# Gluon imaging using azimuthal correlations in diffractive scattering

RIKEN Seminar
Dec 17th, 2020

**Farid Salazar**

H. Mäntysaari, K. Roy, FS, B. Schenke. 2011.02464

See also Hatta, Yuan, Xiao. 1703.02085

# Outline

I. DVCS and Vector Meson production in the CGC

II. Final state azimuthal correlations with electron plane

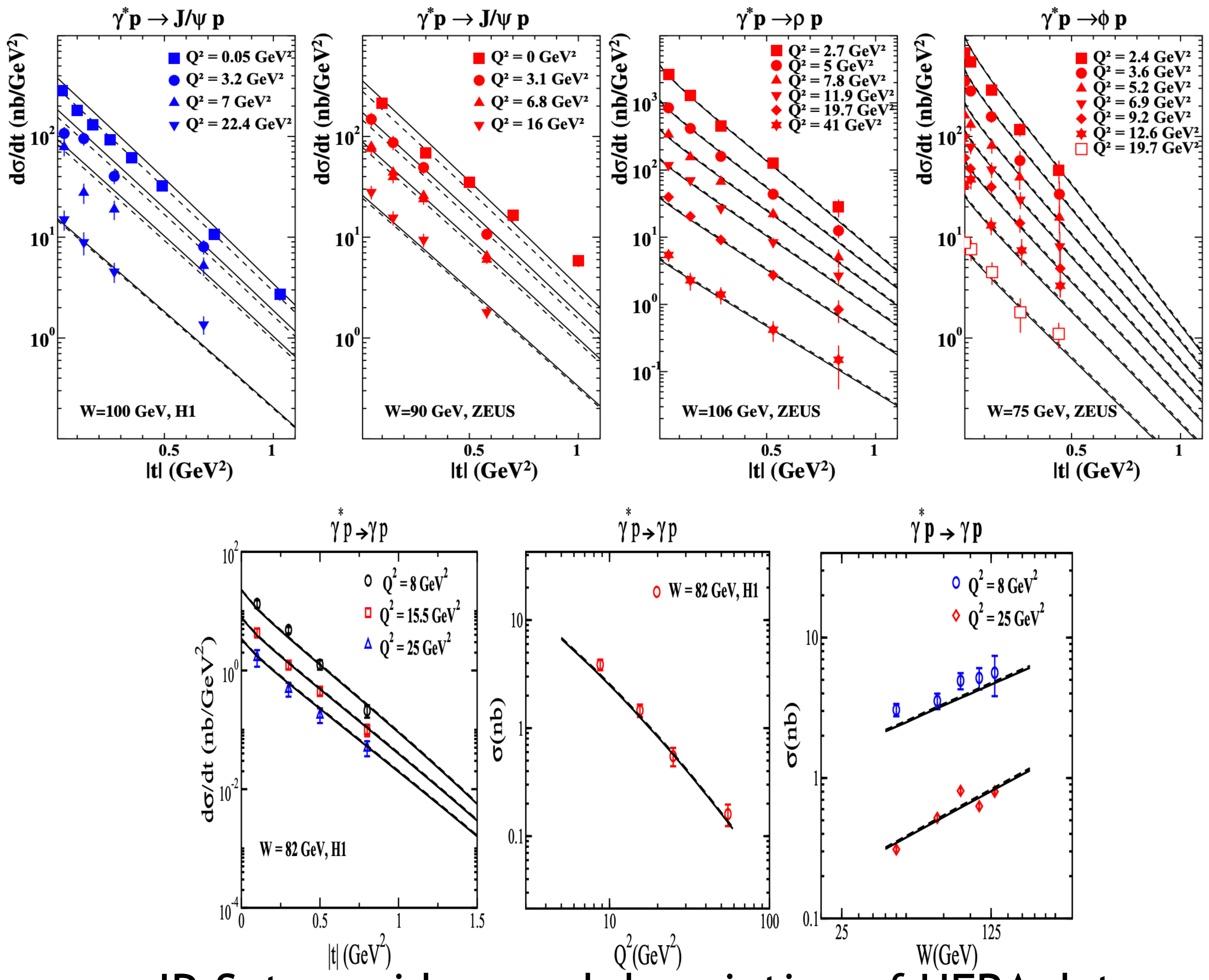
III. Our predictions for the EIC

IV. Incoherent diffraction and fluctuations

# 0. DVCS and VM studies from HERA

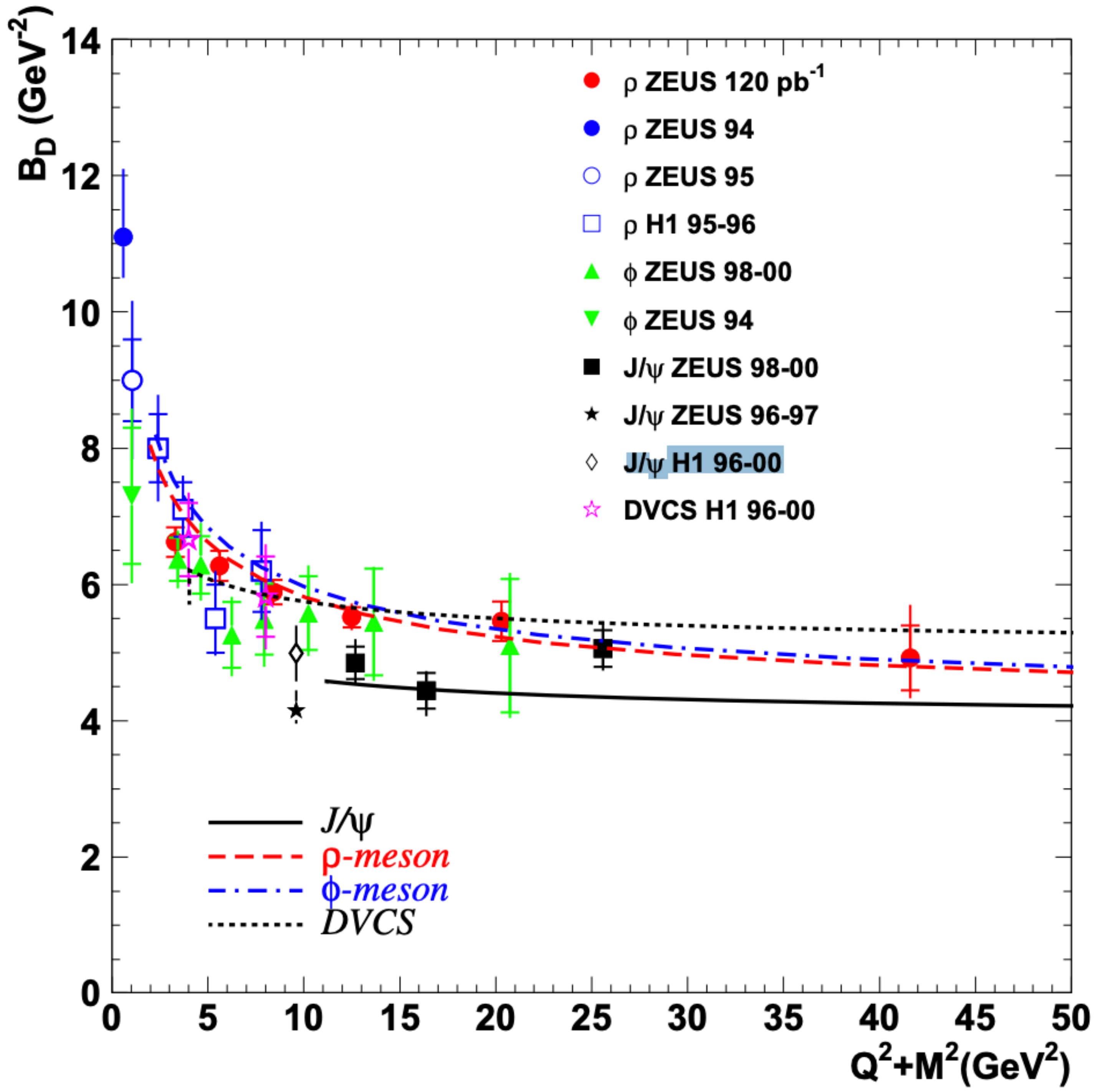
# DVCS and VM studies from HERA

## The size of the proton from exclusive spectra




IP-Sat provides good description of HERA data

Momentum transfer conjugate to impact parameter $b_\perp \leftrightarrow \Delta_\perp$ .




Extract proton size from slope of exclusive spectra

Rezaeian, Siddikov, Klundert, Venugopalan 1212.2974

# What else can we learn from diffraction?

**Previous studies:**

Spectra ($|t|-$dependence) only sensitive to proton impact parameter $b_\perp$ dependence.

**Goal:**

Learn about angle correlations of momentum and impact parameter of gluons

More specifically correlations between $\boldsymbol{r}_\perp$ and $\boldsymbol{b}_\perp$ in $D_Y(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)$ dipole correlator.

**Observables:**

Exclusive dijet production

Hatta, Yuan, Xiao. 1601.01585
Mäntysaari, Mueller, Schenke. 1902.05087
FS, Schenke. 1905.03763

At small-x, limited to small invariant masses (i.e. small $p_\perp$ jets ).
Experimentally challenging.

DVCS/exclusive VM
(correlated with electron plane!)

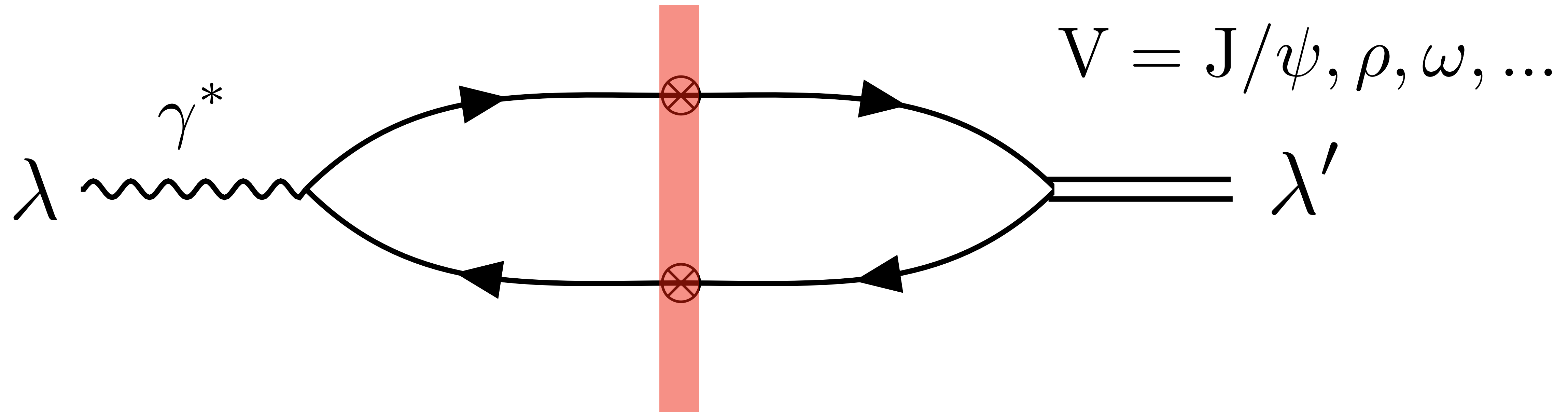
Hatta, Yuan, Xiao. 1703.02085
Mäntysaari, Roy, FS, Schenke. 2011.02464

Sufficiently small-x since invariant mass is small!

**Approach:**

Need to go beyond IP-sat, we will use impact-parameter dependent MV + JIMWLK.

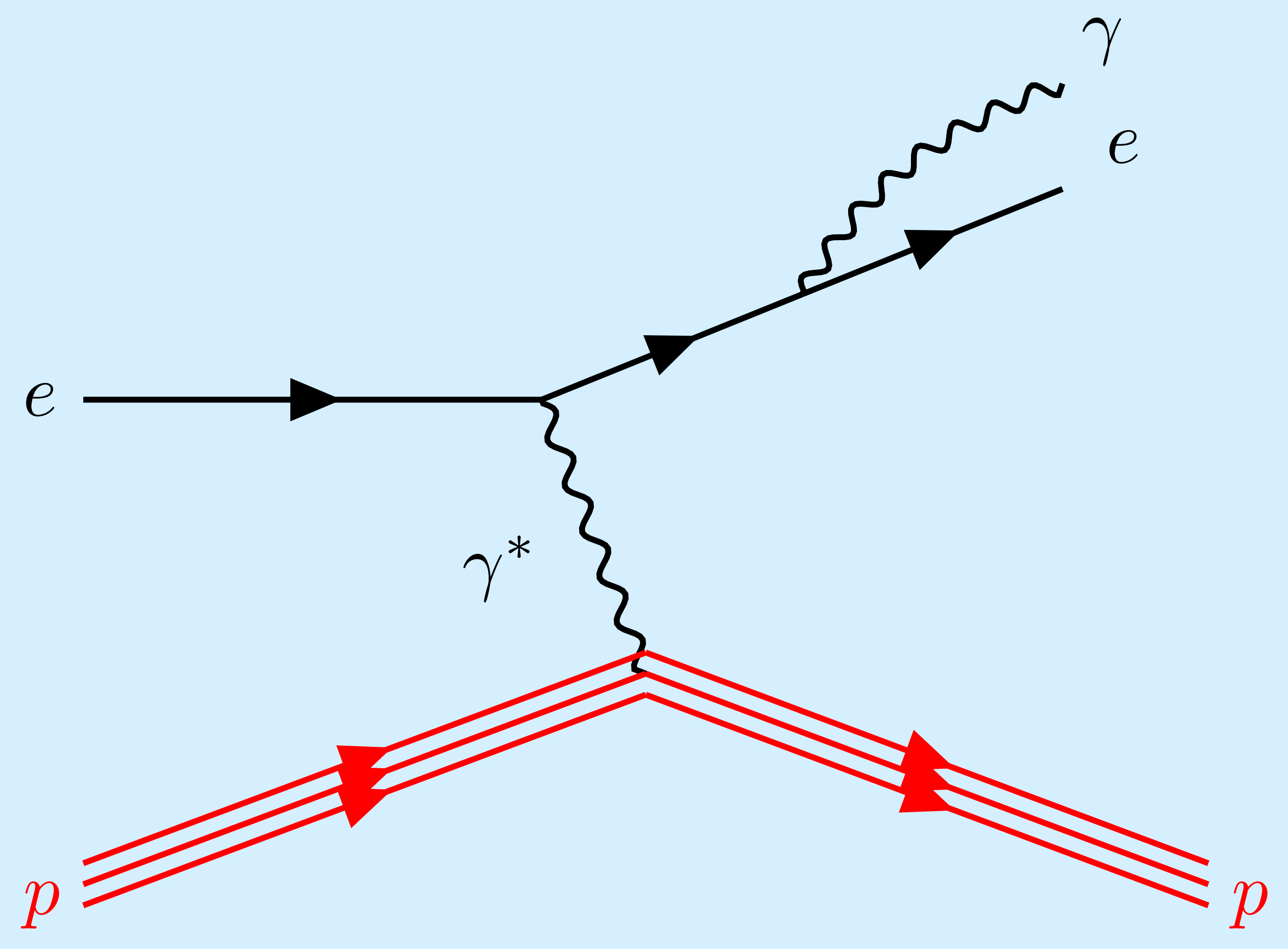
# I. DVCS and Vector Meson production in the CGC



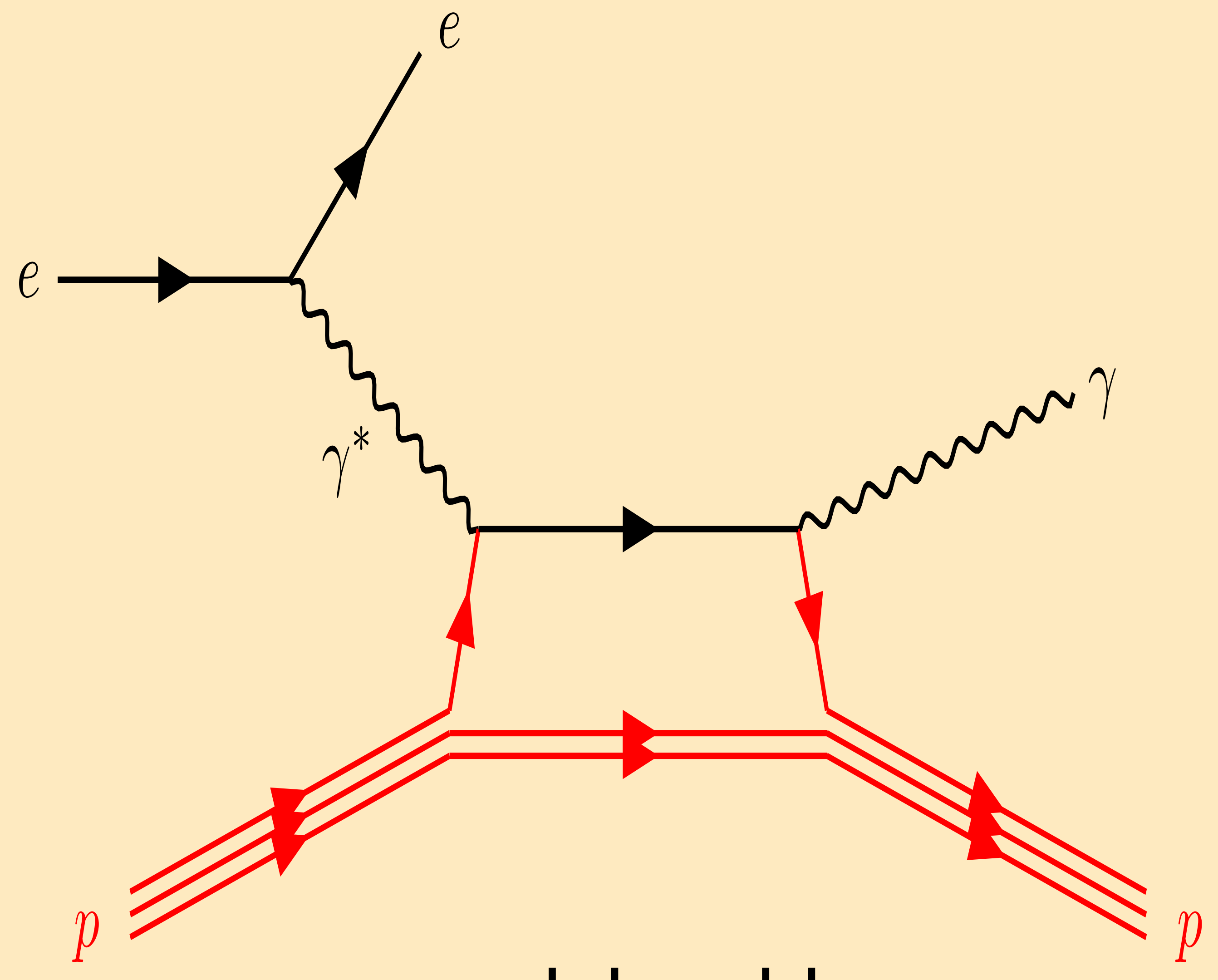
# Deeply Virtual Compton Scattering

DVCS: quark and dipole/gluon channel $e + p \to e + p + \gamma$

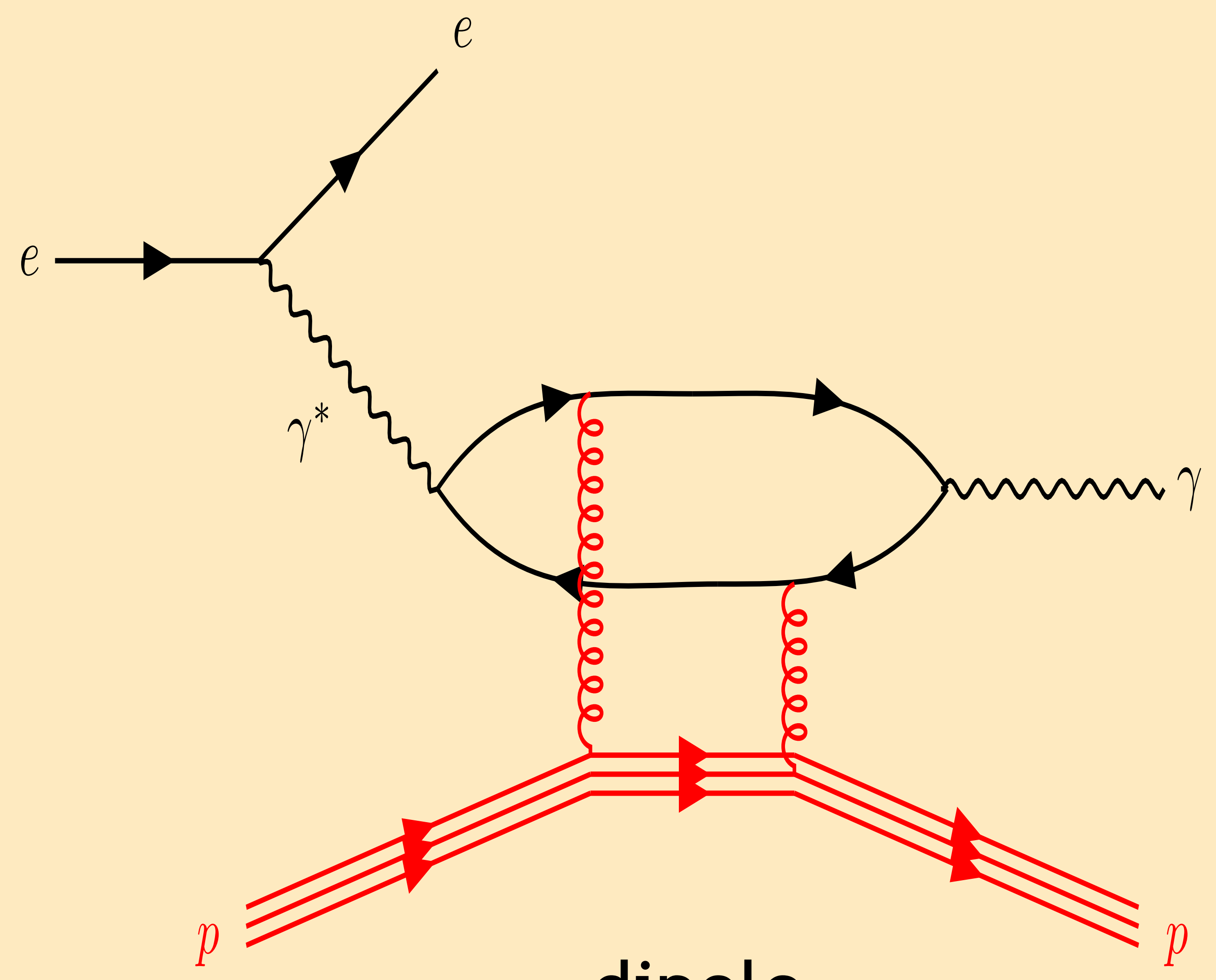
Bethe-Heitler




DVCS channels




quark hand-bag diagram




dipole

dominant channel at small x!

For DVCS and BH see

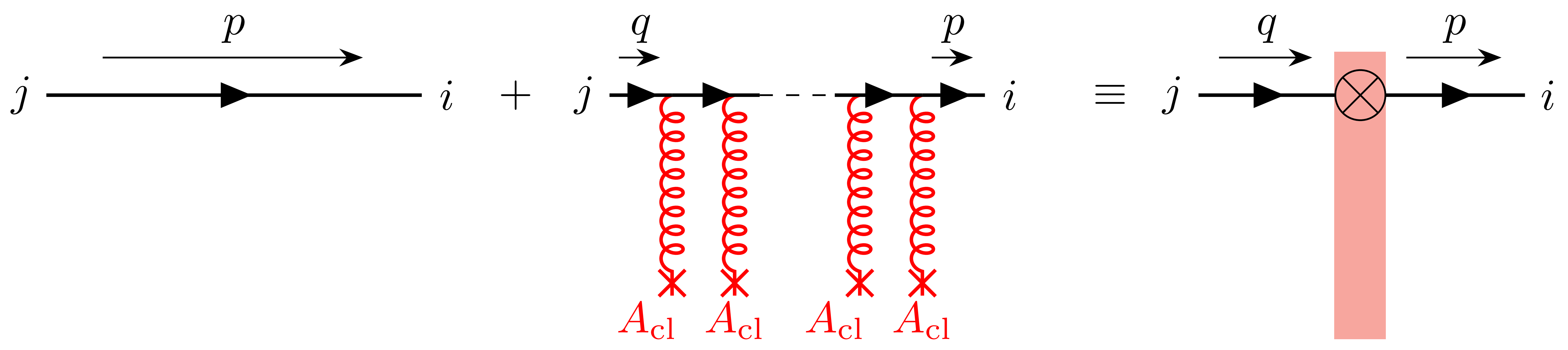
Aschenauer, Fazio, Kumericki, Müller 1304.0077

# Deeply Virtual Compton Scattering

## CGC EFT and Multiple scattering

McLerran, Venugopalan.
hep-ph/9309289 hep-ph/9311205

Dense gluon field $A_{cl} \sim 1/g$ needs resummation of multiple gluon interactions



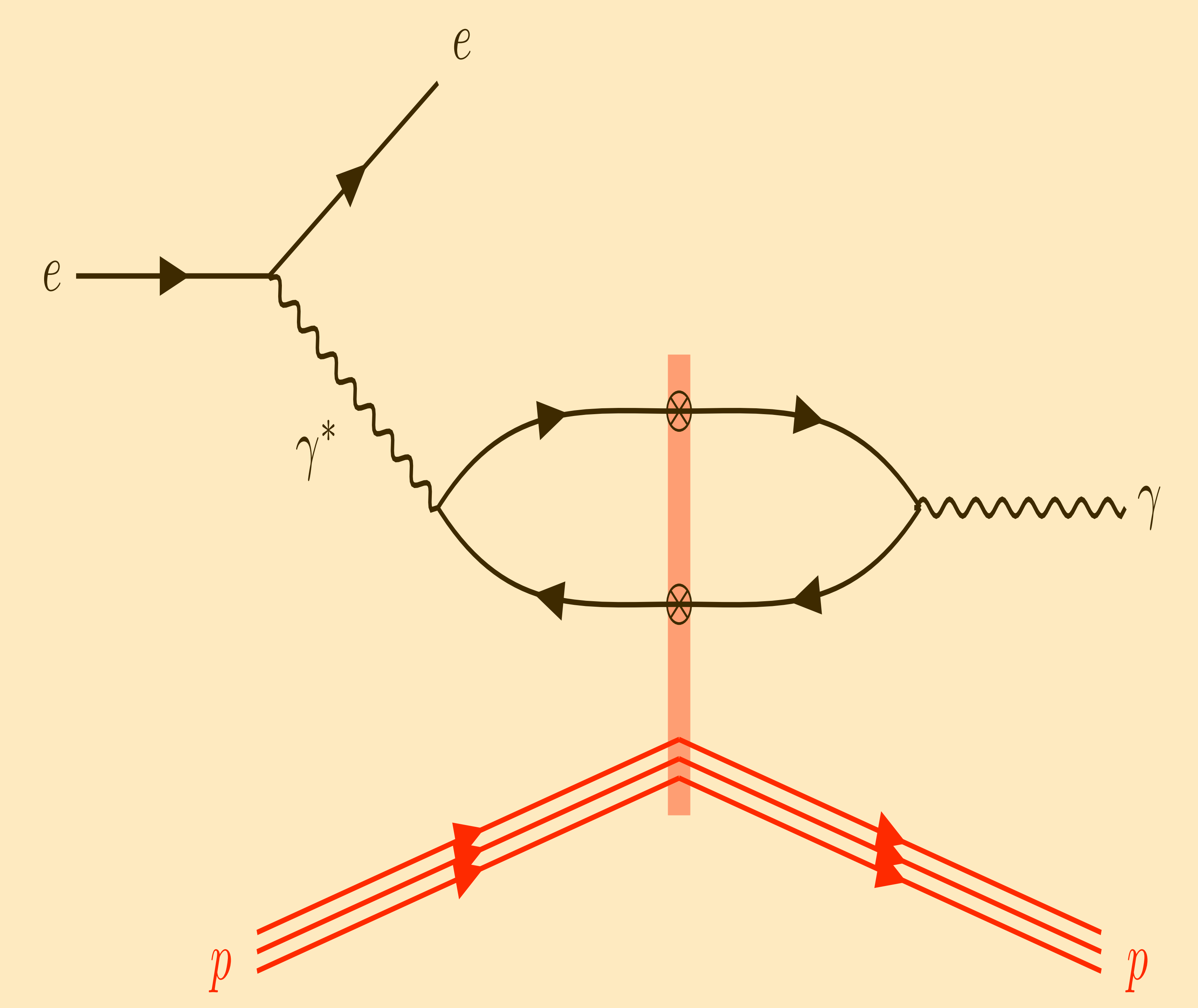

Effective CGC eikonal vertex:

$$\mathcal{T}_{ij}(p,q) = (2\pi)\delta(p^- - q^-)\gamma^- \mathrm{sign}(p^-) \int_{\boldsymbol{z}_\perp} e^{-i(\boldsymbol{p}_\perp - \boldsymbol{q}_\perp)\cdot \boldsymbol{z}_\perp} V_{ij}^{\mathrm{sign}(p^-)}(\boldsymbol{z}_\perp)$$

Light-like Wilson line:

$$V_{ij}(\boldsymbol{x}) = P \exp\left\{ ig \int dx^- A_{cl}^{+,a}(\boldsymbol{x}, x^-) t^a \right\}$$

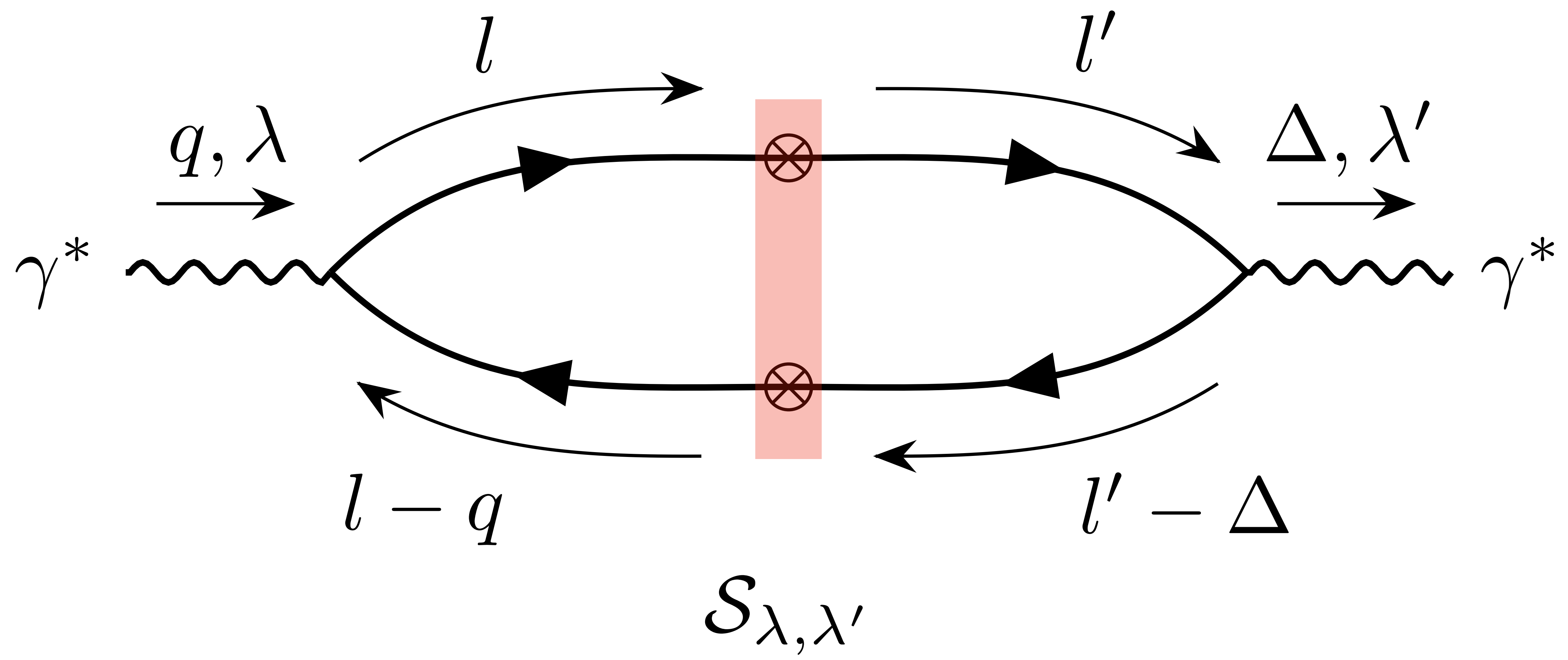
Classical small-x field → $A_{cl}^{+,a} = -\dfrac{\rho^a}{\nabla_\perp^2}$ ← large-x sources




LO diagram in CGC

# Deeply Virtual Compton Scattering*

## At leading order in the CGC EFT $\gamma^*_\lambda + p \rightarrow \gamma^*_{\lambda'} + p$




**Scattering amplitude at LO in the CGC**

$$\mathcal{S}_{\lambda,\lambda'}[\rho_A] =$$
$$(eq_f)^2 \int_{l,l'} \mathrm{Tr}[S^0(l)\not{\epsilon}(\lambda,q)S^0(l-q)\mathcal{T}(l-q,l'-\Delta)$$
$$\times S^0(l'-\Delta)\not{\epsilon}^*(\lambda',\Delta)S^0(l')\mathcal{T}(l',l)]$$

**Kinematics in LC coordinates**

incoming (outgoing) photon momentum and polarization

$$q = \left(-\frac{Q^2}{2q^-}, q^-, \mathbf{0}_\perp\right), \quad \lambda$$
$$\Delta = \left(-\frac{Q'^2}{2\Delta^-}, \Delta^-, \mathbf{\Delta}_\perp\right), \quad \lambda'$$

incoming (outgoing) virtualities

$$Q^2 = -q^2 \quad Q'^2 = -\Delta^2$$

Polarization

$\lambda, \lambda' = 0$ longitudinal pol

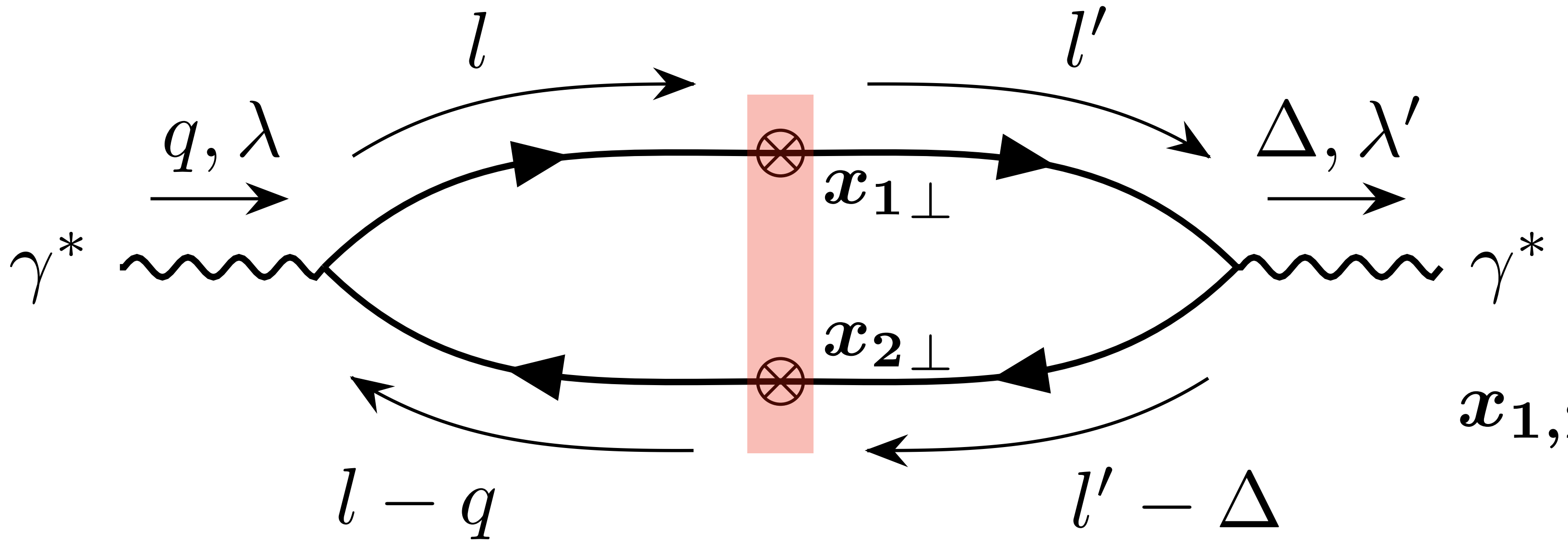
$\lambda, \lambda' = \pm 1$ 2 transverse pol

* We let the virtuality of the outgoing photon to be non-zero (for DVCS let $Q'^2 = 0$), and we consider massive quarks.

# Deeply Virtual Compton Scattering*

## At leading order in the CGC EFT $\quad \gamma^*_\lambda + p \to \gamma^*_{\lambda'} + p$

$$(2\pi)\delta(q^- - \Delta^-)\,\langle \mathcal{M}_{\lambda,\lambda'}\rangle_Y = \langle \mathcal{S}_{\lambda,\lambda'}[0]\rangle_Y - \langle \mathcal{S}_{\lambda,\lambda'}[\rho^a_A]\rangle_Y$$




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

$$\langle \mathcal{M}_{0,0}\rangle_Y \sim \int_{\boldsymbol{b}_\perp} e^{-i\boldsymbol{\Delta}_\perp\cdot\boldsymbol{b}_\perp} \int_{\boldsymbol{r}_\perp} D_Y(\boldsymbol{r}_\perp,\boldsymbol{b}_\perp) \int_z e^{-i\boldsymbol{\delta}_\perp\cdot\boldsymbol{r}_\perp} z^2\bar{z}^2\; QK_0(\varepsilon_f r_\perp)Q'K_0(\varepsilon'_f r_\perp)$$

$$\langle \mathcal{M}_{\pm1,\mp1}\rangle_Y \sim e^{\pm 2i\phi_\Delta} \int_{\boldsymbol{b}_\perp} e^{-i\boldsymbol{\Delta}_\perp\cdot\boldsymbol{b}_\perp} \int_{\boldsymbol{r}_\perp} e^{\pm 2i\phi_{r\Delta}} D_Y(\boldsymbol{r}_\perp,\boldsymbol{b}_\perp) \int_z e^{-i\boldsymbol{\delta}_\perp\cdot\boldsymbol{r}_\perp} z\bar{z}\; \varepsilon_f K_1(\varepsilon_f r_\perp)\varepsilon'_f K_1(\varepsilon'_f r_\perp)$$

Similar expressions for other amplitudes: $\langle \mathcal{M}_{\pm1,\pm1}\rangle_Y$, $\langle \mathcal{M}_{\pm1,0}\rangle_Y$, and $\langle \mathcal{M}_{0,\pm1}\rangle_Y$ .

$$D_Y(\boldsymbol{r}_\perp,\boldsymbol{b}_\perp) = 1 - \frac{1}{N_c}\left\langle \mathrm{Tr}\left[V(\boldsymbol{x}_{1\perp})\,V^\dagger(\boldsymbol{x}_{2\perp})\right]\right\rangle_Y$$

$$\boldsymbol{\delta}_\perp = \left(\frac{z-\bar{z}}{2}\right)\boldsymbol{\Delta}_\perp$$

Our expressions consistent with Hatta, Yuan, Xiao. 1703.02085, when $Q'^2 = 0$ and $m_f = 0$.

# Deeply Virtual Compton Scattering*

## Off forward and dipole angular correlations

$$D_Y(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) = D_{Y,0}(r_\perp, b_\perp) + 2D_{Y,2}(r_\perp, b_\perp)\cos(2\phi_{\boldsymbol{r}_\perp \boldsymbol{b}_\perp}) + \dots$$

Isotropic — Elliptic

In the absence of off-forward phase $e^{-i\boldsymbol{\delta}_\perp \cdot \boldsymbol{r}_\perp}$ we have clear relation between dipole modes and amplitudes

$$\langle \mathcal{M}_{0,0} \rangle_Y \sim \int_{\boldsymbol{b}_\perp} e^{-i\boldsymbol{\Delta}_\perp \cdot \boldsymbol{b}_\perp} \int_{\boldsymbol{r}_\perp} D_Y(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) \int_z z^2 \bar{z}^2 \; Q K_0(\varepsilon_f r_\perp) Q' K_0(\varepsilon'_f r_\perp)$$

Only isotropic $D_{Y,0}$ contributes

Study impact parameter dependence of dipole

$$\langle \mathcal{M}_{\pm 1, \mp 1} \rangle_Y \sim e^{\pm 2i\phi_\Delta} \int_{\boldsymbol{b}_\perp} e^{-i\boldsymbol{\Delta}_\perp \cdot \boldsymbol{b}_\perp} \int_{\boldsymbol{r}_\perp} e^{\pm 2i\phi_{r\Delta}} D_Y(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) \int_z z\bar{z} \; \varepsilon_f K_1(\varepsilon_f r_\perp) \varepsilon'_f K_1(\varepsilon'_f r_\perp)$$

Only elliptic $D_{Y,2}$ contributes

Study angular correlations in dipole amplitude

$$\boxed{\langle \mathcal{M}_{\lambda,\lambda'} \rangle_Y \leftrightarrow D_{Y,|\lambda - \lambda'|}}$$

# Deeply Virtual Compton Scattering*

## Off forward and dipole angular correlations

$$D_Y(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) = D_{Y,0}(r_\perp, b_\perp) + 2D_{Y,2}(r_\perp, b_\perp)\cos(2\phi_{\boldsymbol{r}_\perp \boldsymbol{b}_\perp}) + \ldots$$

Isotropic Elliptic

Including the off-forward phase $e^{-i\boldsymbol{\delta}_\perp \cdot \boldsymbol{r}_\perp}$ mixes the contribution of different modes...

$$\langle \mathcal{M}_{0,0} \rangle_Y \sim \int_{\boldsymbol{b}_\perp} e^{-i\boldsymbol{\Delta}_\perp \cdot \boldsymbol{b}_\perp} \int_{\boldsymbol{r}_\perp} D_Y(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) \int_z e^{-i\boldsymbol{\delta}_\perp \cdot \boldsymbol{r}_\perp} z^2 \bar{z}^2 \; Q K_0(\varepsilon_f r_\perp) Q' K_0(\varepsilon'_f r_\perp)$$

Contributions from all modes, but mostly $D_{Y,0}$ when $\Delta_\perp \ll Q$

$$\langle \mathcal{M}_{\pm 1, \mp 1} \rangle_Y \sim e^{\pm 2i\phi_\Delta} \int_{\boldsymbol{b}_\perp} e^{-i\boldsymbol{\Delta}_\perp \cdot \boldsymbol{b}_\perp} \int_{\boldsymbol{r}_\perp} e^{\pm 2i\phi_{r\Delta}} D_Y(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) \int_z e^{-i\boldsymbol{\delta}_\perp \cdot \boldsymbol{r}_\perp} z\bar{z} \; \varepsilon_f K_1(\varepsilon_f r_\perp) \varepsilon'_f K_1(\varepsilon'_f r_\perp)$$

Contributions from all modes, but mostly $D_{Y,2}$ when $\Delta_\perp \ll Q$

The off-forward phase $e^{-i\boldsymbol{\delta}_\perp \cdot \boldsymbol{r}_\perp} \sim 1$ when $\Delta_\perp \ll Q$

# Deeply Virtual Compton Scattering*

## Off forward and dipole angular correlations

$$D_Y(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) = D_{Y,0}(r_\perp, b_\perp) + 2D_{Y,2}(r_\perp, b_\perp)\cos(2\phi_{\boldsymbol{r}_\perp \boldsymbol{b}_\perp}) + \ldots$$

Isotropic Elliptic

Including the off-forward phase $e^{-i\boldsymbol{\delta}_\perp \cdot \boldsymbol{r}_\perp}$ mixes the contribution of different modes…

$$\langle \mathcal{M}_{\pm 1, \mp 1} \rangle_Y \sim e^{\pm 2i\phi_\Delta} \int_{\boldsymbol{b}_\perp} e^{-i\boldsymbol{\Delta}_\perp \cdot \boldsymbol{b}_\perp} \int_{\boldsymbol{r}_\perp} e^{\pm 2i\phi_{r\Delta}} D_Y(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) \int_z e^{-i\boldsymbol{\delta}_\perp \cdot \boldsymbol{r}_\perp} z\bar{z}\; \varepsilon_f K_1(\varepsilon_f r_\perp) \varepsilon'_f K_1(\varepsilon'_f r_\perp)$$

Two sources of correlation between $\boldsymbol{r}_\perp$ and $\boldsymbol{\Delta}_\perp$ :

Kinematic: off-forward phase $e^{-i\boldsymbol{\delta}_\perp \cdot \boldsymbol{r}_\perp}$ $\quad \boldsymbol{\delta}_\perp = \left(\frac{z-\bar{z}}{2}\right)\boldsymbol{\Delta}_\perp$

Intrinsic: correlation between $\boldsymbol{r}_\perp$ and $\boldsymbol{b}_\perp$ in the dipole (e.g. $D_{Y,2}$)

# Deeply Virtual Compton Scattering*

## Collinear limit and GPDs

Hatta, Yuan, Xiao. 1703.02085

Dipole FT to momentum space:

$$F_Y(\boldsymbol{q}_\perp, \boldsymbol{\Delta}_\perp) = F_Y^0(q_\perp, \Delta_\perp) + 2F_Y^\epsilon(q_\perp, \Delta_\perp)\cos(2\phi_{q\Delta}) + \ldots$$

At small-x, one can compute gluon GPDs:

Unpolarized gluon GPD

$$xH_g(x, \boldsymbol{\Delta}_\perp) = \frac{2N_c}{\alpha_s}\int_{\boldsymbol{q}_\perp} q_\perp^2 F_Y^0(q_\perp, \Delta_\perp)$$

Elliptic gluon GPD

$$xE_{Tg}(x, \boldsymbol{\Delta}_\perp) = \frac{4N_c M^2}{\alpha_s \Delta_\perp^2}\int_{\boldsymbol{q}_\perp} q_\perp^2 F_Y^\epsilon(q_\perp, \Delta_\perp)$$

Possible to constrain the Wigner distribution from GPD

At small-x and in the collinear limit:

Helicity preserving

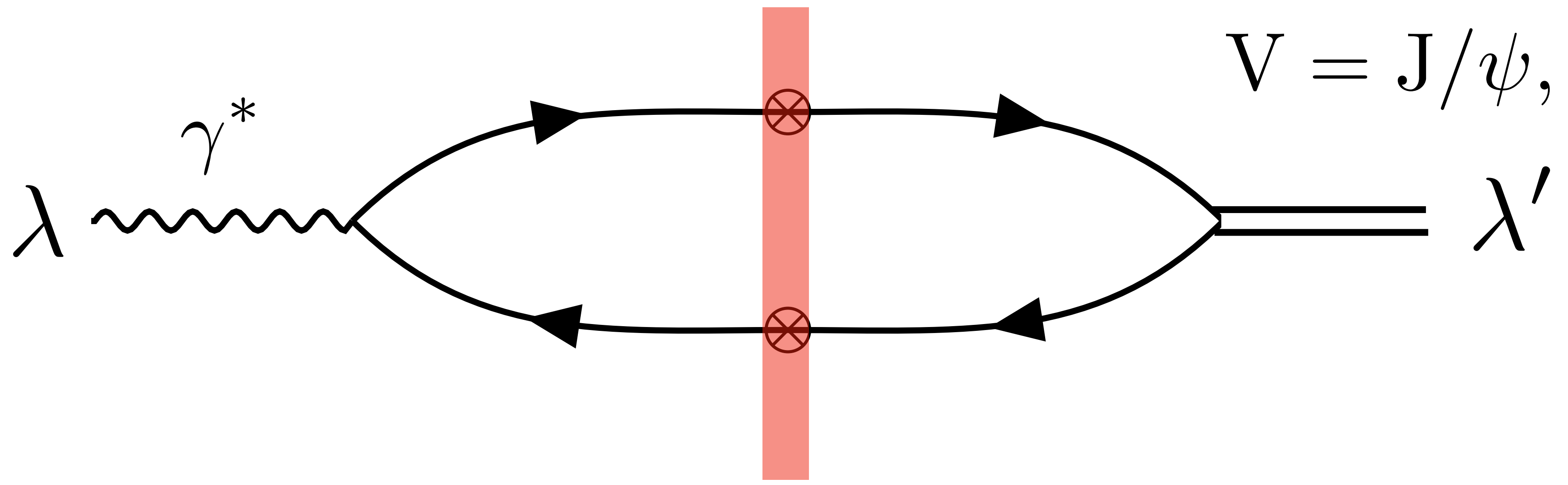
$$\langle \mathcal{M}_{\pm1,\pm1}\rangle_Y \sim xH_g(x, \boldsymbol{\Delta}_\perp)$$

Helicity flip

$$\langle \mathcal{M}_{\pm1,\mp1}\rangle_Y \sim xE_{Tg}(x, \boldsymbol{\Delta}_\perp)$$

# Vector Meson Production

From DVCS* to VM production $\gamma^*_\lambda + p \to \gamma^*_{\lambda'} + p$ ➡ $\gamma^*_\lambda + p \to V_{\lambda'} + p$




$\mathrm{V} = \mathrm{J}/\psi, \rho, \omega, \ldots$

massive quarks $m_f$

can have longitudinal polarization

need model for light-cone wave-function (e.g Boosted Gaussian) $\phi_{L/T}(r_\perp, z)$

We follow the prescription in hep-ph/0606272 and replace the LC wave-function of final state (virtual) photon with:

| longitudinal | transverse | VM LC wave-function |
|---|---|---|
| $\left(\frac{eq_f}{2\pi}\right) z\bar{z}K_0(\varepsilon'_f r_\perp) \to \phi_L(r_\perp, z)$ | $\left(\frac{eq_f}{2\pi}\right) z\bar{z}\varepsilon'_f K_1(\varepsilon'_f r_\perp) \to -\partial_\perp \phi_T(r_\perp, z)$ | $\phi_{L,T} = \mathcal{N}_{L,T} z\bar{z}$ $\times \exp\left[-\frac{m_f^2\mathcal{R}^2}{8z\bar{z}} - \frac{2z\bar{z}r^2}{\mathcal{R}^2} + \frac{m_f^2\mathcal{R}^2}{2}\right]$ |
| $2Q' \to M_V + \delta \frac{m_f^2 - \nabla_\perp^2}{z\bar{z}M_V}$ | $\left(\frac{eq_f}{2\pi}\right) z\bar{z}K_0(\varepsilon'_f r_\perp) \to \phi_T(r_\perp, z)$ | |

Kowalski, Motyka, Watt. hep-ph/0606272

# II. Final state azimuthal correlations with electron plane

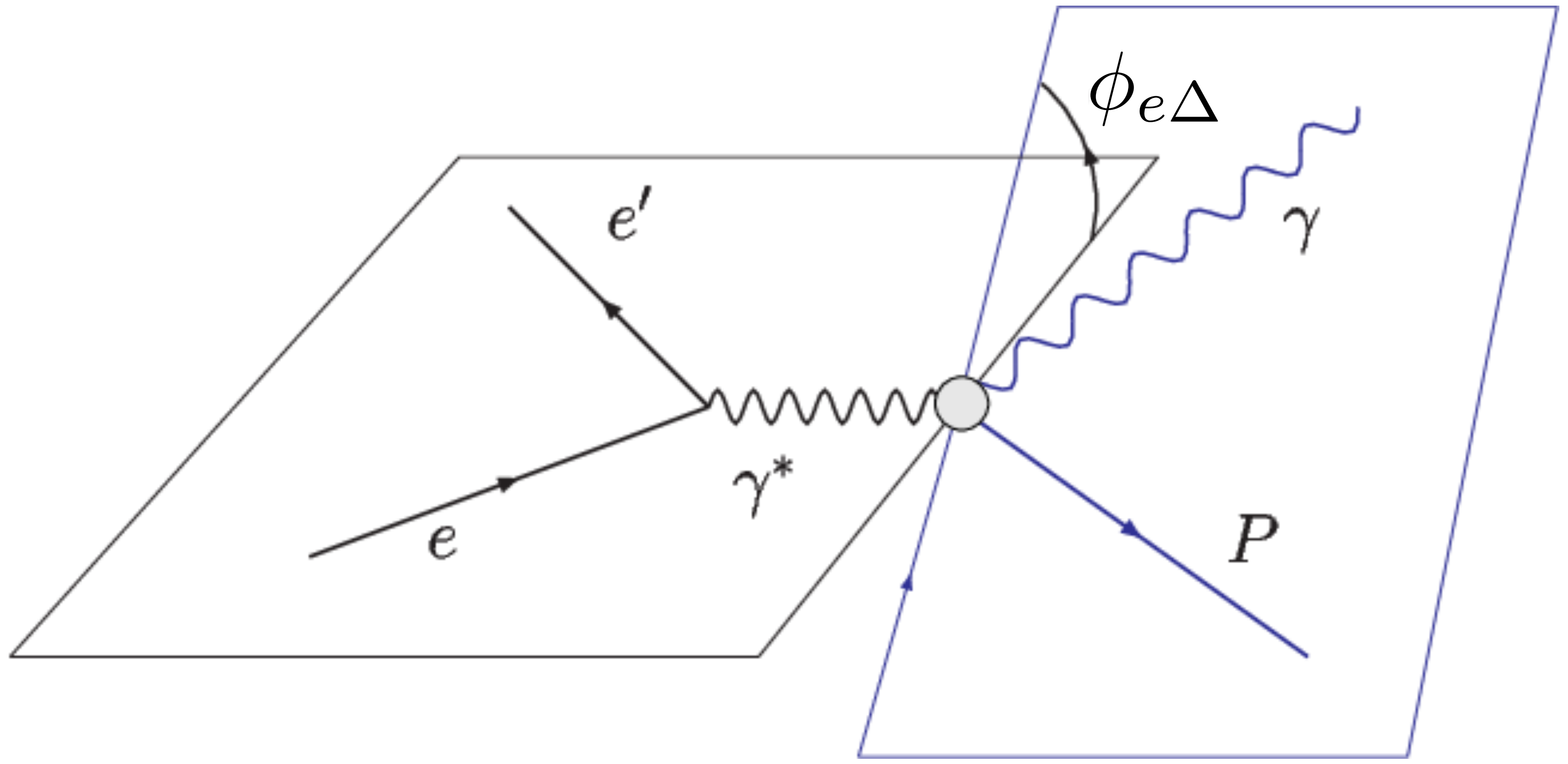



Image source: CLAS collaboration

# Azimuthal correlations with electron

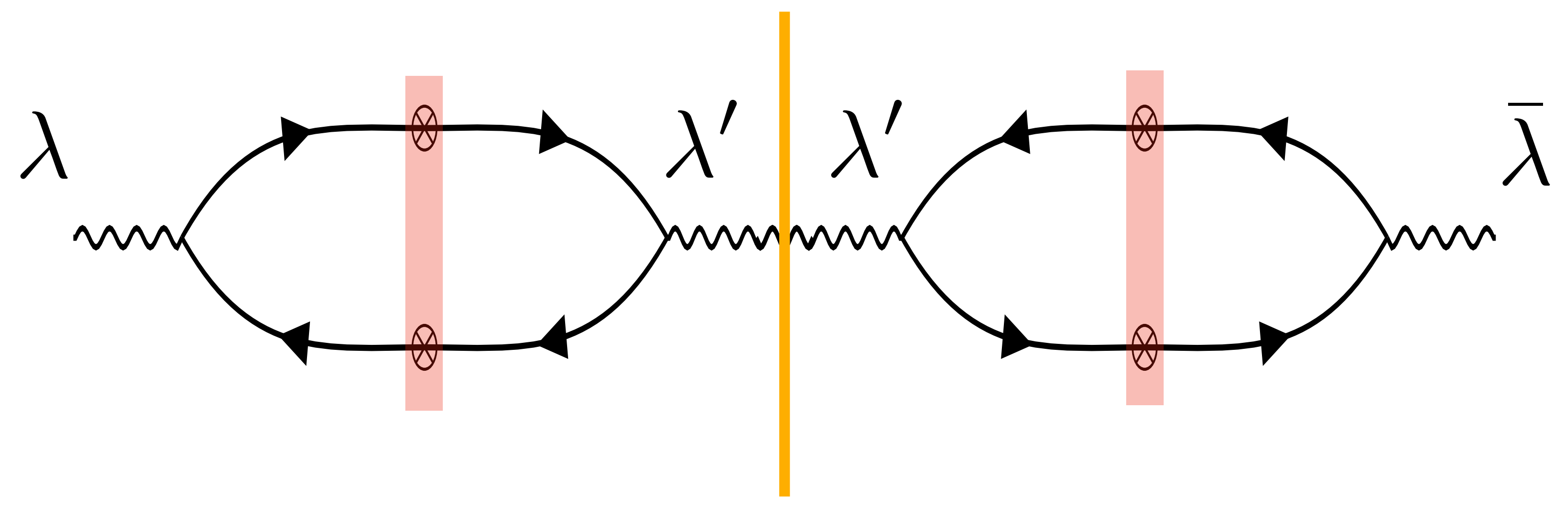
## Polarization basis and electron plane correlation

$$\mathcal{M}^2 \sim L^{\mu\nu} X_{\mu\nu}$$

Lepton-hadron tensor decomposition

Insert completeness relation

$$g_{\mu\nu} = \frac{n_{(\mu} q_{\nu)}}{q^-} + \sum_{\lambda} (-1)^{\lambda} \epsilon^*_{\mu}(\lambda, q) \epsilon_{\nu}(\lambda, q)$$




$$\mathcal{M}^2 \sim L^{\lambda\bar{\lambda}} X_{\lambda\bar{\lambda}}$$

Lepton-hadron tensor decomposition in polarization basis

$$L_{\lambda\bar{\lambda}} \equiv L^{\mu\nu} \epsilon_{\mu}(\lambda, q) \epsilon^*_{\nu}(\bar{\lambda}, q)$$

$$L_{\lambda\bar{\lambda}} \sim e^{i(\lambda - \bar{\lambda})\phi_e} f_{\lambda\bar{\lambda}}$$

electron azimuthal angle

photon flux factors

$$X_{\lambda\bar{\lambda}} \equiv X^{\alpha\beta} \epsilon^*_{\alpha}(\lambda, q) \epsilon_{\beta}(\bar{\lambda}, q)$$

$$X_{\lambda\bar{\lambda}} \sim e^{-i(\lambda - \bar{\lambda})\phi_{\Delta}} \sum_{\lambda'} \mathcal{M}^{\dagger}_{\lambda,\lambda'} \mathcal{M}_{\bar{\lambda},\lambda'}$$

photon azimuthal angle

Photon-proton amplitude squared

# Azimuthal correlations with electron

## DVCS azimuthal correlations with electron plane

Hatta, Yuan, Xiao. 1703.02085

$$d\sigma^{ep\to e\gamma p} \sim f_{TT}(y)\left[\mathcal{M}_{TT}^2 + \mathcal{M}_{TT,\text{flip}}^2\right] + f_{TT,\text{flip}}(y)\mathcal{M}_{LT}^2$$
$$-f_{LT}(y)\mathcal{M}_{LT}\left[\mathcal{M}_{TT} + \mathcal{M}_{TT,\text{flip}}\right]\cos(\phi_{e\Delta})$$
$$+f_{TT,\text{flip}}(y)\mathcal{M}_{TT}\mathcal{M}_{TT,\text{flip}}\cos(2\phi_{e\Delta})$$

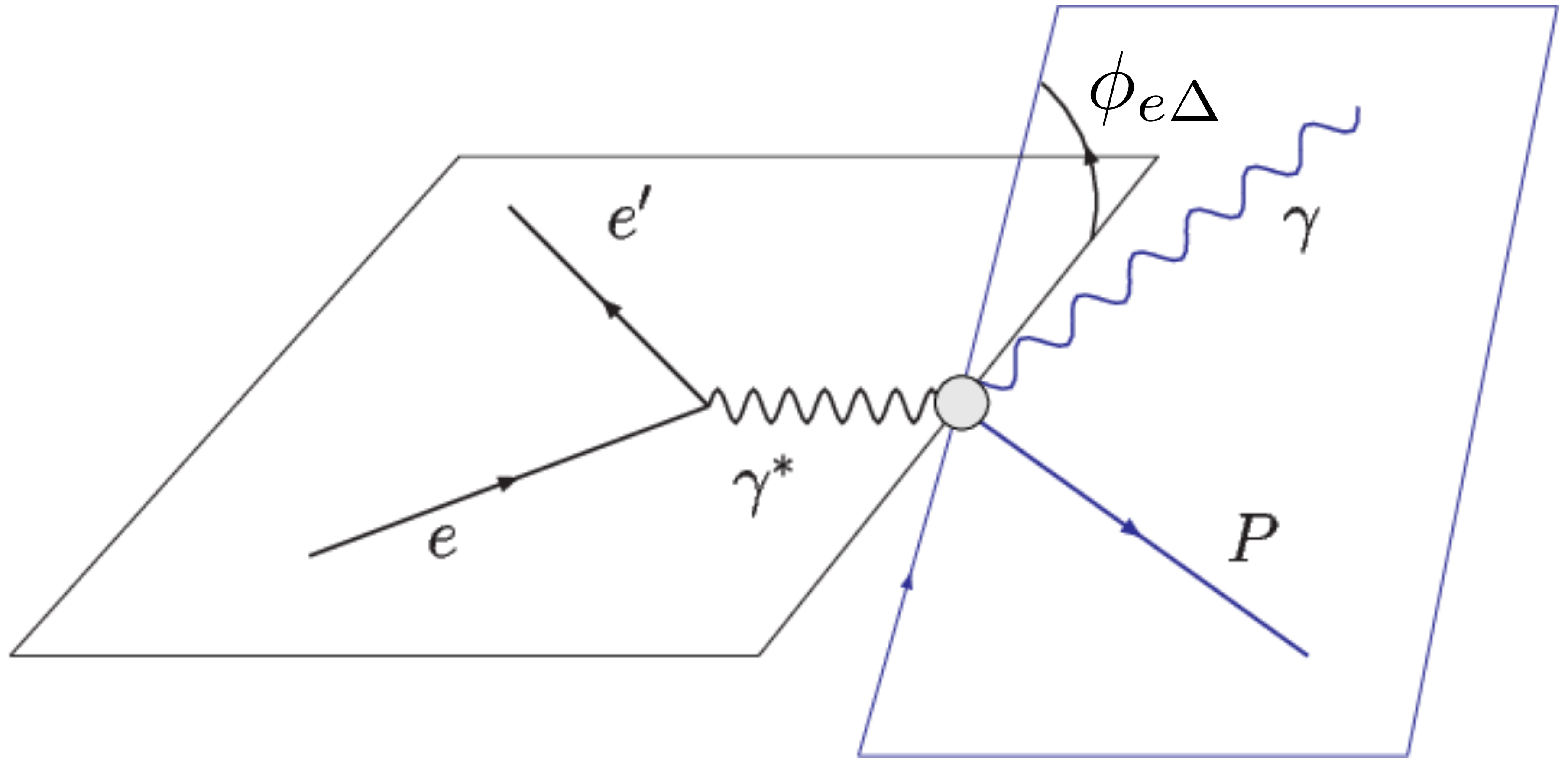



Image source: CLAS collaboration

| | |
|---|---|
| $\mathcal{M}_{TT} \equiv \langle \mathcal{M}_{\pm1,\pm1}\rangle_Y$ | Helicity preserving |
| $\mathcal{M}_{LT} \equiv \langle \mathcal{M}_{0,\pm1}\rangle_Y$ | Pol changing |
| $\mathcal{M}_{TT,\text{flip}} \equiv \langle \mathcal{M}_{\pm1,\mp1}\rangle_Y$ | Helicity flip |

At small/moderate ( $\Delta_\perp \lesssim 1.5\ \text{GeV}$ ): $\mathcal{M}_{LT}^2, \mathcal{M}_{TT,\text{flip}}^2 \ll \mathcal{M}_{TT}^2$

$$\langle\cos\phi_{e\Delta}\rangle_\phi \sim \mathcal{M}_{LT}/\mathcal{M}_{TT}$$
$$\langle\cos 2\phi_{e\Delta}\rangle_\phi \sim \mathcal{M}_{TT,\text{flip}}/\mathcal{M}_{TT}$$

Similar result for $J/\psi$ production
(also includes $\mathcal{M}_{LL}$ and $\mathcal{M}_{TL}$)

H. Mäntysaari, K. Roy, FS, B. Schenke. 2011.02464

# Numerical results

## DVCS from GBW type dipole

$$D_Y(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) = 1 - \exp\left[-\frac{r_\perp^2 Q_{s0}^2}{4} T_p(b_\perp) C_\phi(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)\right]$$

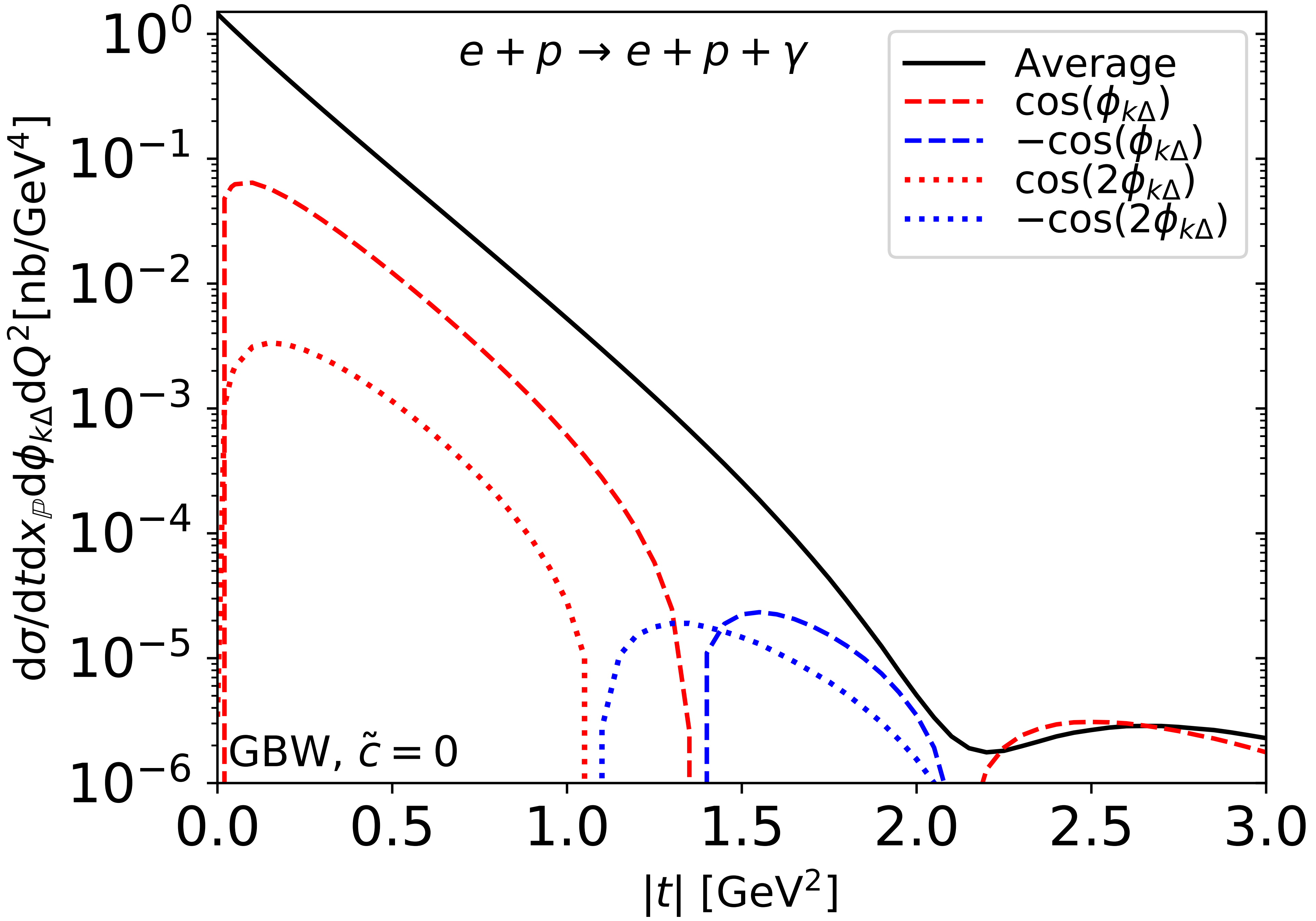
Proton transverse profile

$$T_p(b_\perp) = e^{-b_\perp^2/(2B_p)}$$

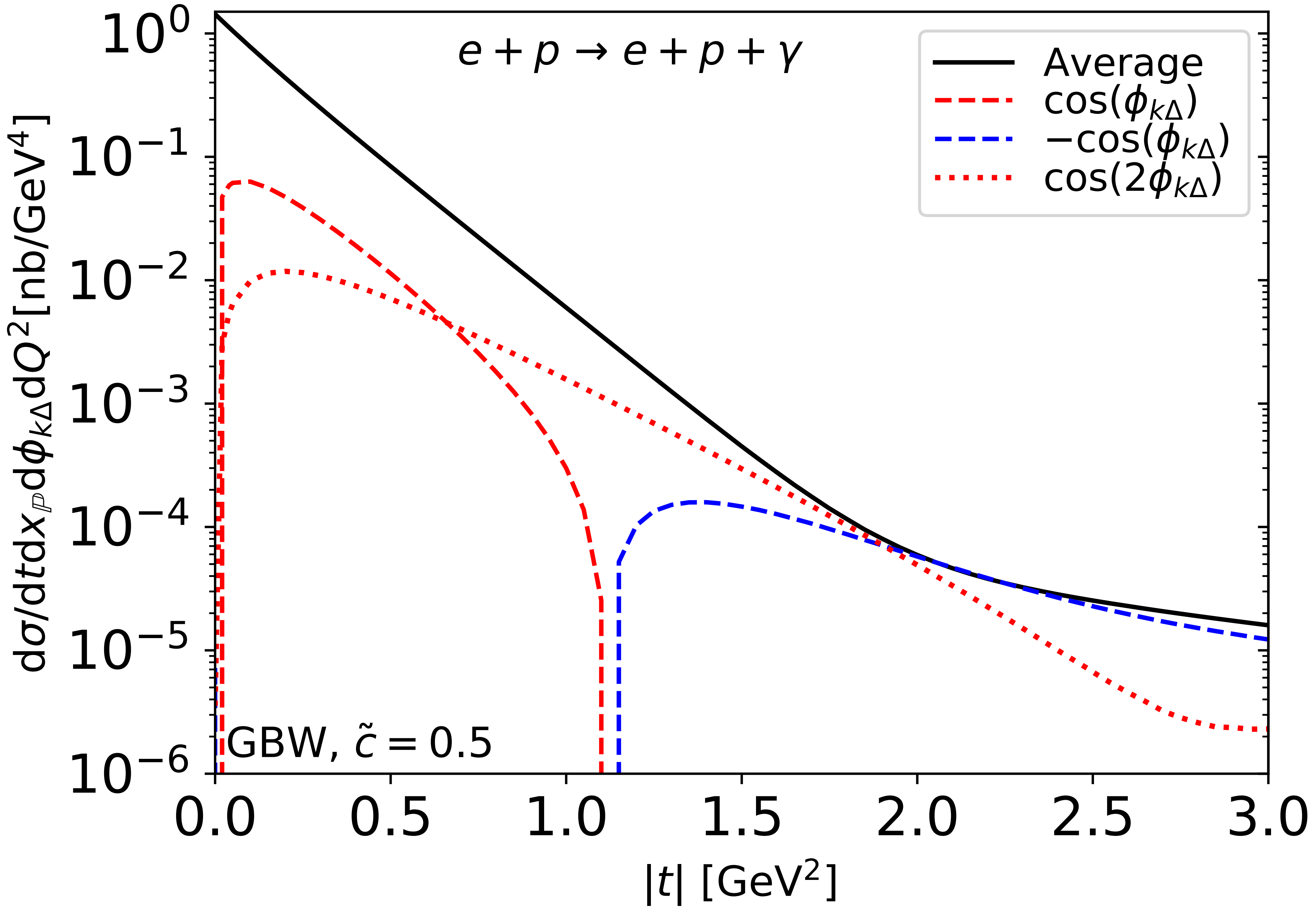
Azimuthal correlations

$$C_\phi(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) = 1 + \frac{\tilde{c}}{2}\cos(2\phi_{rb})$$

$\tilde{c} = 0$




$\tilde{c} = 0.5$




Note the increase in the elliptic anisotropy due to dipole angular correlations $\tilde{c} \neq 0$!

# Numerical results

## Exclusive $J/\psi$ from GBW type dipole

$$D_Y(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) = 1 - \exp\left[-\frac{r_\perp^2 Q_{s0}^2}{4} T_p(b_\perp) C_\phi(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)\right]$$

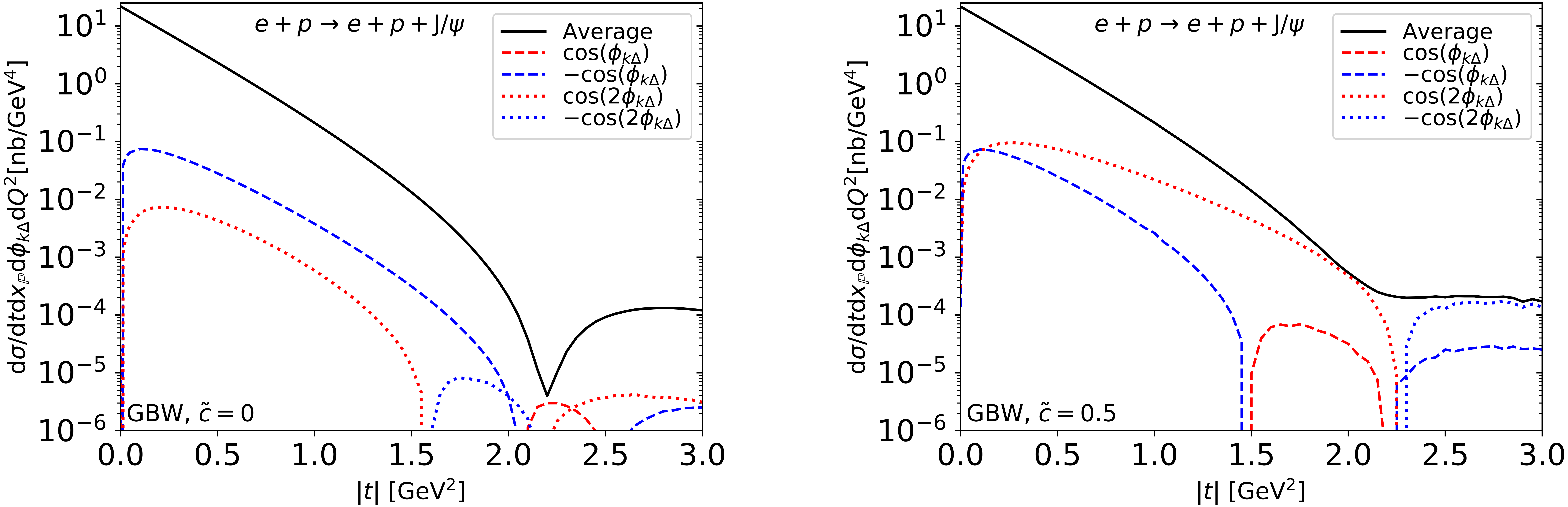
Proton transverse profile

$$T_p(b_\perp) = e^{-b_\perp^2/(2B_p)}$$

Azimuthal correlations

$$C_\phi(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) = 1 + \frac{\tilde{c}}{2}\cos(2\phi_{rb})$$

$\tilde{c} = 0$ $\tilde{c} = 0.5$




Note the increase in the elliptic anisotropy due to dipole angular correlations $\tilde{c} \neq 0$!

# III. Our predictions for the EIC

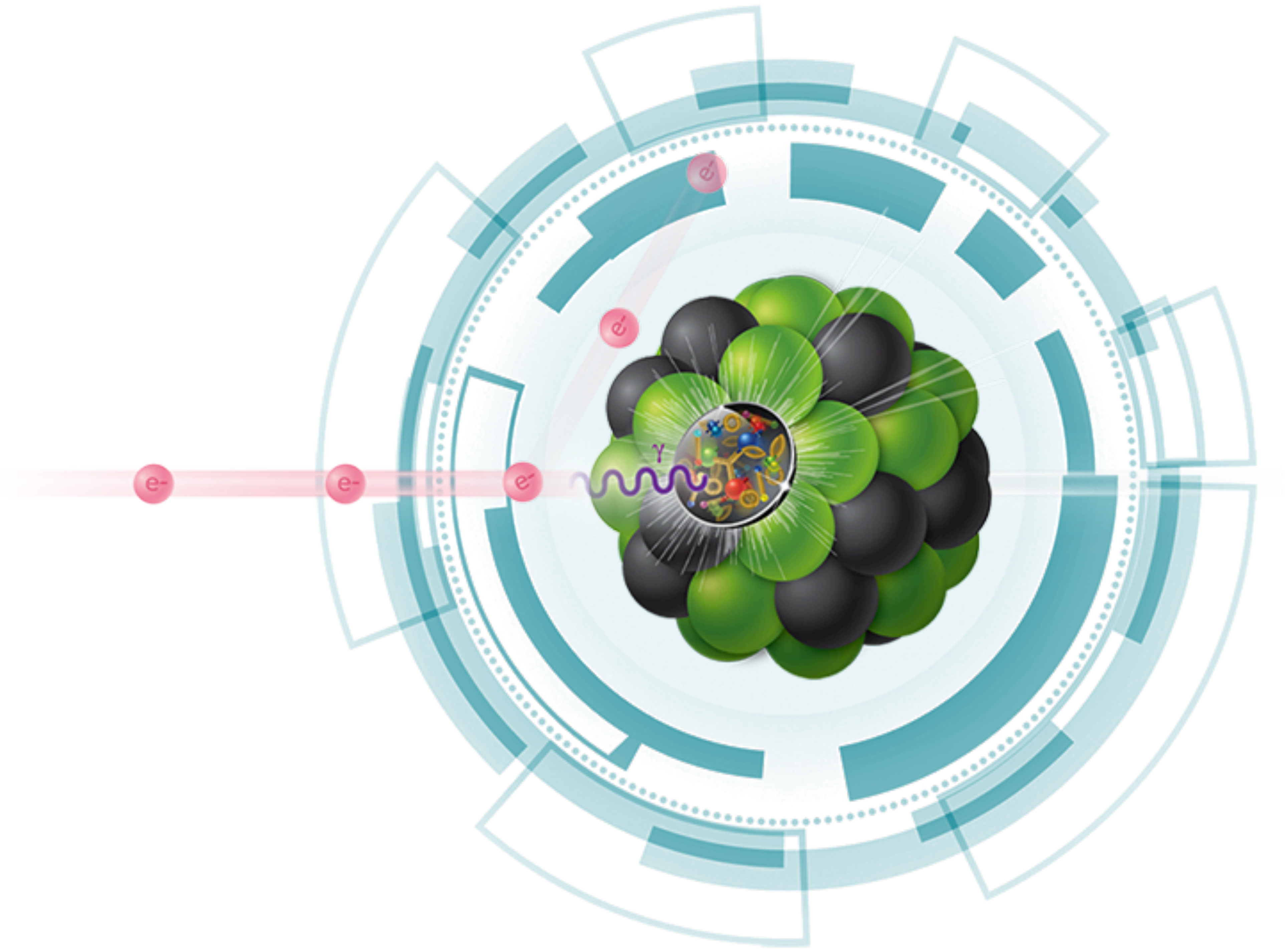



Image source: BNL

# The set-up for our calculation

## Initial conditions and evolution

Similar set-up in exclusive dijet production and Wigner distribution in 1902.05087

- EIC energies: e-p collisions at $\sqrt{s} = 140\ \mathrm{GeV}$ and e-Au collisions at $\sqrt{s} = 90\ \mathrm{GeV}$

- Initial conditions: impact parameter dependent McLerran-Venugopalan model

$$\left\langle \rho^a_A(\boldsymbol{x}_\perp)\rho^b_A(\boldsymbol{y}_\perp)\right\rangle_{Y=0} = g^2\mu^2(\boldsymbol{x}_\perp)\delta^{ab}\delta^{(2)}(\boldsymbol{x}_\perp - \boldsymbol{y}_\perp)$$ color charge 2-point function

$$g^2\mu(\boldsymbol{x}_\perp) \sim Q_s(\boldsymbol{x}_\perp)$$

$Q_s(\boldsymbol{x}_\perp)$ obtained from IP-Sat fitted from HERA data structure functions + $J/\psi$

For nucleus, sample nucleons from Woods-Saxon distribution.

Wilson line obtained from $\rho^a$ $\longrightarrow$ $$V(\boldsymbol{x}_\perp) = \mathrm{P}_-\left\{\exp\left(-ig\int_{-\infty}^{\infty}\mathrm{d}z^-\frac{\rho^a(z^-,\boldsymbol{x}_\perp)t^a}{\boldsymbol{\nabla}^2 - \tilde{m}^2}\right)\right\}$$

For MV see: McLerran, Venugopalan. hep-ph/9309289
For IP-Sat see: Teaney, Kowalski. hep-ph/0304189

# The set-up for our calculation

## Initial conditions and evolution

Similar set-up in exclusive dijet production and Wigner distribution in 1902.05087

- EIC energies: e-p collisions at $\sqrt{s} = 140\ \mathrm{GeV}$ and e-Au collisions at $\sqrt{s} = 90\ \mathrm{GeV}$

- Small-x leading log JIMWLK evolution with IR regulator. Evolution up to $Y = \log(0.01/x_{\mathbb{P}})$

  Langevin form of JIMWLK evolving independent Wilson Lines $V(\boldsymbol{x}_\perp)$

  Construct dipole amplitude from Wilson lines averaging over multiple ensembles $\langle ... \rangle_Y$

$$x_{\mathbb{P}} = \frac{Q^2 + M_V^2 - t}{W^2 + Q^2 - m_N^2}$$

$$\left\langle \mathrm{tr}\left[V(\boldsymbol{x}_\perp)V^\dagger(\boldsymbol{y}_\perp)\right]\right\rangle_Y$$

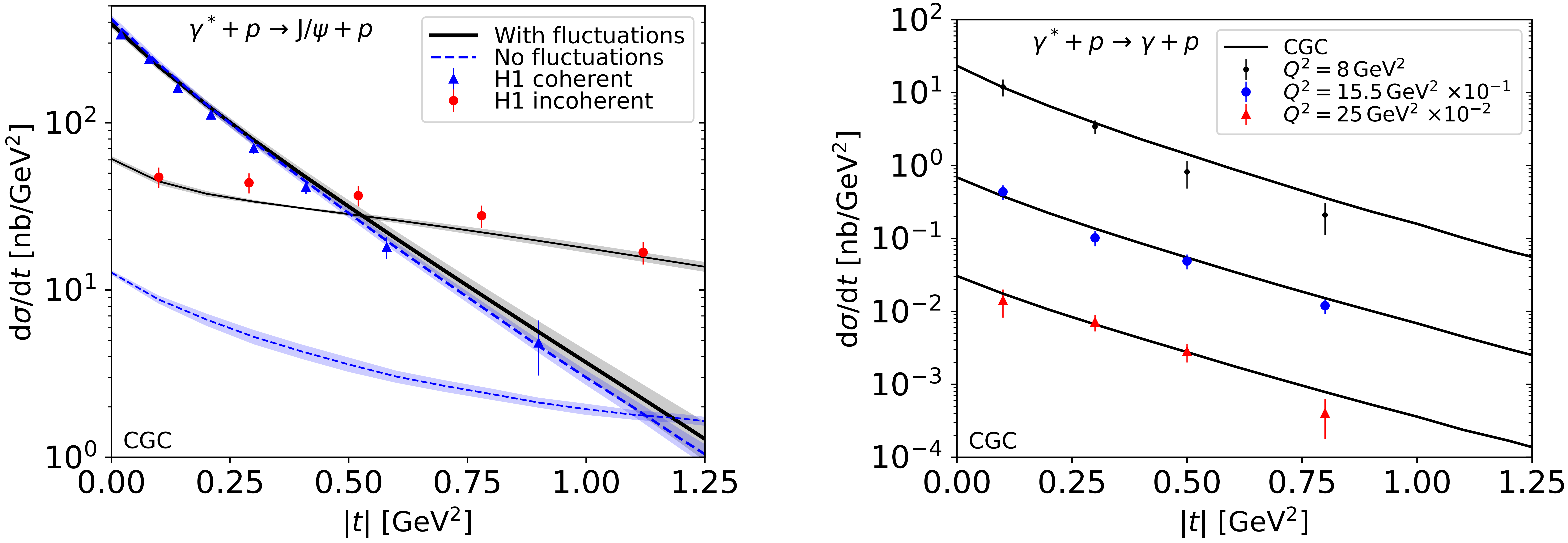
For JIMWLK see

Jalilian-Marian, Kovner, Leonidov, Weigert. hep-ph/9706377
Iancu, Leonidov, McLerran. hep-ph/0102009

# The set-up for our calculation

## HERA data on $J/\psi$ and DVCS

Free parameters constrained by HERA data on exclusive $J/\psi$ at $W = 75\ \mathrm{GeV}$

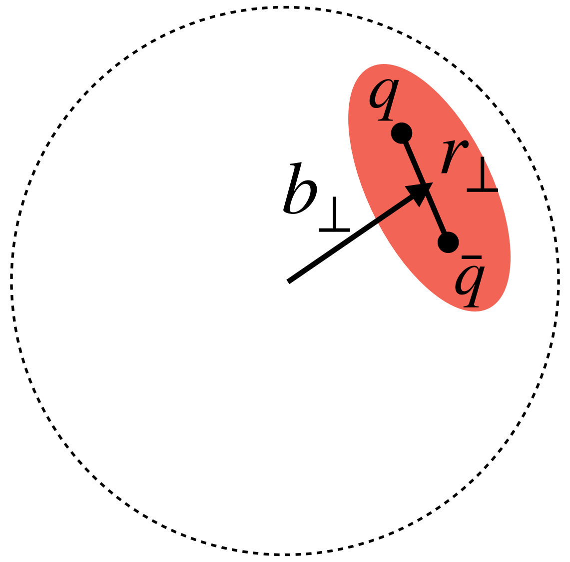



$\gamma^* + p \to \gamma(J/\psi) + p$ photon-proton level (no electron plane correlations)

# The set-up for our calculation

## Azimuthal angle correlations in the dipole from CGC

dipole orientation dependence from gradients of strength of color charge

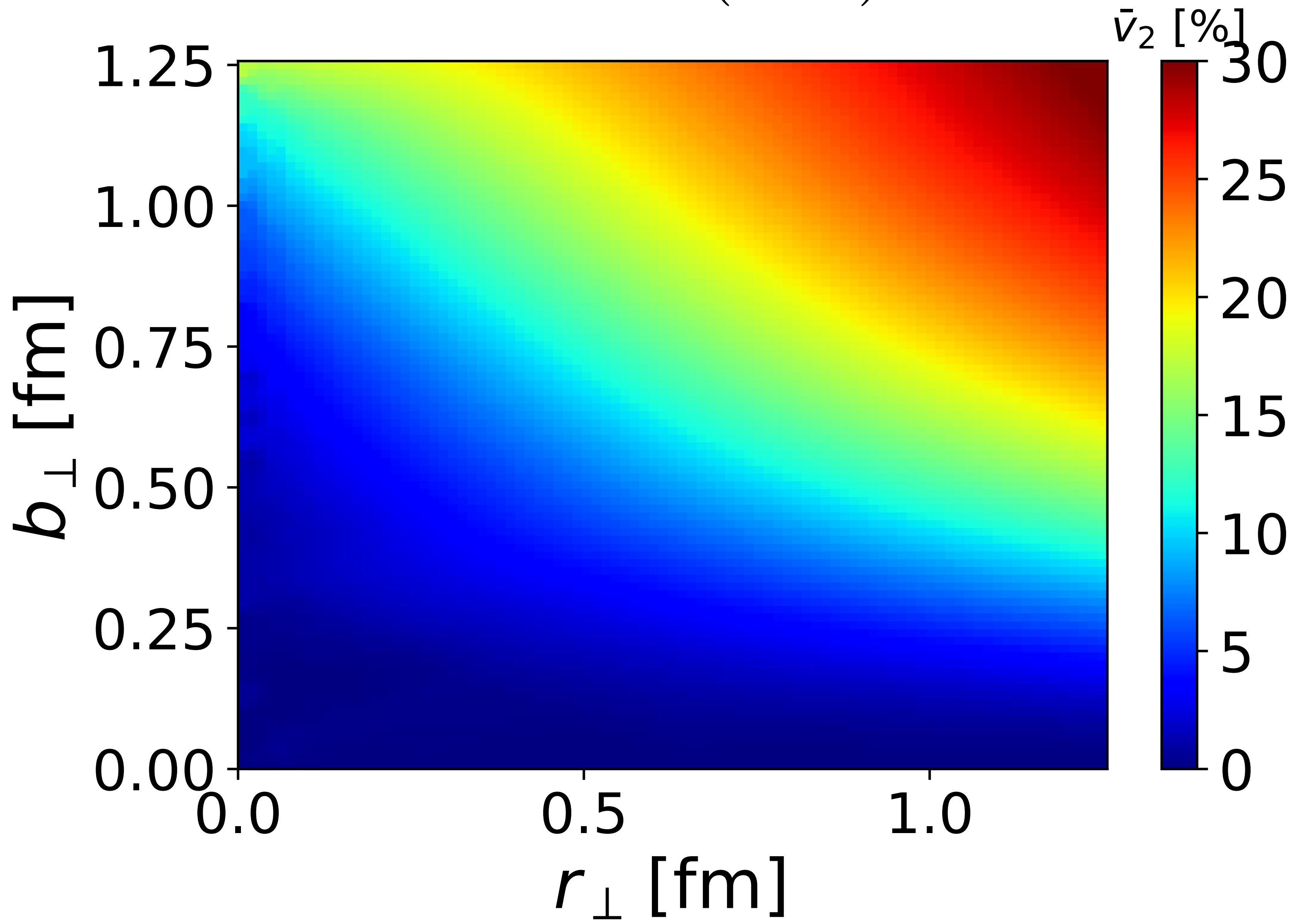



$$D_Y(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) = D_{Y,0}(r_\perp, b_\perp) + 2D_{Y,2}(r_\perp, b_\perp)\cos(2\phi_{rb}) + \ldots$$

Generates dipole angular anisotropies $D_{Y,2}$ , $D_{Y,4}$ , ...

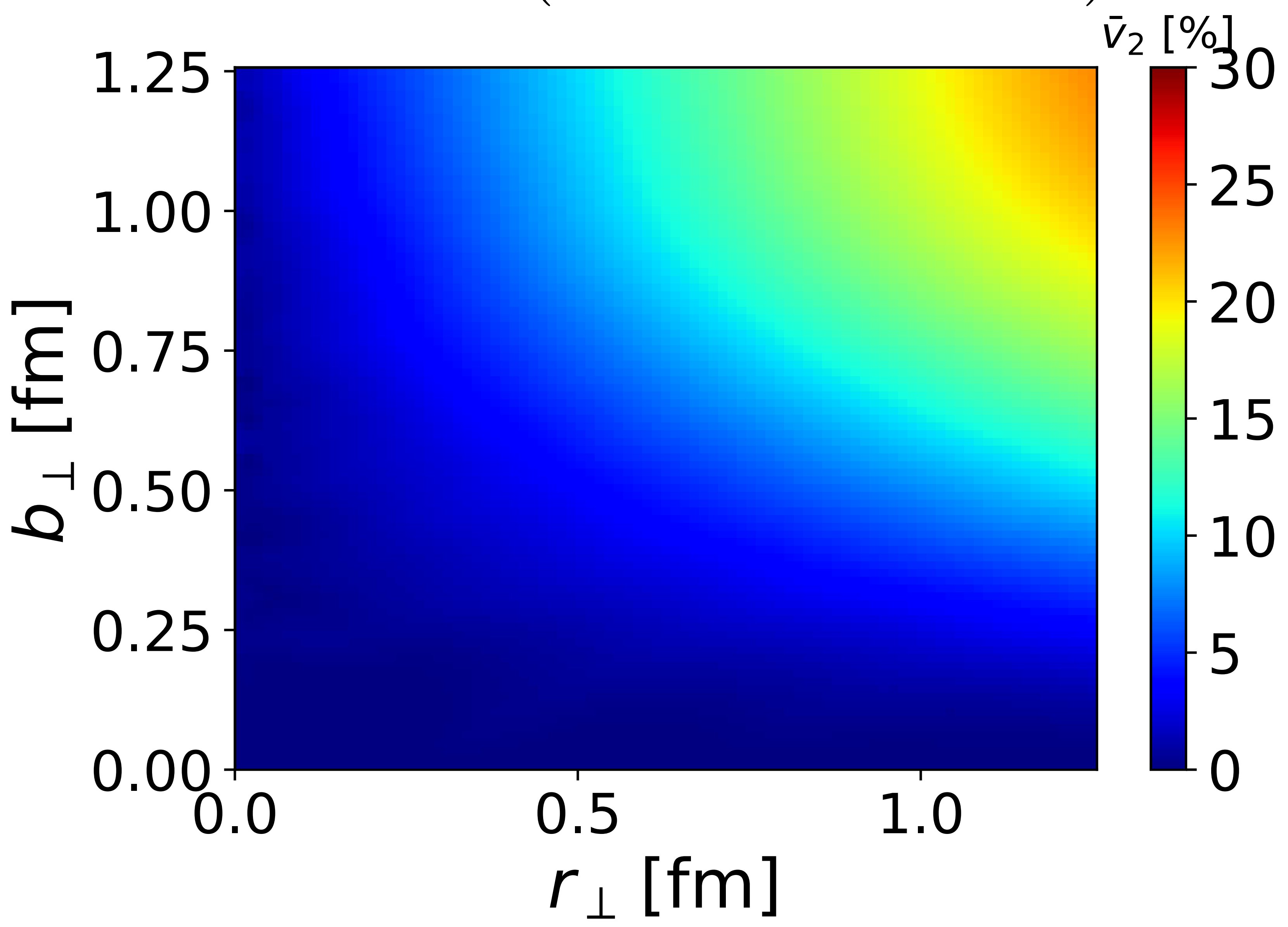
No need to put correlations “by hand”

$Y = 0$ (MV)




JIMWLK evolution

$Y = 2.3$ (MV + JIMWLK)

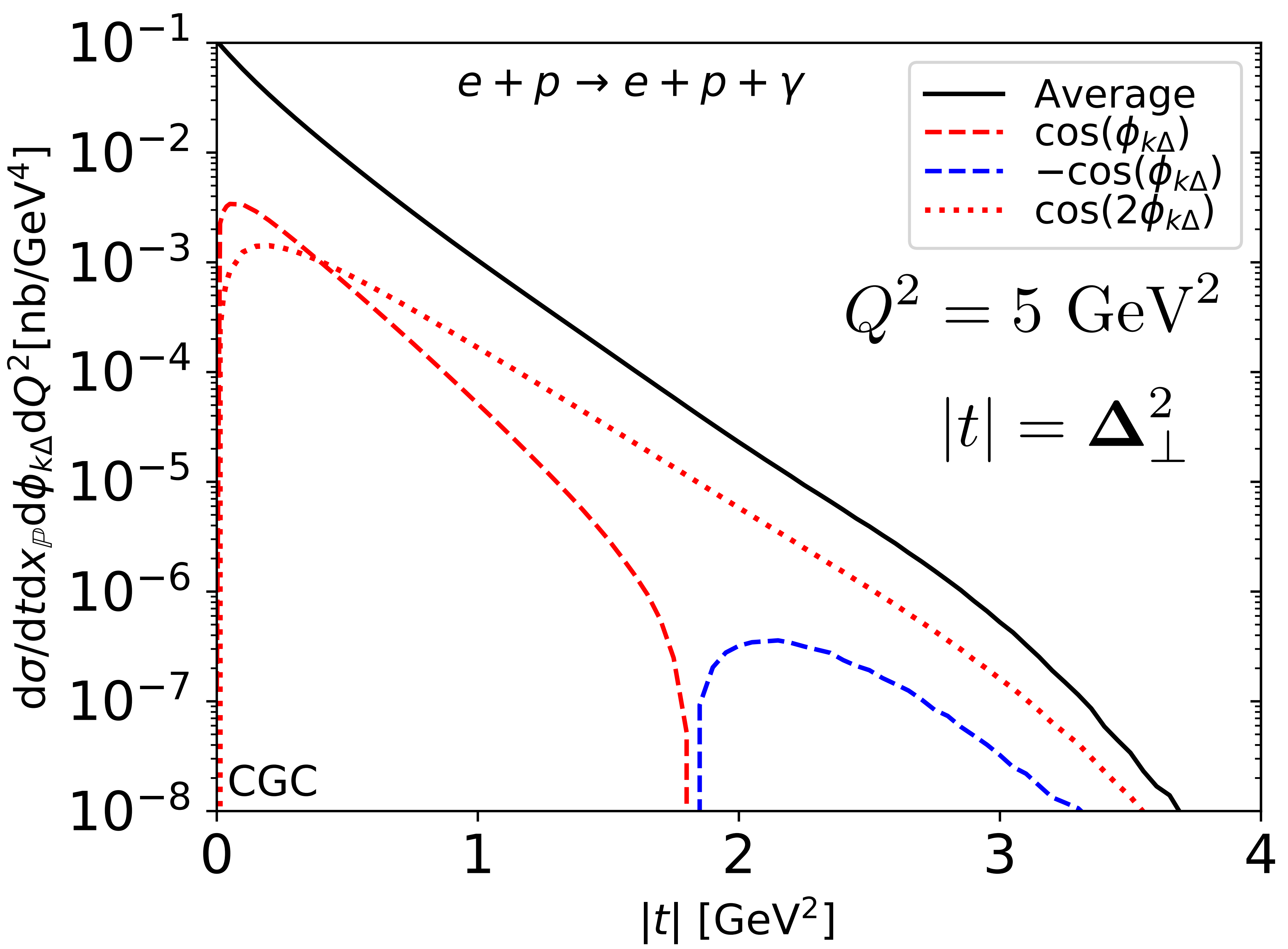



$$\tilde{v}_2 = D_{Y,2}(r_\perp, b_\perp)/D_{Y,0}(r_\perp, b_\perp)$$

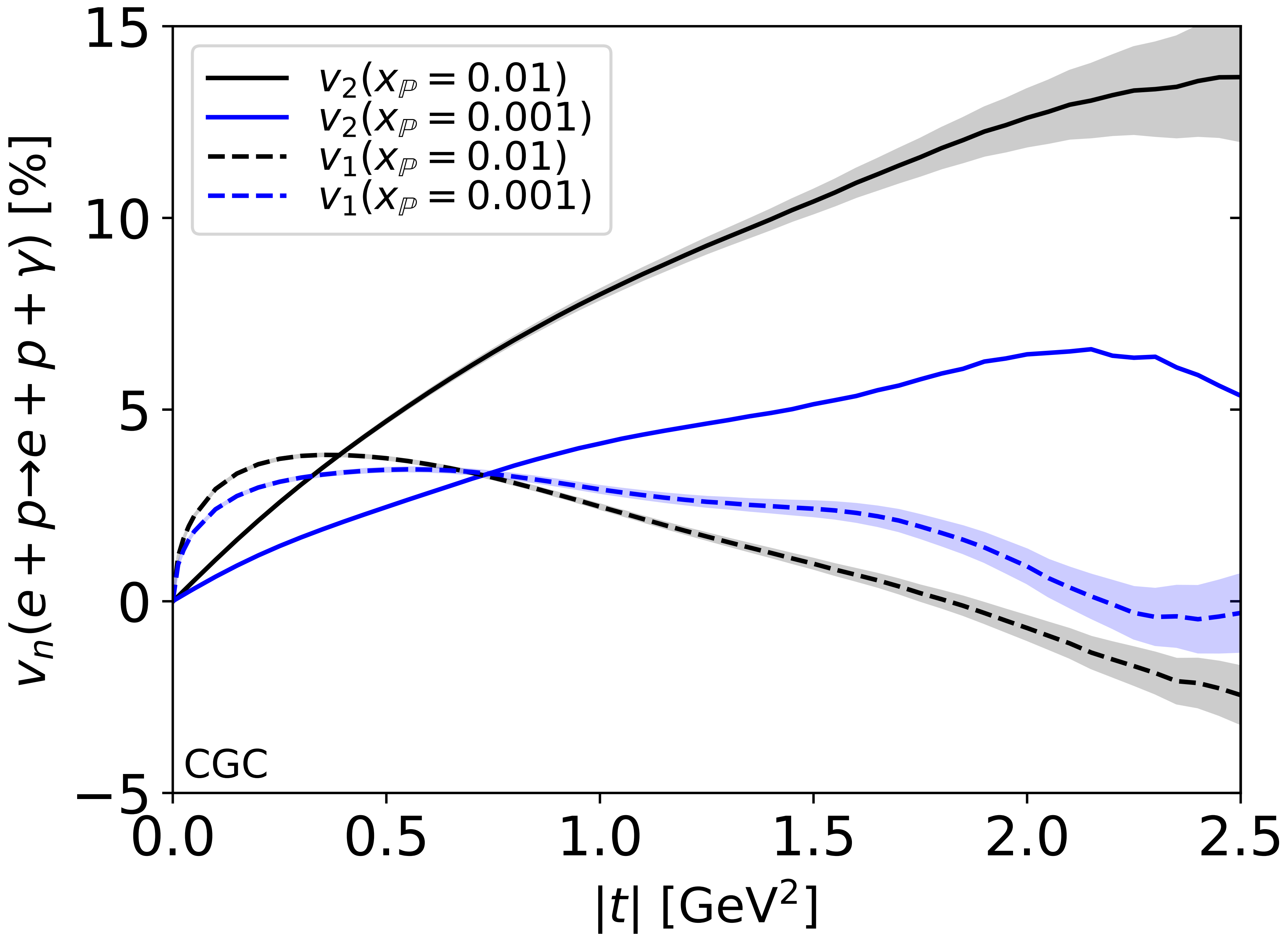
# Predictions for e-p at the EIC

# Predictions for e-p at the future EIC

## DVCS: Spectra and azimuthal modulations




Significant contribution from large dipoles even at large $Q^2$ due to $z \to 0{,}1$

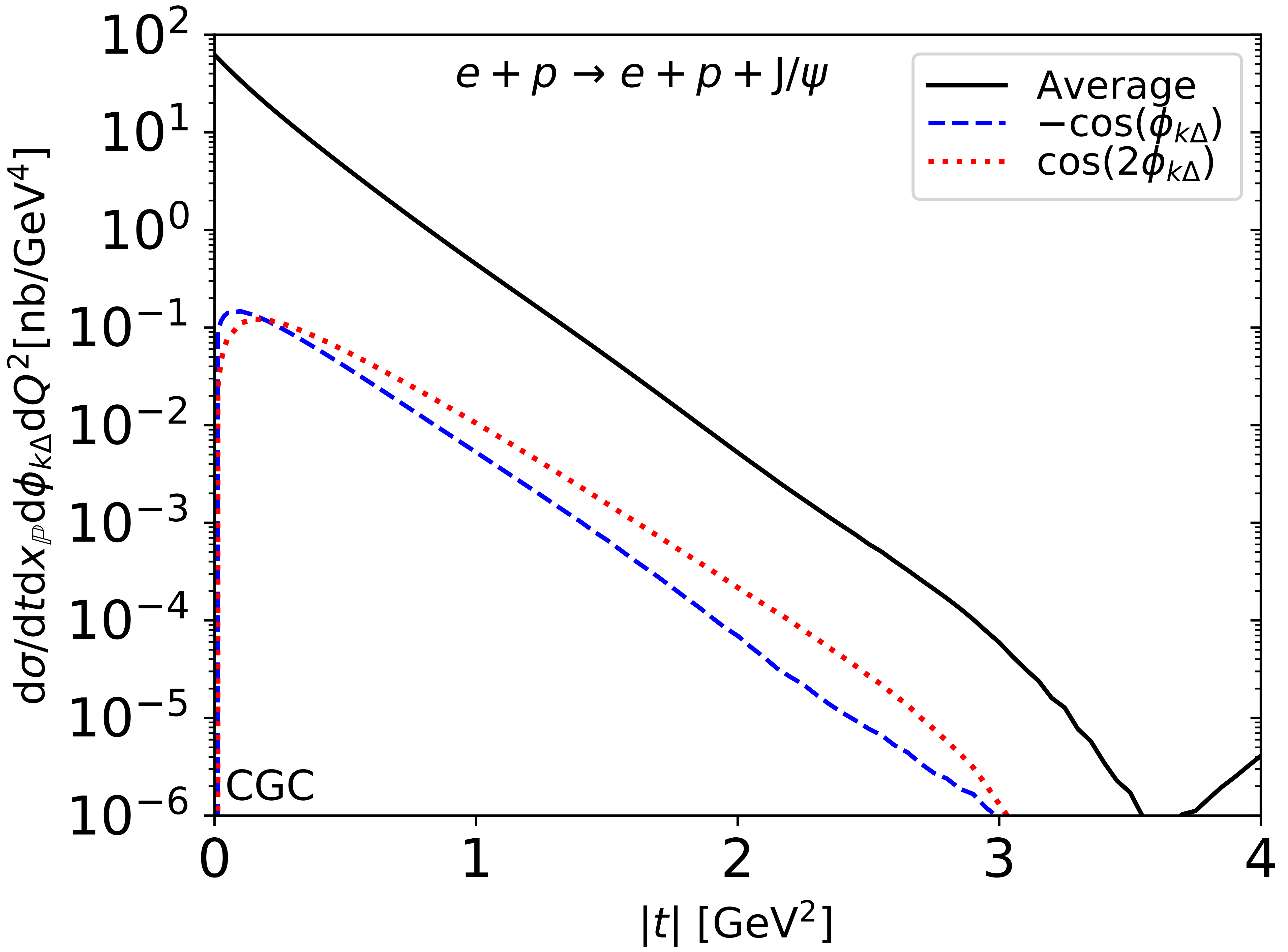


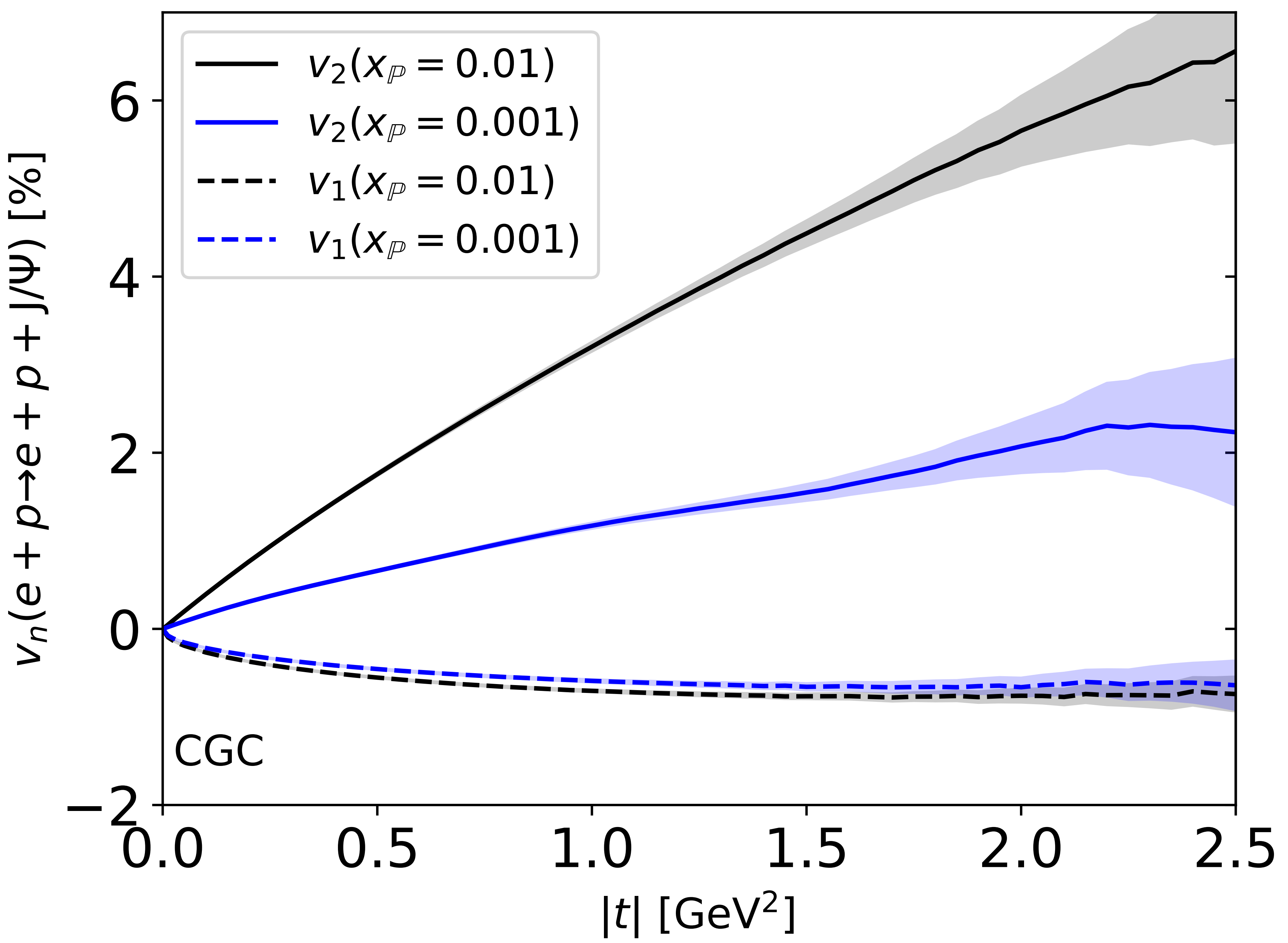

Predict dependence of $v_n$ on |t| and $x_{\mathbb{P}}$

Evolution decreases anisotropies

# Predictions for e-p at the future EIC

## Exclusive $J/\psi$ : Spectra and azimuthal modulations



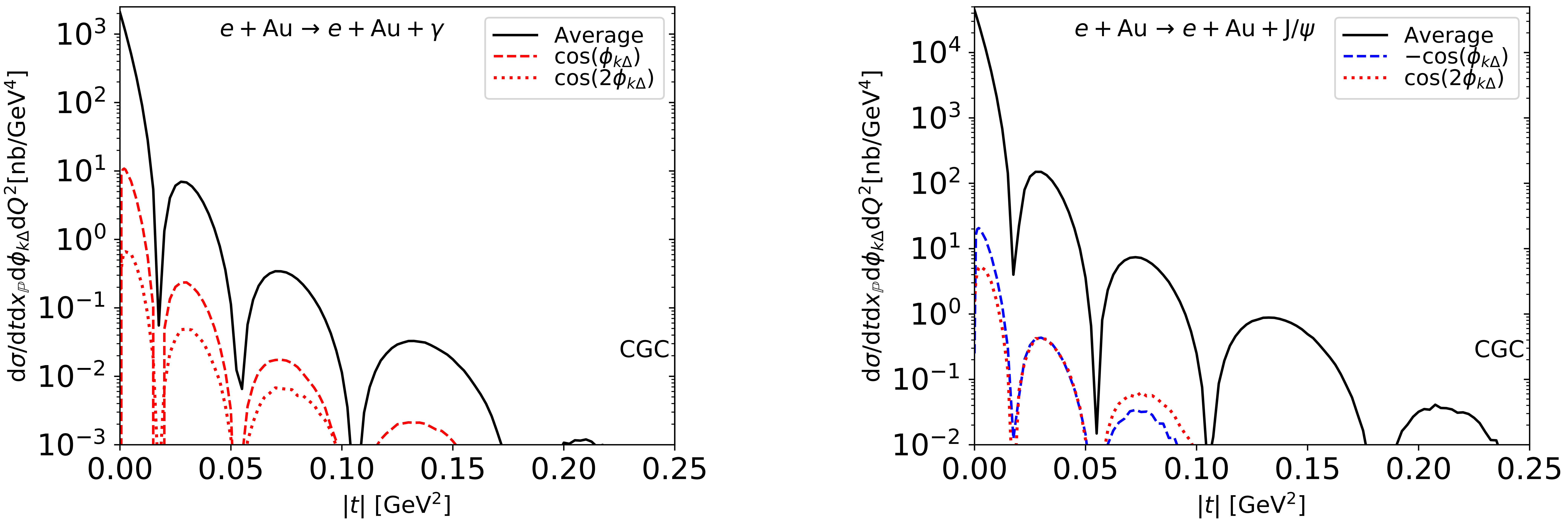

Smaller contribution from large dipole sizes due to charm mass

Anisotropies in $J/\psi$ smaller than DVCS but sizable $v_2$

# Predictions for e-Au at the EIC

# Predictions for e-Au at the future EIC

## DVCS and exclusive $J/\psi$ : Spectra and azimuthal modulations

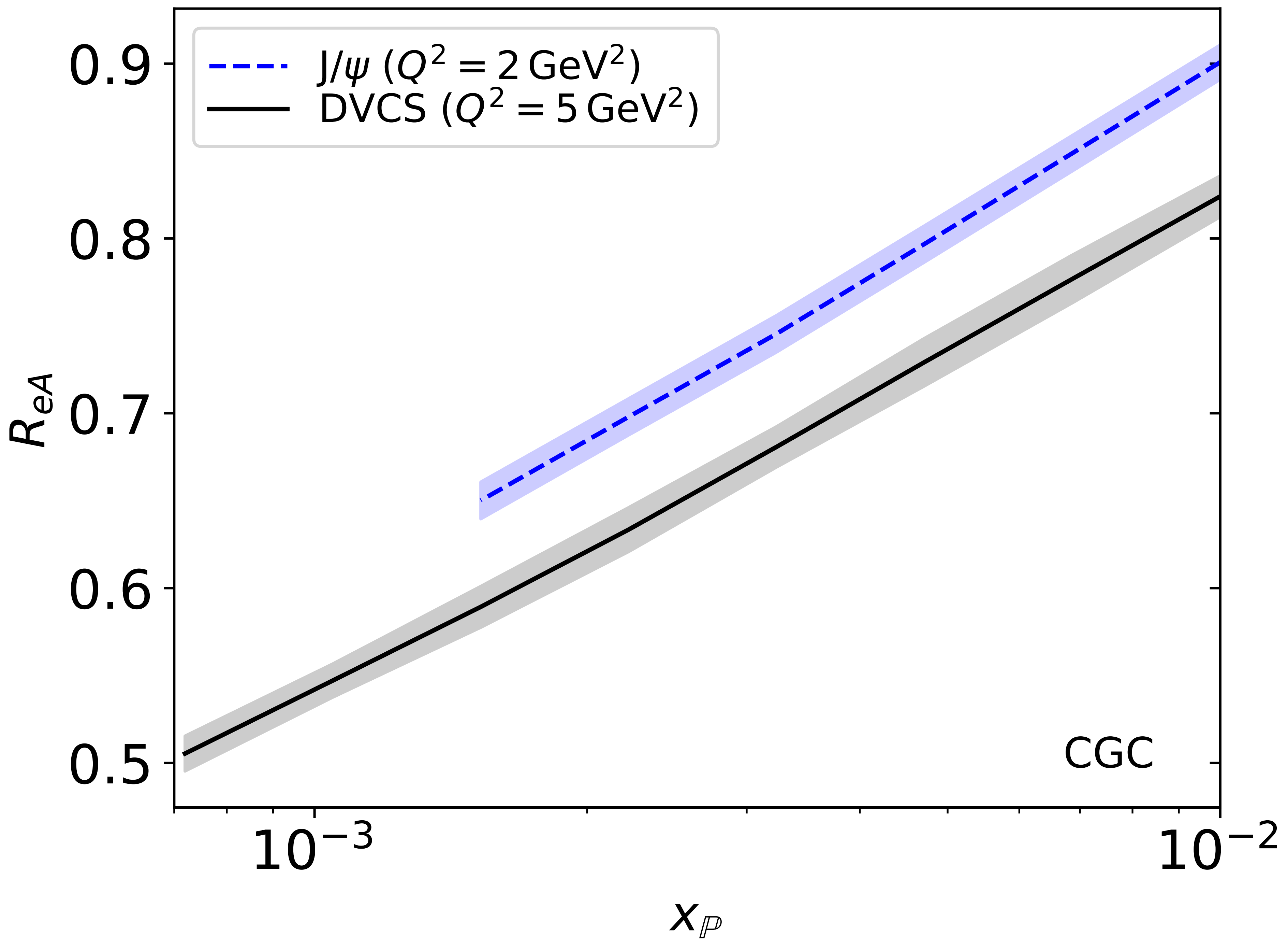



Characteristic dips in spectra due to Woods-Saxon nuclear profile

Azimuthal modulations $v_n$ a few percent for DVCS, and less than 1% for $J/\psi$

# Predictions for e-Au at the future EIC

## Nuclear suppressions factor for DVCS and exclusive $J/\psi$




$$R_{eA} = \left. \frac{\mathrm{d}\sigma^{e+A\to e+A+V}/\mathrm{d}t\mathrm{d}Q^2\mathrm{d}x_{\mathbb{P}}}{A^2\mathrm{d}\sigma^{e+p\to e+p+V}/\mathrm{d}t\mathrm{d}Q^2\mathrm{d}x_{\mathbb{P}}} \right|_{t=0}$$

Expect $R_{eA} = 1$ in the dilute limit.

Mäntysaari, Venugopalan. 1712.02508

Significant suppression that evolves with energy/ $x_{\mathbb{P}}$

Larger suppression for DVCS due to larger dipole contributions.

# IV. Incoherent diffraction and fluctuations

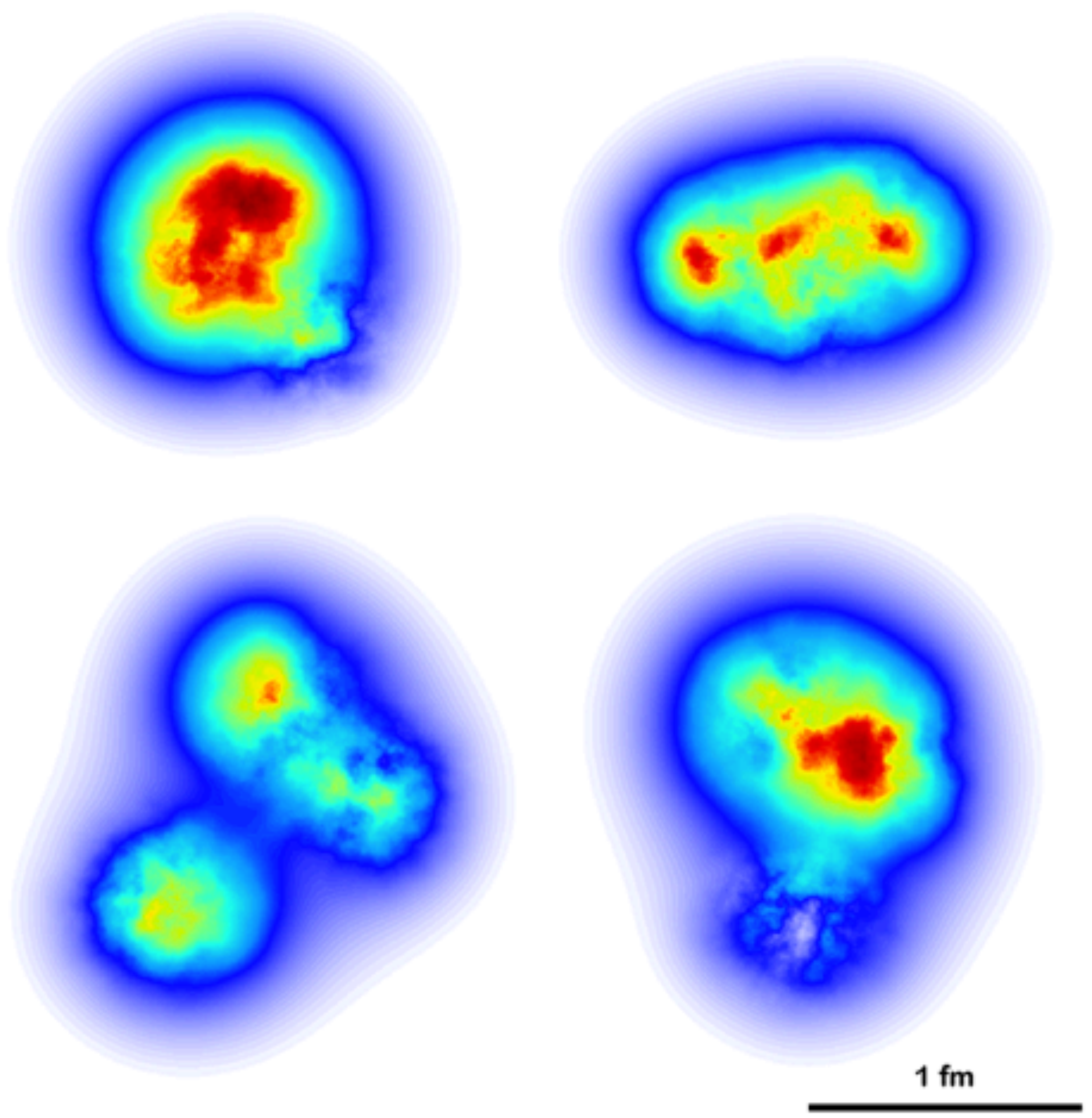



Image source: Björn Schenke and Heikki Mäntysaari

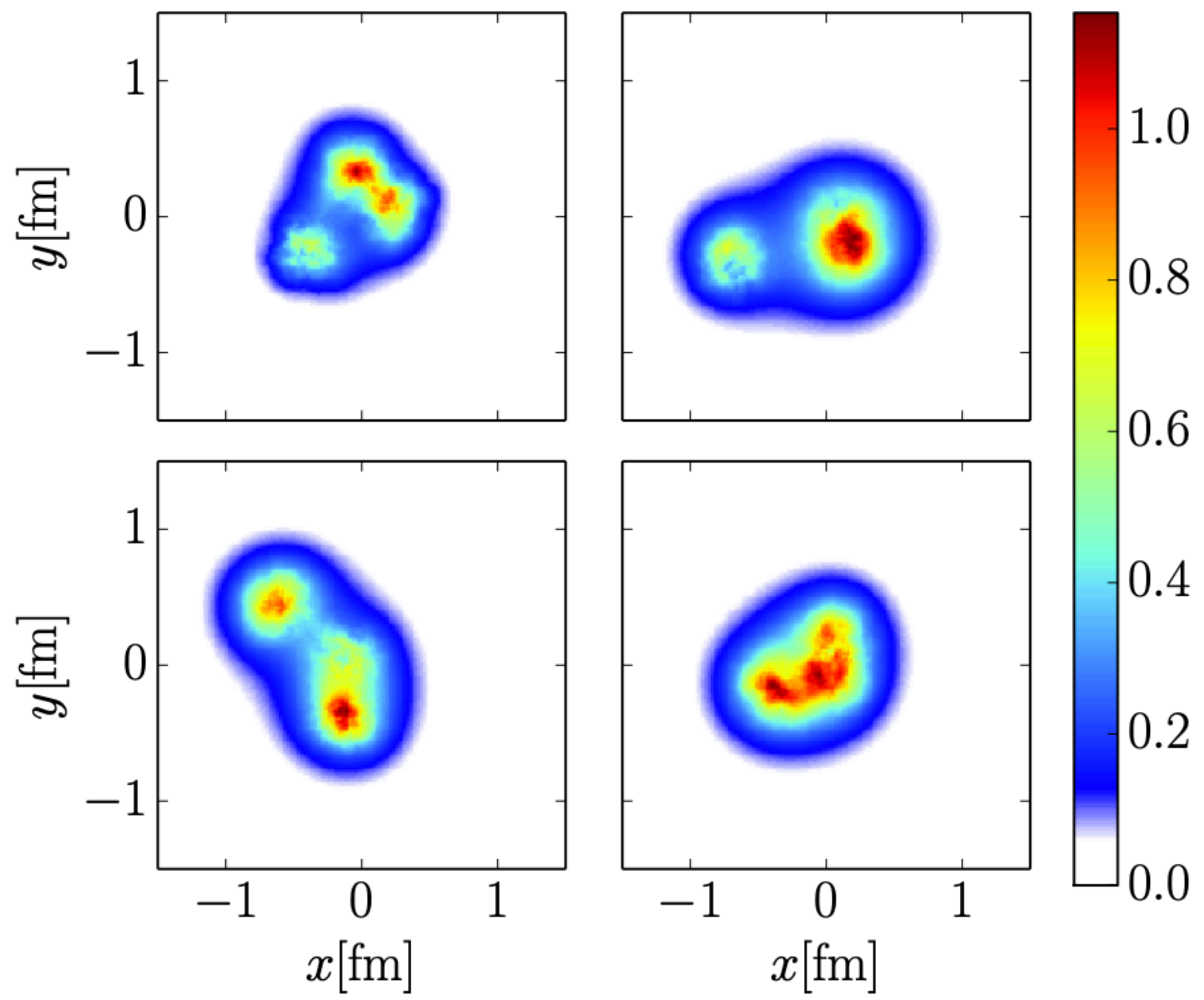
# Incoherent diffraction and fluctuations

## Geometric and color charge fluctuations

Incoherent diffraction:

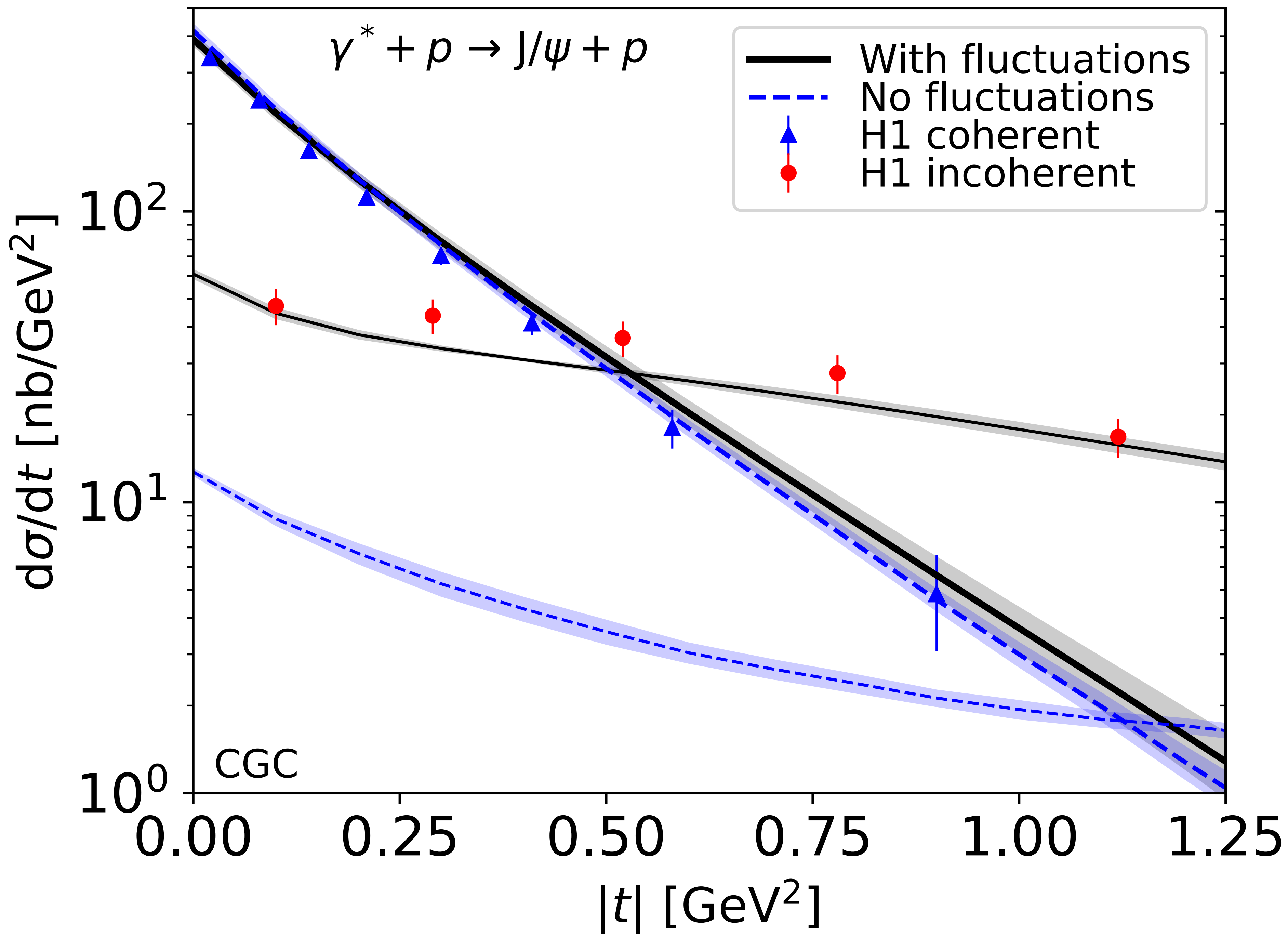
$$\langle \mathcal{M}^\dagger \mathcal{M} \rangle_Y - \langle \mathcal{M}^\dagger \rangle_Y \langle \mathcal{M} \rangle_Y$$

Proton density profile with substructure (hotspots)




Mäntysaari, Schenke. 1603.04349

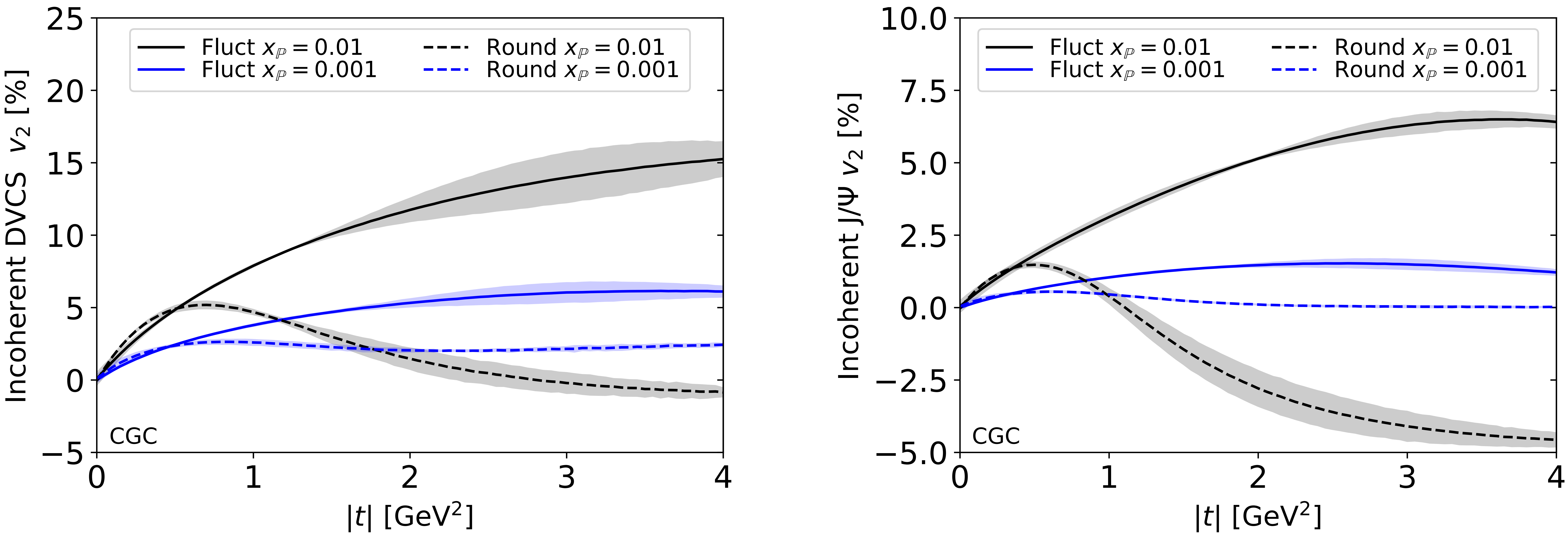
Coherent and incoherent cross-section




Incoherent cross-section needs geometric fluctuations (hotspots) and $Q_s$ fluctuations

# Incoherent diffraction and fluctuations

DVCS and $J/\psi$ correlation with electron plane




Substructure fluctuations change anisotropies at moderate momentum transfer $|t| \gtrsim 0.5\ \mathrm{GeV}^2$, increasing $v_2$

# Outlook

- Promote to NLO

  Impact factor at NLO
  Boussarie, Grabovsky, Szymanowski, Wallon.
  1405.7676, 1612.08026

  Small-x JIMWLK at NLO
  Balistky, Chirlli. 1309.7644
  Kovner, Lublinky, Mulian. 1310.0378

  Jyväskylä small-x group working on $\gamma^* + p \to J/\psi + p$ at NLO!

- An alternative to MV model: color charge 2-point function from proton LC wave-function

  Dumitru, Miller, Venugopalan 1808.02501
  Dumitru, Skokov, Stebel 2001.04516
  Dumitru, Paatelainen 2010.11245

- Distinguish different geometric fluctuations (e.g. hotspots vs stringy proton) using $v_n$

# Happy Holidays!