Diffractive final states at small x

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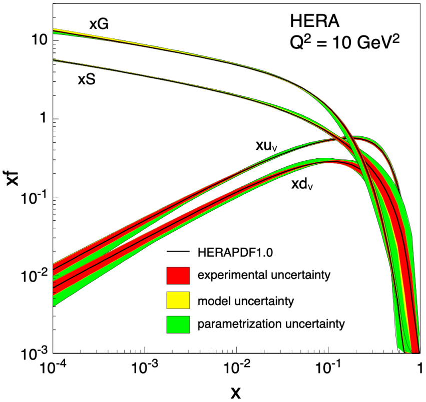
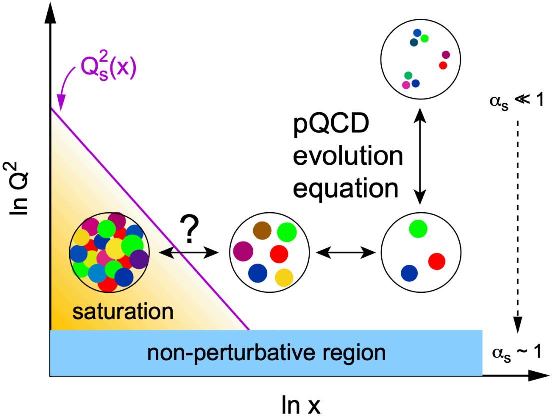
Dec 15, 2021
RBRC Workshop: Small-x Physics in the EIC Era

Gluon saturation and very high parton densities

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

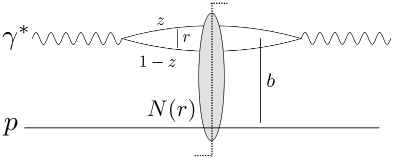


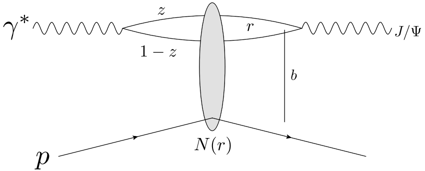


Non-linear QCD effects at small x (e.g. $gg \to g$) should tame the growth

$\Rightarrow$ Saturated gluonic matter (Color Glass Condensate) at small x and moderate Q^2 ($\sim M^2_{J/\Psi}$)

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
  - Non-perturbative initial condition e.g. from F_2 fits

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

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

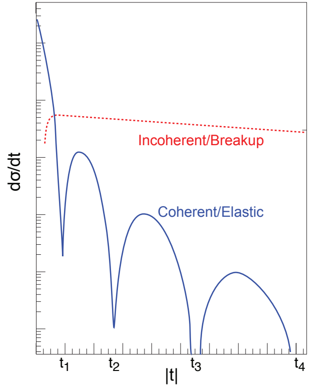
$\langle \rangle_\Omega$: average over target configurations Ω

Incoherent diffraction, the remaining events:

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

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

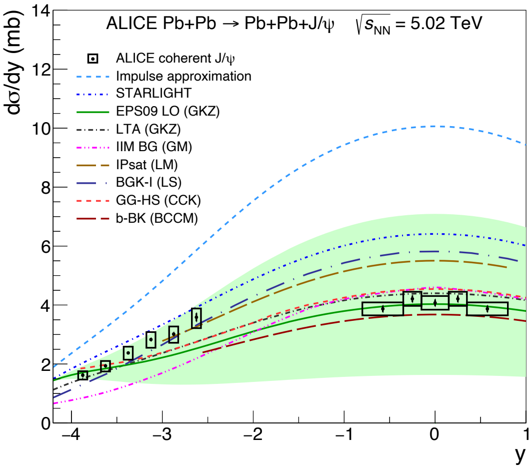
- Variance: sensitive to fluctuations



Good, Walker, PRD 120, 1960
Miettinen, Pumplin, PRD 18, 1978
Kovchegov, McLerran, PRD 60, 1999
Kovner, Wiedemann, PRD 64, 2001
Caldwell, Kowalski, PRC 81, 2010

H.M., Rept. Prog. Phys. 83, 2020

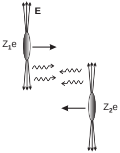
Significant nuclear effects already seen at the LHC (coherent)



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

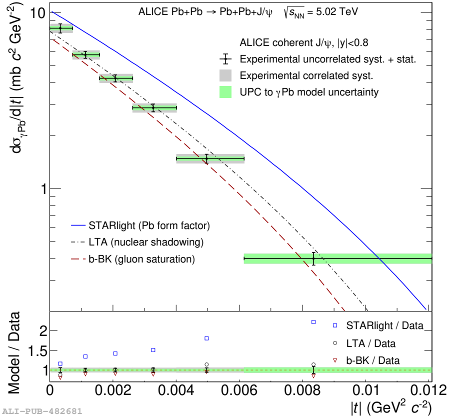
ALICE: 2101.04577

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



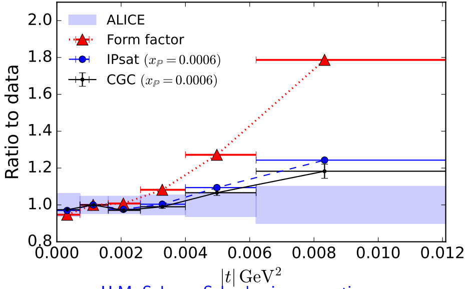
Saturation effects on nuclear geometry

ALICE UPC data:
Pb+Pb $\rightarrow$ Pb+Pb+J/Ψ



ALICE: 2101.04623

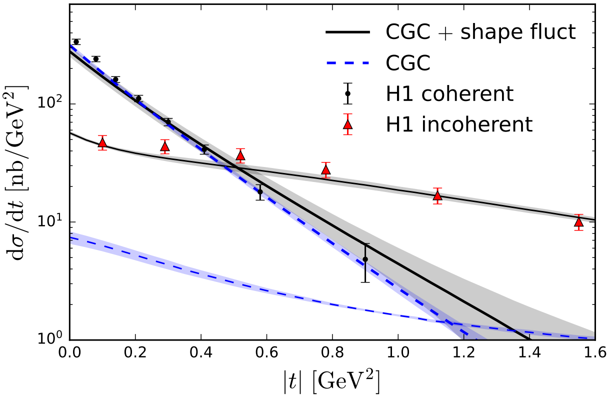
- Naive expectation: $\mathrm{d}\sigma/\mathrm{d}t \sim \mathcal{F}[\text{Woods-Saxon}]^2$
- Nucleons from WS + saturation: works!
  (But the effect of photon k_T?)
- Center of the nucleus closer to the black disc limit, stronger nonlinear effects $\Rightarrow$ effect on geometry
- EIC era: approach towards the black disc limit



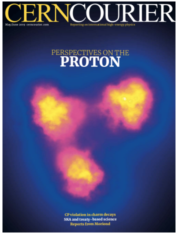
H.M, Salazar, Schenke, in preparation

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

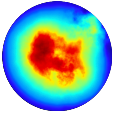
HERA $\gamma + p \to J/\Psi + p^{(*)}$ at $x_{\mathbb{P}} \approx 0.001$



Fluctuations



"No fluctuations"



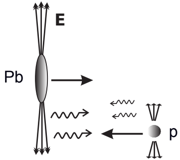
Parametrize e-b-e fluctuating geometry, fit parameters to data

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

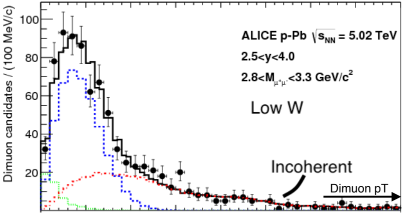
Similar setup later used by other groups, e.g. Bendova, Cepila, Contreras; Cepila, Contreras, Krelina, Takaki; Traini, Blaizot

What happens to the incoherent cross section at high W?

Ultraperipheral $p + A$:
$\gamma + p$ dominates



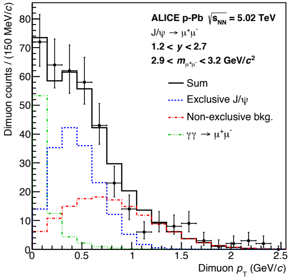
Low energy $\gamma - A$: coherent and incoherent visible ALICE: 1406.7819

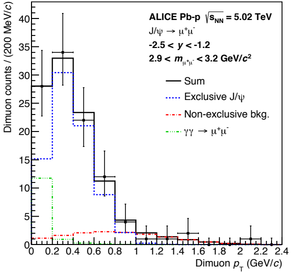


Larger COM energies:
incoherent $\to 0$ (?)
$\Rightarrow$ smoother proton?

ALICE:1809.03235

$x \sim 10^{-2} \to 10^{-5}$





Medium $\to$ high energy

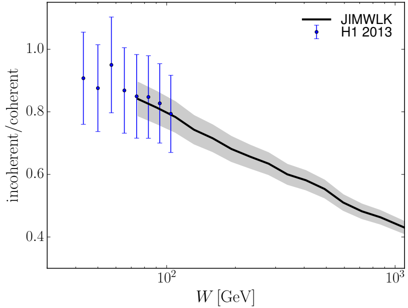
Are we reaching the black disc limit? EIC: $x_{\mathbb{P}}, Q^2, A$ systematics

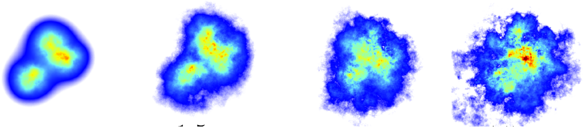
Qualitative explained by CGC based calculations

- Smoother proton at high W/small x
- Coherent cross section dominates at high W
- Qualitatively consistent with LHC "data"
- EIC: substructure evolution in protons...
- ... and nucleons in the nuclear environment
- EIC-LHC synergy (e.g. high multiplicity pp/pA)

JIMWLK evolution event-by-event

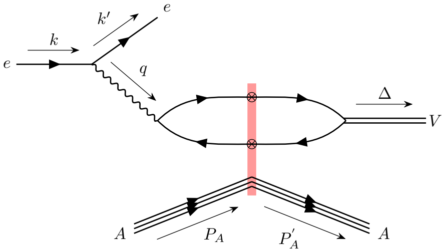
H.M., Schenke, 1806.06783





More differential imaging at the EIC: 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



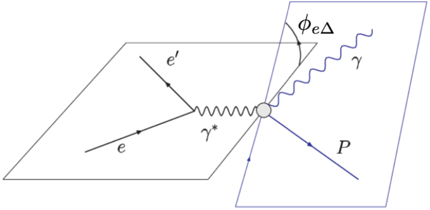
Exclusive t spectra

- FT of the geometry
- Probe density profile

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 $\phi_{e\Delta}$ (at $Q^2 > 0$)
- Another option: dijets (Iancu on Thursday)

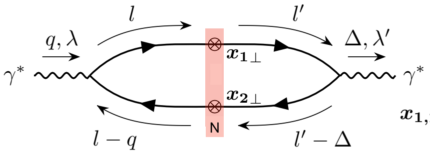


Deeply Virtual Compton Scattering*

$\mathcal{M}_{\lambda\lambda'}$ ($\lambda = 0$: L, $\lambda = \pm 1$: T)

Calculate $\gamma^* + p \to \gamma^* + p$ 2011.02464 ,
later take final state to be a real photon or J/ψ
Now allow also polarization changing processes

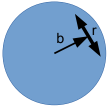
Results in agreement with Hatta, Yuan, Xiao, 1703.02085



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

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

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

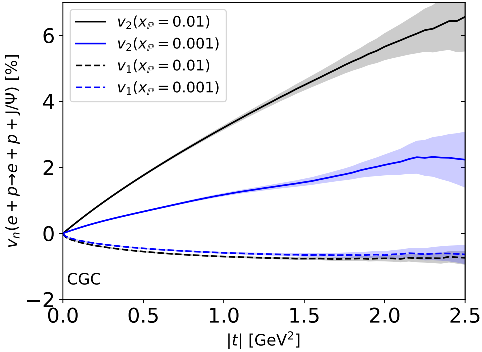


Similar results for $\mathcal{M}_{\pm1,\pm1}, \mathcal{M}_{\pm1,0}, \mathcal{M}_{0,\pm1}$.

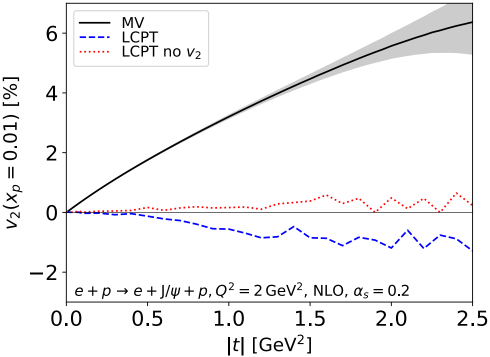
- $\mathcal{M}_{0,0} \sim$ angle independent part of dipole-target amplitude $N(\mathbf{r},\mathbf{b})$
- $\mathcal{M}_{\pm1,\mp1} \sim \cos(2\phi_{r,b})$ modulation of $N \Rightarrow$ elliptic gluon GPD Hatta, Yuan, Xiao, 1703.02085
- Also kinematical contribution from off-forward phase $e^{-i\delta\cdot\mathbf{r}}$ with $\delta = (z-\bar{z})\boldsymbol{\Delta}/2$

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

Extract azimuthal modulations from cross sections: $v_n = \langle \cos(n\phi_{e\Delta}) \rangle$, $v_2 \sim \mathcal{M}_{\pm1,\mp1}$



H.M, Roy, Salazar, Schenke, 2011.02464



Dumitru *et al*, 2105.10144

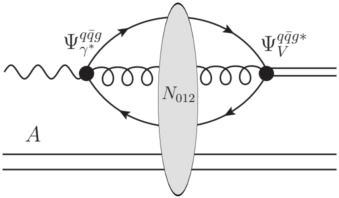
- MV+JIMWLK: large v_2 modulation in J/ψ production (and larger in DVCS)
- Modulation suppressed with increasing energy $\Rightarrow$ smaller gradients
- MV vs LCPT calculation (talk by Dumitru) to describe proton at moderate x? (IC for BK)

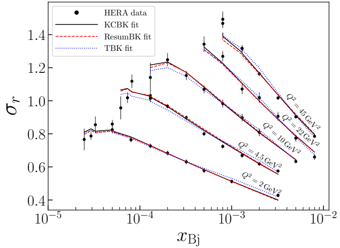
Theory developments: towards NLO

Most of the CGC phenomenology so far: LO (resumming $\alpha_s \ln 1/x$ + RC)

Some recent progress towards NLO CGC (talk by Lappi):

- Photon wave function at NLO Beuf, Hänninen, Paatelainen, Lappi 2018-2021
- Heavy vector meson wave function at NLO Escobedo, Lappi, 2020
- Light meson at NLO Boussarie, Grabovsky, Ivanov, Szymanowski, Wallon, 2016
- Small-x evolution equations Balitsky 2008, Balitsky, Chirilli, 2013
- Initial condition fitted to F_2 data Beuf, Hänninen, Lappi, H.M, 2020
- NLO dijet $(+\gamma)$ in DIS Caucal, Salazar, Venugopalan, 2021; Roy, Venugopalan, 2020
- Particle production in pA Stasto, Xiao, Zaslavsky, 2013; Ducloue, Lappi, Zhu, 2017
- Proton color charge correlations Dumitru, H.M, Paatelainen, 2021



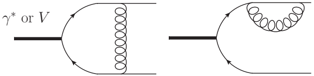


Heavy meson production beyond LO, need

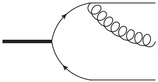
- Relativistic corrections $\sim v^2$ Lappi, H.M, Penttala, 2006.02830
- NLO $\sim \alpha_s$ corrections H.M, Penttala, 2104.02349

Exclusive heavy vector meson production at NLO

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



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



- Non-relativistic limit, calculate $\mathcal{O}(\alpha_s v^0)$ and $\mathcal{O}(\alpha_s^0 v^2)$ contributions
- 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):

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

$\Rightarrow$ 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

$$\mathcal{K}_{q\bar q g}(Y_{\mathrm{q\bar qg}}) = -32\pi m_q\left\{\frac{i\mathbf{x}_{20}^i}{|\mathbf{x}_{20}|}K_1(2m_qz_2|\mathbf{x}_{20}|)\left[\left((1-z_2)^2+z_2^2\right)\mathcal{I}^i_{(f)} + (2z_2^2-1)(1-2z_2)\mathcal{I}^i_{(g)}\right]N_{012}(Y_{\mathrm{q\bar qg}})\right.$$
$$\left.+4m_qz_2^3K_1(2m_qz_2|\mathbf{x}_{20}|)\left[\mathcal{I}_{(f)}-\frac{1-2z_2}{1+2z_2}\mathcal{I}_{(g)}\right]N_{012}(Y_{\mathrm{q\bar qg}}) + \frac{1}{8\pi^2}\left((1-z_2)^2+z_2^2\right)\frac{1}{m_qz_2|\mathbf{x}_{20}|^2}K_0(\zeta)e^{-\mathbf{x}_{20}^2/(\mathbf{x}_{10}^2e^{\gamma_E})}N_{01}(Y_{\mathrm{q\bar qg}})\right\}.$$

Result for transverse production similar but more complicated.

Towards NLO phenomenology

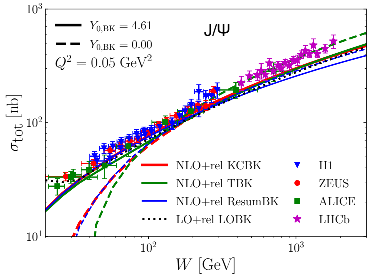
Exclusive heavy meson production at NLO

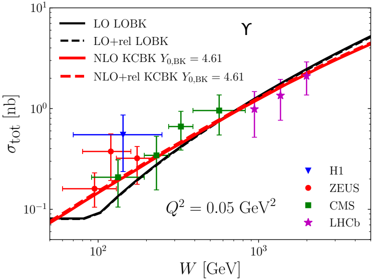
- Corrections $\sim \alpha_s$ and $\sim v^2$
  Both important in J/Ψ production
  Relativistic $\sim v^2$ correction negligible in Υ production
- L polarization published, T in preparation
- Codes for numerical evaluation

H.M, J. Penttala, 2104.02349 and in preparation; Lappi, H.M, Penttala, 2006.02830

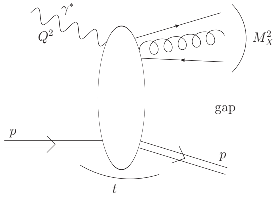
What is needed for full EIC phenomenology

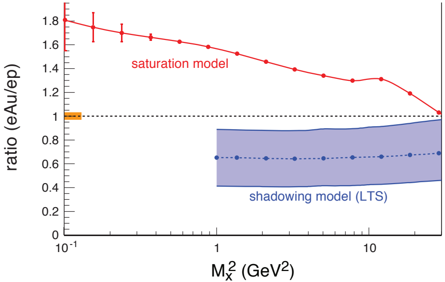
- Initial condition for small-x evolution:
  Fit to HERA F_2 data with quark masses at NLO
- Avoid problems with large dipoles in F_2??
- Geometry and perturbative small-x evolution??





Other observables





EIC WP and 0805.4071

Many observables are needed to "discover" saturation and study non-linear QCD in detail, e.g.

- Diffractive dijets (Iancu on Thursday)
- Goal: *combined analysis at NLO accuracy*
- Diffractive structure functions (also for A), diffractive/total (double) ratio, ...
- Some recent developments:
  - (Inclusive) dijet and trijet
    Caucal, Salazar, Venugopalan, 2021; Iancu, Mulian, 2018
  - Diffractive qqg in asymptotic kinematics Wusthoff 1997
    Successful phenomenology
    Kowalski, Lappi, Marquet, Venugopalan, 2008
  - Diffractive qqg in exact kinematics
    H. Hänninen, PhD thesis 2021, in preparation w. Beuf, Hänninen, Lappi, Mulian
  - Diffractive $q\bar{q}$ at NLO Beuf, Lappi, Mulian et al, in progress

Conclusions and outlook

Diffractive processes

- Powerful probes of small-x hadron structure
  - Approximatively $\mathrm{d}\sigma \sim \mathrm{gluon}^2$
  - Access to geometry (and event-by-event fluctuations)
- Significant nuclear effects at the LHC, qualitatively compatible with CGC expectations

EIC era

- "Discover" saturation, study non-linear QCD dynamics in detail
  - Global analyses at NLO with $x_{\mathbb{P}}, Q^2, A$ systematics
  - More differential observables
- Develop theory and phenomenology to the level comparable with experimental accuracy

Backups

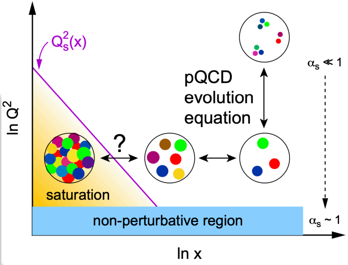
Gluon saturation and the Color Glass Condensate

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

Non-linear dynamics important when

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

Emergent saturation scale $Q^2 = Q_s^2 \gg \Lambda^2_{\text{QCD}}$
Characterizes the target wave function



Color Glass Condensate

- Effective theory of QCD in the high energy limit
- Large x: static color charge ρ
- Small x: classical gluon field A_μ
- Unitarity built in, relevant d.o.f. is dipole-target amplitude $N \leq 1$ in the TRF

Dipole amplitude from the CGC

Color charge distribution at $x = 0.01$

- Event-by-event random color charge distribution ρ^a
- McLerran-Venugopalan model $\langle \rho^a(\mathbf{x})\rho^b(\mathbf{y})\rangle \sim \delta^{ab}\delta(\mathbf{x}-\mathbf{y})g^4\mu^2$
- $g^4\mu^2 \sim Q_s^2(\mathbf{b}) \sim T_p(\mathbf{b})$ e.g. from HERA data

Small-x evolution

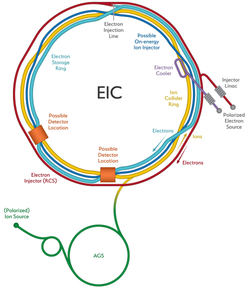
- Perturbative JIMWLK evolution (event-by-event)
- Infrared regulator to suppress gluon emission at long distance

Dipole-target amplitude

- $N(\mathbf{r} = \mathbf{x} - \mathbf{y}) = 1 - \frac{1}{N_\mathrm{c}}\langle V^\dagger(\mathbf{x})V(\mathbf{y})\rangle$
- $V(\mathbf{x}) = P\exp\left(-ig\int \mathrm{d}x^- \frac{\rho(\mathbf{x})}{\nabla^2 - m^2}\right)$

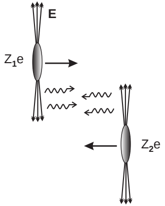
Electron Ion Collider ($\sim$ 2030)

- High luminosity: $\mathcal{L} = 10^{33} - 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Scalable CME: $\sqrt{s} = 20 - 140\ \mathrm{GeV}$
- 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)

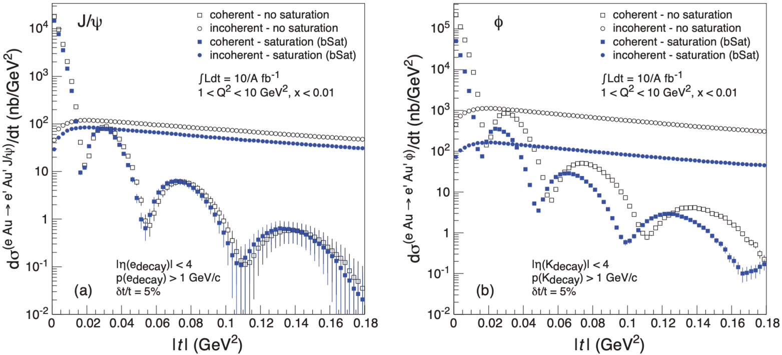


Ultra Peripheral Collisions

- 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



Non-linear dynamics in exclusive vector meson production: EIC simulation



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

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

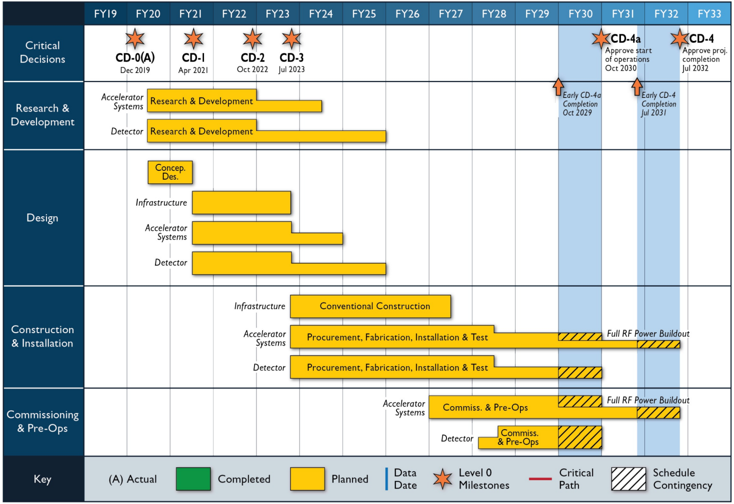
Incoherent:

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?

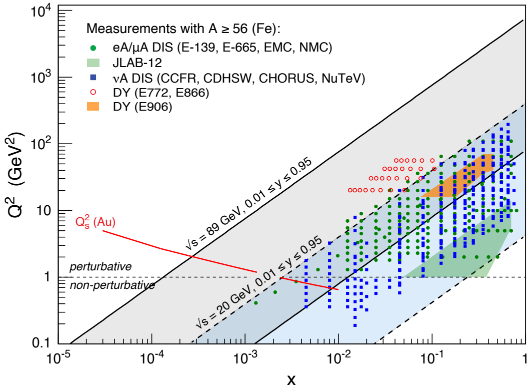
Why nuclear DIS?

- 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

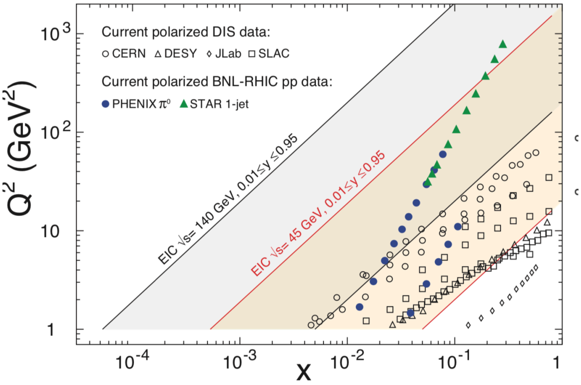
EIC Yellow Report: arXiv:2103.05419

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!

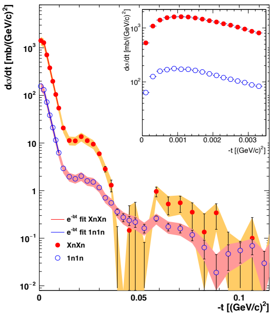
- By definition $\sqrt{|t|}$ is Fourier conjugate to the impact parameter $\Rightarrow$ access to geometry

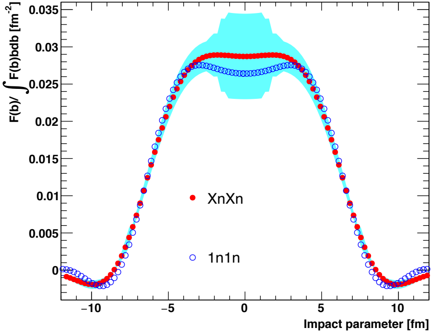
Example: STAR measurement of exclusive $\pi^+\pi^-$ production in Au+Au UPC $\Rightarrow$ b profile

FT: momentum space
$\rightarrow$ coordinate space

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

STAR: 1702.07705

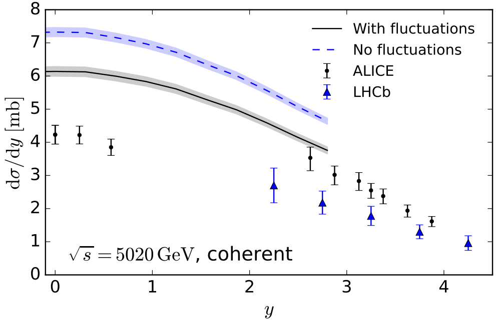




Experimental challenge: how to enough suppress incoherent background 2108.01694
Understanding nuclear breakup processes???

Gluon saturation and event-by-event fluctuations

Pb+Pb→Pb+Pb+J/Ψ, $\sqrt{s} = 5$ TeV



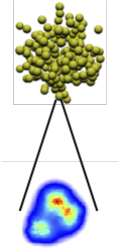
- Nucleon shape fluctuations implemented: $\gamma + p \to J/\Psi + p$ (coherent) cross sections identical
- Substructure $\Rightarrow$ larger saturation effect: Larger local density when hotspots overlap
- Coherent $\mathrm{d}\sigma/\mathrm{d}t$ prefers substructure fluct
- Still less suppression than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

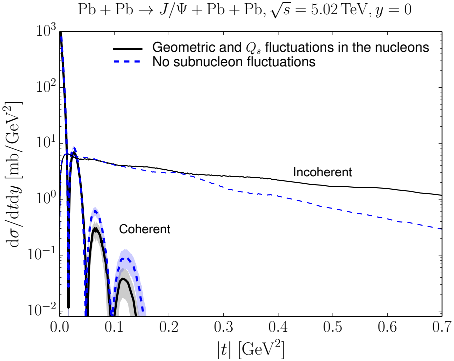
$$T(b) \sim \sum_{i=1}^{3} e^{-(b^2 - b_i^2)/(2B)}$$

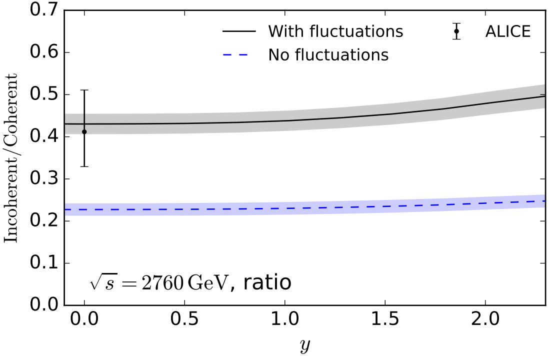
H.M, F. Salazar, B. Schenke, in preparation; ALICE: 2101.04577, 1904.06272, LHCb: 2107.03222

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

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







Subnucleon fluctuations preferred by ALICE data

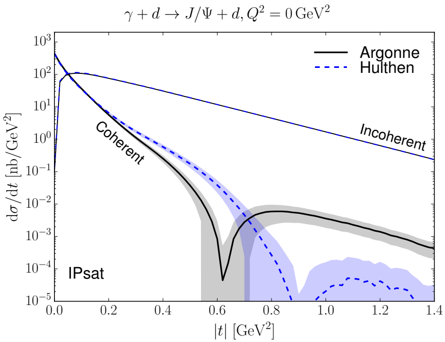
H.M, B. Schenke, 1703.09256 + in preparation w Schenke and Salazar

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

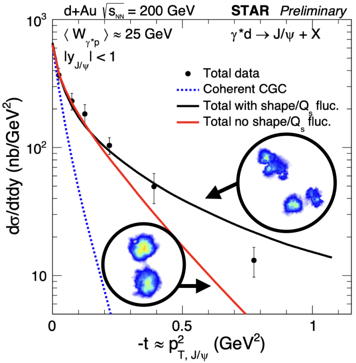
ALICE: 1305.1467

Light ions

RHIC:
UPC in $d + \mathrm{Au}$
(and ${}^3\mathrm{He} + \mathrm{Au}$)
$x_{\mathbb{P}} \sim 10^{-2}$



Distribution of small-x gluons in d:
Does it follow nucleon positions?
Details of the deuteron wf at small x



Nucleon substructure fluctuations in d
Preferred by STAR data (coh+incoh)

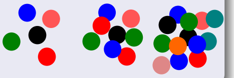
H.M, Schenke, 1910.03297; STAR 2009.04860

Can we understand the energy dependence?

Approach 1: parametrize the number of hot spots

Small-x gluon emissions increase the number of hot spots Cepila, Contreras, Tapia Takaki, 1608.07559

$$N_{hs}(x) \sim x^{p_1}(1 + p_2\sqrt{x})$$



Approach 2: Solve small-x evolution equations

Evolve proton structure by solving evolution perturbatively

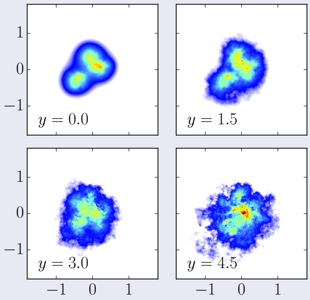
- BK eq. with impact parameter

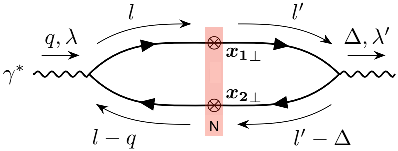
  Berger, Stasto, 1106.5740, Cepila, Contreras, Matas, 1812.02548

- JIMWLK eq. Schlichting, Schenke, 1407.8458, H.M., Schenke, 1806.06783

Fit HERA F_2 and exclusive data. H.M, Schenke, 1806.06783

Difficulty: regulating confinement effects



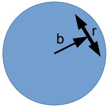


$$\boldsymbol{x}_{1,2\perp} = \boldsymbol{b}_\perp \pm \frac{\boldsymbol{r}_\perp}{2}$$

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

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

- *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 $\delta = (z - \bar{z})\boldsymbol{\Delta}/2$
  - Different propagation axis, mixes polarizations



Azimuthal correlations in DVCS

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

In agreement with hatta, Yuan, Xiao, 1703.02085

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

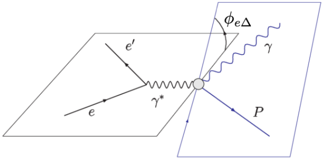


Figure: CLAS

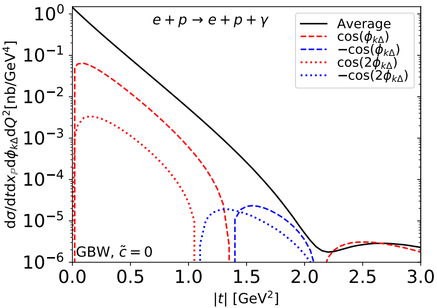
The $\cos(2\phi_{e\Delta})$ modulation in $ep \to e\gamma p$:
Access to $\mathbf{r}, \mathbf{b}$ correlations in the dipole N
via $\mathcal{M}_{\pm1,\mp1}$
$\Rightarrow$ elliptic gluon GPD

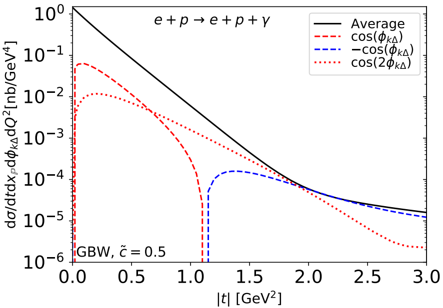
y is the inelasticity in DIS

Toy model example

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

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





$\tilde{c} = 0$, no $\phi_{r,b}$ dependence in N

$\tilde{c} = 0.5$, large $\phi_{r,b}$ dependence in N

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

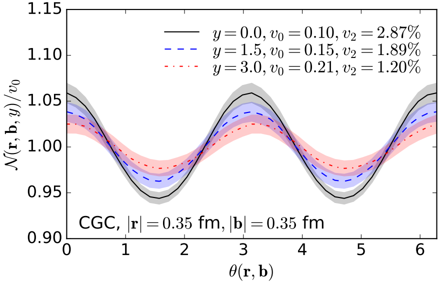
Smaller effect on $\cos(\phi_{k\Delta})$

H.M, Roy, Salazar, Schenke 2011.02464

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

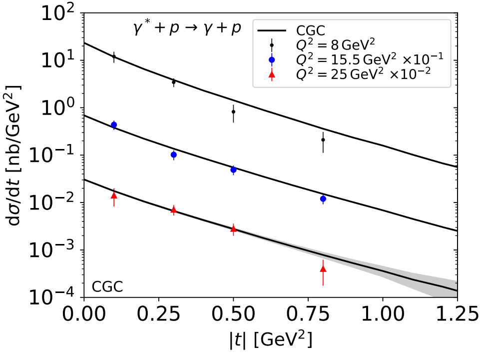
Angular modulation with $x = 0.01e^{-y}$ dependence computed from the CGC setup

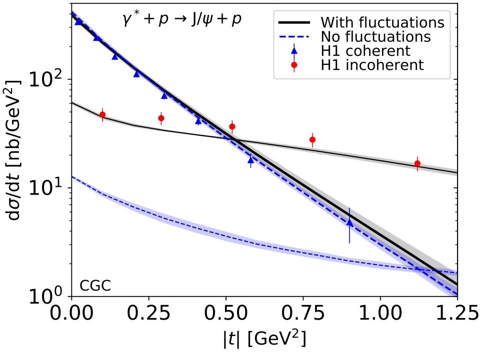
Coordinate space modulation can be related to elliptic gluon GPD or Wigner distribution

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

Predictions for the EIC, setup

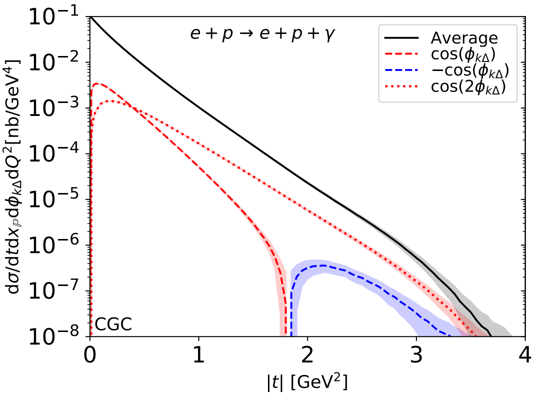
Color Glass Condensate based setup: MV model at $x \sim 0.01$ + JIMWLK evolution.
γ and J/Ψ t spectra not sensitive to the angular dependence

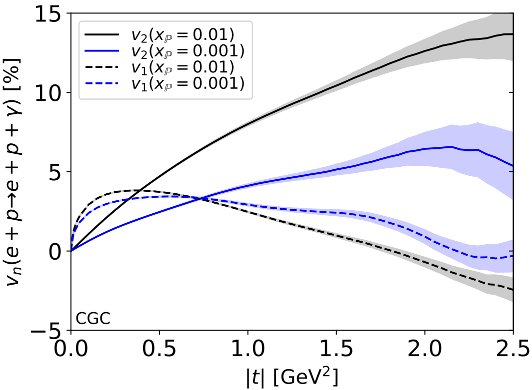




Good description of the HERA DVCS and exclusive J/ψ data.
To compute J/ψ, we replace γ^* wave function by Boosted Gaussian describing vector mesons

Coherent DVCS at the EIC: spectra and relative modulation

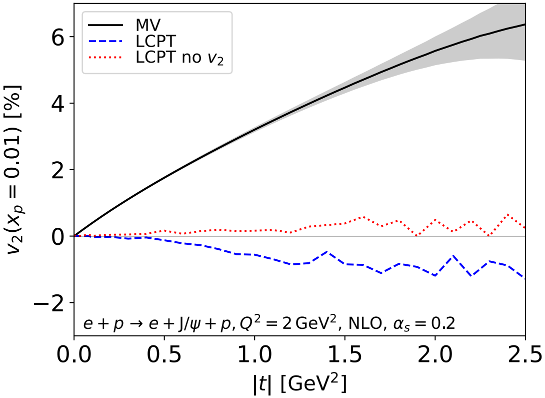




- Significant $5 \ldots 10\%$ $\cos(2\phi_{k\Delta})$ modulation at $|t| \gtrsim 0.5\mathrm{GeV}^2$
- Small-x evolution decreases anisotropies $\Rightarrow$ decreasing $v_n = \langle \cos(n\phi_{k\Delta}) \rangle$

H.M, Roy, Salazar, Schenke 2011.02464

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

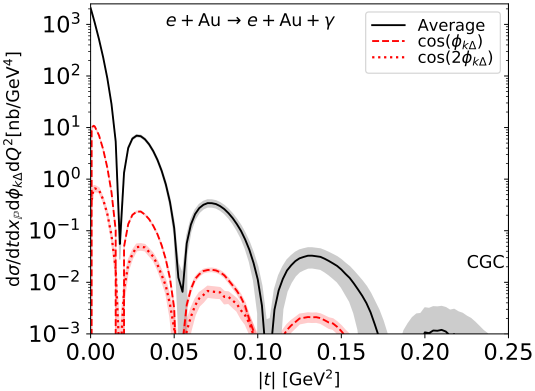
- LCPT: $\langle \rho\rho \rangle$ from perturbative calculation in the dilute region

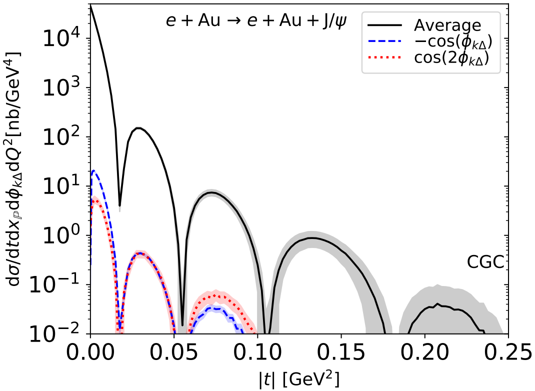
  Dumitru, H.M, Paatelainen, arXiv:2103.11682

- LCPT no v_2: elliptic gluon GPD set to 0

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

Nuclear targets at the EIC



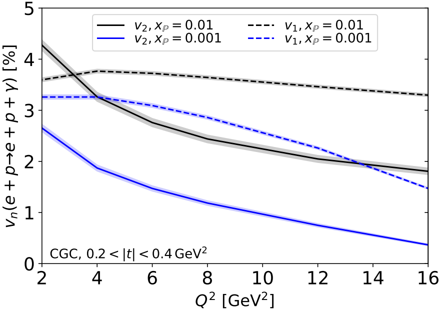


Much smaller modulations with nuclear targets:

Smoother target, smaller density gradients $\Rightarrow$ smaller dependence on $\phi_{r,b}$

H.M, Roy, Salazar, Schenke 2011.02464

Virtuality dependence



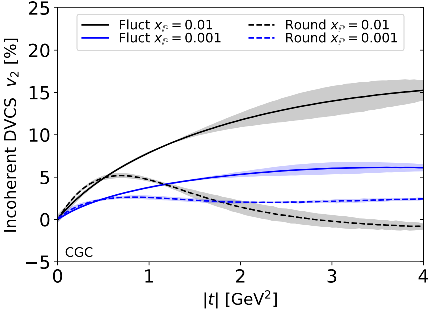
$0.2 < |t| < 0.4\,\mathrm{GeV}^2$

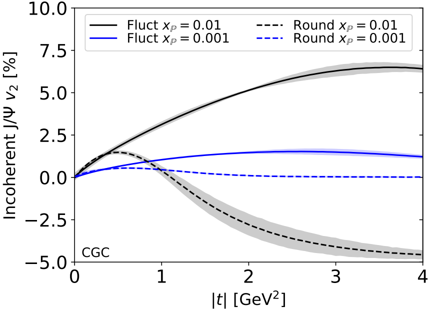
H.M, Roy, Salazar, Schenke 2011.02464

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 $Q^2 \approx 20\mathrm{GeV}^2$.

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