UNIVERSITÀ DEGLI STUDI DI TRIESTE
Department of Physics
Trieste, Italy

Theory and Phenomenology of GPDs - Overview

(*Can't be comprehensive in 30 minutes*)

- ❑ Inclusive vs. Exclusive – Explore Hadron's Partonic Structure without Breaking it!
- ❑ GPDs, 3D Tomographic Images & Beyond
- ❑ Exclusive Processes for Extracting GPDs
- ❑ QCD Factorization, Angular Modulations, …
- ❑ Summary and Outlook

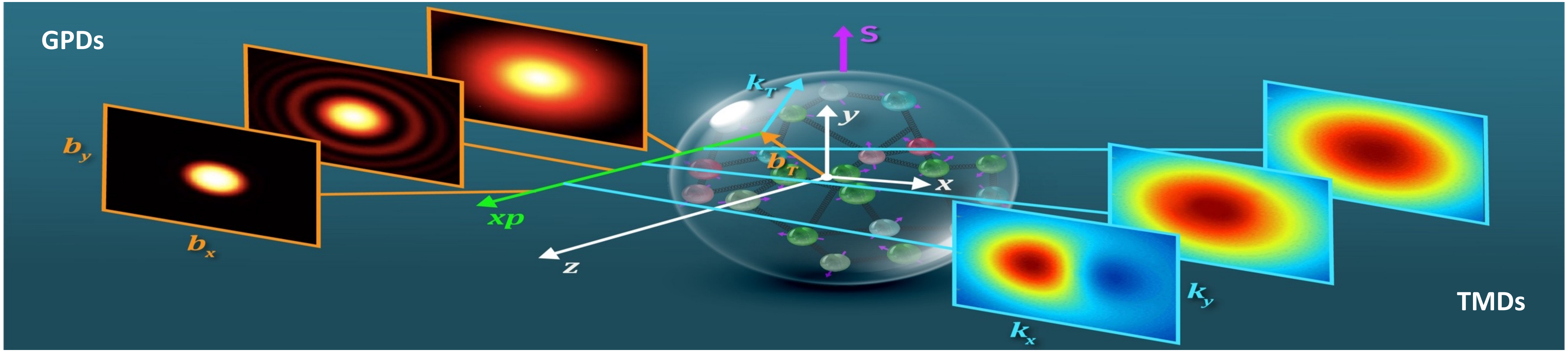
See talks by Nicole D'Hose, Charlotte Van Hulse, Valerio Bertone, Cedric Mezrag, Silvia Niccolai, …
See also talk by Herve Dutrieux @ QCD Evolution

Jianwei Qiu
Jefferson Lab, Theory Center

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

❑ 3D hadron structure:

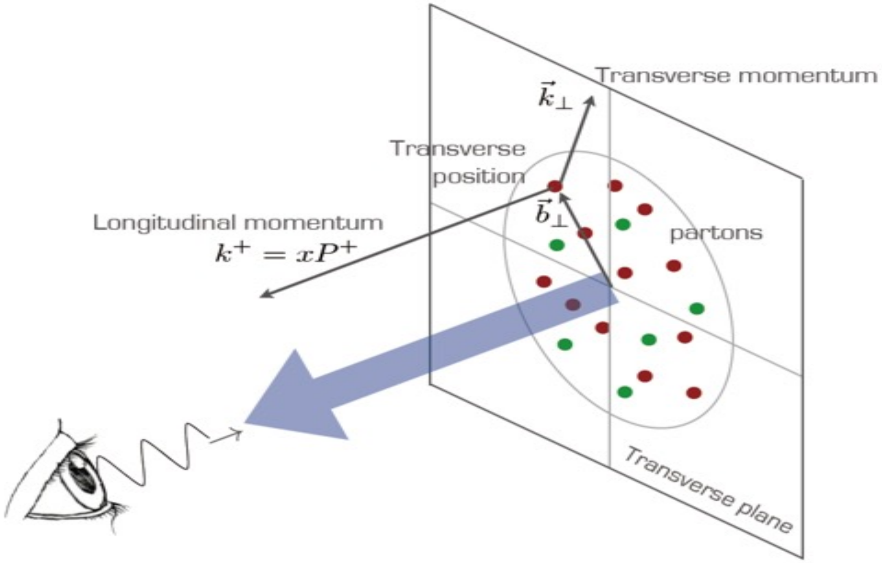
NO quarks and gluons can be seen in isolation!



❑ Need new observables with two distinctive scales:

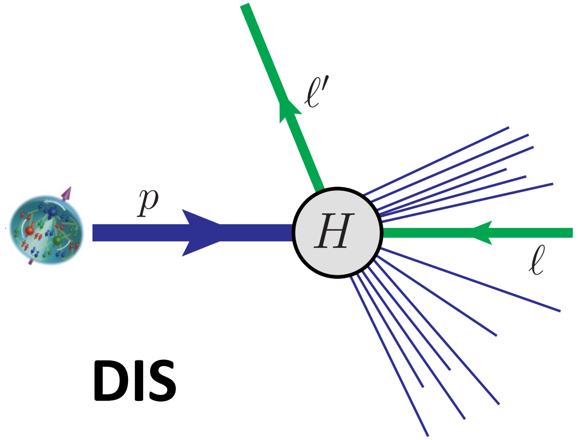
$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\mathrm{QCD}}$$

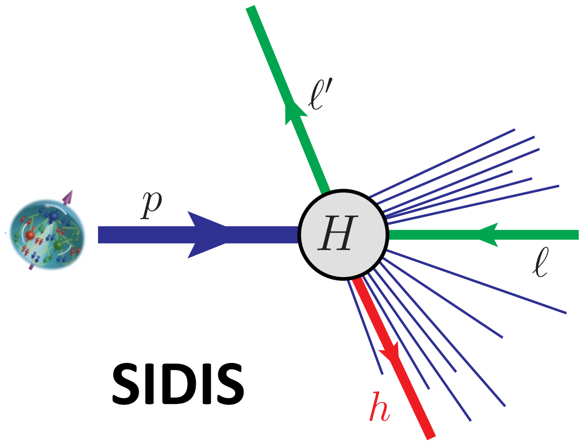
- **Hard scale:** Q_1 **to localize the probe to see the particle nature of quarks/gluons**
- **"Soft" scale:** Q_2 **to be more sensitive to the emergent regime of hadron structure ~ 1/fm**

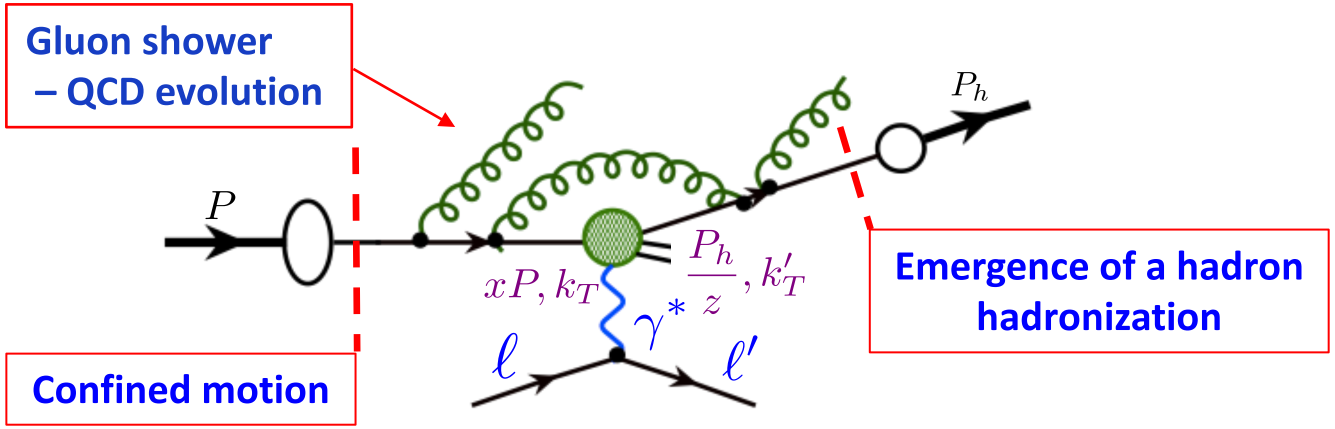


Inclusive vs. Exclusive – Partonic structure without breaking the hadron!

Inclusive scattering

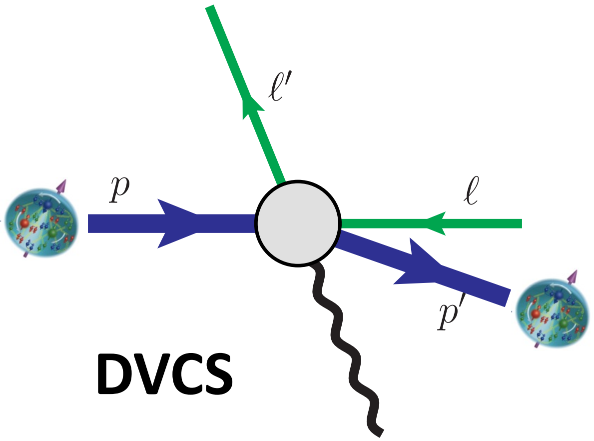






$$e + P \to e + h + X$$

Exclusive diffraction



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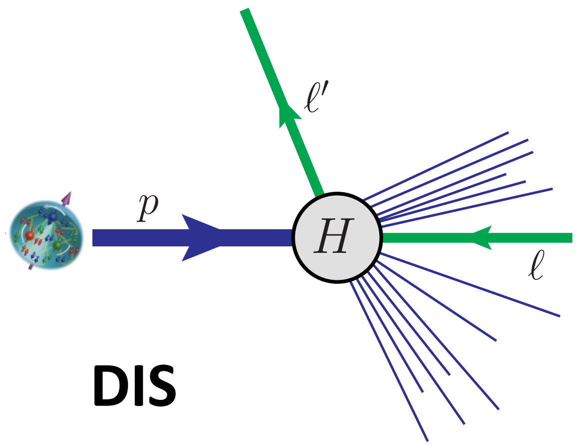
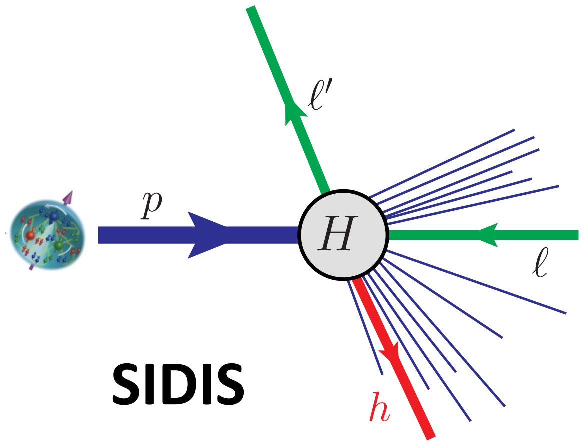
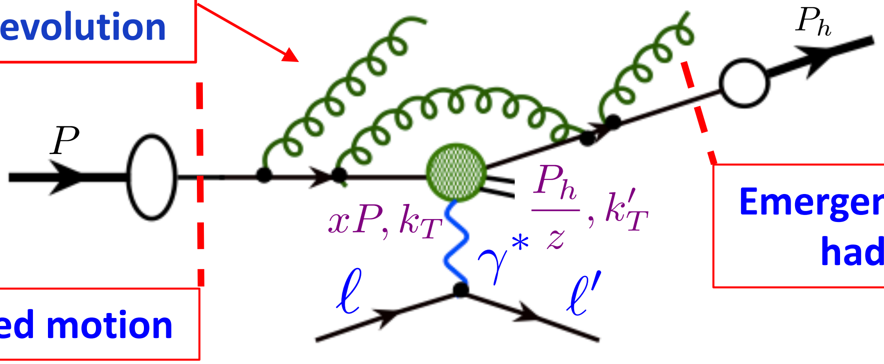


DIS



SIDIS

Gluon shower
– QCD evolution

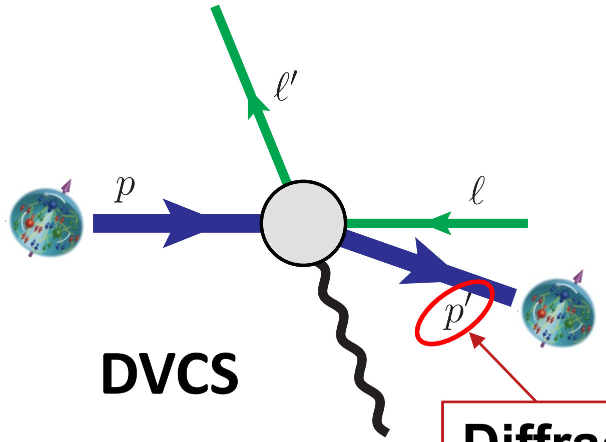


Confined motion

Emergence of a hadron
hadronization

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

Exclusive diffraction



DVCS

Diffraction

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

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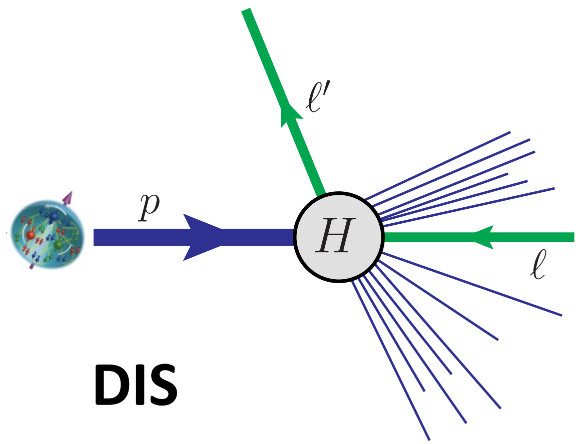
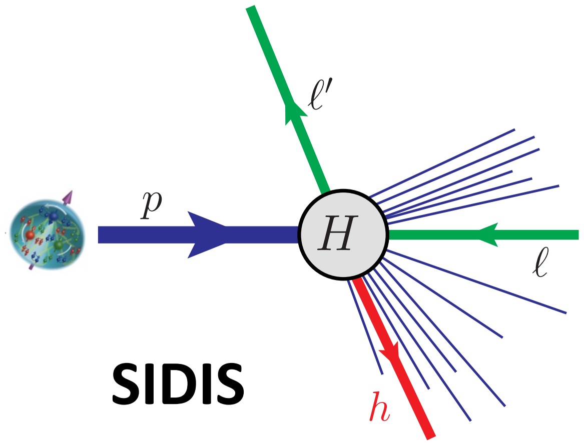
Inclusive vs. Exclusive – Partonic structure without breaking the hadron!

Inclusive scattering





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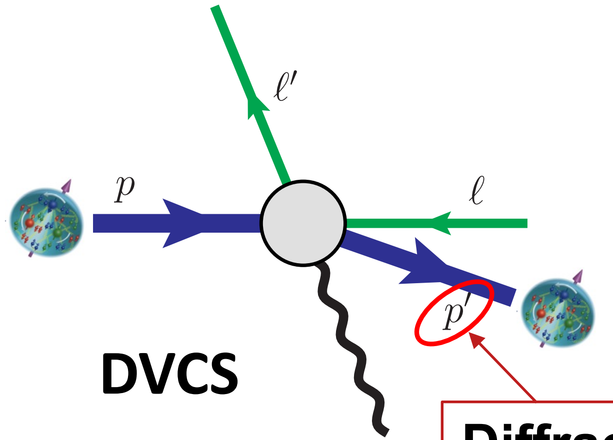

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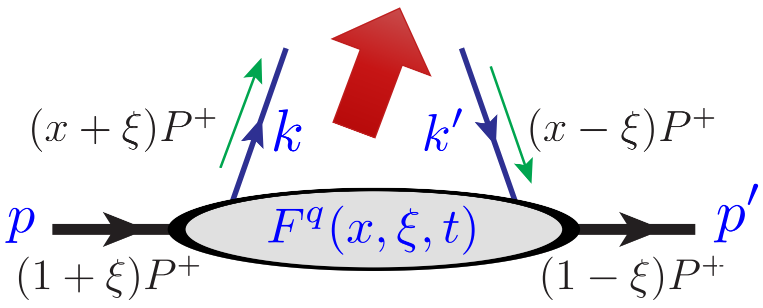

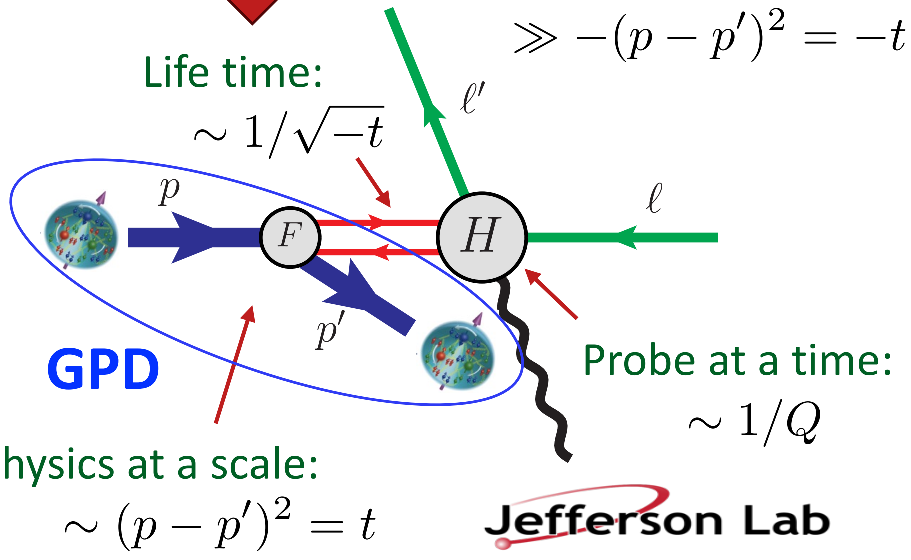

$$F^q(x,\xi,t) = \int \frac{\mathrm{d}z^-}{4\pi} e^{-ixP^+z^-} \langle p'|\bar{q}(z^-/2)\gamma^+ q(-z^-/2)|p\rangle$$

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

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Generalized Parton Distributions (GPDs)

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

- **Definition:**

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

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

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

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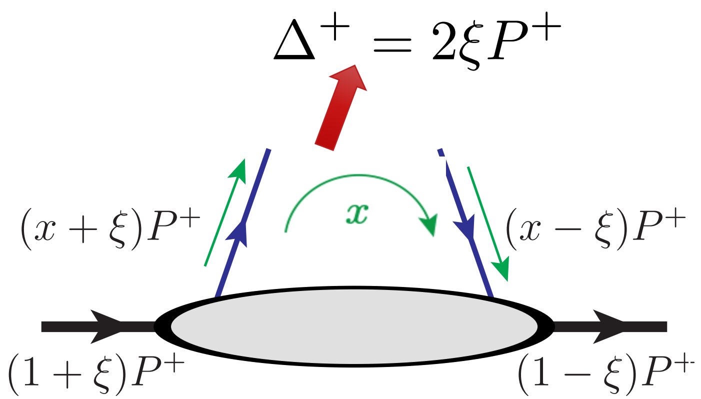


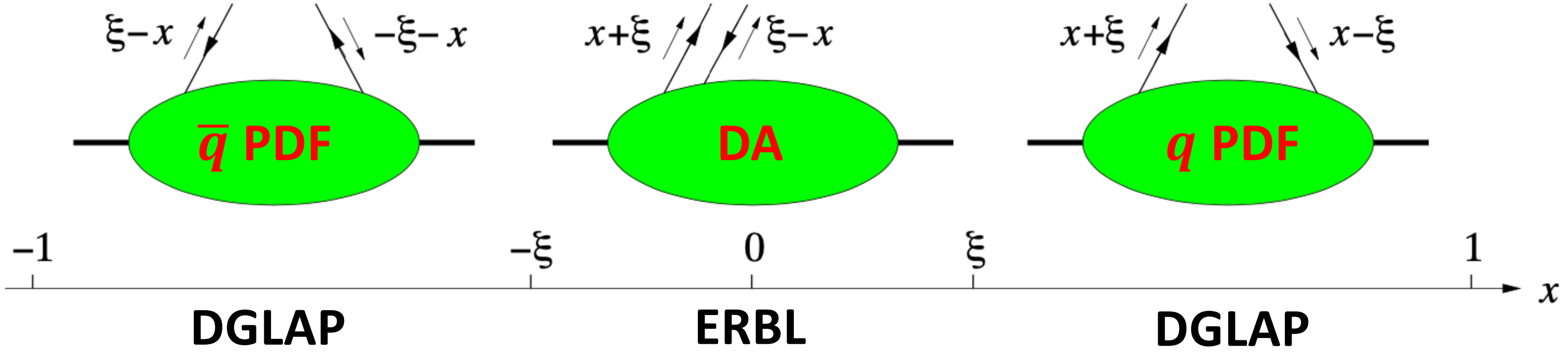
$$P^+ = \frac{p^+ + p'^+}{2}$$

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

Similar definition for gluon GPDs

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

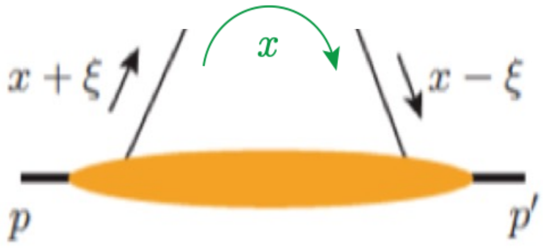
Forward limit $\xi = t = 0$ **:** $\quad H^q(x,0,0) = q(x), \quad \tilde{H}^q(x,0,0) = \Delta q(x)$



Properties of GPDs – Partonic

- **Impact parameter dependent parton density distribution:**

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



Measurement of p' fixes (t, ξ)

x = momentum flow between the pair

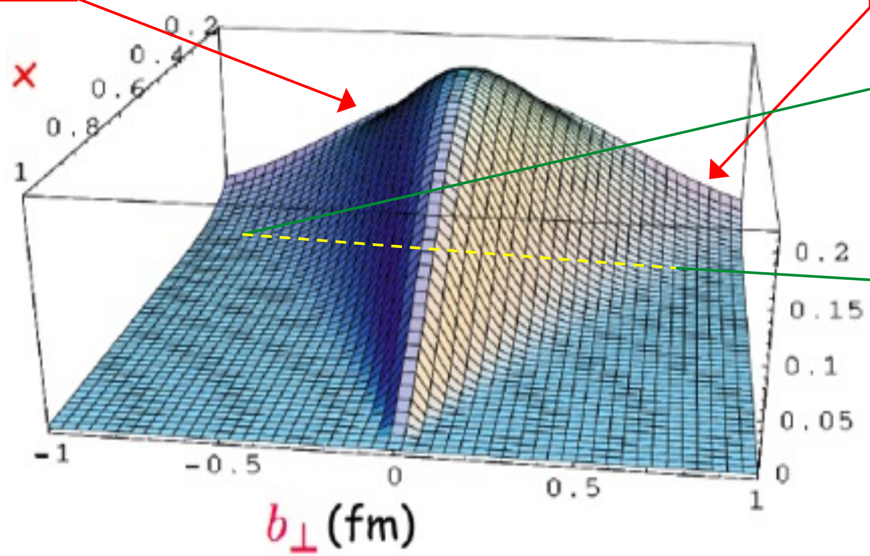
➡ **Quark density in** $\mathrm{d}x\,\mathrm{d}^2\boldsymbol{b}_T$

How fast does glue density fall?

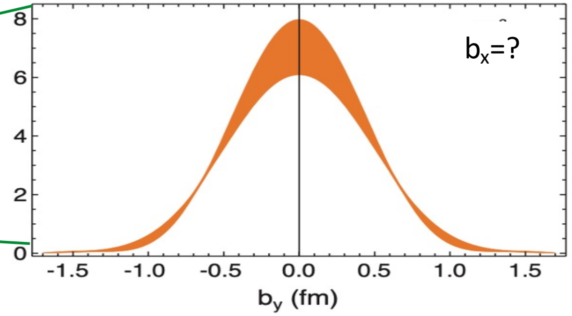
Tomographic image of hadron in slice of x

How far does glue density spread?

➡



Modeled by M. Burkdart, PRD 2000



Slice in (x,Q)

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

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

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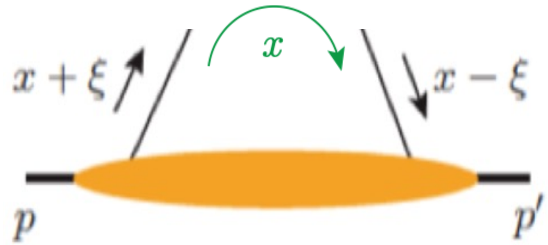

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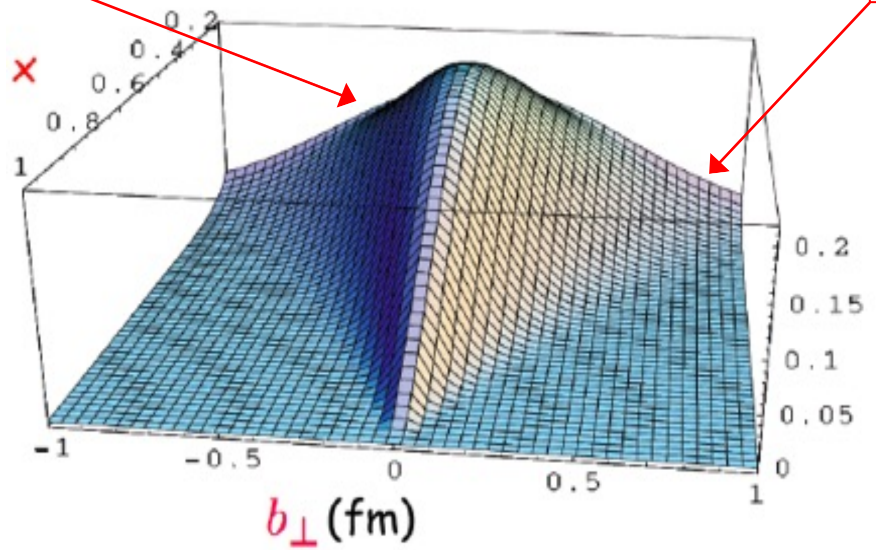

Modeled by M. Burkdart, PRD 2000

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

- **Should** $r_q(x)$ **>** $r_g(x)$**, or vice versa?**
- **Could** $r_g(x)$ **saturates as** $x \to 0$
- **How do they compare with known radius (EM charge radius, mass radius, …), & why?**
- **How the image correlate to hadron spin, … ?**
- …

Properties of GPDs – Hadronic = Moments of GPDs

Ji, PRL78, 1997
V. D. Burkert, et al. RMP 95 (2023) 041002

❑ 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 factors:

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

❑ Connection to GPD moments:

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

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

Related to pressure & stress force inside h

Polyakov, schweitzer, Inntt. J. Mod. Phys. A33, 1830025 (2018)
Burkert, Elouadrhiri , Girod Nature 557, 396 (2018)

❑ Angular momentum sum rule:

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

➡ **3D tomography**
Relation to GFFs
Angular Momentum ➡ ***x*-dependence of GPDs!**

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

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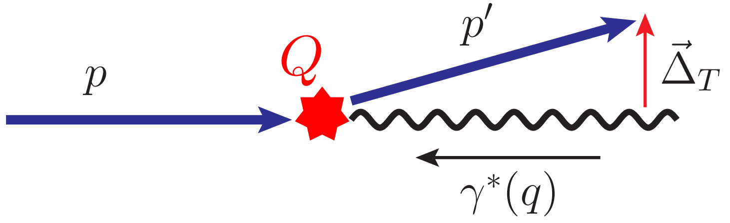
Known Physical Processes for Extracting GPDs

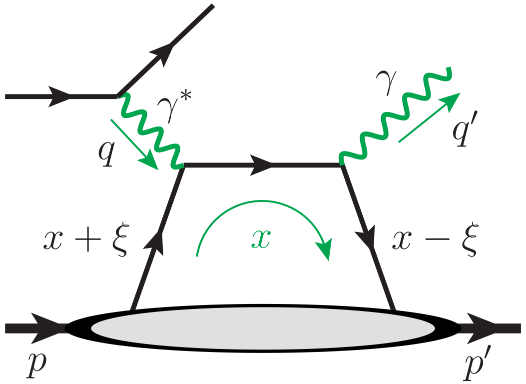
- **Hit the proton hard without breaking it** $\Longrightarrow$ **Diffractive scattering to keep proton intact**



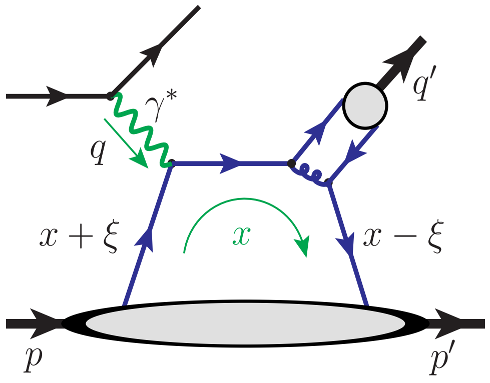
HERA discovery:

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

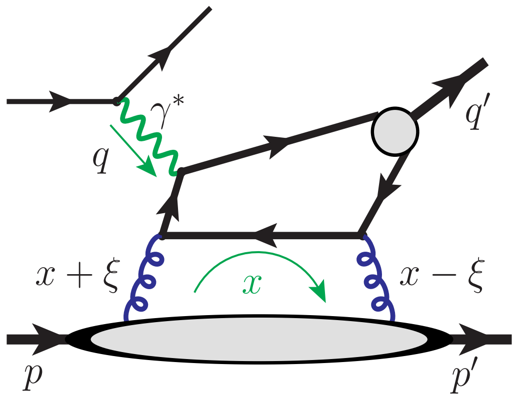
- **Known exclusive processes for extracting GPDs:**



DVCS: Q² >> |t|



DVMP



DVQP

+ DDVCS, …

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

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

Factorization

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

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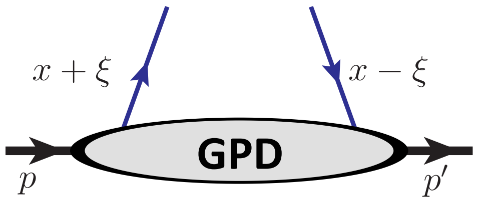
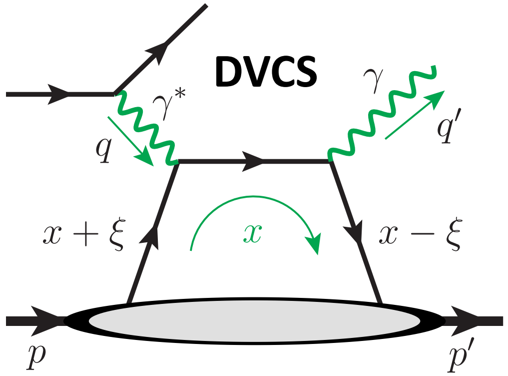
Why is the GPD's *x*-dependence so *difficult* to measure?

❑ Amplitude nature: exclusive processes



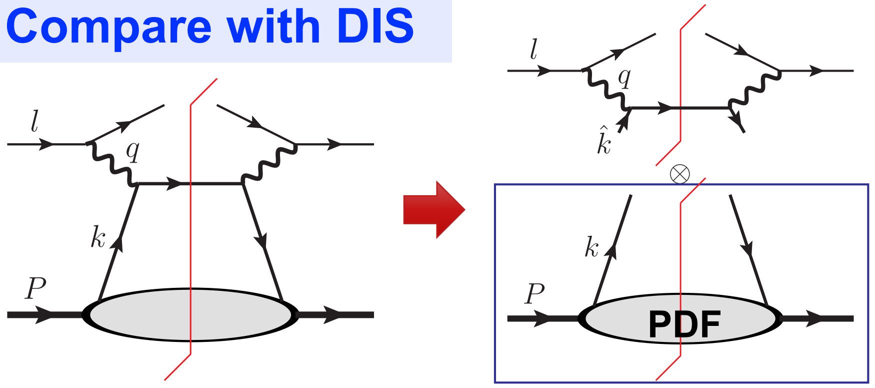
x **~ loop momentum**



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

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

Compare with DIS



cross section**: cut diagram**

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

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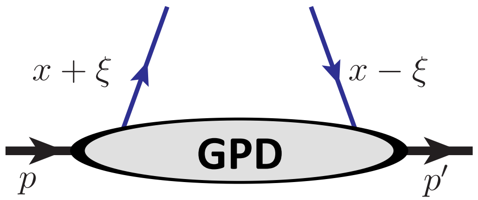

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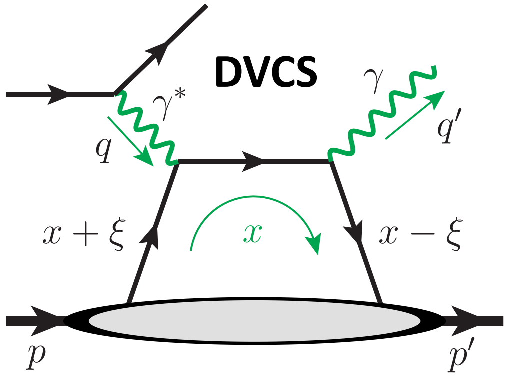

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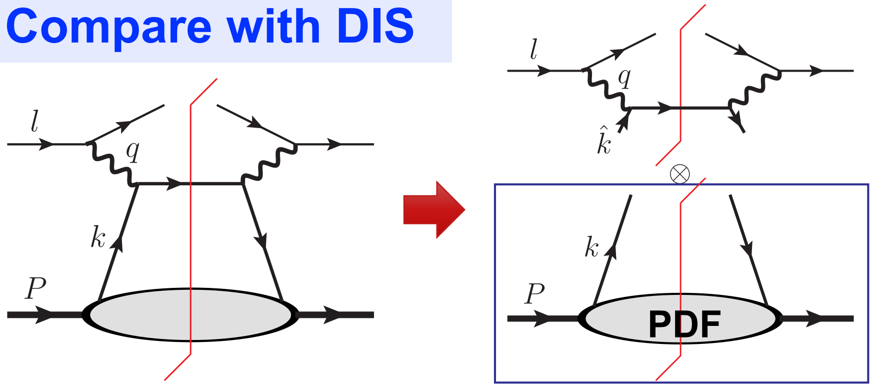


***cross section*: cut diagram**

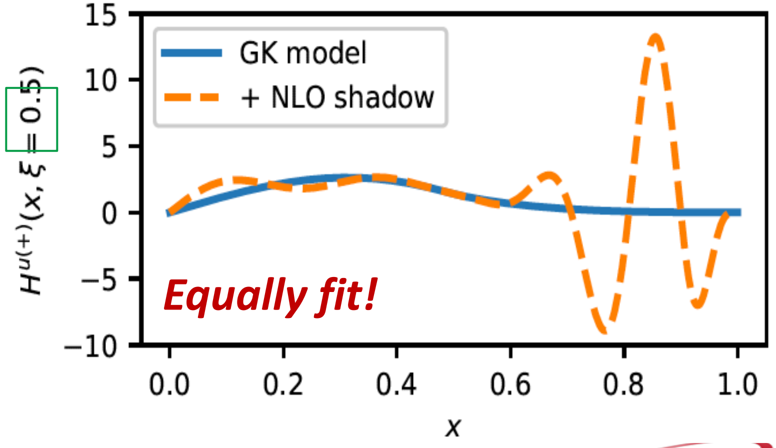
$$\sigma_{\mathrm{DIS}} \simeq \int_{x_B}^{1} \mathrm{d}x\, f(x)\, \hat{\sigma}(x/x_B)$$

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

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

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

“moment”



[Bertone et al. PRD `21]

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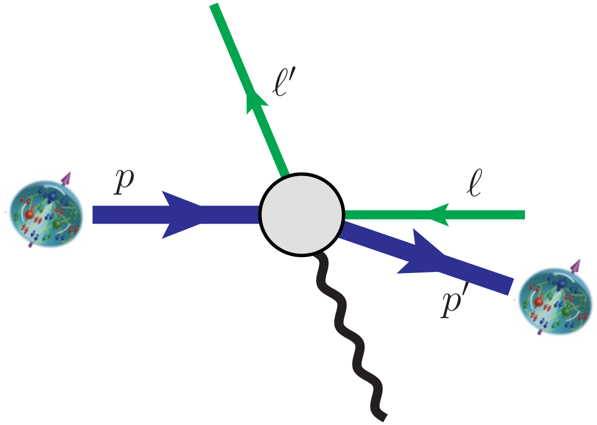
How to Find Physical Processes to be Sensitive to GPDs?

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

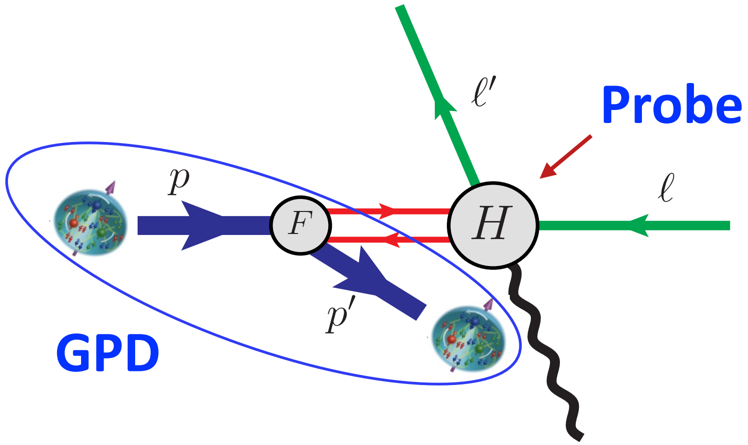
- **Single diffractive hard exclusive processes (SDHEPs):**

DVCS in Lab Frame: $h(p) + B(p_2) \to h'(p') + C(q_1) + D(q_2)$



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

$$Q^2 \gg -t$$



2 → 3
Minimal
kinematic configuration!

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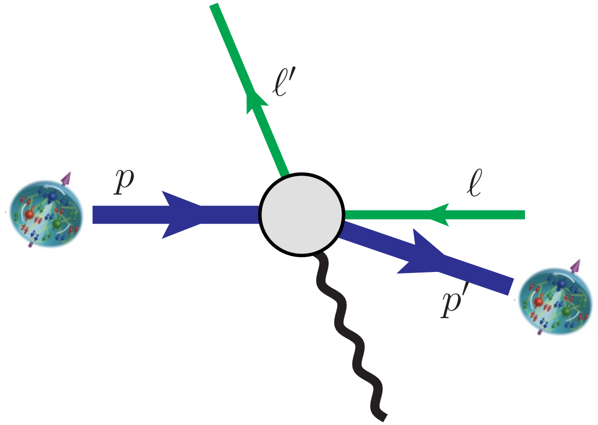
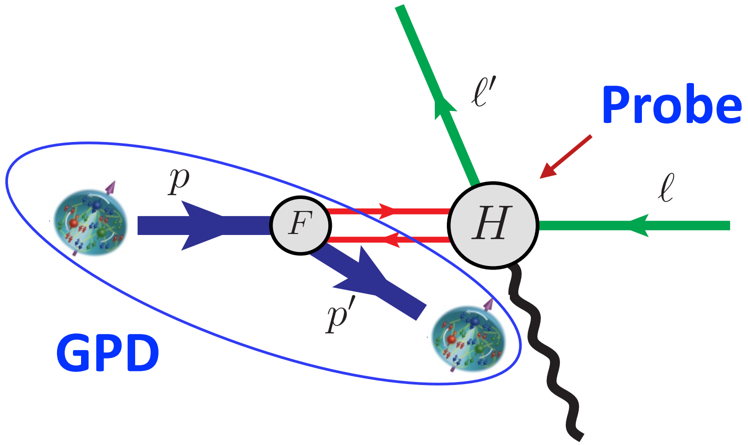


$$Q^2 = -(\ell - \ell')^2$$
$$-t = -(p - p')^2$$

$$\boxed{Q^2 \gg -t}$$



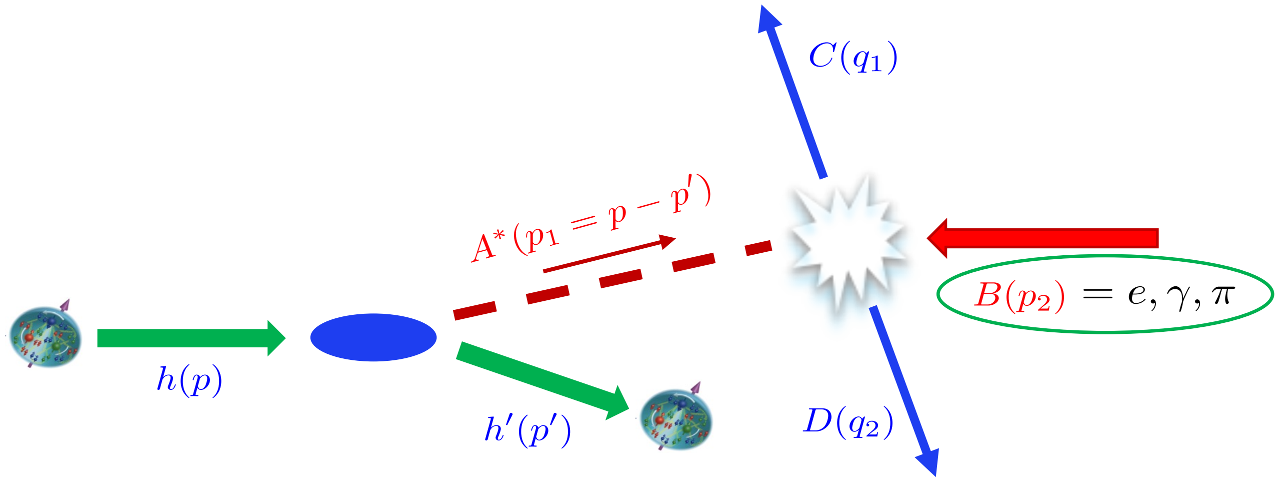
2 → 3
Minimal
kinematic configuration!

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

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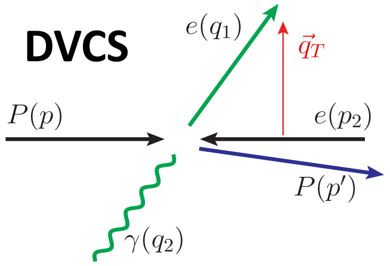
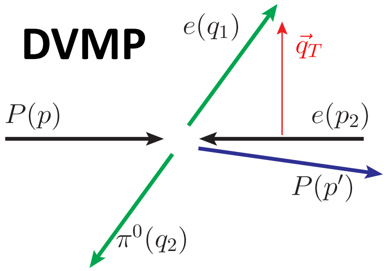
Classification of SDHEPs

❑ Electro-production (JLab, EIC, …)

DVCS

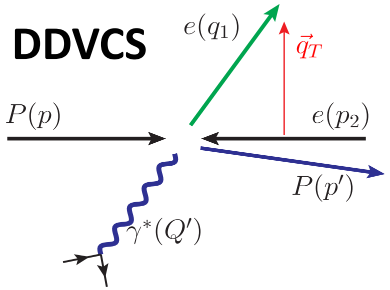


DVMP



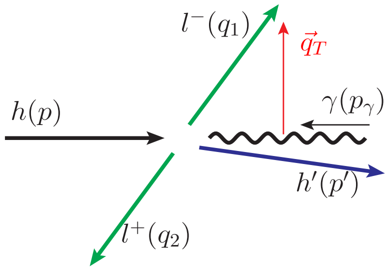
add virtuality

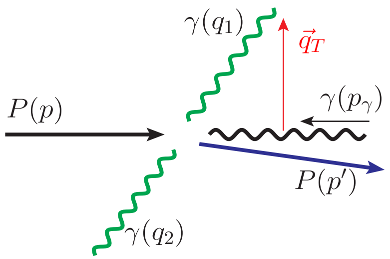
DDVCS

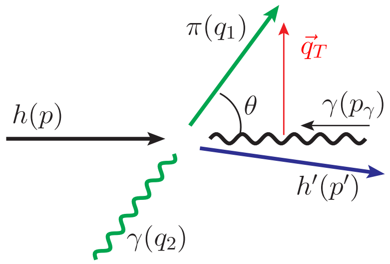


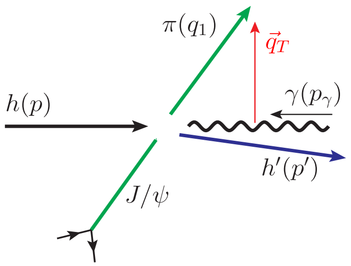
DHQP…

❑ Photo-production (JLab, EIC, …)

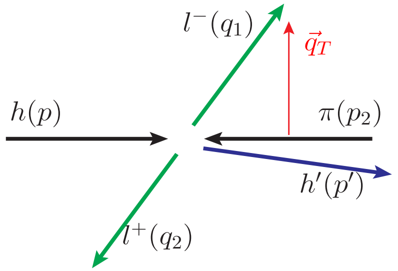


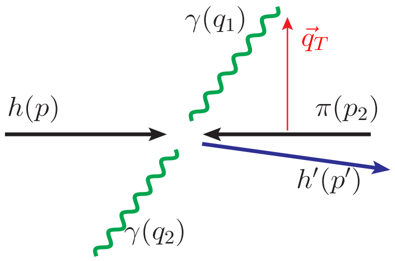






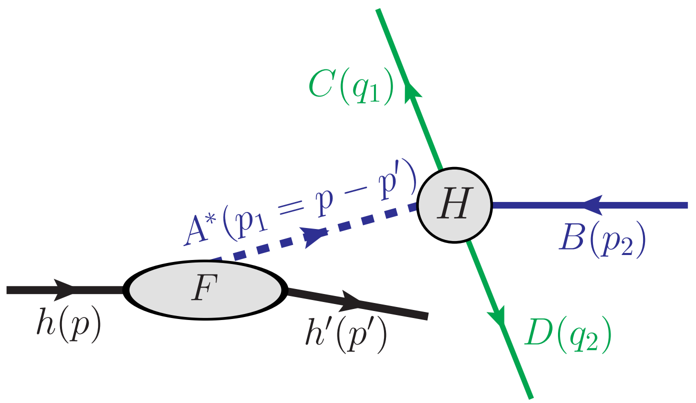
❑ Meso-production (AMBER, J-PARC, …)



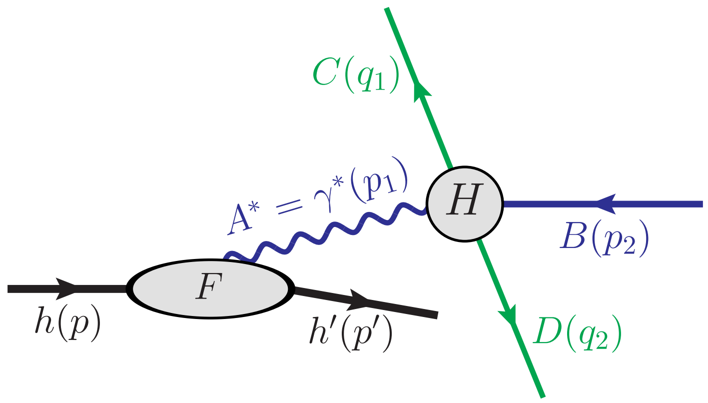


…

SDHEP: Two-stage Paradigm and Power Expansion

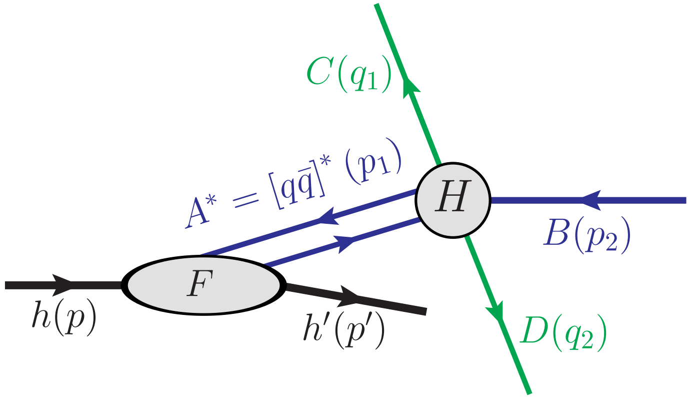


$=$

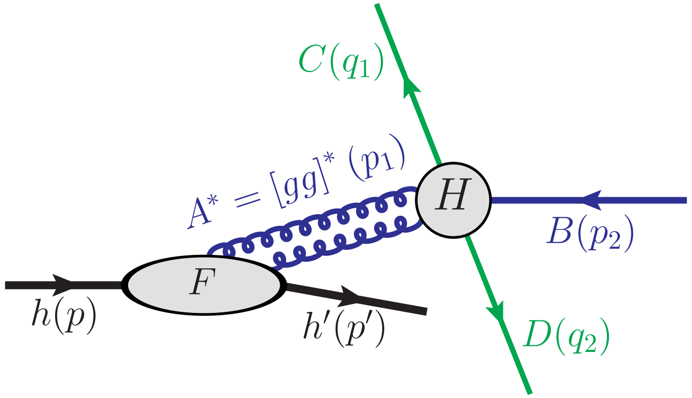


Leading Power in 1/Q

$+$



$+$

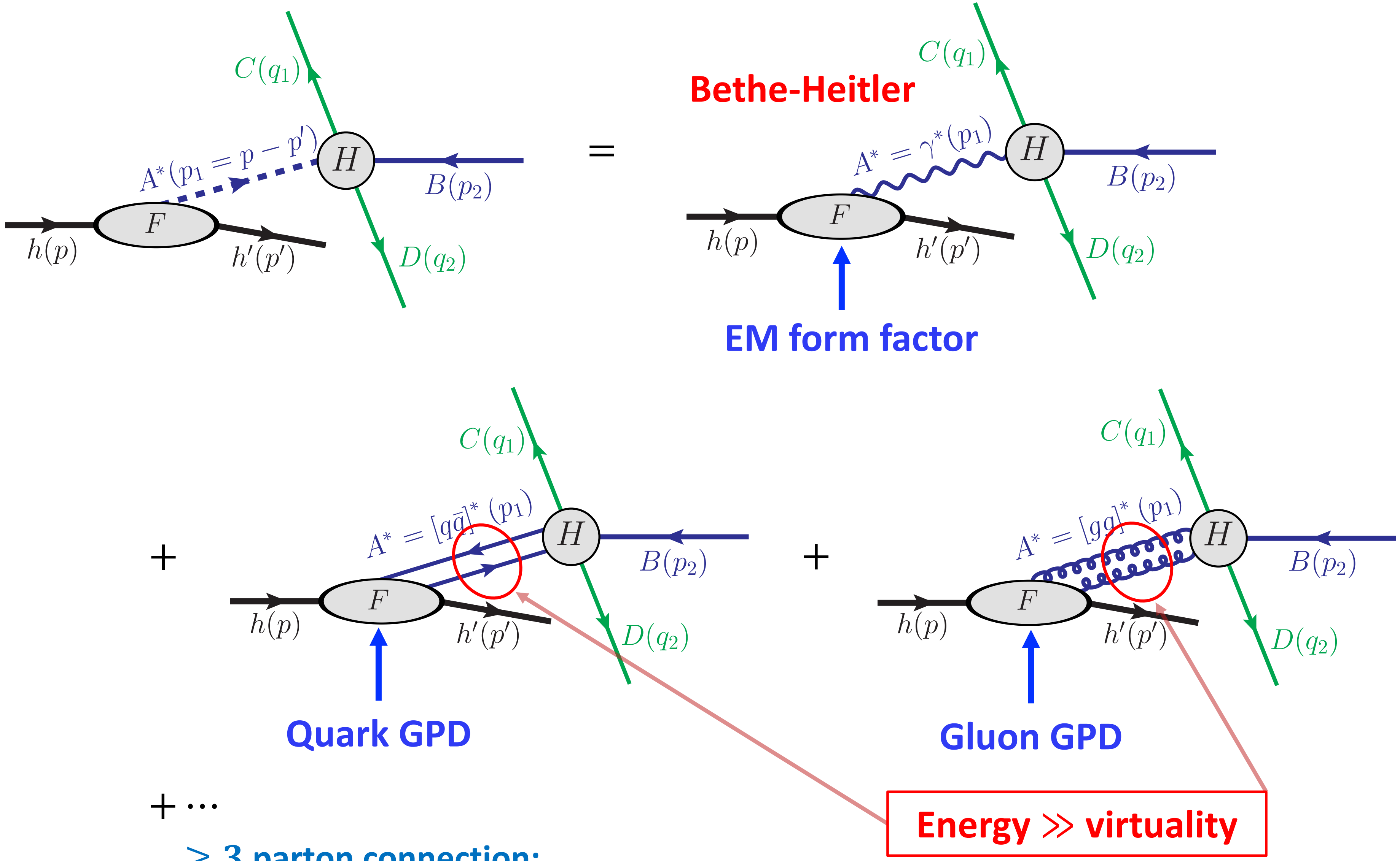


Next Leading Power in 1/Q

$+ \cdots$

$\geq$ 3 parton connection: further Power suppressed

SDHEP: Two-stage Paradigm and Power Expansion



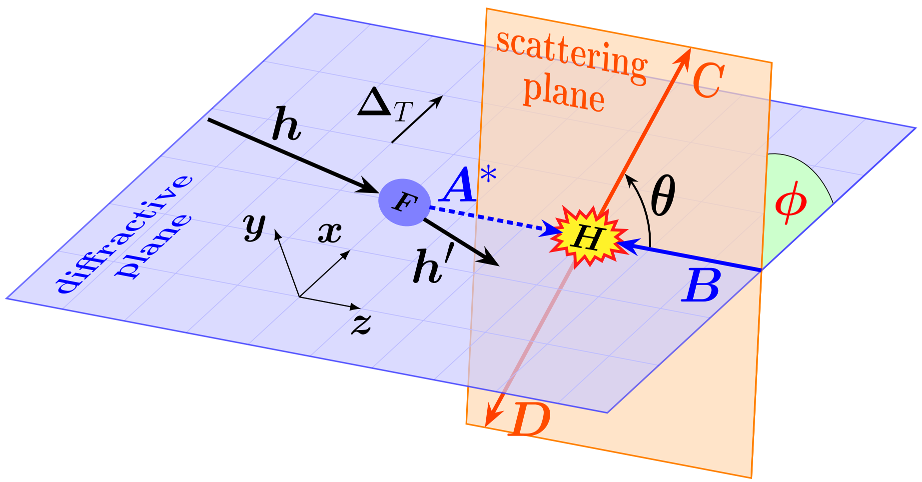
Leading Power in 1/Q

Next Leading Power in 1/Q

$\geq$ 3 parton connection:
further Power suppressed

→ To be factorized into GPD

Where does the *x*-sensitivity come from?



- **x-sensitivity ⇔ 2 → 2 hard scattering:**

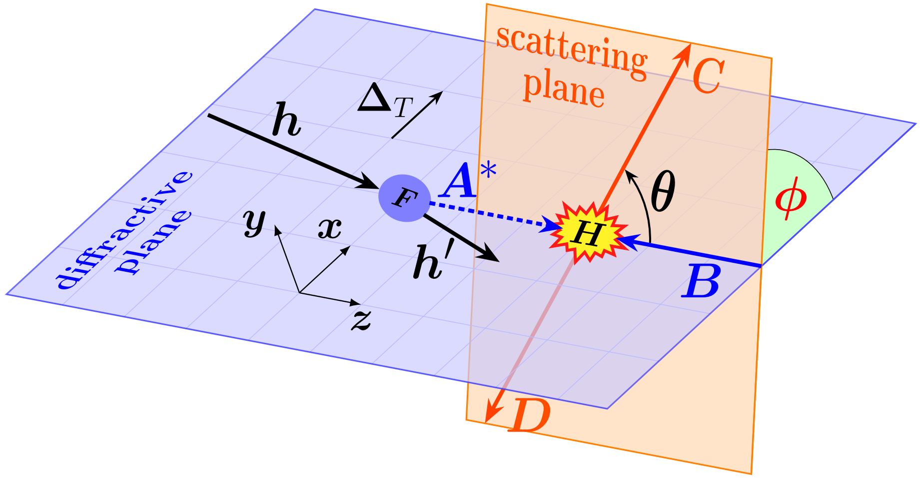
Kinematics:

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 does the x-sensitivity come from?



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

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[suppressing t and ξ dependence]

- **Moment-type sensitivity:** $C(x;Q) = G(x)\cdot T(Q)$ ⟶ $F_G = \int_{-1}^{1} dx\, G(x)\, F(x,\xi,t)$ **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:** $C(x;Q) \neq G(x)\cdot T(Q)$ ⟶ $d\sigma/dQ \sim |C(x;Q)\otimes_x F(x,\xi,t)|^2$

Moment-type Sensitivity: $h(p) + B(p_2) \to h'(p') + C(q_1) + D(q_2)$

PRD56 (1997) 5524; PRD58 (1998) 094018; PRD59 (1999) 074009

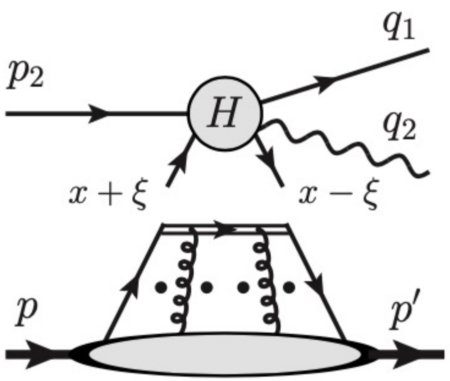
- **DVCS:**

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

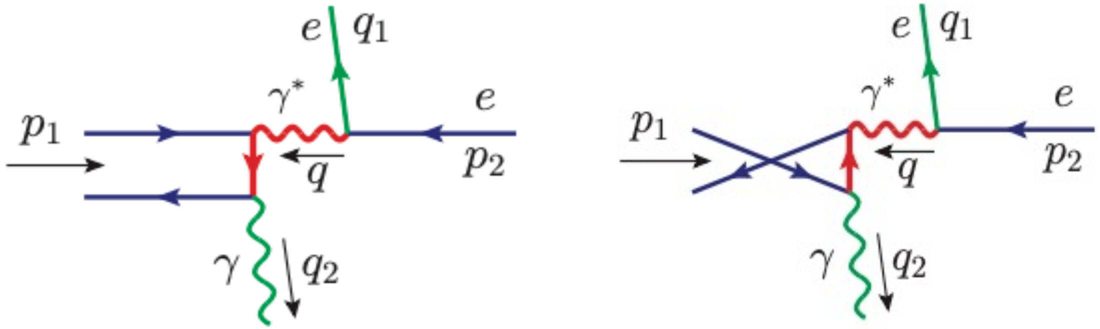
Factorization:

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

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



LO:



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

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

The x-integration is NOT sensitive to externally measured hard scale, q_T or Q^2!

Need a very large range of Q^2, but, cross section is strongly suppressed!

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Moment-type Sensitivity: $h(p)+B(p_2)\to h'(p')+C(q_1)+D(q_2)$

❑ DVCS:

PRD56 (1997) 5524; PRD58 (1998) 094018; PRD59 (1999) 074009

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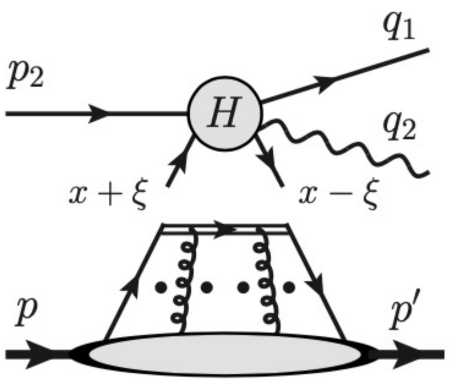
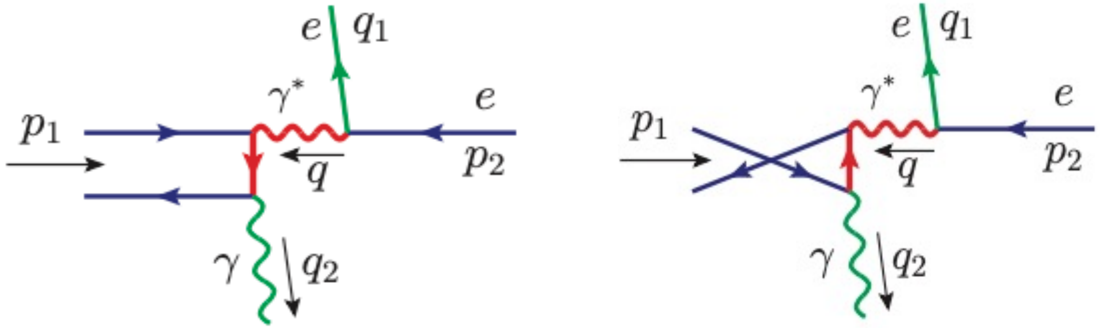


LO:



$$\Rightarrow\quad C^{(0)}\propto\frac{1}{x-\xi+i\varepsilon}-\frac{1}{x+\xi-i\varepsilon}\quad\Rightarrow\quad \mathcal{M}^{(2)}_{he\to h'e\gamma}=\sum_i\int_{-1}^{1}\mathrm{d}x\,F_i^h(x,\xi,t)\,C_{ie\to e\gamma}(x,\xi,q_T),$$

The x-integration is NOT sensitive to externally measured hard scale, q_T or Q^2!

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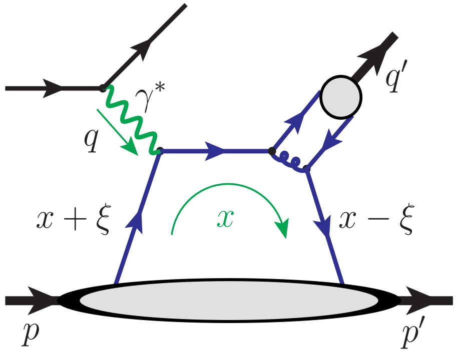
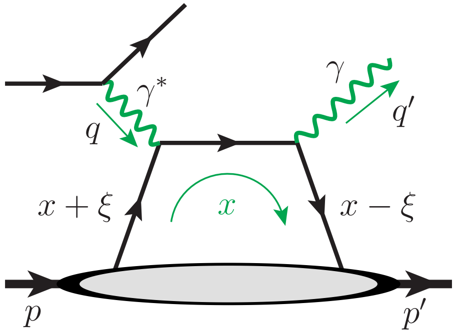
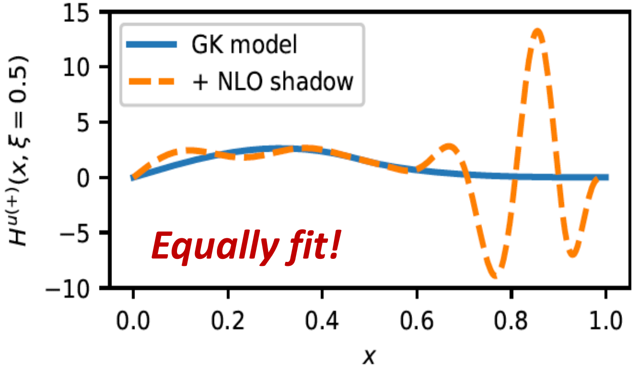
❑ DVMP:



Similar to





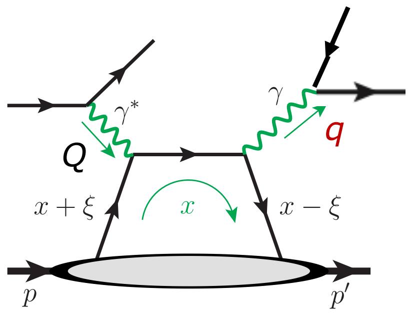
[Bertone et al. PRD `21]

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):**

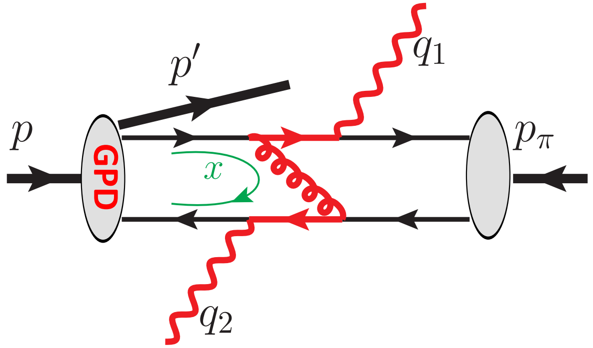
$$x_p(\xi,q) = \xi \left(\frac{1 - q^2/Q^2}{1 + q^2/Q^2}\right) \to \xi \quad \text{same as DVCS if } q \to 0$$

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

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

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

Qiu & Yu
JHEP 08 (2022) 103



- **Factorization:**

[*suppressing pion DA factor*]

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

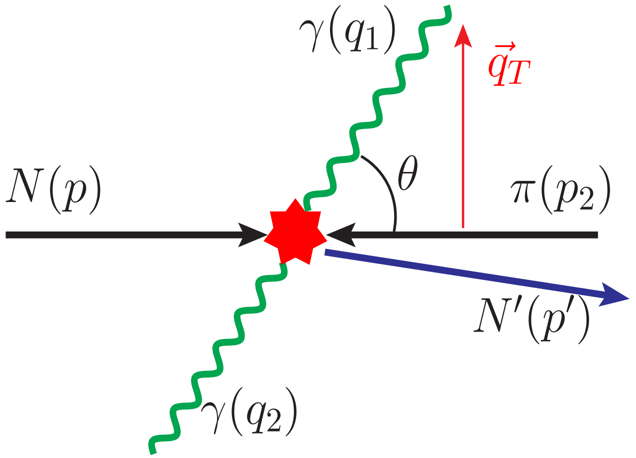
$$\frac{\mathrm{d}\sigma}{\mathrm{d}t\ \mathrm{d}\xi\ \mathrm{d}q_T} \sim |\mathcal{M}(t,\xi,q_T)|^2$$

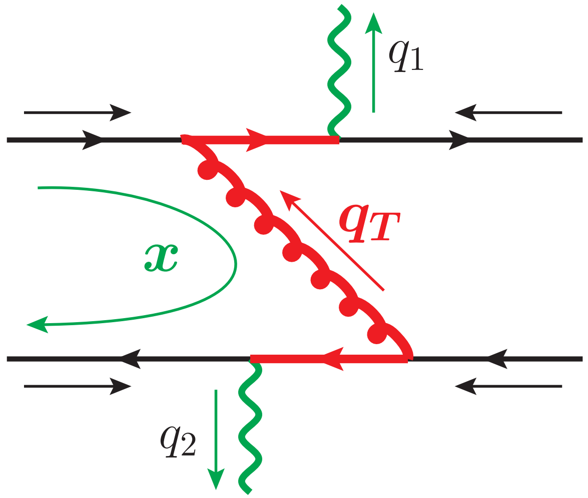
q_T distribution is "conjugate" to *x* distribution

$$x \leftrightarrow q_T$$

Enhanced x-Sensitivity: (1) Diphoton Meso-production

Qiu & Yu, PRD 109 (2024) 074023





In addition to

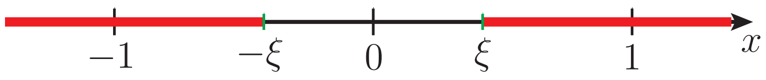
$$F_0(\xi, t) = \int_{-1}^{1} \frac{dx\, F(x, \xi, t)}{x - \xi + i\epsilon}$$

When two photons are radiated from the same charged line

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

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

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



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Enhanced x-Sensitivity: (1) Diphoton Meso-production

Qiu & Yu, PRD 109 (2024) 074023

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

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

Nucleon transition GPDs

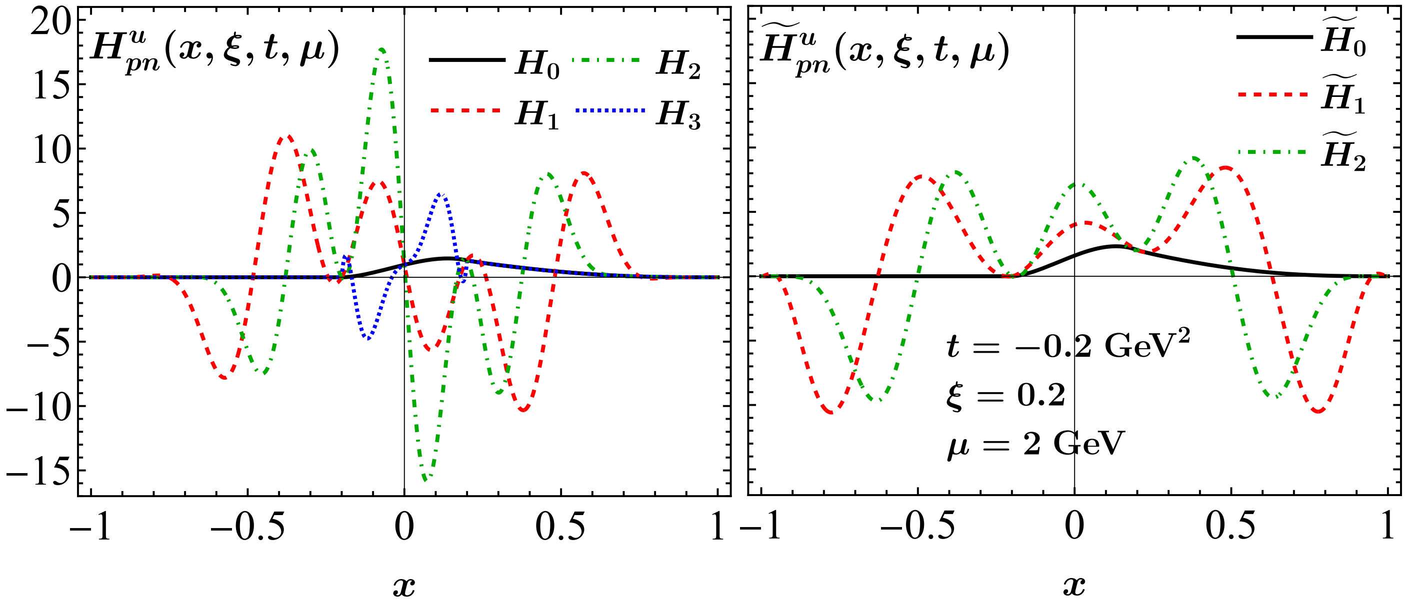
$$H^u_{pn} = H^u_p - H^d_p, \text{ etc.}$$

GPD models = GK model + shadow GPDs

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

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

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



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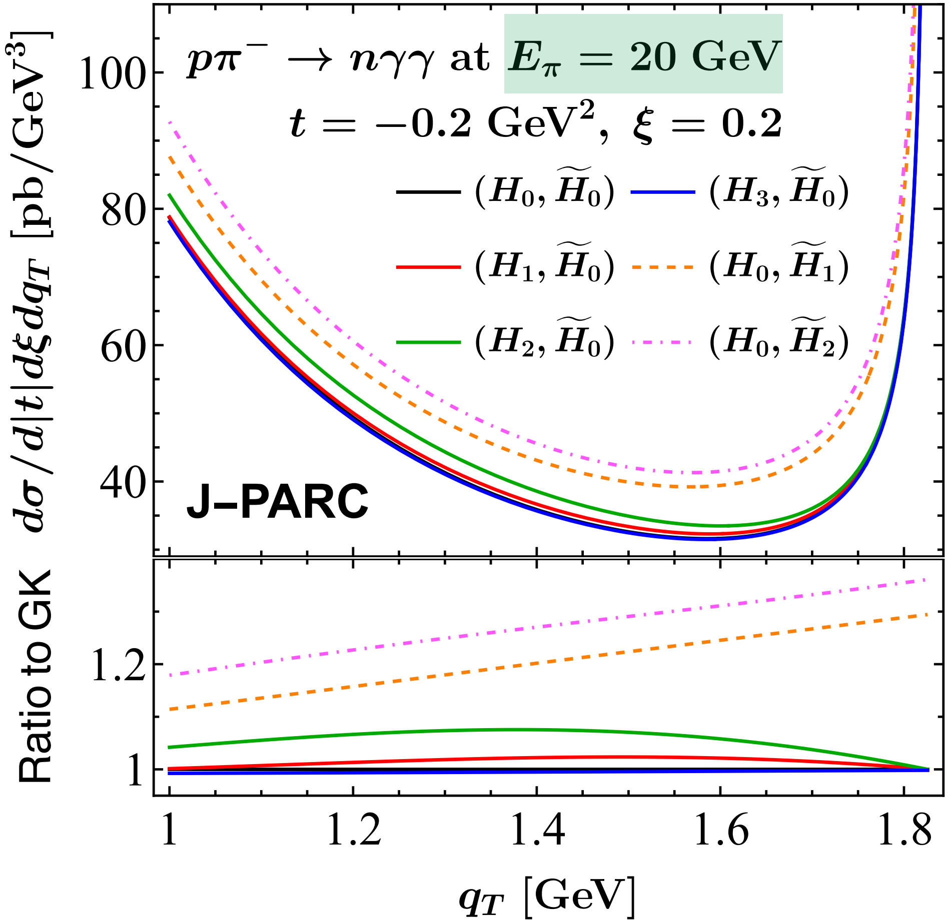
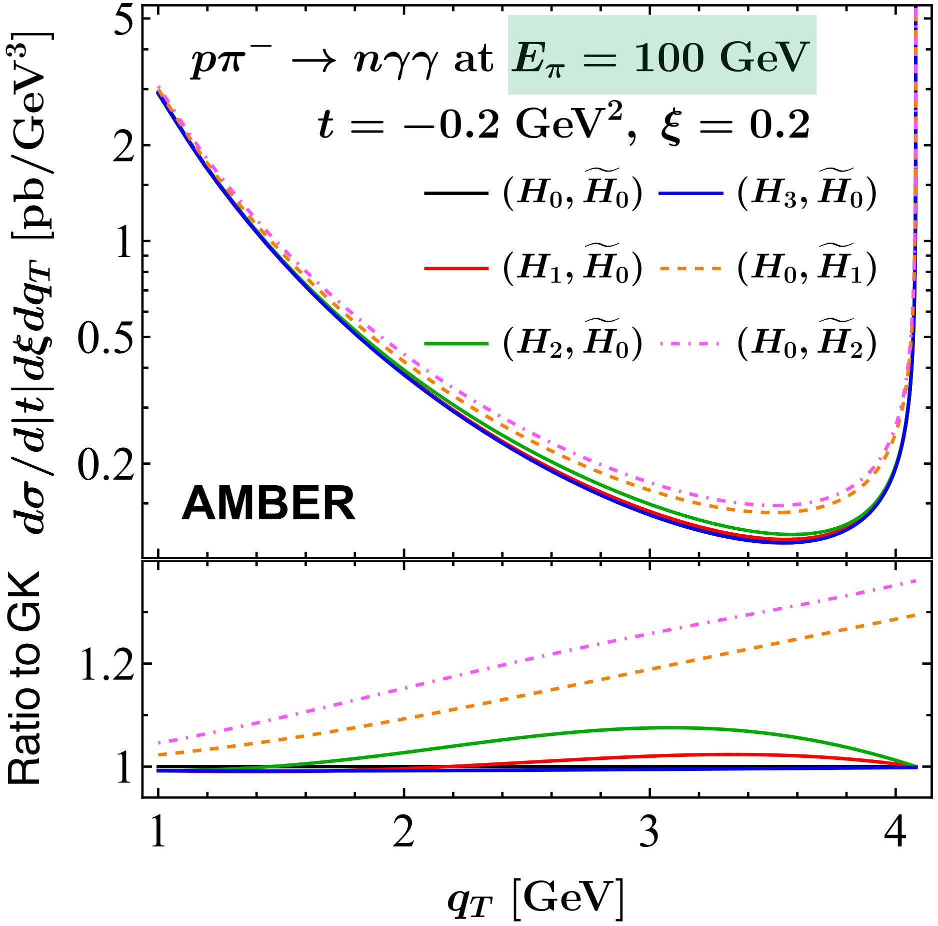
Qiu & Yu, PRD 109 (2024) 074023





Jefferson Lab

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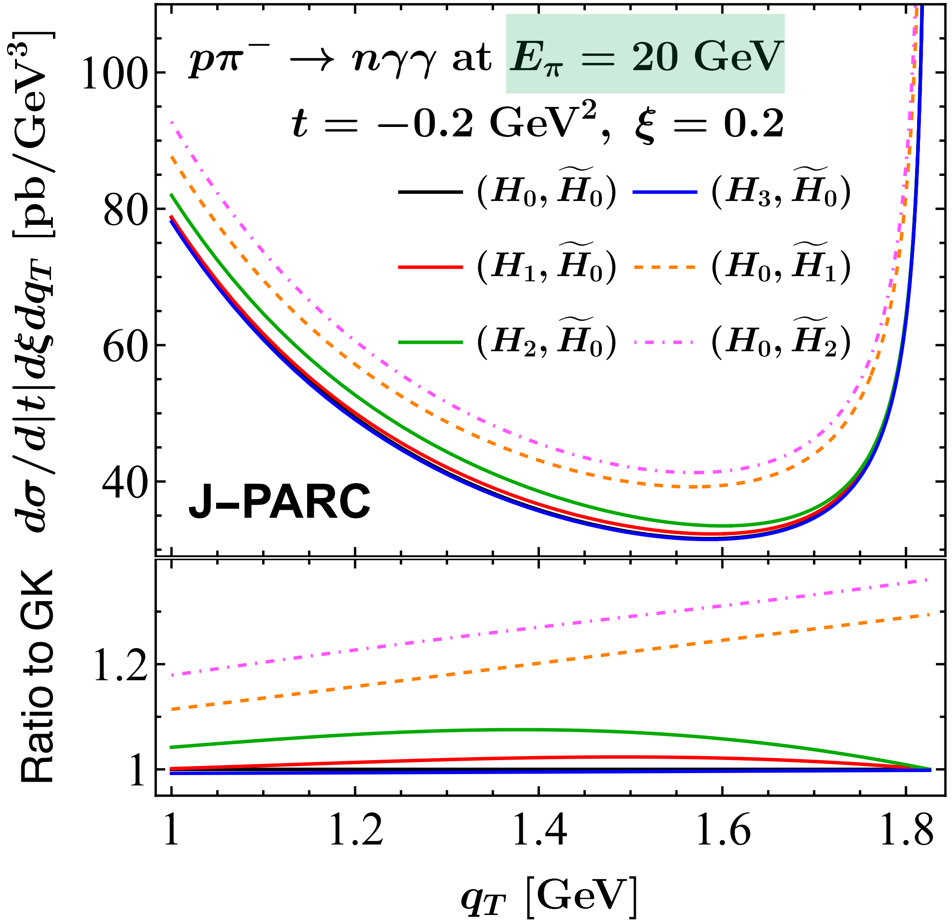
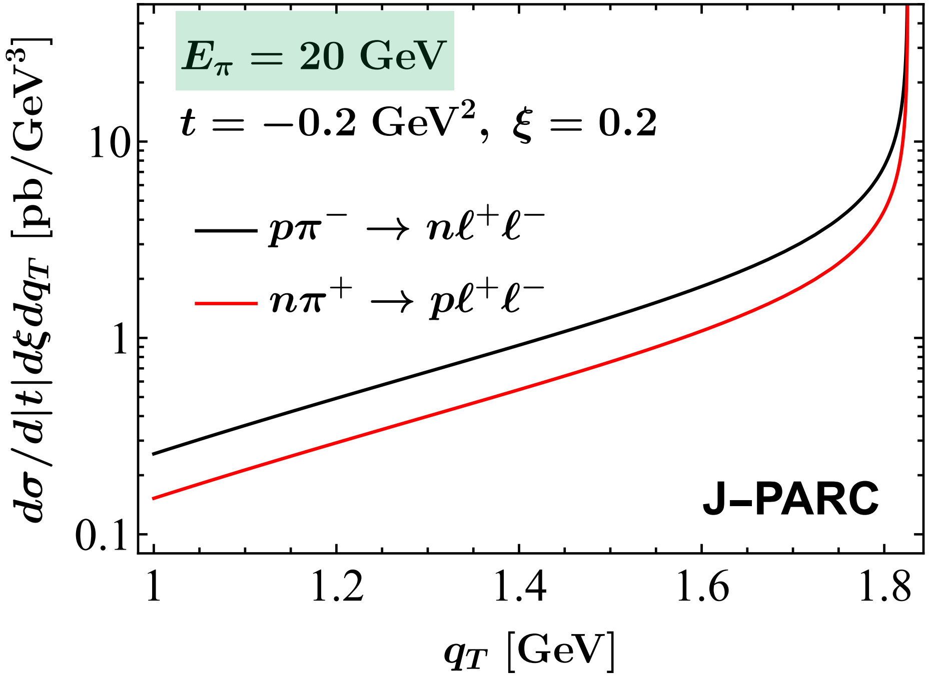
Qiu & Yu, PRD 109 (2024) 074023



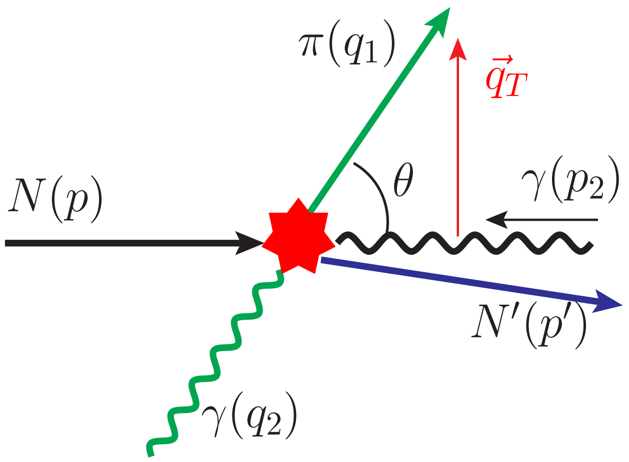
❑ Exclusive Drell-Yan dilepton production

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



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

Enhanced x-Sensitivity: (2) γ-π Pair Photoproduction

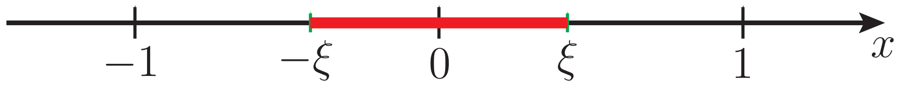


$i\mathcal{M}$ **also contains the special integral:**

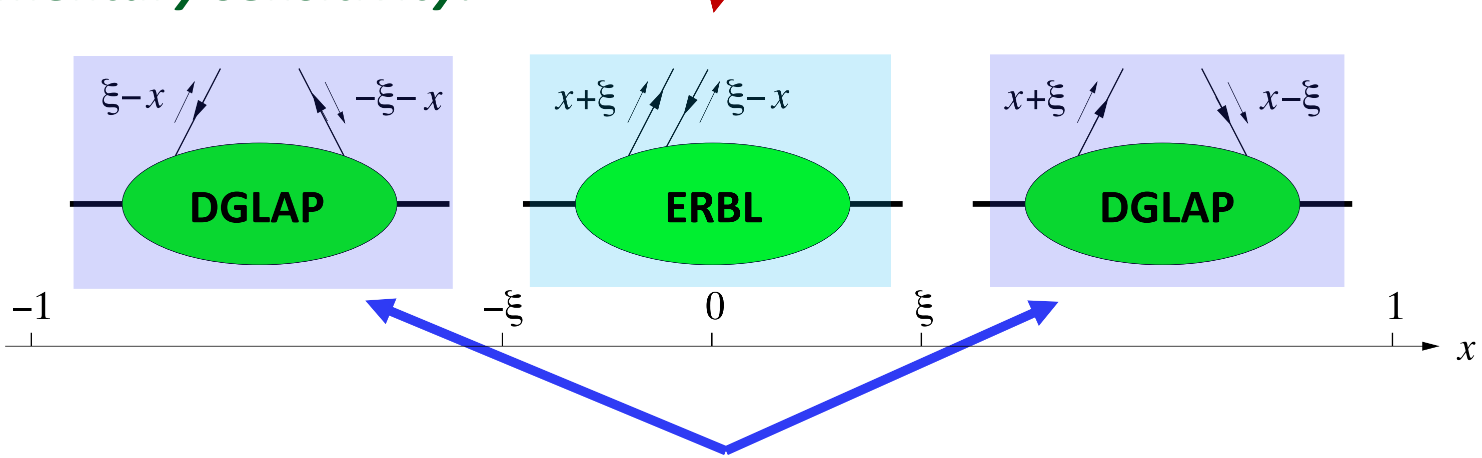
G. Duplancic et al., JHEP 11 (2018) 179
G. Duplancic et al., JHEP 03 (2023) 241
G. Duplancic et al., PRD 107 (2023), 094023
Qiu & Yu, PRL 131 (2023), 161902

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

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



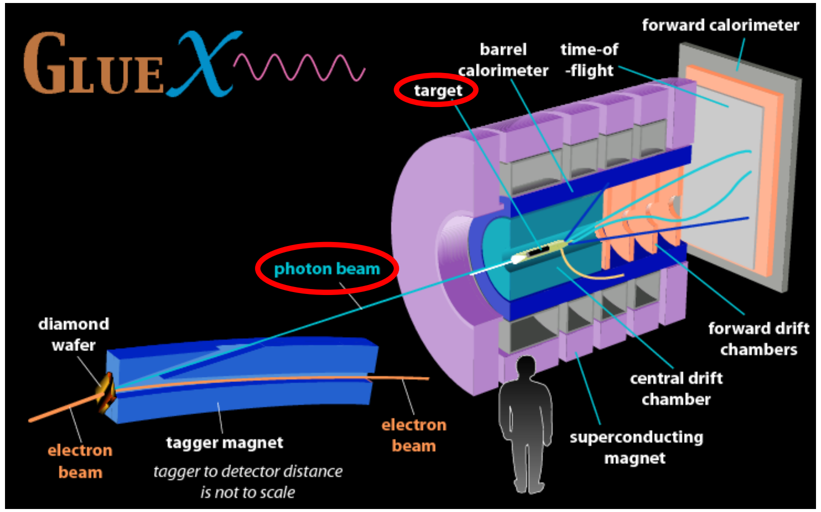
Complementary sensitivity:

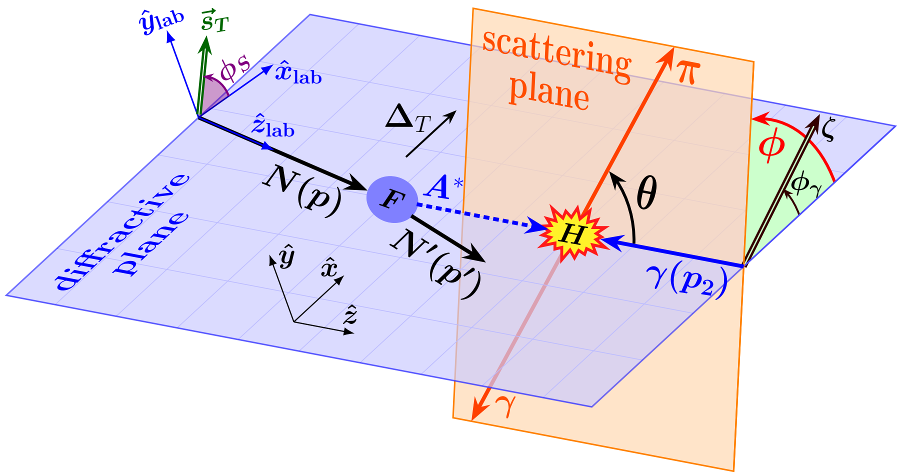


$N\,\pi \to N'\,\gamma\,\gamma$

Enhanced x-Sensitivity: (2) γ-π Pair Photoproduction (at JLab Hall D)

Qiu & Yu, PRL 131 (2023), 161902





❑ Polarization asymmetries:

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

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

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

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

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

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

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

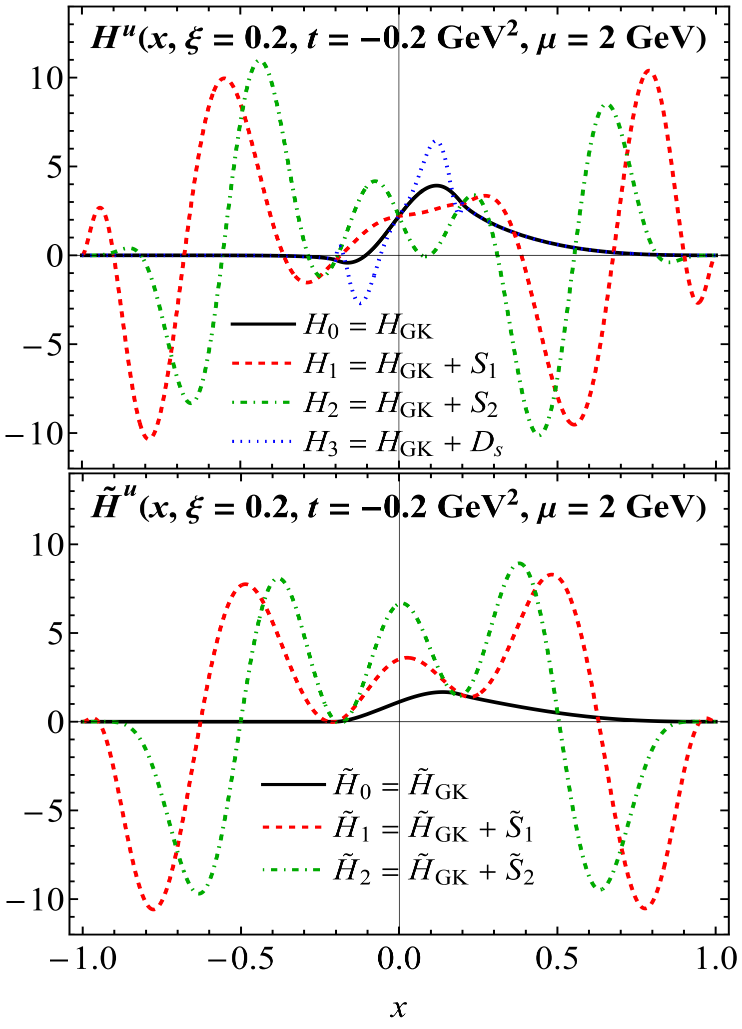
27

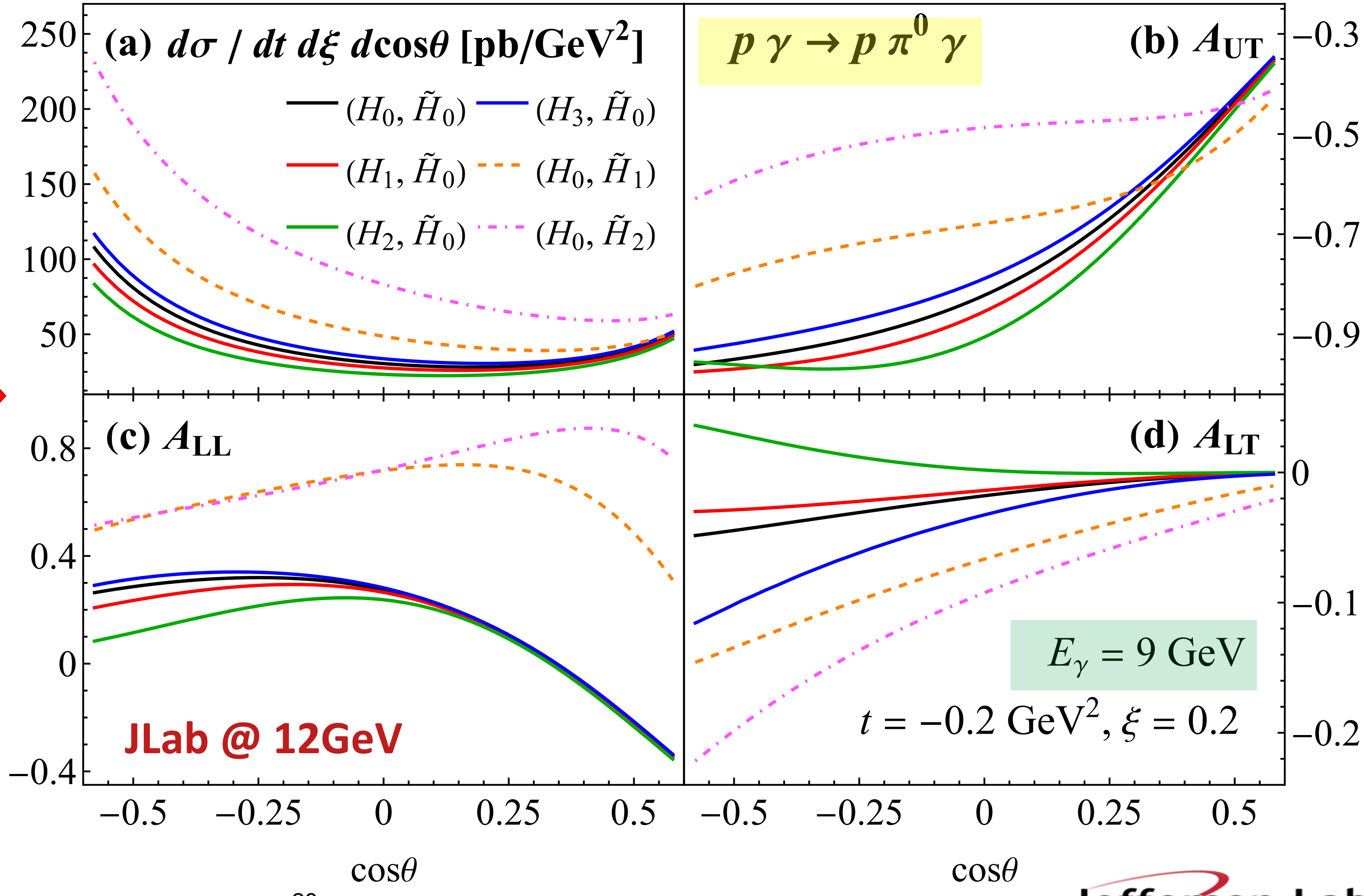
Enhanced x-sensitivity: (2) γ-π pair photoproduction (at JLab Hall D)

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

GPD models = GK model + shadow GPDs

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





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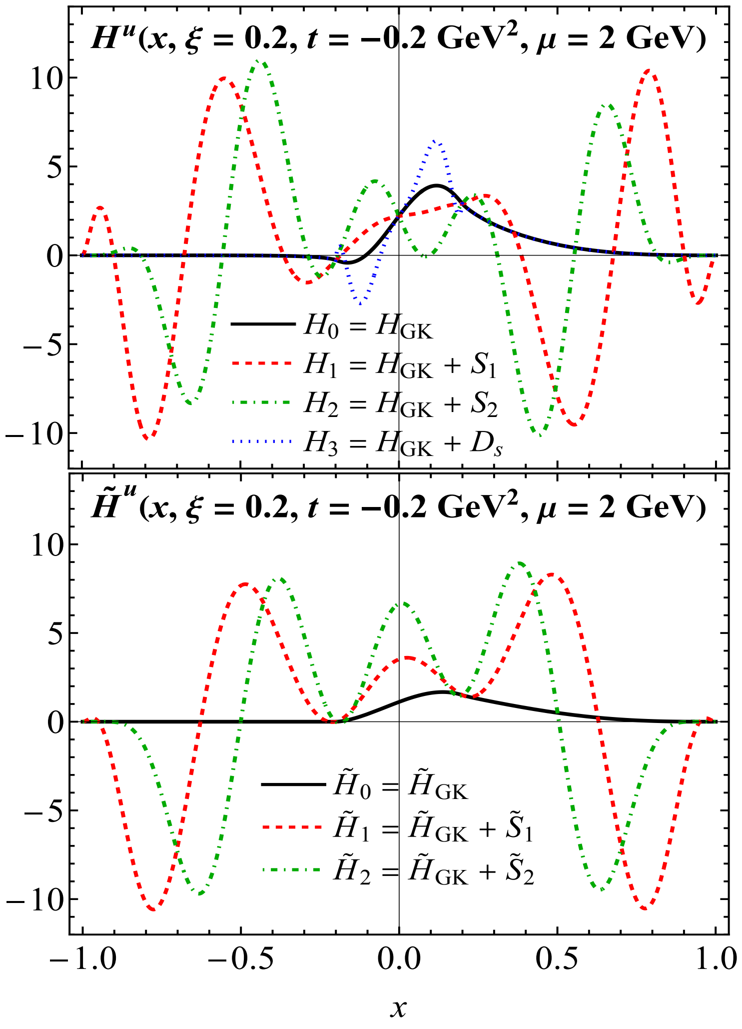
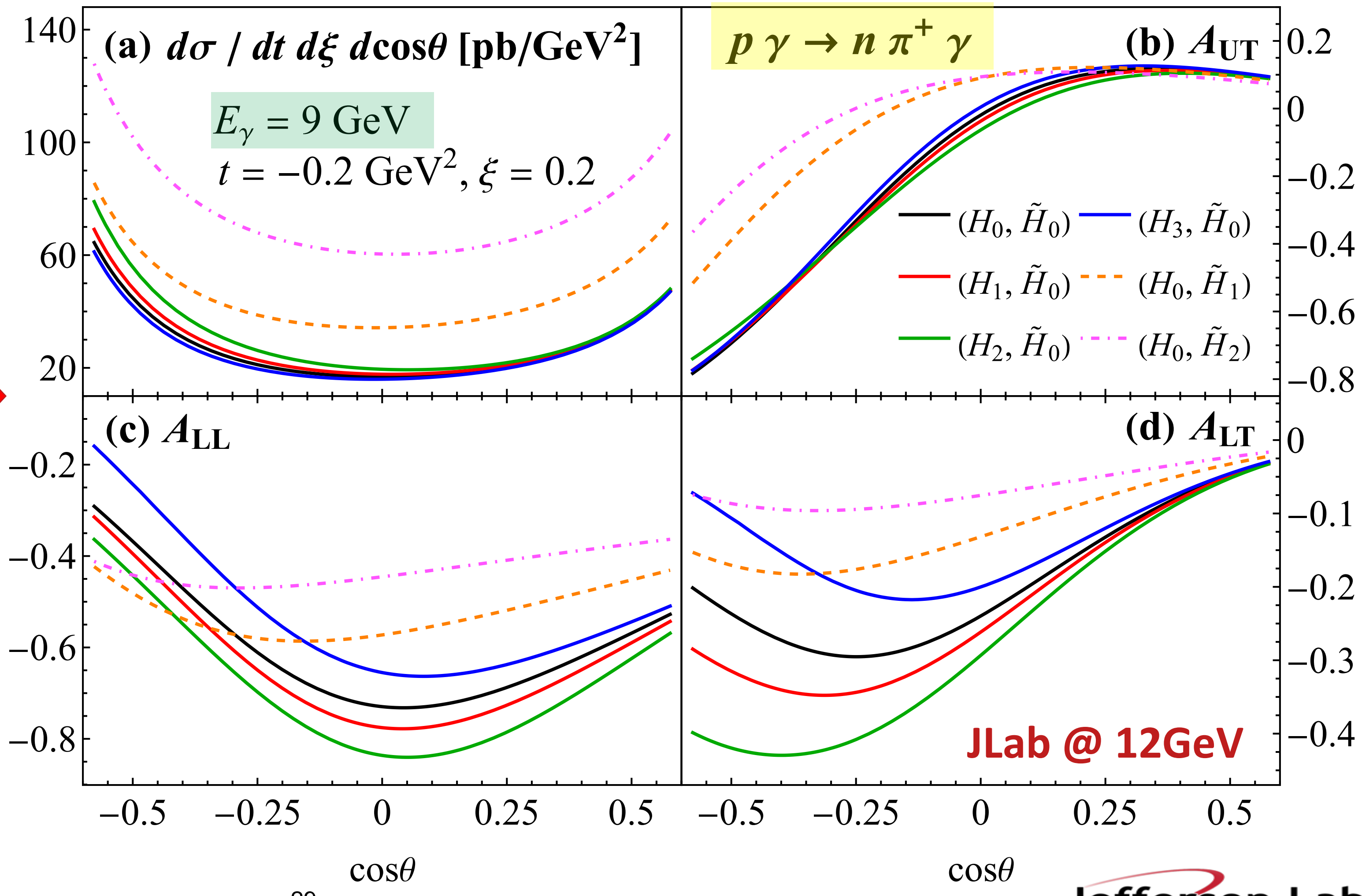
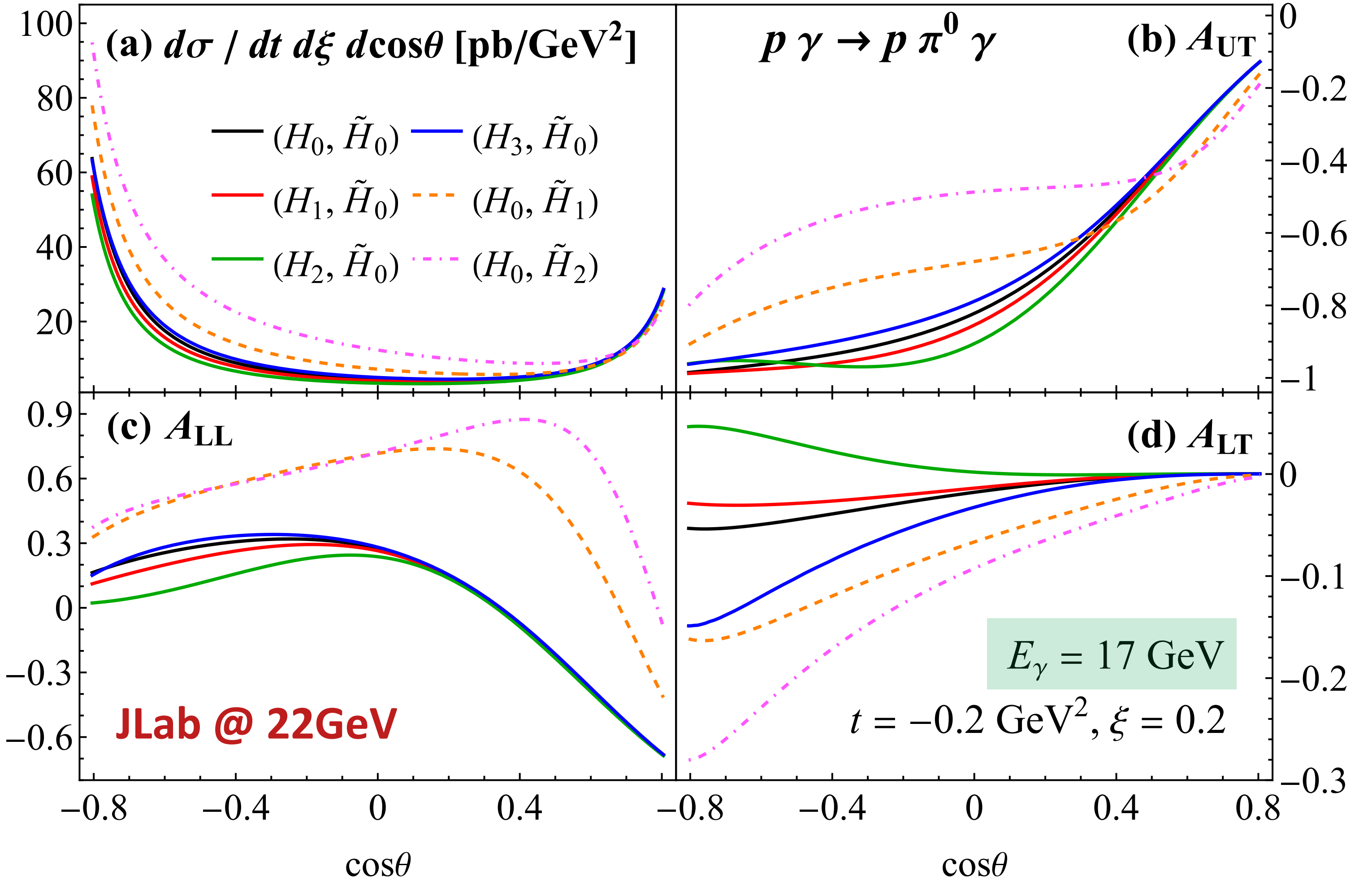


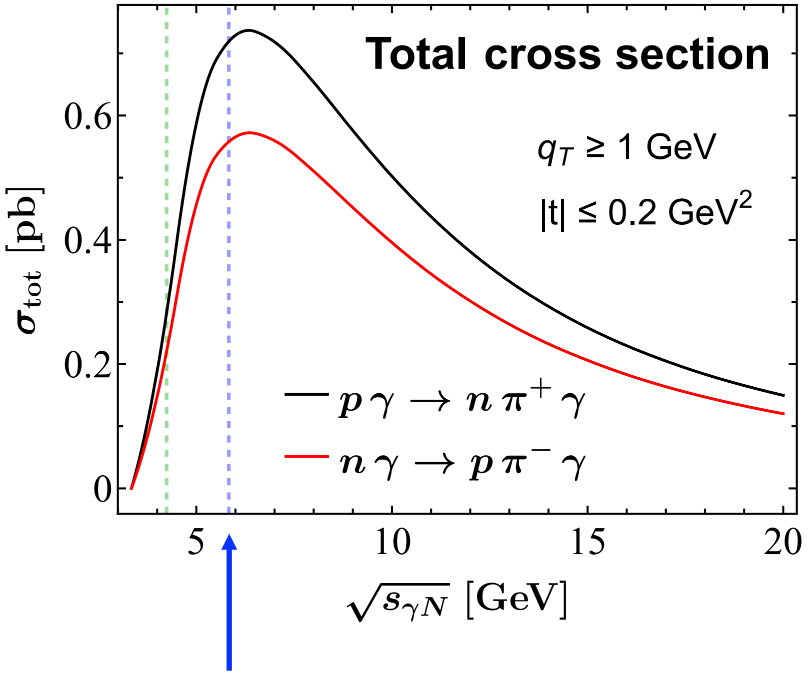


Enhanced x-sensitivity: (2) γ-π pair photoproduction (at upgraded energy)

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



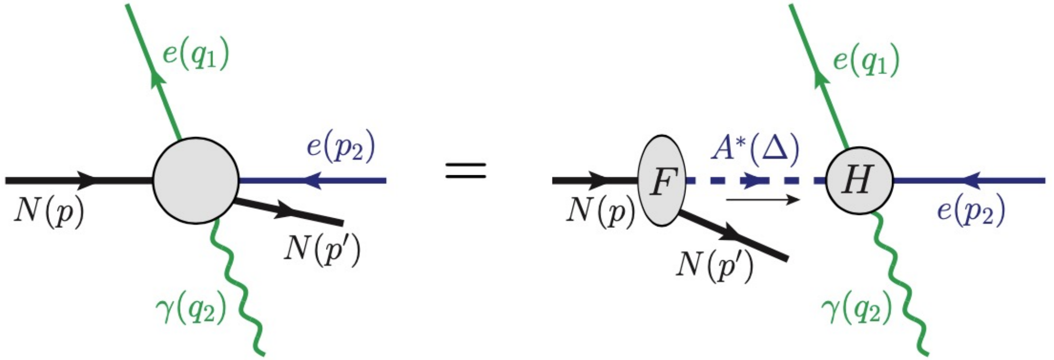


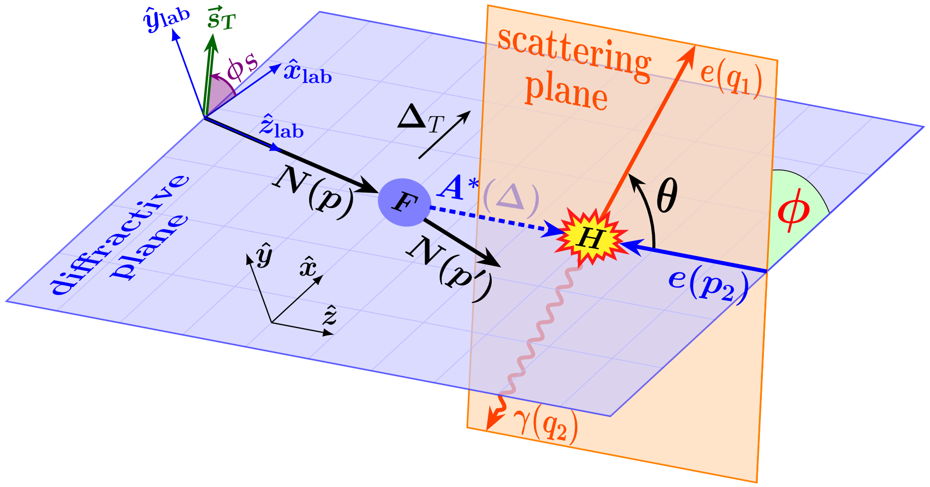
JLab @ 22GeV

A. Accardi et al.
[arXiv:2306.09360]

Angular Modulations – Separation of Different GPDs & Global Analyses

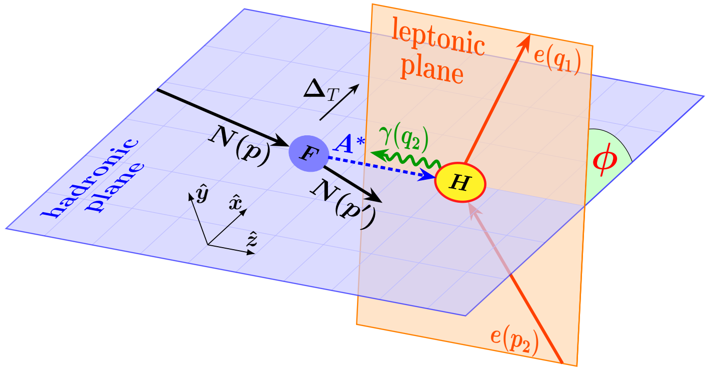
- GPDs depend on the choice of Frame (light-cone n-vector to define the "+" component):

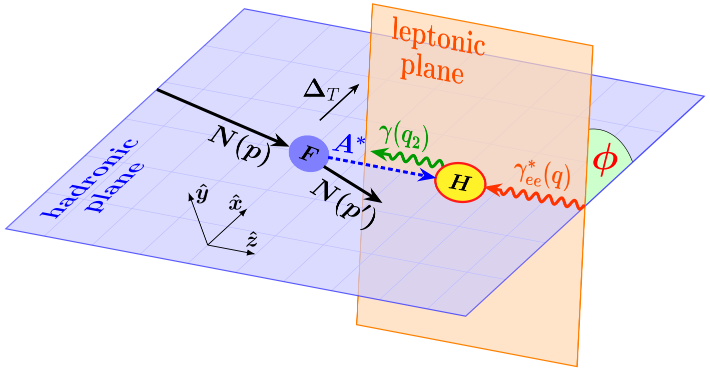




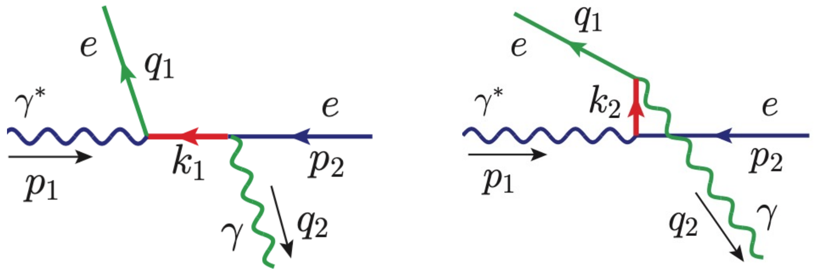
Angular modulation between "diffractive" and "scattering" planes to select the spin-state of A* - different GPDs

- Experimental Breit frame is not ideal:





BH is not a "t"-channel process:



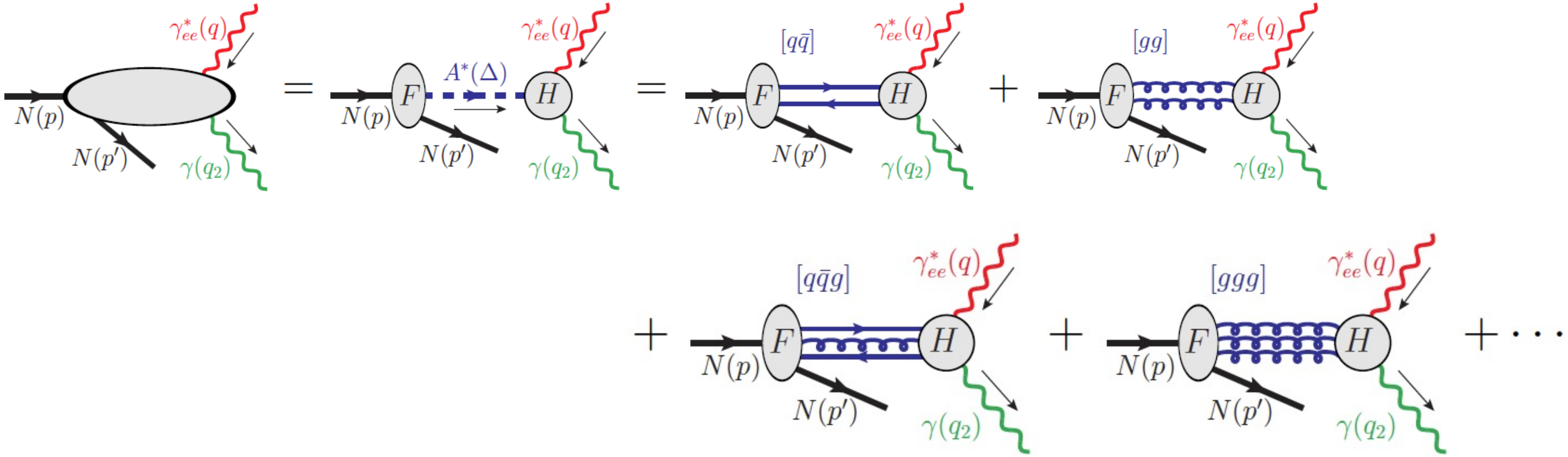
Propagators of k_1 & k_2 have ϕ-dependence!

Angular modulation between "leptonic" and "hadronic" planes do not necessarily select the definite spin-state of A* - different GPDs!

DVCS Compton Form Factors (CFFs)

Qiu, Sato & Yu in preparation

- Like structure functions, CFFs include all power contributions:



In terms of EM gauge invariance, this virtual photon Compton scattering amplitude can be decomposed into 18 scalar Compton Form Factors.

- Extraction of GPDs from QCD global analyses:

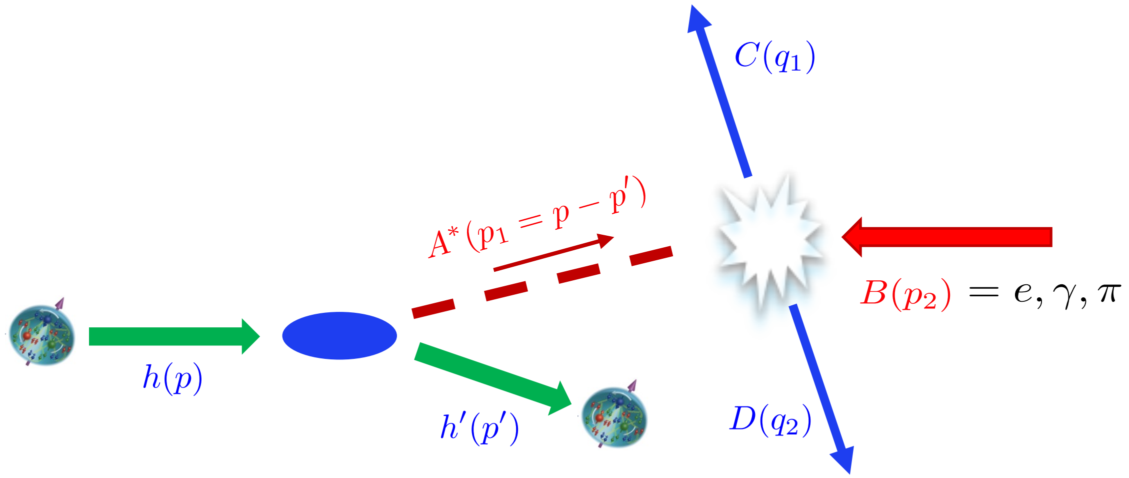
1) Universality of GPDs – unlike PDFs, the choice of the light-cone vector to define "+" component is not unique! When considering the power corrections, it is critical to carefully define the GPDs!

2) Angular modulation is critically important for separating different GPDs, but, consistent choice of the "angle" to define the modulation is crucial!

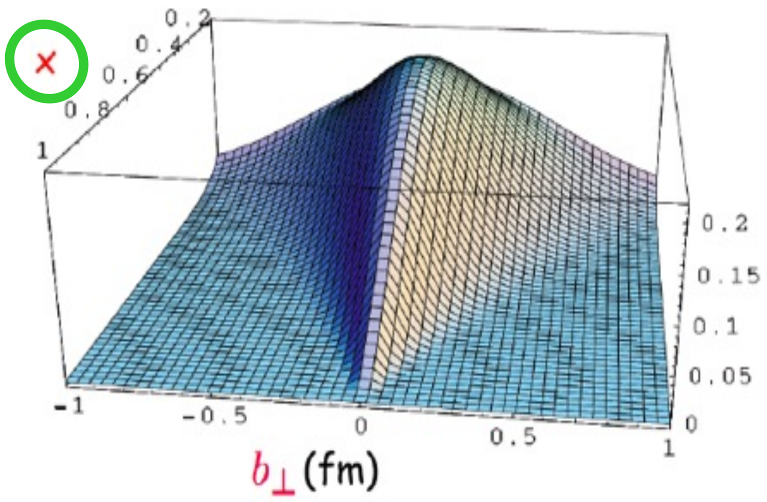
Summary and Outlook

- ❑ **GPDs are fundamental, carrying rich information on:**
  - Tomographic images of confined quarks and gluons
  - Underline dynamics of hadronic properties
- ❑ **It is challenging to extract the *x*-dependence of GPDs**
  - The relative momentum fraction *x* needs to be entangled with externally measured hard scales!
- ❑ **QCD Global analyses to extract GPDs:**
  - Need more processes, more observables (see Silvia's talk)
  - Need input from lattice QCD (see Herve's talk at QCD Evolution)
  - Controlled GPD evolution (see Valerio's talk)
  - Need to solve the end point issues of exclusive processes (momentum of active parton goes to zero)
  - …

A long but challenging & exciting way to go!



3D image



Many on-going efforts:
PARTON Collab, QuantOM Collab,
QGT Collab, FemtoNET, …

Thanks!

Jefferson Lab