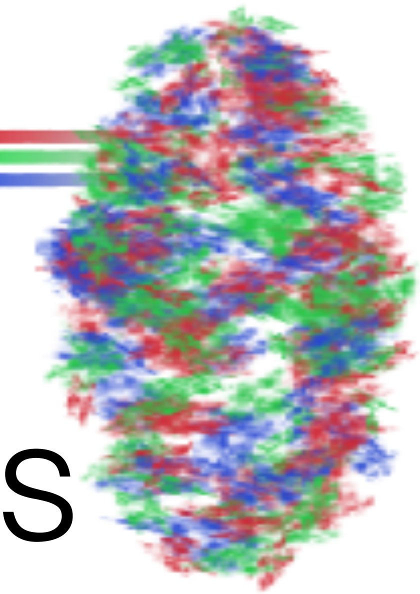


Multi-particle correlations and collectivity in small systems from the initial state

Mark Mace

Stony Brook University and Brookhaven National Lab

RHIC/AGS Users Meeting

June 13, 2018

Stony Brook University

BROOKHAVEN NATIONAL LABORATORY

Outline

1. Introduction and motivation

2. Demonstration of multi-particle collectivity with proof of principle parton model

   K. Dusling, MM, R. Venugopalan PRL 120, 042002 (2018) [arXiv:1705.00745], PRD 97, 016014 (2018) [arXiv:1706.06260]

3. Demonstration of hierarchy of v_2 and v_3 across small systems in CGC EFT at RHIC, and Nch dependence at the LHC

   MM, V. Skokov, P. Tribedy, R. Venugopalan, arXiv:1805.09342

4. Simple power counting argument for v_n multiplicity dependence at LHC

   MM, V. Skokov, P. Tribedy, R. Venugopalan, in preparation

Initial State Flow

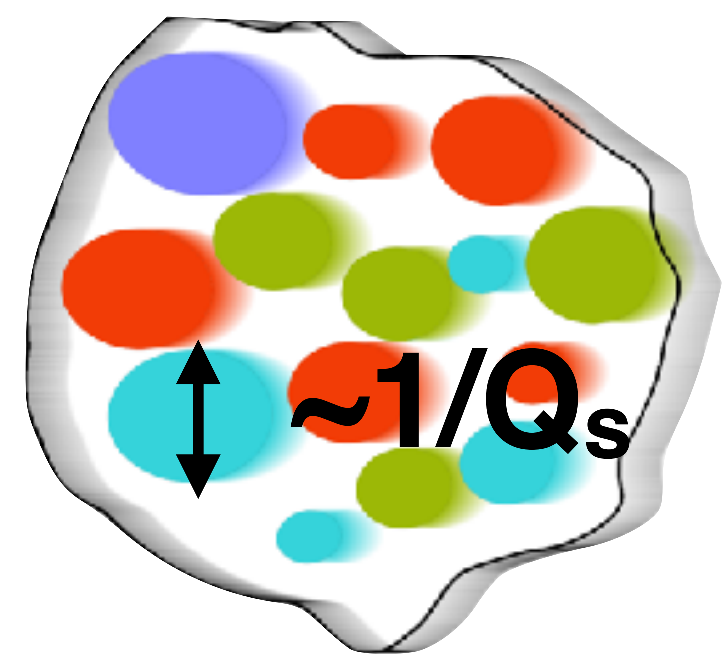
At high energy → high density gluon matter described by the Color Glass Condensate Effective Field Theory

McLerran, Venugopalan, PRD 49 (1994), Iancu, Venugopalan hep-ph/0303204

High gluon density in QCD generates dynamical saturation scale, Q_s

$$Q_s^2 \sim A^{1/3} s^\lambda$$

Intuitive picture of CGC:
Nucleus becomes saturated with high occupancy gluons for $k_T < Q_s$
For $k_T \gg Q_s$ smooth matching of framework to pQCD



Note: Very strongly correlated system. Dependence on coupling drops out

This talk: CGC has "flow" in line with observations

A parton model

Consider eikonal quark scattering off dense nuclear target with color domains of size $\sim 1/Q_S$

Work in dilute-dense limit: $Q_S(\text{target}) \gg Q_S(\text{projectile})$

Lappi, PLB 744, 315 (2015); Lappi, Schenke, Schlichting, Venugopalan, JHEP 1601 (2016) 061; Dusling, MM, Venugopalan PRL 120 (2018), PRD 97 (2018)

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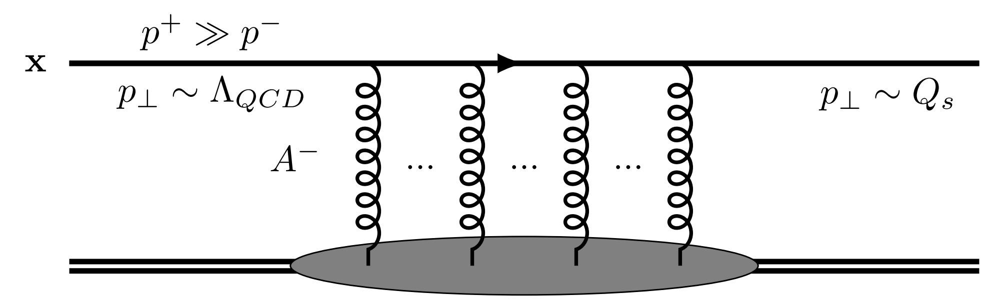
Quark coherent multiple scattering off target represented by Wilson line phase

Bjorken, Kogut, Soper, PRD (1971), Dumitru, Jalilian-Marian,PRL 89 (2002)

$$U(\mathbf{x}) = \mathcal{P}\exp\Big(-ig \int dz^+ A^{a-}(\mathbf{x}, z^+)\, t^a \Big)$$



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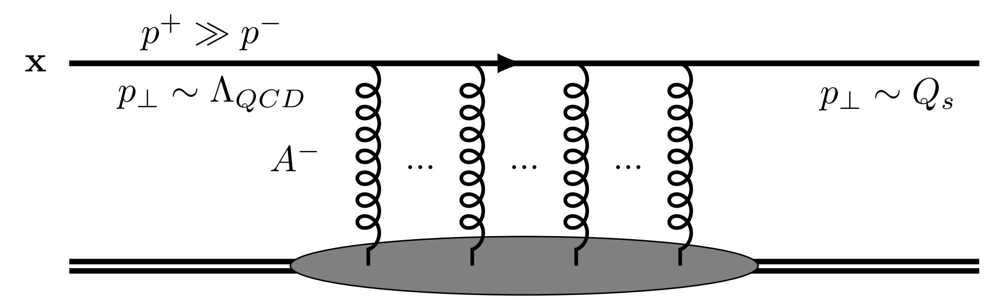


Single quark inclusive distribution

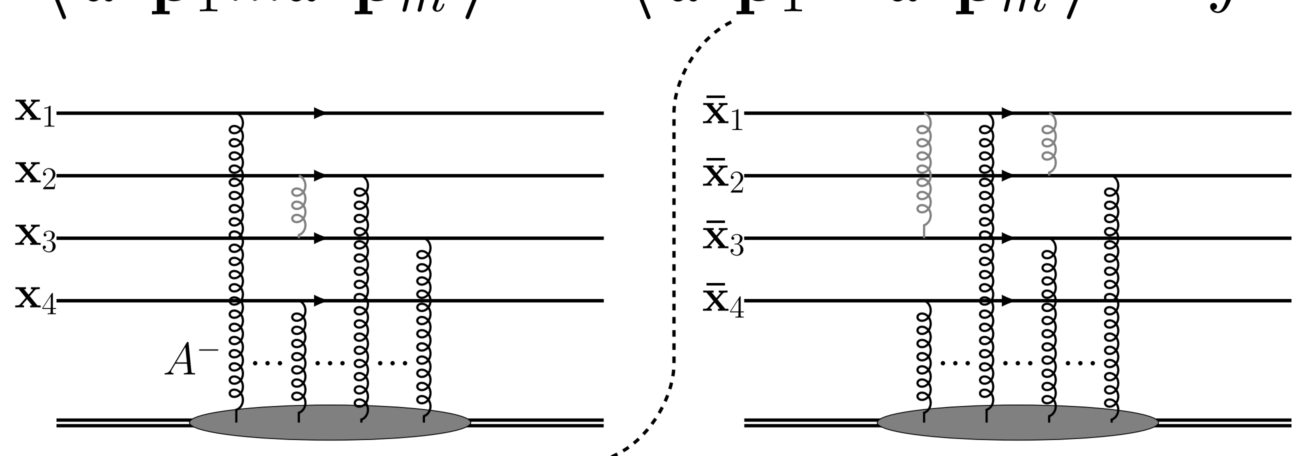
$$\left\langle \frac{dN_q}{d^2\mathbf{p}} \right\rangle \simeq \int_{\mathbf{b},\mathbf{r},\mathbf{k}} \underbrace{e^{-|\mathbf{b}|^2/B_p} e^{-|\mathbf{k}|^2 B_p}\; e^{i(\mathbf{p}-\mathbf{k})\cdot\mathbf{r}}}_{\text{Projectile: Wigner function}} \underbrace{\left\langle \frac{1}{N_c} \mathrm{Tr}\left(U(\mathbf{b}+\frac{\mathbf{r}}{2}) U^\dagger(\mathbf{b}-\frac{\mathbf{r}}{2}) \right) \right\rangle}_{\text{Target scattering: Dipole operator D(x,y)}}$$

*Single scale to defines projectile $B_p = 4\ \mathrm{GeV}^{-2}$ from HERA DIS fits

A parton model

Generalizing for multiple particle correlations for *simple* model of multi particle correlations

$$\left\langle \frac{d^m N}{d^2\mathbf{p}_1 ... d^2\mathbf{p}_m} \right\rangle = \left\langle \frac{dN}{d^2\mathbf{p}_1} \cdots \frac{dN}{d^2\mathbf{p}_m} \right\rangle \sim \int \langle D ... D \rangle$$



Introduced novel method to compute arbitrary Wilson line correlators in MV - arXiv:1706.06260

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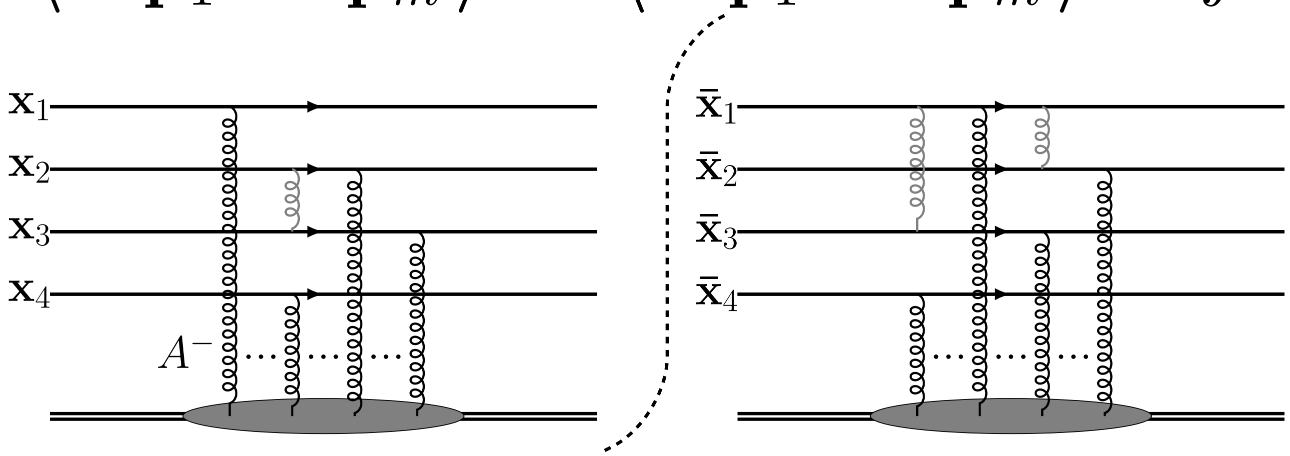

Introduced novel method to compute arbitrary Wilson line correlators in MV - arXiv:1706.06260

$dN/d^2\mathbf{p}$ itself is not well defined. Average over classical configurations and over all events using MV model

McLerran, Venugopalan, PRD 49, 3352, 2233 (1994)

A parton model

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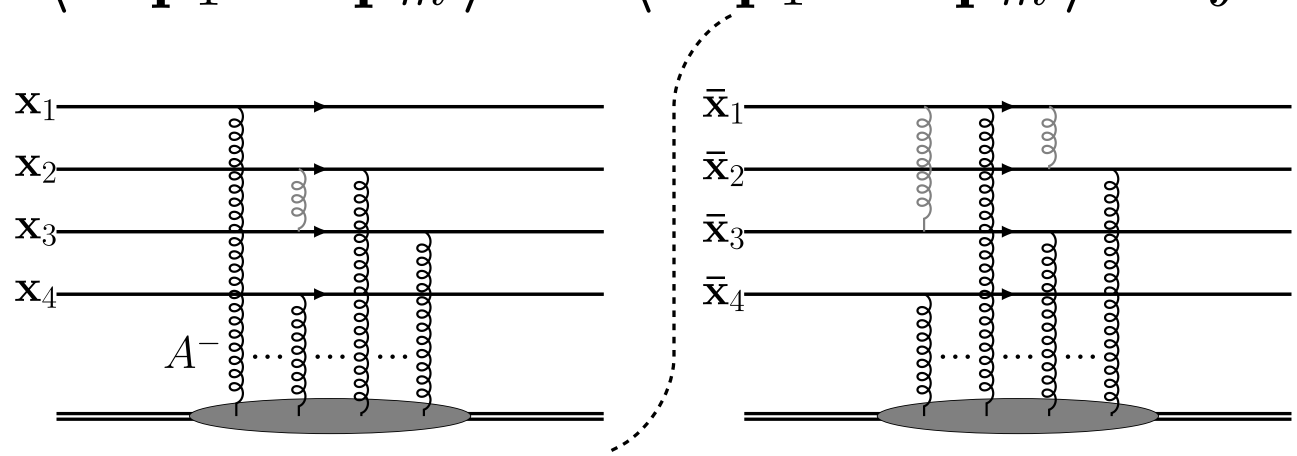

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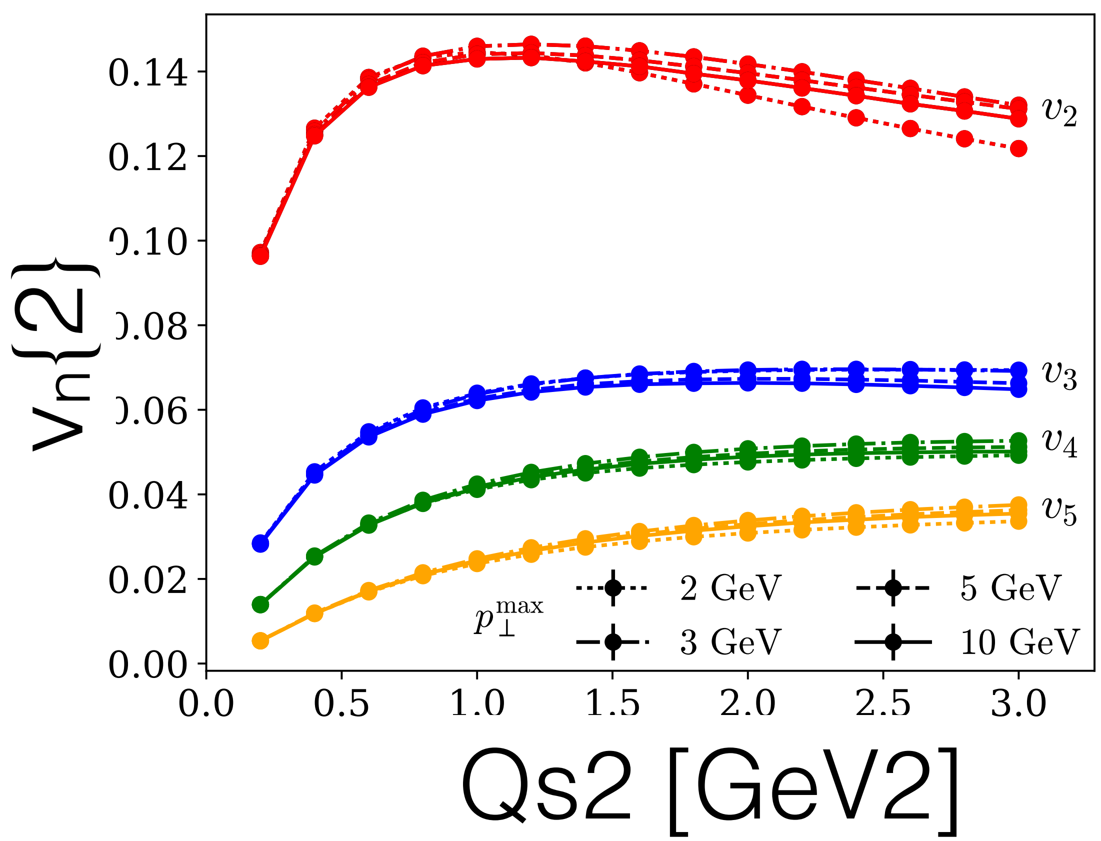
Generate cumulants, integrate to scale $p_\perp^{max}$

$$\kappa_n\{m\} = \int_{\mathbf{p}_1 ... \mathbf{p}_m} \cos\left(n\left(\phi_1^p + ... - \phi_m^p\right)\right) \left\langle \frac{d^m N}{d^2\mathbf{p}_1 ... d^2\mathbf{p}_m} \right\rangle$$

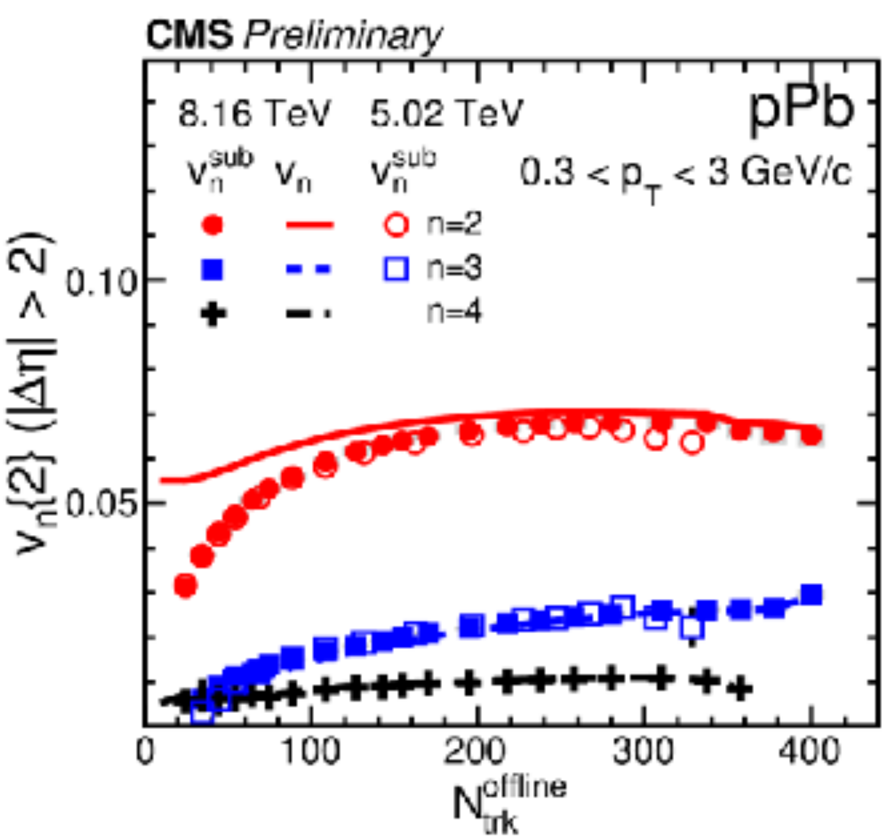
$$c_2\{2\} = \frac{\kappa_2\{2\}}{\kappa_0\{2\}}\,, \quad c_2\{4\} = \frac{\kappa_2\{4\}}{\kappa_0\{4\}} - 2\left(\frac{\kappa_2\{2\}}{\kappa_0\{2\}}\right)^2\,, \ \ldots$$

Multi-particle quark correlations

Ordering in two particle Fourier harmonics similar to data



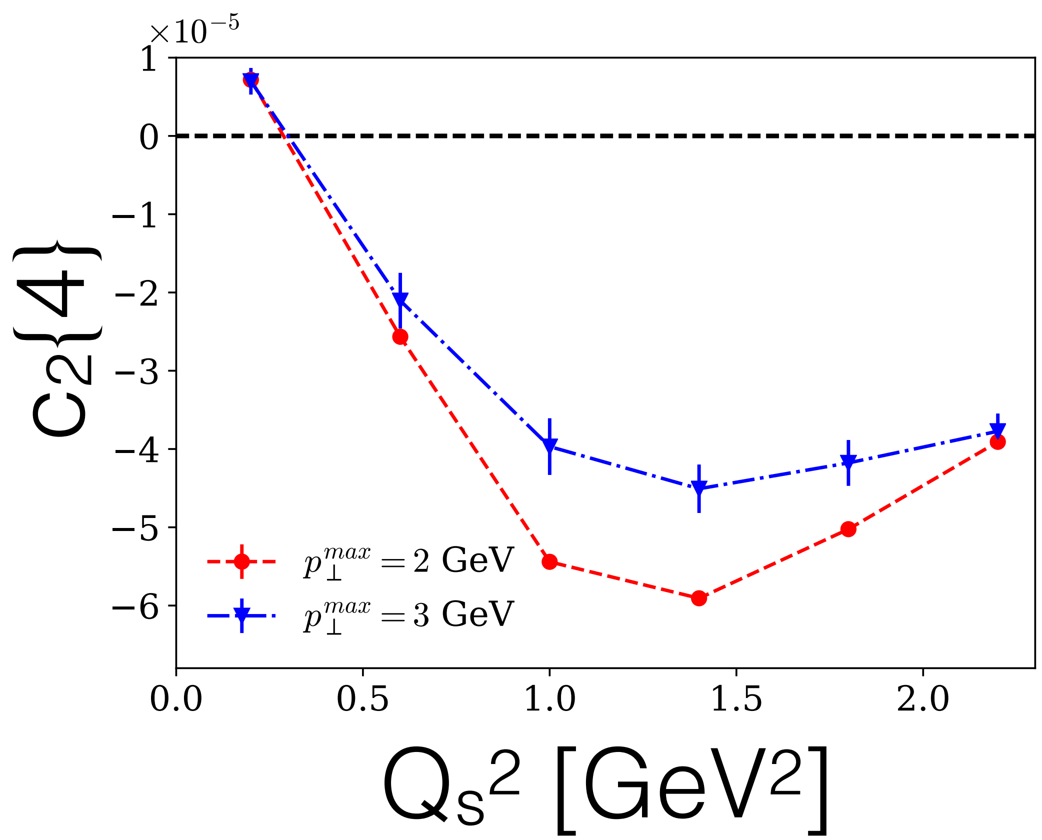
Dusling, MM, Venugopalan PRL 120 (2018)



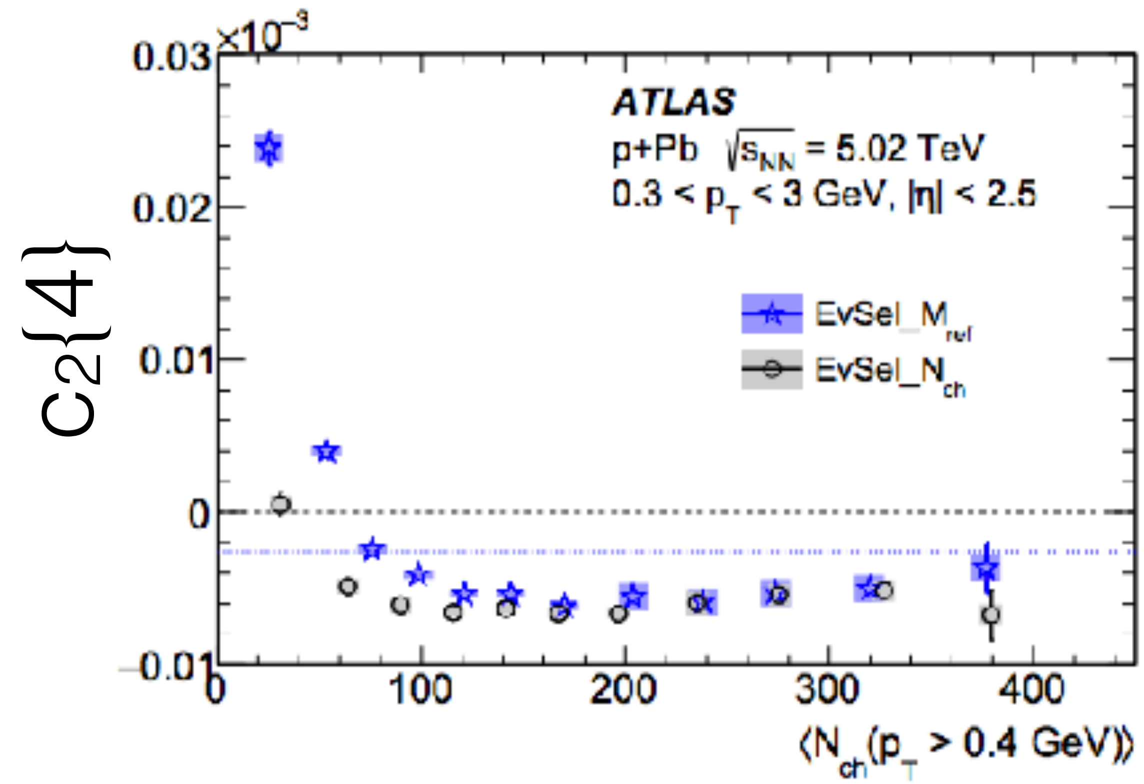
CMS-PAS-HIN-16-022

Multi-particle quark correlations

$c_2\{4\}$ becomes negative for increasing Q_s



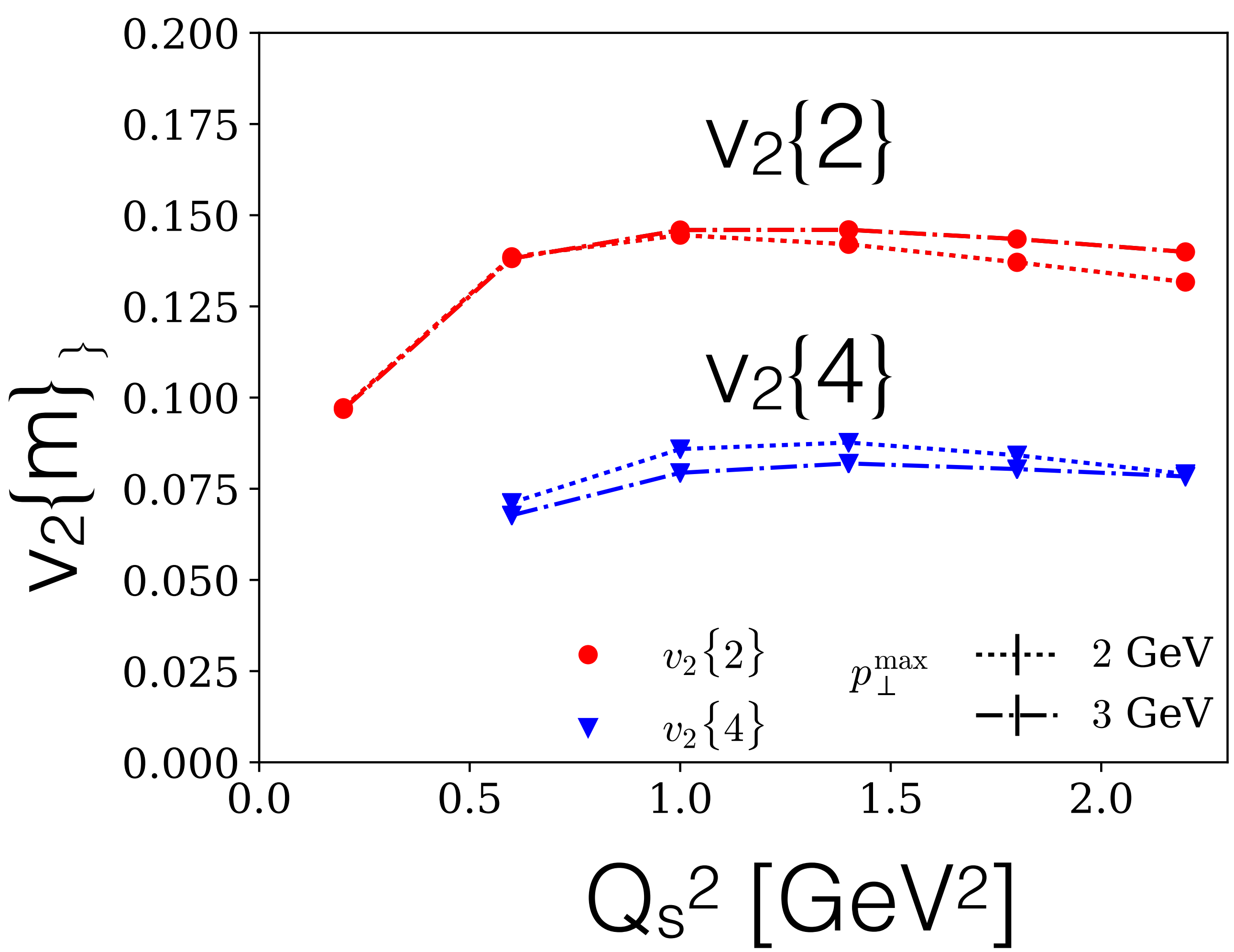
Dusling, MM, Venugopalan PRD 97 (2018)



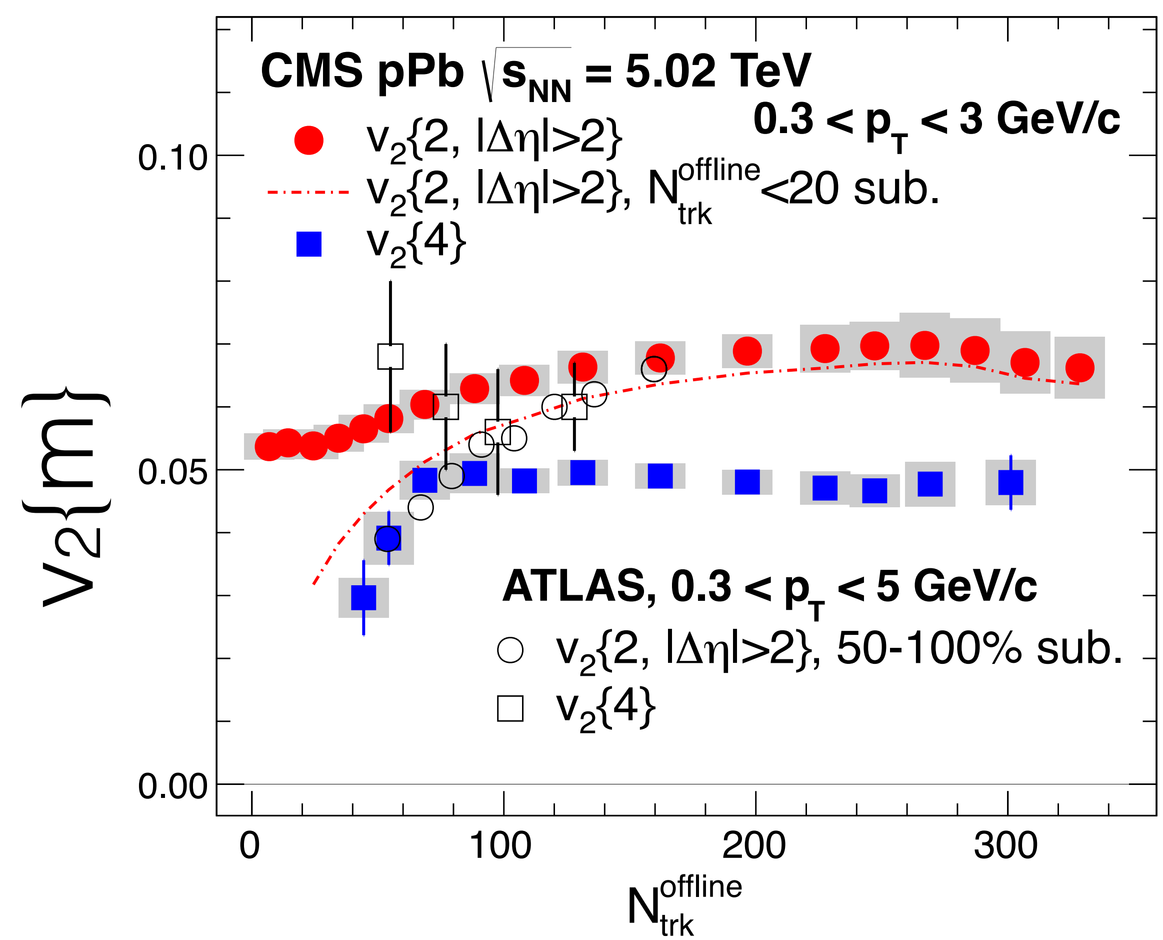
ATLAS EPJC 77 (2017)

Mild dependence on maximum integrated $p_\perp$

Multi-particle quark correlations



Dusling, MM, Venugopalan PRL 120 (2018)

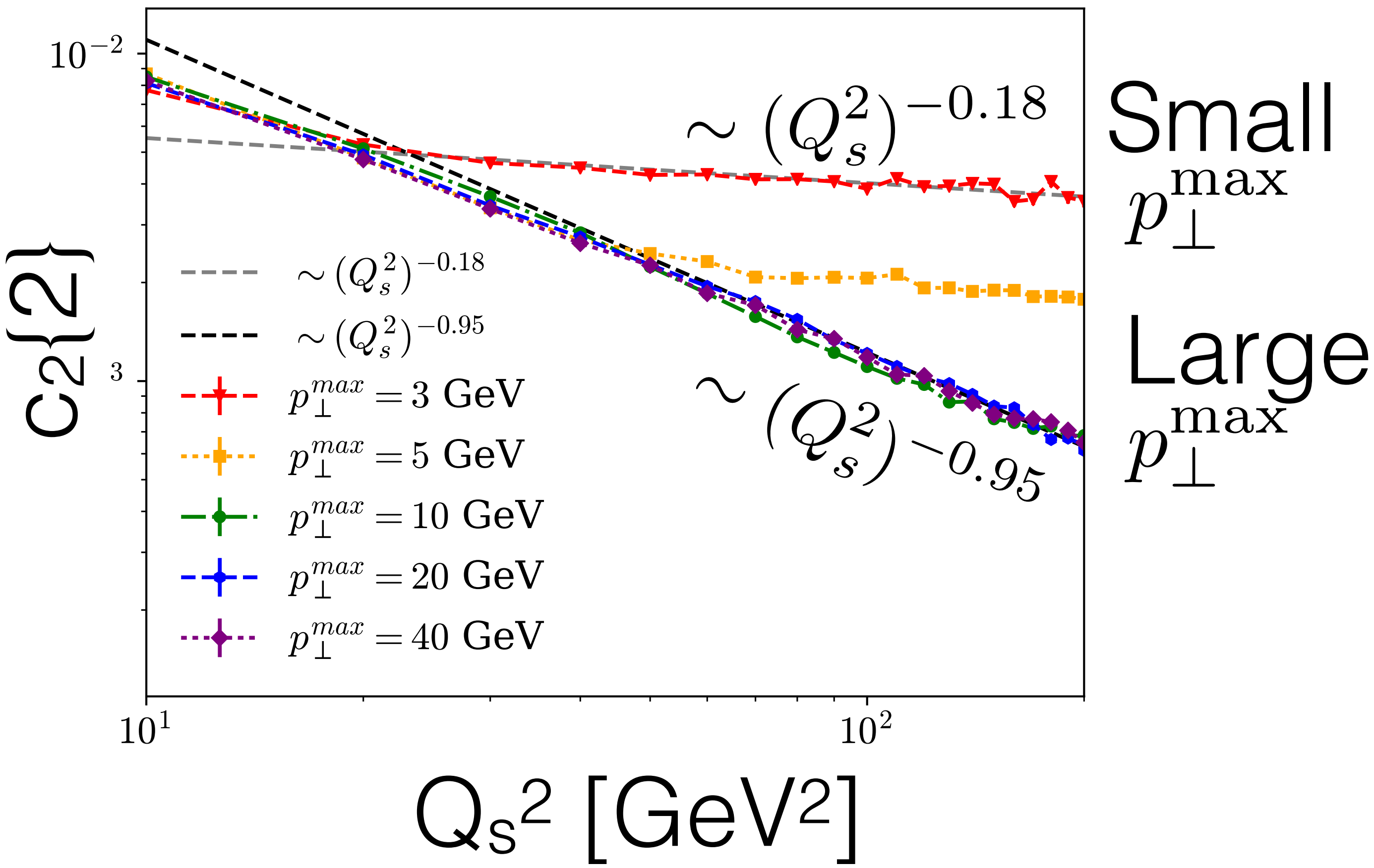


CMS PLB 724 (2013) 213

No inverse scaling by number of domains in CGC and data

Scale dependence

Two dimensionless scales: $Q_s^2 B_p$, the number of domains, and the ratio of resolution scales, $Q_s^2/(p_\perp^{\max})^2$.



$(p_\perp^{\max})^2 \lesssim Q_s^2$: probe coarse graining over multiple domains

$(p_\perp^{\max})^2 \gtrsim Q_s^2$: probe resolves area less than domain size

Scaling with inverse number of domains seen only for large $p_\perp^{\max}$

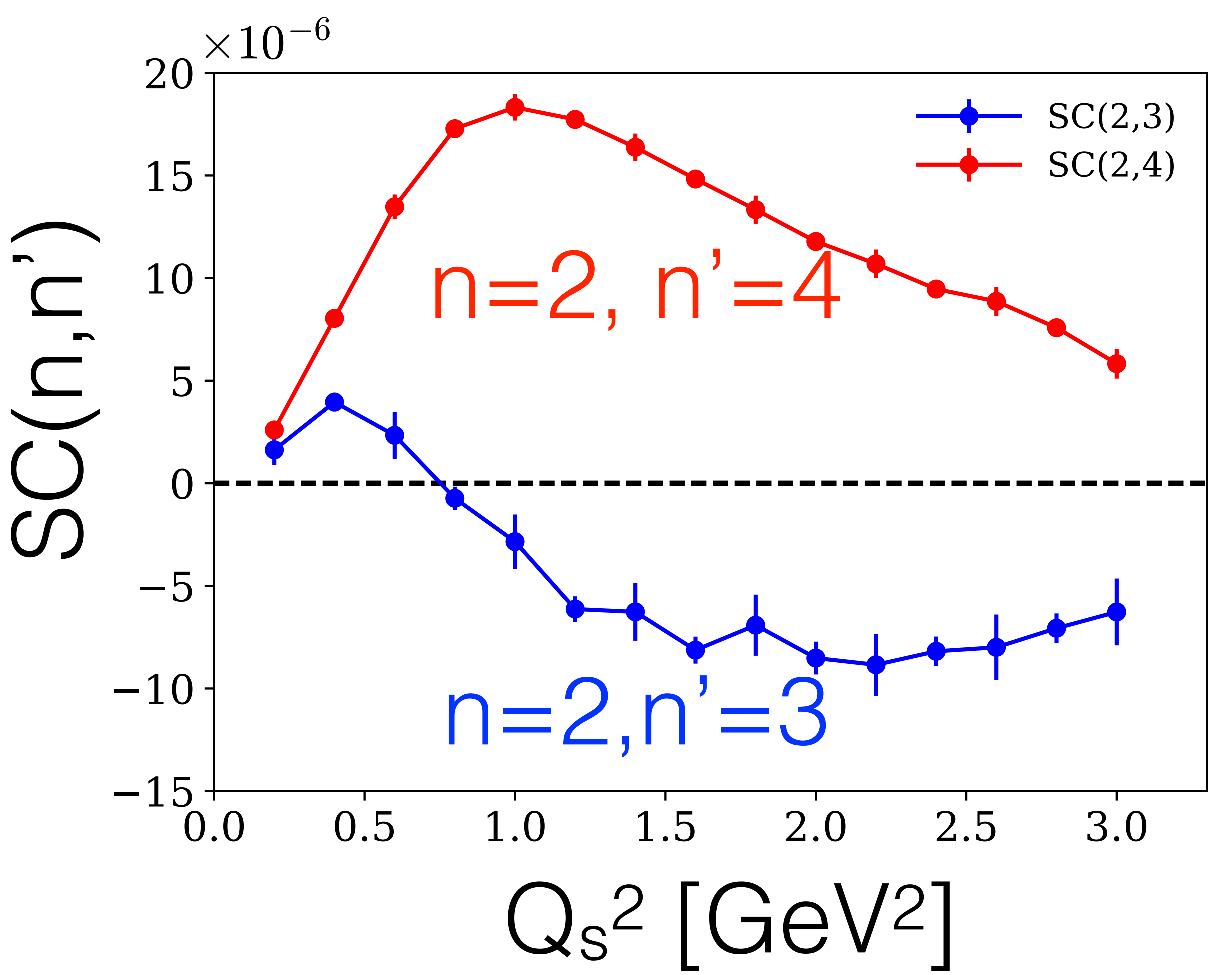
Dusling, MM, Venugopalan PRD 97 (2018)

Symmetric Quark Cumulants

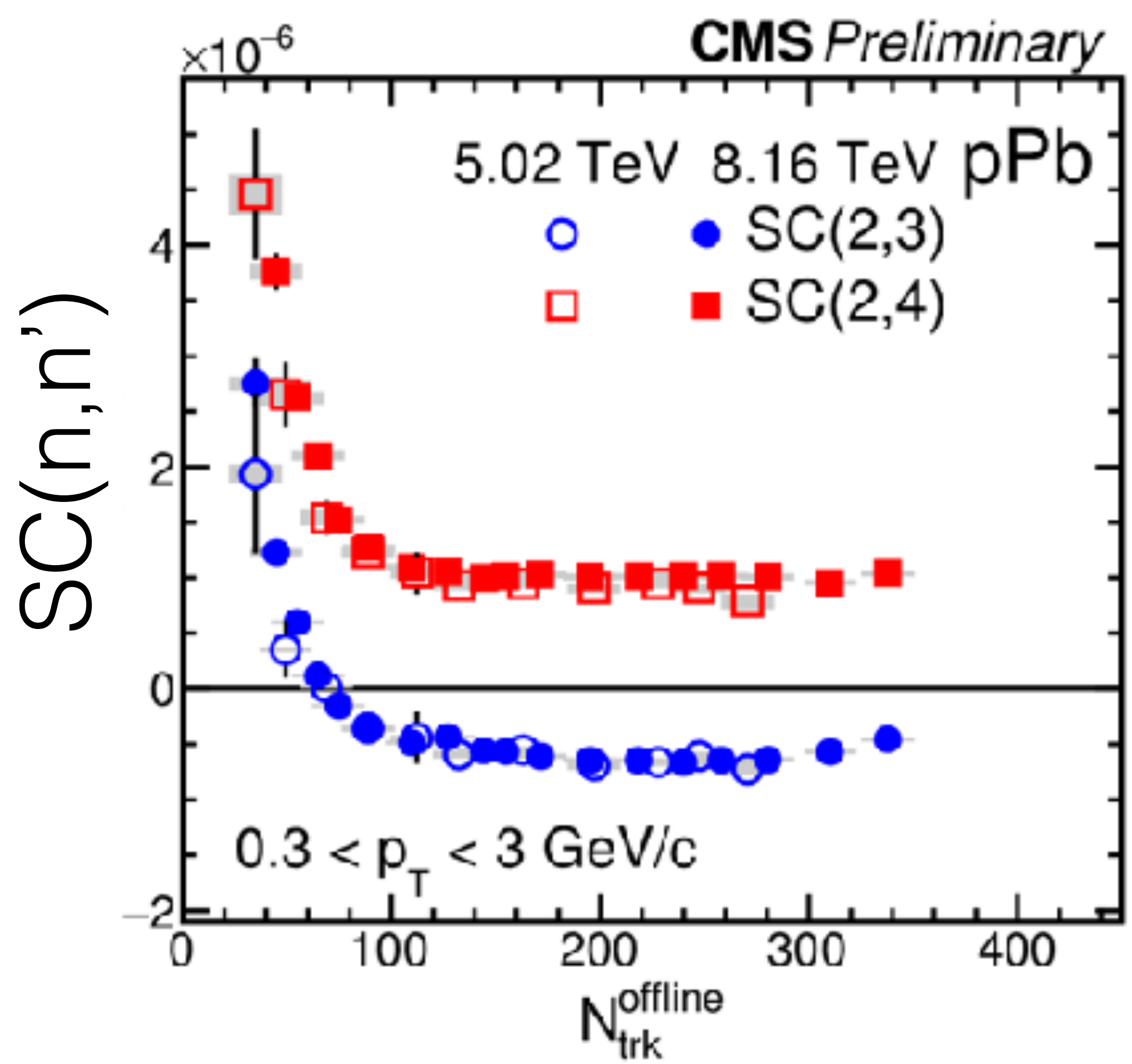
Symmetric cumulants: mixed harmonic cumulants

$$\mathrm{SC}(n,n') = \langle e^{i(n(\phi_1-\phi_3)-n'(\phi_2-\phi_4))}\rangle - \langle e^{in(\phi_1-\phi_3)}\rangle\langle e^{in'(\phi_2-\phi_4)}\rangle$$

Bilandzic et al, PRC 89, no. 6, 064904 (2014)



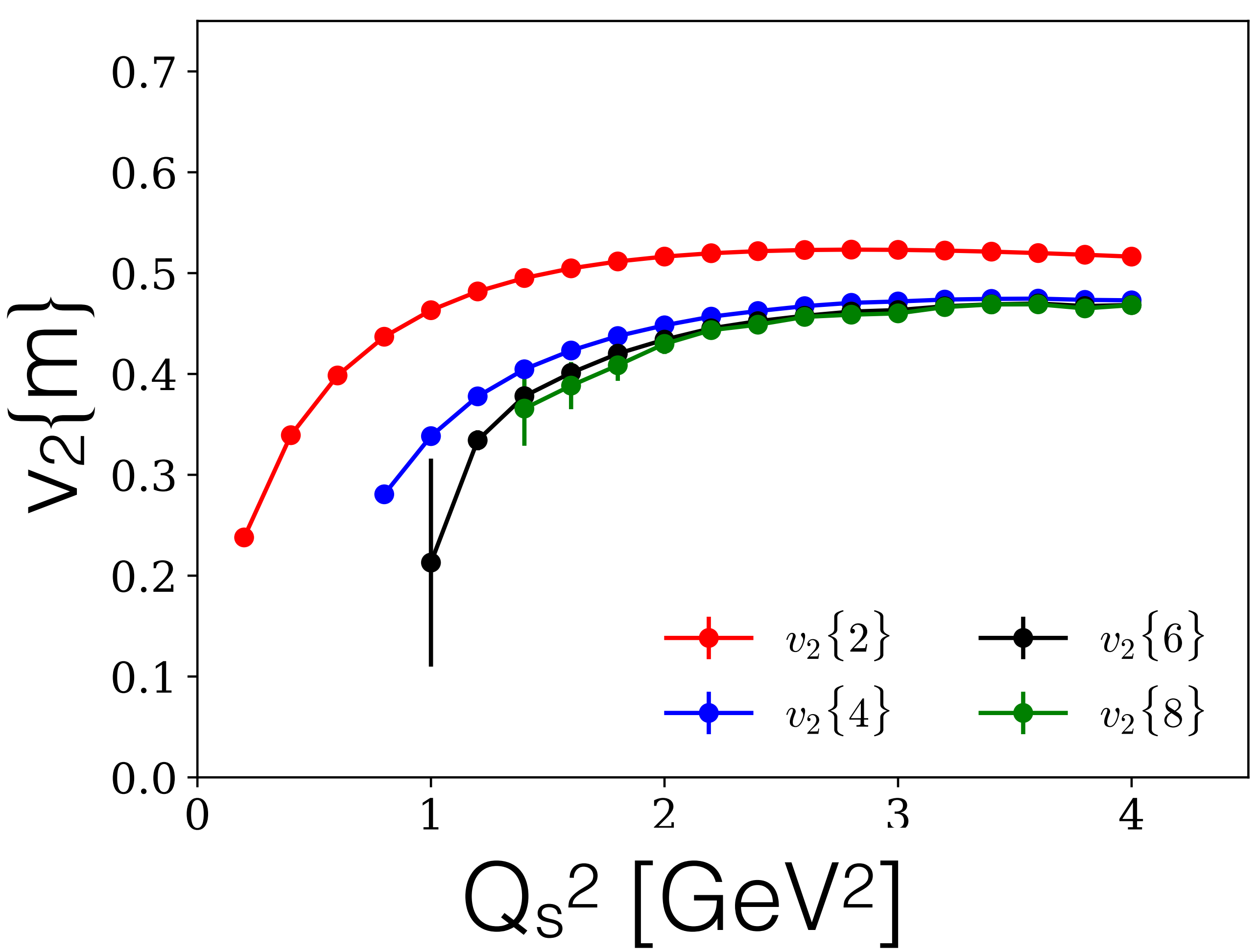
Dusling, MM, Venugopalan PRD 97 (2018)



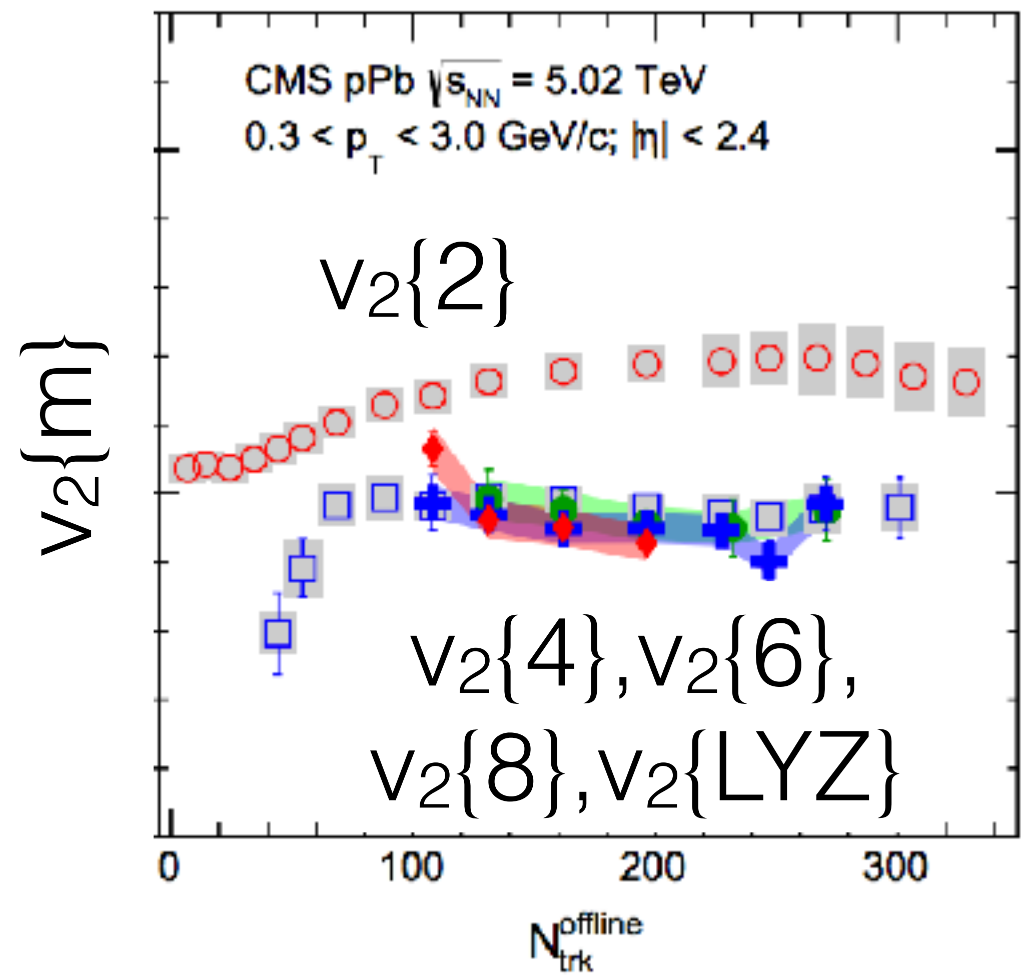
CMS-PAS-HIN-16-022

Collectivity from parton model

For computational reduction, consider Abelian version



Dusling, MM, Venugopalan PRL 120 (2018)



CMS PRL 115 (2015) 012301

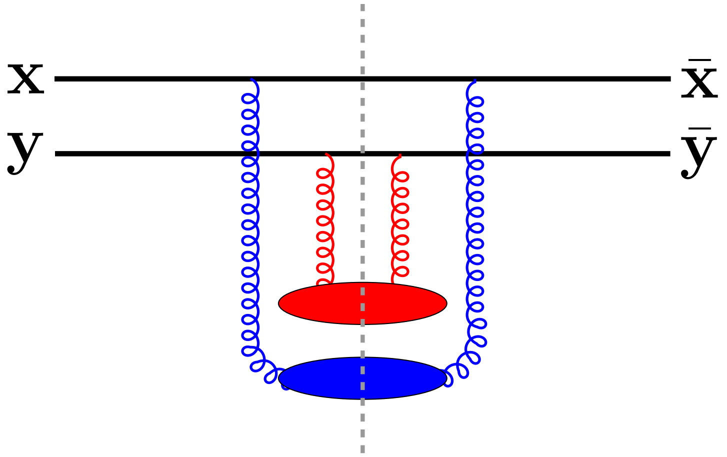
Clear demonstration that $v_2\{2\} \geq v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$

collectivity not unique to hydrodynamics

Comparison to glasma graphs

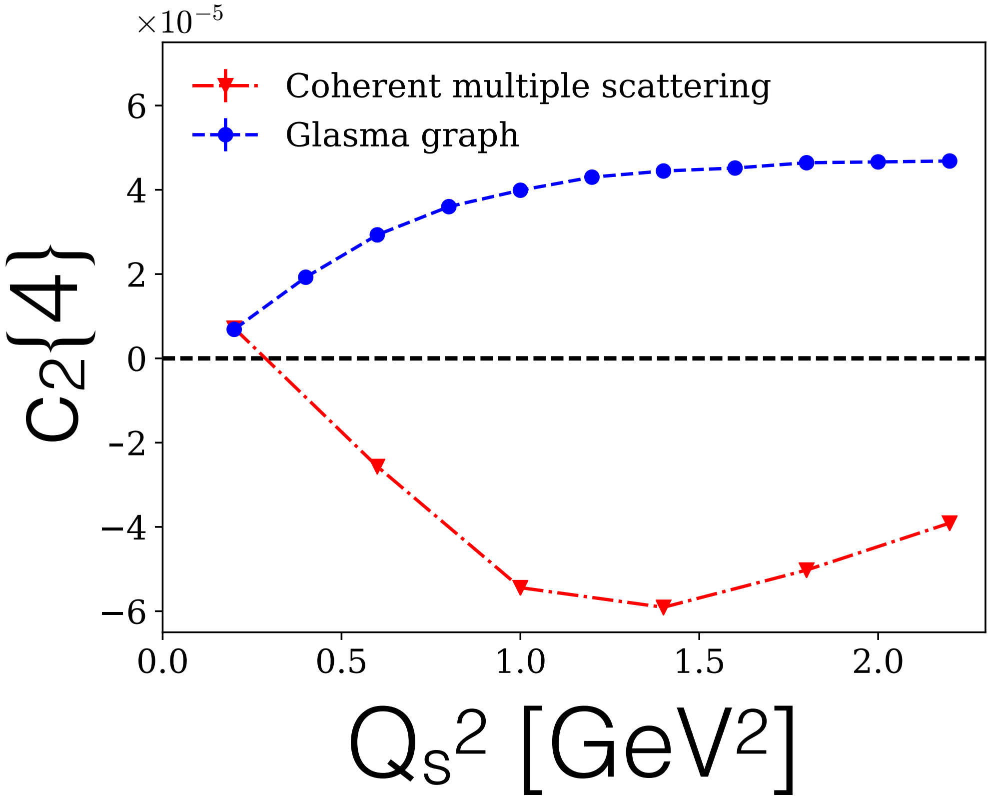
Glasma graph approximation, valid only for $p_\perp > Q_s$, only considers single gluon exchange

Dumitru, Gelis, McLerran, Venugopalan, NPA 810 (2008), Dusling, Venugopalan PRL 108 (2012), PRD 87 (2013)



Glasma graphs have very strong correlations, close to a Bose distribution (as in a laser)

Gelis, Lappi, McLerran NPA 828 (2009)

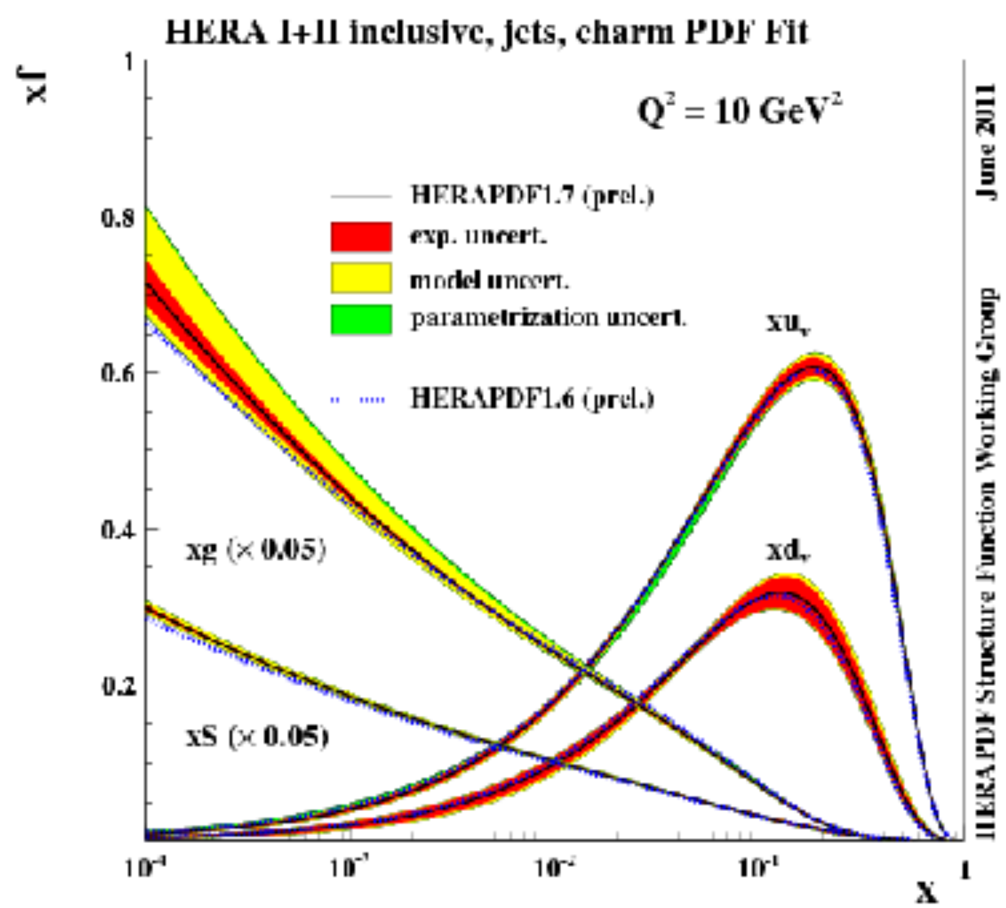


Multiple scattering suppresses higher cumulants $\rightarrow c_2\{2\}<0$

Dusling, MM, Venugopalan PRD 97 (2018)

The role of glue?

Previous discussion only included quarks scattering off CGC…



Zeus and H1 - arXiv:1112.2107

What about gluons, which are dominant at small x or high energies?

Dilute-dense CGC EFT

Determine initial gluon densities with MC-Glauber+IP-Sat (IP-Glasma IC)

Kowalski, Teaney, Phys.Rev. D68 (2003),
Schenke, Tribedy, Venugopalan PRL 108 (2012)

Compute scattering of gluons off saturated nuclear target in dilute-dense CGC

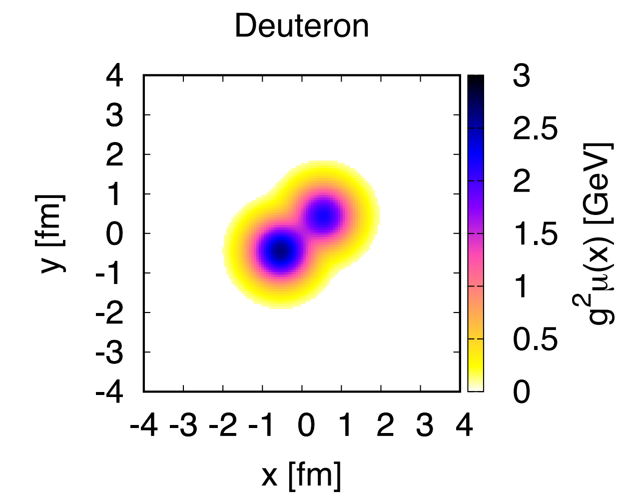
Kovner, Wiedemann PRD 64 (2001)
Dumitru, McLerran NPA 700 (2002),
Blaizot, Gelis, Venugopalan NPA 743 (2004)
McLerran, Skokov NPA 959 (2017)

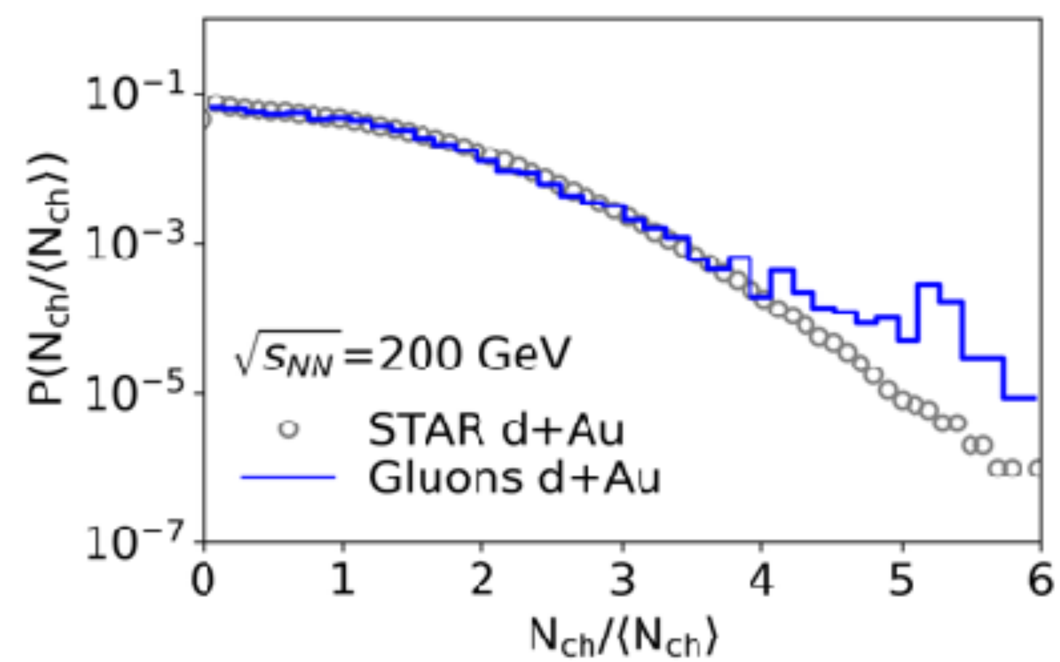
Generates negative binomial distributions from first principles, not an input!

Schenke, Tribedy, Venugopalan PRC 86 (2012)
McLerran, Tribedy NPA 945 (2016)

Good agreement found with STAR d+Au multiplicity distribution

Color charge density

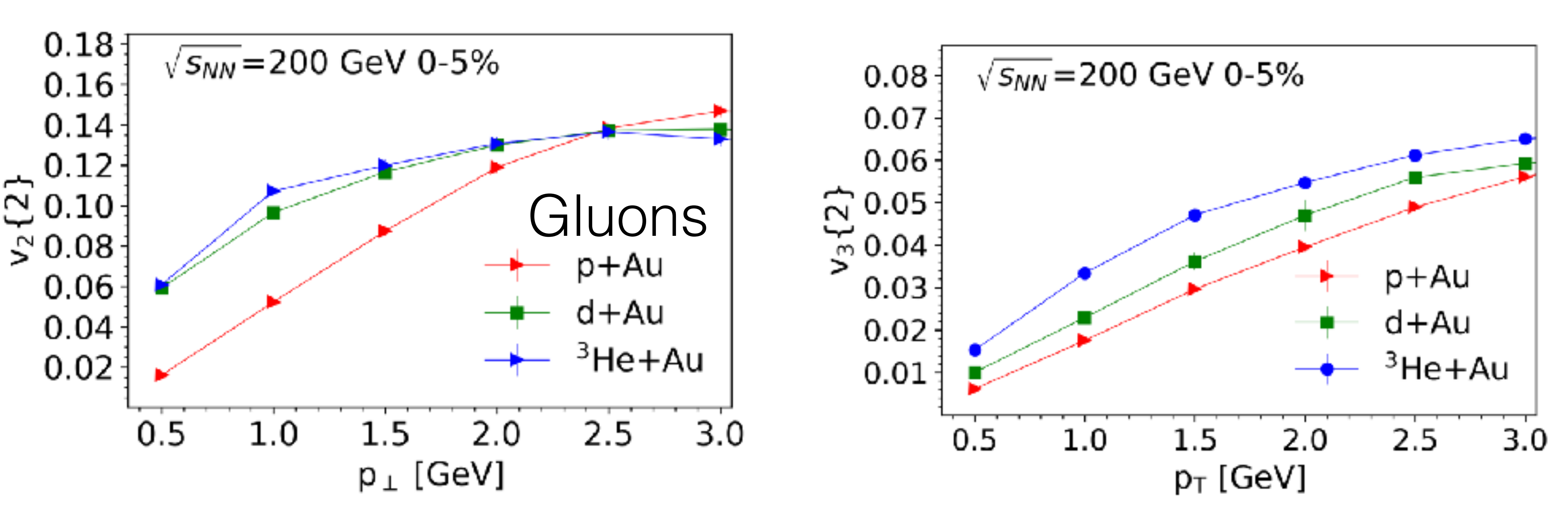




MM, Skokov, Tribedy, Venugopalan arXiv:1805.09342
STAR PRC 79 (2009)

Hierarchy of anisotropies across systems

System size dependence at RHIC captured by CGC initial state gluon correlations



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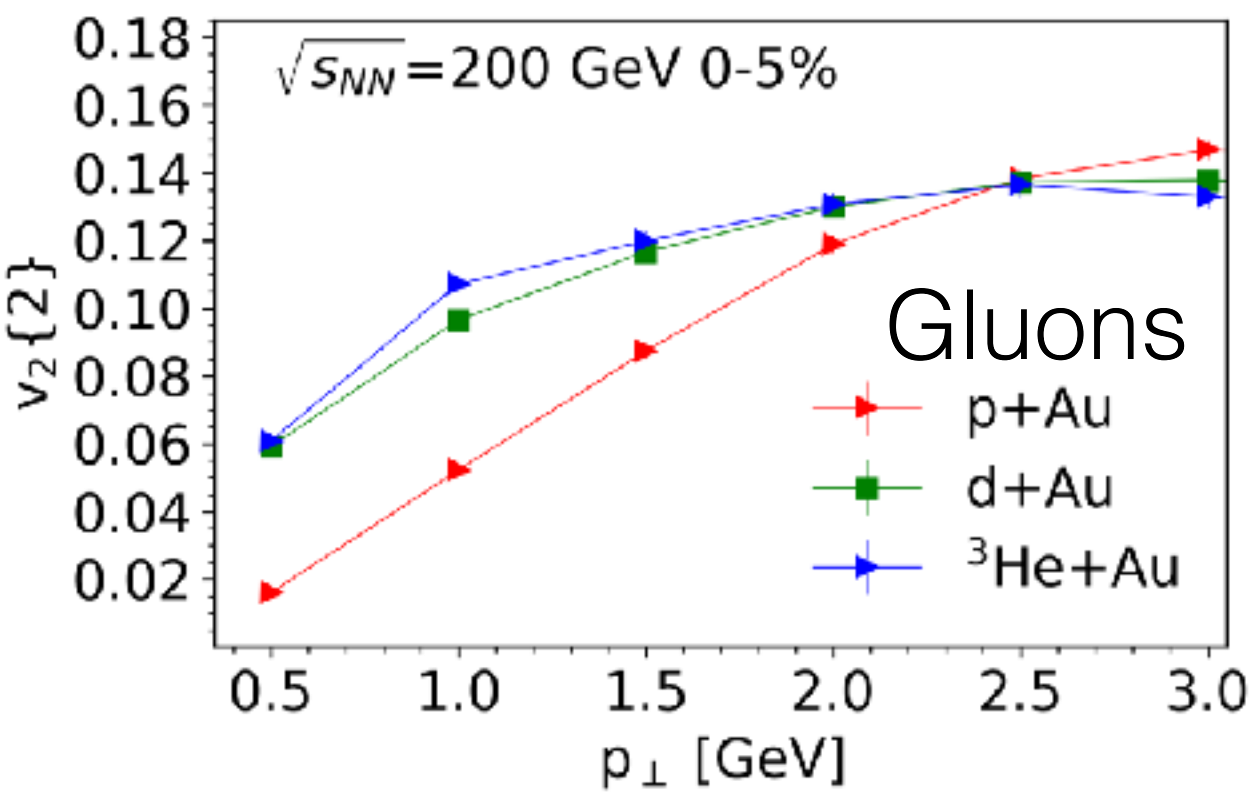

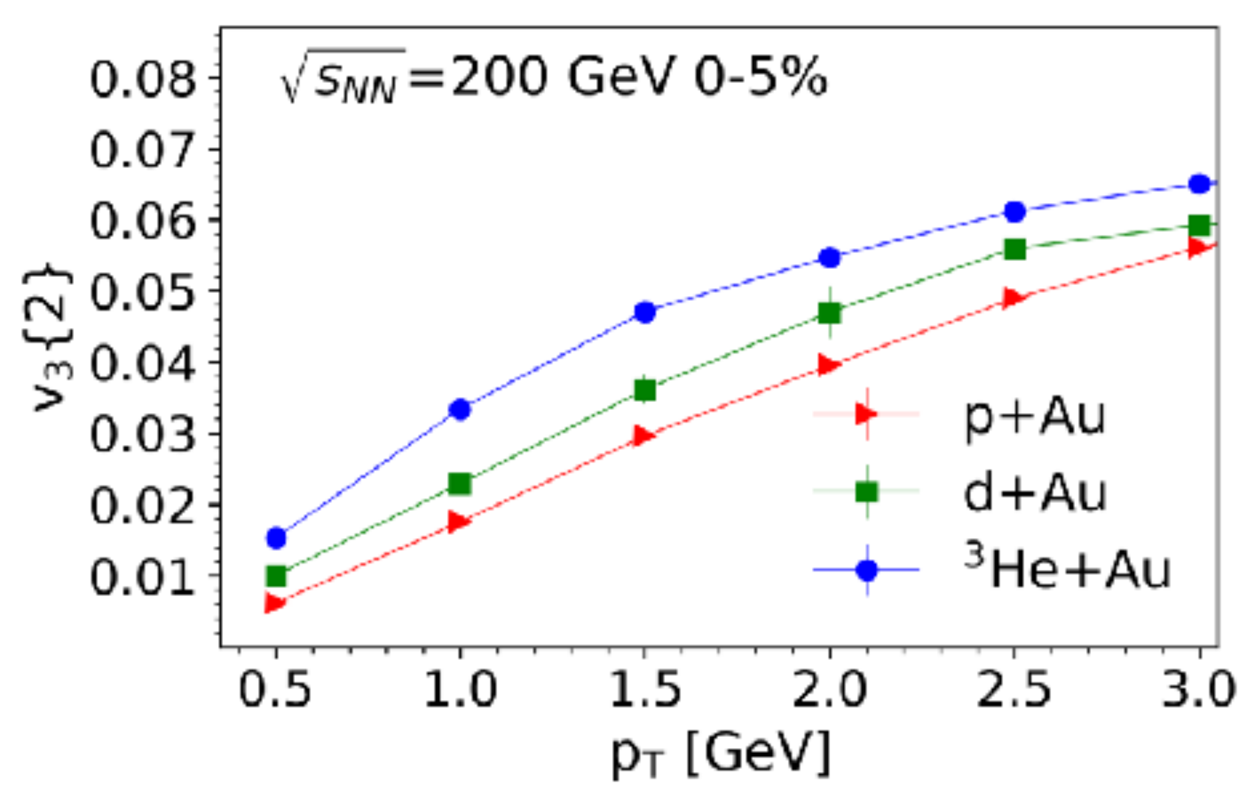

MM, Skokov, Tribedy, Venugopalan arXiv:1805.09342

Fixed centrality bin $\longmapsto$ larger average N_{ch} for larger systems

$\longmapsto$ larger average Q_s $\longmapsto$ more correlations

Quantifying systematic uncertainties

Dilute-dense approximation: high density effects need to be quantified

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All parameters are fixed, even for p and ^{3}He, by fit to STAR d+Au multiplicity distribution. Would be useful to have p/^{3}He+Au multiplicity distributions

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Nuclear wave function: strong short-range correlations (measured at JLab). Exciting prospect; quantify influence on high multiplicity events in ^{3}He+Au

c.f. Hen, Miller, Piasetzky, Weinstein Rev.Mod.Phys. 89 (2017);
Cruz-Torres, Schmidt, Miller, Weinstein, Barnea, Weiss, Piasetzky, Hen arXiv:1710.07966
Hen, MM, Schmidt, Venugopalan, in progress.

Quantifying systematic uncertainties

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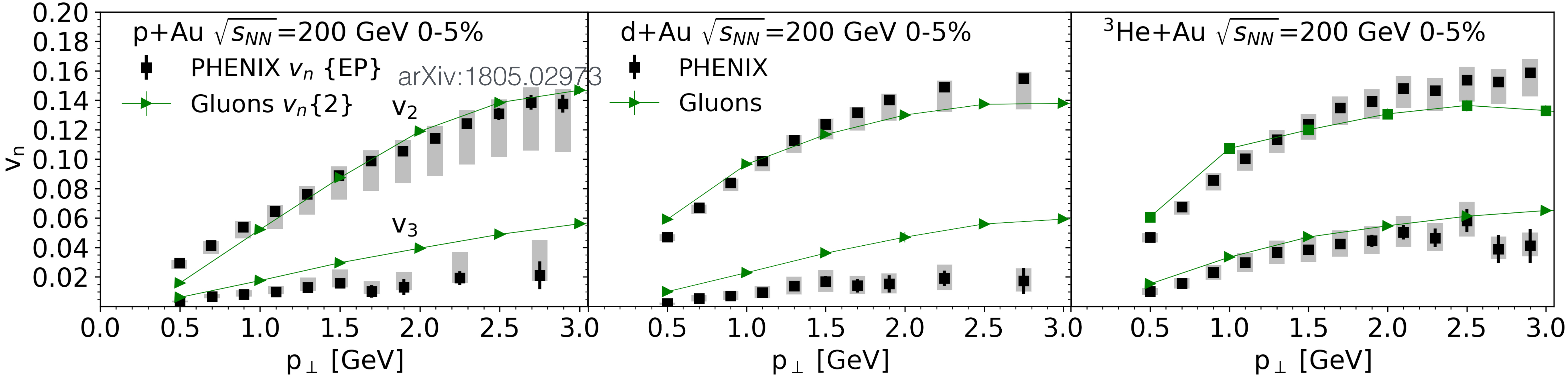
Hen, MM, Schmidt, Venugopalan, in progress.

Fragmentation: CGC+ Lund string model phenomenologically successful for mass ordering, can be applied here

e.g. Schenke, Schlichting, Tribedy, Venugopalan, PRL 117 (2016) no.16, 162301

Gluon correlations vs RHIC data for small systems



MM, Skokov, Tribedy, Venugopalan, arXiv:1805.09342

Key features of system dependence captured by initial state gluon correlations

v_3 known to be fluctuation dominated — mismatch on high multiplicity tail needs to be better understood

Alver, Roland PRC 81 (2010)

Dilute-dense CGC scaling

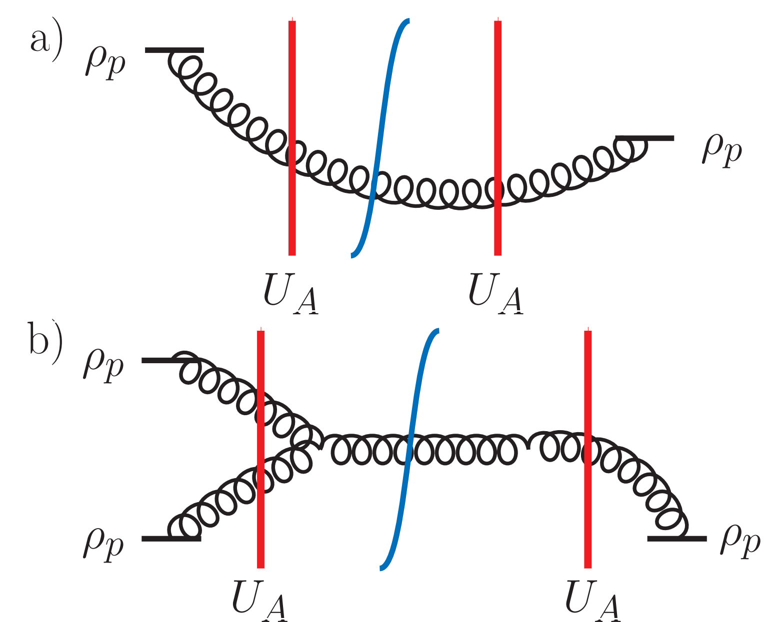
In dilute-dense CGC, consider all orders of color charge density ρ in target, first order for projectile

Odd harmonics come about via additional gluon interaction: first saturation correction

McLerran, Skokov NPA 959 (2017), Kovchegov, Skokov PRD 97 (2018)

$$\frac{dN^{\mathrm{even}}(\mathbf{k}_\perp)}{d^2k\,dy} \sim \int \Omega^2 \sim \#\rho^2$$

$$\frac{dN^{\mathrm{odd}}(\mathbf{k}_\perp)}{d^2k\,dy} \sim \int \Omega^3 \sim \#\rho^3$$



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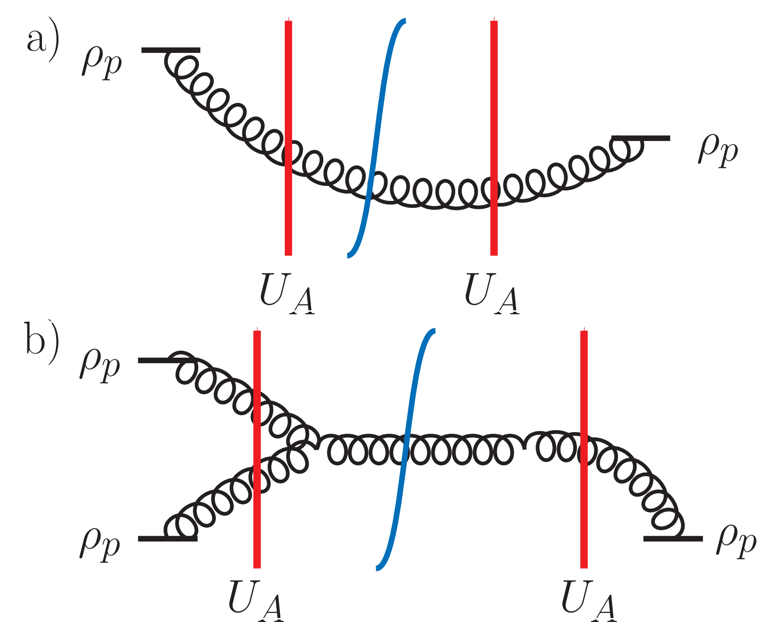

Even/odd harmonics depend on different factors of ρ_p

MM, Skokov, Tribedy, Venugopalan, in preparation

Dilute-dense CGC scaling

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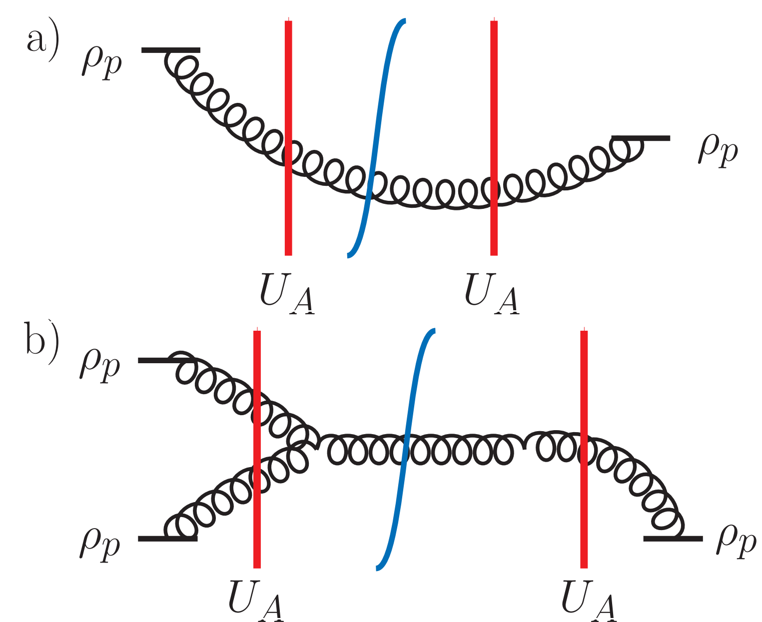


Even/odd harmonics depend on different factors of ρ_p

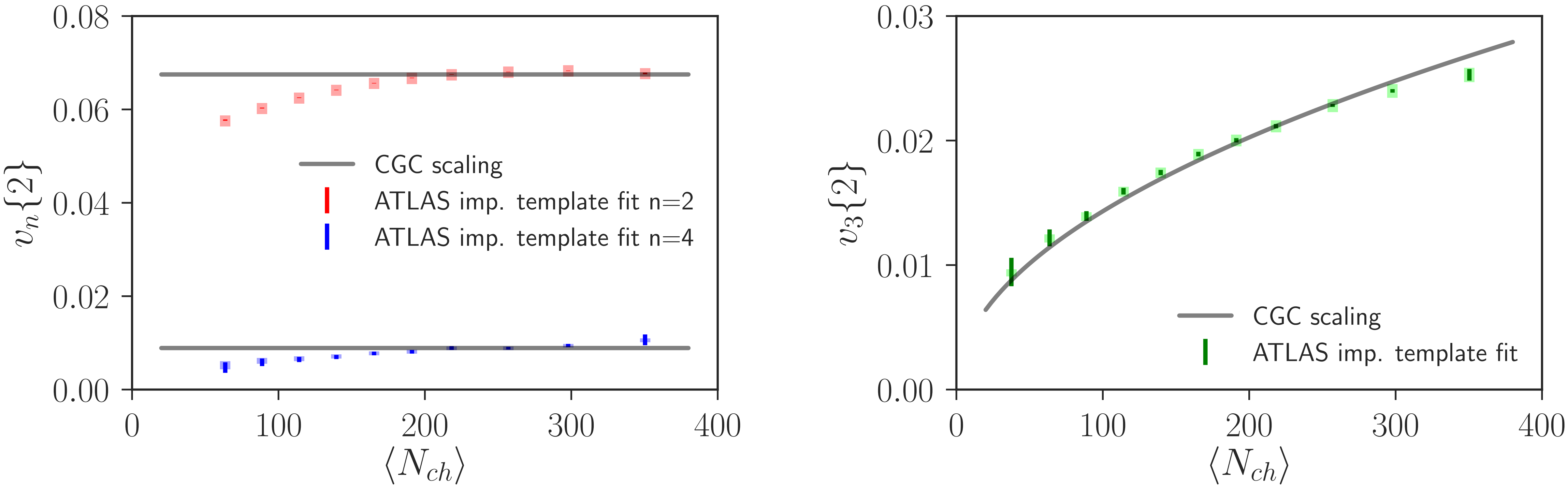
Multiplicity driven by ρ_p, so dilute-dense CGC scaling is then

$$\boxed{v_{2n}\{2\} \sim N_{ch}^{0}\ ,\ \ v_{2n+1}\{2\} \sim N_{ch}^{1/2}}$$

MM, Skokov, Tribedy, Venugopalan, in preparation

Dilute-dense CGC scaling

Fixing proportionality coefficient at a single multiplicity for each v_n



MM, Skokov, Tribedy, Venugopalan, in preparation

High projectile density effects probably responsible for large N_{ch} deviation

Scaling from fluctuations, may then explain some of peripheral A+A signal

Basar, Teaney PRC 90 (2014)

Conclusions

Multiparticle collectivity demonstrated through purely initial state correlations with simple proof of principle parton model

Dusling, MM, Venugopalan PRL 120, 042002 (2018), PRD 97, 016014 (2018)

Full dilute-dense CGC framework able to describe system size hierarchy of v_2 and v_3 at RHIC — systematic uncertainties need to be quantified further

MM, Skokov, Tribedy, Venugopalan, arXiv:1805.09342

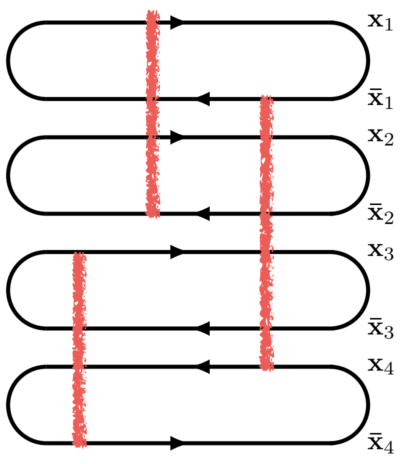
CGC can explain multiplicity of $v_n$dependence at LHC

MM, Skokov, Tribedy, Venugopalan, in preparation

To distinguish between hydro and initial state explanation, important to have p/^{3}He+Au multiplicity distributions and anisotropies in different event classes

Can compute $v_n\{m\}$ in framework and compare to data, such comparison also important to do in hydrodynamical models for definitive conclusions

Thanks!


$\mathbf{x}_1$
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$\bar{\mathbf{x}}_3$
$\mathbf{x}_4$
$\bar{\mathbf{x}}_4$

BACKUP