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Institute of Physics, Academia Sinica

# Transition GPDs and nondiagonal DVCS at the EIC


In collaboration with

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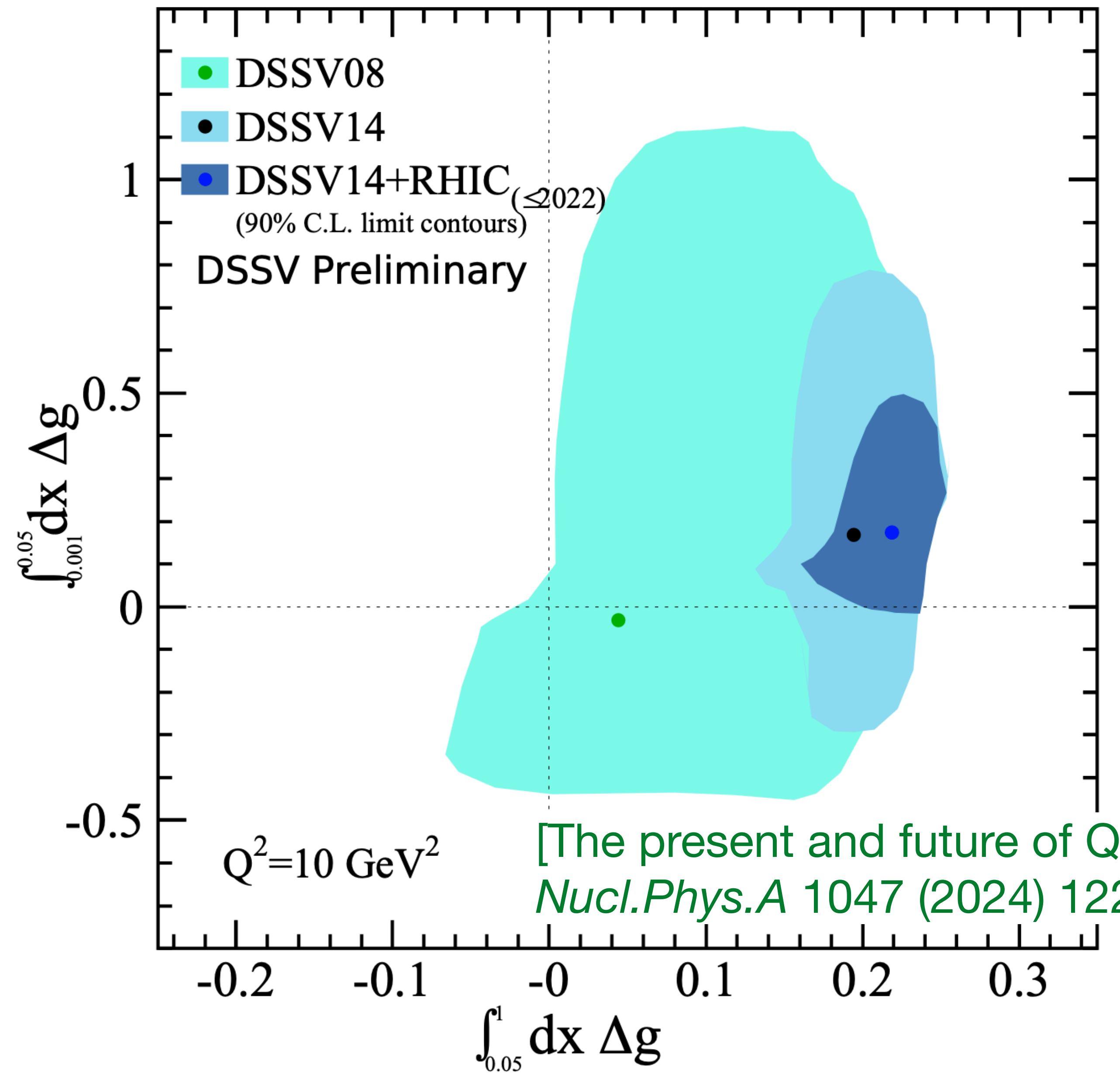
# Outline

- Introduction
- Nondiagonal DVCS amplitudes
- N-Δ transition GPDs
- Numerical estimations for N-Δ DVCS at the EIC
- Summary

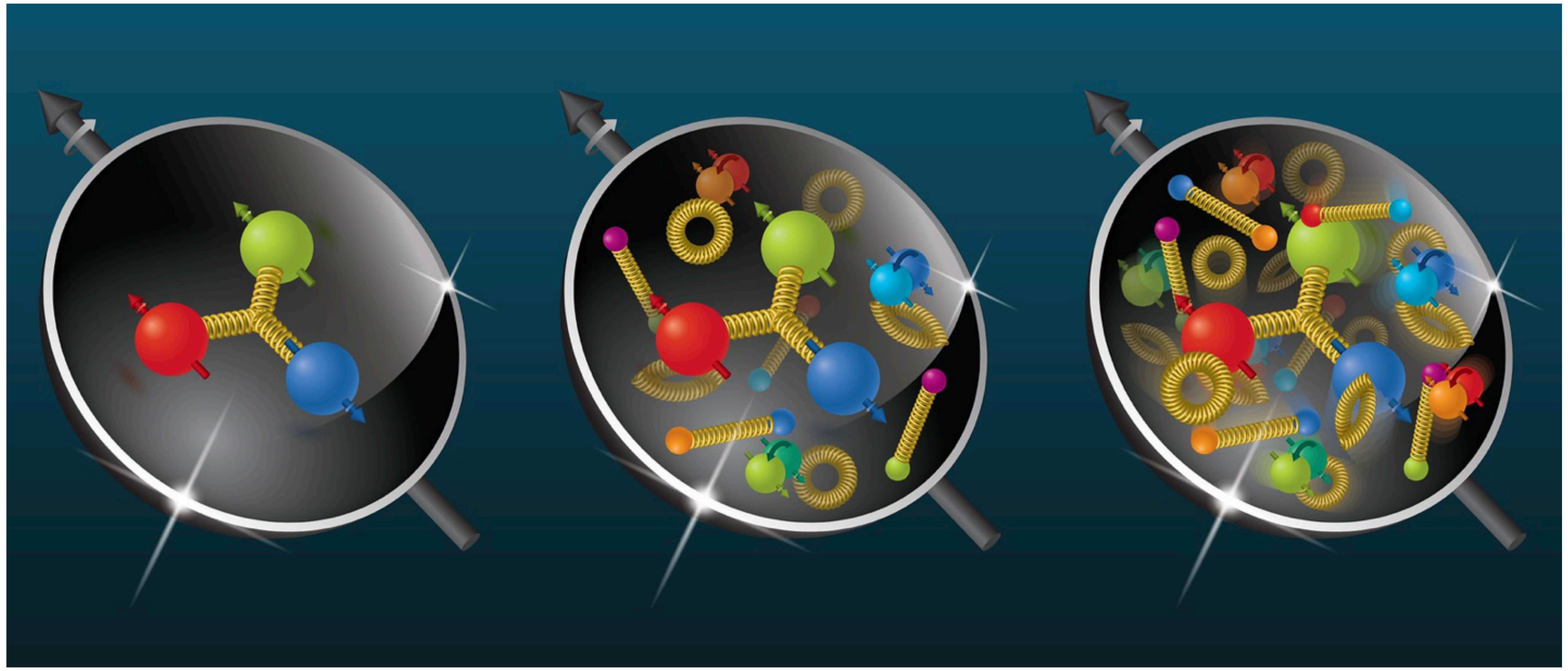
# Introduction

# EIC missions towards parton structure of hadrons

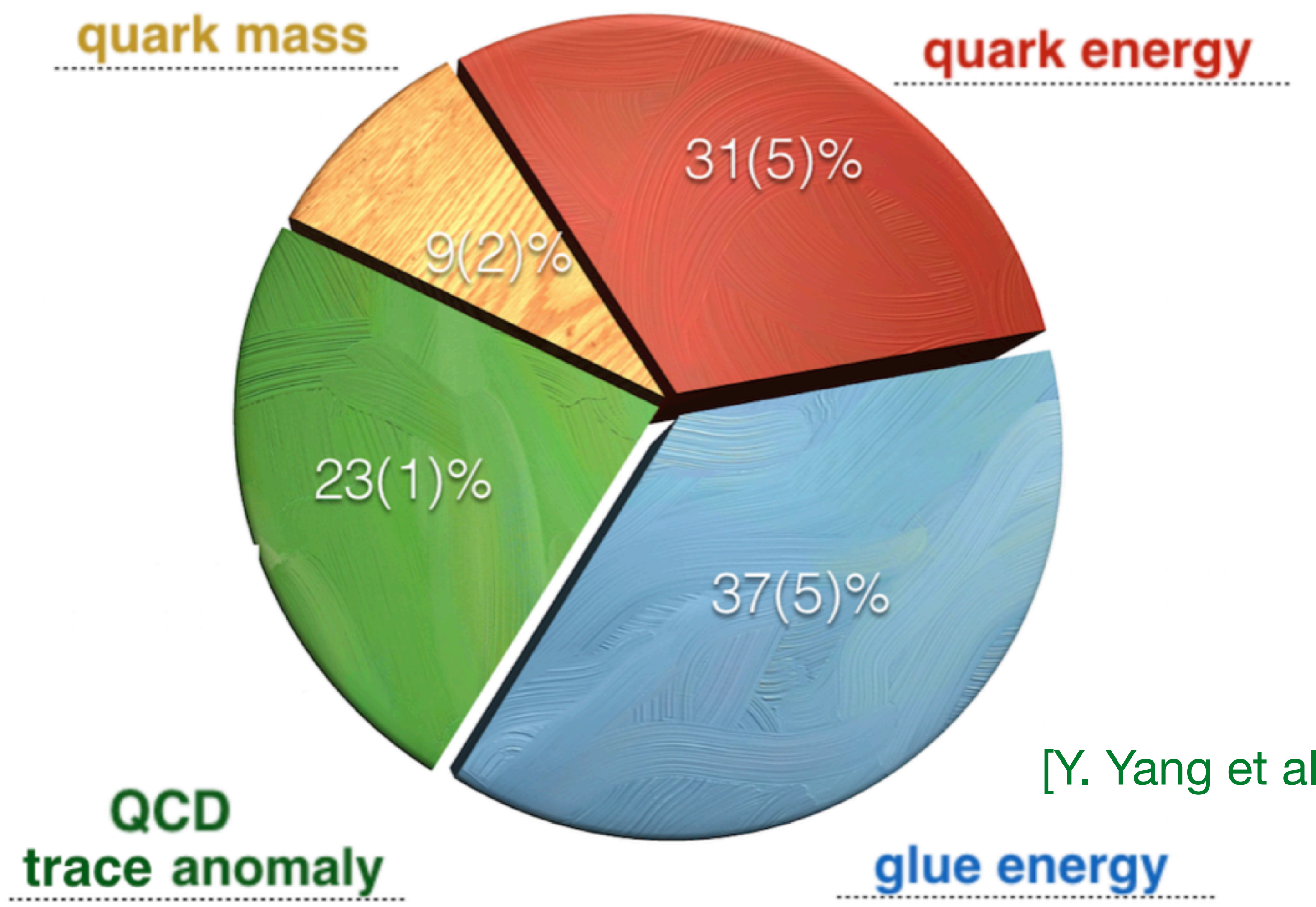
- **Mass and spin decomposition into quarks and gluons**
- **3-dimensional partonic picture**




[The present and future of QCD, *Nucl.Phys.A* 1047 (2024) 122874]

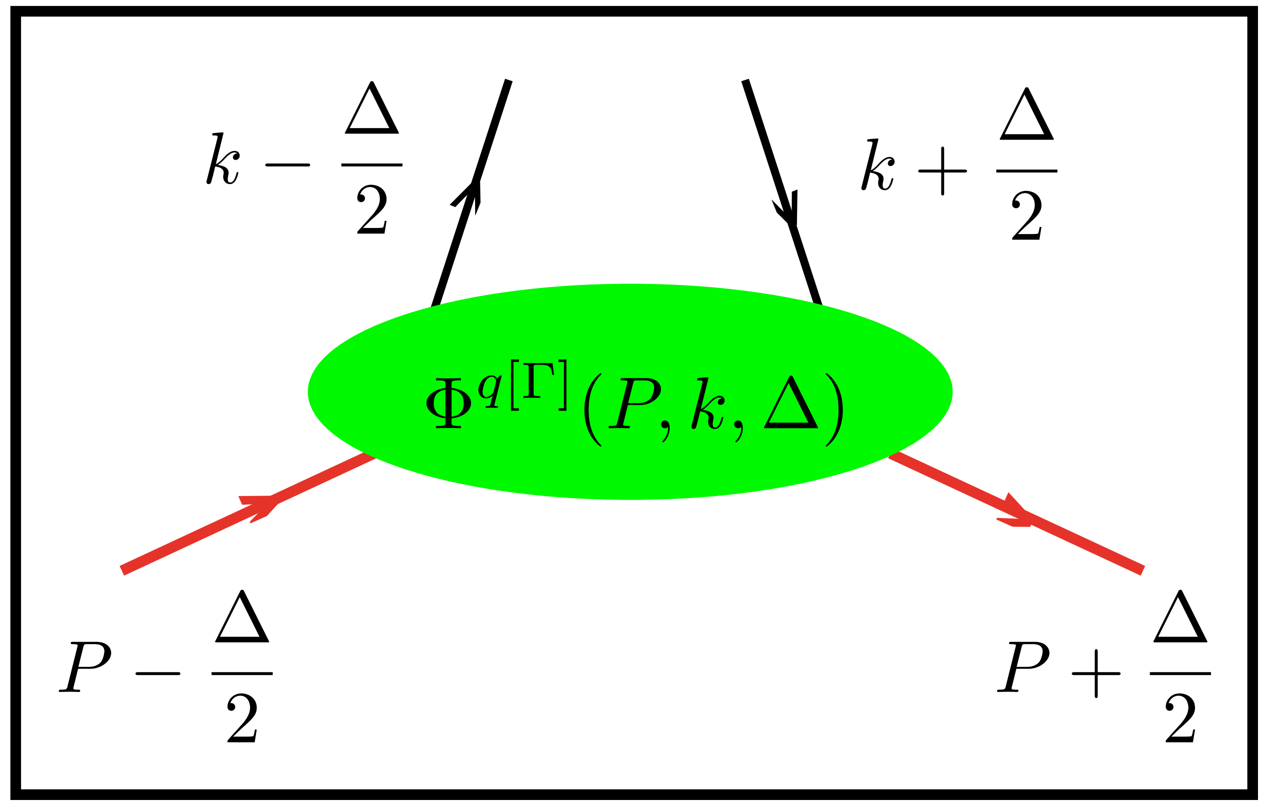


Indico page of this workshop :)




[Y. Yang et al., PRL (2018)]

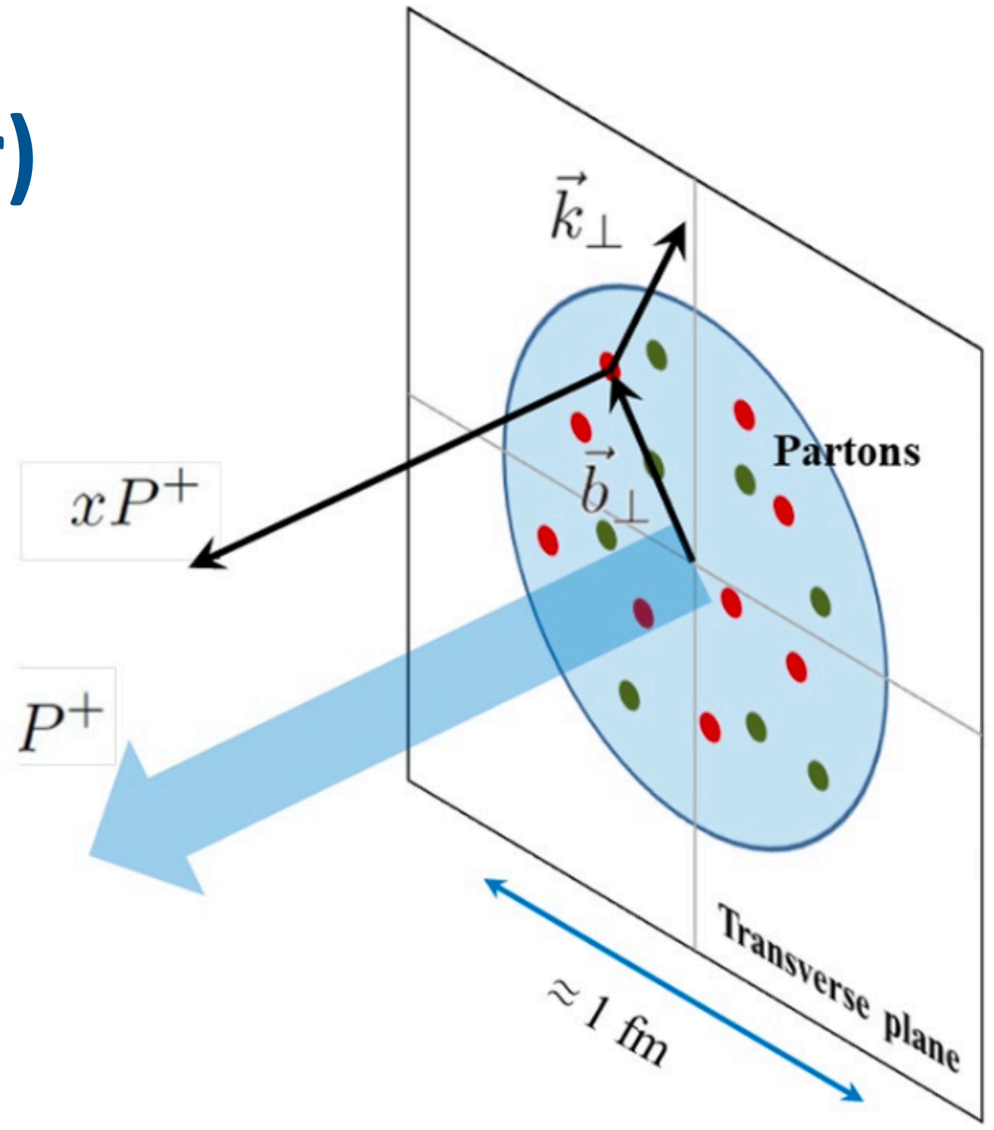
# General QCD quark correlator matrix elements to GPDs




$$\Phi^{q[\Gamma]}(P,k,\Delta) = \frac{1}{2}\int \frac{d^4 z}{(2\pi)^4} \langle p', S'|\bar{\psi}_q\left(-\frac{z}{2}\right)\Gamma\, W\left[-\frac{z}{2},\frac{z}{2}\right]\psi_q\left(\frac{z}{2}\right)|p,S\rangle$$

## Generalized TMD: Joint probability of space & momentum distribution (Wigner)

$$\Phi^{q[\Gamma]}_{\mathrm{GTMD}}(P,x,\vec{k}_\perp,\xi,\vec{\Delta}_\perp) = \int dk^+ dk^-\ \Phi^{q[\Gamma]}(P,k,\Delta)\delta(k^+ - xP^+)$$




## Generalized parton distributions

D. Müller, Fortsch.Phys. 42 (1994) 101-141

$\int d\vec{k}_\perp$ →

$$\Phi^{q[\Gamma]}_{\mathrm{GPD}}(P,x,\xi,\vec{\Delta}_\perp) = \int d^4k\ \Phi^{q[\Gamma]}(P,k,\Delta)\delta(k^+ - xP^+)$$

$$x = k^+/P^+,\quad \xi = -\Delta^+/(2P^+)$$

# Generalized Parton Distributions (nucleon, chirality even, twist-2)

## Unpolarized quarks

$$\frac{P^+}{2\pi}\int dy^-\, e^{ixP^+y^-}\langle P'|\,\bar{\psi}_q(0)\,\gamma^+\,\psi_q(y)\,|P\rangle\Big|_{y^+=\mathbf{y}_\perp=0}$$

$$= \boxed{H^q(x,\xi,t)}\,\bar{N}(P')\,\gamma^+\,N(P) + \boxed{E^q(x,\xi,t)}\,\bar{N}(P')\,i\sigma^{+\nu}\frac{\Delta_\nu}{2M_N}\,N(P)$$

## Longitudinally polarized quarks

$$\frac{P^+}{2\pi}\int dy^-\, e^{ixP^+y^-}\langle P'|\,\bar{\psi}_q(0)\,\gamma^+\gamma_5\,\psi_q(y)\,|P\rangle\Big|_{y^+=\mathbf{y}_\perp=0}$$

$$= \boxed{\tilde{H}^q(x,\xi,t)}\,\bar{N}(P')\,\gamma^+\gamma_5\,N(P) + \boxed{\tilde{E}^q(x,\xi,t)}\,\bar{N}(P')\,i\gamma_5\frac{\Delta^+}{2M_N}\,N(P)$$

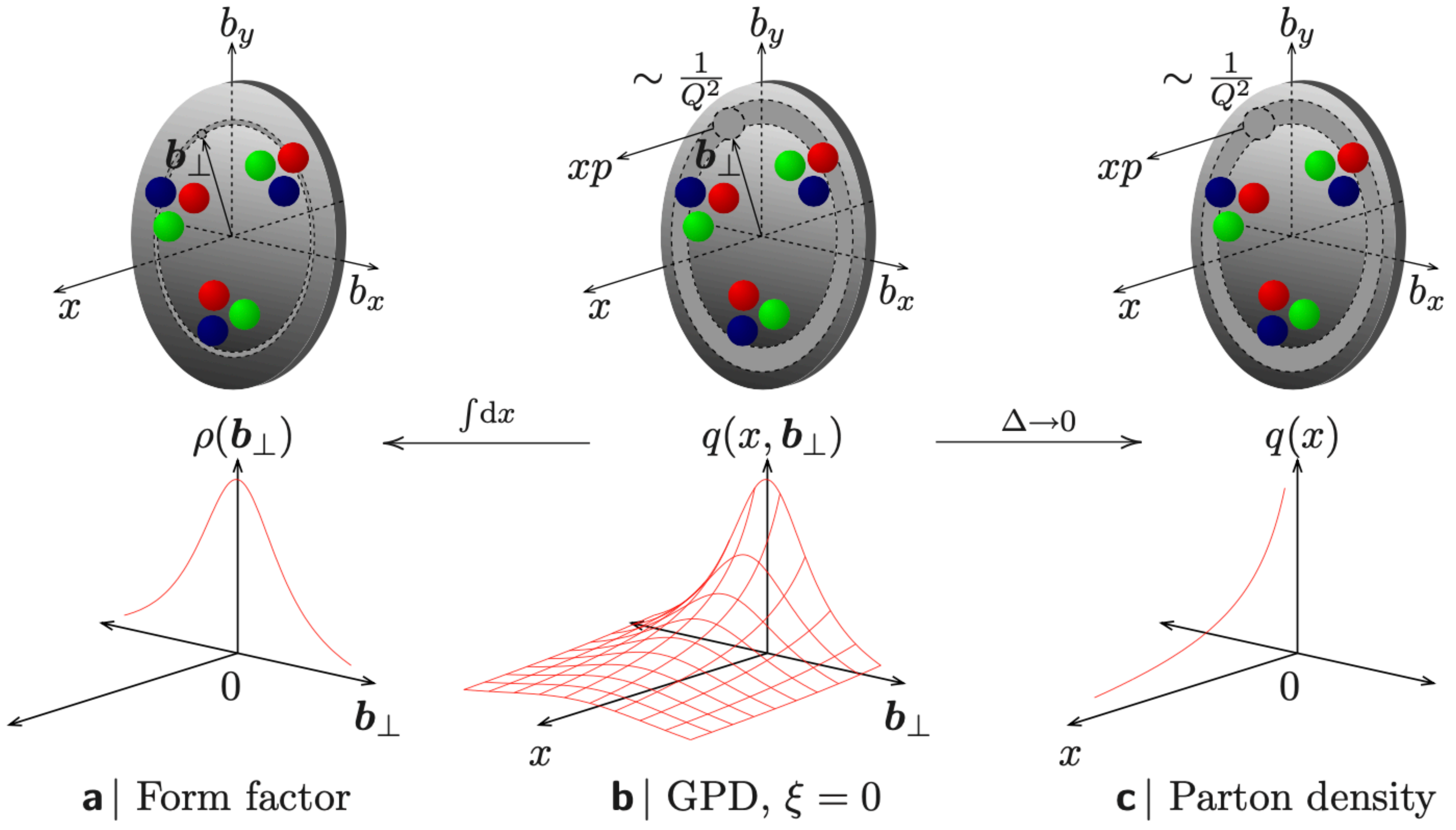
**+ gluon GPDs…**

# Properties of GPDs

**Forward limit of the target hadron → PDFs**

$$H^q(x,\,0,\,0) = f_1(x)$$ **Unpolarized quark distribution**

$$\tilde{H}^q(x,\,0,\,0) = g_1(x)$$ **Helicity quark distribution**




**Mellin moments (Polynomiality)**

$$\int_{-1}^{1} dx\, H^a(x,\xi,t) = F_1(t)$$

$$\int_{-1}^{1} dx\, E^a(x,\xi,t) = F_2(t)$$

**Electromagnetic form factors**

$$\int_{-1}^{1} dx\; x\, H^a(x,\xi,t) = A^a(t) + \xi^2 D^a(t)$$

$$\int_{-1}^{1} dx\; x\, E^a(x,\xi,t) = 2J^a(t) - A^a(t) - \xi^2 D^a(t)$$

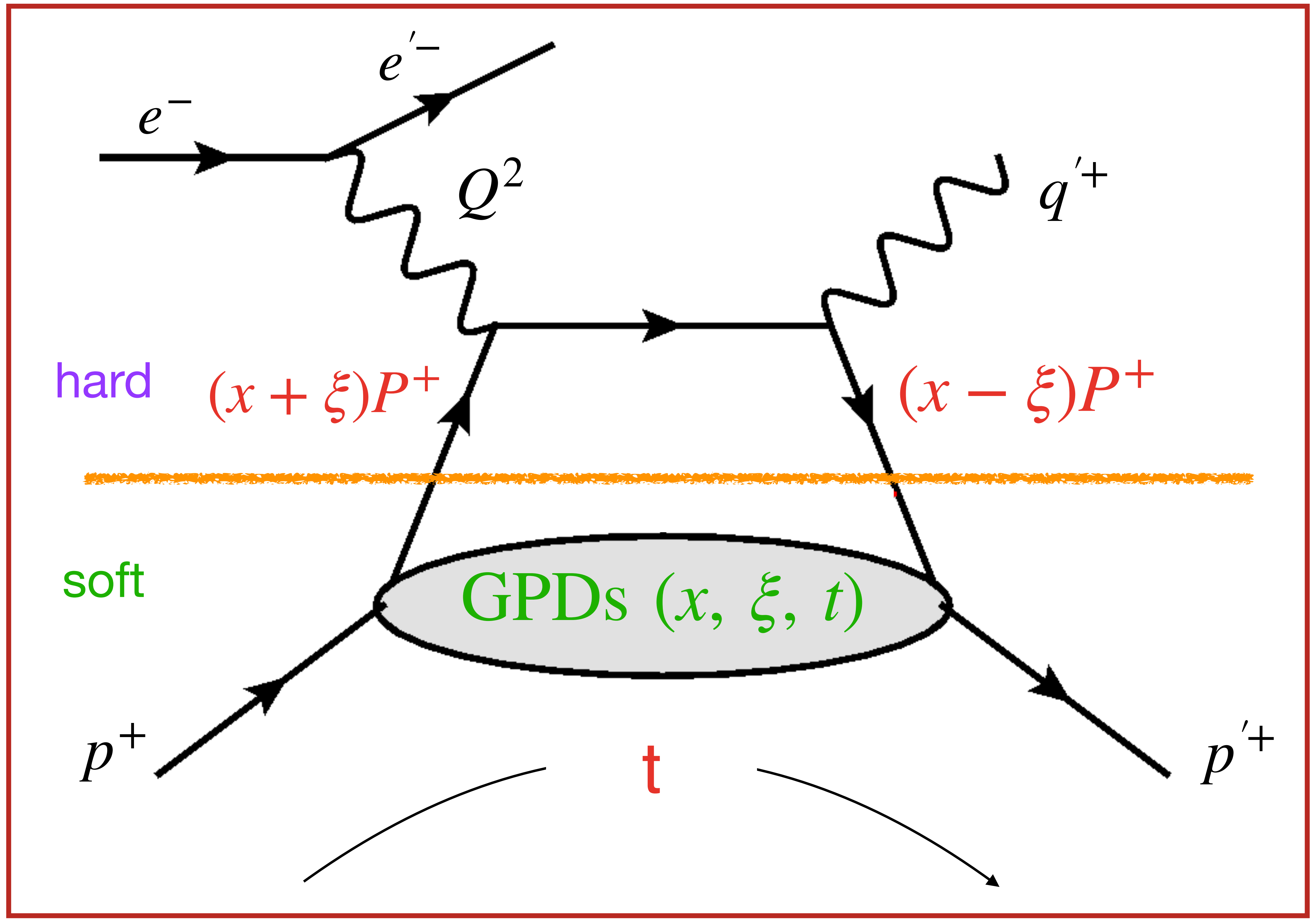
Twist-2 gravitational form factors

H+E = Ji's spin sum rule

# Deeply Virtual Compton Scattering

$ep \to e'\gamma p'$

Xiangdong Ji
*Phys.Rev.Lett.* 78 (1997) 610-613
*Phys.Rev.D* 55 (1997) 7114-7125

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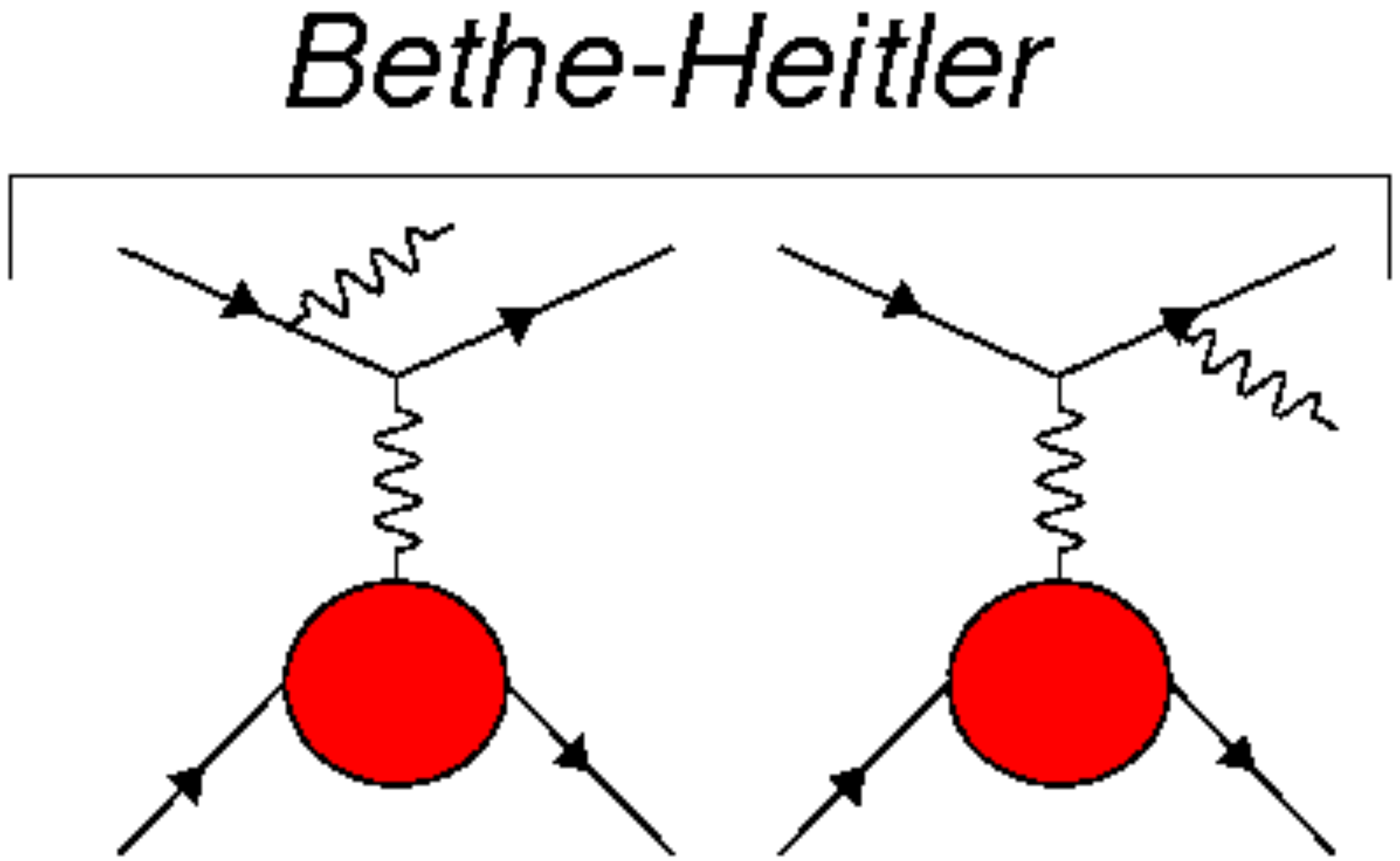



Scattering cross-section factorizes as:

hard part (pQCD) $\otimes$ soft part

# Mechanical structure of hadrons

**In DVCS, Compton form factors are measurable quantities,**

$$\mathcal{H}(\xi,t) = \int_{-1}^{1} dx \left( \frac{1}{\xi - x - i0} - \frac{1}{\xi + x - i0} \right) H(x,\xi,t)$$

**→ Extraction of the GPDs from experiments is model dependent**

**D-term** can be obtained using the **dispersion relation** of the Compton form factors, **model independently**

**Dispersion relation of the CFFs**

$$\mathrm{Re}\,\mathcal{H}(\xi,t) = \left( \frac{4}{5}\Sigma_q e_q^2\, D^q(t) + \ldots \right) + \frac{1}{\pi}\mathrm{PV}\int_0^1 d\xi'\ \mathrm{Im}\,\mathcal{H}(\xi',t) \left( \frac{1}{\xi - \xi'} - \frac{1}{\xi + \xi'} \right)$$

**Polyakov 2003**
**Teryaev 2005**
**Anikin, Teryaev 2007**
**Dlehl, Ivanov 2007**

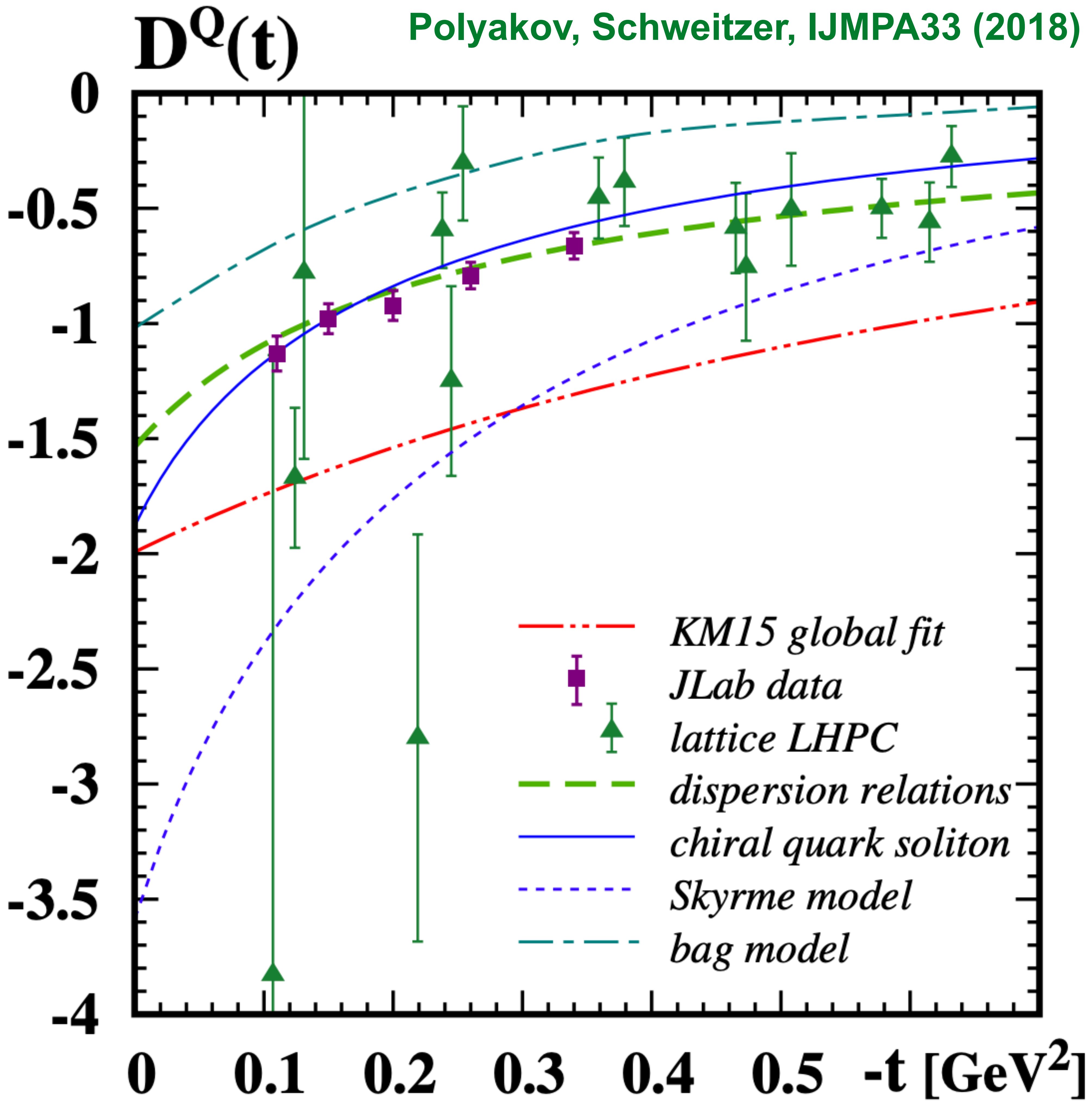
*D(t) as the (first) subtraction constant!*

M. Polyakov, *Phys.Lett.B* 555 (2003) 57-62

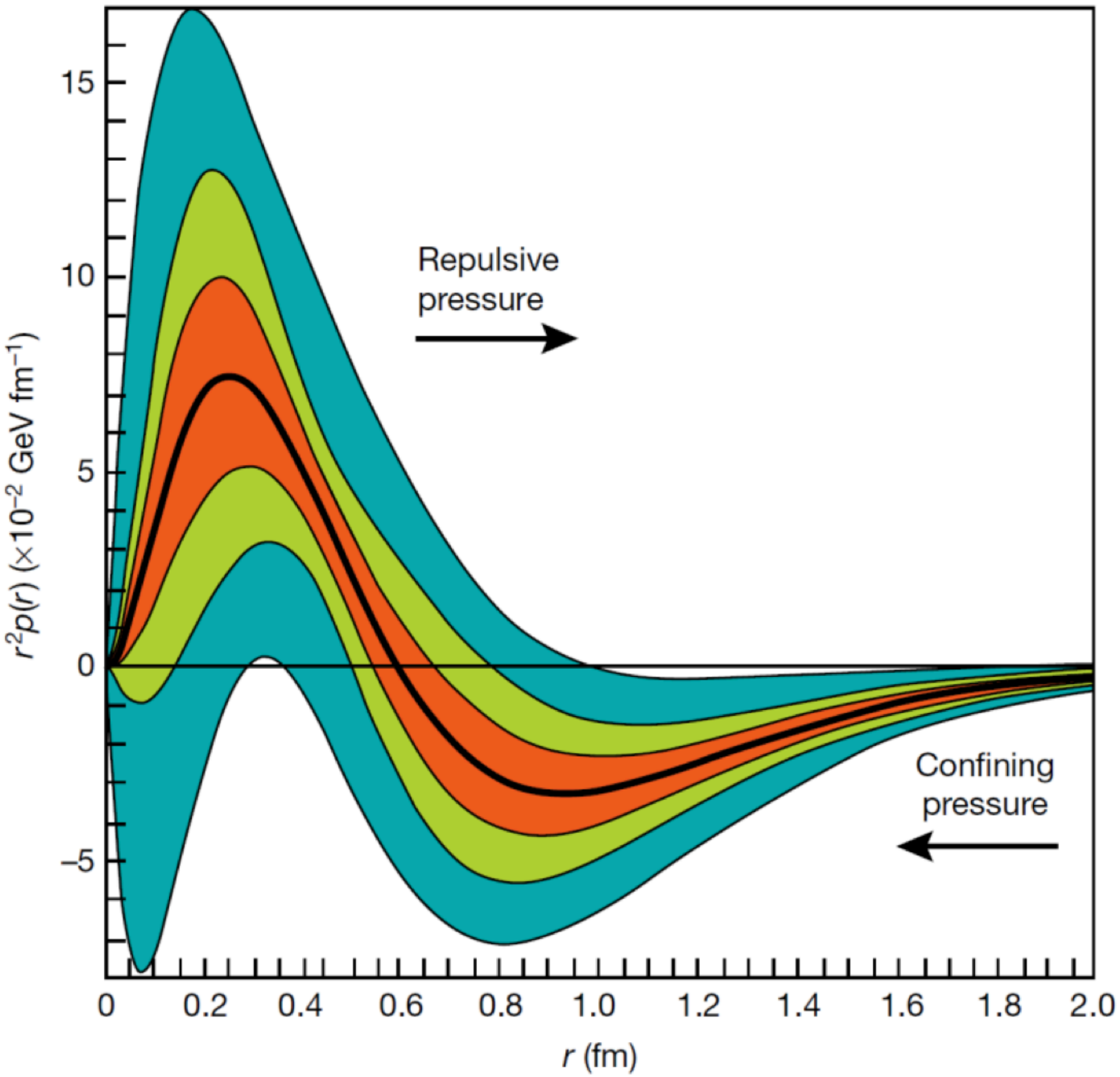
# ‘Pressure distribution’

$$p^a(r) = \frac{1}{6M_N}\frac{1}{r^2}\frac{d}{dr}r^2\frac{d}{dr}\int\frac{d^3\Delta}{(2\pi)^3}\, e^{-i\vec{\Delta}\cdot\vec{r}}\, D^a(t) - M_N\int\frac{d^3\Delta}{(2\pi)^3}\, e^{-i\vec{\Delta}\cdot\vec{r}}\, \bar{c}^a(t)$$

Polyakov, Schweitzer, IJMPA33 (2018)

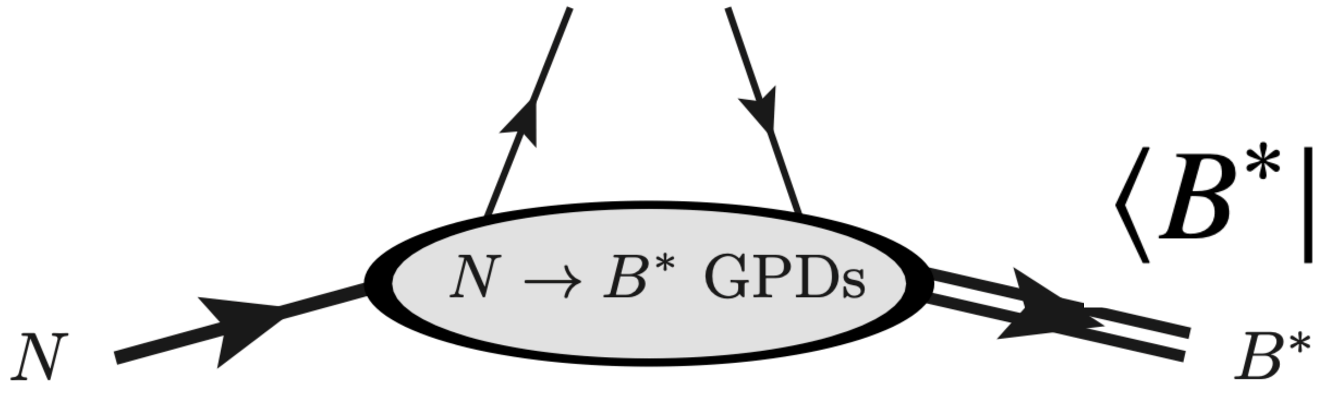



Burkert,Elouadrhiri,Girod, Nature 557(2018)



# Transition FFs and GPDs

Example: N → Δ transition (V,A)




$$\langle B^* | \bar{\psi}_q(0)\,[0;z]\,\psi_q(z) | N \rangle$$

| Operator | | Diagonal: $N \to N$ | Transition: $N \to \Delta$ |
|---|---|---|---|
| **Local** | Vector | $G_E(t),\ G_M(t)$<br>Sachs EM form factors | $g_M(t),\ g_E(t),\ g_C(t)$<br>Jones–Scadron |
| | Axial | $G_A(t),\ G_P(t)$<br>axial-vector & induced pseudoscalar | $C_3^A,\ C_4^A,\ C_5^A,\ C_6^A$<br>Adler axial transition FFs |
| | Gravitational ($n$=2) | $A(t),\ J(t),\ \mathbf{D(t)}$<br>EMT form factors | **transition gravitational FFs** |
| **Nonlocal** | Vector | $H(x,\xi,t),\ E(x,\xi,t)$ | $h_M,\ h_E,\ h_C,\ h_X\ \ (x,\xi,t)$ |
| | Axial | $\tilde{H}(x,\xi,t),\ \tilde{E}(x,\xi,t)$ | $C_1,\ C_2,\ C_3,\ C_X\ \ (x,\xi,t)$ |

**Production of the resonances in terms of quarks and gluons**

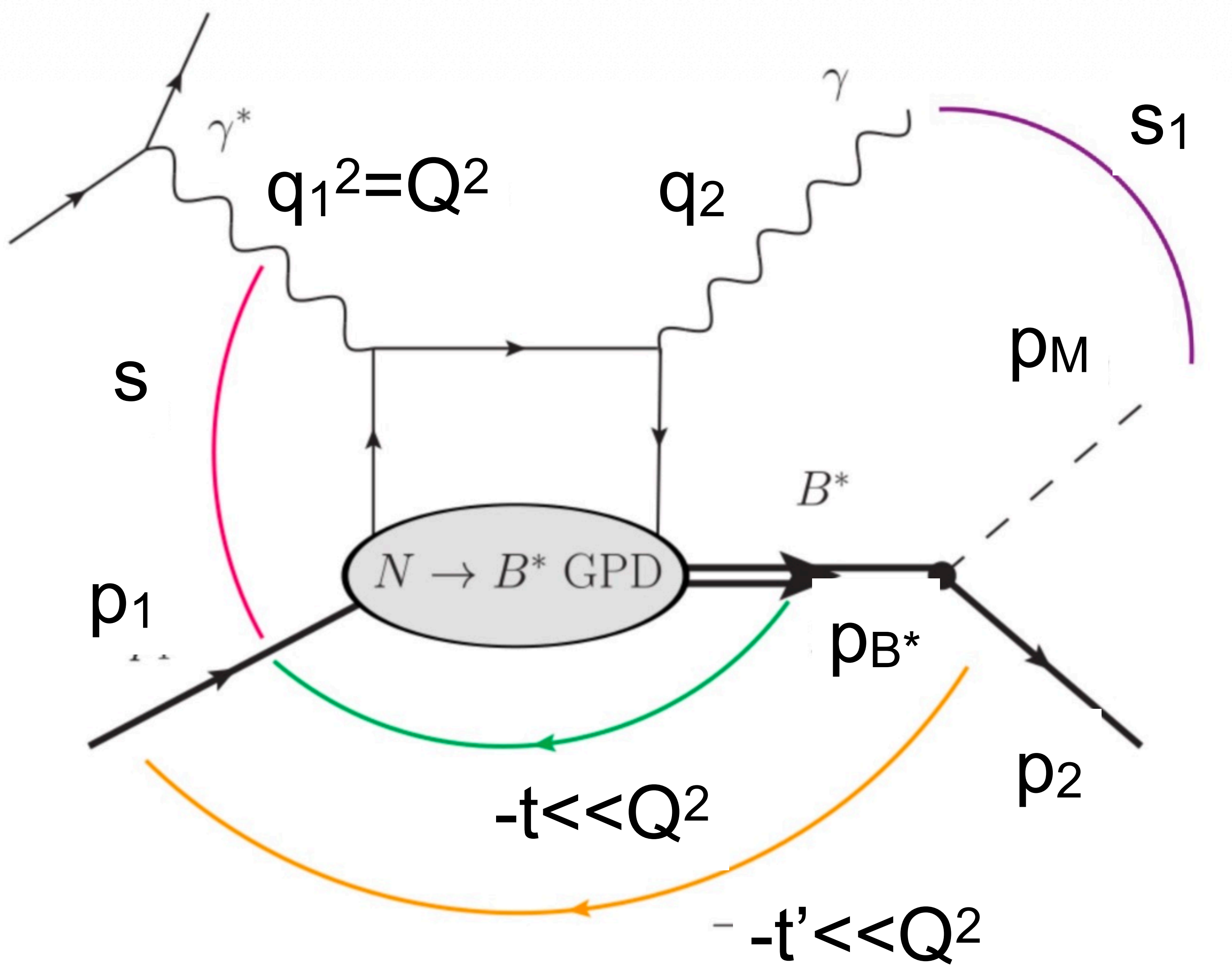
**Nonlocal parton operators: resonance production with arbitrary spin QCD operator**

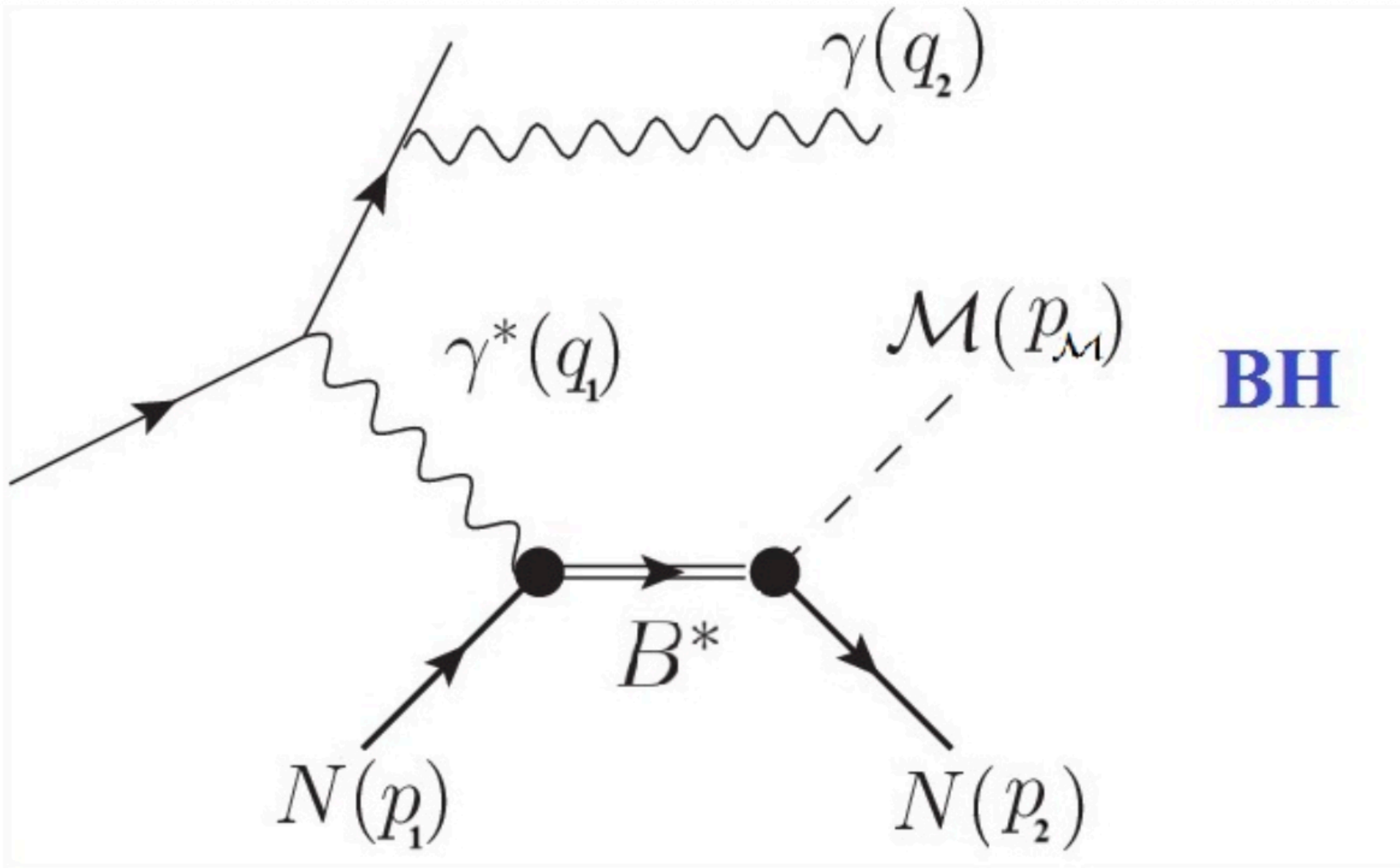
**N=2 Mellin moments: Transition gravitational from factors** H. Alharazin et al. *JHEP* 03 (2024) 007

**Forward limit: quark 'density' in the transition** J. Kim Phys.Rev.D 108 (2023) 3, 034024

## Nondiagonal DVCS

$$\gamma^*(q) + N(p) \to \gamma(q') + [\mathcal{M}(p_{\mathcal{M}})N(p')]; \quad \mathcal{M} = \pi, \eta, \rho, \omega, \ldots$$




**Factorization in terms of N → B* GPDs in the generalized Bjorken kinematics:**

$$-q_1^2;\ s = (p_1 + q_1)^2;\ s_1 = (p_{\mathcal{M}} + q_2)^2 - \text{ large}; \quad x_B = \frac{-q_1^2}{2p_1 \cdot q_1} - \text{ fixed};$$

$$-t = -(p_{B^*} - p_1)^2; \quad -t' = -(p_2 - p_1)^2; \quad W_{\mathcal{M}N}^2 = (p_1 + p_{\mathcal{M}})^2 \quad \text{of hadronic scale.}$$

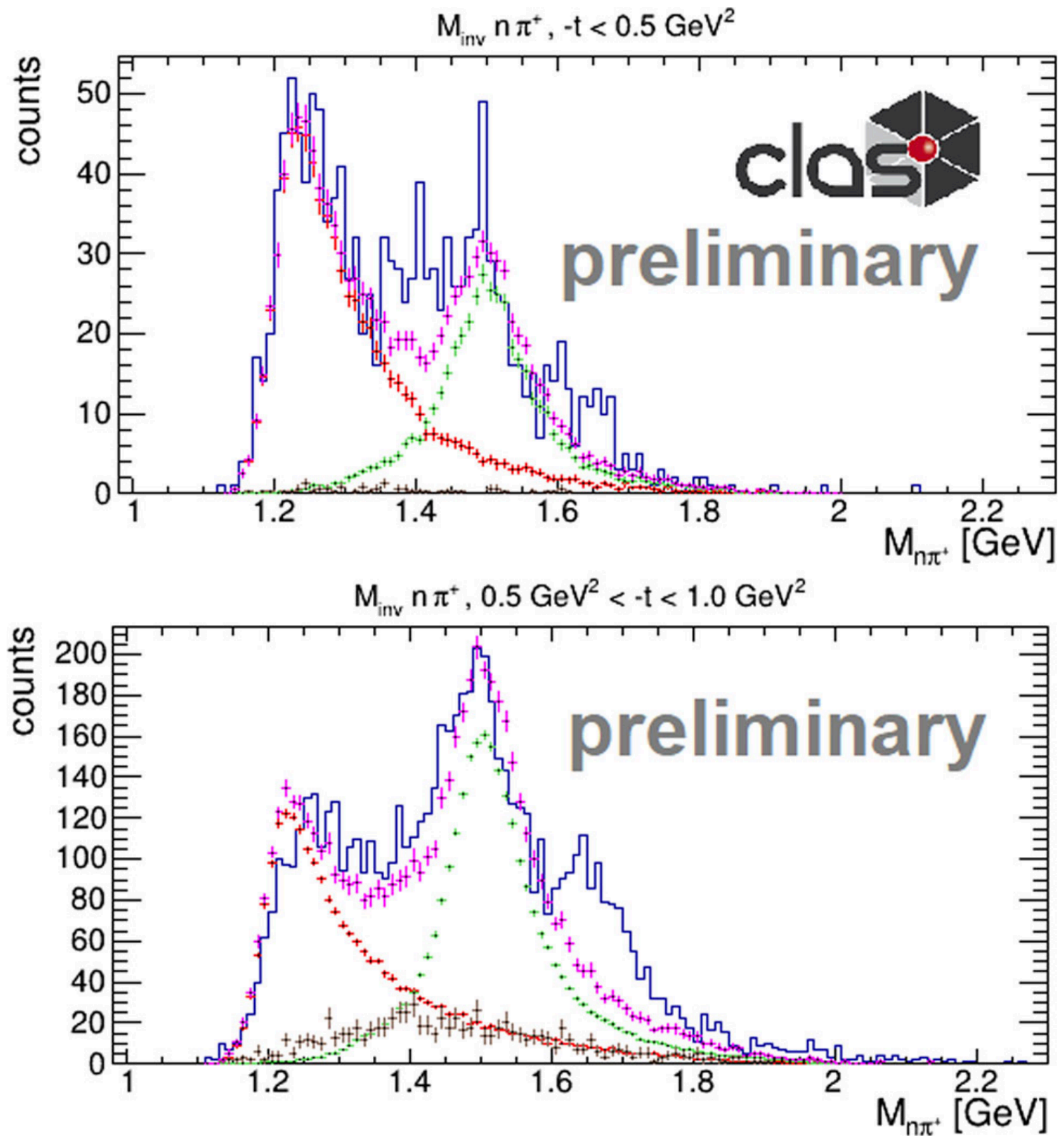
# First nondiagonal DVMP measurement from CLAS12

## $\sigma_{LT'}/\sigma_0$ sensitive to the transversity transition GPDs

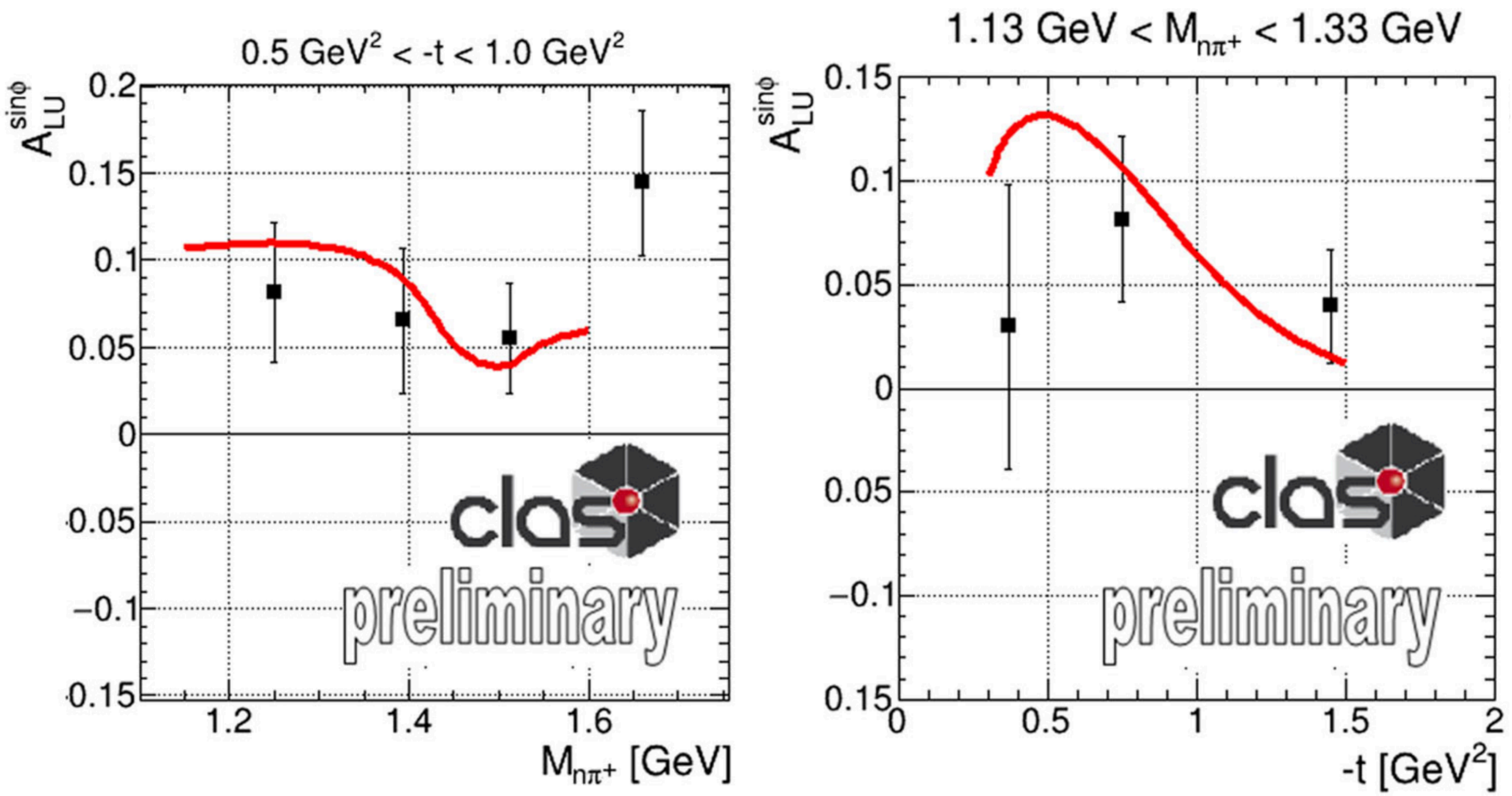
S. Diehl et. al.,*Phys.Rev.Lett.* 131 (2023) 2, 021901

# Invariant mass distributions for $e^- p \rightarrow e^- \gamma n \pi^+$

## Cross section



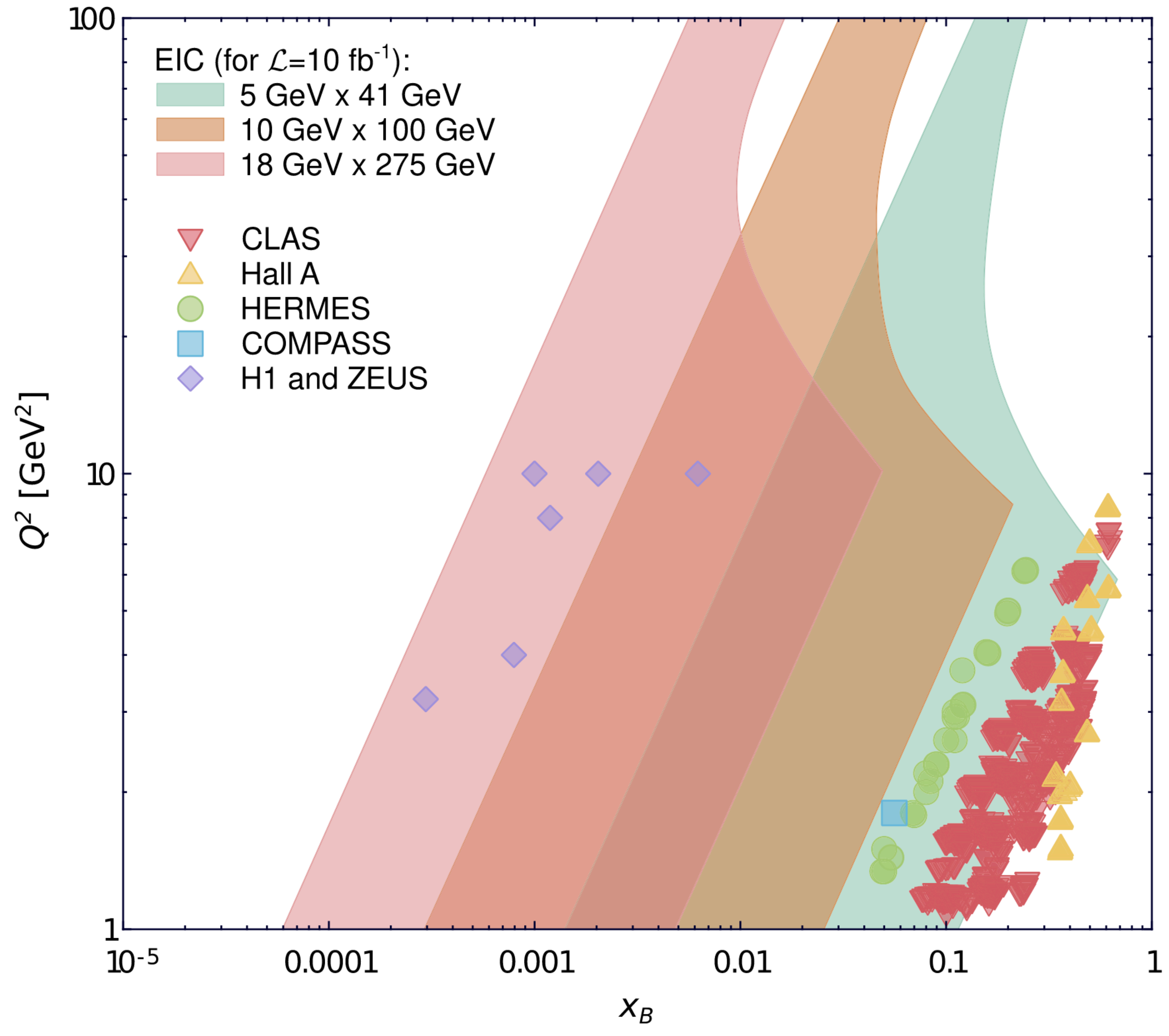

## BSA




Preliminary results from S. Diehl,
TGPD white paper *Eur.Phys.J.A* 61 (2025) 6, 131
Theoretical curve: K. Semenov and M. Vanderhaeghen
*Phys.Rev.D* 108 (2023) 3, 034021

Shows the applicability of GPD framework under the collinear factorization in non-diagonal processes

# Opportunities for DVCS at the EIC

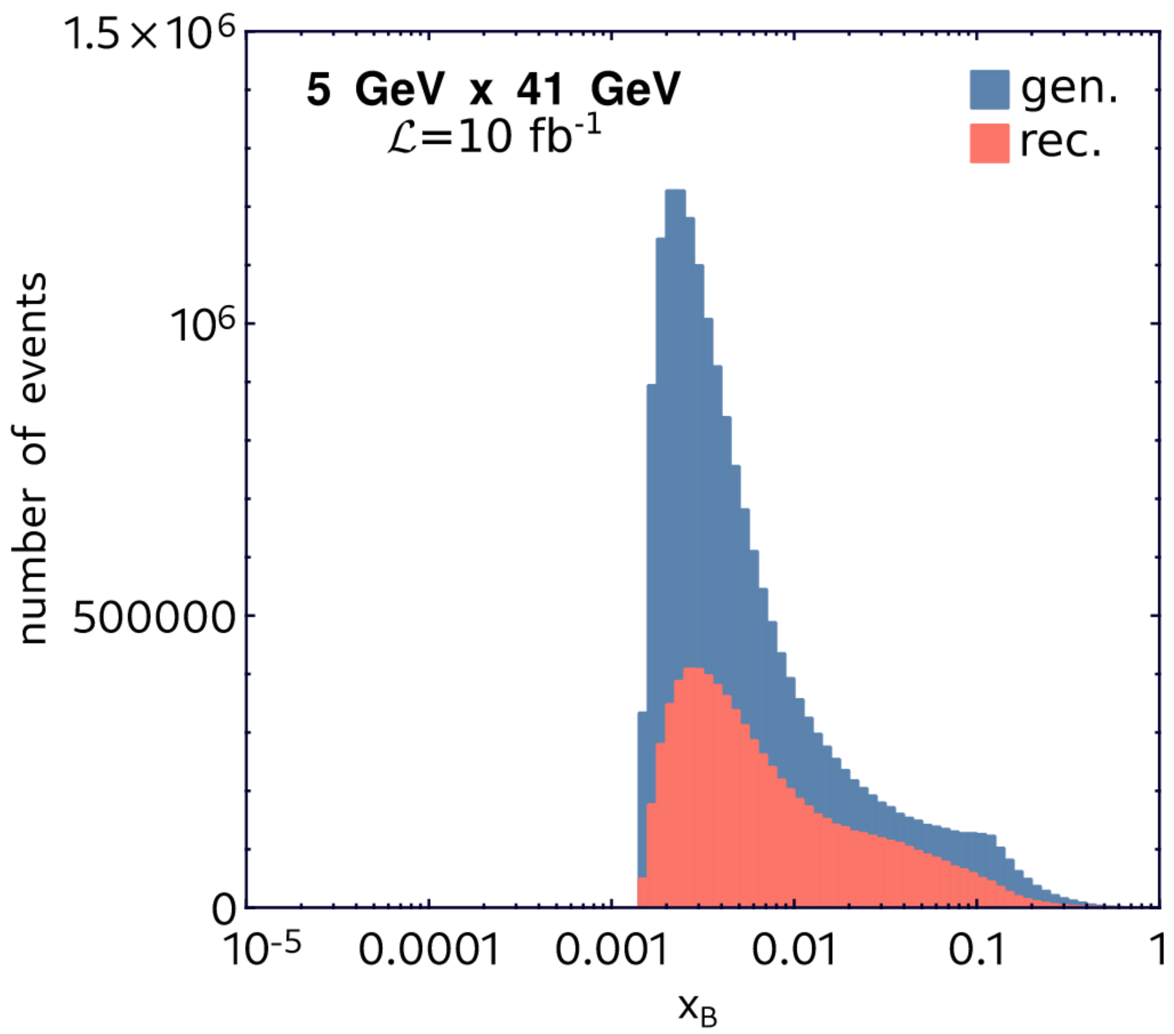


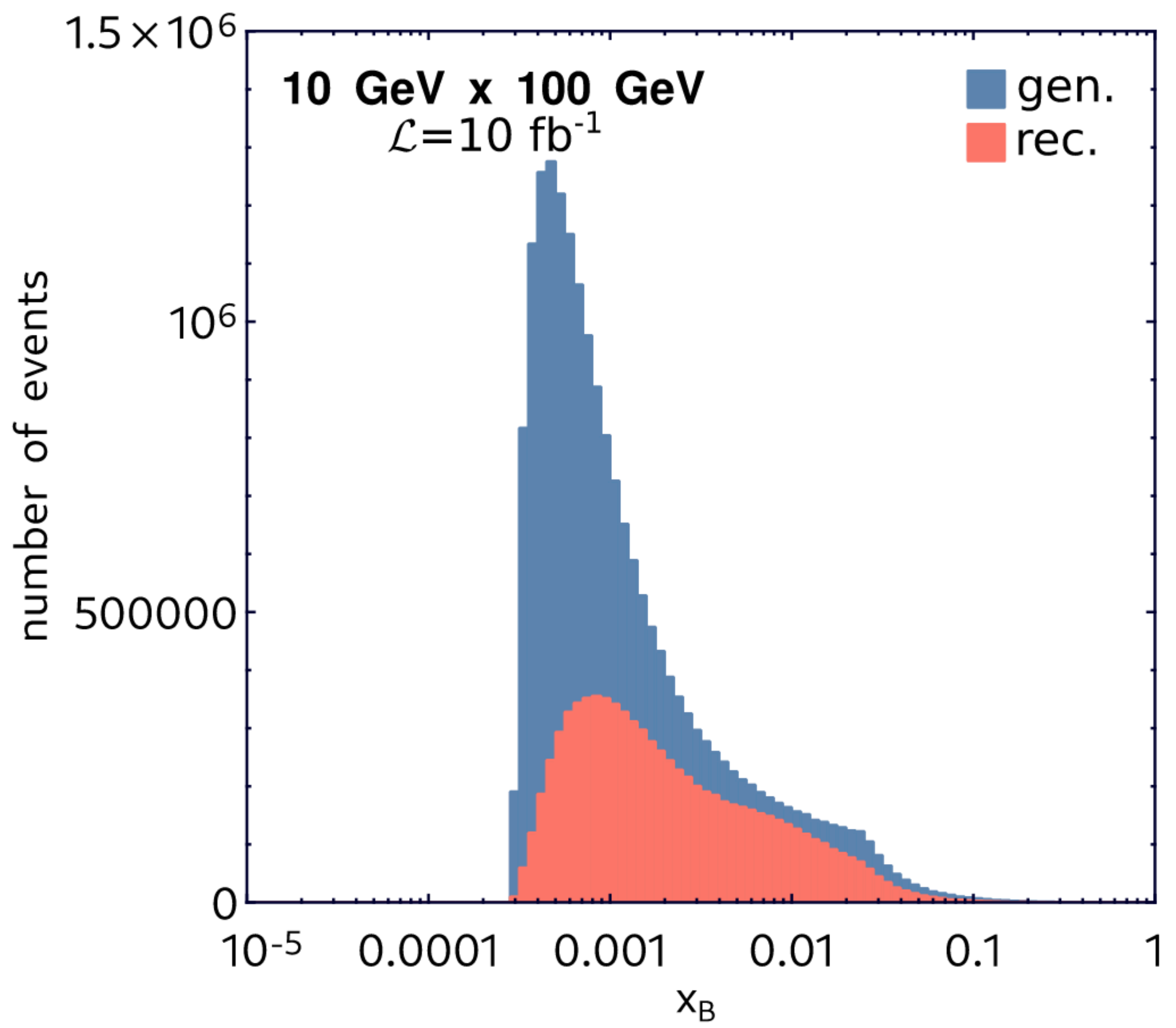

## EIC promises

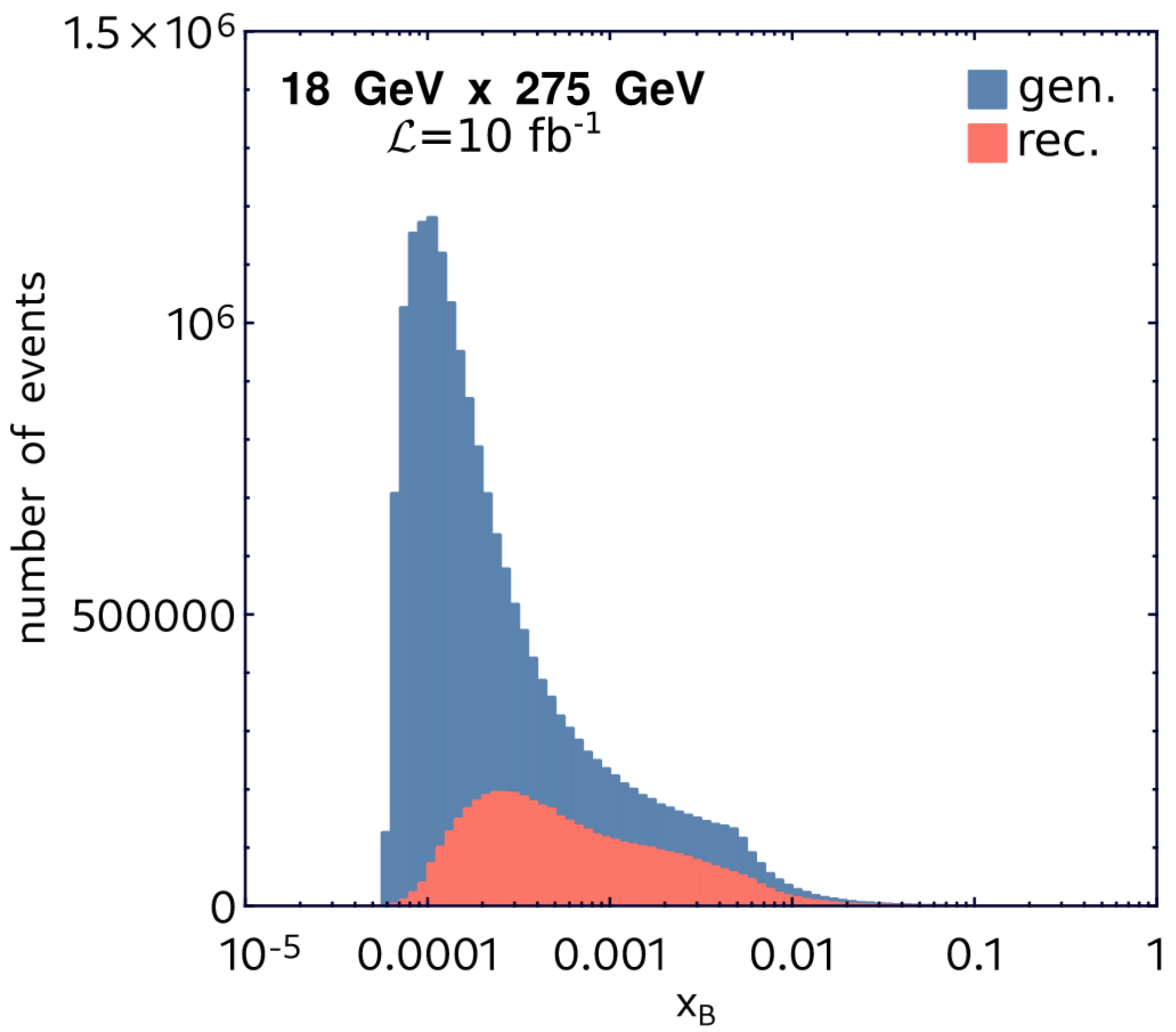
EIC Yellow report, 2022

- Broad kinematic coverage across the valence and sea regions
- Polarized lepton and proton beams
- High luminosity

Dedicated study for diagonal DVCS off a proton,
E. Aschenauer et. al., PRD 112 (2025)



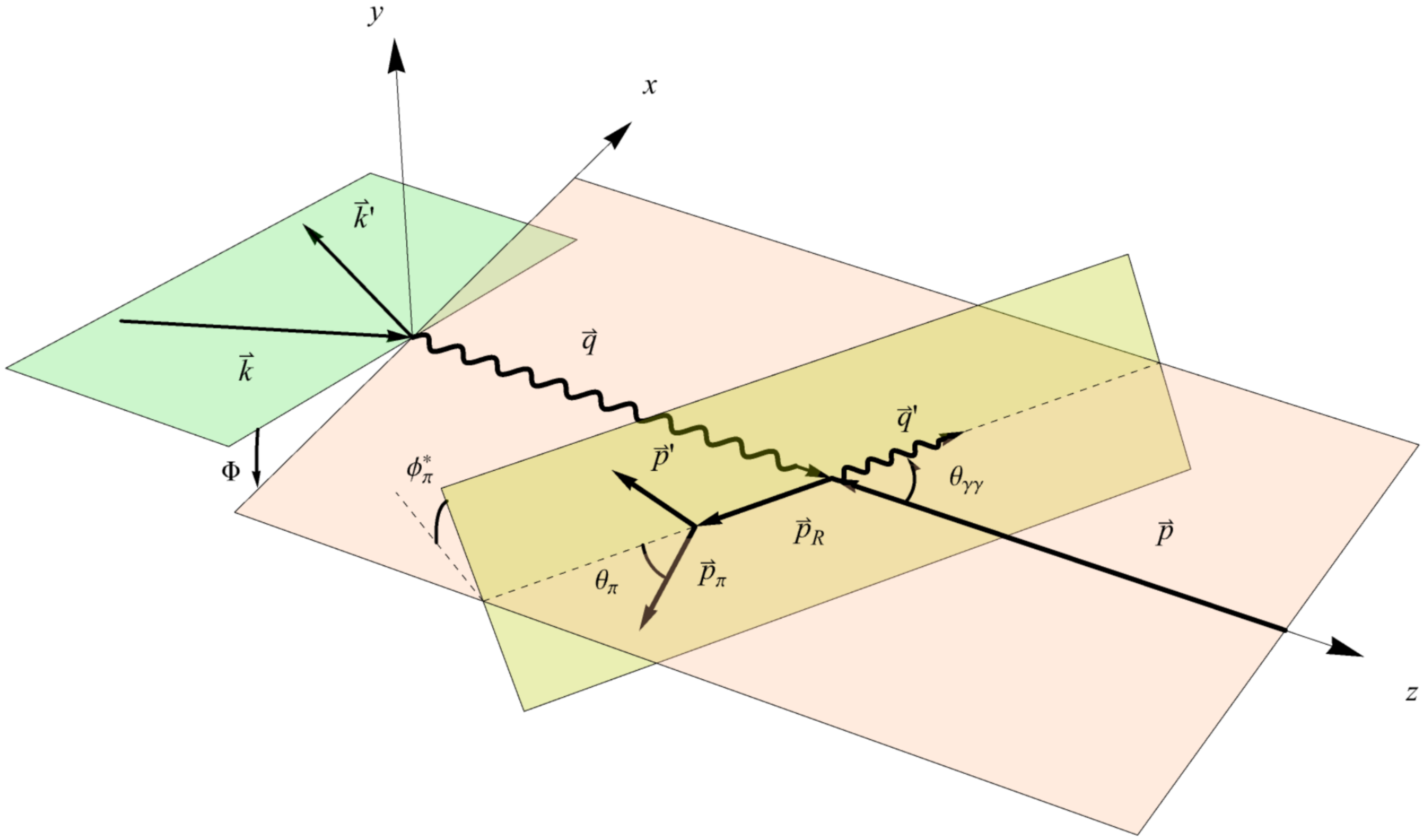



# Nondiagonal N-Δ DVCS amplitudes

# Nondiagonal DVCS

K. Semenov and M. Vanderhaeghen *Phys.Rev.D* 108 (2023) 3, 034021

$$e(k) + N(p) \to e'(k') + \gamma^*(q) + N(p) \to e'(k') + \gamma(q') + \pi(p_\pi) + N'(p')$$




## Differential cross section:

$$\frac{d^7\sigma}{dQ^2 dx_B\, dt\, d\phi\, dW^2_{\pi N}\, d\Omega^*_\pi}$$

$\gamma^* N \to B^* \gamma$ Transition subprocess

$B^* \to \pi N'$ Resonance decay

# N-Δ DVCS

## Narrow decay width approximation

P. Guichon, L. Mossé, and M. Vanderhaeghen, 2003

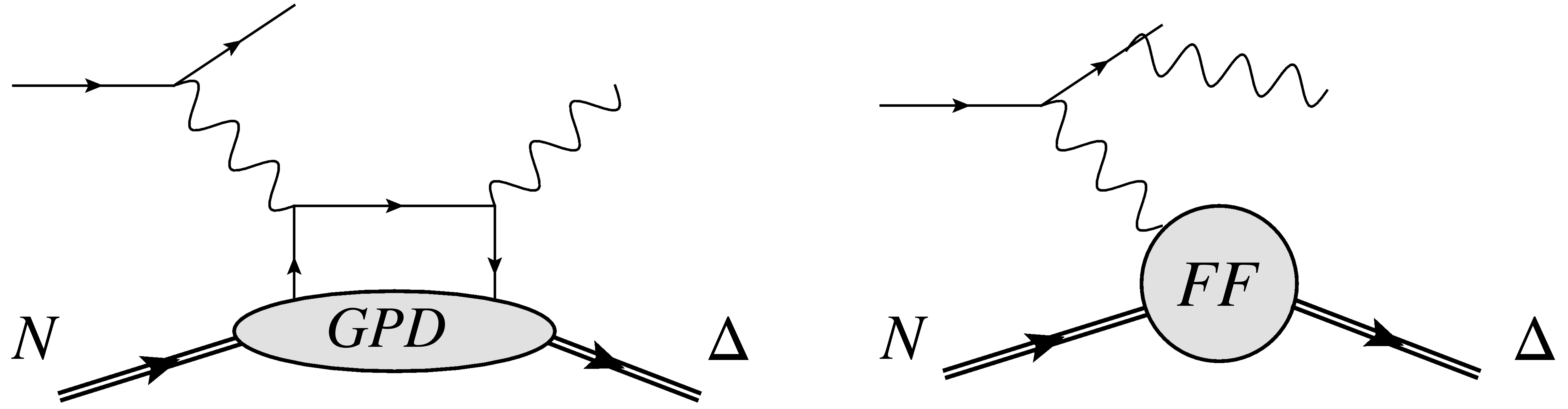
$$\int_{(m_N+m_\pi)^2}^{\infty} dW_{\pi N}^2 \, \frac{d\sigma(eN \to e\gamma B^* \to e\gamma\pi N)}{dQ^2\, dx_B\, dt\, d\Phi\, dW_{\pi N}^2}$$

$$\propto \boxed{\frac{d\sigma(eN \to e\gamma B^*)}{dQ^2\, dx_B\, dt\, d\Phi}} \underbrace{\int_{(m_N+m_\pi)^2}^{\infty} dW_{\pi N}^2 \, \frac{W_{\pi N}\Gamma(W_{\pi N})}{(W_{\pi N}^2 - m_{B^*}^2)^2 + m_{B^*}^2\Gamma^2(W_{\pi N})}}_{\sim \mathcal{O}(1) \quad \text{for} \quad \Gamma(m_{B^*})/m_{B^*} \ll 1}$$

## $eN \to e'\gamma\Delta$ amplitude: VCS + BH

$$\frac{\Gamma(m_\Delta)}{m_\Delta} \simeq 10\ \%$$

**We treat the Δ as a stable hadron state**



# N-Δ DVCS amplitudes

**Harmonic expansion in the angle $\phi$ bin the leptonic and production planes**

$$|\mathcal{M}_{\mathrm{BH}}|^2 = \frac{e^6}{x_B^2 y^2 t \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[ \sum_{n=0}^{2} c_n^{\mathrm{BH}} \cos(n\phi) + s_1^{\mathrm{BH}} \sin\phi \right],$$

$$|\mathcal{M}_{\mathrm{VCS}}|^2 = \frac{e^6}{y^2 Q^2} \left[ \sum_{n=0}^{2} c_n^{\mathrm{VCS}} \cos(n\phi) \right],$$

$$\mathcal{I} = \frac{e^6}{x_B y^3 t \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{\mathcal{I}} + \sum_{n=1}^{3} \left[ c_n^{\mathcal{I}} \cos(n\phi) + s_n^{\mathcal{I}} \sin(n\phi) \right] \right\}$$

**Cf. Diagonal DVCS:**
**Belitsky, Müller, Kirchner,**
***Nucl.Phys.B* 629 (2002) 323-392**

# N-Δ DVCS amplitudes

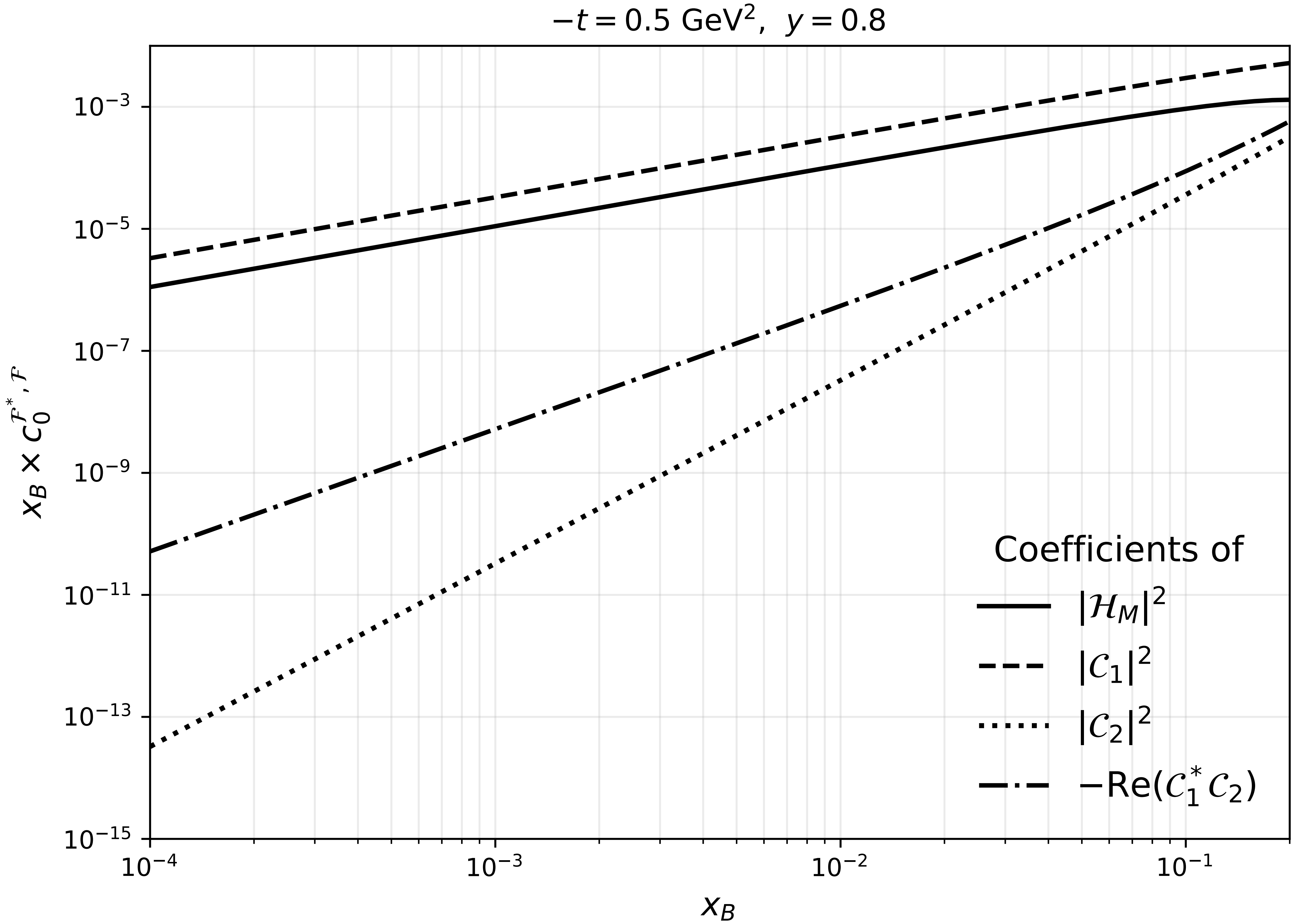
## Harmonic coefficients for DVCS

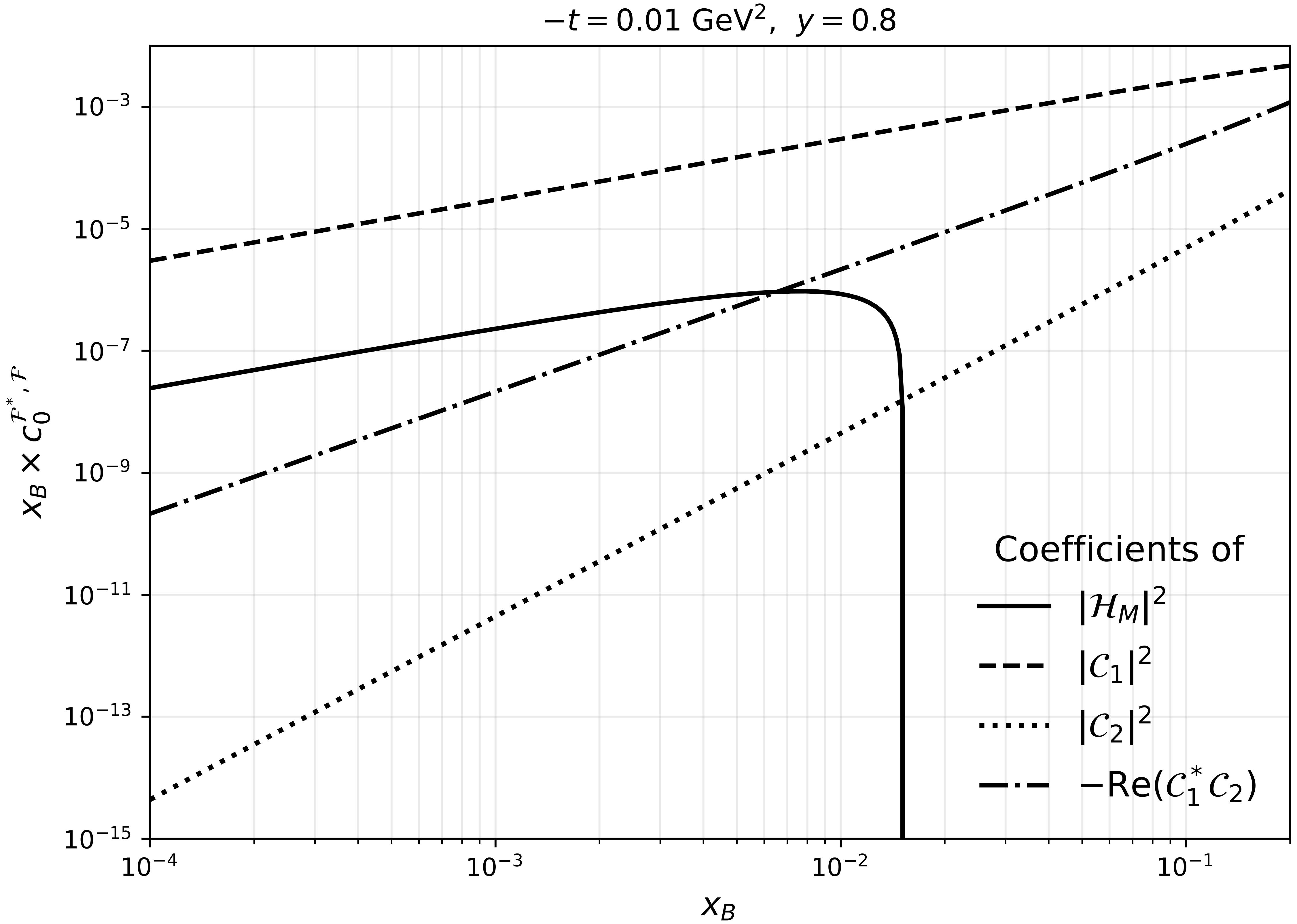
$$c_n^{\mathrm{VCS}} \propto (t_{\mathrm{min}} - t)|\mathcal{H}_M|^2 + \text{Other CFFs}.$$

**Magnetic dipole CFF HM becomes less important**

**near t =**

$$t_{\mathrm{min}} = -\frac{x_B}{1-x_B}\left[W_{\pi N}^2 - (1-x_B)m_N^2\right] + \mathcal{O}(Q^{-2})$$



# Spin asymmetries and azimuthal angle modulations

| Type | CFFs | φ modulation (Leading twist-2) |
|---|---|---|
| $A_{LU}$ | $\mathrm{Im}\,H_M$, $\mathrm{Im}\,C_I$ | sinφ, sin2φ |
| $A_{UL}$ | $\mathrm{Im}\,H_M$, $\mathrm{Im}\,C_I$, $\mathrm{Im}\,C_2$ | sinφ, sin2φ, sin3φ |
| $A_{LL}$ | $\mathrm{Re}\,H_M$, $\mathrm{Re}\,C_I$, $\mathrm{Re}\,C_2$ | cosφ |

Polarization power of the EIC gives access to all CFFs in the large Nc

through the longitudinal spin asymmetries!

# N-Δ Transition GPDs in the large Nc limit

# N-Δ Transition GPDs

L.L. Frankfurt et al. PRL 84 (2000) 2589

J.-Y. Kim et al. PRD 111 (2025)

## Vector GPDs

$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle \Delta(p_\Delta) | \bar{\psi}(-\lambda n/2) \not{n} \tau^3 \psi(\lambda n/2) | N(p_N) \rangle$$

$$= \sqrt{\frac{2}{3}} \bar{R}_\beta(p_\Delta) \left[ h_M(x,\xi,t) \mathcal{K}_M^{\beta\mu} n_\mu + h_E(x,\xi,t) \mathcal{K}_E^{\beta\mu} n_\mu + h_C(x,\xi,t) \mathcal{K}_C^{\beta\mu} n_\mu + h_X(x,\xi,t) \mathcal{K}_X^{\beta\mu} n_\mu \right] N(p_N),$$

## Mellin moments of vector GPDs

$h_M(x,\xi,t)$ → $2g_M(t)$

$h_E(x,\xi,t)$ → $2g_E(t)$

$h_C(x,\xi,t)$ → $2g_C(t)$

$h_X(x,\xi,t)$ → $0$

$\int_{-1}^{1} dx$

N-Delta vector transition ffs (related to Jones-Scadron)

Pascalutsa, Vanderhaeghen, Yang, Phys. Rept. 437 125 (2007)

# N-Δ Transition GPDs

L.L. Frankfurt et al. PRL 84 (2000) 2589

J.-Y. Kim et al. PRD 111 (2025)

## Axial vector GPDs

$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle \Delta(p_\Delta) | \bar{\psi}(-\lambda n/2) \not{n} \gamma_5 \tau^3 \psi(\lambda n/2) | N(p_N) \rangle$$

$$= \bar{R}_\beta(p_\Delta) \left[ \boxed{C_1(x,\xi,t)} \tilde{\mathcal{K}}_1^{\beta\mu} n_\mu + \boxed{C_2(x,\xi,t)} \tilde{\mathcal{K}}_2^{\beta\mu} n_\mu + \boxed{C_3(x,\xi,t)} \tilde{\mathcal{K}}_3^{\beta\mu} n_\mu + \boxed{C_X(x,\xi,t)} \tilde{\mathcal{K}}_X^{\beta\mu} n_\mu \right] N(p_N)$$

## Mellin moments of axial vector GPDs

$$\sqrt{\frac{2}{3}} \int_{-1}^{1} dx \quad \longrightarrow$$

$$C_1(x,\xi,t) \to 2\left[ C_5^A(t) + \frac{m_\Delta^2 - m_N^2}{m_N^2} C_4^A(t) \right]$$

$$C_2(x,\xi,t) \to 2\left[ C_6^A(t) + \frac{1}{\xi} C_4^A(t) \right]$$

$$C_3(x,\xi,t) \to 2C_3^A(t)$$

$$C_X(x,\xi,t) \to 0$$

} N-Delta axialvector transition ffs

Pascalutsa, Vanderhaeghen, Yang, Phys. Rept. 437 125 (2007)

# Transition GPDs in the large Nc limit

L.L. Frankfurt et al. PRL 84 (2000) 2589
Goeke, Polyakov, Vanderhaeghen PPNP 47 (2001) 401

Large Nc limit of QCD:

nucleon and Δ are different rotational excitation (1/Nc) states

in the same classical soliton

→Large Nc relation of the N-Δ GPDs and nucleon GPDs

$$H_M(x,\xi,t) = \sqrt{2}\,[E_u(x,\xi,t) - E_d(x,\xi,t)]\,,$$
$$C_1(x,\xi,t) = \sqrt{3}\left[\tilde{H}_u(x,\xi,t) - \tilde{H}_d(x,\xi,t)\right],$$
$$C_2(x,\xi,t) = \frac{\sqrt{3}}{4}\left[\tilde{E}_u(x,\xi,t) - \tilde{E}_d(x,\xi,t)\right].$$

Isovector dominance follows from the nucleon GPDs

All other GPDs are 1/Nc suppressed; set to zero

Cx!

# Phenomenological model for the N-Δ transition GPDs

## Regge-motivated t-dependence

S. Goloskokov and P. Kroll, 2007, 2014

$$H_q(x, \xi = 0, t) = q(x)e^{t[f(x)]}$$

$$\tilde{H}_q(x, \xi = 0, t) = \Delta q(x)e^{t[f(x)]}$$

$$E_q(x, \xi = 0, t) = \mathcal{N} x^{-r}(1-x)^s e^{t[f(x)]}$$

Regge trajectory

$$f(x) = -\alpha'(1-x)^3 \ln x + B_q(1-x)^3 + A_q x(1-x)^3$$

## Forward limit of the helicity-flip GPD E

M. Diehl and W. Kugler, 2007

Ansatz $e(x) = Nx^{-\alpha}(1-x)^{\beta}$, satisfying the constraints from the first moment and the EMT conservation, etc.

$$0 = \int_0^1 \mathrm{d}x\, E^g(x,0,0) + \sum_q \int_{-1}^1 \mathrm{d}x\, x E^q(x,0,0)$$

$$= \int_0^1 \mathrm{d}x\, x e^g(x) + \sum_q \int_0^1 \mathrm{d}x\, x\,[e_{q_v}(x) + 2e_{\bar{q}}(x)]$$

**Also, $\tilde{H}$: DSSVpol, $\tilde{E}$: pion pole dominance**

## Full GPD: Radyushkin double distribution ansatz

A. Radyushkin, 1999

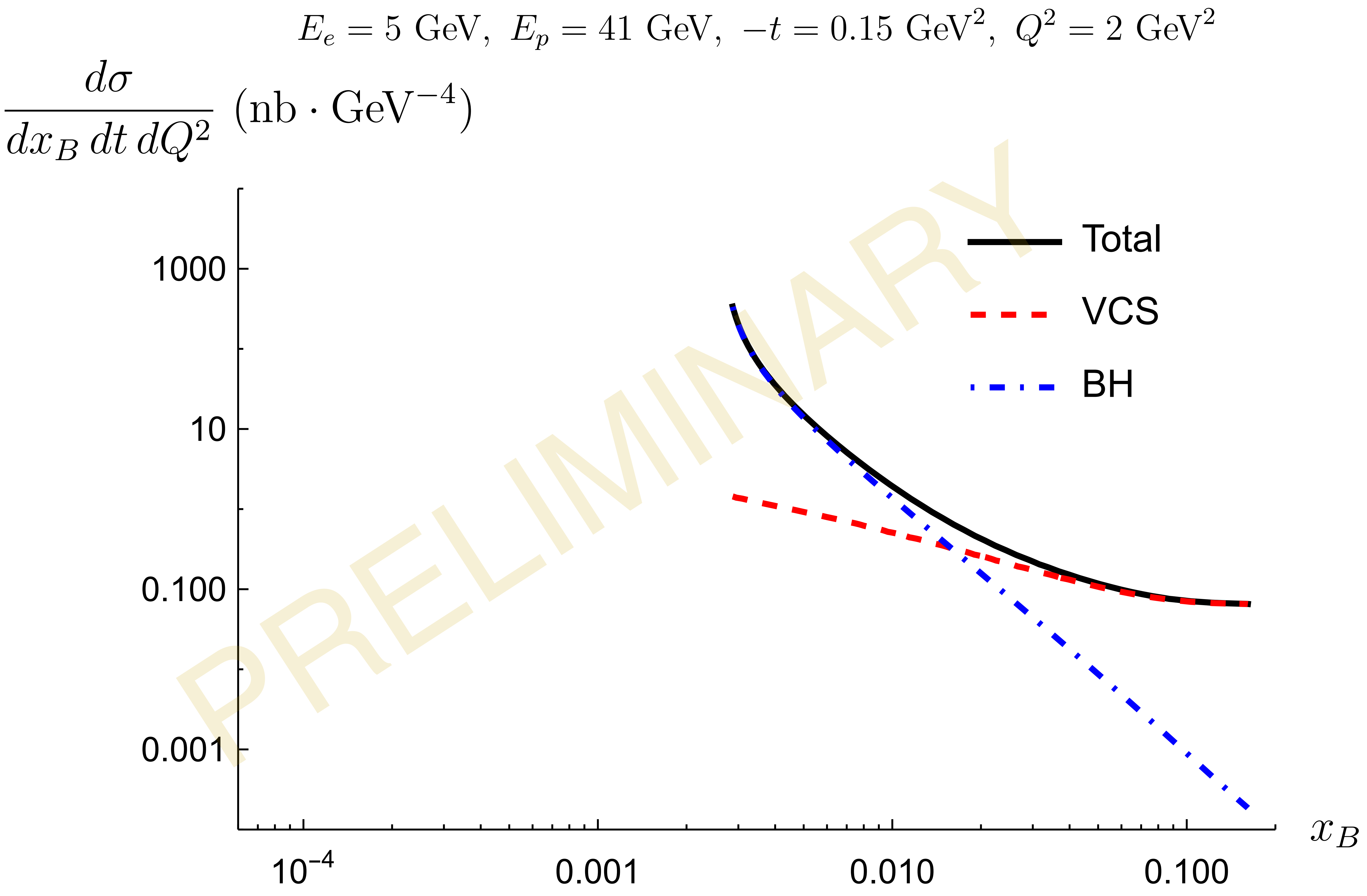
$$F_q(x,\xi,t) = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha \delta(x - \xi\alpha - \beta) h(\beta,\alpha) F_q(\beta, \xi = 0, t)$$

$$h(\alpha,\beta) = \frac{\Gamma(2n+2)}{2^{2n+1}[\Gamma(n+1)]^2} \frac{[(1-|\beta|)^2 - \alpha^2]^n}{(1-|\beta|)^{2n+1}}$$

# Numerical Results and Discussions (preliminary )

# Differential Cross sections $e^- p \to e^- \gamma \Delta^+$

*For each $s_{ep}$, Bjorken-$x_B$ ranges are bounded by the lepton energy loss cut $0.01 \le y \le 0.85$



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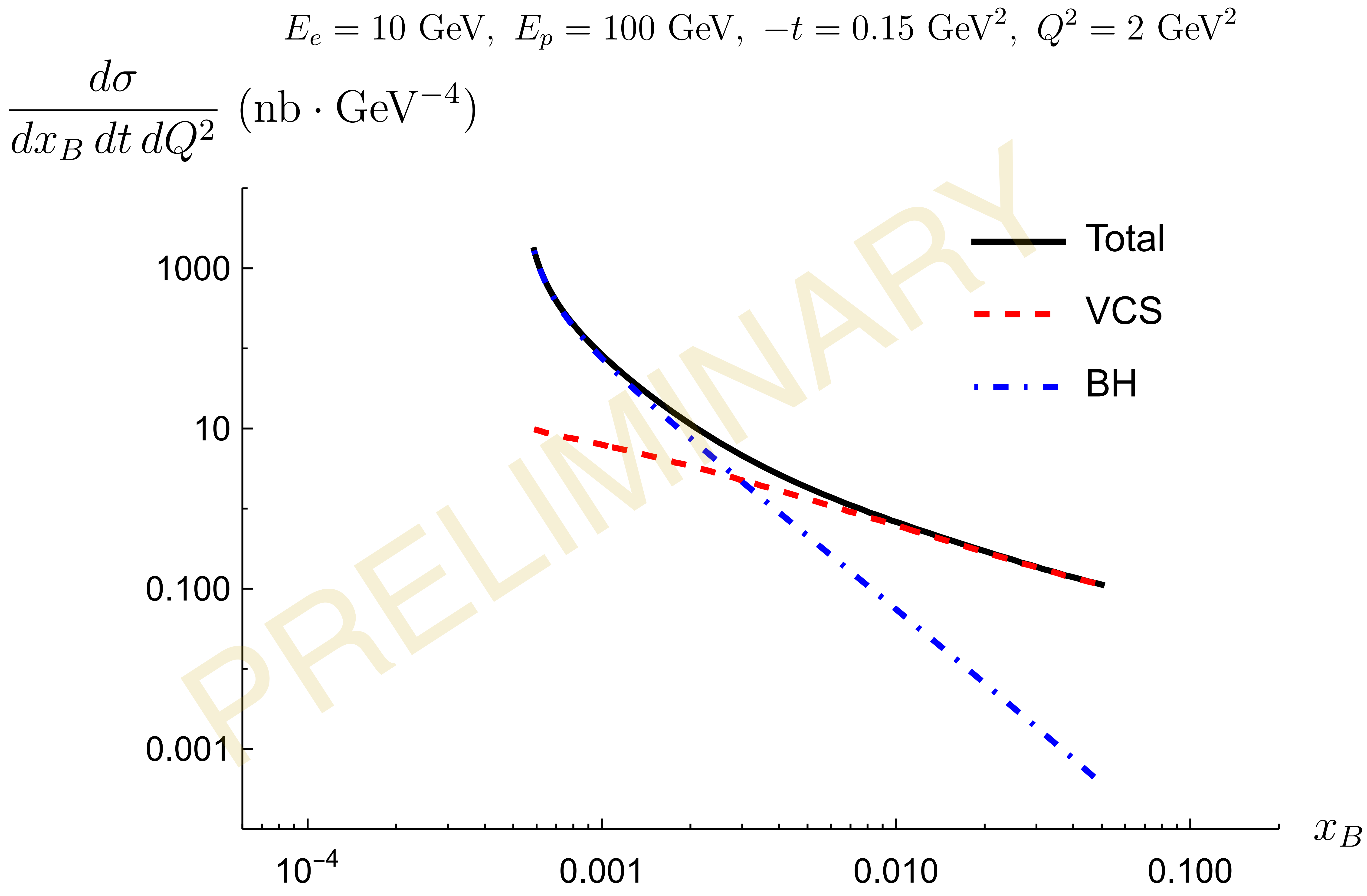


**VCS dominates the sea quark region x~0.01!**

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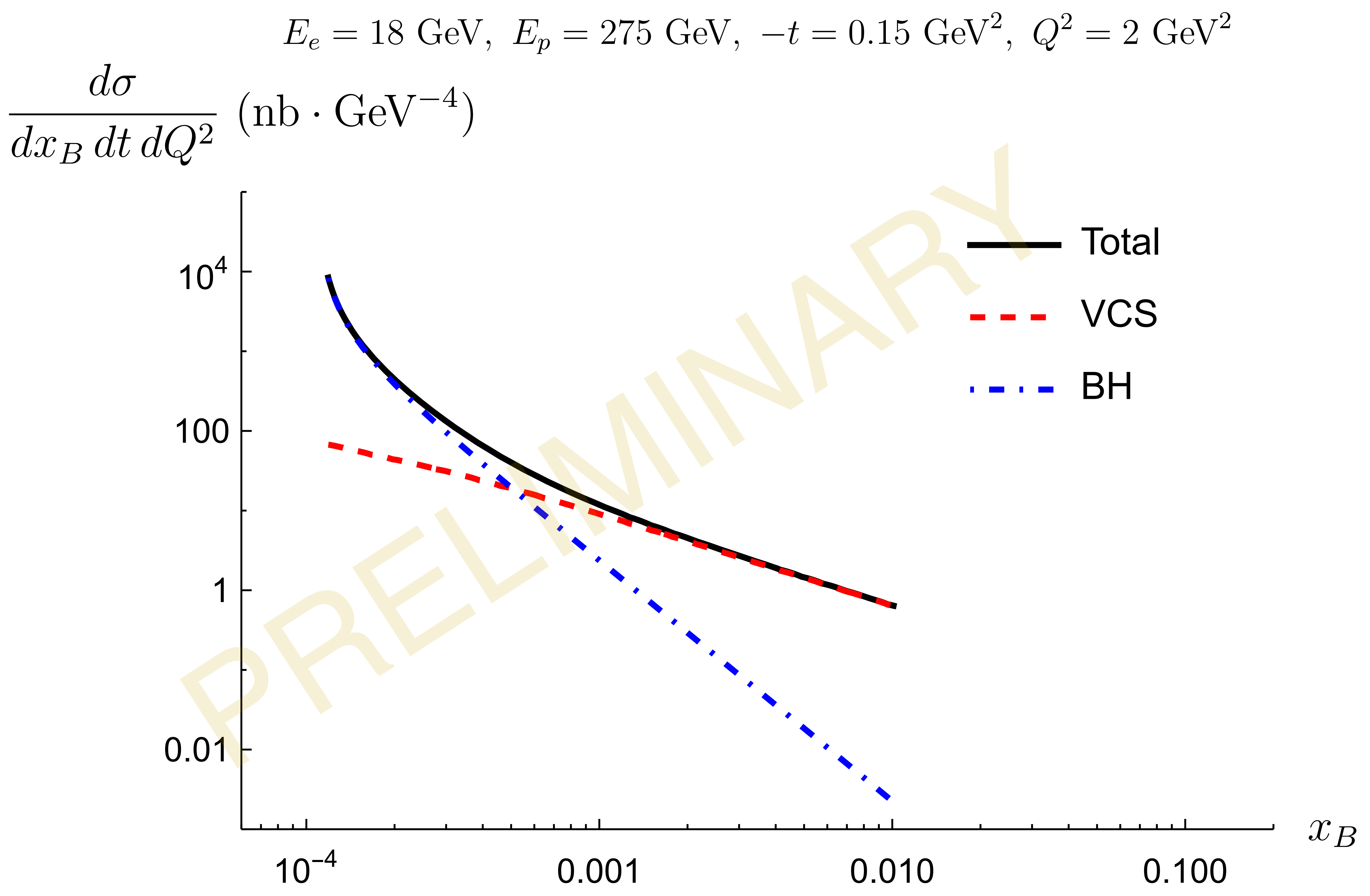
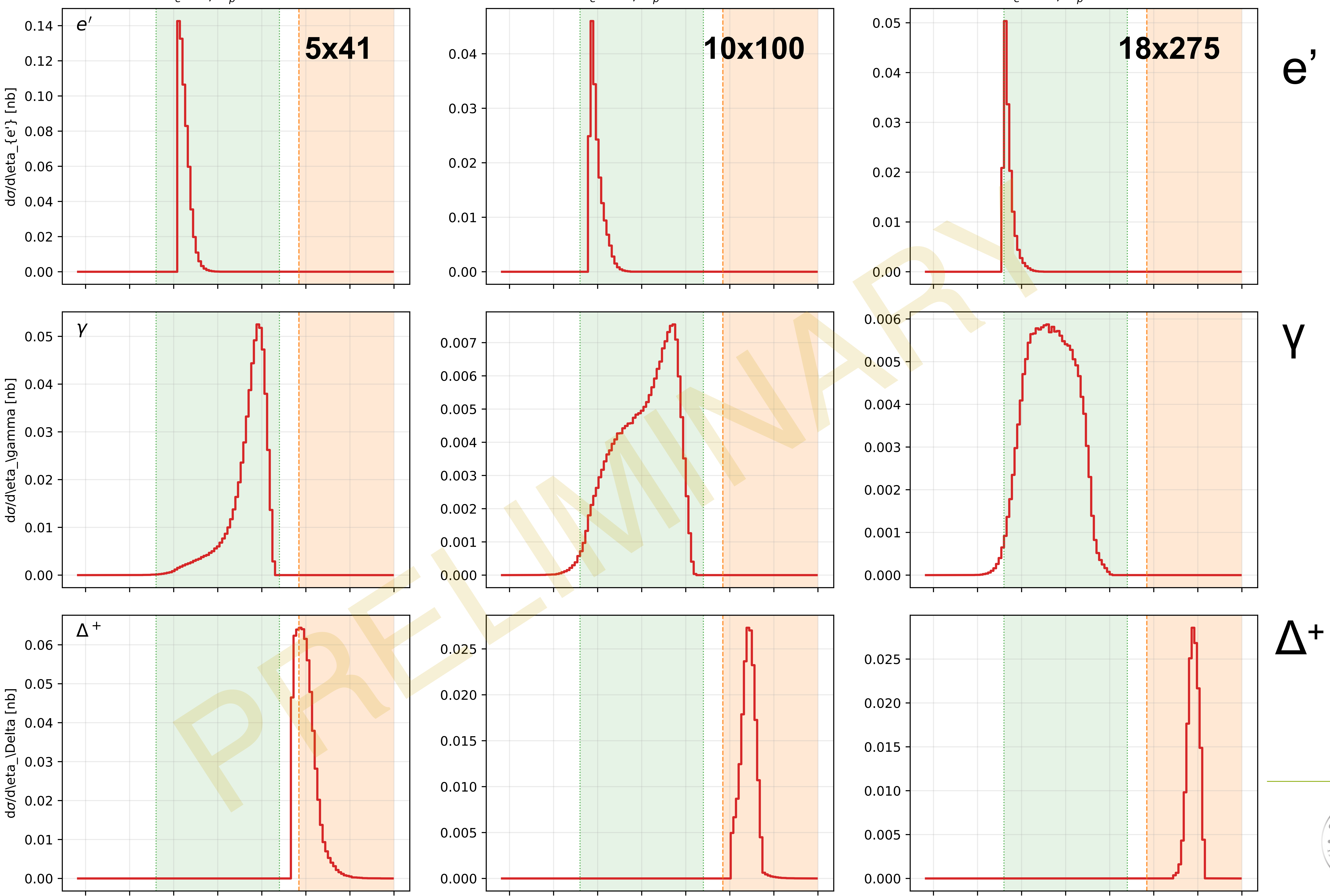



VCS dominates the sea quark region x~0.01!

# vs. diagonal DVCS


$$\frac{d\sigma_{\mathrm{DVCS}}(p \to \Delta^+)}{d\sigma_{\mathrm{DVCS}}(p \to p)}$$ ~ 1/10 of the DVCS cross section is expected

# Rapidity distribution



# Summary and outlook

- **EIC will provide a great opportunity for studying the transition GPDs**

  Kinematic range: small xB, larger $Q^2$

  Polarized beams access to various BSAs thus to the transition CFFs

- **Feasibility studies at the EIC**

  Sea quark region of the transition GPDs

  Naive ~1/10 cross section vs. DVCS

- **Tasks**

  Realistic simulation of the process

  PARTONs add-on: NDeltaDVCS, …

  Other reaction mechanisms for transition GPDs: Meson production, Hyperons, …

  SDHEP @ J-PARC with meson beams (N. Tomida)

  Transition D-term; Helicity transition GPD Cx from ChQSM, …

  Complete description of $\gamma^* N \to \gamma N \pi$ **M. Polyakov and S. Stratmann, hep-ph/0609045**
  **Pion case: S. Son and K. Semenov *JHEP* 01 (2025) 119**

*Thank you very much!*