Initial State Effects and Azimuthal Correlations in Small Systems

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Physical Review Letters
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Contents

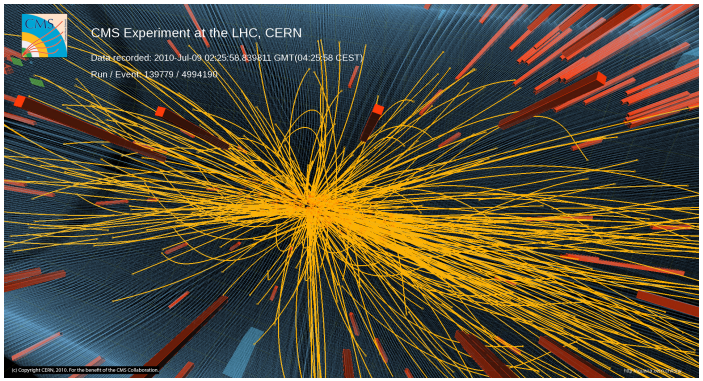
1. A review of the ridge
   from (connected) glasma graphs
   at high p_T (i.e. $> 1 - 2$ GeV --- *hard* ridge)

2. $\cos(3\phi)$ in the *hard* & *soft* ridge

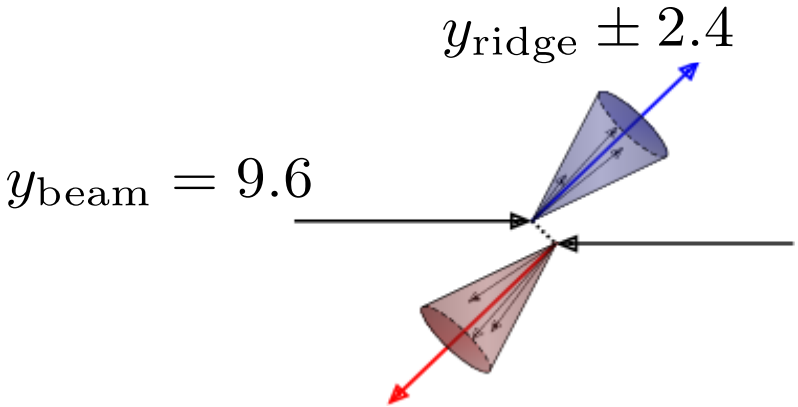
3. collectivity in the *soft* ridge

Initial State Effects and Azimuthal Correlations in Small (*high multiplicity*) Systems

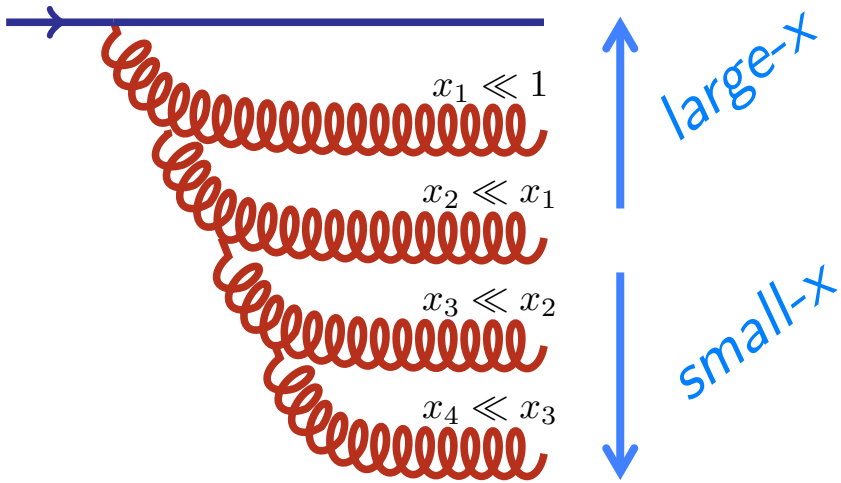
1. We are interested in rare, fluctuation driven events producing over 100 charged particles



2. There is *at least* 6 units of rapidity between beam and produced gluons



Many-body high energy QCD: The Color Glass Condensate (CGC)

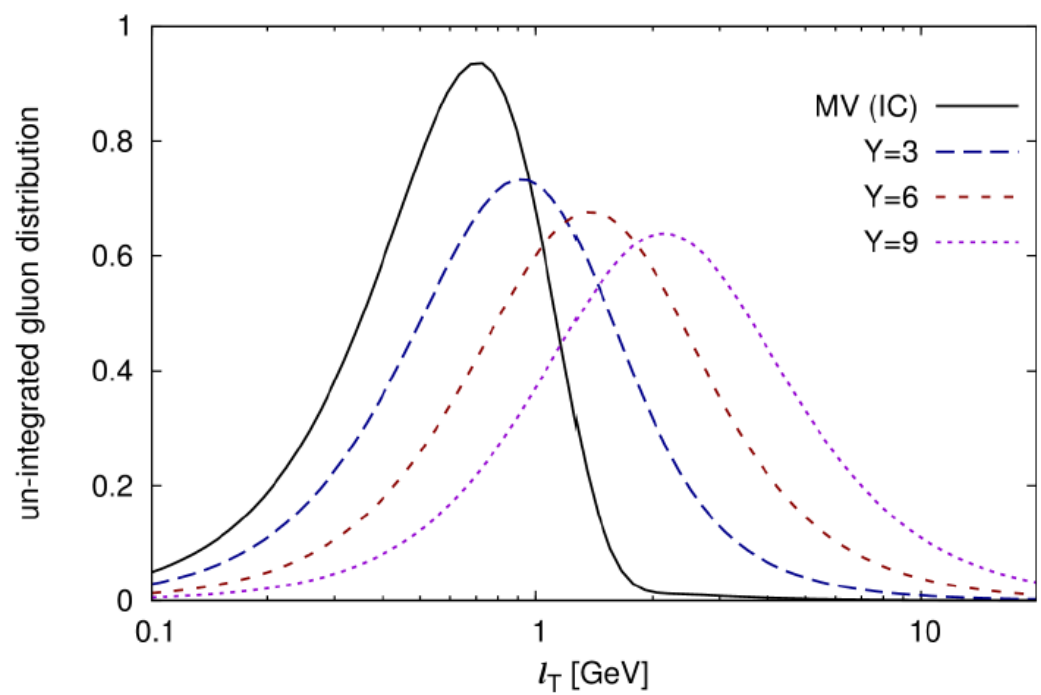


Observables must be independent from how the large-x and small-x degrees of freedom are separated:
Functional Renormalization Group equation

(JIMWLK - Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner).

$$\langle \mathcal{O} \rangle_Y = \int [d\rho]\, W_Y[\rho]\, \mathcal{O}[\rho]$$

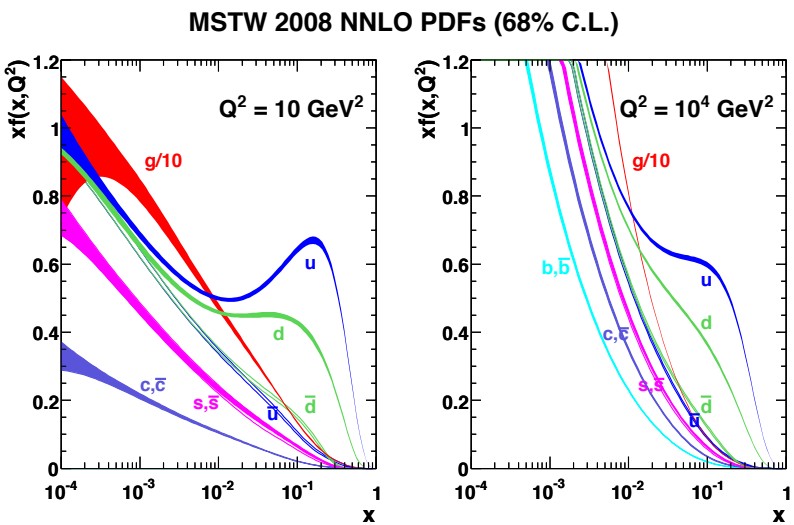
$$\frac{\partial W_Y[\rho]}{\partial Y} = \mathcal{H}[\rho]\, W_Y[\rho]$$

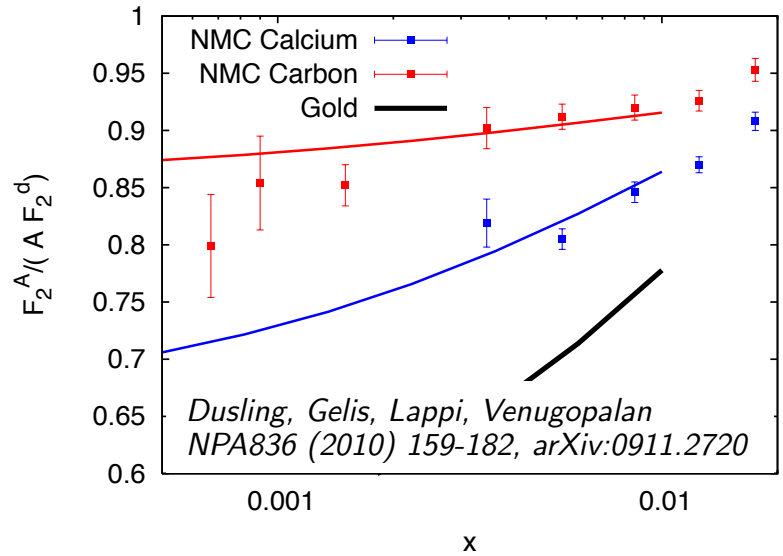


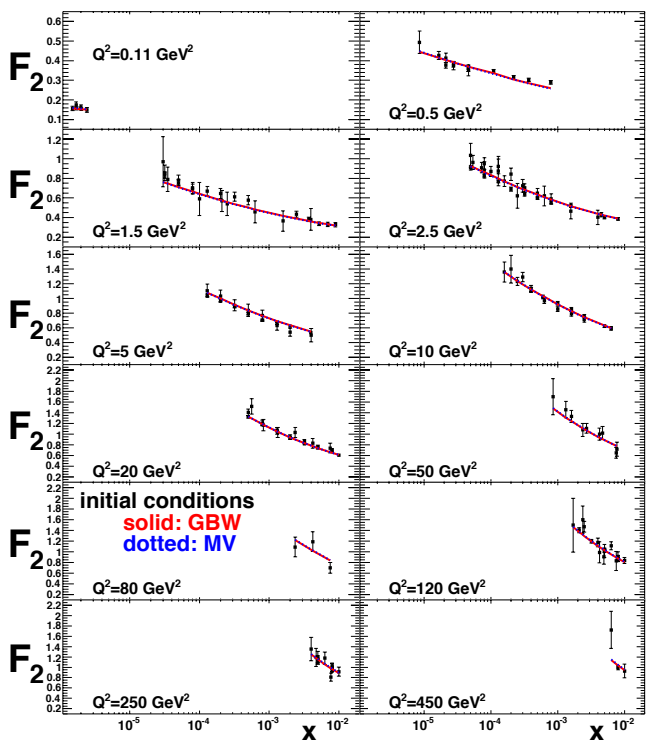
For reviews see:
McLerran, Lect. Notes Phys.583:291-334 (2002), arXiv:hep-ph/0104285

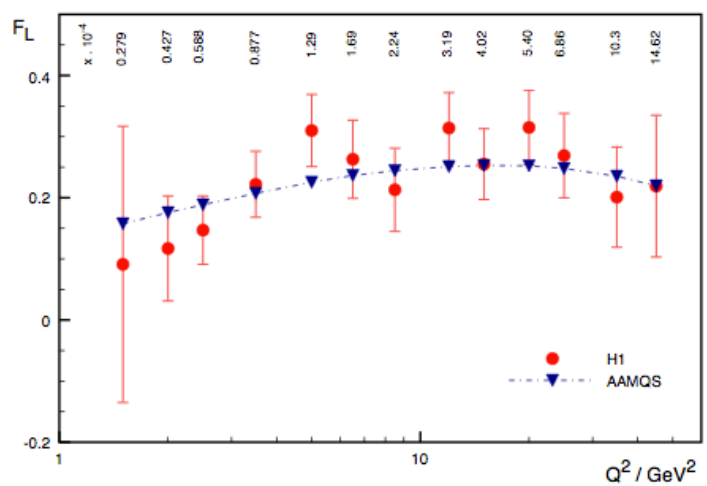
Gelis, Iancu, Jalilian-Marian, Venugopalan: Ann. Rev. Nucl. Part. Sci. (2010), arXiv: 1002.0333

There's a wealth of information on the proton wavefunction



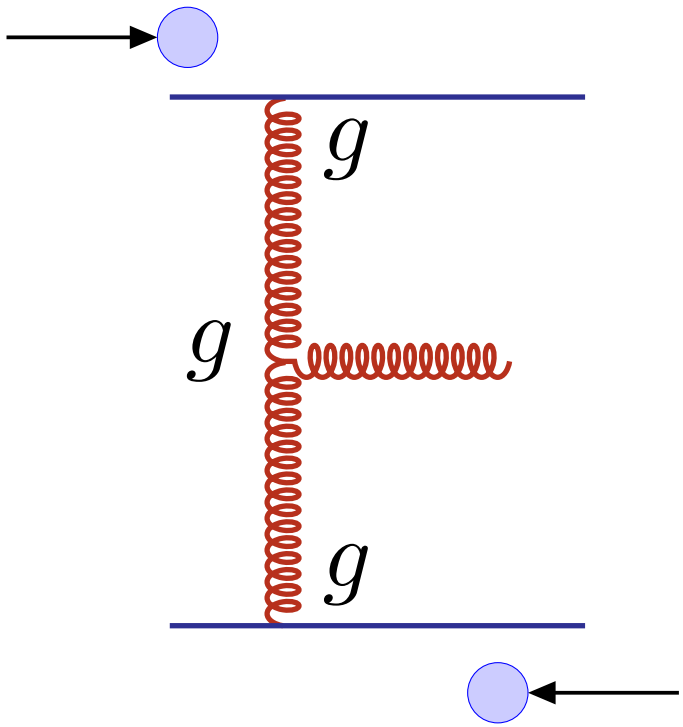




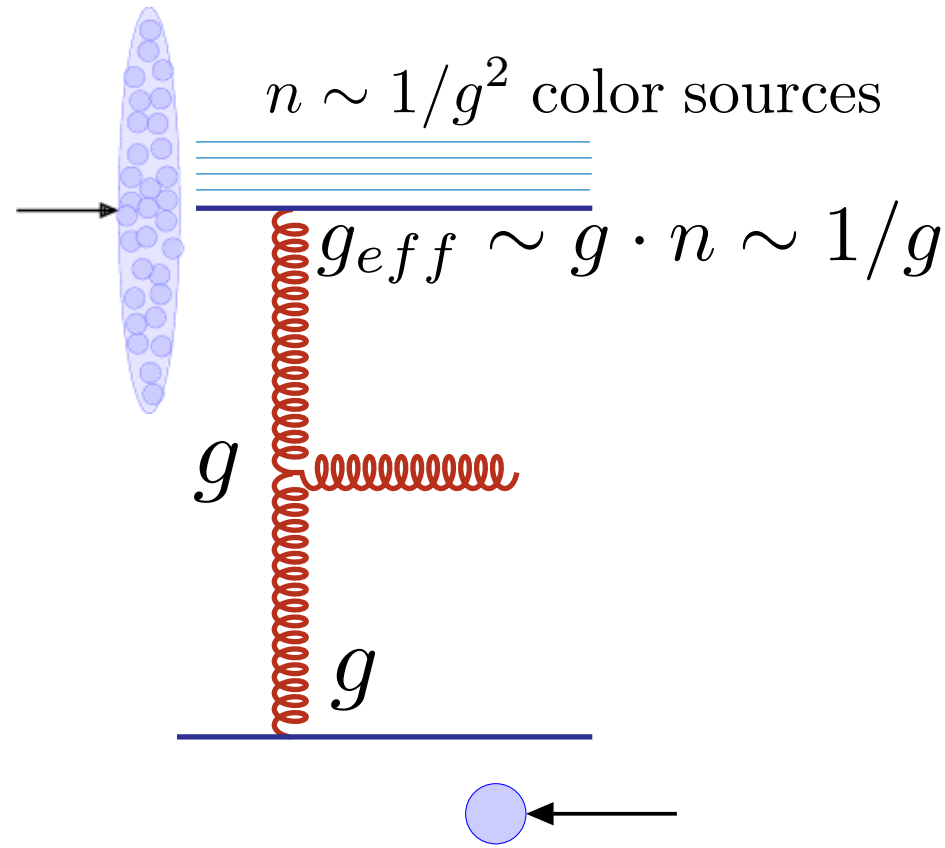


Albacete, Milhano, Quiroga-Arias ,Rojo
arXiv:1203.1043 (2012).
Quiroga-Arias, Albacete, Armesto, Milhano, Salgado
J.Phys.G G38 (2011) 124124.
Albacete, Armesto, Milhano, Salgado
PRD80 (2009) 034031.

Power counting in p+A



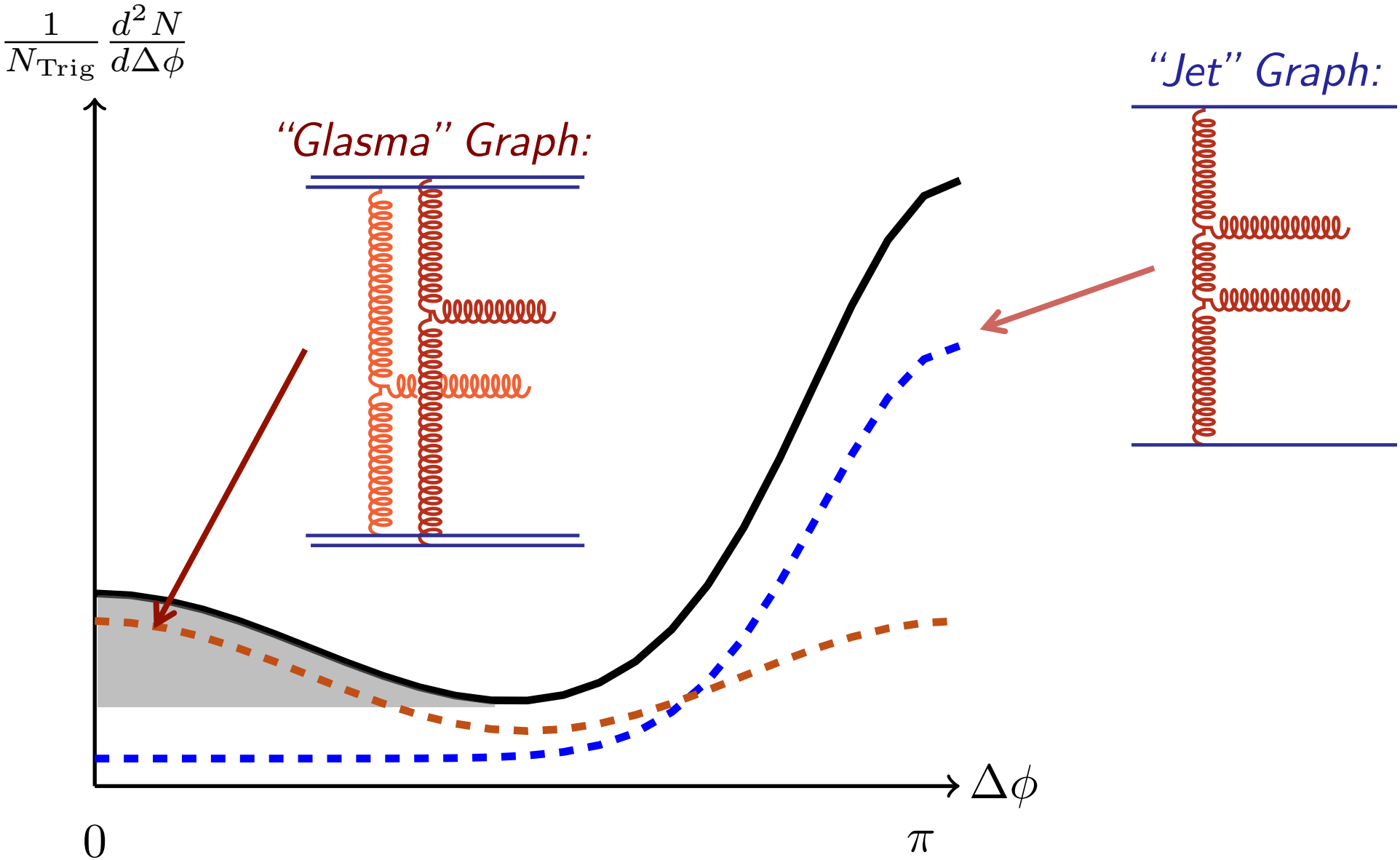
$$\mathcal{O}\left(\alpha_s^3\right)$$



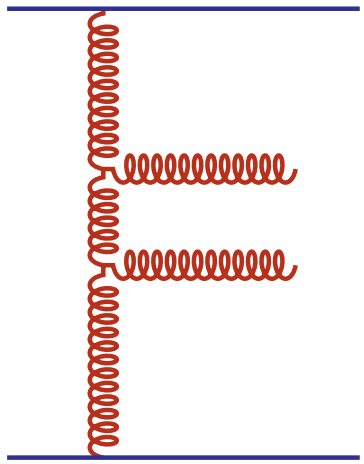
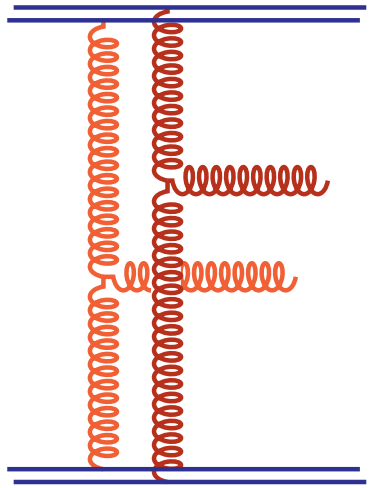
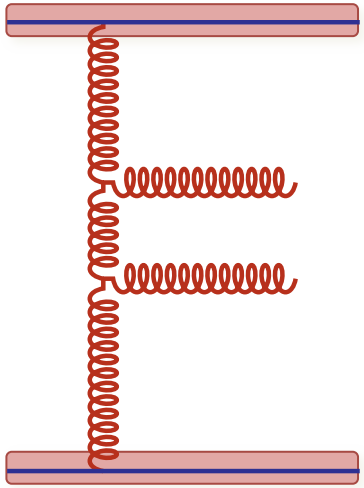
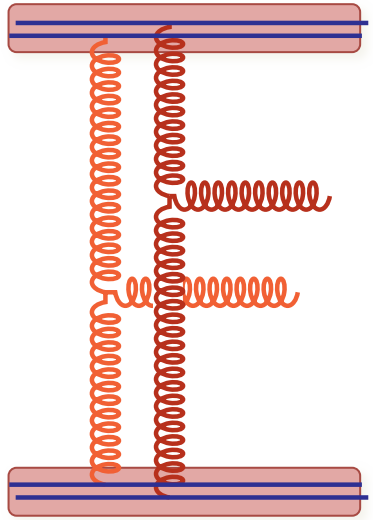
$$\mathcal{O}\left(\alpha_s\right)$$

Can obtain saturation by large A, small x or high energy

Di-hadron production

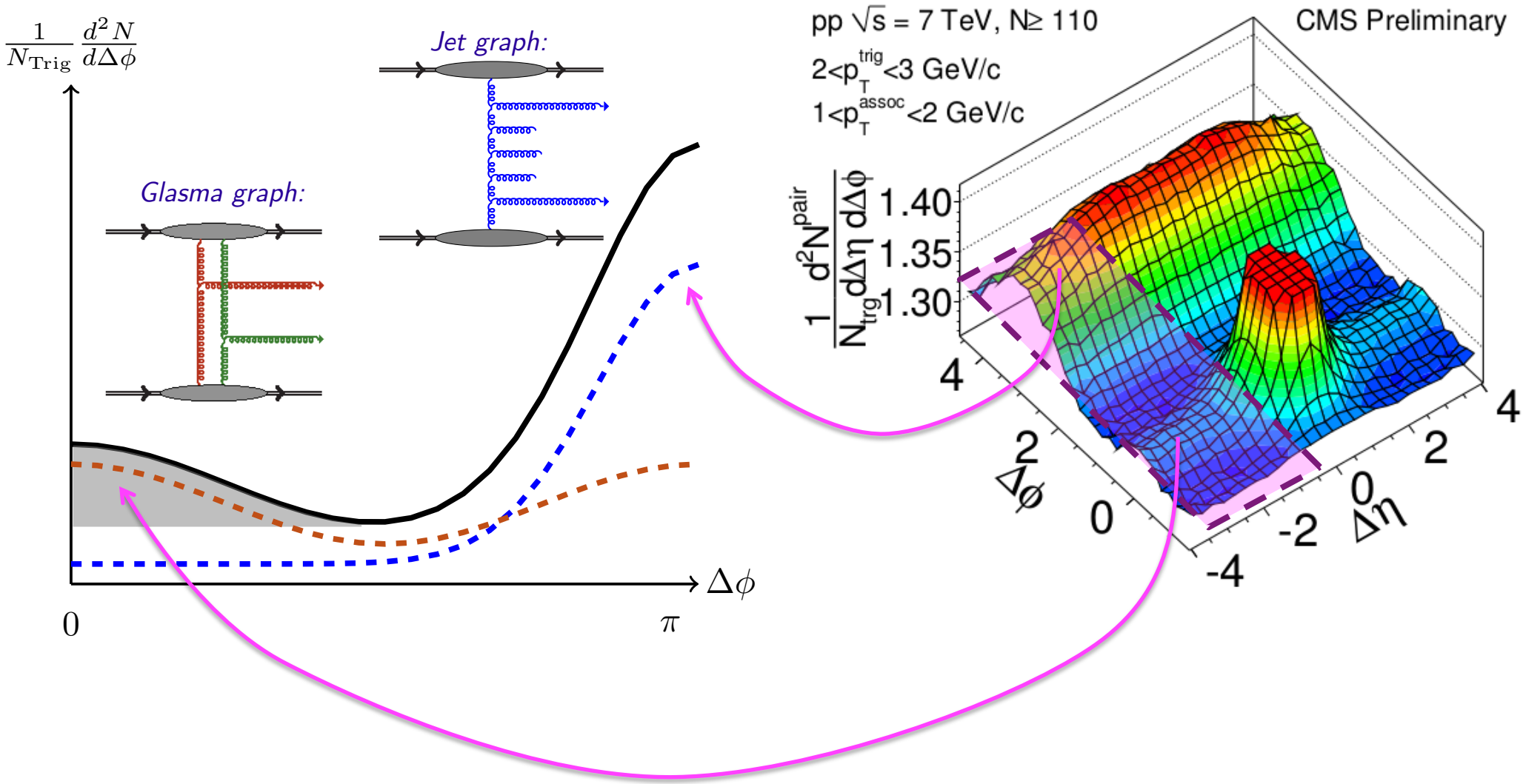


Power counting in QCD: multi-particle production

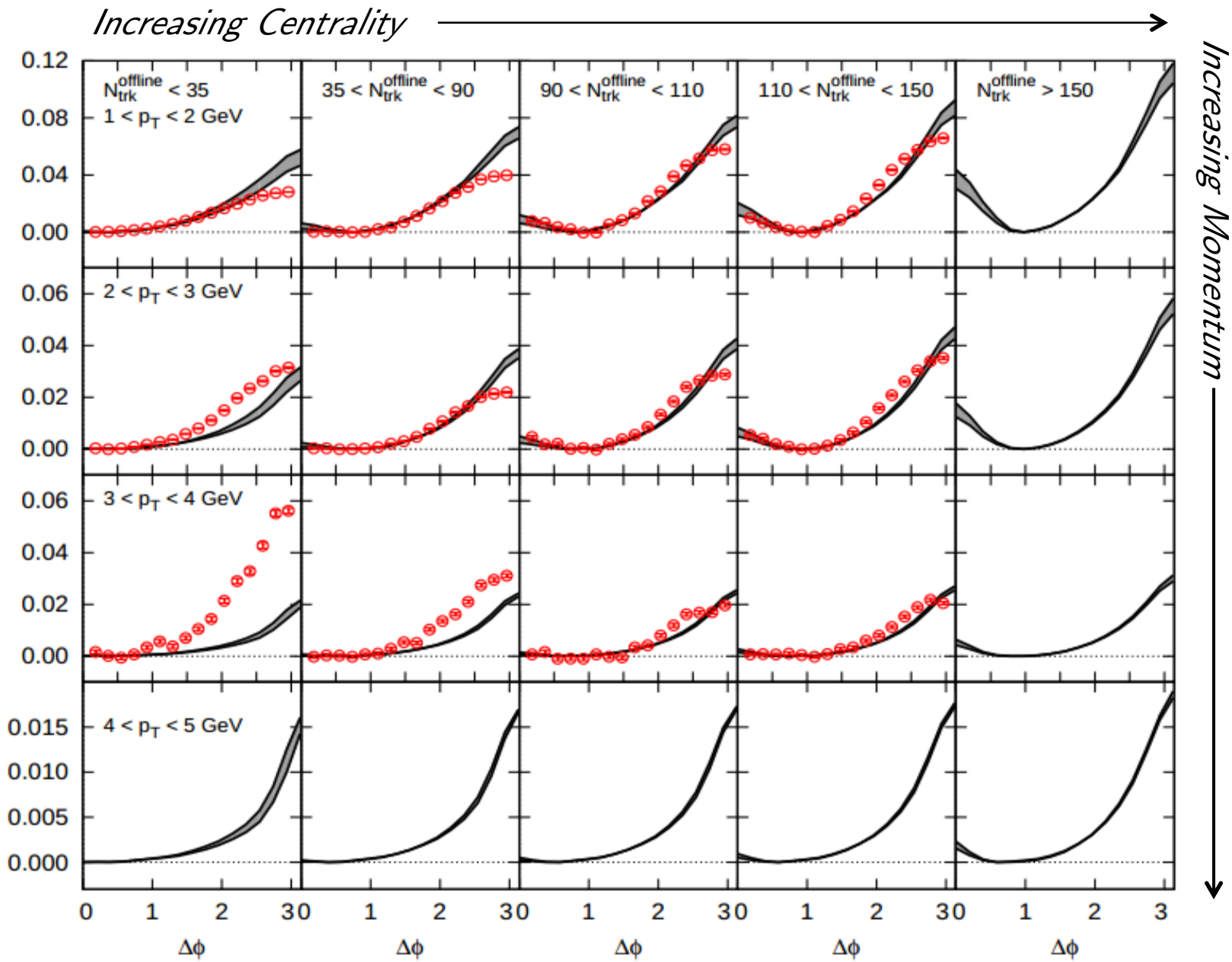
	"jet" graph	*"glasma" graph*
Low color density (min. bias events)	 $\mathcal{O}\left(\alpha_s^4\right)$	 $\mathcal{O}\left(\alpha_s^6\right)$
High color density ("central" events)	 $\mathcal{O}\left(1\right)$	 $\mathcal{O}\left(1/\alpha_s^2\right)$

Expect large enhancement of glasma graph over jet for central events

Anatomy of a proton-proton collision

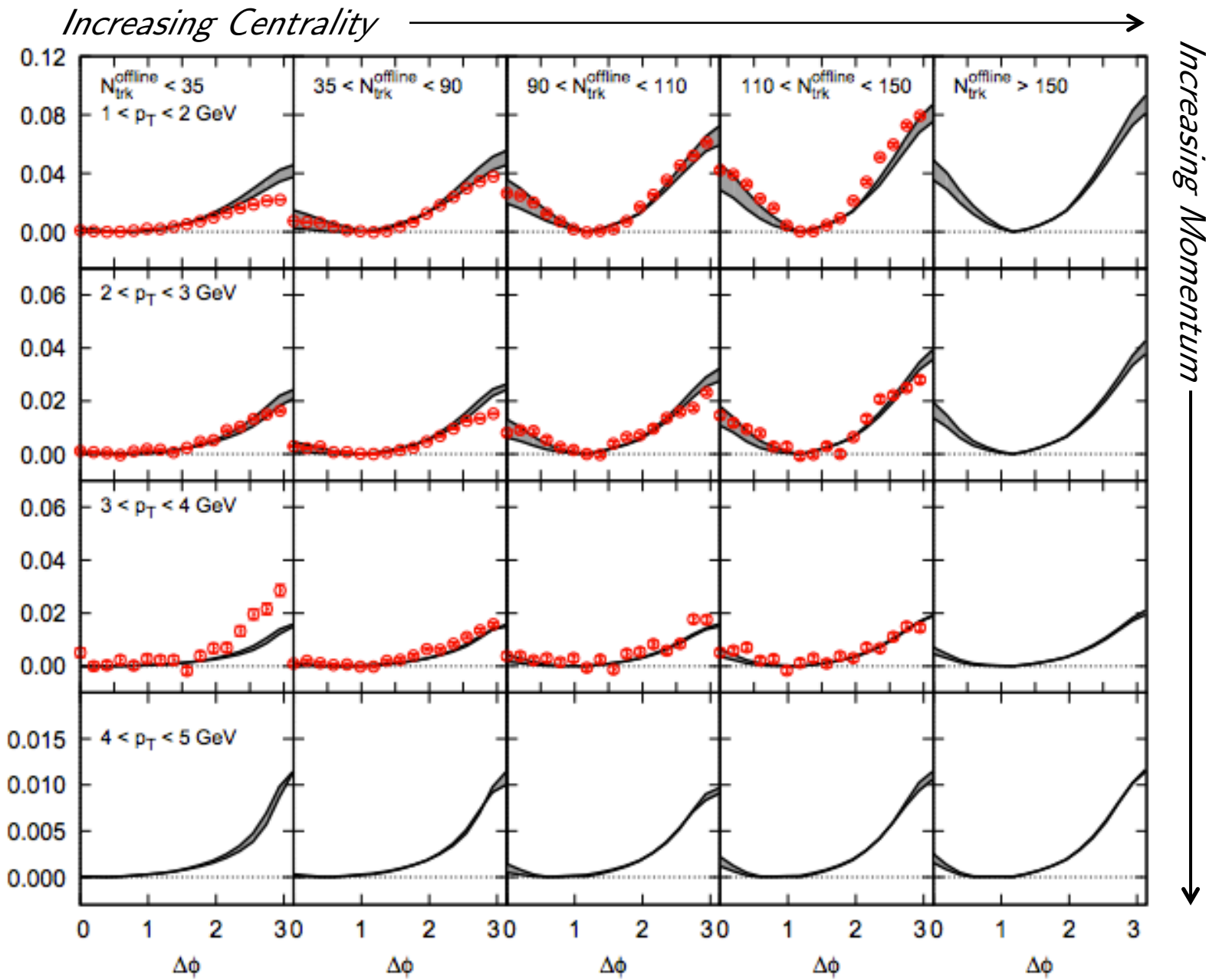


Proton-Proton systematics



Dusling, Venugopalan, Phys.Rev. D87 (2013) 094034, arXiv:1302.7018

Proton-Lead systematics

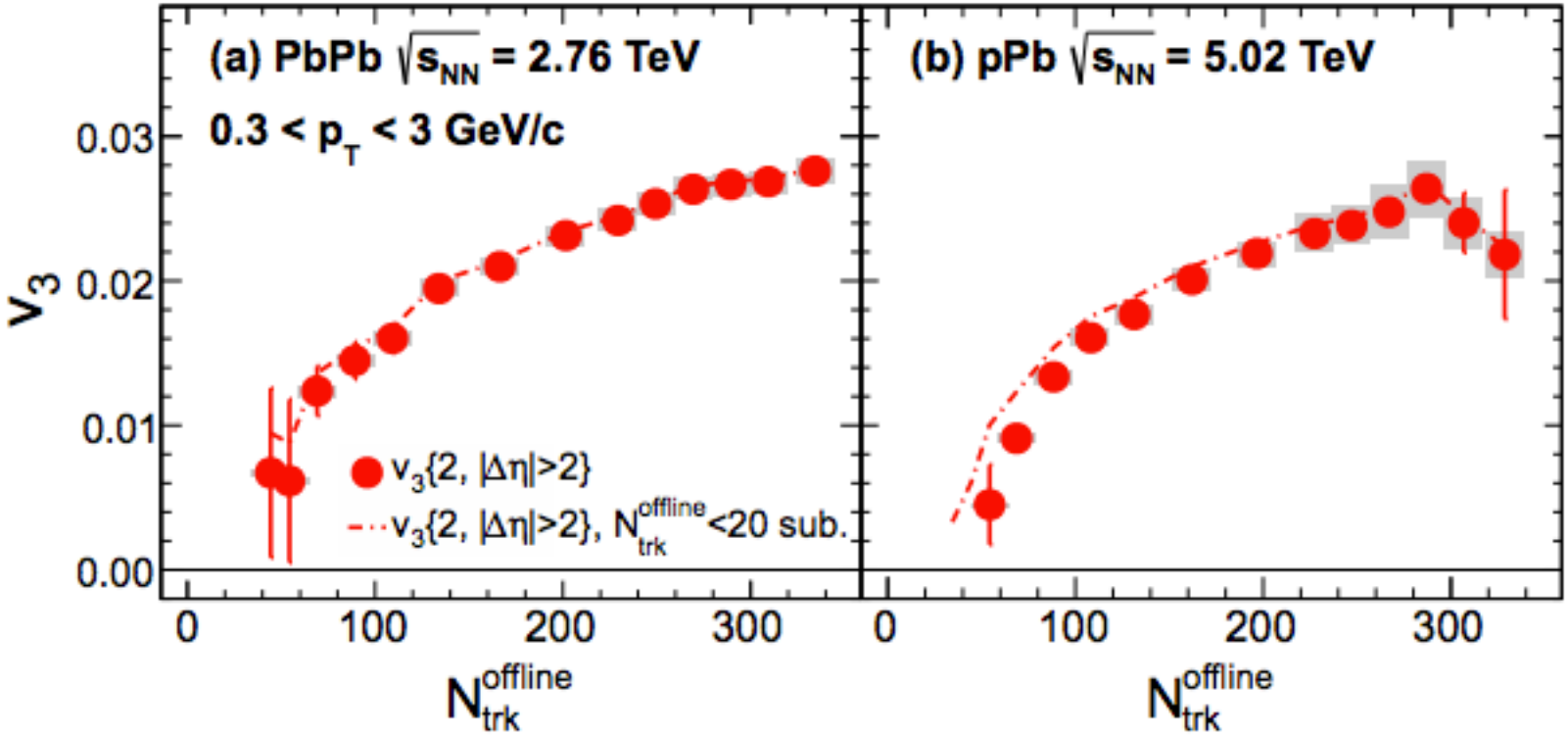


Dusling, Venugopalan, Phys.Rev. D87 (2013) 094034, arXiv:1302.7018

Part II: More Questions than Answers

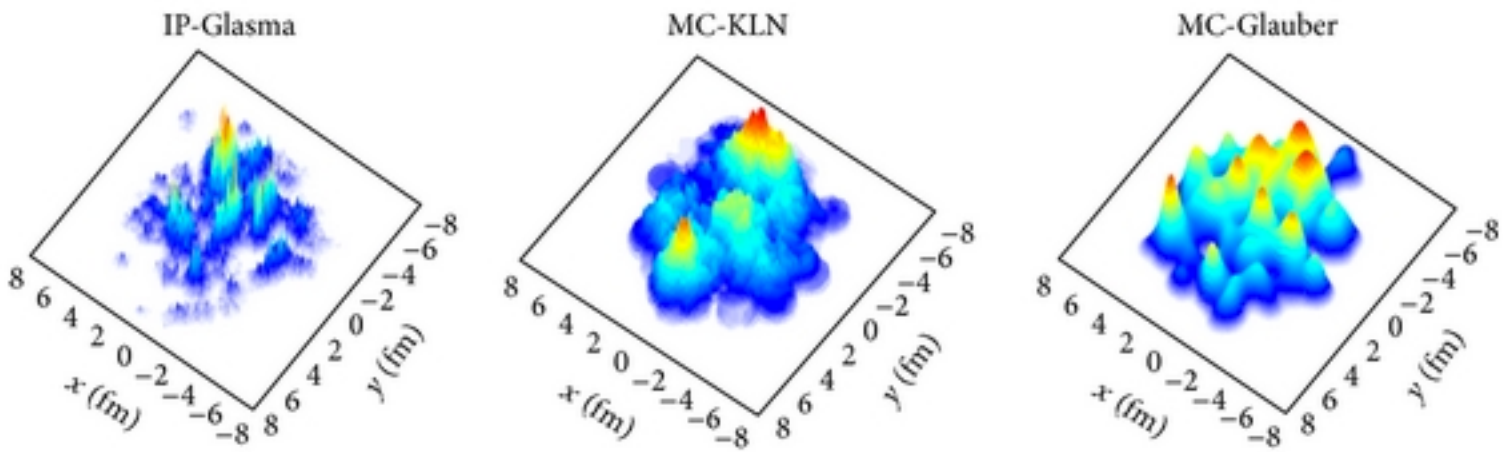
This cannot be the whole story...

Part II: The v3 puzzle

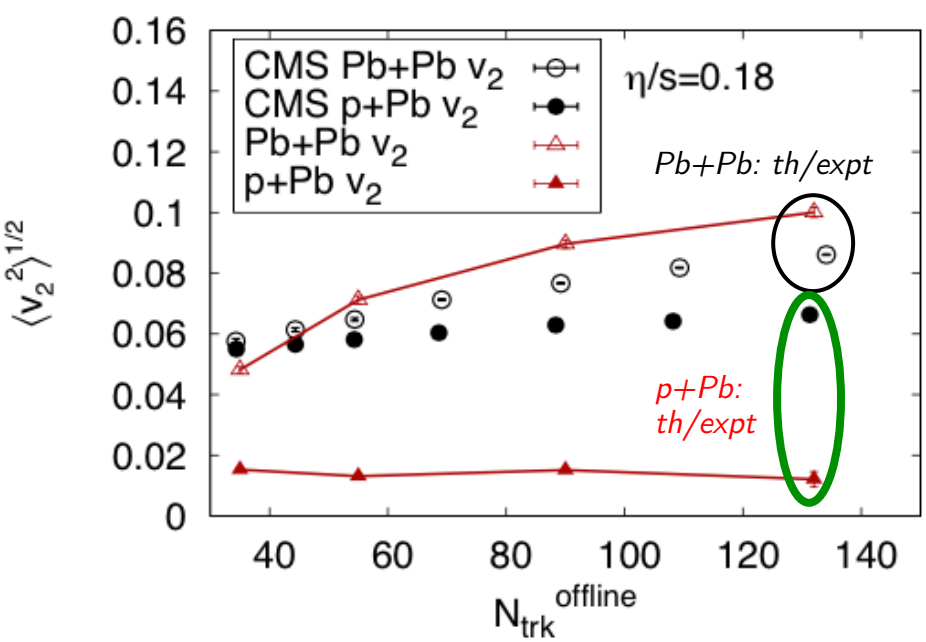


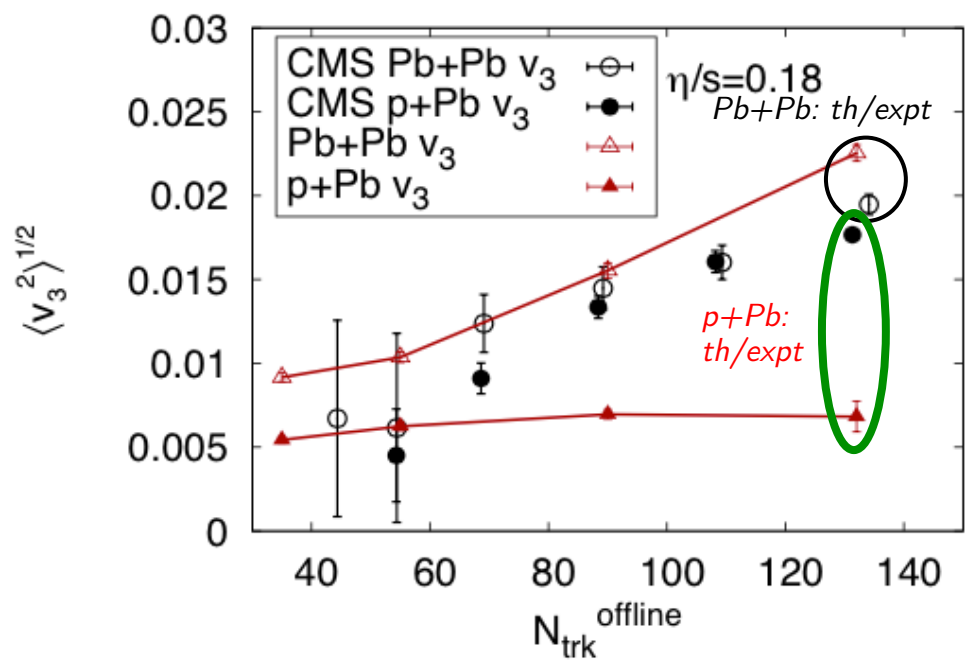
CMS Collaboration, Phys.Lett. B724 (2013) 213-240

Hydrodynamics in p+Pb ?



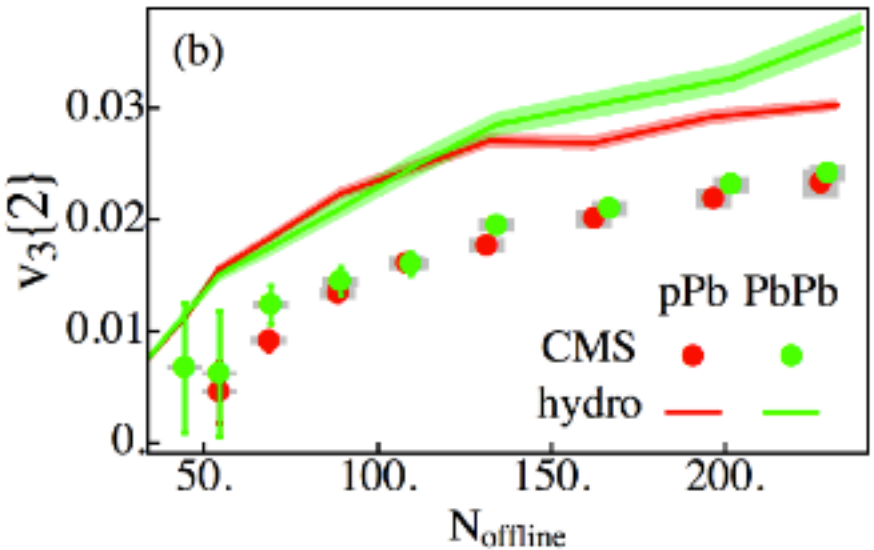
B. Schenke, P. Tribedy, R. Venugopalan
PRL 108 , 252301 (2012) , PRC 86, 034908 (2012)



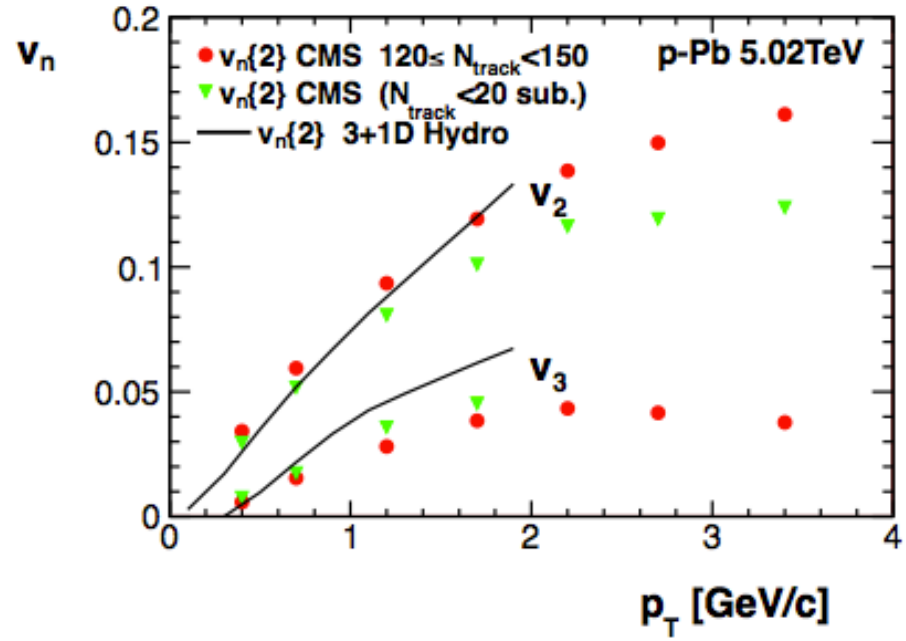


Schenke, Venugopalan PRL 113, 102301 (2014)

Hydrodynamics in p+Pb ?



Igor Kozlov, Matthew Luzum, Gabriel Denicol, Sangyong Jeon, Charles Gale arXiv:1412.3147



P. Bozek, W. Broniowski, G.Torrieri
Phys.Rev.Lett. 111 (2013) 172303

See also:
K. Werner, M. Bleicher, B. Guiot, Iu. Karpenko, T. Pierog,
Phys.Rev.Lett. 112 (2014) 23, 232301

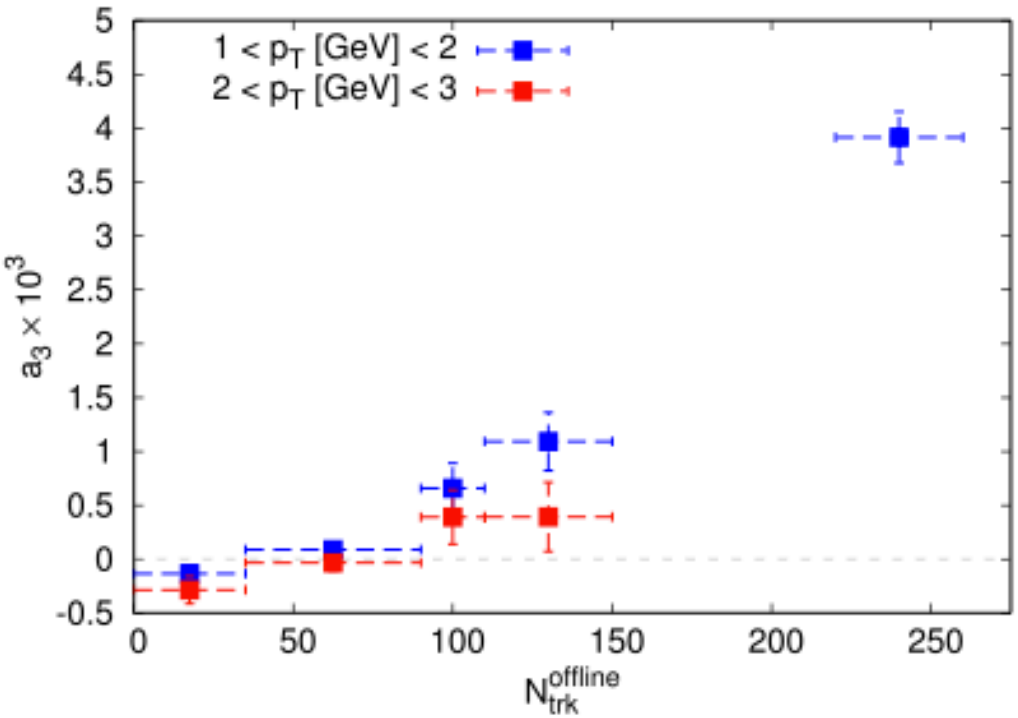
1> Which initial state is correct?

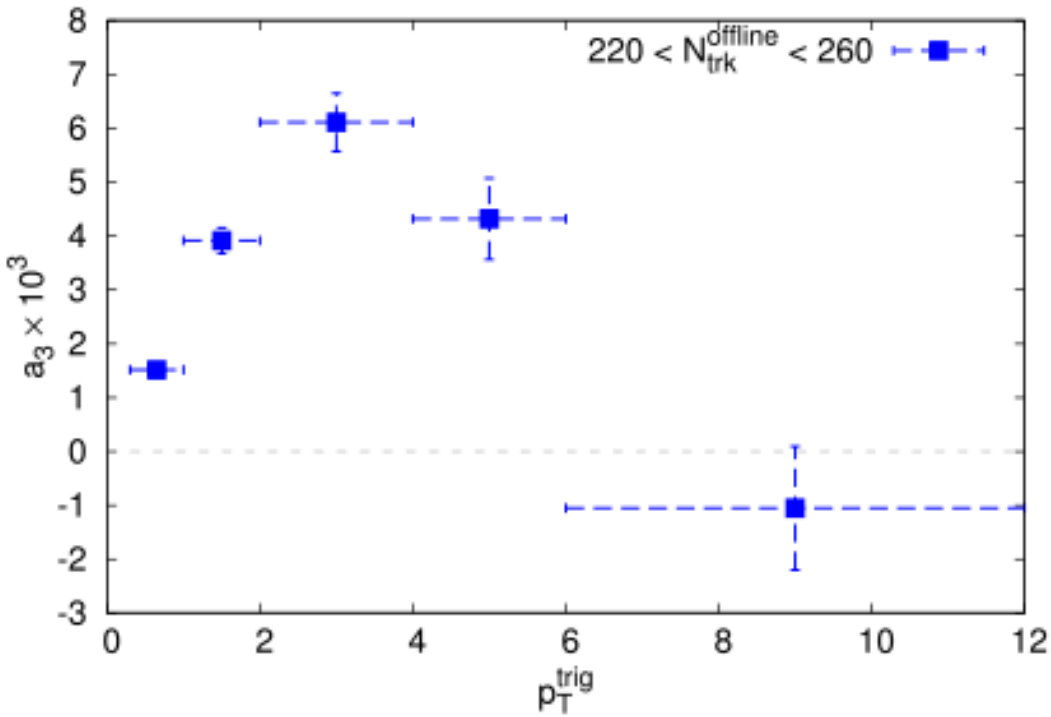
2> What about v_2 fluctuations, δv_2 ?

3> Tuning of Glauber initial conditions between p+A and A+A required to get correct two particle correlation matrix $V_{n\Delta}\left(p_T^a, p_T^b\right)$

And v_3 persists to very high momentum...

$$\frac{1}{N_{\rm trig}}\frac{d^2N}{d\Delta\phi} = a_0 + 2\sum_{n=1} a_n \cos(n\Delta\phi)$$

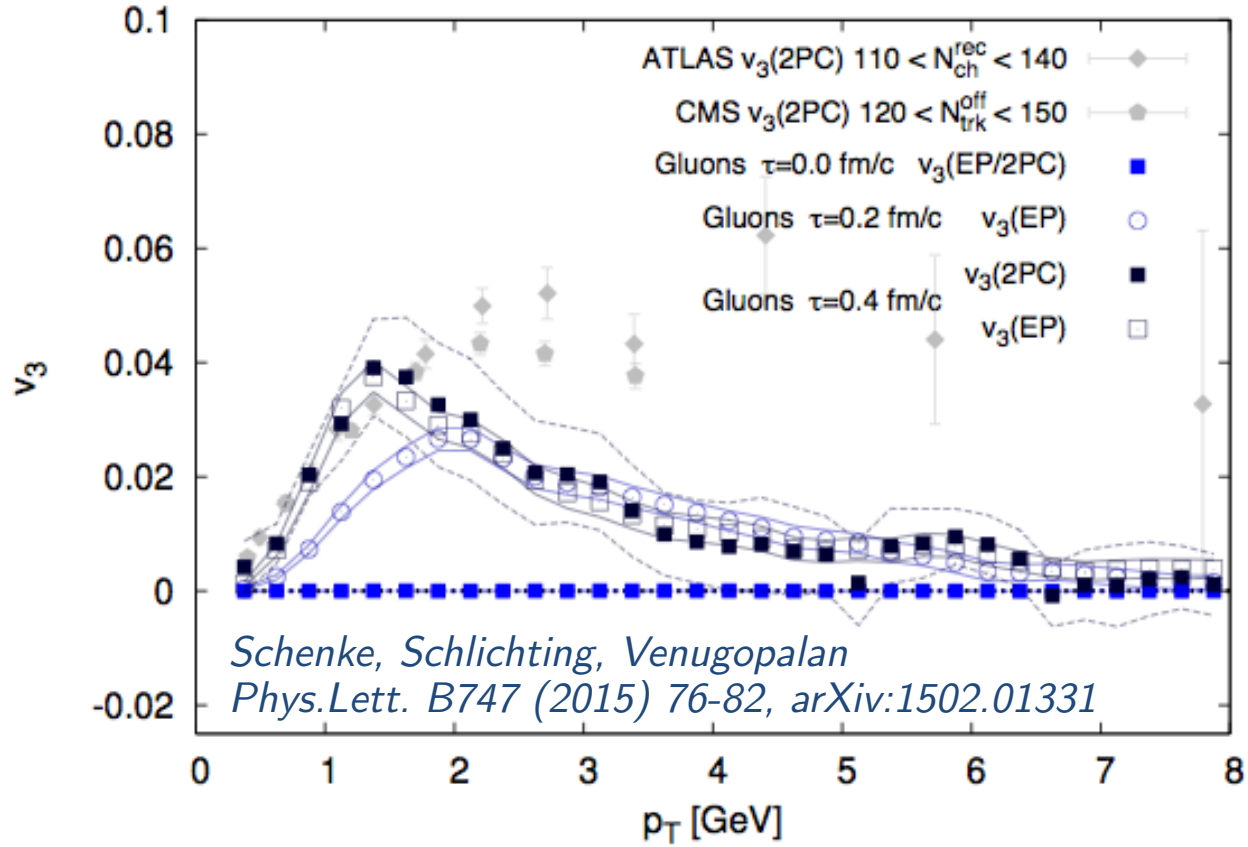




Can "flow" generate v_3 out to 5 GeV ?

Dusling, Venugopalan, Nucl.Phys. A931 (2014) 283-287

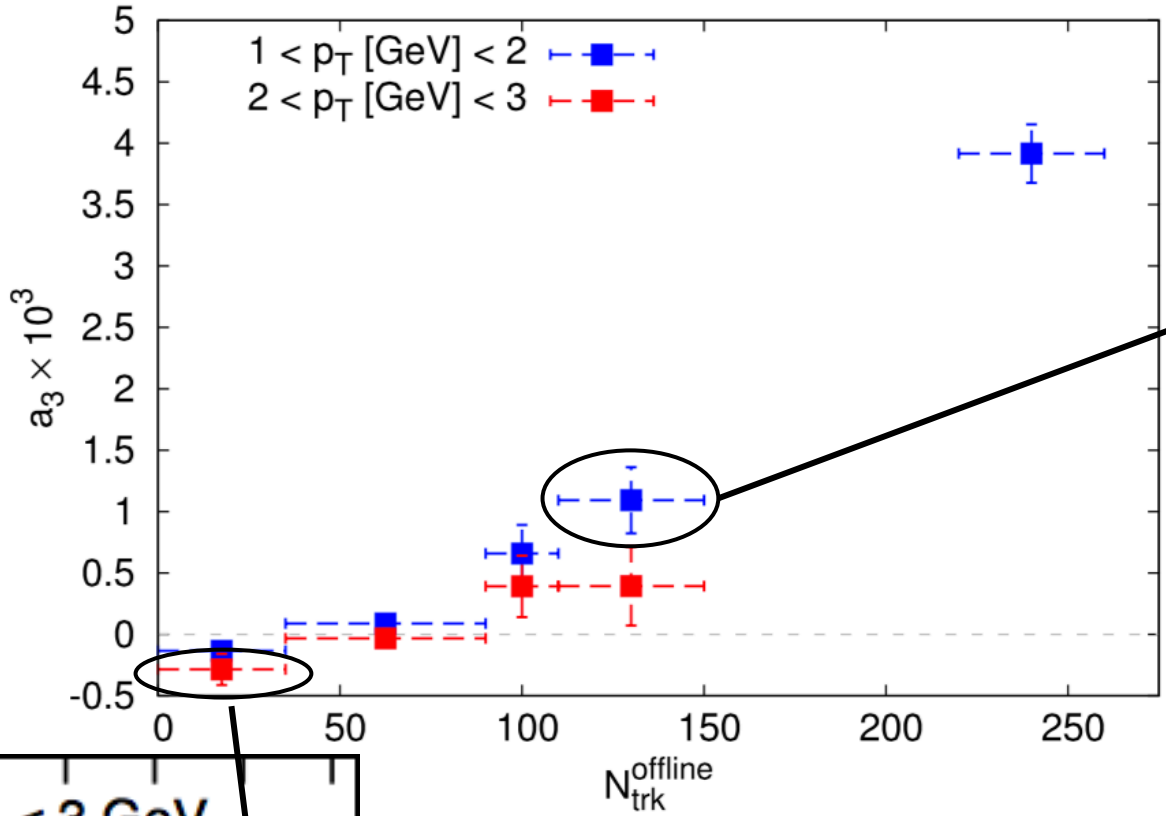
Classical Yang-Mills and v_3 in the soft ridge

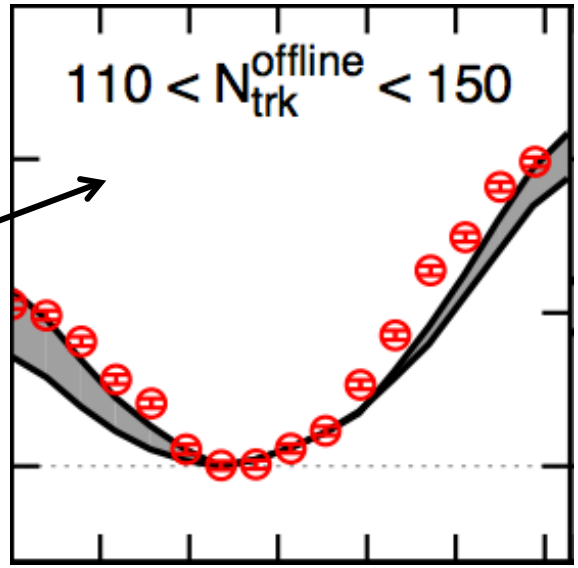


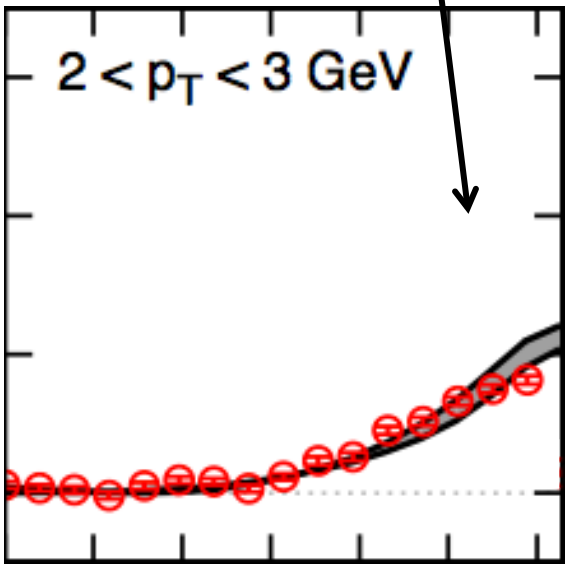
1> v_3 identically zero at τ=0 (consistent with glasma diagrams)

2> v_3 not correlated with ε_3

cos(3ϕ) in the hard ridge





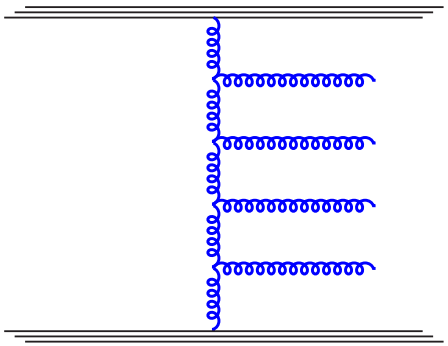


This is a small correction!

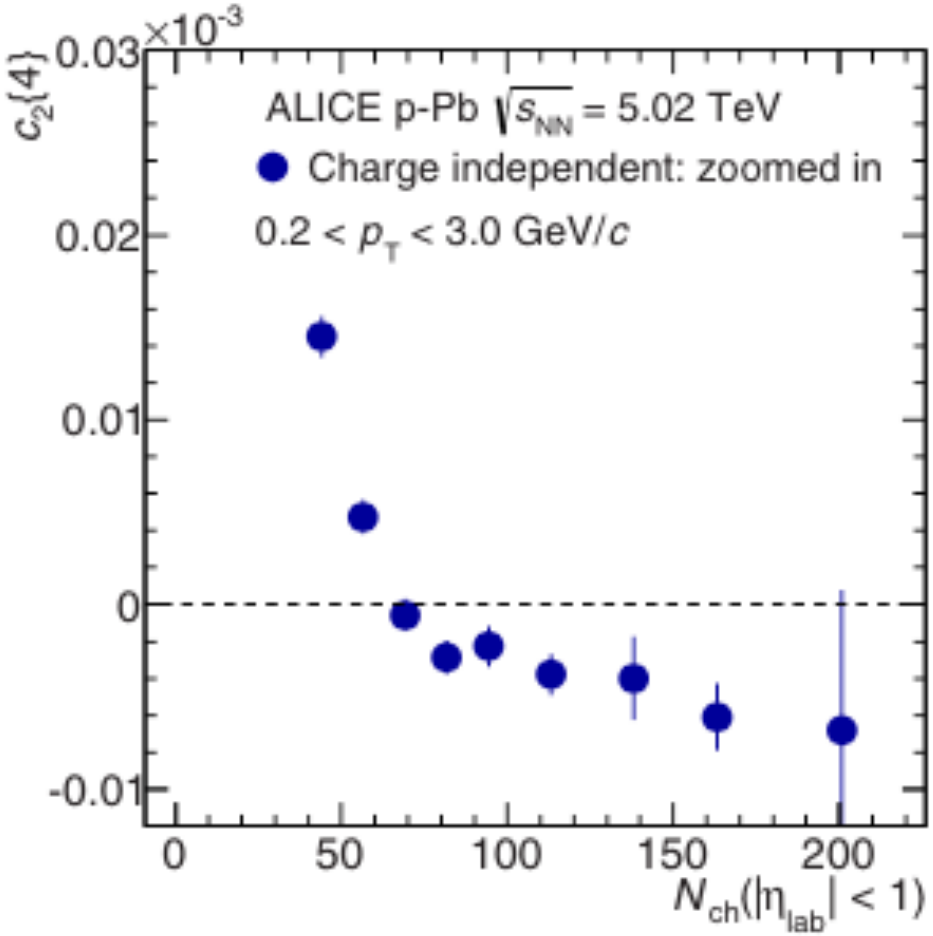
Possibilities:

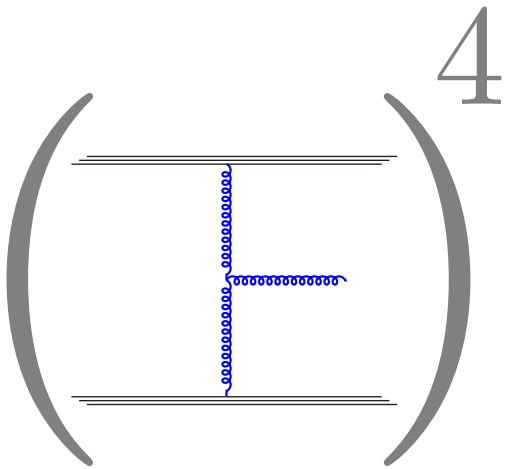
- *single soft rescattering off jet graph*
- *more careful treatment of jet and fragmentation*

Part III: Four particle correlations and collectivity



Connected (intrinsic)





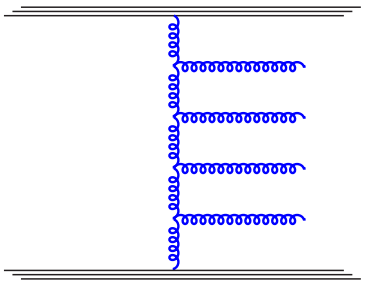
"Disconnected" (single-particle factorizable)

$$c_2\{4\} \sim \left\langle e^{2i(\phi_1+\phi_2-\phi_3-\phi_4)} \right\rangle_c - v_2^4$$

Dumitru, McLerran, Skokov, Phys.Lett. B743 (2015) 134-137

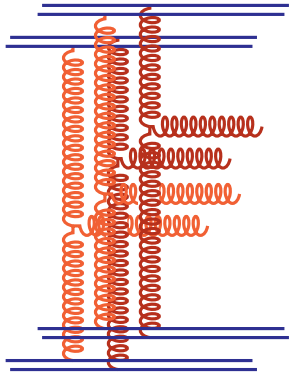
Intrinsic (connected) contributions

"Jet" Graph:



$$\frac{\alpha_s^n N_c^n}{4\pi^{2n+4}(N_c^2-1)}\left(\prod_{i=1}^{n}\frac{1}{\mathbf{k}_{i\perp}^2}\right) S_\perp \int d^2\mathbf{k}_{0\perp}\Phi(\mathbf{k}_{0\perp})\Phi\left(\mathbf{k}_{0\perp}+\mathbf{k}_{1\perp}+\cdots+\mathbf{k}_{n\perp}\right)$$

"Glasma" Graph:

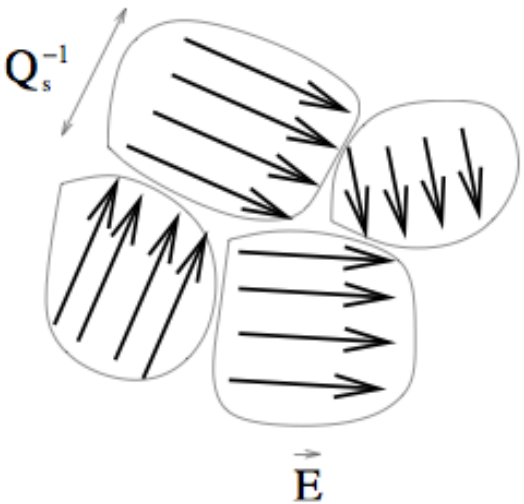


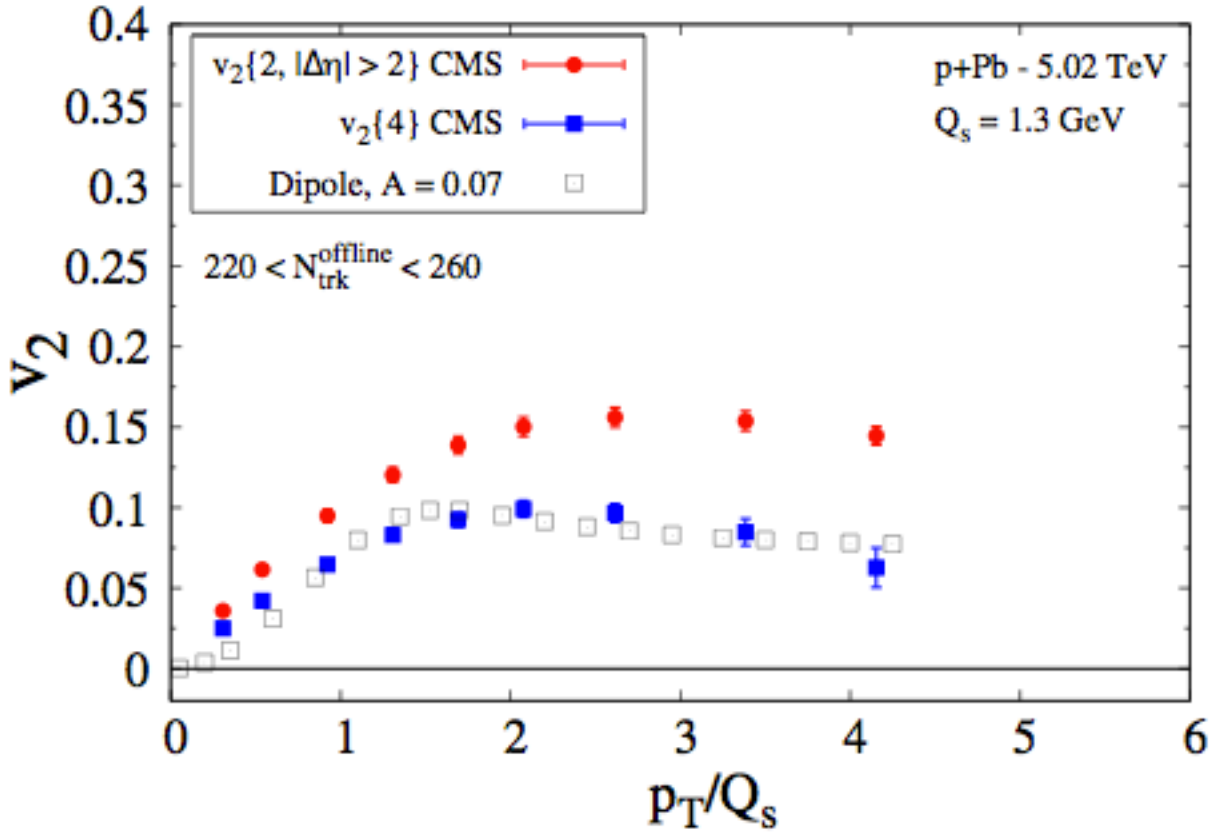
$$\frac{(n-1)!\,N_c^n}{\pi^{4n}(N_c^2-1)^{2n-1}}\frac{\alpha_s^n S_\perp}{\mathbf{k}_{1\perp}^2\cdots\mathbf{k}_{n\perp}^2}\int\frac{d^2\mathbf{p}_\perp}{(2\pi)^2}\Phi^n(\mathbf{p}_\perp)\left[\Phi(\mathbf{k}_{1\perp}\pm\mathbf{p}_\perp)\cdots\Phi(\mathbf{k}_{n\perp}\pm\mathbf{p}_\perp)\right]$$

1. Both jet and glasma graphs have $c_2\{4\}>0$ (at high pT)
2. Experimentally does $c_2\{4\}>0$ at high pT?
3. Low multiplicity $c_2\{4,6,8\}$ contains interesting QCD physics.
4. How can we understand the negative $c_2\{4\}$ of soft particles?

Symmetry breaking by color domains

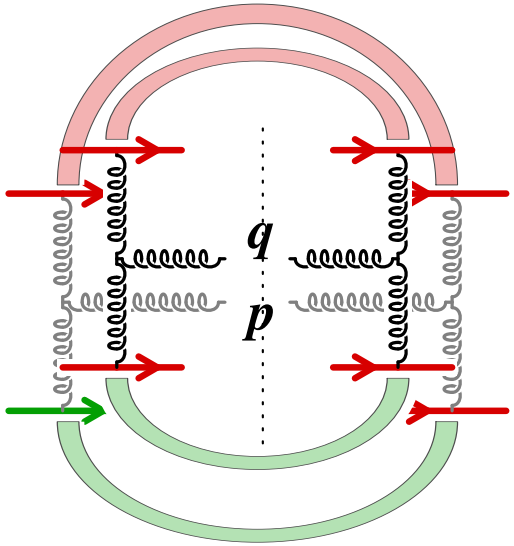
Kovner, M. Lublinsky
Phys. Rev. D84 (2011) 094011

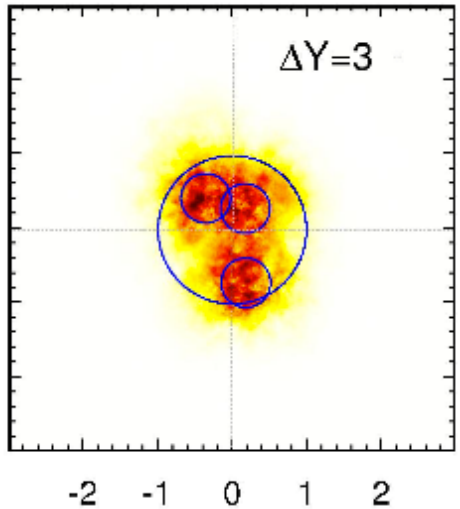




Dumitru, Giannini, Nucl.Phys. A933 (2015) 212

Symmetry breaking by color domains



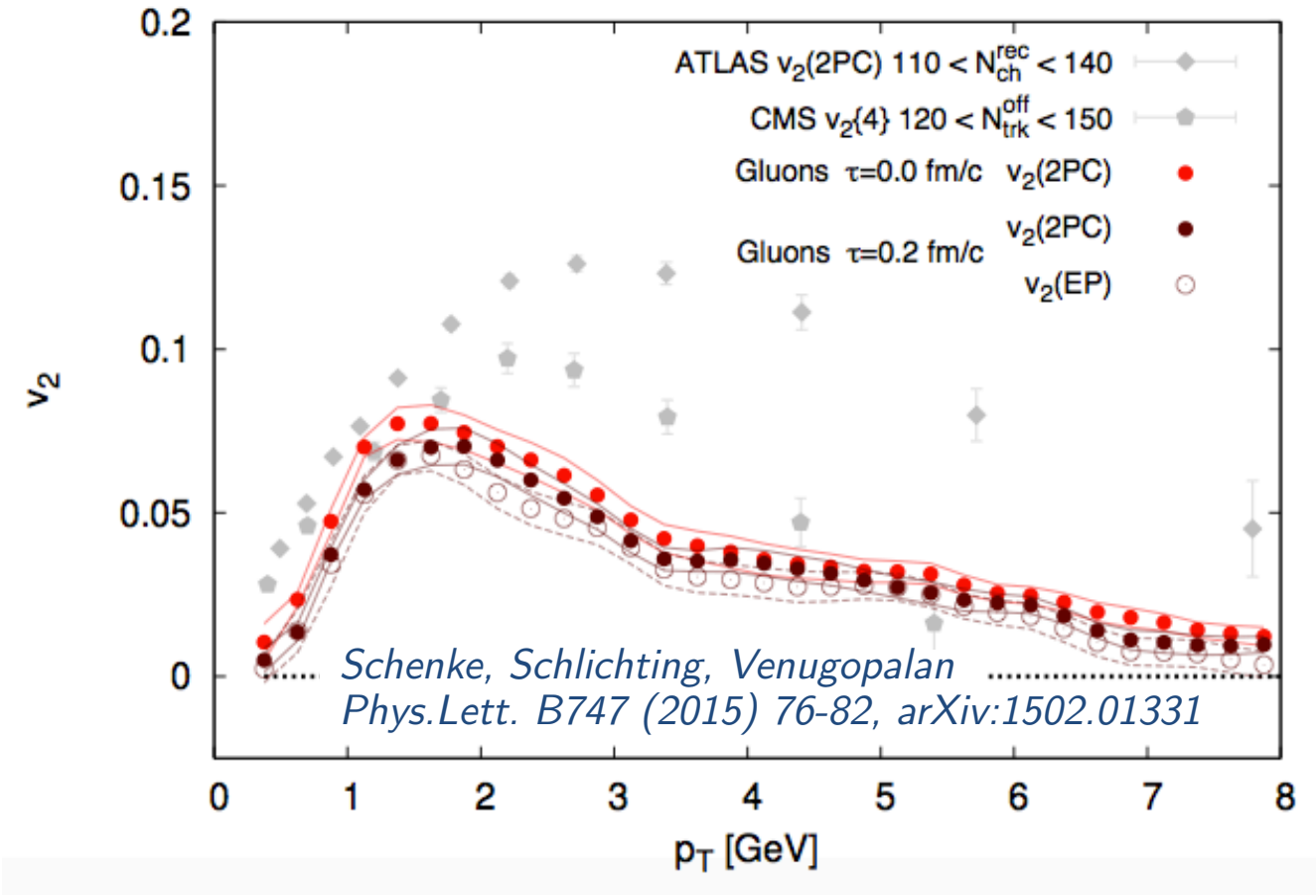


$$\langle \rho^a(\mathbf{x})\rho^b(\mathbf{y})\rangle = \delta^{ab}\delta^{(2)}(\mathbf{x}-\mathbf{y})S\left(\frac{\mathbf{x}+\mathbf{y}}{2}\right)$$

1> This symmetry breaking is enough for the "disconnected" glasma graphs to give v_2

2> As the v_2 comes from the single particle spectra: $c_2\{4\}<0$

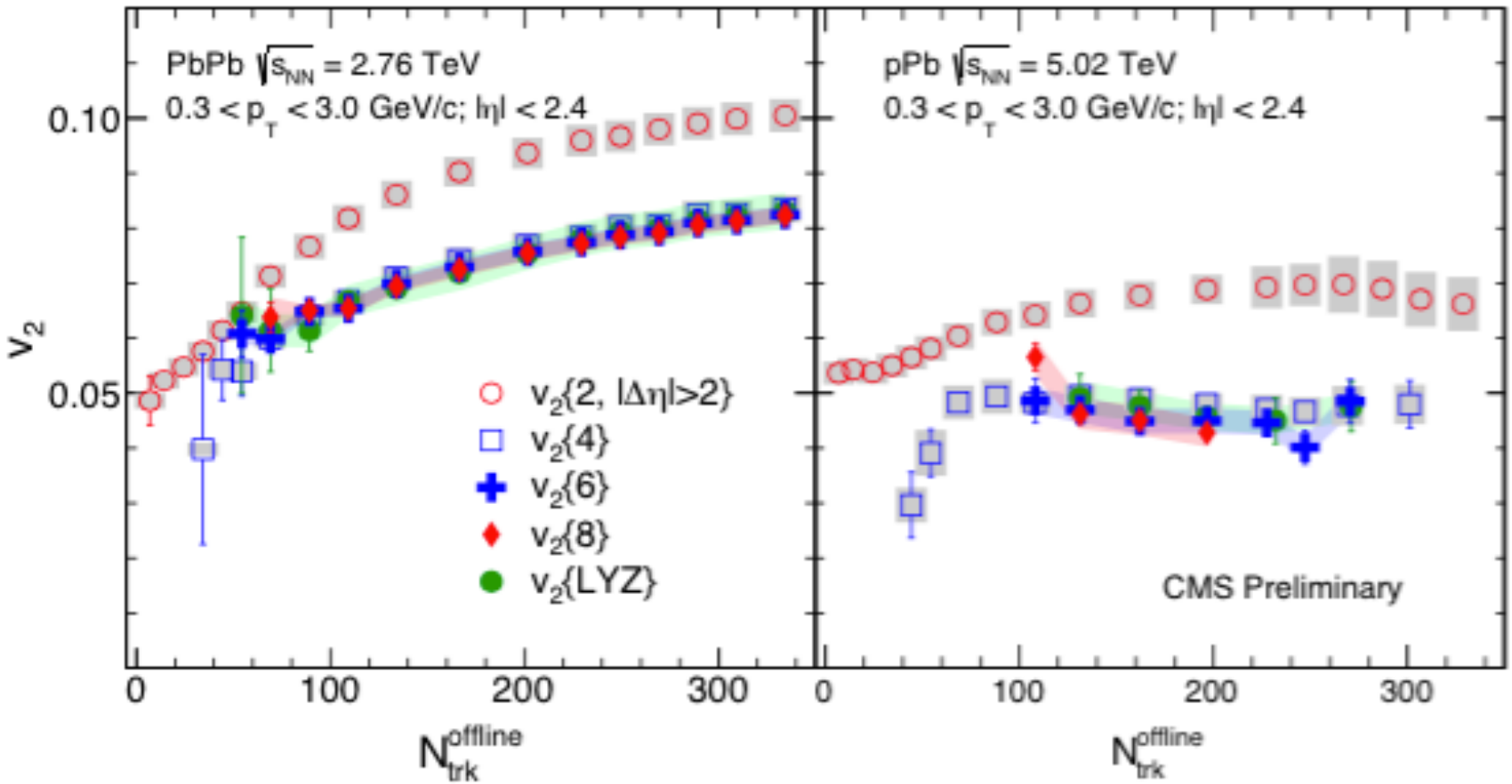
v_2 from CYM



1> Above calculation has both connected and disconnected graphs

2> Need to think about how to disentangle contributions

Further evidence for collectivity



1> Connected (i.e. glasma, jet) contributions will lead to a breaking of $v_2\{n\}$ scaling

2> Does the breaking increase with higher minimum p_T?

3> Does $c_2\{4\}$ change sign at higher minimum p_T?

Summary

1. Multi-particle production can be computed in a framework consist with the nuclear wave-function obtained from deep inelastic scattering

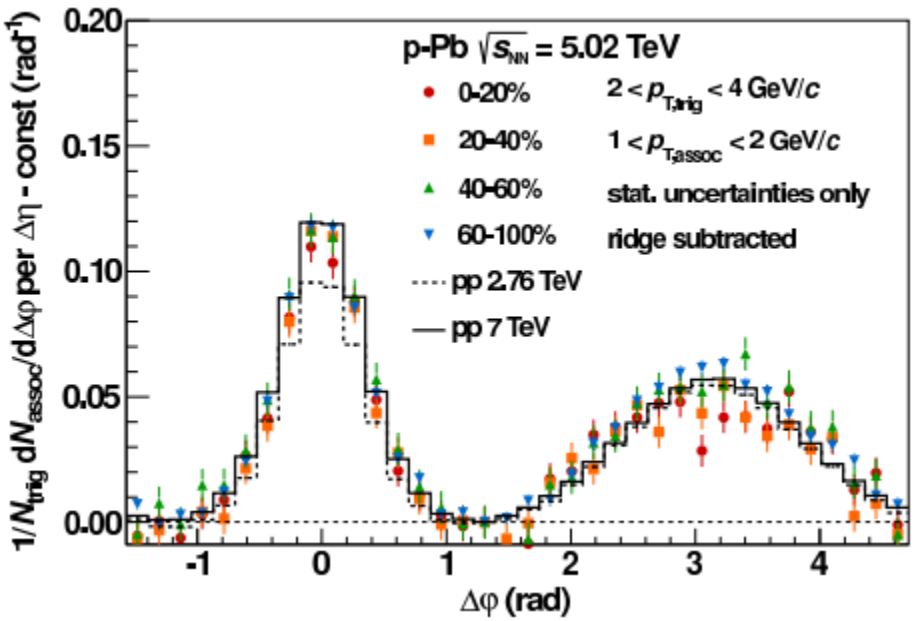
2. Glasma graphs successfully describe the *hard* ridge (i.e. $p_T. > 1 - 2$ GeV)

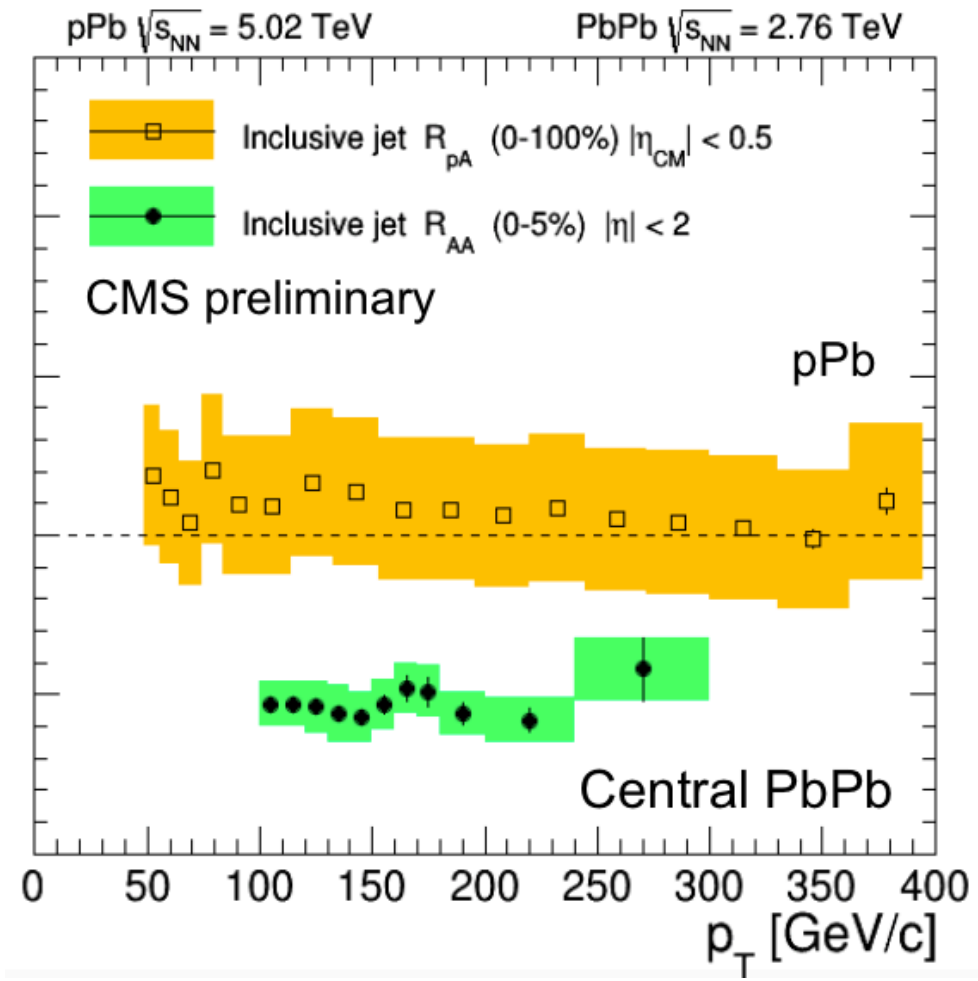
3. The *soft* ridge is another story: it is collective (i.e. $c_2\{4\}<0$)
   a. Classical Yang-Mills provides a natural framework (consistent with "glasma graphs")
   b. Rotational symmetry breaking by color domains

4. Decisive measurements:
   a. systematics of $c_2\{4\}$ with low pT cutoff

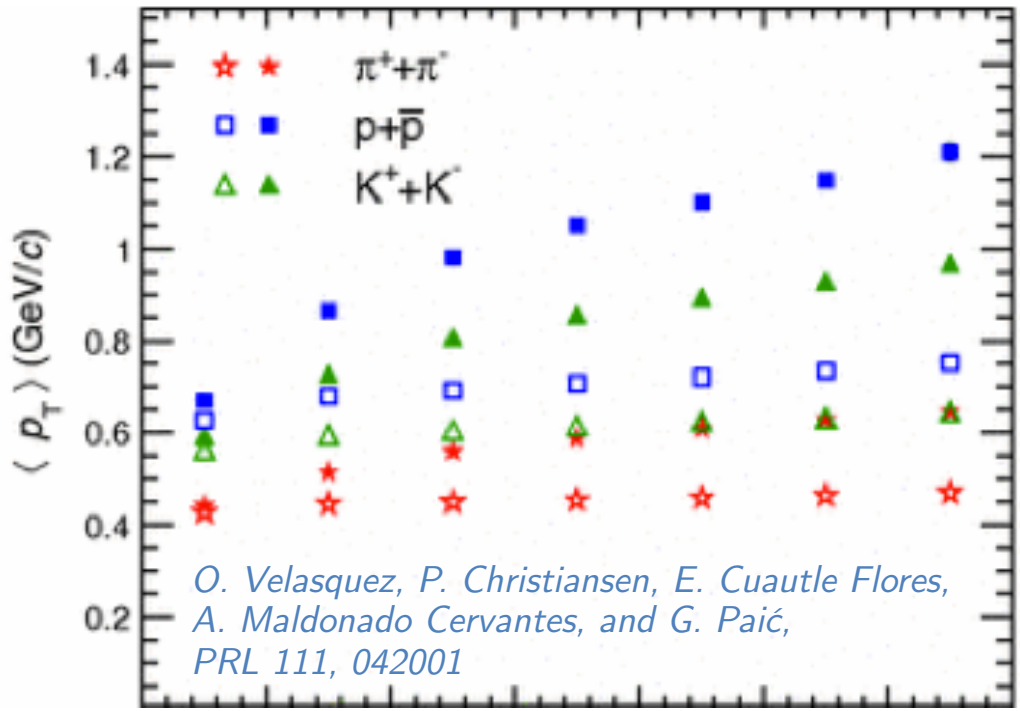
Mini-jets are unmodified … what about "real" jets?

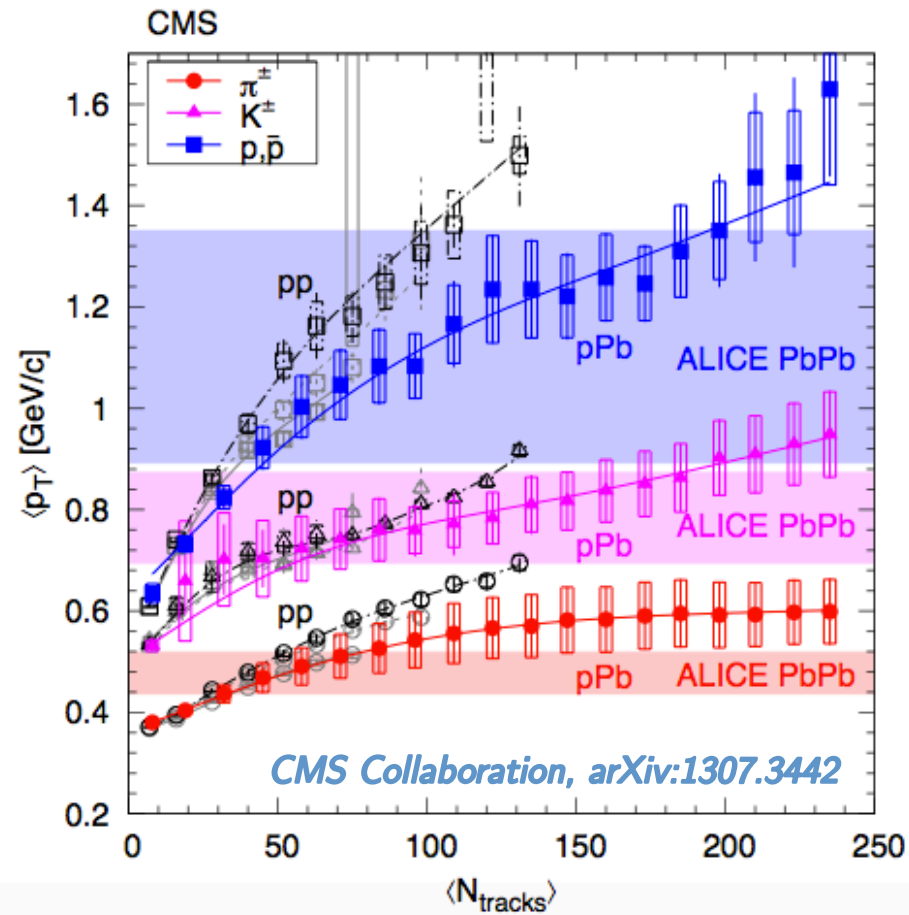
ALICE Collaboration, Phys.Lett. B719 (2013) 29-41





The radial flow





1> Mass splitting observed in peripheral pp

2> Rate of change of mass splitting largest for pp:
Larger flow in pp or color reconnection?

3> Largest effect is for protons:
We don't understand the proton yields in central Pb+Pb

4> v_2 mass splitting really isn't an independent piece of evidence:
The push out of protons can be driven by denominator.