Exclusive dijet production as a probe of generalised parton distributions

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Overview

Introduction to generalised parton distributions (GPDs)

Introduction to exclusive production of dijet

Analytical results

- Quark dijet production (QED+QCD)
- Gluon dijet production

New!

Numerical results at EIC and HERA kinematics

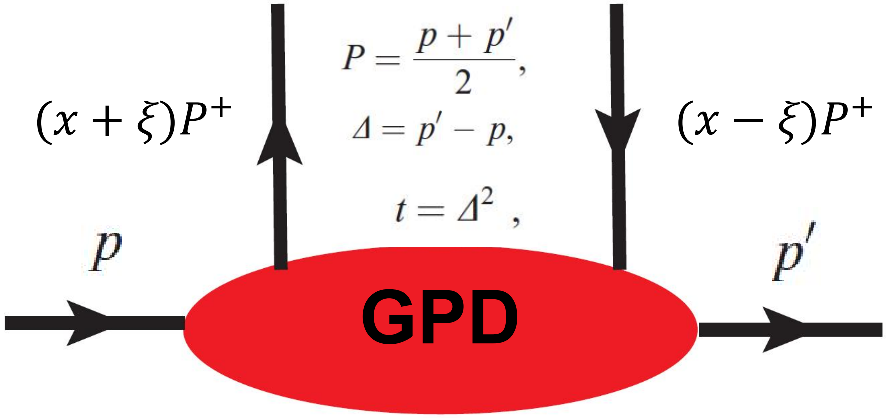
Introduction to generalised parton distributions (GPDs)

Müller et al.,1994; Ji, 1996; Radyushkin, 1997

Unpolarized GPDs:

$$F_{qu}(x,\xi,t) = \frac{1}{2}\int \frac{\mathrm{d}z^-}{2\pi}\, \mathrm{e}^{\mathrm{i}xP^+z^-} \langle p'|\bar{q}(-\tfrac{1}{2}z)\gamma^+ W(-\tfrac{1}{2}z,\tfrac{1}{2}z) q(\tfrac{1}{2}z)|p\rangle|_{z^+=0,z_\perp=0}$$
$$= \frac{1}{2P^+}\left[H^q(x,\xi,t)\bar{u}(p')\gamma^+ u(p) + E^q(x,\xi,t)\bar{u}(p')\frac{\mathrm{i}\sigma^{+\alpha}\Delta_\alpha}{2m_p}u(p)\right],$$

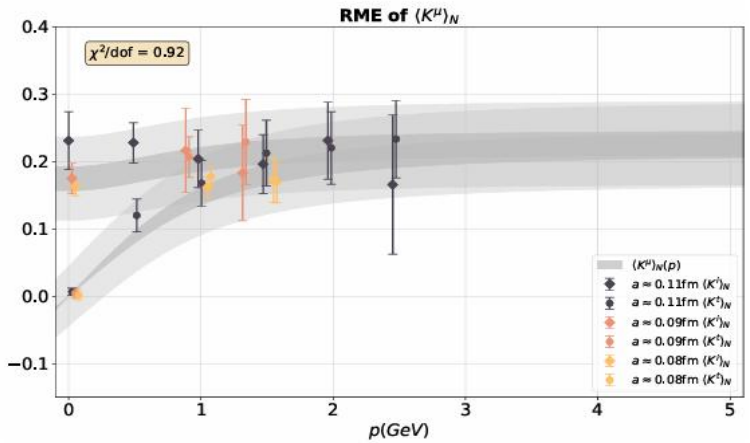
$$F_{gu}(x,\xi,t) = \frac{1}{P^+}\int \frac{\mathrm{d}z^-}{2\pi}\, \mathrm{e}^{\mathrm{i}xP^+z^-} \langle p'|G^{+\mu}(-\tfrac{1}{2}z) W(-\tfrac{1}{2}z,\tfrac{1}{2}z) G^+_\mu(\tfrac{1}{2}z)|p\rangle|_{z^+=0,z_\perp=0}$$
$$= \frac{1}{2P^+}\left[H^g(x,\xi,t)\bar{u}(p')\gamma^+ u(p) + E^g(x,\xi,t)\bar{u}(p')\frac{\mathrm{i}\sigma^{+\alpha}\Delta_\alpha}{2m_p}u(p)\right],$$



The moments of GPDs in the forward limit can give different terms in the spin sum-rule:

$$J_{q,g} = \frac{1}{2}\int dx\, x(H_{q,g}(x,0,0) + E_{q,g}(x,0,0)),$$

Ji,1996



The latest lattice result of total gluon helicity (ΔG) is 46(9)% of the proton spin. (The first work implementing renormalization, the conversion factor from RI/MOM scheme to $\overline{MS}$ scheme was calculated up to N^3LO)

Zhao, **Pang**, etc, 2512.24315

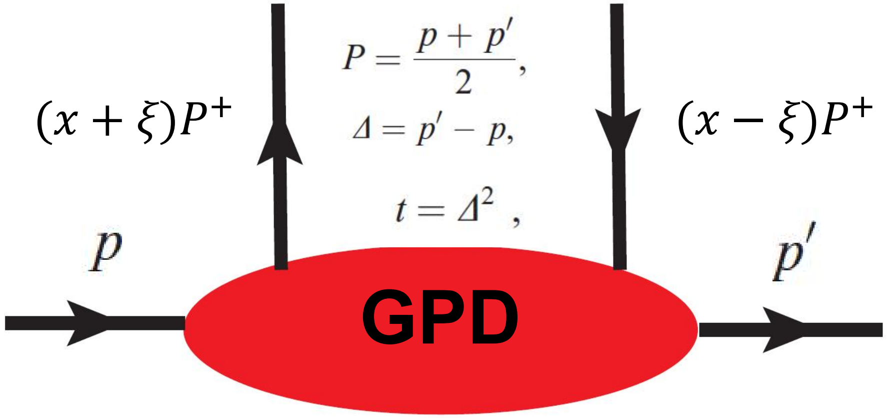
Introduction to generalised parton distributions (GPDs)

Müller et al.,1994; Ji, 1996; Radyushkin, 1997

Unpolarized GPDs:

$$F_{qu}(x,\xi,t) = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle p'|\bar{q}(-\frac{1}{2}z)\gamma^+ W(-\frac{1}{2}z,\frac{1}{2}z)q(\frac{1}{2}z)|p\rangle|_{z^+=0,z_\perp=0}$$
$$= \frac{1}{2P^+}\left[H^q(x,\xi,t)\bar{u}(p')\gamma^+ u(p) + E^q(x,\xi,t)\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m_p}u(p)\right],$$

$$F_{gu}(x,\xi,t) = \frac{1}{P^+}\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle p'|G^{+\mu}(-\frac{1}{2}z)W(-\frac{1}{2}z,\frac{1}{2}z)G^+_\mu(\frac{1}{2}z)|p\rangle|_{z^+=0,z_\perp=0}$$
$$= \frac{1}{2P^+}\left[H^g(x,\xi,t)\bar{u}(p')\gamma^+ u(p) + E^g(x,\xi,t)\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m_p}u(p)\right],$$



The moments of GPDs in the forward limit can give different terms in the spin sum-rule:

$$J_{q,g} = \frac{1}{2}\int dx x(H_{q,g}(x,0,0) + E_{q,g}(x,0,0)),$$

Ji,1996

“GPDs contain information about how the usual PDFs (the forward matrix elements) are distributed in position space”.

M. Burkardt, 2002

“GPD carry information about the spatial distribution of forces experienced by quarks and gluons inside hadrons”.

M. Polyakov, 2002

Studies of exclusive production of dijet in QCD context

In collinear factorisation framework:

Braun and Ivanov, 2005 (First paper discussing this process using collinear factorisation (unpol GPDs))

Chall et al., 2026 (Recent paper with phenomenology at HERA kinematics)

In small-x framework:

Altinoluk et al., 2015

Hatta,Xiao,Yuan, 2016

Mäntysaari,Mueller,Schenke,2019

Boussarie et al., 2019

…

In k_t factorisation/GTMD framework:

Bartels et al., 1996

Boer, Setyadi, 2021,2023

Linek et al., 2024

…

As a probe of gluon orbital angular momentum (OAM):

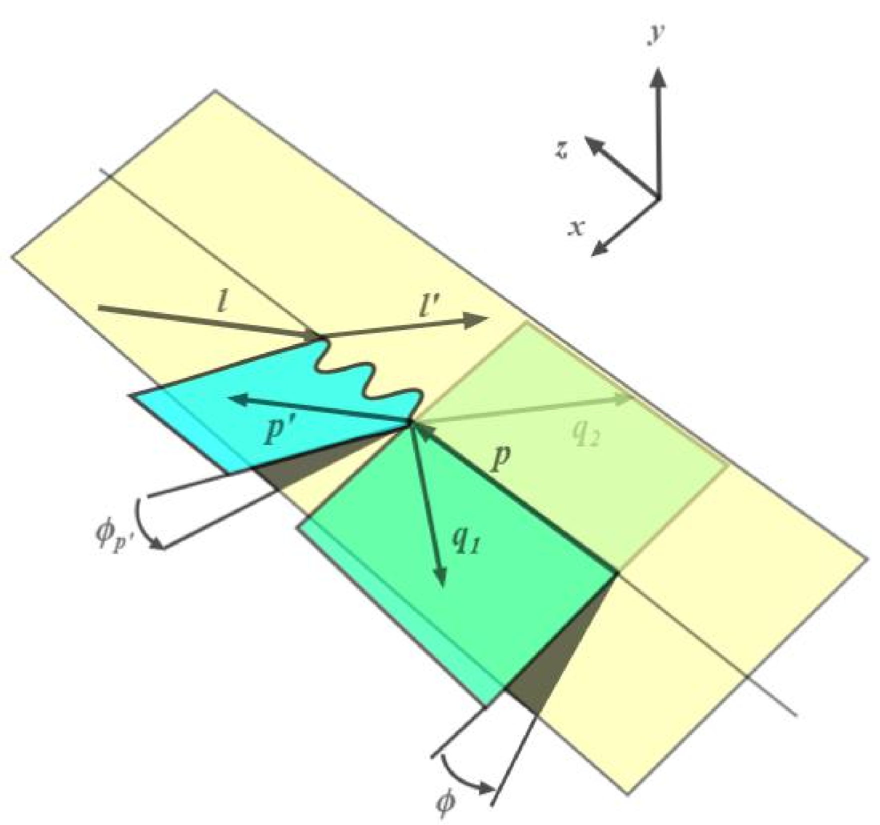
Ji,Yuan,Zhao, 2017

Bhattacharya,Boussarie,Hatta, 2022,2025

…

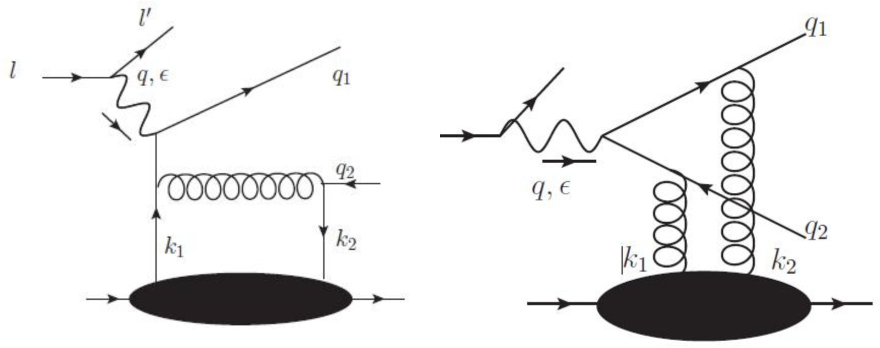
Exclusive production of dijet: kinematics

$\gamma^* - p$ back-to back frame:



$$y = \frac{q \cdot p}{l \cdot p}, \quad Q^2 = -q^2, \quad W^2 = (p+q)^2, \quad x_{\rm Bj} = \frac{Q^2}{2p \cdot q} \approx \frac{Q^2}{Q^2 + W^2}.$$

Quark dijet production (LO):

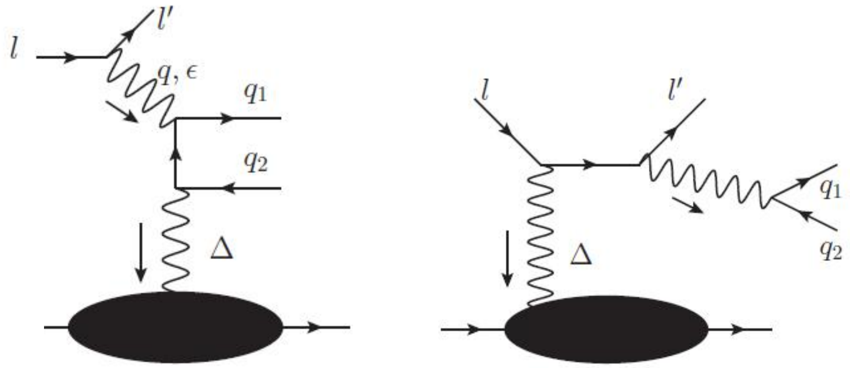


QCD channel

(sensitive to GPDs)

$$\beta = \frac{Q^2 z\bar{z} + m_q^2}{q_\perp^2 + m_q^2 + Q^2 z\bar{z}}$$

+

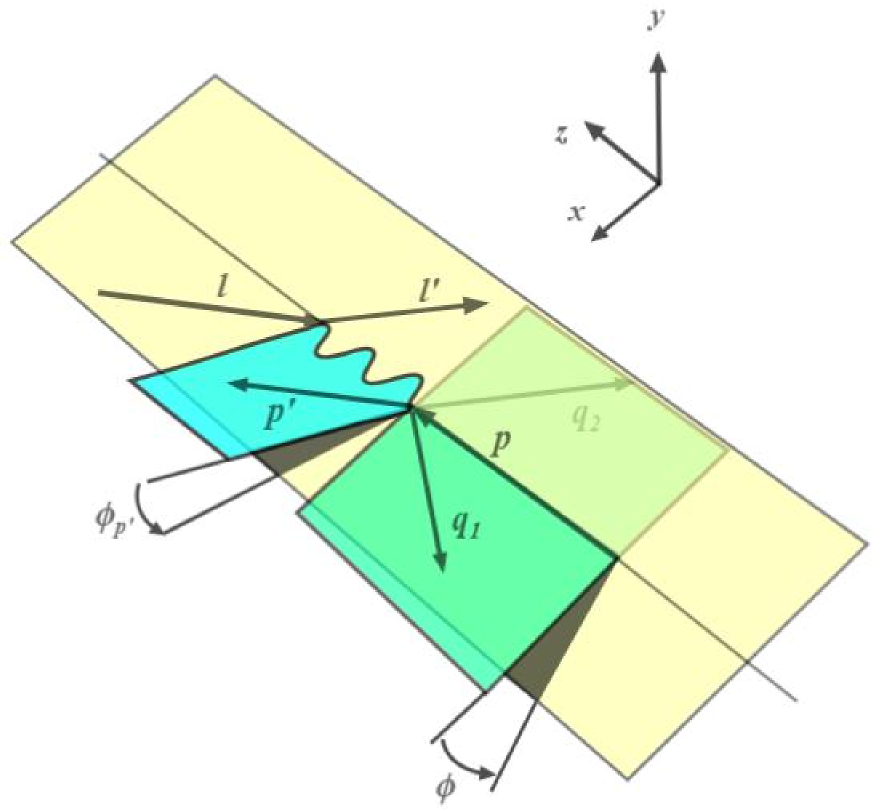


QED/Primakoff channel

(sensitive to EFFs)

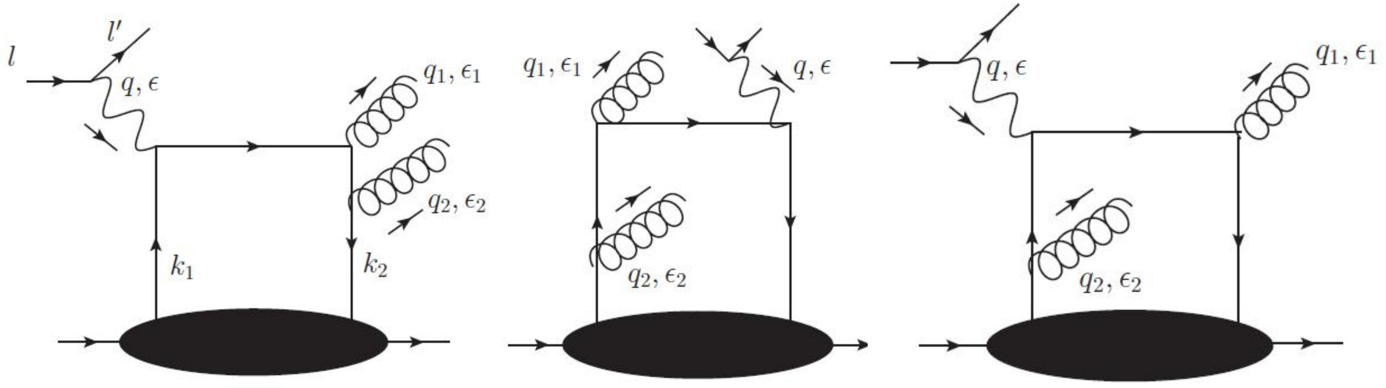
Exclusive production of dijet: kinematics

$\gamma^* - p$ back-to back frame:



$$y = \frac{q \cdot p}{l \cdot p}, \quad Q^2 = -q^2, \quad W^2 = (p+q)^2, \quad x_{\rm Bj} = \frac{Q^2}{2p \cdot q} \approx \frac{Q^2}{Q^2 + W^2}.$$

Gluon dijet production (LO):



Due to charge conjugation symmetry, only valence quark GPDs contribute to gluon dijet production.

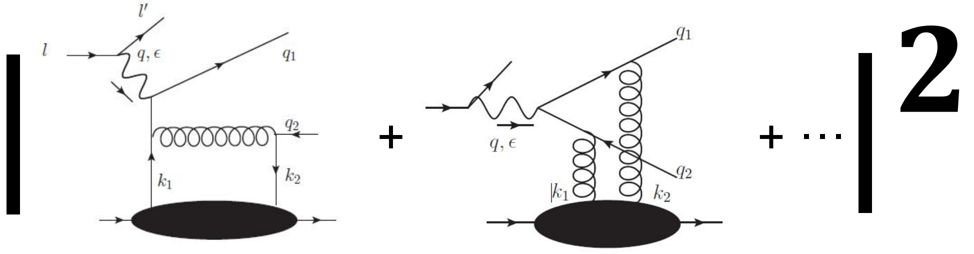
For gluon dijet production, the QED channel starts from NLO.

Analytical results: quark dijet production

$$|M^{q\bar{q}}|^2 = \left|M^{q\bar{q}}_{QCD}\right|^2 + \left|M^{q\bar{q}}_{QED}\right|^2 + 2Re(M^{q\bar{q}}_{QCD} M^{q\bar{q}*}_{QED})$$

10 diagrams   scale chosen to be $Q^2 z\bar{z} + q_\perp^2 + m_q^2$

Bartels,Lotter,Wusthoff,1996



$$|M^{q\bar{q},aa}_{\text{QCD}}|^2 = \frac{2\pi\alpha_{\text{em}}}{Q^4}\left[\frac{8Q^2(1-y)}{y^2}|\mathcal{A}^{q\bar{q}}_L|^2 + \frac{8Q^2\sqrt{1-y}(2-y)}{y^2}\text{Re}(\mathcal{A}^{q\bar{q},x}_T \mathcal{A}^{q\bar{q}*}_L) + \frac{2Q^2(2-y)^2}{y^2}|\mathcal{A}^{q\bar{q},x}_T|^2 + 2Q^2|\mathcal{A}^{q\bar{q},y}_T|^2\right],$$

$$|\mathcal{A}^{q\bar{q},x}_T|^2 = \frac{|C|^2 N_c}{(\mu^2+\mathbf{q}_\perp^2)^2}\Big[\frac{2m_q^2}{\bar{z}z}|I_{gu1}|^2 + \frac{\bar{z}\mathbf{q}_\perp^2}{2z}|4C_F I^{q\bar{q}}_{qu2} + I_{gu2}|^2 + \frac{z\mathbf{q}_\perp^2}{2\bar{z}}|4C_F I^{q\bar{q}}_{qu3} - I_{gu2}|^2$$
$$+ \cos(2\phi)\mathbf{q}_\perp^2 \text{Re}\big((4C_F I^{q\bar{q}}_{qu2} + I_{gu2})(4C_F I^{q\bar{q}}_{qu3} - I_{gu2})^*\big)\Big],$$
$$|\mathcal{A}^{q\bar{q},y}_T|^2 = |\mathcal{A}^{q\bar{q},x}_T|^2\big(\cos(2\phi) \to -\cos(2\phi)\big),$$
$$\text{Re}(\mathcal{A}^{q\bar{q},x}_T \mathcal{A}^{q\bar{q}*}_L) = -\frac{2|C|^2 N_c \cos(\phi) Q|q_\perp|}{(\mu^2+\mathbf{q}_\perp^2)^2}\Big[\bar{z}\text{Re}\big((4C_F I^{q\bar{q}}_{qu2} + I_{gu2})(2C_F I^{q\bar{q}}_{qu1} + I_{gu1})^*\big)$$
$$+ z\text{Re}\big((4C_F I^{q\bar{q}}_{qu3} - I_{gu2})(2C_F I^{q\bar{q}}_{qu1} + I_{gu1})^*\big)\Big],$$
$$|\mathcal{A}^{q\bar{q}}_L|^2 = \frac{8|C|^2 N_c Q^2 \bar{z}z}{(\mu^2+\mathbf{q}_\perp^2)^2}|2C_F I^{q\bar{q}}_{qu1} + I_{gu1}|^2.$$

$$|\mathcal{A}^{q\bar{q},x}_T|^2 = \frac{8|C|^2 N_c \mathbf{q}_\perp^2}{(\mu^2+\mathbf{q}_\perp^2)^2}\Big[\frac{C_F^2\bar{z}}{z}|I^{q\bar{q}}_{qh2}|^2 + \frac{C_F^2 z}{\bar{z}}|I^{q\bar{q}}_{qh3}|^2 + \frac{(2\bar{z}z(\cos(2\phi)-1)+1)}{4\bar{z}z}|I_{gh}|^2 + 2C_F^2\cos(2\phi)\text{Re}(I^{q\bar{q}}_{qh2} I^{q\bar{q}*}_{qh3})$$
$$- \frac{C_F\big(z(1-\cos(2\phi))-1\big)}{z}\text{Re}\big(I^{q\bar{q}}_{qh2} I^*_{gh}\big) - \frac{C_F\big(\cos(2\phi)(z-1)-z\big)}{\bar{z}}\text{Re}\big(I^{q\bar{q}}_{qh3} I^*_{gh}\big)\Big],$$
$$|\mathcal{A}^{q\bar{q},y}_T|^2 = |\mathcal{A}^{q\bar{q},x}_T|^2\big(\cos(2\phi) \to -\cos(2\phi)\big),$$
$$\text{Re}\big(\mathcal{A}^{q\bar{q},x}_T \mathcal{A}^{q\bar{q}*}_L\big) = \frac{16|C|^2 N_c}{(\mu^2+\mathbf{q}_\perp^2)^2}\Big[-C_F^2 Q|q_\perp|\bar{z}\cos(\phi)\text{Re}(I^{q\bar{q}}_{qh1} I^{q\bar{q}*}_{qh2}) - C_F^2 Q|q_\perp|z\cos(\phi)\text{Re}(I^{q\bar{q}}_{qh1} I^{q\bar{q}*}_{qh3})$$
$$- \frac{1}{2}C_F Q|q_\perp|\cos(\phi)\text{Re}(I^{q\bar{q}}_{qh1} I^*_{gh})\Big],$$
$$|\mathcal{A}^{q\bar{q}}_L|^2 = \frac{32|C|^2 N_c \bar{z}z}{(\mu^2+\mathbf{q}_\perp^2)^2}C_F^2 Q^2 |I^{q\bar{q}}_{qh1}|^2.$$

$$C = \frac{2i\pi\alpha_s\sqrt{4\pi\alpha_{em}}e_q}{N_c}$$

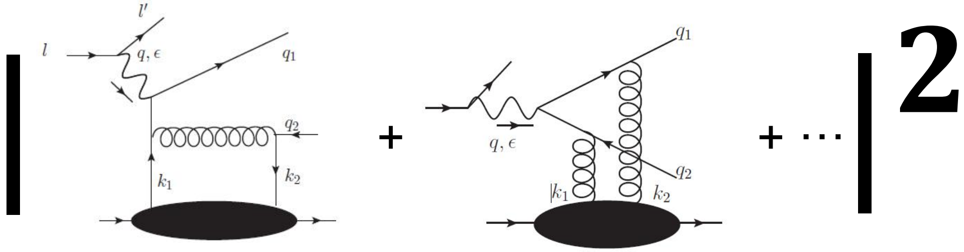
Contribution from unpolarized GPDs

Contribution from helicity GPDs

Analytical results: quark dijet production

$$|M^{q\bar{q}}|^2 = \left|M^{q\bar{q}}_{QCD}\right|^2 + \left|M^{q\bar{q}}_{QED}\right|^2 + 2Re(M^{q\bar{q}}_{QCD} M^{q\bar{q}*}_{QED})$$

10 diagrams



$$|M^{q\bar{q},aa}_{\rm QCD}|^2 = \frac{2\pi\alpha_{\rm em}}{Q^4}\left[\frac{8Q^2(1-y)}{y^2}|A^{q\bar{q}}_L|^2 + \frac{8Q^2\sqrt{1-y}(2-y)}{y^2}{\rm Re}(A^{q\bar{q},x}_T A^{q\bar{q}*}_L) + \frac{2Q^2(2-y)^2}{y^2}|A^{q\bar{q},x}_T|^2 + 2Q^2|A^{q\bar{q},y}_T|^2\right],$$

$$I^{q\bar{q}}_{qu2/qh2} = \int_{-1}^{1} dx F_{qu/h}(x,\xi,t)\left(\frac{z}{x-\xi+i\varepsilon} - \frac{\beta\bar{z}}{\bar{\beta}(x+\xi-i\varepsilon)} + \frac{\bar{z}}{\bar{\beta}(x-\xi(1-2\beta)-i\varepsilon)}\right),$$

$$\beta = \frac{Q^2 z\bar{z} + m_q^2}{q_\perp^2 + m_q^2 + Q^2 z\bar{z}}$$

Some CFFs are sensitive to GPDs at $x \neq \xi$.

$$I_{gu1} = \int_{-1}^{1} dx F_{gu}(x,\xi,t)\left(\frac{\bar{\beta}}{(x+\xi-i\varepsilon)^2} + \frac{\bar{\beta}}{(x-\xi+i\varepsilon)^2} - \frac{1-2\beta}{(x+\xi-i\varepsilon)(x-\xi+i\varepsilon)}\right), \quad \frac{F_{gu/h}(x,\xi,t)}{(x+\xi-i\varepsilon)^2} \to \frac{1}{(x+\xi-i\varepsilon)}\frac{\partial}{\partial x}F_{gu/h}(x,\xi,t),$$

We have analysed the LO evolution of $\frac{\partial}{\partial x}F_g(x,\xi,t)$, and found it won't generate discontinuities at $x = \pm\,\xi$ (backup).

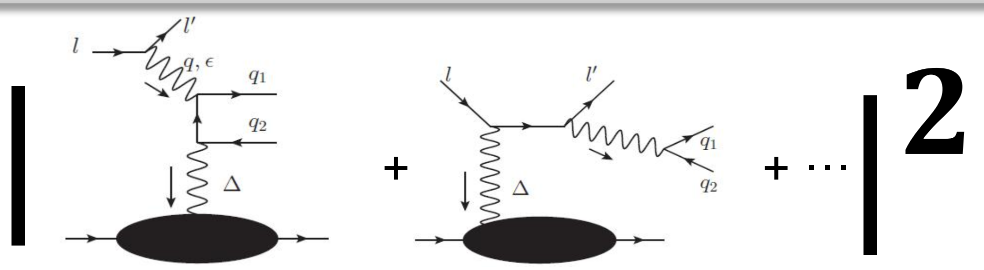
$$F_{qu}(x,\xi,t) = \frac{1}{2P^+}\left[H^q(x,\xi,t)\bar{u}(p')\gamma^+ u(p) + E^q(x,\xi,t)\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m_p}u(p)\right].$$

Radyushkin, 1999
Müller, Schäfer, 2005

Analytical results: quark dijet production

$$|M^{q\bar{q}}|^2 = \left|M^{q\bar{q}}_{QCD}\right|^2 + \left|\boldsymbol{M^{q\bar{q}}_{QED}}\right|^2 + 2Re(M^{q\bar{q}}_{QCD} M^{q\bar{q}*}_{QED})$$

4 diagrams



e_q^2 e_q

$$|M^{q\bar{q}}_{\rm QED}|^2 = \frac{1}{2} \cdot \frac{256\pi^4 \alpha_{\rm em}^4 e_q^2 N_c}{t^2(\mu^2 + \mathbf{q}_\perp^2)^4} \Big[(\Sigma_f e_f \tilde{J}_f^x)(\Sigma_{f'} e_{f'} \tilde{J}_{f'}^{x*}) \cdot \Sigma_{i=0}^4 a_{xx}^i \cos(i\phi) + (\Sigma_f e_f \tilde{J}_f^y)(\Sigma_{f'} e_{f'} \tilde{J}_{f'}^{y*}) \cdot \Sigma_{i=0}^4 a_{yy}^i \cos(i\phi)$$
$$+ {\rm Re}\Big[(\Sigma_f e_f \tilde{J}_f^x)(\Sigma_{f'} e_{f'} \tilde{J}_{f'}^{y*}) \Big] \cdot \Sigma_{i=1}^4 a_{xy}^i \sin(i\phi) \Big],$$

$$\tilde{J}_f^\alpha = (g^{\alpha\beta} - \frac{\Delta^\alpha n_-^\beta}{\Delta \cdot n_-}) \langle p' | \overline{\psi}_f(0) \gamma_\beta \psi_f(0) | p \rangle$$

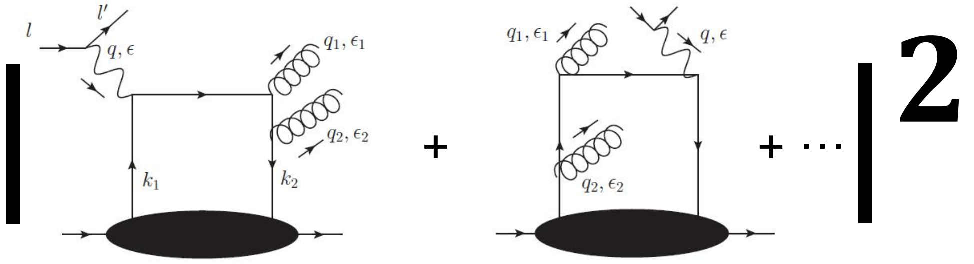
$$a_{xx}^2 = 16\mathbf{q}_\perp^2 \Bigg\{ \frac{e_q^2 (\mu^2 + \mathbf{q}_\perp^2)^2 \left[2m_q^2 (y-2)^2 + Q^2 \left(2((y-8)y+8) z\bar{z} - (y-1)^2 - 1 \right) \right]}{Q^2 y^2} - \frac{2z^2\bar{z}^2 \left((m_q^2 + \mathbf{q}_\perp^2)^2 - Q^4 z^2 \bar{z}^2 \right)^2}{(m_q^2 + \mathbf{q}_\perp^2)^2}$$
$$+ \frac{2e_q (y-2) z (2z-1) \bar{z} (\mu^2 + \mathbf{q}_\perp^2)^2 (3m_q^2 - Q^2 z\bar{z} + 3\mathbf{q}_\perp^2)}{y (m_q^2 + \mathbf{q}_\perp^2)} \Bigg\},$$

Compared to the QED channel in DDVCS, the QED channel in exclusive dijet production has more complicated charge structures, which results in nontrivial cancellation or enhancement between diagrams depending on the outgoing jet type.

Analytical results: gluon dijet production

$$|M^{gg}|^2 = |\boldsymbol{M^{gg,uu}}|^2 + \left|\boldsymbol{M^{gg,hh}}\right|^2$$

6 diagrams



$$|M^{gg,aa}|^2 = \frac{2\pi\alpha_{\rm em}}{Q^4}\Big[\frac{8Q^2(1-y)}{y^2}|\mathcal{A}_L^{gg}|^2 + \frac{8Q^2\sqrt{1-y}(2-y)}{y^2}\mathrm{Re}\big(\mathcal{A}_T^{gg,x}\mathcal{A}_L^{gg*}\big) + \frac{2Q^2(2-y)^2}{y^2}|\mathcal{A}_T^{gg,x}|^2 + 2Q^2|\mathcal{A}_T^{gg,y}|^2\Big].$$

$$\begin{aligned}
|\mathcal{A}_T^{gg,x}|^2 &= \frac{8C_F^2}{\mathbf{q}_\perp^2}\Big[-2\cos(2\phi)z\bar{z} - 2\bar{z}z + 1\Big](\Sigma_f C_f I^{gg}_{qu2,f})(\Sigma_{f'} C^*_{f'} I^{gg*}_{qu2,f'}),\\
|\mathcal{A}_T^{gg,y}|^2 &= |\mathcal{A}_T^{gg,x}|^2\big(\cos(2\phi)\to -\cos(2\phi)\big),\\
\mathrm{Re}\big(\mathcal{A}_T^{gg,x}\mathcal{A}_L^{gg*}\big) &= \frac{32C_F^2 Qz\bar{z}(1-2z)\cos(\phi)}{|q_\perp|(\mu^2+\mathbf{q}_\perp^2)}\mathrm{Re}\Big[(\Sigma_f C_f I^{gg}_{qu1,f})(\Sigma_{f'} C^*_{f'} I^{gg*}_{qu2,f'})\Big],\\
|\mathcal{A}_L^{gg}|^2 &= \frac{128C_F^2 Q^2\bar{z}^2 z^2}{(\mu^2+\mathbf{q}_\perp^2)^2}(\Sigma_f C_f I^{gg}_{qu1,f})(\Sigma_{f'} C^*_{f'} I^{gg*}_{qu1,f'}).
\end{aligned}$$

Contribution from unpolarized GPDs

$$\begin{aligned}
|\mathcal{A}_T^{gg,x}|^2 &= \frac{8C_F^2}{\mathbf{q}_\perp^2}\Big[2\cos(2\phi)z\bar{z} - 2z\bar{z} + 1\Big](\Sigma_f C_f I'^{gg}_{qh1,f})(\Sigma_{f'} C^*_{f'} I'^{gg*}_{qh1,f'}),\\
|\mathcal{A}_T^{gg,y}|^2 &= |\mathcal{A}_T^{gg,x}|^2\big(\cos(2\phi)\to -\cos(2\phi)\big),\\
\mathrm{Re}\big(\mathcal{A}_T^{gg,x}\mathcal{A}_L^{gg*}\big) &= 0,\\
|\mathcal{A}_L^{gg}|^2 &= 0.
\end{aligned}$$

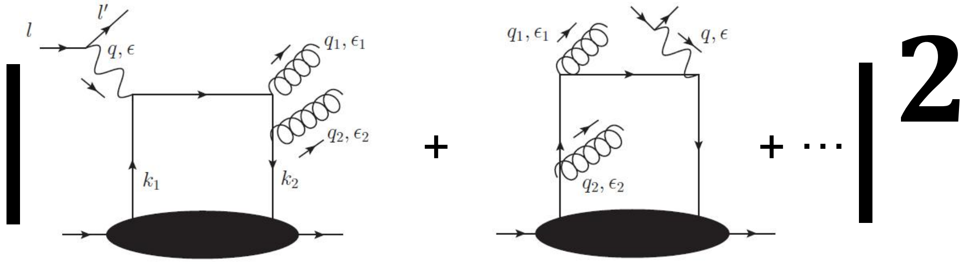
$$C_f = 2i\pi\alpha_s\sqrt{4\pi\alpha_{em}}e_f$$

Contribution from helicity GPDs

Analytical results: gluon dijet production

$$|M^{gg}|^2 = |\boldsymbol{M^{gg,uu}}|^2 + \left|\boldsymbol{M^{gg,hh}}\right|^{\boldsymbol{2}}$$

6 diagrams



CFFs that appear in the cross section:

Contribute

$$I^{gg}_{qu1,f} = \int_{-1}^{1} dx F_{qu,f}(x,\xi,t)\left(\frac{1}{x+\xi-i\varepsilon} - \frac{1}{x-\xi+i\varepsilon}\right)$$

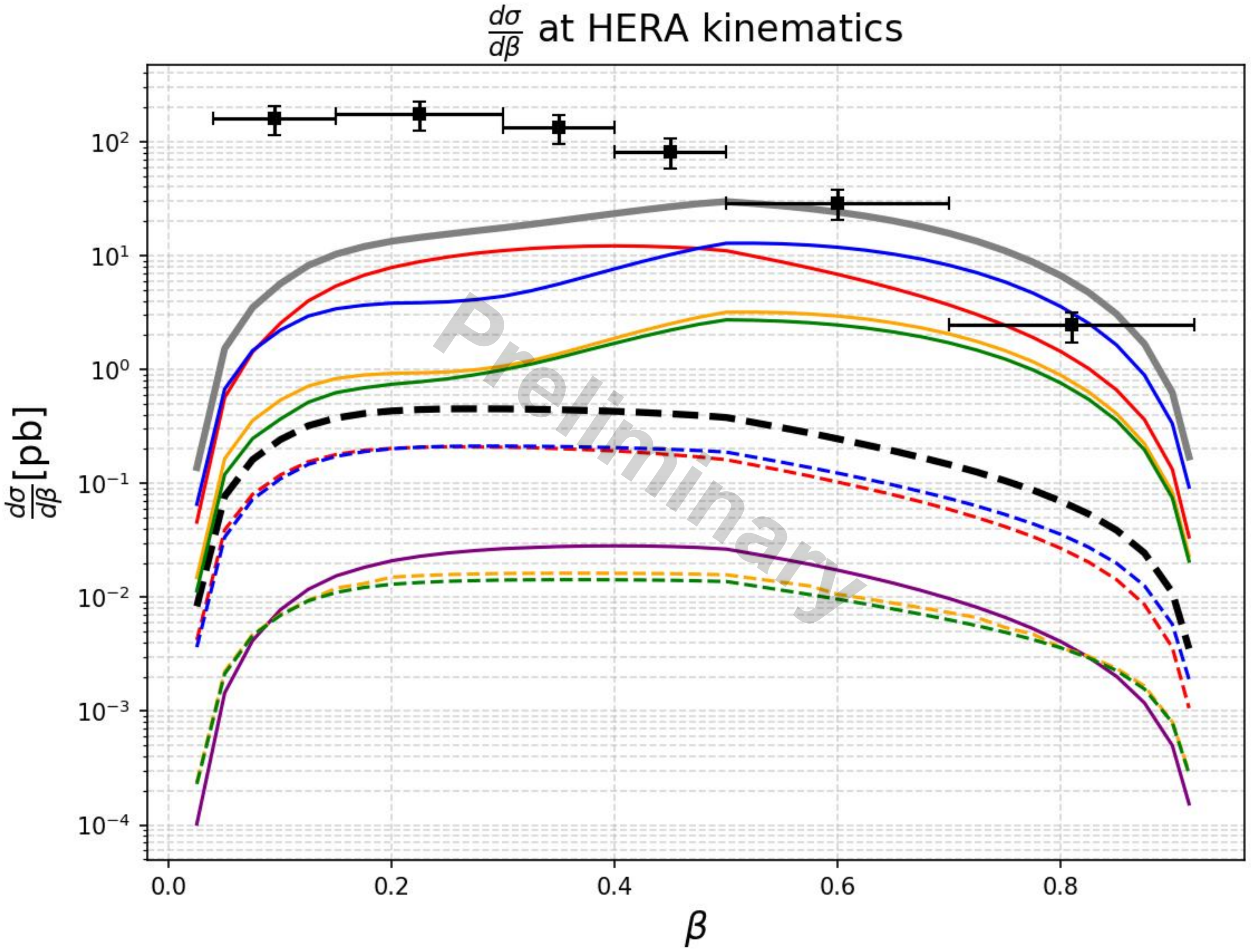
$$I^{gg}_{qu2,f} = \int_{-1}^{1} dx F_{qu,f}(x,\xi,t)\left((1-2\beta)\left(\frac{1}{x+\xi-i\varepsilon} - \frac{1}{x-\xi+i\varepsilon}\right) + \frac{1}{x+\xi(1-2\beta)+i\varepsilon} - \frac{1}{x-\xi(1-2\beta)-i\varepsilon}\right)$$

$$I^{gg}_{qh1,f} = \int_{-1}^{1} dx F_{qh,f}(x,\xi,t)\left(\frac{1}{x+\xi-i\varepsilon} + \frac{1}{x-\xi+i\varepsilon} - \frac{1}{x+\xi(1-2\beta)+i\varepsilon} - \frac{1}{x-\xi(1-2\beta)-i\varepsilon}\right)$$

Only C-odd combination of quark GPDs survives under convolution.

The CFFs are sensitive to quark GPDs at $x \neq \xi$, due to two independent hard scales.

Numerical results with HERA kinematics



$$\beta = \frac{Q^2 z\bar{z} + m_q^2}{Q^2 z\bar{z} + q_\perp^2 + m_q^2}$$

Integration range:

$y \in [0.1, 0.64]$,
$t \in [-1.5, -0.01] GeV^2$,
$z \in [0,1], q_\perp^2 \in [4,50] GeV^2$,
$\phi \in [0, 2\pi], \phi_{p'} \in [0, 2\pi]$,
$Q^2 \in [25, 300] GeV^2$,
$\eta < 2$,
$W^2 \in [90, 250] GeV^2$.

The QCD contribution dominates at HERA energies.

At smaller value of β, the invariant mass of dijet system gets larger, the contribution from gluon radiation ($q\bar{q}g$ configuration) becomes more important.

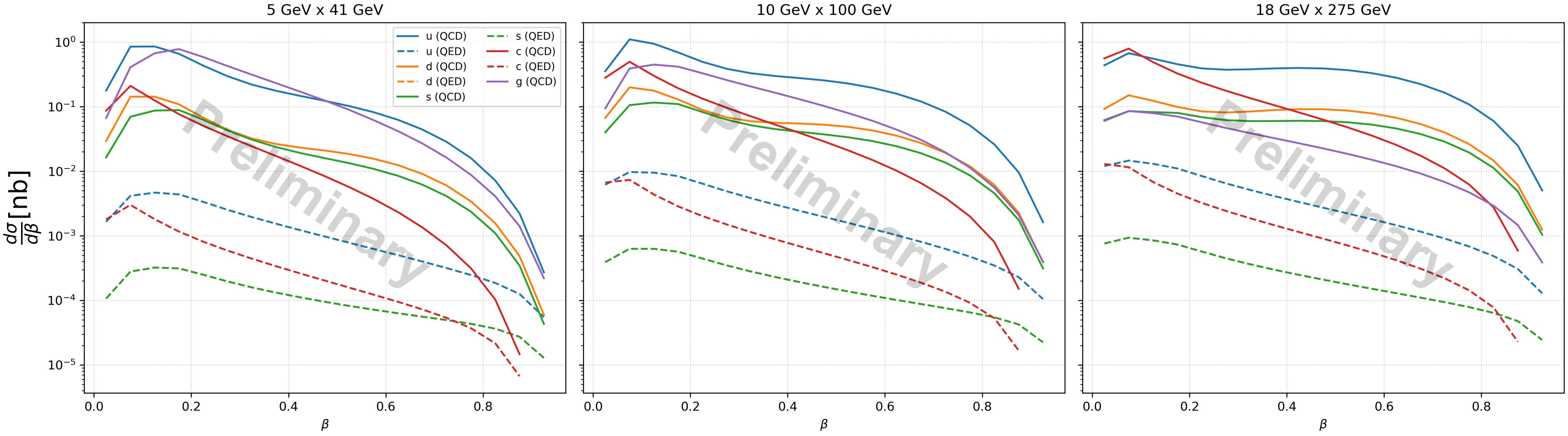
Bartels, Jung, Wusthoff, 1999
Boussarie et al., 2019

Chall et al., 2026; Goloskokov, Kroll, 2007; Abramowicz et al., 2016 (ZEUS)

Numerical results with EIC kinematics

$\frac{d\sigma}{d\beta}$ at different EIC kinematics

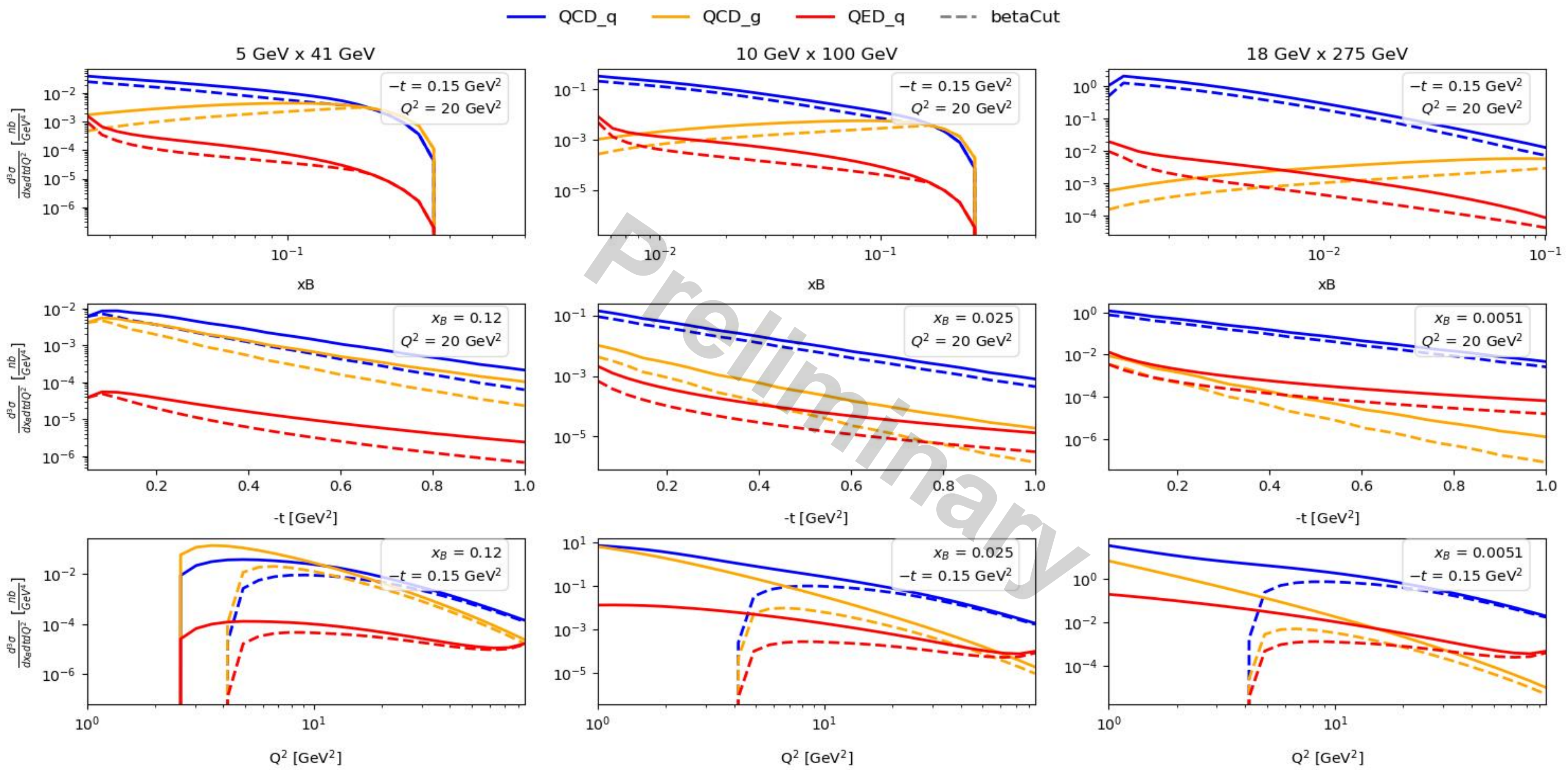
$$\beta = \frac{Q^2 z\bar{z} + m_q^2}{Q^2 z\bar{z} + q_\perp^2 + m_q^2}$$



Integration range:

$Q^2 \in [1,100]GeV^2, t \in [-1.5, -0.01]GeV^2, z \in [0.05,0.95], q_\perp^2 \in [1,50]GeV^2, \phi \in [0,2\pi], \phi_{p'} \in [0,2\pi], y \in [0.01,0.95].$

Numerical results with EIC kinematics



Integration range:

$$z \in [0.05, 0.95],$$
$$q_\perp^2 \in [1, 50] GeV^2,$$
$$\phi \in [0, 2\pi],$$
$$\phi_{p'} \in [0, 2\pi],$$

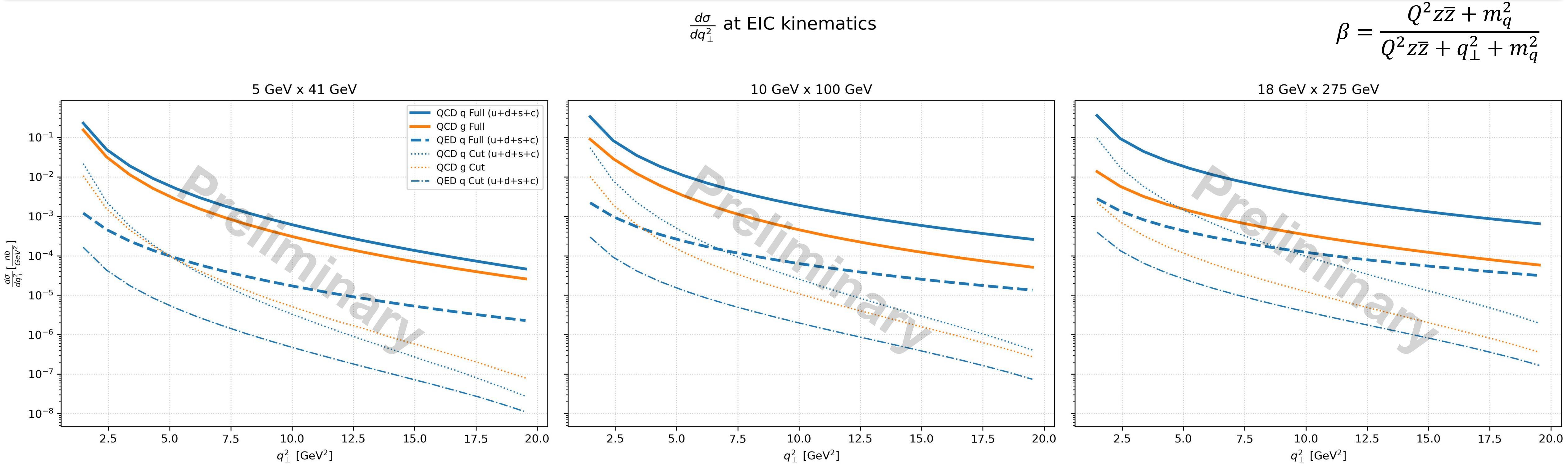
$$\boldsymbol{Q^2 z\bar{z} + q_\perp^2 + m_q^2 > 1GeV^2}.$$

The effect of β cutoff ($\beta > 0.5$) is less important for larger Q^2 ($\sim 20GeV^2$), as expected from $\beta = \frac{Q^2 + \frac{m_q^2}{z\bar{z}}}{Q^2 + M^2}$.

The gluon dijet production becomes more significant at larger x_B, due to it is only sensitive to valence quark GPDs.

Numerical results with EIC kinematics

$$\beta = \frac{Q^2 z\bar{z} + m_q^2}{Q^2 z\bar{z} + q_\perp^2 + m_q^2}$$

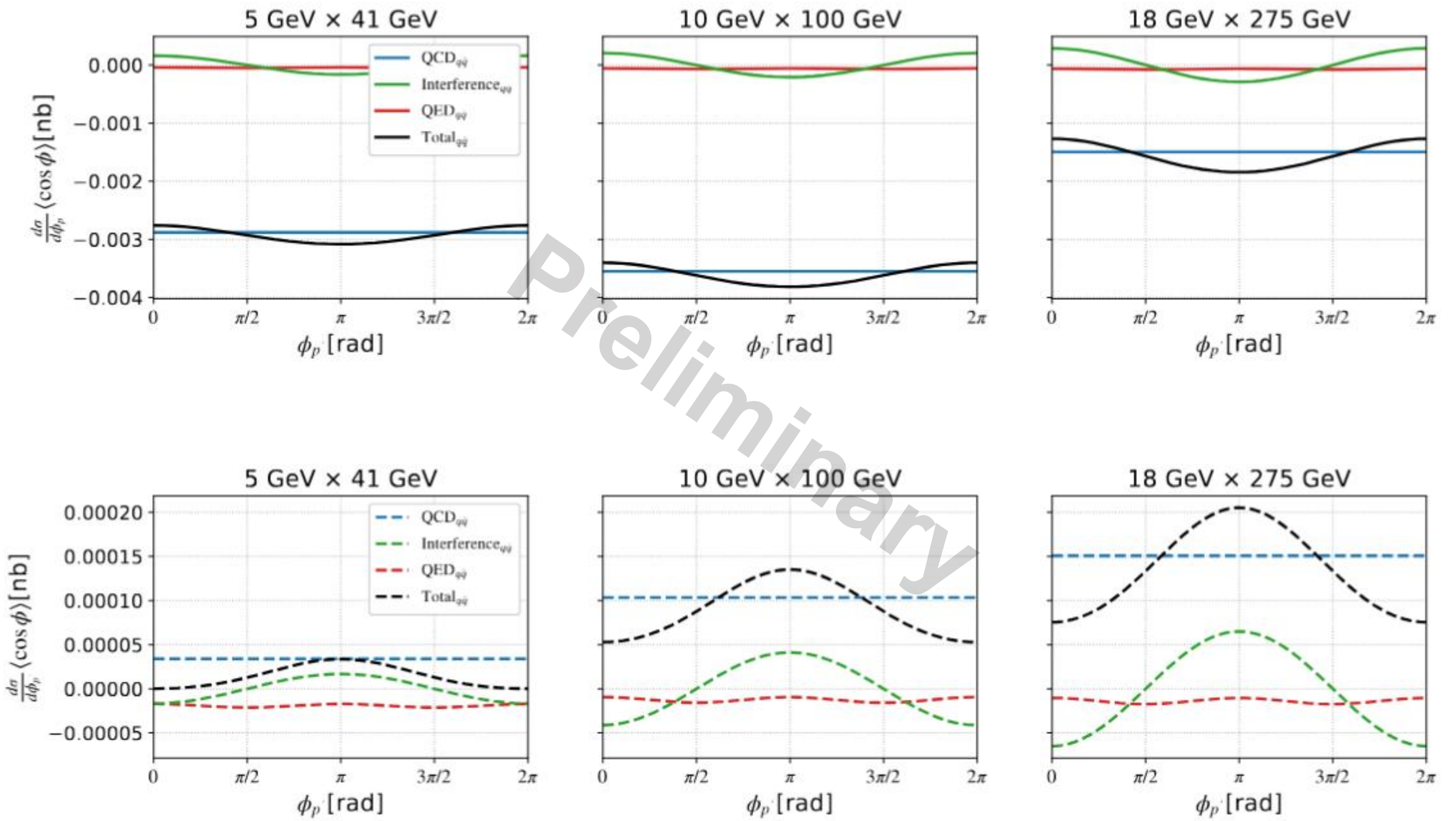


$Q^2 \in [1,100]GeV^2, t \in [-1.5, -0.01]GeV^2, \phi \in [0,2\pi], \phi_{p'} \in [0,2\pi], y \in [0.01,0.95], z \in [0.05,0.95].$

For small values of $q_\perp^2$, jet reconstruction becomes difficult (pileup of particles from different jets).

As $q_\perp^2$ gets larger, the contribution from QED channel becomes more significant, one of the reasons is $\frac{|QED|^2}{|QCD|^2} \propto \frac{\alpha_{em}^2}{\alpha_s^2}$ with μ^2 in α_s chosen to be $Q^2 z\bar{z} + q_\perp^2 + m_q^2$.

Numerical results with EIC kinematics



Integration range:

$z \in [0.05, 0.95]$,
$q_\perp^2 \in [1, 50] GeV^2$,
$\phi \in [0, 2\pi]$,
$y \in [0.01, 0.95]$,
$Q^2 \in [1, 100] GeV^2$,
$t \in [-1.5, -0.01] GeV^2$

The observable $\frac{d\sigma}{d\phi_{p'}}\langle cos\phi \rangle$ receives sizable contributions from the QED channel, especially for the lower panels.

$Re(M_{QCD}^{q\bar{q}} M_{QED}^{q\bar{q}*}) \propto cos\phi_{p'}, sin\phi_{p'}$ from Lorentz covariance.

Summary and outlook

In this work, we consider LO factorisation of exclusive production of dijet. The phenomenology analyses are made at HERA kinematics, such process is also found to be promising in probing GPDs at the future EIC.

Our work includes hadronization effects (not discussed here), the related phenomenology analyses are realized within PARTONS and EpIC framework.

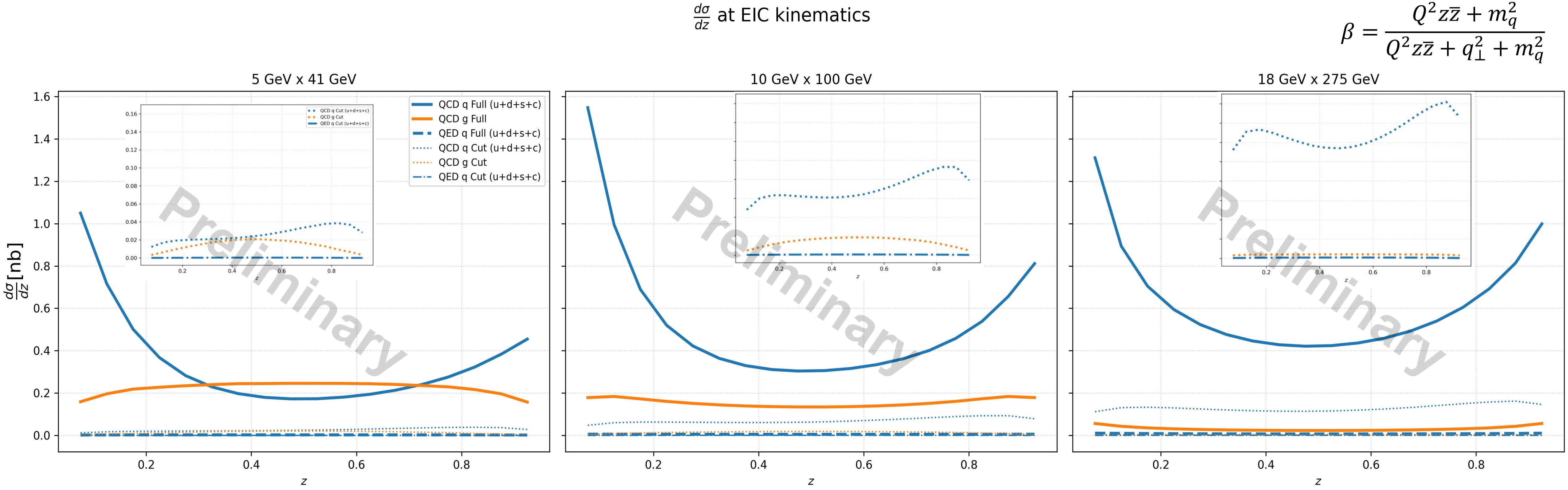
The exclusive electroproduction of quark dijets also receives contributions from the elusive transversity GPDs at leading order. The detailed study of polarization effects (both for beam and target) is in progress.

Thanks for your attention!

Back-up

Distribution in z at EIC kinematics

$$\beta = \frac{Q^2 z\bar{z} + m_q^2}{Q^2 z\bar{z} + q_\perp^2 + m_q^2}$$



Integration range:

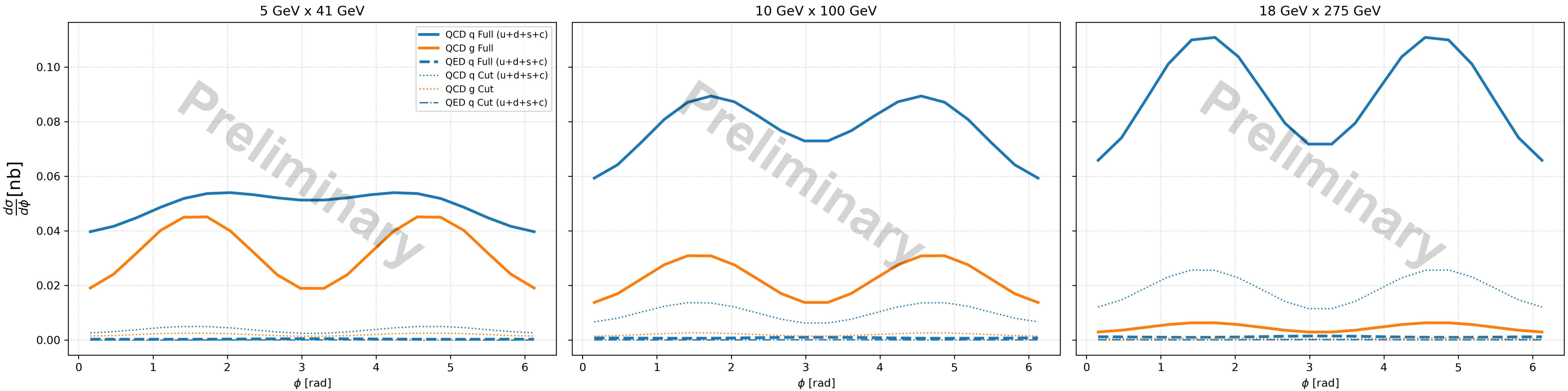
$Q^2 \in [1,100]GeV^2, t \in [-1.5, -0.01]GeV^2, q_\perp^2 \in [1,50]GeV^2, \phi \in [0,2\pi], \phi_{p'} \in [0,2\pi], y \in [0.01,0.95].$

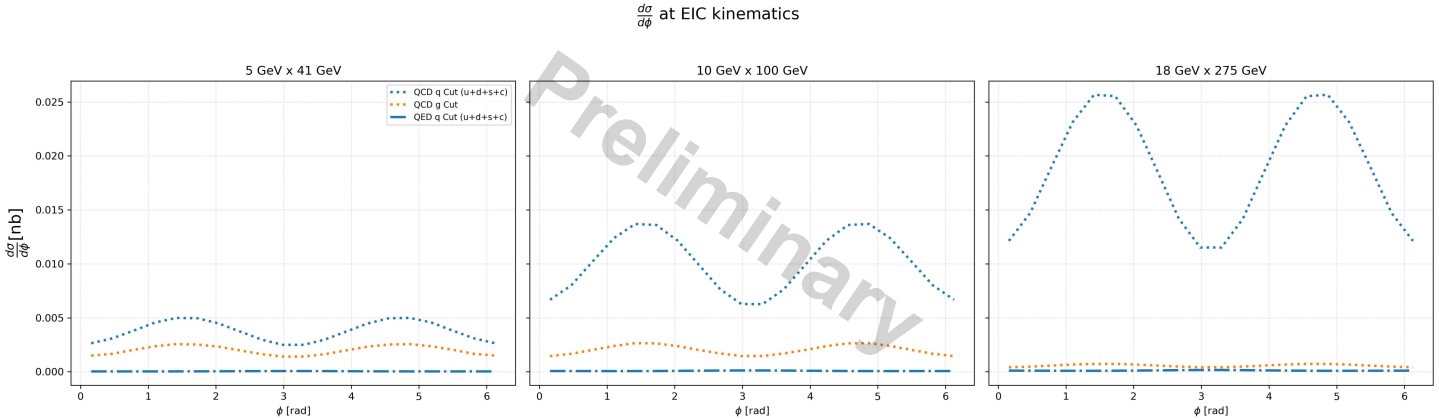
The asymmetry with respect to $z = 0.5$ indicates the **contributions from valence quark GPDs become significant** at the endpoint region of z.

Distribution in ϕ at EIC kinematics

$$\beta = \frac{Q^2 z\bar{z} + m_q^2}{Q^2 z\bar{z} + q_\perp^2 + m_q^2}$$

$\frac{d\sigma}{d\phi}$ at EIC kinematics





Integration range:
$Q^2 \in [1,100] GeV^2$,
$t \in [-1.5, -0.01] GeV^2$,
$q_\perp^2 \in [1,50] GeV^2, z \in [0.05,0.95]$,
$\phi_{p'} \in [0,2\pi], y \in [0.01,0.95]$.

LO evolution of gluon GPDs

From evolution of gluon GPDs (0504030):

$$\frac{d}{d\ln\mu}\boldsymbol{F}(x,\eta) = -\int_{-1}^{1} dy\, \boldsymbol{K}\left(\frac{\eta+x}{2}, \frac{\eta-x}{2} \middle| \frac{\eta+y}{2}, \frac{\eta-y}{2}\right) \boldsymbol{F}(y,\eta)\,,$$

$$F_g^{(1)}(x,\xi,t) = \frac{\partial}{\partial x} F_g(x,\xi,t)$$

Unpolarized gluon-in-quark channel (denoted by superscript “gq”):

$$K_{(0)}^{gq;V}(x_1,x_2|y_1,y_2) = C_F\left[(y_1-y_2)\vartheta^0_{111}(x_1,-x_2,x_1-y_1) + x_1 x_2 \vartheta^1_{111}(x_1,-x_2,x_1-y_1)\right]\,,$$

$$\frac{d}{dln\mu}\left(F_{gu}^{(1)gq}(\xi^+,\xi,t) - F_{gu}^{(1)gq}(\xi^-,\xi,t)\right) = \int_{-1}^{1} dy \frac{1}{\xi} F_{qu}^{s}(y,\xi,t)$$ $= 0$ due to $F_{qu}^{s}(y,\xi,t)$ is **odd** in y.

Polarized gluon-in-quark channel:

$$K_{(0)}^{gq;A}(x_1,x_2|y_1,y_2) = C_F\left[(x_1-x_2)\vartheta^0_{111}(x_1,-x_2,x_1-y_1) + x_1 x_2 \vartheta^1_{111}(x_1,-x_2,x_1-y_1)\right]\,,$$

$$\frac{d}{dln\mu}\left(F_{gh}^{(1)gq}(\xi^+,\xi,t) - F_{gh}^{(1)gq}(\xi^-,\xi,t)\right) = 0.$$

LO evolution of gluon GPDs

Gluon-in-gluon channel (denoted by superscript "gg", $i = \{u, h, t\}$):

$$\frac{d}{d\ln\mu} F_{gi}^{gg}(x,\xi,t) = \int_{-1}^{1} dy \Bigg\{ \left[\frac{x_1}{y_1} \frac{x_1}{x_1 - y_1} \theta_{11}^{0}(x_1, x_1 - y_1) + \frac{x_2}{y_2} \frac{x_2}{x_2 - y_2} \theta_{11}^{0}(x_2, x_2 - y_2) \right] \left(F_{gi}(y,\xi,t) - F_{gi}(x,\xi,t) \right)$$
$$+ \left[\frac{x_1}{y_1} \frac{x_1}{x_1 - y_1} \theta_{11}^{0}(x_1, x_1 - y_1) + \frac{x_2}{y_2} \frac{x_2}{x_2 - y_2} \theta_{11}^{0}(x_2, x_2 - y_2) - \frac{y_1}{y_1 - x_1} \theta_{11}^{0}(y_1, y_1 - x_1) \right.$$
$$\left. - \frac{y_2}{y_2 - x_2} \theta_{11}^{0}(y_2, y_2 - x_2) \right] F_{gi}(x,\xi,t)$$
$$+ \Delta K_{ggi}(x,y,\xi) F_{gi}(y,\xi,t) + \left(\frac{1}{2} \frac{\beta_0}{C_A} + 2 \right) F_{gi}(x,\xi,t) \Bigg\},$$

The contribution from fourth line:

$$\Delta K_{ggi}(x,y,\xi) = \begin{cases} 2 \frac{x_1 x_2 + y_1 y_2}{y_1 y_2} \vartheta_{111}^{0}(x_1, -x_2, x_1 - y_1) + 2 \frac{x_1 x_2}{y_1 y_2} \frac{x_1 y_1 + x_2 y_2}{(x_1 + x_2)^2} \vartheta_{11}^{0}(x_1, -x_2), i = u \\ 2 \frac{x_1 y_2 + y_1 x_2}{y_1 y_2} \vartheta_{111}^{0}(x_1, -x_2, x_1 - y_1) + 2 \frac{x_1 x_2}{y_1 y_2} \vartheta_{11}^{0}(x_1, -x_2), i = h \\ 0, i = t \end{cases}$$

$\Rightarrow$

$$\frac{d}{d\ln\mu} \left(F_{gi}^{(1)gg}(\xi^+, \xi, t) - F_{gi}^{(1)gg}(\xi^-, \xi, t) \right) \supset 0,$$

for $i = u, h, t$.

LO evolution of gluon GPDs

Gluon-in-gluon channel (denoted by superscript “gg”, $i = \{u, h, t\}$):

$$
\begin{aligned}
\frac{d}{d\ln\mu}F^{gg}_{gi}(x,\xi,t) = \int_{-1}^{1} dy \Bigg\{ & \left[\frac{x_1}{y_1}\frac{x_1}{x_1-y_1}\theta^0_{11}(x_1,x_1-y_1) + \frac{x_2}{y_2}\frac{x_2}{x_2-y_2}\theta^0_{11}(x_2,x_2-y_2)\right]\left(F_{gi}(y,\xi,t) - F_{gi}(x,\xi,t)\right) \\
& + \left[\frac{x_1}{y_1}\frac{x_1}{x_1-y_1}\theta^0_{11}(x_1,x_1-y_1) + \frac{x_2}{y_2}\frac{x_2}{x_2-y_2}\theta^0_{11}(x_2,x_2-y_2) - \frac{y_1}{y_1-x_1}\theta^0_{11}(y_1,y_1-x_1)\right. \\
& \left. - \frac{y_2}{y_2-x_2}\theta^0_{11}(y_2,y_2-x_2)\right] F_{gi}(x,\xi,t) \\
& + \Delta K_{ggi}(x,y,\xi)F_{gi}(y,\xi,t) + \left(\frac{1}{2}\frac{\beta_0}{C_A} + 2\right)F_{gi}(x,\xi,t)\Bigg\},
\end{aligned}
$$

The contribution from second and third lines:

$$
\frac{d}{d\ln\mu}F^{gg}_{gi}(x,\xi,t) \supset F_{gi}(x,\xi,t)\cdot\begin{cases} 4\ln\left(1-\xi^2\right) + \frac{8(x-\xi^2)}{\xi^2-1} - 8\ln(1-x), & x > \xi \\ -\frac{8\xi}{\xi+1} + 8\ln(\xi+1) - 4\ln\left(1-x^2\right), & 0 < x < \xi \end{cases}
$$

The r.h.s. and the first derivative of it with respect to x are continuous at $x = \xi$.

LO evolution of gluon GPDs

Gluon-in-gluon channel (denoted by superscript "gg", $i=\{u,h,t\}$):

$$\frac{d}{d\ln\mu}F^{gg}_{gi}(x,\xi,t)=\int_{-1}^{1}dy\Big\{\Big[\frac{x_1}{y_1}\frac{x_1}{x_1-y_1}\theta^0_{11}(x_1,x_1-y_1)+\frac{x_2}{y_2}\frac{x_2}{x_2-y_2}\theta^0_{11}(x_2,x_2-y_2)\Big]\big(F_{gi}(y,\xi,t)-F_{gi}(x,\xi,t)\big)$$
$$+\Big[\frac{x_1}{y_1}\frac{x_1}{x_1-y_1}\theta^0_{11}(x_1,x_1-y_1)+\frac{x_2}{y_2}\frac{x_2}{x_2-y_2}\theta^0_{11}(x_2,x_2-y_2)-\frac{y_1}{y_1-x_1}\theta^0_{11}(y_1,y_1-x_1)$$
$$-\frac{y_2}{y_2-x_2}\theta^0_{11}(y_2,y_2-x_2)\Big]F_{gi}(x,\xi,t)$$
$$+\Delta K_{ggi}(x,y,\xi)F_{gi}(y,\xi,t)+\Big(\frac{1}{2}\frac{\beta_0}{C_A}+2\Big)F_{gi}(x,\xi,t)\Big\},$$

$$\int_{-1}^{x}\frac{\partial_x G(x,y)}{(y-\xi)^2}dy,\ \int_{x}^{1}\frac{\partial_x G(x,y)}{(y-\xi)^2}dy\propto\frac{1}{x-\xi},$$

At scale μ^2, $F_g^{(1)}(x,\xi,t)$ is continuous at $x=\xi$ & $F_g^{(2)}(x,\xi,t)$ is finite in the neighbourhood of $x=\xi$.

The contribution from first line: $\left(G(x,y)=\frac{F_g(y,\xi,t)-F_g(x,\xi,t)}{x-y}\right)$

$$\frac{d}{d\ln\mu}\left(F^{(1)gg}_{gi}(\xi^+,\xi,t)-F^{(1)gg}_{gi}(\xi^-,\xi,t)\right)$$
$$\supset\ \lim_{x\to\xi^+}\left(2(x-\xi)\int_x^1\frac{G(x,y)}{(y-\xi)^2}+F_g^{(1)}(x,\xi,t)+(x-\xi)^2\int_x^1\frac{\partial_x G(x,y)}{(y-\xi)^2}dy\right)$$
$$-\lim_{x\to\xi^-}\left(-2(x-\xi)\int_{-1}^x\frac{G(x,y)}{(y-\xi)^2}+F_g^{(1)}(x,\xi,t)-(x-\xi)^2\int_{-1}^x\frac{\partial_x G(x,y)}{(y-\xi)^2}dy\right)$$
$$=-F_g^{(1)}(\xi^+,\xi,t)+F_g^{(1)}(\xi^-,\xi,t)=0.$$

$$\lim_{x\to\xi^+}2(x-\xi)\int_x^1\frac{G(x,y)}{(y-\xi)^2}dy=\lim_{x\to\xi^+}2(x-\xi)\left(\int_x^1\frac{G(x,y)-G(x,\xi)}{(y-\xi)^2}dy+\int_x^1\frac{G(x,\xi)}{(y-\xi)^2}dy\right)$$
$$=\lim_{x\to\xi^+}2(x-\xi)\left(\int_x^1\frac{\frac{\partial G(x,y)}{\partial y}}{(y-\xi)}dy-F_g^{(1)}(\xi^+,\xi,t)\Big(\frac{1}{x-\xi}-\frac{1}{1-\xi}\Big)\right)$$
$$=-2F_g^{(1)}(\xi^+,\xi,t),$$

IBP