growth of gluon dist. In such events...

Saturation regulates this by adding increasingly "smaller" gluons of size $1/Q_s(x)$ with decreasing x (increasing energy)

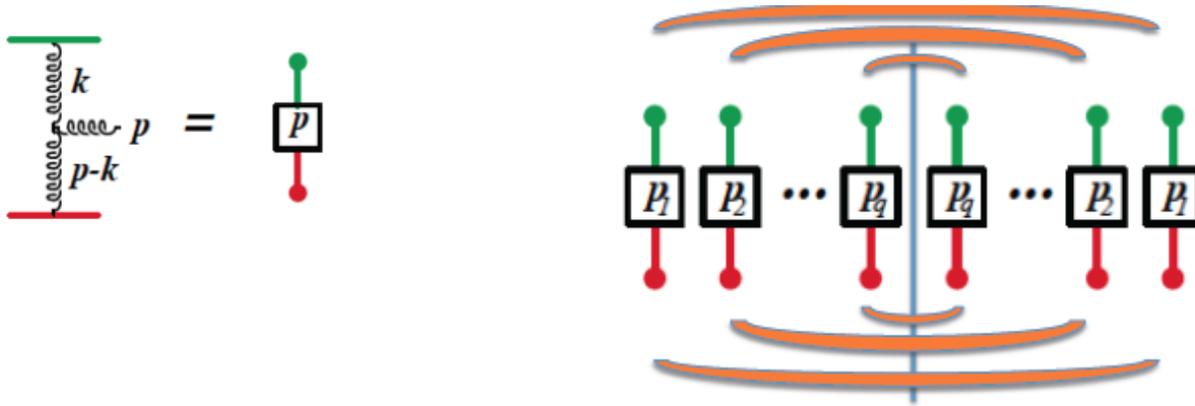


$$\frac{dN_g^{\text{prot.}}}{d\eta} \approx \frac{1.1C_F}{2\pi^2} \frac{S_{\perp} Q_{S,\text{prot.}}^2}{\alpha_S}$$

Lappi:
arXiv 0711.3039

$N_g \sim 100$ in 5 units for $Q_s^2 \sim 2 \text{ GeV}^2$: a semi-hard scale !

Multiparticle production: lasing gluons



Gelis, Lappi, McLerran,
arXiv:0905.3234

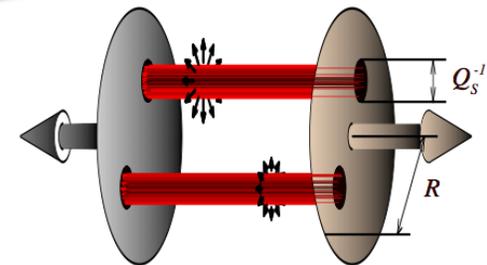
Multiparticle production in the Glasma naturally gives:
Long range rapidity correlations – **key input** into hydro

Negative Binomial Distributions (NBDs):

Output of model – no additional parameter unlike “Glauber”
Fluctuations related to shapes – also unlike Glauber.

$$P_n^{\text{NB}} = \frac{\Gamma(k+n)}{\Gamma(k)\Gamma(n+1)} \frac{\bar{n}^n k^k}{(\bar{n}+k)^{n+k}} \quad k = \kappa \frac{(N_c^2 - 1) Q_s^2 S_\perp}{2\pi}$$

k=1: Bose-Einstein dist.; k=∞: Poisson distribution

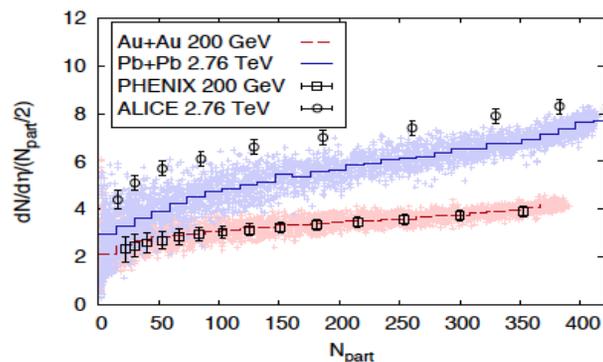
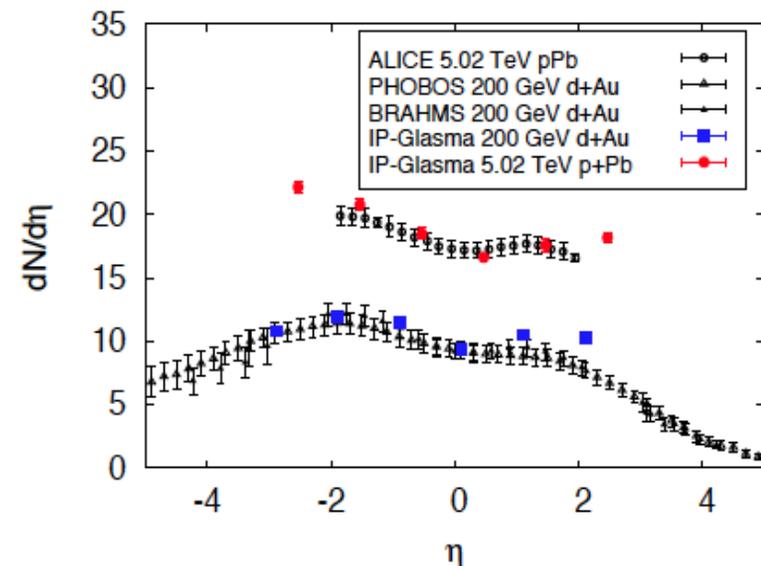
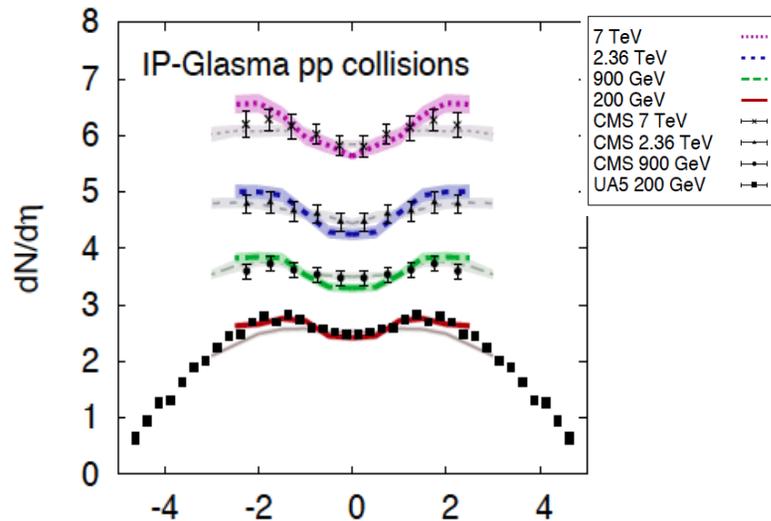


IP-Glasma model: single inclusive distributions

Schenke, Tribedy, Venugopalan, arXiv 1311.3636

These ideas for multi-particle production incorporated in the IP-Glasma model: **Yang-Mills dynamics** with stochastic color charge sources

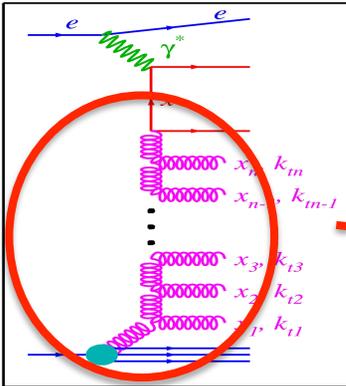
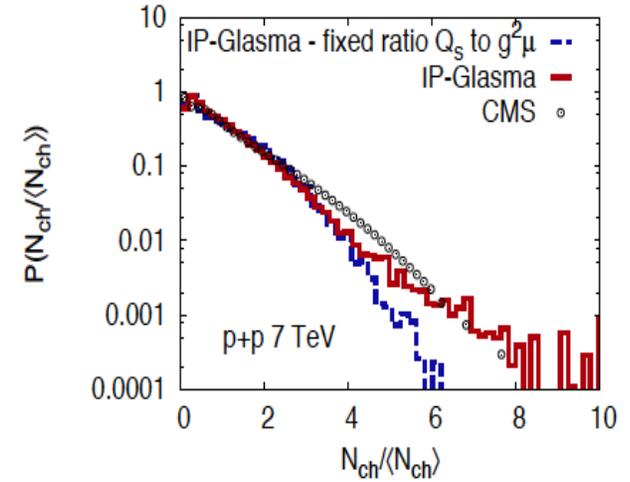
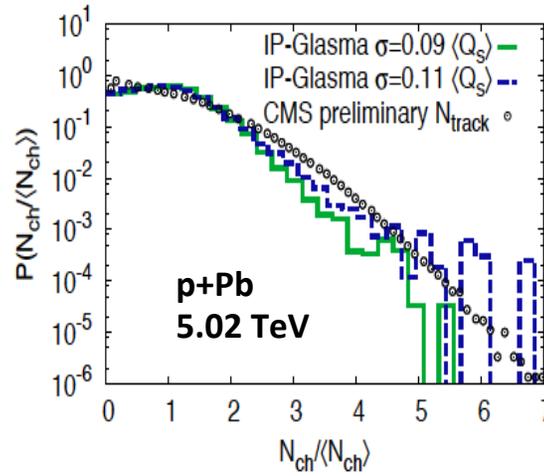
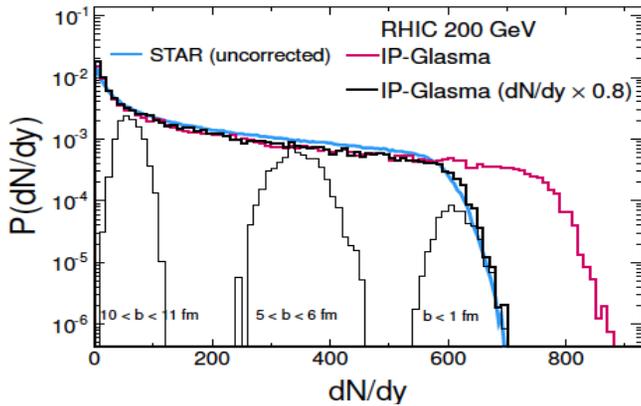
(see Tribedy talk this session and Schenke talk on Wednesday for further details)



15% (30 %) shortfall for large N_{part} (low N_{part}) possibly due to $\sim 70\%$ greater η/s at LHC

IP-Glasma model: multiplicity distributions

Schenke, Tribedy, Venugopalan, arXiv 1311.3636

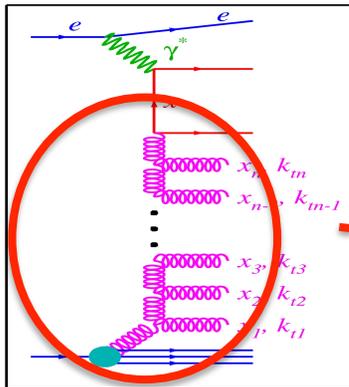
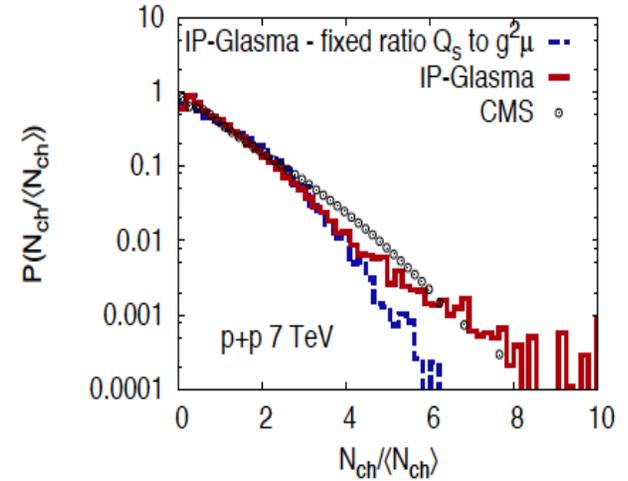
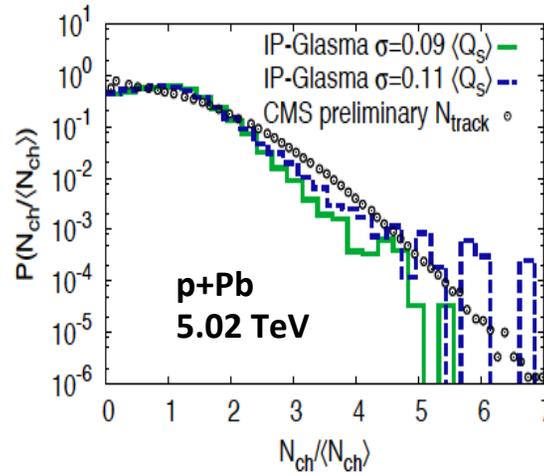
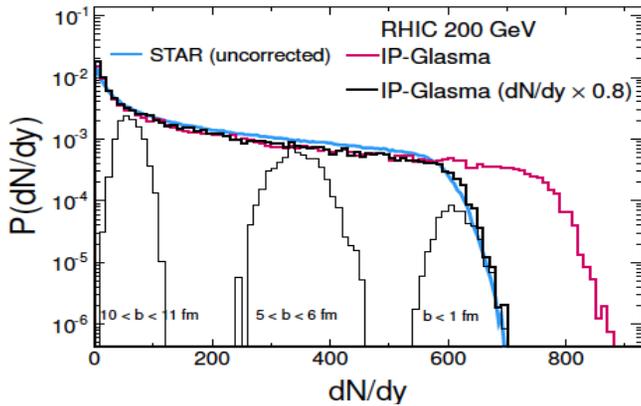


Color charge fluctuations: different color configurations for same gluon number

But gluon # in wave functions can fluctuate too. Required to explain tails of multiplicity distributions.

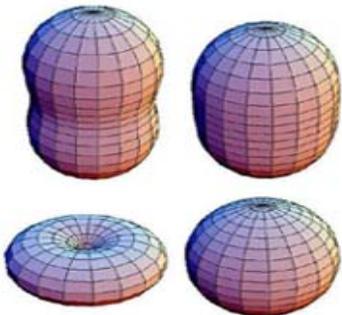
IP-Glasma model: multiplicity distributions

Schenke, Tribedy, Venugopalan, arXiv 1311.3636



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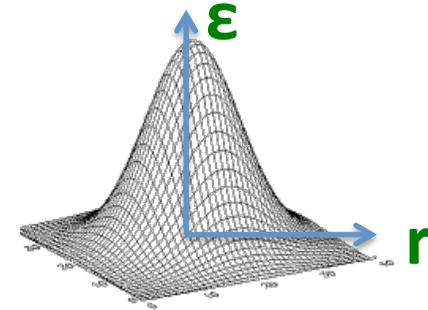
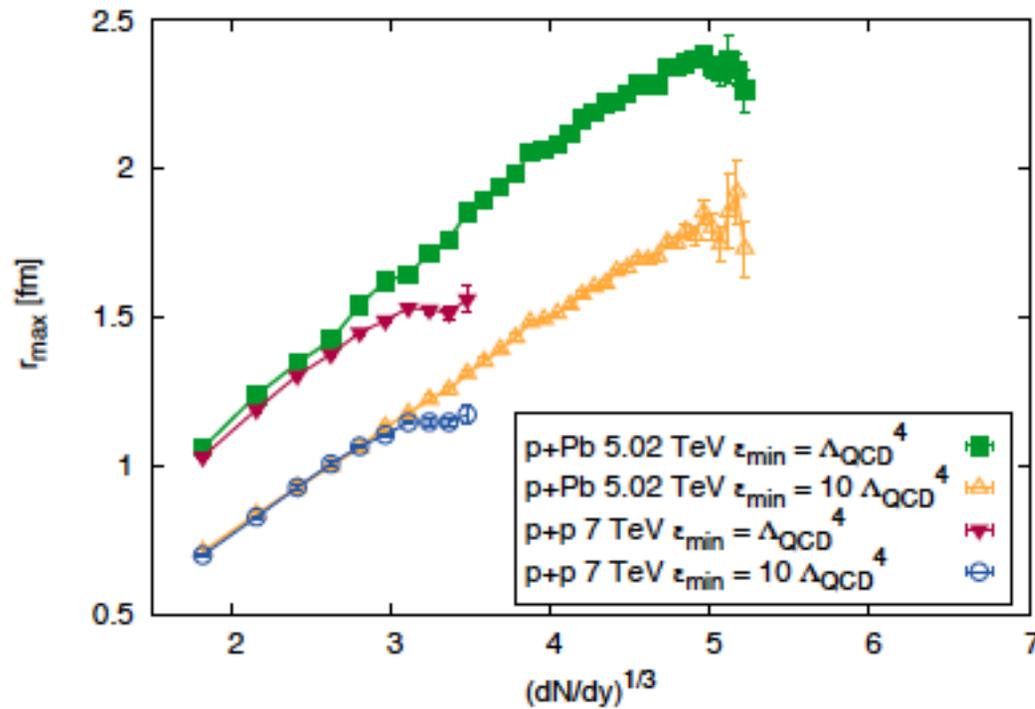
Large x quarks in proton can have “eccentric” shapes.

G. A. Miller, arXiv:0802.3731

Is this feasible for radiated gluons that pack the proton within constraints from confinement, causality & unitarity...?

IP-Glasma model: system size

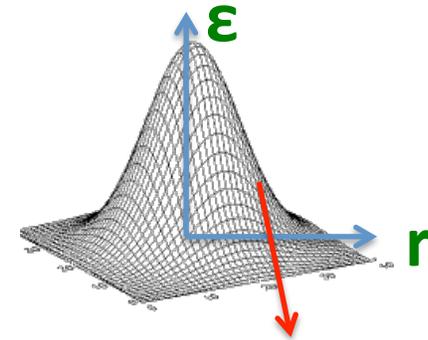
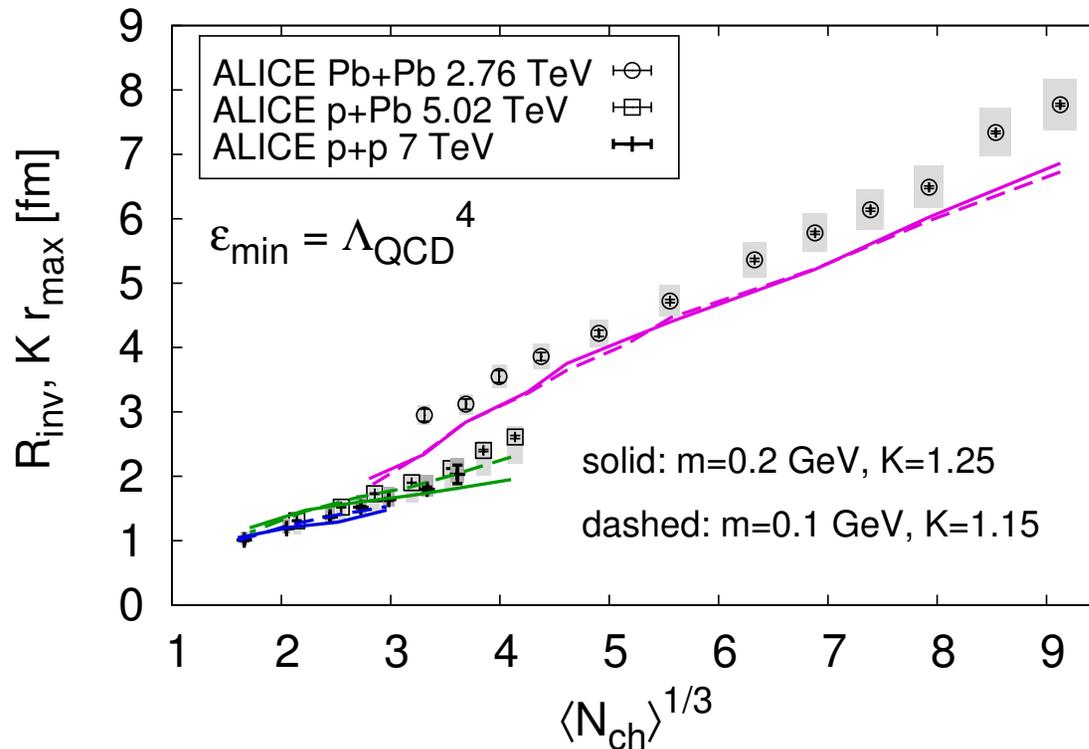
Bzdak, Schenke, Tribedy, Venugopalan, arXiv 1304.3403



System size in IP-Glasma nearly the same in p+p and p+Pb

IP-Glasma model: system size

Schenke, Venugopalan: 1405.3605



m regulates the tail of gluon distributions

Results for system size in the Glasma clearly leaves room for flow in Pb+Pb

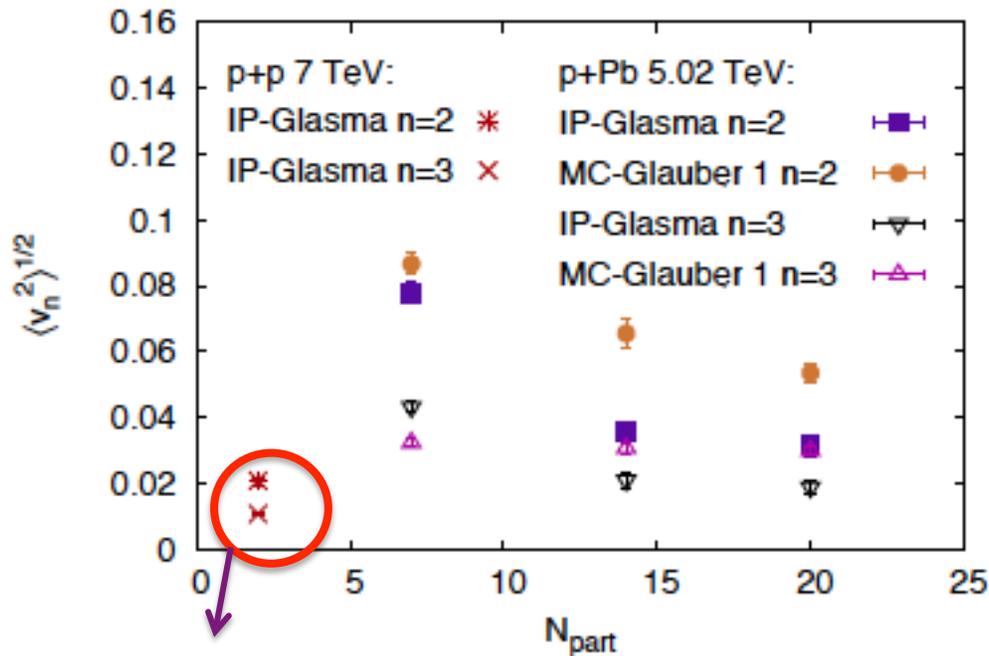
Flow not necessary in p+p to explain data up to quite rare $N_{ch} = 27$.

In p+Pb, whether there is room for flow in rare events

is sensitive to how the tail of the gluon distribution is regulated...

The ridge: flow in p+p and p+Pb ?

Bzdak,Schenke,Tribedy,Venugopalan: 1304.3403



p+p at b=0

IP-Glasma+ MUSIC (hydro) gives much less v_2 than Glauber models that have significantly larger spatial sizes and shapes

Bozek,Torrieri,Broniowski, arXiv: 1307.5060

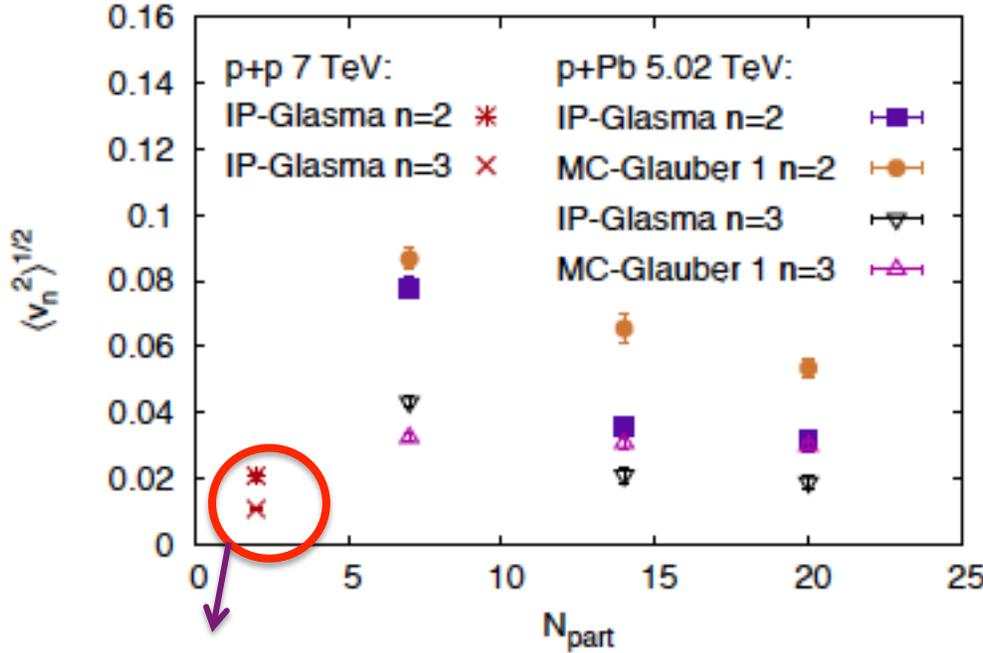
Kozlov,Luzum,Denicol,Jeon,Gale, arXiv:1405.3976

EPOS: non-Glauber approach with aspects similar to IP-Glasma

Werner,Bleicher,Guiot,Karpenko,Pierog, arXiv:1312.1233

The ridge: flow in p+p and p+Pb ?

Bzdak,Schenke,Tribedy,Venugopalan: 1304.3403



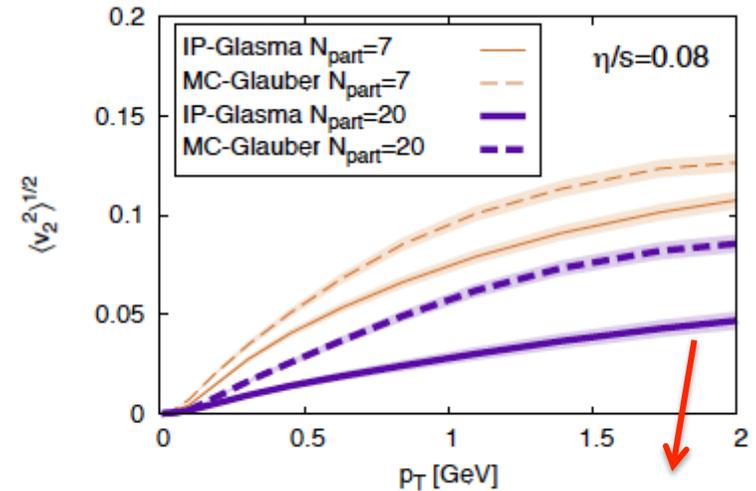
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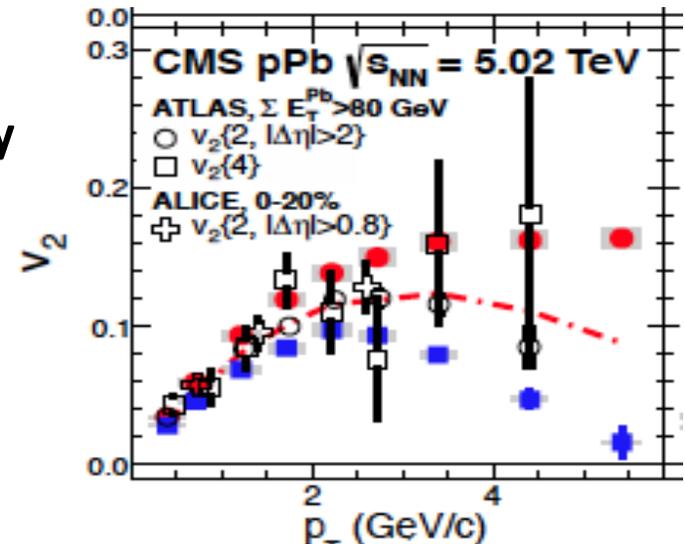
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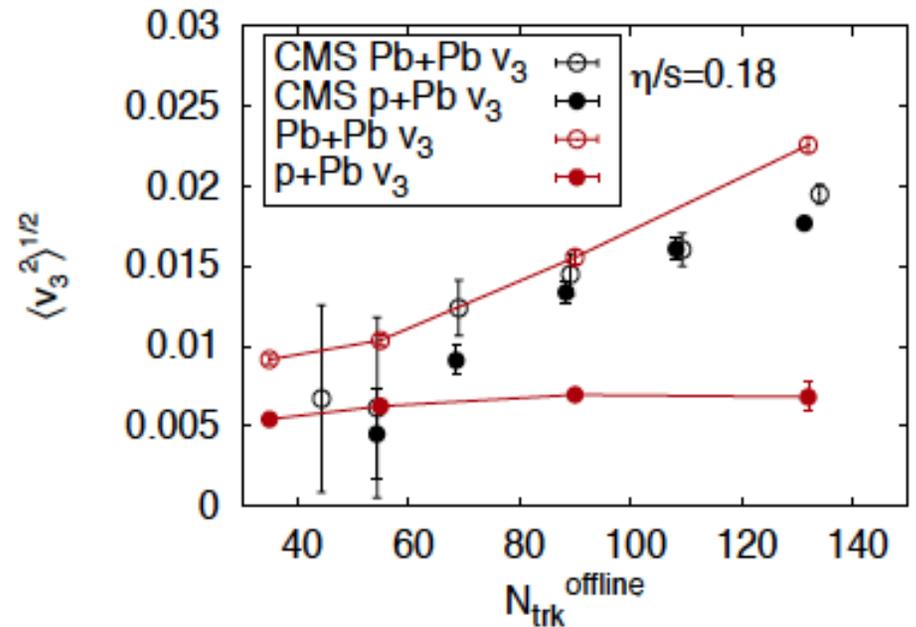
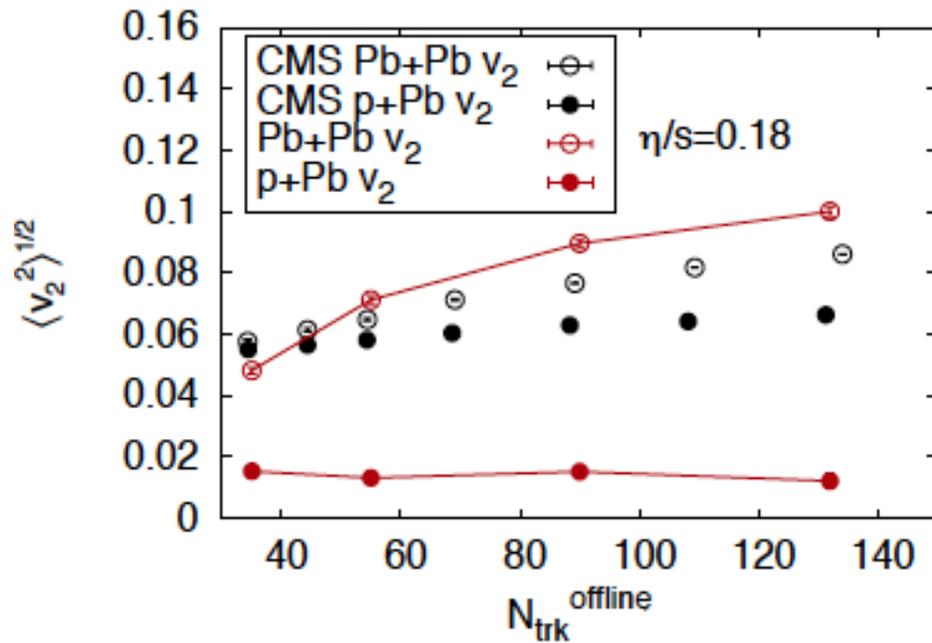


IP-Glasma more than a factor 2 < data for $\eta/s = 0.08$



The ridge: flow in p+Pb?

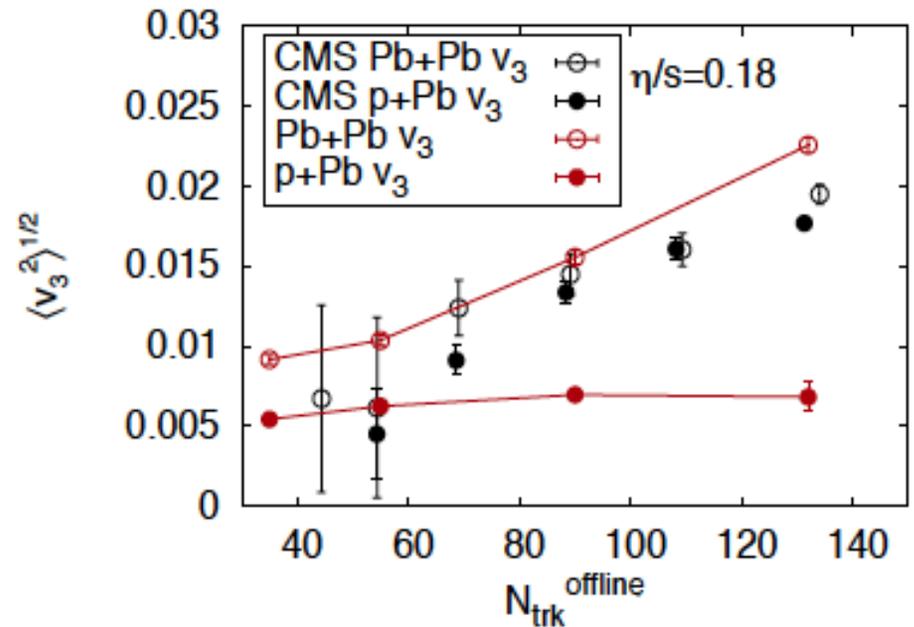
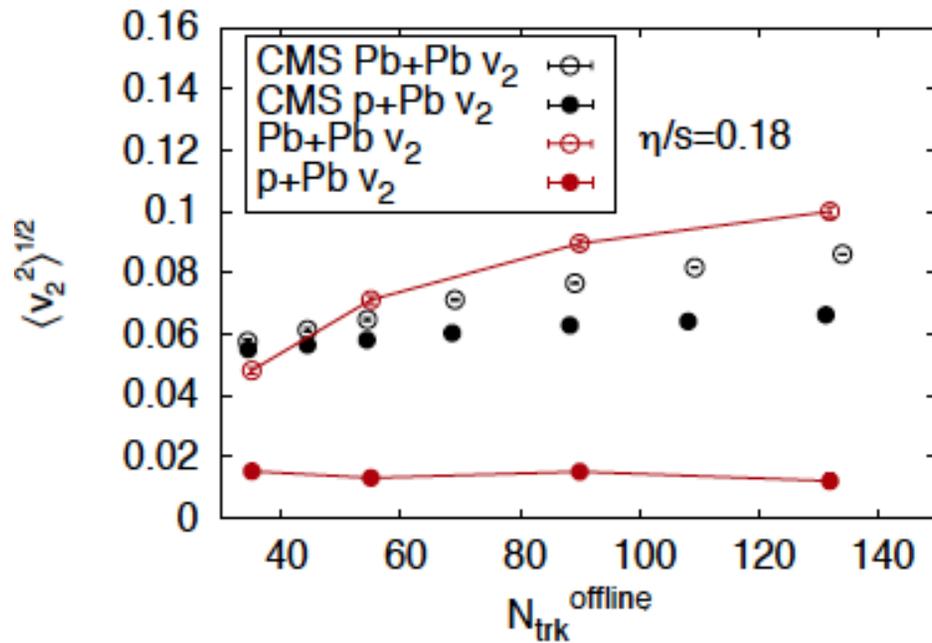
Schenke and Venugopalan, arXiv:1405.3605



In contrast to A+A, both shape and magnitude of **IP-Glasma+MUSIC p+Pb results completely off from data**

The ridge: flow in p+Pb?

Schenke and Venugopalan, arXiv:1405.3605



In contrast to A+A, both shape and magnitude of **IP-Glasma+MUSIC p+Pb results completely off from data**

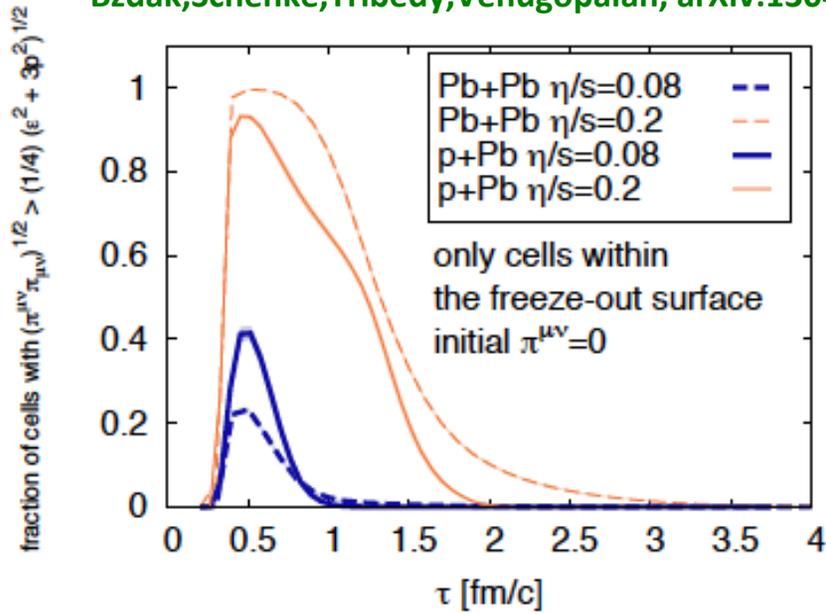
Maybe shapes are treated incorrectly in IP-Glasma? Note they seem off even for multiplicities where the IP-Glasma multiplicity distribution agrees with the data...

Alternative: hydro shouldn't work for small size systems?

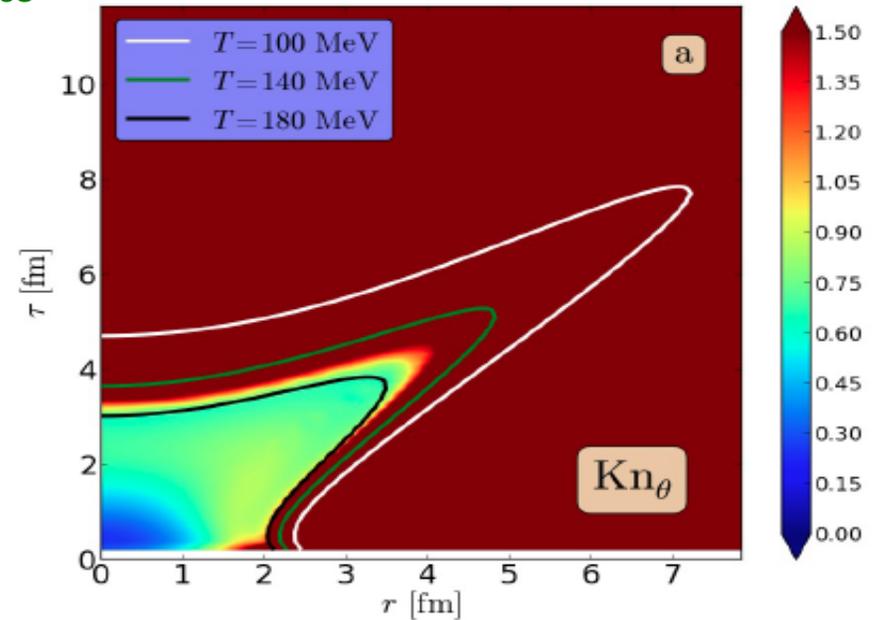
Hydro in small size systems: sensible or not ?

Two frequently used measures: Reynolds # and Knudsen #

Bzdak, Schenke, Tribedy, Venugopalan, arXiv:1304.3403



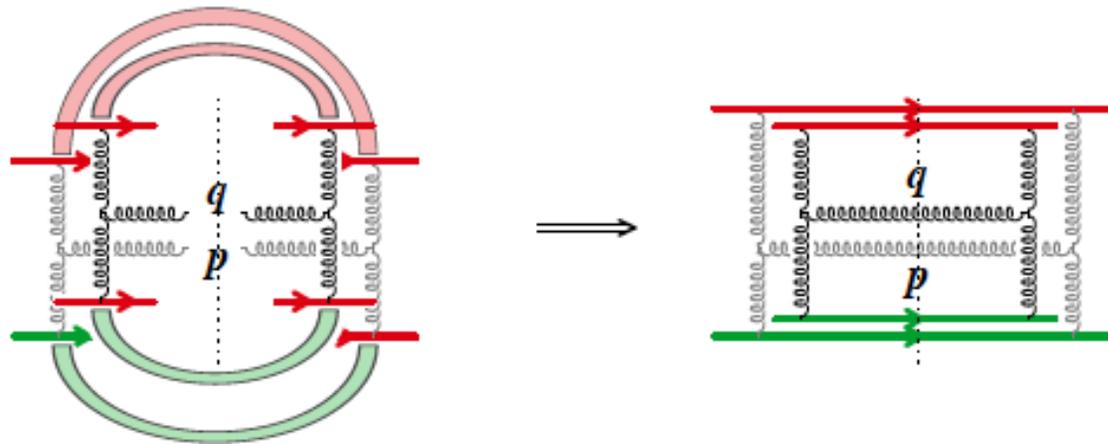
Denicol, Niemi, arXiv:1404.7327



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

The ridge: initial state gluon correlations

Dumitru, Gelis, McLerran, Venugopalan, arXiv:0804.3858

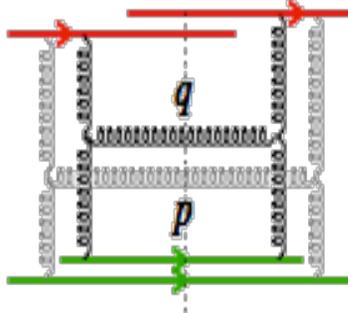
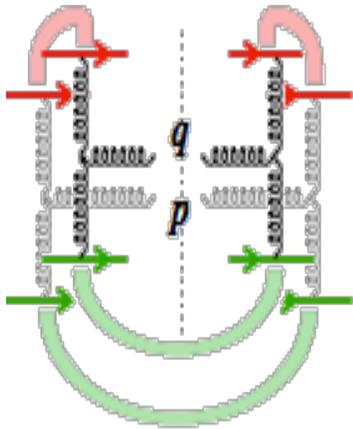


In the Glasma framework, the dominant long range rapidity contribution is uncollimated in $\Delta\phi$

It's this contribution that generates the energy density/multiplicity in the IP-Glasma

Initial state gluon correlations: the ridge

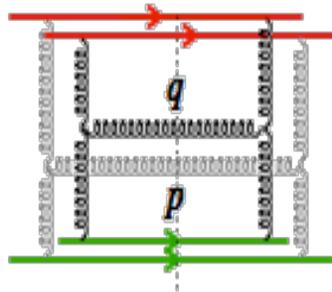
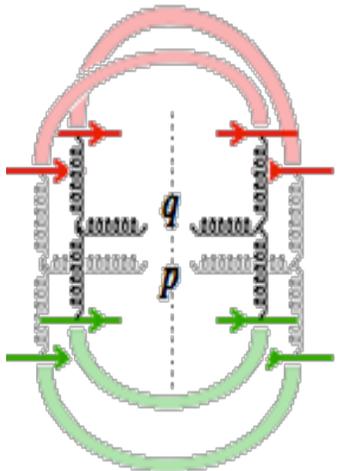
Dumitru,Dusling,Gelis,Jalilian-Marian,Lappi,Venugopalan, arXiv:1009.5295
Dusling,Venugopalan, arXiv:1201.2658



In the same framework there exist correlations that generate a quadrupole anisotropy in $\Delta\phi$

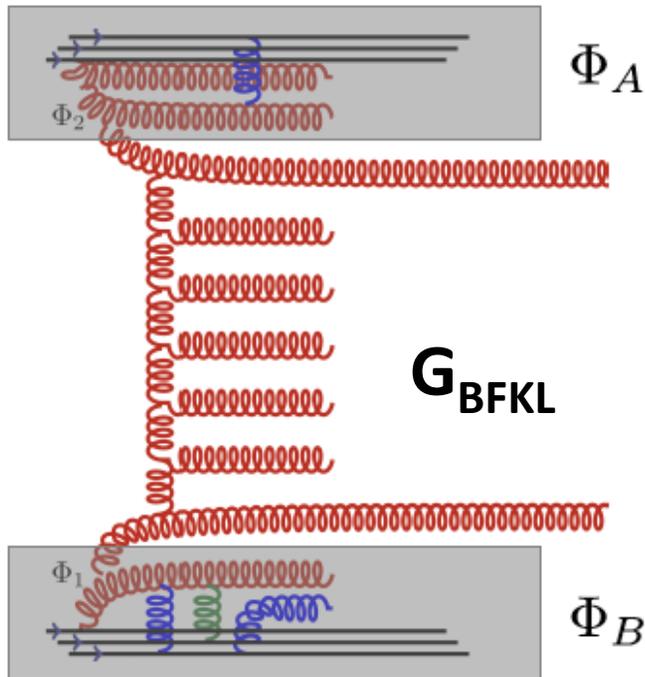
These are analogous yet distinct from HBT-like correlations

Suppressed by powers and α_s and N_C for $Q_S \ll p_T$ and large b



They are hugely enhanced α_s^{-8} for $Q_S \sim p_T$ and $b \sim 0$

Initial state correlations: mini-jets



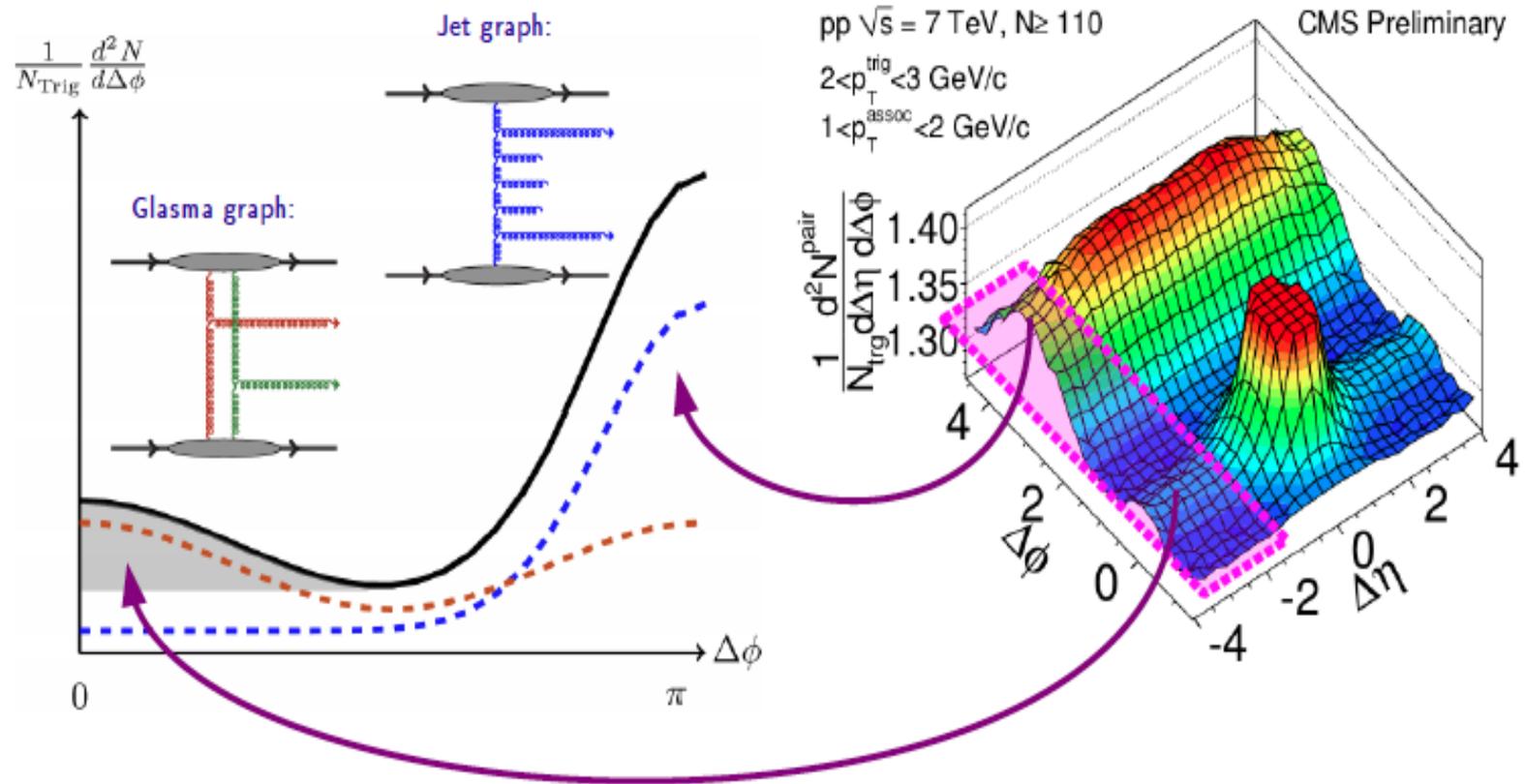
Mini-jets are also enhanced in high multiplicity events

The width of the away-side ridge is sensitive to the antenna pattern of emission –whether BFKL or DGLAP

If gluons produced via the “Glasma graphs” strongly rescatter, so should the mini-jets

As in heavy ion collisions, strong modification of away-side jets would be a strong indicator of flow

Initial state collimation from jet+Glasma



Quantitative modeling of these initial state correlations gives good description of p+p high multiplicity correlation data and features of p+A correlation data

(Next talk by Kevin Dusling)

Dusling, Venugopalan, arXiv:1210.3701,
arXiv:1211.3701, arXiv:1302.7018

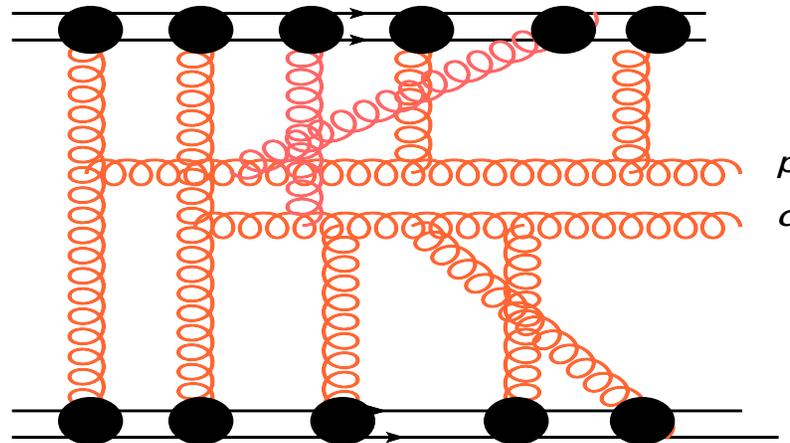
Initial state correlations: open questions

v_3 not generated by Glasma+jet contributions – possible explanation is from the interference between the two (**Dusling talk**)

$$2\text{Re} \left\{ \left[\text{Feynman diagram 1} \right] \times \left[\text{Feynman diagram 2} \right]^* \right\}$$

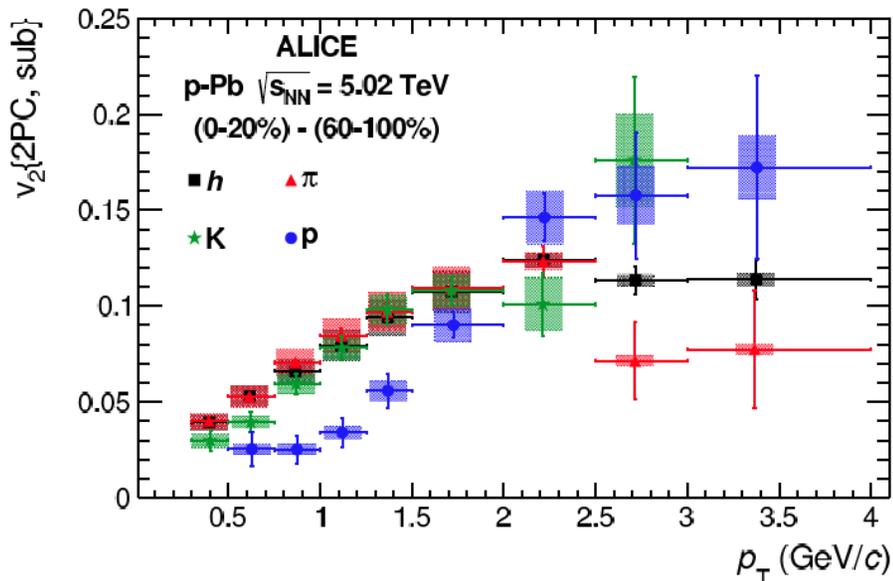
$v_2\{4\}$, $v_2\{6\}$, etc. while feasible in model, not known at present

How do rescattering contributions modify these initial state correlations ?



Schenke, Venugopalan, in progress

Mass ordering: prima facie evidence of flow ?



Striking mass splitting seen in the long range correlation data

Very similar to that seen in heavy ion collisions where flow gives a good description

Seen in hydro simulations

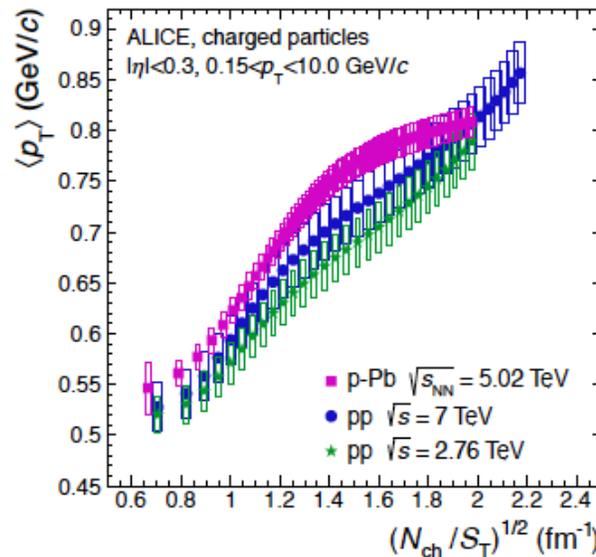
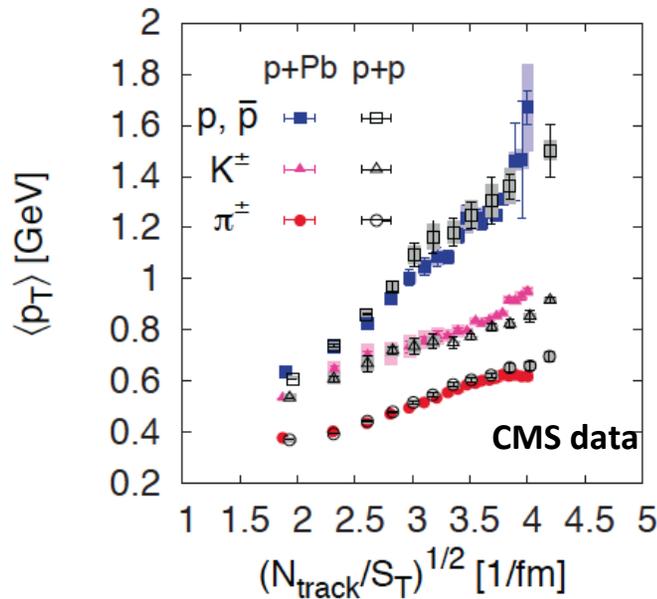
Bozek, Broniowski, Torrieri
Werner et al.

The initial state picture here is of correlations of gluons – and does not include hadronization.

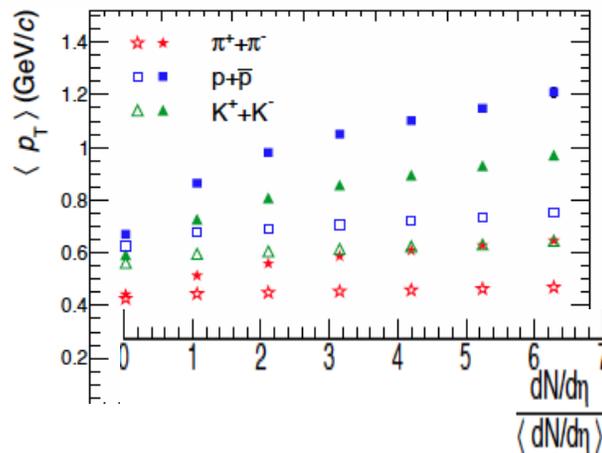
To describe this pattern, would need such patterns to be universal-- not generated exclusively by flow

Mass ordering: prima facie evidence of flow ?

Mass ordering patterns however described in a geometrical scaling picture



McLerran, Praszalowicz, Schenke, arXiv:1306.2350



Other geometrical scaling scenarios:
 Basar, Teaney, arXiv:1312.6770
 Andres et al., arXiv:1405.2177

PYTHIA with color reconnections (no rescattering) can reproduce flow like patterns

Ortiz et al., arXiv:1303.6326



Summary



- ◆ Very high multiplicity events in small size systems require a semi-hard scale Q_s
- ◆ Multi-particle production well described in the IP-Glasma framework.
- ◆ In A+A collisions, Yang-Mills dynamics+hydro (IPGlasma-MUSIC model) provides an excellent description of the data
- ◆ In p+A and p+p, IP-Glasma+MUSIC consistent with N_{ch} dependence of HBT radius
However, v_2 and v_3 in complete disagreement with the data
- ◆ Initial state long range correlations explain some of the systematics of measured collimated yields in p+p and p+Pb. However, features of the data such as mass ordering are not understood.

See talks by Dusling, Tribedy and Schenke for further detailed discussion of these issues

