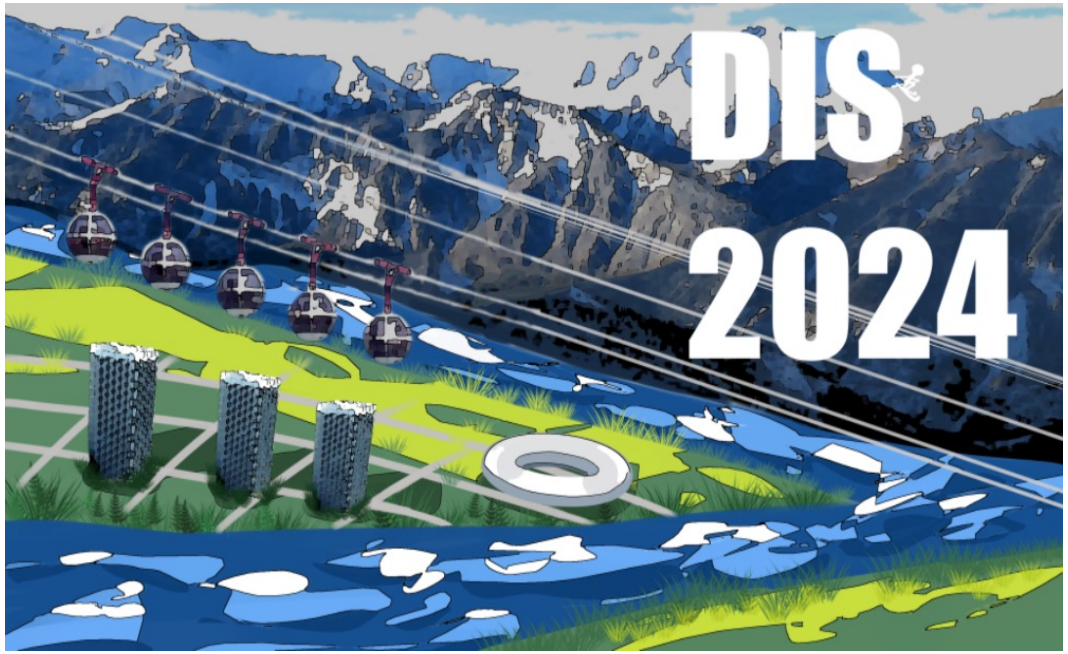
New physical processes for extracting generalized parton distributions with a better sensitivity to partonic structure

- ❑ Explore hadron's partonic structure without breaking it!
- ❑ Challenges for studying exclusive processes
- ❑ Need new processes
- ❑ QCD factorization for exclusive processes
- ❑ Summary and Outlook



In collaboration with Zhite Yu, Nobuo Sato, …

Jianwei Qiu
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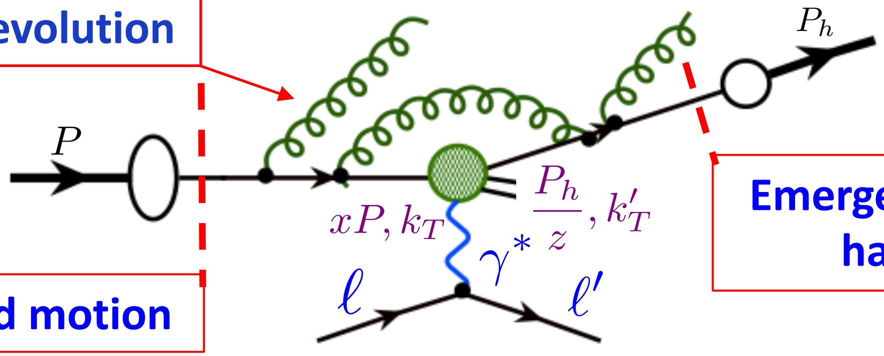
How to see internal structure of a hadron – breaking it?

- **If the hadron is broken, the hard hitting induces gluon radiations, like in SIDIS, …**

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

Gluon shower – QCD evolution



Confined motion

Emergence of a hadron hadronization

Transverse momentum Broadening from the shower:

$$\Delta k_T^2 \propto \Lambda_{\rm QCD}^2 \left.\begin{aligned} &\times \alpha_s(C_F, C_A) \\ &\times \log(Q^2/\Lambda_{\rm QCD}^2) \\ &\times \log(s/Q^2) \end{aligned}\right\} \gtrsim 1$$

Structure information can be diluted by the collision induced shower!

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

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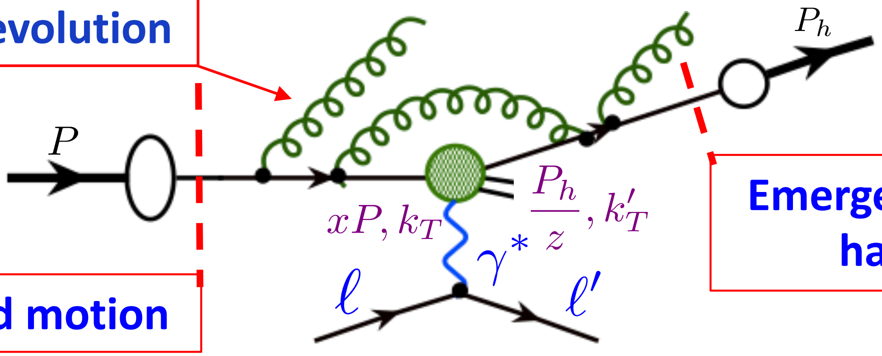

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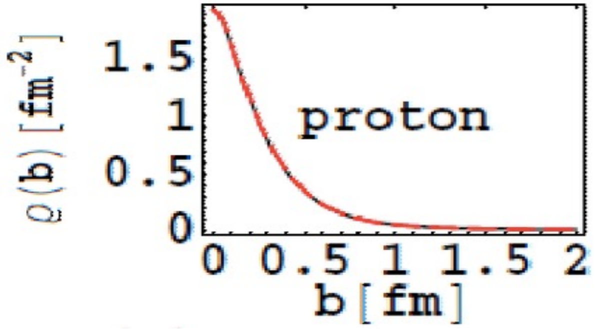
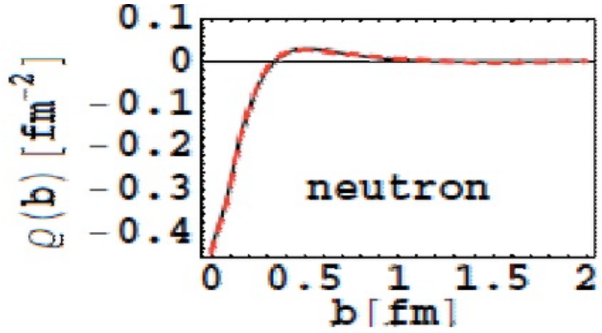
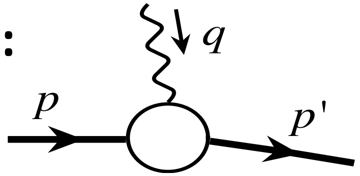
Structure information can be diluted by the collision induced shower!

- **Not breaking the hadron?**



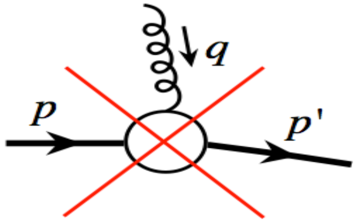


Elastic electric form factor:



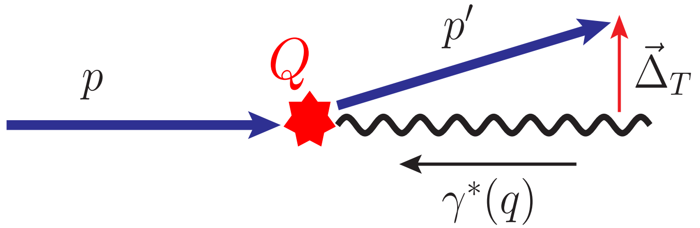
Proton "Radius" in terms of EM charge distribution

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



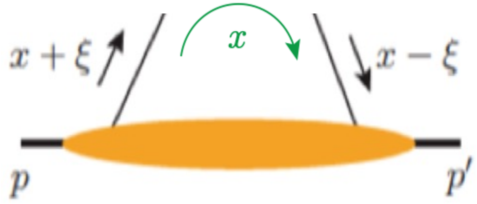
Explore hadron's partonic structure without breaking it!

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



Generalized PDFs (GPDs):

$F_{q/h}(x, \xi, t)$ **skewness** $\xi = \dfrac{(p-p')^+}{(p+p')^+}$



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

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

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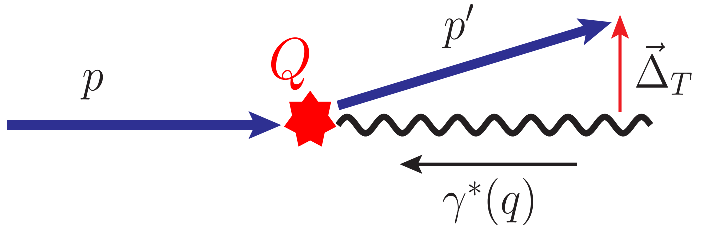

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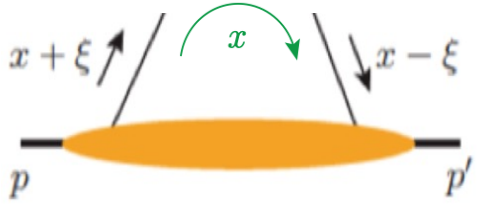

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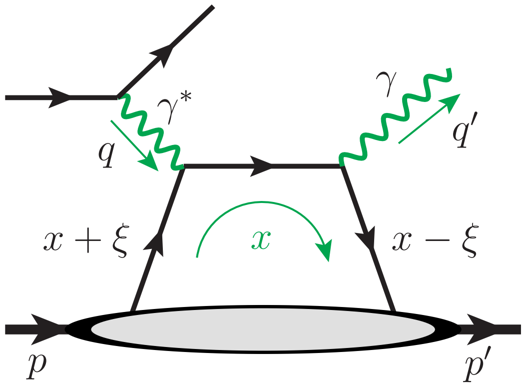
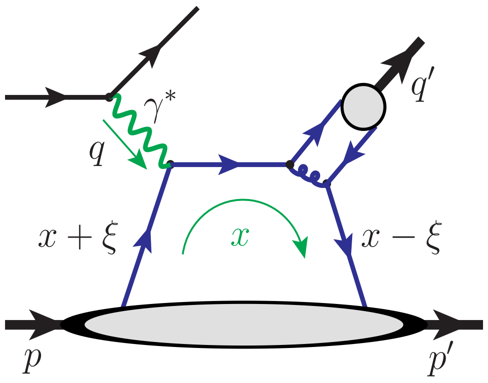
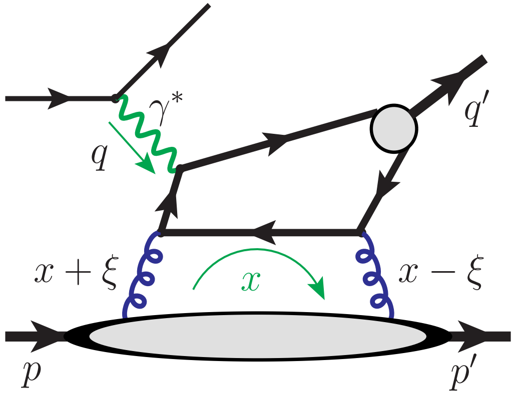
- **Hard exclusive processes for extracting GPDs:**



DVCS: Q² >> |t|



DVMP



DVQP

+ DDVCS, …

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

Factorization

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

Moments of GPDs = Emerged hadronic properties

Ji, PRL78, 1997

- **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 GFF
Angular Momentum

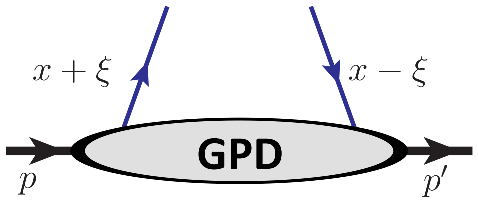
→ ***x*-dependence of GPDs!**

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

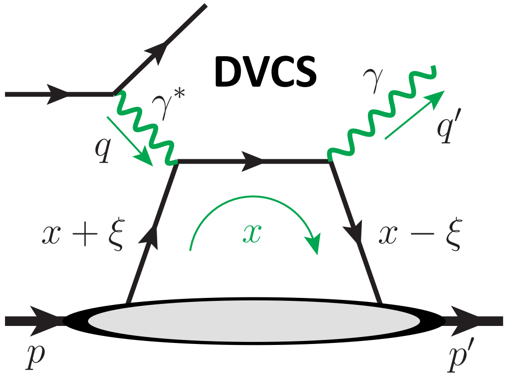
Jefferson Lab

Limitation of exclusive processes: x-dependence

❑ Amplitude nature: exclusive processes



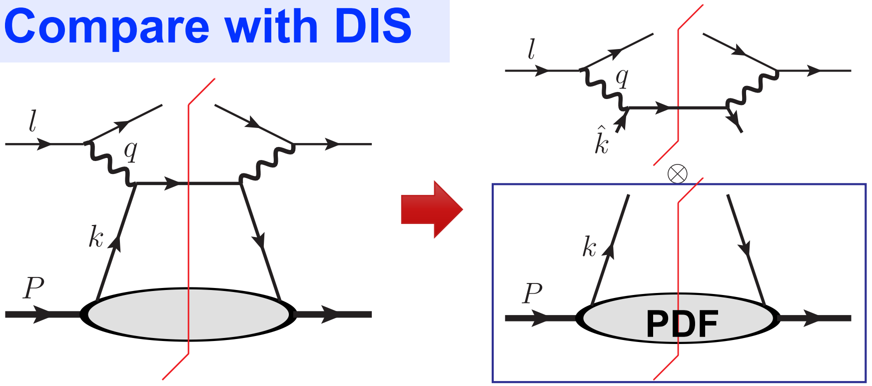
***x* ~ loop momentum**



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

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

Compare with DIS



***cross section*: cut diagram**

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

Limitation of exclusive processes: x-dependence

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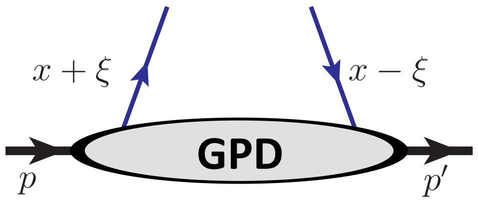
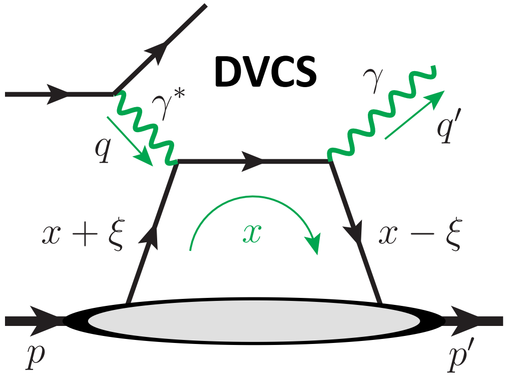


x ~ loop momentum



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

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

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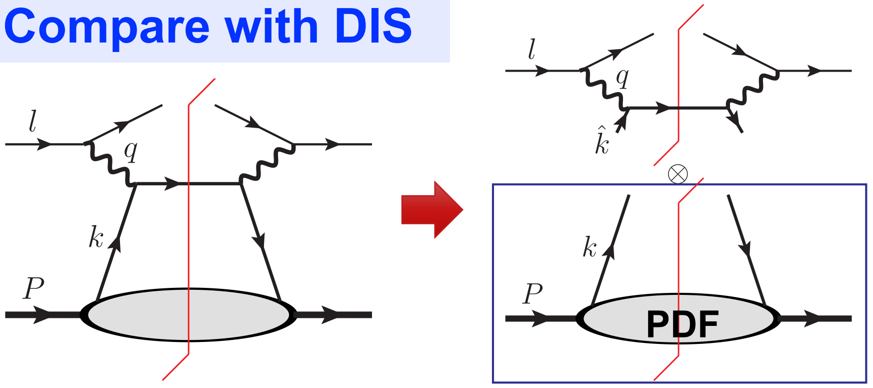


***cross section*: cut diagram**

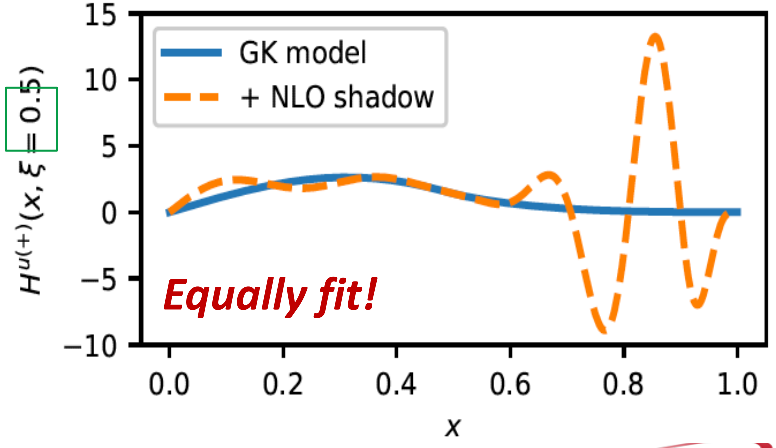
$$\sigma_{\mathrm{DIS}} \simeq \int_{x_B}^{1} \mathrm{d}x\, f(x)\,\hat{\sigma}(x/x_B)$$

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

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

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

“moment”



[Bertone et al. PRD `21]

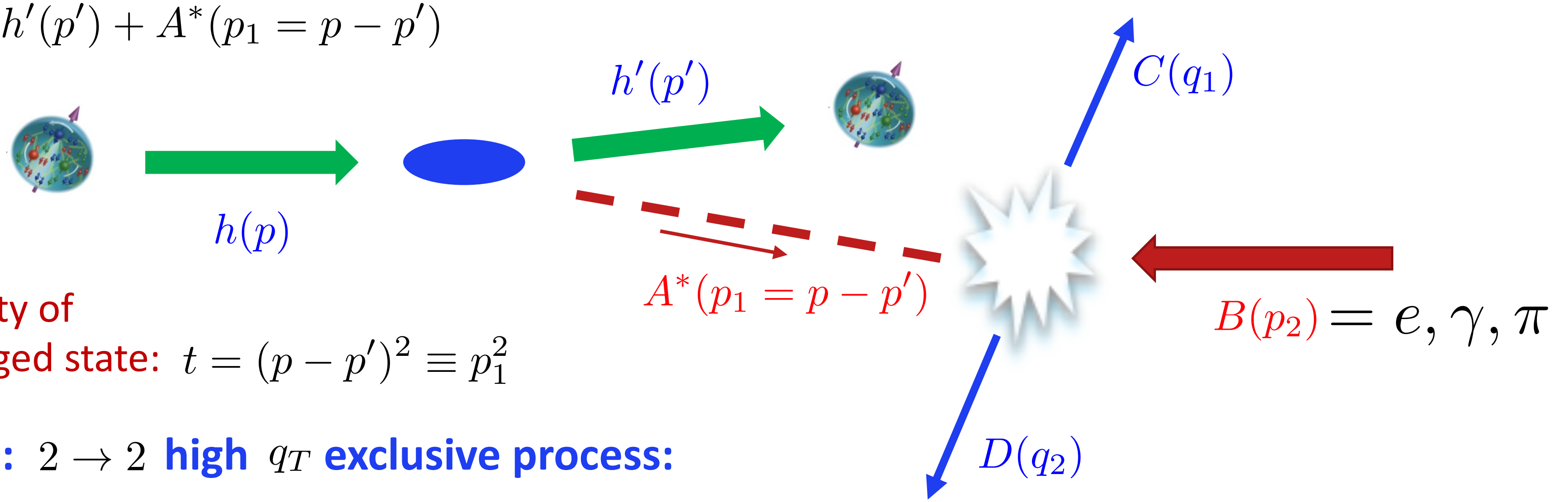
Single-diffractive hard exclusive processes (SDHEP)

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

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

- **Single diffractive – keep the hadron intact:**

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



Virtuality of
exchanged state: $t = (p - p')^2 \equiv p_1^2$

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

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

Probing time: $\sim 1/|q_{1T}| \approx 1/|q_{2T}|$

- **Necessary condition for QCD factorization:**

Lifetime of $A^*(p_1)$ is much longer than collision time of the probe! ➡ $|q_{1_T}| = |q_{2_T}| \gg \sqrt{-t}$

Not necessarily sufficient!

➡ **The single diffractive $2 \to 3$ exclusive hard processes (SDHEP):**

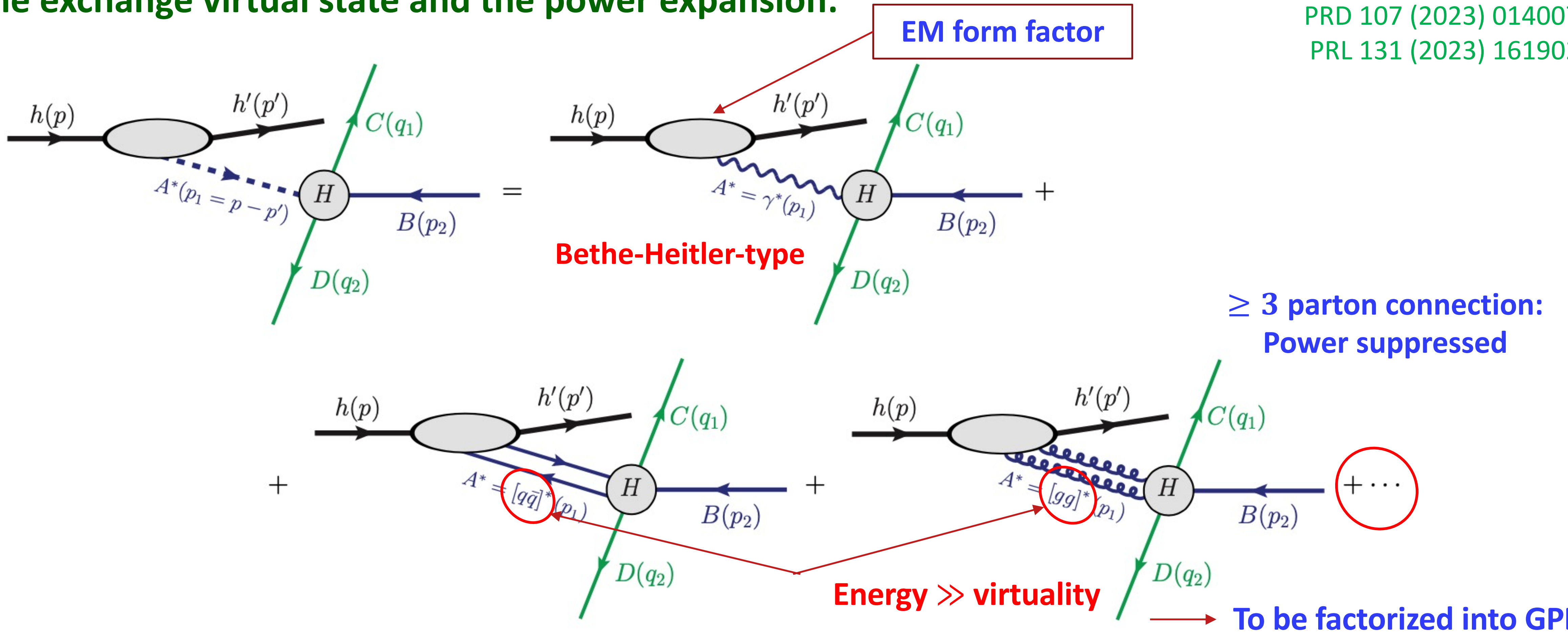
$$h(p) + B(p_2) \to h'(p') + C(q_1) + D(q_2)$$

A 2-scale observable!

Single-Diffractive Hard Exclusive Processes (SDHEP)

❑ The exchange virtual state and the power expansion:

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



→ To be factorized into GPD

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

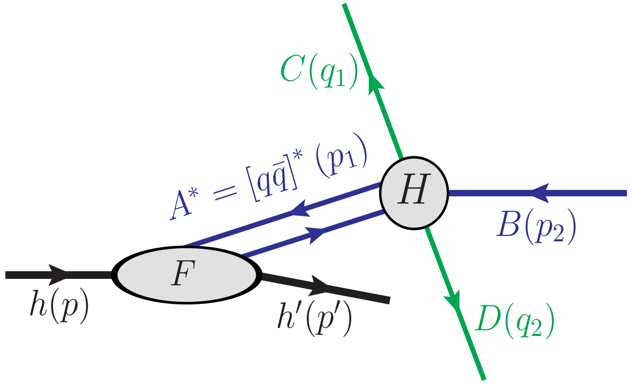
- **Quantum numbers of *h(p) – h'(p')***
- **Symmetry of producing non-vanishing *H***

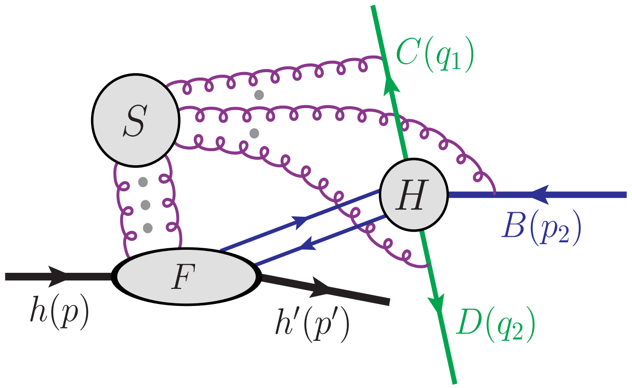
Need entanglement between q_T and loop momentum fraction x for the sensitivity on the x-dependence of GPDs!

Factorization for SDHEP in the two-stage paradigm

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

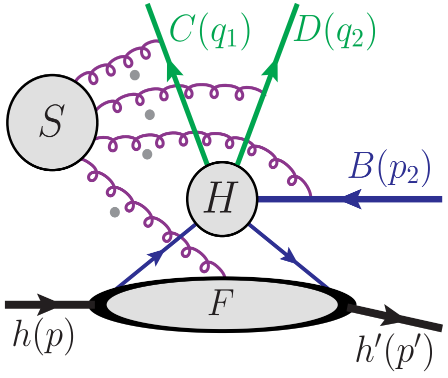
❑ Factorization for 2-parton channels (CO gluons are easy to factorize):





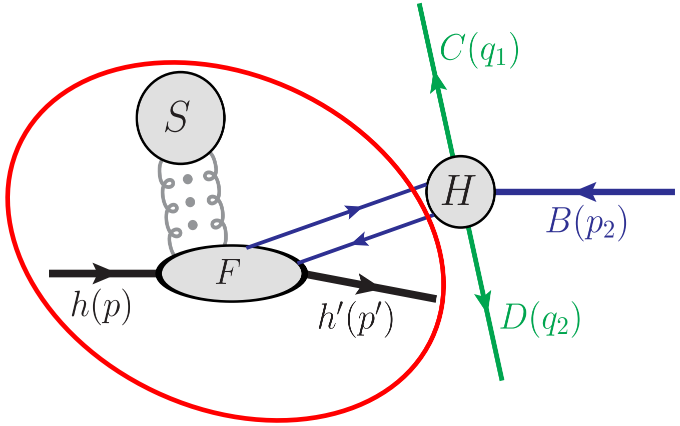
ERBL region: $[q\bar{q}'] \sim$ meson

+



DGLAP region: Glauber pinch

❑ Soft gluons cancel when coupling to color neutral hadrons:



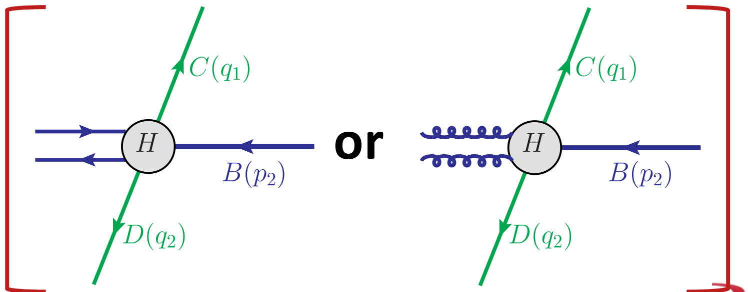
No factorization for double diffractive scattering! Soper, 1997

Glauber gluons of SDHEP (*only* k_s^- is pinched in Glauber region):

$$k_s^+ \mapsto k_s^+ \pm i\mathcal{O}(Q) \quad \Longrightarrow \quad k_s = (\lambda^2, \lambda^2, \lambda) \; \rightarrow \; (1, \lambda^2, \lambda)$$

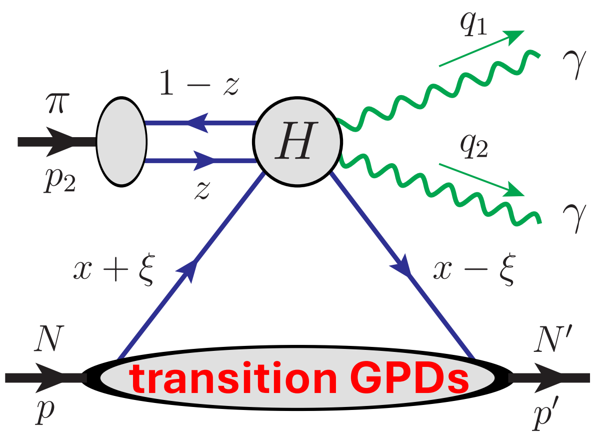
CO gluons

GPD $\otimes$

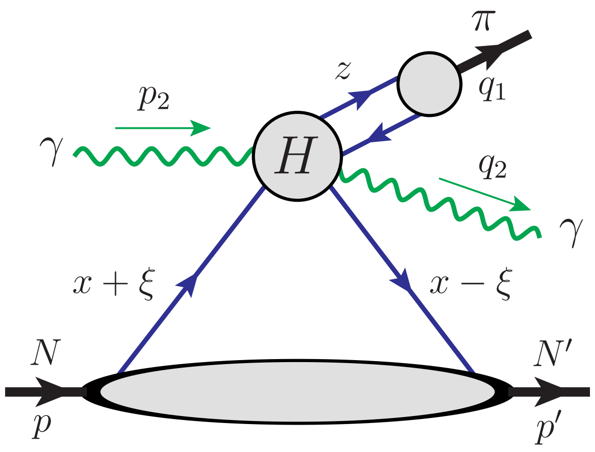


Hard probes

Two new example processes with enhanced x-sensitivity



J-PARC, AMBER



JLab Hall D

Qiu & Yu, JHEP 08 (2022) 103
Qiu & Yu, 2401.13207 (PRD in press)

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, 2401.13207 (PRD in press)]

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

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

Nucleon transition GPDs

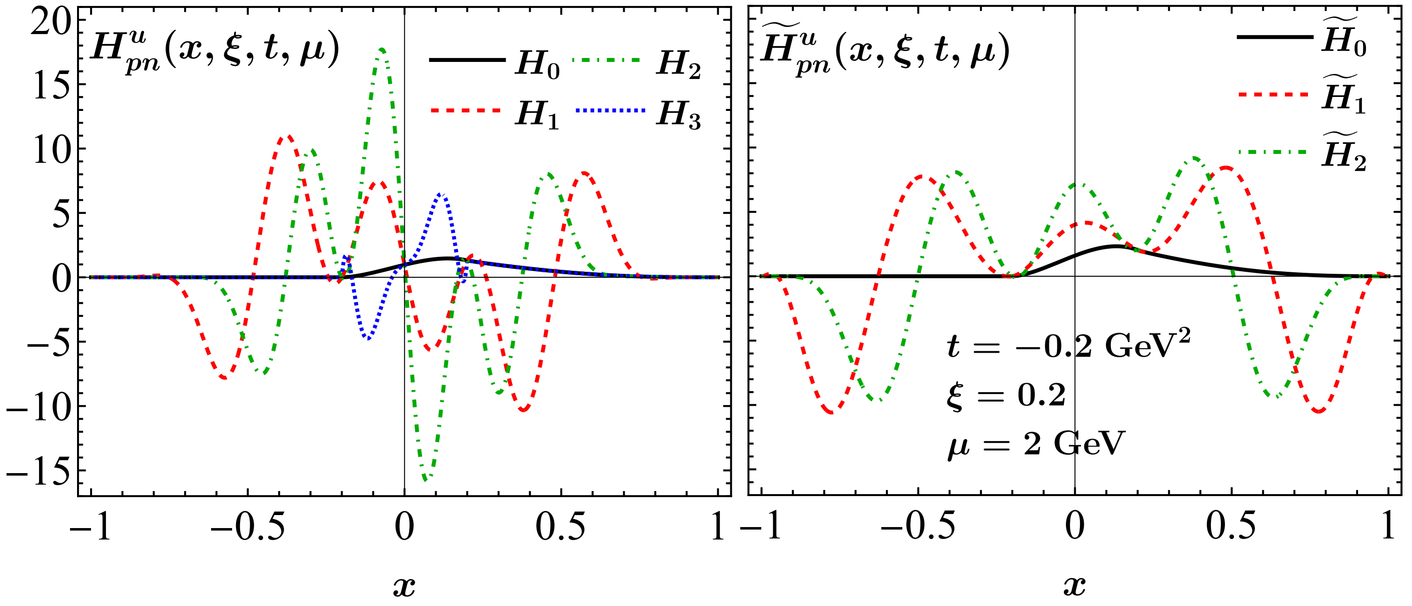
$$H_{pn}^u = H_p^u - H_p^d,\ \text{etc.}$$

GPD models = GK model + shadow GPDs

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

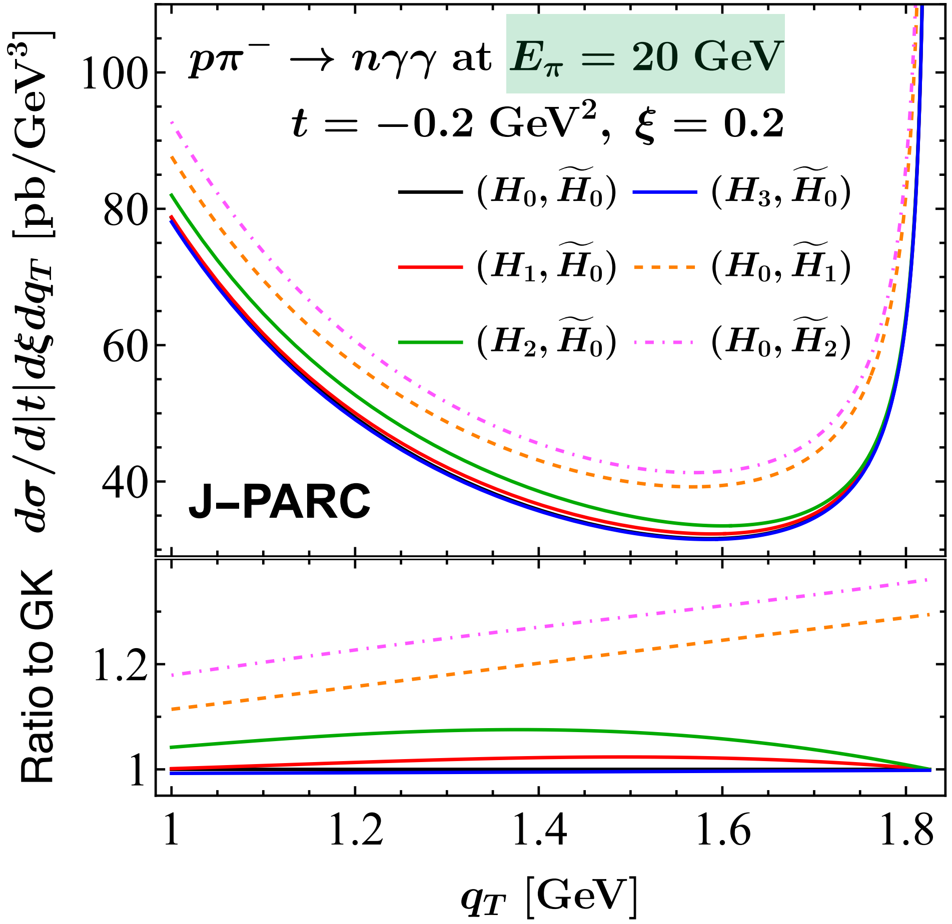
Bertone et al. \`21
Moffat et al. \`23

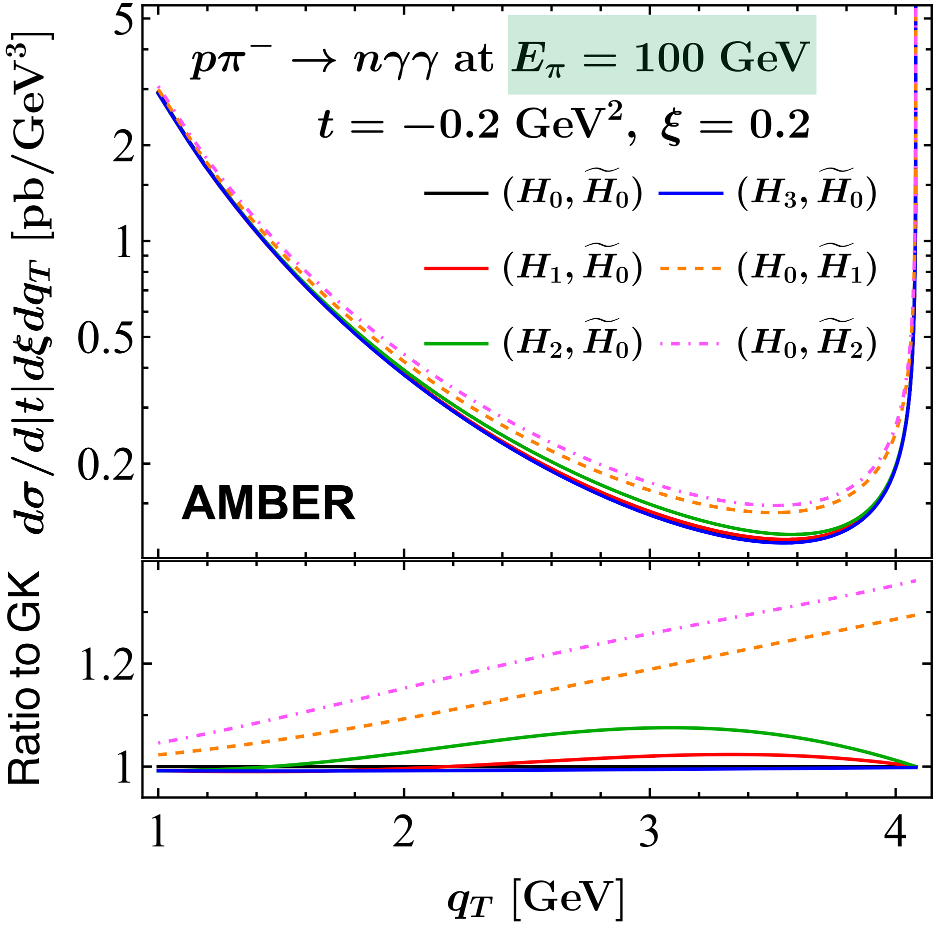
$$\int_{-1}^{1}\frac{dx\,S(x,\xi)}{x-\xi\pm i\epsilon}=0$$



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

[Qiu & Yu, 2401.13207 (PRD in press)]





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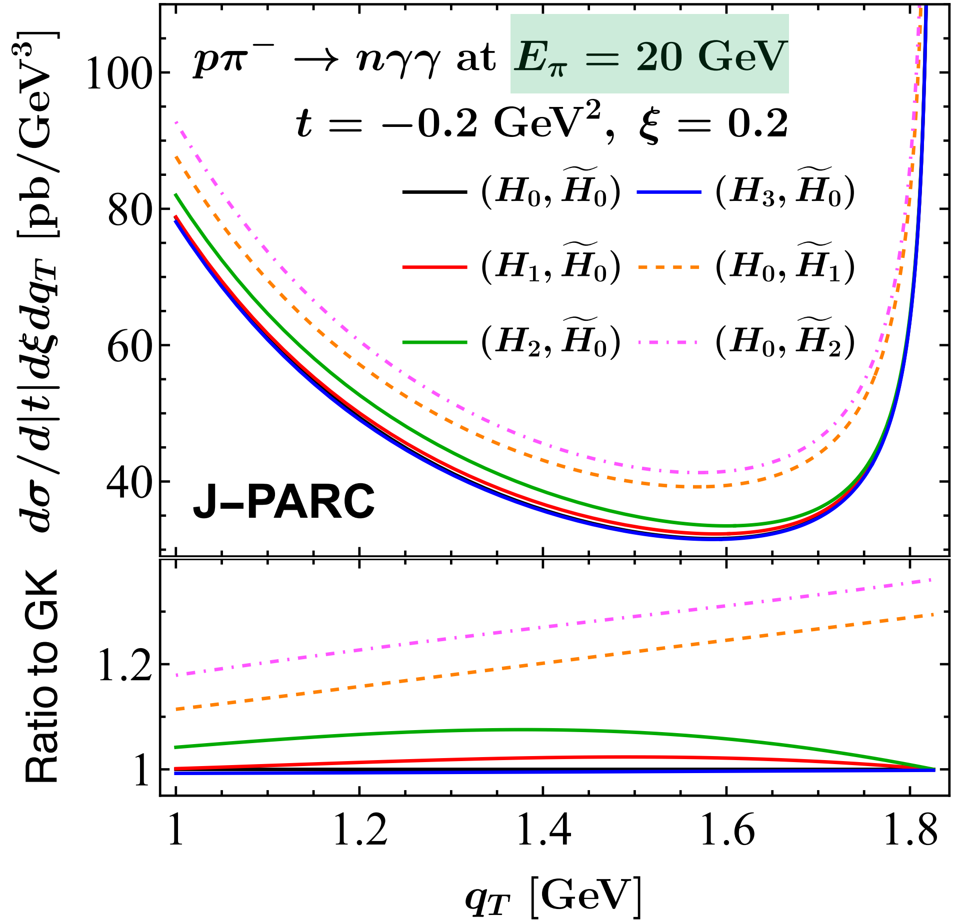
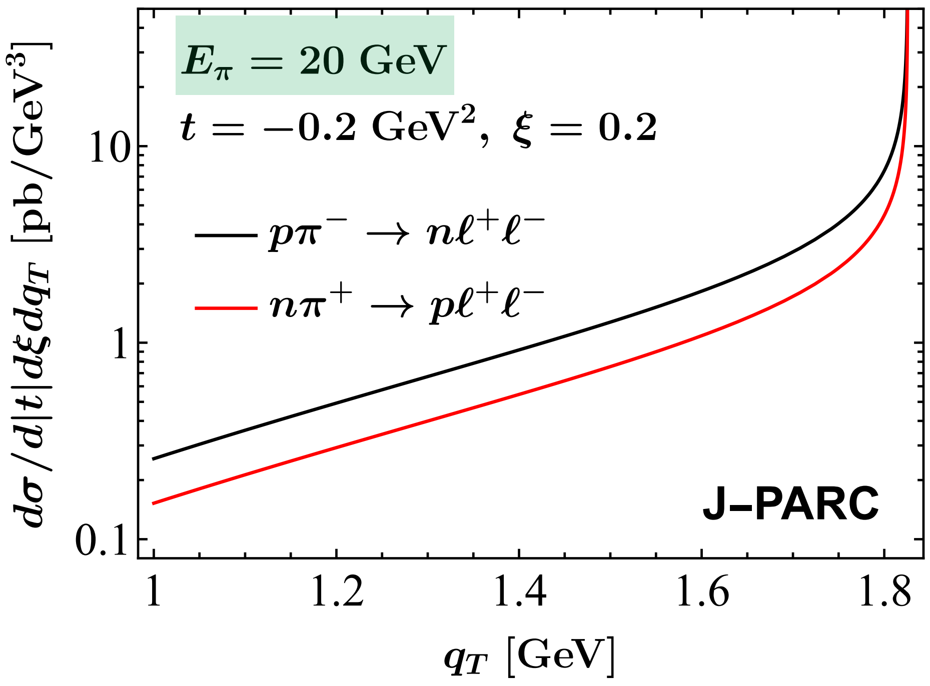


❑ Exclusive Drell-Yan dilepton production

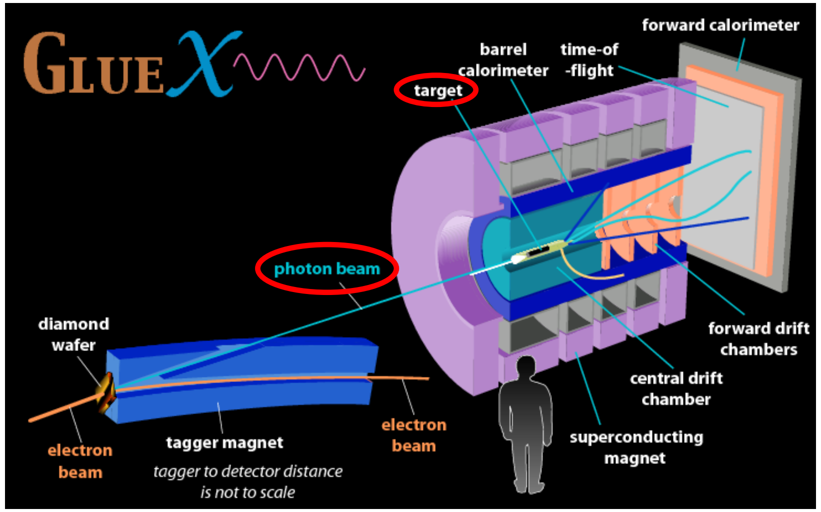
$$N + \pi \to N' + \gamma^* [\to \ell^+ + \ell^-]$$

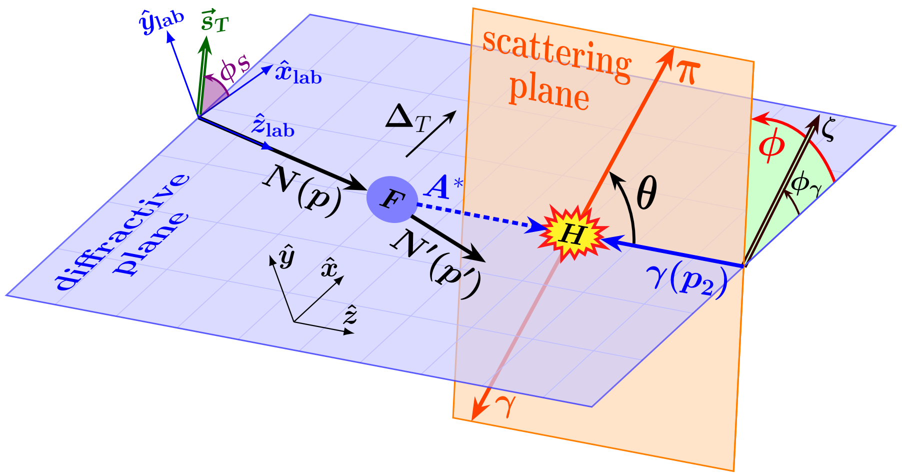


- Lower rate
- Blind to shadow GPDs

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

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





❑ Polarization asymmetries:

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

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

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

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

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

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

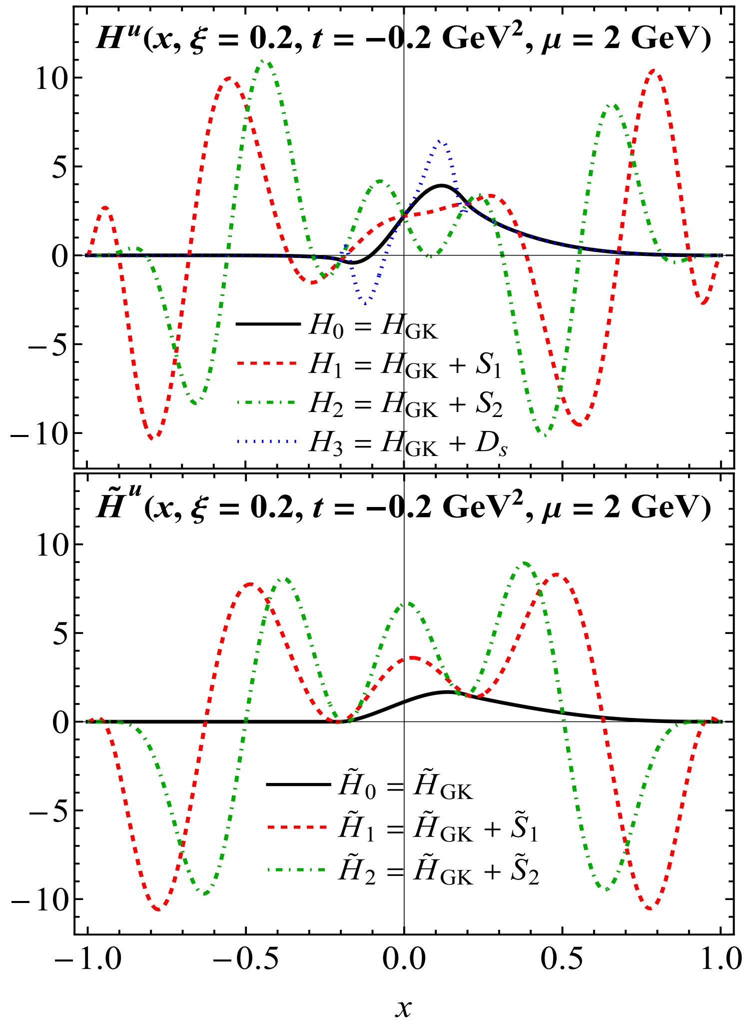
Neglecting: (1) E and $\tilde{E}$; (2) gluon channel

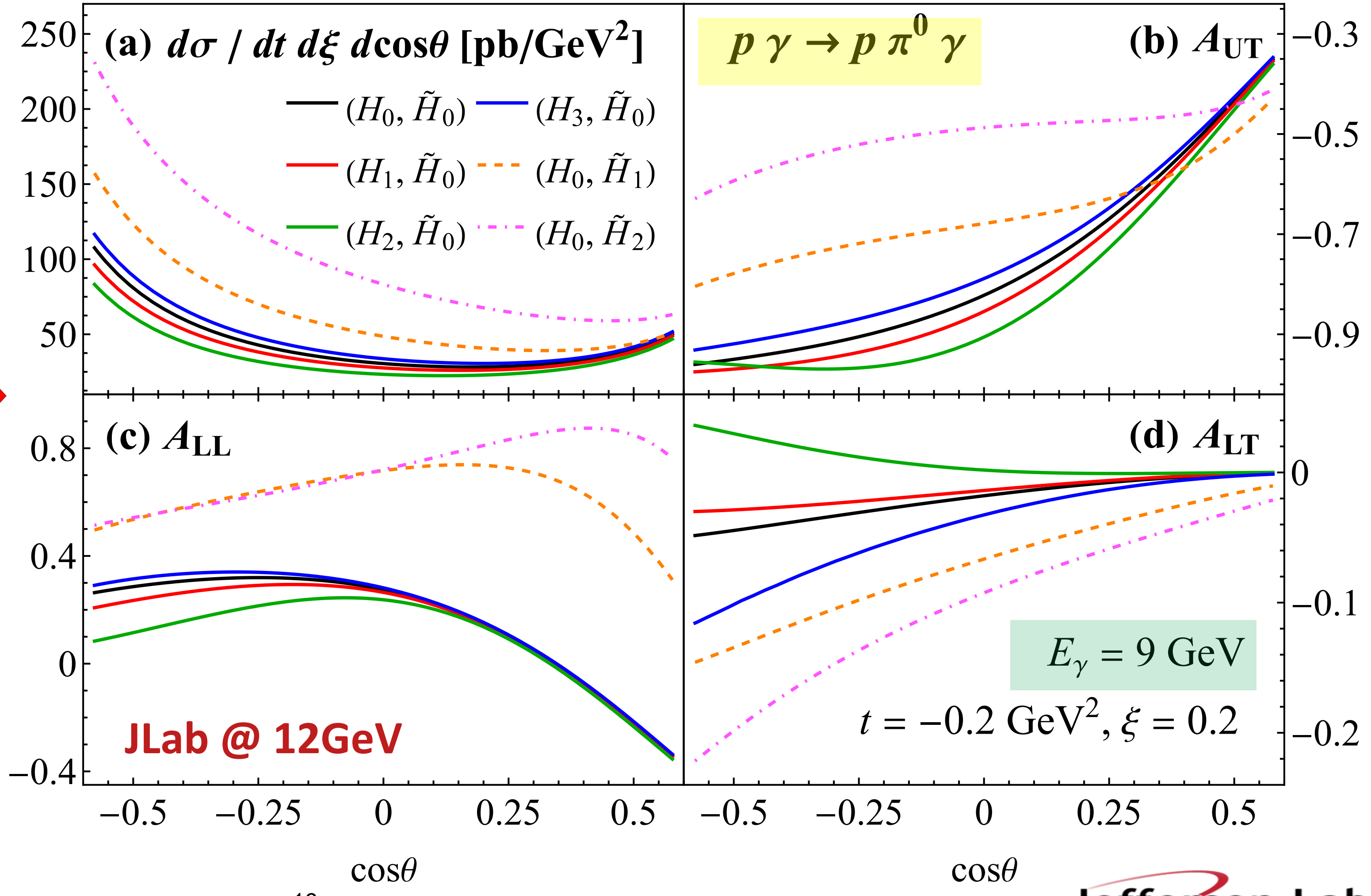
Enhanced x-sensitivity: (2) γ-π pair photoproduction (at JLab Hall D)

GPD models = GK model + shadow GPDs

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

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





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

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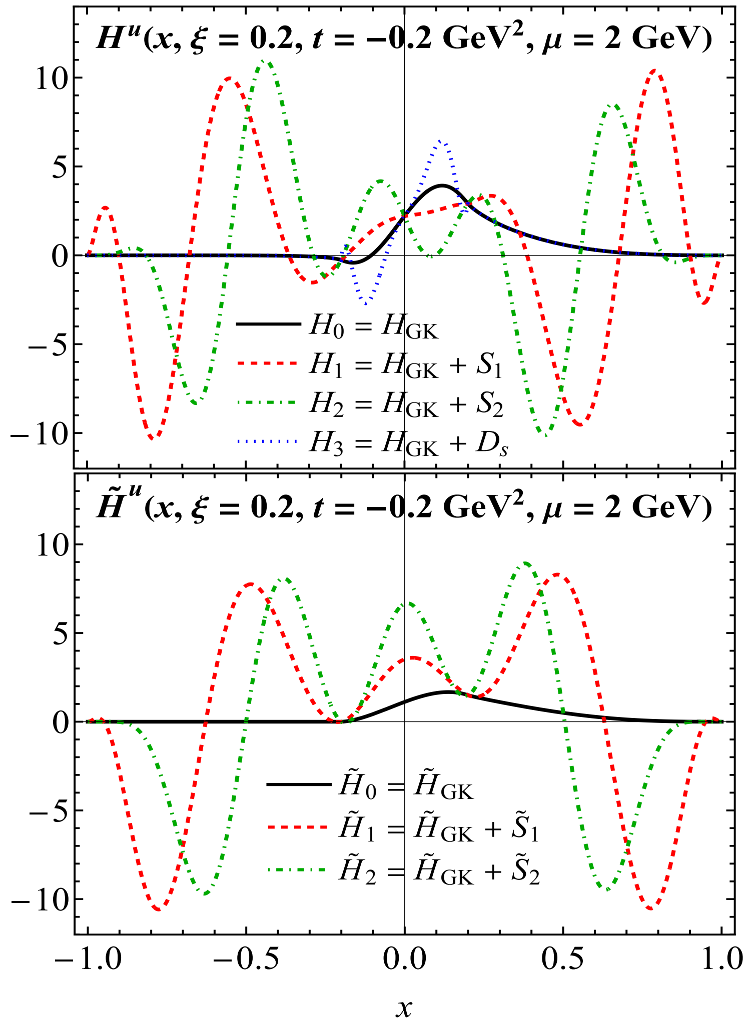
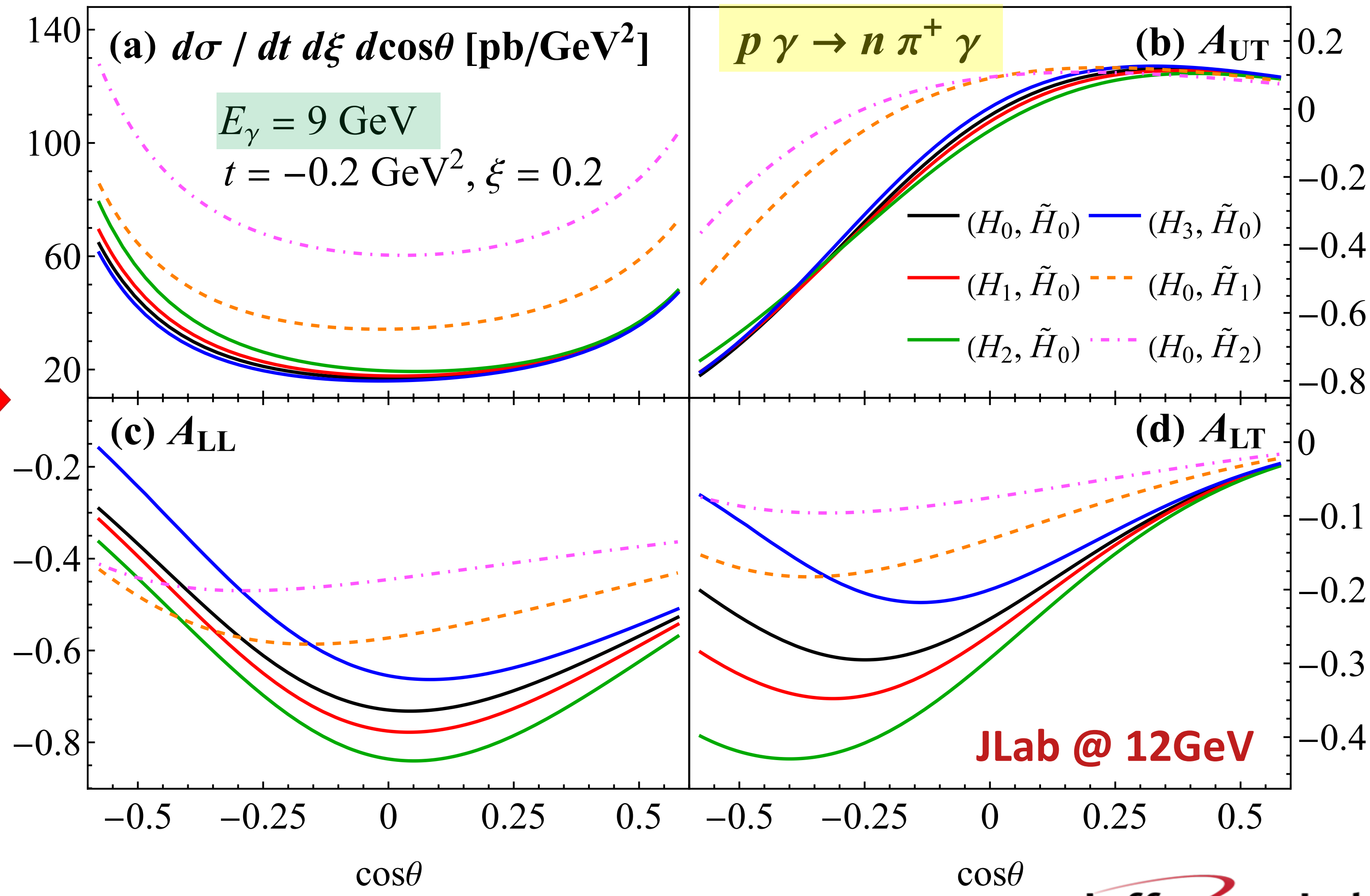




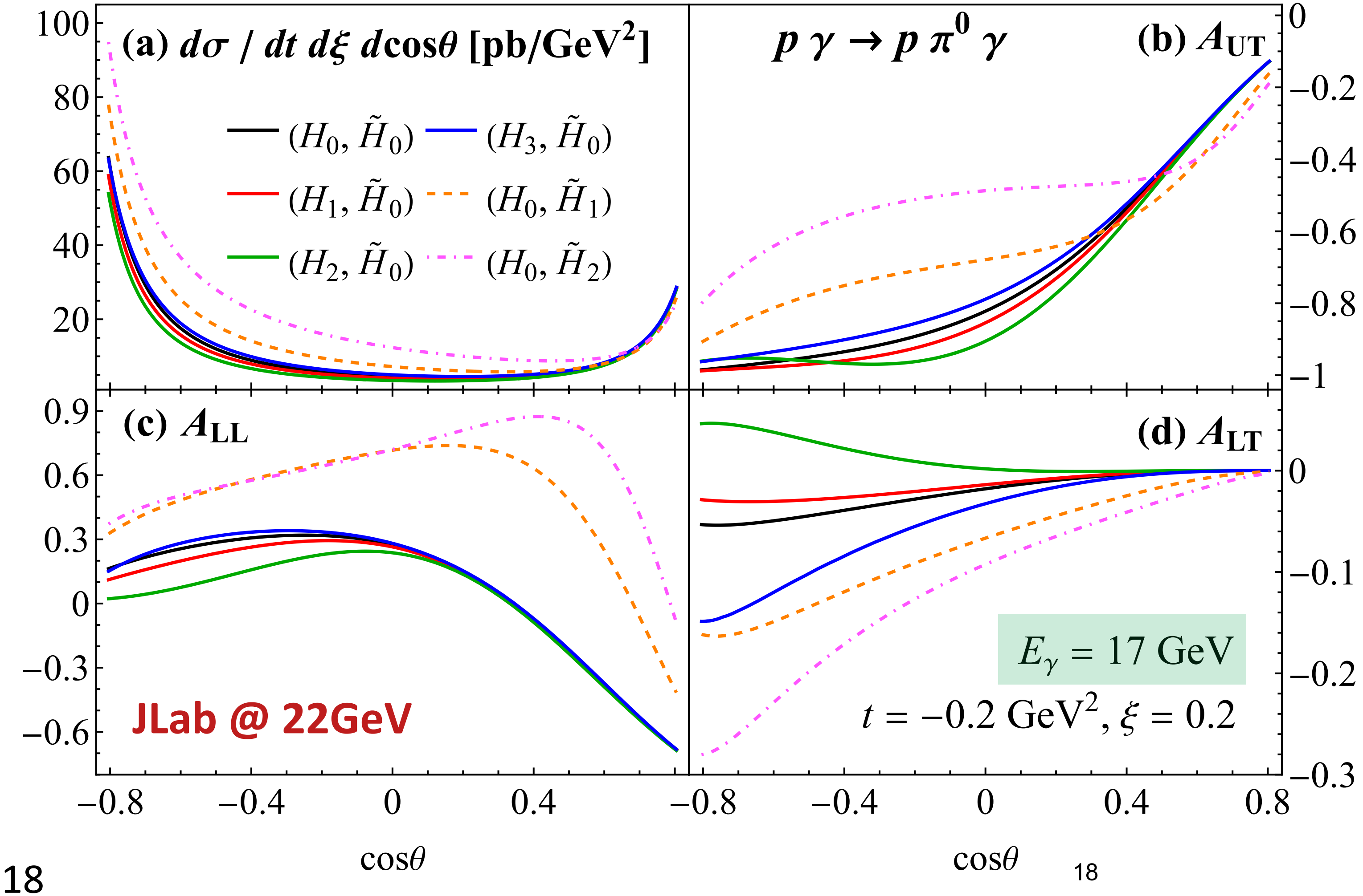
Jefferson Lab

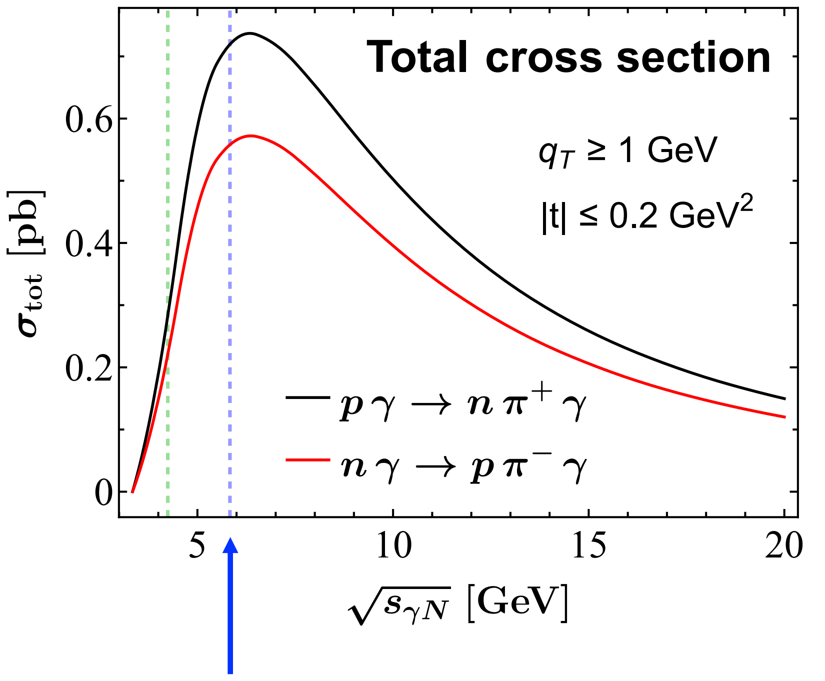
Enhanced x-sensitivity: (2) γ-π pair photoproduction (at upgraded JLab energy)

GPD models = GK model + shadow GPDs

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

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



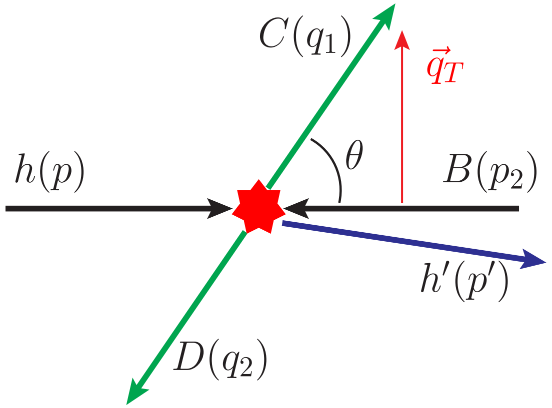


JLab @ 22GeV

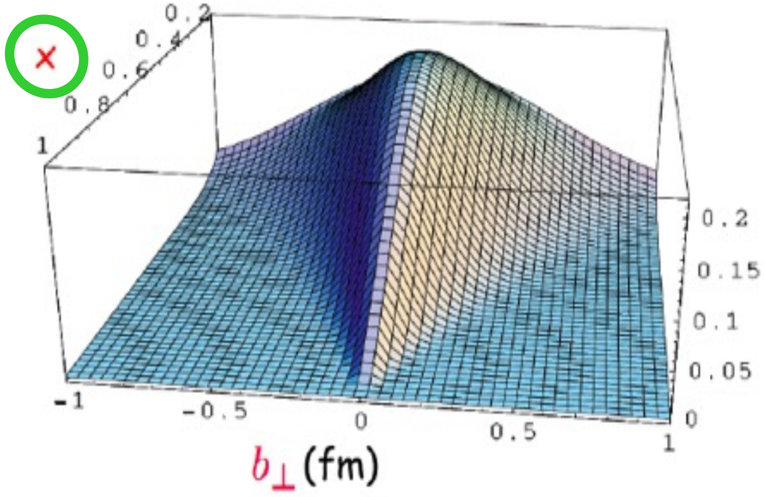
[arXiv:2306.09360]

Summary

- QCD **Factorization** allows to probe **proton structure**
- Single Diffractive **Hard Exclusive Processes** → **GPDs**
- GPDs provide **tomographic images**
- But suffer from the challenging ***x*-dependence problem**
- Two new processes to give **enhanced *x*-sensitivity**
- Still not there yet:
  - Need more processes, more observables
  - Need input from lattice QCD
  - Need global fit
  - Need to solve the end point issues of exclusive processes (momentum of active parton goes to zero)



3D image



A long but challenging & exciting way to go!

Thanks!

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