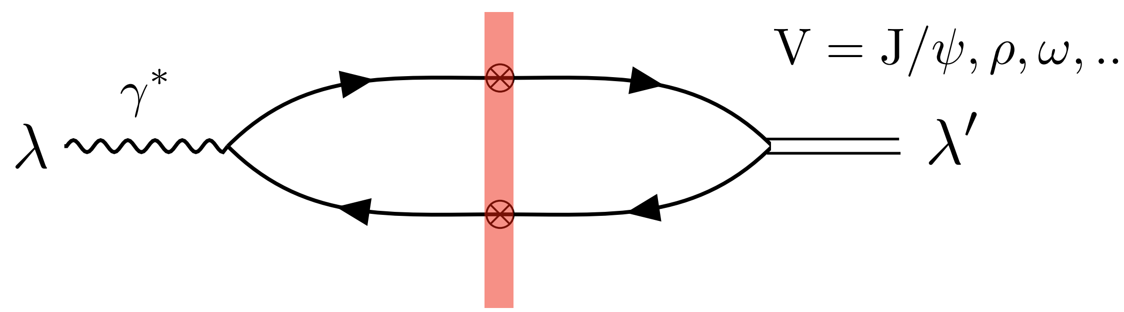
Gluon imaging using azimuthal correlations in diffractive J/ψ electro-production



Saturation and Diffraction
at the LHC and the EIC

ECT* workshop
June 29th, 2021

Farid Salazar

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Outline

- Diffractive heavy vector meson electro-production in the CGC EFT
  *with a detour to DVCS**

- Azimuthal correlations with electron plane

- Numerical results for J/ψ production at the EIC
  from an impact parameter dependent MV model

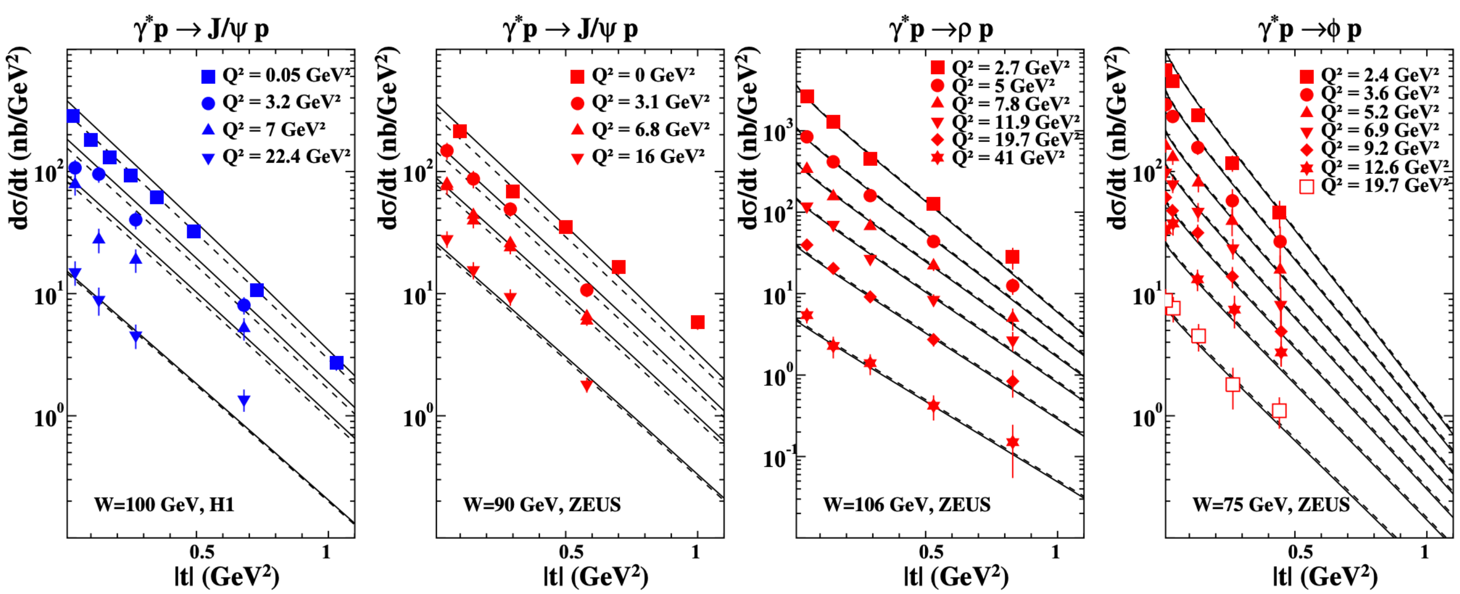
- Incoherent diffraction and fluctuations

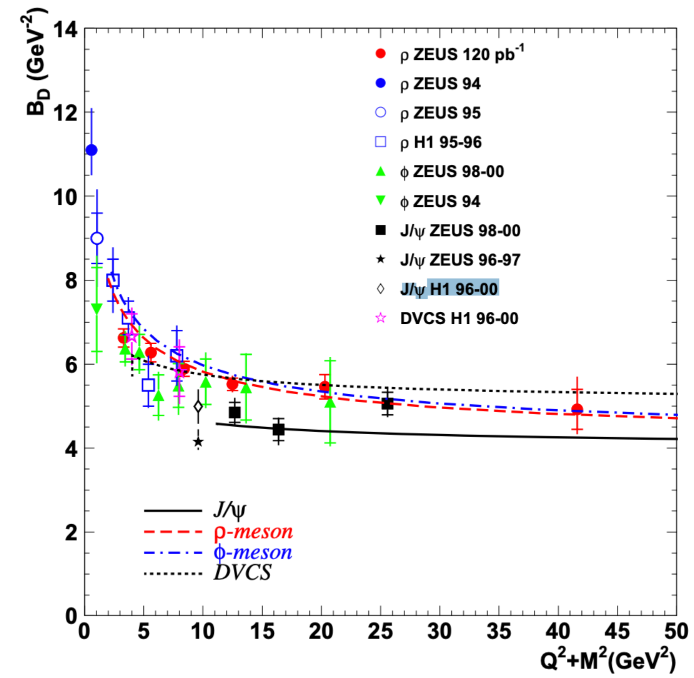
Based on:
H. Mäntysaari, K. Roy, FS, B. Schenke. 2011.02464
Phys.Rev.D 103 (2021) 9, 094026

Inspired by:
Hatta, Yuan, Xiao. 1703.02085
Phys. Rev. D 95, 114026 (2017)

Why diffractive measurements?

- Momentum transfer conjugate to impact parameter $\boldsymbol{b}_\perp \leftrightarrow \boldsymbol{\Delta}_\perp$.



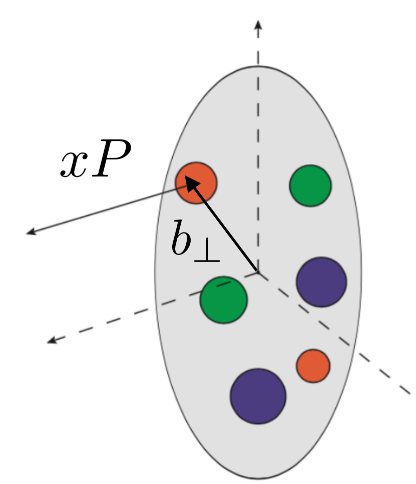


IP-Sat provides good description of HERA data

Rezaeian, Siddikov, Klundert, Venugopalan
1212.2974

Extract proton size from slope of exclusive spectra

- Exclusive process allows to access Generalized Parton Distributions (GPDs) $xH_g(x, \boldsymbol{\Delta}_\perp)$



For semi-inclusive processes and TMDs see
Cyrille's and Piotr's talks on Thursday

What else can we learn from diffraction?

Previous studies:

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

Goal:

Azimuthal correlations of momentum and impact parameter of gluons (Wigner distribution)

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).

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!

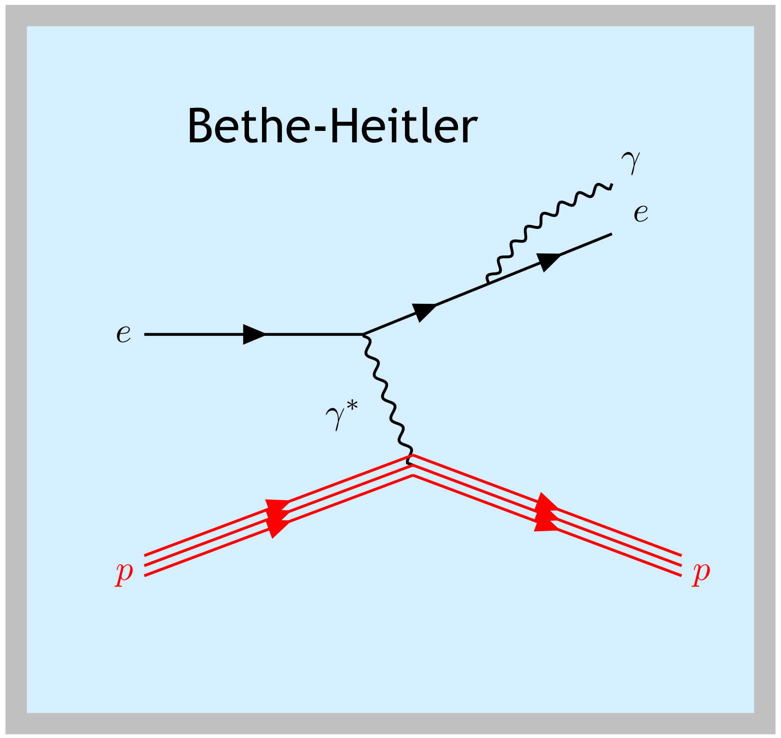
Also diffractive pion pair production in UPCs
Hagiwara, Zhang, Zhou, Zhou. 2106.13466

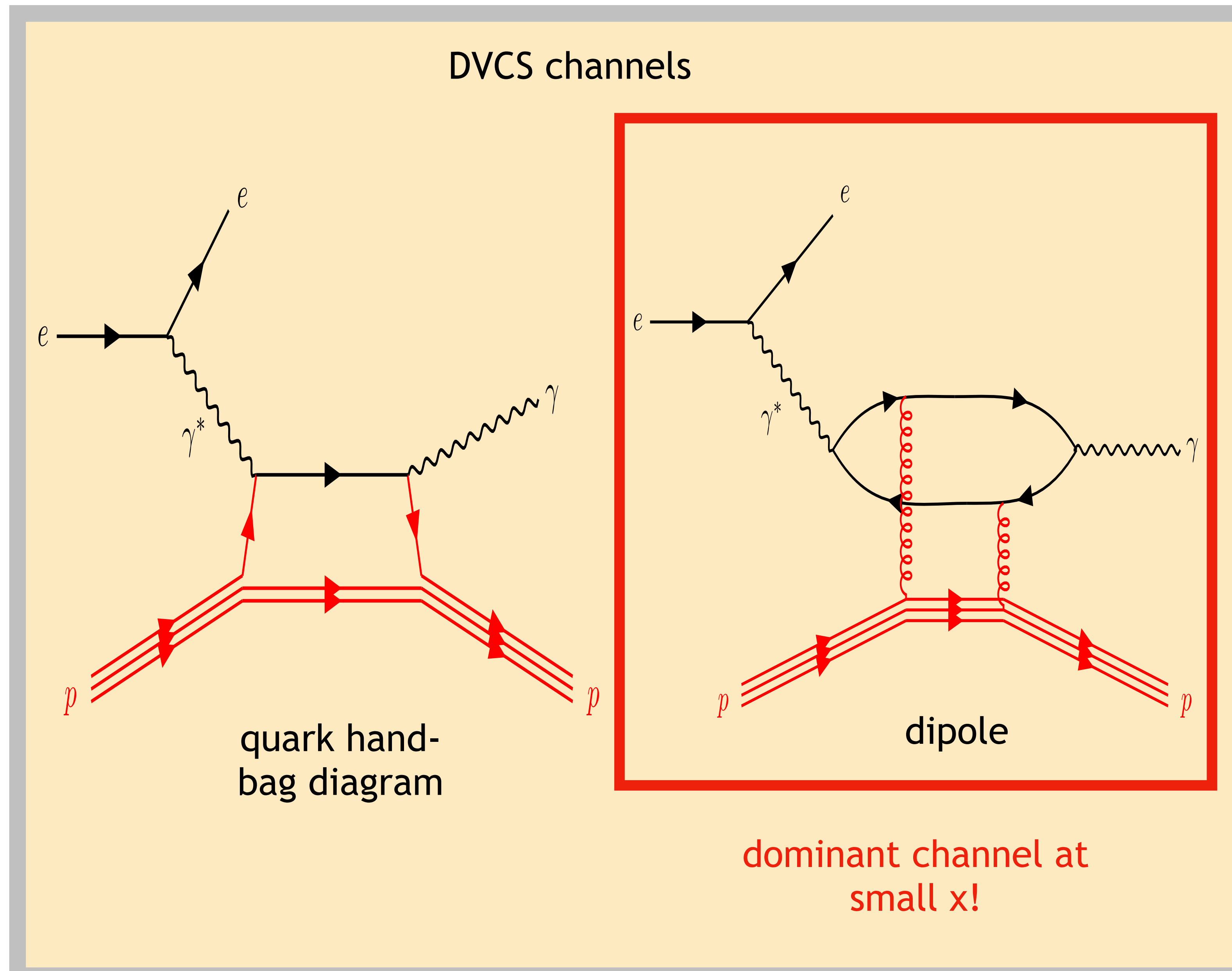
Approach:

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

A detour: deeply virtual Compton scattering

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



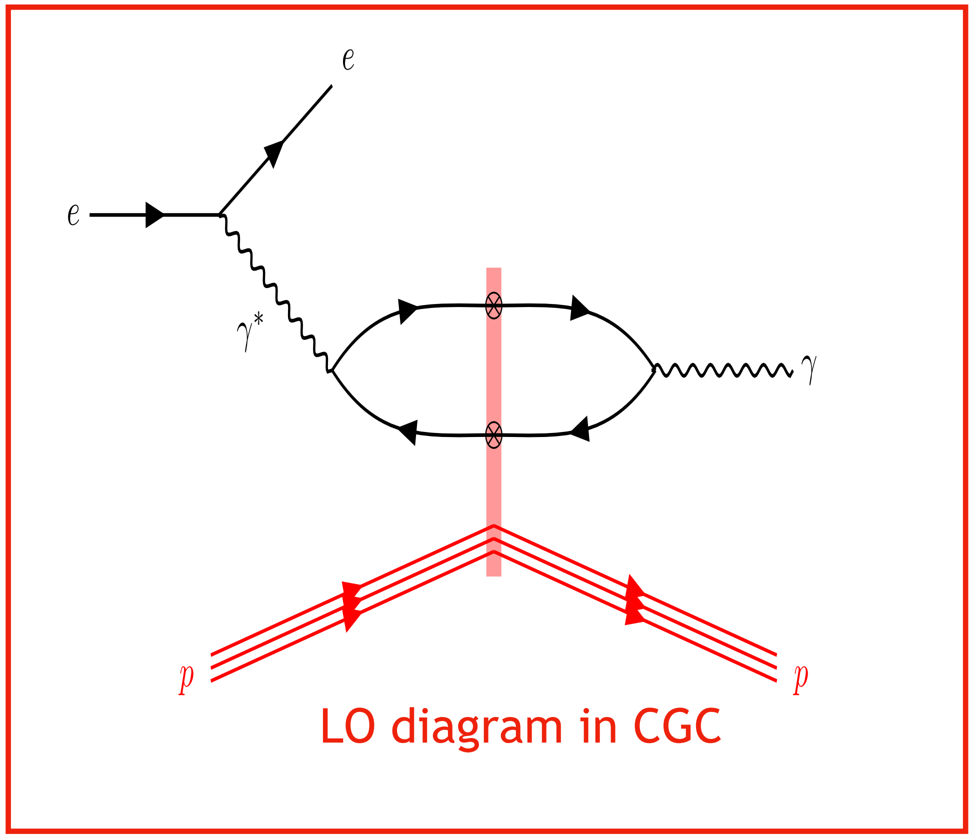


For DVCS and BH see

Aschenauer, Fazio,
Kumericki, Müller 1304.0077

A detour: deeply virtual Compton scattering

CGC* EFT and Multiple scattering



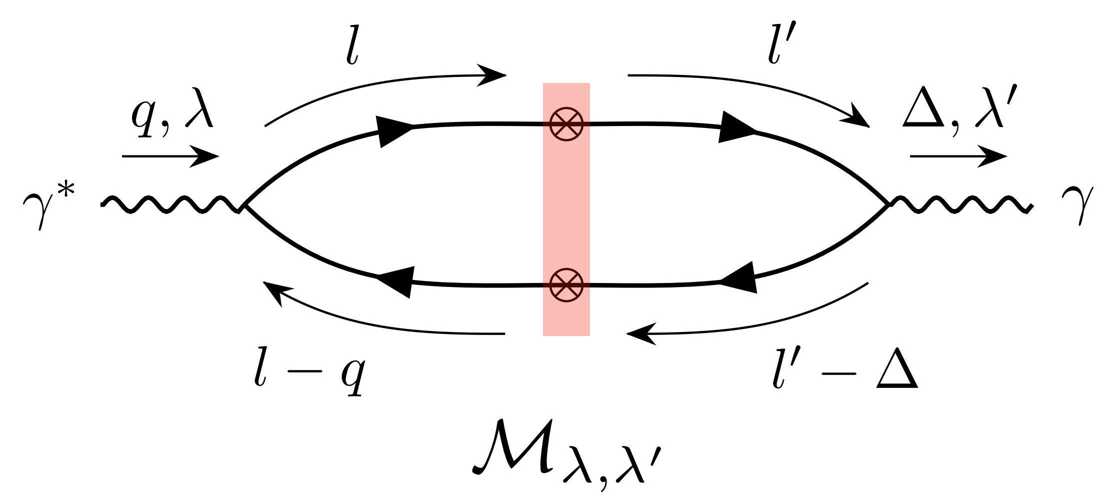
LO diagram in CGC

Sub-hadronic process

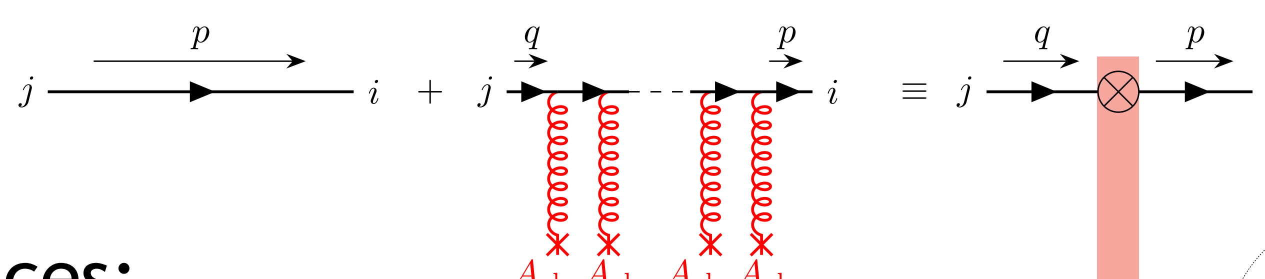
λ incoming photon polarization

λ' outgoing photon polarization

We follow a momentum space covariant PT approach** (as opposed to LCPT):

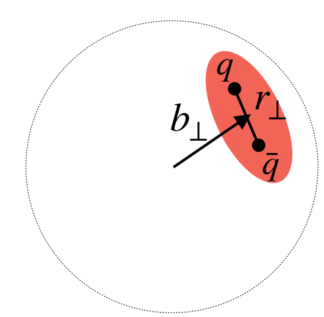


CGC effective vertex



Two CGC vertices:

$$V\left(\boldsymbol{b}_\perp + \frac{\boldsymbol{r}_\perp}{2}\right) V^\dagger\left(\boldsymbol{b}_\perp - \frac{\boldsymbol{r}_\perp}{2}\right)$$



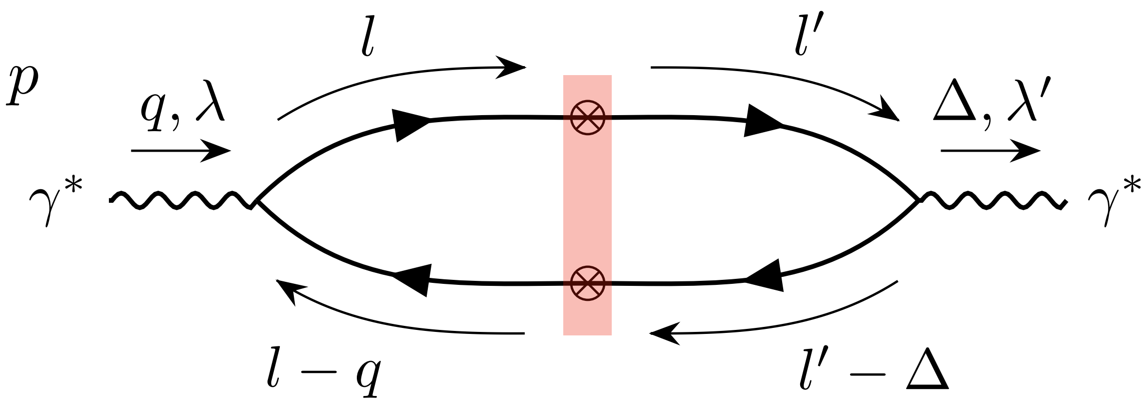
*See **Kong's talk** (previous session) for more on CGC and saturation

See **Paul's talk on Thursday for how covariant PT approach is employed to NLO processes

A detour: deeply virtual Compton scattering

At leading order in the CGC EFT

$$\gamma^*_\lambda + p \to \gamma^*_{\lambda'} + p$$



Let the photon have non-zero virtuality Q' and consider non-zero quark masses*

Helicity preserving amplitude

$$\langle \mathcal{M}_{\pm1,\pm1} \rangle_Y \sim \int_{\boldsymbol{b}_\perp} e^{-i\boldsymbol{\Delta}_\perp \cdot \boldsymbol{b}_\perp} \int_{\boldsymbol{r}_\perp} D_Y(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) \int_z e^{-i\boldsymbol{\delta}_\perp \cdot \boldsymbol{r}_\perp} \left[(z^2 + \bar{z}^2)\ \varepsilon_f K_1(\varepsilon_f r_\perp) \varepsilon'_f K_1(\varepsilon'_f r_\perp) + m_f K_0(\varepsilon_f r_\perp) m_f K_0(\varepsilon'_f r_\perp) \right]$$

Helicity flip amplitude

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

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

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

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

*Expressions consistent with 1703.02085 when $Q'^2 = 0$ and $m_f = 0$.

A detour: 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

Helicity preserving amplitude

$$\langle \mathcal{M}_{\pm1,\pm1} \rangle_Y \sim \int_{\boldsymbol{b}_\perp} e^{-i\boldsymbol{\Delta}_\perp \cdot \boldsymbol{b}_\perp} \int_{\boldsymbol{r}_\perp} D_Y(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) \int_z e^{-i\boldsymbol{\delta}_\perp \cdot \boldsymbol{r}_\perp} \left[(z^2 + \bar{z}^2)\ \varepsilon_f K_1(\varepsilon_f r_\perp) \varepsilon'_f K_1(\varepsilon'_f r_\perp) + m_f K_0(\varepsilon_f r_\perp) m_f K_0(\varepsilon'_f r_\perp) \right]$$

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

Helicity flip amplitude

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

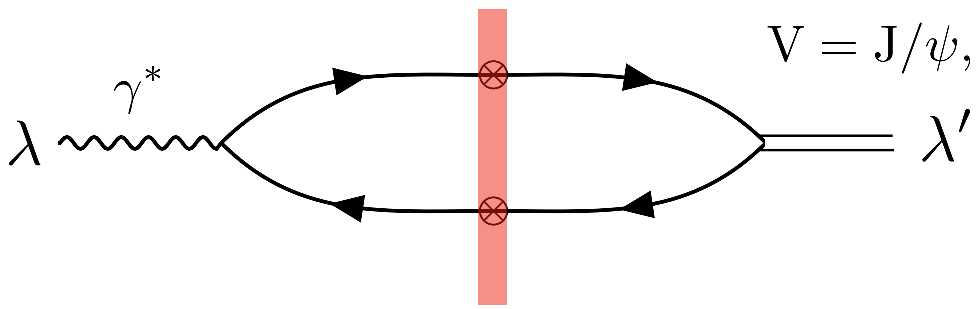
Contributions from all modes, but mostly $D_{Y,2}$ when $\Delta_\perp \ll Q$

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

- Kinematic: off-forward phase $e^{-i\boldsymbol{\delta}_\perp \cdot \boldsymbol{r}_\perp}$ $\quad \delta_\perp = \left(\frac{z - \bar{z}}{2}\right) \boldsymbol{\Delta}_\perp$
- Intrinsic: correlation between $\boldsymbol{r}_\perp$ and $\boldsymbol{b}_\perp$ in the dipole (e.g. $D_{Y,2}$)

Heavy vector meson production

From DVCS* to VM production



$$\gamma^*_\lambda + p \to \gamma^*_{\lambda'} + p \longrightarrow \gamma^*_\lambda + p \to V_{\lambda'} + p$$

massive quarks m_f

can have longitudinal polarization

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

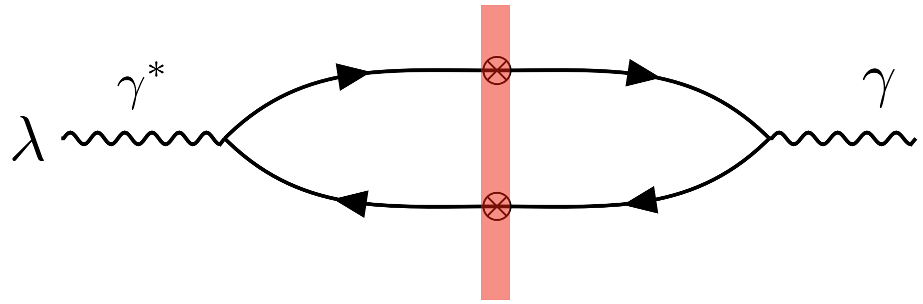
Follow prescription in hep-ph/0606272 and replace the LC wave-function of final state (virtual) photon with:

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

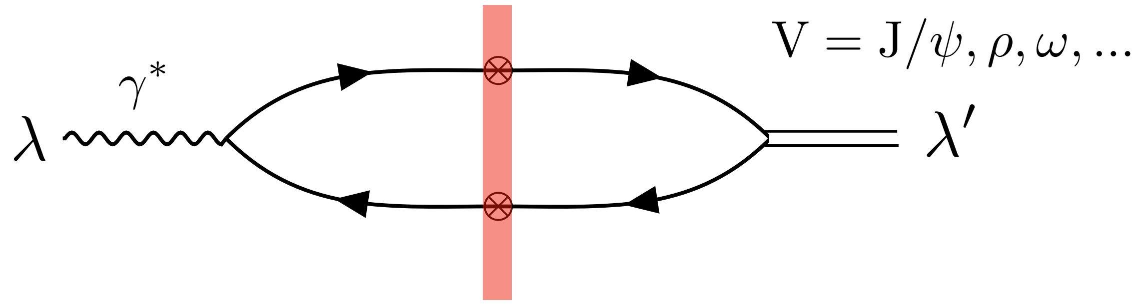
Kowalski, Motyka, Watt. hep-ph/0606272

See **Jani's talk** tomorrow for more on VM LC wave functions

Why heavy vector meson over DVCS?



Hatta, Yuan, Xiao. 1703.02085



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

Advantages

- Massive quarks reduce contribution from large dipoles
- J/ψ has less sensitivity to off-forward phase
- No Bethe-Heitler contribution

Disadvantages

- Uncertainties in the vector meson wave-function

Azimuthal correlations with electron

Polarization basis and electron plane correlation

Lepton-hadron tensor decomposition

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

Insert completeness relation

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

Lepton-hadron tensor decomposition in polarization basis

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

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

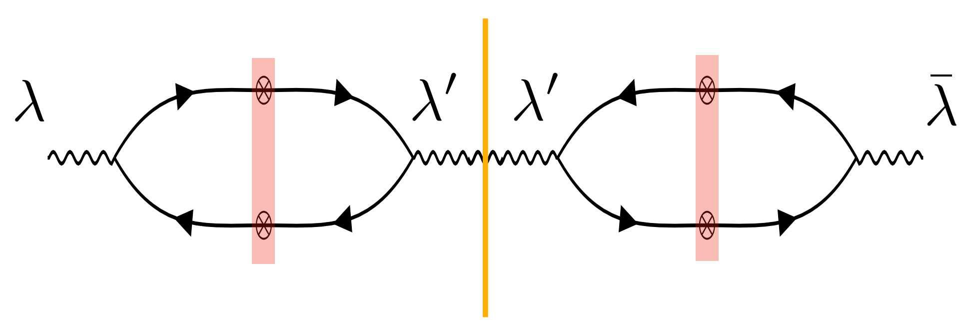
$$L_{\lambda\bar{\lambda}} \sim e^{i(\lambda-\bar{\lambda})\phi_e} f_{\lambda\bar{\lambda}}$$

electron azimuthal angle ($e^{i(\lambda-\bar{\lambda})\phi_e}$); photon flux factors ($f_{\lambda\bar{\lambda}}$)

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

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

photon azimuthal angle ($e^{-i(\lambda-\bar{\lambda})\phi_{\Delta}}$); Photon-proton amplitude squared ($\sum_{\lambda'} \mathcal{M}^{\dagger}_{\lambda,\lambda'} \mathcal{M}_{\bar{\lambda},\lambda'}$)



$\mathcal{M}^{\dagger}_{\lambda,\lambda'}$ $\mathcal{M}_{\bar{\lambda},\lambda'}$

Azimuthal correlations with electron

Vector meson azimuthal correlations with electron plane

$$d\sigma^{ep\to eVp} \sim f_{TT}(y)\mathcal{M}_{TT}^2 + f_{LL}(y)\mathcal{M}_{LL}^2$$
$$-f_{LT}(y)\mathcal{M}_{LT}\mathcal{M}_{TT}\cos(\phi_{e\Delta})$$
$$+f_{TT,\text{flip}}(y)\mathcal{M}_{TT}\mathcal{M}_{TT,\text{flip}}\cos(2\phi_{e\Delta})$$

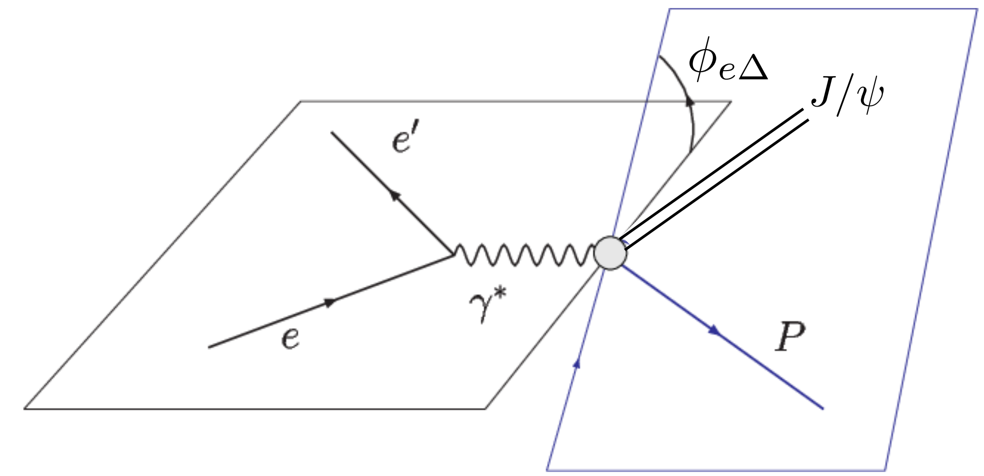


Image source: CLAS collaboration (edited)

Here I assumed (for this conceptual discussion)

$\mathcal{M}_{LT}^2, \mathcal{M}_{TT,\text{flip}}^2 \ll \mathcal{M}_{TT}^2$ valid for $|t| \lesssim 2\ \text{GeV}^2$

For full expression see 2011.02464

Helicity preserving:	$\mathcal{M}_{TT} \equiv \langle \mathcal{M}_{\pm1,\pm1}\rangle_Y$ $\mathcal{M}_{LL} \equiv \langle \mathcal{M}_{0,0}\rangle_Y$
Pol changing:	$\mathcal{M}_{LT} = \mathcal{M}_{TL} \equiv \langle \mathcal{M}_{0,\pm1}\rangle_Y$
Helicity flip:	$\mathcal{M}_{TT,\text{flip}} \equiv \langle \mathcal{M}_{\pm1,\mp1}\rangle_Y$

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

electron-J/ψ azimuthal correlations

$$\langle \cos\phi_{e\Delta}\rangle_\phi \sim -\frac{f_{LT}\mathcal{M}_{LT}}{f_{TT}\mathcal{M}_{TT}}$$

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

For simplicity I ignored $\mathcal{M}_{LL}$

See **Piotr's talk** on Thursday for electron-plane correlations in inclusive dijet production

Numerical results for J/ψ production

A toy model: GBW type dipole (without dipole modulations)

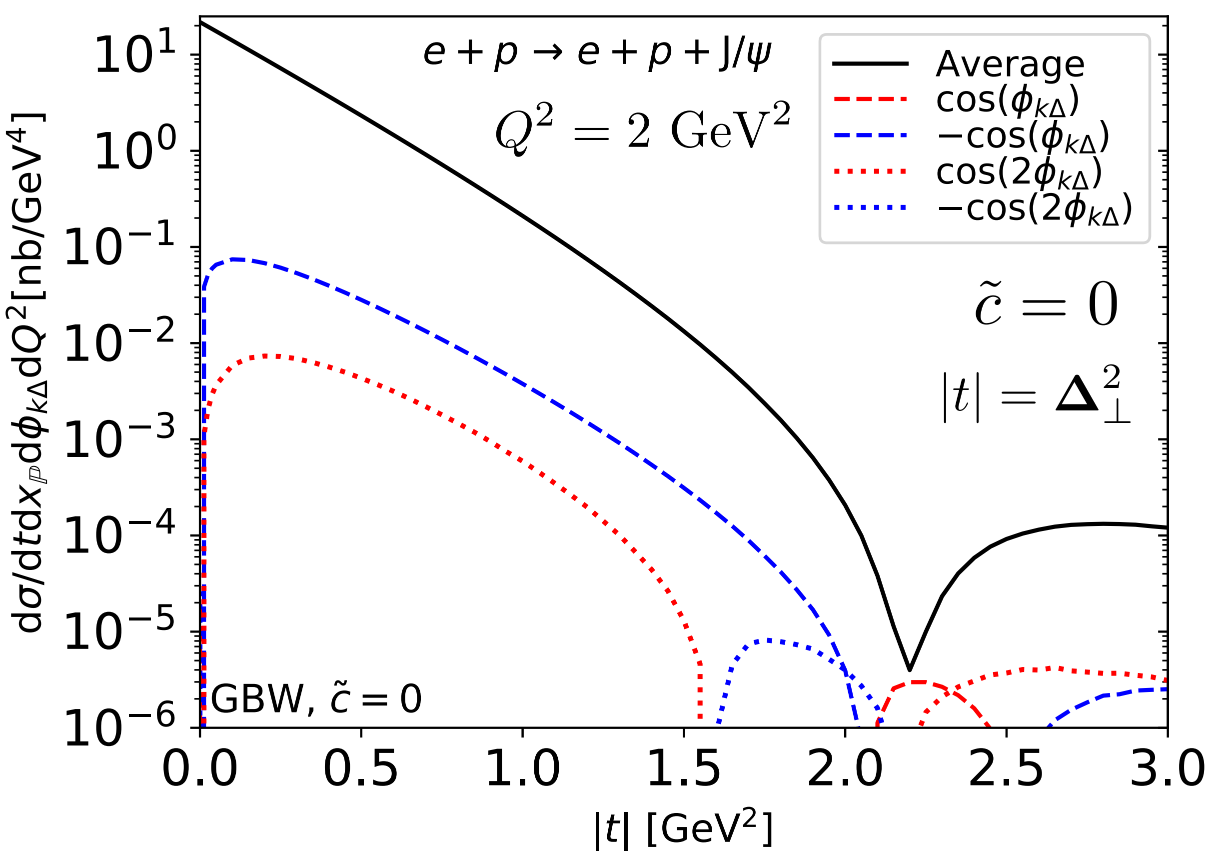
$$D_Y(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) = 1 - \exp\left[-\frac{r_\perp^2 Q_{s0}^2}{4} T_p(b_\perp) C_\phi(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)\right]$$

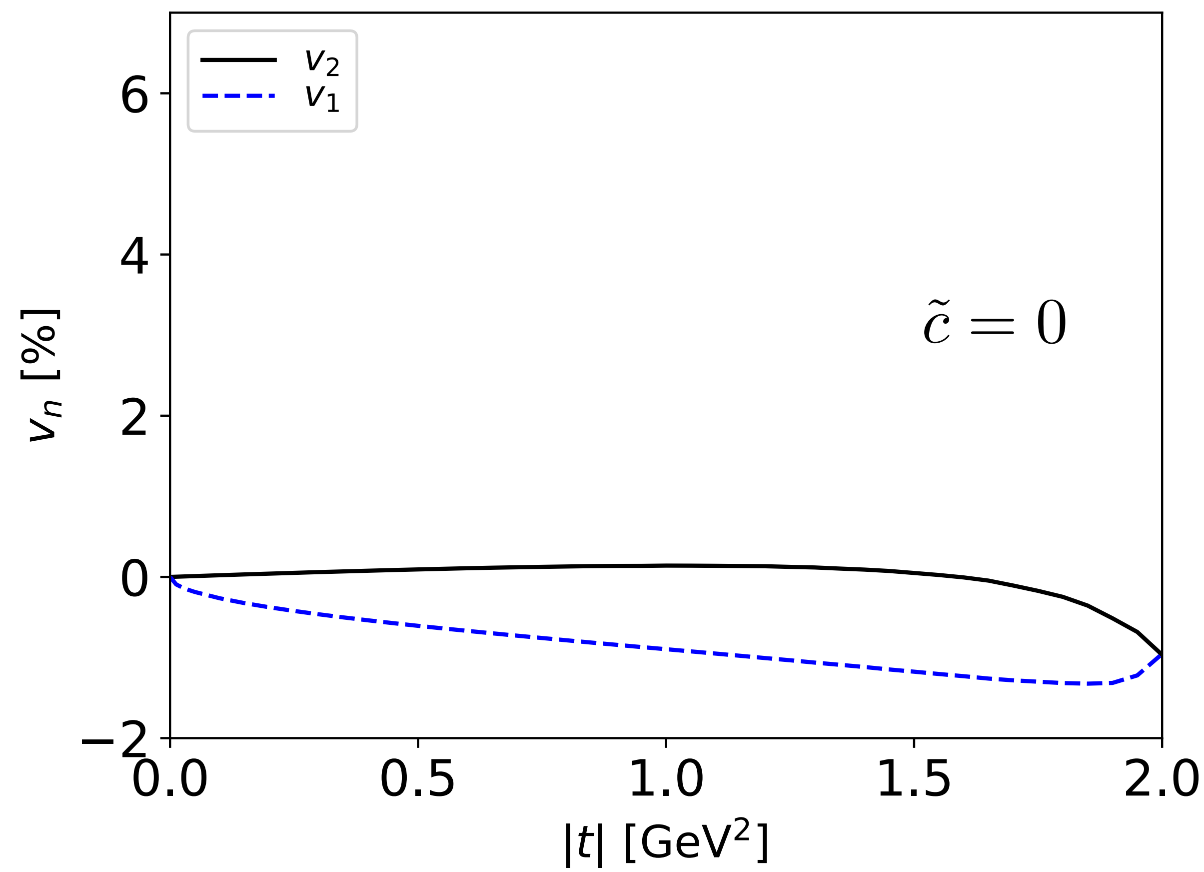
Proton transverse profile

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

Azimuthal correlations

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





Small elliptic anisotropy in the absence of dipole modulations $\tilde{c} = 0$.

Non-zero due to off-forward phase $e^{-i\boldsymbol{\delta}_\perp \cdot \boldsymbol{r}_\perp}$

Numerical results for J/ψ production

A toy model: GBW type dipole (with dipole modulations)

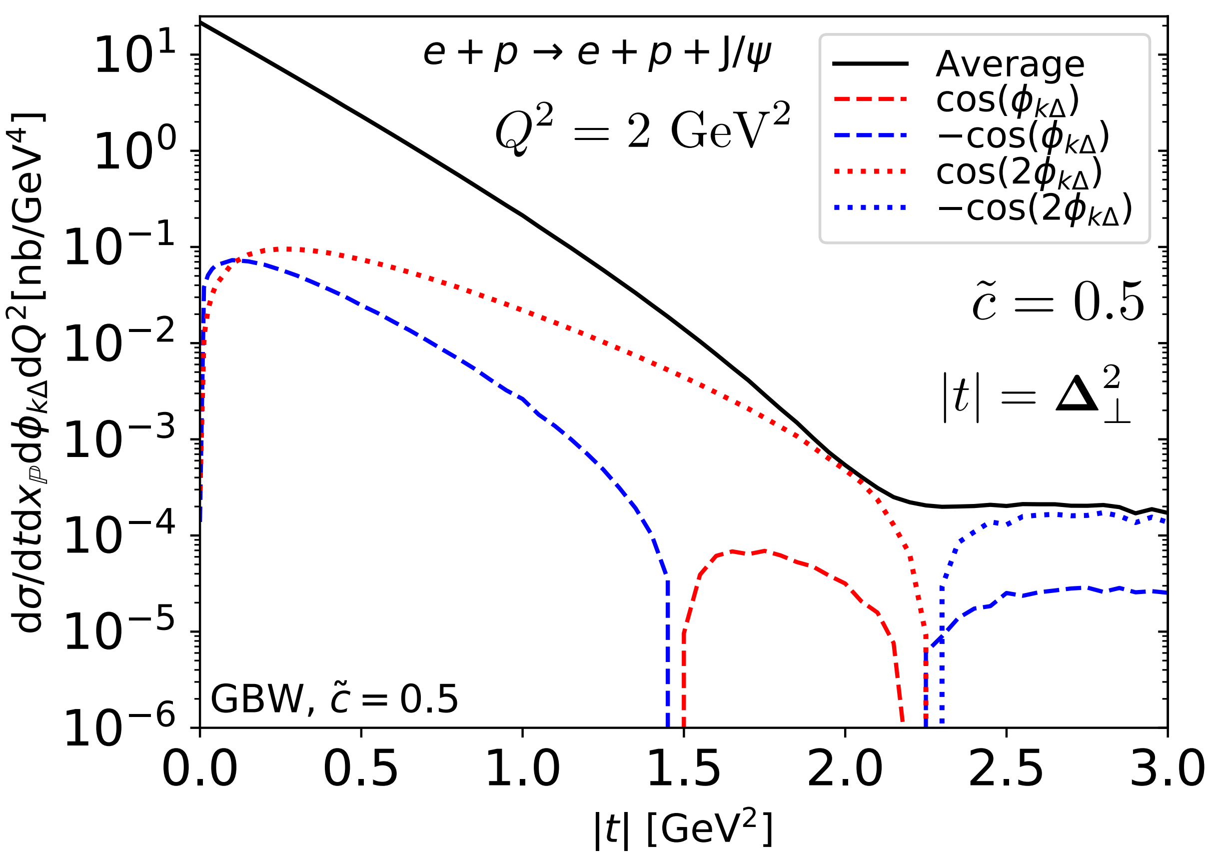
$$D_Y(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) = 1 - \exp\left[-\frac{r_\perp^2 Q_{s0}^2}{4} T_p(b_\perp) C_\phi(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)\right]$$

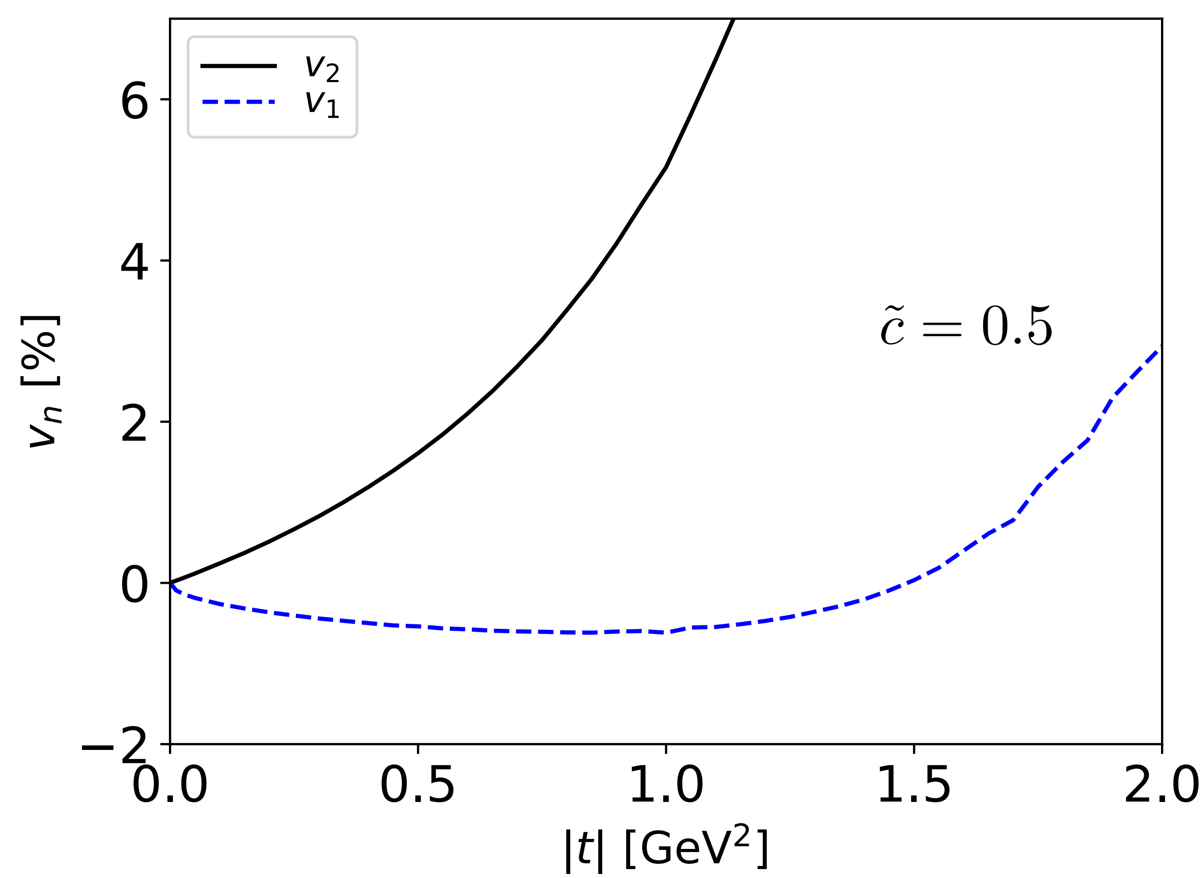
Proton transverse profile

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

Azimuthal correlations

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



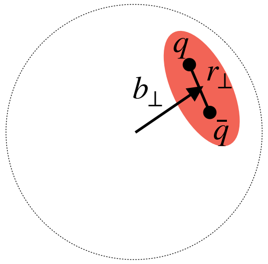


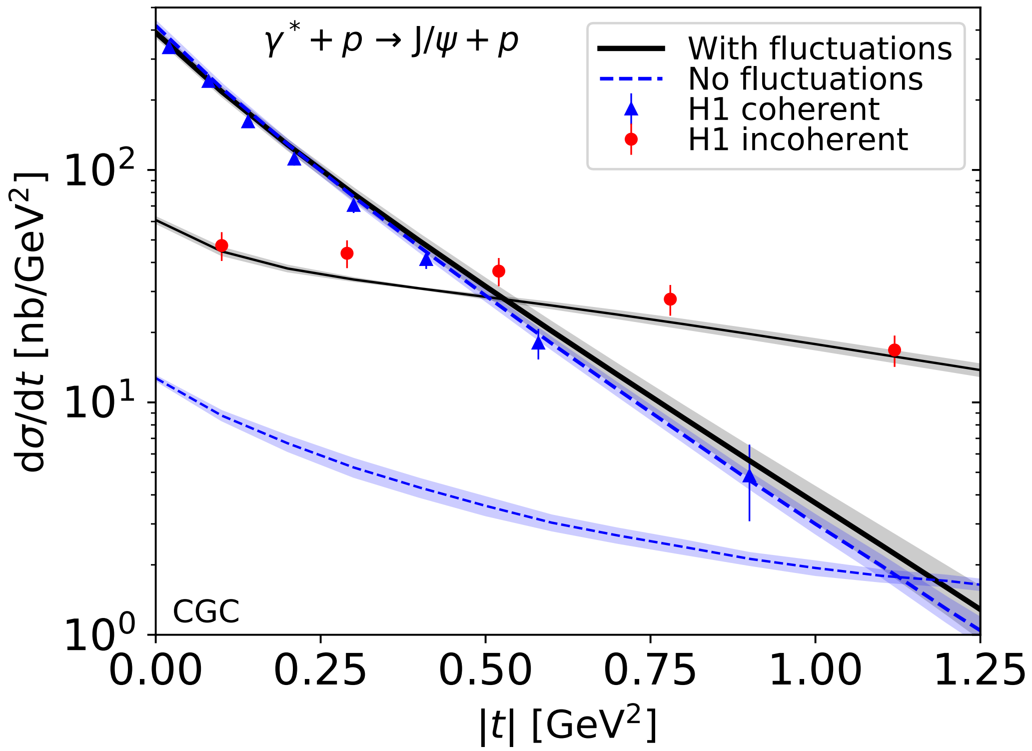
Large azimuthal anisotropy when turning on dipole modulations $\tilde{c} > 0$
(i.e. non-zero D_2)

Numerical results for J/ψ production

A more realistic setup: IP dependent MV+JIMWLK

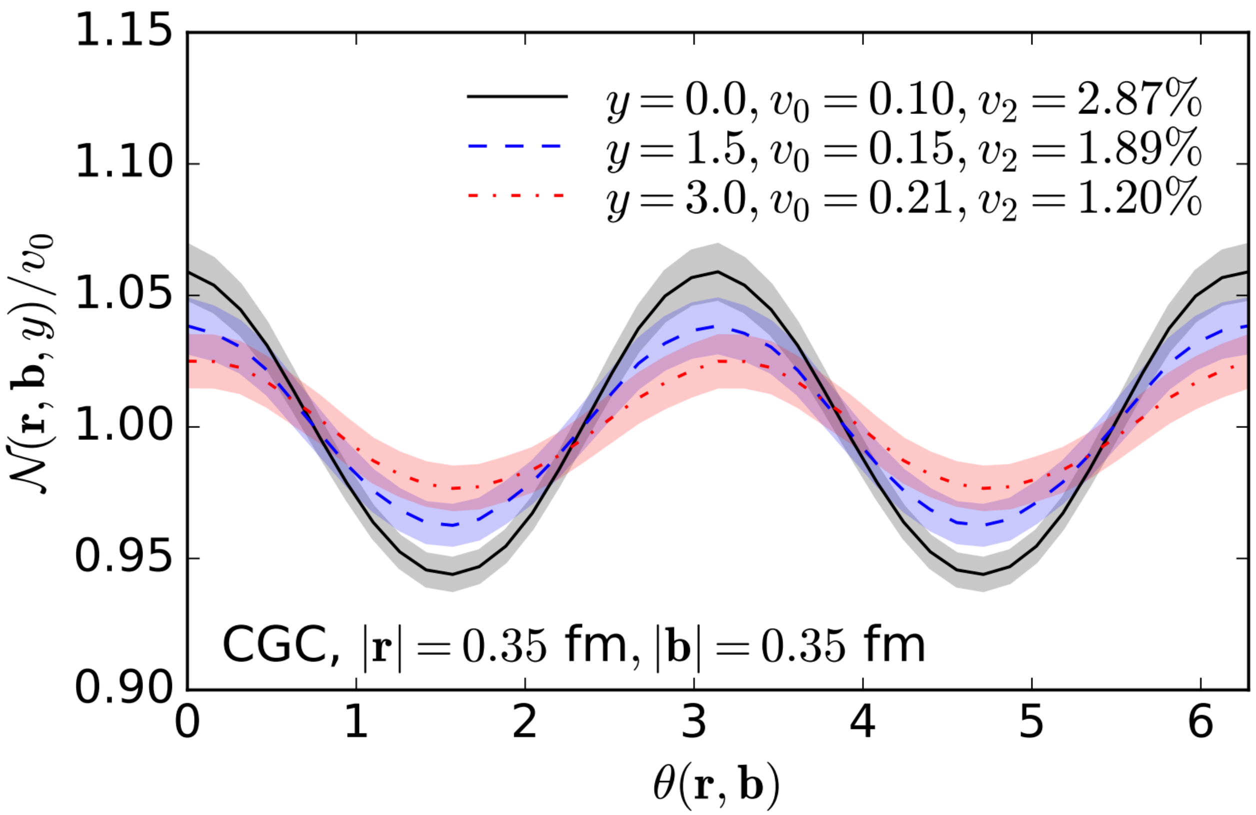
- Initial conditions: MV model with $\langle\rho\rho\rangle \sim g^4\mu^2 \sim Q_s^2 \sim T_p(\boldsymbol{b}_\perp)$
- Small-x JIMWLK evolution up to $Y = \ln(1/x_{\mathbb{P}})$
- Wilson Lines evolved event-by-event
- Dipole obtained from ensemble average $\langle \mathrm{Tr}(VV^\dagger)\rangle_Y$





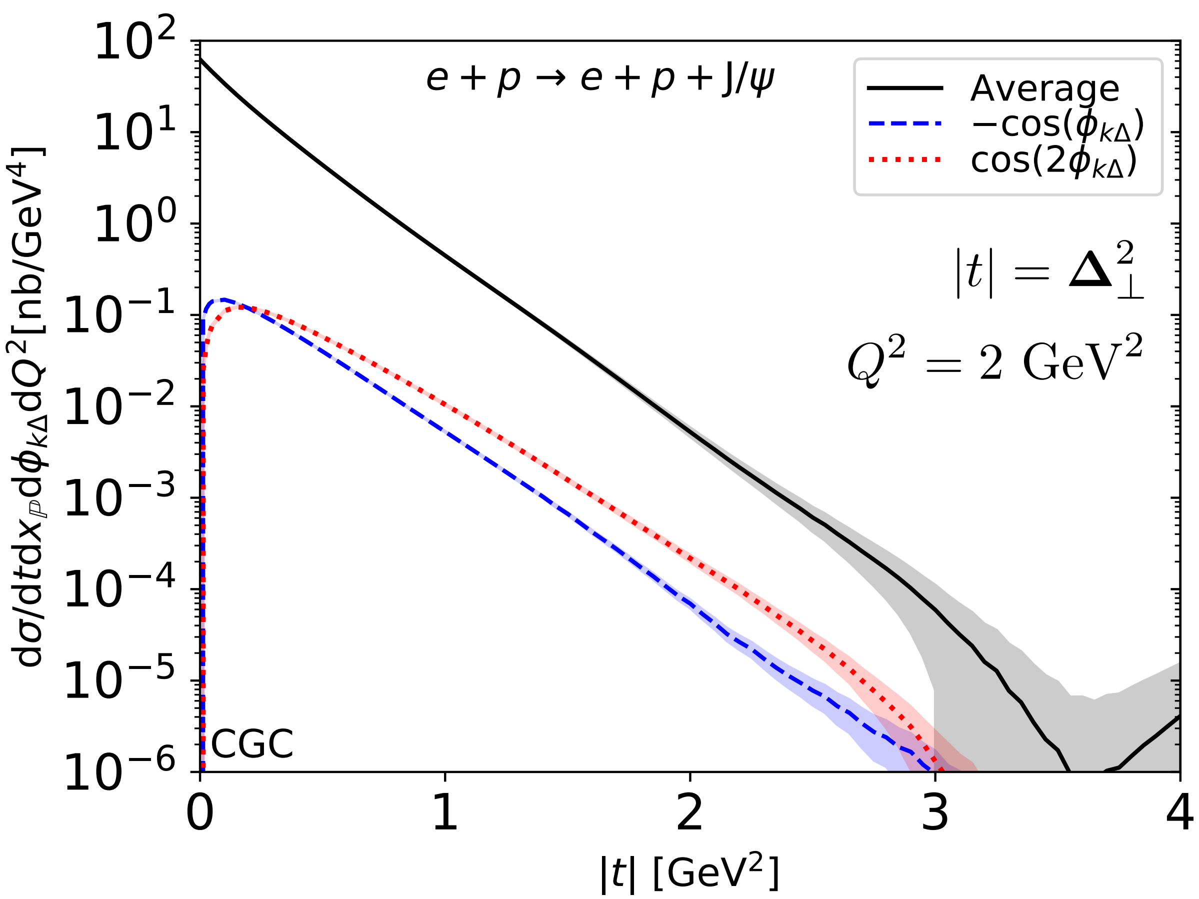
Free parameters constrained by HERA data on exclusive J/ψ at $W = 75$ GeV

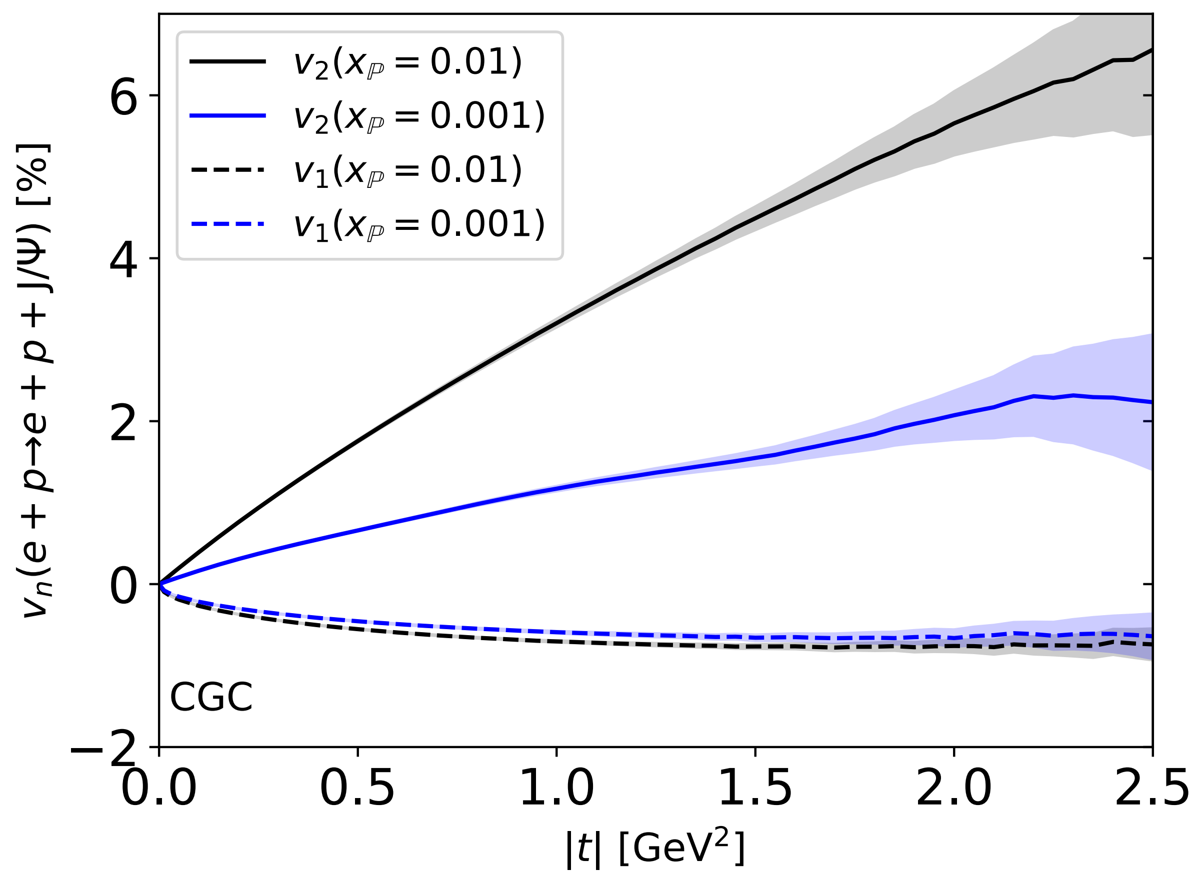
Resultant dipole modulations



Numerical results for J/ψ production for electron-proton collisions

From impact parameter dependent MV model



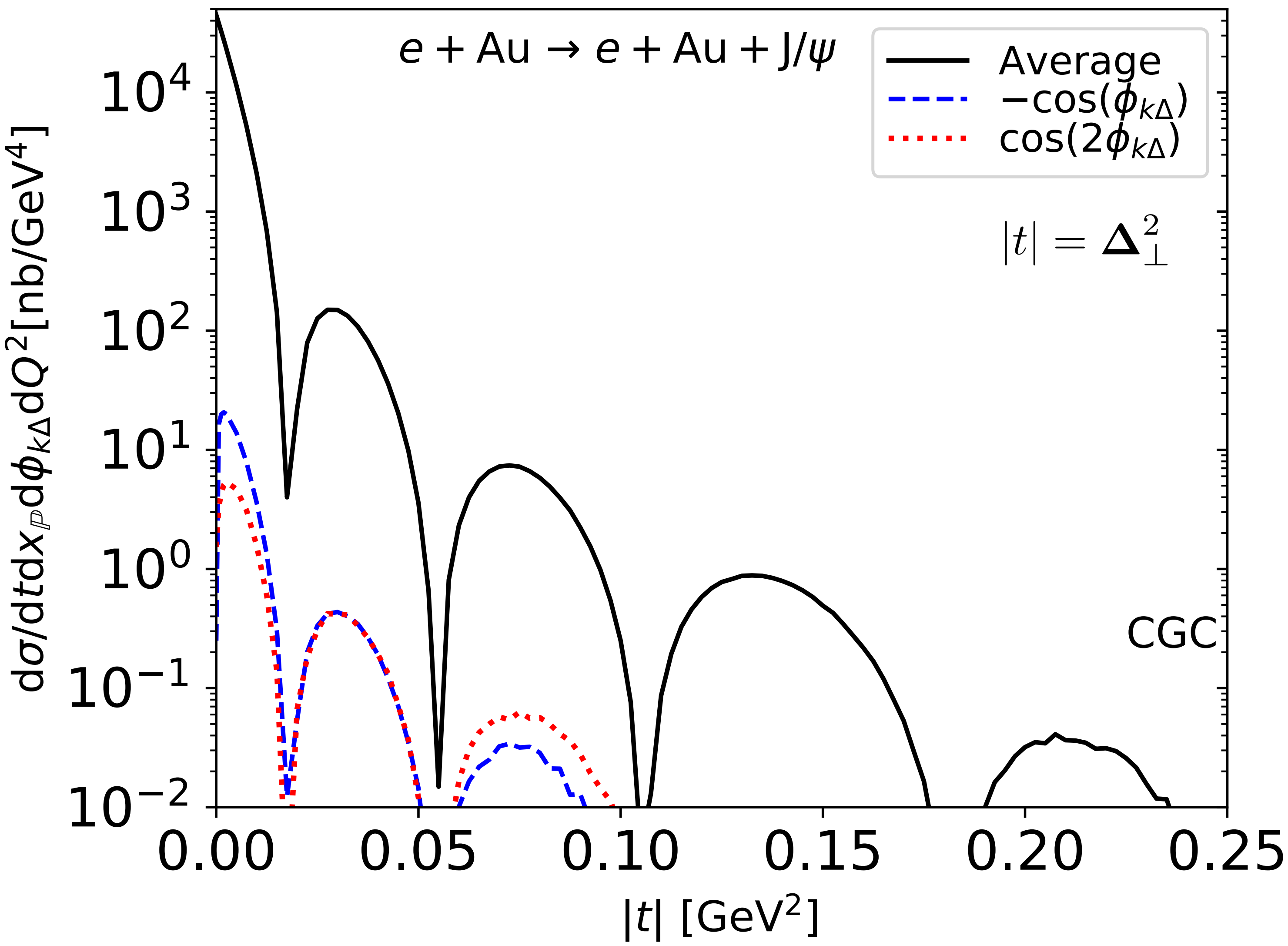


Sizeable azimuthal anisotropies (a few percent) which decrease with small-x evolution

Color charge gradients drive azimuthal anisotropy

Numerical results for J/ψ production for electron-nucleus collisions

From impact parameter dependent MV model



Characteristic dips in spectra due to Woods-Saxon nuclear profile

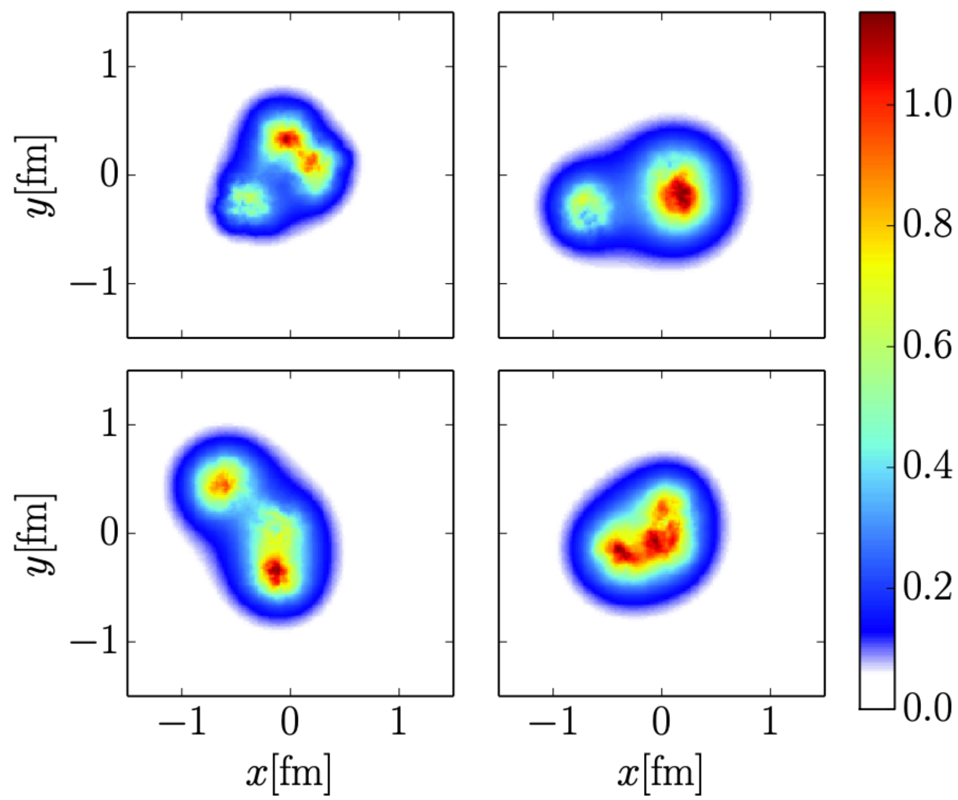
Azimuthal modulations v_n less than 1% due to smooth color charge (small gradients)

Incoherent diffraction and fluctuations

Geometric and color charge fluctuations

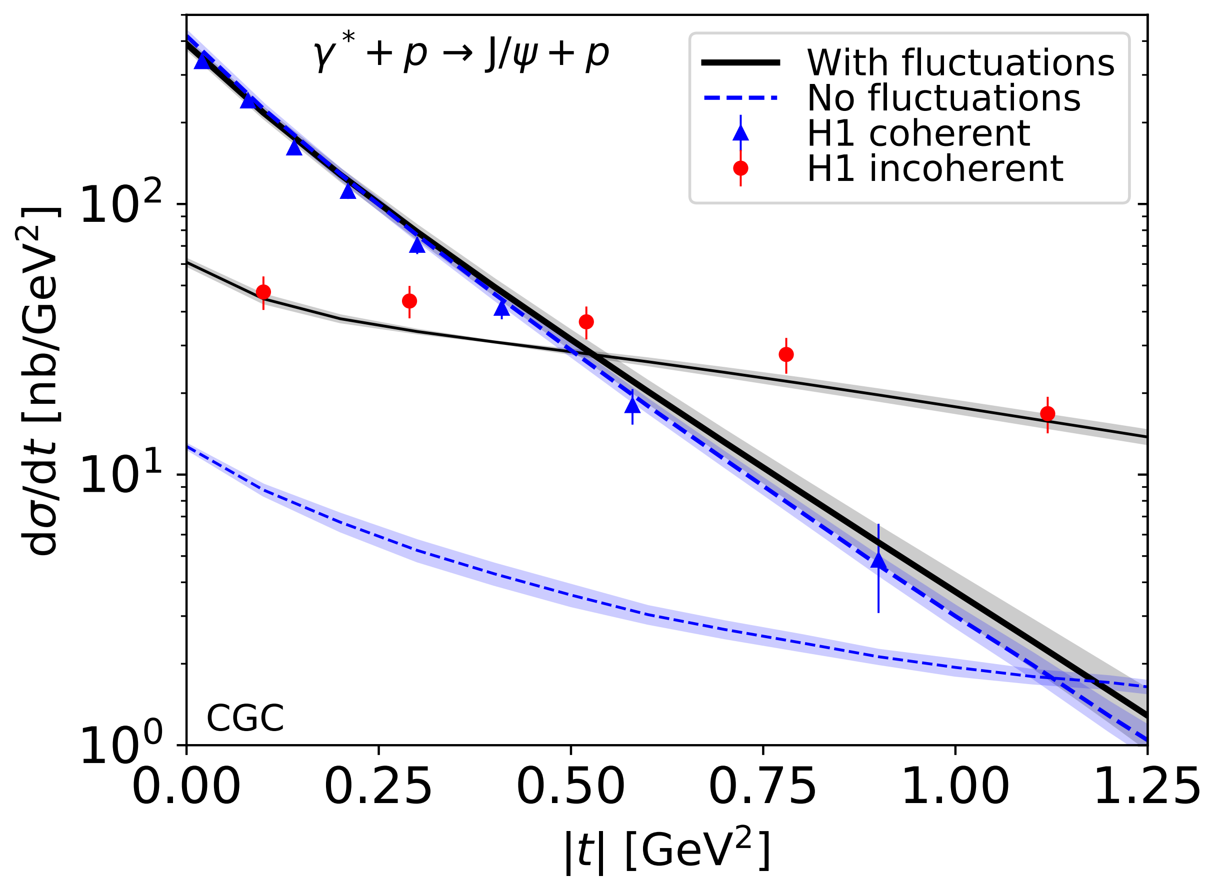
Incoherent diffraction: $\langle \mathcal{M}^\dagger \mathcal{M} \rangle_Y - \langle \mathcal{M}^\dagger \rangle_Y \langle \mathcal{M} \rangle_Y$

Proton density profile with substructure (hotspots)



Mäntysaari, Schenke. 1603.04349

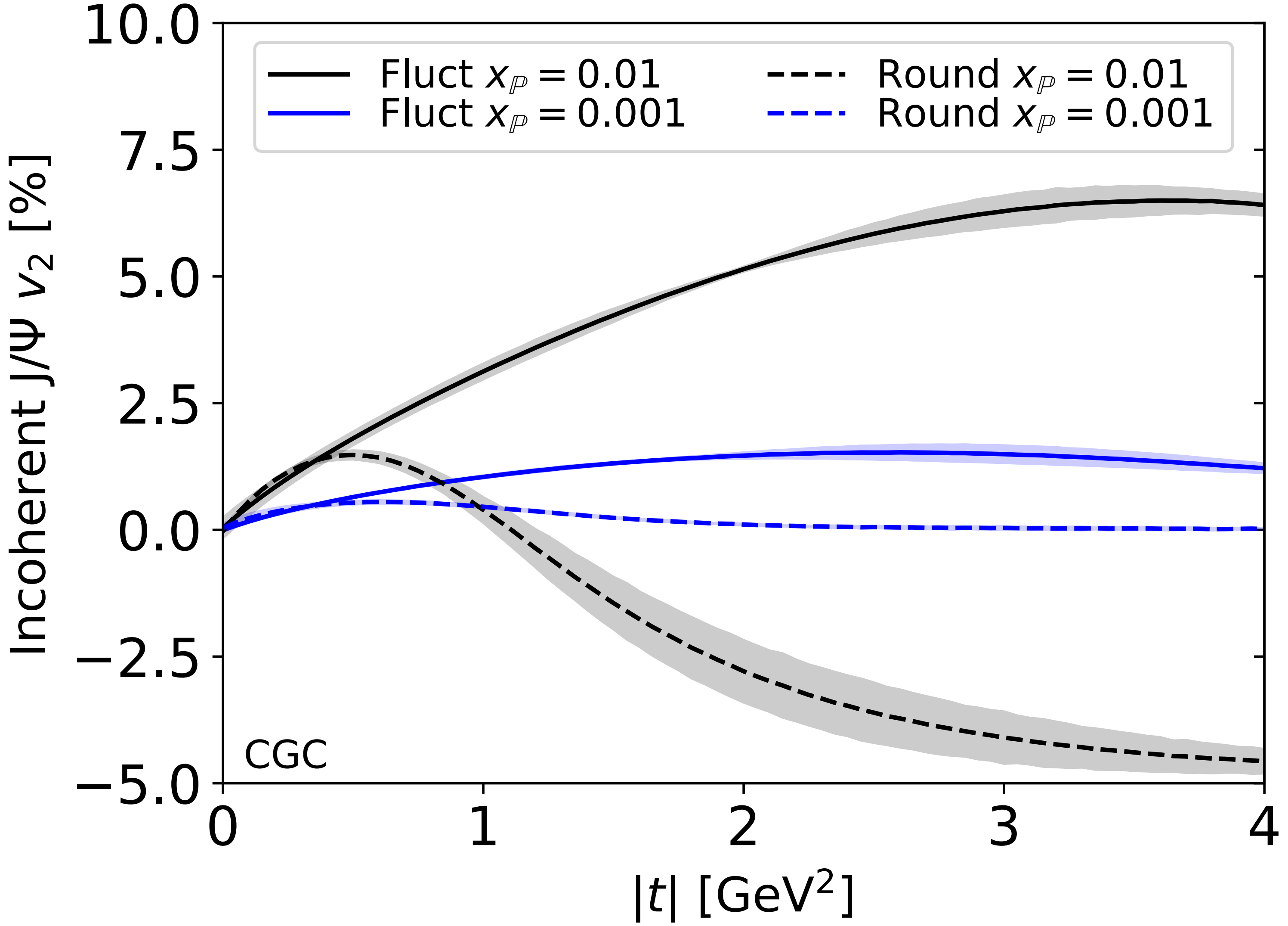
Coherent and incoherent cross-section



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

Incoherent diffraction and fluctuations

J/ψ correlation with electron plane



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

Summary and Outlook

- Identified an observable to access dipole azimuthal correlations at the EIC using diffractive J/ψ production

- Computed expected azimuthal anisotropies at the EIC using impact parameter dependent MV model

  - Promote to our result NLO

    See **Jani's talk** tomorrow for exclusive VM at NLO

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

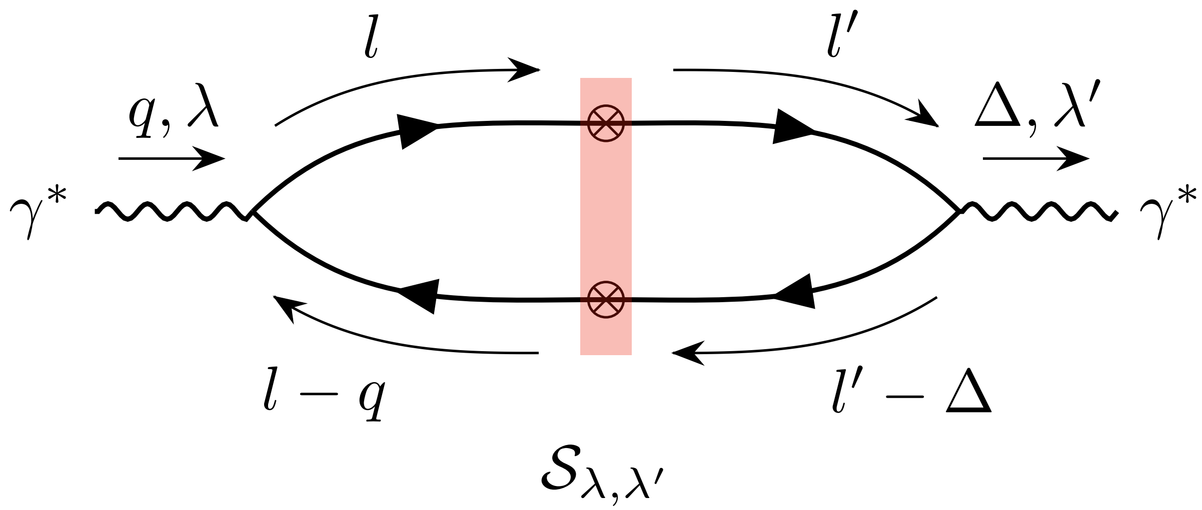
    See **Heikki's talk** right after this talk for more on these correlators and implications

  - Distinguish different geometric fluctuations (e.g. hotspots vs stringy proton) using azimuthal anisotropies

Back-up Slides

Deeply Virtual Compton Scattering

At leading order in the CGC EFT



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 $Q'^2 = 0$).

CGC quark eikonal vertex

$$\mathcal{T}^q_{\sigma\sigma',ij}(l,l') = (2\pi)\delta(l^- - l'^-)\gamma^-_{\sigma\sigma'}\mathrm{sgn}(l^-)\int \mathrm{d}^2\boldsymbol{x}_\perp e^{-i(\boldsymbol{l}_\perp - \boldsymbol{l}'_\perp)\cdot\boldsymbol{x}_\perp} V_{ij}^{\mathrm{sgn}(l^-)}(\boldsymbol{x}_\perp)$$

$$V_{ij}(\boldsymbol{x}_\perp) = P_-\left(\exp\left\{ig\int_{-\infty}^{\infty}\mathrm{d}z^- A^{+,a}_{\mathrm{cl}}(z^-,\boldsymbol{x}_\perp)t^a_{ij}\right\}\right)$$

DVCS and VM production

Collinear limit and GPDs Hatta, Yuan, Xiao. 1703.02085

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

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

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

Helicity preserving

$$\langle \mathcal{M}_{\pm 1, \pm 1}\rangle_Y \sim xH_g(x, \boldsymbol{\Delta}_\perp)$$

Elliptic gluon GPD

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

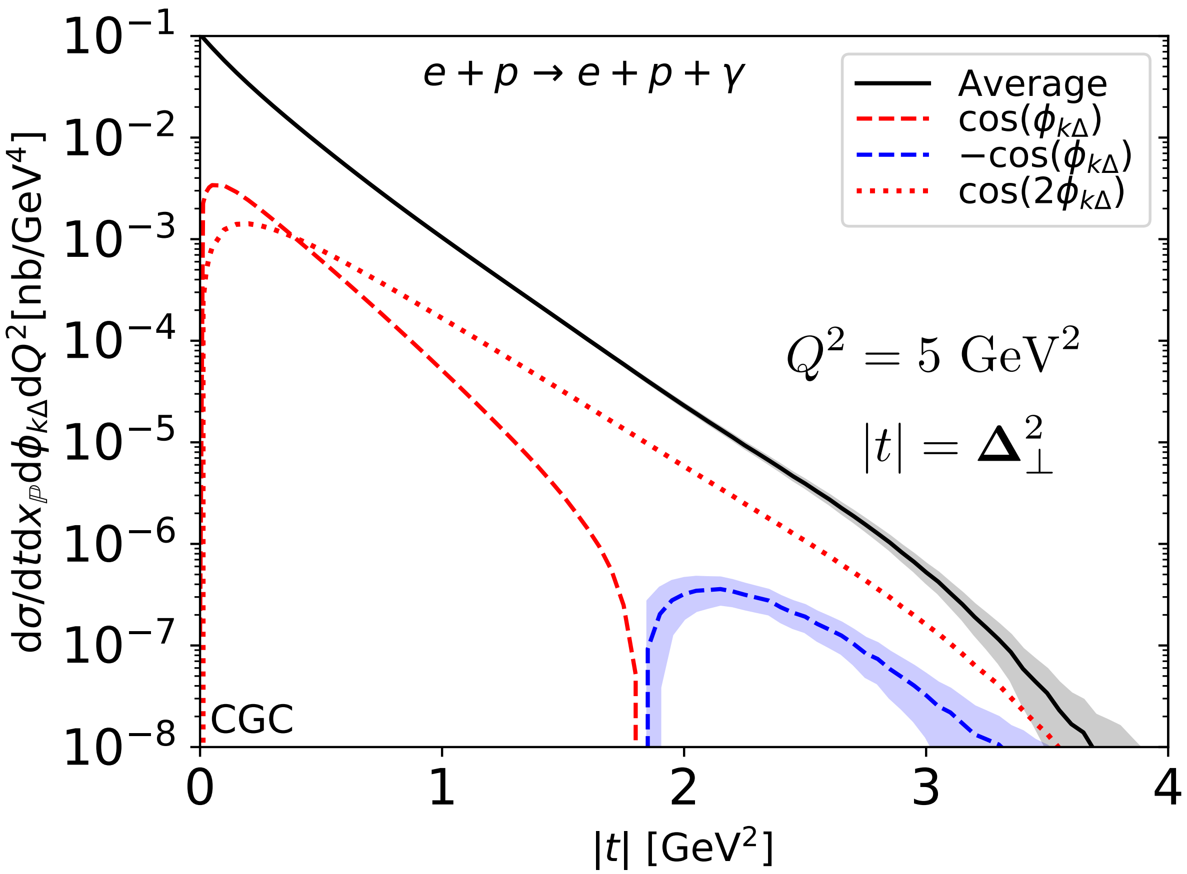
Helicity flip

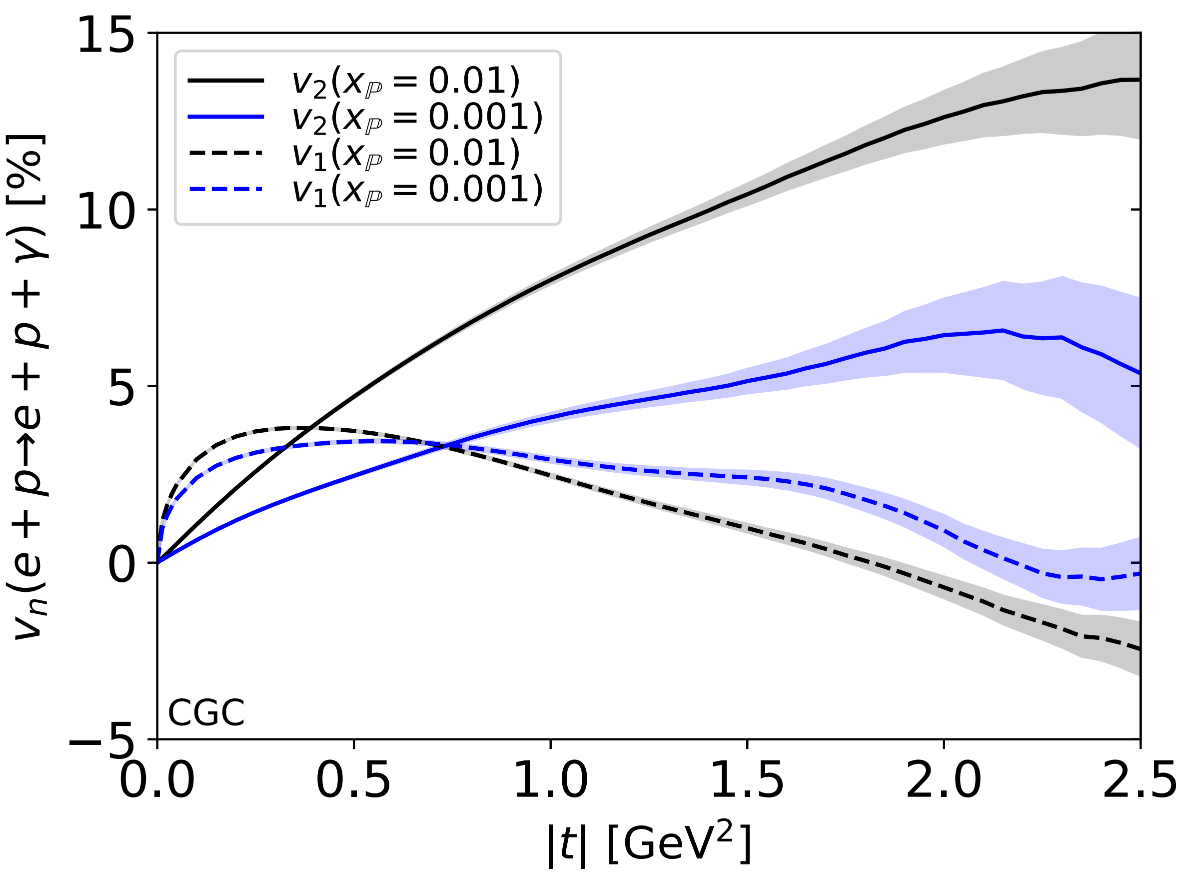
$$\langle \mathcal{M}_{\pm 1, \mp 1}\rangle_Y \sim xE_{Tg}(x, \boldsymbol{\Delta}_\perp)$$

Possible to constrain the Wigner distribution from GPD

Numerical results for DVCS for electron-proton collisions

From impact parameter dependent MV model





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

Azimuthal anisotropies significantly larger than in J/ψ with large contributions for large dipoles