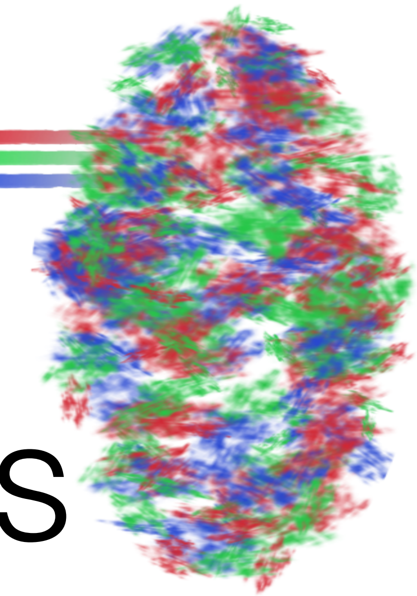


Multi-particle correlations and collectivity in small systems from the initial state

Mark Mace
Stony Brook University and Brookhaven National Lab

Probing QCD at the high energy frontier
ECT*, Trento, Italy
5/23/2018

Stony Brook University

BROOKHAVEN NATIONAL LABORATORY

Outline

1. Introduction and motivation

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

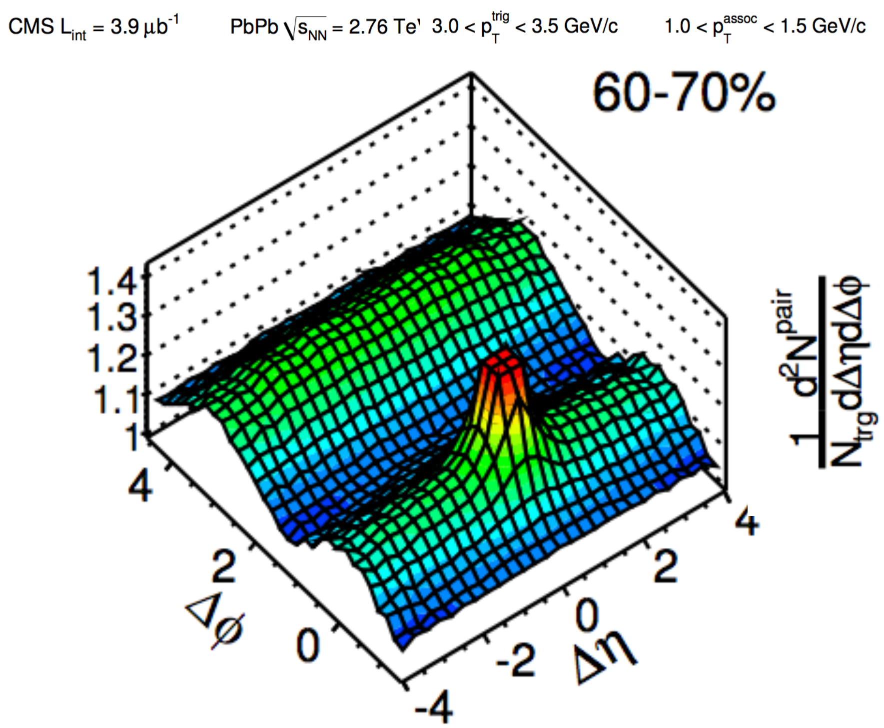
   K. Dusling, MM, R. Venugopalan PRL 120, 042002 (2018) [arXiv:1705.00745], PRD 97, 016014 (2018) [arXiv:1706.06260]

3. Demonstration of hierarchy of v_2 and v_3 across small systems in CGC EFT

   MM, V. Skokov, P. Tribedy, R. Venugopalan, arXiv:1805:XXXX

the Ridge and Collectivity

PbPb



CMS EPC 72 (2012) 10052

Flow paradigm: Event-by-event fluctuations of initial transverse geometry transported via hydrodynamics, resulting in a final state momentum correlations

Alver, Roland, PRC 81 (2010), Alver, Gombeaud, Luzum, Ollitrault, PRC 82 (2010)

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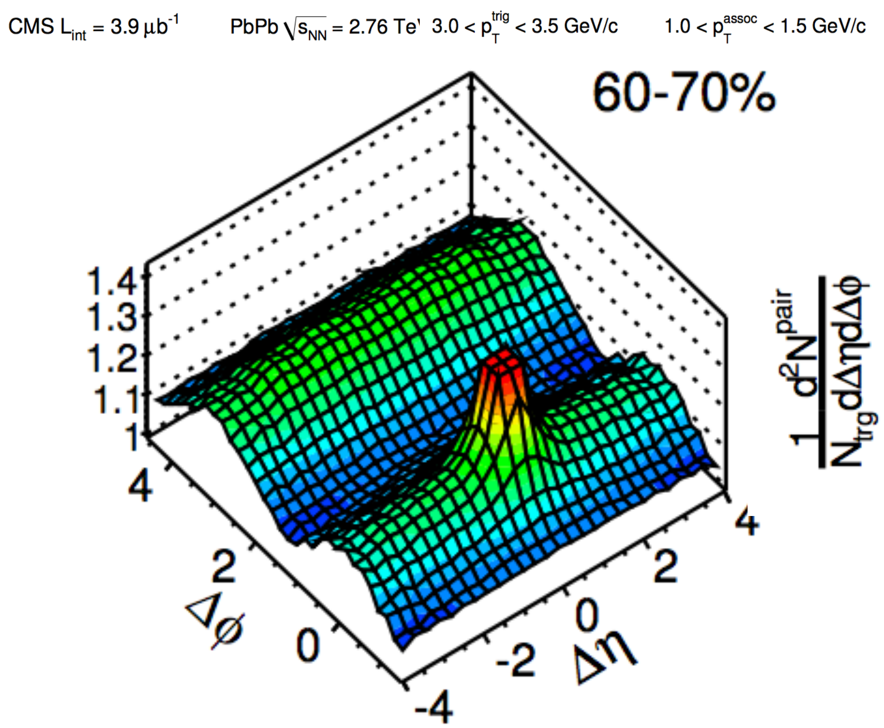

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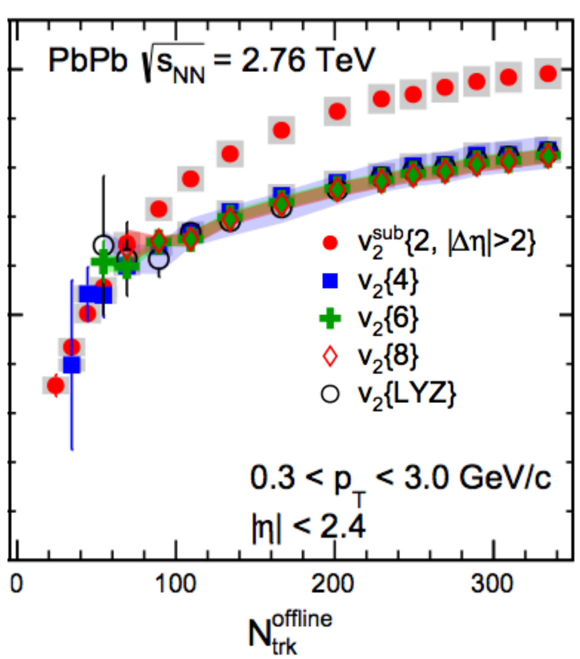

CMS PRL 115 (2015) 012301

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From single *collective* fluid source, multi-particle distribution factorizes into product of single particle distributions

Naturally embedded in a hydrodynamic description of particle production

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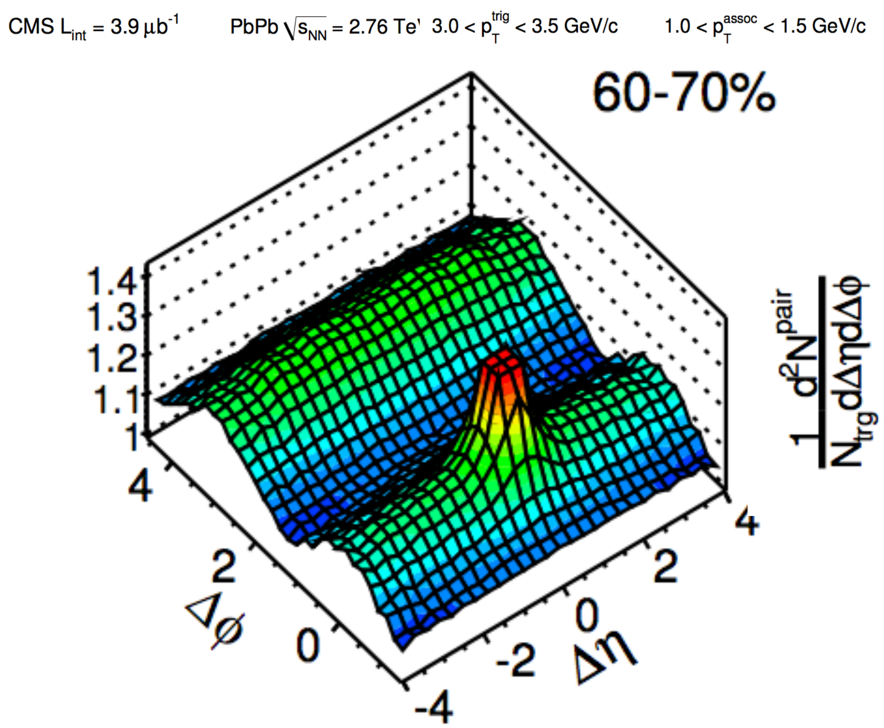

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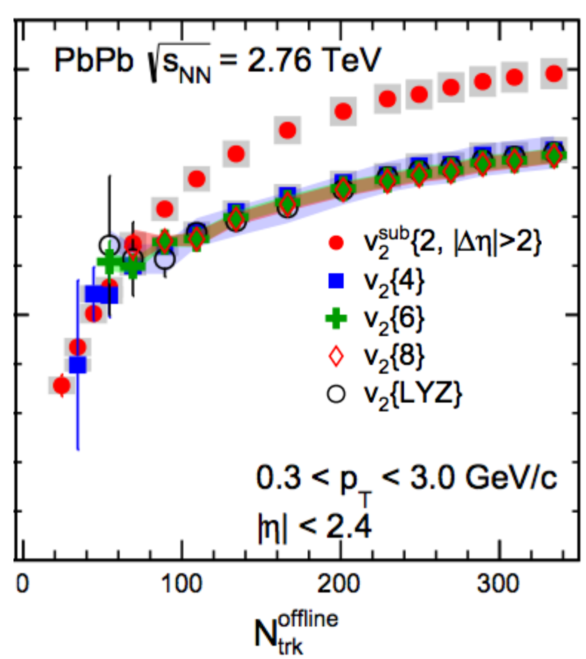

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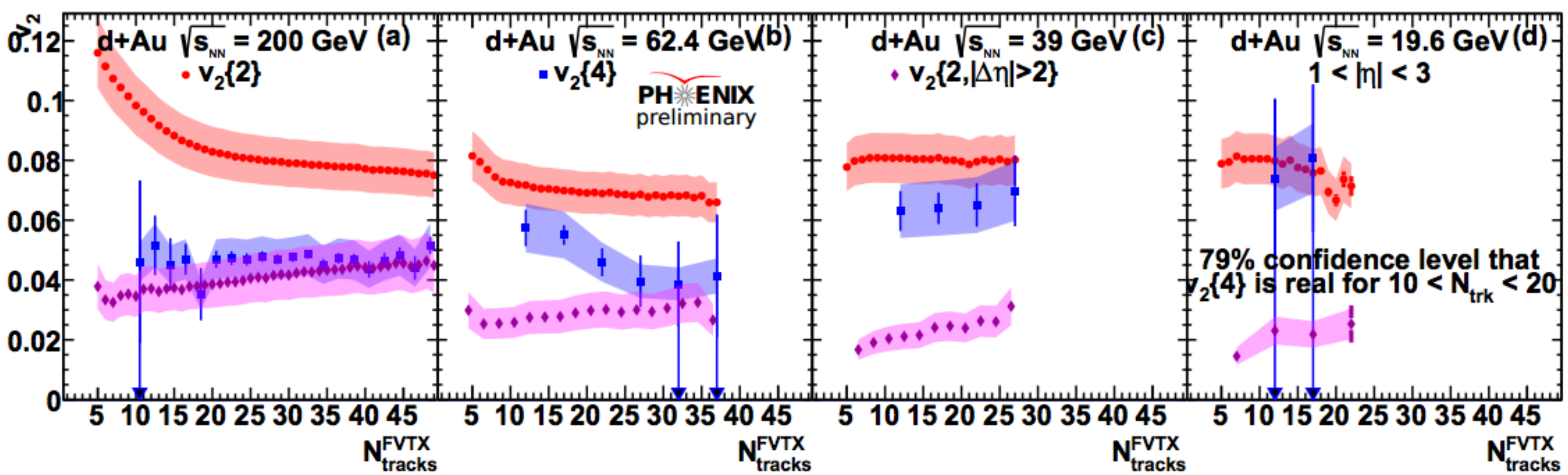
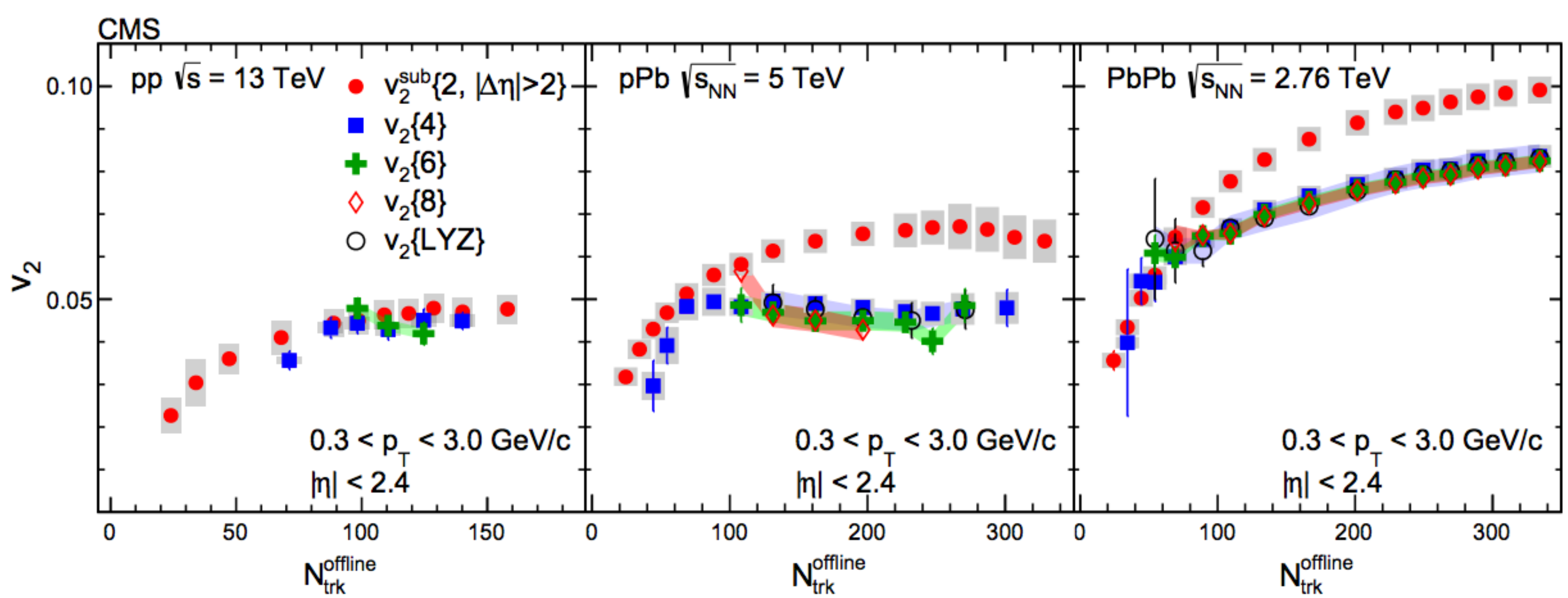
Is there a limit to the applicability of this paradigm?

Collectivity is everywhere



RHIC

PHENIX arXiv:1704.04570



LHC

CMS PRL 115 (2015) 012301

Are we seeing smallest droplets of QGP? Rare QCD configurations? Both?

Collectivity in small systems

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… is ambiguous

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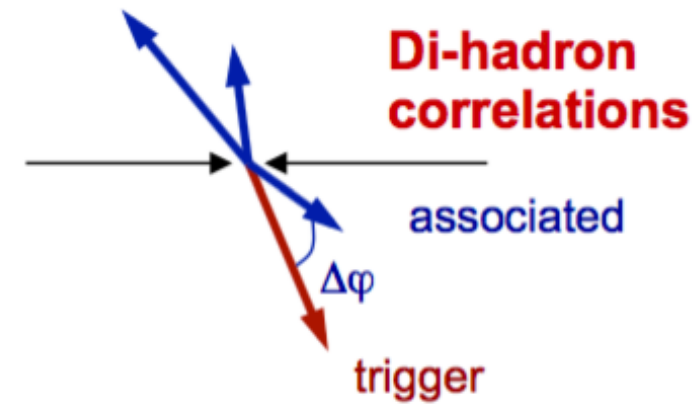

Define cumulants and corresponding Fourier harmonics

Borghini, Dinh, Ollitault PRC 64, 054901 (2001)

$$c_n\{2\} = \langle e^{ni(\phi_1-\phi_2)}\rangle \longrightarrow v_n\{2\} = (c_n\{2\})^{1/2}$$

$$c_n\{4\} = \langle e^{ni(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle^2 - 2\langle e^{ni(\phi_1-\phi_2)}\rangle^2 \rightarrow v_n\{4\} = (-c_n\{4\})^{1/4}$$

$$\cdots$$

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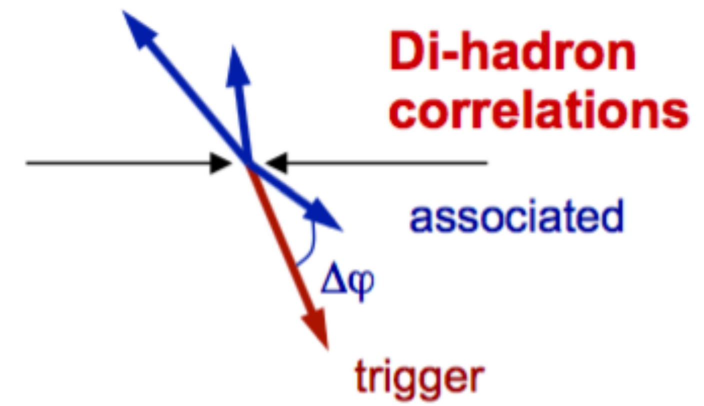

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$$\dots$$

Linear response (hydrodynamics)

$$\epsilon\{2\} \geq \epsilon\{4\} \approx \epsilon\{6\} \approx \cdots \longrightarrow v_n\{m\} \approx c_n \epsilon_n\{m\}$$

Yan, Ollitrault PRL 112 (2014) 082301, Bzdak, Skokov NPA 943 (2015)

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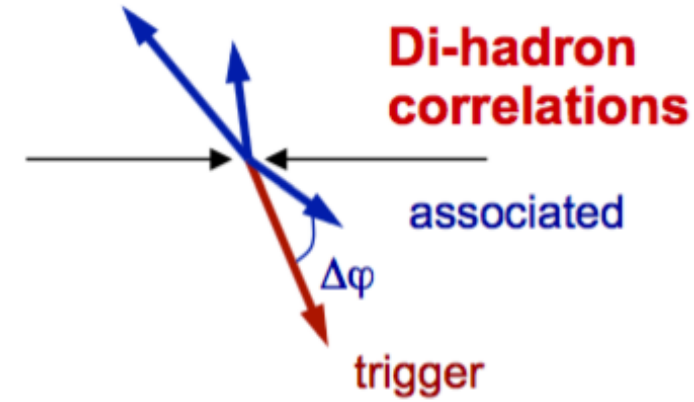

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Linear response (hydrodynamics)

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Without an absolute definition for collectivity, we take:

$$v_2\{2\} \geq v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$$

Yan, Ollitrault PRL 112 (2014) 082301, Bzdak, Skokov NPA 943 (2015)

Nonlinear Gaussian Model

Consider eikonal quark scattering off dense nuclear target with color domains of size ~$1/Q_S$, in dilute-dense/hybrid limit

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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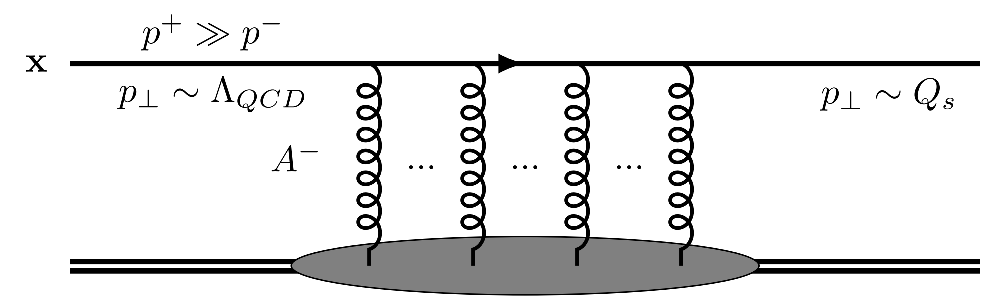

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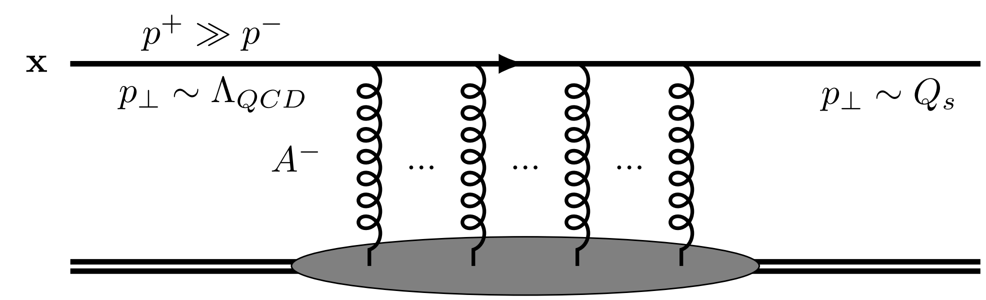


Single quark inclusive distribution

$$\left\langle \frac{dN_q}{d^2\mathbf{p}} \right\rangle \simeq \int_{\mathbf{b},\mathbf{r},\mathbf{k}} \underbrace{e^{-|\mathbf{b}|^2/B_p} e^{-|\mathbf{k}|^2 B_p}\ e^{i(\mathbf{p}-\mathbf{k})\cdot\mathbf{r}}}_{} \underbrace{\left\langle \frac{1}{N_c} \mathrm{Tr}\left(U(\mathbf{b}+\frac{\mathbf{r}}{2}) U^\dagger(\mathbf{b}-\frac{\mathbf{r}}{2}) \right) \right\rangle}_{}$$

Projectile: Wigner function

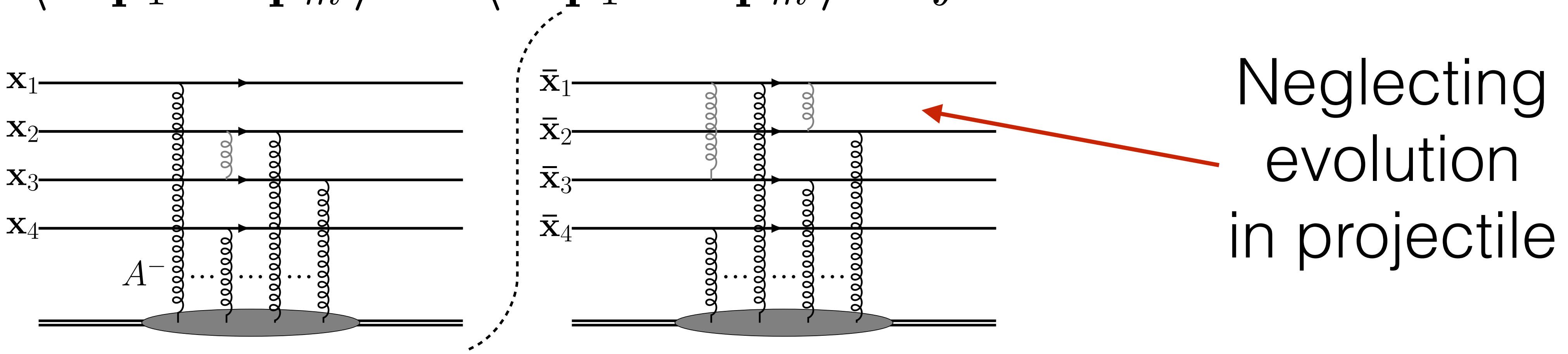
Target scattering: Dipole operator D(x,y)

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

Nonlinear Gaussian Model

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

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



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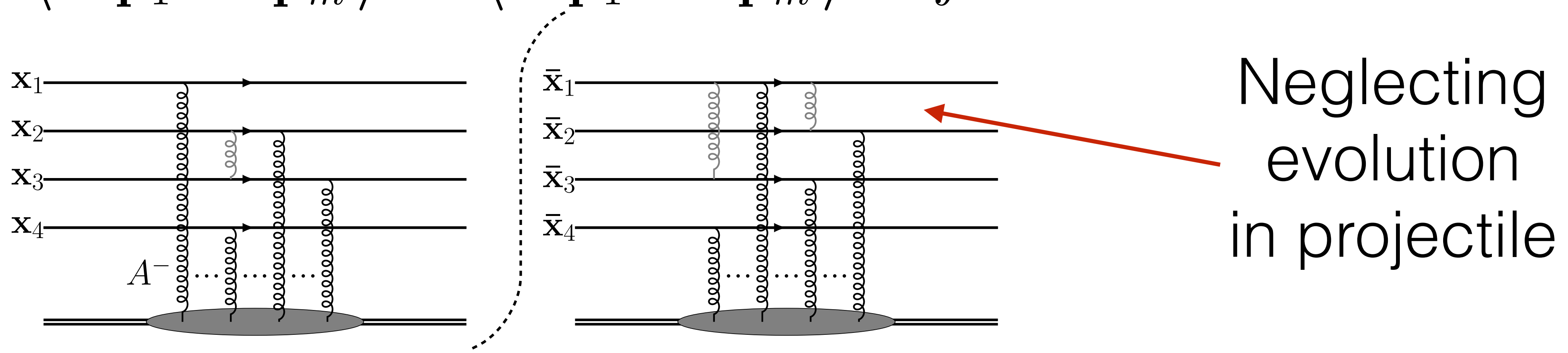

$dN/d^2\mathbf{p}$ itself is not well defined. Average over classical configurations and over all events using MV model

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

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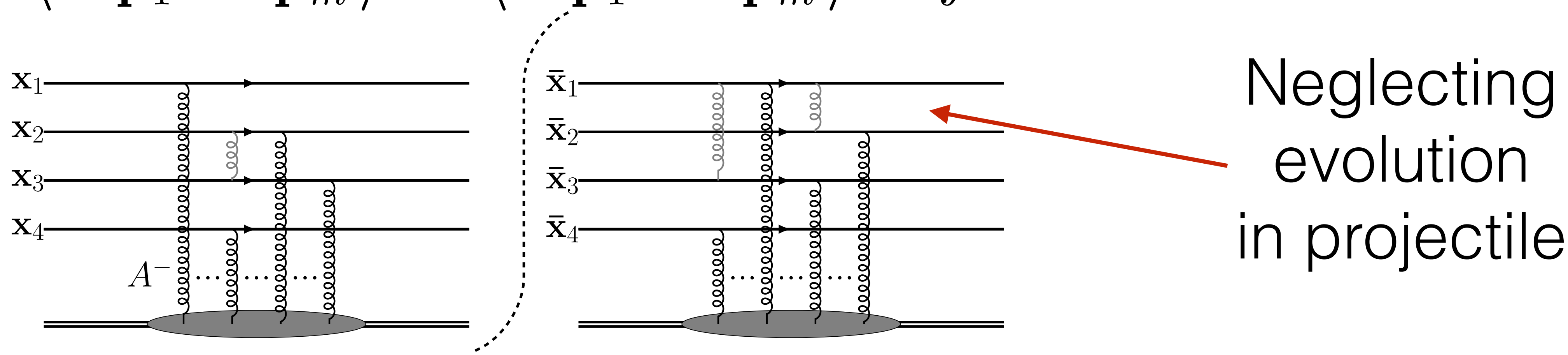

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Generate cumulants, integrate to scale $p_\perp^{max}$

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

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

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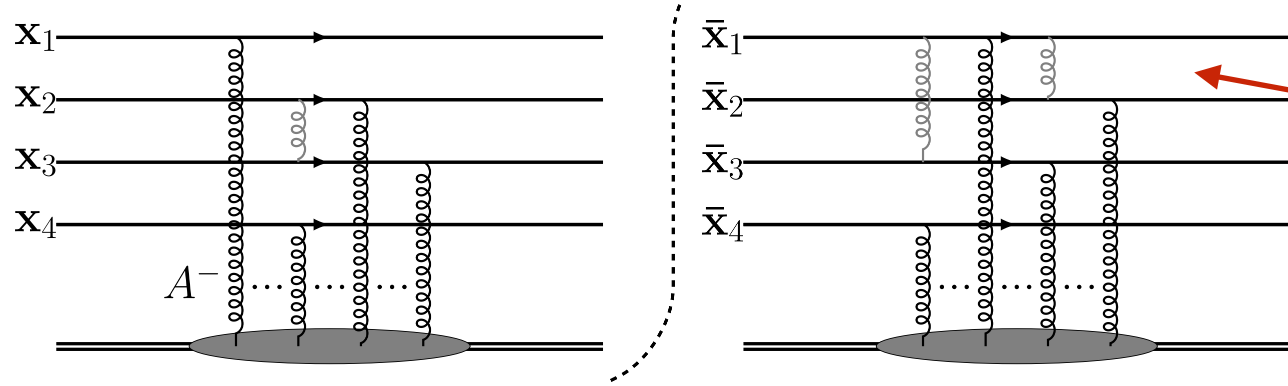

Neglecting evolution in projectile

Can also consider higher point traces (e.g. ⟨Q⟩), however for simplicity consider only dipoles — changes only quantitative

Kovner, Rezaeian Phys.Rev. D95,96 (2017)

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Dipole correlators

First, need to be able to compute correlation functions expectation values of dipoles

Consider dipole scattering matrix

$$\langle D(\mathbf{x},\mathbf{y})\rangle_U = \left\langle \frac{1}{N_c}\mathrm{tr}(U(\mathbf{x})U^\dagger(\mathbf{y})) \right\rangle$$

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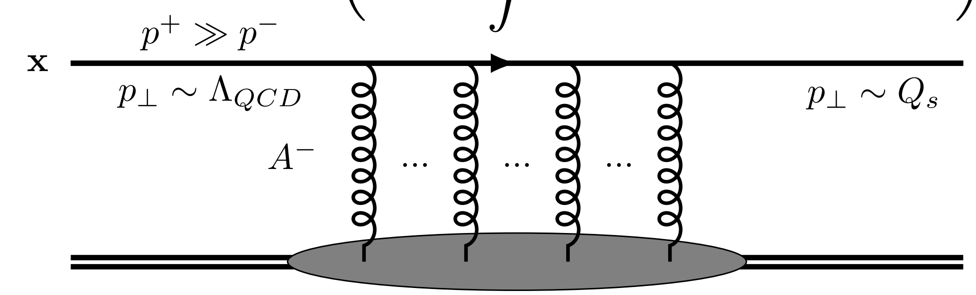

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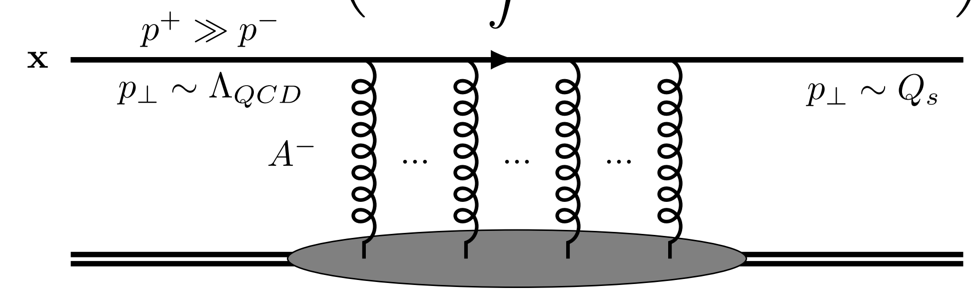

Expand out Wilson line in slices in rapidity

$$U(\mathbf{x}) = \mathcal{P}\exp\left(-ig\int dx^+ A^{a-}(\mathbf{x},x^+)t^a\right) \simeq V(\mathbf{x})[1 - igA^{a-}(\zeta,\mathbf{x})t^a + ...]$$

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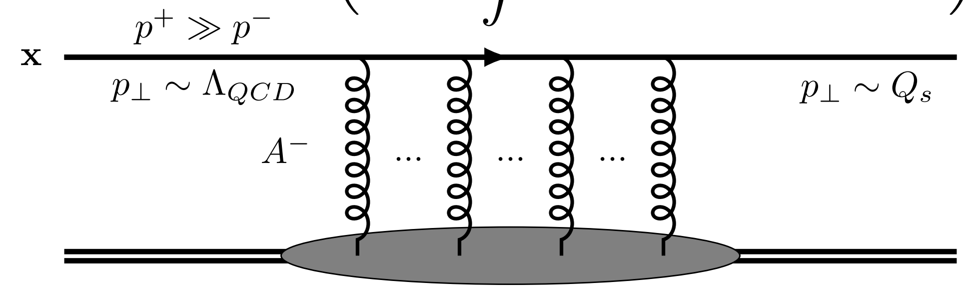

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Then gluons emissions with MV model

$$g^2 \langle A_a^-(x^+, \mathbf{x}_\perp) A_b^-(y^+, \mathbf{y}_\perp) \rangle = \delta_{ab} \delta(x^+ - y^+) L_{\mathbf{xy}}$$

where $L_{\mathbf{x}_\perp, \mathbf{y}_\perp} = -\frac{(g^2\mu)^2}{16\pi^2} |\mathbf{x} - \mathbf{y}|^2 \log\left(\frac{1}{|\mathbf{x}_\perp - \mathbf{y}_\perp| \Lambda} + e \right)$

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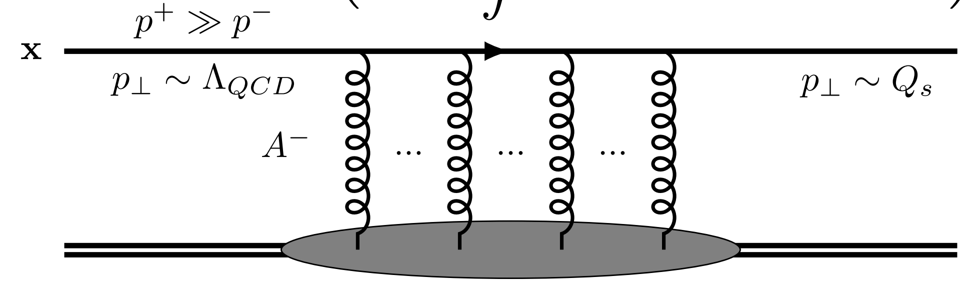

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We can re-exponentiate

$$\langle D(\mathbf{x},\mathbf{y})\rangle_U = \exp(C_F L(\mathbf{x},\mathbf{y}))$$

See arXiv:1706.06260 for details

Dipole correlators

Multiple dipole correlation functions encode projectile nucleus scattering, depends on scale Q_s

Kovner, Wiedemann, PRD 64 (2001), Blaizot, Gelis, Venugopalan. NPA 743 (2004), Dominguez, Marquet, Wu NPA 823 (2009), Dusling, MM, Venugopalan PRL 120 (2018), PRD 97 (2018), Fukushima, Hidaka JHEP (2007,2017),…

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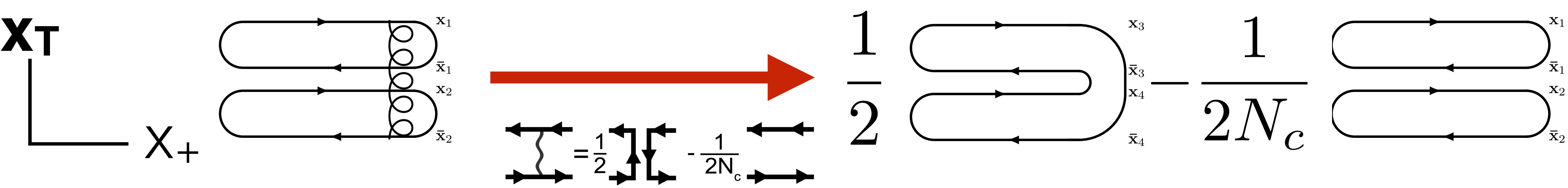

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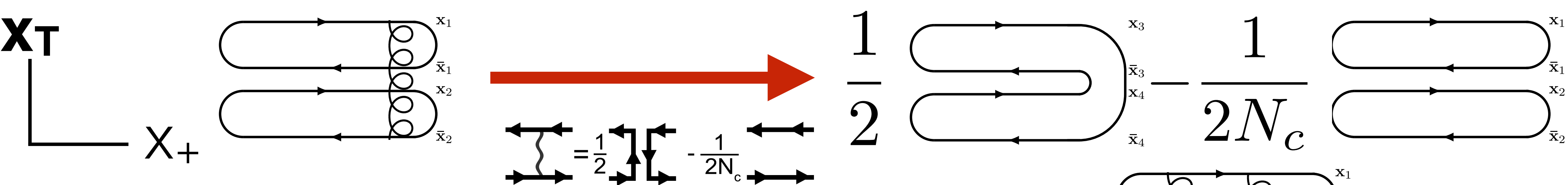
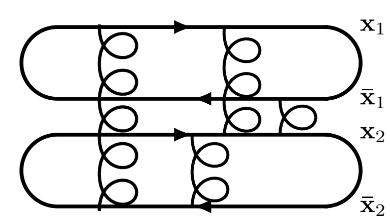


Doing this for all possible exchanges:



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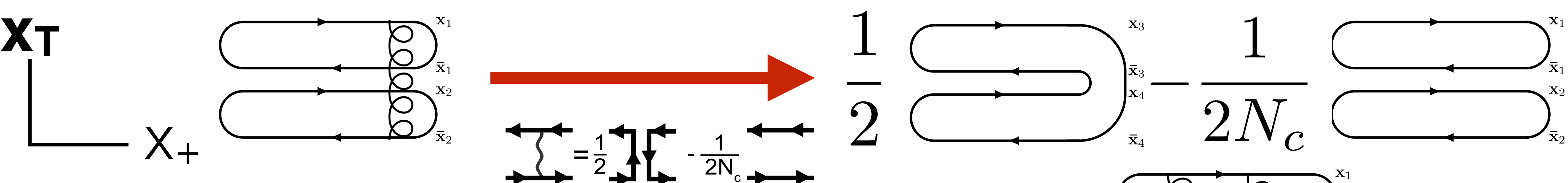

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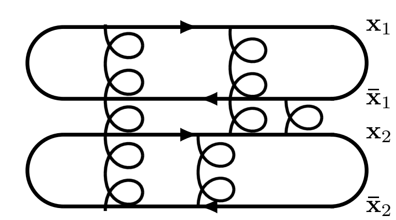

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Straightforward to generalize $\frac{d^4 N}{d^2\mathbf{p}_1 \cdots d^2\mathbf{p}_4} \simeq \int \langle DDDD \rangle$

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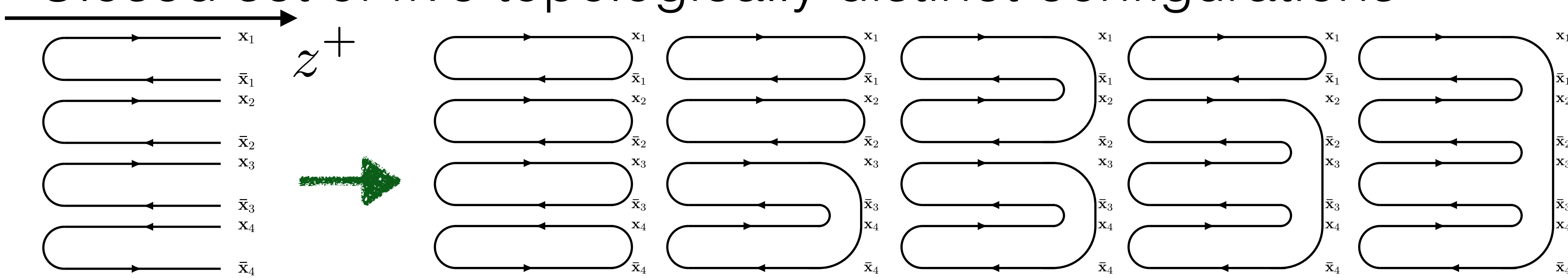
Four dipole correlators

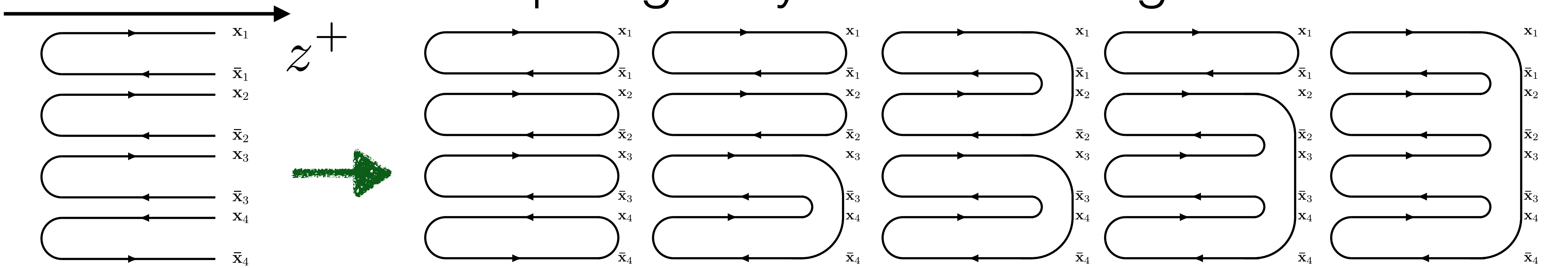
Closed set of five topologically distinct configurations



Permutations for each topology for closing on $z^+ = +\infty$

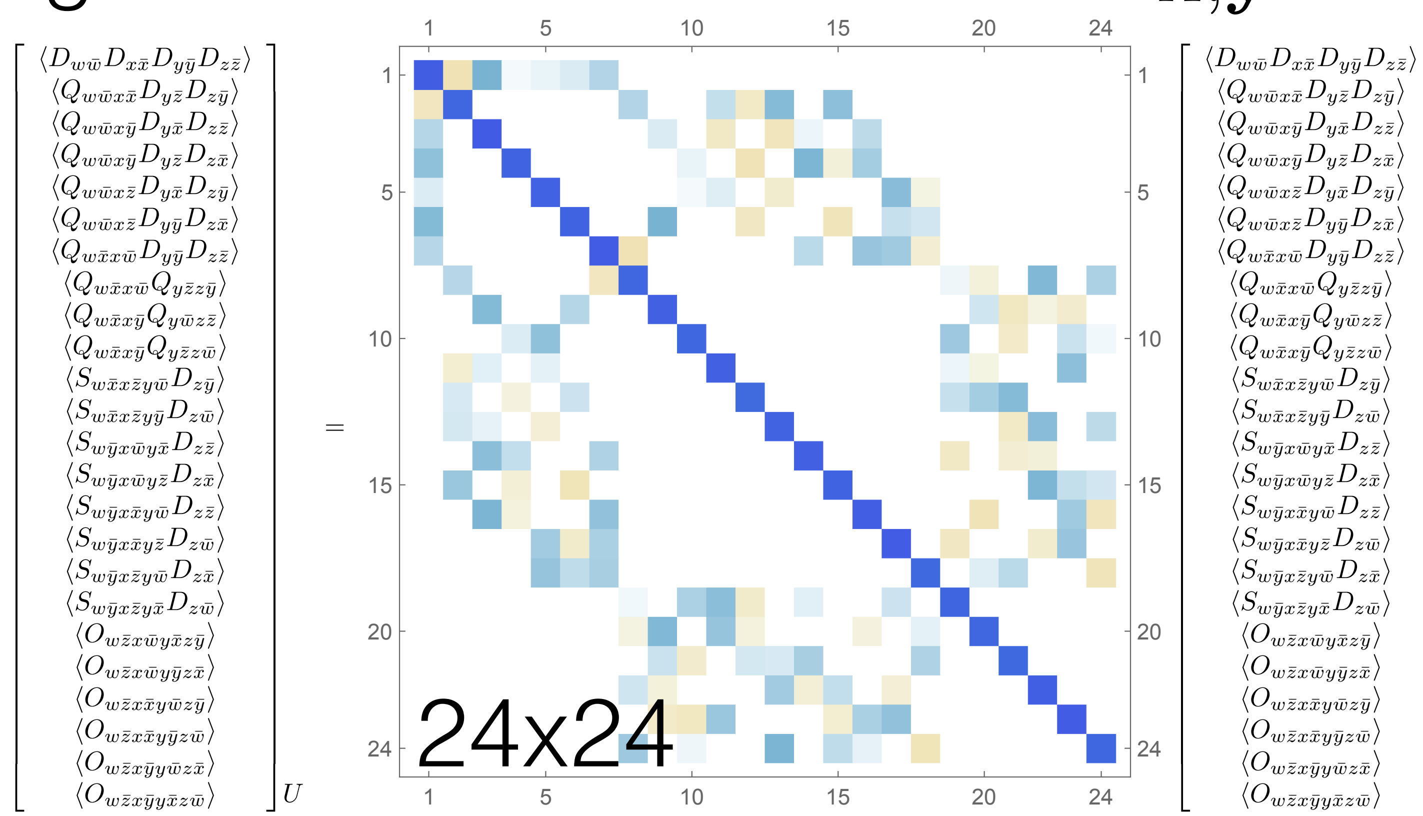
Four dipole correlators

Closed set of five topologically distinct configurations



Permutations for each topology for closing on $z^+ = +\infty$

Define single gluon exchange matrix in terms of $L_{\mathbf{x},\mathbf{y}}$



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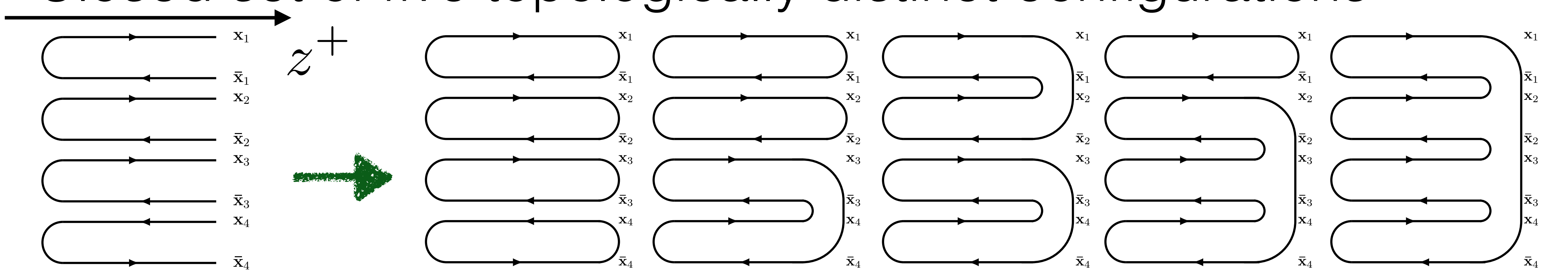

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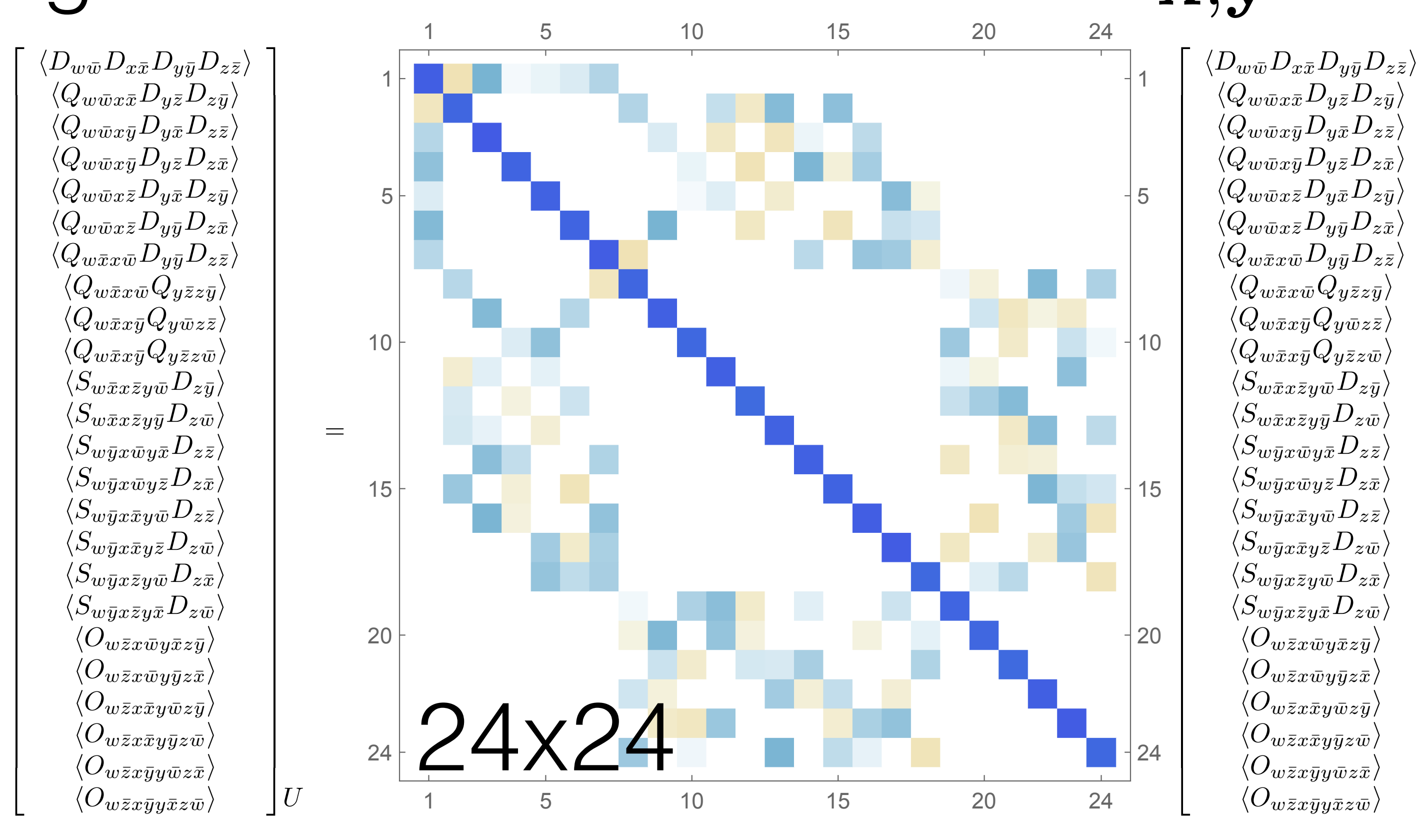

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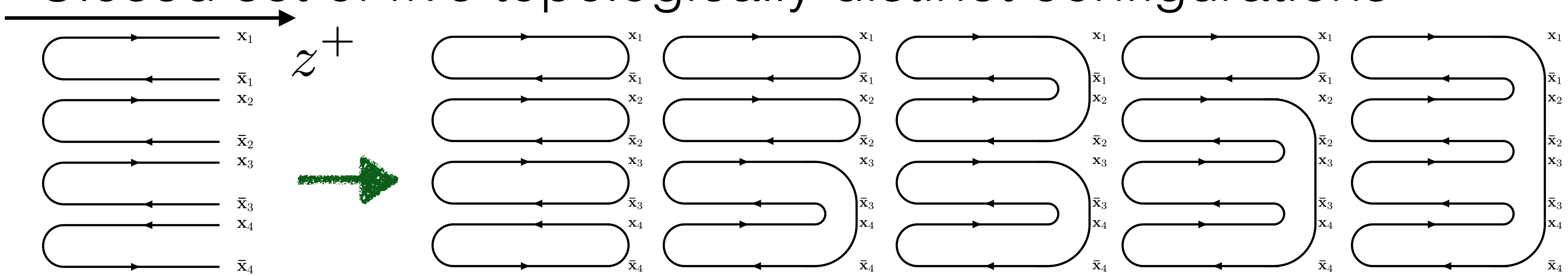

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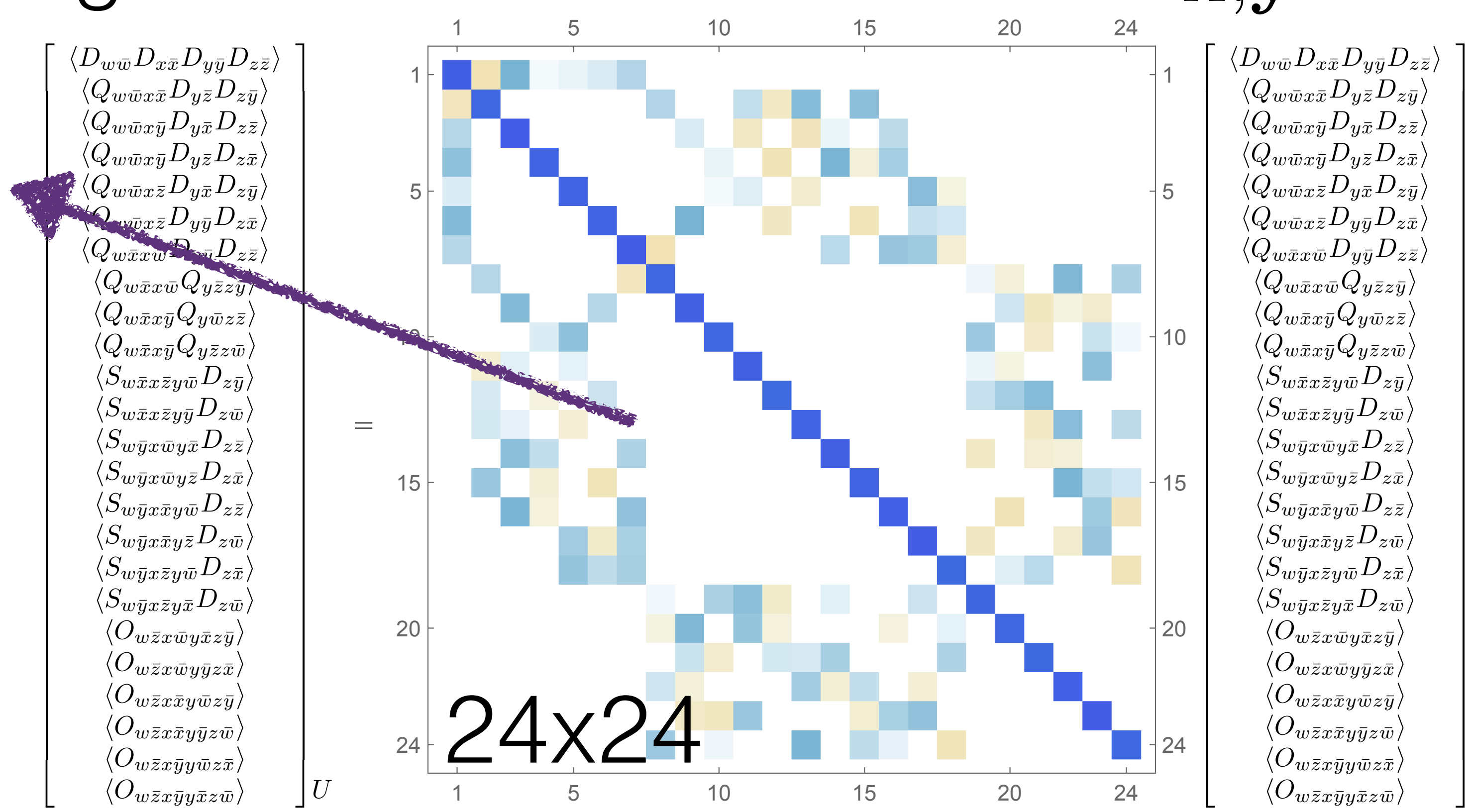

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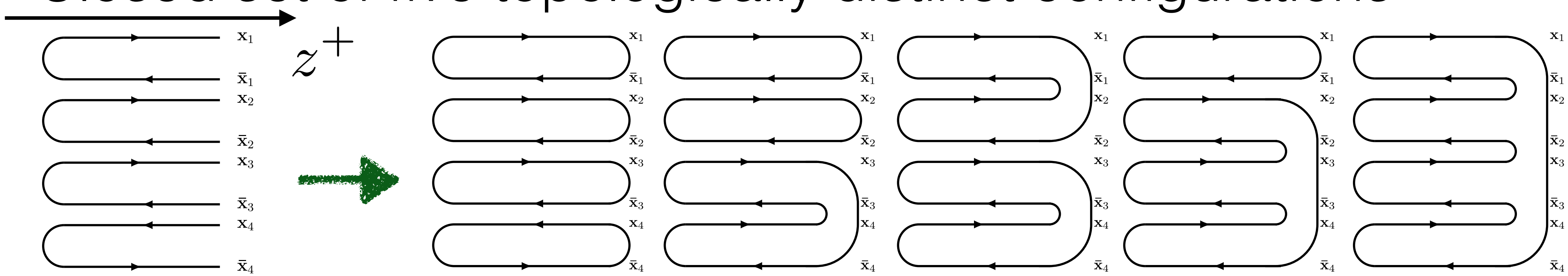

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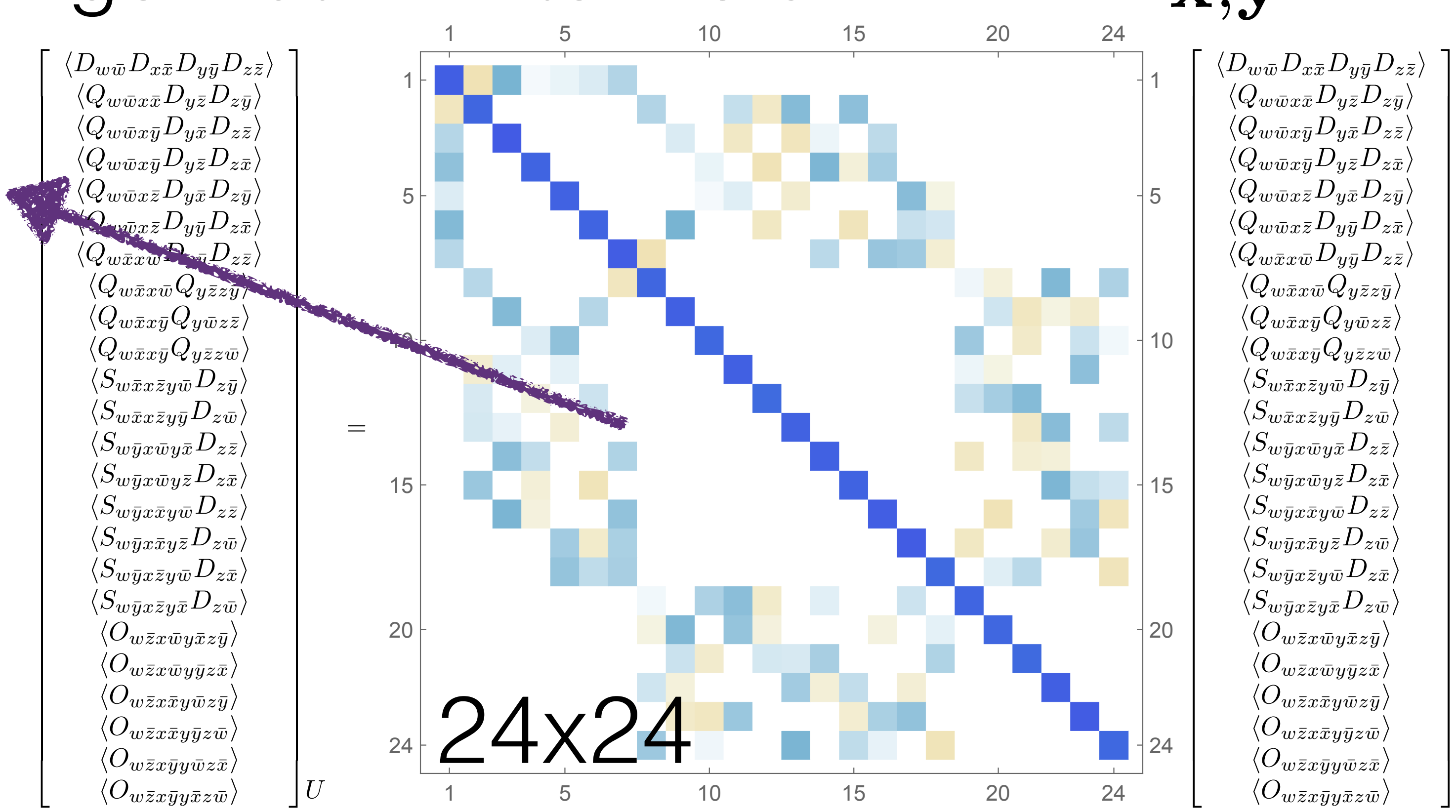
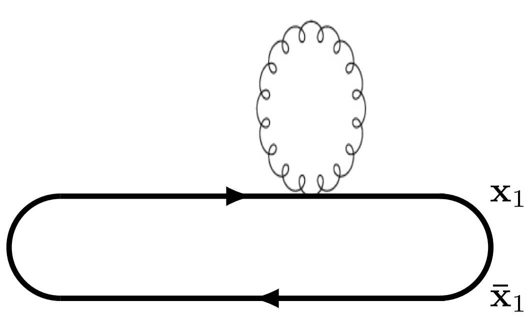


Also includes tadpole contribution



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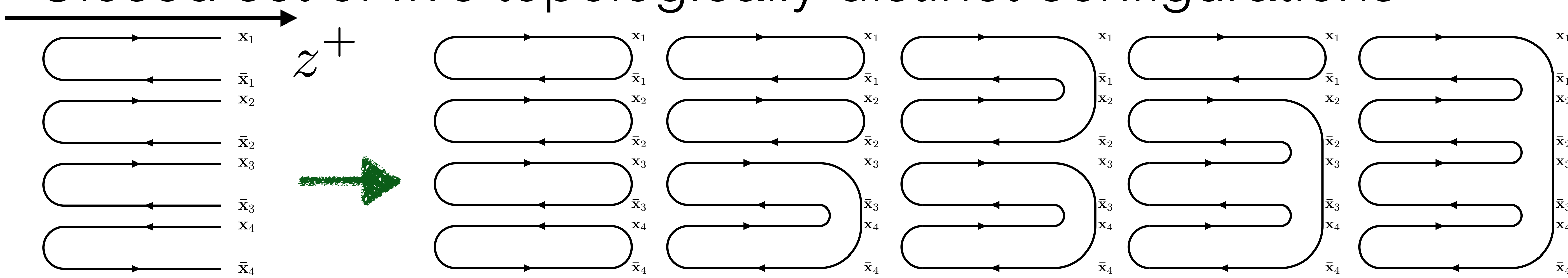

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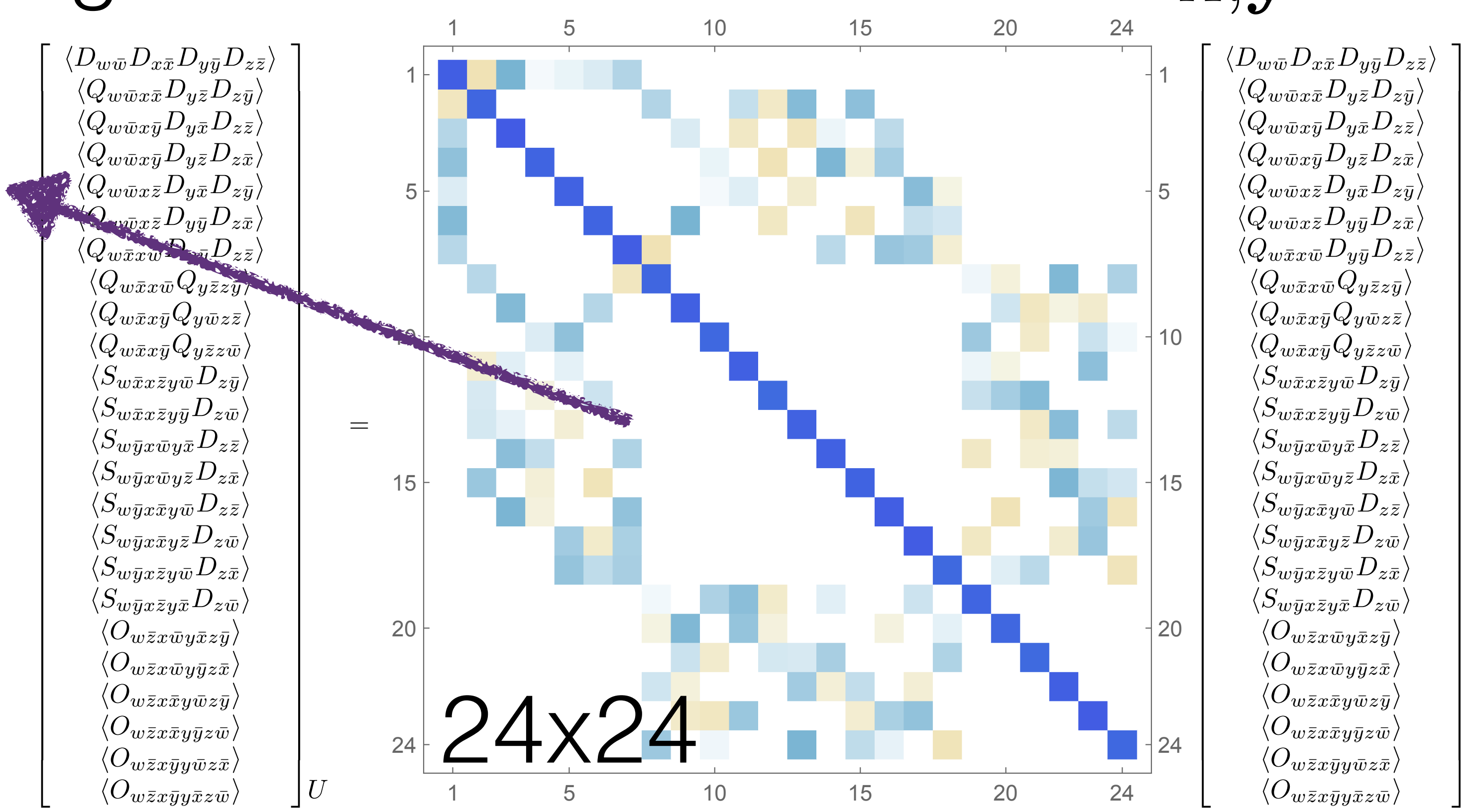

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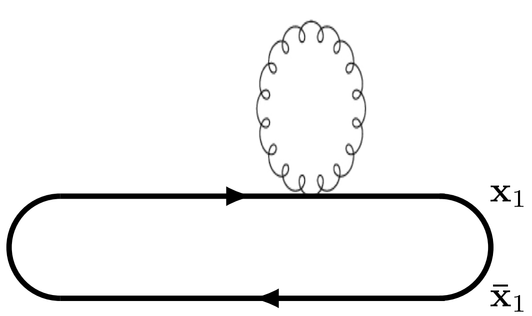
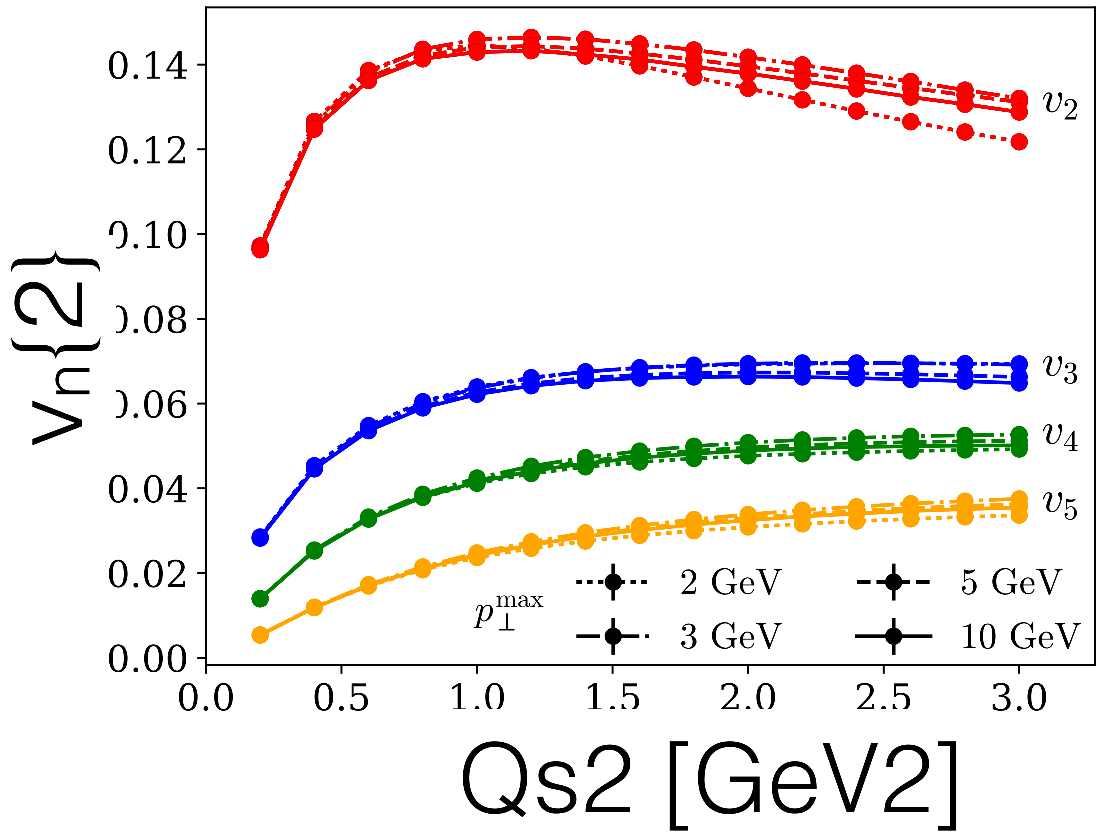


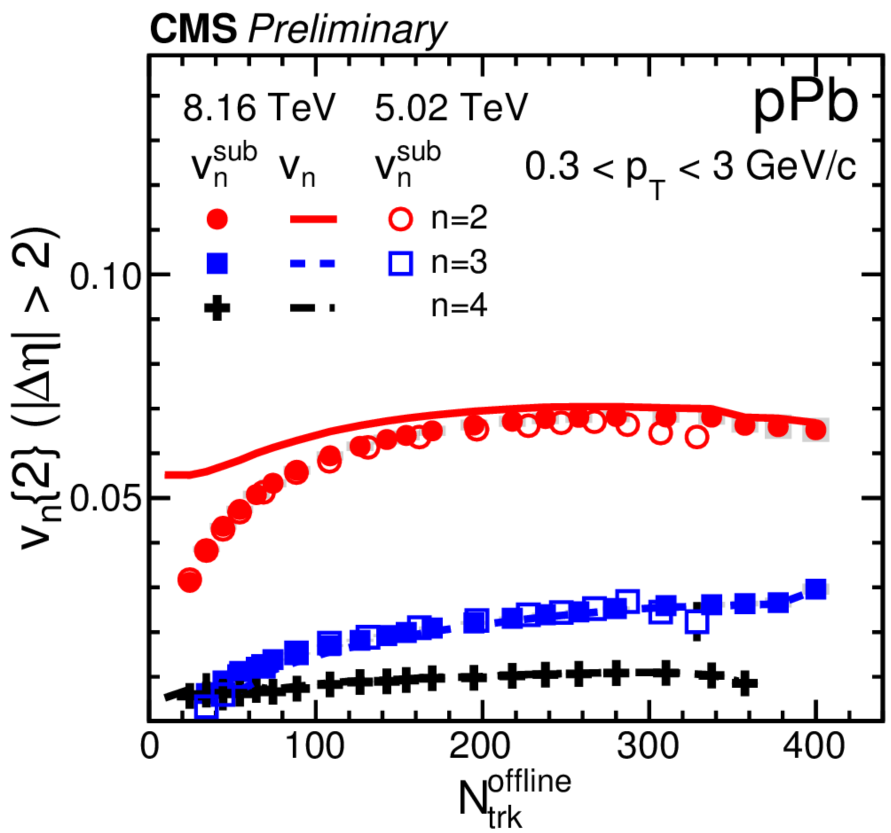
Algorithm can be used to compute other configurations, arbitrary number of Wilson lines

Multi-particle quark correlations

Ordering in two particle Fourier harmonics similar to data



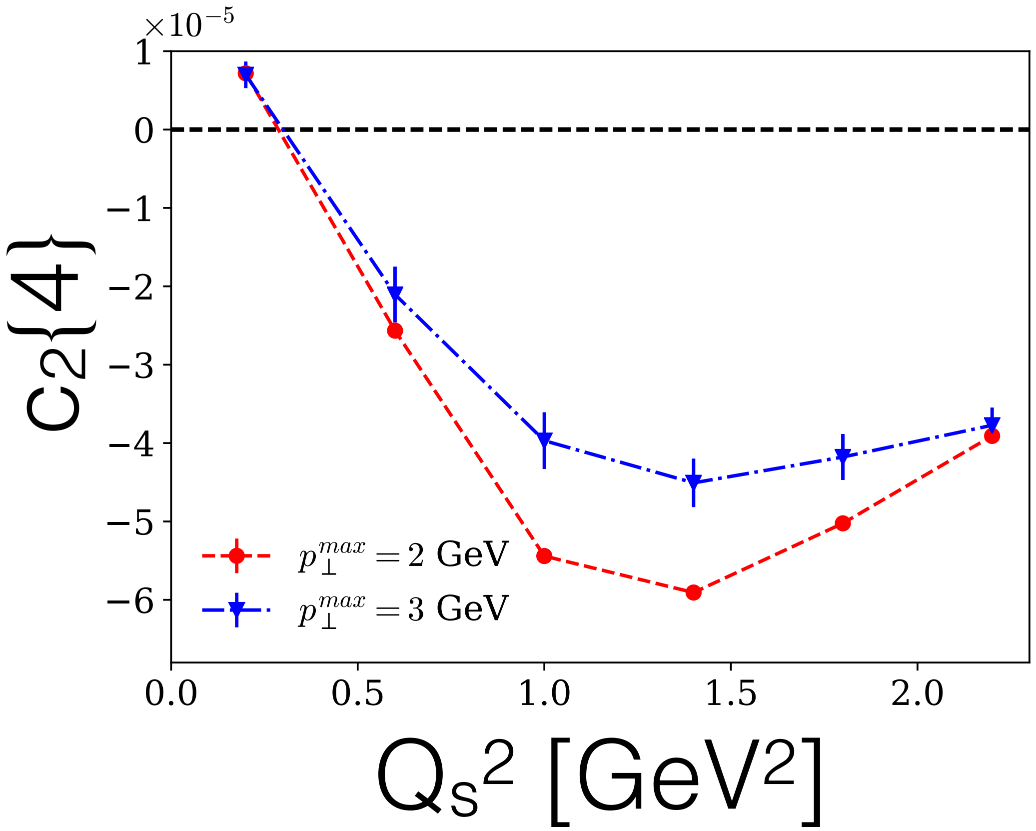
Dusling, MM, Venugopalan PRL 120 (2018)



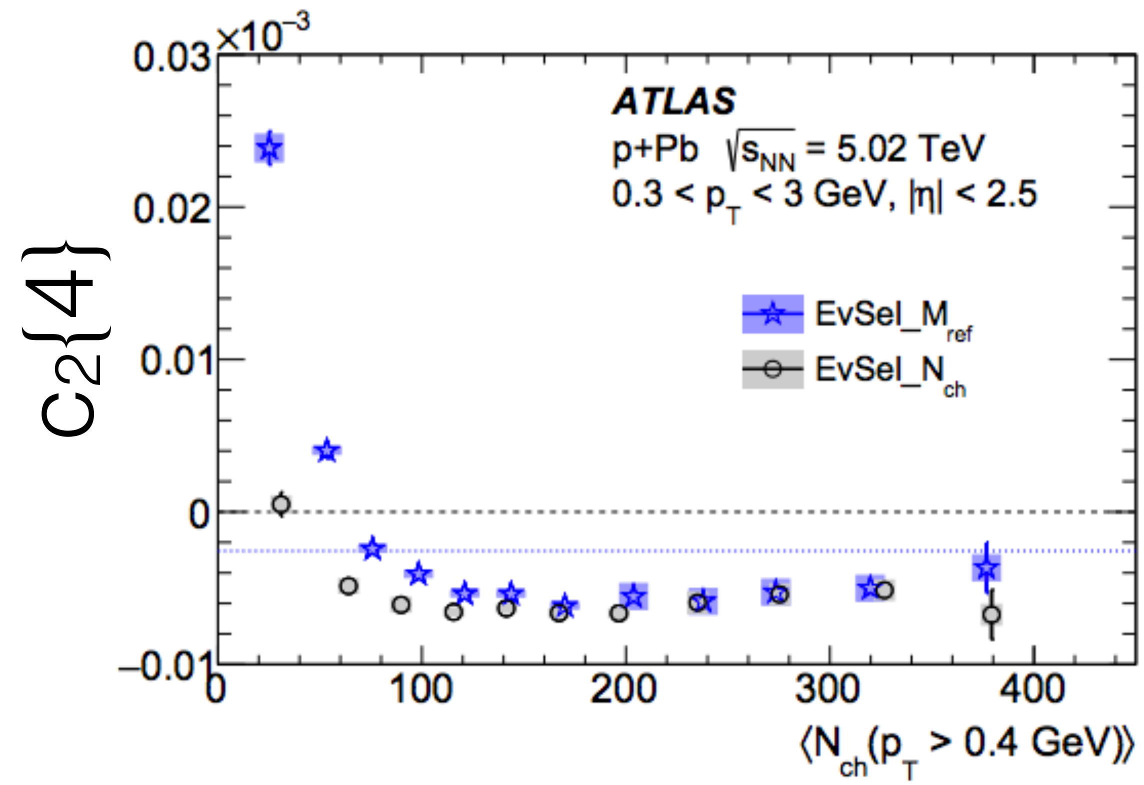
CMS-PAS-HIN-16-022

Multi-particle quark correlations

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



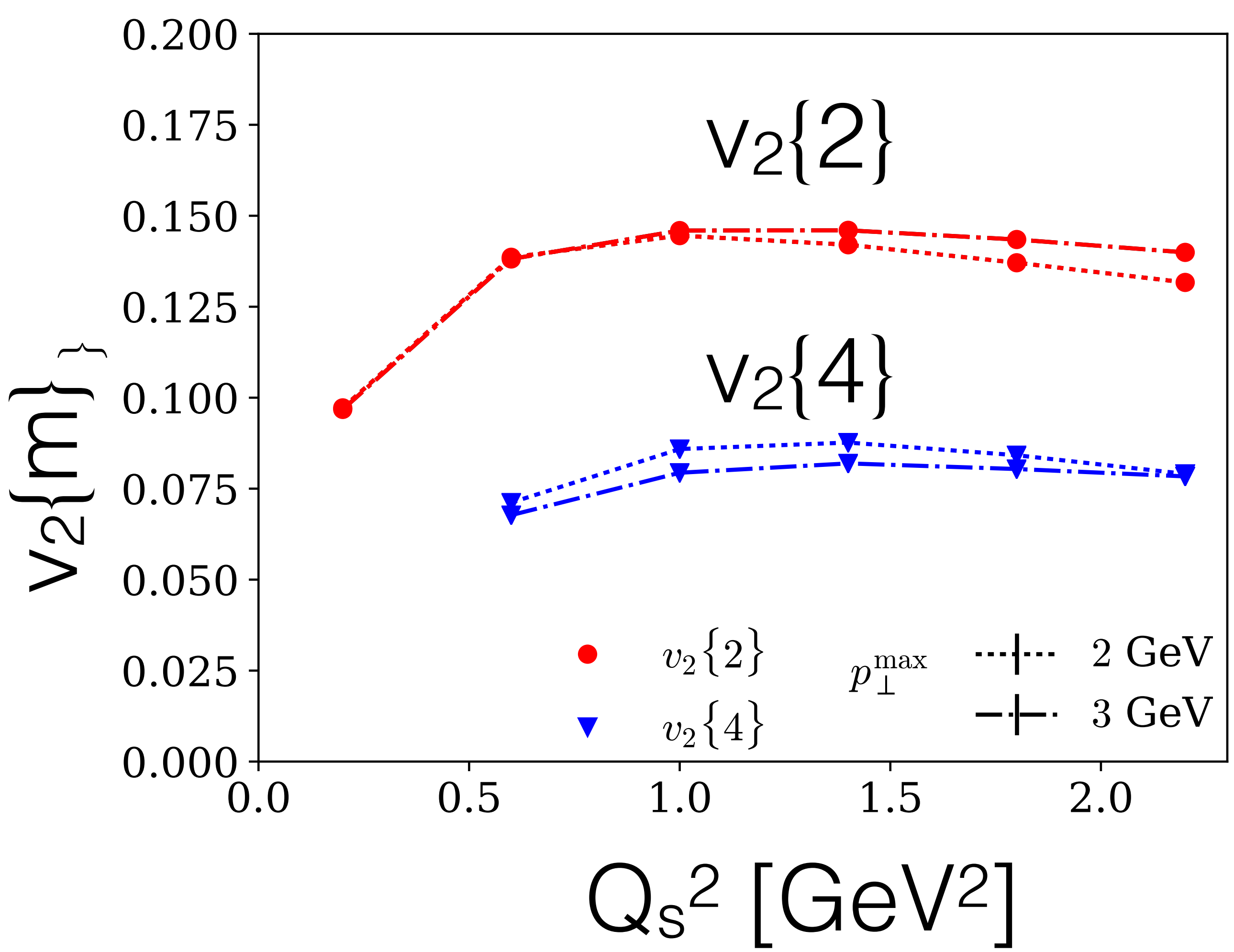
Dusling, MM, Venugopalan PRD 97 (2018)



ATLAS EPJC 77 (2017)

Mild dependence on maximum integrated $p_\perp$

Multi-particle quark correlations



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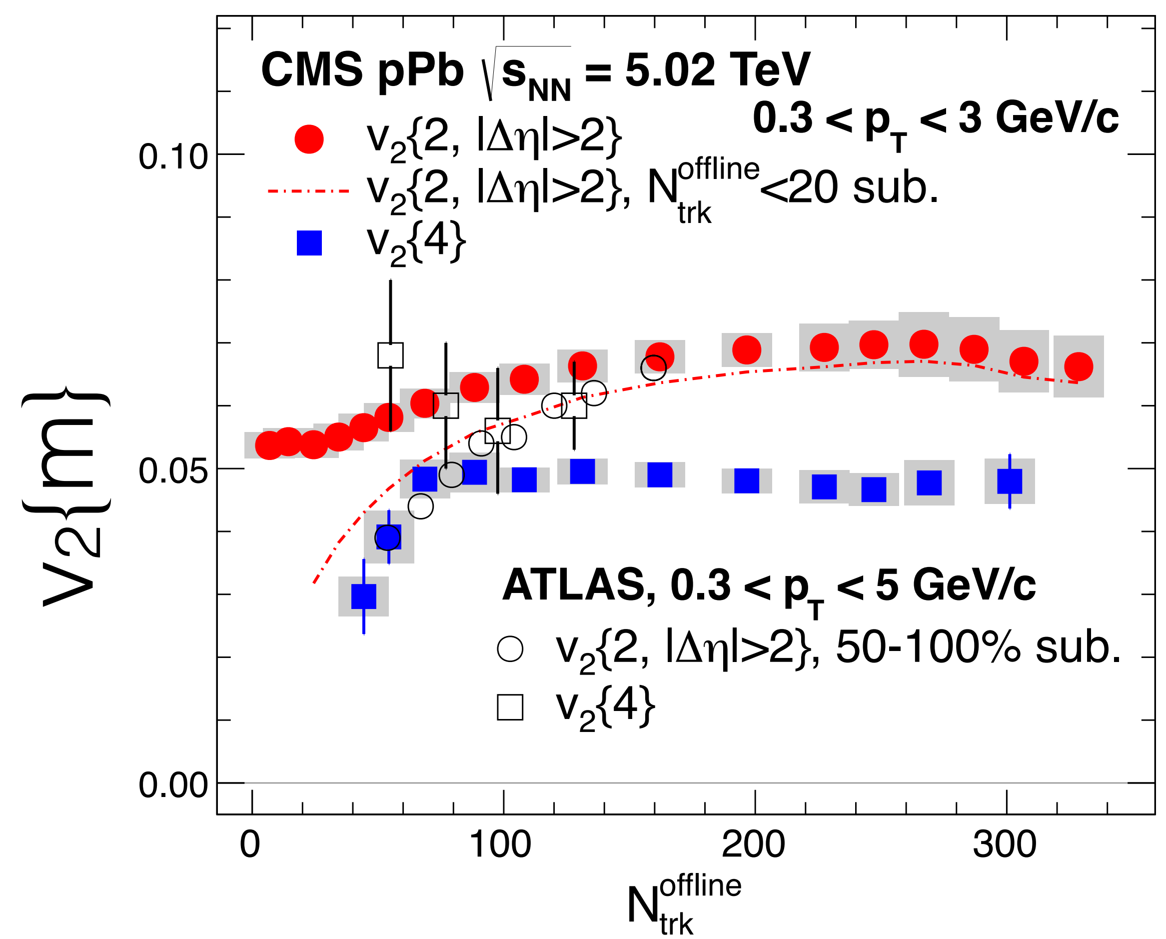


CMS PLB 724 (2013) 213

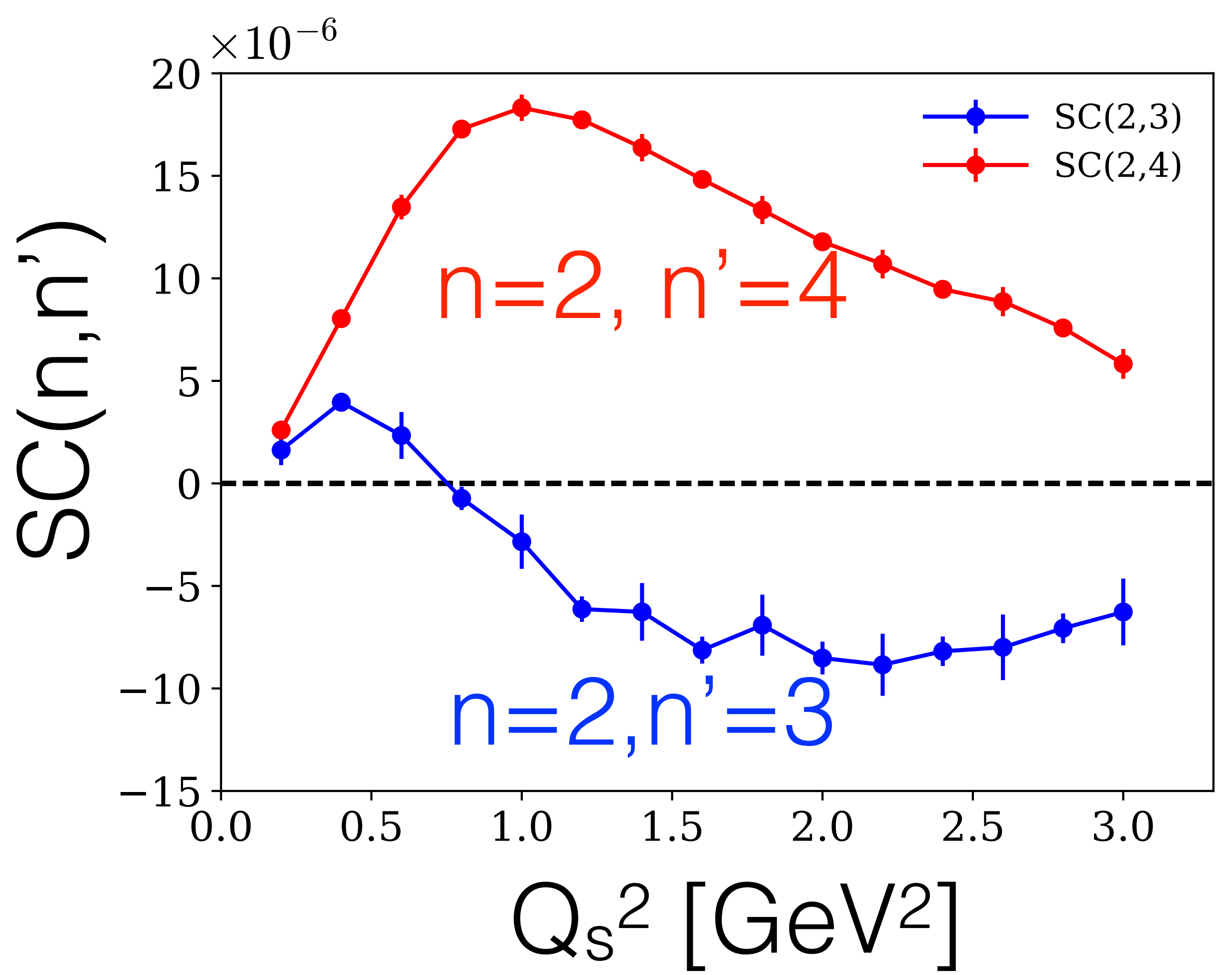
No inverse scaling by number of domains in CGC and data

Symmetric Quark Cumulants

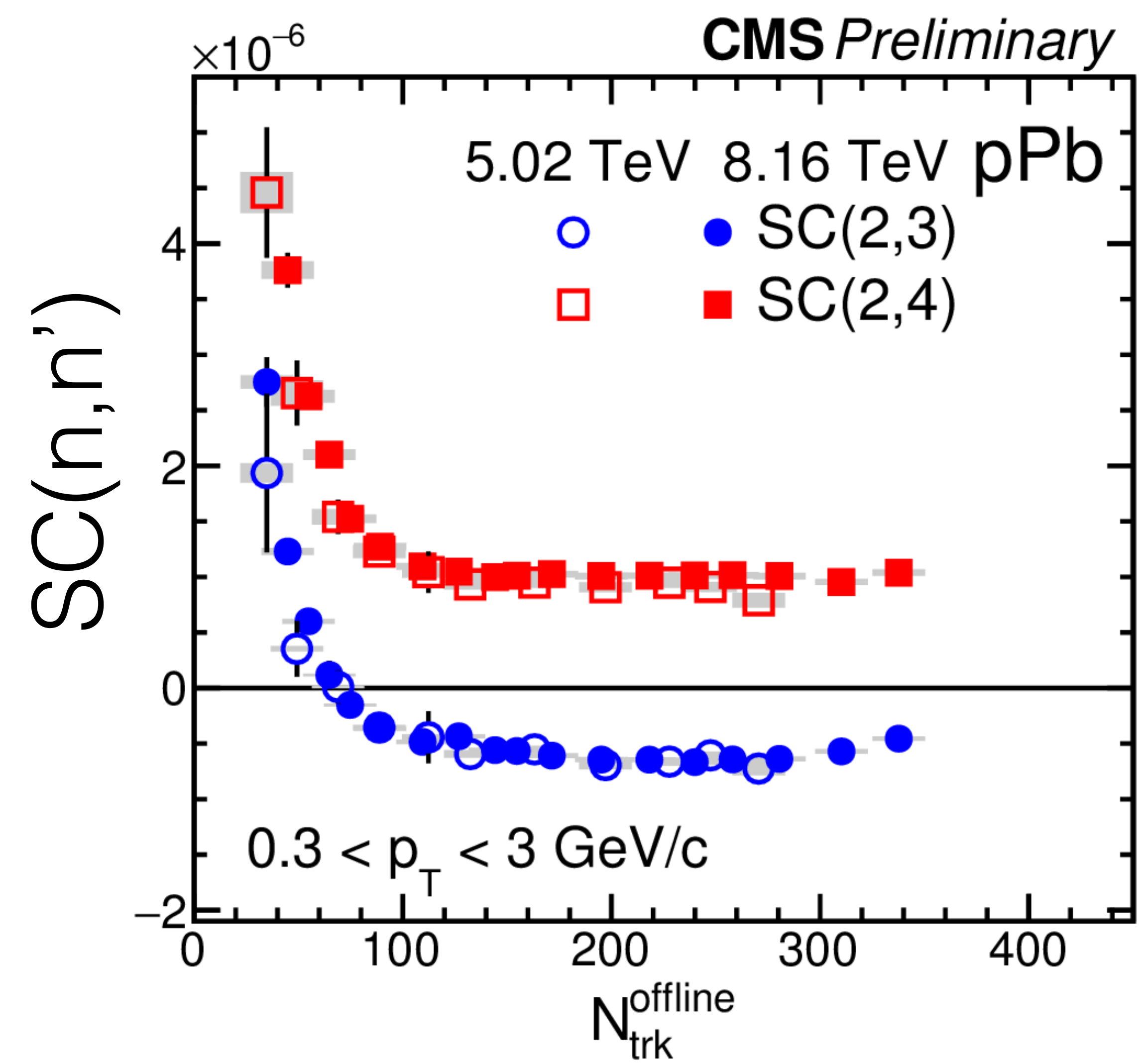
Symmetric cumulants: mixed harmonic cumulants

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

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



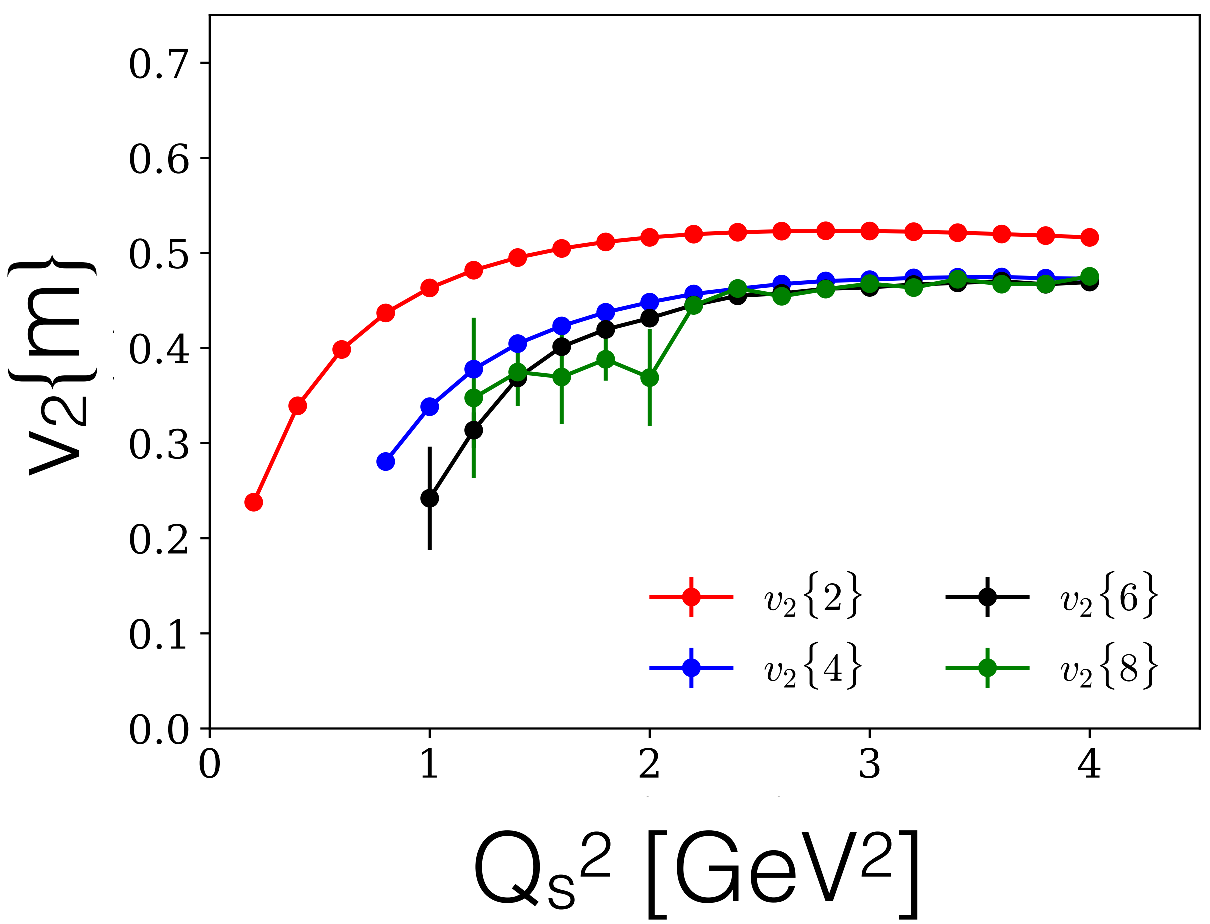
Dusling, MM, Venugopalan PRD 97 (2018)



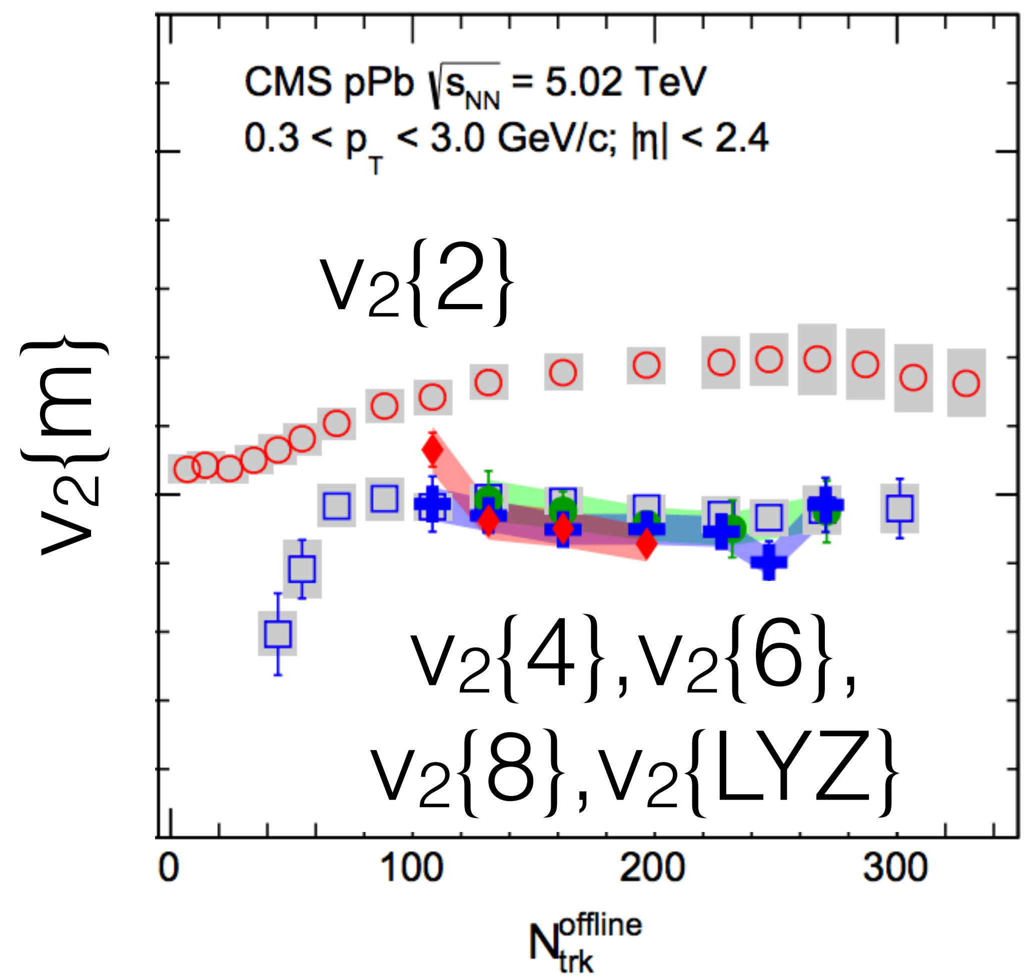
CMS-PAS-HIN-16-022

Collectivity from parton model

For computational reduction, consider Abelian version



Dusling, MM, Venugopalan PRL 120 (2018)

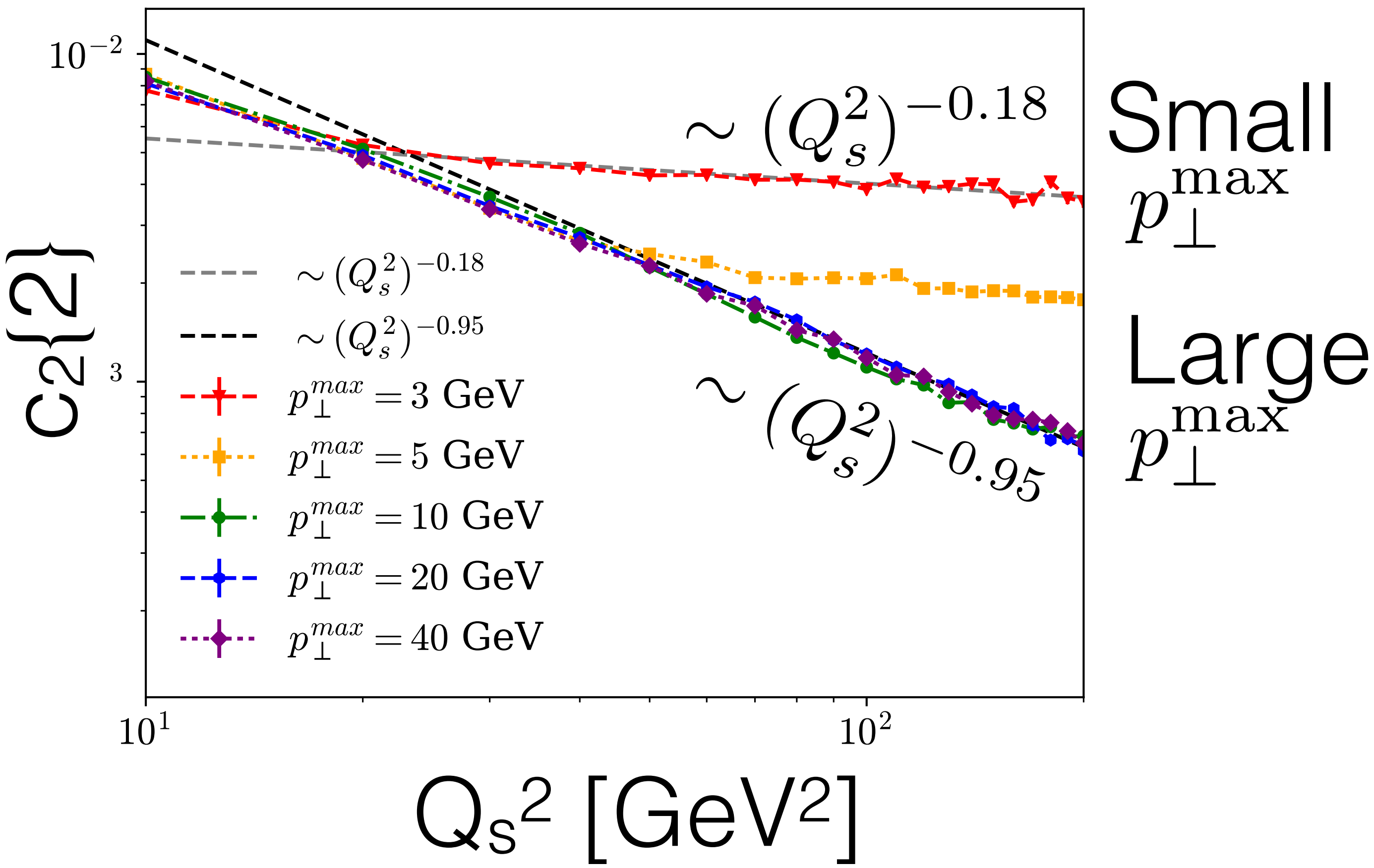


CMS PRL 115 (2015) 012301

Clear demonstration that $v_2\{2\} \geq v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
collectivity not unique to hydrodynamics

Scale dependence

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



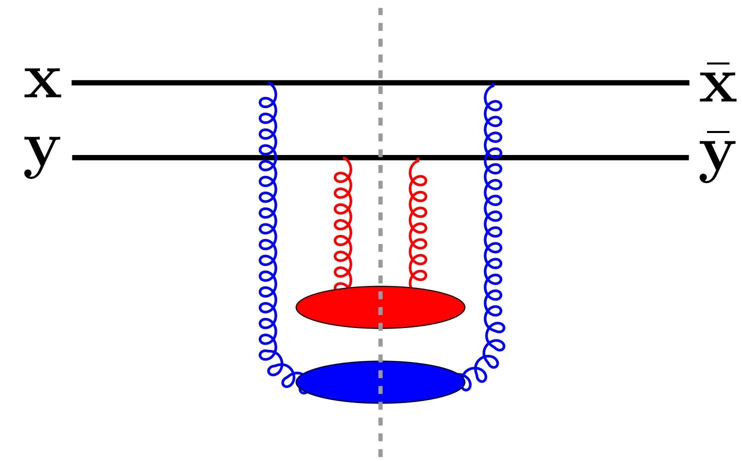
$(p_\perp^{\max})^2 \lesssim Q_s^2$: probe coarse graining over multiple domains

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

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

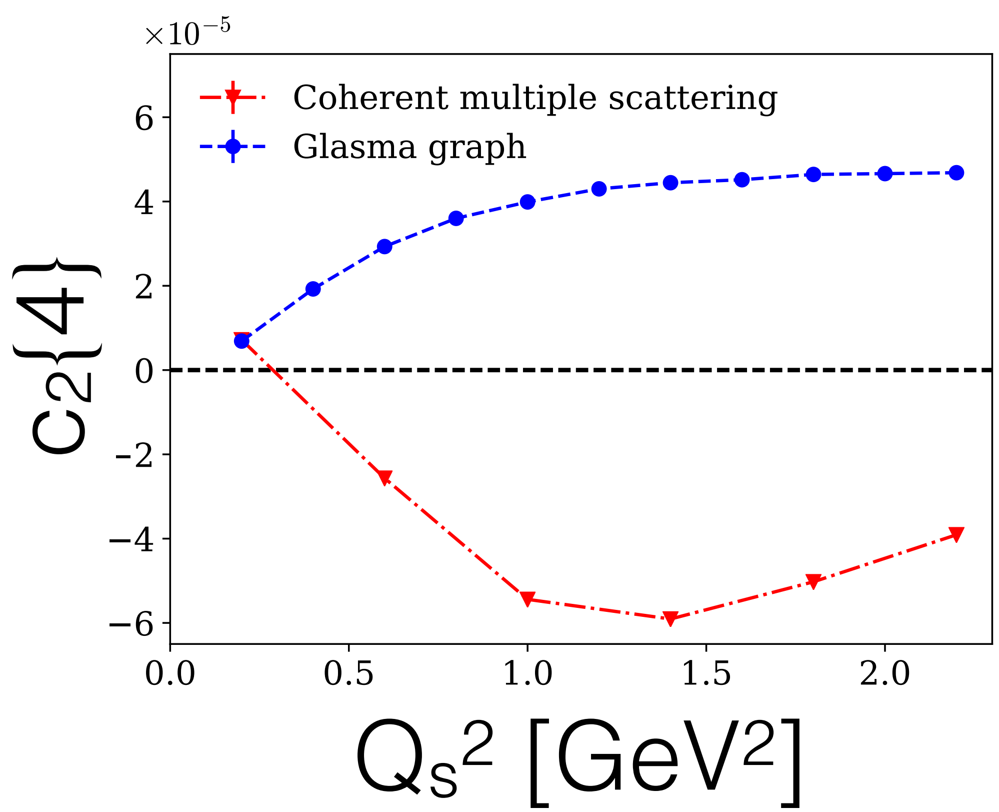
Dusling, MM, Venugopalan PRD 97 (2018)

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)



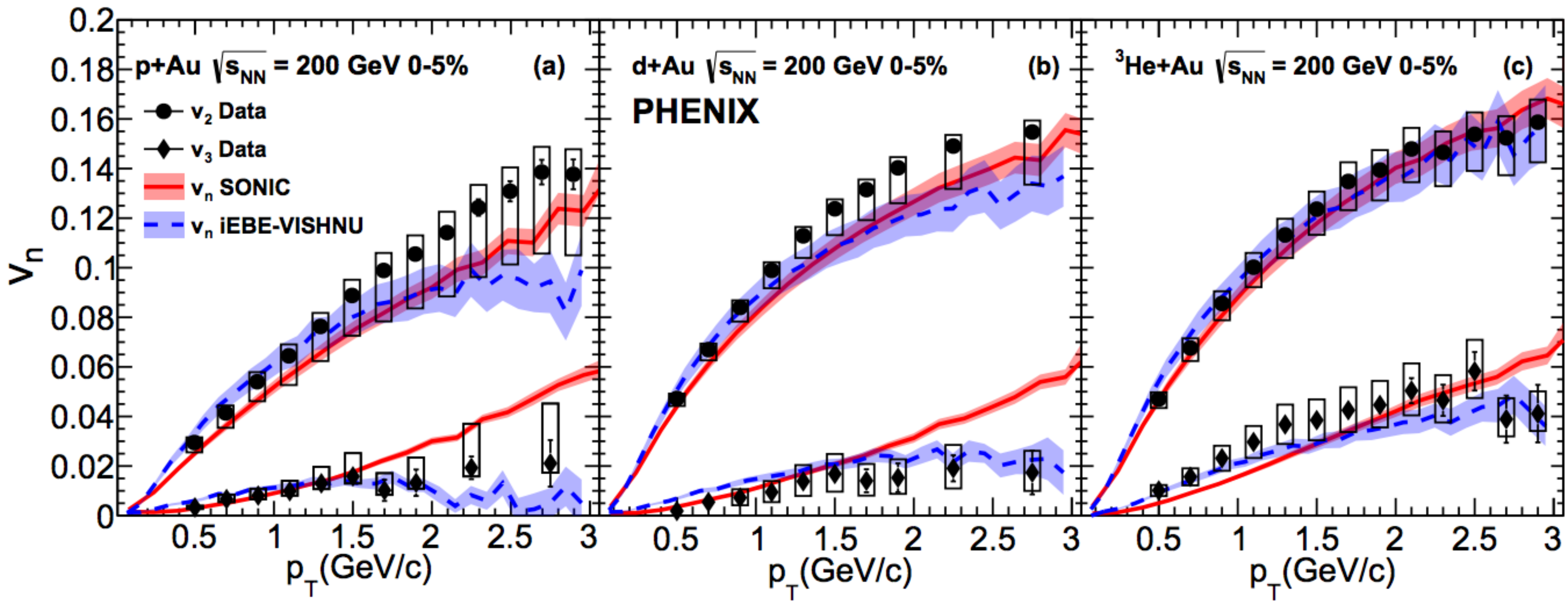
Glasma graphs have very strong correlations, close to a Bose distribution (as in a laser)

Gelis, Lappi, McLerran NPA 828 (2009)

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

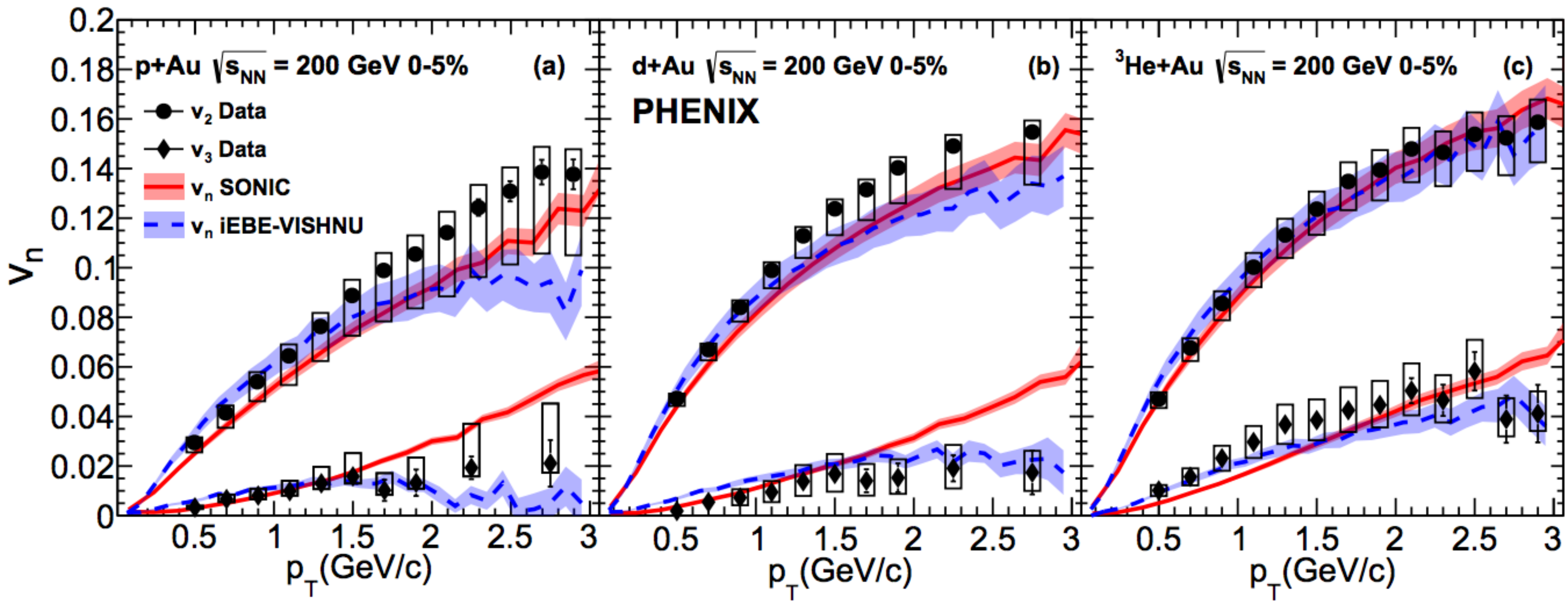
Dusling, MM, Venugopalan PRD 97 (2018)

System size scan



PHENIX arXiv:1805.02973

System size scan

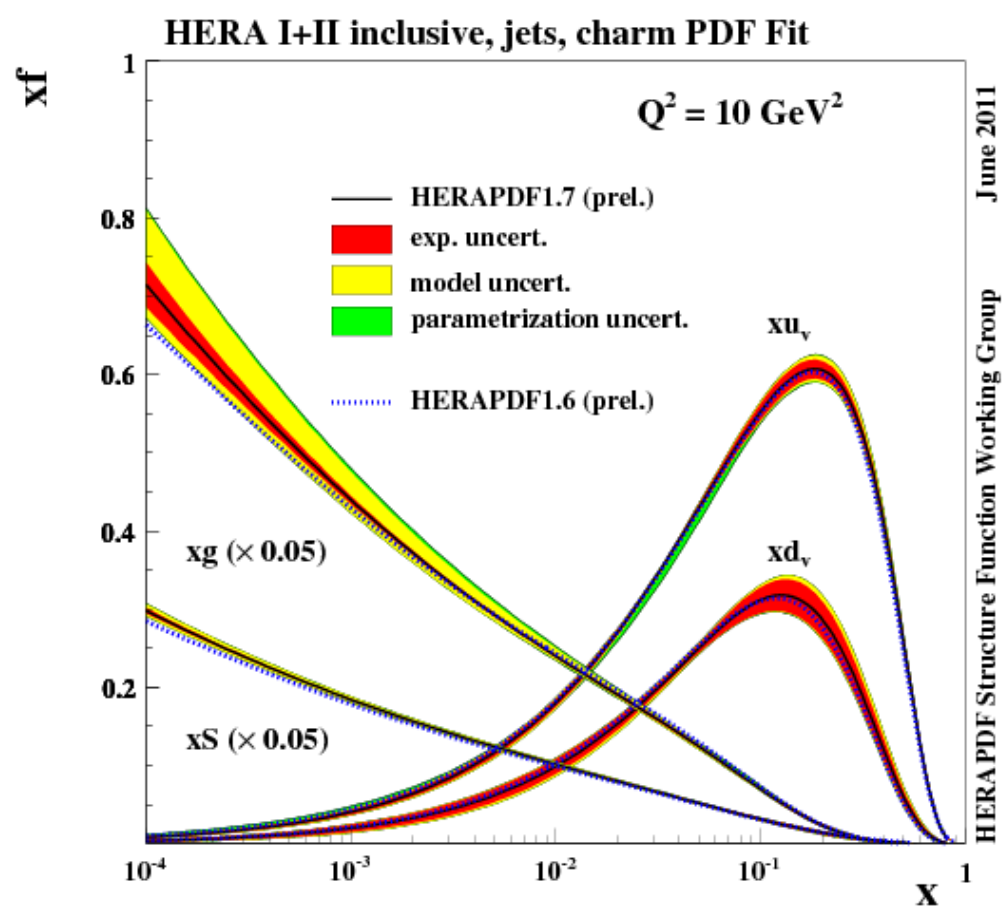


PHENIX arXiv:1805.02973

Can this be understood from the initial state?

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 for gluons

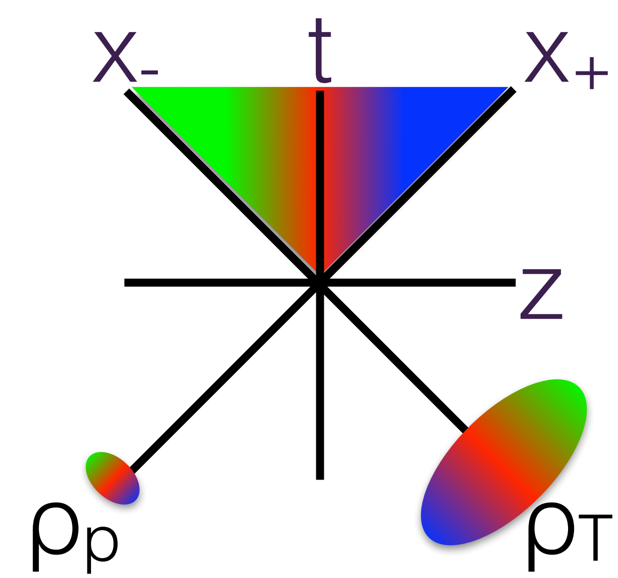
CGC EFT: solve CYM with static color sources

$$[D_\mu, F^{\mu\nu}] = J^\nu$$

$$J^\nu = g\delta^{\nu +}\delta(x^-)\rho_{p,a}(\mathbf{x}_\perp) + g\delta^{\nu -}\delta(x^+)\rho_{A,a}(\mathbf{x}_\perp)$$

All orders in ρ_T, ρ_p only known numerically

Dilute-dense limit: $\rho_T \gg \rho_p$



Kovchegov,. Mueller NPB 529 (1998), Kovner, Wiedemann PRD 64 (2001), Dumitru, McLerran NPA 700 (2002),, Blaizot, Gelis, Venugopalan NPA 743 (2004), McLerran, Skokov NPA 959 (2017), Kovchegov, Skokov PRD 97 (2018),…

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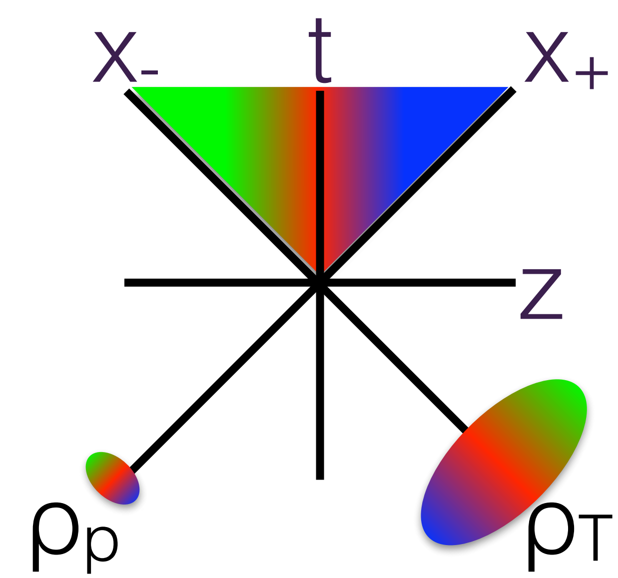

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Calculate for A^μ to all order in ρ_T, first order in ρ_p
a.k.a. the dilute-dense, analytically accessible

e.g. Dumitru, McLerran NPA 700 (2002), McLerran, Skokov NPA 959 (2017)

$$\frac{dN}{d^2k} \sim g^2\rho_p^2 f_{(1)}(\rho_T) + g^4\rho_p^4 f_{(2)}(\rho_T) + \cdots$$

$f_{(1)}$ well known, no complete results for $f_{(2)}$ yet

Kovchegov,. Mueller NPB 529 (1998),Dumitru, McLerran NPA 700 (2002), Blaizot, Gelis, Venugopalan NPA 743 (2004)
Balitsky, PRD 70 (2004), Chirilli, Kovchegov, Wertepny, JHEP 03 (2015)

The v_3 Problem

Leading order dilute-dense limit highly amenable to numerics

Lappi EPJC 55 (2008)

The v_3 Problem

Leading order dilute-dense limit highly amenable to numerics

Lappi EPJC 55 (2008)

For double inclusive, $\frac{d^2N}{d^3k_1 d^3k_2}$, leading order is also known

Kovner. Lublinsky, IJMPE 22 (2013), Kovchegov, Wertepny, NPA 906, (2013),

$$\frac{d^2N}{d^2k_1 dy_1 d^2k_2 dy_2} = \frac{d^2N}{k_1 dk_1 dy_1 k_2 dk_2 dy_2}$$
$$\times \left(1 + 2v_2^2\{2\}\cos 2(\phi_1 - \phi_2) + 2v_3^2\{2\}\cos 3(\phi_1 - \phi_2) + \cdots\right)$$

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For a non-zero v_3

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

$$\int_0^{2\pi} d\Delta\phi \cos 3\Delta\phi \frac{d^2N}{d^2k_1 d^2k_2}\left(\delta\phi\right) = \int_0^{\pi} d\Delta\phi \cos 3\Delta\phi \frac{d^2N}{d^2k_1 d^2k_2}\left(\delta\phi\right) - \int_0^{\pi} d\Delta\phi \cos 3\Delta\phi \frac{d^2N}{d^2k_1 d^2k_2}\left(\delta\phi + \pi\right)$$
$$= \int_0^{\pi} d\Delta\phi \cos 3\Delta\phi \quad \left[\frac{d^2N}{d^2k_1 d^2k_2}\left(\mathbf{k}_1, \mathbf{k}_2\right) - \frac{d^2N}{d^2k_1 d^2k_2}\left(\mathbf{k}_1, -\mathbf{k}_2\right)\right]$$

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Lappi EPJC 55 (2008)

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Must be non-vanishing

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Must be non-vanishing

However, at leading order (ρ_p^4) it is exactly zero, but not in dense-dense

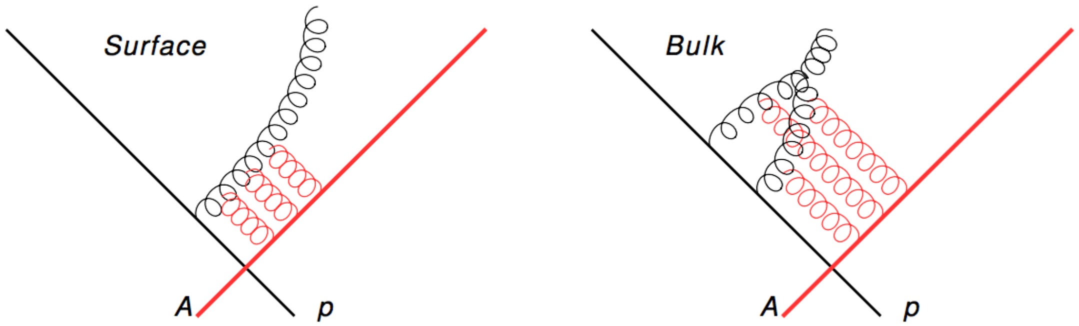
Kovner, Lublinsky, PRD 83 (2011), Kovchegov, Wertepny, NPA 906 (2013), Kovchegov, Skokov PRD 97 (2018)
Lappi, Srednyak, Venugopalan JHEP 1001 (2010), Schenke, Schlichting, Venugopalan PLB 747 (2015)

Dilute dense for gluons

Issue resolved at next order in ρ_p

Symmetry broken in $\frac{d^2N}{d^3k_1 d^3k_2}$ by first saturation correction $O(\rho_p{}^6)$

McLerran, Skokov NPA 959 (2017)



McLerran, Skokov NPA 959 (2017)

Final state matters!

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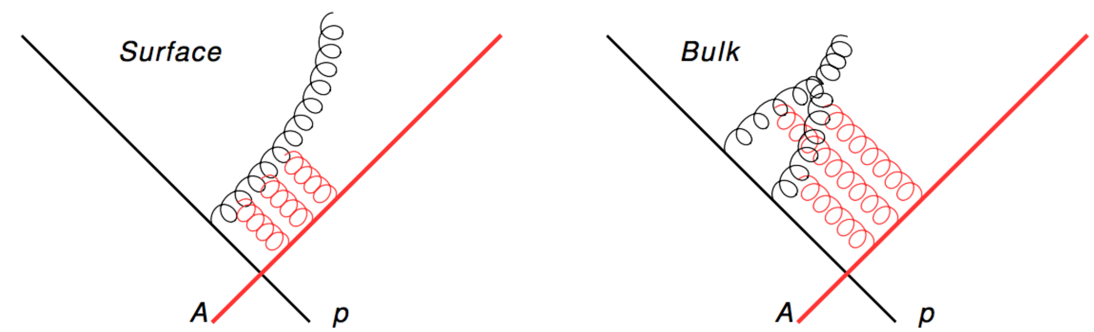

McLerran, Skokov NPA 959 (2017)

Then in Fock-Schwinger gauge (A_τ=0)

Final state matters!

$$\frac{dN^{\rm even}(\mathbf{k})}{d^2kdy}\left[\rho_p,\rho_t\right] = \frac{2}{(2\pi)^3}\frac{\delta_{ij}\delta_{lm}+\epsilon_{ij}\epsilon_{lm}}{k^2}\Omega^a_{ij}(\mathbf{k})\left[\Omega^a_{lm}(\mathbf{k})\right]^\star$$

$$\frac{dN^{\rm odd}(\mathbf{k})}{d^2kdy}\left[\rho_p,\rho_T\right] = \frac{2}{(2\pi)^3}{\rm Im}\left\{\frac{g}{\mathbf{k}^2}\int\frac{d^2l}{(2\pi)^2}\frac{{\rm Sign}(\mathbf{k}\times\mathbf{l})}{l^2|\mathbf{k}-\mathbf{l}|^2}f^{abc}\Omega^a_{ij}(\mathbf{l})\Omega^b_{mn}(\mathbf{k}-\mathbf{l})\left[\Omega^c_{rp}(\mathbf{k})\right]^\star\times\right.$$
$$\left.\left[\left(\mathbf{k}^2\epsilon^{ij}\epsilon^{mn}-\mathbf{l}\cdot(\mathbf{k}-\mathbf{l})(\epsilon^{ij}\epsilon^{mn}+\delta^{ij}\delta^{mn})\right)\epsilon^{rp}+2\mathbf{k}\cdot(\mathbf{k}-\mathbf{l})\epsilon^{ij}\delta^{mn}\delta^{rp}\right]\right\}$$

Projectile Target

In terms of: $\Omega^a_{ij}(\mathbf{x}) = g\left[\frac{\partial_i}{\partial^2}\rho^b_p(\mathbf{x})\right]\partial_j U^{ab}(\mathbf{x})$

Valence sources rotated by target

Dilute dense for gluons

Issue resolved at next order in ρ_p
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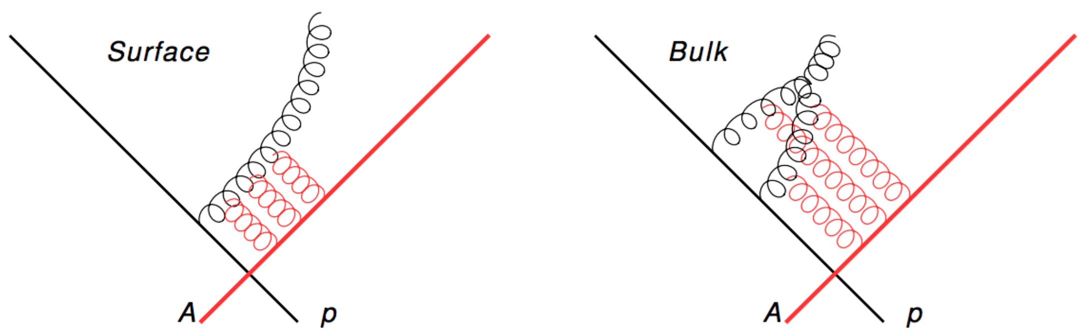

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$$\frac{dN^{\rm even}(\mathbf{k})}{d^2k dy}\left[\rho_p,\rho_t\right] = \frac{2}{(2\pi)^3}\frac{\delta_{ij}\delta_{lm}+\epsilon_{ij}\epsilon_{lm}}{k^2}\Omega^a_{ij}(\mathbf{k})\left[\Omega^a_{lm}(\mathbf{k})\right]^\star$$

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$$\left[\left(\mathbf{k}^2\epsilon^{ij}\epsilon^{mn}-\mathbf{l}\cdot(\mathbf{k}-\mathbf{l})(\epsilon^{ij}\epsilon^{mn}+\delta^{ij}\delta^{mn})\right)\epsilon^{rp}+2\mathbf{k}\cdot(\mathbf{k}-\mathbf{l})\epsilon^{ij}\delta^{mn}\delta^{rp}\right]\Bigg\}$$

Projectile Target

In terms of: $$\Omega^a_{ij}(\mathbf{x}) = g\left[\frac{\partial_i}{\partial^2}\rho^b_p(\mathbf{x})\right]\partial_j U^{ab}(\mathbf{x})$$

Valence sources rotated by target

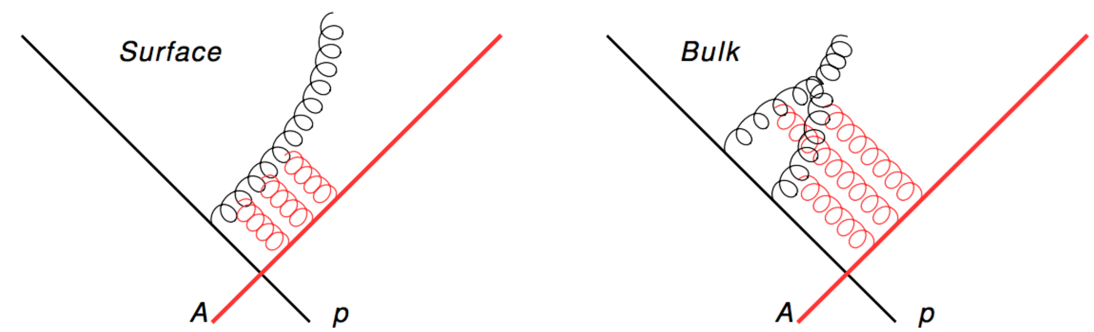
Same results in LC gauge (A^+=0), resolution similar to STSA

Kovchegov, Skokov PRD 97 (2018), Brodsky, Hwang, Kovchegov, Schmidt, Sievert, PRD 88 (2013)

Dilute dense for gluons

Issue resolved at next order in ρ_p
Symmetry broken in $\frac{d^2N}{d^3k_1 d^3k_2}$ by first saturation correction $O(\rho_p{}^6)$

McLerran, Skokov NPA 959 (2017)



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Valence sources rotated by target

Also non-zero contribution to v_3 from proj. JIMWLK evolution

Kovner, Lublinsky, Skokov PRD 96 (2017)

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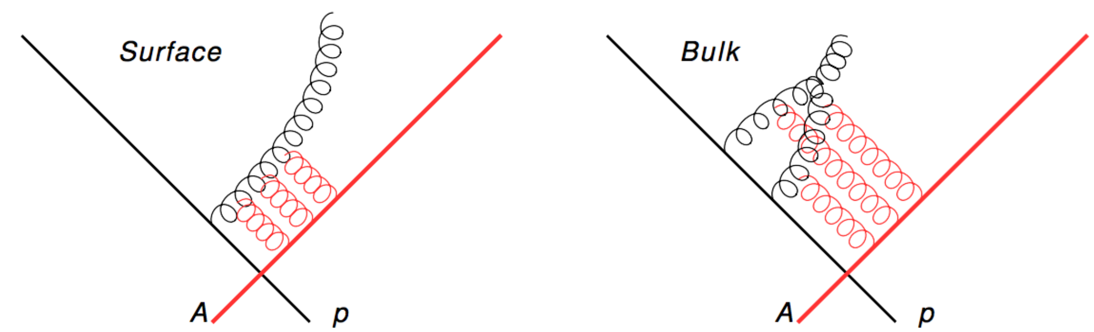

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Multi-particle distributions then defined as

$$\frac{d^2N}{d^2k_1dy_1...d^2k_ndy_n} = \left\langle\left\langle\frac{dN}{d^2k_1dy_1}\Big|_{\rho_p,\rho_T}\cdots\frac{dN}{d^2k_ndy_n}\Big|_{\rho_p,\rho_T}\right\rangle_p\right\rangle_T$$

Only well defined for ensemble over $W[\rho_T,\rho_p]$

Glauber IP-Sat model

For data-guided initial conditions, consider initial conditions based on very successful IP-Glasma model

Schenke, Tribedy, Venugopalan PRL 108 (2012), PRC 86 (2012)

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Sample nucleons through Monte-Carlo Glauber

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Kowalski, Teaney, Phys.Rev. D68 (2003) 114005

- Based on dipole model fits to HERA DIS data

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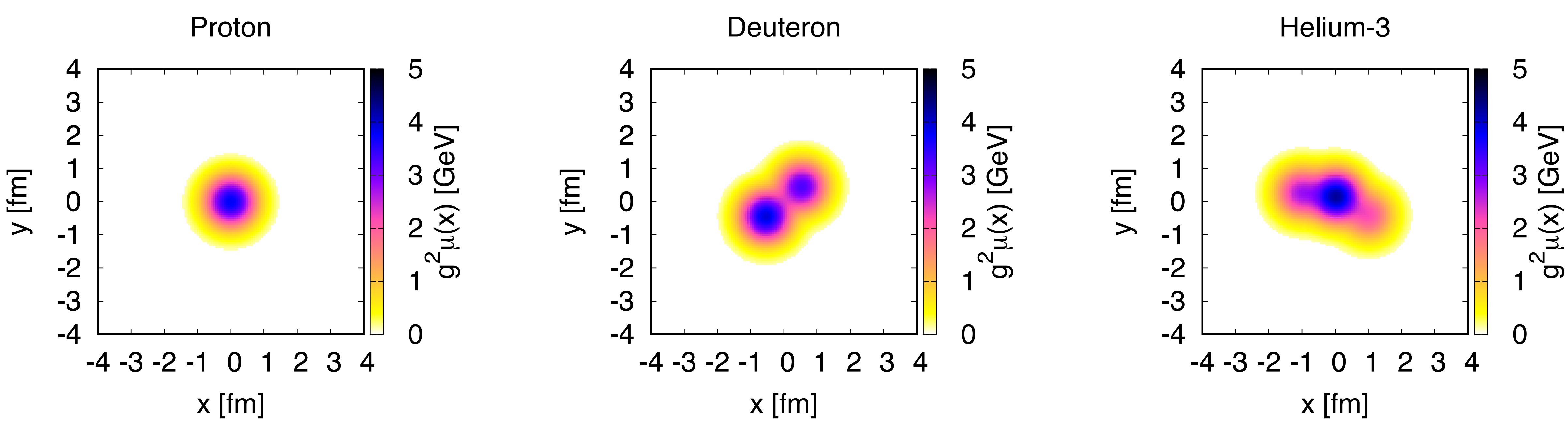
Example of three high multiplicity (0-5%) configurations

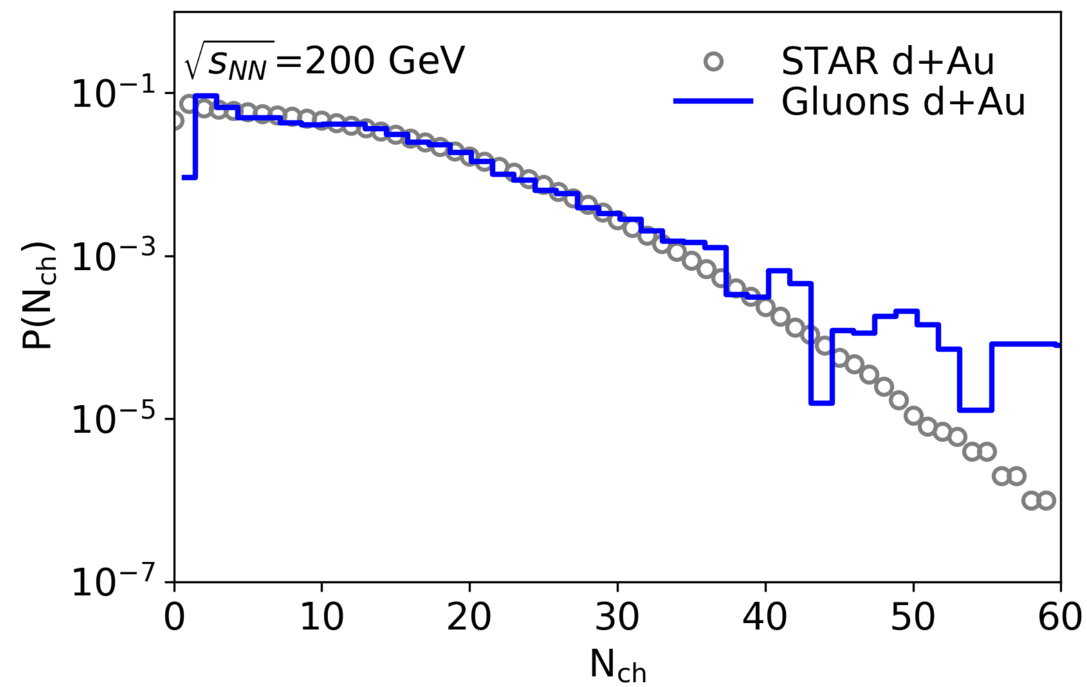


Dilute-dense CGC EFT framework

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

Gelis, Lappi, McLerran NPA 828 (2009)
Schenke, Tribedy, Venugopalan PRC 86 (2012)
McLerran, Tribedy NPA 945 (2016)

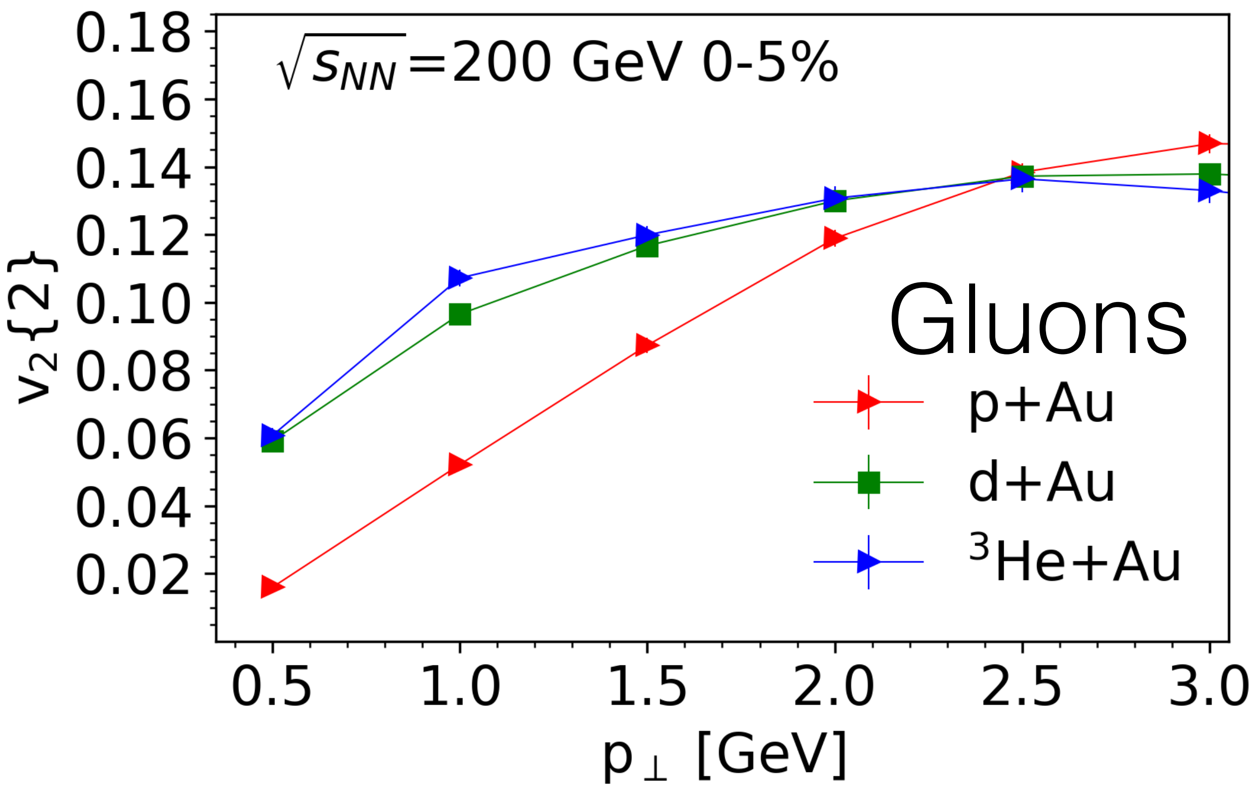
Good agreement found with STAR d+Au multiplicity distribution

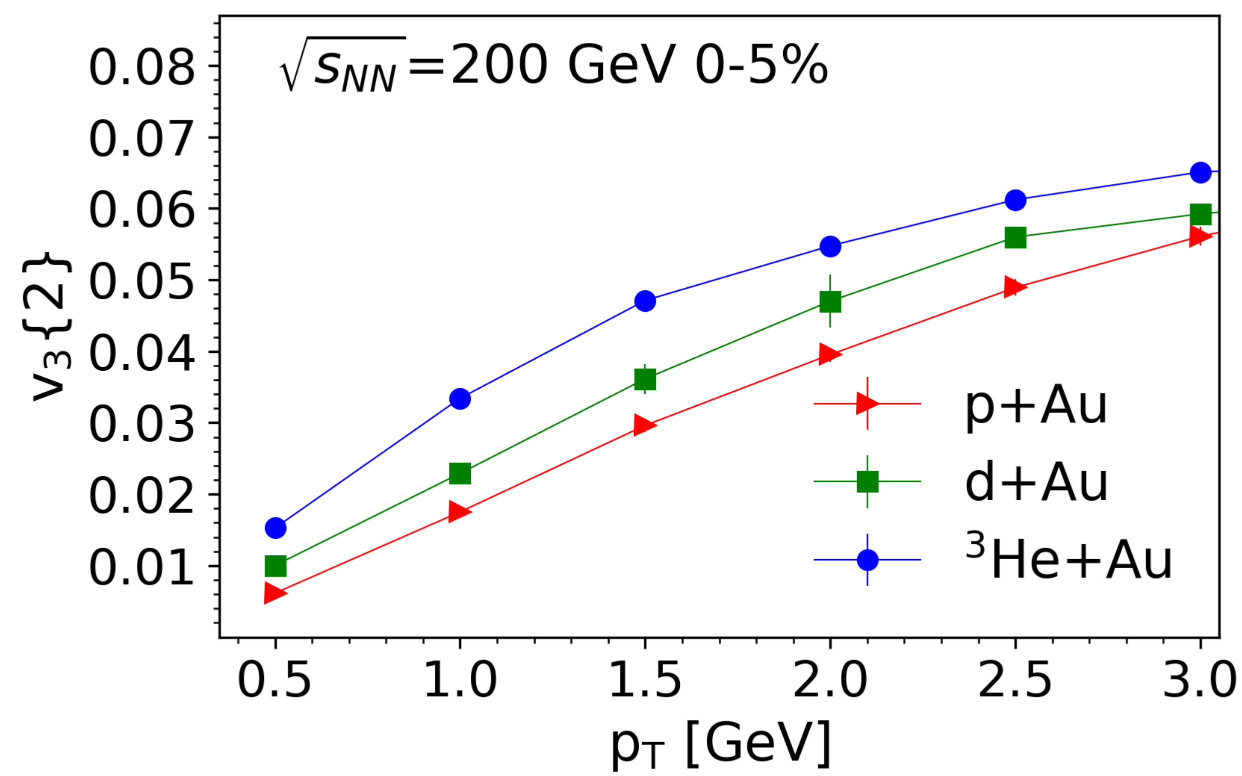


MM, Skokov, Tribedy, Venugopalan, in preparation
STAR PRC 79 (2009)

Hierarchy of anisotropies across systems

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





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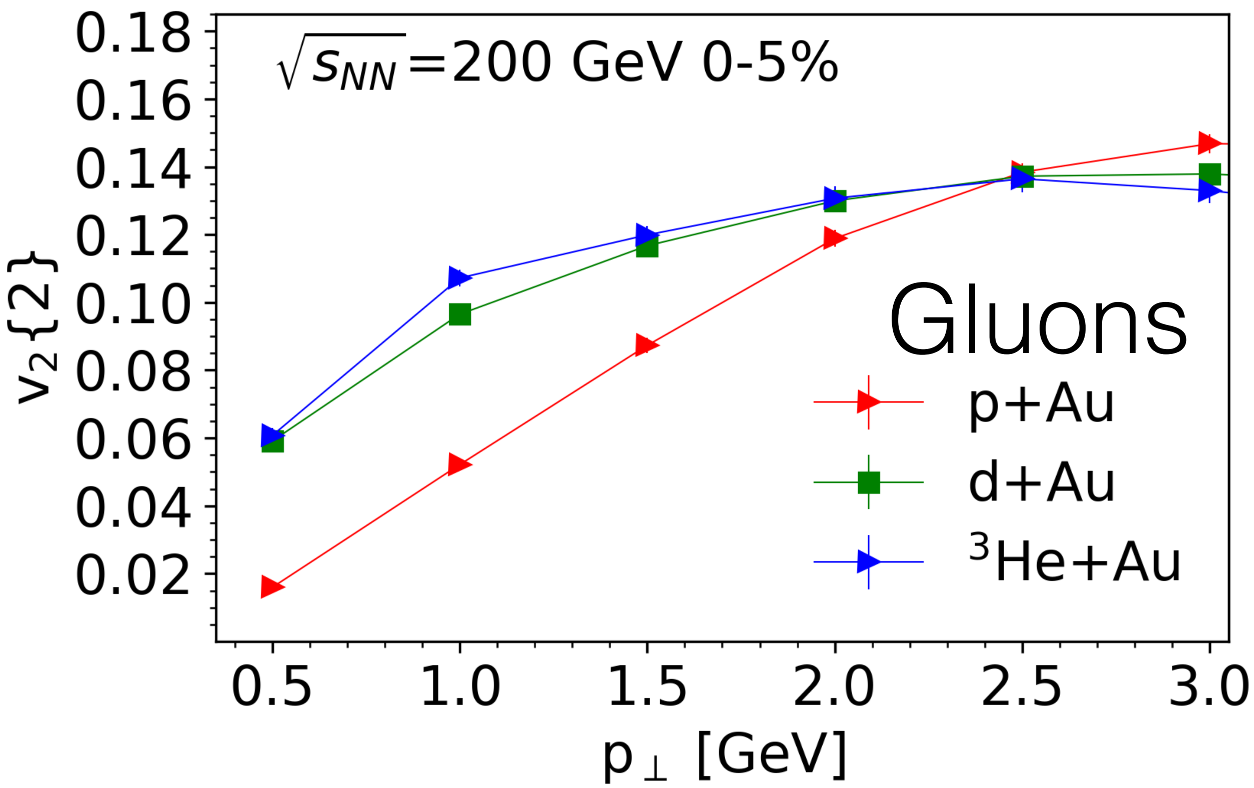

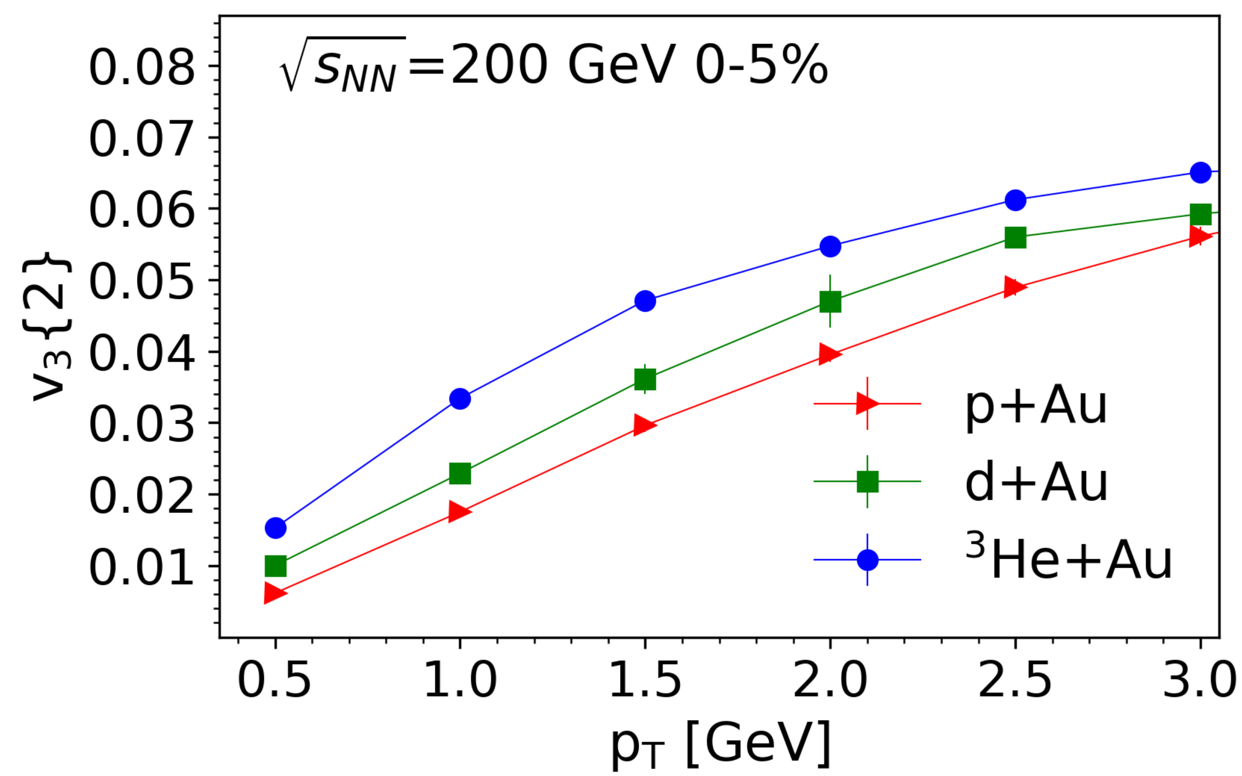

Fixed centrality bin $\longmapsto$ larger average N_{ch} for larger systems

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

Quantifying systematic uncertainties

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

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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.

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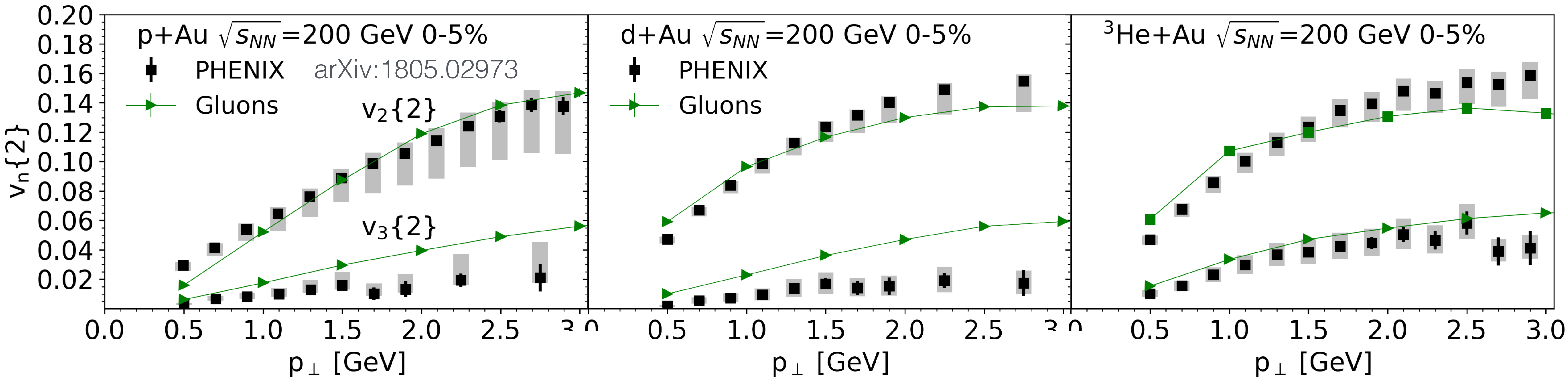
Hen, MM, Schmidt, Venugopalan, in progress.

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



Key features of system dependence captured by initial state gluon correlations

MM, Skokov, Tribedy, Venugopalan, in preparation

Conclusions

Small systems represent exciting domain to study high energy QCD, however more modeling and differential measurements needed to disentangle initial state and hydrodynamics

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, in preparation, McLerran, Skokov NPA 959 (2017)

Can compute $v_n\{m\}$ in framework and compare to data, also can consider different systems and energies (pp, LHC,...

Thanks!