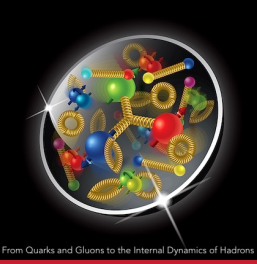


From Quarks and Gluons to the Internal Dynamics of Hadrons



New physical processes for extracting GPDs with a better sensitivity to partonic structure

Zhite Yu
(Jefferson Lab, Theory Center)

In collaboration with Jianwei Qiu

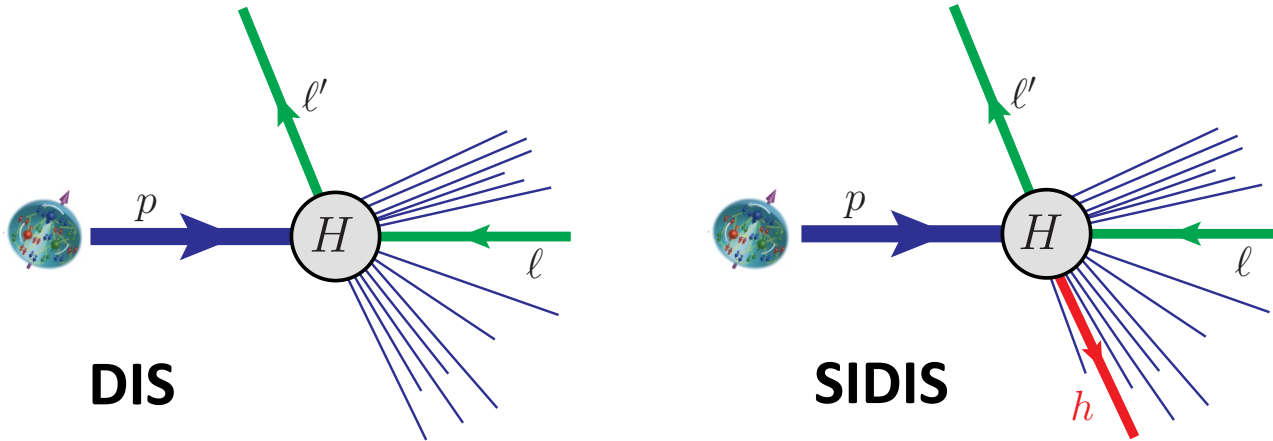
JHEP 08 (2022) 103
PRD 107 (2023) 014007
PRL 131 (2023) 161902
PRD 109 (2024) 074023

CFNS workshop @ Stony Brook
May/16/2024

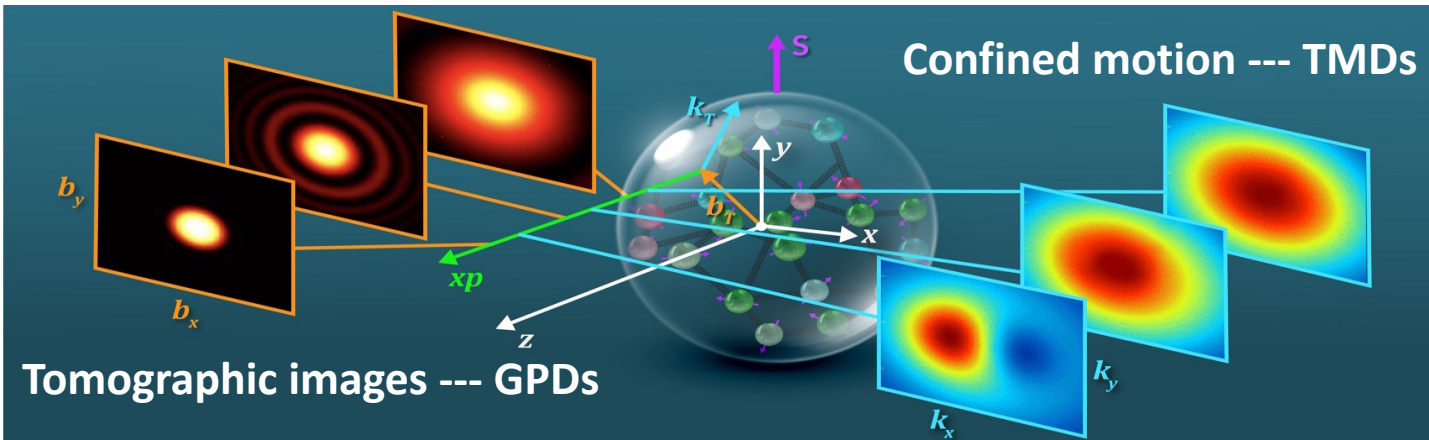
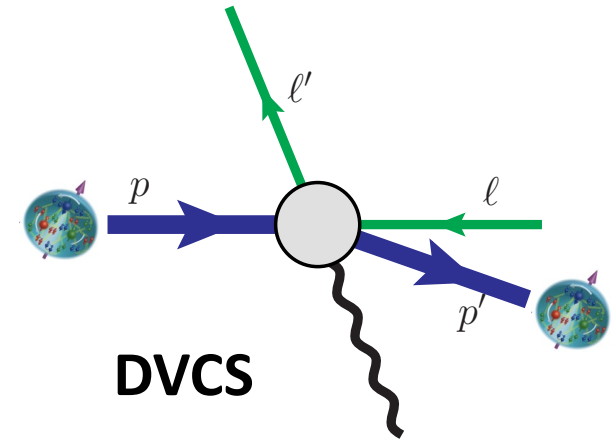


Hard probes and proton structure

Inclusive scattering

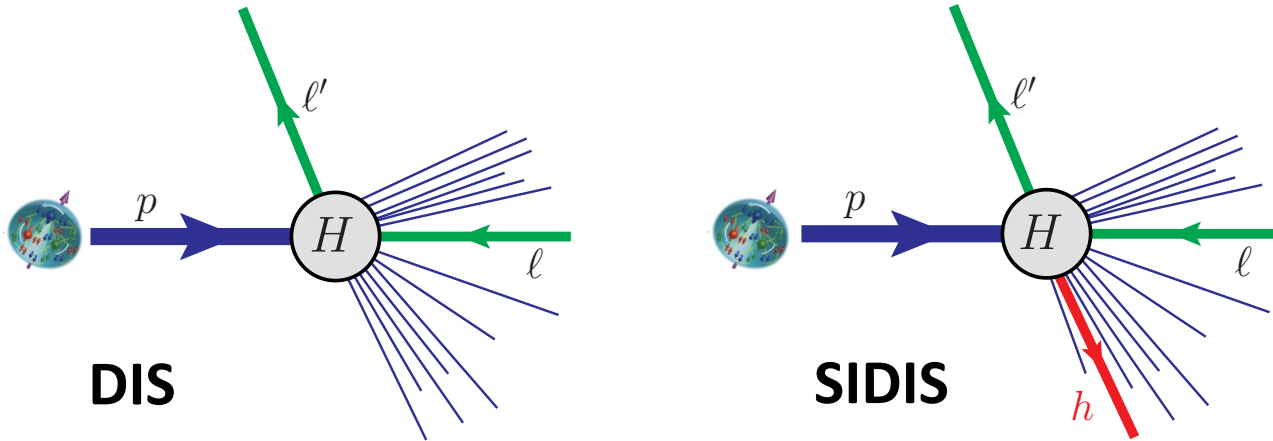


Exclusive diffraction

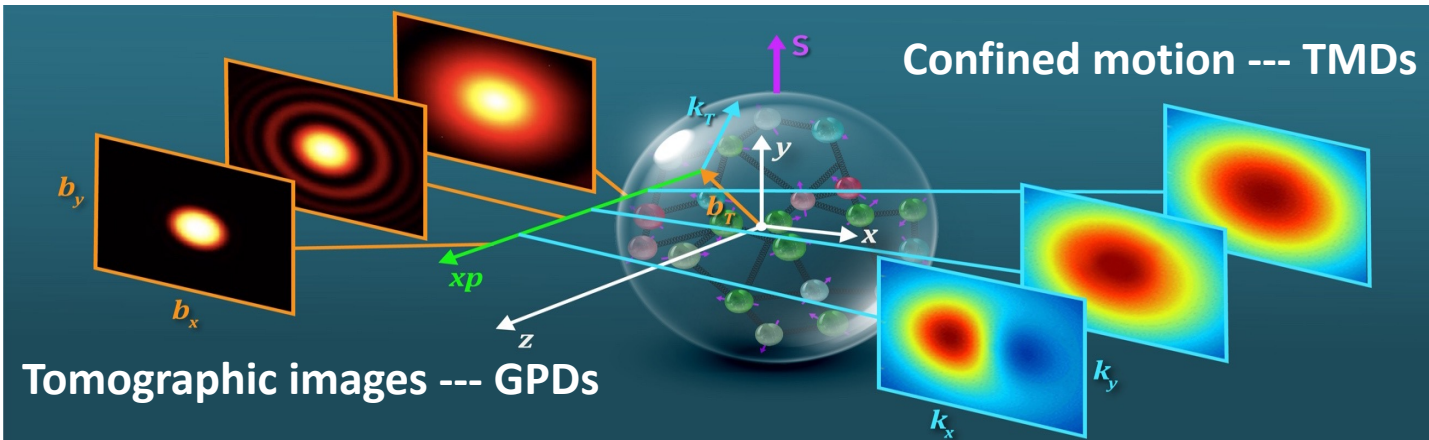
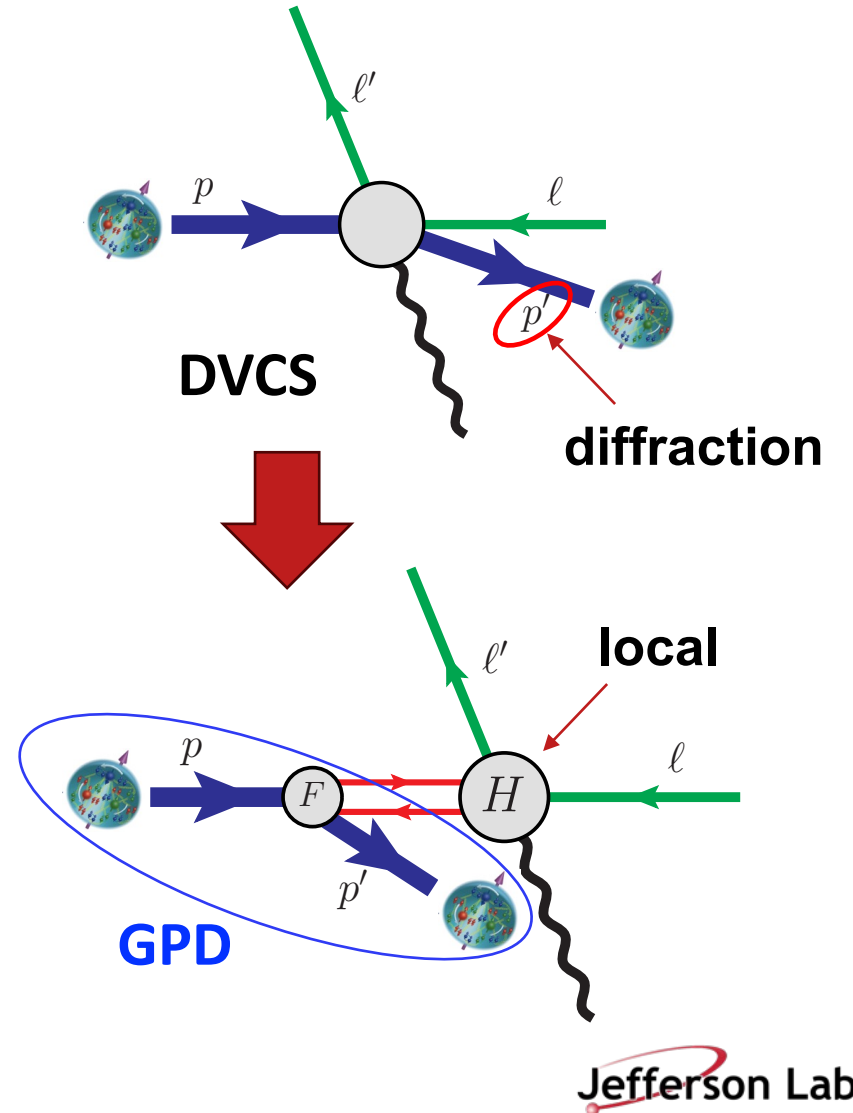


Exclusive processes and GPDs

Inclusive scattering

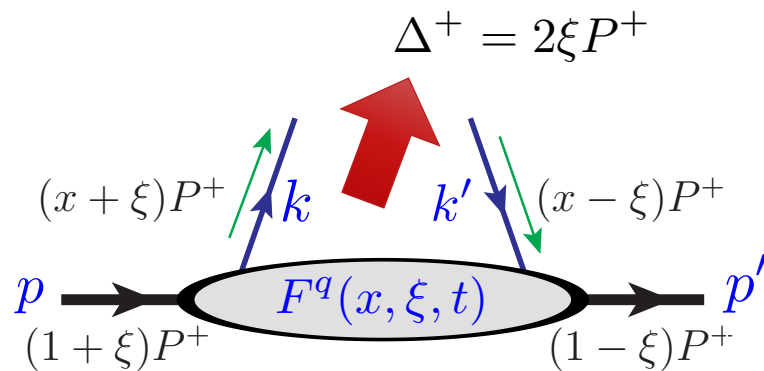
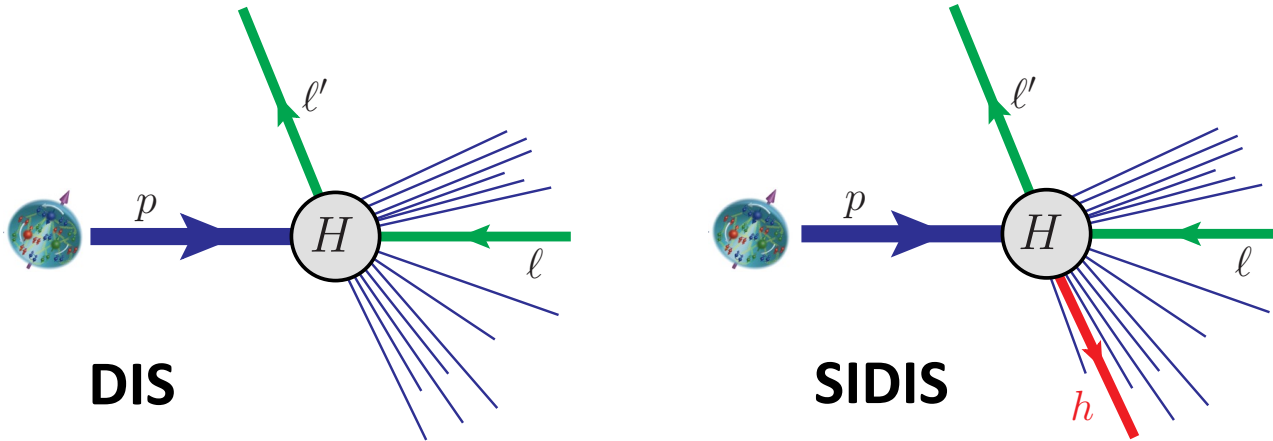


Exclusive diffraction



Exclusive processes and GPDs

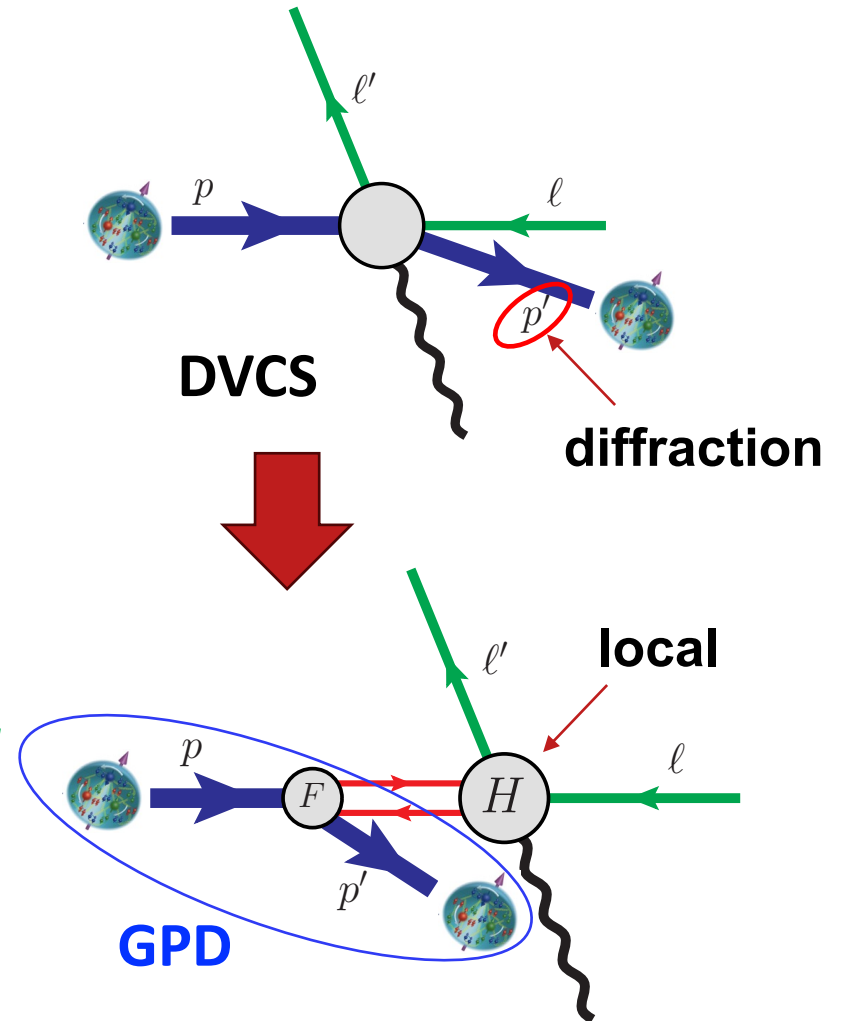
Inclusive scattering



$$F^q(x, \xi, t) = \int \frac{dz^-}{4\pi} e^{-ixP^+z^-} \langle p' | \bar{q}(z^-/2) \gamma^+ q(-z^-/2) | p \rangle$$

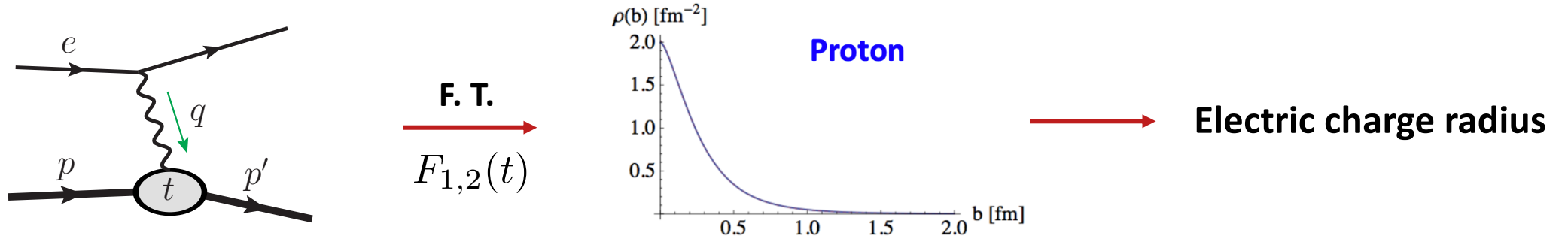
$$= \frac{1}{2P^+} \left[H^q(x, \xi, t) \bar{u}(p') \gamma^+ u(p) - E^q(x, \xi, t) \bar{u}(p') \frac{i\sigma^{+\alpha} \Delta_\alpha}{2m} u(p) \right]$$

Exclusive diffraction

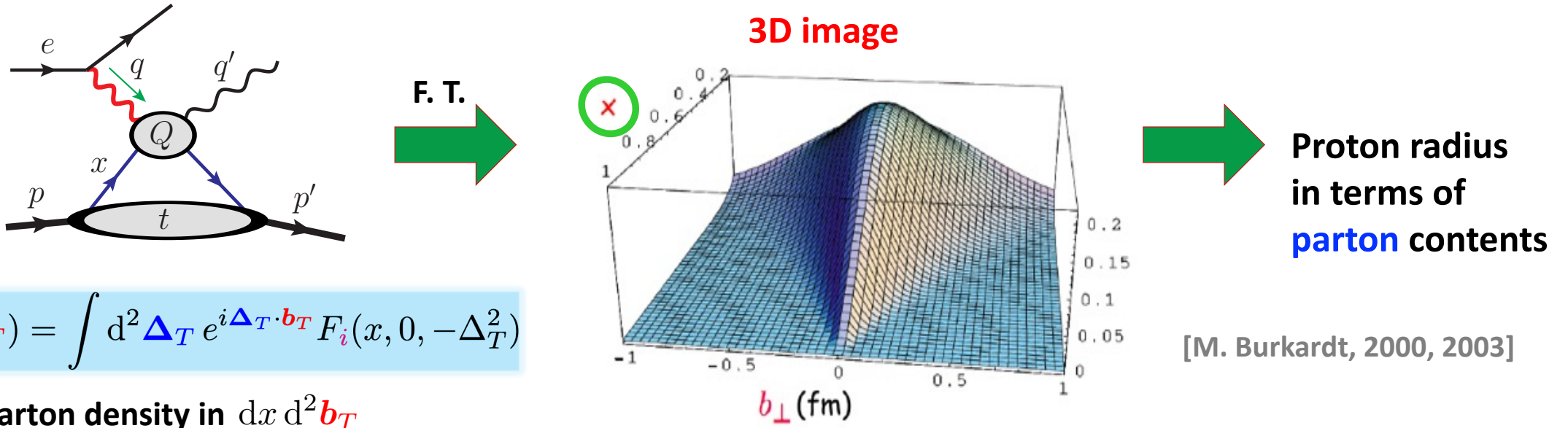


GPD and 3D tomography

□ Diffraction probes form factors and **spatial density**



□ **Two-scale** diffraction probes 3D tomography



GPD and Hadronic Property

□ QCD energy-momentum tensor

$$T^{\mu\nu} = \sum_{i=q,g} T_i^{\mu\nu} \quad \text{with} \quad T_q^{\mu\nu} = \bar{\psi}_q i\gamma^{(\mu} \overleftrightarrow{D}^{\nu)} \psi_q - g^{\mu\nu} \bar{\psi}_q (i\gamma \cdot \overleftrightarrow{D} - m_q) \psi_q \quad \text{and} \quad T_g^{\mu\nu} = F^{a,\mu\eta} F^a_{\eta}{}^{\nu} + \frac{1}{4} g^{\mu\nu} (F^a_{\rho\eta})^2$$

□ Gravitational form factor

$$\langle p' | T_i^{\mu\nu} | p \rangle = \bar{u}(p') \left[A_i(t) \frac{P^\mu P^\nu}{m} + J_i(t) \frac{iP^{(\mu} \sigma^{\nu)\Delta}}{2m} + D_i(t) \frac{\Delta^\mu \Delta^\nu - g^{\mu\nu} \Delta^2}{4m} + m \bar{c}_i(t) g^{\mu\nu} \right] u(p)$$

□ Connection to GPD moments

$$\int_{-1}^1 dx x F_i(x, \xi, t) \propto \langle p' | T_i^{++} | p \rangle \propto \bar{u}(p') \left[\underbrace{(A_i + \xi^2 D_i)}_{\int_{-1}^1 dx x H_i(x, \xi, t)} \gamma^+ + \underbrace{(B_i - \xi^2 D_i)}_{\int_{-1}^1 dx x E_i(x, \xi, t)} \frac{i\sigma^{+\Delta}}{2m} \right] u(p)$$

□ Angular momentum sum rule

$$J_i = \lim_{t \rightarrow 0} \int_{-1}^1 dx x [H_i(x, \xi, t) + E_i(x, \xi, t)]$$

$$i = q, g$$

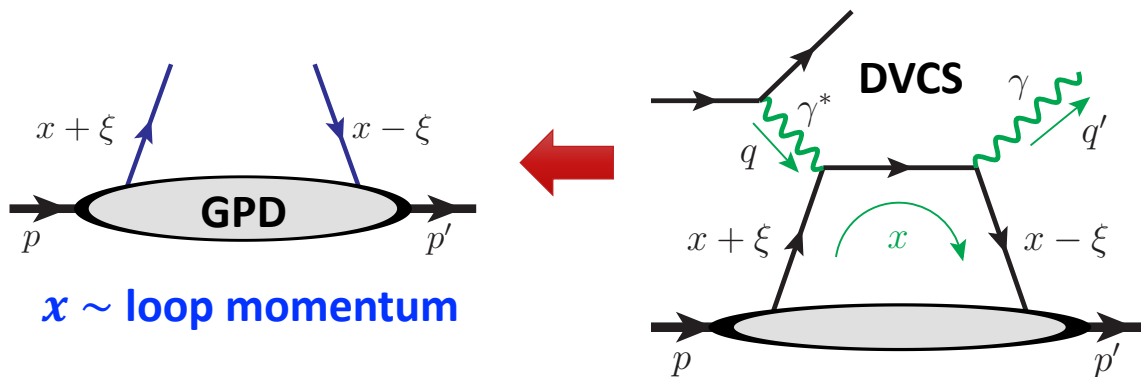
[X.-D. Ji, 1997]

- 3D tomography
- relations to GFF
- angular momentum
- ...

 **x-dependence!**

Why is the GPD x -dependence so *difficult* to measure?

□ Amplitude nature: exclusive processes

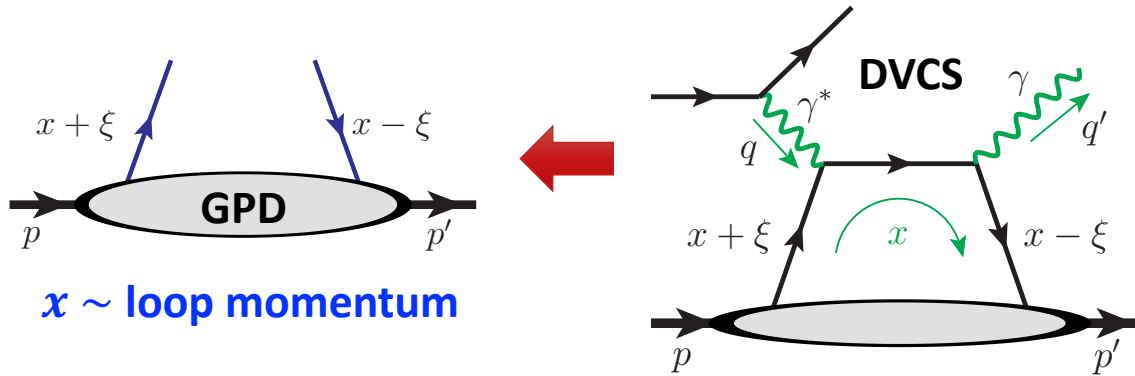


$$i\mathcal{M} \sim \int_{-1}^1 d\mathbf{x} F(\mathbf{x}, \xi, t) \cdot C(\mathbf{x}, \xi; Q/\mu)$$

never pin down to some x

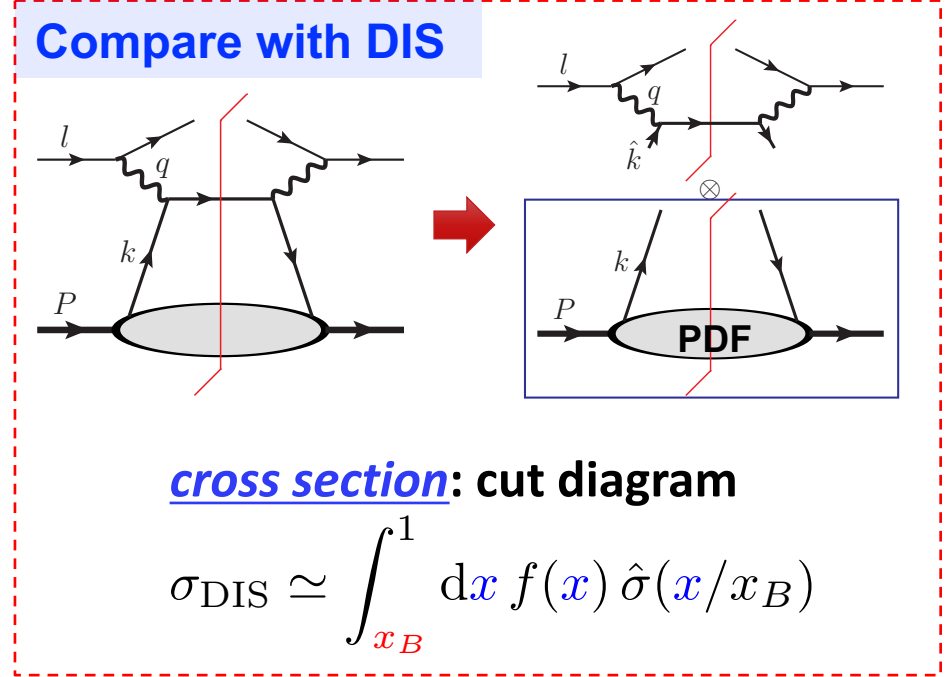
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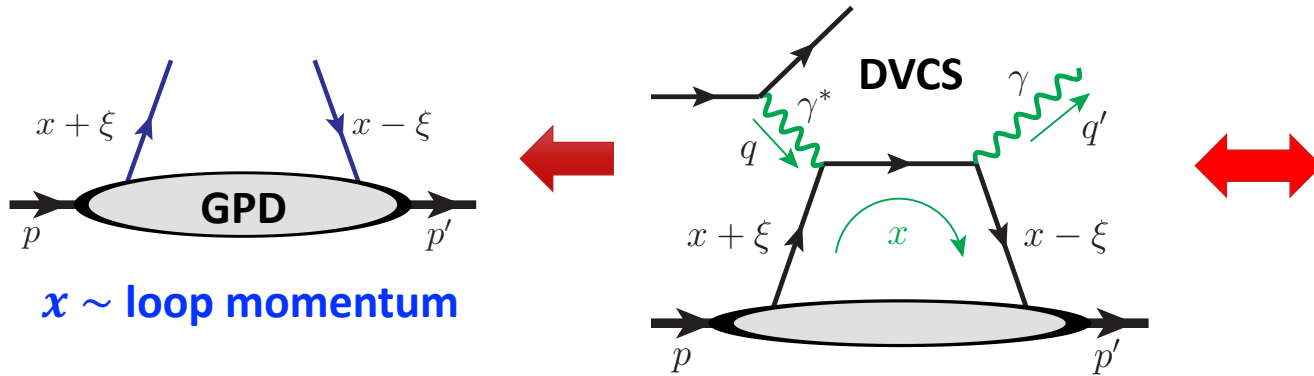
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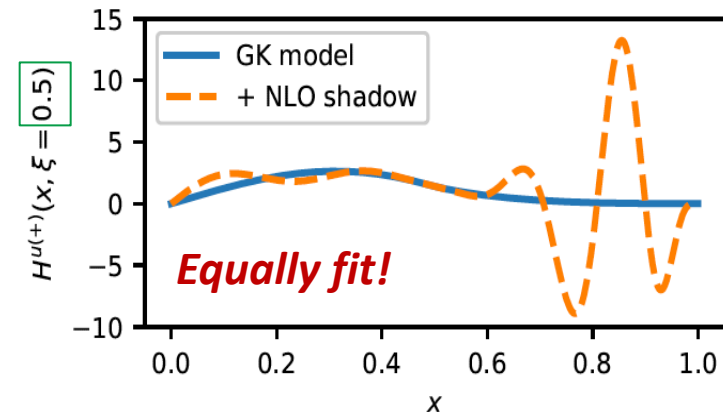
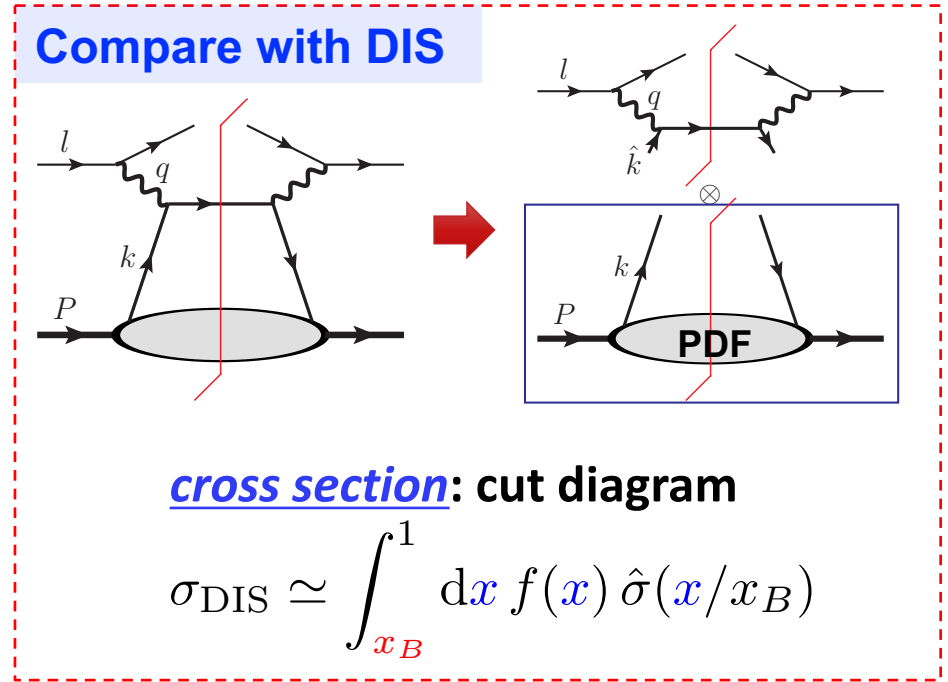
□ Sensitivity to x : comes from $C(x, \xi; Q/\mu)$

$$C(x, \xi; Q/\mu) = T(Q/\mu) \cdot G(x, \xi) \propto \frac{1}{x - \xi + i\epsilon} \dots$$

$$\Rightarrow i\mathcal{M} \propto \int_{-1}^1 d\mathbf{x} \frac{F(\mathbf{x}, \xi, t)}{\mathbf{x} - \xi + i\epsilon} \equiv "F_0(\xi, t)" \quad \text{"moment"}$$

"LO scaling"

8



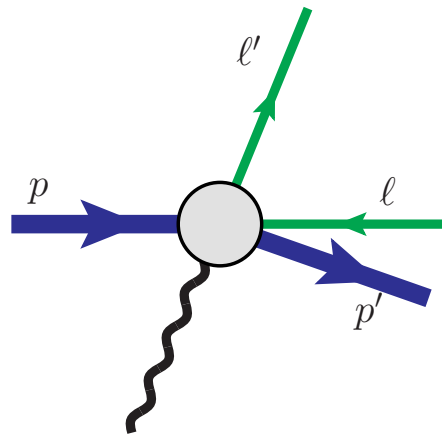
[Bertone et al. PRD '21]

How to *think* about the GPD processes?

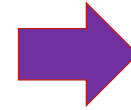
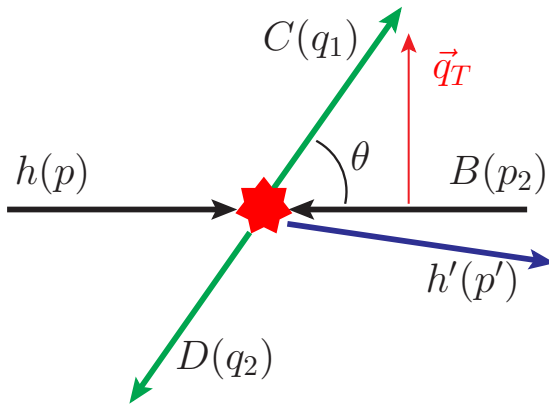
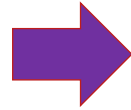
□ Single diffractive hard exclusive process (SDHEP)

[Qiu & Yu, PRD 107 (2023) 014007]

DVCS in lab frame



$$h(p) + B(p_2) \rightarrow h'(p') + C(q_1) + D(q_2)$$



**2 → 3: minimal
kinematic configuration!**

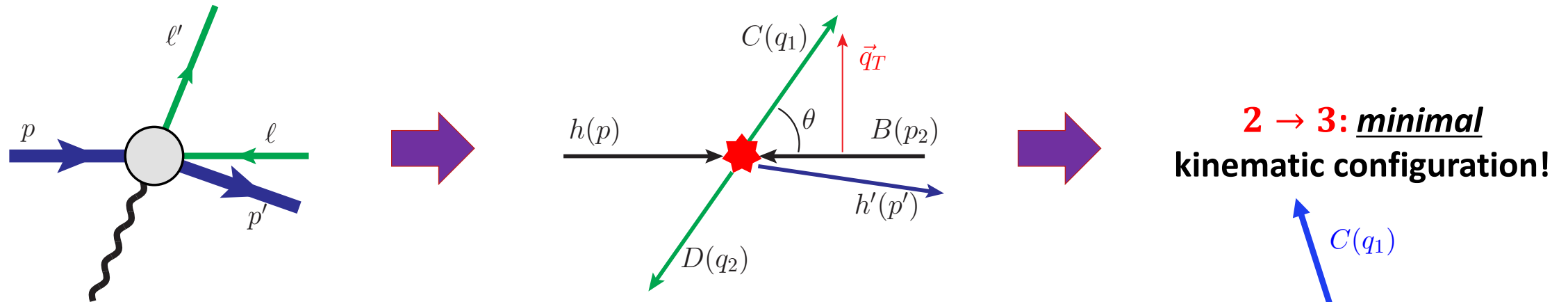
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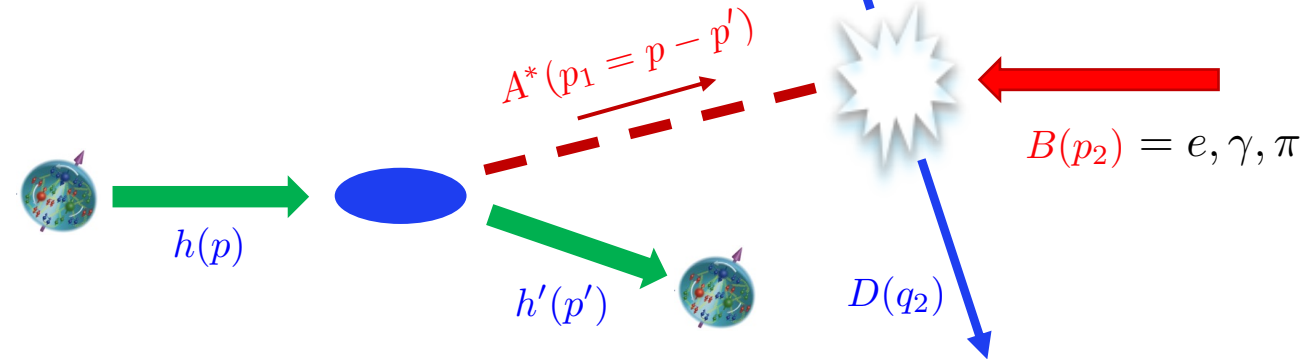


□ Two-stage process paradigm

Single diffractive: $h(p) \rightarrow h'(p') + A^*(p_1 = p - p')$

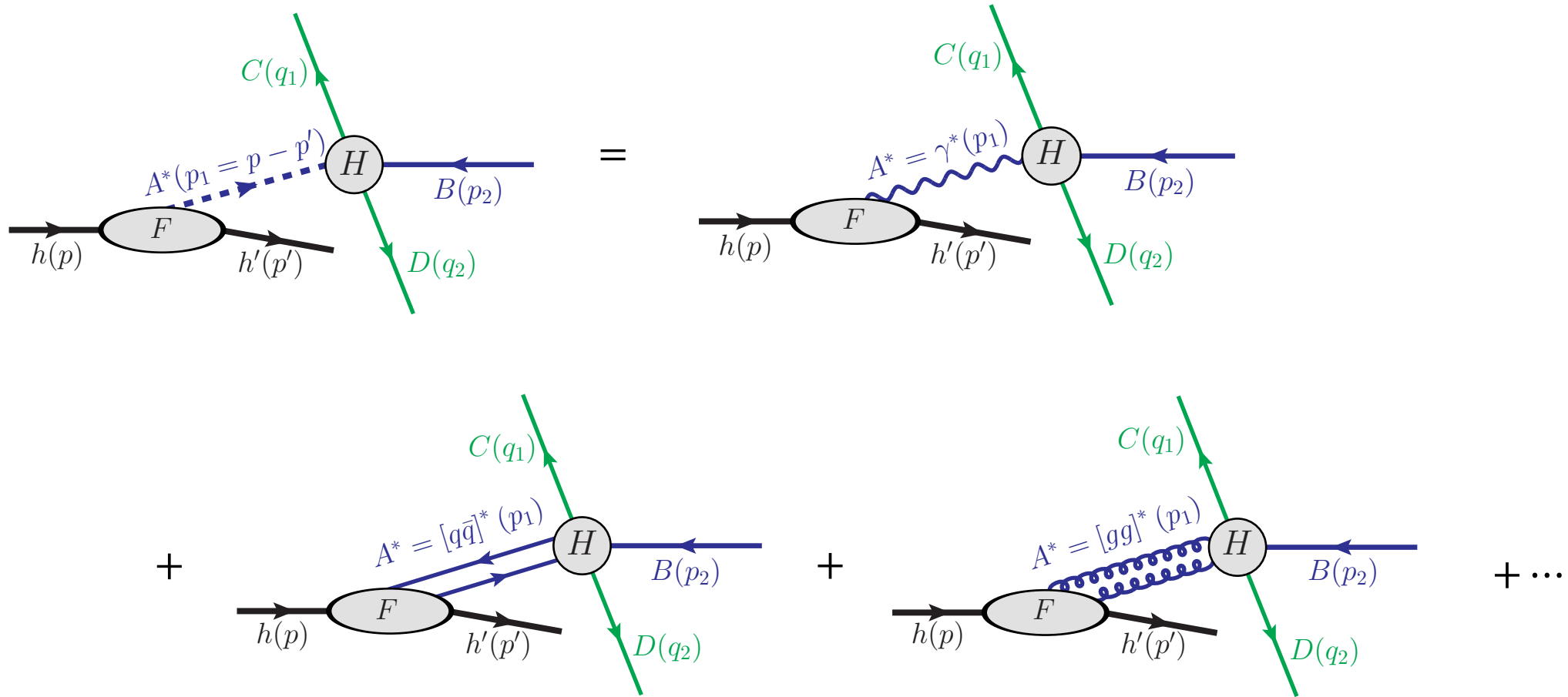
factorize

Hard exclusive: $A^*(p_1) + B(p_2) \rightarrow C(p_3) + D(p_4)$

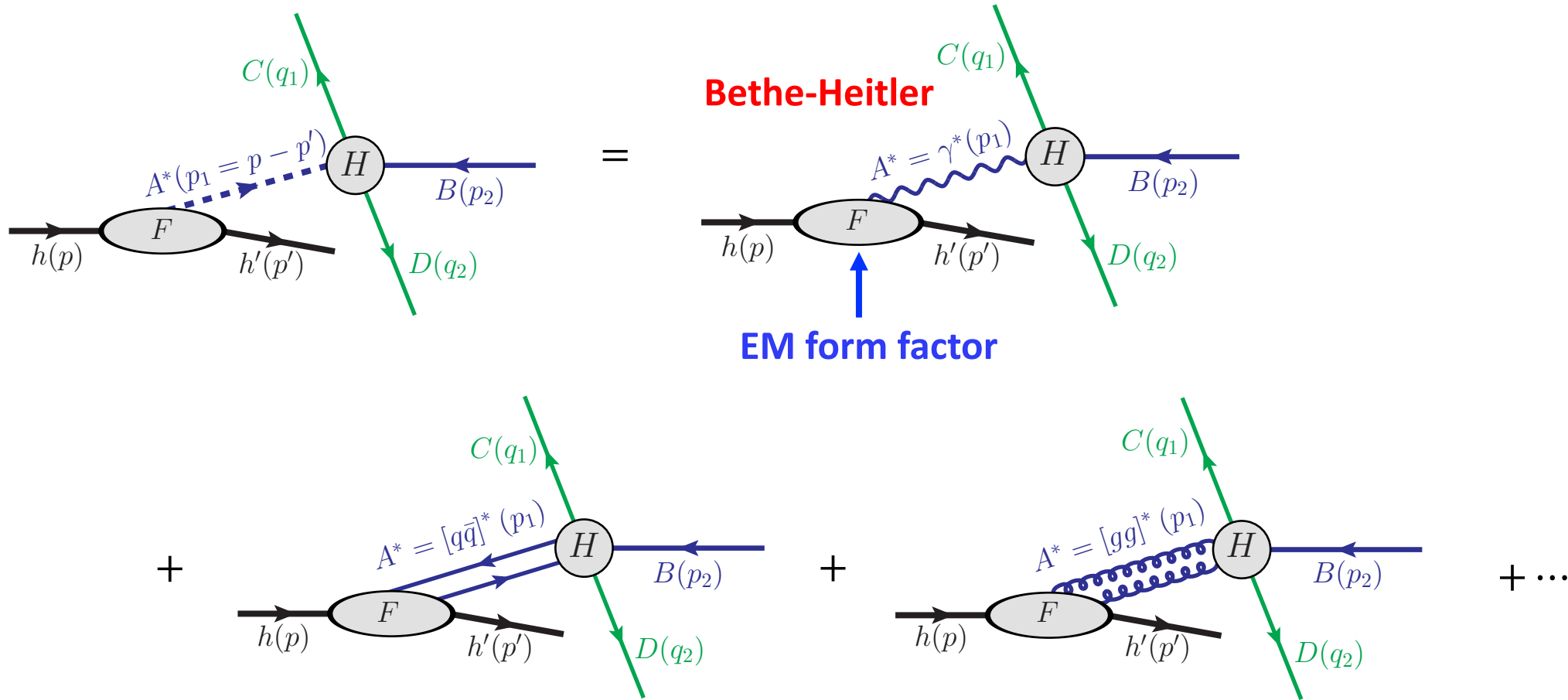


Necessary condition for factorization: $q_T \gg \sqrt{-t} \simeq \Lambda_{\text{QCD}} \quad t = (p - p')^2$

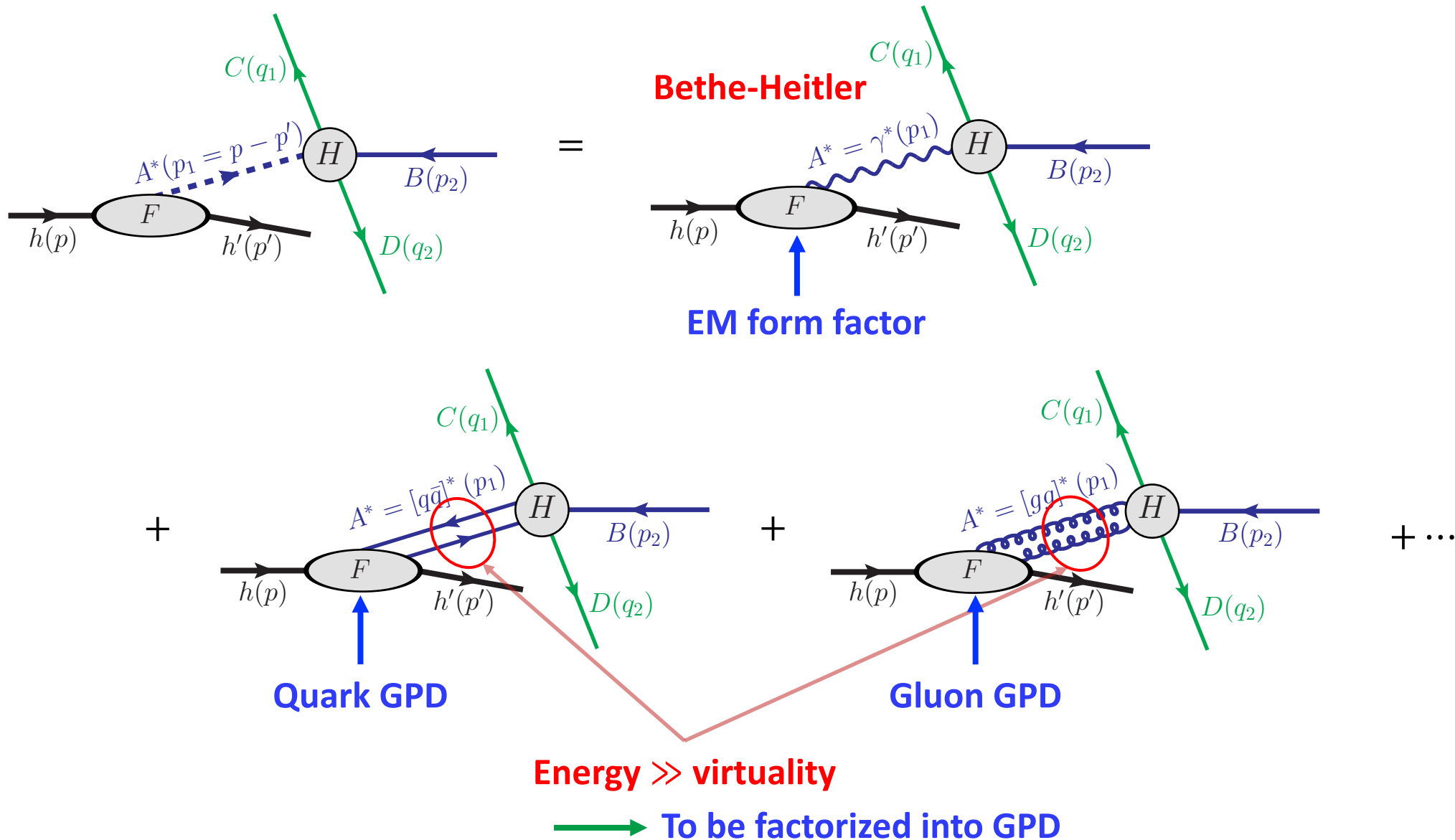
SDHEP: Two-stage paradigm and channel expansion



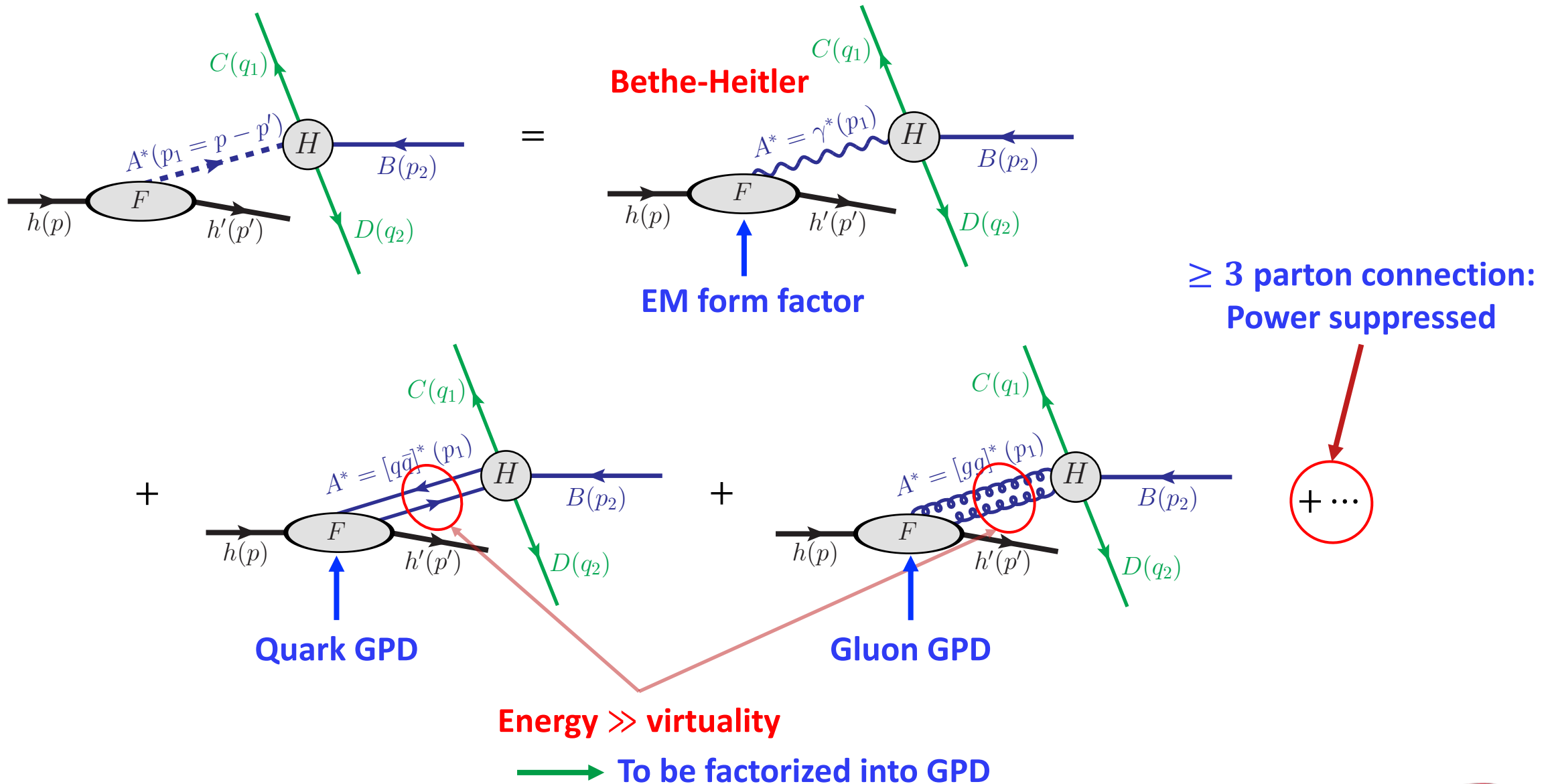
SDHEP: Two-stage paradigm and channel expansion



SDHEP: Two-stage paradigm and channel expansion

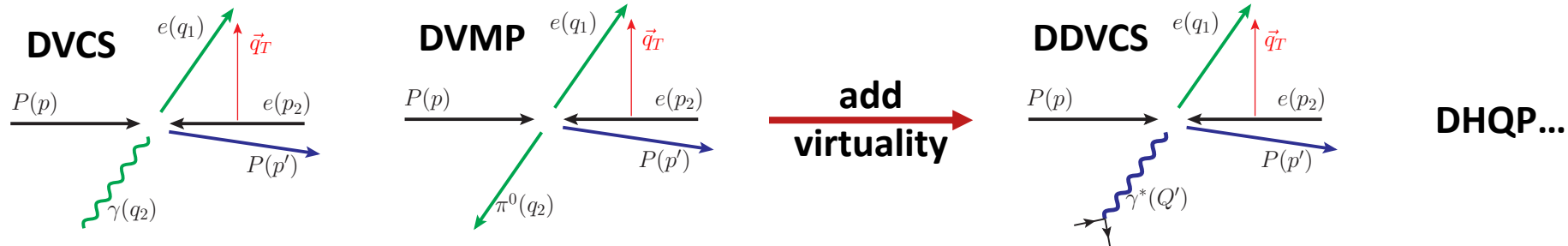


SDHEP: Two-stage paradigm and channel expansion (**twist expansion**)

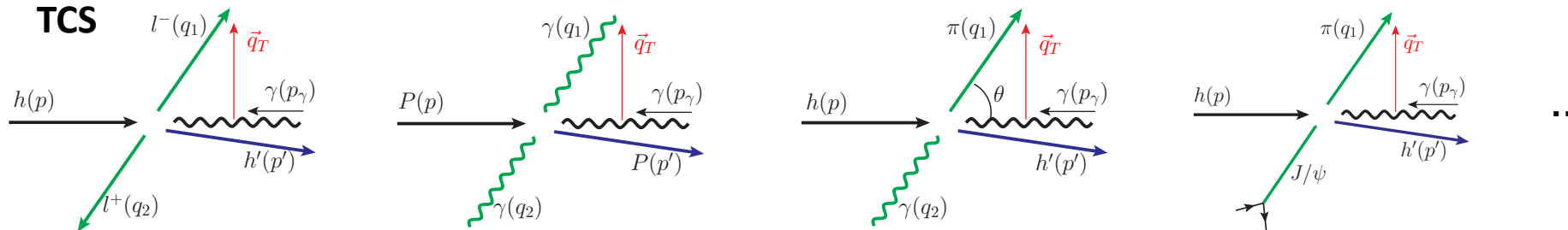


Classification of SDHEPs

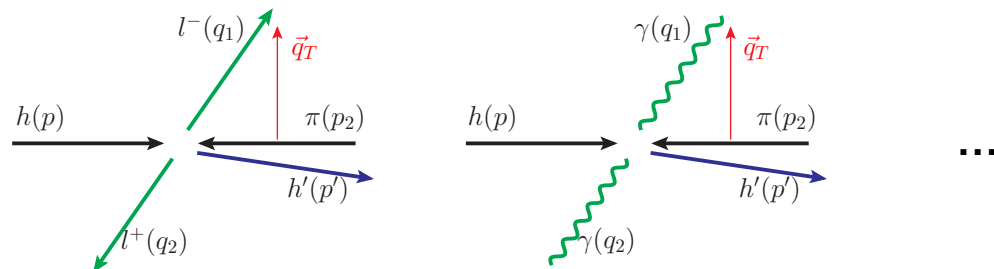
□ Electro-production (JLab, EIC, ...)



□ Photo-production (JLab, EIC, ...)



□ Meso-production (AMBER, J-PARC, ...)

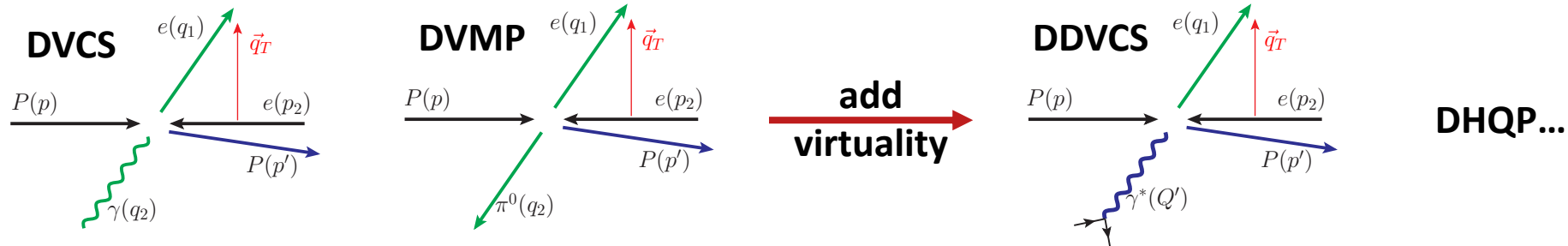


Generic discussion

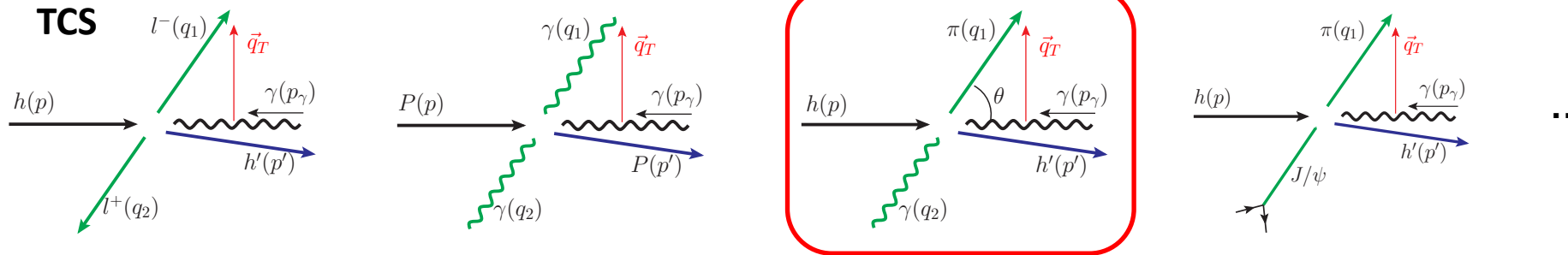
[Qiu, Yu, PRD 107 (2023), 014007]

Classification of SDHEPs

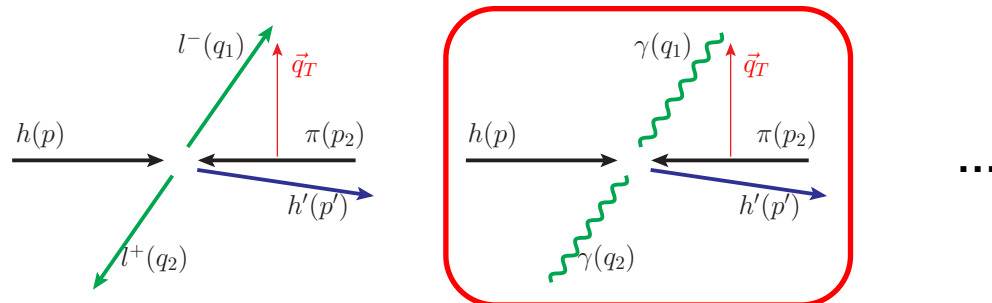
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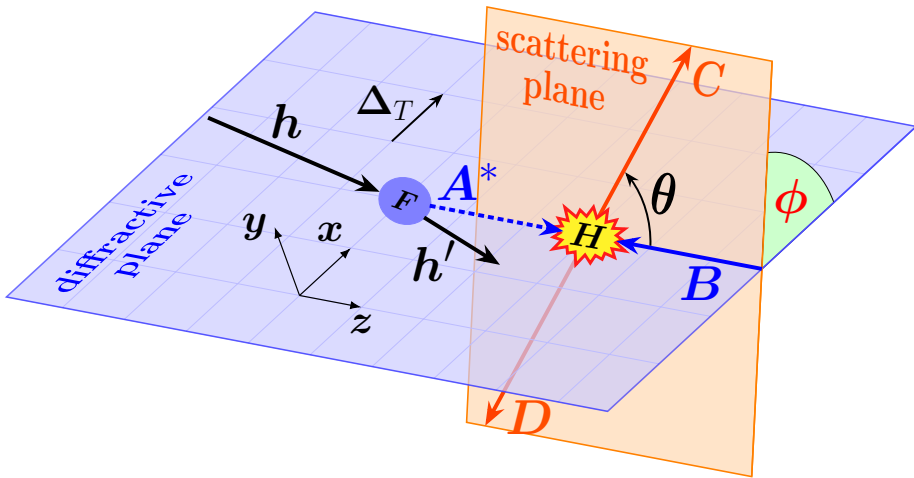
□ Meso-production (AMBER, J-PARC, ...)



Generic discussion

[Qiu, Yu, PRD 107 (2023), 014007]

Where does the ***x*-sensitivity** come from?



□ ***x*-sensitivity** $\Leftrightarrow 2 \rightarrow 2$ hard scattering

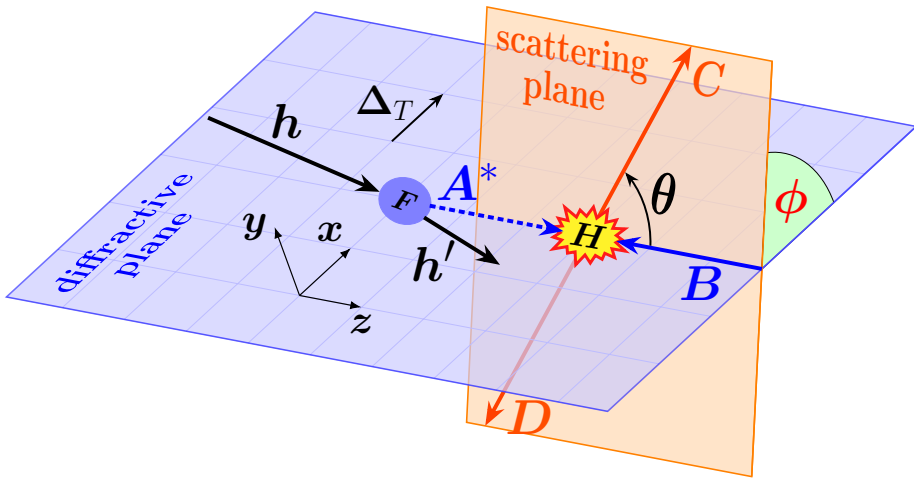
Kinematics:

1. $\hat{s} = 2 \xi s / (1 + \xi)$ $\leftarrow \xi$
2. θ or $q_T = (\sqrt{\hat{s}}/2) \sin \theta$ $\longleftrightarrow x$
3. ϕ $\leftarrow (A^* B)$ spin states

$$\mathcal{M}(Q, \phi) \simeq \sum_A e^{i(\lambda_A - \lambda_B)\phi} \cdot \int_{-1}^1 dx F_A(x) C_A(x; Q) \quad (Q = \theta \text{ or } q_T)$$

[suppressing t and ξ dependence]

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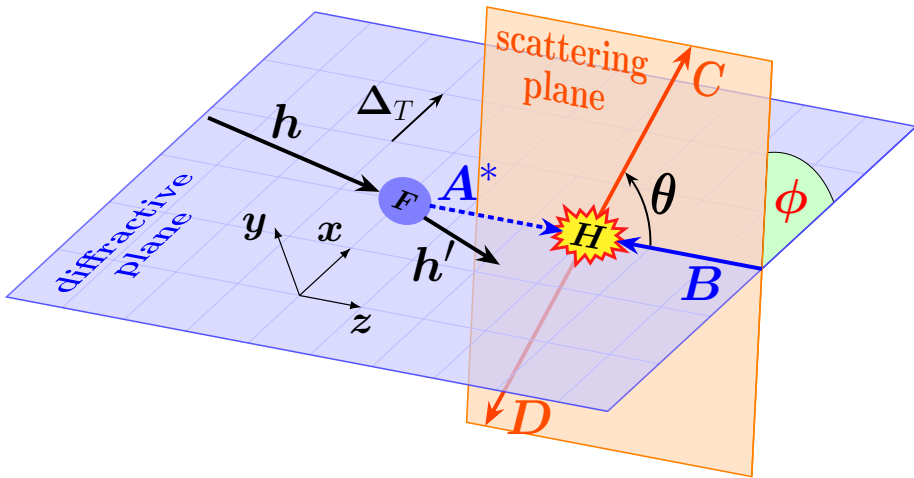
[suppressing t and ξ dependence]

➤ **Moment-type sensitivity** $C(x; Q) = G(x) \cdot T(Q)$ $\longrightarrow F_G = \int_{-1}^1 dx G(x) F(x, \xi, t)$ **Independent of Q .
Scaling for F_G .**

$\longrightarrow$ **Inversion problem:** shadow GPD

$$S_G = \int_{-1}^1 dx G(x) S(x, \xi) = 0 \quad [\text{Bertone et al. PRD '21}]$$

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← ξ

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↔ x

3. ϕ

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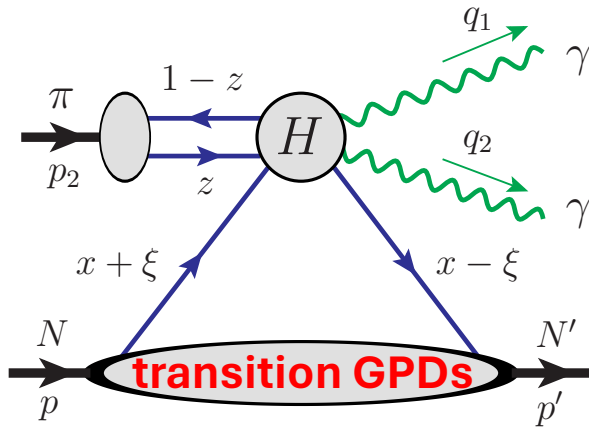
➔ **Inversion problem: shadow GPD**

$$S_G = \int_{-1}^1 dx G(x) S(x, \xi) = 0 \quad [\text{Bertone et al. PRD '21}]$$

➤ **Enhanced sensitivity** $C(x; Q) \neq G(x) \cdot T(Q)$ $\longrightarrow d\sigma/dQ \sim |C(x; Q) \otimes_x F(x, \xi, t)|^2$

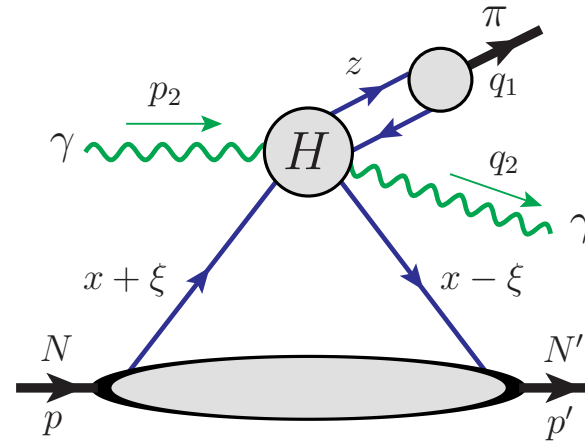
Scaling breaking at LO

Two new example processes with enhanced x -sensitivity



J-PARC, AMBER

Qiu & Yu, JHEP 08 (2022) 103
Qiu & Yu, PRD 109 (2024) 074023

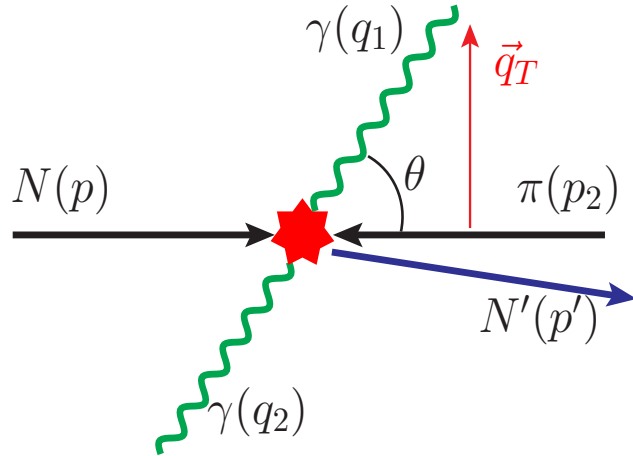


JLab Hall D

G. Duplancic et al., JHEP 11 (2018) 179
G. Duplancic et al., JHEP 03 (2023) 241
G. Duplancic et al., PRD 107 (2023), 094023
Qiu & Yu, PRD 107 (2023), 014007
Qiu & Yu, PRL 131 (2023), 161902

Enhanced x -sensitivity: (1) diphoton mesoproduction

[Qiu & Yu, JHEP 08 (2022) 103;
PRD 109 (2024) 074023]



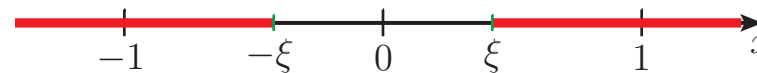
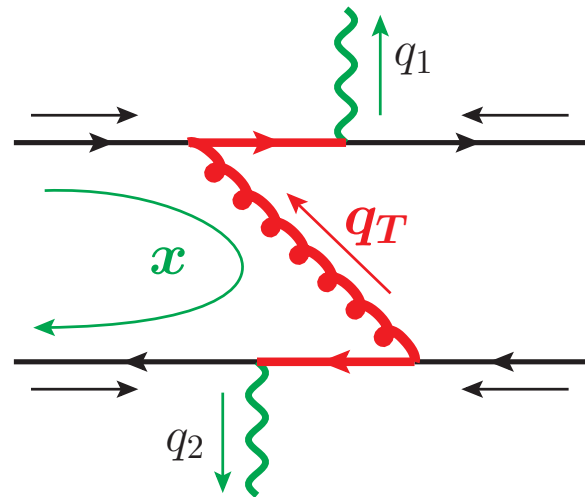
In addition to

$$F_0(\xi, t) = \int_{-1}^1 \frac{dx F(x, \xi, t)}{x - \xi + i\epsilon}$$

$i\mathcal{M}$ also contains

$$I(t, \xi; z, \theta) = \int_{-1}^1 \frac{dx F(x, \xi, t)}{x - \rho(z; \theta) + i\epsilon \operatorname{sgn} [\cos^2(\theta/2) - z]}$$

$$\rho(z; \theta) = \xi \cdot \left[\frac{1 - z + \tan^2(\theta/2) z}{1 - z - \tan^2(\theta/2) z} \right] \in (-\infty, -\xi] \cup [\xi, \infty)$$



Enhanced x -sensitivity: (1) diphoton mesoproduction

[Qiu & Yu, PRD 109 (2024) 074023]

□ **Diphoton process:** $N\pi \rightarrow N'\gamma\gamma$: (1) $p\pi^- \rightarrow n\gamma\gamma$; (2) $n\pi^+ \rightarrow p\gamma\gamma$

$$\frac{d\sigma}{d|t| d\xi d\cos\theta} = 2\pi \left(\alpha_e \alpha_s \frac{C_F}{N_c} \right)^2 \frac{1}{\xi^2 s^3} \cdot \left[(1 - \xi^2) \sum_{\alpha=\pm} \left(|\mathcal{M}_\alpha^{[\tilde{H}]}|^2 + |\widetilde{\mathcal{M}}_\alpha^{[H]}|^2 \right) - \left(\xi^2 + \frac{t}{4m^2} \right) \sum_{\alpha=\pm} |\widetilde{\mathcal{M}}_\alpha^{[E]}|^2 \right. \\ \left. - \frac{\xi^2 t}{4m^2} \sum_{\alpha=\pm} |\mathcal{M}_\alpha^{[\tilde{E}]}|^2 - 2\xi^2 \sum_{\alpha=\pm} \text{Re} \left(\widetilde{\mathcal{M}}_\alpha^{[H]} \widetilde{\mathcal{M}}_\alpha^{[E]*} + \mathcal{M}_\alpha^{[\tilde{H}]} \mathcal{M}_\alpha^{[\tilde{E}]*} \right) \right]$$

Nucleon transition GPDs

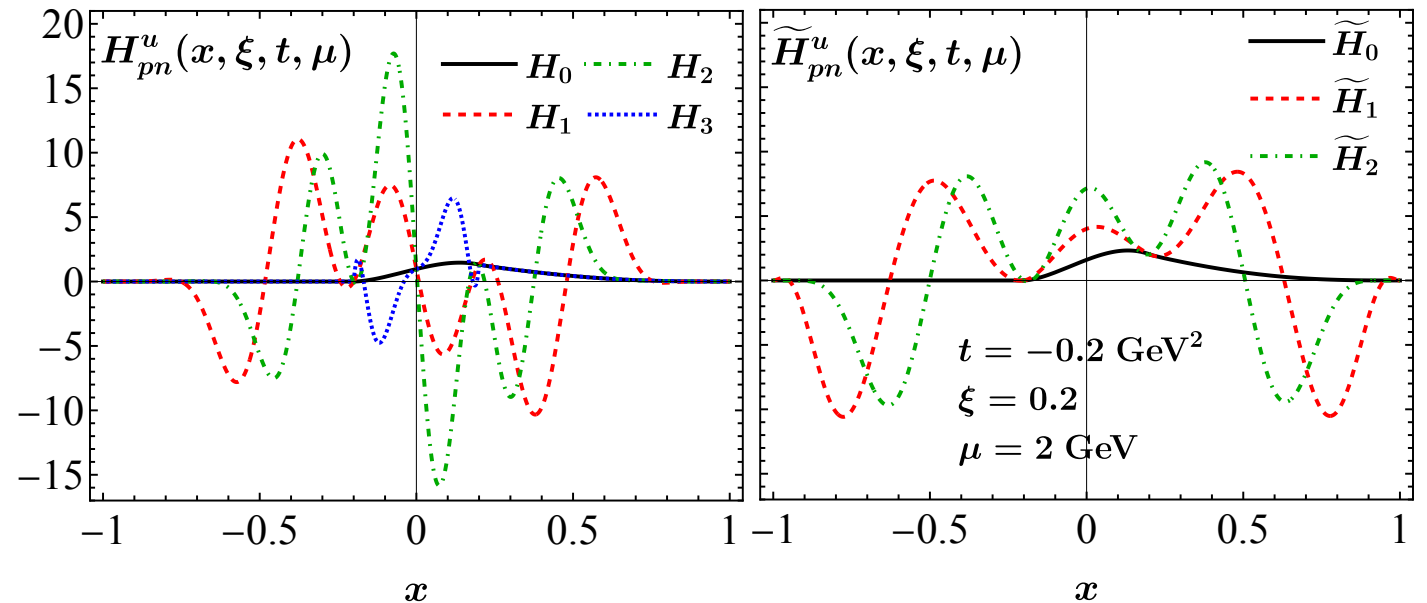
$$H_{pn}^u = H_p^u - H_p^d, \text{ etc.}$$

GPD models = GK model + shadow GPDs

Goloskokov & Kroll, '05, '07, '09

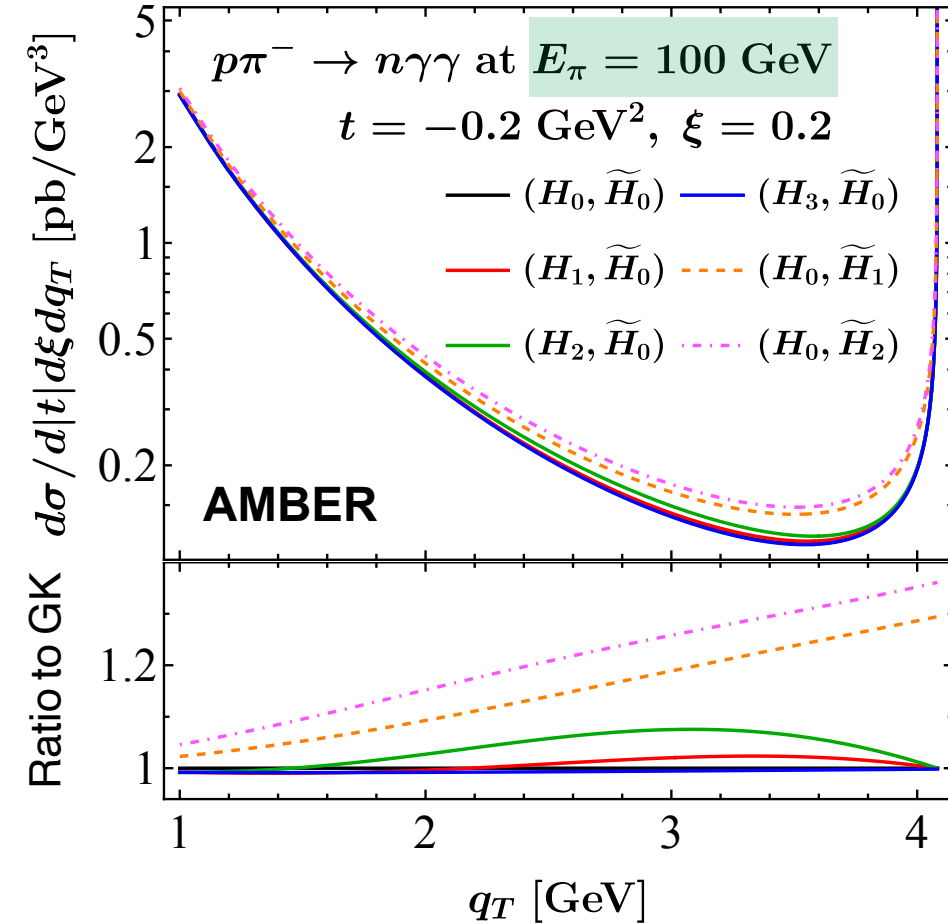
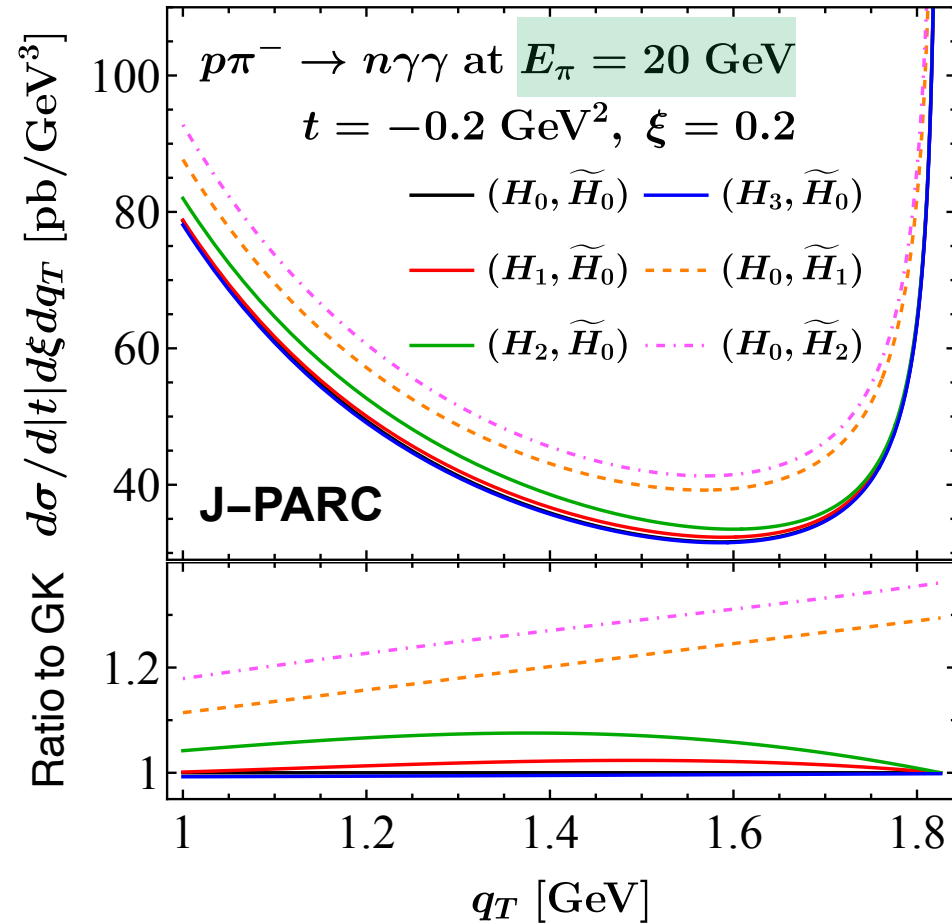
Bertone et al. '21
Moffat et al. '23

$$\int_{-1}^1 \frac{dx S(x, \xi)}{x - \xi \pm i\epsilon} = 0$$



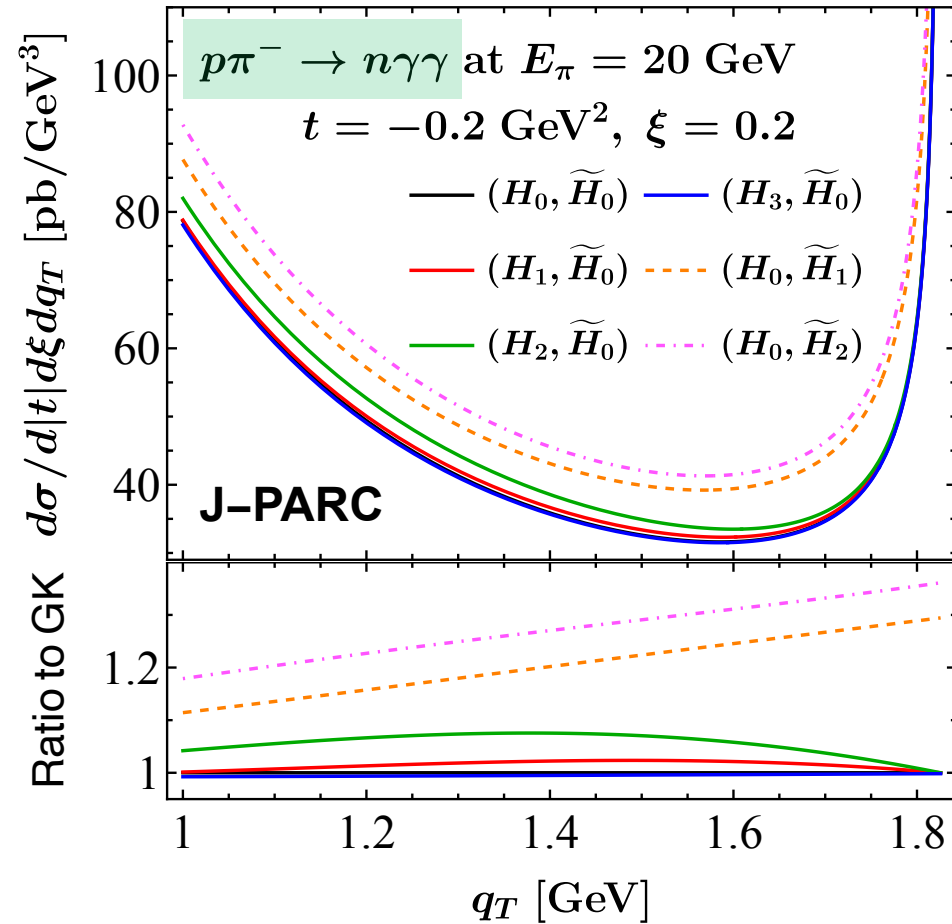
Enhanced x -sensitivity: (1) diphoton mesoproduction (at J-PARC or AMBER)

[Qiu & Yu, PRD 109 (2024) 074023]



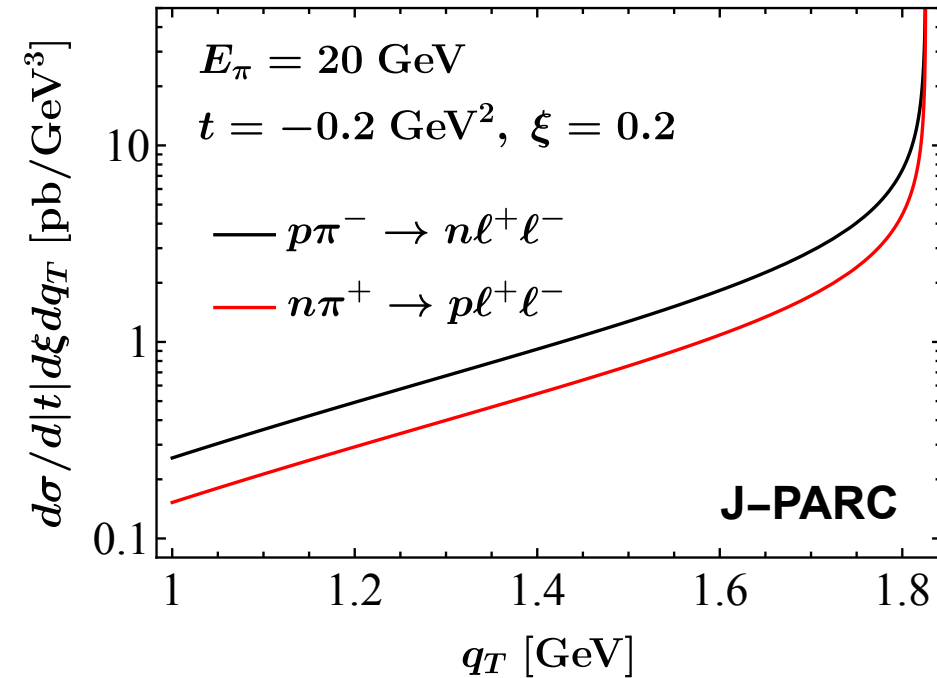
Enhanced x -sensitivity: (1) diphoton mesoproduction (at J-PARC or AMBER)

[Qiu & Yu, PRD 109 (2024) 074023]



Exclusive Drell-Yan dilepton mesoproduction

$$N + \pi \rightarrow N' + \gamma^* [\rightarrow \ell^+ + \ell^-]$$



- Lower rate
- Blind to shadow GPDs

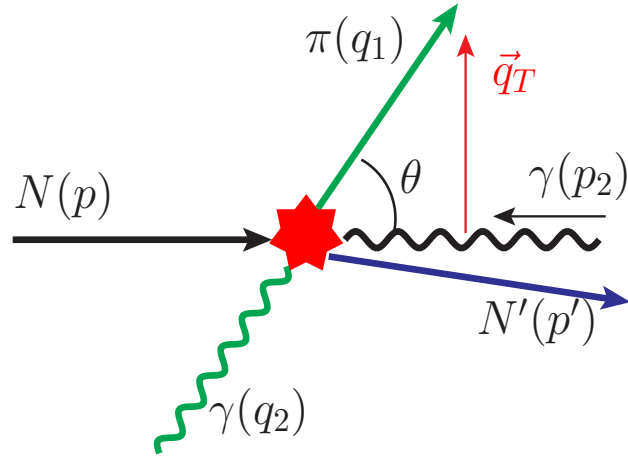
Enhanced x -sensitivity: (2) γ - π pair photoproduction

[Qiu & Yu, PRL 131 (2023) 161902]

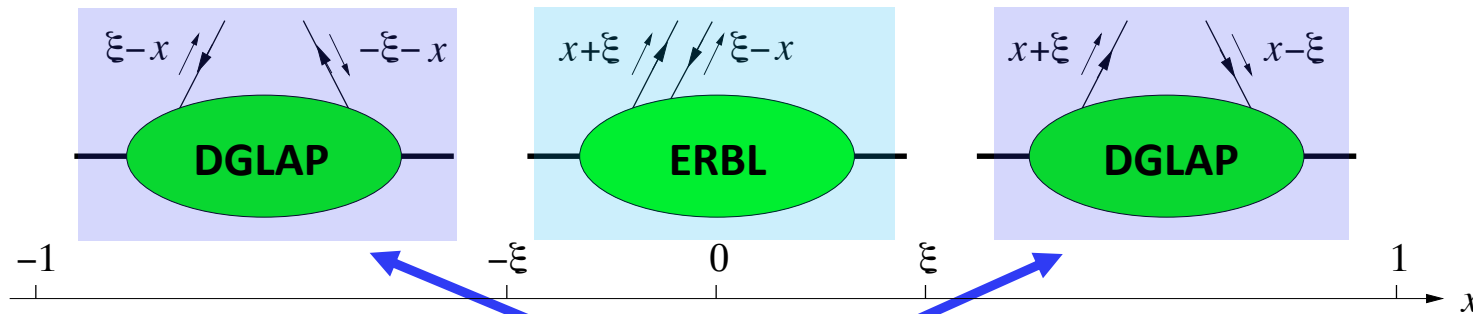
$i\mathcal{M}$ also contains the special integral

$$I'(t, \xi; z, \theta) = \int_{-1}^1 \frac{dx F(x, \xi, t)}{x - \rho'(z; \theta) + i\epsilon}$$

$$\rho'(z; \theta) = \xi \cdot \left[\frac{\cos^2(\theta/2) (1 - z) - z}{\cos^2(\theta/2) (1 - z) + z} \right] \in [-\xi, \xi]$$



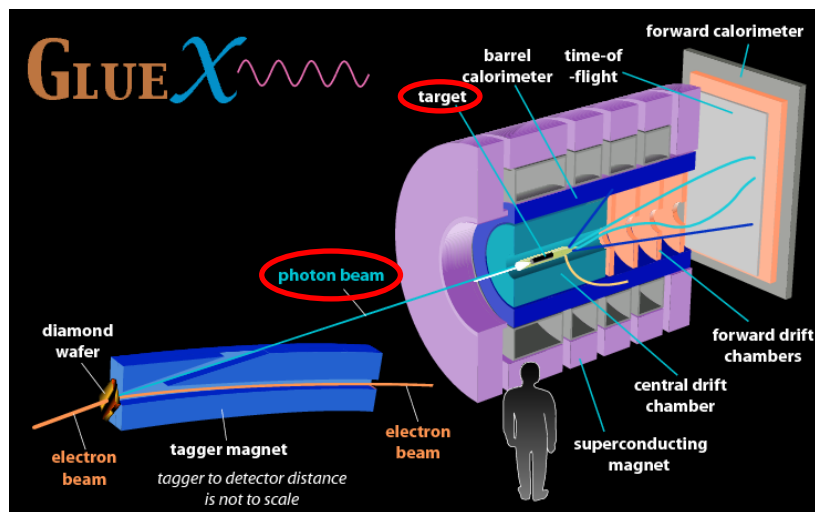
Complementary sensitivity



$$N \pi \rightarrow N' \gamma \gamma$$

Enhanced x -sensitivity: (2) γ - π pair photoproduction (at JLab Hall D)

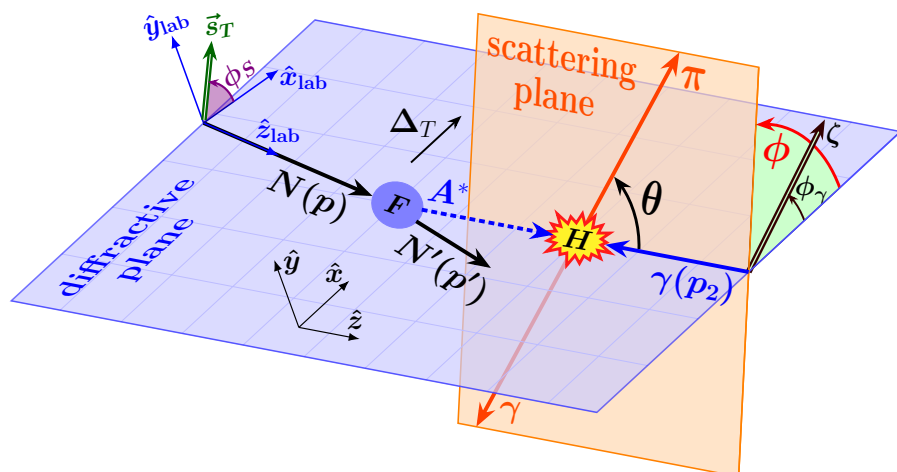
[Qiu & Yu, PRL 131 (2023) 161902]



Polarization asymmetries

$$\frac{d\sigma}{d|t| d\xi d\cos\theta d\phi} = \frac{1}{2\pi} \frac{d\sigma}{d|t| d\xi d\cos\theta} \cdot [1 + \lambda_N \lambda_\gamma A_{LL} + \zeta A_{UT} \cos 2(\phi - \phi_\gamma) + \lambda_N \zeta A_{LT} \sin 2(\phi - \phi_\gamma)]$$

$$\frac{d\sigma}{d|t| d\xi d\cos\theta} = \pi (\alpha_e \alpha_s)^2 \left(\frac{C_F}{N_c} \right)^2 \frac{1 - \xi^2}{\xi^2 s^3} \Sigma_{UU}$$



$$\begin{aligned} \Sigma_{UU} &= |\mathcal{M}_+^{[\tilde{H}]}|^2 + |\mathcal{M}_-^{[\tilde{H}]}|^2 + |\tilde{\mathcal{M}}_+^{[H]}|^2 + |\tilde{\mathcal{M}}_-^{[H]}|^2, \\ A_{LL} &= 2 \Sigma_{UU}^{-1} \text{Re} \left[\mathcal{M}_+^{[\tilde{H}]} \tilde{\mathcal{M}}_+^{[H]*} + \mathcal{M}_-^{[\tilde{H}]} \tilde{\mathcal{M}}_-^{[H]*} \right], \\ A_{UT} &= 2 \Sigma_{UU}^{-1} \text{Re} \left[\tilde{\mathcal{M}}_+^{[H]} \tilde{\mathcal{M}}_-^{[H]*} - \mathcal{M}_+^{[\tilde{H}]} \mathcal{M}_-^{[\tilde{H}]*} \right], \\ A_{LT} &= 2 \Sigma_{UU}^{-1} \text{Im} \left[\mathcal{M}_+^{[\tilde{H}]} \tilde{\mathcal{M}}_-^{[H]*} + \mathcal{M}_-^{[\tilde{H}]} \tilde{\mathcal{M}}_+^{[H]*} \right]. \end{aligned}$$

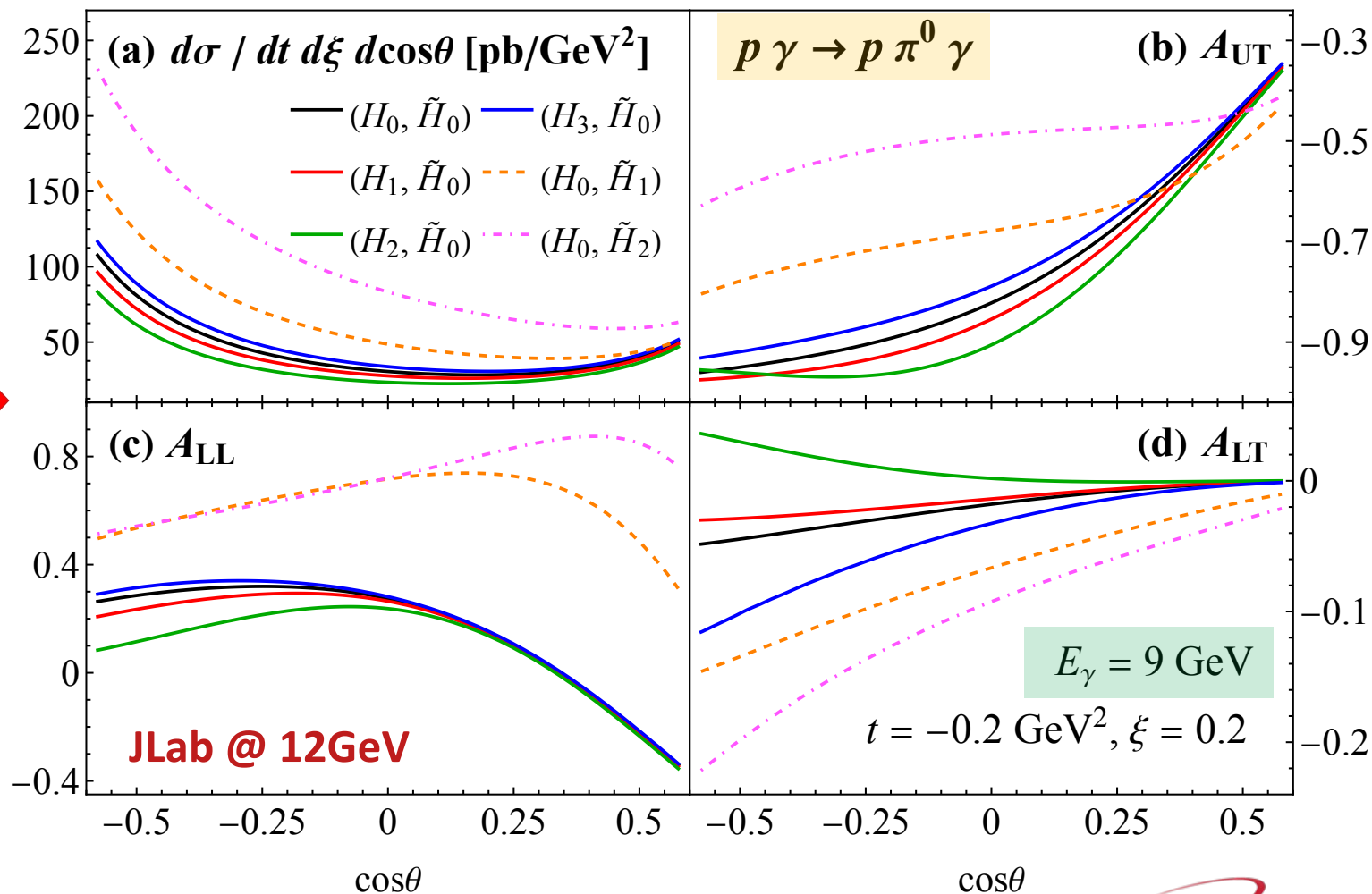
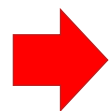
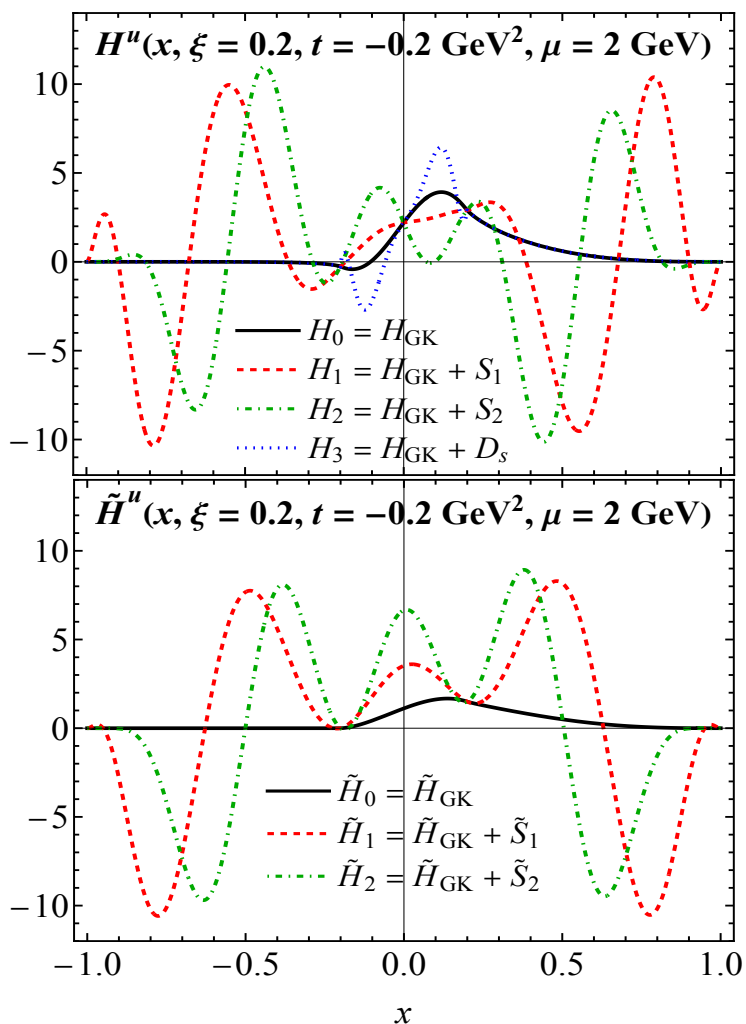
Neglecting: (1) E and $\tilde{E}$; (2) gluon channel

Enhanced x -sensitivity: (2) γ - π pair photoproduction (at JLab Hall D)

GPD models = GK model + shadow GPDs

$$\int_{-1}^1 \frac{dx S(x, \xi)}{x - \xi \pm i\epsilon} = 0$$

Goloskokov, Kroll, '05, '07, '09
Bertone et al. '21
Moffat et al. '23

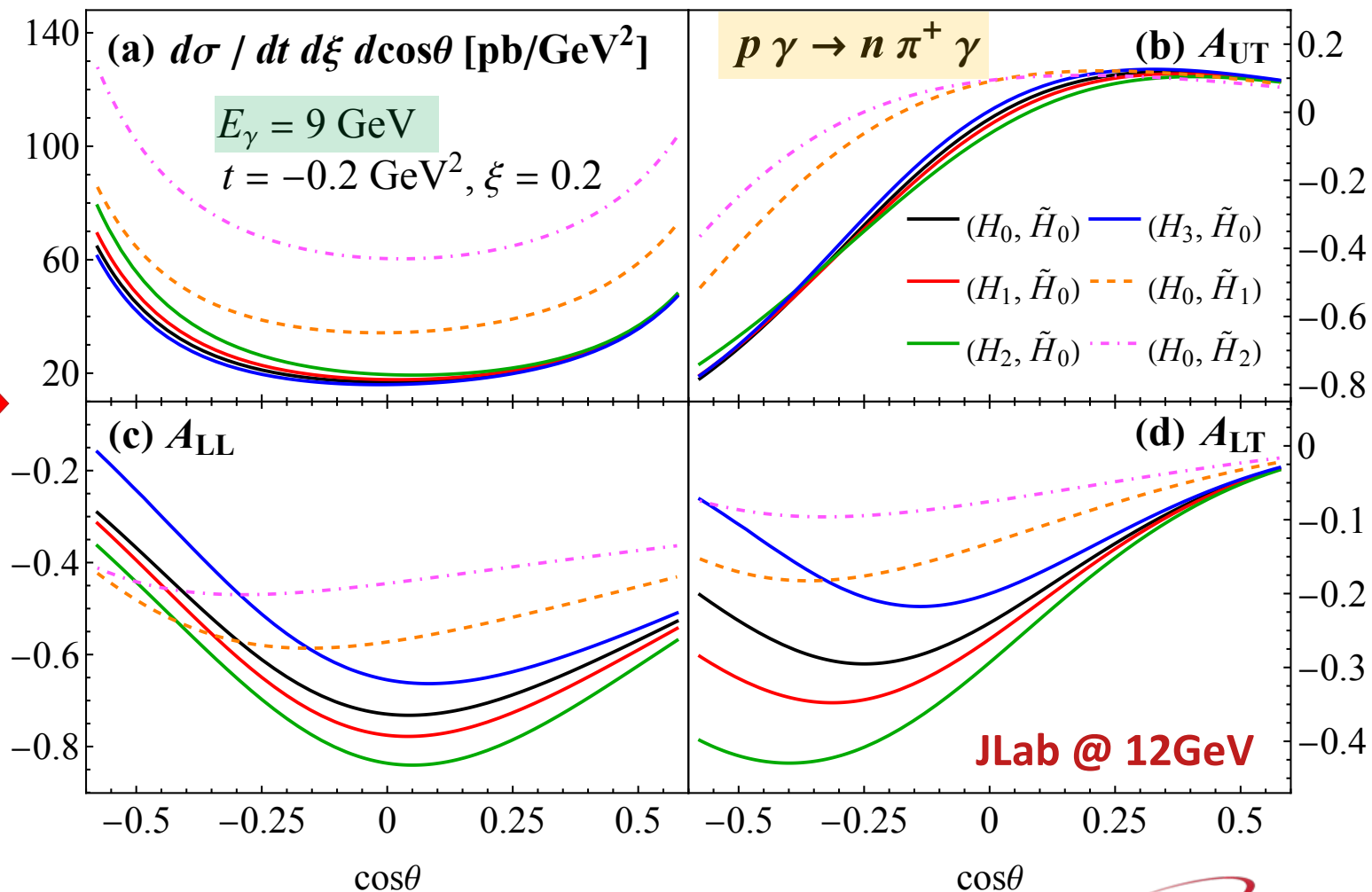
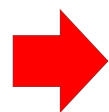
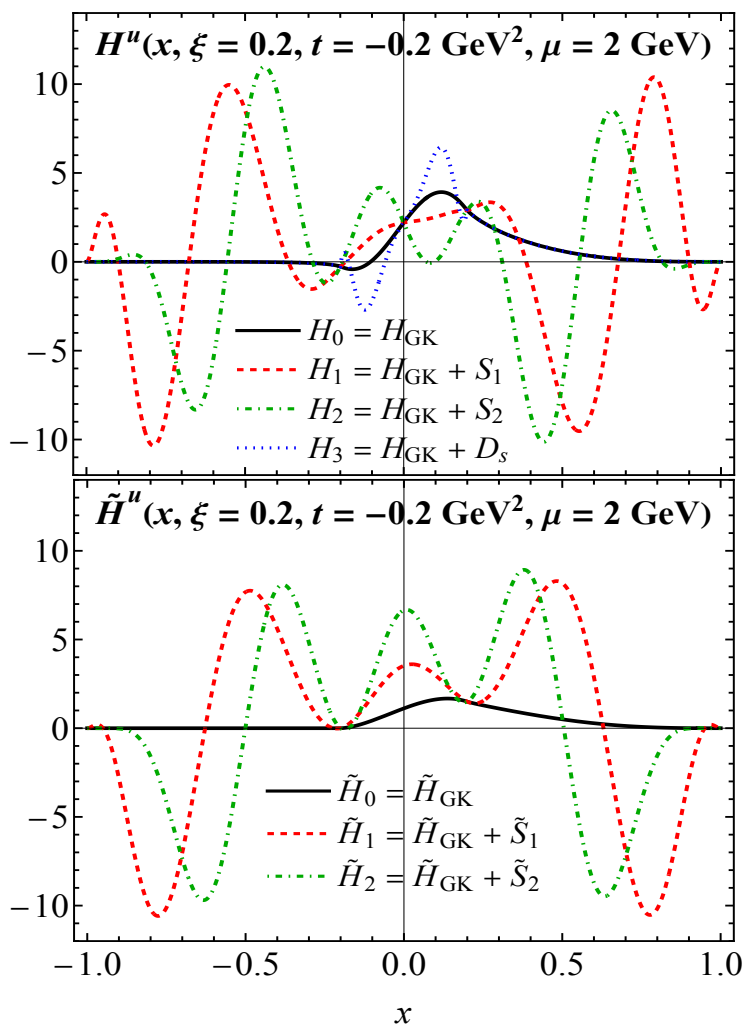


Enhanced x -sensitivity: (2) γ - π pair photoproduction (at JLab Hall D)

GPD models = GK model + shadow GPDs

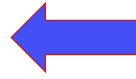
$$\int_{-1}^1 \frac{dx S(x, \xi)}{x - \xi \pm i\epsilon} = 0$$

Goloskokov, Kroll, '05, '07, '09
Bertone et al. '21
Moffat et al. '23



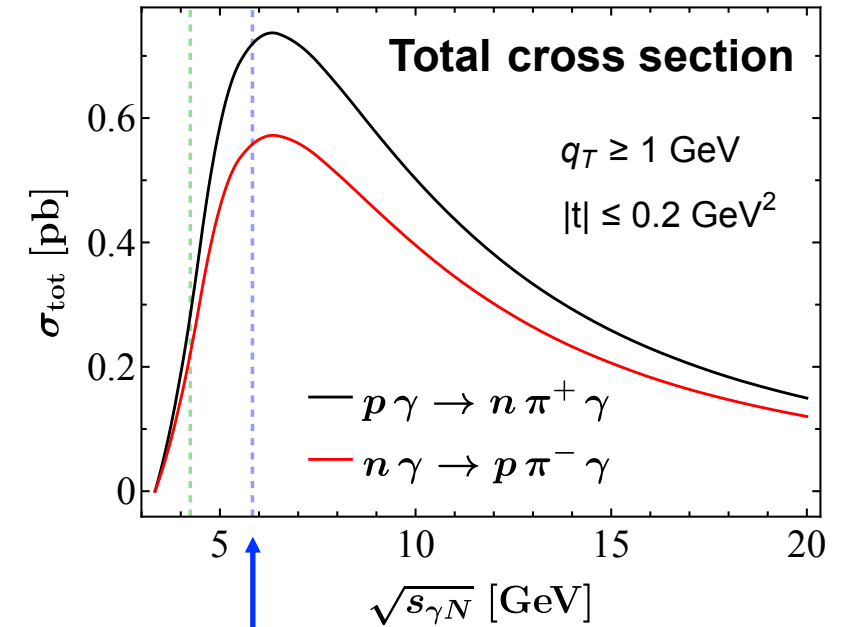
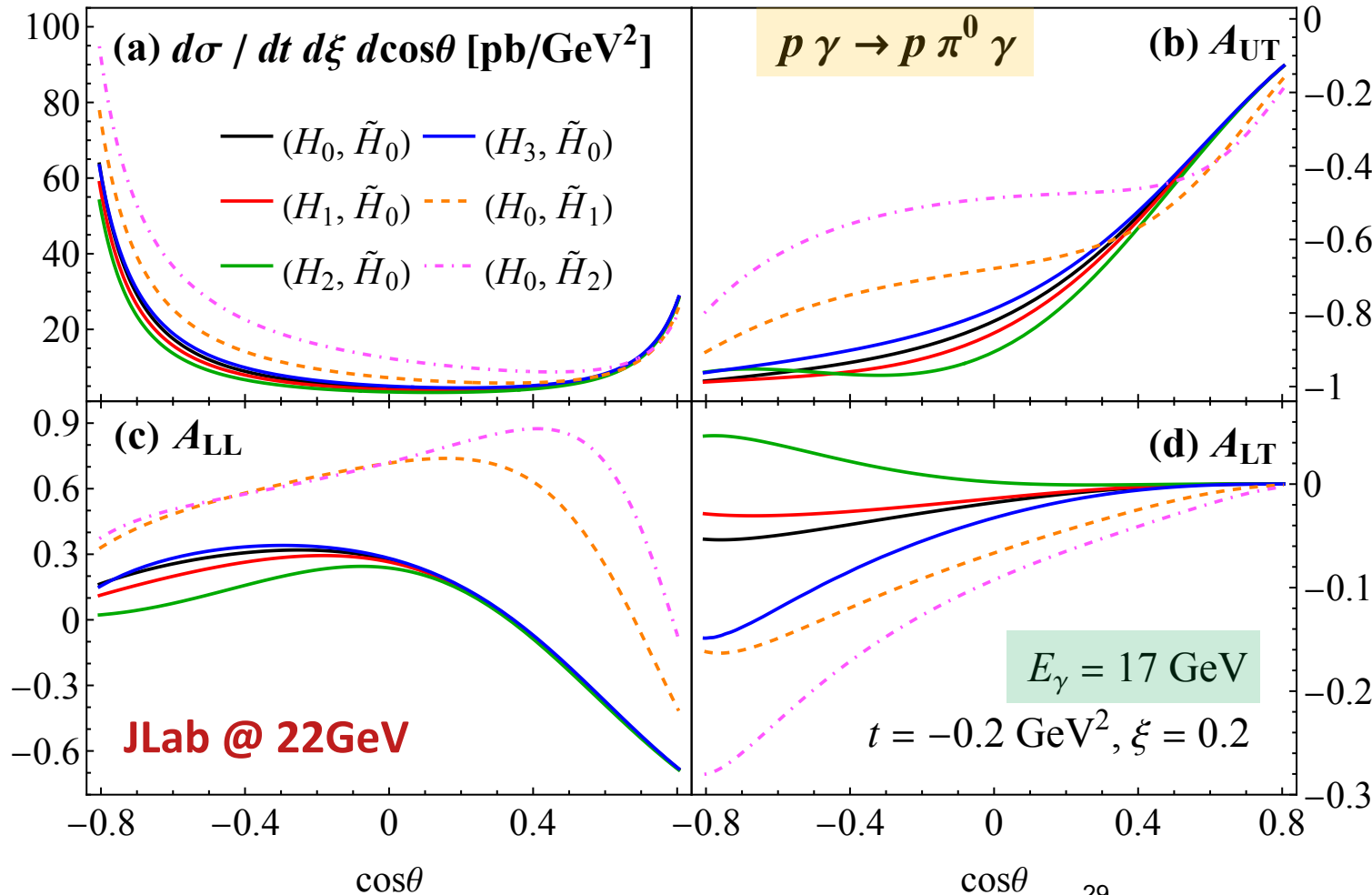
Enhanced x -sensitivity: (2) γ - π pair photoproduction (at upgraded JLab energy)

GPD models = GK model + shadow GPDs



$$\int_{-1}^1 \frac{dx S(x, \xi)}{x - \xi \pm i\epsilon} = 0$$

Goloskokov, Kroll, '05, '07, '09
Bertone et al. '21
Moffat et al. '23



JLab @ 22GeV [arXiv:2306.09360]

Summary

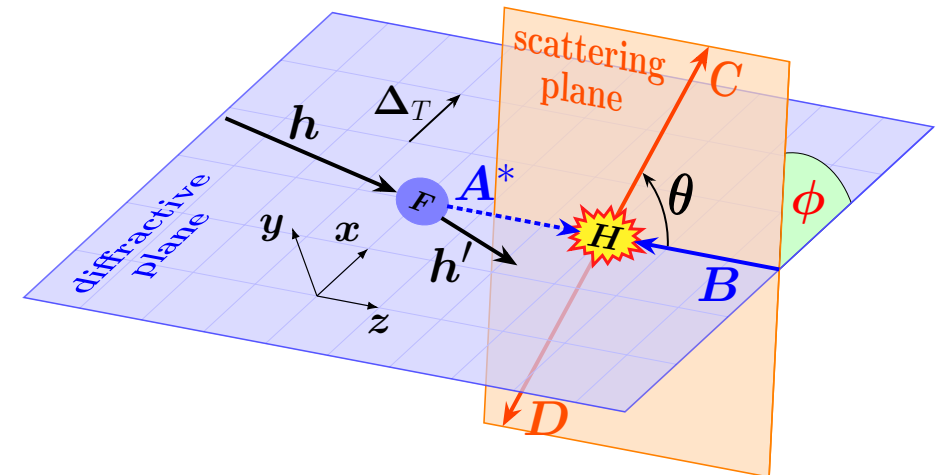
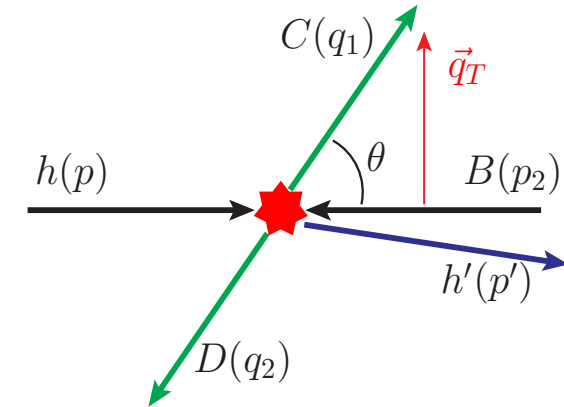
❑ A new perspective to frame GPD processes

- Single diffractive hard exclusive processes
- Unified description
- Two new processes to give **enhanced x-sensitivity**

❑ Still not there yet

- Need more processes, more observables
- Need input from lattice QCD
- Need global fit

--- A long challenging but exciting way to go!



Thank you!