Multi-particle correlations from the initial state

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Probing Nucleons and Nuclei in High Energy Collisions
Institute for Nuclear Theory
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JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

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Outline

1.) Introduction and motivation

2.) Dilute-dense CGC

3.) Simple power counting argument for v_n multiplicity dependence at LHC

MM, V. Skokov, P. Tribedy, R. Venugopalan PLB (in press) [arXiv:1807.00825]

4.) Demonstration of hierarchy of v_2 and v_3 across small systems in CGC EFT at RHIC

MM, V. Skokov, P. Tribedy, R. Venugopalan PRL 121 (2018) [arXiv:1805.09342], and in preparation

5.) Outlook

Initial State Flow

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

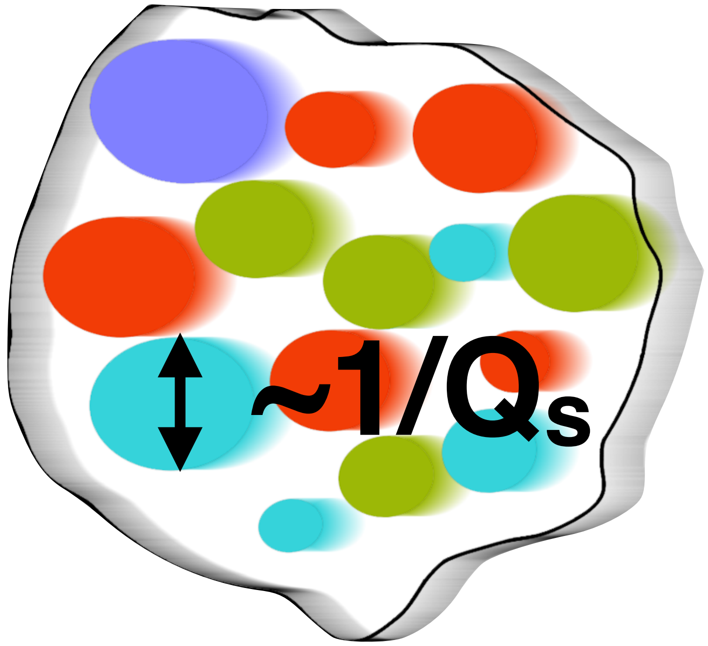
McLerran, Venugopalan, PRD 49 (1994), Iancu, Venugopalan hep-ph/0303204

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

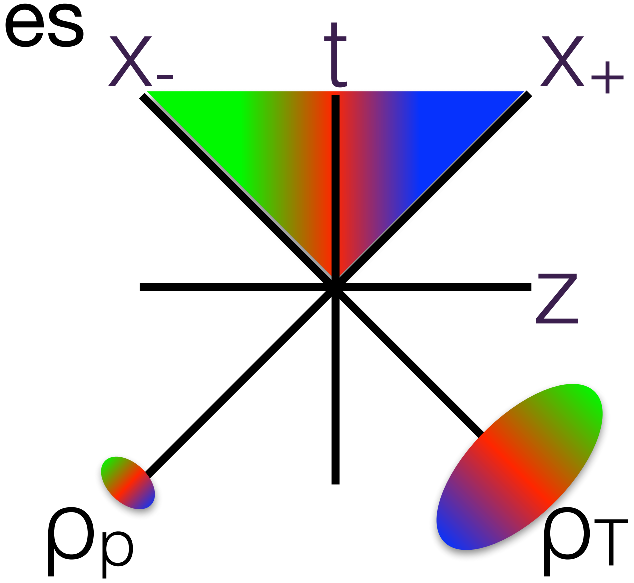


Note: *Very strongly correlated system*. Dependence on coupling drops out, effective classical description

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

Dilute-dense for gluons

CGC EFT: solve QCD CYM with static color sources



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

$$J^\nu = g\delta^{\nu+}\delta(x^-)\rho_p(\mathbf{x}_\perp) + g\delta^{\nu-}\delta(x^+)\rho_T(\mathbf{x}_\perp)$$

Dilute-dense regime: $\rho_T/k_T^2 \gg \rho_p/k_T^2$

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

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

Dilute-dense for gluons

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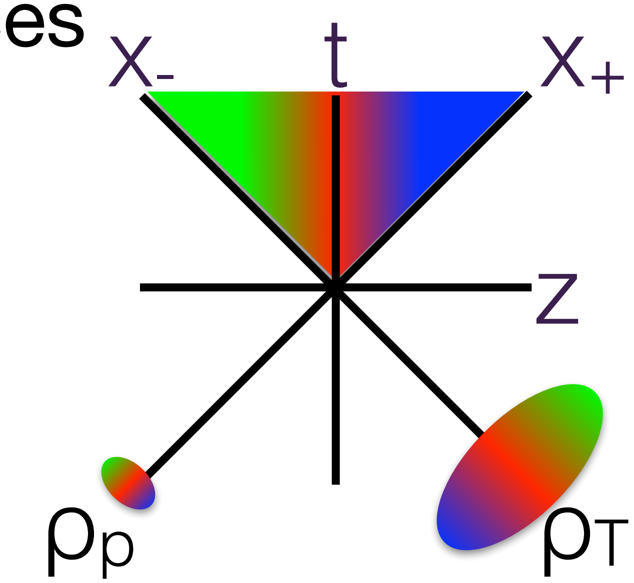

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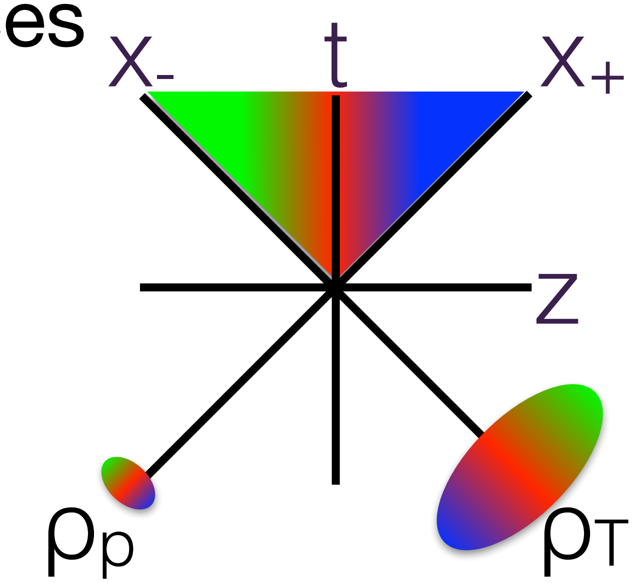

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Framework has been applied to study numerous final states at RHIC and LHC (quarkonia, photons,…)

Talks by S. Benic Wednesday, K. Watanabe Thursday

Dense-dense (all $O(\rho_p^\#)$) leads to IP-Glasma model

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

Includes quantum correlations (BE, HBT)

Gelis, Lappi, McLerran NPA 828 (2009), Kovner, Rezaeian, PRD 95, 96 (2017), Altinoluk, Armesto, Beuf, Kovner, Lublinsky, PLB 751 (2015), PRD 95 (2017), Kovner, Skokov PRD 98 (2018), PLB 785 (2018), …

The v_3 problem

Well known analytical solutions at leading order — $O(\rho_p^4)$

McLerran NPA 700 (2002), Blaizot, Gelis, Venugopalan NPA 743 (2004), Lappi EPJC 55 (2008)

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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)

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

Must be non-vanishing

However, at LO, exactly zero — but non-zero at all orders

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

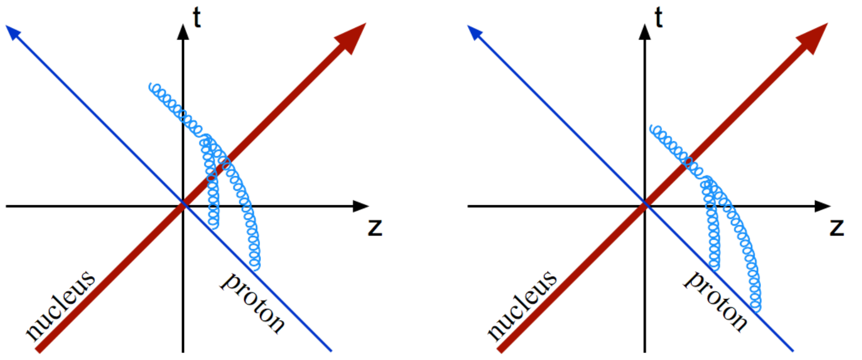
Lappi, Srednyak, Venugopalan JHEP 1001 (2010), Schenke, Schlichting, Venugopalan PLB 747 (2015)

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)



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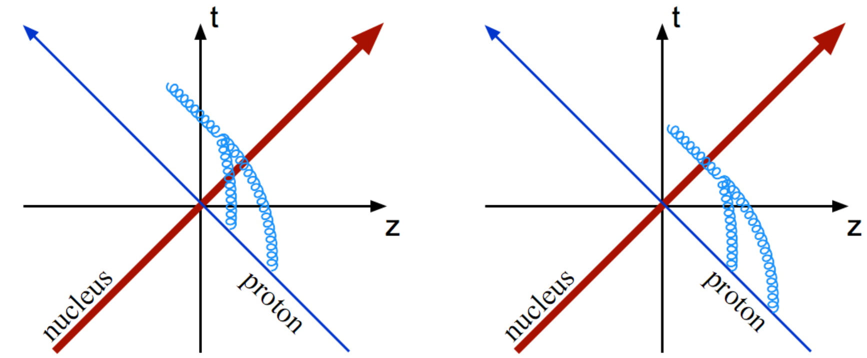

McLerran, Skokov NPA 959 (2017)

Then in Fock-Schwinger gauge (A_τ=0)

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

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

In terms of:

Projectile Target

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

Valence sources rotated by target

Dilute dense for gluons

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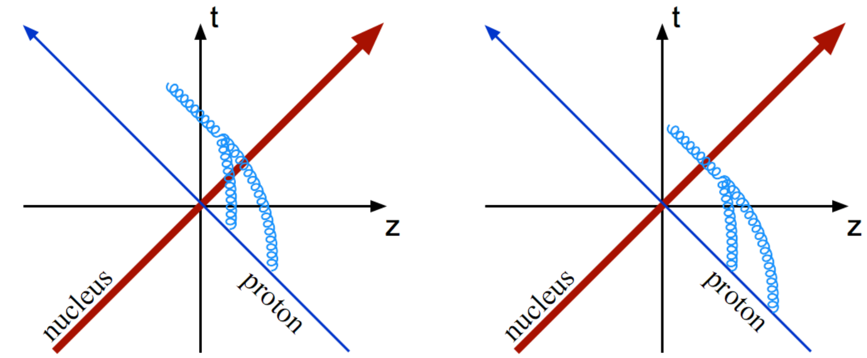

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Projectile Target

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)

Kovchegov, Skokov PRD 97 (2018)

For more details: see talk by V. Skokov week 6

Dilute dense for gluons

Issue resolved at next order in ρ_p
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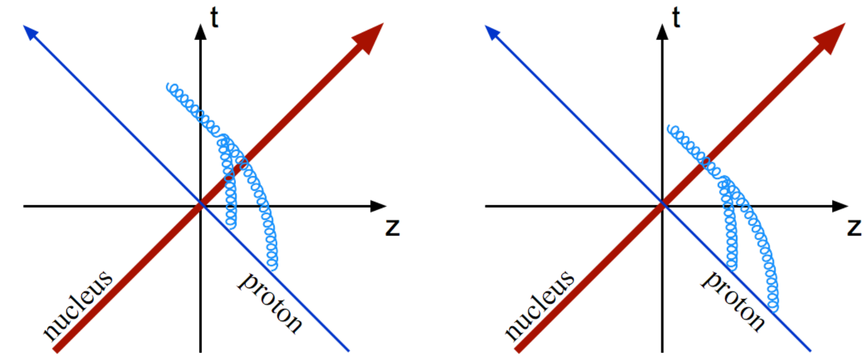
McLerran, Skokov NPA 959 (2017)



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Multi-particle distributions then defined as

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

Armesto, McLerran, Para NPA 781 (2006), Gelis, Lappi, Venugopalan PRD 78 (2008)

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

Dilute-dense CGC scaling

Even harmonics appear at LO dilute-dense

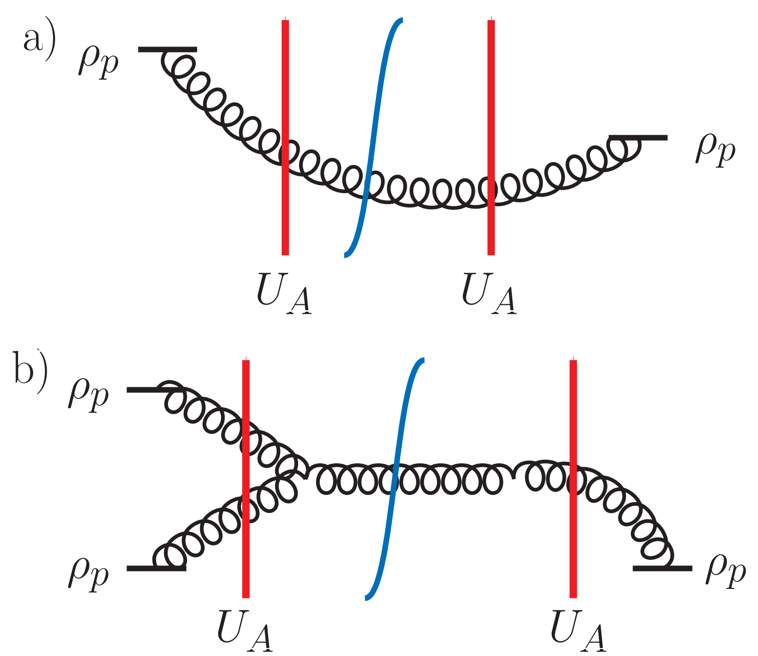
Odd harmonics only non-zero at next to leading order in ρ_p
—first saturation correction *(full result still elusive)*

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

$$\frac{dN^{\text{even}}(\mathbf{k}_\perp)}{d^2k dy} \sim \rho_p^2$$

$$\frac{dN^{\text{odd}}(\mathbf{k}_\perp)}{d^2k dy} \sim \rho_p^3$$

Full expressions in arXiv:1807.00825



Consider rescaling by a constant *c*

$$\rho_p \to c\rho_p \quad \Longrightarrow \quad \Omega \to c\Omega$$

MM, Skokov, Tribedy, Venugopalan, PLB (in press) arXiv:1807.00825

Dilute-dense CGC scaling

Singe-event multiplicity rescales as: $$\frac{dN}{d^2kdy}[\rho_p,\rho_t] \to c^2 \frac{dN}{d^2kdy}[\rho_p,\rho_t] + \mathcal{O}(c^3)$$

Rescaling Fourier harmonics

$$v_n^2\{2\}(N_{ch}) = \int W[\rho_p]W[\rho_t]\ |Q_n[\rho_p,\rho_t]|^2\ \delta(N_{ch} - \frac{dN}{dy}[\rho_p,\rho_t])$$

In terms of moments

$$Q_{2n}\left[\rho_p,\rho_t\right] = \frac{\int_{p_1}^{p_2}\int_{k_\perp,\phi} e^{i2n\phi}\frac{dN^{\rm even}(\mathbf{k}_\perp)}{d^2k_\perp dy}\left[\rho_p,\rho_t\right]}{\int_{p_1}^{p_2}\int_{k_\perp,\phi}\frac{dN^{\rm even}(\mathbf{k}_\perp)}{d^2k_\perp dy}\left[\rho_p,\rho_t\right]} \to c^0\ Q_{2n}\left[\rho_p,\rho_t\right] \quad , \quad |Q_{2n}|^2 \sim \left(\frac{dN}{dy}[\rho_p,\rho_t]\right)^0$$

$$Q_{2n+1}\left[\rho_p,\rho_t\right] = \frac{\int_{p_1}^{p_2}\int_{k_\perp,\phi} e^{i(2n+1)\phi}\frac{dN^{\rm odd}(\mathbf{k}_\perp)}{d^2k_\perp dy}\left[\rho_p,\rho_t\right]}{\int_{p_1}^{p_2}\int_{k_\perp,\phi}\frac{dN^{\rm even}(\mathbf{k}_\perp)}{d^2k_\perp dy}\left[\rho_p,\rho_t\right]} \to c\ Q_{2n+1}\left[\rho_p,\rho_t\right], \quad |Q_{2n+1}|^2 \sim \left(\frac{dN}{dy}[\rho_p,\rho_t]\right)^1$$

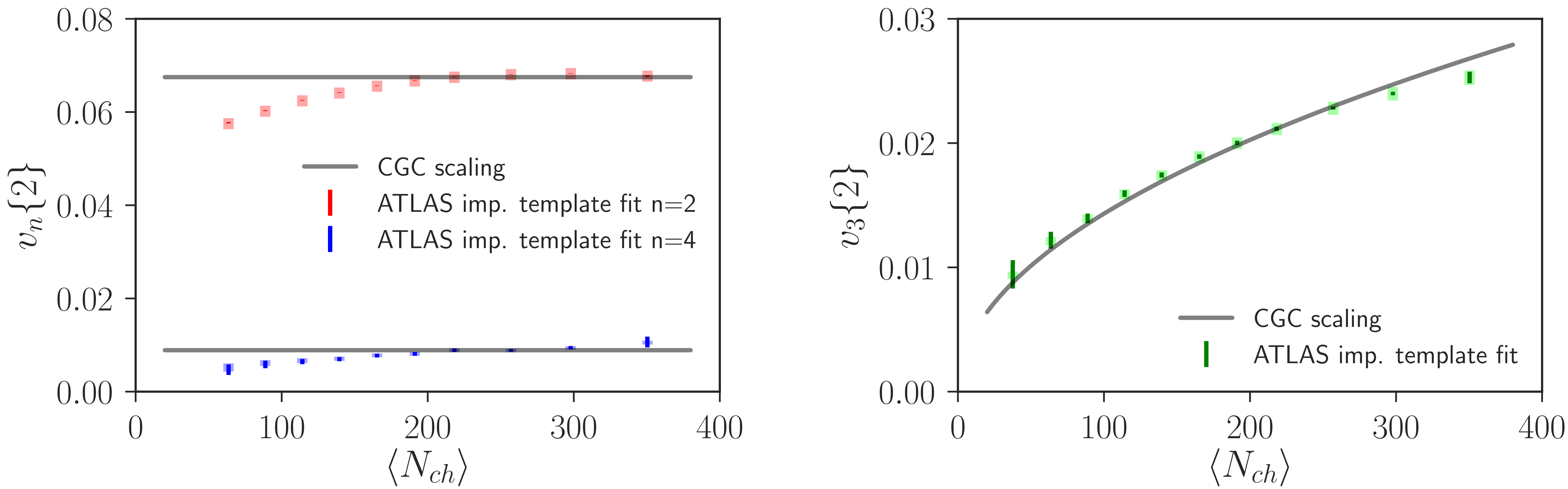
Dilute-dense CGC scaling is then

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

MM, Skokov, Tribedy, Venugopalan, PLB (in press) arXiv:1807.00825

Dilute-dense CGC scaling

Fixing proportionality coefficient at a single multiplicity for each v_n



High projectile density effects may explain large N_{ch} deviation

MM, Skokov, Tribedy, Venugopalan, PLB (in press) arXiv:1807.00825

Dilute-dense CGC scaling

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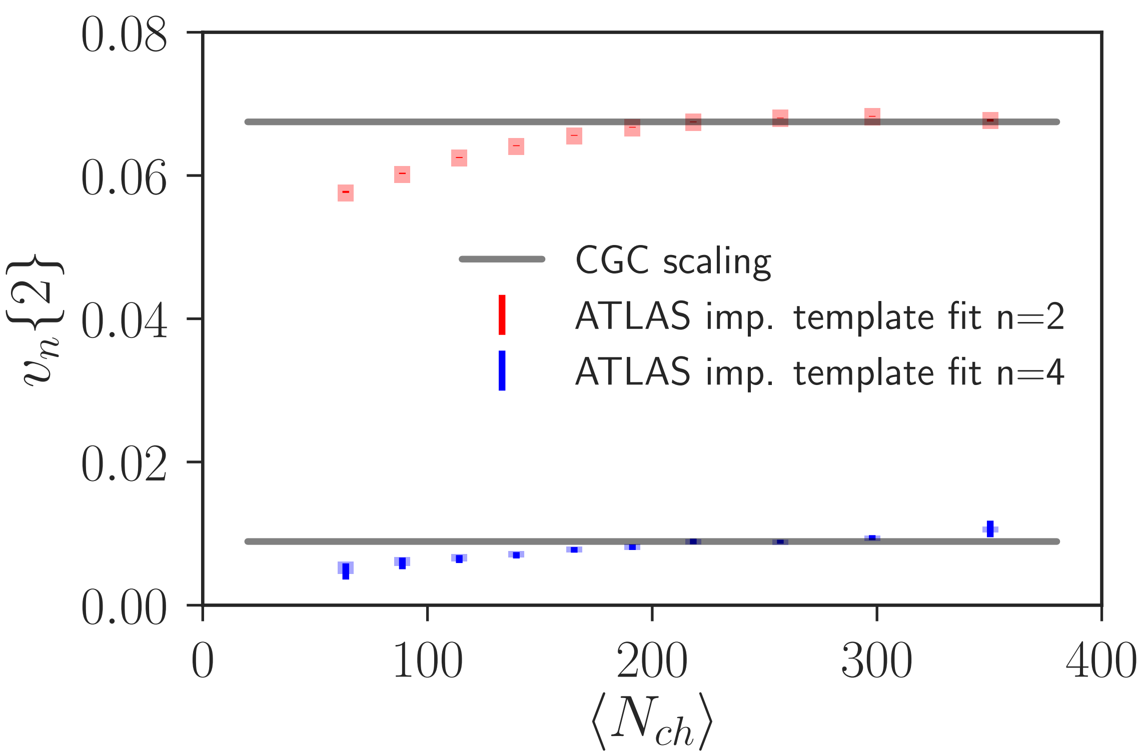
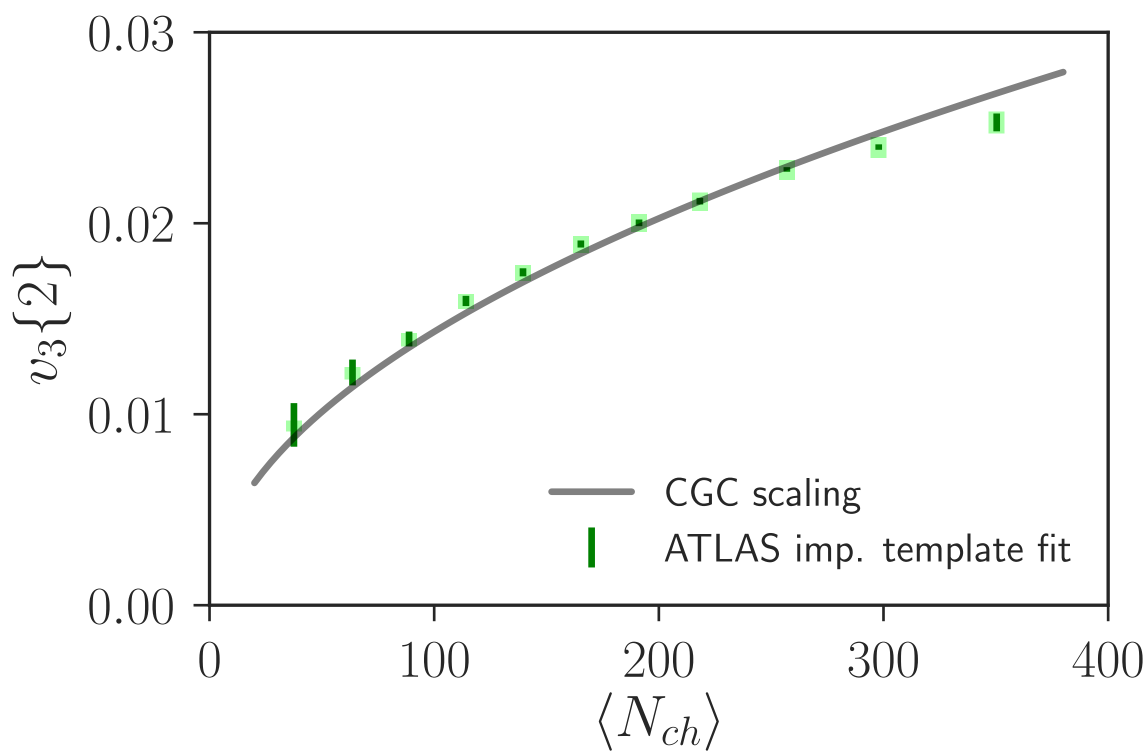
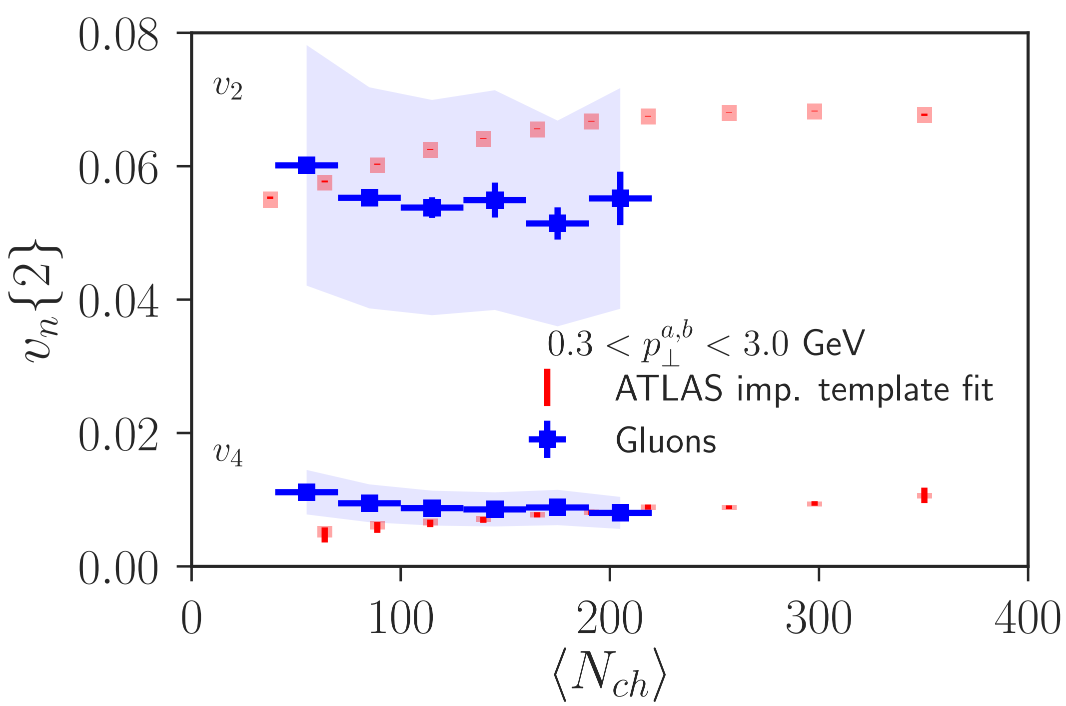






Realized with numerics!

Initial configurations

For initial nuclear configurations, use data-guided approach similar to IP-Glasma model

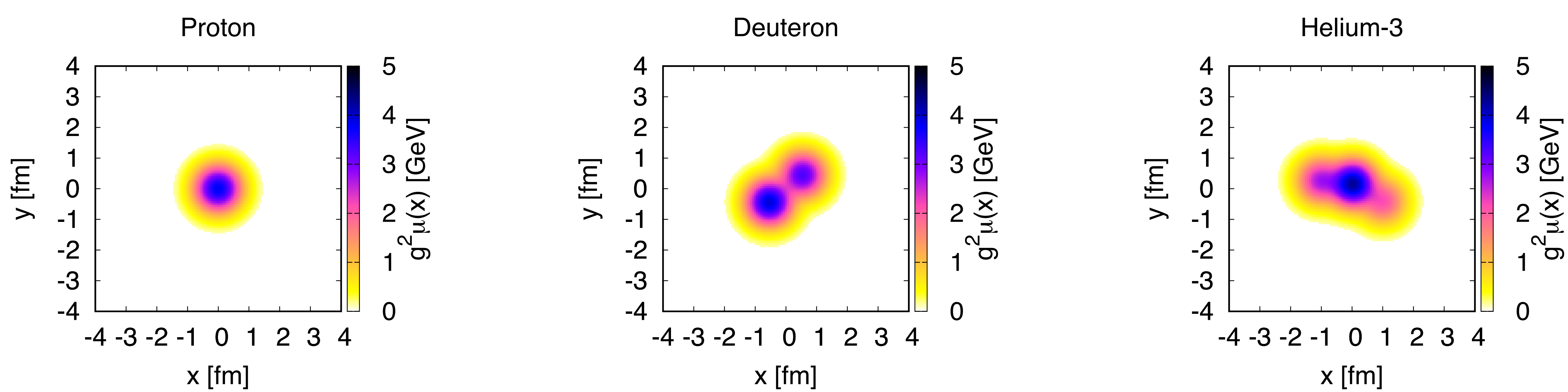
Schenke, Tribedy, Venugopalan PRL 108 (2012), PRC 86 (2012)

Sample nucleon positions as is done in Monte-Carlo Glauber

IP-Sat model (+fluctuations) provides $Q_s^2(x,\mathbf{b})$ for each nucleon

Kowalski, Teaney, Phys.Rev. D68 (2003) 114005, McLerran, Tribedy NPA 945 (2016)

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



Color charge fluctuations sampled event-by-event with MV model: $\langle \rho^a_{p/T}(\mathbf{x}_\perp)\rho^b_{p/T}(\mathbf{y}_\perp)\rangle = g^2\mu^2(x,\mathbf{b}=(\mathbf{x}_\perp+\mathbf{y}_\perp)/2)\delta^{ab}\delta^2(\mathbf{x}_\perp-\mathbf{y}_\perp)$

MM, Skokov, Tribedy, Venugopalan, PRL 121 (2018) arXiv:1805.09342, and in progress

Dilute-dense CGC EFT framework

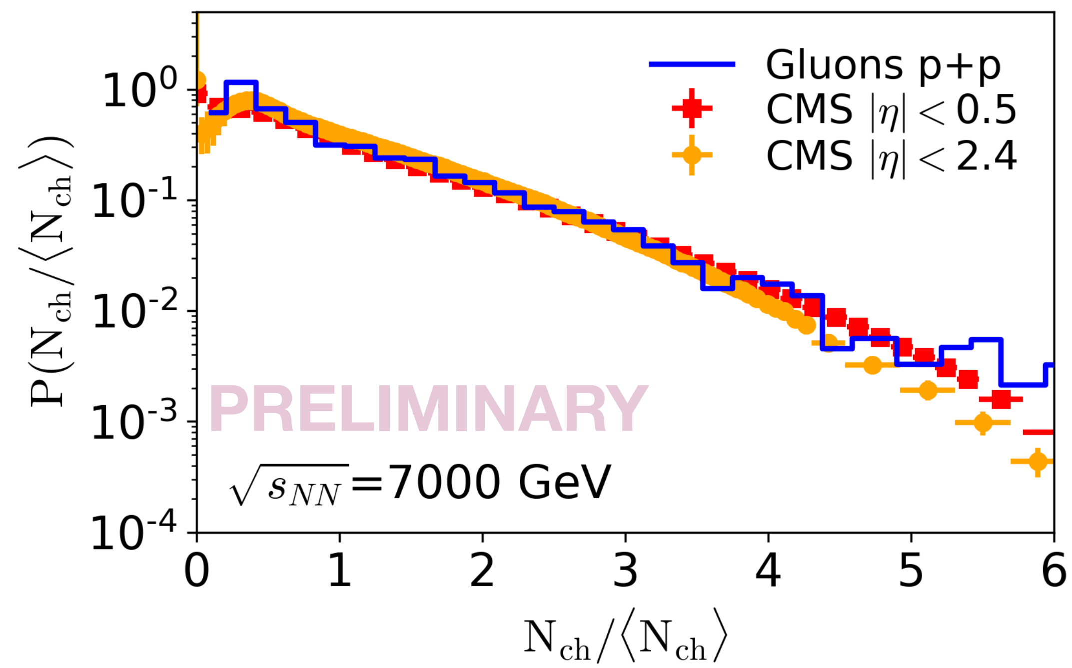
From initial ρ's, calculate particle production — includes quantum effects (BE, HBT)

Essential to account for color charge fluctuations; in particular for p+p

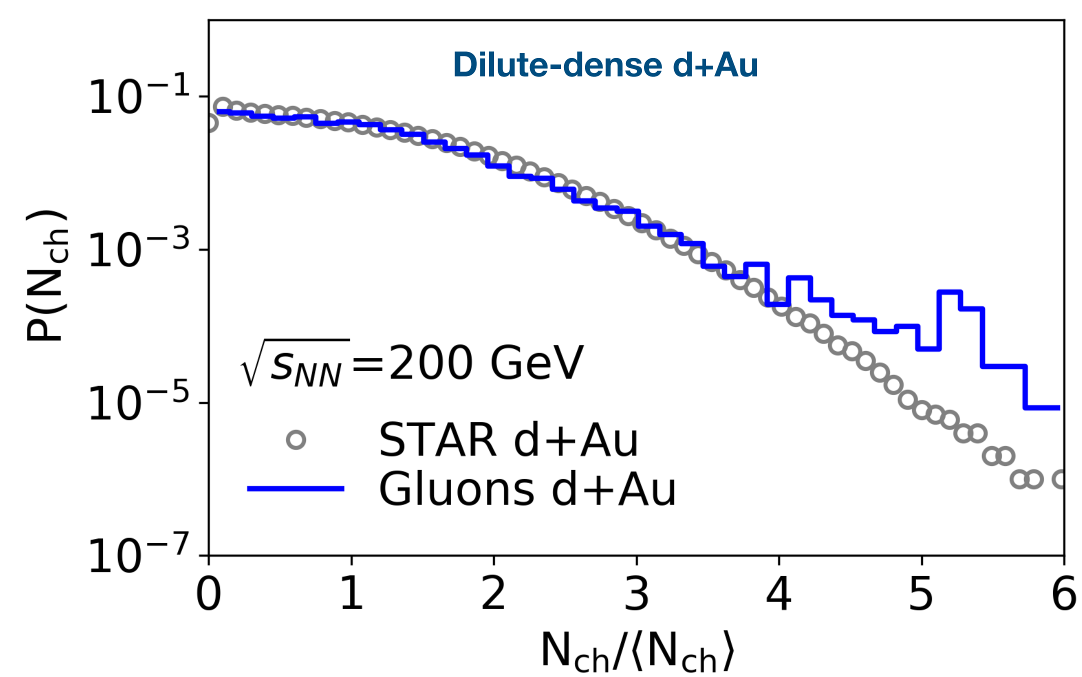
Generates negative binomial distributions from first principles, not an input!

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

Reasonable agreement found with STAR d+Au multiplicity distribution

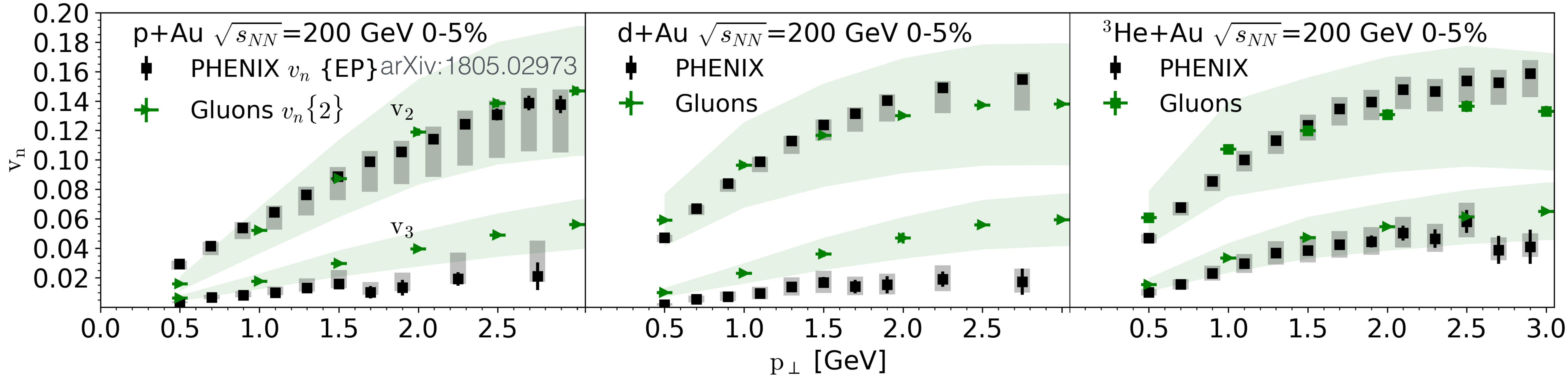


CMS JHEP 01 (2011)



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

Gluon correlations vs RHIC data for small systems



MM, Skokov, Tribedy, Venugopalan, PRL 121 (2018) arXiv:1805.09342, and in preparation

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)

Quantifying systematic uncertainties

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

Nuclear wave function: strong short-range correlations (measured at JLab). Exciting prospect; quantify influence on high multiplicity events

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.

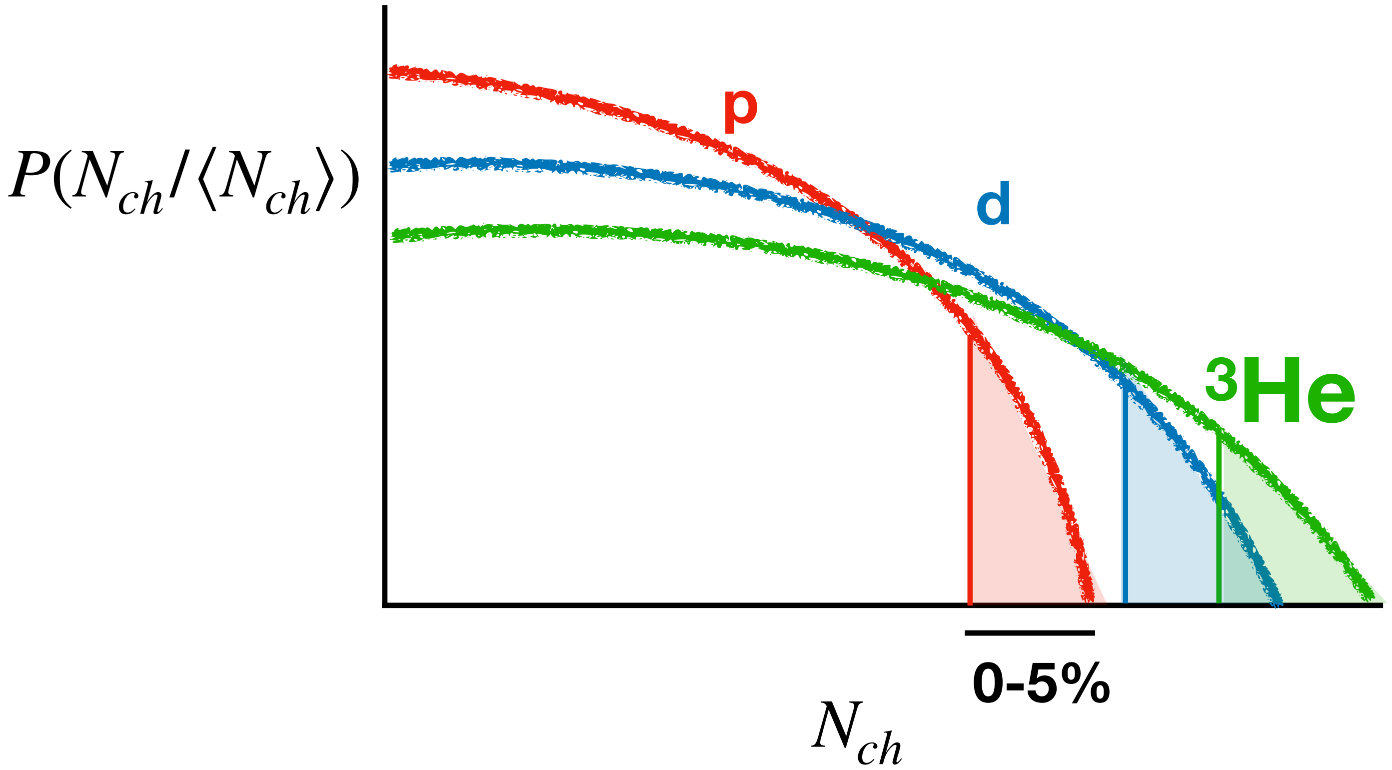
Talk by O. Hen during week 5

Fragmentation — uncertainty which enters in multiplicity spectrum and v_n: CGC+Lund string model can be applied here

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

Qu'est-ce que c'est?

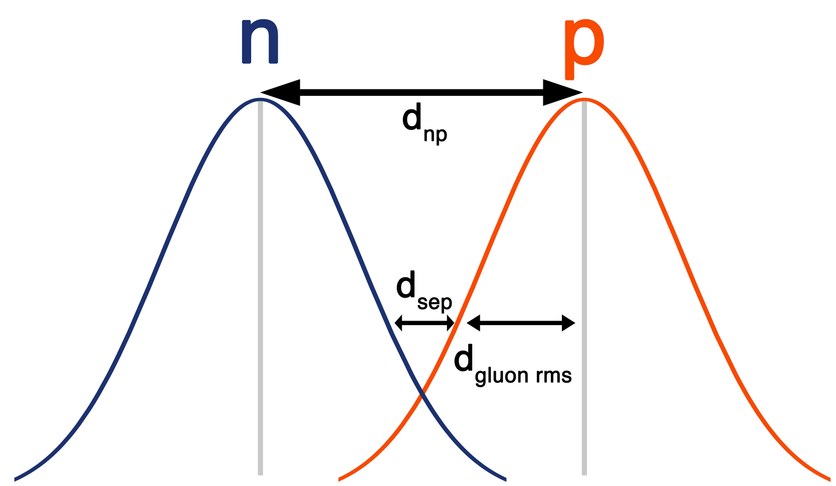
A naïve interpretation of results: Fixed multiplicity class $\longmapsto$ larger average N_{ch} for larger systems $\longmapsto$ larger average $Q_s^2 S_{perp} \longmapsto$ more correlations



Natural consequence: same multiplicity ~ similar correlations

However, we are considering non-linear QCD with quantum effects, classical intuition may be misleading

Qu'est-ce que c'est?

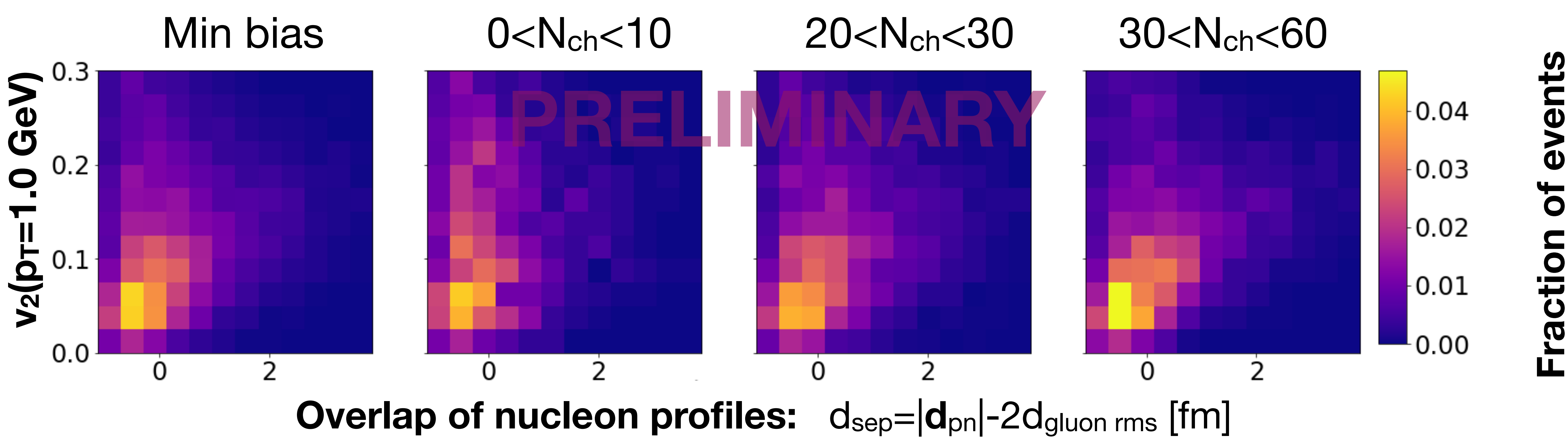


$d_{gluon\ rms} = (2\ B_G)^{1/2} \simeq 0.56$ fm

$d_{sep} = |\mathbf{d}_{pn}| - 2d_{gluon\ rms}$

$d_{sep} \simeq -1$ fm — full overlap

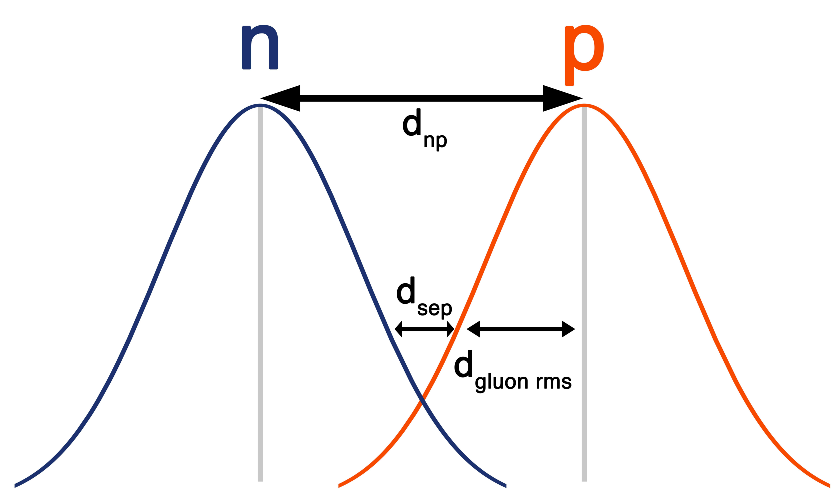
$d_{sep} \simeq 0$ fm — overlapping tails



Many sources of fluctuations

MM, Skokov, Tribedy, Venugopalan, in preparation

Qu’est-ce que c’est?

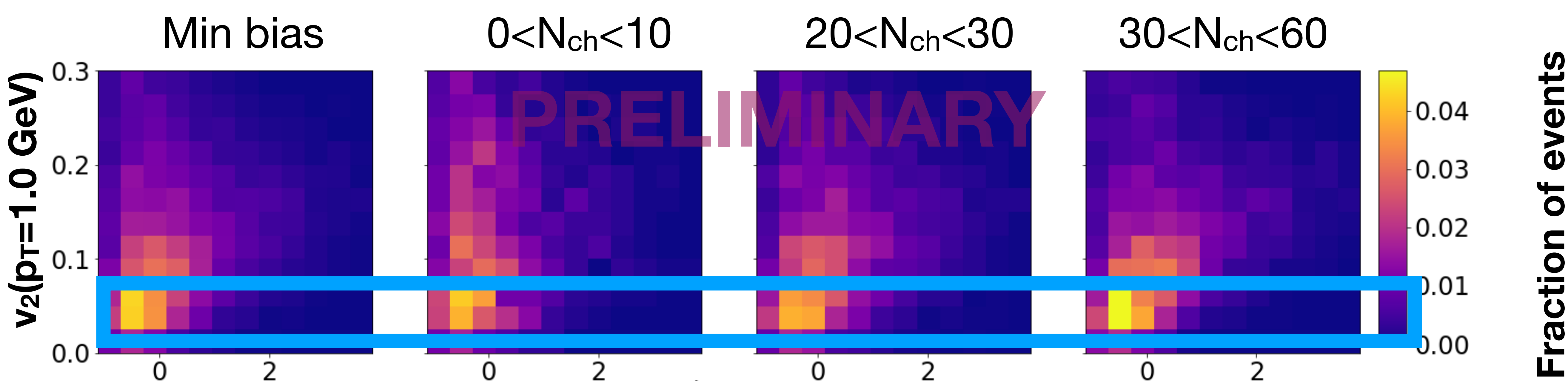


$d_{sep}=|\mathbf{d}_{pn}|-2d_{gluon\ rms}$

$d_{sep}\simeq-1$ fm — full overlap

$d_{sep}\simeq 0$ fm — overlapping tails

$d_{gluon\ rms}=(2\ B_G)^{1/2}\simeq 0.56$ fm



Overlap of nucleon profiles: $d_{sep}=|\mathbf{d}_{pn}|-2d_{gluon\ rms}$ [fm]

Many sources of fluctuations

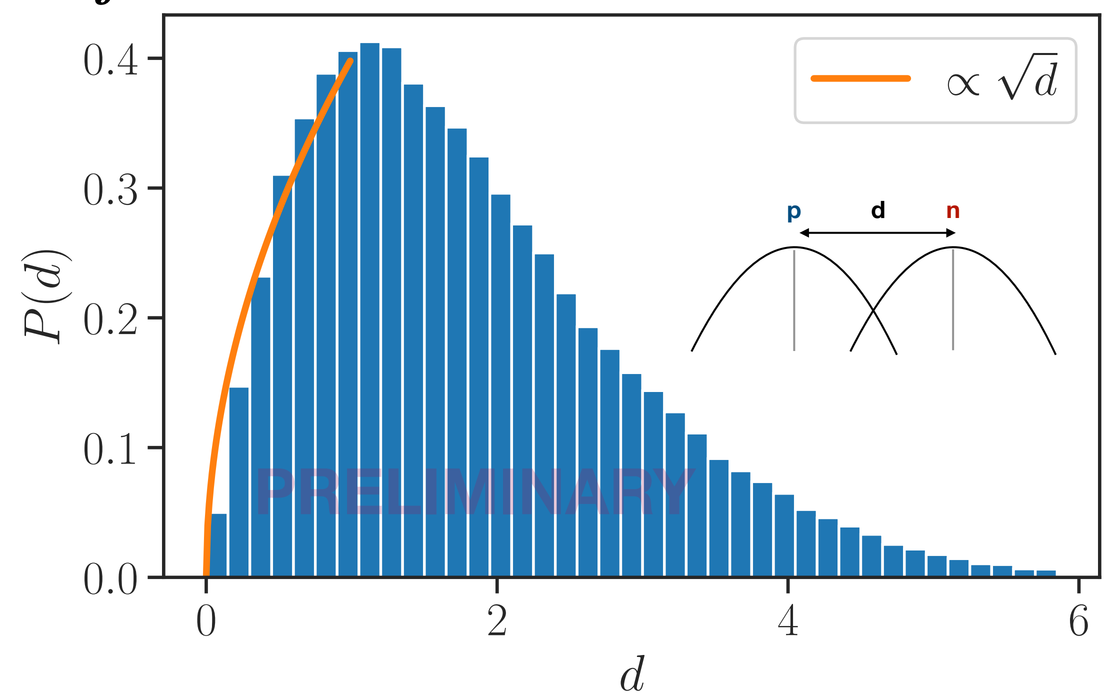
High multiplicity events bias towards overlapping nucleons in deuteron

MM, Skokov, Tribedy, Venugopalan, in preparation

Case study: MV

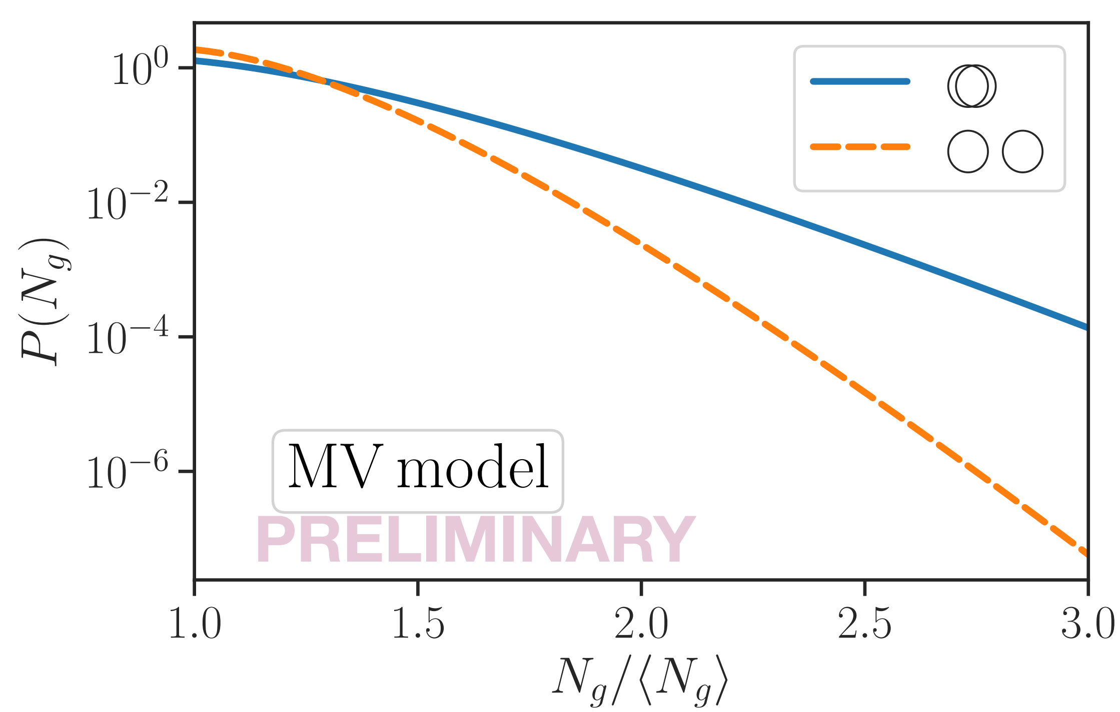
$$P(d) = \int d^3x d^3x' \; P_n^{\text{Hult.}}(r) \; P_n^{\text{Hult.}}(r') \; \delta(d - |\mathbf{x}_\perp - \mathbf{x}'_\perp|)$$

Consider simplified infinite MV target



Deuteron positions determined by Hulthén wavefunction

For small separation, P(d=d_{np})~$d^{1/2}$, thus close configurations suppressed

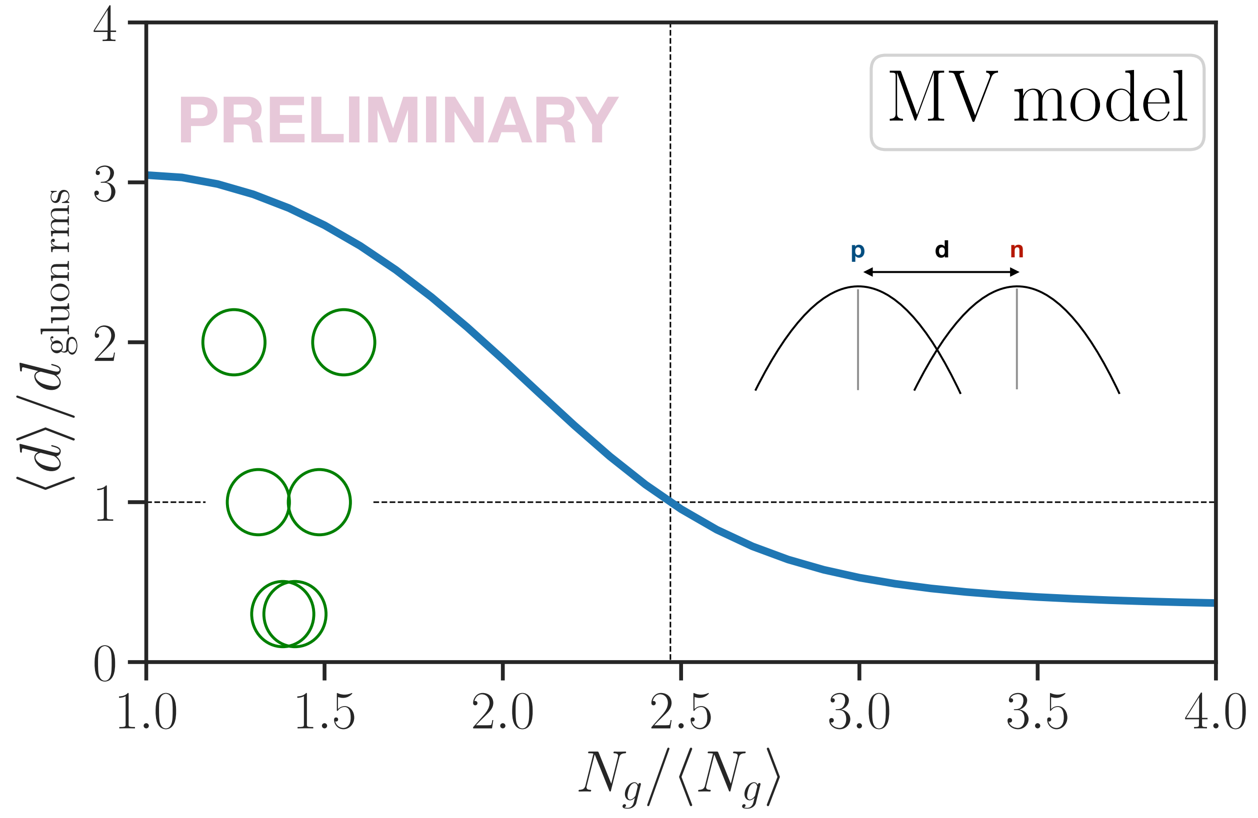


But, in dilute-dense CGC, high-multiplicity events are exponentially biased to 'close' configurations

Case study: MV

Since close configurations dominate high-multiplicity events, effect is seemingly different than geometry

Parametrically in dilute-dense CGC
$N_{ch} \sim Q^2_{s,\text{proj}} S_\perp$
means that close configurations have greater *effective* $Q_{s,\text{proj}}$ — may drive v_n's

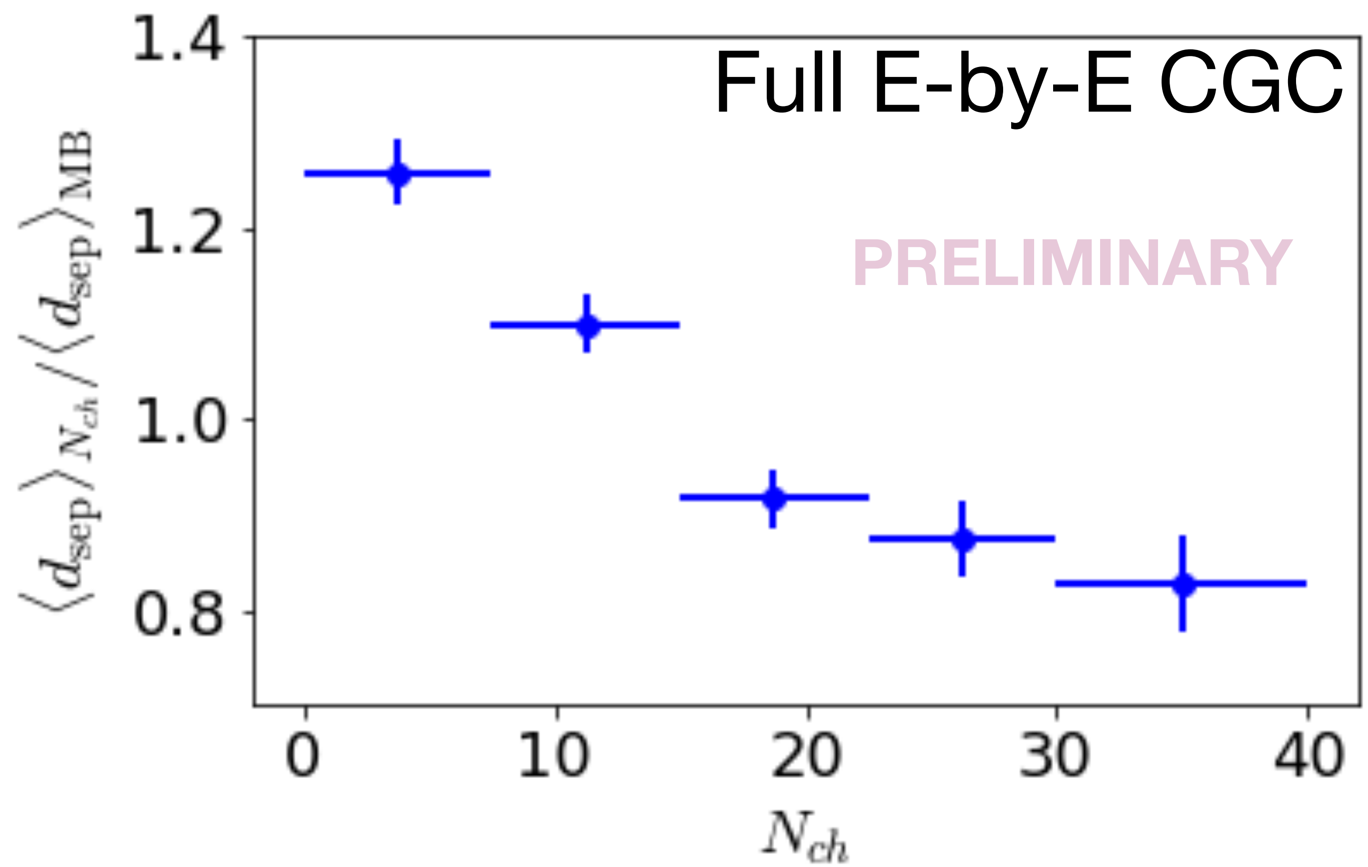


Qu’est-ce que c’est?

Similar results for full event-by-event model

Contribution from target fluctuations, etc, needs to be better understood

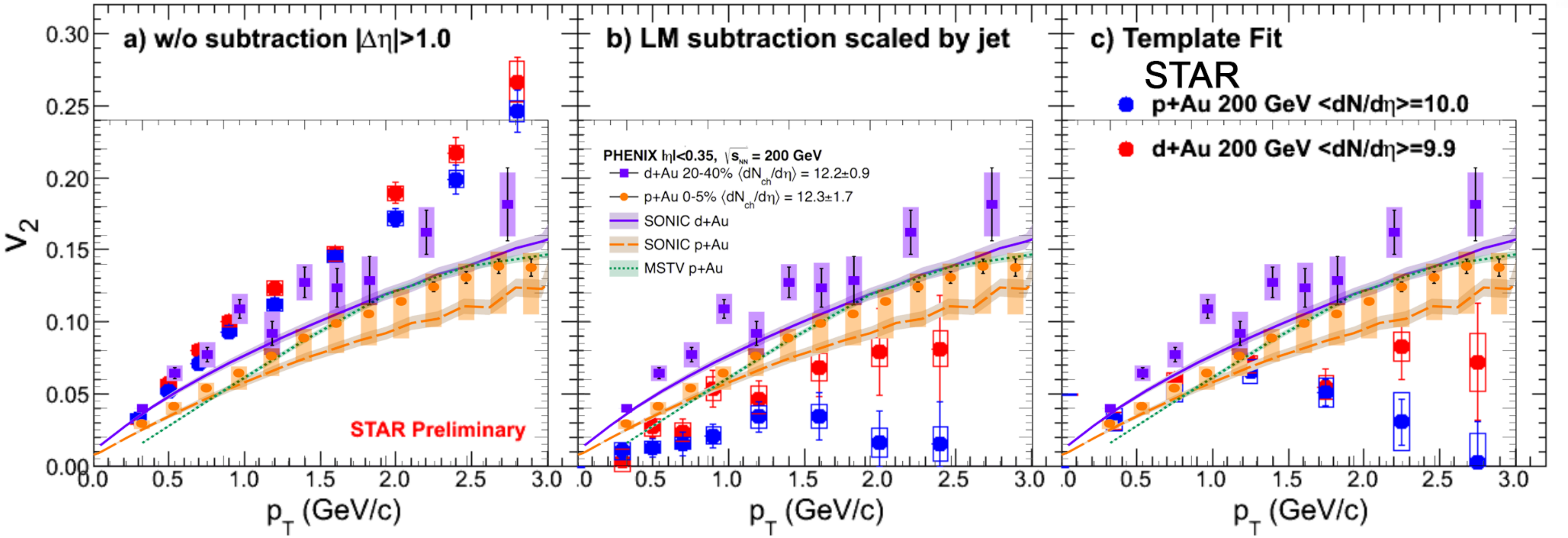
Determining origin of v_2 more complicated — work in progress



Same multiplicity p/d+Au

Dilute-dense CGC conjecture: same multiplicity ~ similar correlations

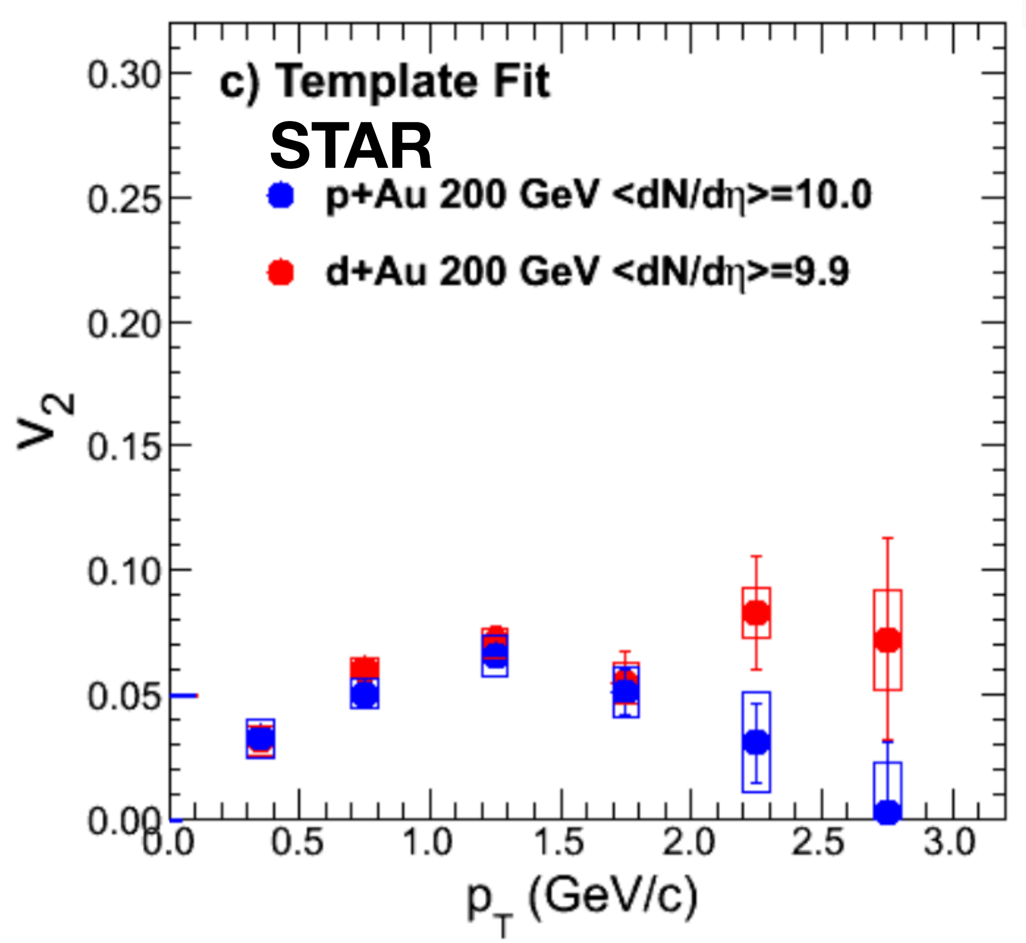
MM, Skokov, Tribedy, Venugopalan, PRL 121 (2018) arXiv:1805.09342



STAR from QM18 presentation by S Huang: https://tinyurl.com/y95aeupu, PHENIX arXiv:1805.02973

Systematic uncertainties between experiments, methods

Same multiplicity p/d+Au



STAR data from QM18 presentation by S Huang: https://tinyurl.com/y95aeupu

Intriguing result that p/d+Au at same multiplicity are compatible

Conclusions

Dilute-dense CGC gives multiplicity dependence in line with v_n at LHC

MM, Skokov, Tribedy, Venugopalan, PLB (in press) arXiv:1807.00825

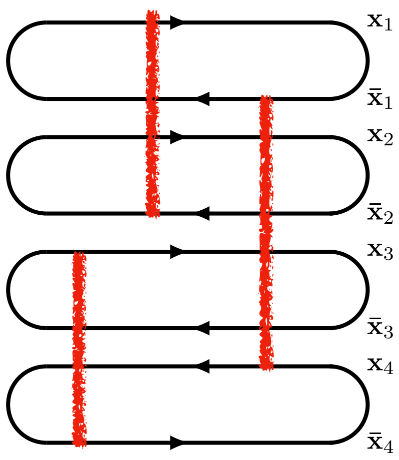
Full dilute-dense CGC framework able to describe system size hierarchy of v_2 and v_3 at RHIC

MM, Skokov, Tribedy, Venugopalan, PRL 121 (2018) arXiv:1805.09342

Color charge fluctuations and quantum correlations crucial features of framework, cannot be reproduced by classical intuitions

MM, Skokov, Tribedy, Venugopalan, PRL 121 (2018) arXiv:1805.09342, and in progress

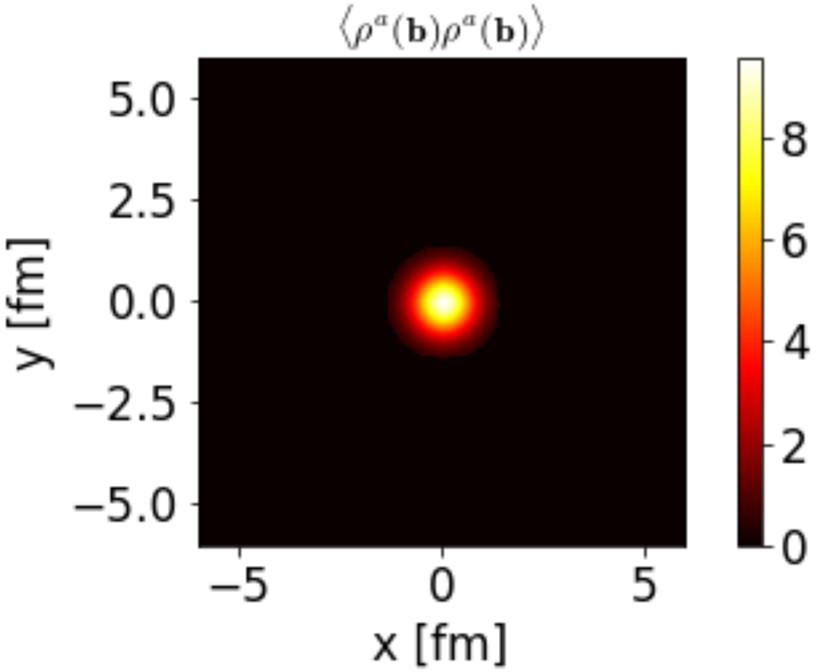
To quantify the roles of initial state and hydrodynamics, important to have p/^{3}He+Au multiplicity distributions and anisotropies in different event classes, different observables

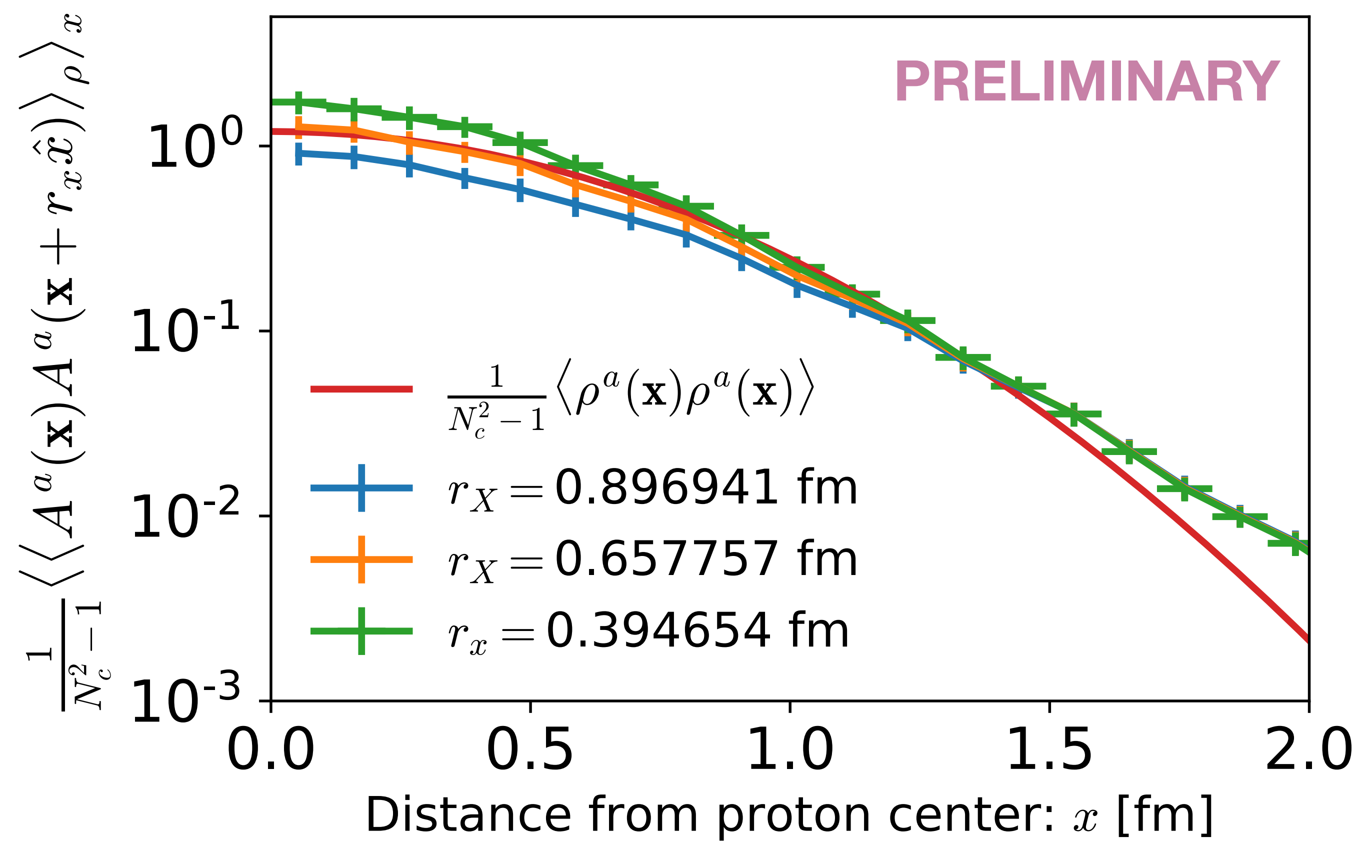


$\mathbf{x}_1$
$\bar{\mathbf{x}}_1$
$\mathbf{x}_2$
$\bar{\mathbf{x}}_2$
$\mathbf{x}_3$
$\bar{\mathbf{x}}_3$
$\mathbf{x}_4$
$\bar{\mathbf{x}}_4$

BACKUP

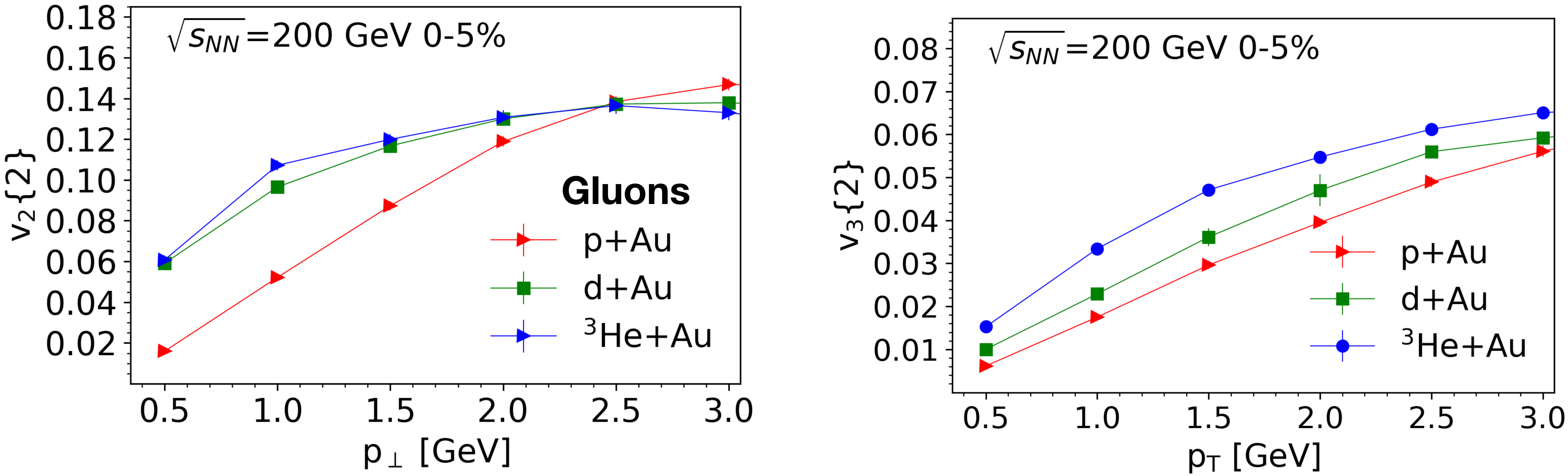
Charge and fields





Hierarchy of anisotropies across systems

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



MM, Skokov, Tribedy, Venugopalan, PRL 121 (2018) arXiv:1805.09342

Fluctuating initial shape

Constrain proton shape fluctuations from comparison to exclusive J/Ψ production (HERA)

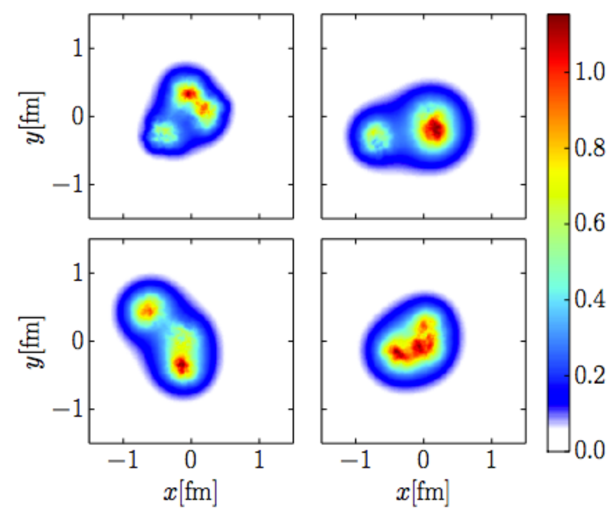


Fig. 3. Example of the proton density profiles at $x \approx 10^{-3}$. The quantity shown is $1 - \mathrm{Re\,Tr}V(\mathbf{x})/N_c$.

Incoherent cross section sensitive to fluctuations

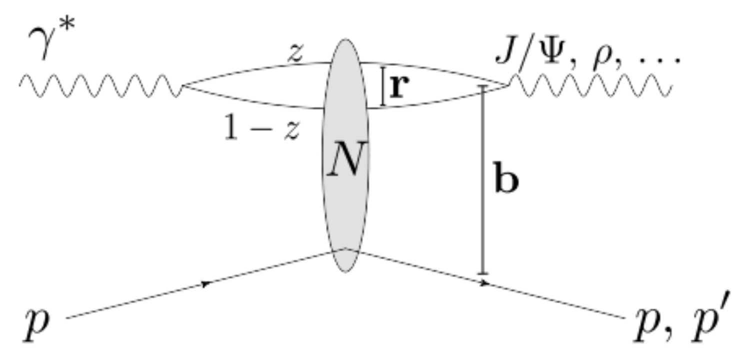
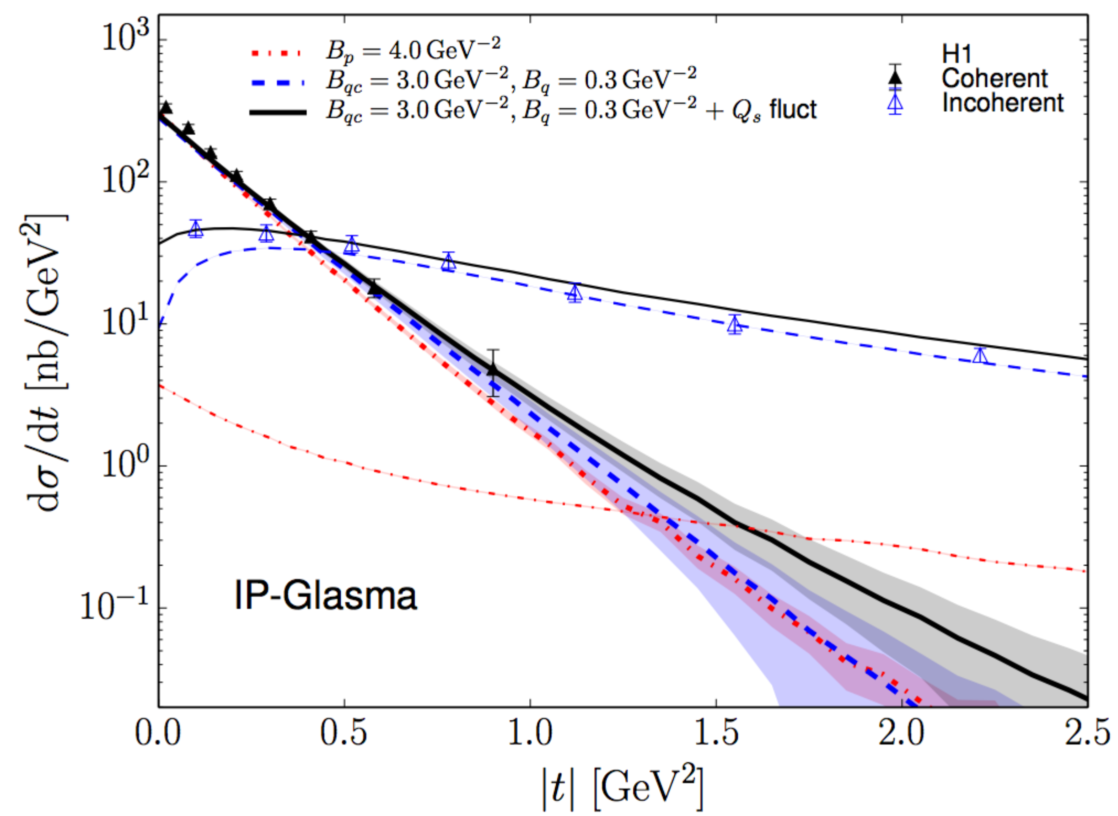


Fig. 1. Diffractive vector meson production in dipole picture.

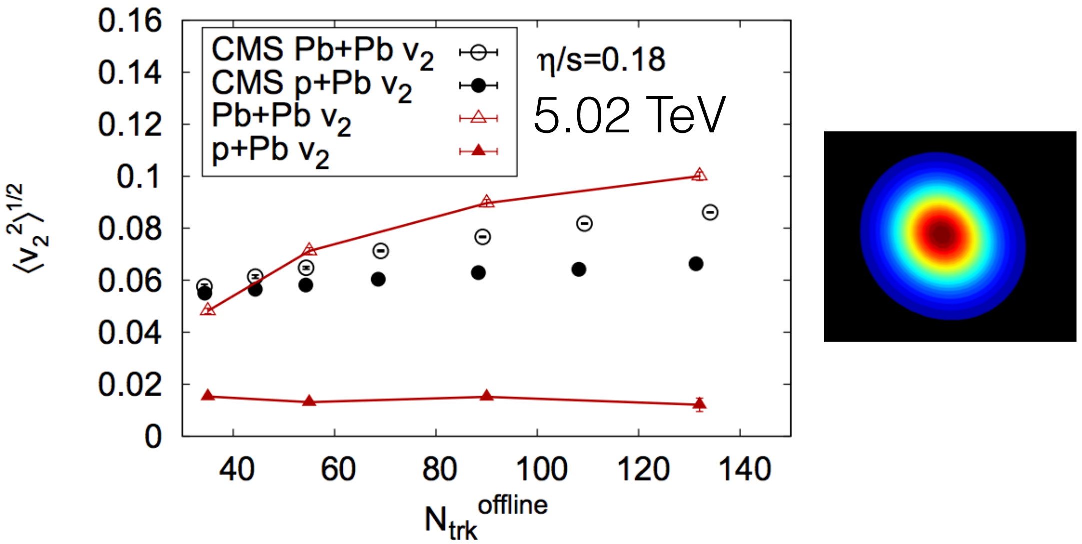


Mäntysaari, Schenke, PRL 117 (2016) 052301; PRD 94 (2016) 034042

Fluctuating projectile

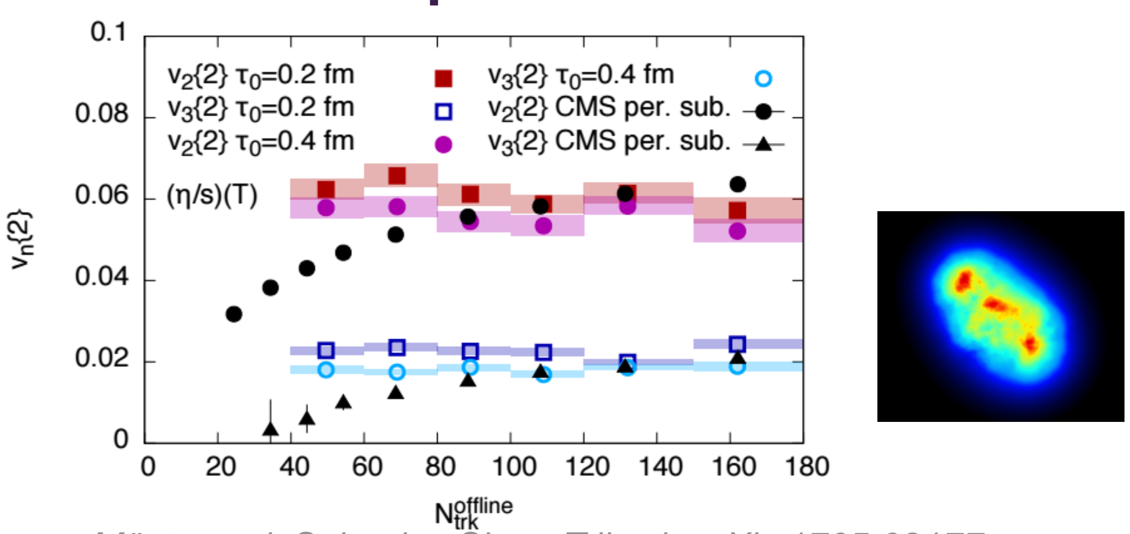
Important for spatial eccentricity driven models (hydro)

IP-Glasma+MUSIC



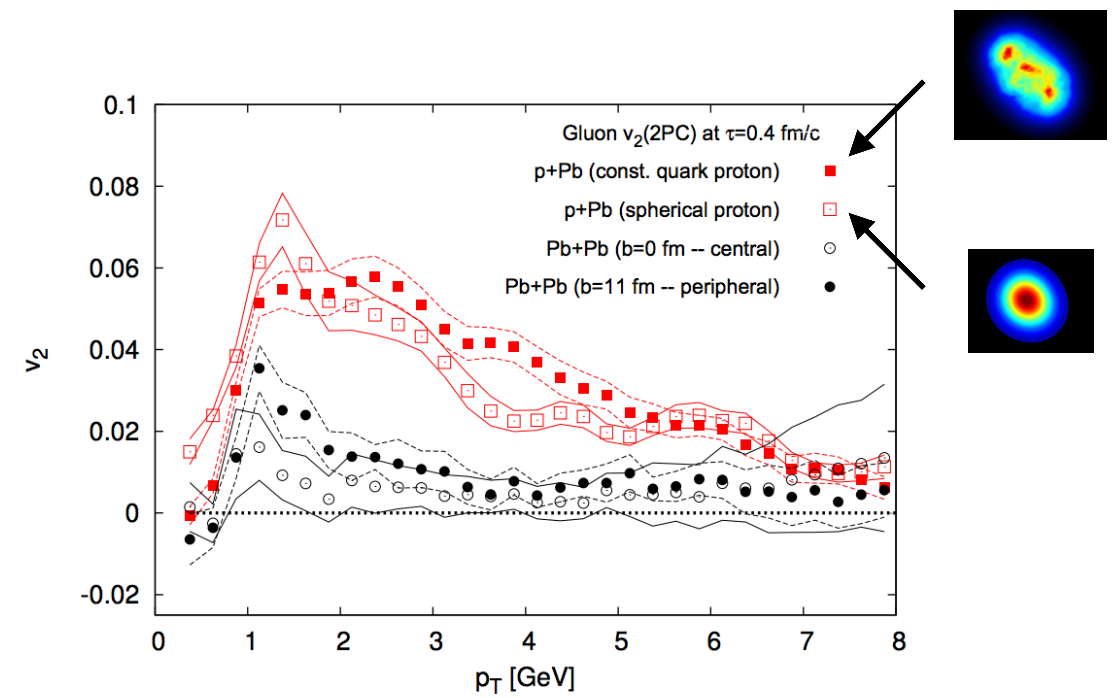
Schenke, Venugopalan PRL 113 (2014) 102301

IP-Glasma+**Fluct. proton**+MUSIC+UrQMD



Mäntysaari, Schenke, Shen, Tribedy arXiv:1705.03177

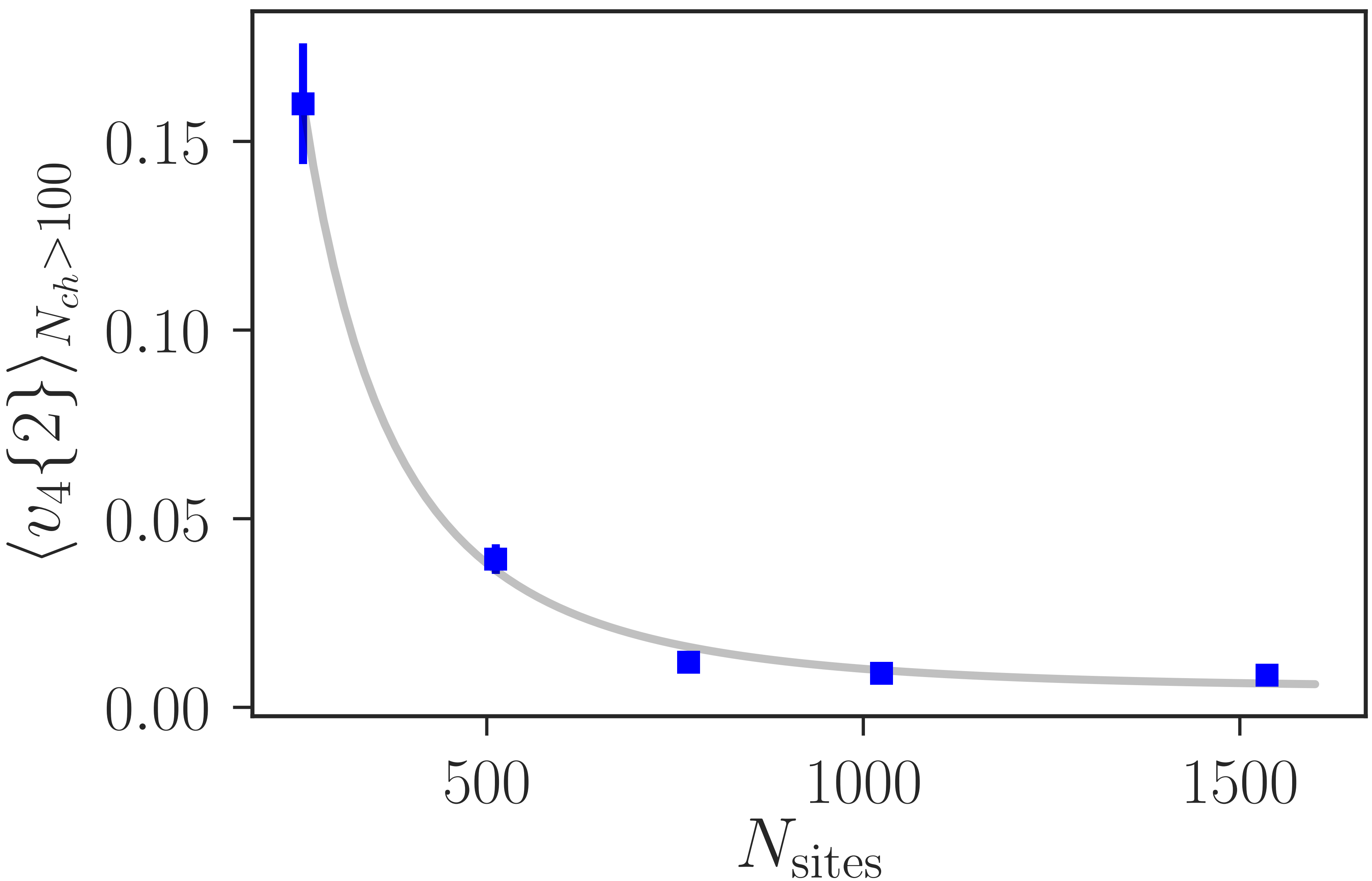
CGC has only momentum-space correlations



Schlichting, Schenke, Venugopalan PLB 742 (2015)

No qualitative difference observed

Continuum limit v_4



MM, Skokov, Tribedy, Venugopalan, PLB (in press) arXiv:1807.00825

A parton model

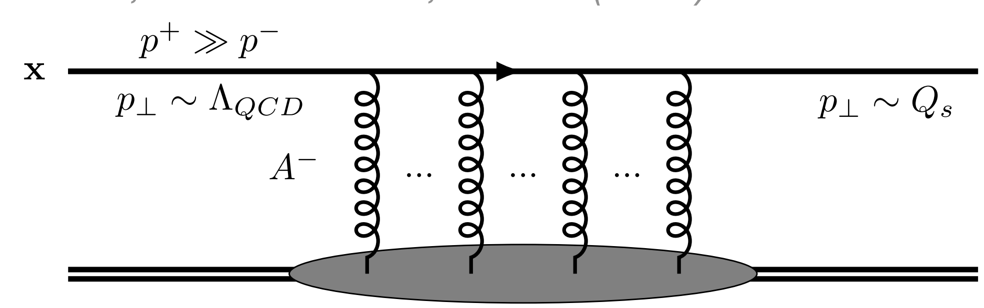
Working in dilute-dense limit: Q_s(target) ≫ Q_s(projectile), consider eikonal quark scattering off dense nuclear target with color domains of size ~$1/Q_{s,T}$

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

Quark coherent multiple scattering off target represented by Wilson line phase

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

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



Single quark inclusive distribution

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

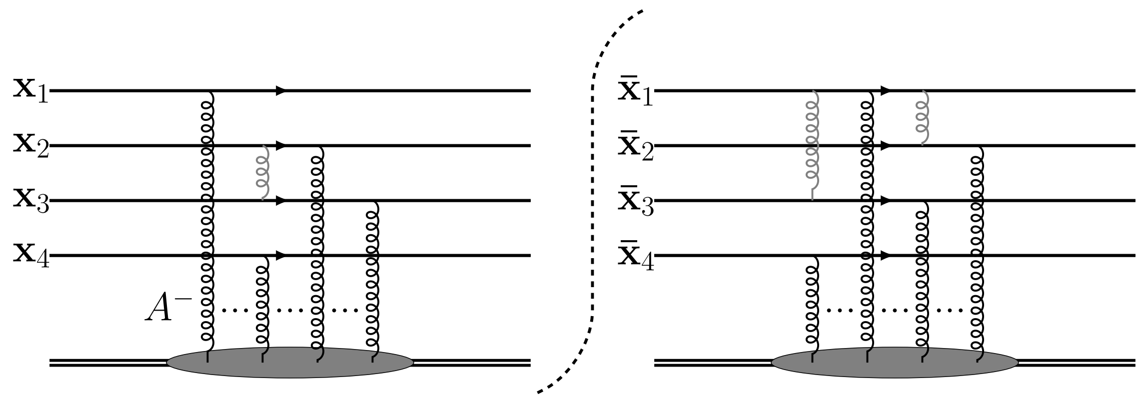
Projectile: Wigner function

Target scattering:
Dipole operator D(x,y)

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

A parton model

Generalizing for multiple particle correlations for *simple* model of multi particle correlations $\left\langle \frac{d^m N}{d^2\mathbf{p}_1 ... d^2\mathbf{p}_m} \right\rangle = \left\langle \frac{dN}{d^2\mathbf{p}_1} ... \frac{dN}{d^2\mathbf{p}_m} \right\rangle \sim \int \langle D ... D \rangle$



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)

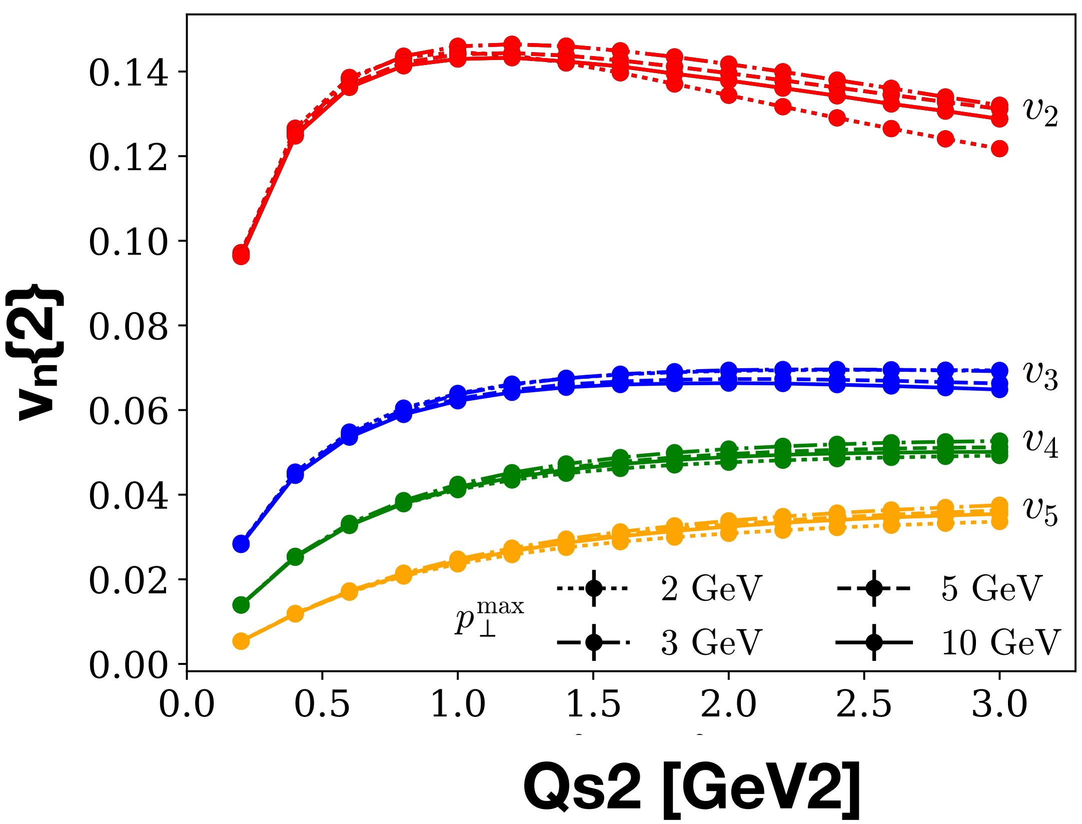
Generate cumulants, integrate to scale $p_\perp^{max}$

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

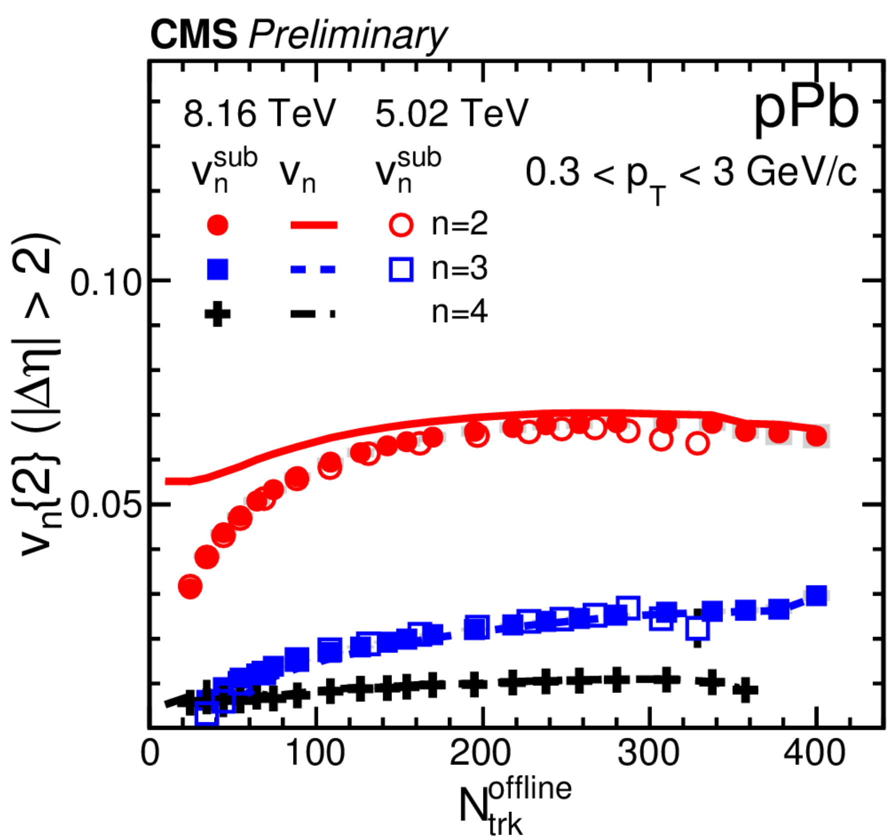
$$c_2\{2\} = \frac{\kappa_2\{2\}}{\kappa_0\{2\}}, \quad c_2\{4\} = \frac{\kappa_2\{4\}}{\kappa_0\{4\}} - 2\left(\frac{\kappa_2\{2\}}{\kappa_0\{2\}}\right)^2, ...$$

Multi-particle quark correlations

Ordering in two particle Fourier harmonics similar to data



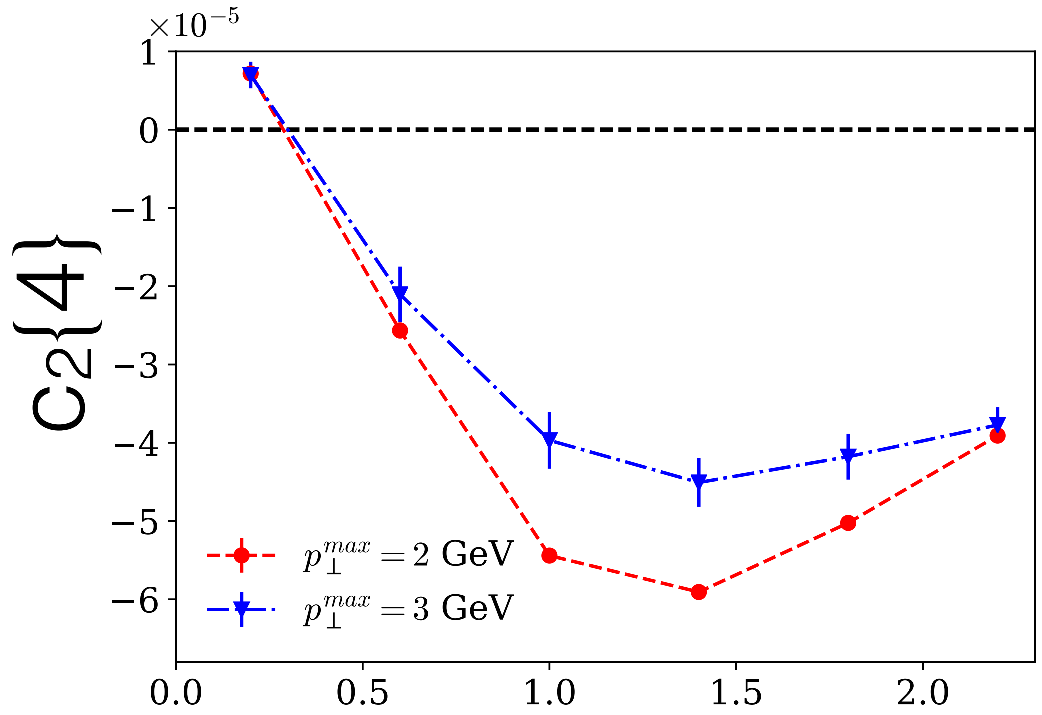
Dusling, MM, Venugopalan PRL 120 (2018)



CMS-PAS-HIN-16-022

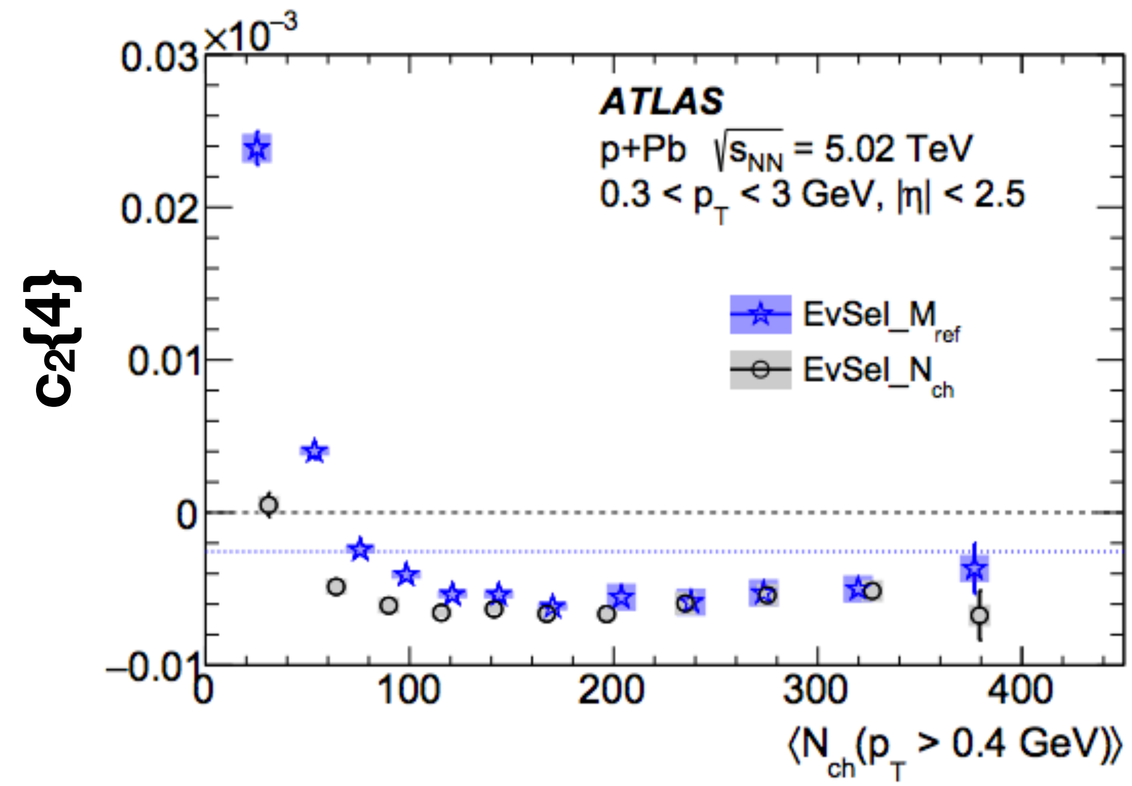
Multi-particle quark correlations

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



Q_s^2 [GeV²]

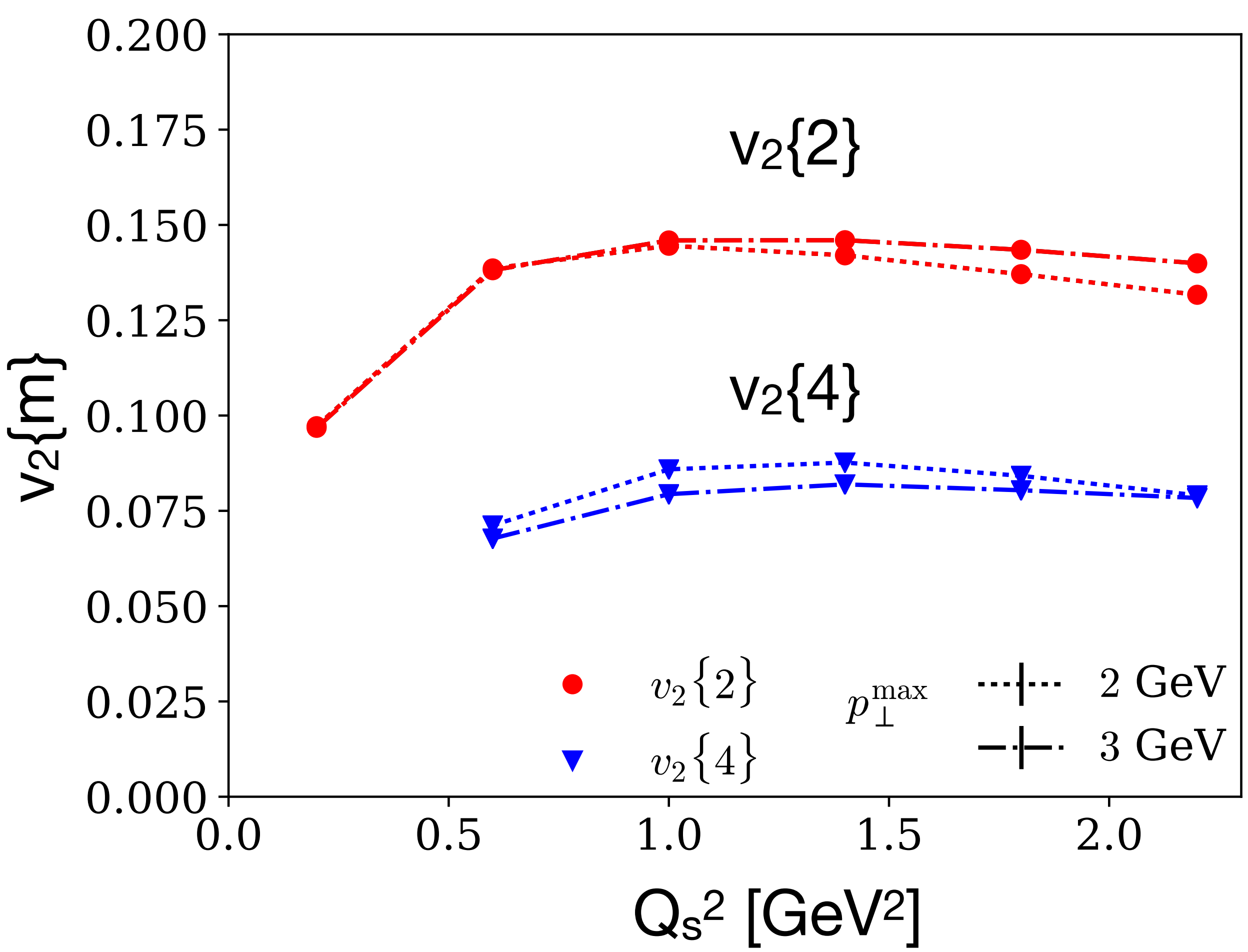
Dusling, MM, Venugopalan PRD 97 (2018)

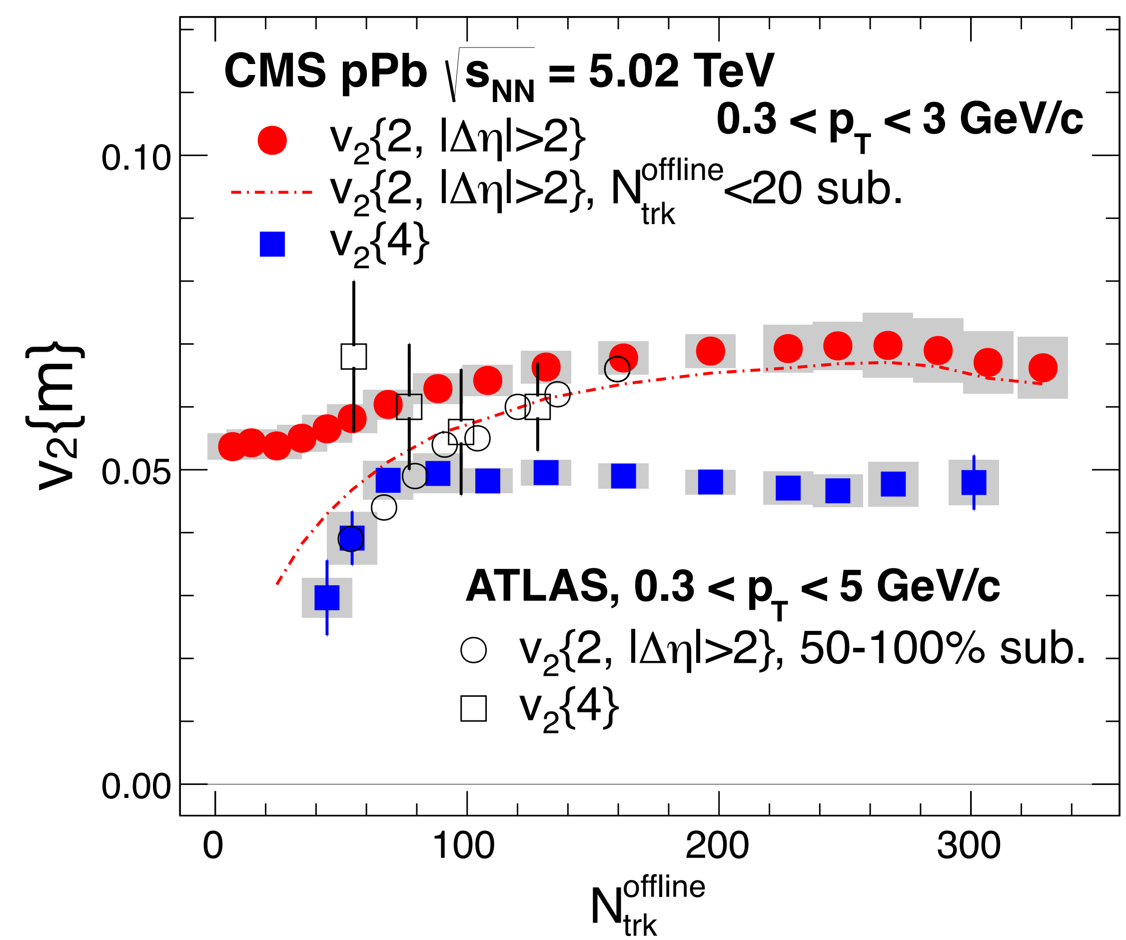


ATLAS EPJC 77 (2017)

Mild dependence on maximum integrated $p_\perp$

Multi-particle quark correlations





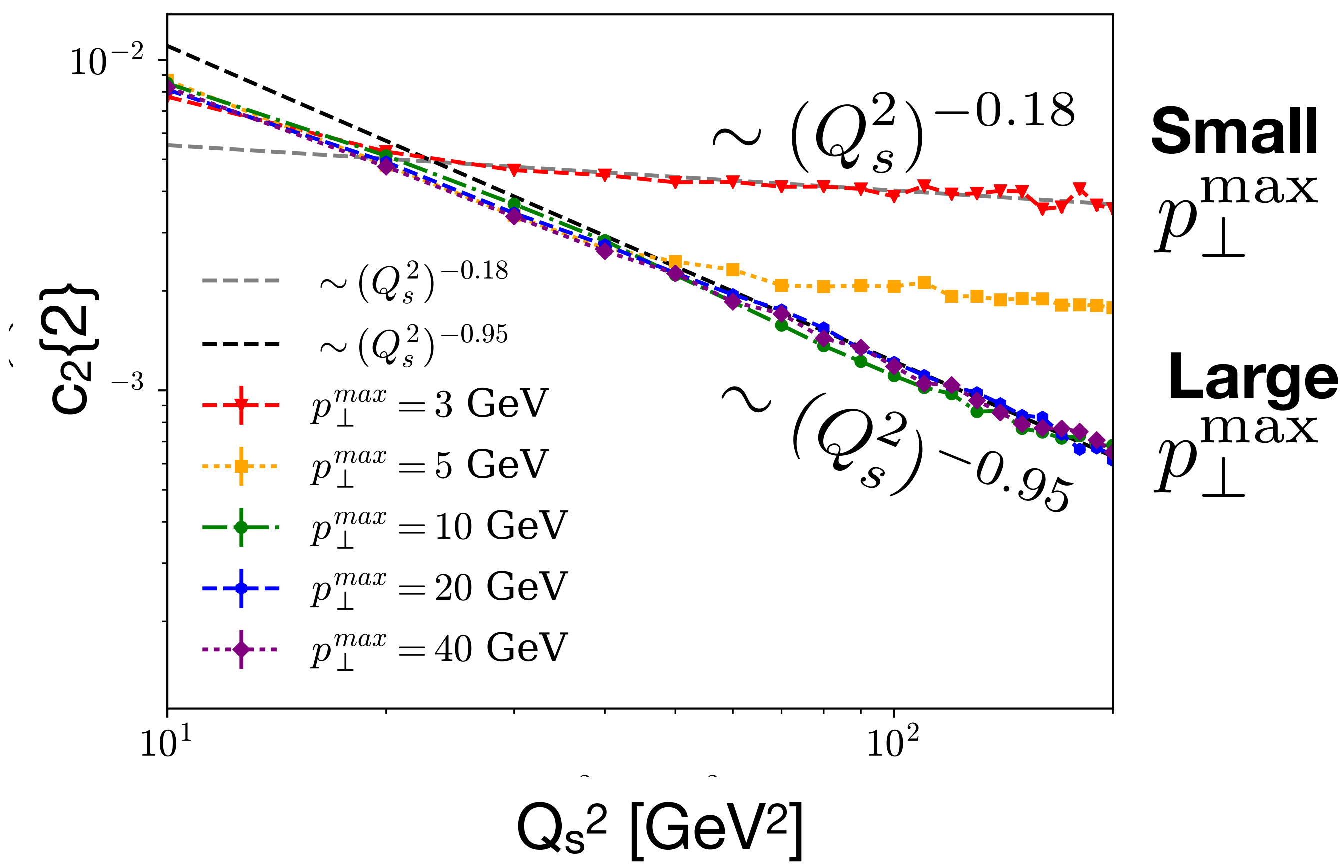
Dusling, MM, Venugopalan PRL 120 (2018)

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

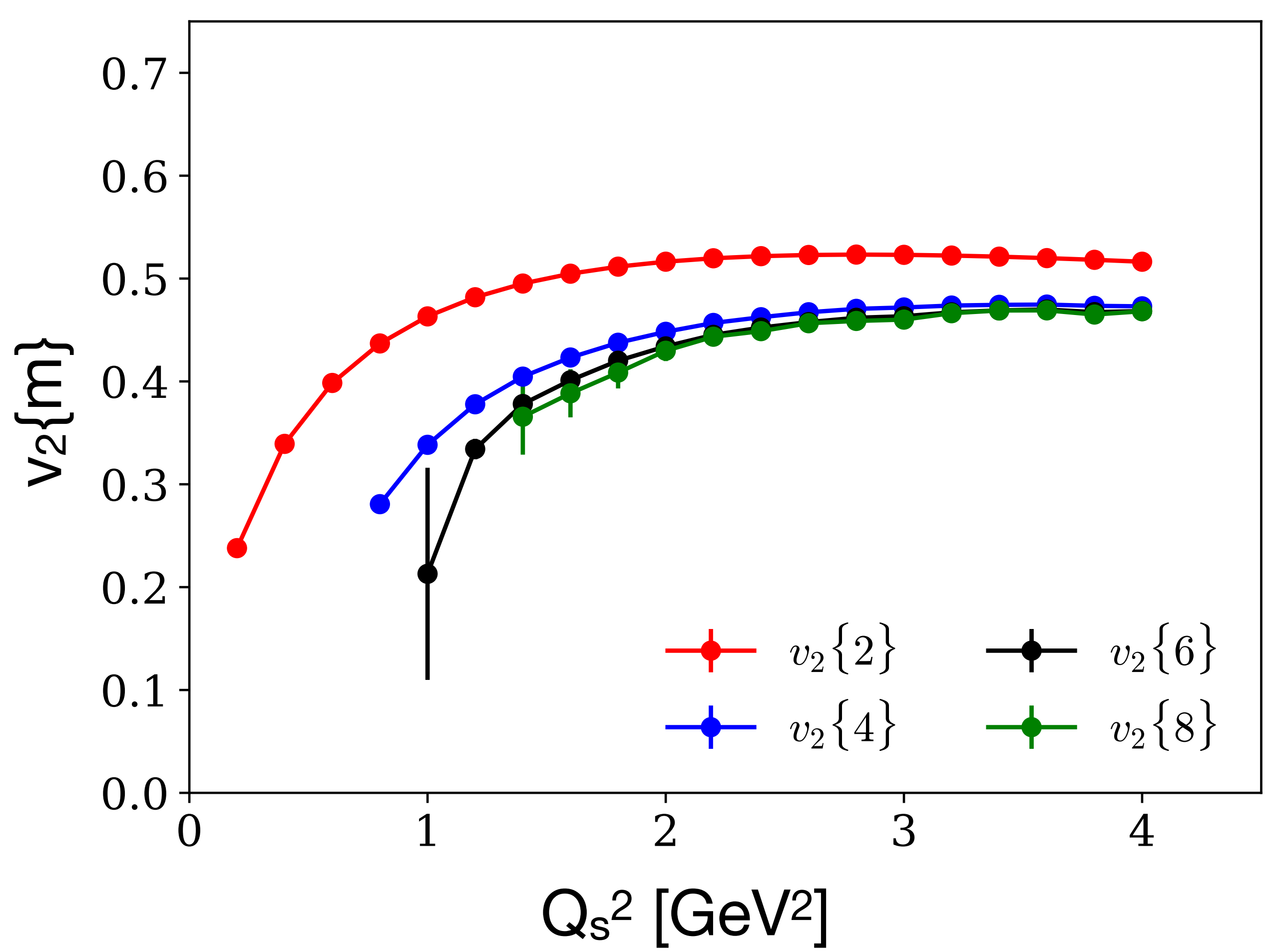
$(p_\perp^{\max})^2 \gtrsim Q_s^2$: probe resolves area less than domain size

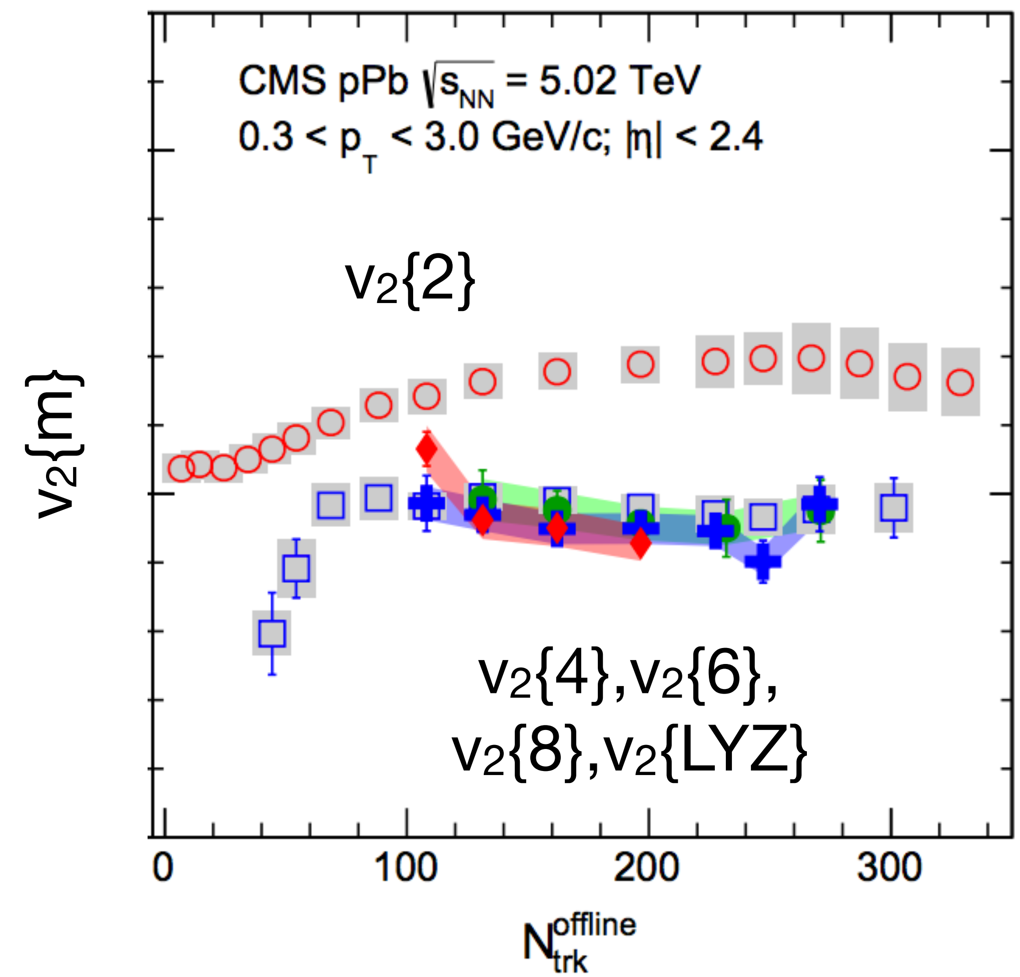
Scaling with inverse number of domains seen only for large $p_\perp^{\max}$

Dusling, MM, Venugopalan PRD 97 (2018)

Collectivity from parton model

For computational reduction, consider Abelian version





Dusling, MM, Venugopalan PRL 120 (2018)

CMS PRL 115 (2015) 012301

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

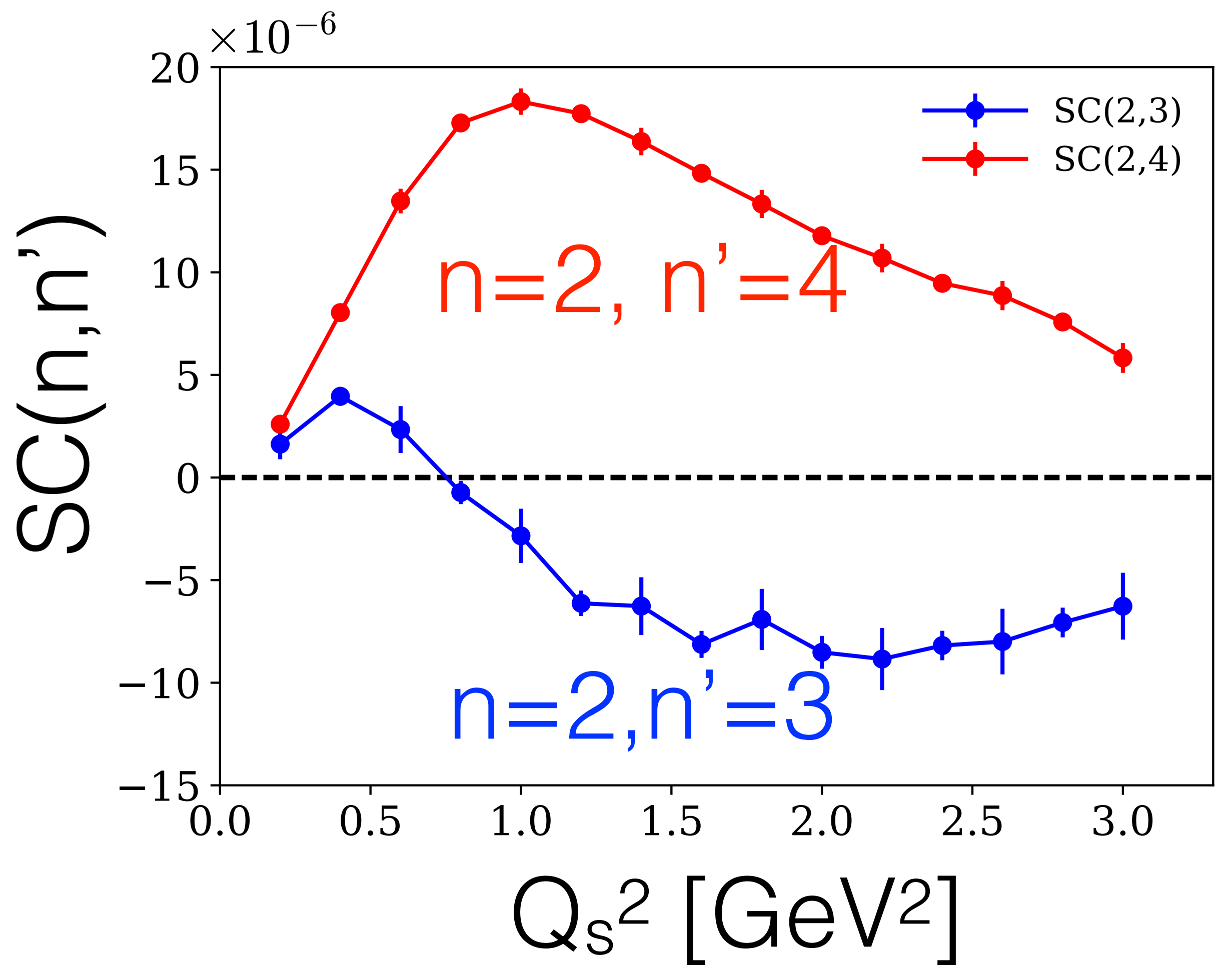
collectivity not unique to hydrodynamics

Symmetric Quark Cumulants

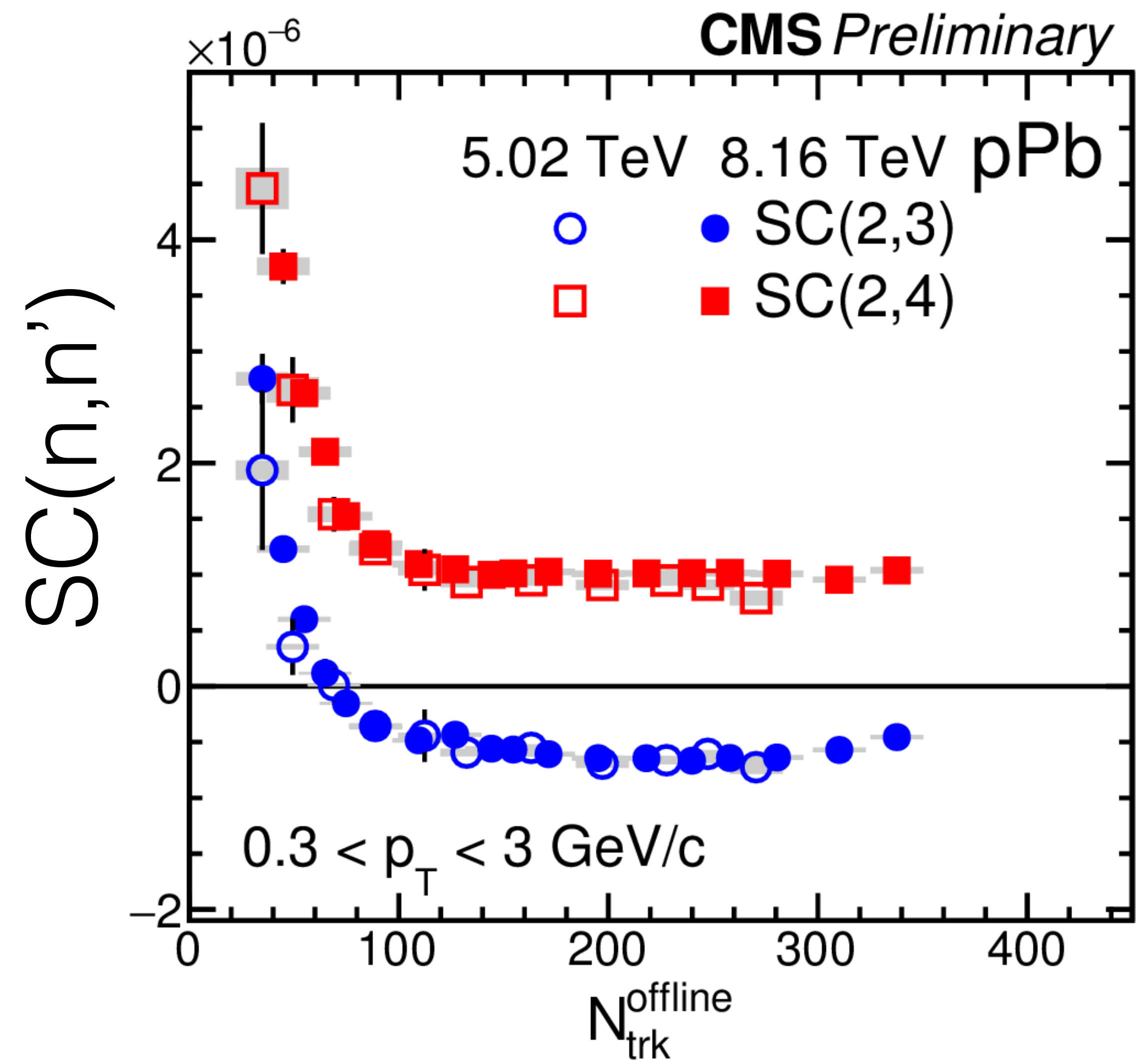
Symmetric cumulants: mixed harmonic cumulants

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

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



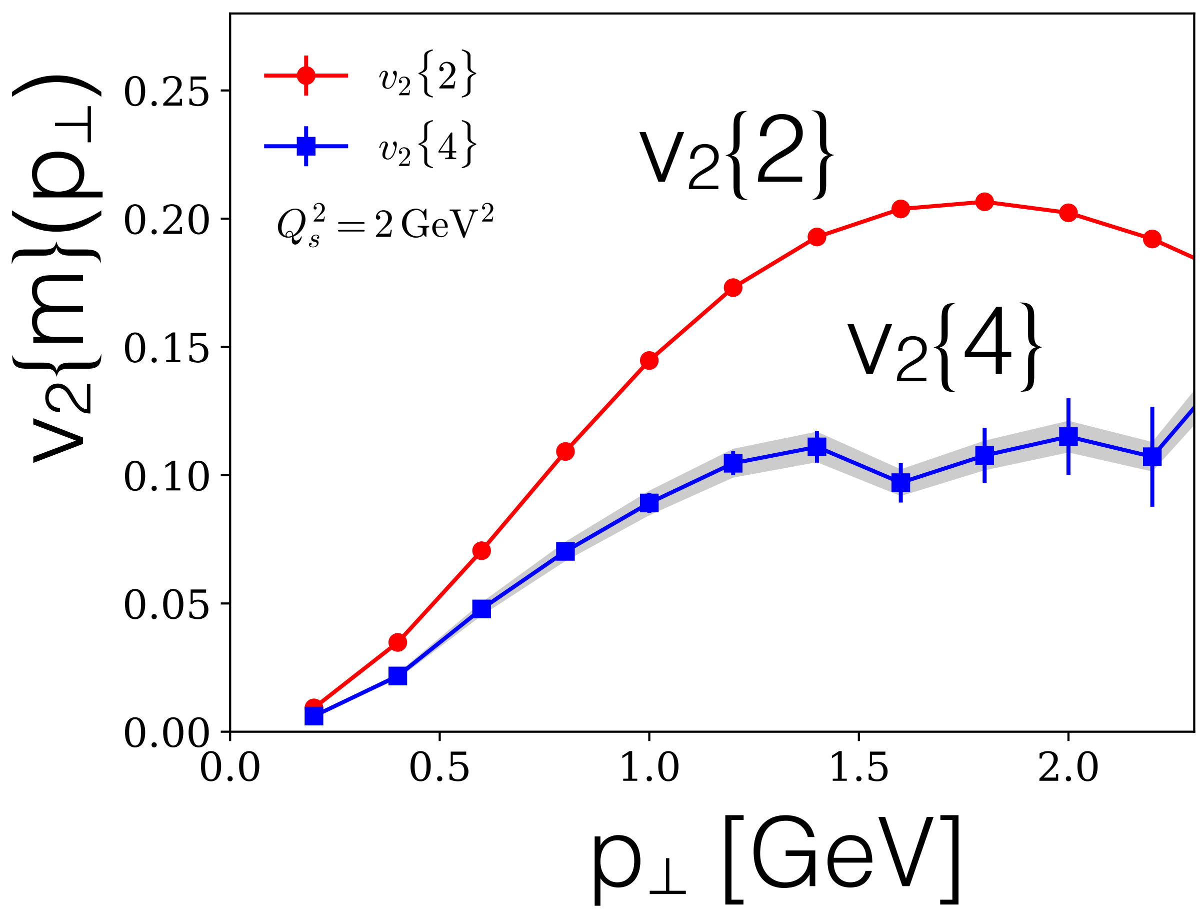
Dusling, MM, Venugopalan PRD 97 (2018)



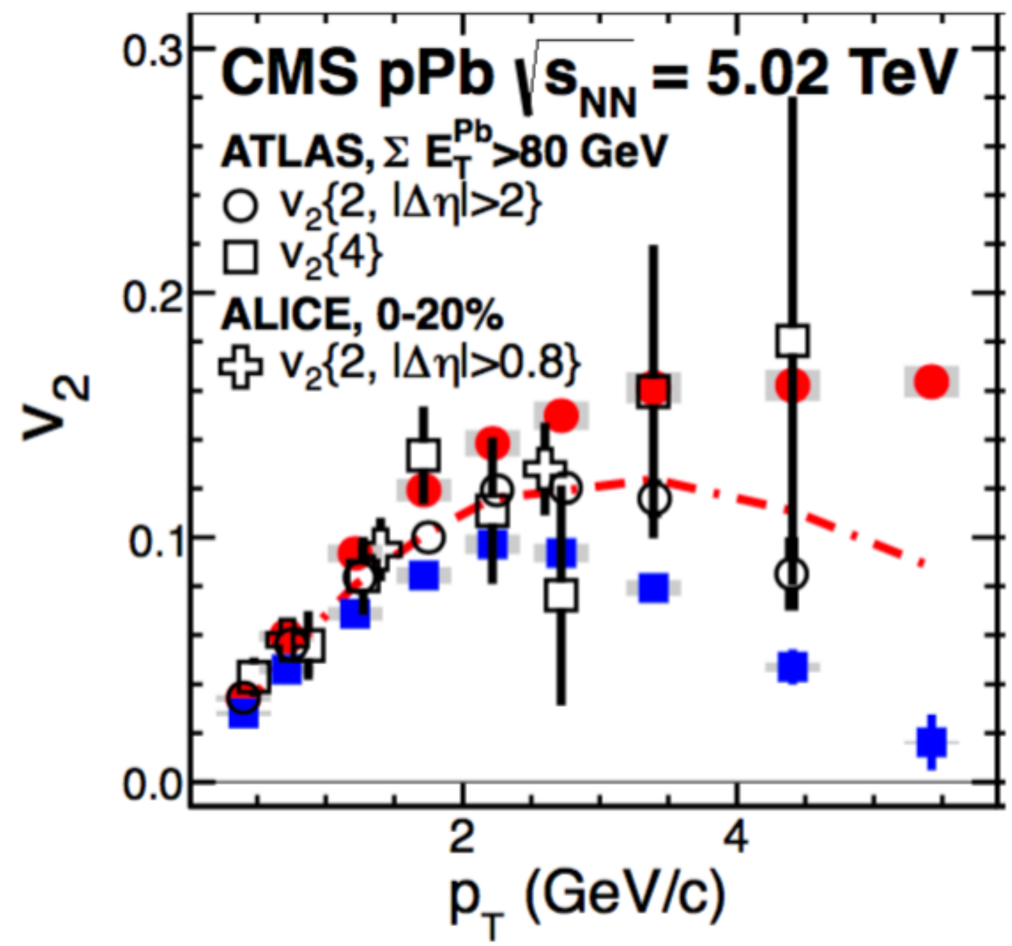
CMS-PAS-HIN-16-022

Multiparticle correlations

Integrating momentum of m-1 particles



Dusling, MM, Venugopalan PRD 97 (2018)



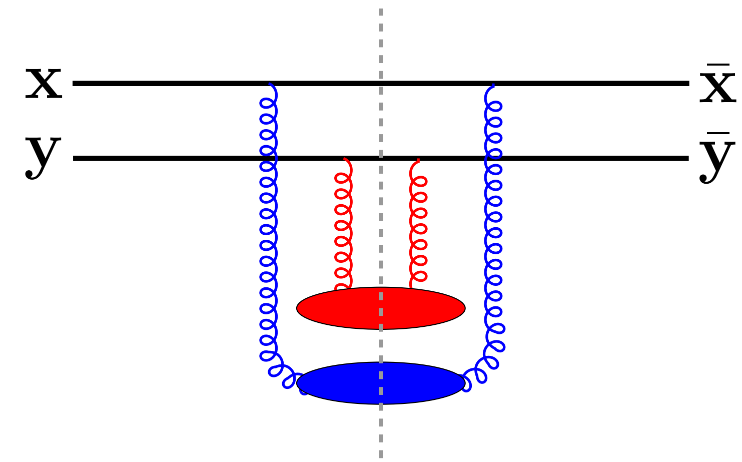
CMS PLB 724 (2013) 213

Similar characteristic shape

Comparison to glasma graphs

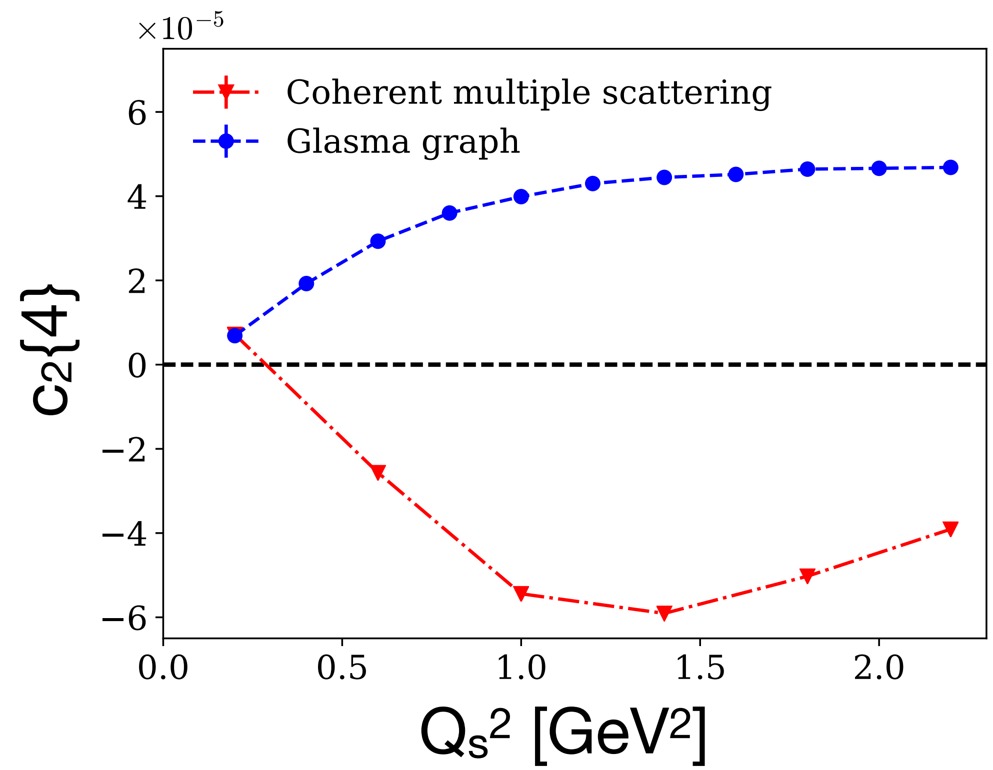
Glasma graph approximation, valid only for $p_\perp > Q_s$, only considers single gluon exchange

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)