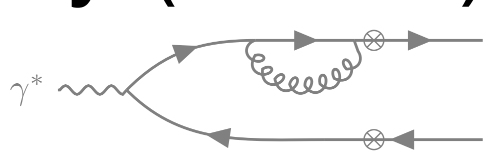
Some Exclusive Processes in DIS at small-x from CGC

Weekly (Virtual) Meeting Exclusive Processes WG



May 15th, 2020

Farid Salazar

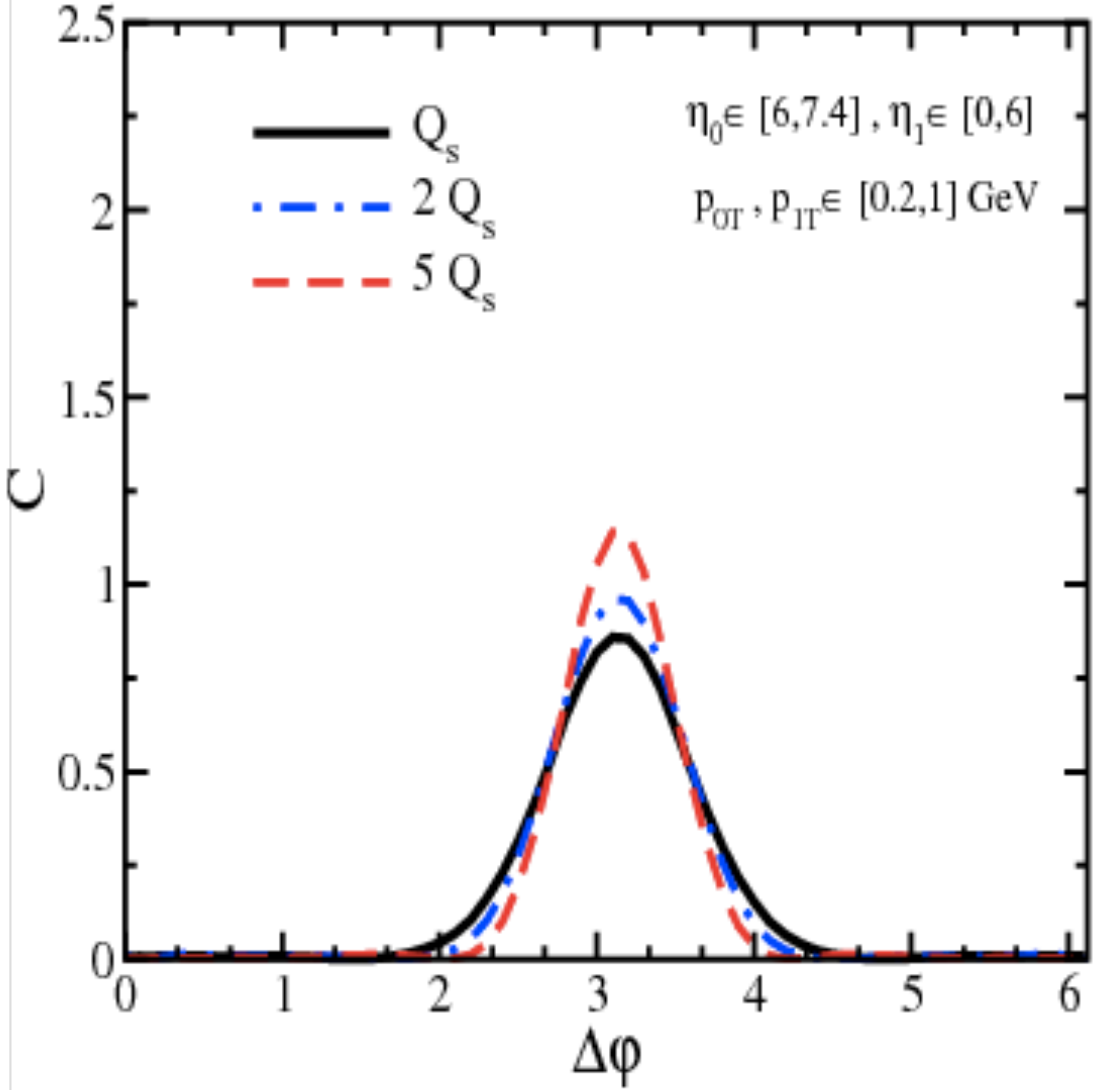
Stony Brook University

Diffractive dijet production in impact parameter dependent saturation models
FS, B. Schenke. Phys. Rev. D 100, 034007 (2019)

Virtual Compton Scattering and Vector Meson production azimuthal correlation with electron plane:
(work in progress with **H. Mäntysaari, K. Roy, B. Schenke)**

Exclusive processes (at small-x) from IP-SAT

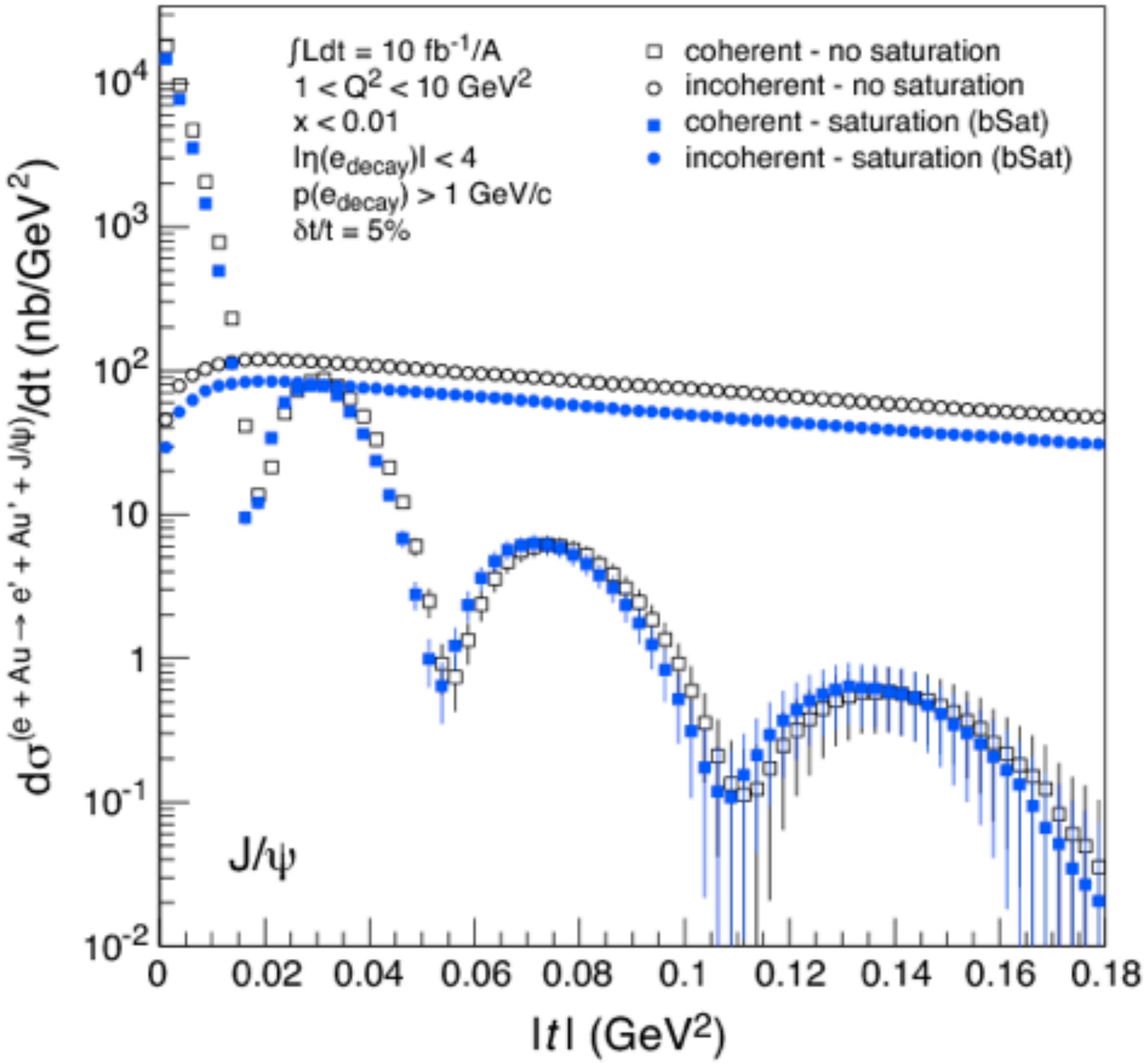
Exclusive Dijets



Back-to-back **enhancement** of Exclusive Dijet production from Impact parameter Saturation **(IP-SAT)** dipole model

T. Altonoluk, N. Armesto, G. Beuf. A, Rezaeian. **Phys.Lett.B 758 (2016) 373-383**

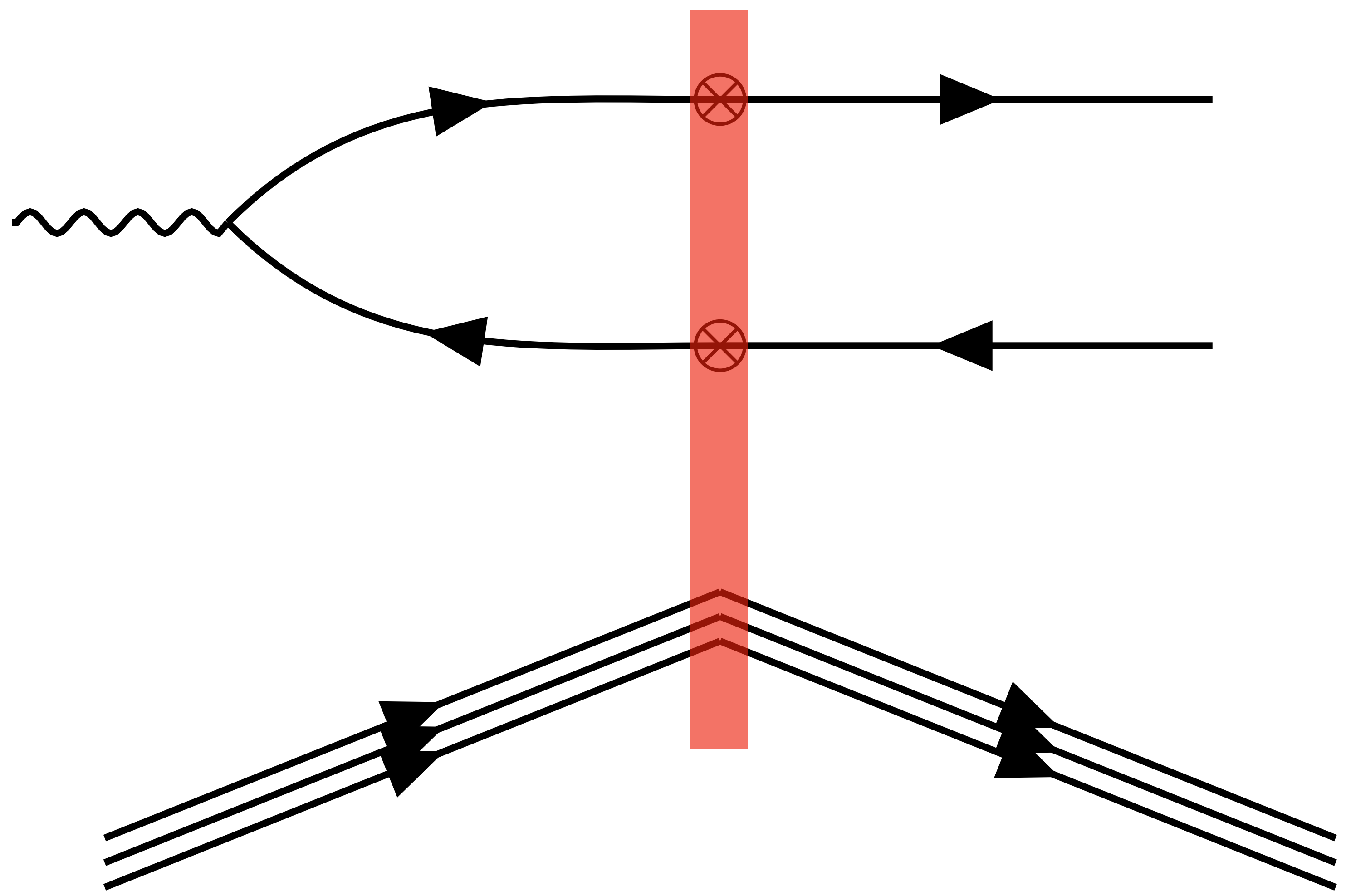
Vector Meson production



Coherent and Incoherent Vector Meson production from **IP-SAT (=bSat)** dipole model (compared to no saturation)

EIC White Paper

Exclusive dijet production at small-x from CGC



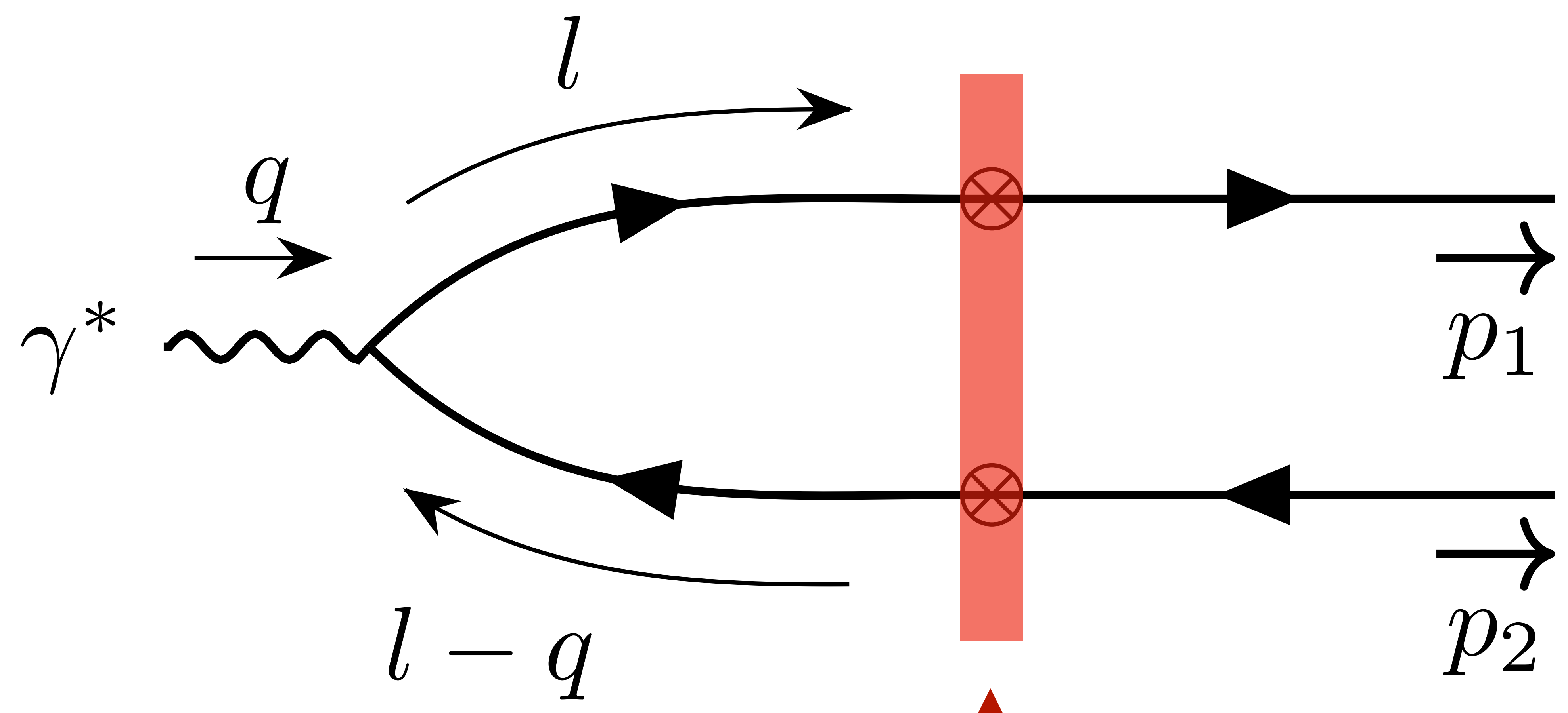
Diffractive dijet production and Wigner distributions from the color glass condensate
H. Mäntysaari, N. Mueller, B. Schenke. **Phys. Rev. D 99, 074004 (2019)**

Diffractive dijet production in impact parameter dependent saturation models
FS, B. Schenke. **Phys. Rev. D 100, 034007 (2019)**

Look also at Heikki's talk at Temple meeting: https://indico.bnl.gov/event/7449/contributions/35851/).

Exclusive dijet production from CGC

The dipole picture: Wilson lines correlators

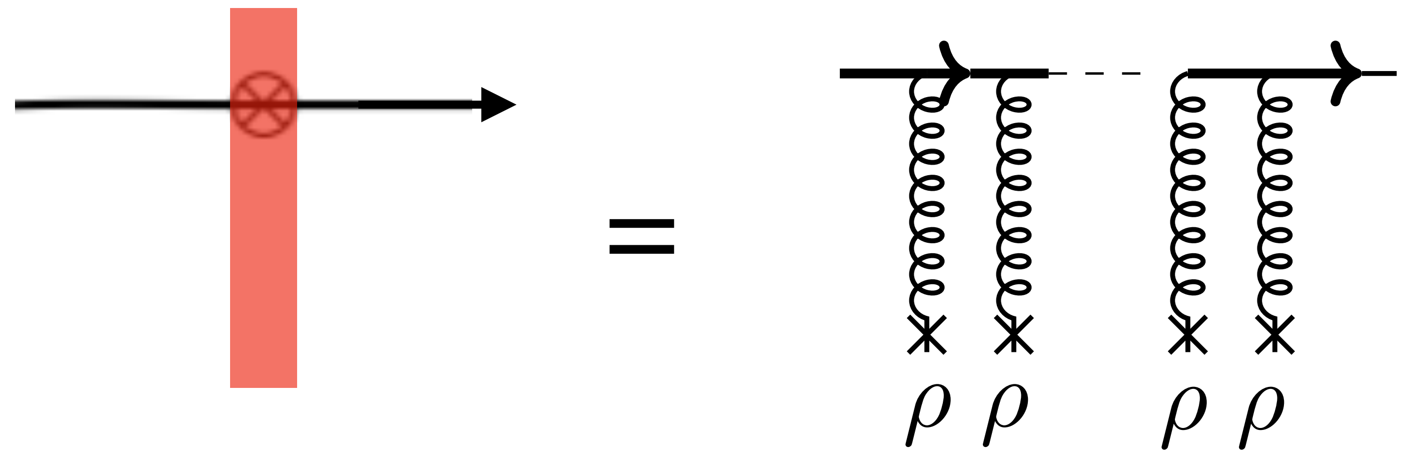


Exclusive process is sensitive to 2-point Wilson line correlator (project to color singlet)

Effective vertices dipole interaction with target through Wilson lines, the rest is pQCD (at partonic level)

$$S^{(2)}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp) = \frac{1}{N_c} \left\langle \mathrm{Tr}\left[V(\boldsymbol{x}_\perp)V^\dagger(\boldsymbol{y}_\perp)\right]\right\rangle_{x_g}$$

$$V(\boldsymbol{x}_\perp) = P\exp\left\{ig\int dx^- A^{+,a}(\boldsymbol{x}_\perp, x^-)t^a\right\}$$



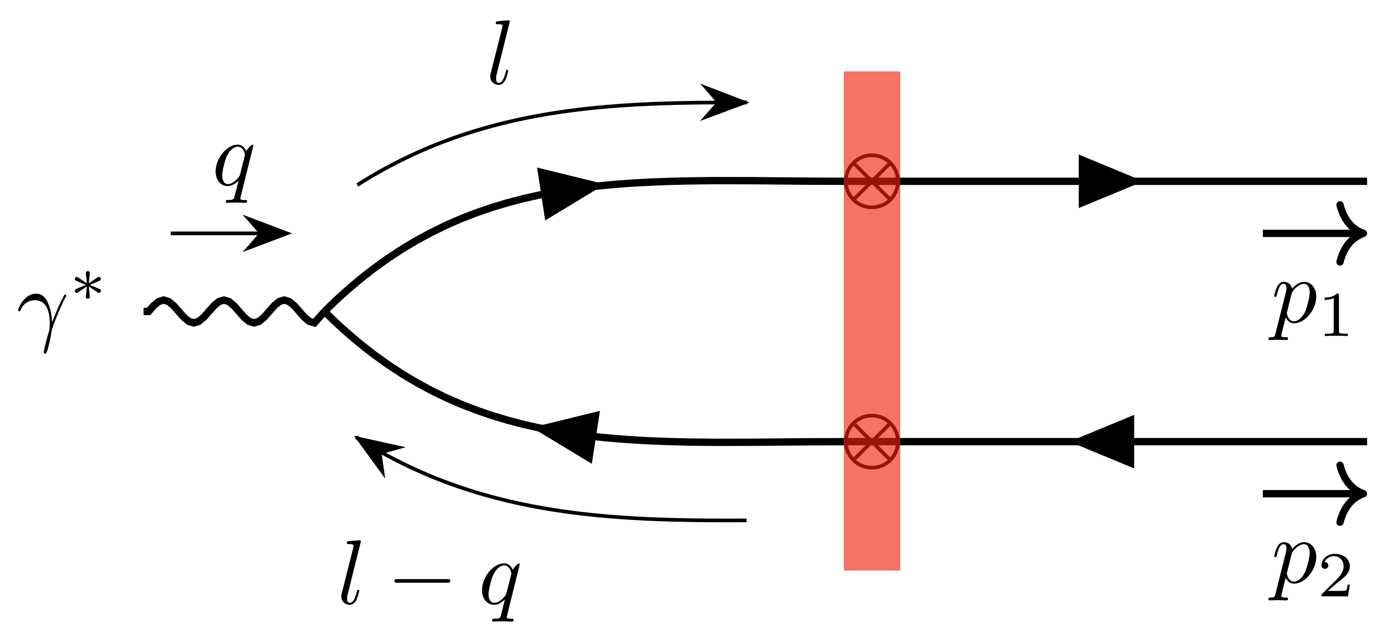
Effective vertex resums multiple gluon exchanges

ρ^a **static color sources (large-x)**

$$A^{+,a} = -\frac{g\rho^a}{\nabla^2 + m^2}$$ **gauge field (small-x)**

Exclusive dijet production from CGC

The dipole picture: Kinematics



$Q^2 = -q^2$ photon virtuality

W^2 center of momentum energy $\gamma^* p$

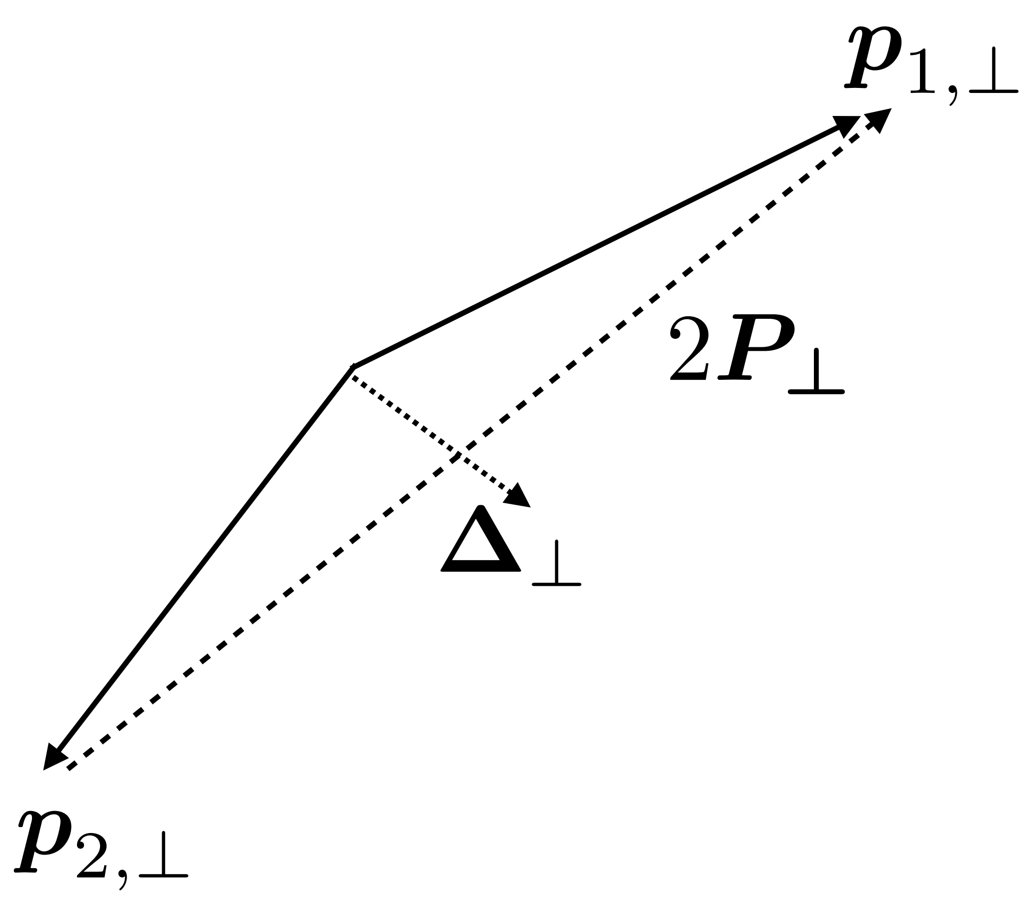
x_g probed depends on final state kinematics

$$\boldsymbol{P}_\perp = \frac{1}{2}\left(\boldsymbol{p}_{\perp,1} - \boldsymbol{p}_{\perp,2}\right)$$

~ mean jet momenta

$$\boldsymbol{\Delta}_\perp = \boldsymbol{p}_{1,\perp} + \boldsymbol{p}_{2,\perp}$$

momentum imbalance



$$x_g = \frac{Q^2 + M_{\mathrm{inv}}^2 + \Delta_\perp^2}{W^2} \qquad M_{\mathrm{inv}}^2 \approx 4P_\perp^2$$

Requirement of small $x_g \leq 10^{-2}$ restricts the phase space, large invariant mass probes large x_g

At EIC energies: $P_\perp \lesssim \ 4\mathrm{GeV}\ (\mathrm{Gold}), \quad 6\ \mathrm{GeV}\ (\mathrm{proton})$

Exclusive dijet production

Dipole picture and IPSAT

Cross-section: $$d\sigma^{\gamma^* p\to q\bar{q}p} = \frac{1}{2q^-}\left|\mathcal{A}^{\gamma^* p\to q\bar{q}p}\right|^2 d\Pi_{PS}$$

QED QCD

Amplitude: $$\mathcal{A}^{\gamma^* p\to q\bar{q}p}(\boldsymbol{P}_\perp,\boldsymbol{\Delta}_\perp) \sim \int_{\boldsymbol{r}_\perp,\boldsymbol{b}_\perp} e^{-i\boldsymbol{P}_\perp\cdot\boldsymbol{r}_\perp} e^{-i\boldsymbol{\Delta}_\perp\cdot\boldsymbol{b}_\perp} \boxed{\Psi^{\gamma^*\to q\bar{q}}(\boldsymbol{r}_\perp)} \boxed{\left(1 - S^{(2)}(\boldsymbol{r}_\perp,\boldsymbol{b}_\perp)_{x_g}\right)}$$

Impact Parameter Saturation (IP-SAT)

Impact parameter $b_\perp$ dependence

$$\boxed{S^{(2)}(r_\perp,b_\perp)_{x_g}} = \exp\left\{-\frac{\pi^2}{2N_c} r_\perp^2 \alpha_s(\mu^2) x_g g(x_g,\mu^2) T_p(b_\perp)\right\} \qquad T_p(b_\perp) = \frac{1}{2\pi B_p}\exp\left\{-\frac{b_\perp^2}{2B_p}\right\}$$

IP-SAT and b-CGC include impact parameter dependence, but **do not include** dependence on dipole **orientation.**

$\longrightarrow$ **no angular correlations between $P_\perp$ and $\Delta_\perp$**

IP-SAT. H. Kowalski, D. Teaney. **Phys.Rev.D 68 (2003) 114005**

b-CGC. Watt and H. Kowalski. **Phys. Rev. D78 (2008) 014016**

Exclusive dijet production

Color Glass Condensate and dipole angular correlations

Cross-section: $$d\sigma^{\gamma^* p \to q\bar{q}p} = \frac{1}{2q^-}\left|\mathcal{A}^{\gamma^* p\to q\bar{q}p}\right|^2 d\Pi_{PS}$$

QED QCD

Amplitude: $$\mathcal{A}^{\gamma^* p \to q\bar{q}p}(\boldsymbol{P}_\perp, \boldsymbol{\Delta}_\perp) \sim \int_{\boldsymbol{r}_\perp, \boldsymbol{b}_\perp} e^{-i\boldsymbol{P}_\perp\cdot\boldsymbol{r}_\perp} e^{-i\boldsymbol{\Delta}_\perp\cdot\boldsymbol{b}_\perp} \Psi^{\gamma^*\to q\bar{q}}(\boldsymbol{r}_\perp)\left(1 - S^{(2)}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)_{x_g}\right)$$

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

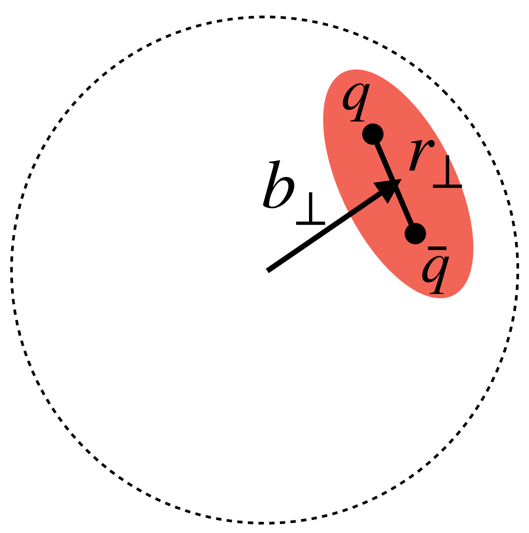
Correlator of 2-light-like Wilson lines
(scattering of dipole)

Color Glass Condensate: $$\langle \rho^a(\boldsymbol{x}_\perp, x^-)\rho^b(\boldsymbol{y}_\perp, y^-)\rangle_{x_0} = \mu^2\delta^{ab}\delta^{(2)}(\boldsymbol{x}_\perp - \boldsymbol{y}_\perp)\,\delta(x^- - y^-)T_p(\boldsymbol{x}_\perp)$$

strength of color charge fluctuations depends on impact parameter

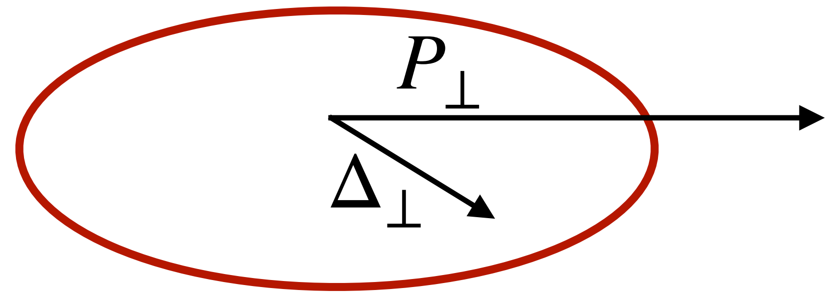
$$S^{(2)}(r_\perp, b_\perp, \phi_{\boldsymbol{rb}})_{x_g}$$

dipole orientation dependence from gradients of strength of color charge*



$$\longrightarrow \quad d\sigma^{\gamma^* p\to q\bar{q}p}(P_\perp, \Delta_\perp, \phi_{\boldsymbol{P\Delta}})$$

angular correlations between $\boldsymbol{P}_\perp$ and $\boldsymbol{\Delta}_\perp$



For analytic model of dipole from modified MV model.
E. Iancu, A. Rezaeian. **Phys. Rev. D 95, 094003 (2017)**

*decreased by JIMWLK evolution from x_0 to x_g

Exclusive dijet production from CGC

Color Glass Condensate and dipole angular correlations

Cross-section: $$d\sigma^{\gamma^* p\to q\bar{q}p} = \frac{1}{2q^-}\left|\mathcal{A}^{\gamma^* p\to q\bar{q}p}\right|^2 d\Pi_{PS}$$

QED QCD

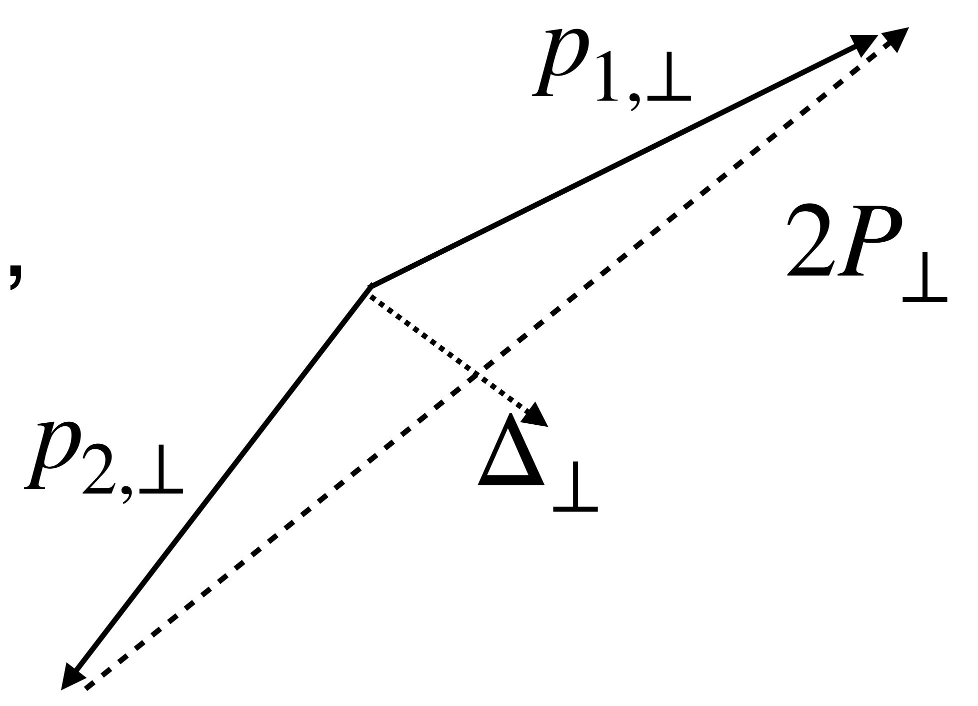
Amplitude: $$\mathcal{A}^{\gamma^* p\to q\bar{q}p}(\boldsymbol{P}_\perp,\boldsymbol{\Delta}_\perp) \sim \int_{\boldsymbol{r}_\perp,\boldsymbol{b}_\perp} e^{-i\boldsymbol{P}_\perp\cdot\boldsymbol{r}_\perp} e^{-i\boldsymbol{\Delta}_\perp\cdot\boldsymbol{b}_\perp} \Psi^{\gamma^*\to q\bar{q}}(\boldsymbol{r}_\perp)\left(1 - S^{(2)}(\boldsymbol{r}_\perp,\boldsymbol{b}_\perp)_{x_g}\right)$$

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

Correlator of 2-light-like Wilson lines
(scattering of dipole)

A beautiful connection:

In the **back-to-back limit** $(\Delta_\perp \ll P_\perp)$ and **photo-production** $Q^2 \approx 0$, there is a direct relation with gluon dipole **Wigner distribution**.



Angular dependence allows access to elliptic part of Wigner.

Y. Hatta, B. Xiao, F. Yuan. **Phys. Rev. Lett. 116, 202301 (2016)**

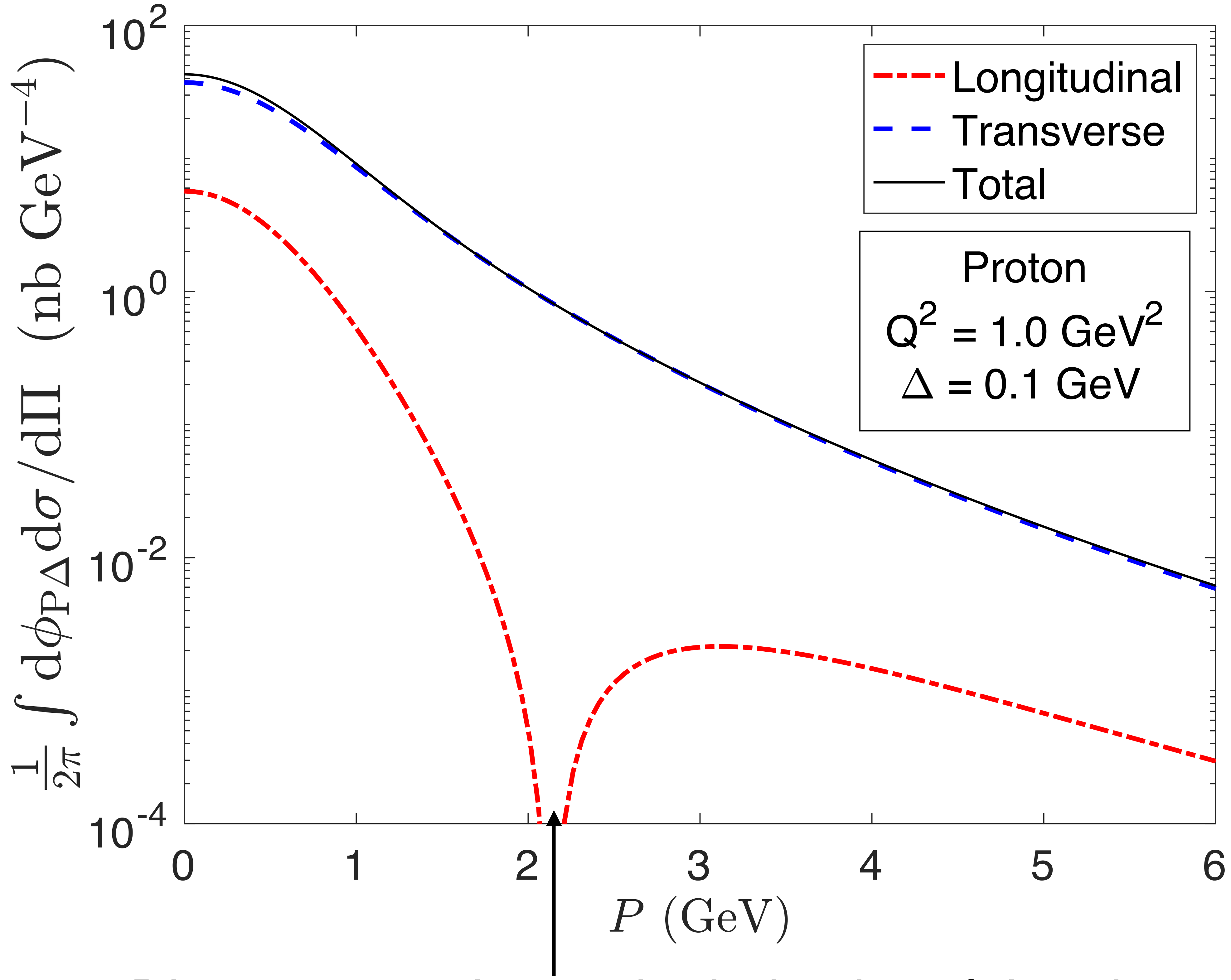
Y. Haggiwara et al. **Phys. Rev. D 96, 034009 (2017)**

Exclusive dijet production from CGC

Numerical results: differential cross section*

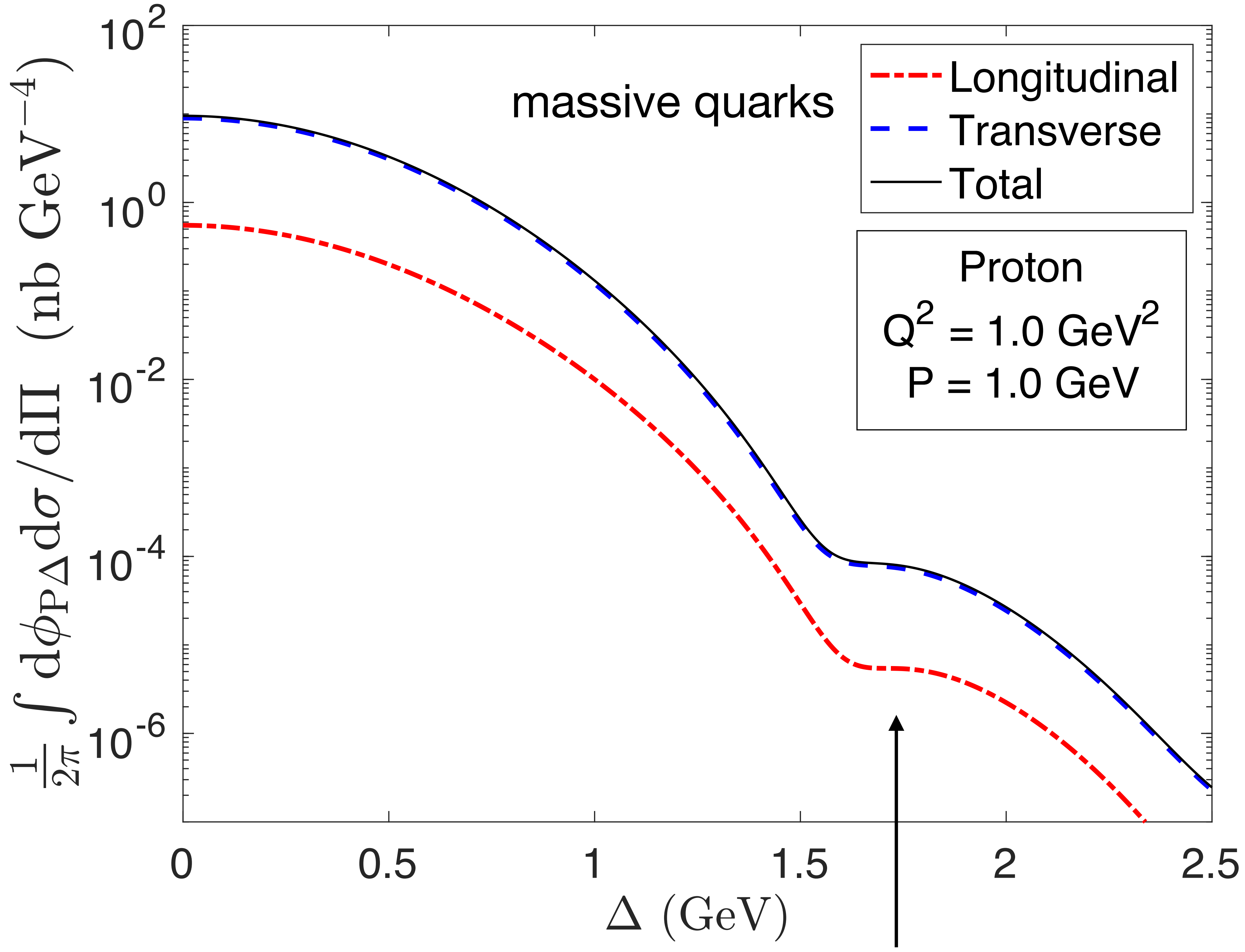
$$\frac{d\sigma}{d\Pi} = \frac{d\sigma^{\gamma^* p \to q\bar{q}p}}{dz_1 dz_2 d^2\boldsymbol{P}_\perp d^2\boldsymbol{\Delta}_\perp}$$

P-dependence of angle averaged differential cross section



Dip structure due to the behavior of the photon-dipole splitting function (longitudinal)

P-dependence of angle averaged differential cross section



Dip-like structures due to saturation (otherwise Gaussian).

*massive quarks

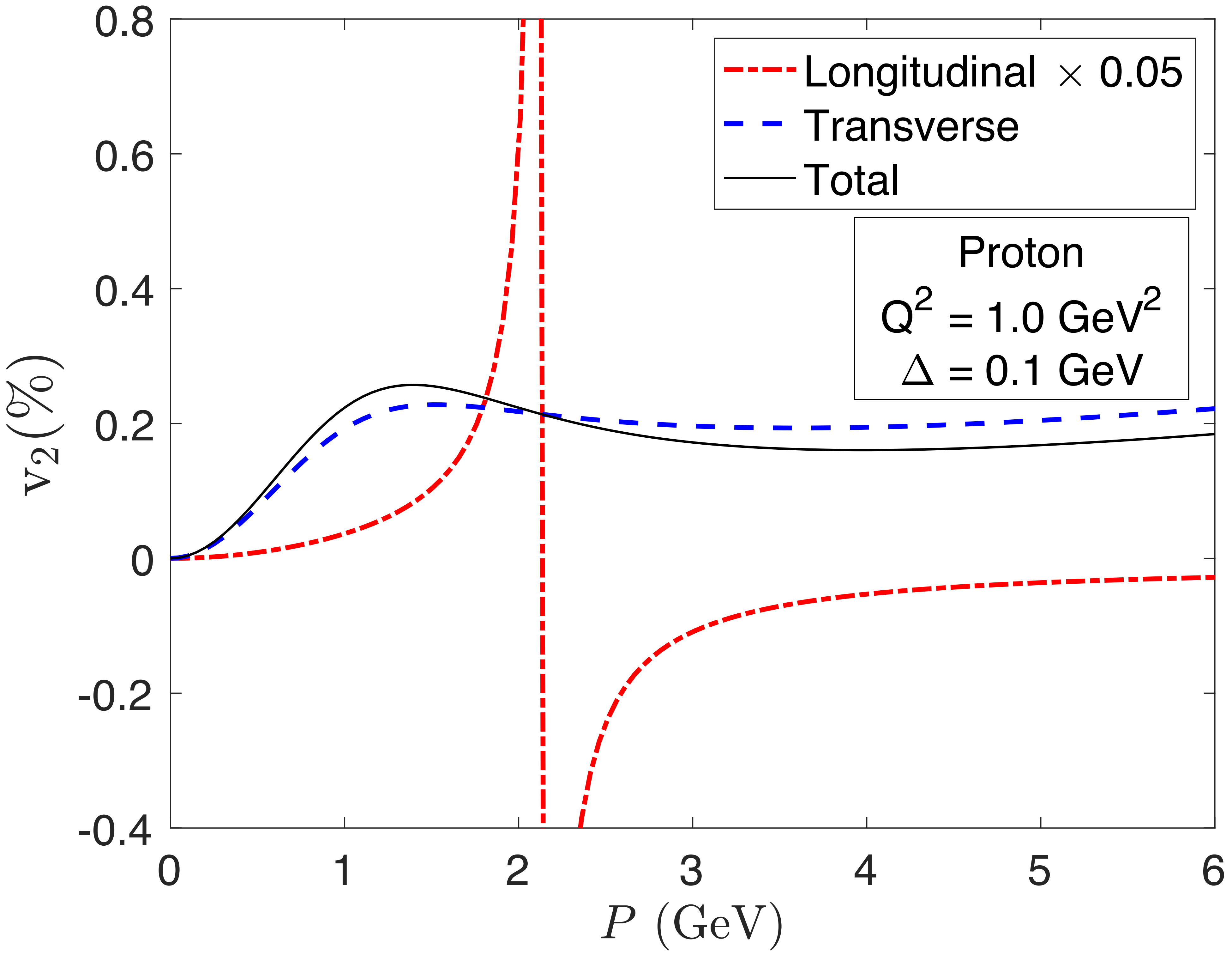
H. Mäntysaari, N. Mueller, B. Schenke. **Phys. Rev. D 99, 074004 (2019)**
FS, B. Schenke. **Phys. Rev. D 100, 034007 (2019)**

Exclusive dijet production from CGC

Numerical results: Elliptic anisotropy*

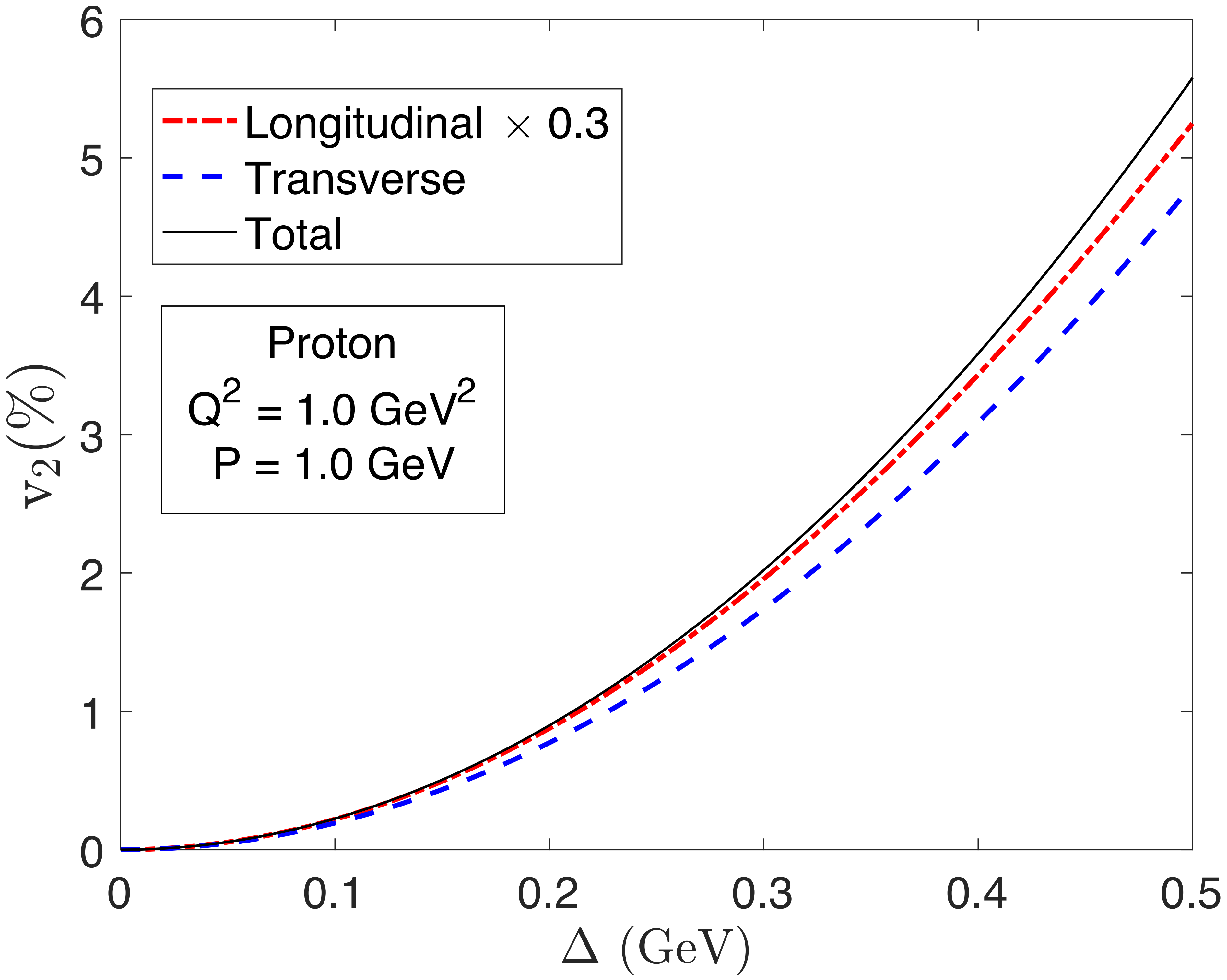
$$v_2 = \frac{\int d\phi_{P\Delta} \cos 2\phi_{P\Delta} \frac{d\sigma}{d\Pi}}{\int d\phi_{P\Delta} \frac{d\sigma}{d\Pi}}$$

P-dependence of elliptic anisotropy



At small Δ the (total) elliptic anisotropy is a few tenths of percent across different values of P.

Δ-dependence of elliptic anisotropy



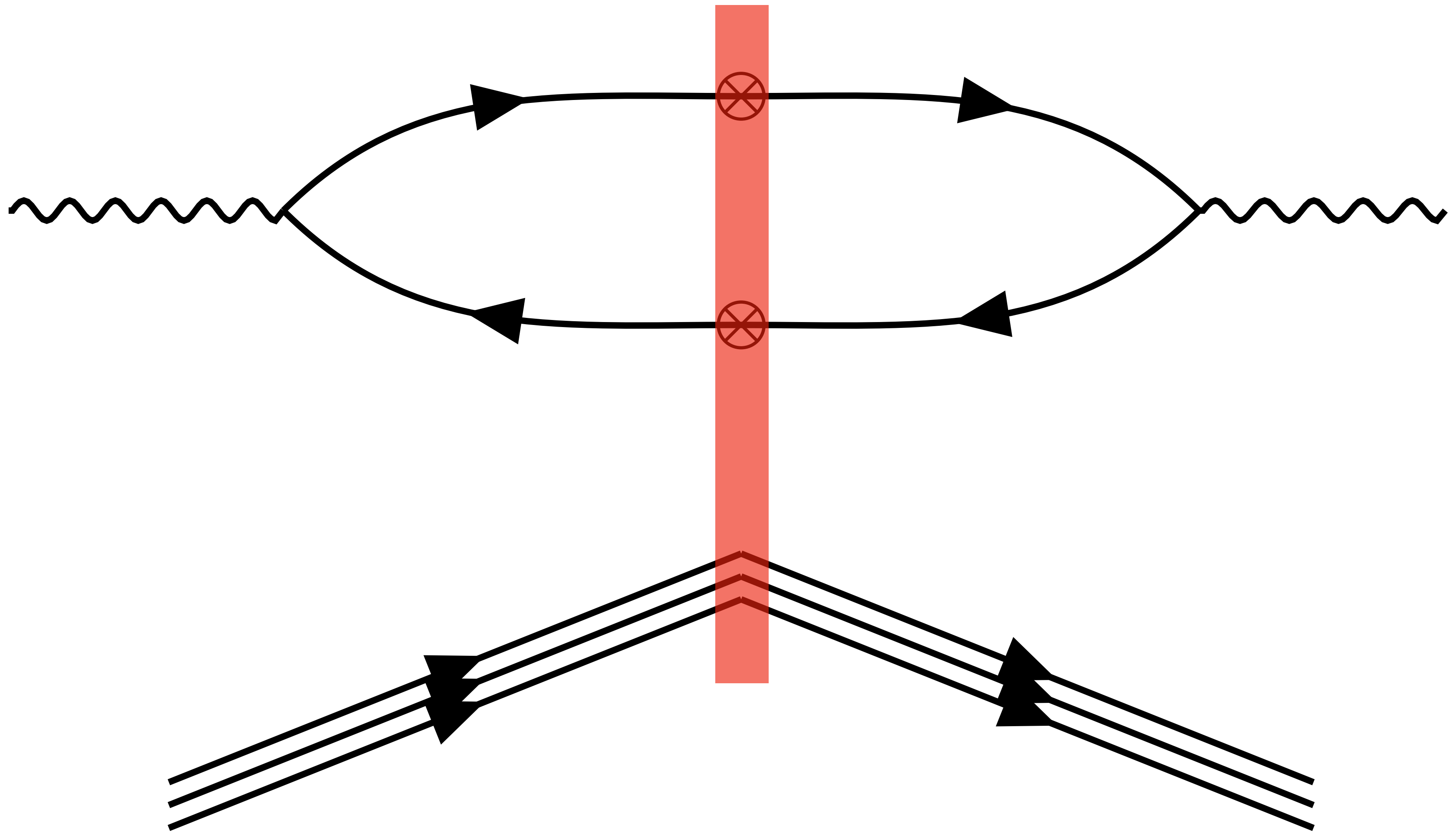
Increasing Δ results in larger values of (total) elliptic anisotropy of several percent.

*massive quarks

H. Mäntysaari, N. Mueller, B. Schenke. **Phys. Rev. D 99, 074004 (2019)**

FS, B. Schenke. **Phys. Rev. D 100, 034007 (2019)**

Virtual Compton Scattering and Vector Meson production at small-x from CGC



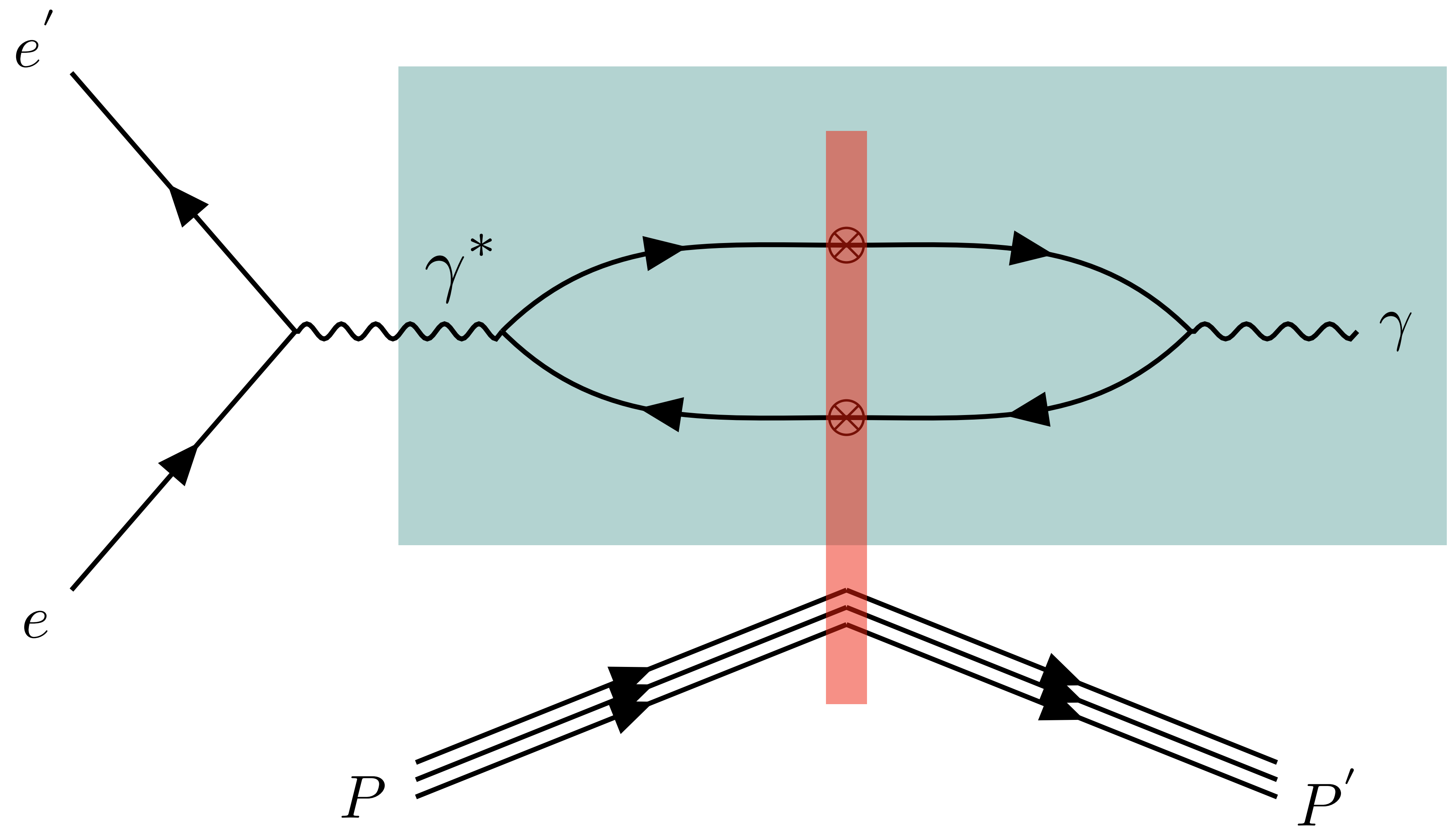
Virtual Compton Scattering and Vector Meson production: correlation with electron angle from CGC

(work in progress with H. Mäntysaari, K. Roy, B. Schenke)

Virtual Compton Scattering

Amplitude, electron-photon correlations and polarization change

Y. Hatta, B. Xiao, F. Yuan. **Phys. Rev. D 95, 114026 (2017)**



$\mathcal{A}_{\lambda\lambda'}$ amplitude for hadronic sub-process

λ polarization virtual photon γ^*

λ' polarization real photon γ

$\mathcal{A}_{TT}$ dominant contribution (polarization preserving)

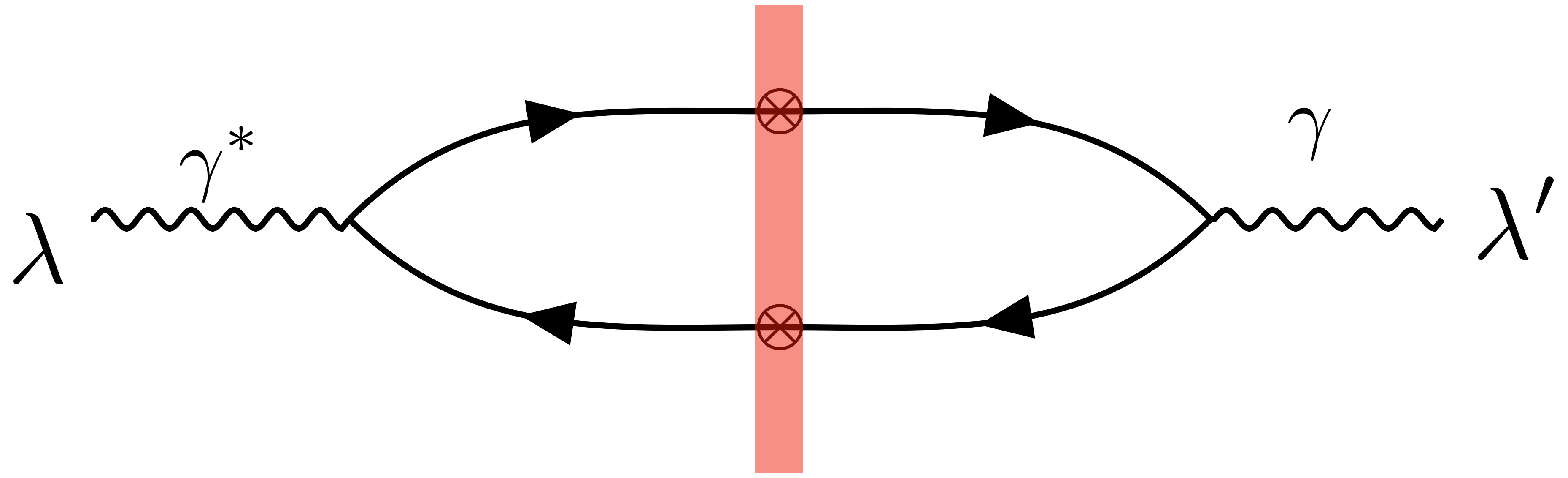
$$\frac{d\sigma^{ep\to e'\gamma p}}{\Delta_\perp d\Delta_\perp d\phi_{e\Delta_\perp} dx_B dQ^2} = \frac{\alpha_{em}^3}{\pi x_B Q^2}\left\{\frac{1}{2}\left[1+(1-y)^2\right]\left[\mathcal{A}_{TT}^2+\mathcal{A}_{TT,\text{flip}}^2\right]+2(1-y)\mathcal{A}_{LT}^2 \right.$$
$$-\sqrt{2}(2-y)\sqrt{1-y}\mathcal{A}_{LT}\left[\mathcal{A}_{TT}+\mathcal{A}_{TT,\text{flip}}\right]\cos\left(\phi_{e\Delta_\perp}\right)$$
$$\left. +2(1-y)\mathcal{A}_{TT}\mathcal{A}_{TT,\text{flip}}\cos\left(2\phi_{e\Delta_\perp}\right)\right\}$$

$\phi_{e\Delta_\perp}$ angle between electron plane and real photon

*Not considering Bethe-Heitler contribution (supressed at small-x)

Virtual Compton Scattering

Non-forward phase and dipole angular correlations



Polarization changes due to:

- non-forward phase (kinematic) $\boldsymbol{\delta}_\perp = \left(\frac{2z-1}{2}\right)\boldsymbol{\Delta}_\perp$
- dipole angular correlations between $\boldsymbol{r}_\perp$ and $\boldsymbol{b}_\perp$ (dynamical)*

$$\mathcal{A}_{TT} = \frac{4N_c q_f^2}{(2\pi)^2}\int d^2\boldsymbol{b}_\perp e^{-i\boldsymbol{\Delta}_\perp\cdot\boldsymbol{b}_\perp}\int_0^1 \frac{dz}{4\pi}\left[z^2+(1-z)^2\right]\int d^2\boldsymbol{r}_\perp e^{-i\boldsymbol{\delta}_\perp\cdot\boldsymbol{r}_\perp}\varepsilon K_1(\varepsilon r_\perp)\frac{1}{r_\perp}D\left(\boldsymbol{r}_\perp,\boldsymbol{b}_\perp\right)$$

$$\mathcal{A}_{TT,\text{flip}} = -\frac{8N_c q_f^2}{(2\pi)^2}\int d^2\boldsymbol{b}_\perp e^{-i\boldsymbol{\Delta}_\perp\cdot\boldsymbol{b}_\perp}\int_0^1 \frac{dz}{4\pi}z(1-z)\int d^2\boldsymbol{r}_\perp e^{-i\boldsymbol{\delta}_\perp\cdot\boldsymbol{r}_\perp}e^{2i\phi_{\boldsymbol{r}\boldsymbol{\Delta}}}\varepsilon K_1(\varepsilon r_\perp)\frac{1}{r_\perp}D\left(\boldsymbol{r}_\perp,\boldsymbol{b}_\perp\right)$$

$$\mathcal{A}_{LT} = -\frac{i4\sqrt{2}N_c q_f^2}{(2\pi)^2}\int d^2\boldsymbol{b}_\perp e^{-i\boldsymbol{\Delta}_\perp\cdot\boldsymbol{b}_\perp}\int_0^1 \frac{dz}{4\pi}z(1-z)(2z-1)\int d^2\boldsymbol{r}_\perp e^{-i\boldsymbol{\delta}_\perp\cdot\boldsymbol{r}_\perp}e^{i\phi_{\boldsymbol{r}\boldsymbol{\Delta}}}QK_0(\varepsilon r_\perp)\frac{1}{r_\perp}D\left(\boldsymbol{r}_\perp,\boldsymbol{b}_\perp\right)$$

$$D(\boldsymbol{r}_\perp,\boldsymbol{b}_\perp) = 1 - S^{(2)}(\boldsymbol{r}_\perp,\boldsymbol{b}_\perp)_{x_g} \qquad \varepsilon^2 = z(1-z)Q^2$$

Expressions for $\mathcal{A}_{\lambda\lambda'}$ are consistent with results in

Y. Hatta, B. Xiao, F. Yuan. **Phys. Rev. D 95, 114026 (2017)**

*Connection to GPDs in the collinear limit. Access helicity flip gluon GPD.

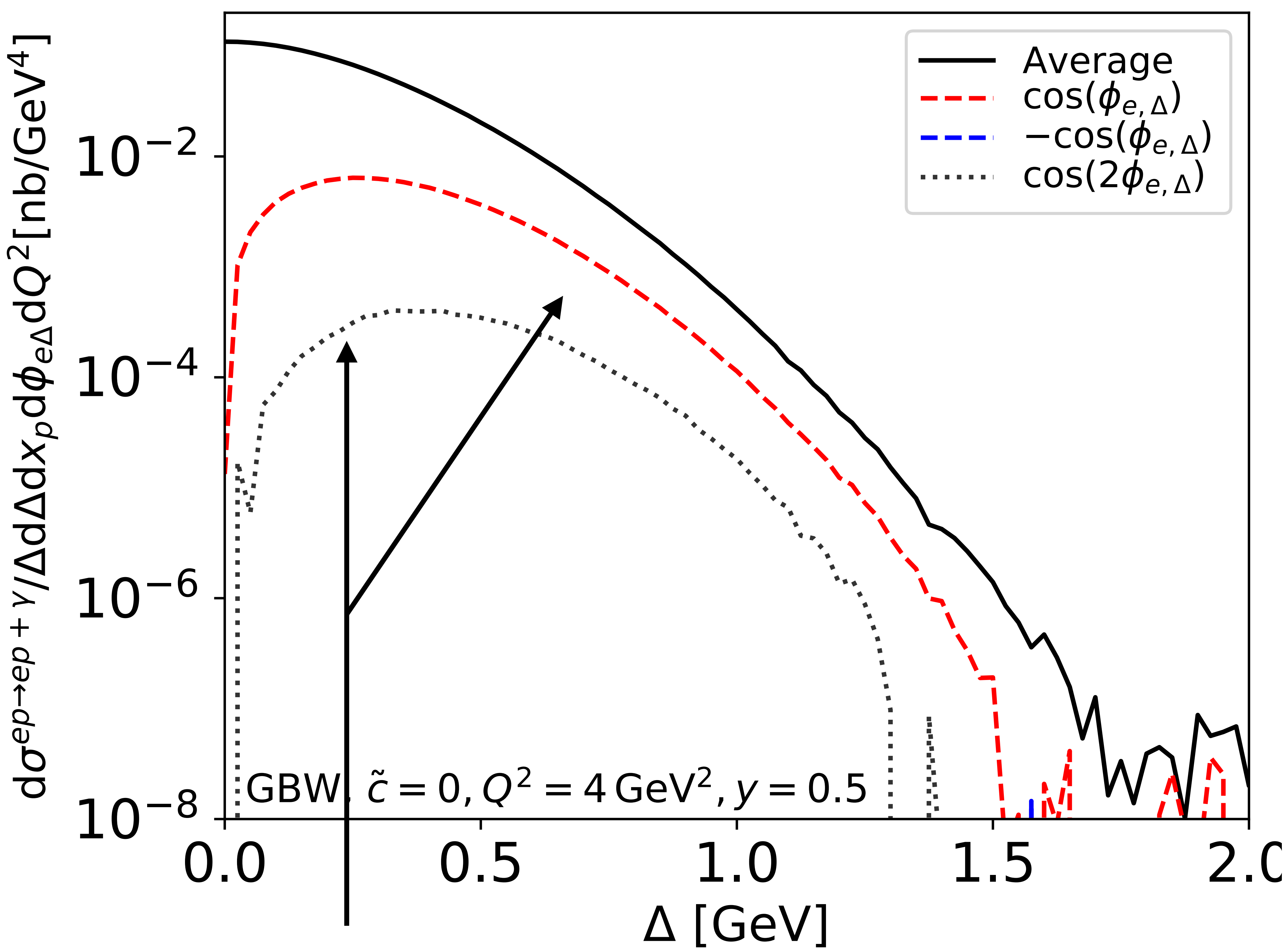
Virtual Compton Scattering

GBW dipole, proton (work in progress)

GBW dipole:

$$S^{(2)}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) = \exp\left\{-\frac{1}{4}Q_s^2 r_\perp^2 T_p(b_\perp)\left(1 + \tilde{c}\cos(2\phi_{\boldsymbol{rb}})\right)\right\}$$

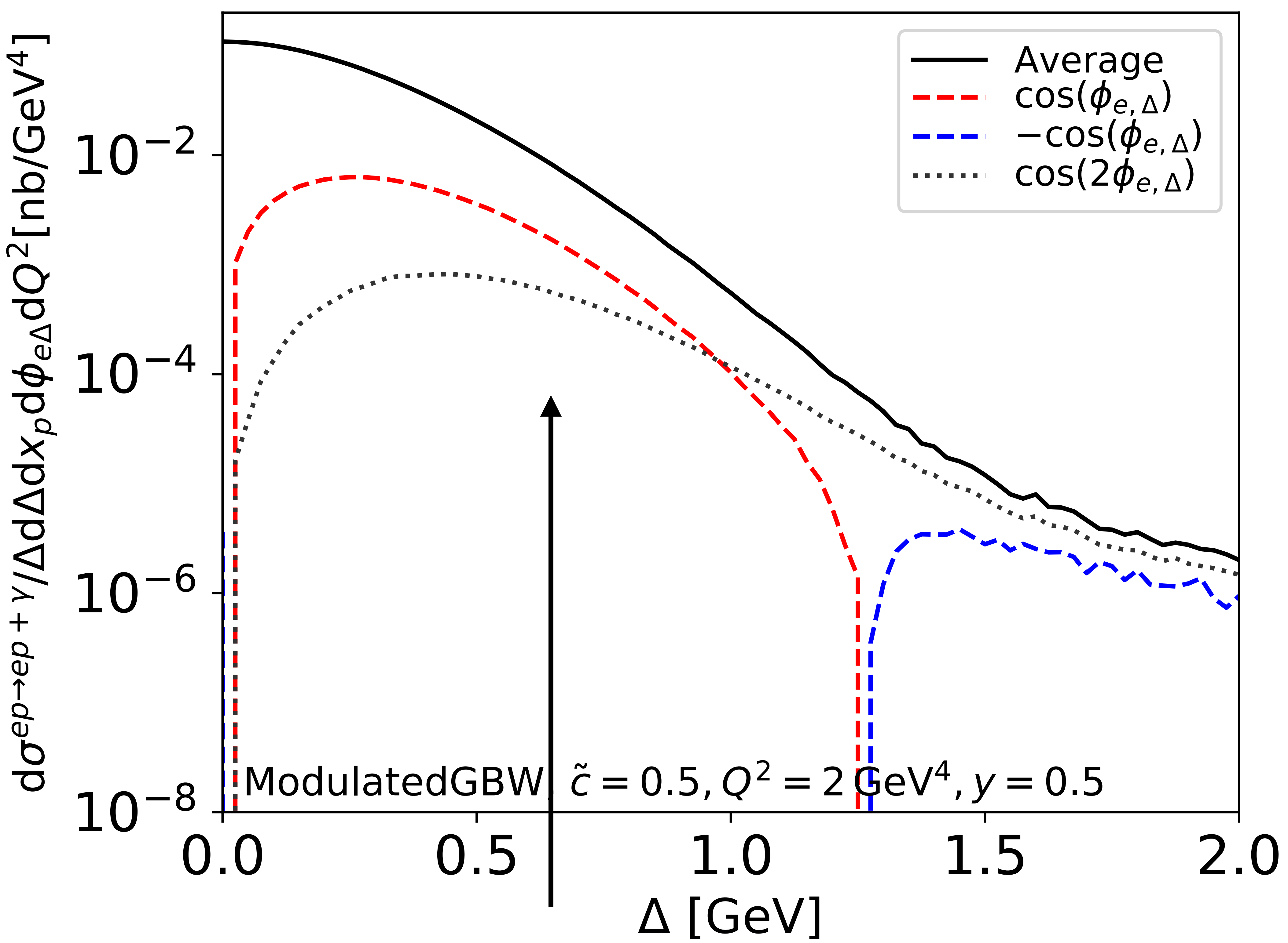
GBW dipole $\tilde{c} = 0$



angular modulation due solely non-forward phase

$\cos(\phi_{e\Delta})$ dominant modulation

GBW dipole with modulations ($\tilde{c}$ nonzero)

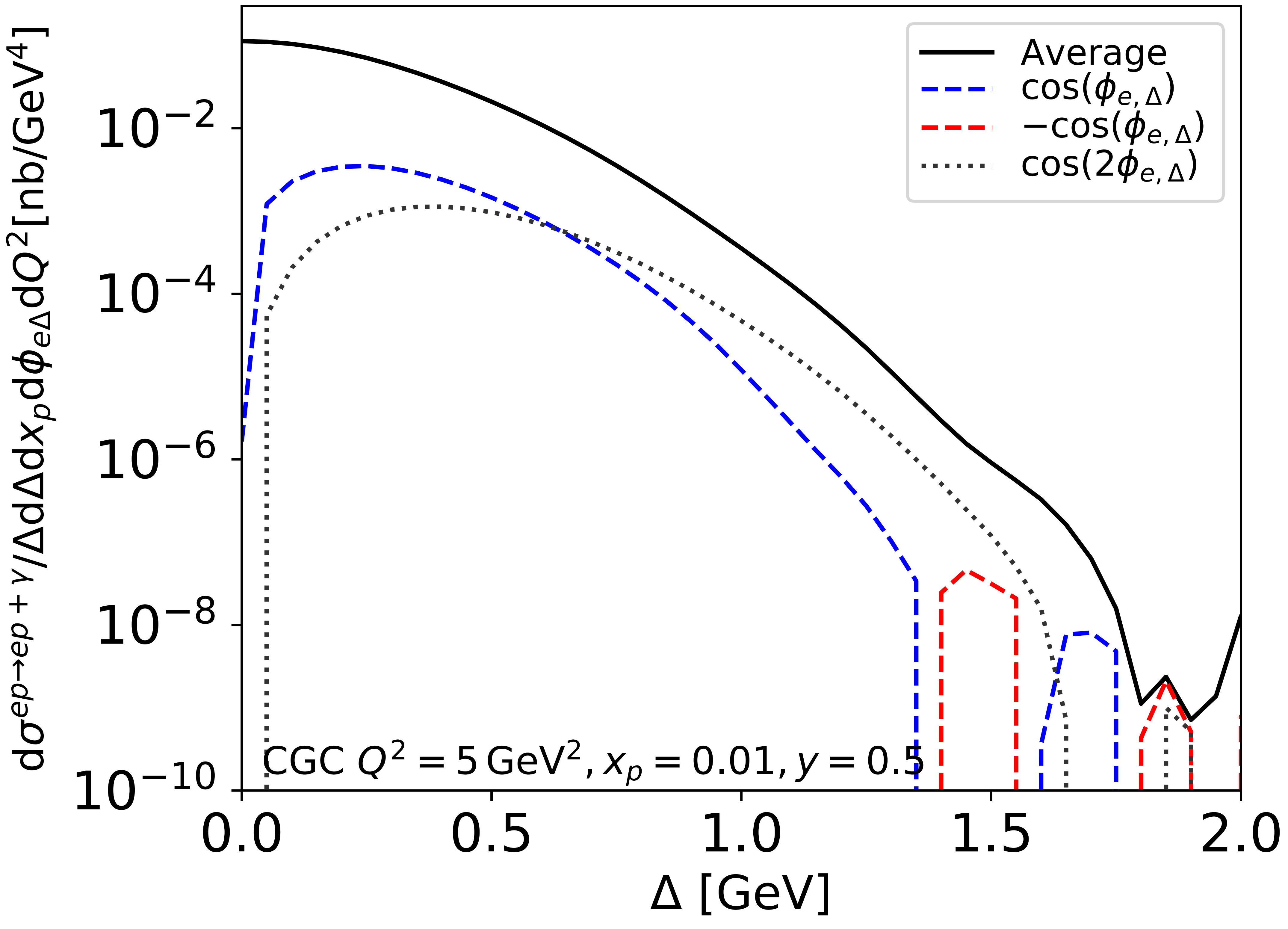


significant increase in $\cos(2\phi_{e\Delta})$ modulation due to dipole angular modulation

Virtual Compton Scattering

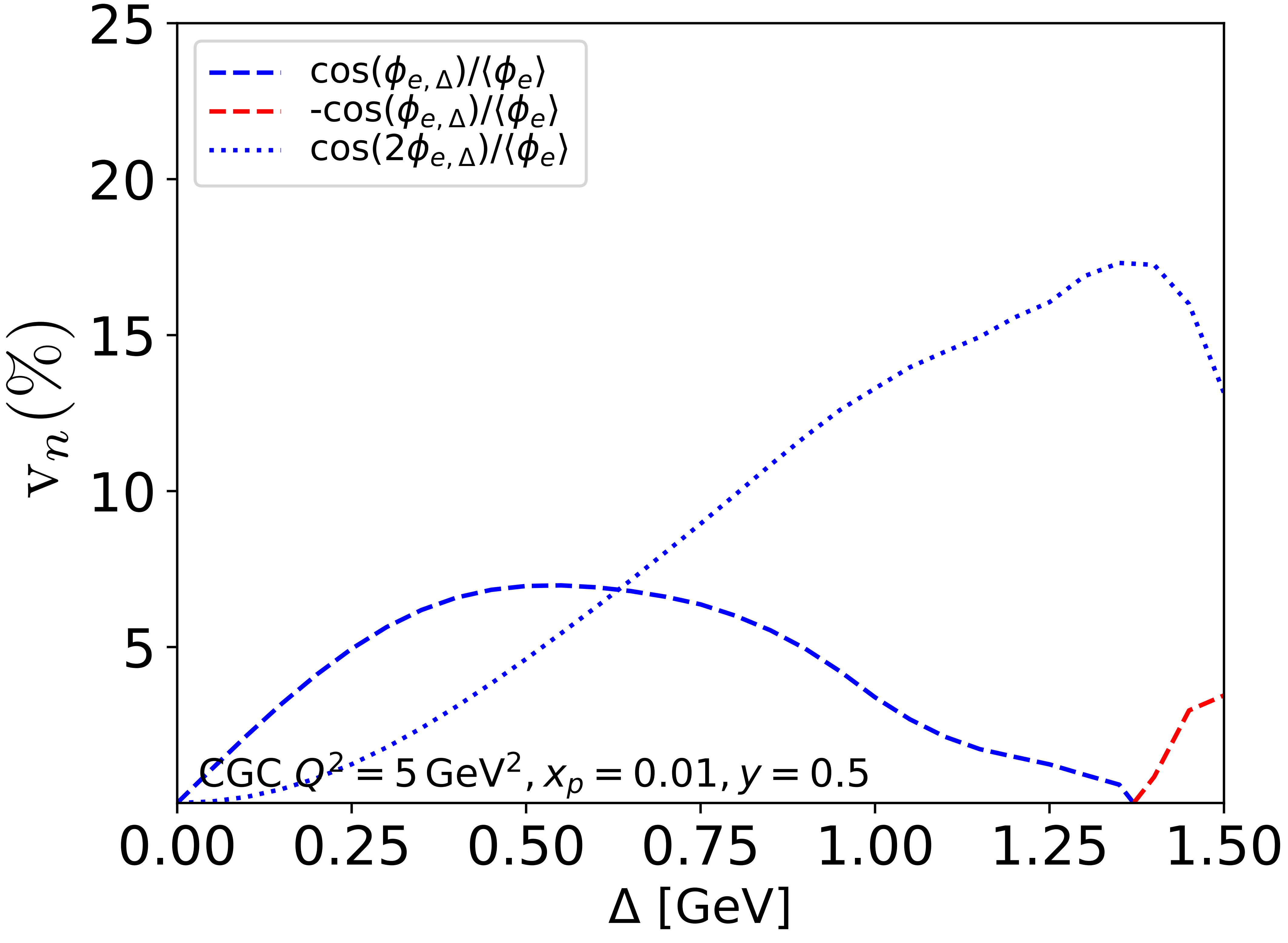
CGC dipole, proton (work in progress)

Differential cross section VCS from CGC dipole



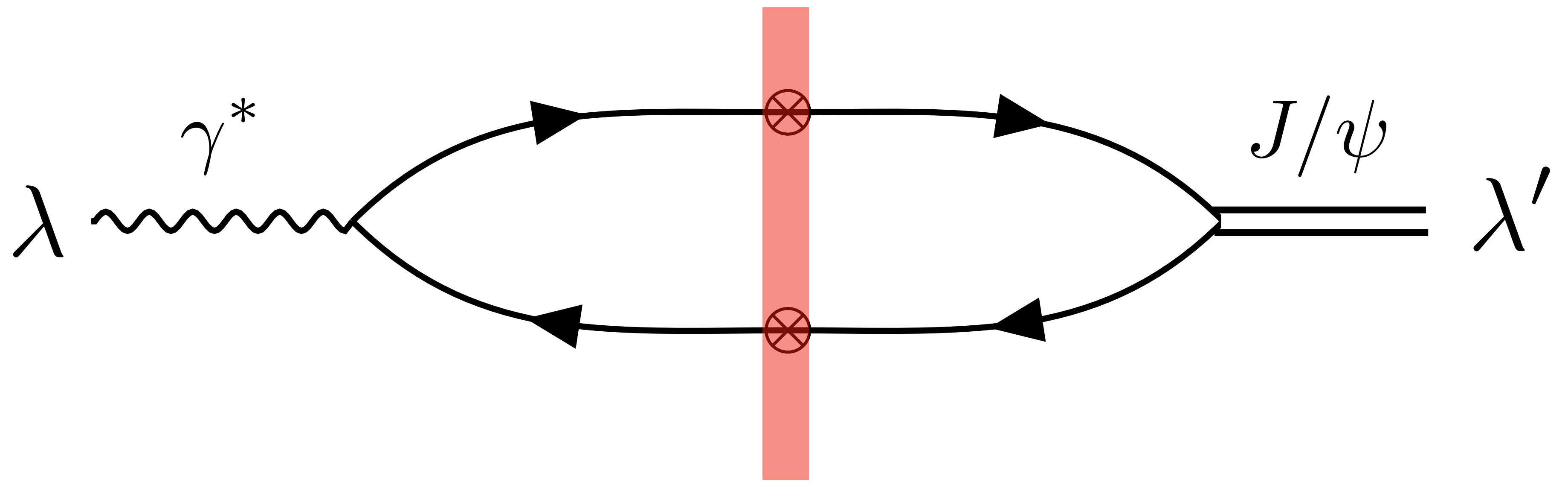
*does not include JIMWLK evolution

Angular modulation between electron and photon



$\cos(2\phi_{e\Delta})$ modulation of 15-20% for $\Delta \gtrsim 1.0$ GeV

Vector Meson Production



Following a similar calculation to that of VCS we computed J/ψ production.

- massive quarks m_f
- J/ψ can have longitudinal polarization
- need model for J/ψ light-cone wave-function $\phi_{L/T}(r_\perp, z)$ (e.g Boosted Gaussian)

$$\frac{d\sigma^{ep\to e' J/\Psi p}}{\Delta_\perp d\Delta_\perp d\phi_{e\boldsymbol{\Delta}} dx_B dQ^2} = \frac{\alpha_{em}^2}{x_B Q^2}\Bigg\{\frac{1}{2}\left[1+(1-y)^2\right]\left[\mathcal{A}_{TT}^2 + \mathcal{A}_{TT,\text{flip}}^2 + \mathcal{A}_{TL}^2\right] + 2(1-y)\left[\mathcal{A}_{LL}^2 + \mathcal{A}_{LT}^2\right]$$
$$-\sqrt{2}(2-y)\sqrt{1-y}\left[\mathcal{A}_{LL}\mathcal{A}_{TL} + \mathcal{A}_{LT}\mathcal{A}_{TT} + \mathcal{A}_{LT}\mathcal{A}_{TT,\text{flip}}\right]\cos(\phi_{e\boldsymbol{\Delta}})$$
$$+(1-y)\left[2\mathcal{A}_{TT}\mathcal{A}_{TT,\text{flip}} + \mathcal{A}_{TL}^2\right]\cos(2\phi_{e\boldsymbol{\Delta}})\Bigg\}$$

The amplitude have the form

$$\mathcal{A}_{LL} = \frac{8N_c q_f}{(2\pi)^2}\int d^2\boldsymbol{b}_\perp e^{-i\boldsymbol{\Delta}_\perp\cdot\boldsymbol{b}_\perp}\int_0^1 \frac{dz}{4\pi}\frac{\left[z^2(1-z)^2\right]}{z(1-z)}\int d^2\boldsymbol{r}_\perp e^{-i\boldsymbol{\delta}_\perp\cdot\boldsymbol{r}_\perp} Q K_0(\varepsilon_f r_\perp) M_{J/\psi}\phi_L(r_\perp, z) D\left(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp\right)$$

and so on….

$$D(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) = 1 - S^{(2)}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)_{x_g} \qquad \varepsilon_f^2 = m_f^2 + z(1-z)Q^2$$

Numerical results for cross section and anisotropy coming soon!

Outlook

- Include jet fragmentation to our partonic “dijet” cross-sections (e.g. Pythia)
- Couple our DVCS/VM results to MC Event Generator (e.g. Sartre)
- Include NLO contributions

Impact factor exclusive processes at NLO
R. Boussarie et al.
Phys.Rev.Lett. 119 (2017)
JHEP 11 (2016) 149

NLO BK evolution
T. Lappi, H. Mäntysaari,
Phys. Rev. D 93, 094004 (2016)

Soft Gluon ressumation
Y. Hatta, N. Mueller, T. Ueda, F. Yuan
Phys.Lett.B 802, 135211 (2020)

- Study incoherent processes:

incoherent diffractive dijets

Some results can be found here:
H. Mäntysaari, N. Mueller, FS, B. Schenke.
Phys. Rev. Lett. 124, 112301 (2020)

incoherent DVCS/VM
(electron angle correlations)

currently working on this
with H. Mäntysaari, K. Roy, B. Schenke

Thank you.

Any questions?