Gamma + Meson Photoproduction for Extracting GPDs

- ❑ **Explore Hadron's Partonic Structure without Breaking it – GPDs!**
- ❑ **Why GPD's x-dependence is important, but, hard to measure?**
- ❑ **Single Diffractive Hard Exclusive Processes (SDHEP) for Extracting GPDs**
- ❑ **Gamma + Meson Photonproduction for extracting GPDs**
- ❑ **Summary and Outlook**

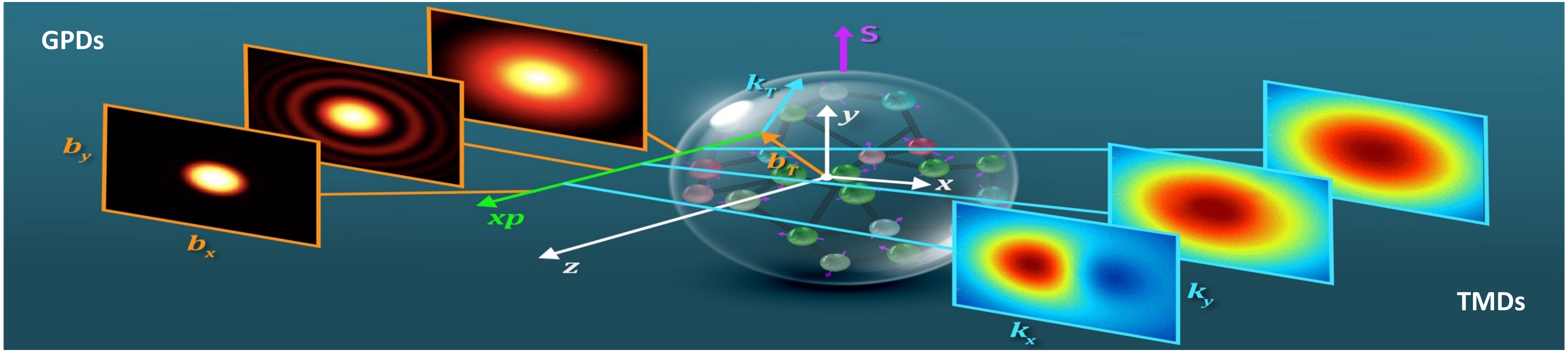
In collaboration with N. Sato, Z. Yu, …
See also talk by Z. Yu later tomorrow

Jianwei Qiu
Jefferson Lab, Theory Center

Explore Hadron's Partonic Structure without seeing quarks/gluons directly

- 3D hadron structure:

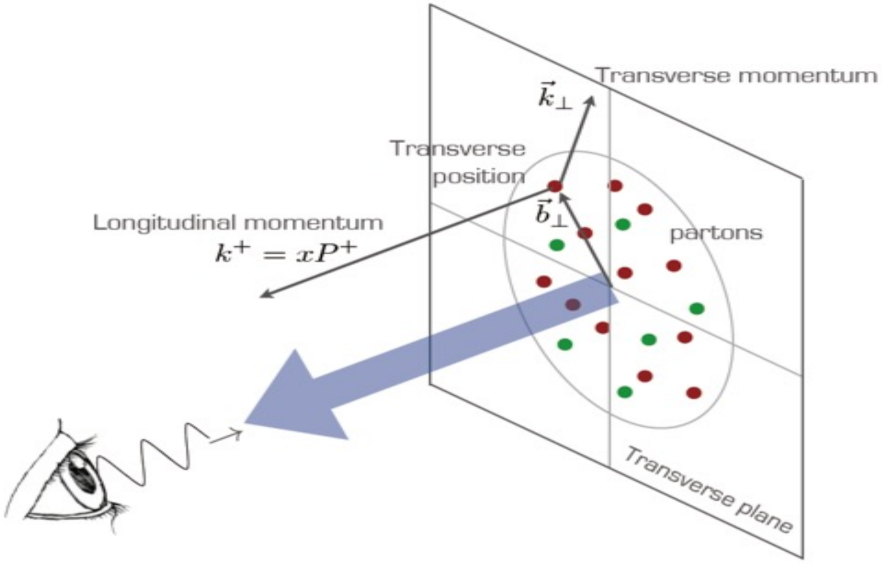
NO quarks and gluons can be seen in isolation!



- Need new observables with two distinctive scales:

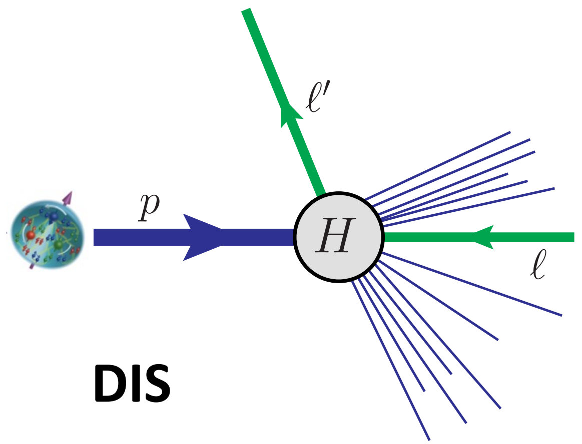
$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\rm QCD}$$

- Hard scale: Q_1 to localize the probe to see the particle nature of quarks/gluons
- "Soft" scale: Q_2 to be more sensitive to the emergent regime of hadron structure ~ 1/fm

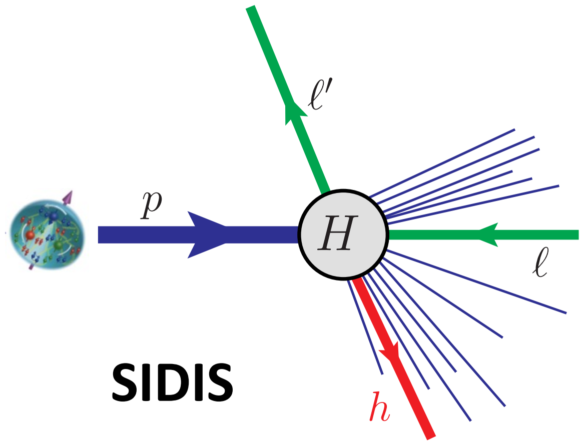


Partonic Structure with or without Breaking the Hadron

Inclusive scattering

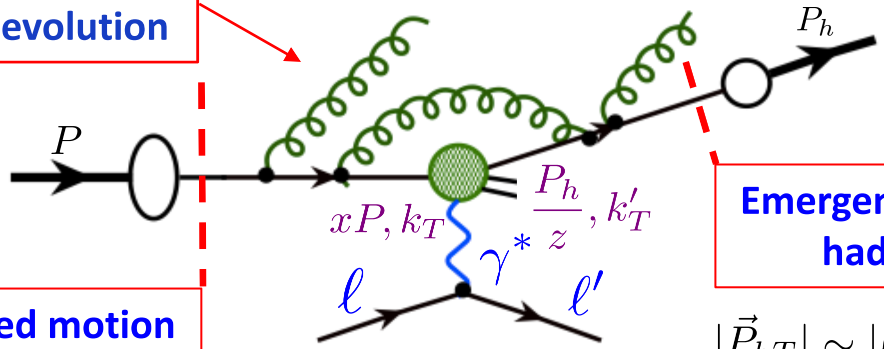


DIS



SIDIS

Gluon shower
– QCD evolution



Confined motion

Emergence of a hadron
hadronization

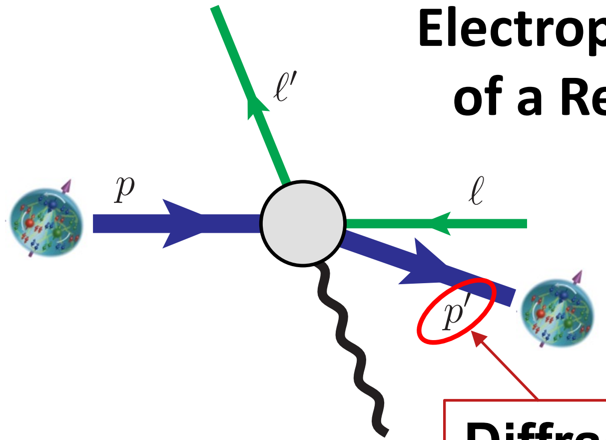
$$|\vec{P}_{hT}| \sim |\vec{\ell}'_T| \gg |\vec{P}_{hT} + \vec{\ell}'_T|$$

$$e + P \to e + h + X$$

Measured k_T of TMDs =\= the *confined* motion inside the hadron!

Exclusive diffraction

Electroproduction of a Real Photon

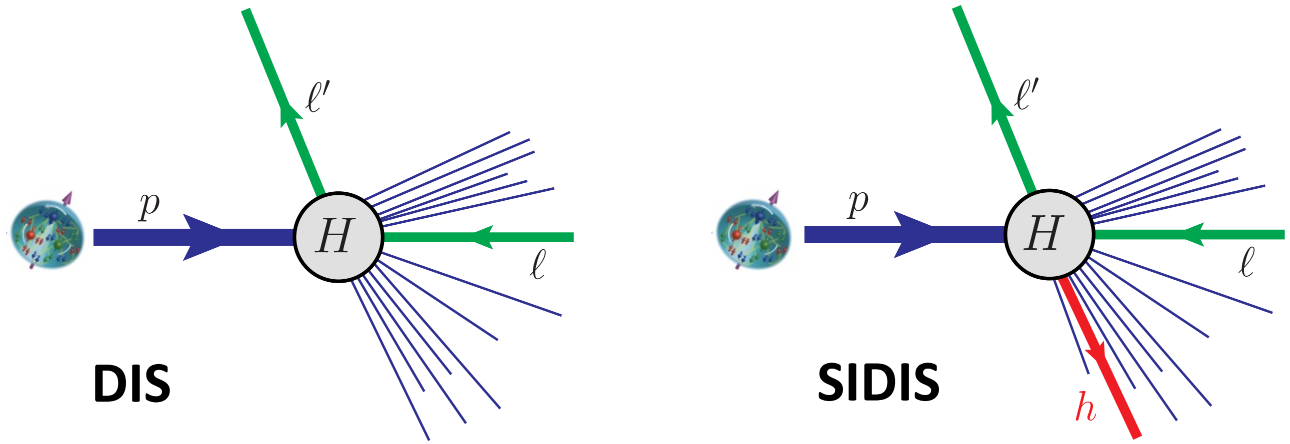


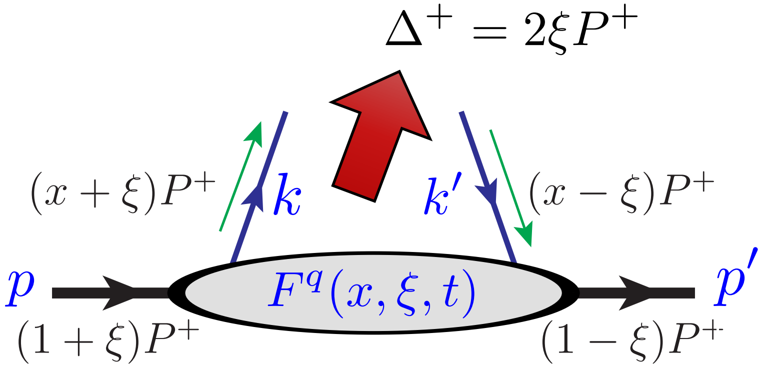
Diffraction

$$Q^2 = -(\ell - \ell')^2 \gg -(p - p')^2 = -t$$

Partonic Structure with or without Breaking the Hadron

Inclusive scattering



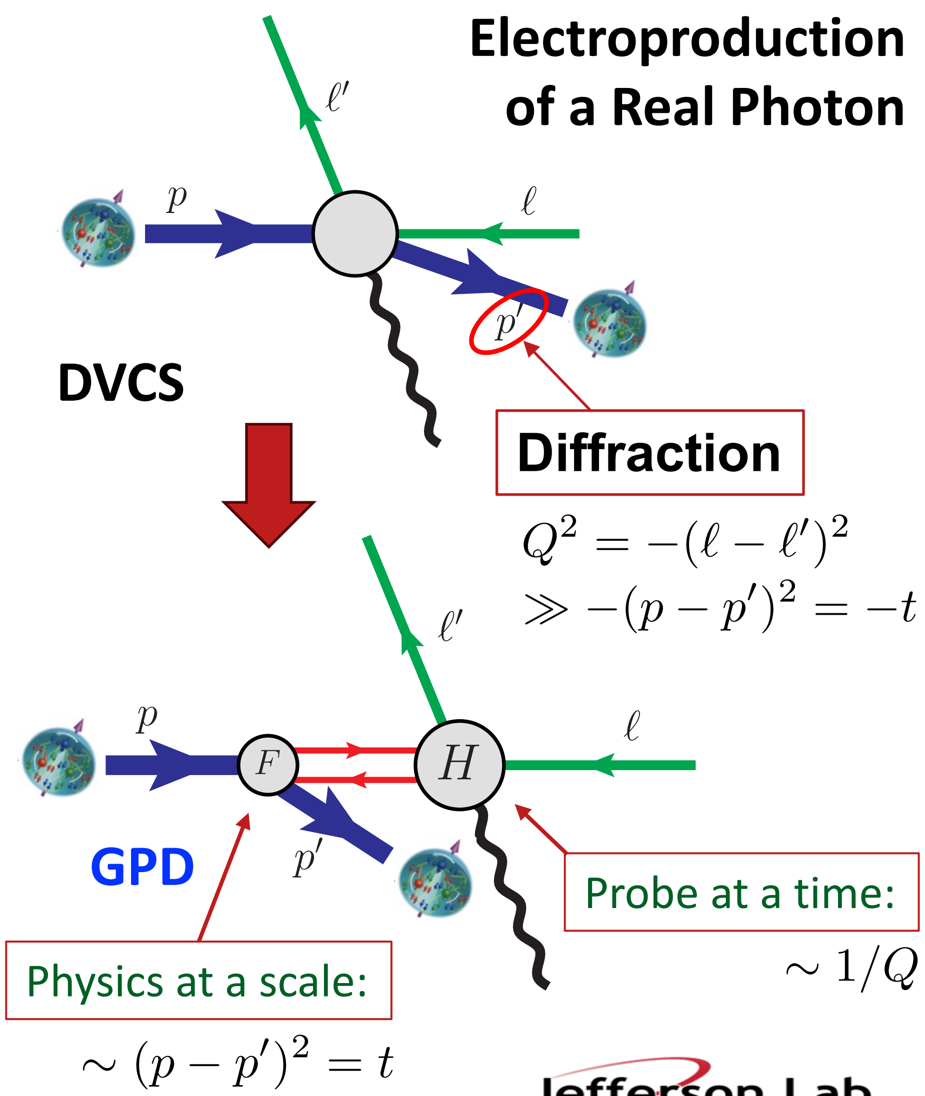


$$F^q(x,\xi,t) = \int \frac{\mathrm{d}z^-}{4\pi} e^{-ixP^+z^-} \langle p'|\bar{q}(z^-/2)\gamma^+ q(-z^-/2)|p\rangle$$

$$\widetilde{F}^q(x,\xi,t) = \int \frac{\mathrm{d}z^-}{4\pi} e^{-ixP^+z^-} \langle p'|\bar{q}(z^-/2)\gamma^+\gamma_5 q(-z^-/2)|p\rangle$$

FAC

Exclusive diffraction



Generalized Parton Distributions (GPDs)

D. Müller, D. Robaschik, B. Geyer, F.-M. Dittes, J. Hořejši, *Fortsch. Phys.* 42 (1994) 101

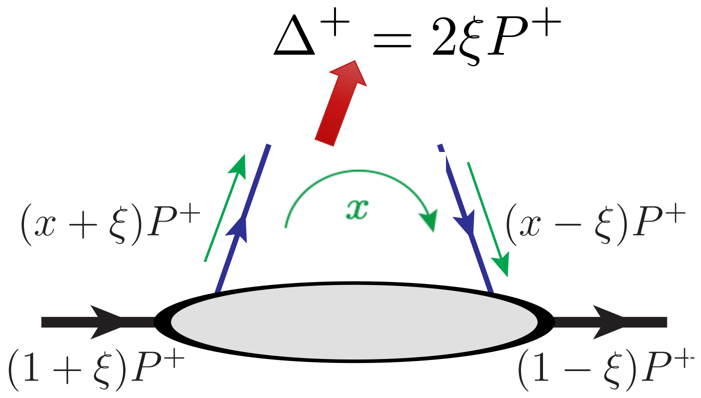
❑ Definition:

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

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

$$\widetilde{F}^q(x,\xi,t) = \int \frac{\mathrm{d}z^-}{4\pi} e^{-ixP^+z^-} \langle p'|\bar{q}(z^-/2)\gamma^+\gamma_5 q(-z^-/2)|p\rangle$$

$$= \frac{1}{2P^+}\left[\widetilde{H}^q(x,\xi,t)\,\bar{u}(p')\,\gamma^+\gamma_5 u(p) - \widetilde{E}^q(x,\xi,t)\,\bar{u}(p')\,\frac{\gamma_5\Delta^+}{2m}u(p)\right].$$



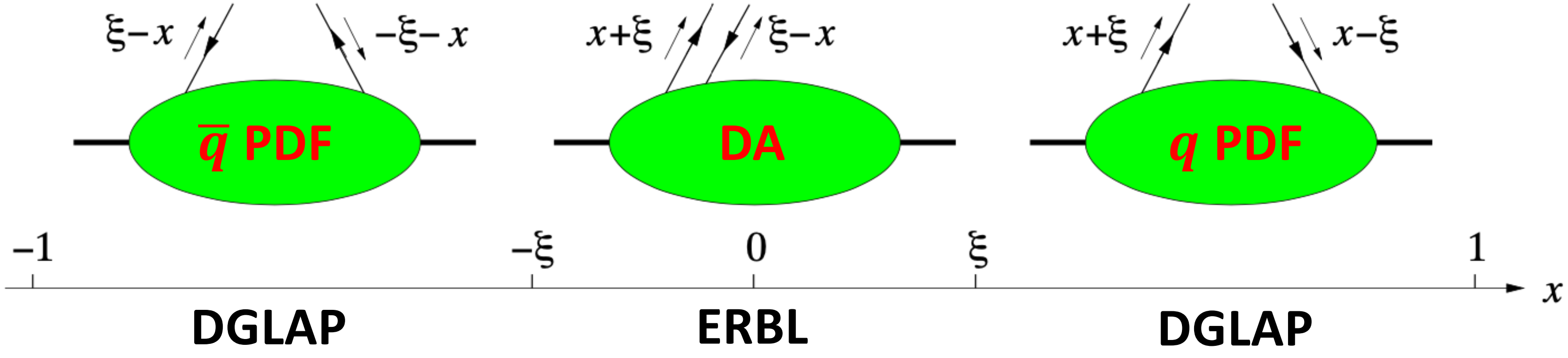
$$P^+ = \frac{p^+ + p'^+}{2}$$

$$\Delta = p - p' \qquad t = \Delta^2$$

❑ Combine *PDF* and *Distribution Amplitude (DA)*:

Forward limit $\xi = t = 0$ **:** $\quad H^q(x,0,0) = q(x), \quad \tilde{H}^q(x,0,0) = \Delta q(x)$

Similar definition for gluon GPDs



GPDs depend on the choice of "+" component for given p and p' !

GPDs and Hadron Structure

- **Partonic Properties – 3D Femtography (F.T. of GPDs):**

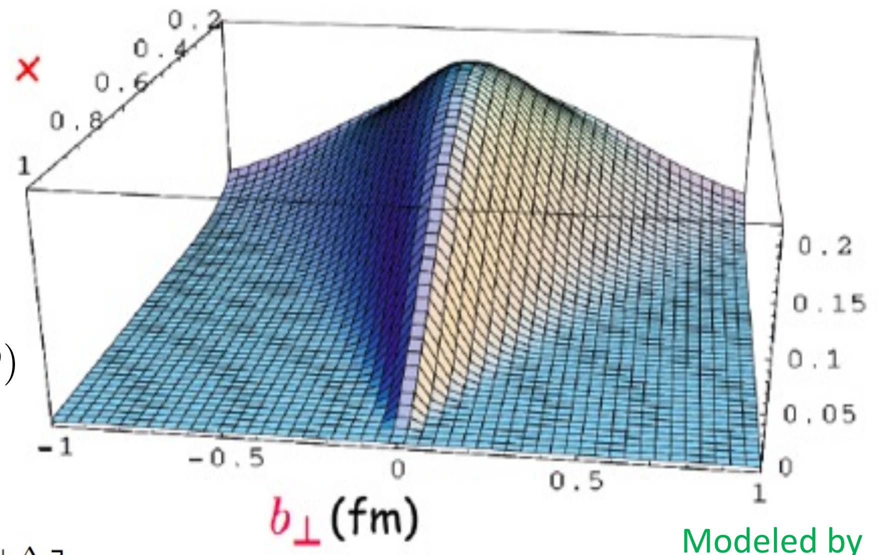
$$q(x, b_\perp, Q) = \int d^2\Delta_\perp e^{-i\Delta_\perp \cdot b_\perp} H_q(x, \xi = 0, t = -\Delta_\perp^2, Q)$$

➡ **Quark density in** $\mathrm{d}x\,\mathrm{d}^2\boldsymbol{b}_T$ ➡

➡ **Proton radii from quark and gluon spatial density distribution,** $r_q(x)$ **&** $r_g(x)$

In slice in (x,Q) $\langle q_\perp^N \rangle \equiv \int db_\perp b_\perp^N\, q(x, b_\perp, Q)$

Tomographic image of hadron in slice of x



Modeled by M. Burkdart, 2000, 2003

- **Emergent Hadronic Properties – Moments of GPDs:**

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

QCD energy-momentum tensor

In terms of "gravitational" FFs

➡ **Angular momentum sum rule:**

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

$$i = q, g$$

➡ ***Need to know the x-dependence of GPDs to construct the proper moments!***

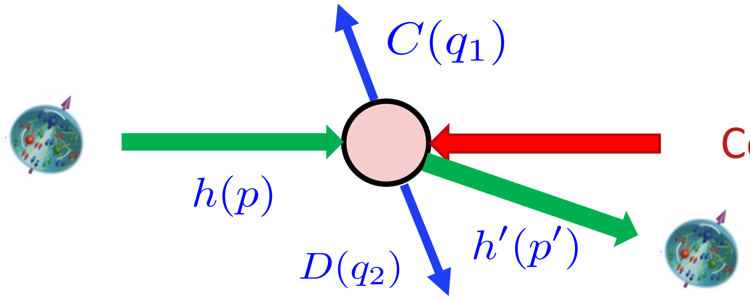
Jefferson Lab

Physical Processes to be Sensitive to GPDs?

❑ Two-scale exclusive processes – minimal $2 \to 3$ configuration:

Qiu & Yu, JHEP 08 (2022) 103
PRD 107 (2023) 014007
PRL 131 (2023) 161902

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



Colliding beam: $B(p_2) = e, \gamma, \pi$

Including: $\gamma^* \to C(q_1) + D(q_2)$ (TCS)

$J/\psi \to C(q_1) + D(q_2)$

…

Two scales: $Q^2 = -(p_2 - q_1)^2 \gg -(p - p')^2 = -t$

or $q_T \sim q_{1T} \sim q_{2T} \gg \sqrt{-t}$

Single diffractive hard exclusive process

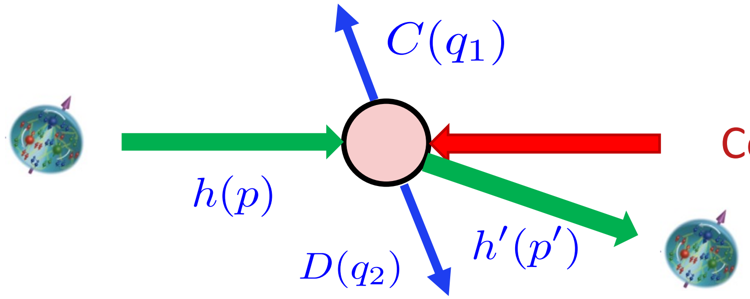
(SDHEP)

Physical Processes to be Sensitive to GPDs?

Qiu & Yu, JHEP 08 (2022) 103
PRD 107 (2023) 014007
PRL 131 (2023) 161902

- **Two-scale exclusive processes – minimal $2 \to 3$ configuration:**

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



Colliding beam: $B(p_2) = e, \gamma, \pi$

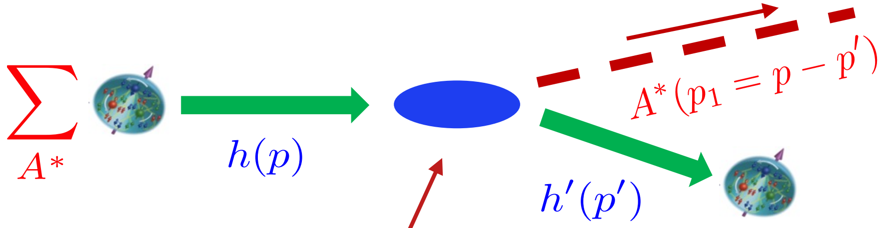
Including: $\gamma^* \to C(q_1) + D(q_2)$ (TCS)
$J/\psi \to C(q_1) + D(q_2)$
…

Two scales: $Q^2 = -(p_2 - q_1)^2 \gg -(p - p')^2 = -t$
or $q_T \sim q_{1T} \sim q_{2T} \gg \sqrt{-t}$

$\Rightarrow$ **Single diffractive hard exclusive process (SDHEP)**

- **SDHEP – Two-stage paradigm:**

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



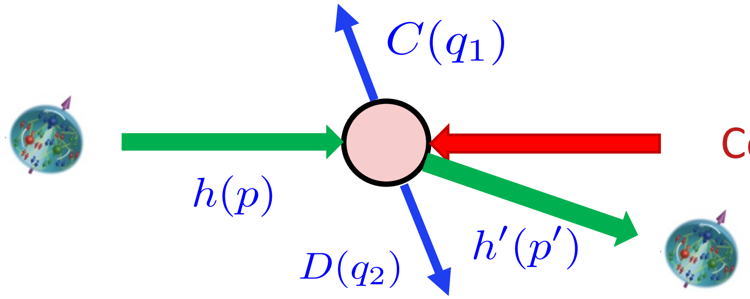
Diffractive at a scale: $\sim (p - p')^2 = t$

Physical Processes to be Sensitive to GPDs?

Qiu & Yu, JHEP 08 (2022) 103
PRD 107 (2023) 014007
PRL 131 (2023) 161902

❑ Two-scale exclusive processes – minimal $2 \to 3$ configuration:

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



Colliding beam: $B(p_2) = e, \gamma, \pi$

Including: $\gamma^* \to C(q_1) + D(q_2)$ (TCS)

$J/\psi \to C(q_1) + D(q_2)$

…

Two scales: $Q^2 = -(p_2 - q_1)^2 \gg -(p - p')^2 = -t$

or $q_T \sim q_{1T} \sim q_{2T} \gg \sqrt{-t}$

➡ **Single diffractive hard exclusive process (SDHEP)**

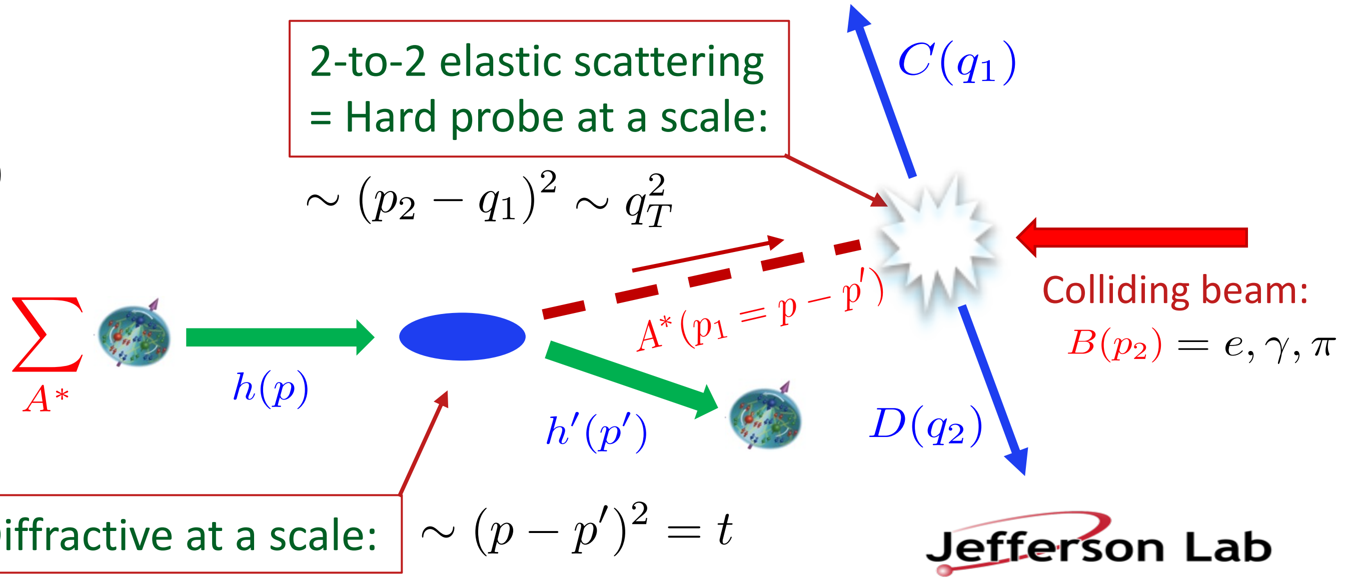
❑ SDHEP – Two-stage paradigm:

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

Necessary **condition for factorization:**

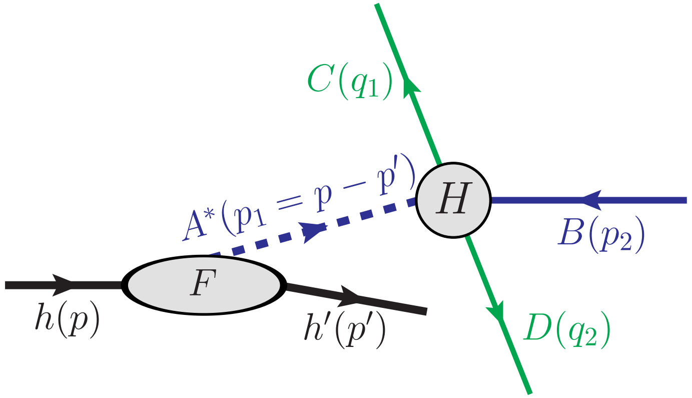
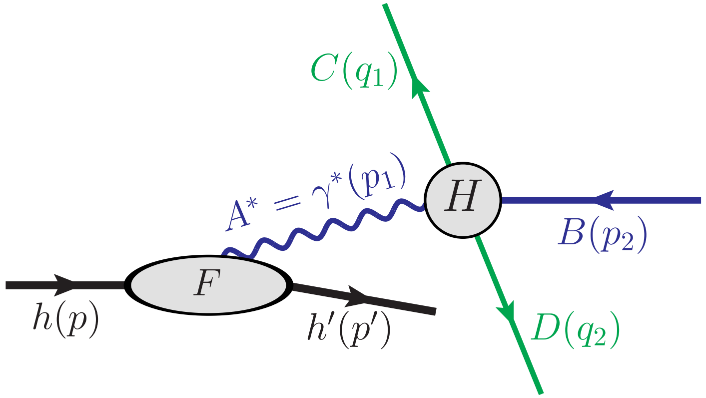
$q_T \gg \sqrt{-t} \simeq \Lambda_{\rm QCD}$

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

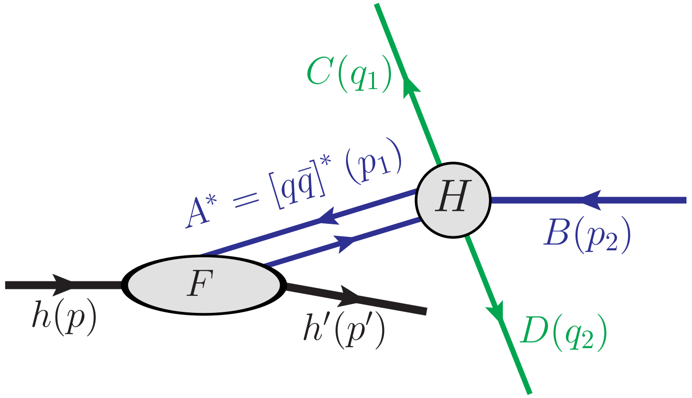
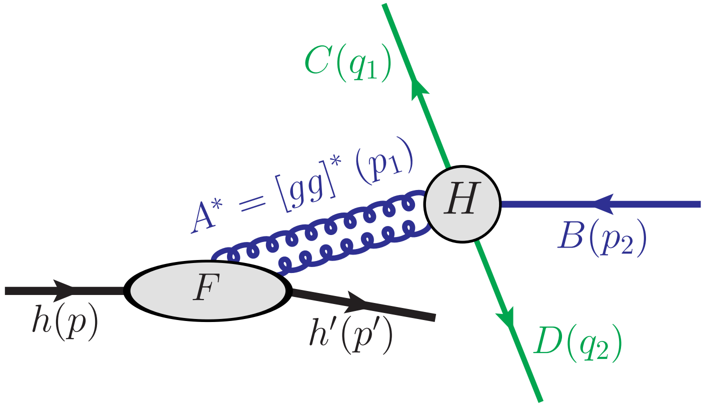


Jefferson Lab

SDHEP: Two-stage Paradigm plus Power Expansion in $\sqrt{-t}/q_T$

$\sum_{A^*}$  = 

Leading Power in $\dfrac{\sqrt{-t}}{Q}$

$+$  $+$ 

Next Leading Power in $\dfrac{\sqrt{-t}}{Q}$

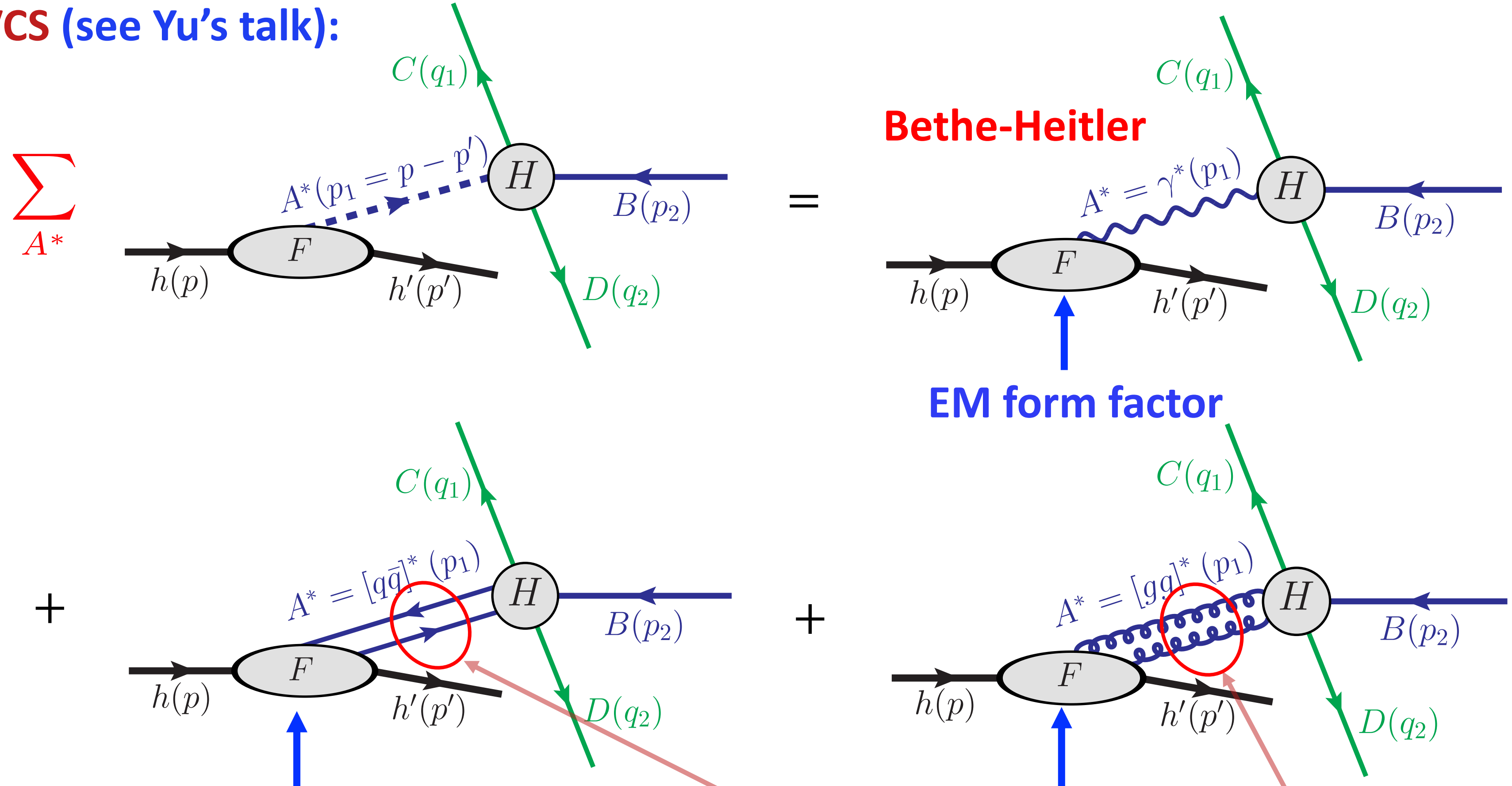
$+\cdots$

$\geq$ 3 parton connection:
further Power suppressed

Jefferson Lab

SDHEP: Two-stage Paradigm plus Power Expansion in $\sqrt{-t}/q_T$

DVCS (see Yu's talk):



Leading Power in $\frac{\sqrt{-t}}{Q}$

Next Leading Power in $\frac{\sqrt{-t}}{Q}$

Quark GPD

Gluon GPD

$+\cdots$

$\geq$ 3 parton connection: further Power suppressed

Ensured by $\sqrt{-t}/q_T \ll 1$

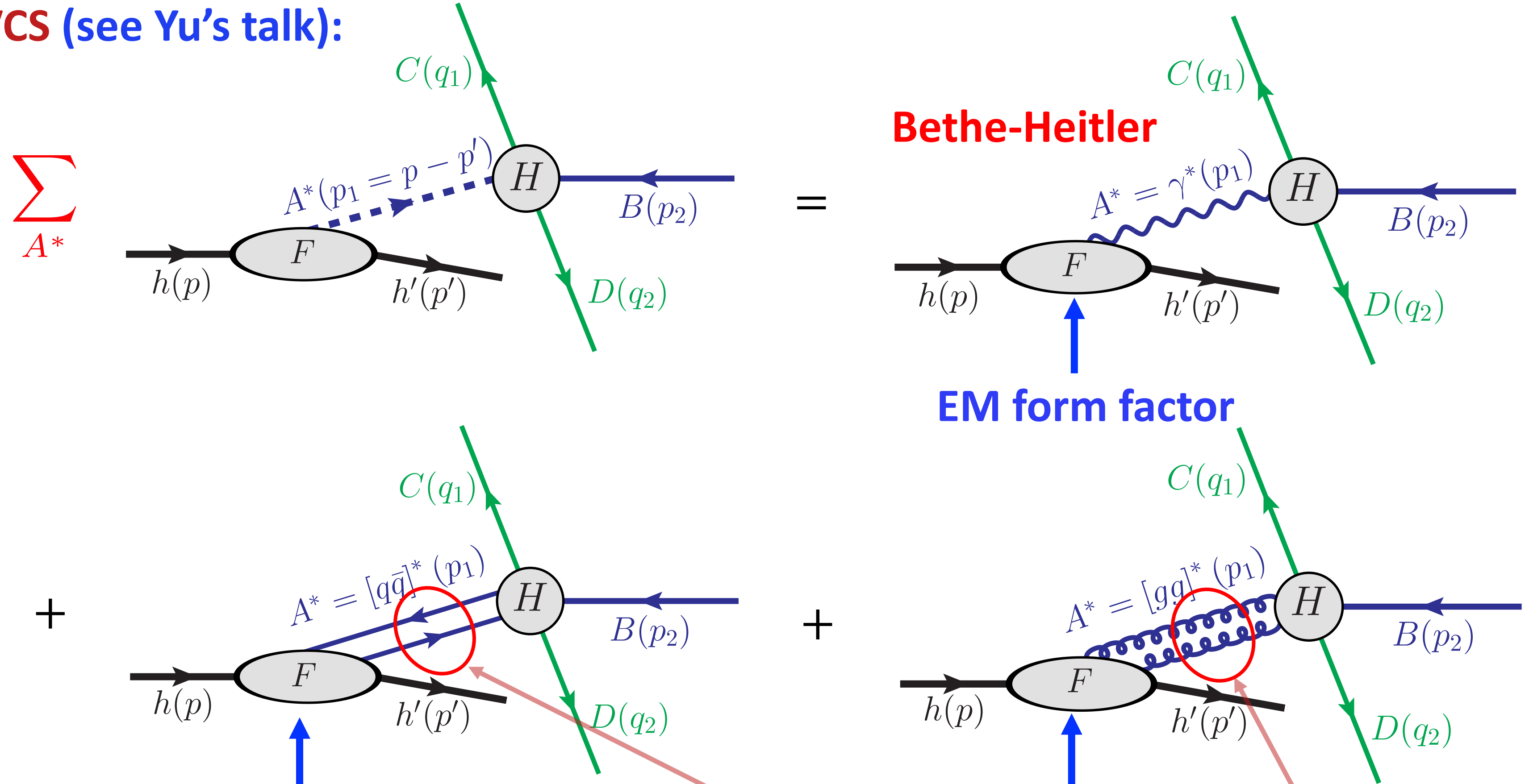
Energy $\gg$ virtuality

Factorization into GPDs

Jefferson Lab

SDHEP: Two-stage Paradigm plus Power Expansion in $\sqrt{-t}/q_T$

DVCS (see Yu's talk):



Bethe-Heitler

EM form factor

Leading Power in $\frac{\sqrt{-t}}{Q}$

Next Leading Power in $\frac{\sqrt{-t}}{Q}$

Quark GPD

Gluon GPD

$+ \cdots$

$\geq$ 3 parton connection: further Power suppressed

Ensured by $\sqrt{-t}/q_T \ll 1$

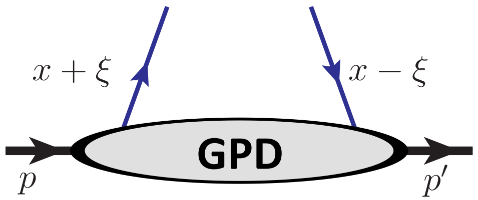
Energy $\gg$ virtuality

GPDs are defined by the quantum states of *A**

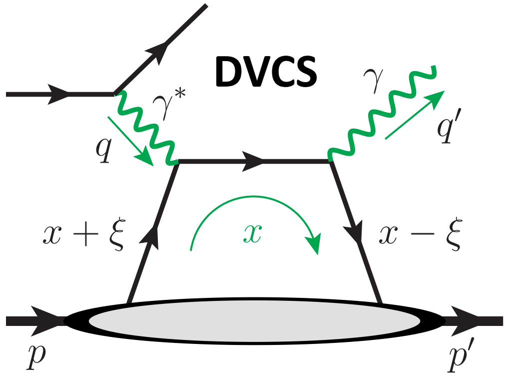
Factorization into GPDs

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

- **Amplitude nature of the exclusive processes:**



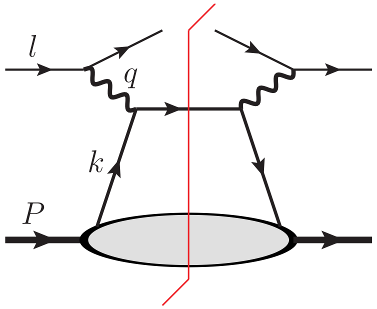
***x* ~ loop momentum**

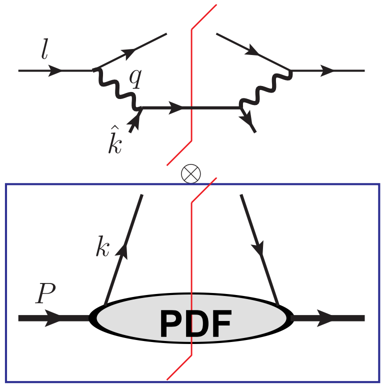


$$iM \sim \int_{-1}^{1} \mathrm{d}x\, F(x,\xi,t)\cdot C(x,\xi;Q/\mu)$$

Full range of *x*, including $x=0;\quad x=\pm\xi$

Compare with DIS



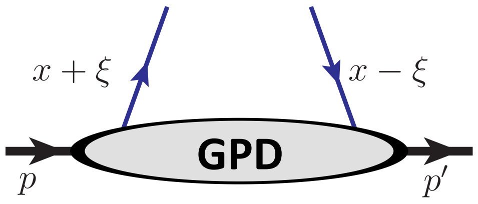


***cross section*: cut diagram**

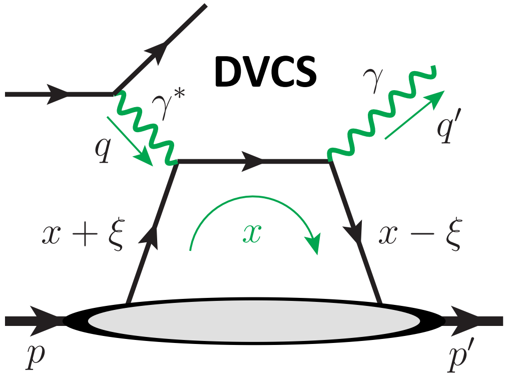
$$\sigma_{\mathrm{DIS}} \simeq \int_{x_B}^{1} \mathrm{d}x\, f(x)\,\hat{\sigma}(x/x_B)$$

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

- **Amplitude nature of the exclusive processes:**



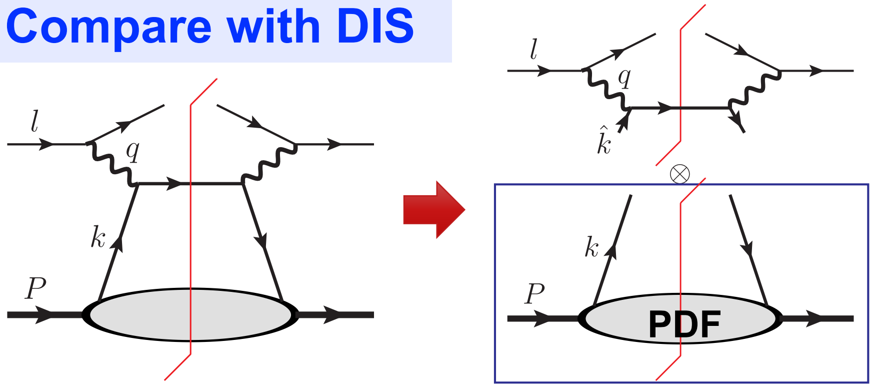
x ~ loop momentum



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

Full range of x, including $x = 0; \quad x = \pm\xi$

Compare with DIS



***cross section*: cut diagram**

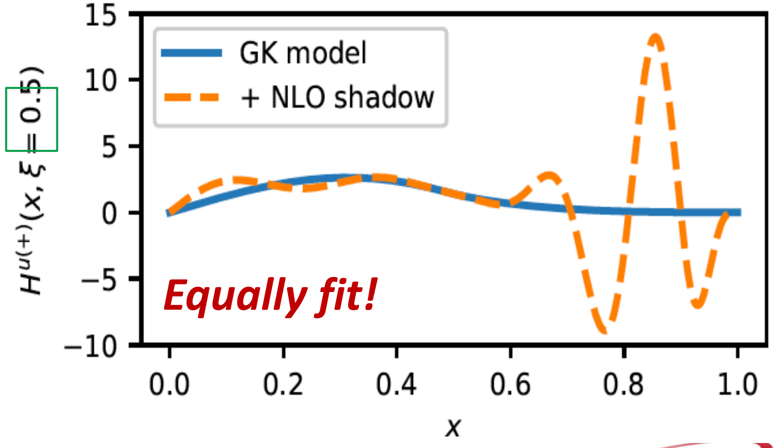
$$\sigma_{\mathrm{DIS}} \simeq \int_{x_B}^{1} \mathrm{d}x\, f(x)\, \hat{\sigma}(x/x_B)$$

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

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

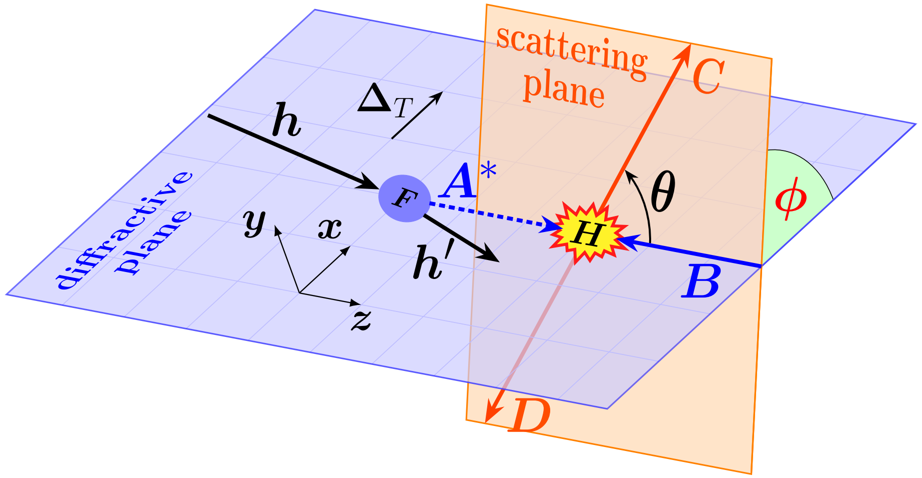
$$\Rightarrow iM \propto \int_{-1}^{1} \mathrm{d}x\, \frac{F(x,\xi,t)}{x-\xi+i\varepsilon} \equiv \text{“}F_0(\xi,t)\text{”}$$ **“moment”**

DVCS is an example



[Bertone et al. PRD `21]

Where can the SDHEP get the x-sensitivity?



- x-sensitivity ⇔ 2 → 2 hard scattering:

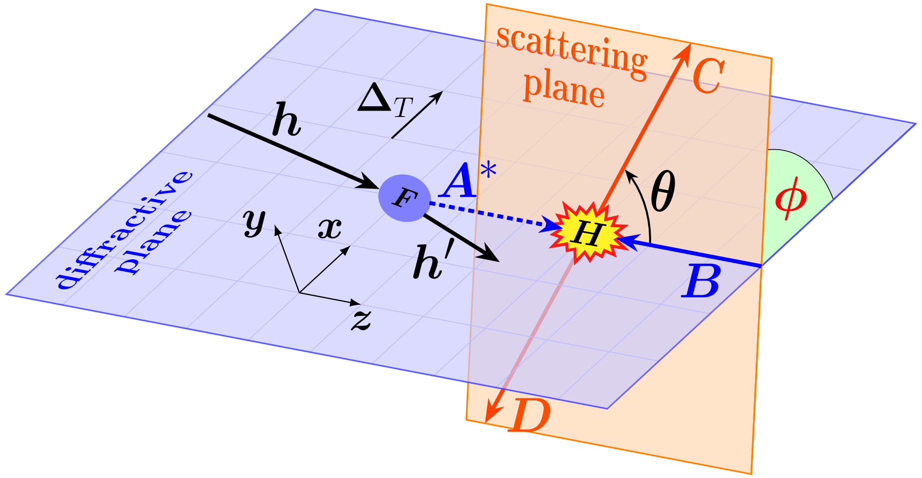
  Kinematics: (ξ, t) is fixed by $p \to p'$ and the collision axis

  1. $\hat{s} = 2\,\xi\,s\,/\,(1+\xi)$ ⬅ ξ
  2. θ or $q_T = (\sqrt{\hat{s}}/2)\,\sin\theta$ ⬌ 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]

Where can the SDHEP get the x-sensitivity?



❑ **x-sensitivity $\Leftrightarrow$ 2 $\rightarrow$ 2 hard scattering:**

Kinematics: (ξ, t) is fixed by $p \to p'$ and the collision axis

1. $\hat{s} = 2\,\xi\, s\,/\,(1+\xi)$ ⟸ ξ
2. θ or $q_T = (\sqrt{\hat{s}}/2)\sin\theta$ ⟺ 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]

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

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

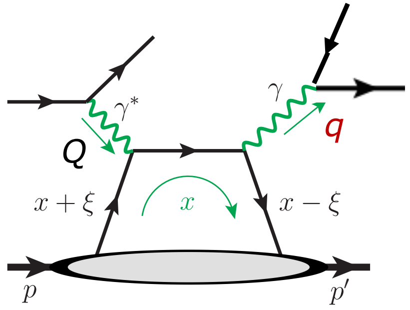
- **Enhanced sensitivity:** $\boxed{C(x;Q) \neq G(x)\cdot T(Q)}$ ⟹ $d\sigma/dQ \sim \left|C(x;Q) \otimes_x F(x,\xi,t)\right|^2$

What Kind of Process Could be Sensitive to the *x*-Dependence?

- **Create an entanglement between the internal *x* and an externally measured variable?**

$$i\mathcal{M} \propto \int_{-1}^{1} \mathrm{d}x \frac{F(x,\xi,t)}{x - x_p(\xi,q) + i\varepsilon}$$

Change external *q* to sample different part of x.



- **Double DVCS (two scales):**

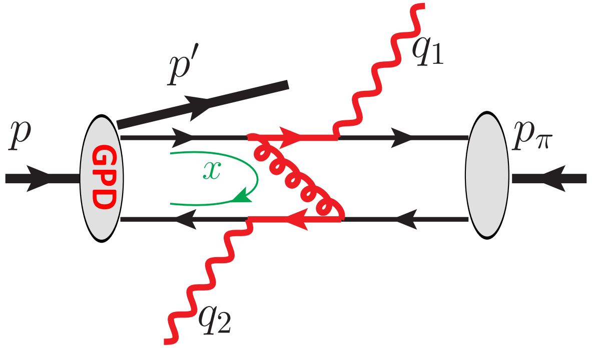
$$x_p(\xi,q) = \xi\left(\frac{1-q^2/Q^2}{1+q^2/Q^2}\right) \to \xi \quad \text{same as} \quad \text{DVCS} \quad \text{if } q \to 0$$

- **Production of two back-to-back high pT particles (say, two photons):**

$$\pi^-(p_\pi) + P(p) \to \gamma(q_1) + \gamma(q_2) + N(p')$$

Qiu & Yu
JHEP 08 (2022) 103

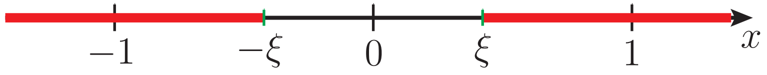
Hard scale: $q_T \gg \Lambda_{\mathrm{QCD}}$ Soft scale: $t \sim \Lambda^2_{\mathrm{QCD}}$



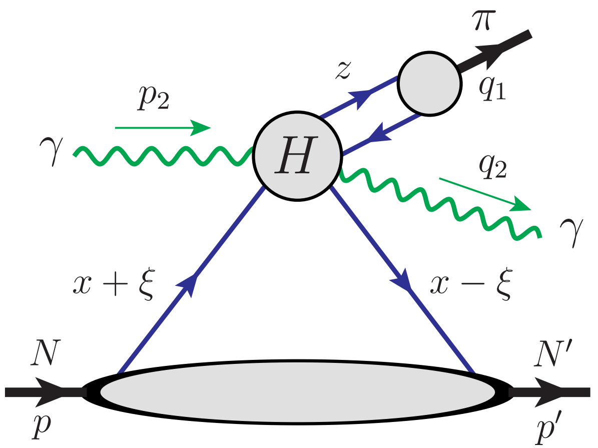
$i\mathcal{M}$ **also contains**

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

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



Gamma + Meson Exclusive Photoproduction



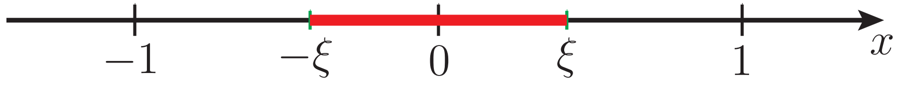
JLab Hall D

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

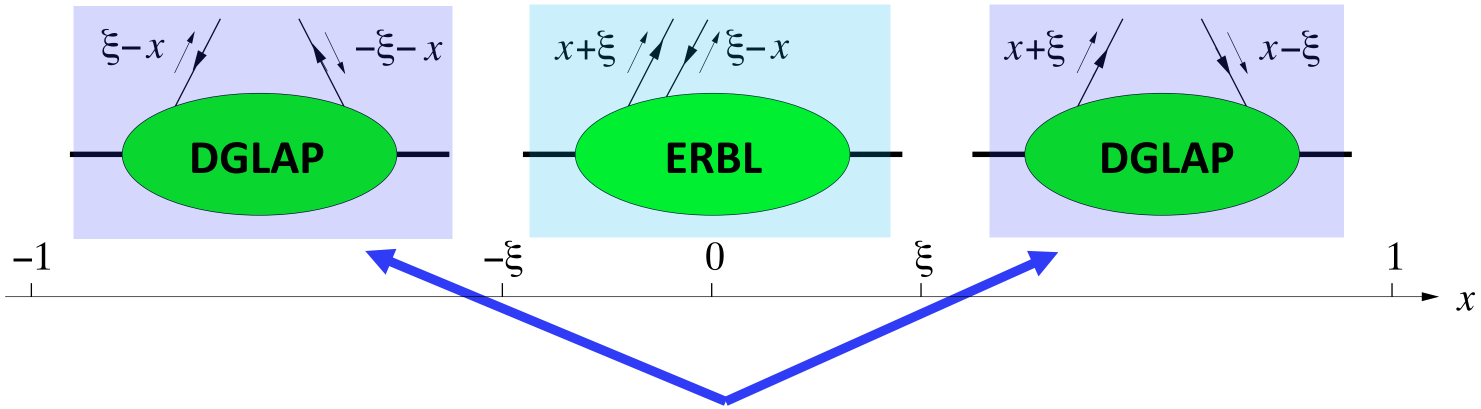
G. Duplancic et al., JHEP 11 (2018) 179
G. Duplancic et al., JHEP 03 (2023) 241
G. Duplancic et al., PRD 107 (2023), 094023
Qiu & Yu, PRD 107 (2023) 014007
Qiu & Yu, PRL 131 (2023), 161902

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

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

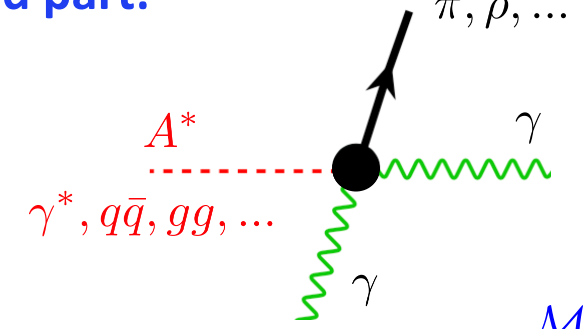


Sensitive to the ERBL region:



$N\,\pi \to N'\,\gamma\,\gamma$

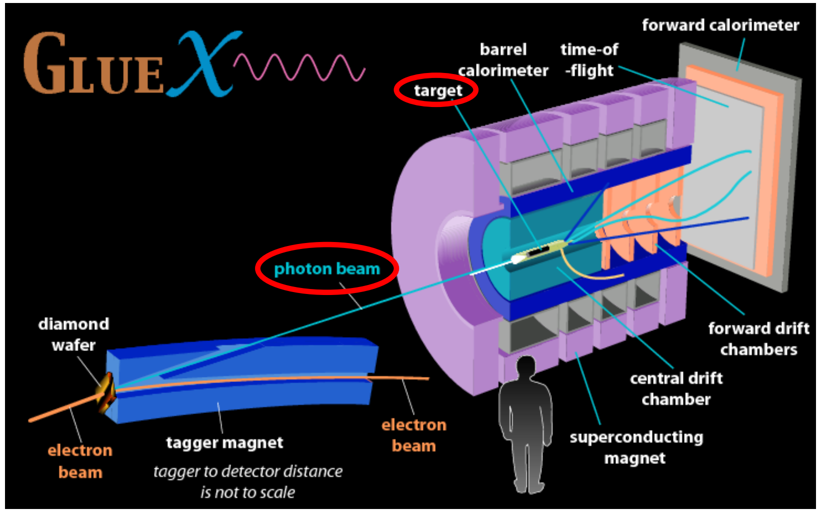
Hard part:

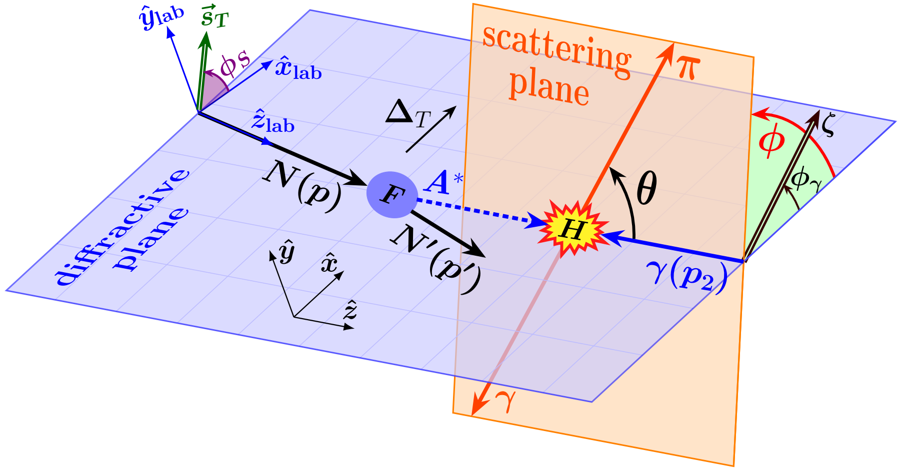


$$\mathcal{M}(q_T,\phi) \propto \sum_{A^*} e^{i(\lambda_{A^*}-\lambda_\gamma)\phi}$$

Enhanced x-Sensitivity at JLab Hall D

Qiu & Yu, PRL 131 (2023), 161902





❑ Polarization asymmetries:

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

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

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

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

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

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

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

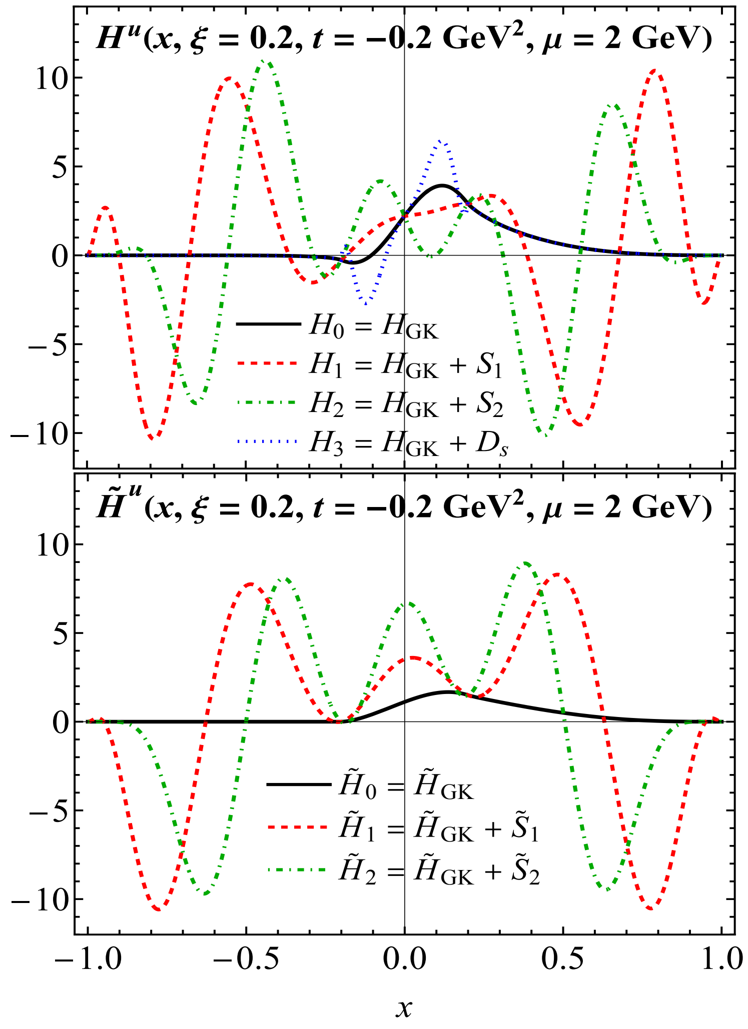
Jefferson Lab

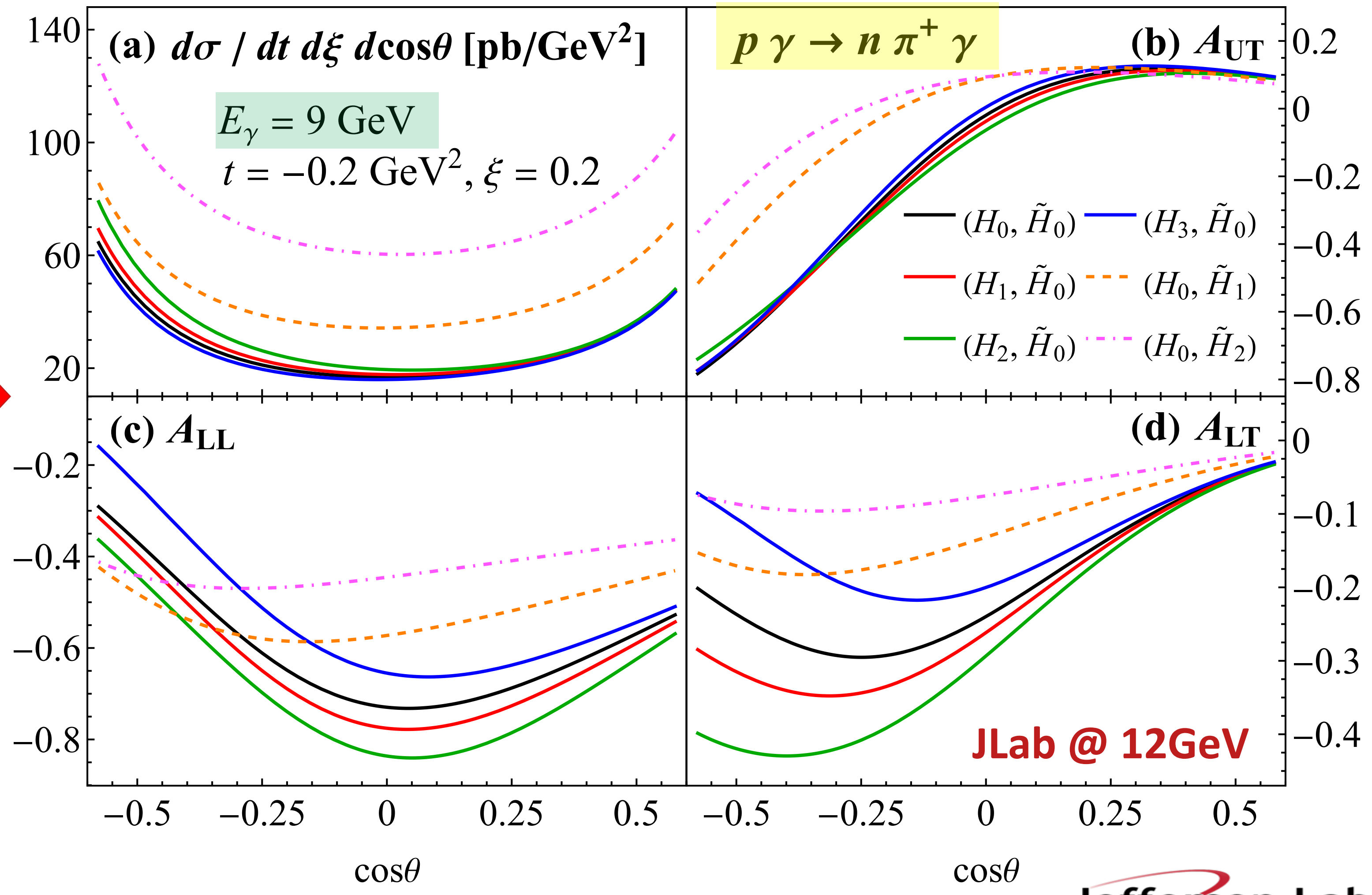
Enhanced x-Sensitivity at JLab Hall D

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



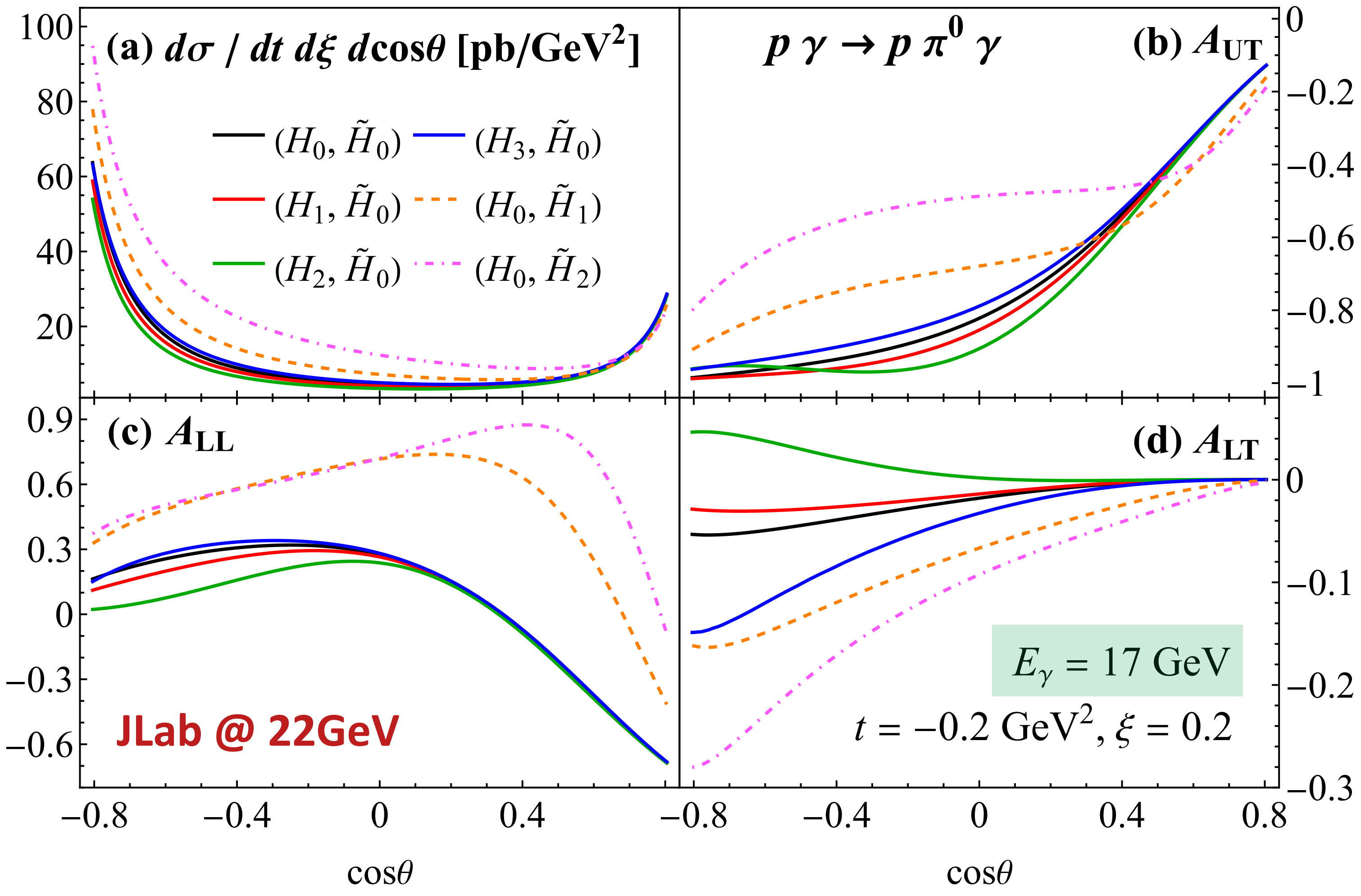


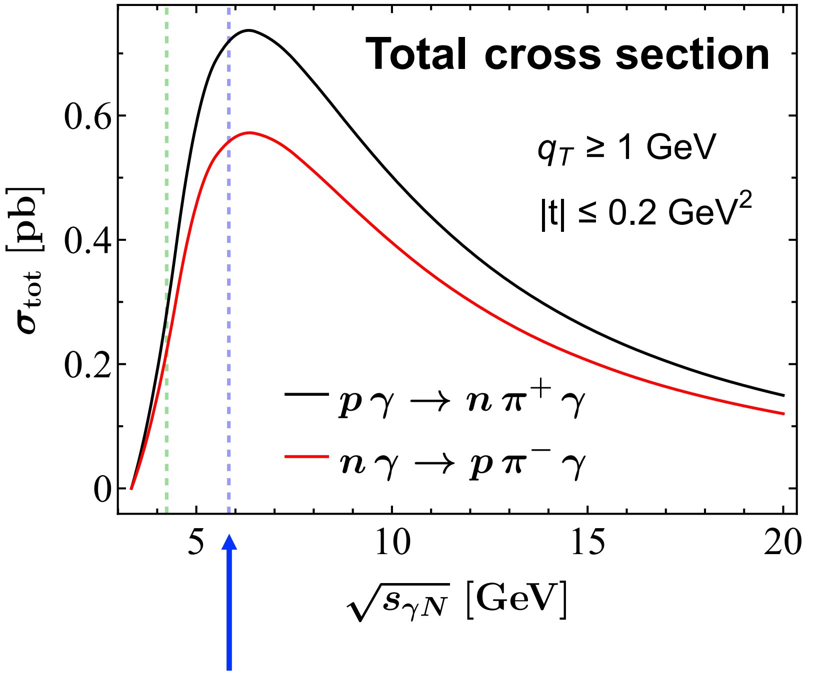
Jefferson Lab

Enhanced x-Sensitivity at JLab Hall D with the upgraded 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
Qiu & Yu, \`23





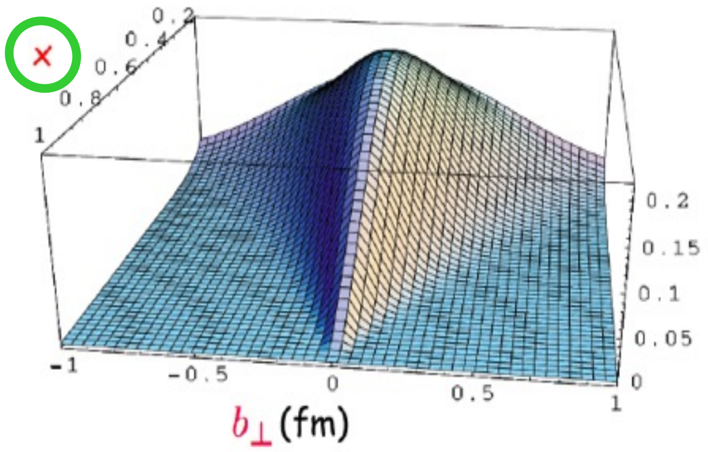
JLab @ 22GeV

A. Accardi et al. [arXiv:2306.09360]

Summary and Outlook

- GPDs are fundamental, carrying rich information on:
  - Tomographic images of confined quarks and gluons
  - Underline dynamics of hadronic properties

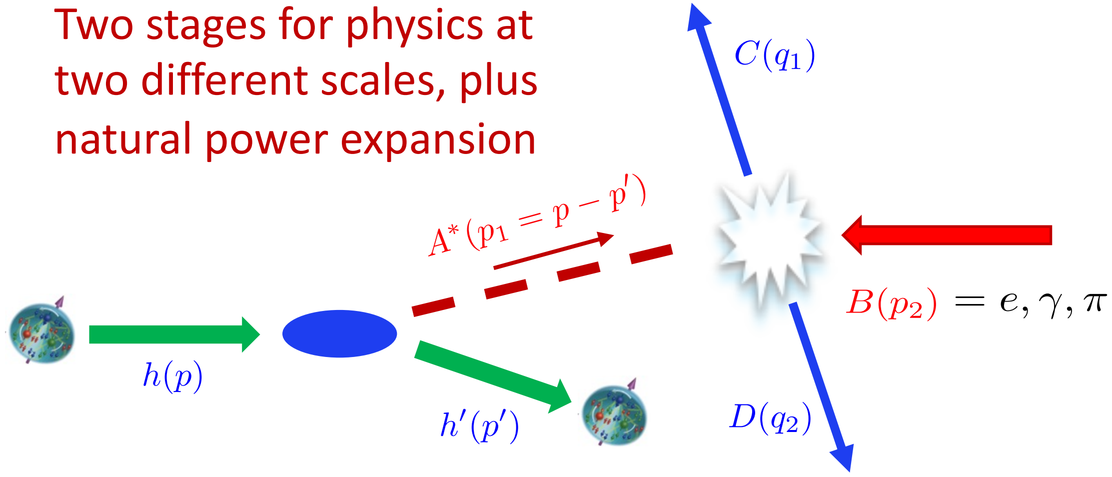
3D image



- The $2 \to 3$ SDHEPs are necessary physical processes for extracting of GPDs

SDHEPs:

Two stages for physics at two different scales, plus natural power expansion



- With $p \neq p'$, the choice of "+" component is not unique
- SDHEP frame for all known SDHEPs provides a unique way to define the GPDs, necessary for Global analyses
- Need to identify more factorizable SDHEPs for extracting GPDs through Global analyses

- Gamma + Meson exclusive photoproduction at Hall D

  is a valuable process with good sensitivity to GPDs' x-dependence

Thanks!