Exclusive vector meson production as a probe of gluon saturation

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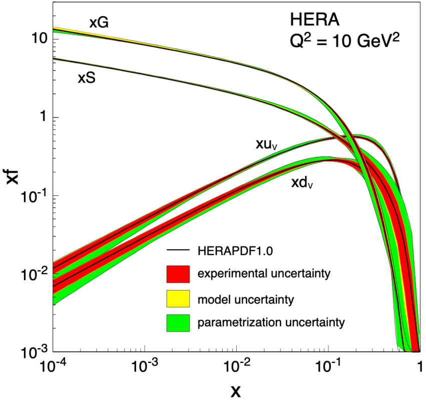
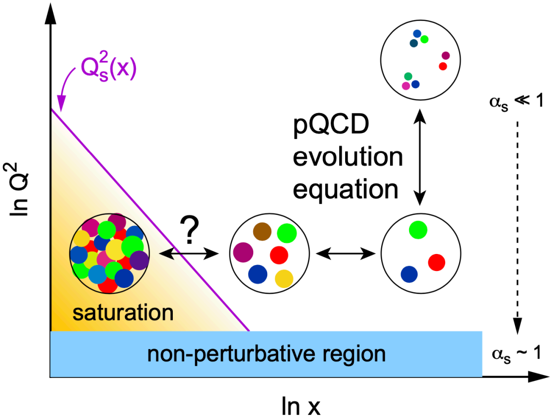
Gluon saturation and very high parton densities

HERA total $\gamma^* + p$ cross section data: parton densities $\sim x^{-\lambda}$, eventually violates unitarity



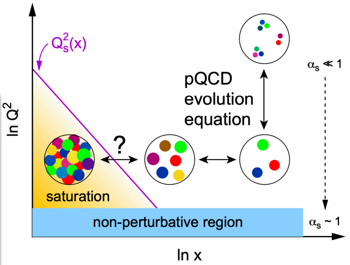


Non-linear QCD effects at small x (e.g. $gg \to g$) should tame the growth

$\Rightarrow$ Saturated state of gluonic matter

Gluon saturation and the Color Glass Condensate

- Very high occupation number $xg(x, Q^2)$
- Apparent gluon size $1/Q^2$



Non-linear dynamics important when

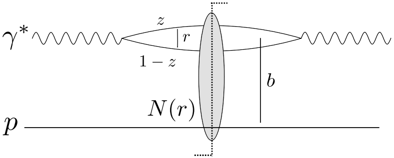
$$\pi R_p^2 = \alpha_s xg(x, Q_s^2)\frac{1}{Q_s^2}$$

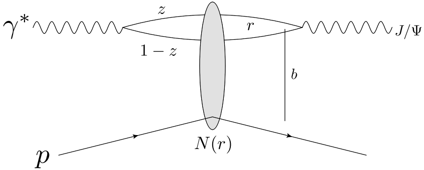
Emergent saturation scale $Q^2 = Q_s^2 \gg \Lambda_{\mathrm{QCD}}^2$
Characterizes the target wave function

Color Glass Condensate

- Effective theory of QCD in the high energy limit
- Unitarity built in, relevant d.o.f. is dipole-target amplitude $N \leq 1$ in the TRF

Probing high density gluonic matter in DIS: CGC and dipole picture





Inclusive cross section

Optical theorem:

$\sigma^{\gamma^* p} \sim \Psi^* \otimes \Psi \otimes N$

$\sim$ dipole N $\sim$ "gluon structure"

Exclusive processes (focus here)

$\mathcal{A} \sim \int \mathrm{d}^2\mathbf{b} e^{-i\mathbf{b}\cdot\Delta} \Psi^* \otimes \Psi_V \otimes N$

$\sigma \sim |\text{dipole}|^2$

- Very sensitive, and access to geometry

- TRF and high energy: $\gamma^* \to q\bar{q}$ fluctuation has long lifetime
- Dipole amplitude N: eikonal propagation in the color field, resumming multiple scattering
- Perturbative evolution equations describing the center-of-mass energy dependence of N

Exclusive processes: beyond average structure

Exclusive processes: no net color transfer, rapidity gap around the produced particle

Coherent diffraction:

- Target remains in the same quantum state, e.g. $\gamma + p \to J/\Psi + p$
- Probes average interaction

$$\frac{\mathrm{d}\sigma^{\gamma^* A \to VA}}{\mathrm{d}t} \sim |\langle \mathcal{A}^{\gamma^* A \to VA} \rangle_\Omega|^2$$

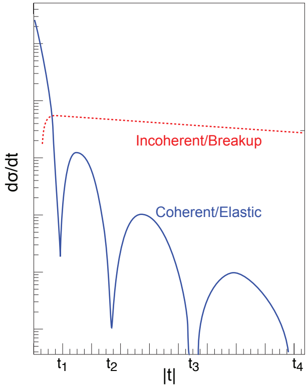
$\langle\,\rangle_\Omega$: average over target configurations Ω

Incoherent diffraction, the remaining events:

- E.g. $\gamma + p \to J/\Psi + p^*$ (+ dissociation $p^* \to X$).
- Total diffractive − coherent

$$\sigma_{\text{incoherent}} \sim \langle |\mathcal{A}|^2 \rangle_\Omega - |\langle \mathcal{A} \rangle_\Omega|^2$$

- Variance: sensitive to fluctuations



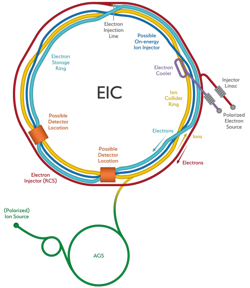
Good, Walker, PRD 120, 1960
Miettinen, Pumplin, PRD 18, 1978
Kovchegov, McLerran, PRD 60, 1999
Kovner, Wiedemann, PRD 64, 2001

Mäntysaari, Rept. Prog. Phys. 83, 2020

Experimental context for γ-nucleus interactions

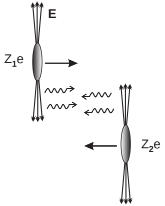
Electron Ion Collider ($\sim$ 2030)

- High luminosity: $\mathcal{L} = 10^{33} - 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Scalable CME: $\sqrt{s} = 20 - 140$ GeV
- Polarized e and hadron beams (up to 70%)
- Hadron beam: from protons to uranium nuclei
- Located at BNL, re-uses RHIC (longer term plans at CERN)

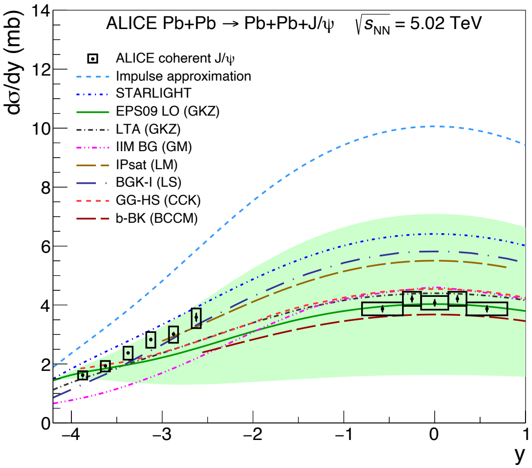


Ultra Peripheral Collisions

- UPC: Hadronic collisions (RHIC, LHC) with $b > 2R_A$
- Strong interaction suppressed, photon mediated
- Very high center-of-mass energies
- Limited to photoproduction ($Q^2 = 0$) and (mostly) Au/Pb



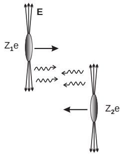
Significant nuclear effects already seen at the LHC (coherent)



$$x = \frac{M_{J/\Psi}}{\sqrt{s}} e^{\pm y}$$

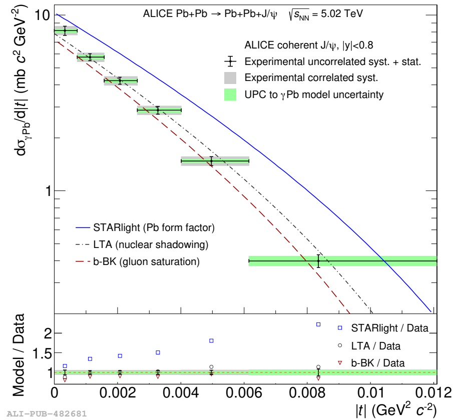
ALICE: 2101.04577

- Extensively studied in UPCs at the LHC by CMS, ALICE, LHCb
- CGC based calculations (e.g. *IPsat (LM)*) relatively successful
- Impulse approximation = scaled $\gamma + p$ from HERA ⇒ large nuclear effect
- EIC advantages:
  - No two-fold ambiquity in kinematics (which Pb emits photon)
  - Q^2, A lever arm



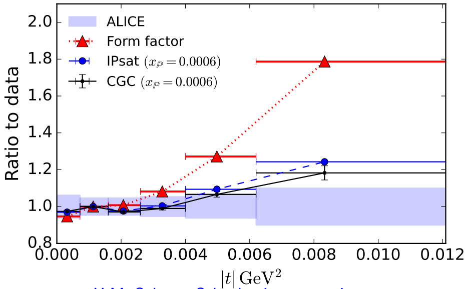
Saturation effects on nuclear geometry

ALICE UPC data:
Pb+Pb $\to$ Pb+Pb+J/Ψ



ALICE: 2101.04623

- Naive expectation: $\mathrm{d}\sigma/\mathrm{d}t \sim \mathcal{F}$[Woods-Saxon]
- Steeper t spectra observed
- And expected from saturation:
  Center of the nucleus closer to the black disc limit
- Saturation model calculations compatible with data

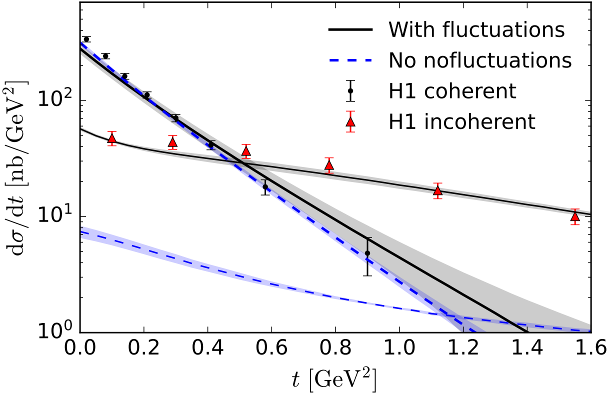


H.M, Salazar, Schenke, in preparation

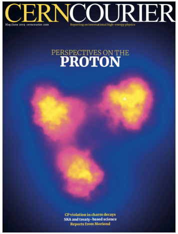
Event-by-event fluctuations at small-x: proton

Study simultaneously coherent ($\sim$ average interaction) and incoherent ($\mathcal{A}$ variance)

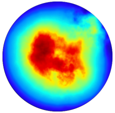
HERA $\gamma + p \to J/\Psi + p^{(*)}$ at $x_{\mathbb{P}} \approx 0.001$



Fluctuations



"No fluctuations"

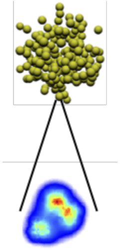


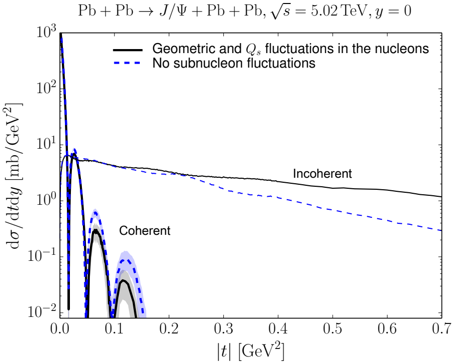
Parametrize e-b-e fluctuating geometry, fit parameters to data

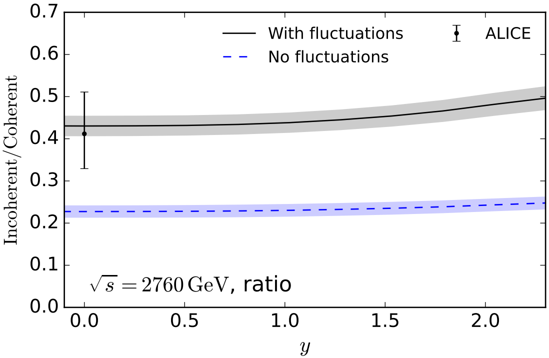
Orignal: H.M, B. Schenke, 1607.01711 (PRL)

Similar setup later used by other groups, e.g. Bendova, Cepila, Contreras; Cepila, Contreras, Krelina, Takaki; Traini, Blaizot

- Small $|t| \lesssim 0.25\text{GeV}^2$: long length scale, fluctuating nucleon positions
- Large $|t| \gtrsim 0.25\text{GeV}^2$: short length scale, fluctuating nucleon substructure







Subnucleon fluctuations preferred by ALICE data

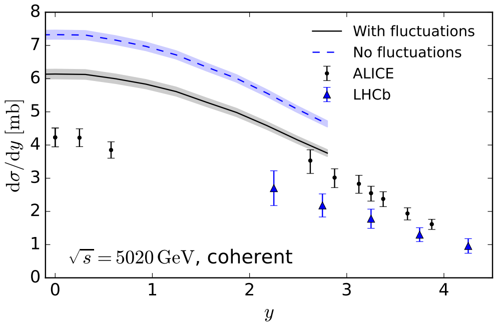
H.M, B. Schenke, 1703.09256 + in preparation w Schenke and Salazar

EIC: nuclear effects on nucleon shape fluctuations as a function of x, A, Q^2

ALICE: 1305.1467

Gluon saturation and event-by-event fluctuations

Pb+Pb→Pb+Pb+J/Ψ, $\sqrt{s} = 5$ TeV



- Nucleon shape fluctuations implemented: $\gamma + p \to J/\Psi + p$ (coherent) cross sections identical
- Substructure $\Rightarrow$ larger saturation effect: Larger local density when hotspots overlap
- Coherent $\mathrm{d}\sigma/\mathrm{d}t$ prefers substructure fluct
- Still less suppression than in the data

$$T(b) \sim \sum_{i=1}^{3} e^{-(b^2 - b_i^2)/(2B)}$$

H.M, F. Salazar, B. Schenke, in preparation; ALICE: 2101.04577, 1904.06272, LHCb: 2107.03222

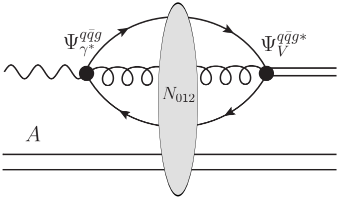
Theory developments: towards NLO (Jyväskylä&Helsinki collaboration)

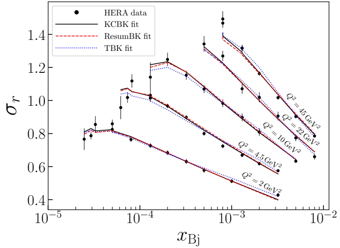
Most of the CGC phenomenology so far: LO (resumming $\alpha_s \ln 1/x$)
Recent progress toward NLO in the CGC framework:

- Photon wave function at NLO Beuf, Hänninen, Paatelainen, Lappi 2018-2021
- Heavy vector meson wave function at NLO Escobedo, Lappi, 2020
- Small-x evolution equations Balitsky 2008
- Initial condition fitted to F_2 data Beuf, Hänninen, Lappi, H.M, 2020
- Sub-eikonal Altinoluk, Beuf, Czajka, Tymowska, 2020
- Particle production in pA Stasto, Xiao, Zaslavsky, 2013; Ducloue, Lappi, Zhu, 2017
- Proton color charge correlations Dumitru, H.M, Paatelainen, 2021

Exclusive processes beyond LO, need

- Relativistic corrections $\sim v^2$ Lappi, H.M, Penttala, 2006.02830
- NLO $\sim \alpha_s$ corrections H.M, Penttala, 2104.02349

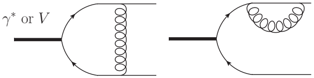




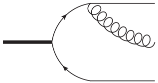
List of references and recent developments far from complete!

NLO in the nonrelativistic limit

$q\bar{q}$ (virtual corrections):



$q\bar{q}g$ (real corrections):



- Corrections from real and virtual gluons to the γ and J/Ψ wave functions
- UV divergences between the $q\bar{q}$ and $q\bar{q}g$ parts of the calculation cancel
- IR divergences cancel when one takes into account:
  - Renormalization of the leading-order J/Ψ wave function $\phi^{q\bar{q}}$ using Γ_{ee}
  - The energy dependence of the dipole amplitude = BK equation (resum soft gluon emission):

$$\frac{\partial}{\partial \ln 1/x} N(\mathbf{x}_{01}) = \frac{N_c \alpha_s}{2\pi^2} \int \mathrm{d}^2\mathbf{x}_2 \, \frac{\mathbf{x}_{01}^2}{\mathbf{x}_{20}^2 \mathbf{x}_{21}^2} \left[N(\mathbf{x}_{02}) + N(\mathbf{x}_{12}) - N(\mathbf{x}_{01}) - N(\mathbf{x}_{02}) N(\mathbf{x}_{12}) \right]$$

⇒ The total production amplitude is finite and can be numerically evaluated H.M, Penttala, 2104.02349

Final expression (longitudinal production)

H.M, J. Penttala, arXiv:2104.02349 (L, published in PLB) and in preparation (T)

$$-i\mathcal{A}^L = -Q\sqrt{\Gamma(V\to e^-e^+)\frac{3M_V}{16\pi^2\alpha_{\mathrm{em}}}}\int \mathrm{d}^2\mathbf{x}_{01}\int \mathrm{d}^2\mathbf{b}\left\{\mathcal{K}^{\mathrm{LO}}_{q\bar q}(Y_0) + \frac{\alpha_s C_F}{2\pi}\mathcal{K}^{\mathrm{NLO}}_{q\bar q}(Y_{\mathrm{dip}}) + \frac{\alpha_s C_F}{2\pi}\int \mathrm{d}^2\mathbf{x}_{20}\int_{z_{\min}}^{1/2}\mathrm{d}z_2\,\mathcal{K}_{q\bar q g}(Y_{\mathrm{qqg}})\right\}$$

where $\mathcal{K}^{\mathrm{LO}}_{q\bar q}(Y_0) = K_0(\zeta)N_{01}(Y_0),\ \zeta = |\mathbf{x}_{01}|\sqrt{\frac{1}{4}Q^2 + m_q^2}$,

$$\mathcal{K}^{\mathrm{NLO}}_{q\bar q}(Y_{\mathrm{dip}}) = \left[\mathcal{K} + \tilde{\mathcal{I}}_\nu\left(z=\frac{1}{2},\mathbf{x}_{01}\right) + K_0(\zeta)\left(6 - \frac{\pi^2}{3} + \Omega_{\mathcal{V}}\left(\gamma; z=\frac{1}{2}\right) + L\left(\gamma; z=\frac{1}{2}\right) - 3\log\left(\frac{|\mathbf{x}_{10}|m_q}{2}\right) - 3\gamma_E\right)\right]N_{01}(Y_{\mathrm{dip}})$$

and

$$\mathcal{K}_{q\bar q g}(Y_{\mathrm{q\bar qg}}) = -32\pi m_q\left\{\frac{i\mathbf{x}_{20}^i}{|\mathbf{x}_{20}|}K_1(2m_q z_2|\mathbf{x}_{20}|)\left[\left((1-z_2)^2+z_2^2\right)\mathcal{I}^i_{(f)} + (2z_2^2-1)(1-2z_2)\mathcal{I}^i_{(g)}\right]N_{012}(Y_{\mathrm{q\bar qg}})\right.$$
$$\left. + 4m_q z_2^3 K_1(2m_q z_2|\mathbf{x}_{20}|)\left[\mathcal{I}_{(f)} - \frac{1-2z_2}{1+2z_2}\mathcal{I}_{(g)}\right]N_{012}(Y_{\mathrm{q\bar qg}}) + \frac{1}{8\pi^2}\left((1-z_2)^2+z_2^2\right)\frac{1}{m_q z_2|\mathbf{x}_{20}|^2}K_0(\zeta)e^{-\mathbf{x}_{20}^2/(\mathbf{x}_{10}^2 e^{\gamma_E})}N_{01}(Y_{\mathrm{q\bar qg}})\right\}.$$

Equation for transverse production similar but more complicated.

Towards NLO phenomenology

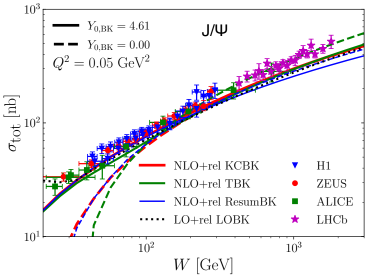
What do we have

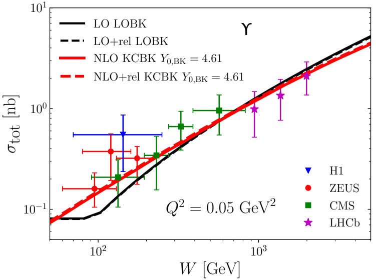
- NLO result for exclusive heavy vector meson production
- Corrections $\sim \alpha_s$ and $\sim v^2$
  Both important in J/Ψ production
  Relativistic $\sim v^2$ correction negligible in Υ production
- L polarization published, T in preparation

  H.M, J. Penttala, 2104.02349, published in PLB
- Codes for numerical evaluation

What is needed for full EIC/LHC phenomenology

- Initial condition for small-x evolution:
  Fit to HERA F_2 data with quark masses at NLO





Conclusions and outlook

Exclusive vector meson production

- Powerful probes of small-x hadron structure
  - Approximatively $\mathrm{d}\sigma \sim \text{gluon}^2$ (see also next talk by C. Flett)
  - Access to geometry (and event-by-event fluctuations)

Lessons learnt

- LHC data from Ultra Peripheral Collisions: significant nuclear effects
- Qualitatively described when gluon saturation is included
- Event-by-event fluctuating nucleon geometry required

Precision era is coming

- NLO level $\mathcal{O}(\alpha_\mathrm{s} \ln 1/x) + \mathcal{O}(\alpha_\mathrm{s}) + \mathcal{O}(\alpha_\mathrm{s}^2 \ln 1/x)$ accuracy is coming
- Precise high-energy data from LHC and future EIC coming

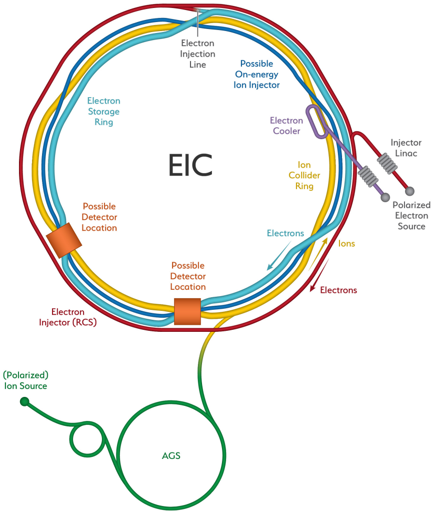
Backups

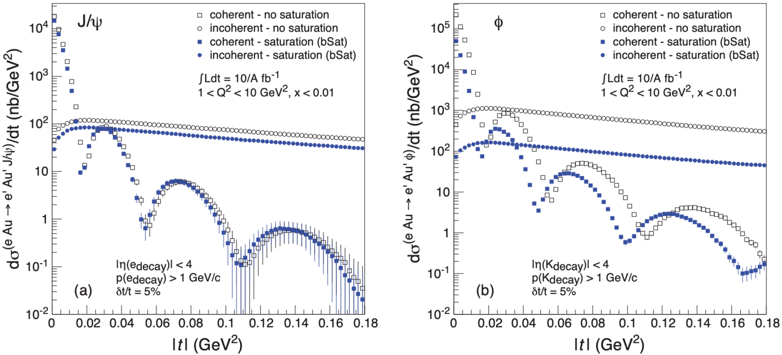
The Electron Ion Collider

Project Goals

- High luminosity: $\mathcal{L} = 10^{33} - 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Scalable CME: $\sqrt{s} = 20 - 140\ \mathrm{GeV}$
- Polarized *e* and hadron beams (up to 70%)
- Hadron beam: from protons to uranium nuclei
- Located at BNL, re-uses RHIC
- Two large acceptance detectors
- First data around 2032

Also: similar longer-term plans at CERN (LHeC/FCC-he) and in China





$$\mathrm{Au}+\mathrm{Au} \to \mathrm{Au}+\mathrm{Au}^*+J/\Psi$$

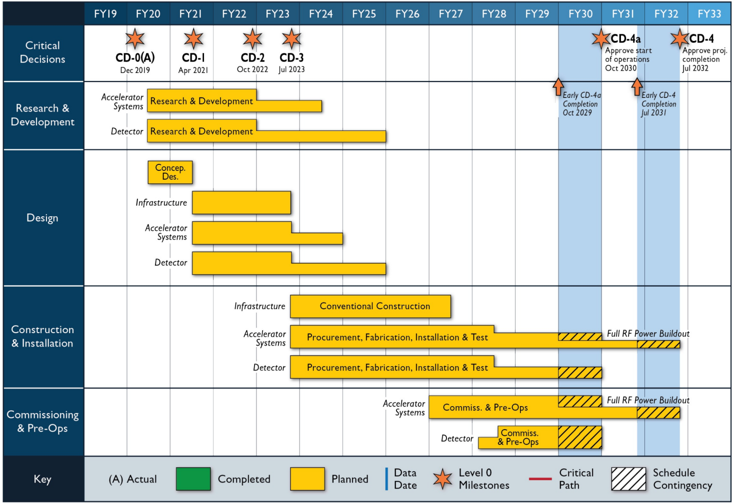
Coherent: $\mathrm{Au}^* = \mathrm{Au}$

Incoherent: target breaks up

- Simulated cross section differentially in $-t = \Delta^2$ for $\gamma^* + \mathrm{Au} \to V + \mathrm{Au}$ $(V = J/\Psi, \rho, \phi, \ldots)$, with and without gluon saturation
- Non-linear effects: significant especially on light meson electroproduction

EIC WP, 1212.1701, also e.g. H.M, Lappi, 1011.1988

EIC Schedule



Tim Hallman (US DOE), DIS2021 conference

EIC Physics Program

Some fundamental physics questions

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What is the 3-dimensional partonic structure of protons, and how does it change in nuclear environment?
- What are the emergent properties of dense systems of gluons?

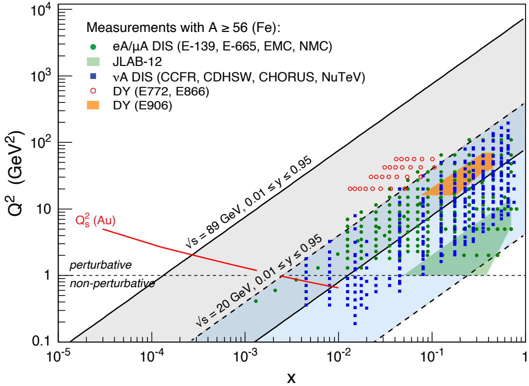
Why nuclear DIS?

- Clean environment for precison studies (e.g. can construct kinematics exactly)
- Parton density $\sim x^{-\lambda} A^{1/3}$
  Increasing A is much cheaper than decreasing x

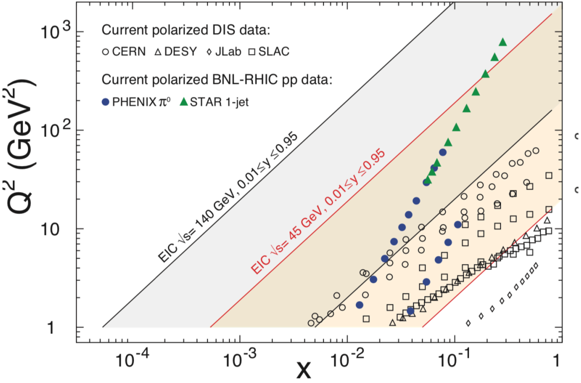
EIC Yellow Report: arXiv:2103.05419

Access to completely new kinematical domain

First nuclear-DIS in collider kinematics



Huge increase in polarized DIS



Reminder: $s = Q^2/(xy)$, $0 < y < 1$

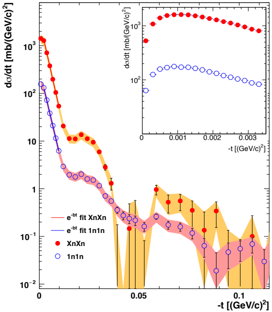
Spatial distribution of nuclear matter at small x

Total momentum transfer t can be measured in exclusive processes

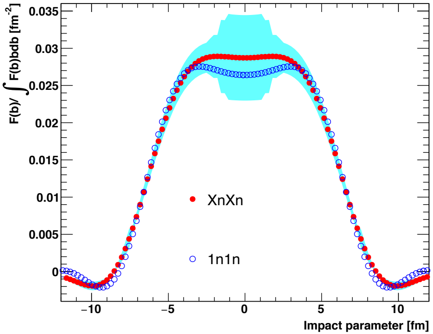
- By definition $\sqrt{|t|}$ is Fourier conjugate to impact parameter, access to geometry

Example: STAR measurement of exclusive $\pi^+\pi^-$ production in Au+Au UPC $\Rightarrow$ b profile

$$F(b) \sim \int \mathrm{d}|\mathbf{k}||\mathbf{k}|J_0(b|\mathbf{k}|)\sqrt{\frac{\mathrm{d}\sigma}{\mathrm{d}t}}$$



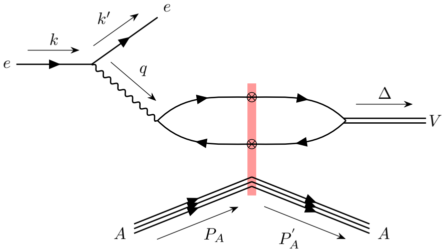
STAR: 1702.07705



More differential imaging: spatial correlations in the color field

Imaging using DVCS and exclusive J/ψ production: $e + p \to \gamma(\mathrm{J}/\psi) + p$

H.M, Roy, Salazar, Schenke, arXiv:2011.02464



Recall: advantages in exclusive scattering

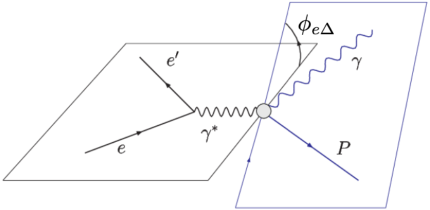
- No net color charge transfer: $\sim$ gluon^2
- Possibility to measure total momentum transfer
  Fourier conjugate to the impact parameter

Our recent work (arXiv:2011.02464)

More differential measurement

$\Rightarrow$ more detailed probe of target structure

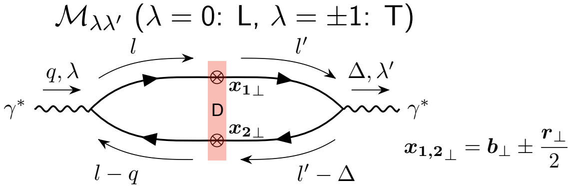
- Exclusive vector particle production differentially in both t and azimuthal angle $\phi_{e\Delta}$



Deeply Virtual Compton Scattering* – coordinate space description

Calculate $\gamma^* + p \to \gamma^* + p$ 2011.02464 ,
later take final state to be a real photon or J/ψ

Results in agreement with Hatta, Yuan, Xiao, 1703.02085

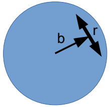


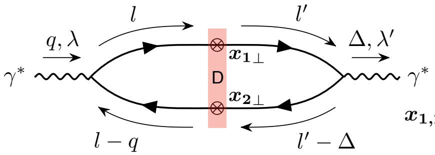
$$\mathcal{M}_{0,0} \sim \int_{\mathbf{b}} e^{-i\boldsymbol{\Delta}\cdot\mathbf{b}} \int_{\mathbf{r}} N(\mathbf{r},\mathbf{b}) \int_z e^{-i\delta\cdot\mathbf{r}} z^2 \bar{z}^2 Q K_0(\varepsilon r) Q' K_0(\varepsilon' r)$$

$$\mathcal{M}_{\pm 1,\mp 1} \sim \int_{\mathbf{b}} e^{-i\boldsymbol{\Delta}\cdot\mathbf{b}} \int_{\mathbf{r}} e^{\pm 2i\phi_{r\Delta}} N(\mathbf{r},\mathbf{b}) \int_z e^{-i\delta\cdot\mathbf{r}} z\bar{z} \varepsilon K_1(\varepsilon r) \varepsilon' K_1(\varepsilon' r)$$

Similar results for $\mathcal{M}_{\pm 1,\pm 1}, \mathcal{M}_{\pm 1,0}, \mathcal{M}_{0,\pm 1}$.
Neglecting the off-forward phase $\delta = (z - \bar{z})\boldsymbol{\Delta}/2$:

- $\mathcal{M}_{0,0} \sim$ angle independent part of dipole-target amplitude $N(\mathbf{r},\mathbf{b})$
- $\mathcal{M}_{\pm 1,\mp 1}$: sensitive to $\cos(2\phi_{r,b})$ modulation of the dipole ($\sim$ gluon distribution)



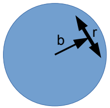


$\boldsymbol{x}_{1,2\perp} = \boldsymbol{b}_\perp \pm \frac{\boldsymbol{r}_\perp}{2}$

$$\mathcal{M}_{\pm1,\mp1} \sim \int_{\mathbf{b}} e^{-i\mathbf{\Delta}\cdot\mathbf{b}} \int_{\mathbf{r}} e^{\pm 2i\phi_{r\Delta}} N(\mathbf{r},\mathbf{b}) \int_z e^{-i\delta\cdot\mathbf{r}} z\bar{z}Q\varepsilon K_1(\varepsilon r)\varepsilon' K_1(\varepsilon' r)$$

Two sources of correlations between $\mathbf{r}$ (which knows about the electron in DIS) and $\mathbf{\Delta}$

- *Intrinsic*: correlation between $\mathbf{r}$ and $\mathbf{b}$ in the dipole $N(\mathbf{r},\mathbf{b})$
  - Related to elliptic gluon GPD Hatta, Yuan, Xiao, 1703.02085
- *Kinematic*: off-forward phase $e^{-i\delta\cdot\mathbf{r}}$ with $\delta = (z-\bar{z})\mathbf{\Delta}/2$
  - Different propagation axis, mixes polarizations



Azimuthal correlations in DVCS in DIS

Full calculation at $Q'^2 = 0$ including the photon flux $f(y)$ in 2011.02464

In agreement with hatta, Yuan, Xiao, 1703.02085

$$\frac{\mathrm{d}\sigma^{ep\to e\gamma p}}{\mathrm{d}t\mathrm{d}\phi_{e\Delta}} \sim f_{TT}(y)[\mathcal{M}^2_{\pm1,\pm1} + \mathcal{M}^2_{\pm1,\mp1}] + f_{TT,\mathrm{flip}}(y)\mathcal{M}^2_{0,\pm1}$$
$$- f_{LT}(y)\mathcal{M}_{0,\pm1}[\mathcal{M}_{\pm1,\pm1} + \mathcal{M}_{\pm1,\mp1}]\cos(\phi_{e\Delta})$$
$$+ f_{TT,\mathrm{flip}}(y)\mathcal{M}_{\pm1,\pm1}\mathcal{M}_{\pm1,\mp1}\cos(2\phi_{e\Delta})$$

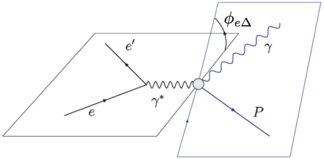


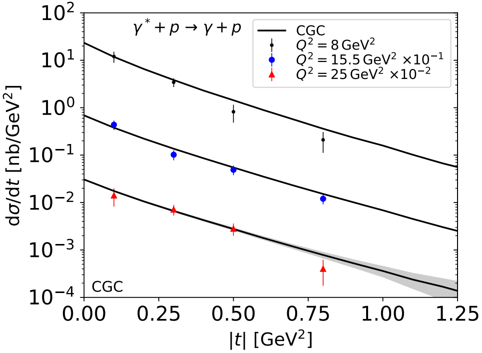
Figure: CLAS

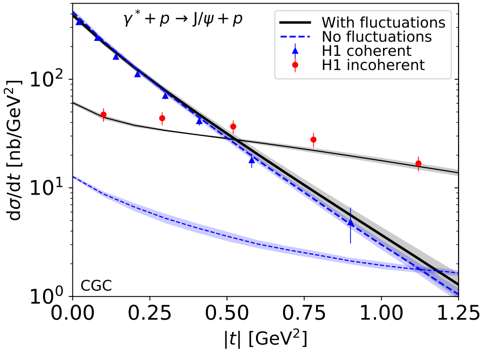
The $\cos(2\phi_{e\Delta})$ modulation in $ep \to e\gamma p$:
Access to $\mathbf{r}, \mathbf{b}$ correlations in the dipole D
via $\mathcal{M}_{\pm1,\mp1}$
$\Rightarrow$ elliptic gluon GPD

y is the inelasticity in DIS

Predictions for the EIC, setup

Color Glass Condensate based setup: MV model at $x \sim 0.01$ + JIMWLK evolution.
γ and J/Ψ t spectra not sensitive to the angular dependence



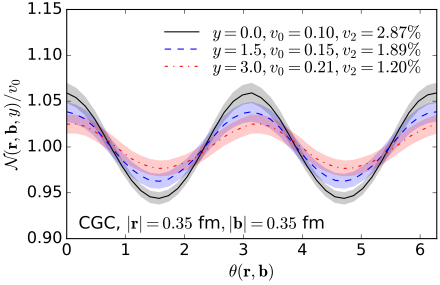


Good description of the HERA DVCS and exclusive J/ψ data.
To compute J/ψ, we replace γ^* wave function by Boosted Gaussian describing vector mesons

Predictions for the EIC, setup

EIC energies, consider $e + p$ collisions at $\sqrt{s} = 140$ GeV and $e + \mathrm{Au}$ at $\sqrt{s} = 90$ GeV

- Initial condition: MV model with $g^4\mu^2 \sim Q_s^2 \sim T_p(\mathbf{b})$
- Small-x JIMWLK evolution up to $Y = \ln(0.01/x_{\mathbb{P}})$
- Wilson lines evolved event-by-event, result averaged over an ensamble of configurations



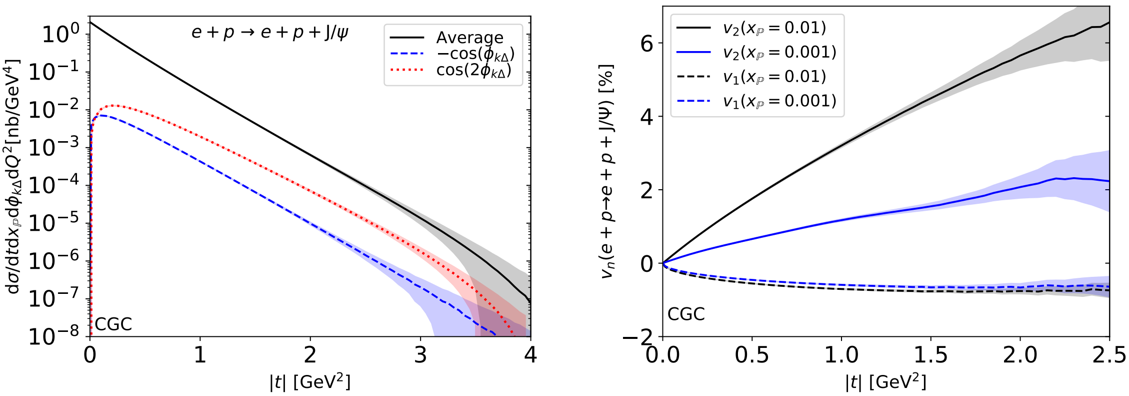
HM, Mueller, Schenke, 1902.05087

Angular modulation with $x = 0.01e^{-y}$ dependence computed from the CGC setup

Coordinate space modulation can be related to elliptic gluon GPD or Wigner distribution

Note: recent developments beyond MV for protons suggest negative v_2, see arXiv:2103.11682

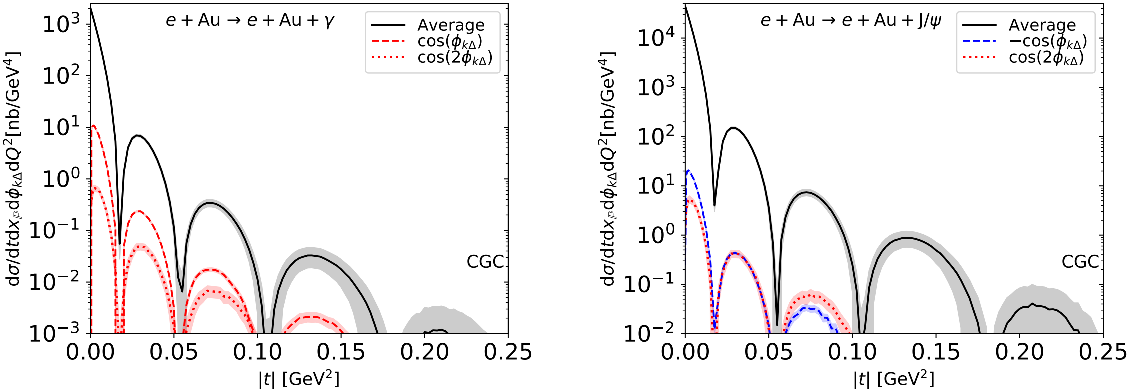
Coherent J/ψ at the EIC: spectra and relative modulation



- Significant $v_2 = \langle\cos(2\phi_{k\Delta})\rangle$ modulation in J/ψ production (and larger in DVCS)
- Modulation suppressed with increasing energy, larger proton with smaller density gradients

H.M, Roy, Salazar, Schenke 2011.02464

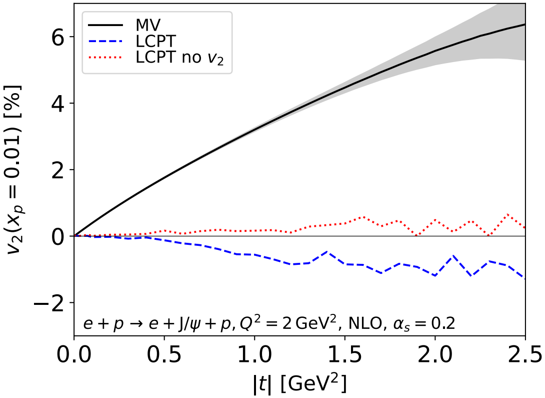
Nuclear targets at the EIC



Much smaller modulations with nuclear targets:
Smoother target, smaller density gradients $\Rightarrow$ smaller dependence on $\phi_{r,b}$

H.M, Roy, Salazar, Schenke 2011.02464

Sensitivity on the correlations in the color field



Dumitru, H.M, Paatelainen, Roy, Salazar, Schenke, arXiv:2105.10144

Modulations in $e + p \to \mathrm{J}/\Psi + p$

Different models for color charge correlation in proton

- MV: $\langle \rho\rho \rangle$ local Gaussian

  HM, Roy, Schenke, arXiv:2011.02464
- LCPT: $\langle \rho\rho \rangle$ from perturbative calculation in the dilute region

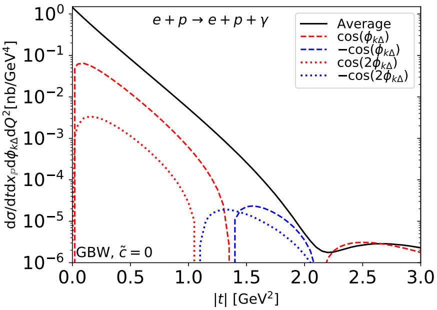
  Dumitru, H.M, Paatelainen, arXiv:2103.11682
- LCPT no v_2: elliptic gluon GPD set to 0

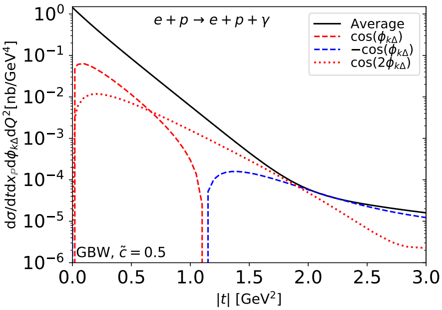
Potentially sensitive observable to extract elliptic gluon GPD or gluon Wigner distribution!

Toy model example

Demonstrate sensitivity on $\mathbf{r}, \mathbf{b}$ angular correlations in the dipole amplitude D, using GBW

$$D(\mathbf{r}, \mathbf{b}) = 1 - \exp\left[-\frac{\mathbf{r}^2 Q_{s0}^2}{4} T_p(\mathbf{b}) \left(1 + \frac{\tilde{c}}{2} \cos(2\phi_{rb})\right)\right] \text{ with } T_p(\mathbf{b}) = e^{-\mathbf{b}^2/(2B_p)}$$



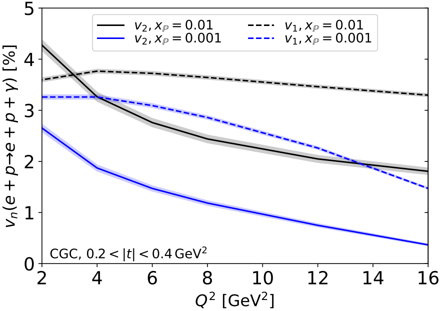


$\tilde{c} = 0$, no $\phi_{r,b}$ dependence in D $\tilde{c} = 0.5$, large $\phi_{r,b}$ dependence in D

$\phi_{r,b}$ dependence in D significantly increases $\cos(2\phi_{k,\Delta})$ modulation in the DVCS cross section

Smaller effect on $\cos(\phi_{k\Delta})$

H.M, Roy, Salazar, Schenke 2011.02464



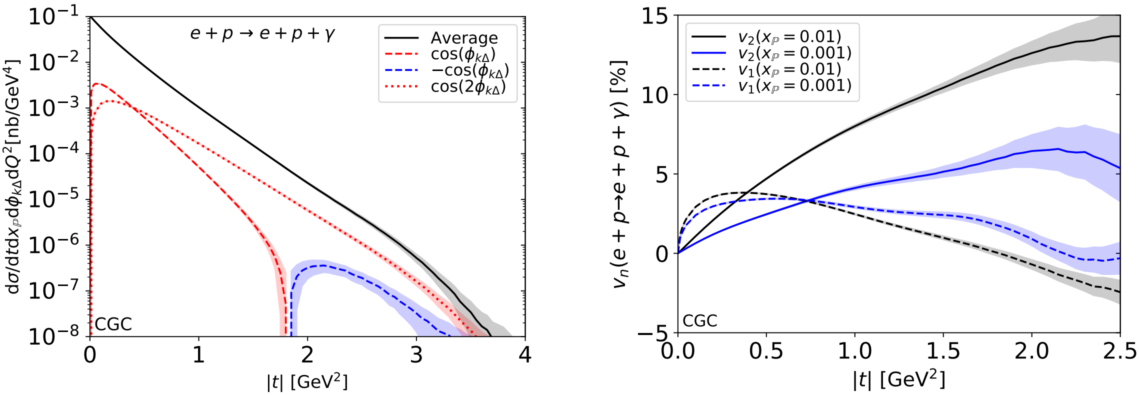
$0.2 < |t| < 0.04$

H.M, Roy, Salazar, Schenke 2011.02464

Dipole size $\sim 1/Q^2$

- Smaller density gradients seen by dipoles at high Q^2 $\Rightarrow$ Smaller *intrisic contrubtion*, decreasing v_2
- Small dipoles also result in small contribution from off-forward phase $e^{-i\delta\cdot\mathbf{r}}$, visible v_1.
- Additional effect: At the kinematical $y = 1$ boundary modulations vanish
  In DVCS at $x_{\mathbb{P}} = 0.001$ this is at $Q^2 \approx 20\mathrm{GeV}^2$.

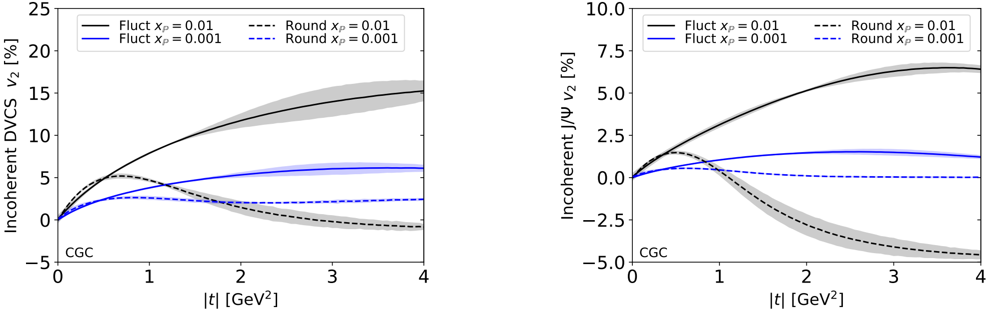
Coherent DVCS at the EIC: spectra and relative modulation



- Significant $5 \ldots 10\%$ $\cos(2\phi_{k\Delta})$ modulation at $|t| \gtrsim 0.5\text{GeV}^2$
- Small-x evolution decreases anisotropies $\Rightarrow$ decreasing $v_n = \langle\cos(n\phi_{k\Delta})\rangle$

H.M, Roy, Salazar, Schenke 2011.02464

Incoherent modulation



- Substructure changes v_2 at $|t| \gtrsim 0.5\text{GeV}^2$ where one is sensitive to small distance scales
- Significantly larger modulations with fluctuations
- JIMWLK evolution also suppresses incoherent v_2

H.M, Roy, Salazar, Schenke 2011.02464