# The Electron Ion Collider
# and Gluon imaging using azimuthal correlations at the EIC

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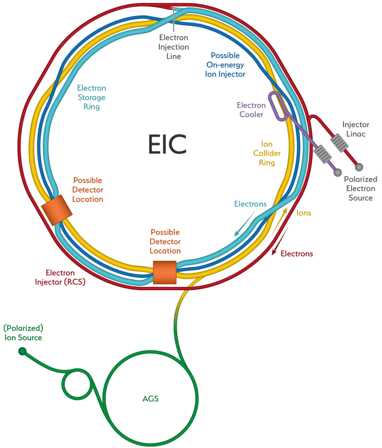
# The Electron Ion Collider

## 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

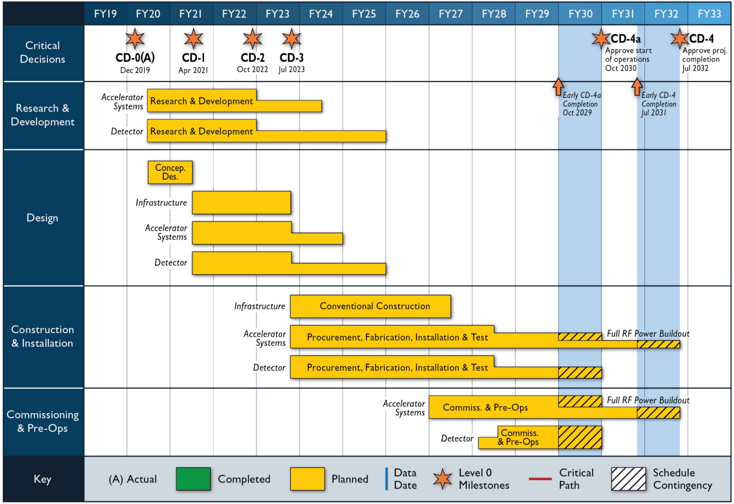
## Schedule

- NSAC Long Range Plan 2015, recomended by NAS 2018
- Mission need (CD0) and cost range (CD1) approved
- Site selected: BNL (EIC will re-use RHIC)
- Construction starts in $\sim$2024, first data-taking in $\sim$2032




picture from bnl.gov

# EIC Schedule




Tim Hallman (US DOE), DIS2021 conference

# EIC Physics Program

## 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?

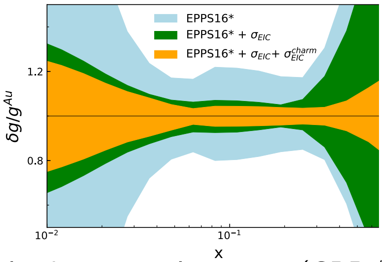
- Clean environment for precison studies (e.g. can construct kinematics exactly)
- Parton density $\sim x^{-\lambda} A^{1/3}$
  Increasing $A$ is much cheaper than decreasing $x$

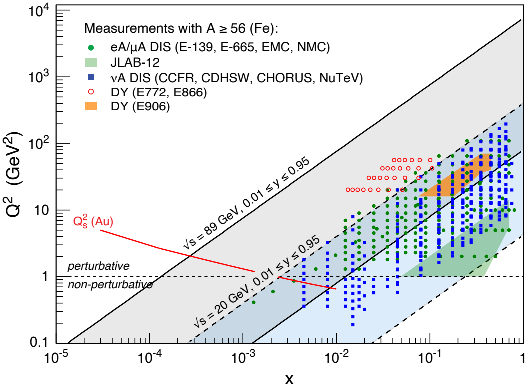
EIC Yellow Report: arXiv:2103.05419

# Access to completely new kinematical domain

- First nuclear-DIS machine in collider kinematics $=$ large $\sqrt{s}$
- Similarly: in polarized $e + p$: huge increase in $x$, $Q^2$ coverage over previous experiments

Example: effect on nuclear PDF uncertainty



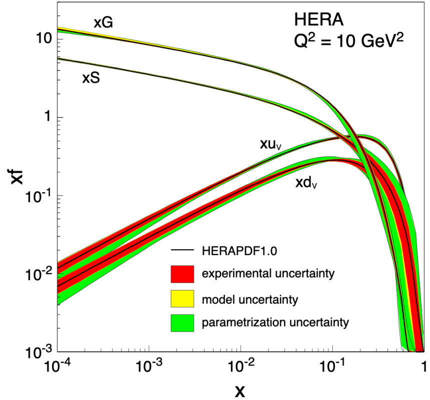



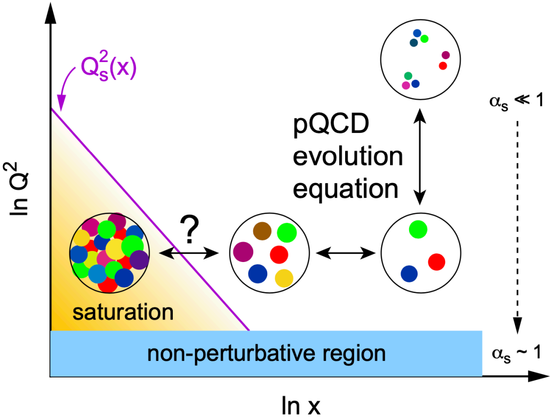

EIC YR, arXiv:2103.05419

Also multi dimensional imaging (GPD/TMD)

# Access very large parton densities and non-linear dynamics

HERA: parton densities $\sim x^{-\lambda}$, eventually violates unitarity




Non-linear QCD effects at small $x$ (e.g. $gg \to g$) should tame the growth
saturated state of gluonic matter, emergent semi-hard saturation scale $Q_s^2 \sim (A/x)^{1/3}$

# MPIs at the EIC at MPI@LHC

## Experimental data from HERA

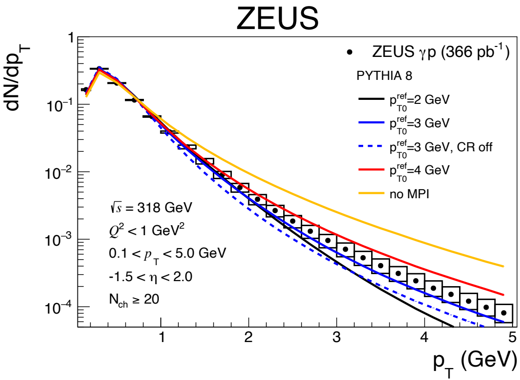
D. Gangadharan on Tuesday:
*Search for collective behaviour and multiparton interactions in ep scattering at HERA*

## Pythia development

M. Utheim on Monday:
*PYTHIA8: soft QCD model, news and updates*

## Theory development

F. Salazar on Mon: *Forward dijet production*
M. Strikman on Thu:
*Neutron production in ZDC as a probe of the dynamics of hard gamma A and pA interactions*



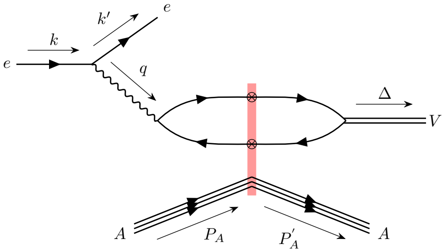

Sensitivity of charged hadron spectra in $e + p$ on Pythia MPI model details

ZEUS, arXiv:2106.12377

# Our recent work: spatial correlations in the gluon field

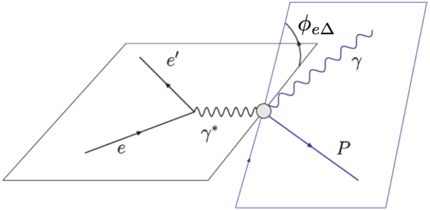
Imaging using DVCS and exclusive $\mathrm{J}/\psi$ production: $e + p \to \gamma(\mathrm{J}/\psi) + p$

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




## 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)

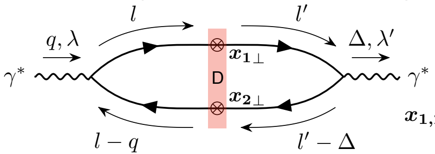
More differential measurement

$\Rightarrow$ more detailed probe of target structure

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

# Deeply Virtual Compton Scattering* – coordinate space description

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




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

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

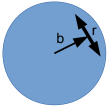
Results in agreement with Hatta, Yuan, Xiao, 1703.02085

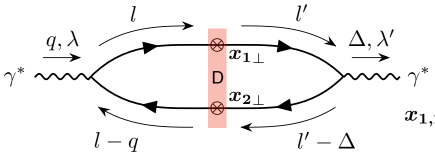
$$\mathcal{M}_{0,0} \sim \int_{\mathbf{b}} e^{-i\boldsymbol{\Delta}\cdot\mathbf{b}} \int_{\mathbf{r}} D(\mathbf{r}, \mathbf{b}) \int_z e^{-i\delta\cdot\mathbf{r}} z^2 \bar{z}^2 Q K_0(\varepsilon r) Q' K_0(\varepsilon' r)$$

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

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 $D(\mathbf{r}, \mathbf{b})$
- $\mathcal{M}_{\pm 1,\mp 1}$: sensitive to $\cos(2\phi_{r,b})$ modulation of the dipole ($\sim$ gluon distribution)



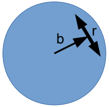



$$\boldsymbol{x}_{\mathbf{1,2}_\perp} = \boldsymbol{b}_\perp \pm \frac{\boldsymbol{r}_\perp}{2}$$

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

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 $D(\mathbf{r}, \mathbf{b})$
  - 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 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

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

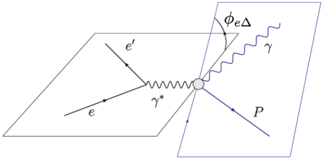


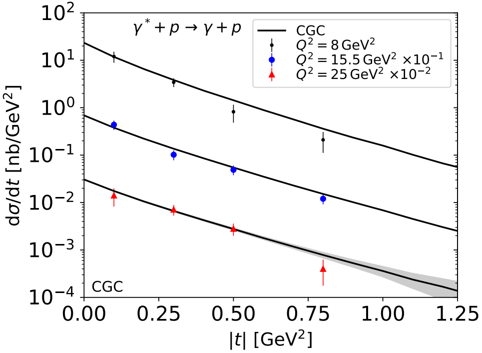

Figure: CLAS

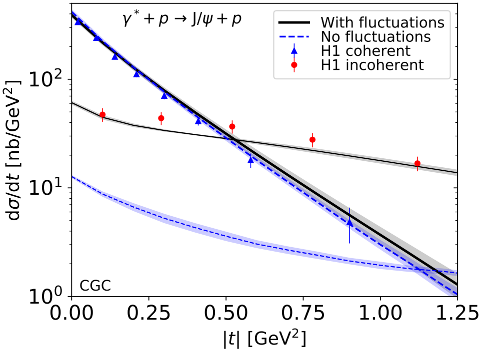
The $\cos(2\phi_{e\Delta})$ modulation in $ep \to e\gamma p$:
Access to $\mathbf{r}, \mathbf{b}$ correlations in the dipole $D$ via $\mathcal{M}_{\pm1,\mp1}$
$\Rightarrow$ elliptic gluon GPD / Wigner distribution

$y$ is the inelasticity in DIS

# Predictions for the EIC, setup

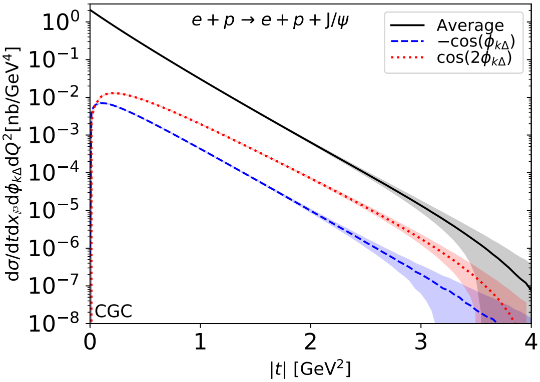
Color Glass Condensate based setup: MV model at $x \sim 0.01$ + JIMWLK evolution.
$\gamma$ and $J/\Psi$ $t$ spectra not sensitive to the angular dependence

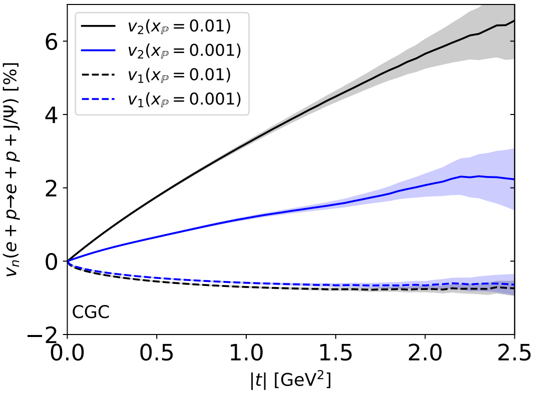



Good description of the HERA DVCS and exclusive $\mathrm{J}/\psi$ data.
To compute $\mathrm{J}/\psi$, we replace $\gamma^*$ wave function by Boosted Gaussian describing vector mesons

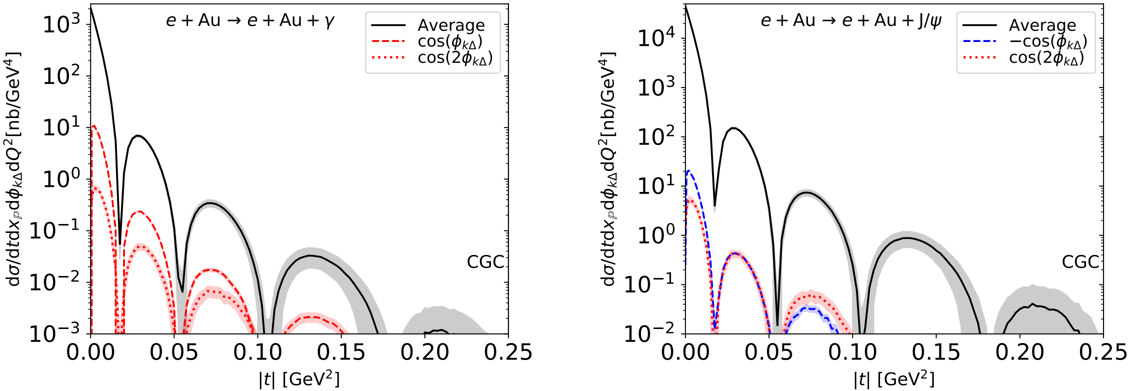
# Coherent $J/\psi$ at the EIC: spectra and relative modulation




- Significant $\cos(2\phi_{k\Delta})$ modulation in $J/\psi$ production (and larger in DVCS)
- Very small $v_1$, as that is dominated by the off-forward phase $e^{-i\delta\cdot\mathbf{r}}$
  $\Rightarrow$ small contribution at small $r \sim 1/M_V$.

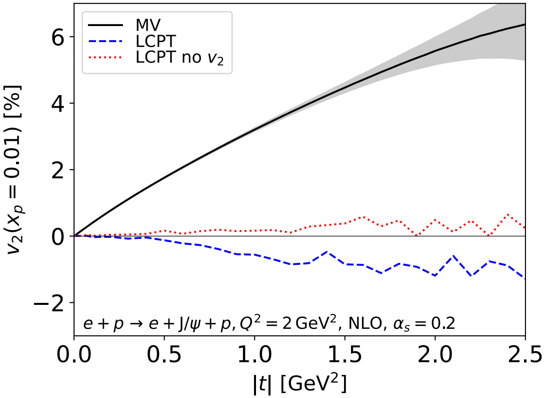
H.M, Roy, Salazar, Schenke 2011.02464




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!

# Conclusions and outlook

## The Electron-Ion Collider in the US

- First ever nuclear DIS measurements in collider kinematics
- High energy, luminosity and polarization
- Broad physics program in unexplored kinematical domain

## Gluon imaging using azimuthal correlations in exclusive scattering

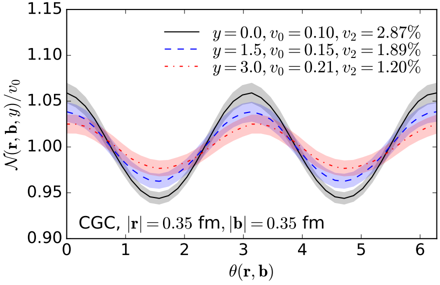
- Calculated azimuthal correlations between $e$ and the exclusively produced $\gamma$ or $\mathrm{J}/\Psi$
- Identify *intrinsic* (related to elliptic gluon GPD) and *kinematical* contributions
- EIC prediction: significant $5\dots10\%$ azimuthal modulations with proton targets
- Modulations suppressed at high $W$/small $x_{\mathbb{P}}$
- Very small modulations with nuclear targets
- Sensitive to details of the theoretical description of the proton color field

# Backups

# 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

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

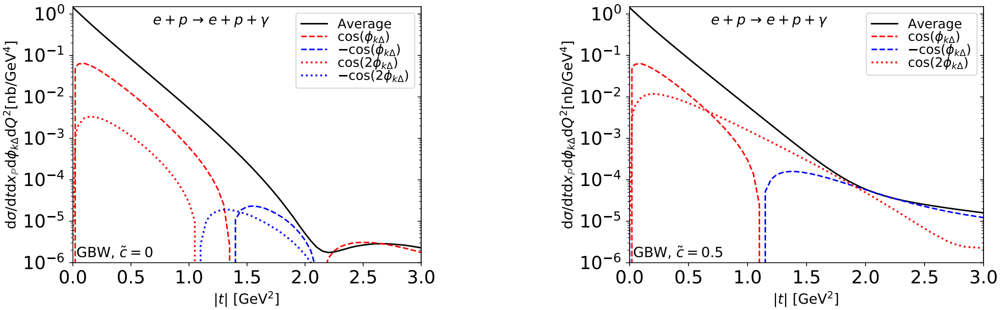
Note: recent developments beyond MV for protons suggest negative $v_2$, see arXiv:2103.11682

HM, Mueller, Schenke, 1902.05087

# Toy model example

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

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



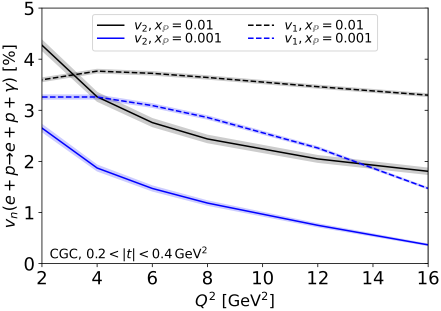

$\tilde{c} = 0$, no $\phi_{r,b}$ dependence in $D$ — $\tilde{c} = 0.5$, large $\phi_{r,b}$ dependence in $D$

$\phi_{r,b}$ 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

# Virtuality dependence



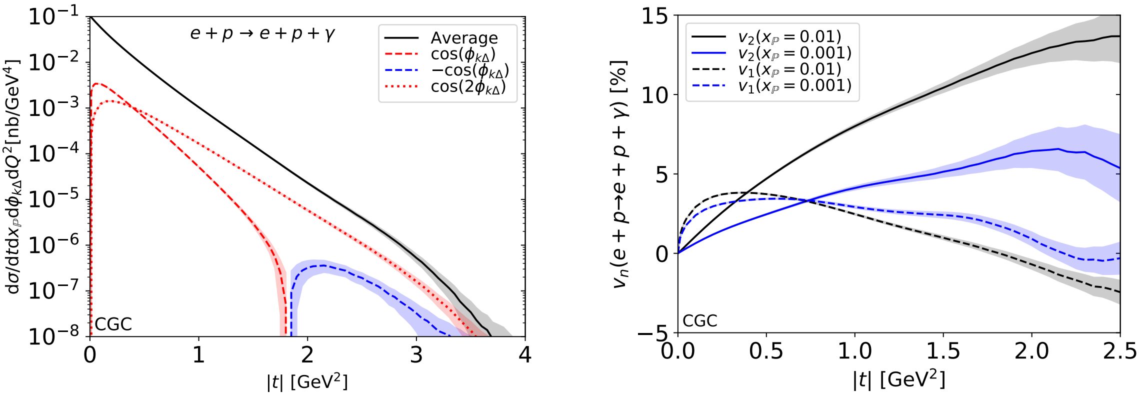

$0.2 < |t| < 0.04$

H.M, Roy, Salazar, Schenke 2011.02464

Dipole size $\sim 1/Q^2$

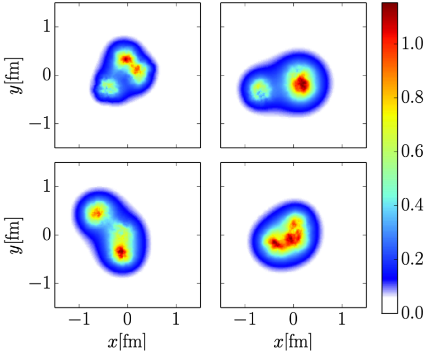
- Smaller density gradients seen by dipoles at high $Q^2$ $\Rightarrow$ Smaller *intrisic contrubtion*, decreasing $v_2$
- Small dipoles also result in small contribution from off-forward phase $e^{-i\delta\cdot\mathbf{r}}$, visible $v_1$.
- Additional effect: At the kinematical $y = 1$ boundary modulations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

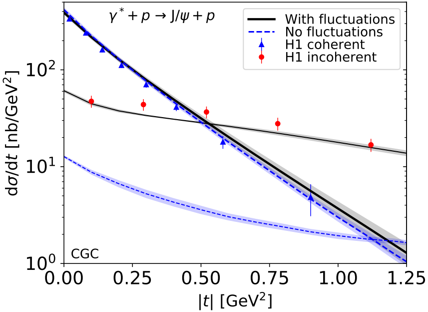
# Coherent DVCS at the EIC: spectra and relative modulation




- Significant $5\ldots10\%$ $\cos(2\phi_{k\Delta})$ 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

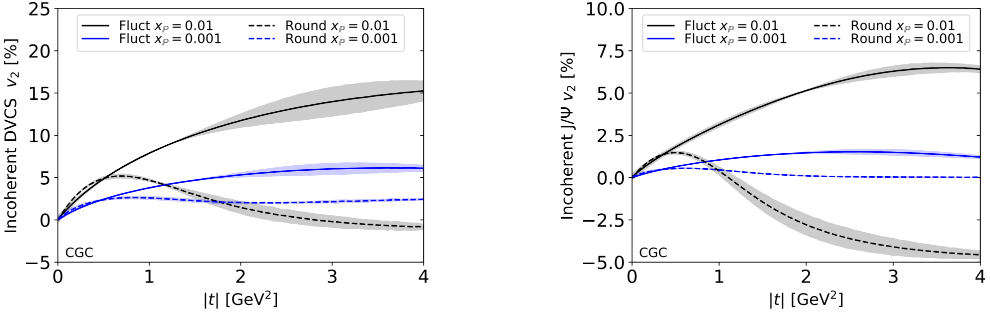



Incoherent cross section $\sim$ covariance $\langle \mathcal{M}^2 \rangle - \langle \mathcal{M} \rangle^2$ is sensitive to the (amount of) fluctuations H.M, Schenke, 1603.04349

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 $|t| \gtrsim 0.5\text{GeV}^2$ 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