Gluon imaging using azimuthal correlations in diffractive scattering at the Electron-Ion Collider

Heikki Mäntysaari

Based on H.M, K. Roy, F. Salazar, B. Schenke, arXiv:2011.02464 [hep-ph]

Accepted for publication in Phys. Rev. D

STRONG-2020 seminar

University of Jyväskylä, Department of Physics
Finland

Exclusive production

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

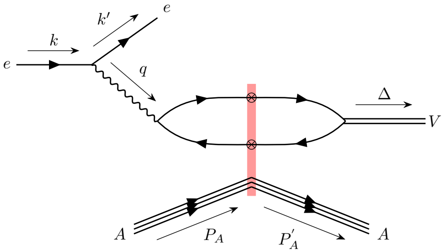
Advantages in exclusive scattering

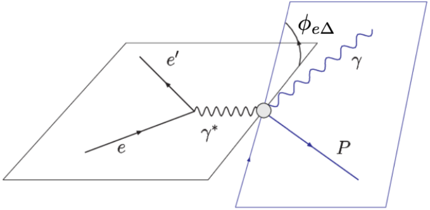
- No net color charge transfer: $\sim$ gluon^2
- Possibility to measure total momentum transfer
  Fourier conjugate to the impact parameter

This work (arXiv:2011.02464)

More differential measurement
$\Rightarrow$ more detailed probe of target structure

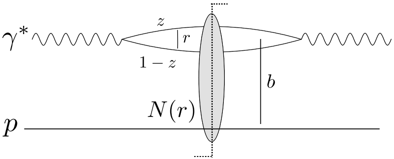
- Exclusive vector particle production differentially in both t and azimuthal angle $\phi_{e\Delta}$

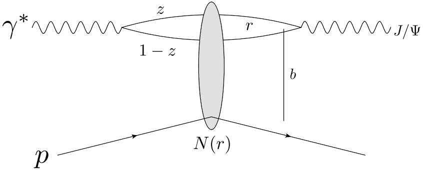




2011.02464 (top), CLAS collaboration (bottom)

Deep inelastic scattering at high energy: dipole picture





Optical theorem:
$\sigma^{\gamma^* p} \sim$ dipole amplitude N

$\sigma^{\gamma^* p \to Vp} \sim |\text{dipole amplitude } N|^2$

Universal dipole amplitude

Same universal QCD evolved dipole amplitude $N = \frac{1}{N_c}\mathrm{Tr}(1 - V(x_T)V^\dagger(y_T))$

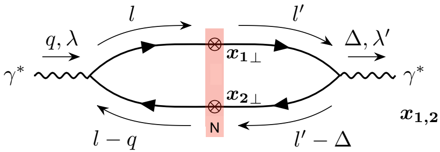
- At high energy $q\bar{q}$ has long lifetime, $\gamma \to q\bar{q}$ and $q\bar{q} \to V$ factorize
- Convenient degrees of freedom a high energy: Wilson lines $V(x_T)$ and dipole N
- Diffractive cross sections $\sim$ gluon$^2 \sim N^2 \Rightarrow$ saturation effects especially in nuclei!
- Perturbative x evolution (BK, JIMWLK), non-perturbative initial condition: fit HERA F_2

Deeply Virtual Compton Scattering*

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

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

Results in agreement with Hatta, Yuan, Xiao, 1703.02085



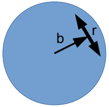
$$x_{1,2\perp} = b_\perp \pm \frac{r_\perp}{2}$$

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

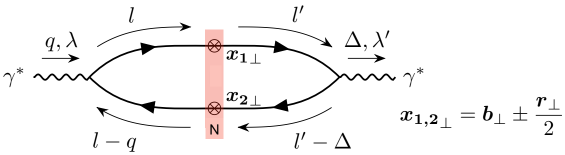
$$\mathcal{M}_{\pm1,\mp1} \sim \int_{\mathbf{b}} e^{-i\boldsymbol{\Delta}\cdot\mathbf{b}} \int_{\mathbf{r}} e^{\pm 2i\phi_{r\Delta}} N(\mathbf{r},\mathbf{b}) \int_z e^{-i\delta\cdot\mathbf{r}} z\bar{z}\varepsilon K_1(\varepsilon r)\varepsilon' K_1(\varepsilon' r)$$

Similar results for $\mathcal{M}_{\pm1,\pm1}, \mathcal{M}_{\pm1,0}, \mathcal{M}_{0,\pm1}$.
Neglecting the off-forward phase $\delta = (z - \bar{z})\boldsymbol{\Delta}/2$:

- $\mathcal{M}_{0,0} \sim$ angle independent part of dipole-target amplitude $N(\mathbf{r},\mathbf{b})$
- $\mathcal{M}_{\pm1,\mp1}$: sensitive to $\cos(2\phi_{r,b})$ modulation of the dipole



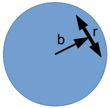
Deeply Virtual Compton Scattering*



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

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
  - In mixed space: (angular) correlation between gluon $\mathbf{x}$ and $\mathbf{p}$
- *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 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

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

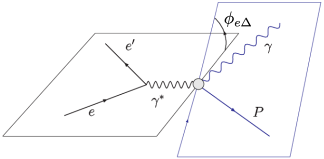


Figure: CLAS

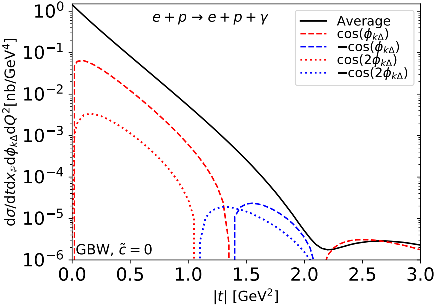
The $\cos(2\phi_{e\Delta})$ modulation in $ep \to e\gamma p$:
Access to $\mathbf{r}, \mathbf{b}$ correlations in the dipole D via $\mathcal{M}_{\pm1,\mp1}$
$\Rightarrow$ elliptic gluon GPD / Wigner distribution

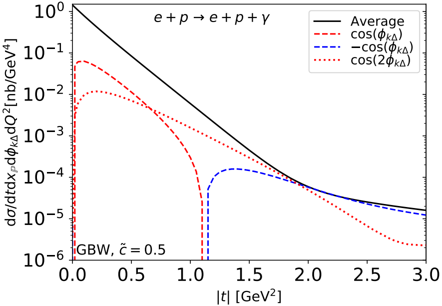
y is the inelasticity in DIS

Toy model example

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

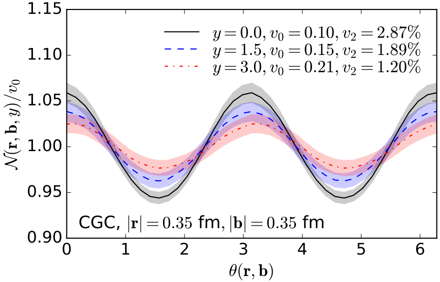
Smaller effect on $\cos(\phi_{k\Delta})$

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



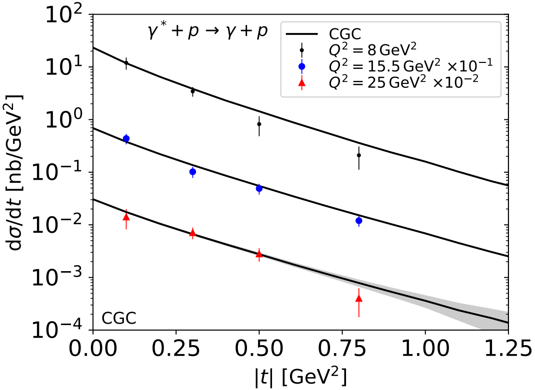
Angular modulation with $x = 0.01e^{-y}$ dependence computed from the CGC setup

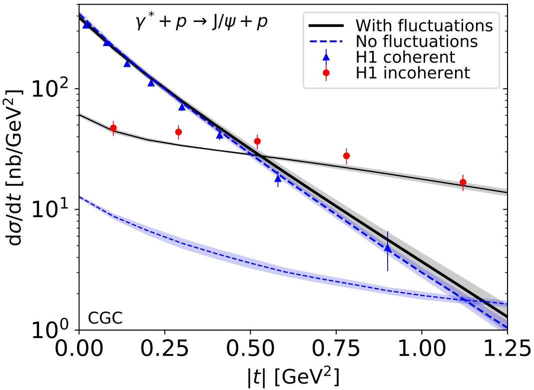
Note: recent developments beyond MV for protons suggest negative v_2, see A. Dumitru, H.M, R. Paatelainen, arXiv:2103.11682

HM, Mueller, Schenke, 1902.05087

Setup

t spectra not sensitive to the angular dependence, only to the **b** profile



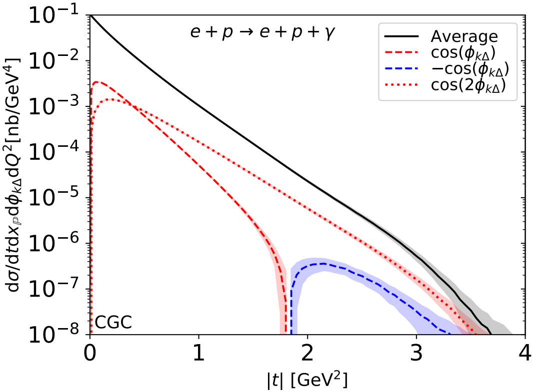


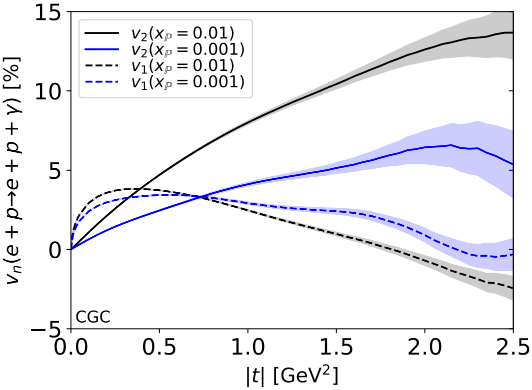
Good description of the HERA DVCS and exclusive J/ψ data.

To compute J/ψ, we replace γ^* wave function by Boosted Gaussian describing vector mesons

H.M, Roy, Salazar, Schenke 2011.02464; beyond Boosted Gaussian: see also T. Lappi, H. M, J. Penttala, 2006.02830

Coherent DVCS at the EIC: spectra and relative modulation

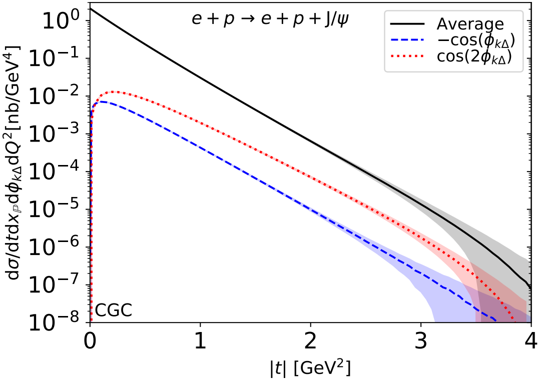


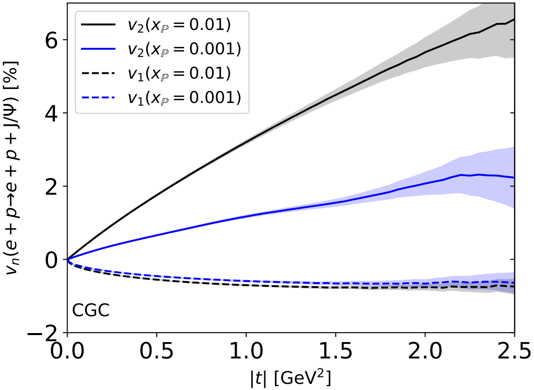


- Significant $5\ldots10\%$ $\cos(2\phi_{k\Delta})$ modulation at $|t| \gtrsim 0.5\text{GeV}^2$
- Small-x evolution decreases gradients $\Rightarrow$ decreasing $v_n = \langle\cos(n\phi_{k\Delta})\rangle$
- Note: Bethe-Heitler not included - negligible at small x but probably not at the EIC

H.M, Roy, Salazar, Schenke 2011.02464

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

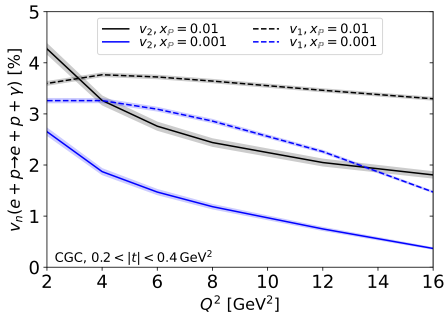




- Smaller but still significant $\cos(2\phi_{k\Delta})$ modulation in J/ψ production (and no BH!)
- Very small v_1, as that is dominated by the off-forward phase $e^{-i\delta\cdot\mathbf{r}}$
  $\Rightarrow$ small contribution at small $r \sim 1/M_V$.

H.M, Roy, Salazar, Schenke 2011.02464

Virtuality dependence, modulations in DVCS

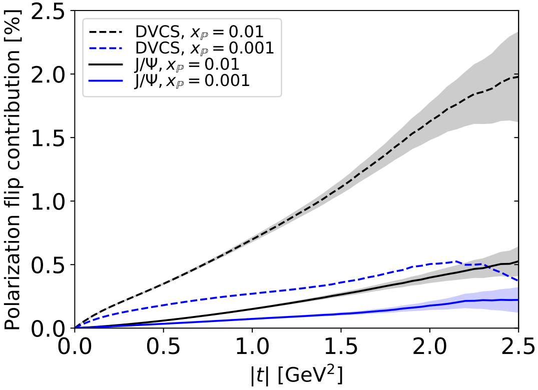


H.M, Roy, Salazar, Schenke 2011.02464

Dipole size $\sim 1/Q^2$

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

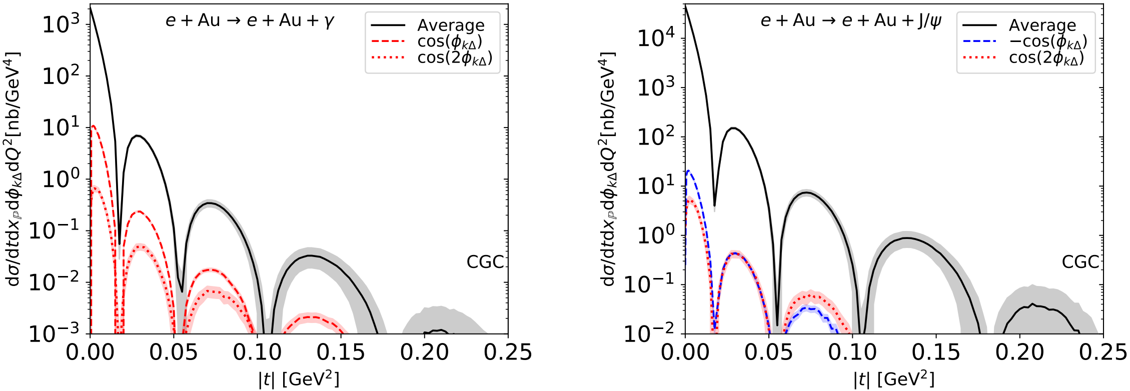
Sidenote: Importance of polarization changing contributions



- Usual assumption that the incoming and ougoing γ and J/ψ have the same polarization is good
- Especially in J/ψ production e.g. meson wave function uncertainty is much larger
- Even smaller contribution at small x (where smaller gradients)

H.M, Roy, Salazar, Schenke 2011.02464

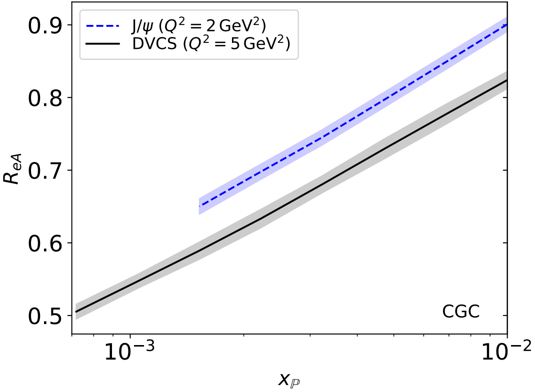
Nuclear targets at the EIC



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

Nuclear targets at the EIC – nuclear suppression



H.M, Roy, Salazar, Schenke 2011.02464

eA collisions:

Probably can't see azimuthal modulations

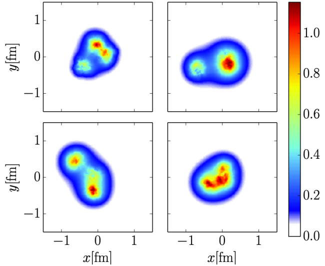
- But significant nuclear suppression that probes saturation effects!

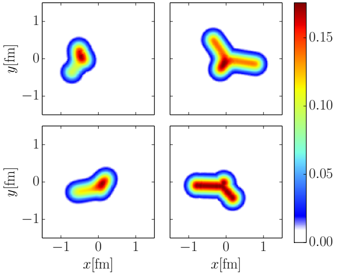
$$R_{eA} = \left. \frac{\mathrm{d}\sigma^{eA}/\mathrm{d}t}{A^2 \mathrm{d}\sigma^{ep}/\mathrm{d}t} \right|_{t=0}$$

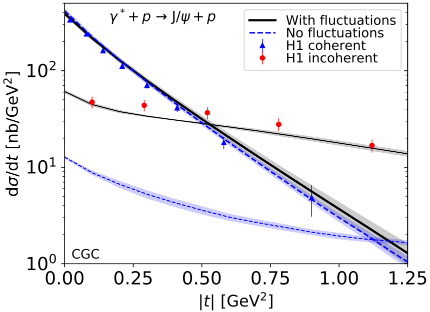
$R_{eA} = 1$ if no non-linear effects

Note: J/ψ wave function does not completely cancel in the ratio, see T. Lappi, H.M, J. Penttala, 2006.02830

Incoherent diffraction





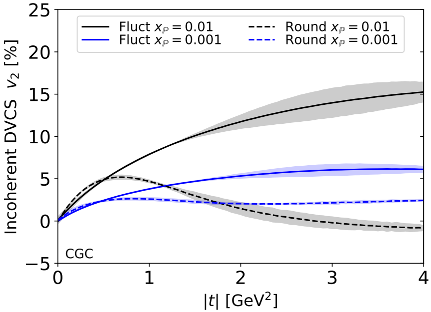


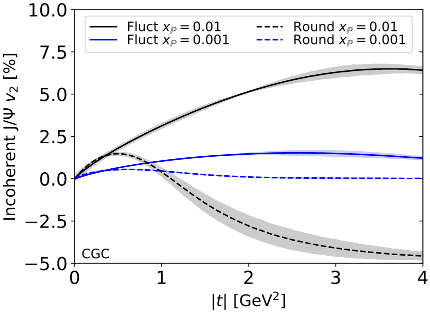
H.M, B. Schenke, 1607.01711

Incoherent cross section ∼ covariance $\langle \mathcal{M}^2 \rangle - \langle \mathcal{M} \rangle^2$ is sensitive to the (amount of) fluctuations H.M, Schenke, 1603.04349

Potential to access fluctuations in detail by studying azimuthal correlations in $e + p \to e + \gamma + p^*$ and $e + p \to e + \mathrm{J}/\psi + p^*$?

Incoherent modulation





- Substructure changes v_2 at $|t| \gtrsim 0.5\mathrm{GeV}^2$ 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

Conclusions and outlook

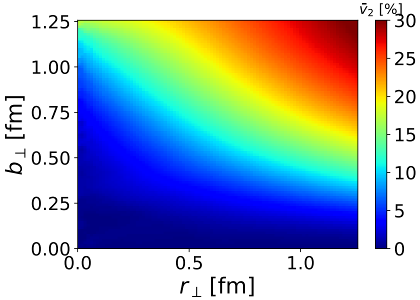
- Calculate azimuthal correlations between e and the exclusively produced γ or J/Ψ
- Identify *intrinsic* (related to elliptic gluon GPD) and *kinematical* contributions
- EIC prediction: significant $5\dots10\%$ azimuthal modulations with proton targets
- Modulations suppressed at high W/small $x_{\mathbb{P}}$
- Very small modulations with nuclear targets

Outlook:

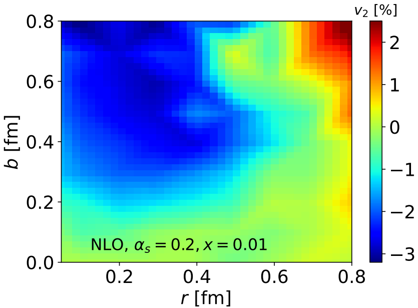
- Distinguish different fluctuating geometries using incoherent v_n?
- LCPT calculation of the dipole-proton amplitude, different $\phi_{r,b}$ systematics (negative dipole v_2), effect here? A. Dumitru, H.M, R: Paatelainen, arXiv:2103.11682
- NLO H.M, J. Penttala, arXiv:2104.02349

Backups

Dipole $v_2 = \langle \cos 2\phi_{rb} \rangle$



MV model with b dep (this work)



LCPT A. Dumitru, H.M, R. Paatelainen, 2103.11682