Single Diffractive Hard Exclusive Scattering for studying Generalized Parton Distributions (GPDs)

Zhite Yu
(Jefferson Lab, Theory Center)

In collaboration with Jianwei Qiu

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Jan/18/2024 at BNL

Jefferson Lab
Brookhaven National Laboratory
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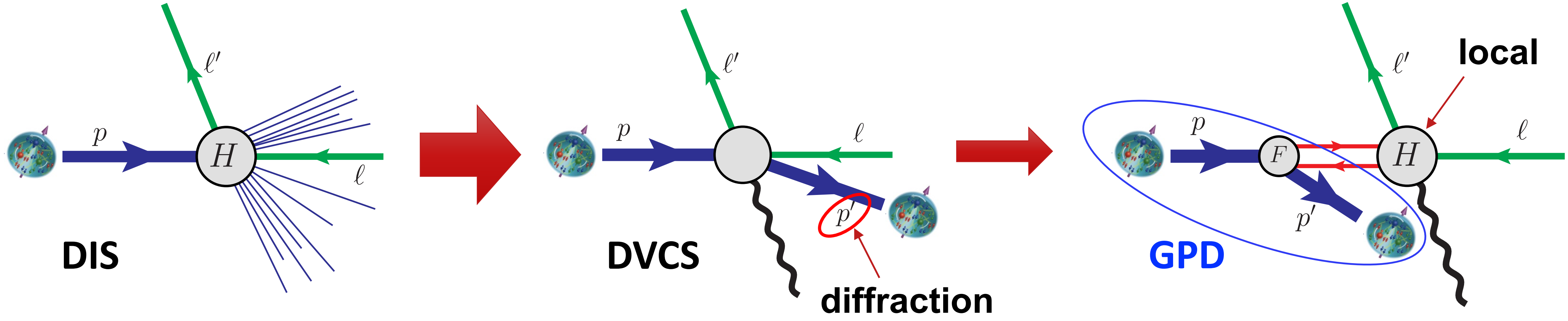
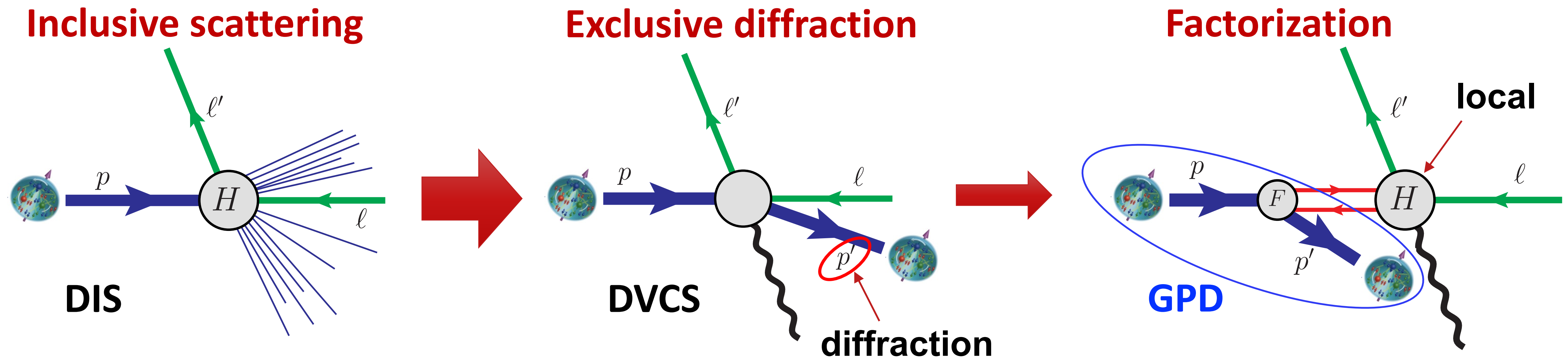
JSA

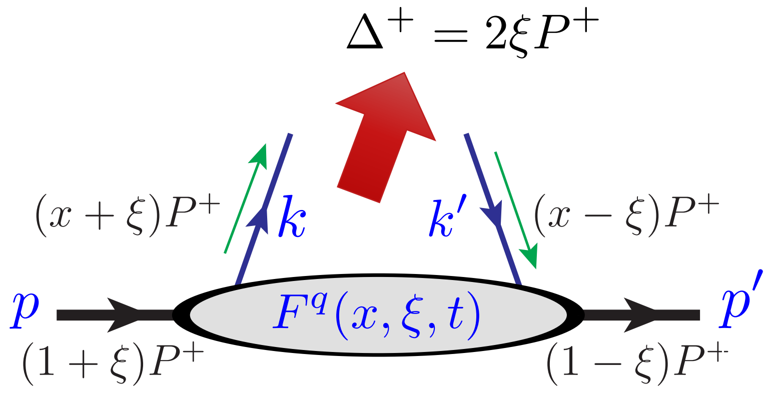
Exclusive Processes and GPDs

Inclusive scattering **Exclusive diffraction** **Factorization**



Exclusive Processes and GPDs





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

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

$$P = \frac{p+p'}{2}$$

$$\Delta = p - p'$$

$$t = \Delta^2$$

$$\xi = \frac{(p-p')^+}{(p+p')^+}$$

Hadron diffraction $p \to p'$

$$x = \frac{(k+k')^+}{(p+p')^+}$$

parton momentum

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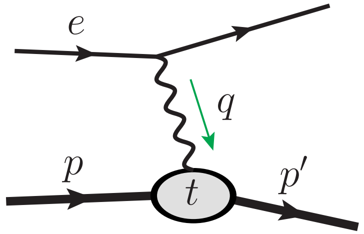
GPD and QCD Tomography

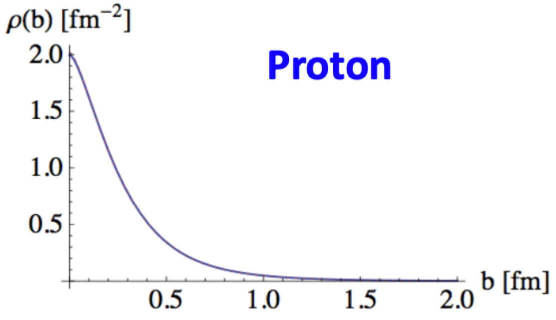
❑ Controllable soft scale *t*

Elastic EM form factor



F. T.

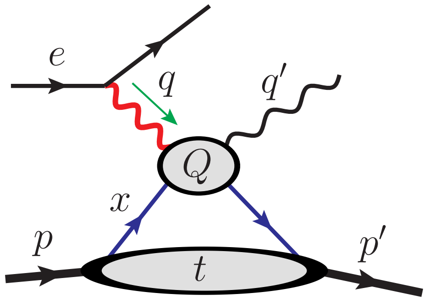
$F_{1,2}(t)$



- **Flavor, color blind**
- **EM charge radius**
- **No color elastic form factor**

no color radius

DVCS



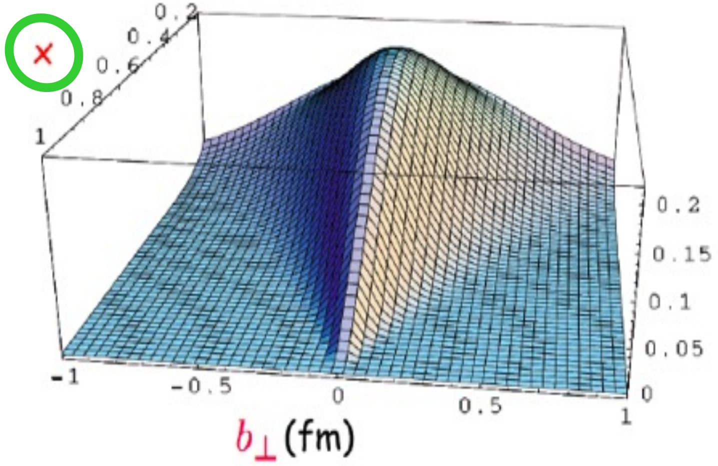
Two distinct scales at the same time

- **Hard *Q*: see partons (with *x*)**
- **Low *t*: probe the confined motion (b_T)**

$$f_i(x, \boldsymbol{b}_T) = \int \mathrm{d}^2\boldsymbol{\Delta}_T \, e^{i\boldsymbol{\Delta}_T\cdot\boldsymbol{b}_T} F_i(x, 0, -\Delta_T^2)$$

Parton density in $\mathrm{d}x\,\mathrm{d}^2\boldsymbol{b}_T$

3D image



"Color" density

confinement; nuclear force; color radius…

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GPD and Hadronic Property

QCD energy-momentum tensor

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

Gravitational form factor

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

Connection to GPD moments

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

Need ξ-dependence to extract the *D*-term

Angular momentum sum rule

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

$$i = q, g$$

- **3D tomography**
- **relations to GFF**
- **angular momentum**
- **…**

→ ***x*-dependence!**

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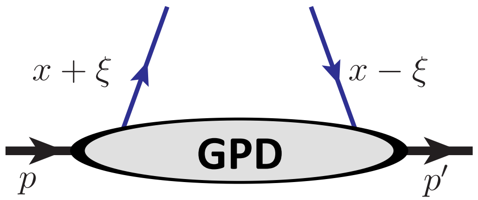
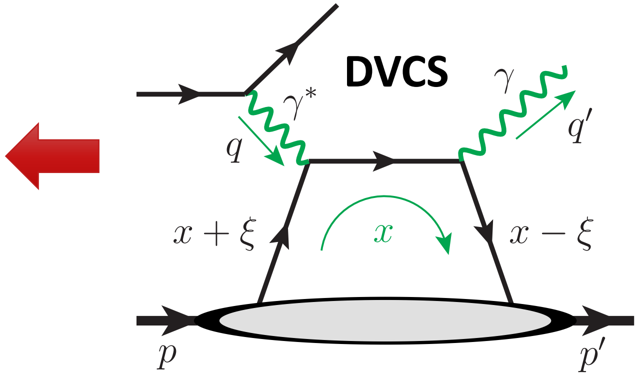
Why is the GPD *x*-dependence so *difficult* to measure?

❑ Amplitude nature: exclusive processes





***x* ~ loop momentum**

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

never pin down to some *x*

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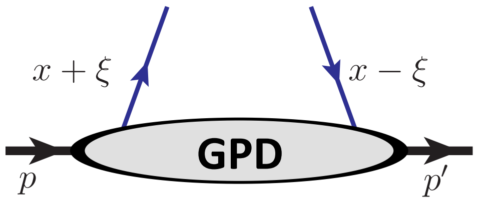

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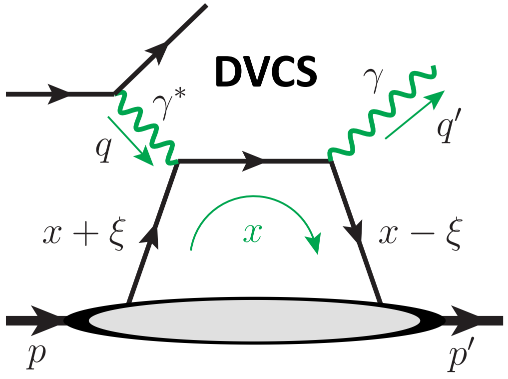

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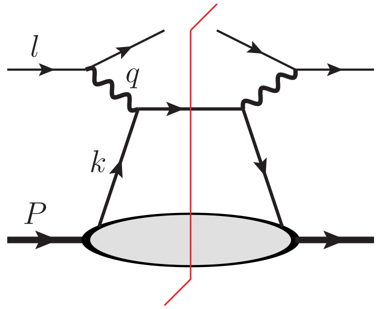
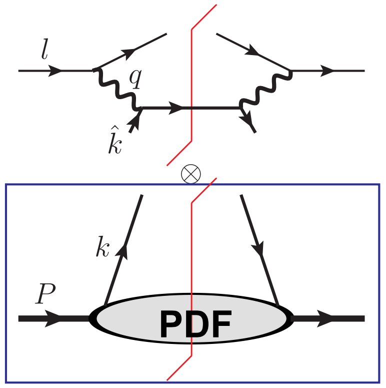
Compare with DIS





***cross section*: cut diagram**

$$\sigma_{\mathrm{DIS}} \simeq \int_{x_B}^{1} \mathrm{d}x\, f(x)\,\hat{\sigma}(x/x_B)$$

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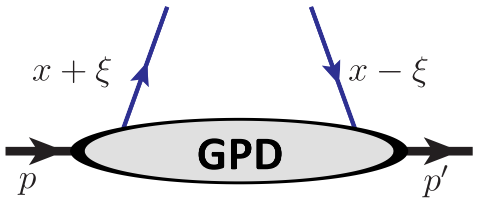

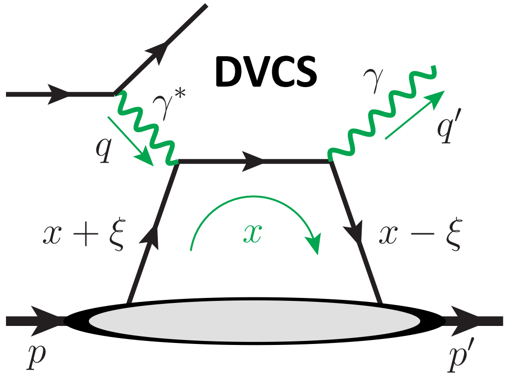

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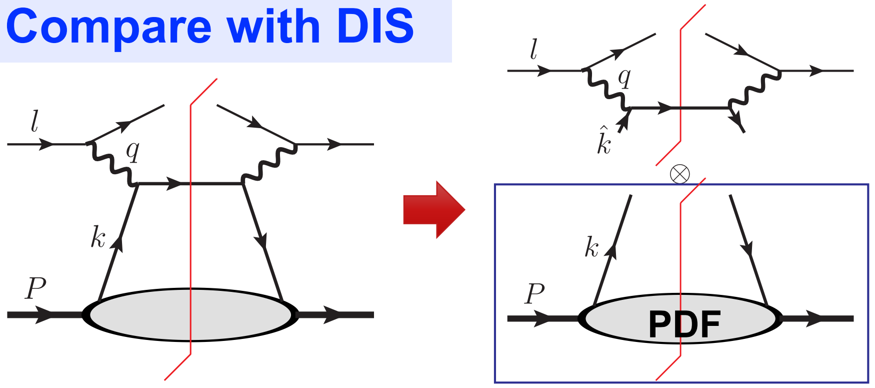


cross section: **cut diagram**

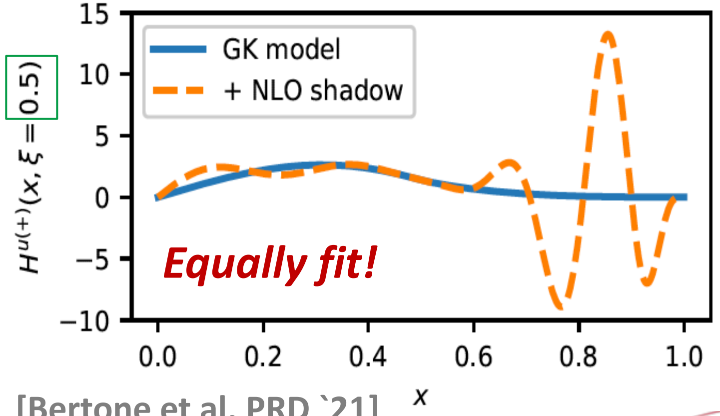
$$\sigma_{\mathrm{DIS}} \simeq \int_{x_B}^{1} \mathrm{d}x\, f(x)\,\hat{\sigma}(x/x_B)$$

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

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

$$i\mathcal{M} \propto \int_{-1}^{1} \mathrm{d}x\, \frac{F(x,\xi,t)}{x-\xi+i\varepsilon} \equiv \text{“}F_0(\xi,t)\text{”}$$

“moment”



[Bertone et al. PRD `21]

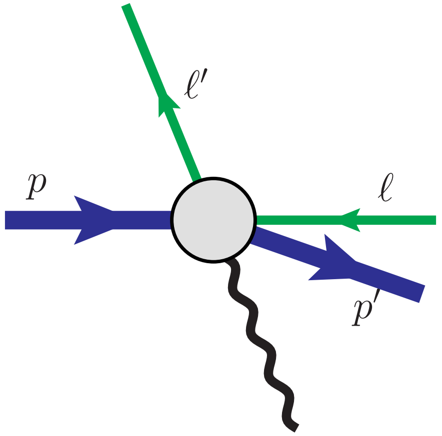
How to *think* about the GPD processes?

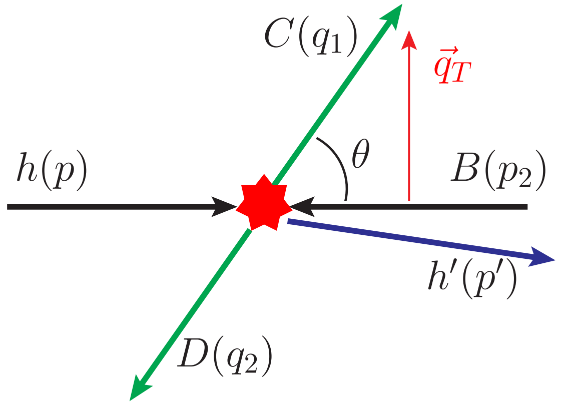
❑ Single diffractive hard exclusive process (SDHEP)

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

DVCS in lab frame

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





2 → 3: *minimal*
kinematic configuration!

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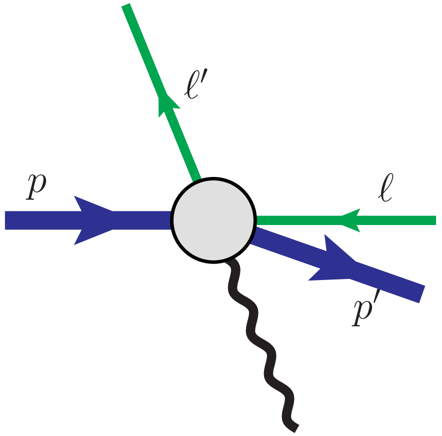
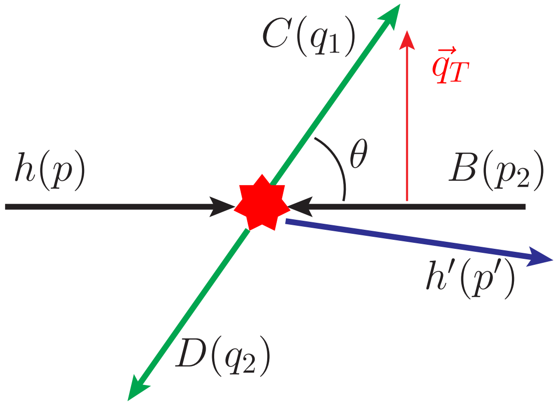


$h(p) + B(p_2) \to h'(p') + C(q_1) + D(q_2)$



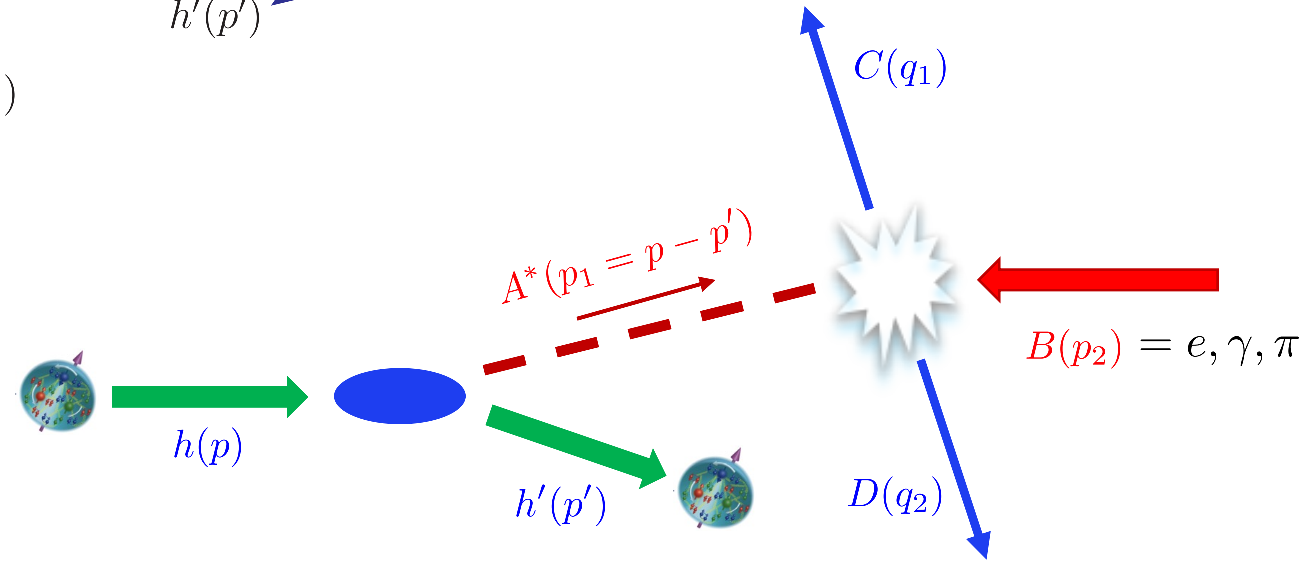
2 → 3: *minimal*
kinematic configuration!

❑ Two-stage process paradigm

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

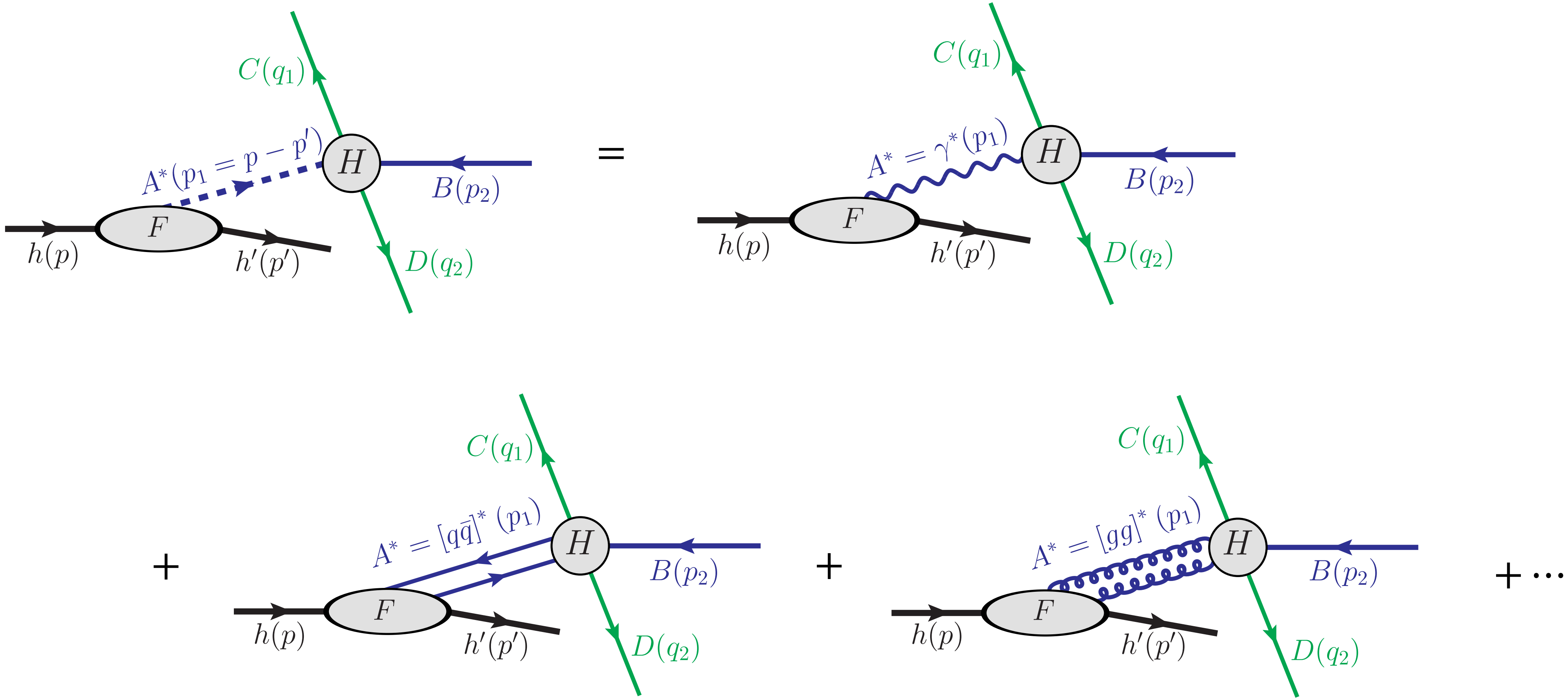
↓ **factorize**

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



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

SDHEP: Two-stage paradigm and channel expansion



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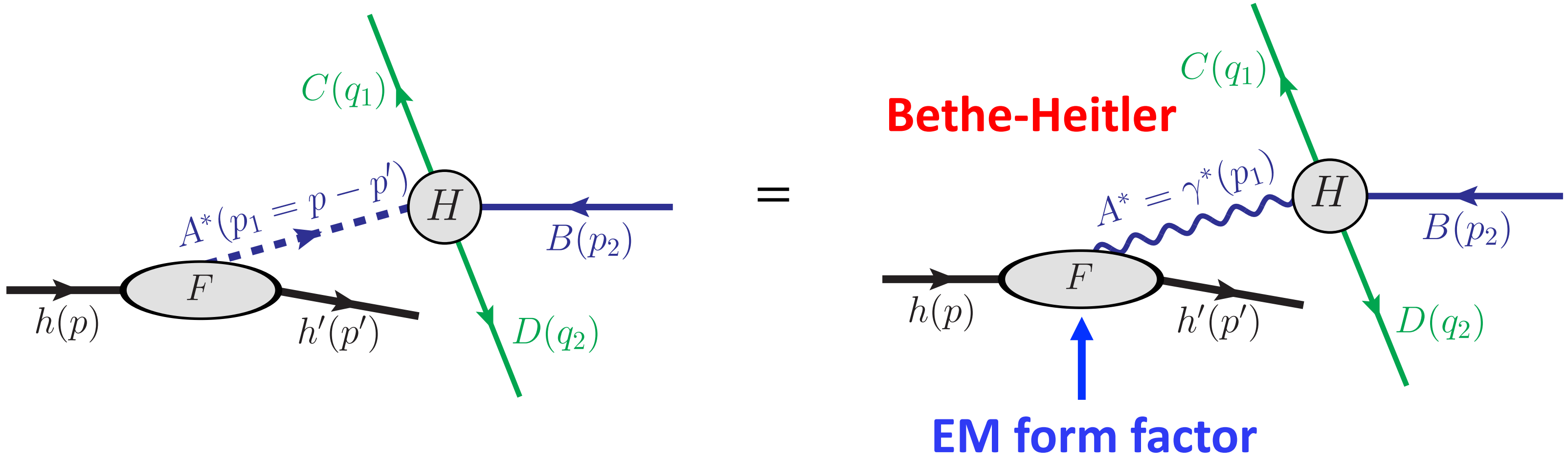
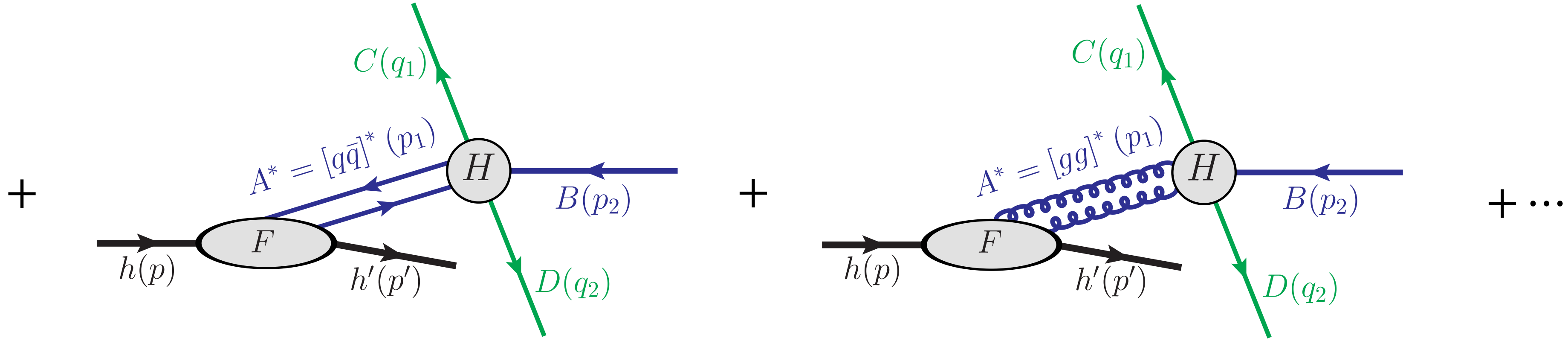


Superleading power in 1/Q, but higher power in α_{em}



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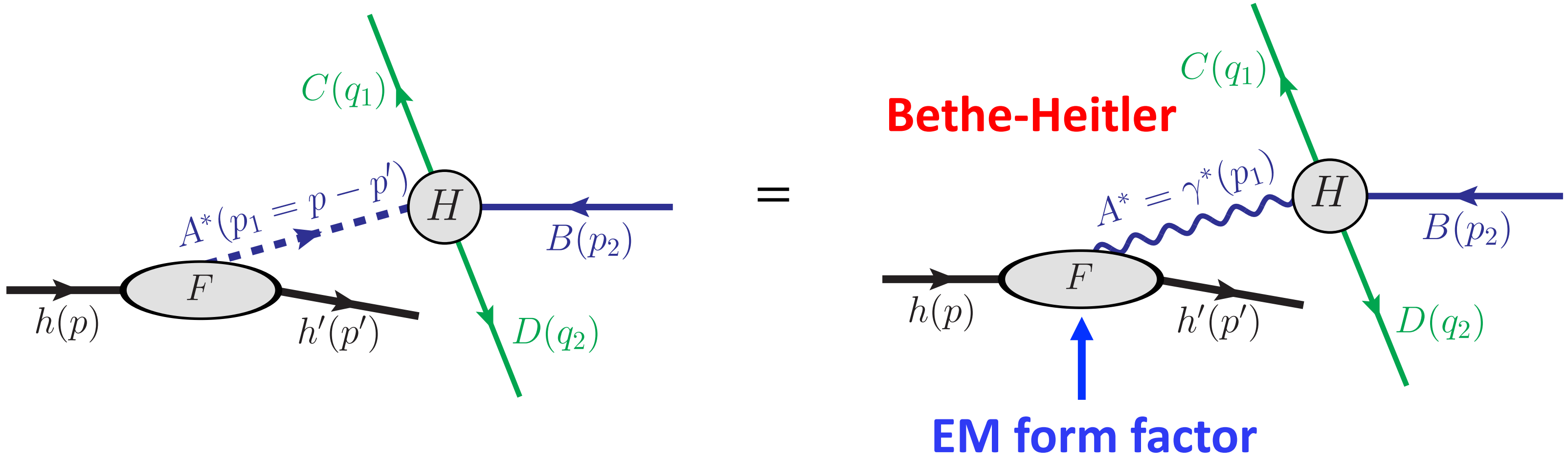

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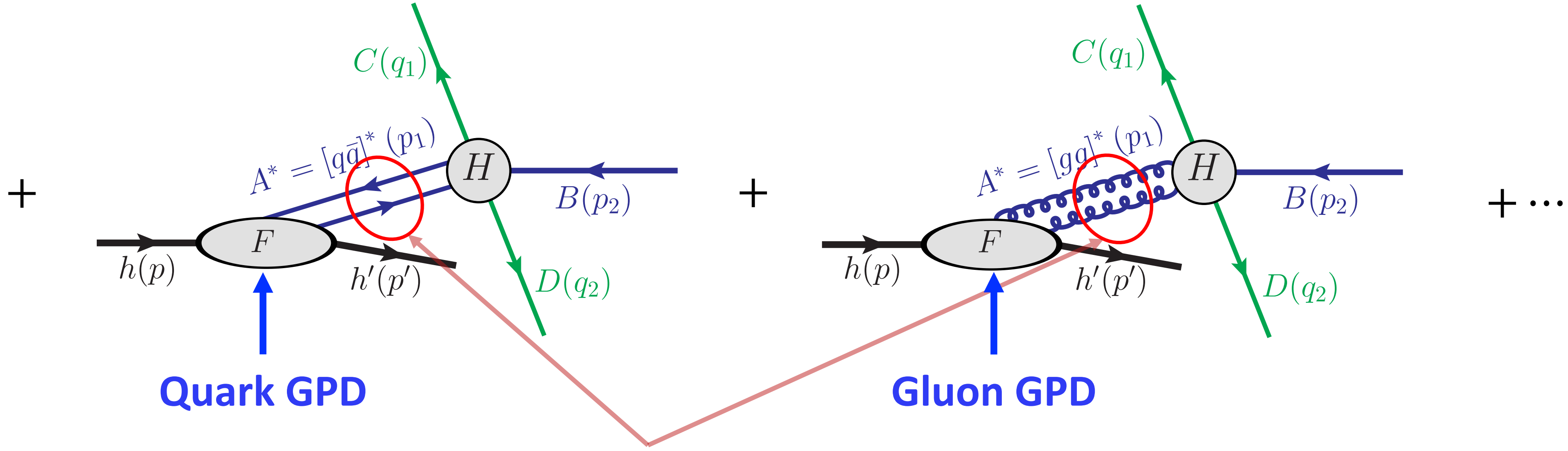
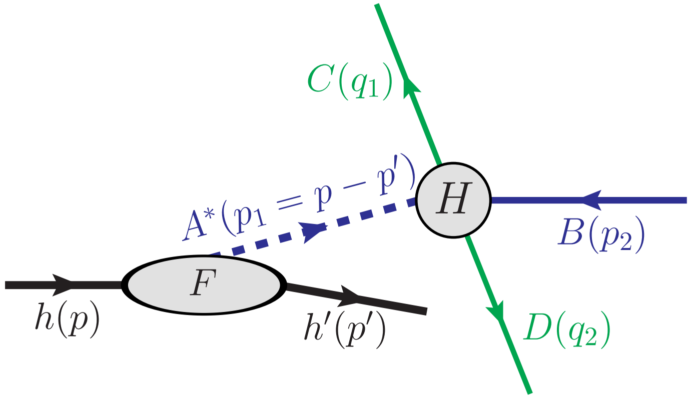


Energy ≫ virtuality

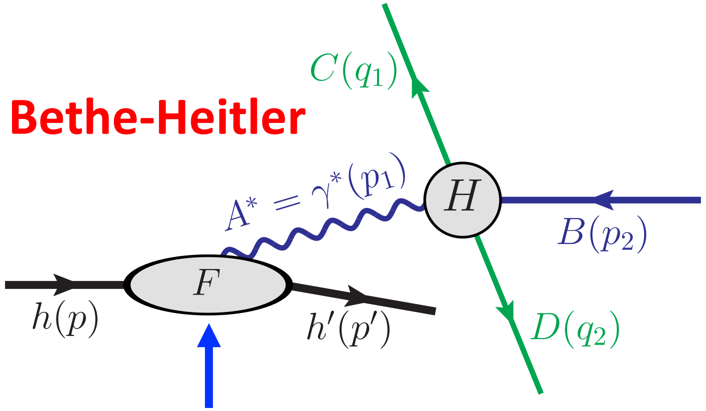
→ To be factorized into GPD

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



$=$

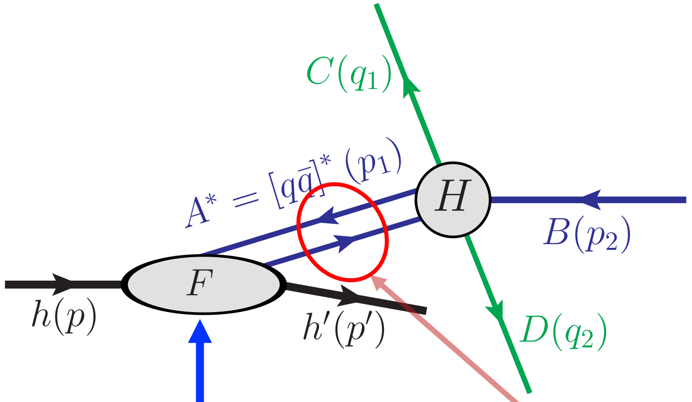
Bethe-Heitler



EM form factor

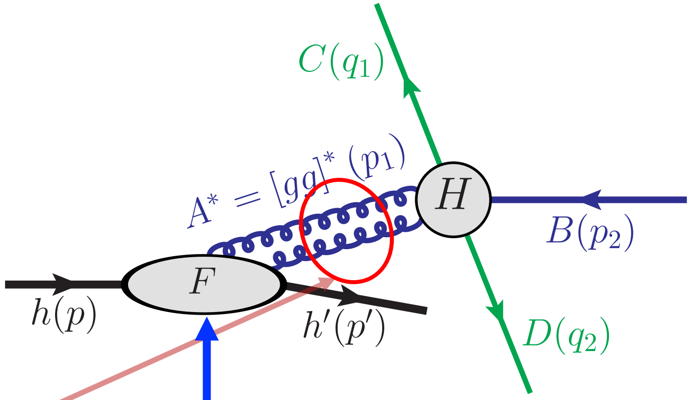
Superleading power in 1/Q, but higher power in α_{em}

$+$



Quark GPD

$+$



Gluon GPD

≥ 3 parton connection: Power suppressed

$+\cdots$

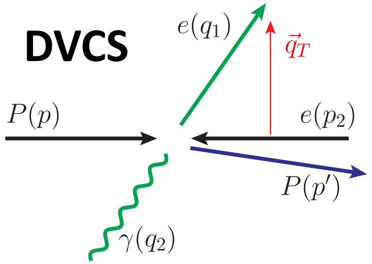
Energy $\gg$ virtuality

$\longrightarrow$ To be factorized into GPD

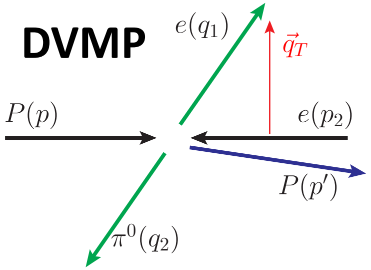
Classification of SDHEPs

❑ Electro-production (JLab, EIC, …)

DVCS

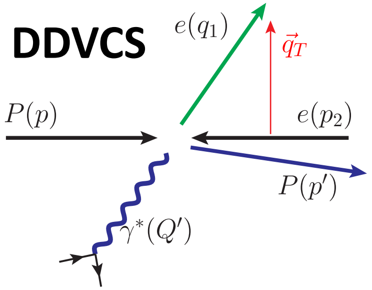


DVMP



add virtuality

DDVCS



DHQP…

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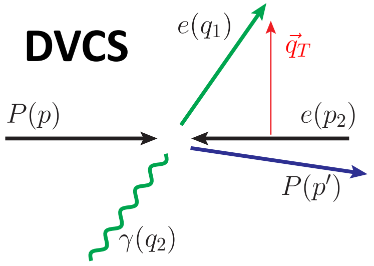

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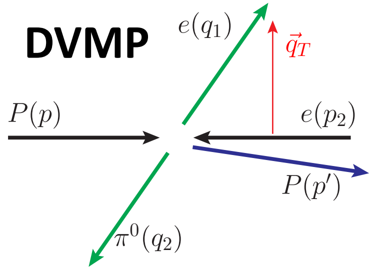

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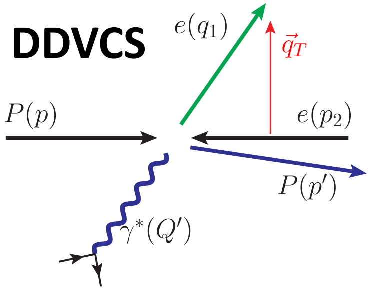
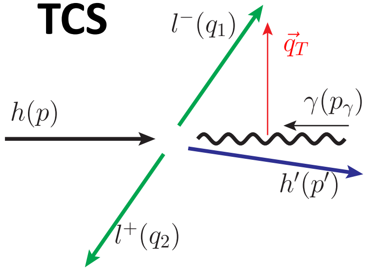
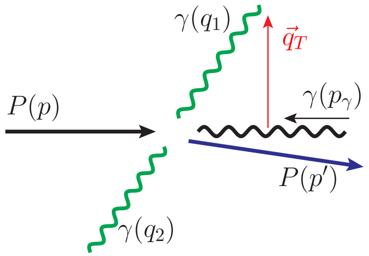


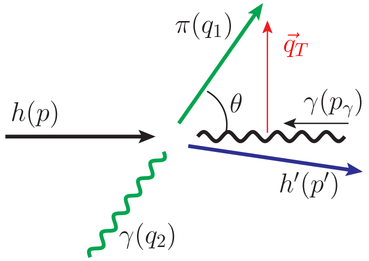
DHQP…

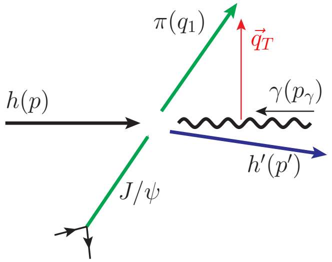
❑ Photo-production (JLab, EIC, …)

TCS









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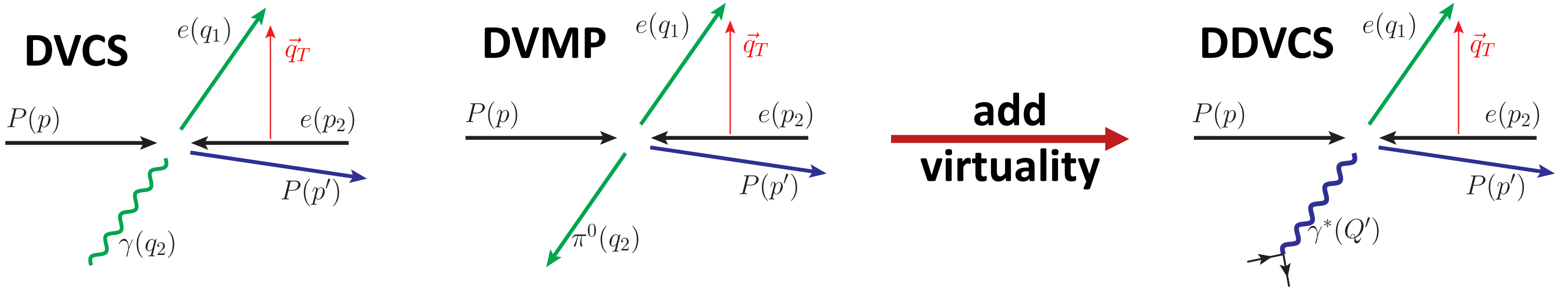

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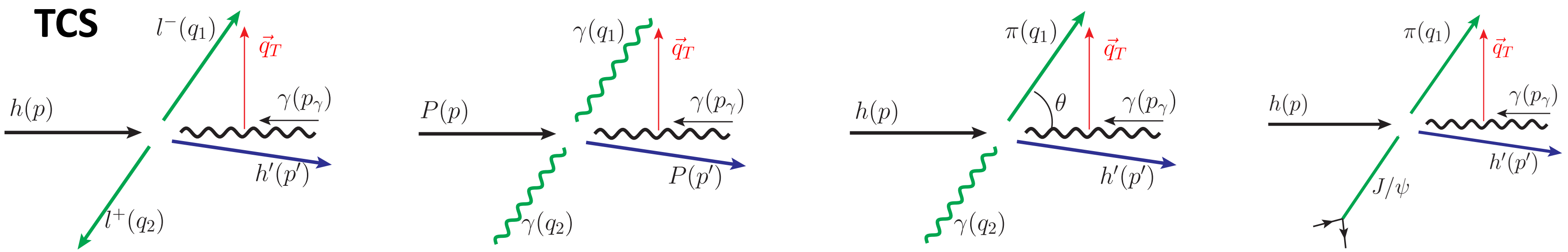

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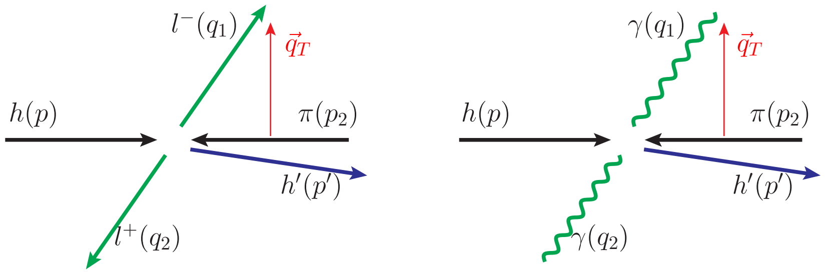
❑ Meso-production (AMBER, J-PARC, …)



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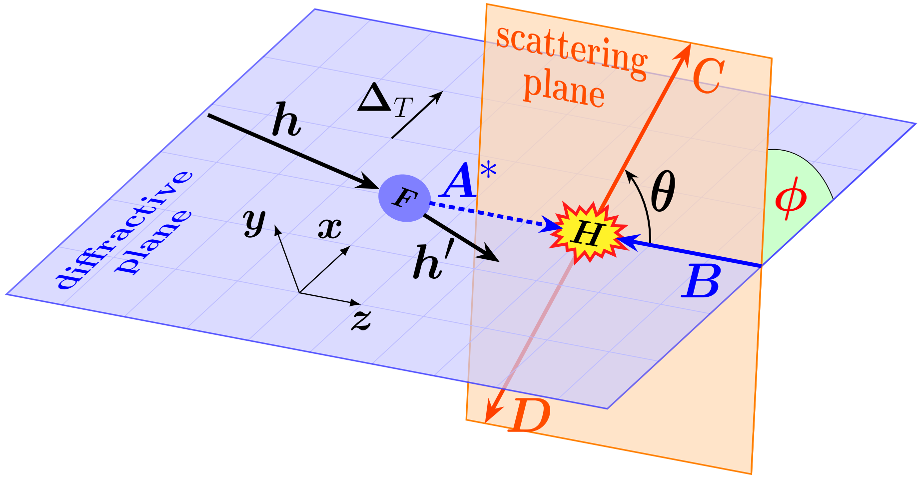
Generic discussion

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

Where does the sensitivity come from?



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

Kinematics:

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

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

[suppressing t and ξ dependence]

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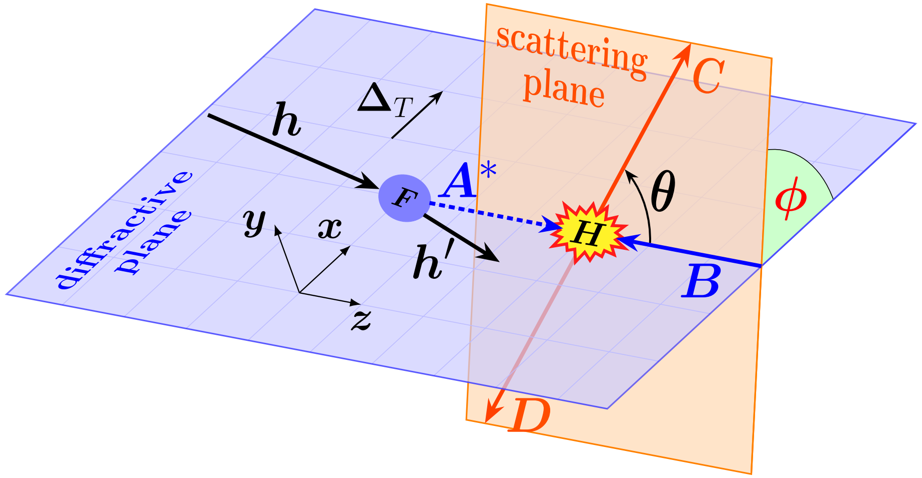

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[suppressing t and ξ dependence]

➢ **Moment-type sensitivity** $\boxed{C(x;Q) = G(x)\cdot T(Q)}$ ⟹ $F_G = \int_{-1}^{1} dx\, G(x)\, F(x,\xi,t)$

⟹ **Inversion problem: *shadow GPD*** $S_G = \int_{-1}^{1} dx\, G(x)\, S(x,\xi) = 0$ [Bertone et al. PRD `21]

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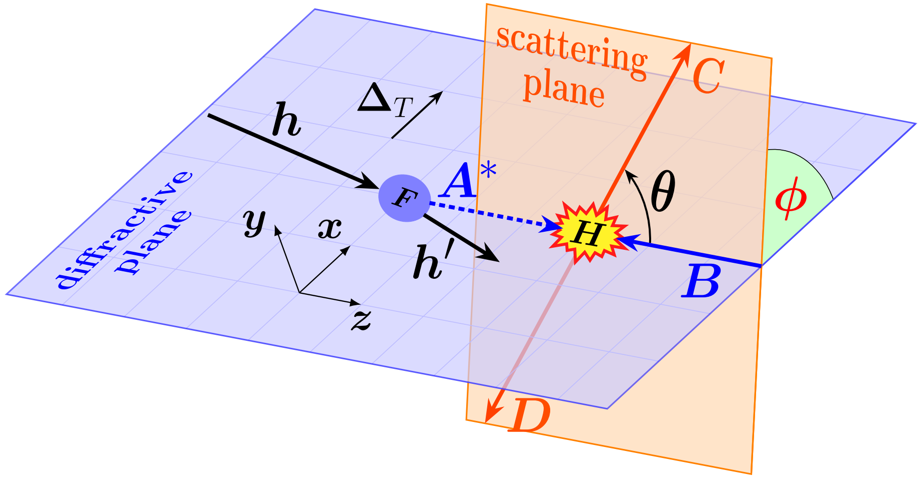

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[suppressing t and ξ dependence]

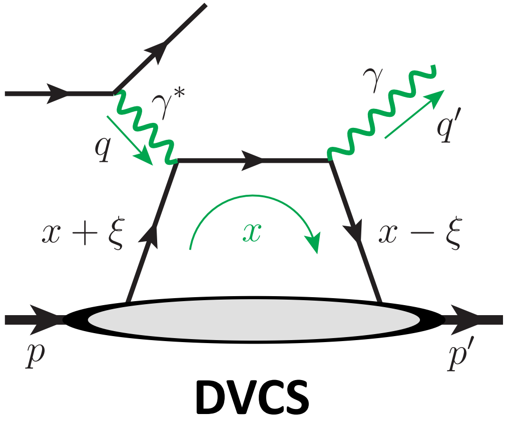
➢ **Moment-type sensitivity** $\boxed{C(x;Q) = G(x)\cdot T(Q)}$ ⟹ $F_G = \int_{-1}^{1} dx\, G(x)\, F(x,\xi,t)$

⟹ **Inversion problem: *shadow GPD*** $S_G = \int_{-1}^{1} dx\, G(x)\, S(x,\xi) = 0$ [Bertone et al. PRD `21]

➢ **Enhanced sensitivity** $\boxed{C(x;Q) \neq G(x)\cdot T(Q)}$ ⟹ $d\sigma/dQ \sim \left|C(x;Q)\otimes_x F(x,\xi,t)\right|^2$

Electroproduction processes: DVCS vs. DDVCS

❑ Moment sensitivity in DVCS

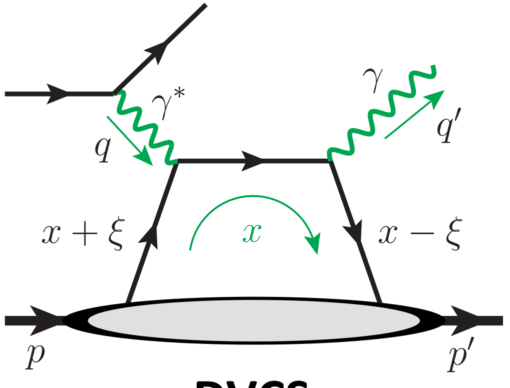


$$i\mathcal{M} \supset \int_{-1}^{1} dx \frac{F(x,\xi,t)}{x-\xi+i\epsilon} = F_0(\xi,t)$$

$q'^2 = 0$ ➡ **Lack of external scale to probe x**

Electroproduction processes: DVCS vs. DDVCS

❑ Moment sensitivity in DVCS

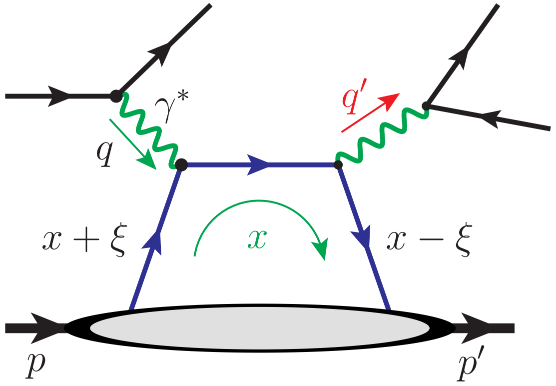


DVCS

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

$q'^2 = 0$ ➡ **Lack of external scale to probe *x***

❑ Enhanced sensitivity in DDVCS



DDVCS

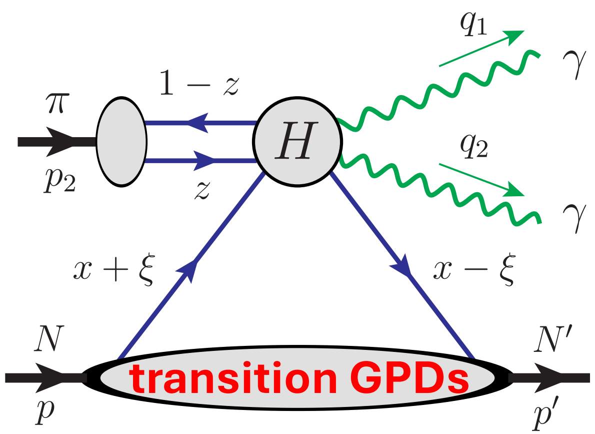
$$i\mathcal{M} \supset \int_{-1}^{1} dx \frac{F(x,\xi,t)}{x-x_p(\xi,Q'/Q)+i\epsilon}$$

$q'^2 = Q'^2$ ➡ **External scale to entangle with *x***

$$x_p(\xi,Q'/Q) = \xi\left[\frac{1-(Q'/Q)^2}{1+(Q'/Q)^2}\right]$$

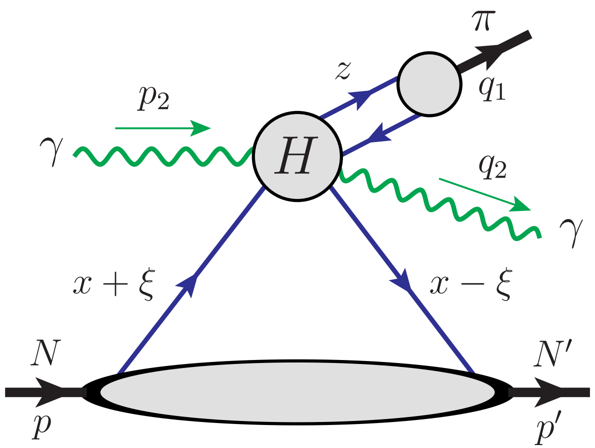
Physically appealing, but experimentally challenging…

Two new example processes with enhanced x-sensitivity



J-PARC, AMBER

Qiu & Yu, JHEP 08 (2022) 103
Qiu & Yu, arXiv:2401.xxxxx

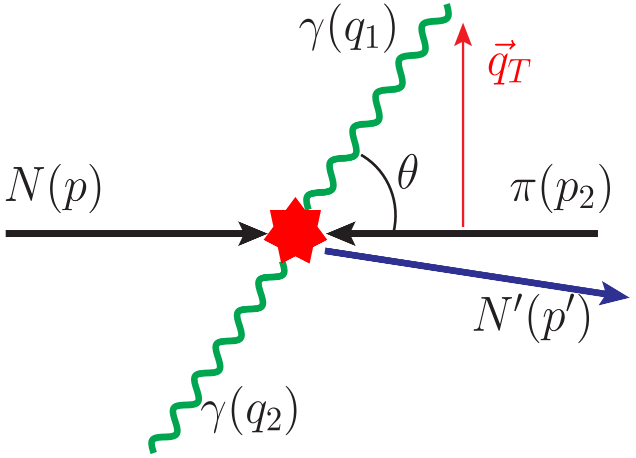


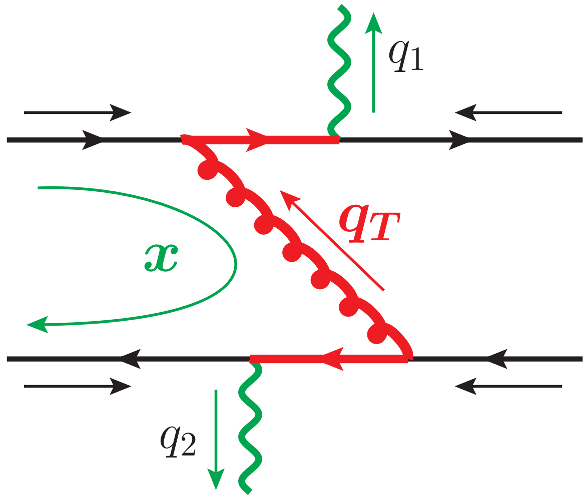
JLab Hall D

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 production

[Qiu & Yu, JHEP 08 (2022) 103]





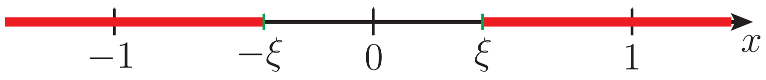
In addition to

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

$i\mathcal{M}$ **also contains**

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

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



Enhanced x-sensitivity: (1) diphoton production

[Qiu & Yu, arXiv:2401.xxxxx]

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

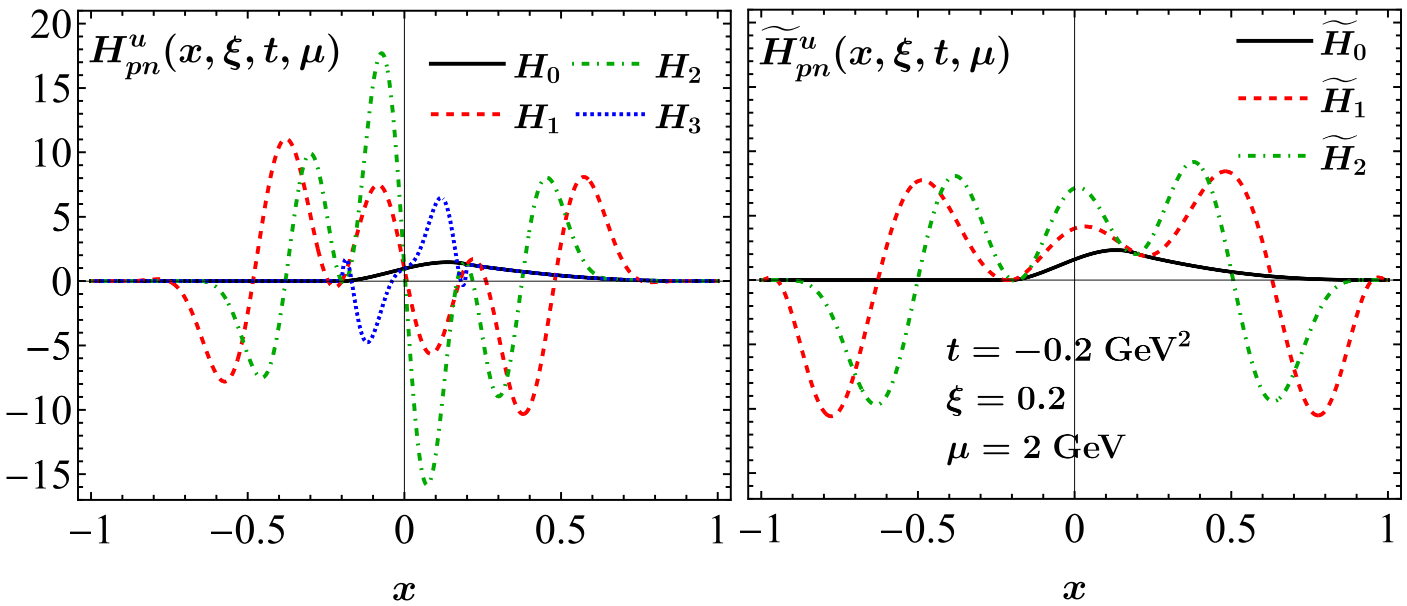
$$H_{pn}^u = H_p^u - H_p^d,\ \text{etc.}$$

GPD models = GK model + shadow GPDs

Goloskokov, Kroll, \`05, \`07, \`09

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

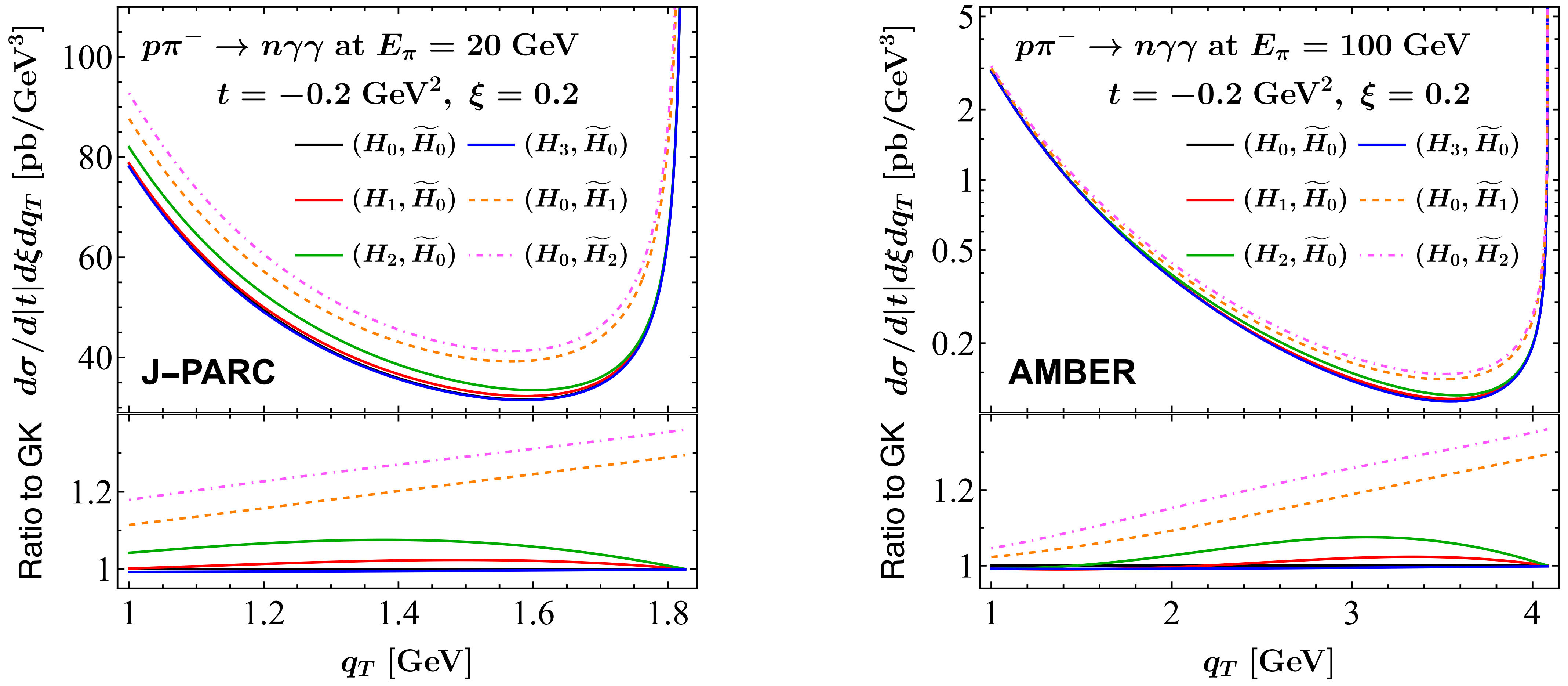
Bertone et al. \`21
Moffat et al. \`23



Jefferson Lab

Enhanced x-sensitivity: (1) diphoton production

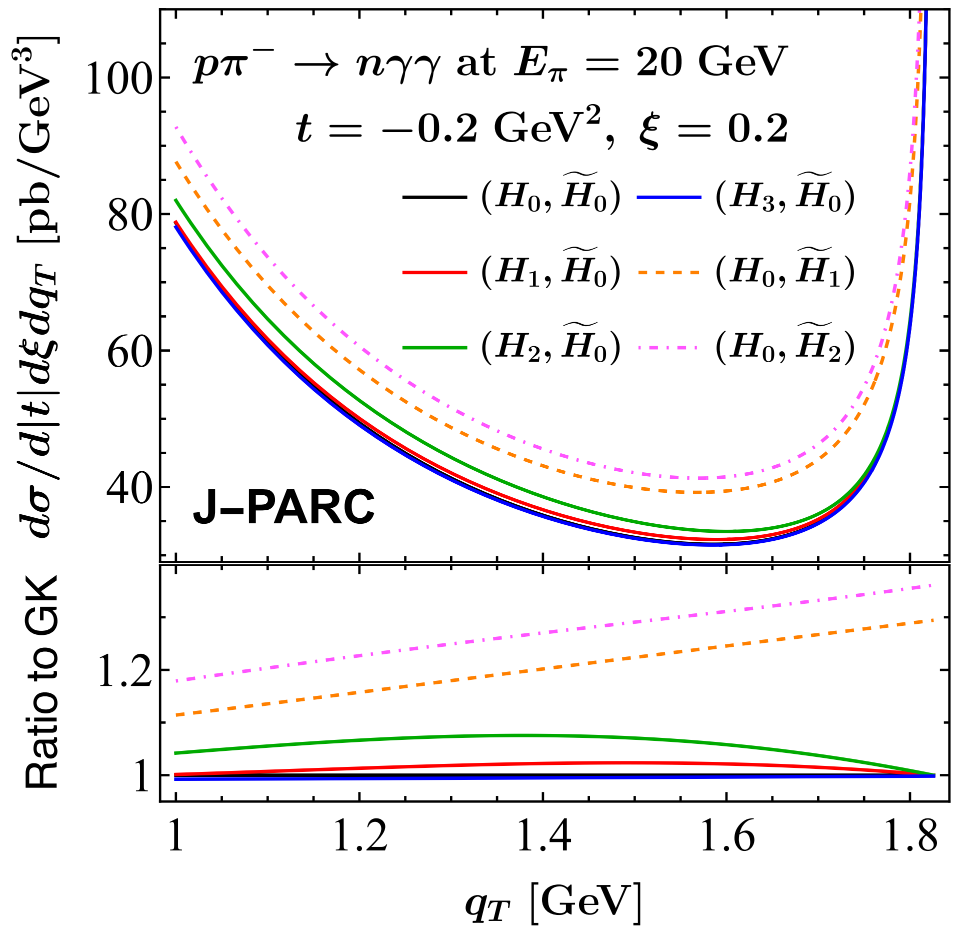
[Qiu & Yu, arXiv:2401.xxxxx]



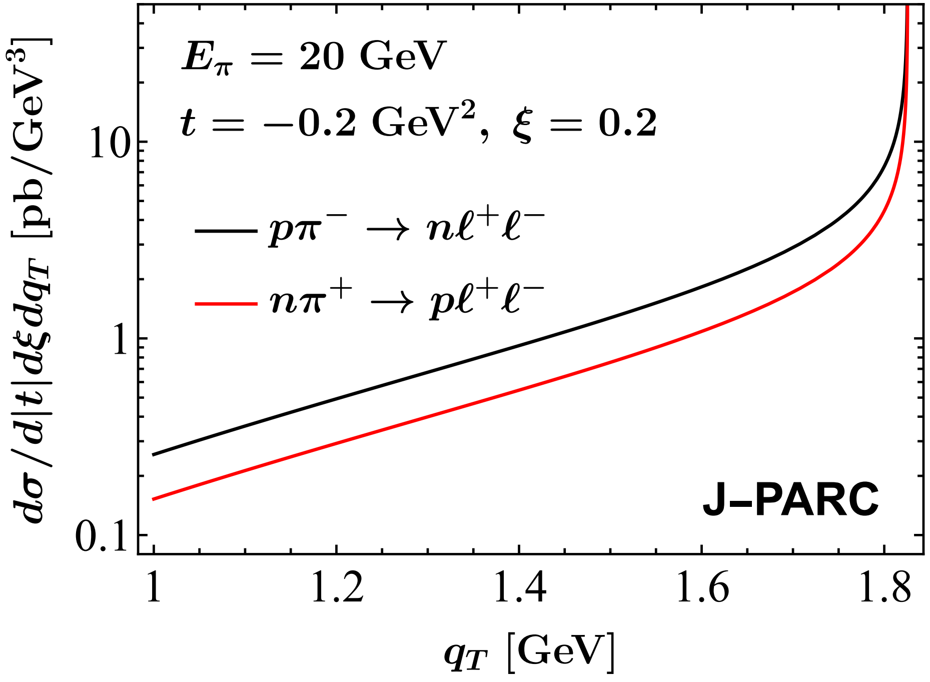
Jefferson Lab

Enhanced x-sensitivity: (1) diphoton production

[Qiu & Yu, arXiv:2401.xxxxx]



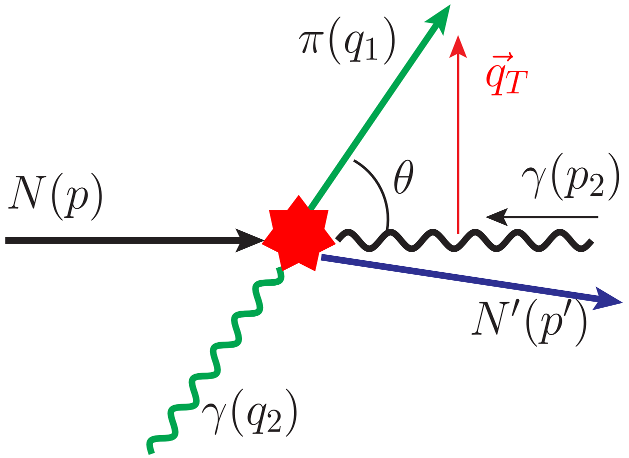
Exclusive Drell-Yan dilepton production



- **Lower rate**
- **Blind to shadow GPDs**

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

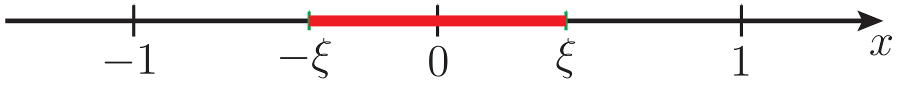
[Qiu & Yu, PRL 131 (2023) 161902]



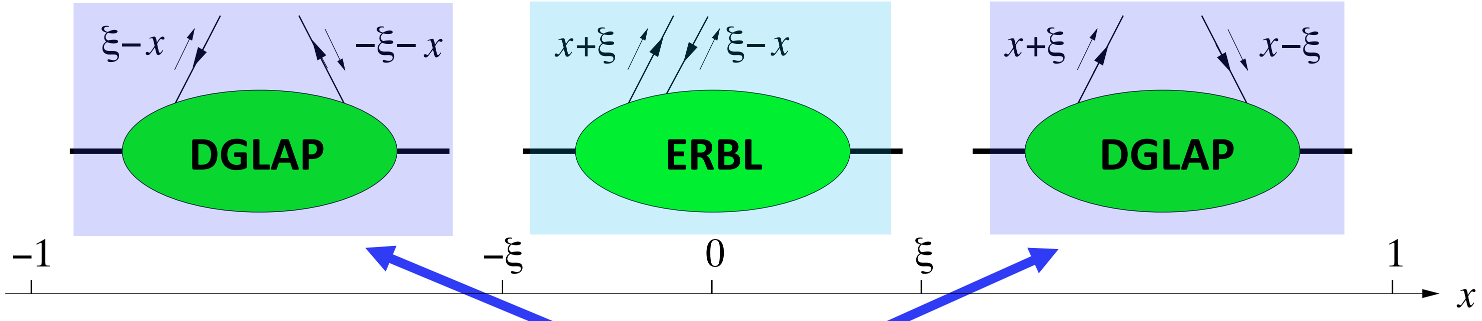
$i\mathcal{M}$ **also contains the special integral**

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

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

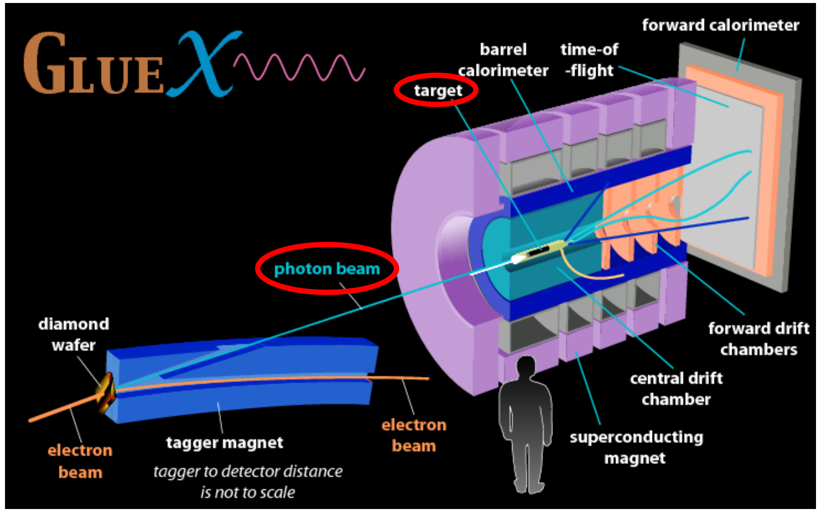


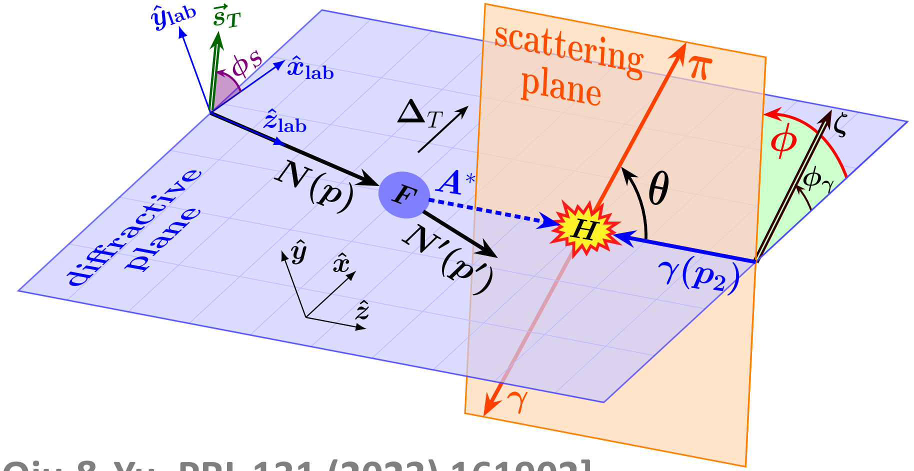
Complementary sensitivity



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

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





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

Polarization asymmetries

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

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

$$\Sigma_{UU} = |\mathcal{M}_+^{[\tilde{H}]}|^2 + |\mathcal{M}_-^{[\tilde{H}]}|^2 + |\widetilde{\mathcal{M}}_+^{[H]}|^2 + |\widetilde{\mathcal{M}}_-^{[H]}|^2,$$

$$A_{LL} = 2\,\Sigma_{UU}^{-1}\,\mathrm{Re}\left[\mathcal{M}_+^{[\tilde{H}]}\widetilde{\mathcal{M}}_+^{[H]*} + \mathcal{M}_-^{[\tilde{H}]}\widetilde{\mathcal{M}}_-^{[H]*}\right],$$

$$A_{UT} = 2\,\Sigma_{UU}^{-1}\,\mathrm{Re}\left[\widetilde{\mathcal{M}}_+^{[H]}\widetilde{\mathcal{M}}_-^{[H]*} - \mathcal{M}_+^{[\tilde{H}]}\mathcal{M}_-^{[\tilde{H}]*}\right],$$

$$A_{LT} = 2\,\Sigma_{UU}^{-1}\,\mathrm{Im}\left[\mathcal{M}_+^{[\tilde{H}]}\widetilde{\mathcal{M}}_-^{[H]*} + \mathcal{M}_-^{[\tilde{H}]}\widetilde{\mathcal{M}}_+^{[H]*}\right].$$

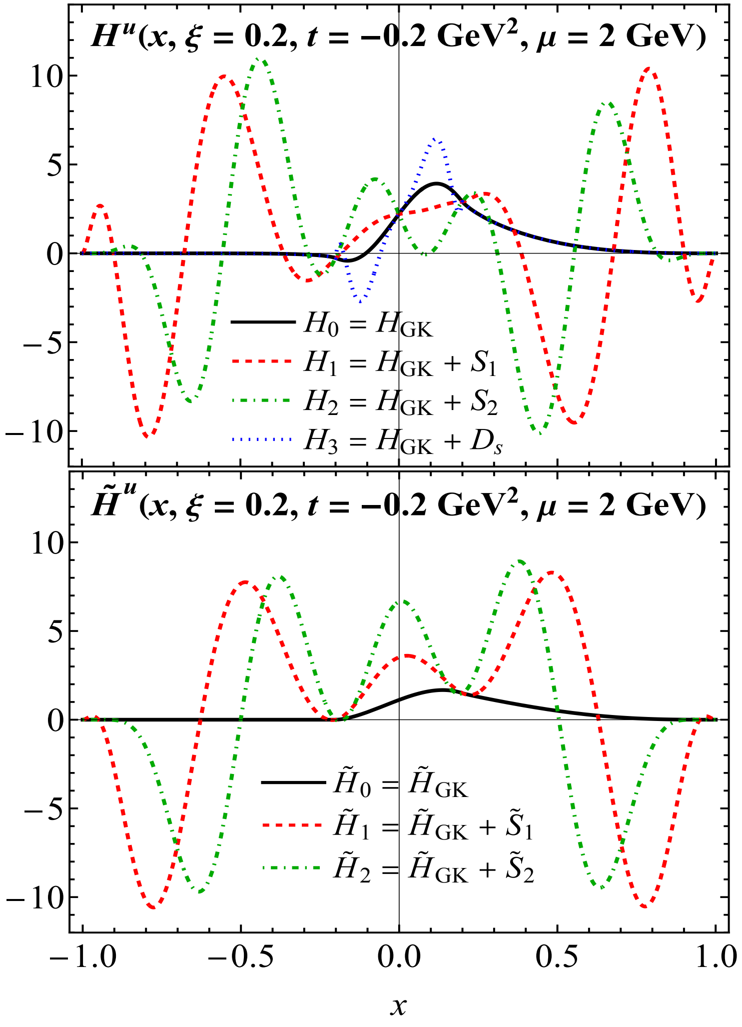
Neglecting: (1) E and $\widetilde{E}$; (2) gluon channel

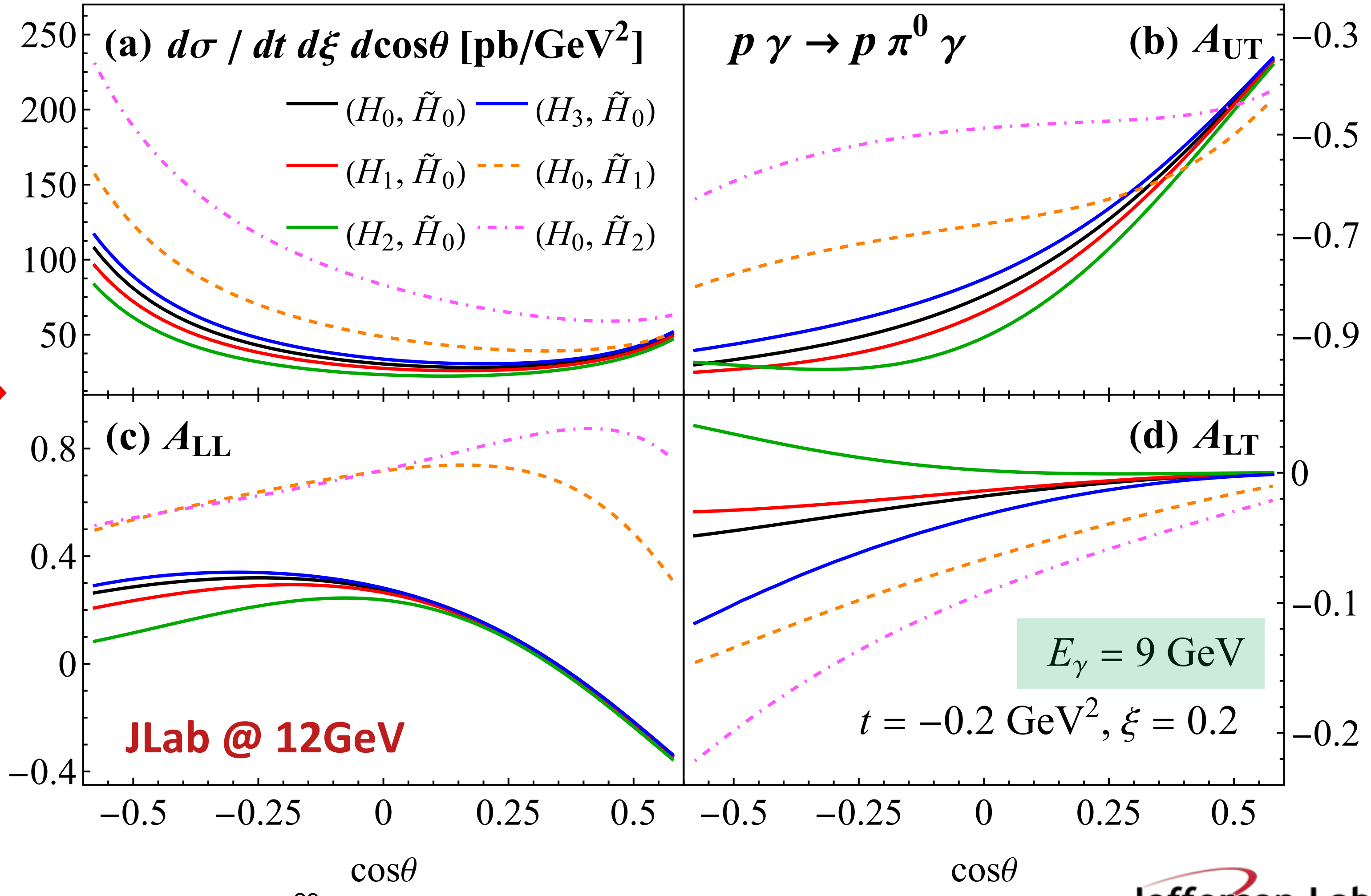
Enhanced x-sensitivity: (2) γ-π pair photoproduction

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

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Goloskokov, Kroll, `05, `07, `09
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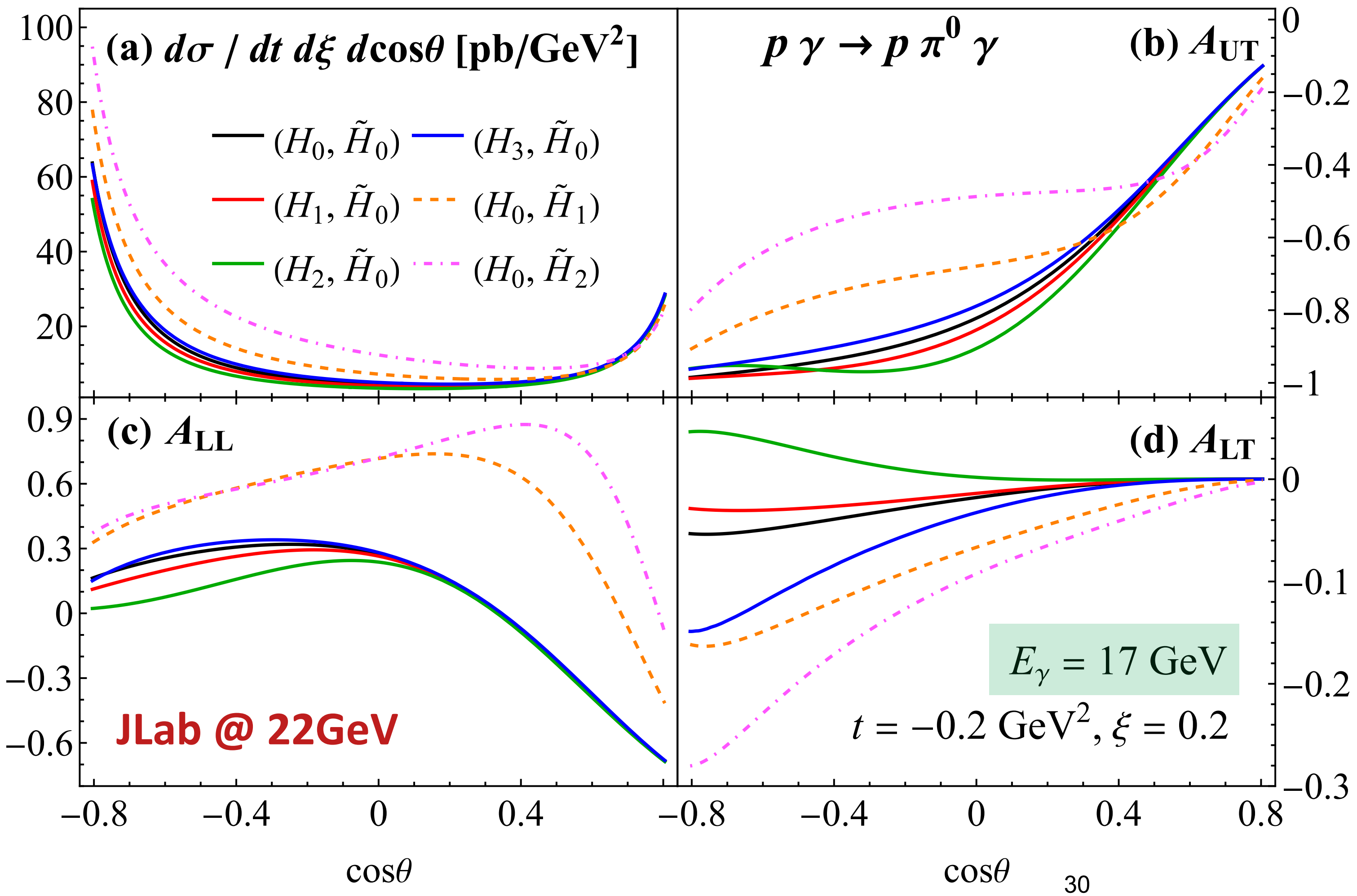
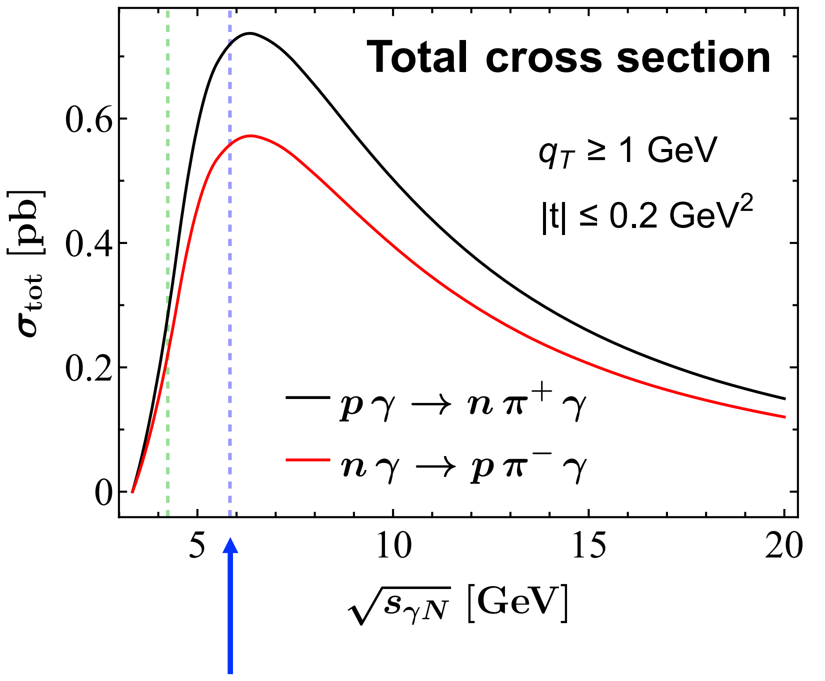


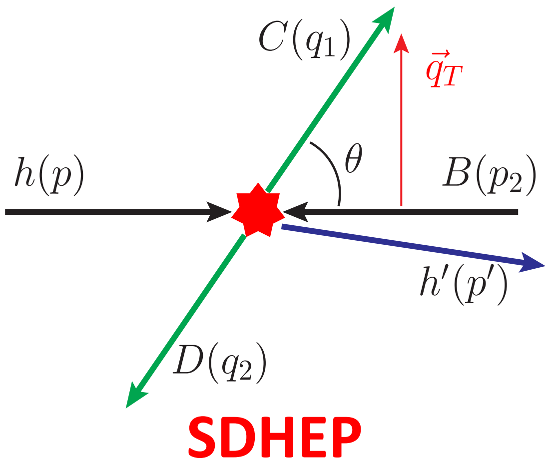


JLab @ 22GeV [arXiv:2306.09360]

Summary

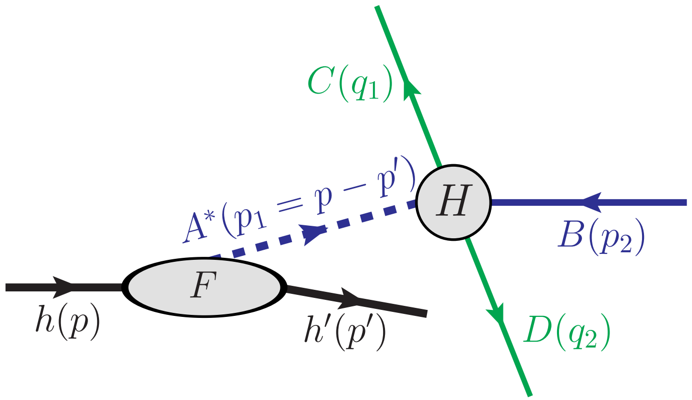
❑ Single Diffractive Hard Exclusive Processes (SDHEP)

- **Systematic factorization.**
- **Roadmap for known and more new processes!**



❑ GPD x dependence is challenging

- **Multi-processes, multi-observables approach**
- **Moment sensitivity is not sufficient**
- **Enhanced sensitivity**
- **JLab Hall D (also other halls and EIC, with good controls of quasi-real photon beams)**



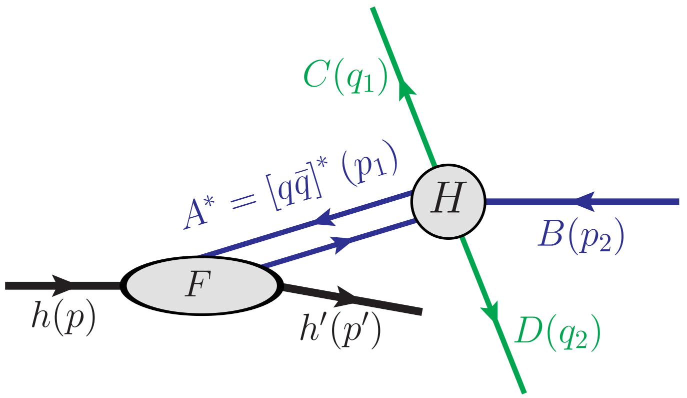
A long but exciting way to go!

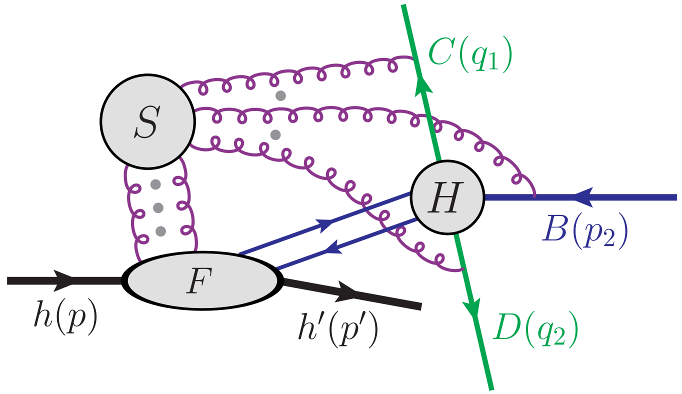
Thank you!

BACK UP

SDHEP: two-stage paradigm and factorization

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





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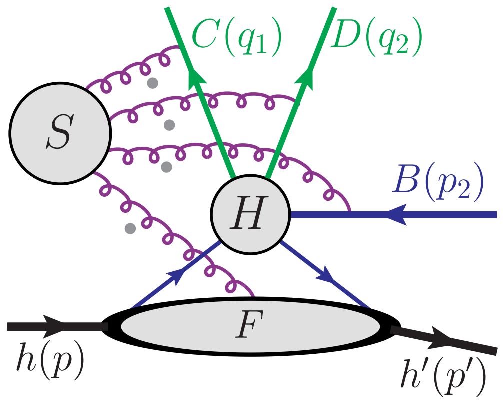
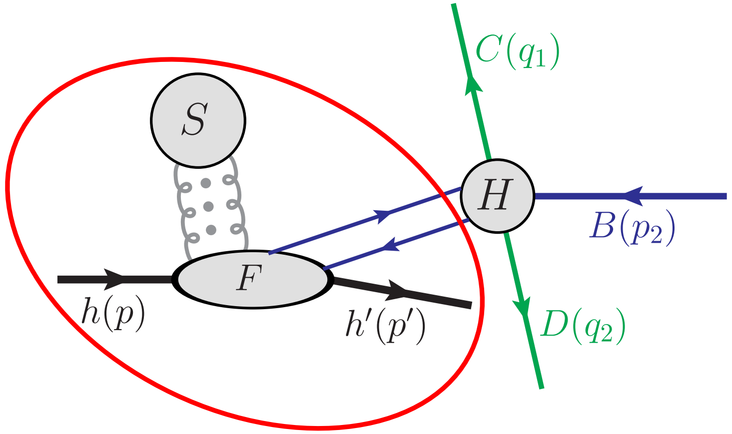
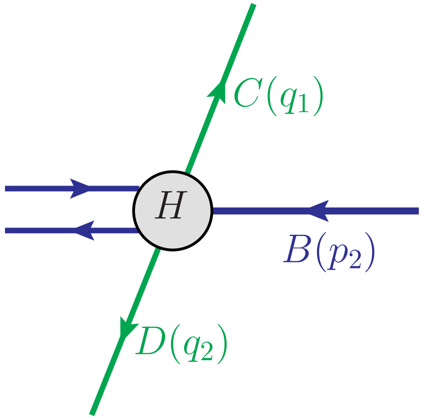


ERBL region: $[q\bar{q}']$ ~ meson **DGLAP region: Glauber pinch**

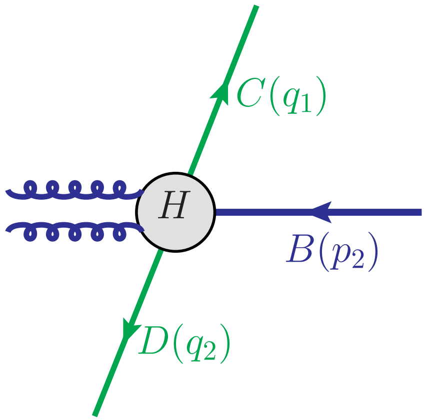
Soft gluons cancel when coupling to (color-neutral) mesons!



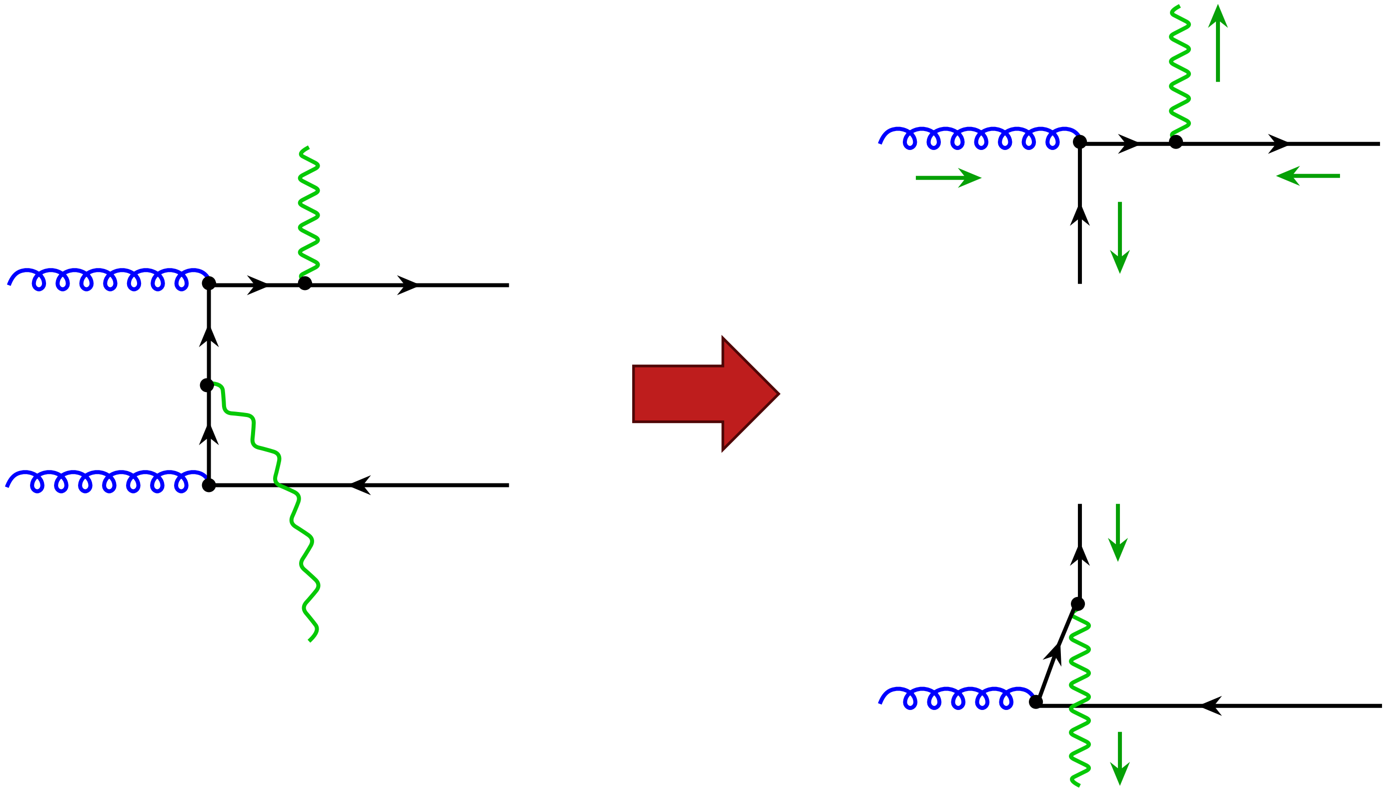
GPD $\otimes$



or



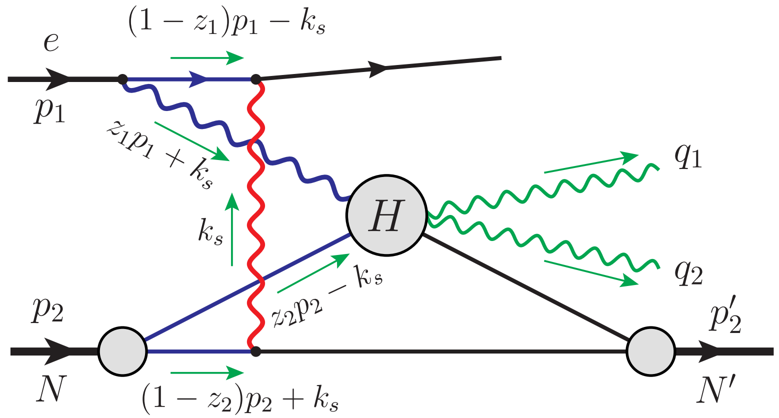
Factorization of gluon channel



- **Perturbative divergence occurs at endpoint: no phase space**
- **Regulated by a finite parton transverse momentum**
- **Collinear factorization artifact**

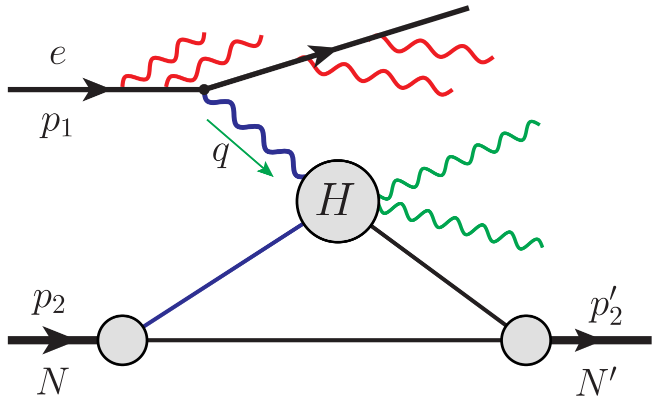
Photoproduction at EIC?

❑ Theoretical challenge: double diffractive factorization?



Both k_s^+ and k_s^- are pinched in Glauber region! ➡ **QED pinch: violates factorization**

❑ Experimental challenge: how "exclusive" can one go?

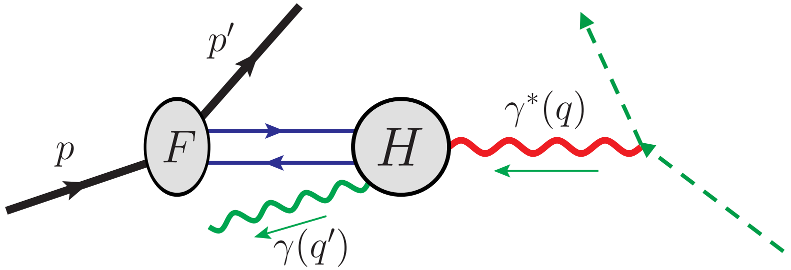


- **Electron scattering induces photon radiation.**
- **Exclusive processes could occur only in QCD due to color singlet nature of the hadron.**

A consistent theoretical formalism (& applicable experimental approach) is still unclear now.

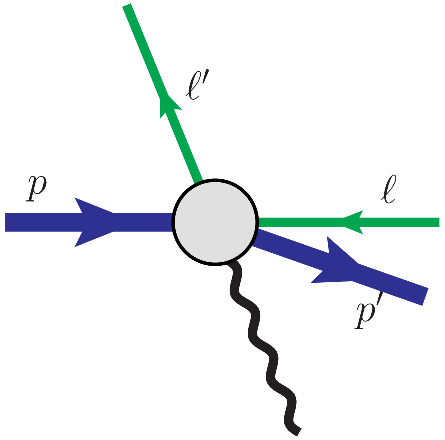
How to *think* about the GPD processes?

DVCS in Breit frame



- **Hard scale Q manifest**
- **Cannot put Bethe-Heitler process in a coherent framework**

DVCS in lab frame



- **Hard scale q_T**