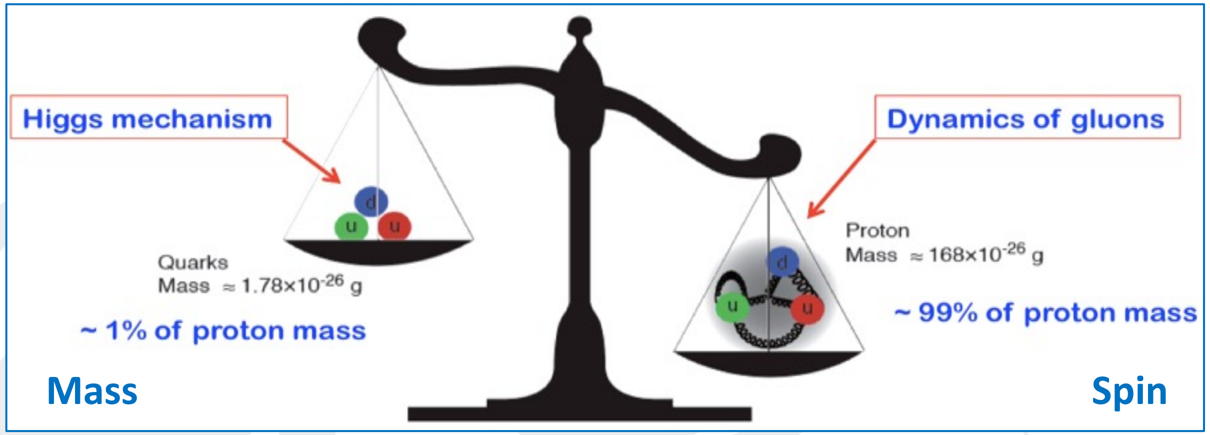
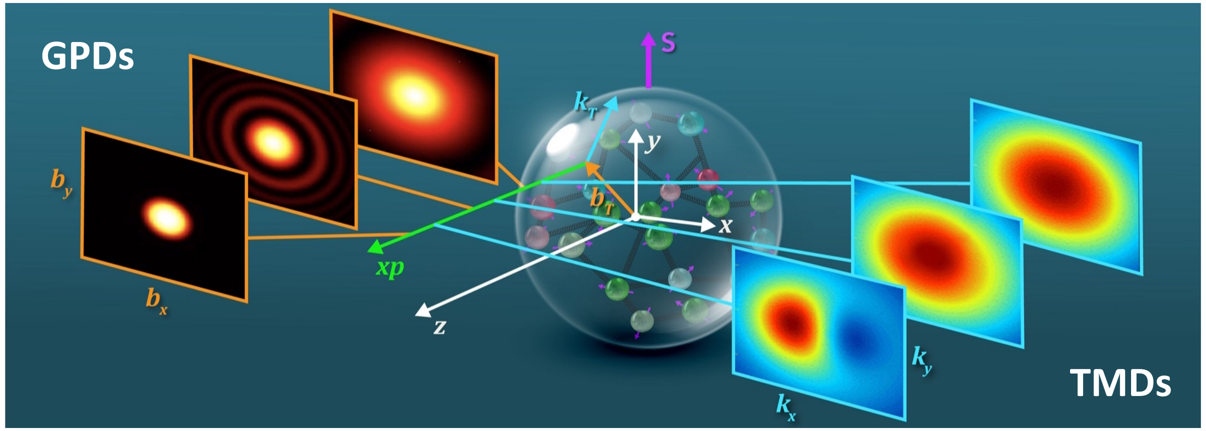
Generalized Parton Distributions from Diffractive Hard Exclusive Processes





Emergent Properties

Dynamical Structure

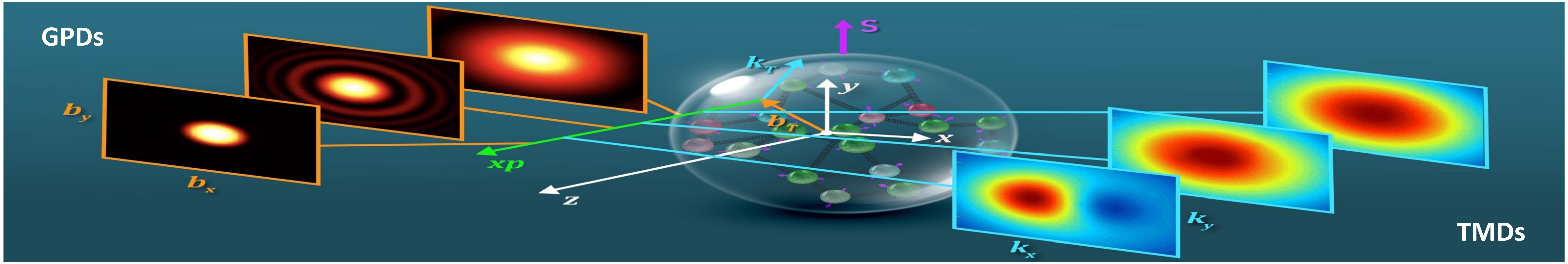
Jianwei Qiu
Jefferson Lab, Theory Center

In collaboration with Zhite Yu (MSU)
JHEP 08 (2022) 103, PRD 107 (2023) 1, arXiv:2305.15397, and in preparation

Jefferson Lab
U.S. Department of Energy | Office of Science
JSA

To "See" Internal Structure of Hadron without seeing quarks/gluons?

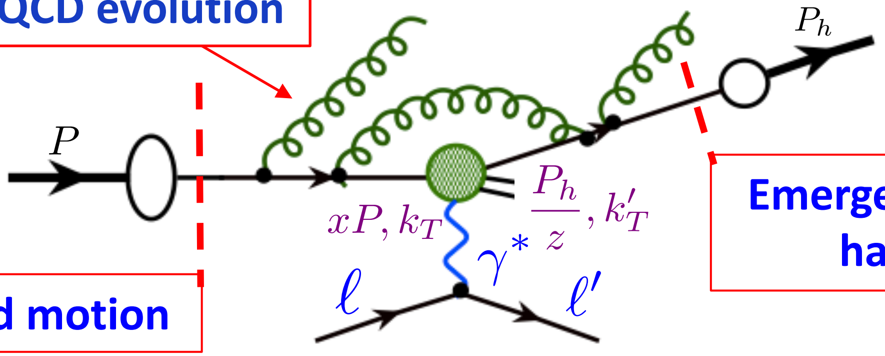
❑ 3D hadron structure:



NO quarks and gluons can be seen in isolation!

❑ If the nucleon is broken, e.g., in SIDIS, …

Gluon shower – QCD evolution



Confined motion

Emergence of a hadron hadronization

Transverse momentum broadening:

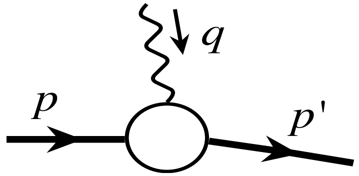
$$\Delta k_T^2 \propto \Lambda_{\rm QCD}^2 \times \alpha_s(C_F, C_A) \times \log(Q^2/\Lambda_{\rm QCD}^2) \times \log(s/Q^2) \quad \Big\} \gtrsim 1$$

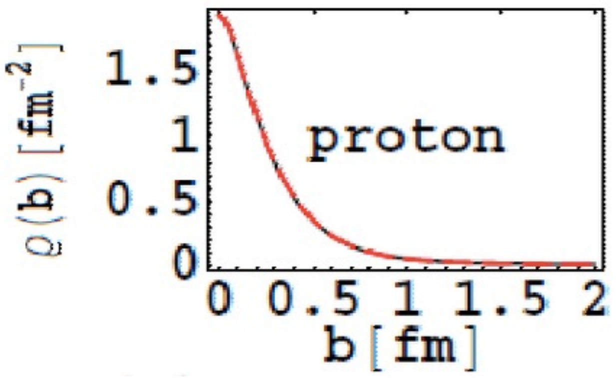
Structure information is diluted by the collision induced shower!

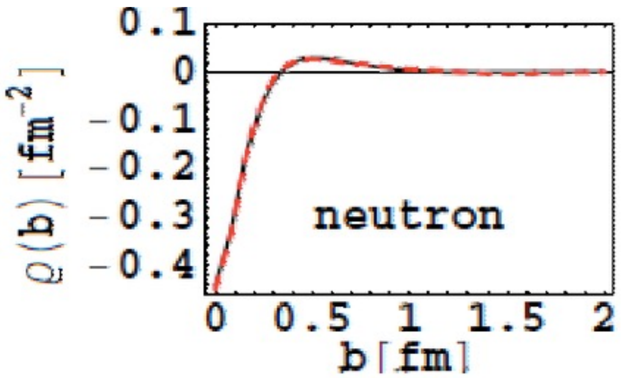
- *Measured k_T is NOT the same as k_T of the confined motion!*
- *Larger Q^2 could weaken our precision to probe the true hadron structure!*

How to Explore Internal Structure of Hadron without Breaking it?

- Form factors: **Elastic electric form factor → Charge distributions**

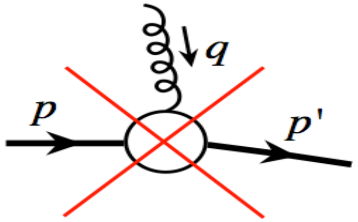






→ **Proton "Radius" in EM charge distribution**

- But, there is NO elastic "color" form factor!

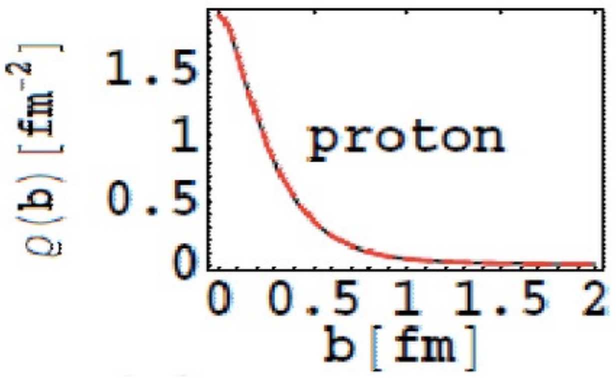


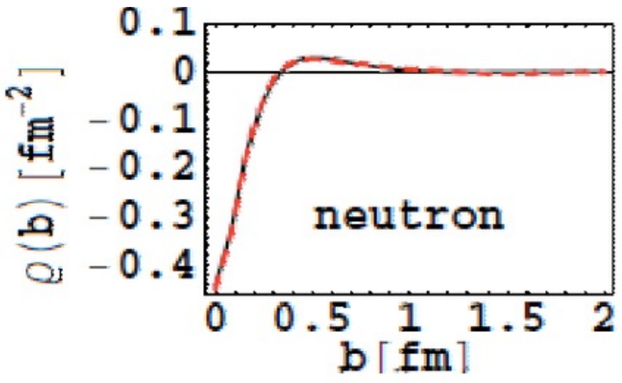
→ **No Proton "Radius" in color charge distribution!**

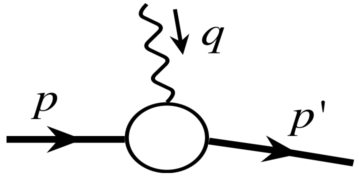
Jefferson Lab

How to Explore Internal Structure of Hadron without Breaking it?

- **Form factors:** Elastic electric form factor ➡ Charge distributions

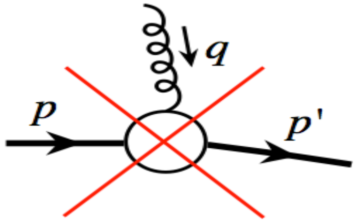






➡ Proton "Radius" in EM charge distribution

- **But, there is NO elastic "color" form factor!**



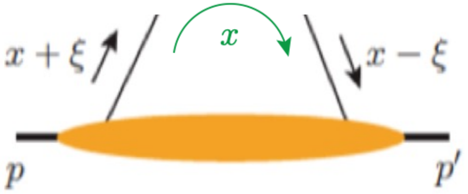
➡ No Proton "Radius" in color charge distribution!

- **3D hadron tomography:**

Generalized "form factor" for quark and gluon "density" distribution

Generalized PDFs (GPDs) – without breaking the proton

$$F_{q/h}(x,\xi,t) \qquad \text{skewness} \quad \xi = \frac{(p-p')^+}{(p+p')^+} \quad t = (p-p')^2$$



$t = (p-p')^2$

Measure p' uniquely fix the t and ξ. It is the x sensitive to partonic structure

GPDs are Fundamental, Responsible for Emergent Hadron Properties

- "Mass" – QCD energy-momentum tensor:

Ji, PRL78, 1997

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

- Gravitational form factors:

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

$$C_i(t) \leftrightarrow D_i(t)/4$$

Related to pressure & stress force inside h

Polyakov, schweitzer, Inntt. J. Mod. Phys. A33, 1830025 (2018)

Burkert, Elouadrhiri , Girod Nature 557, 396 (2018)

- Connection to GPD moments:

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

- "Spin" – Angular momentum sum rule:

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

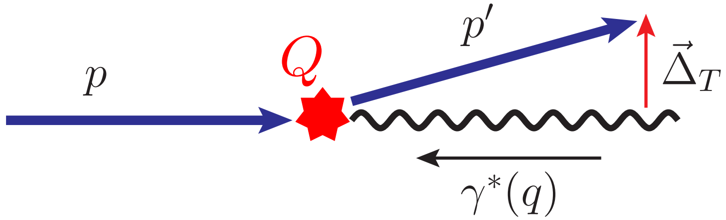
➡ **3D tomography**
Relation to GFF
Angular Momentum

➡ ***x*-dependence of GPDs!**

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

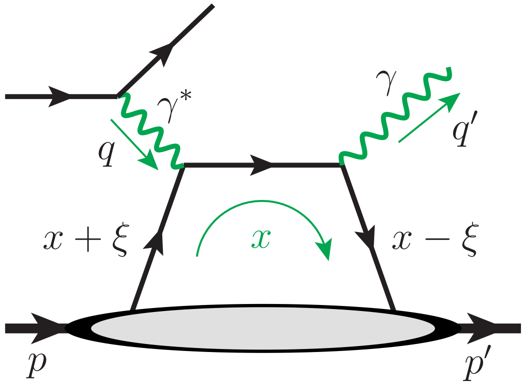
Exclusive Diffractive Process for Extracting GPDs

- **Hit the proton hard without breaking it** $\Longrightarrow$ **Diffractive scattering to keep proton intact**

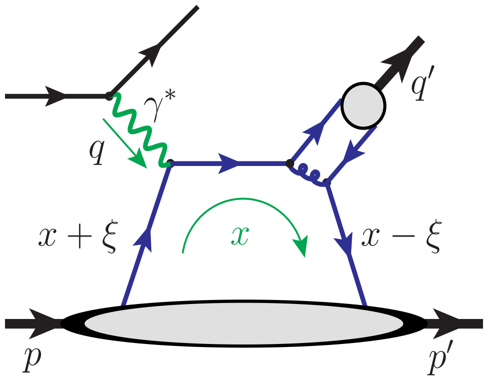


HERA discovery:
~ 10-15% of HERA events with the Proton stayed intact

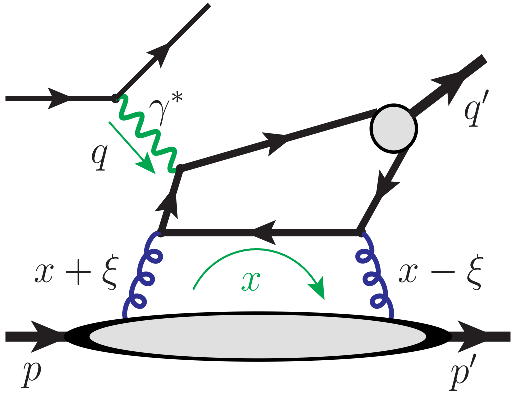
- **Known exclusive processes for extracting GPDs:**



DVCS: Q^2 >> |t|



DVMP



DVQP

+ DDVCS, …

Feature: Two-scale observables $Q^2 \gg |t| \qquad t = (p - p')^2$

- **Hard scale Q: allows pQCD, factorization**
- **Low scale t: probes non-pert. hadron structure**

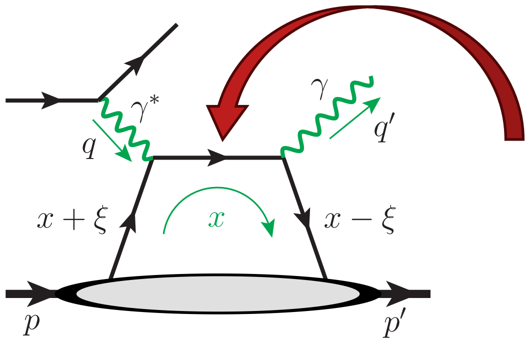
Factorization

GPDs: $f_{i/h}(x, \xi, t; \mu)$

Jefferson Lab

Why it is so Difficult to Extract the x-dependence of GPDs?

❑ **Amplitude nature:** $x \sim$ loop momentum



DVCS

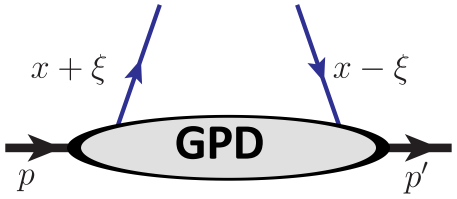
Smaller propagator
= bigger amplitude

$$\propto \frac{1}{x-\xi+i\varepsilon}$$

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

- also true for most other processes
- x-dependence is only constrained by a “moment”
- x-integration decouples from external Q^2

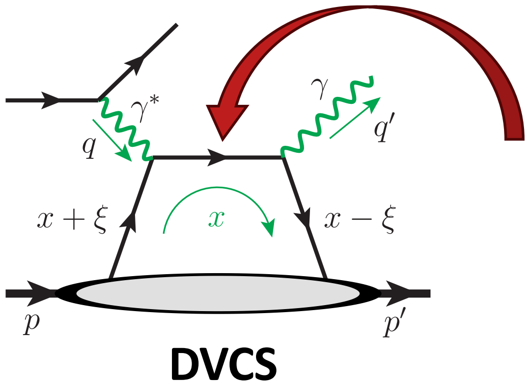
$\Rightarrow$



Not full x-dependence
For given t and ξ

Why it is so Difficult to Extract the x-dependence of GPDs?

❑ Amplitude nature: $x \sim$ loop momentum

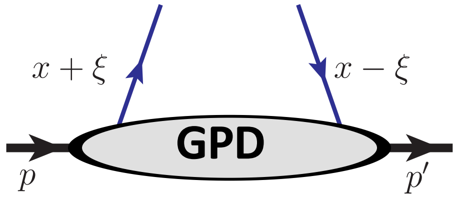


Smaller propagator
= bigger amplitude

$$\propto \frac{1}{x-\xi+i\varepsilon}$$

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

- also true for most other processes
- x-dependence is only constrained by a “moment”
- x-integration decouples from external Q^2



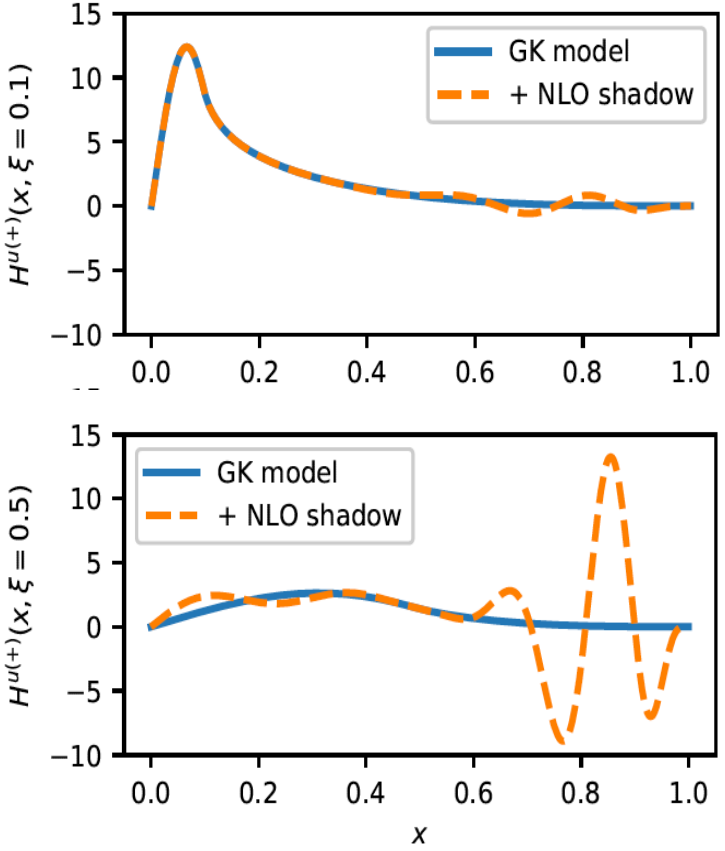
Not full *x*-dependence
For given t and ξ

❑ “Shadow GPDs”

PRD103 (2021) 114019

$$F(x,\xi,t) \to F(x,\xi,t) + S(x,\xi,t)$$

with $$\int_{-1}^{1} \mathrm{d}x\, \frac{S(x,\xi,t)}{x-\xi+i\varepsilon} = 0$$



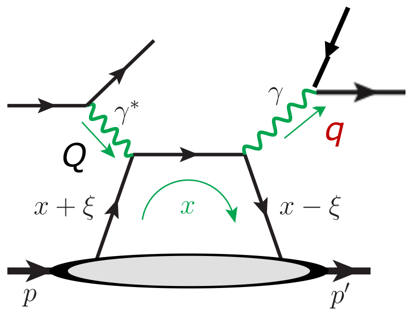
Blue and dashed
Fit the same CFFs !

What kind of process/observable 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):**

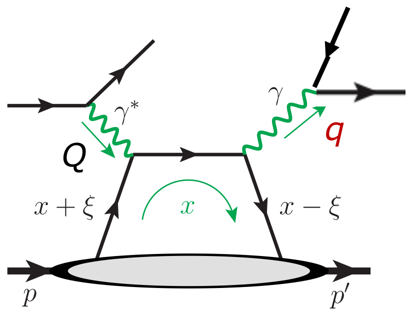
$$x_p(\xi, q) = \xi \left(\frac{1 - q^2/Q^2}{1 + q^2/Q^2} \right) \to \xi \quad \text{same as} \quad \text{DVCS} \quad \text{if } q \to 0$$

What kind of process/observable 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):**

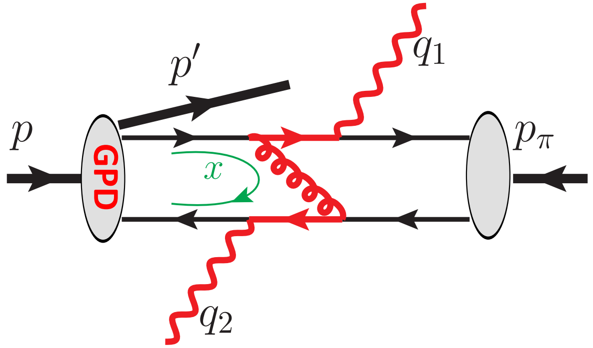
$$x_p(\xi,q) = \xi \left(\frac{1-q^2/Q^2}{1+q^2/Q^2}\right) \to \xi \quad \text{same as} \quad \text{DVCS} \quad \text{if } q \to 0$$

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

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

JHEP 08 (2022) 103

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



- **Factorization:**

[suppressing pion DA factor]

$$\mathcal{M}(t,\xi,q_T) = \int_{-1}^{1} \mathrm{d}x\, F(x,\xi,t;\mu) \cdot C(x,\xi;q_T/\mu) + \mathcal{O}(\Lambda_{\mathrm{QCD}}/q_T)$$

$$\Rightarrow \quad \frac{\mathrm{d}\sigma}{\mathrm{d}t\ \mathrm{d}\xi\ \mathrm{d}q_T} \sim |\mathcal{M}(t,\xi,q_T)|^2$$

q_T distribution is "conjugate" to x distribution

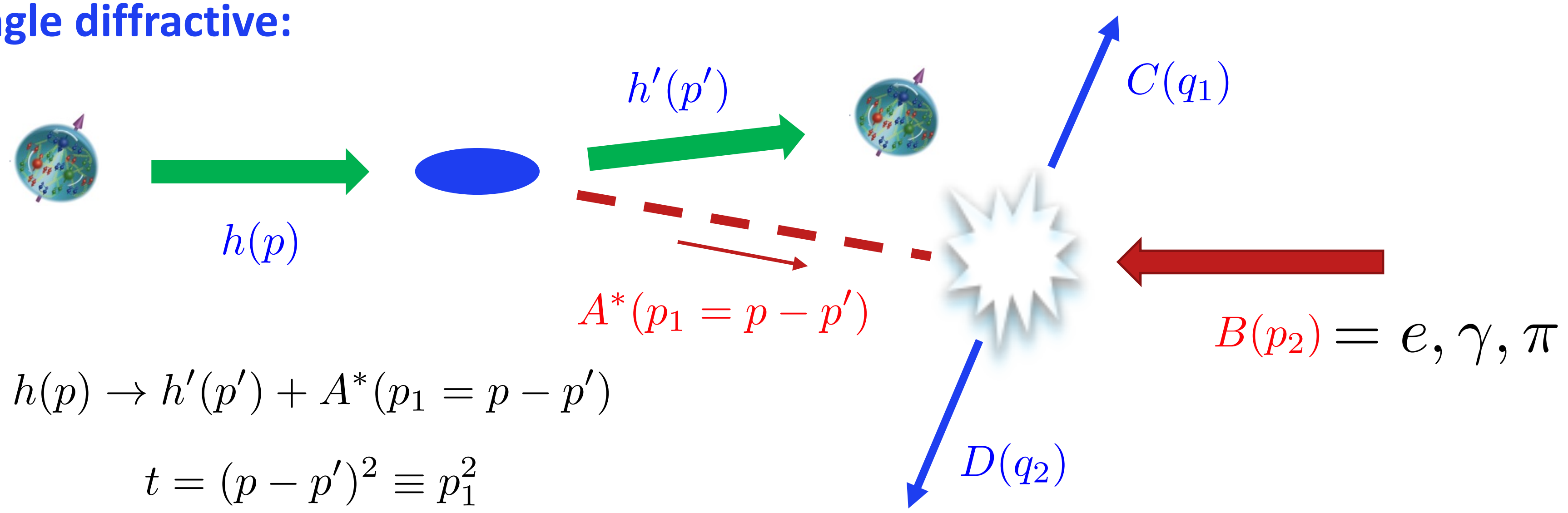
$$x \leftrightarrow q_T$$

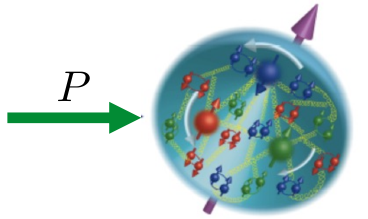
Single-Diffractive Hard Exclusive Processes (SDHEP)

❑ Two-stage diffractive $2 \to 3$ hard exclusive processes:

Qiu & Yu, JHEP 08 (2022) 103
PRD 107 (2023) 1

- **Single diffractive:**





Probing its structure without breaking it!

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

$$t = (p - p')^2 \equiv p_1^2$$

- **Hard probe:** $2 \to 2$ **high** q_T **exclusive process**

$$A^*(p_1) + B(p_2) \to C(q_1) + D(q_2)$$

$$(p - p') \cdot n \gg \sqrt{|t|} \quad \Longleftrightarrow \quad |q_{1_T}| = |q_{2_T}| \gg \sqrt{-t}$$

- **The single diffractive $2 \to 3$ exclusive hard processes:**

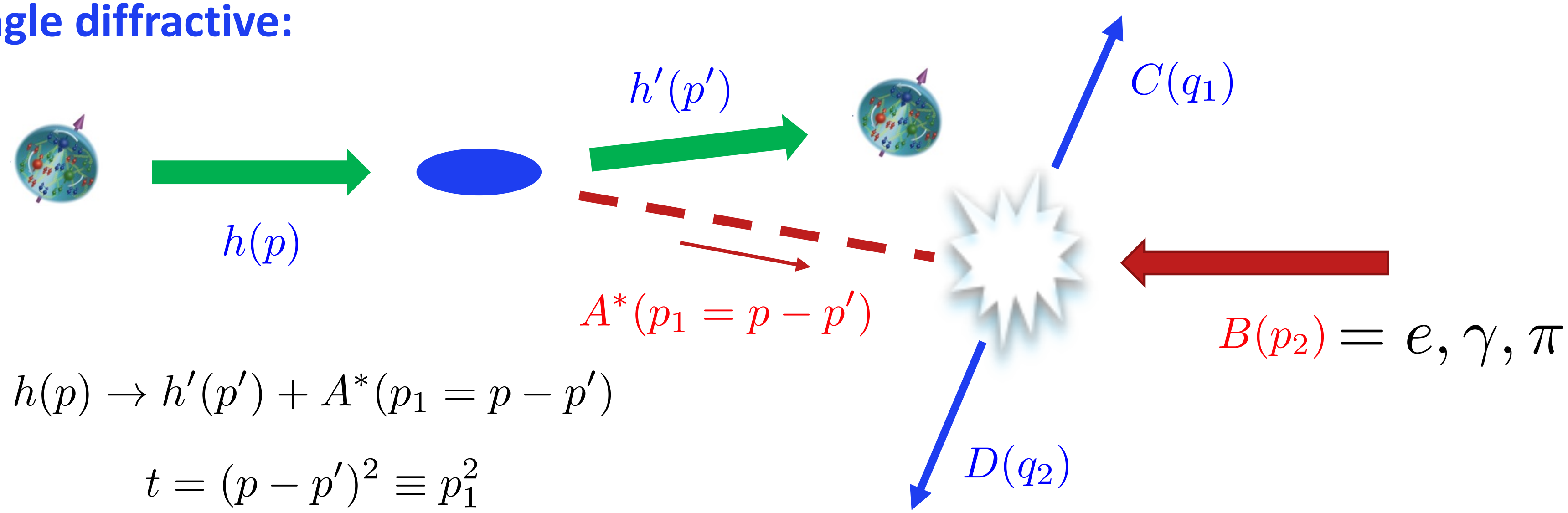
$$h(p) + B(p_2) \to h'(p') + C(q_1) + D(q_2)$$

Single-Diffractive Hard Exclusive Processes (SDHEP)

❑ Two-stage diffractive $2 \to 3$ hard exclusive processes:

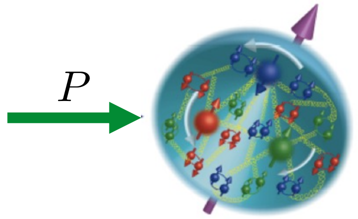
Qiu & Yu, JHEP 08 (2022) 103
PRD 107 (2023) 1

- **Single diffractive:**



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

$$t = (p - p')^2 \equiv p_1^2$$



Probing its structure without breaking it!

- **Hard probe:** $2 \to 2$ **high** q_T **exclusive process**

$$A^*(p_1) + B(p_2) \to C(q_1) + D(q_2)$$

$$(p - p') \cdot n \gg \sqrt{|t|} \iff |q_{1_T}| = |q_{2_T}| \gg \sqrt{-t}$$

- **The single diffractive $2 \to 3$ exclusive hard processes:**

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

- **Necessary condition for QCD factorization:**

$$|q_{1_T}| = |q_{2_T}| \gg \sqrt{-t}$$

The state $A^*(p_1)$ lives much longer than $2 \to 2$ hard exclusive collision!

Not necessarily sufficient!

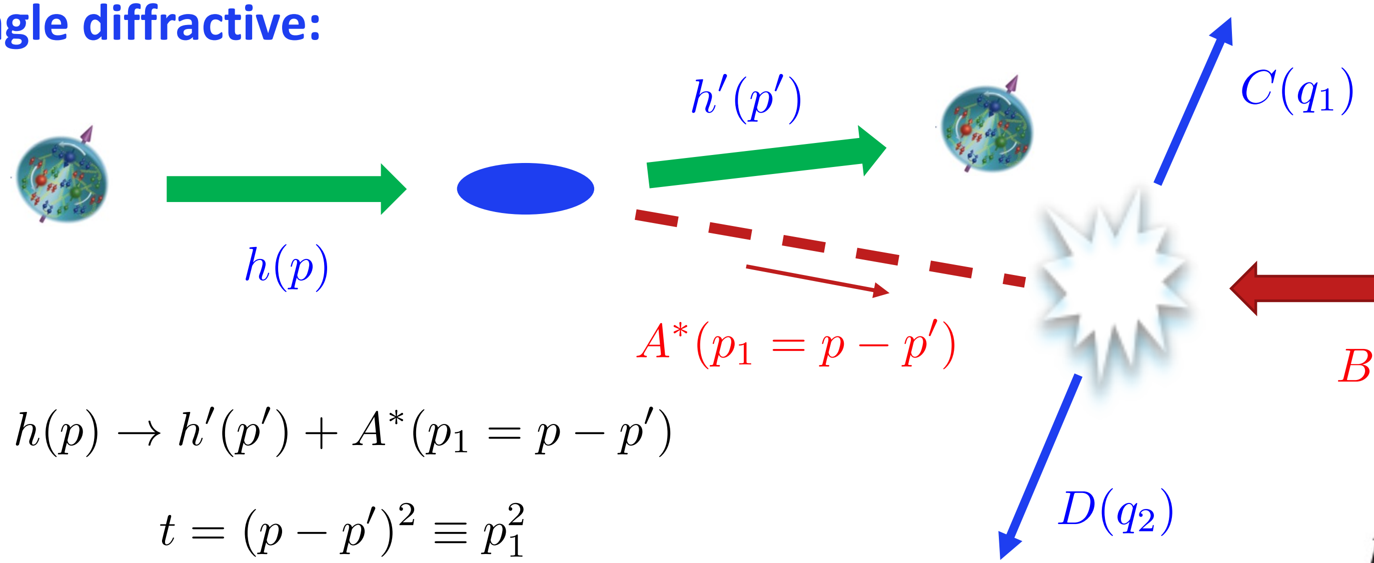
Jefferson Lab

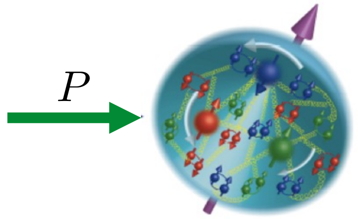
Single-Diffractive Hard Exclusive Processes (SDHEP)

- **Two-stage diffractive $2 \to 3$ hard exclusive processes:**

Qiu & Yu, JHEP 08 (2022) 103
PRD 107 (2023) 1

  - **Single diffractive:**





Probing its structure without breaking it!

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

$$t = (p - p')^2 \equiv p_1^2$$

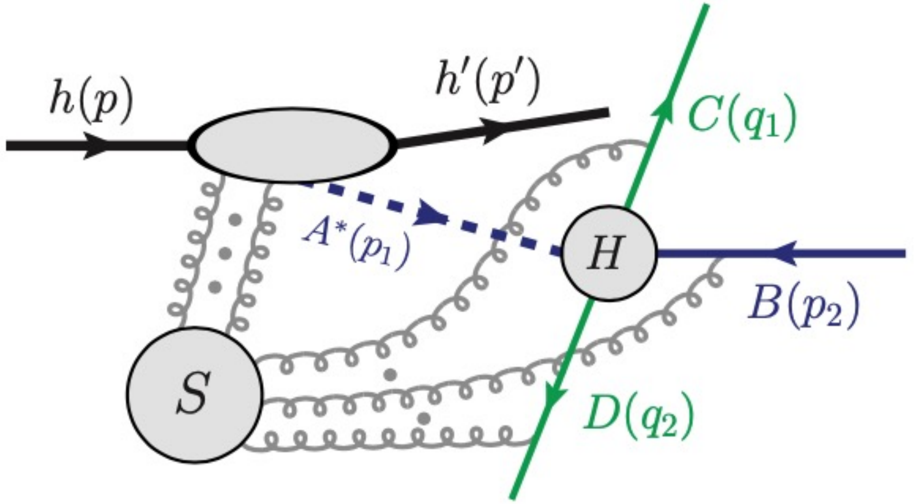
  - **Hard probe:** $2 \to 2$ **high** q_T **exclusive process**

$$A^*(p_1) + B(p_2) \to C(q_1) + D(q_2)$$

$$(p - p') \cdot n \gg \sqrt{|t|} \quad \Longleftrightarrow \quad |q_{1_T}| = |q_{2_T}| \gg \sqrt{-t}$$

  - **The single diffractive $2 \to 3$ exclusive hard processes:**

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

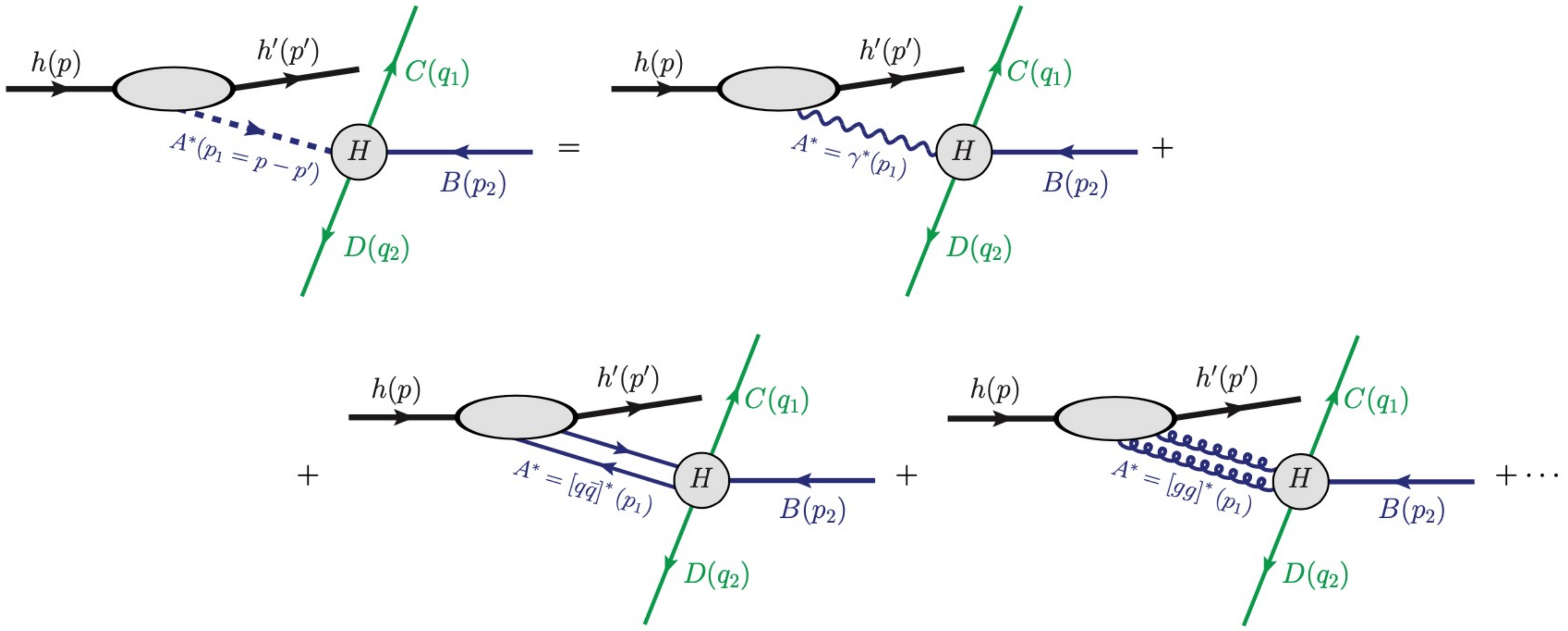


Factorizable if $|q_{1_T}| = |q_{2_T}| \gg \sqrt{-t}$

Single-Diffractive Hard Exclusive Processes (SDHEP)

- **Two-stage diffractive $2 \to 3$ hard exclusive processes:**

Qiu & Yu, JHEP 08 (2022) 103
PRD 107 (2023) 1



The exchanged state $A^*(p-p')$ is a sum of all possible partonic states, $\sum_{n=1,2,..}$, allowed by

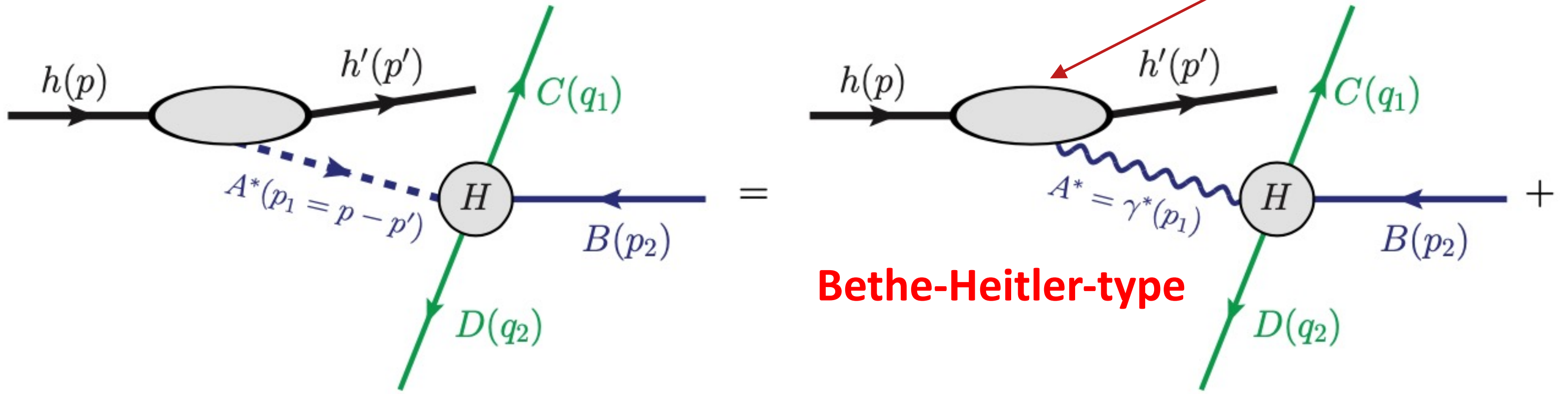
- **Quantum numbers of $h(p) - h'(p')$**
- **Symmetry of producing non-vanishing H**

Single-Diffractive Hard Exclusive Processes (SDHEP)

Qiu & Yu, JHEP 08 (2022) 103
PRD 107 (2023) 1

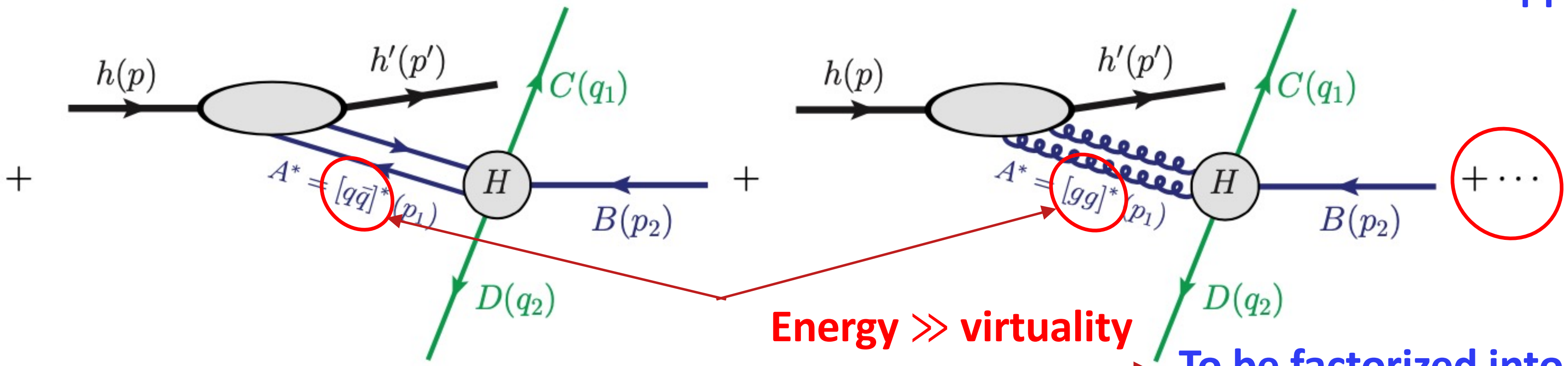
- **Two-stage diffractive $2 \to 3$ hard exclusive processes:**

EM form factor



Bethe-Heitler-type

≥ 3 parton connection: Power suppressed



Energy $\gg$ virtuality

To be factorized into GPD

The exchanged state *A(*p*-*p'*) is a sum of all possible partonic states, $\sum_{n=1,2,..}$, allowed by**

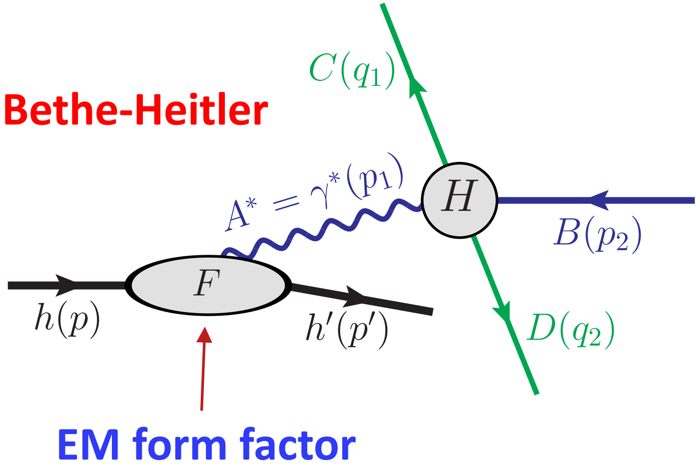
- **Quantum numbers of *h(p) – h'(p')***
- **Symmetry of producing non-vanishing *H***

Jefferson Lab

General Discussion on n=1 state: γ^*

❑ **Exchange of a virtual photon – "GPD background":**

Qiu & Yu, PRD 107 (2023) 1



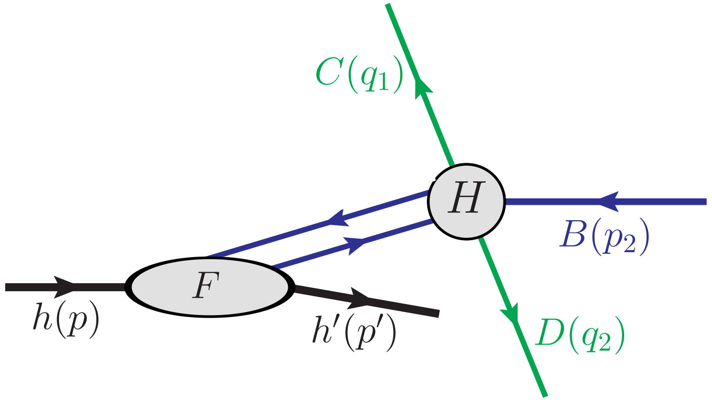
$$\mathcal{M}^{(1)} = \frac{ie^2}{t}\langle h'(p')\,|J^\mu(0)|\,h(p)\rangle\langle C(q_1)\,D(q_2)\,|J_\mu(0)|\,B(p_2)\rangle$$
$$\equiv \frac{ie^2}{t}F^\mu(p,p')\,\mathcal{H}_\mu(p_1,p_2,q_1,q_2)$$

Leading component

$$F^+\mathcal{H}^- = \frac{1}{p_1^+}F^+\left(p_1^+\mathcal{H}^-\right) = \frac{1}{p_1^+}F^+\left(p_1\cdot\mathcal{H} + \boldsymbol{p}_{1\perp}\cdot\mathcal{H}_\perp - p_1^-\mathcal{H}^+\right) \sim \mathcal{O}(\sqrt{|t|})$$

$$\mathcal{M}^{(1)} \sim \mathcal{O}(1/\sqrt{|t|})$$
$$\mathcal{M}^{(2)} \sim \mathcal{O}(1/Q)$$

$$\Rightarrow \quad \mathcal{M}^{(1)}/\mathcal{M}^{(2)} \sim \mathcal{O}(Q/\sqrt{|t|})$$



γ^* **channel is of a *more leading power* than GPD contribution,**
but higher power in α_{EM}

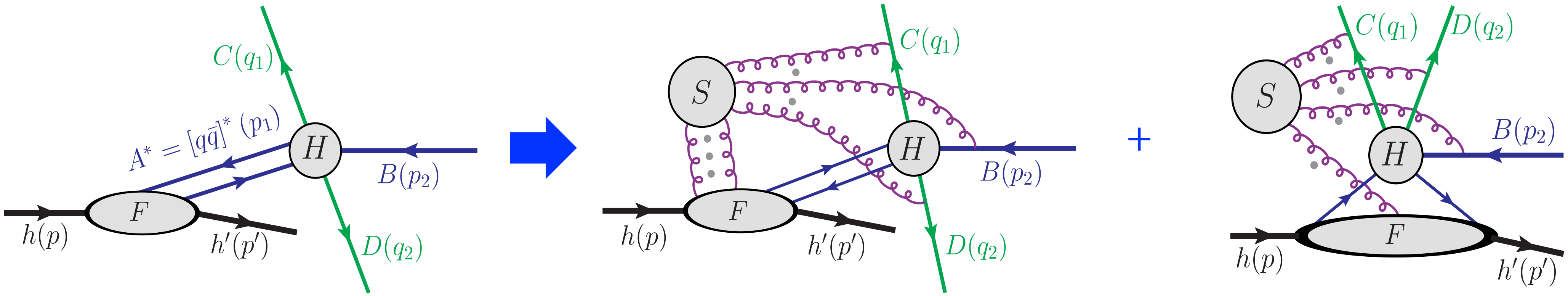
Generally allowed, except
(1) flavor changing ($p \to n$, $n \to p$, etc.)
(2) forbidden by symmetry in the hard part

Jefferson Lab

Factorization for SDHEP in the Two-stage Paradigm

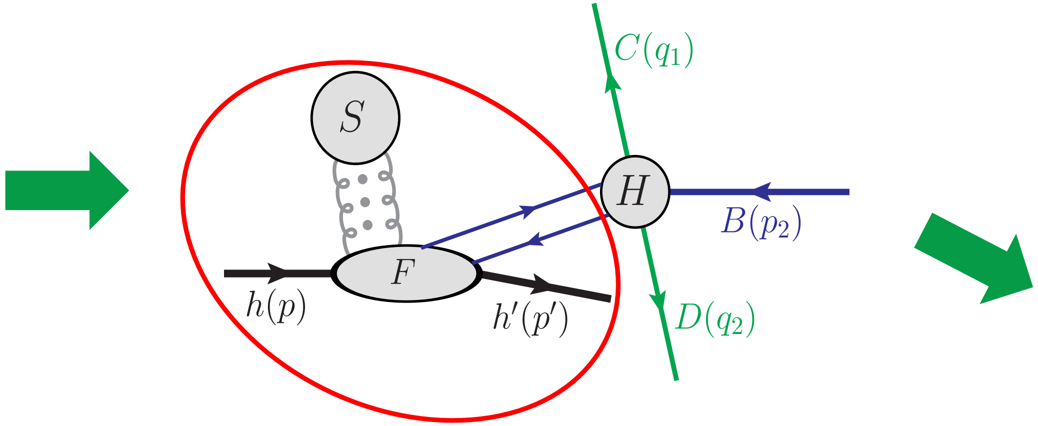
Qiu & Yu, JHEP 08 (2022) 103, PRD 107 (2023) 1

❑ Factorization for 2-parton channel factorization:



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

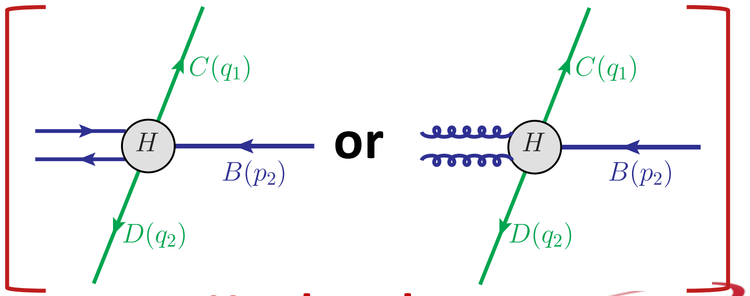
❑ Soft gluons cancel when coupling to color neutral hadrons:



Glauber gluons of SDHEP:

$$k_s = (\lambda^2, \lambda^2, \lambda) \;\to\; (1, \lambda^2, \lambda)$$ **Collinear gluons**

$\mathrm{GPD} \otimes$



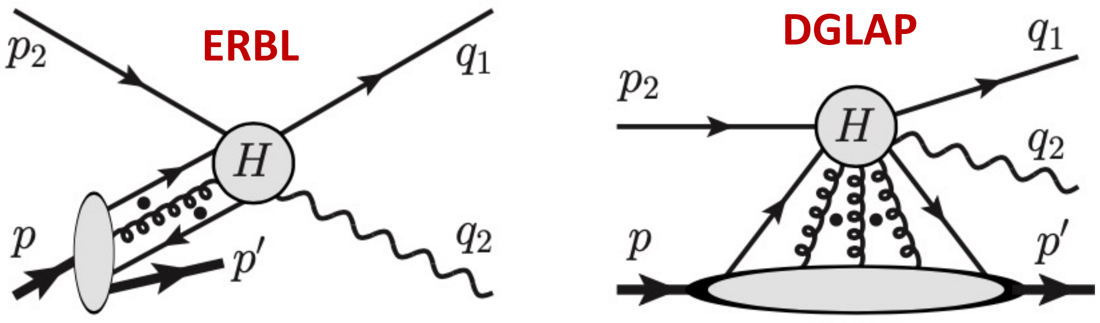
Hard probes

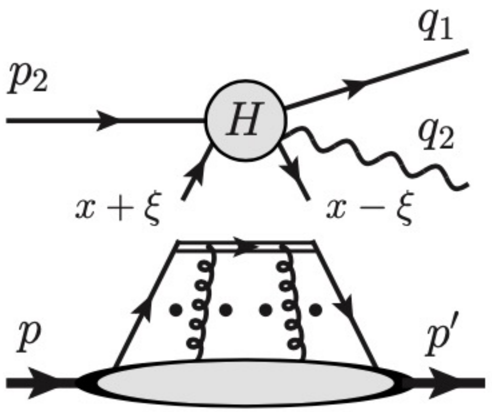
SDHEP with a Lepton Beam – JLab, EIC

- **DVCS:**

$$h(p) = \text{Proton}(p),\ h'(p') = \text{Proton}(p'),\ B(p_2) = \text{electron}(p_2),\ C(q_1) = \text{electron}(q_1),\ D(q_2) = \text{photon}(q_2)$$

- **Leading pinch region:**





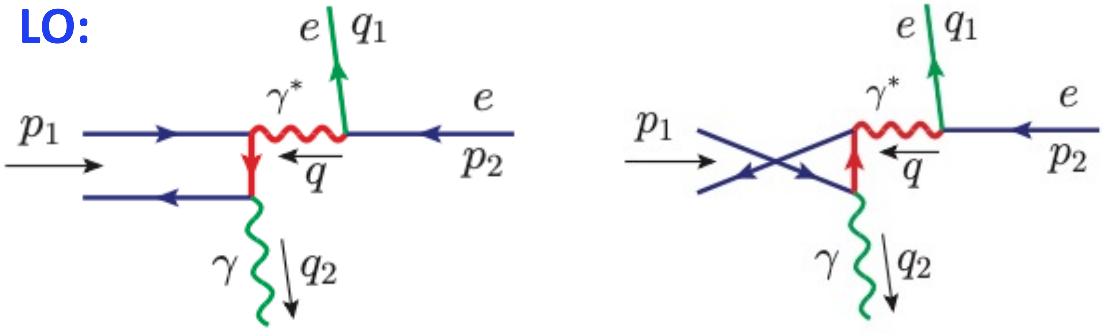
$$x = \frac{(k+k')^+}{(p+p')^+} \qquad \xi = \frac{(p-p')^+}{(p+p')^+}$$

- **Factorization formula:**

$$\mathcal{M}^{(2)}_{he\to h'e\gamma} = \sum_i \int_{-1}^{1} \mathrm{d}x\, F_i^h(x,\xi,t)\, C_{ie\to e\gamma}(x,\xi,q_T),$$

$$\Rightarrow \quad C^{(0)} \propto \frac{1}{x-\xi+i\varepsilon} - \frac{1}{x+\xi-i\varepsilon}$$

LO:



“moment-type” x-dependence

GPD Models for Numerical Results

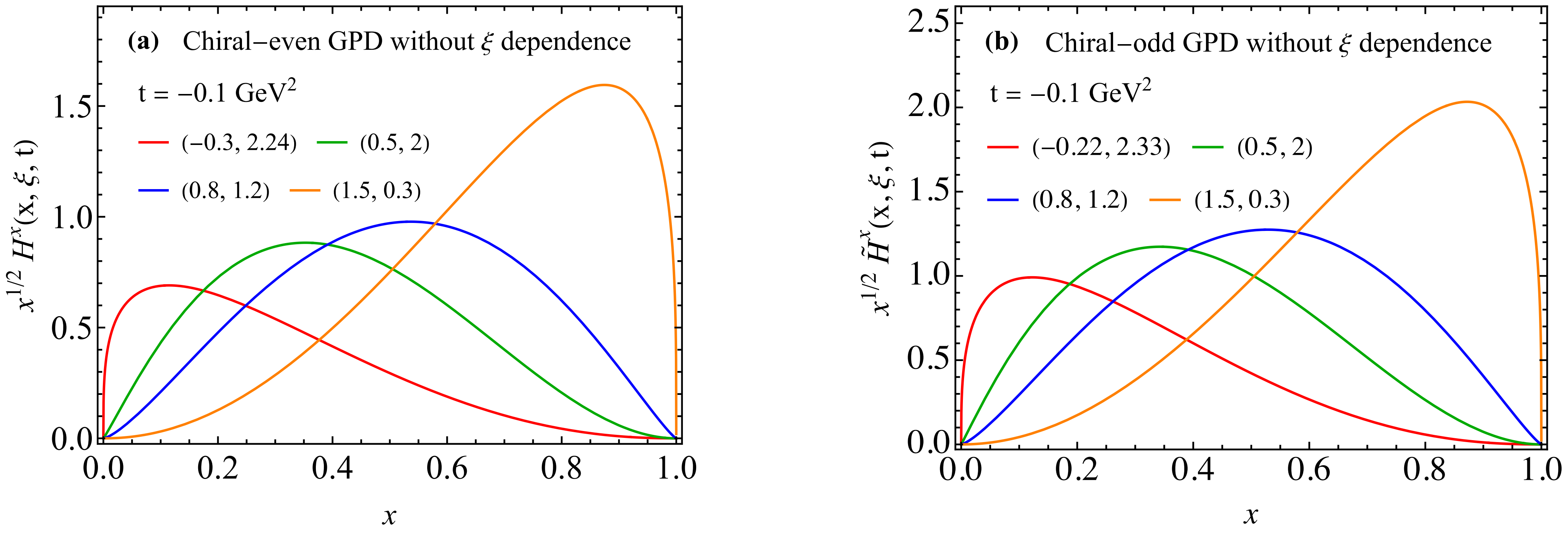
❑ Simplified GK models:

Goloskokov, Kroll
hep-ph/0501242
arXiv: 0708.3569
arXiv: 0906.0460

$$H_{pn}(x,\xi,t) = \theta(x)\, x^{-0.9\,(t/\mathrm{GeV}^2)} \frac{x^\rho (1-x)^\tau}{B(1+\rho, 1+\tau)}$$

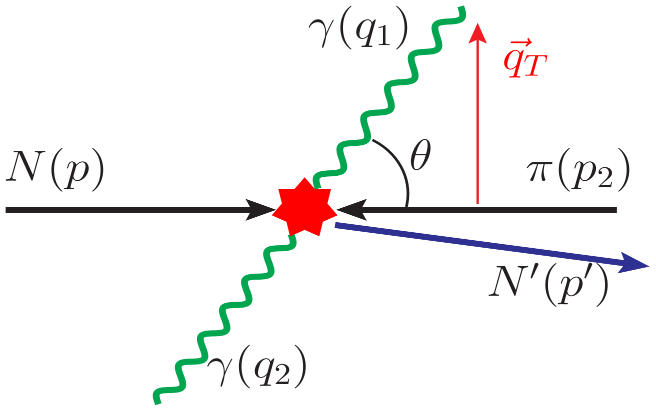
$$\widetilde{H}_{pn}(x,\xi,t) = \theta(x)\, x^{-0.45\,(t/\mathrm{GeV}^2)} \frac{1.267\, x^\rho (1-x)^\tau}{B(1+\rho, 1+\tau)}$$

- **Neglect $E, \widetilde{E}$. Neglect evolution effect.**
- **Tune (ρ, τ) to control x shape.**
- **Fix DA: $D(z) = N\, z^{0.63}(1-z)^{0.63}$**



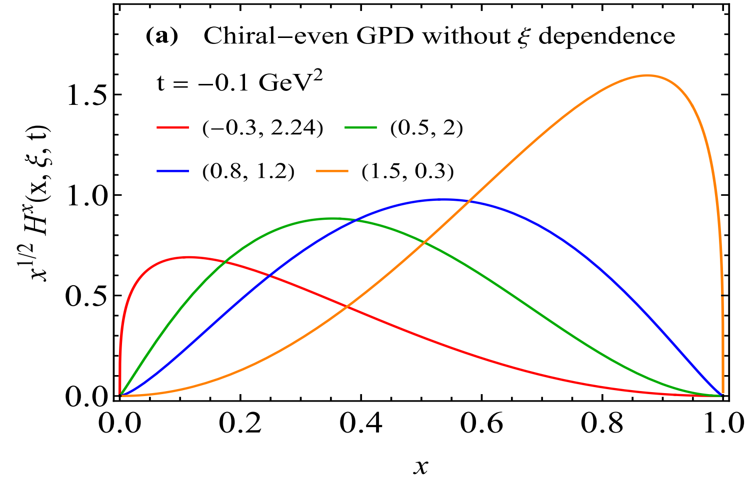
Enhanced Sensitivity on x-dependence of GPDs

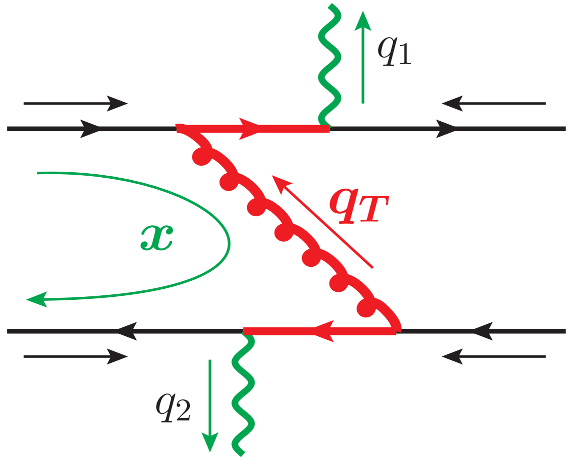
❑ Two-photon production: $\pi^-(p_\pi) + P(p) \to \gamma(q_1) + \gamma(q_2) + N(p')$ **J-PARC, COMPASS** Qiu & Yu, JHEP 08 (2022) 103

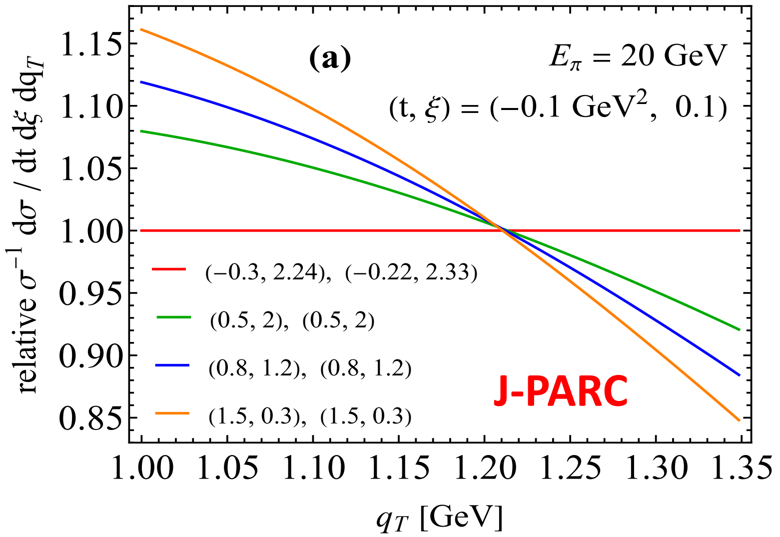


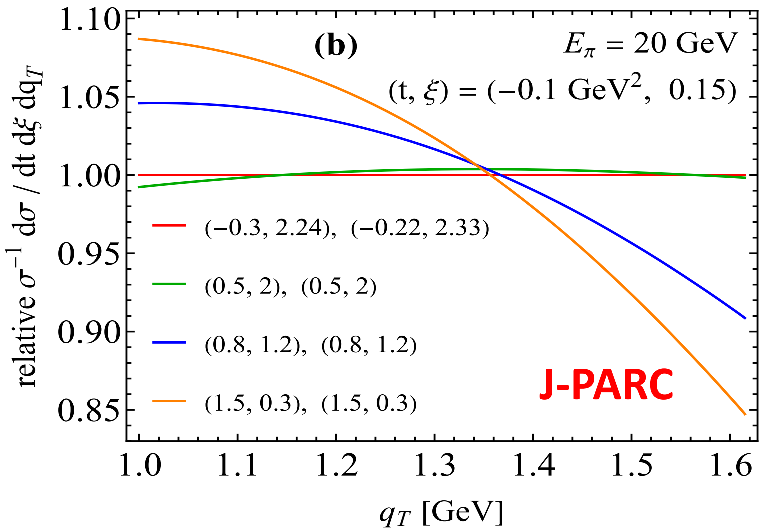
Vary GPD x shapes

Different q_T shapes



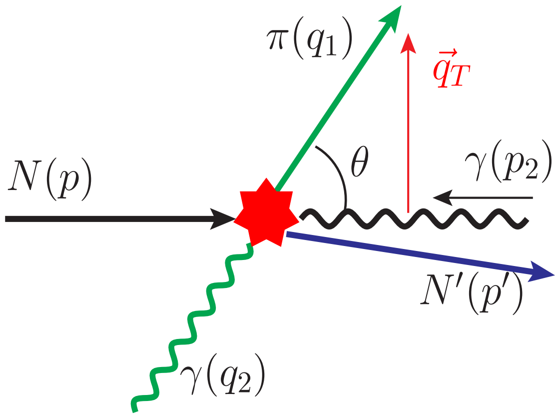






Enhanced Sensitivity on x-dependence of GPDs

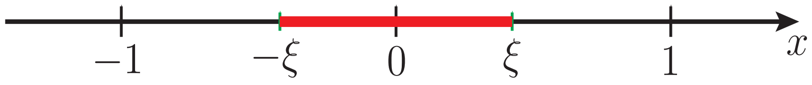
❑ **Pion-photon production:** $\gamma(p_\gamma) + h(p) \to \pi^{\pm}(q_1) + \gamma(q_2) + h'(p')$ **JLab-Hall D, other Halls with quasi-photon beam**

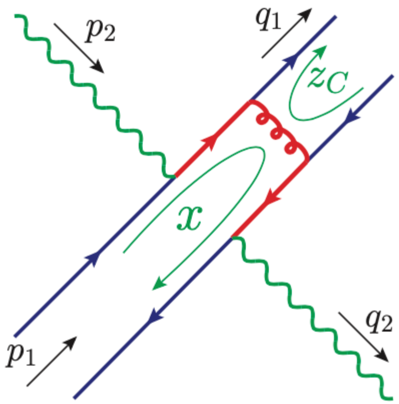


$i\mathcal{M}$ **contains the entanglement between x and qT**

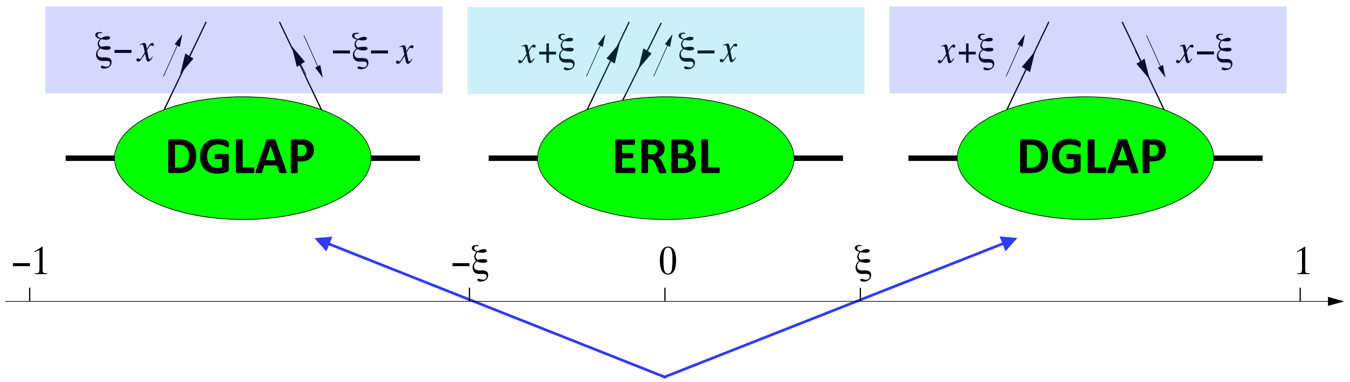
$$I'(t,\xi;z,\theta) = \int_{-1}^{1} \frac{dx\, F(x,\xi,t)}{x - \rho'(z;\theta) + i\epsilon}$$

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





Complementary sensitivity:

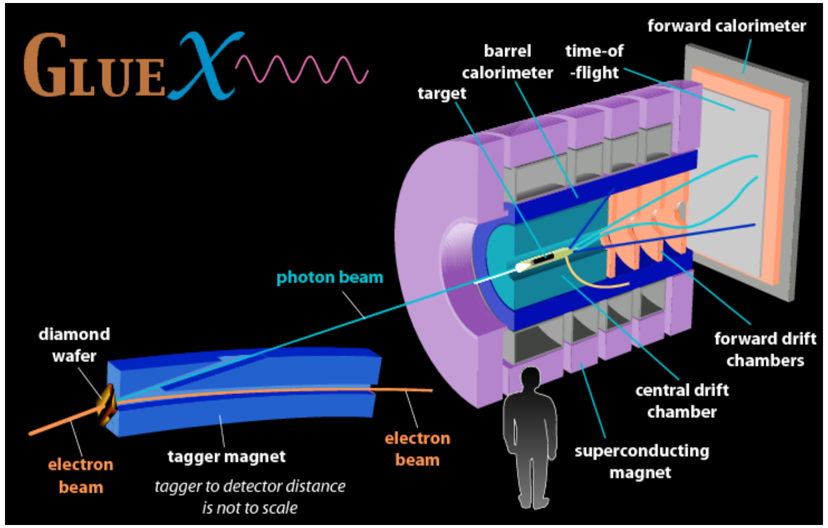


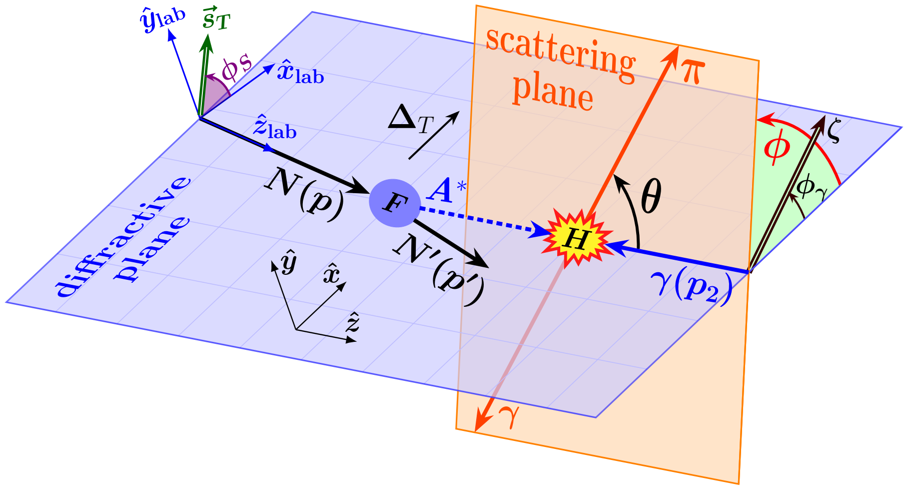
$N\,\pi \to N'\,\gamma\,\gamma$

Jefferson Lab

Exclusive Photo-Production of a π γ Pair – Hall D at JLab

Qiu & Yu, arXiv:2305.15397





❑ Polarization asymmetries

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

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

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

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

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

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

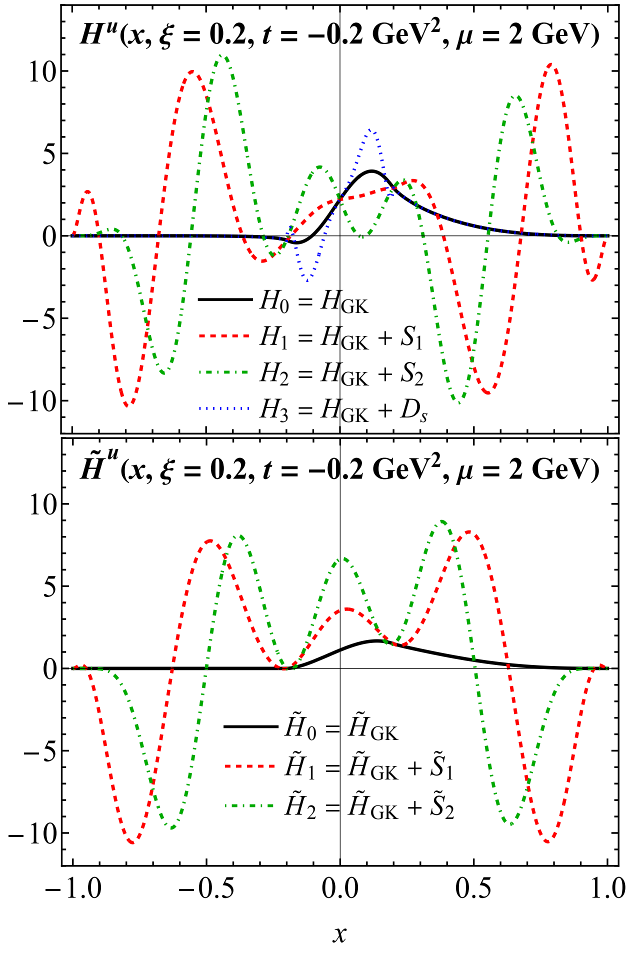
Exclusive Photo-Production of a $\pi\gamma$ Pair – Hall D at JLab

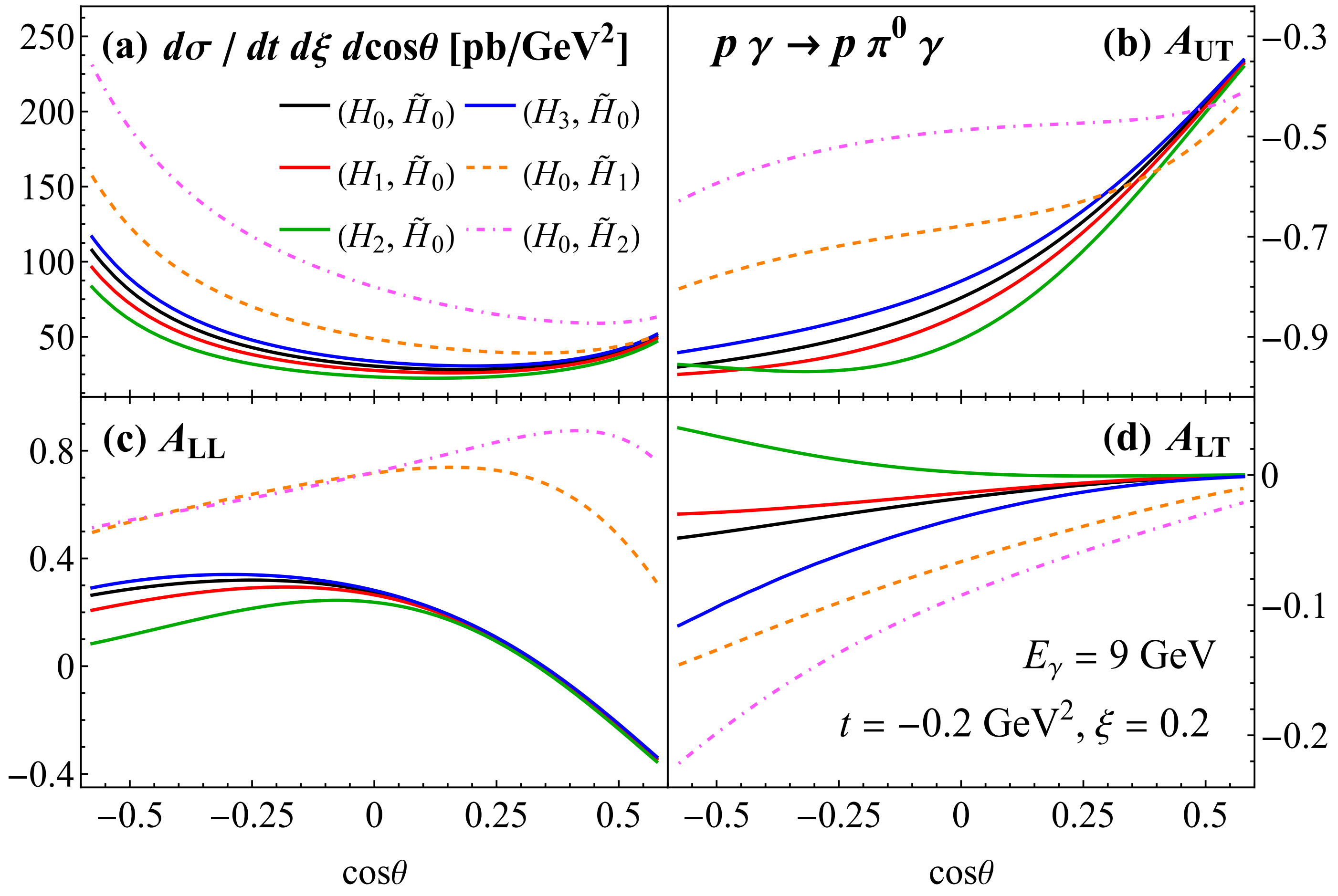
- **GPD Models:**

  = 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

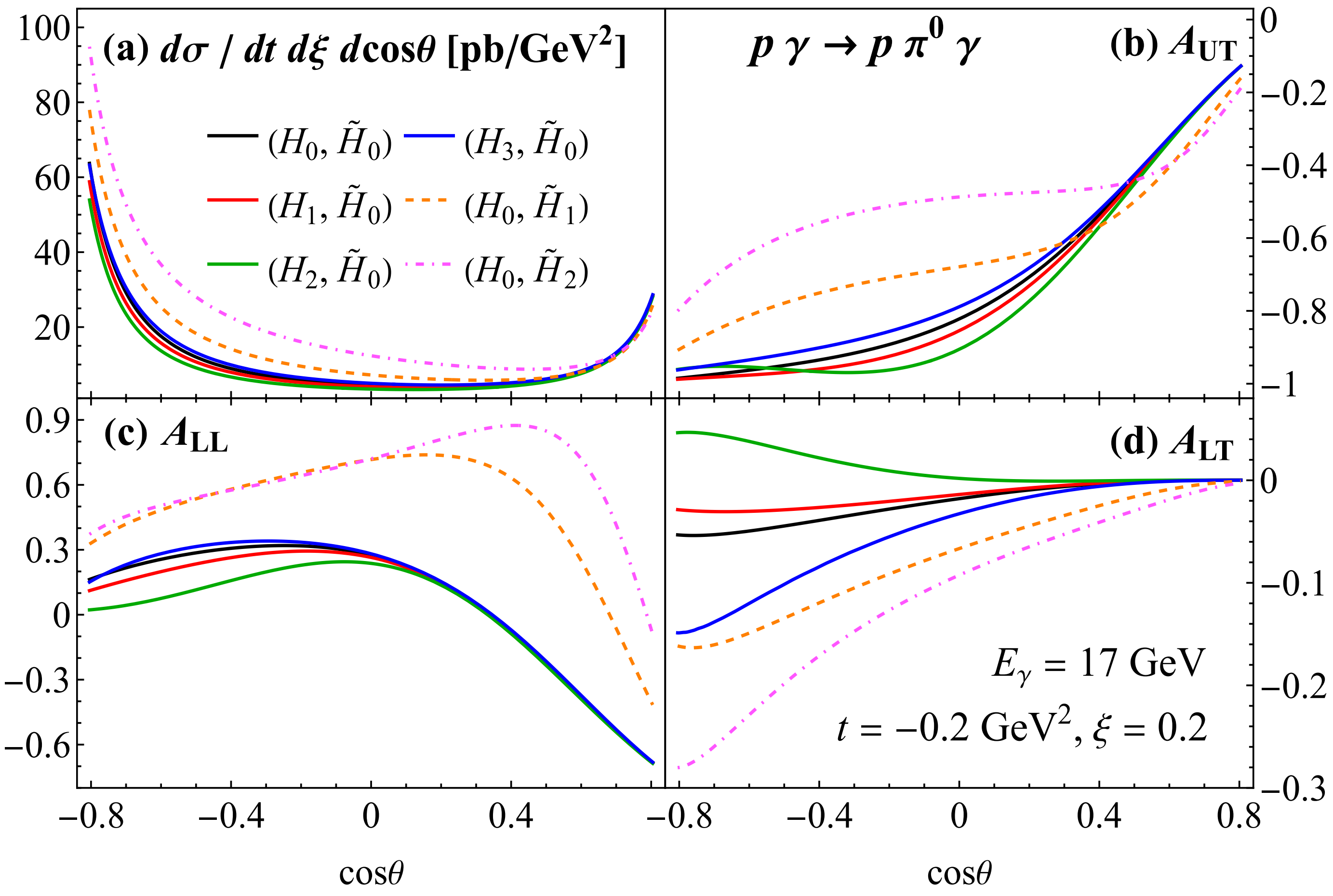
Exclusive Photo-Production of a $\pi\gamma$ Pair – Hall D at JLab

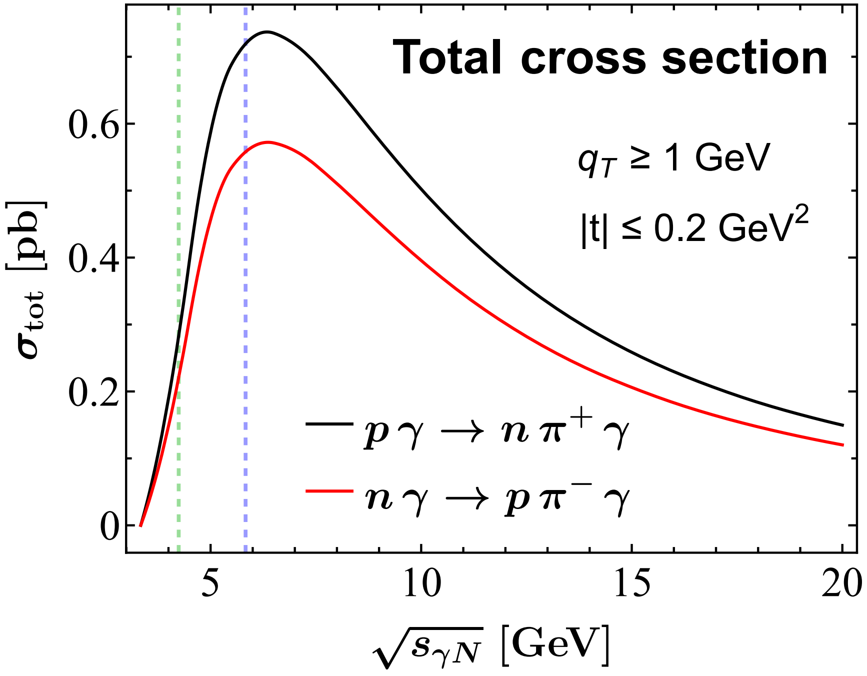
❑ GPD Models:

= 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

Summary and Outlook

- GPDs are fundamental parton correlation functions:
  - Carry rich information on emergent hadron properties (mass, spin, …) from QCD/parton dynamics
  - Are responsible for the tomographic images of confined quarks and gluons inside a bound hadron
  - Provide the much needed hints on how confined quarks/gluons respond to the probing scale, …

  Extracting their x-dependence from experimental observable(s) is non-trivial, but, full of opportunities, …

- Introduced the single diffractive $2 \to 3$ hard exclusive processes (SDHEP) for extracting GPDs, …
  - Covered all existing/known processes for extracting GPDs, plus ideas for new observables, …
  - Introduced a path forward to identify new SDHEPs that could be sensitive to x-dependence of GPDs
  - Angular modulation between diffractive plane and hard scattering plane could provide unique opportunity to separate various GPDs
  - Exclusive photoproduction at JLab provides excellent opportunities for extracting GPDs & x-dependence

  Renewed opportunities for exploring the physics of GPDs and the confined phenomena of QCD.

Thanks!

Jefferson Lab