New Techniques to Access the x-dependence of Generalized Parton Distributions

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In collaboration with: Jian-wei Qiu (Jefferson Lab)

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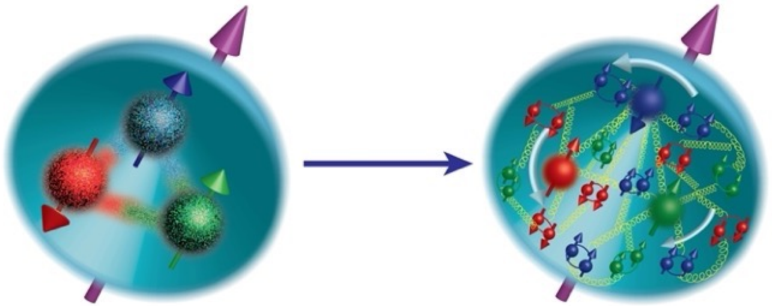
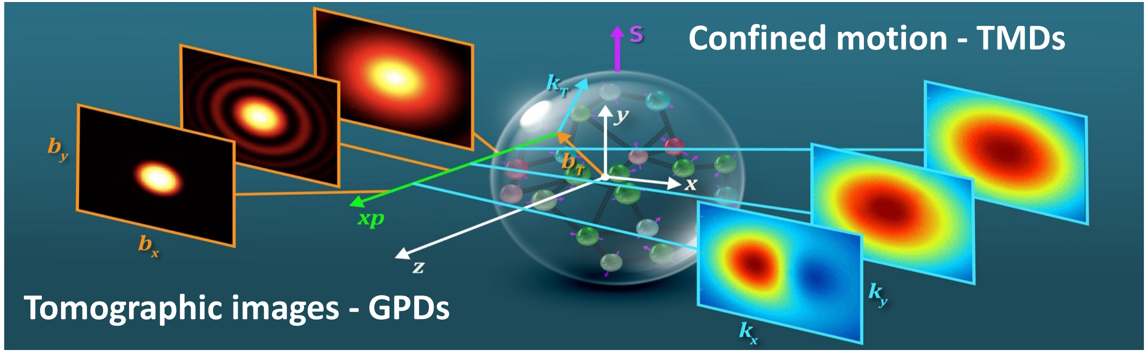
International Workshop on Hadron Structure and Spectroscopy

Jun/27/2023

Jefferson Lab

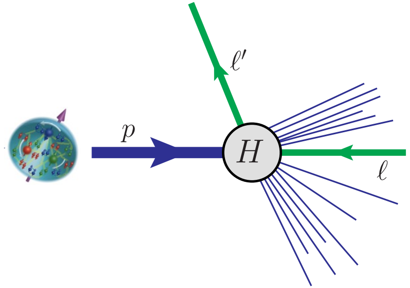
Hadron Structure -- QCD Femtography





QCD Femtography -- Hard inclusive processes as probes

❑ DIS and PDF



Single scale Q ⇒ **One-dim. structure $f_i(x)$**

QCD Femtography -- Hard inclusive processes as probes

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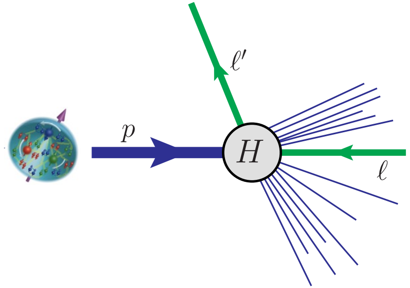
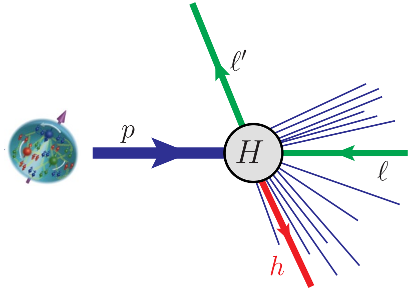
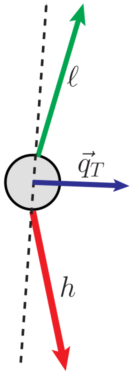


Single scale Q → **One-dim. structure $f_i(x)$**

❑ SIDIS and TMD

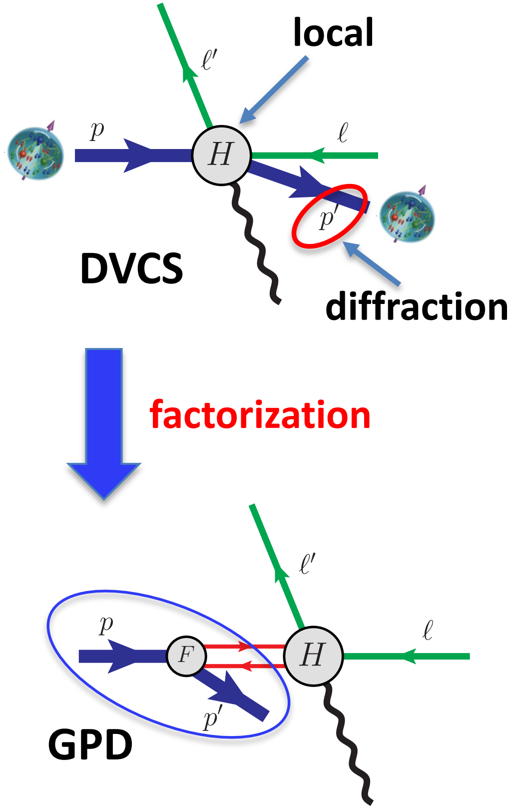




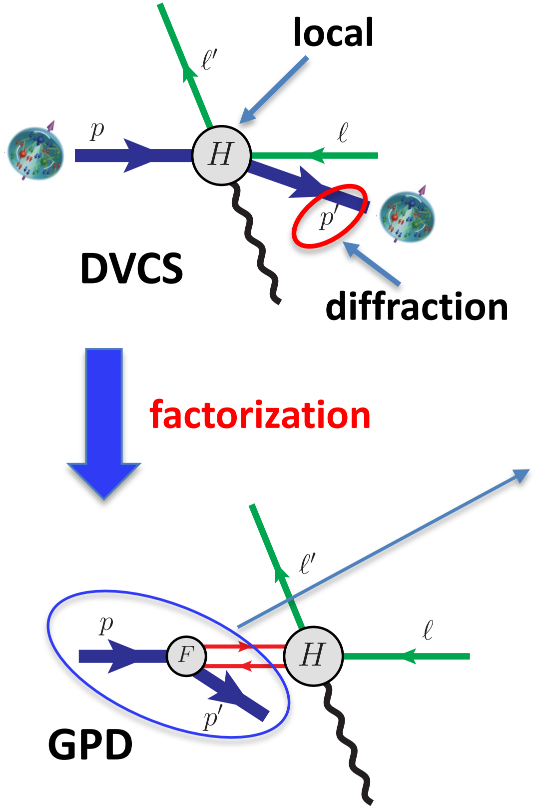
Two scales: $Q \gg q_T \sim \Lambda_{\mathrm{QCD}}$

3-dim. structure $f_i(x, \vec{k}_T)$

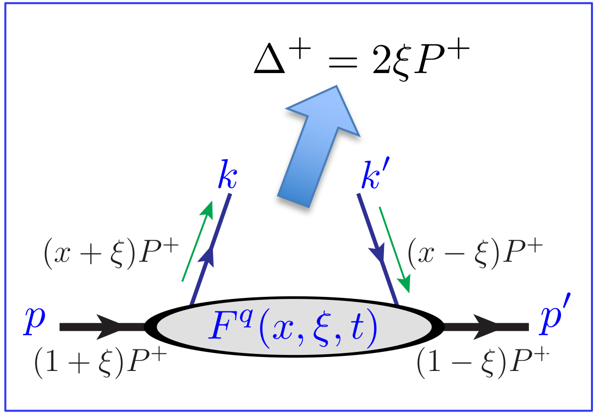
QCD Femtography -- Hard exclusive processes as probes



*QCD Femtography -- Hard **exclusive** processes as probes*



Generalized parton distribution (GPD)



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

$$\Delta = p - p'$$

$$t = \Delta^2$$

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

Hadron diffraction $p \to p'$

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

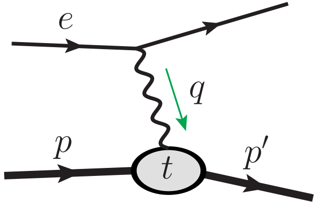
← **parton momentum**

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

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

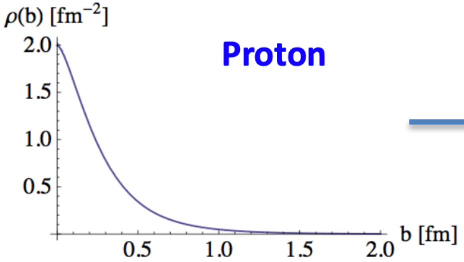
GPD and 3D tomography

- ❑ **Diffraction probes spatial density**



F. T.

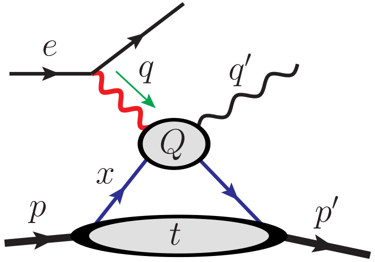
$F_{1,2}(t)$



→ **Electric charge radius**

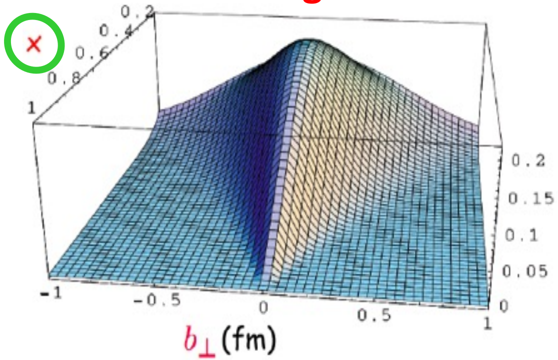
- ❑ ***Two-scale*** **diffraction probes 3D tomography**

DVCS



F. T.

3D image [M. Burkardt, 2000, 2003]



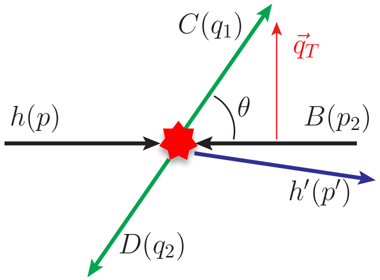
$$f_i(x, \boldsymbol{b}_T) = \int \mathrm{d}^2 \boldsymbol{\Delta}_T \, e^{i \boldsymbol{\Delta}_T \cdot \boldsymbol{b}_T} F_i(x, 0, -\Delta_T^2)$$

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

Single-diffractive hard exclusive process (SDHEP)

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

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



2 → 3: *minimal* kin. configuration!

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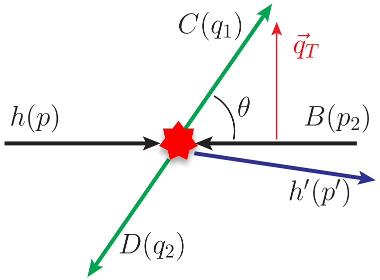

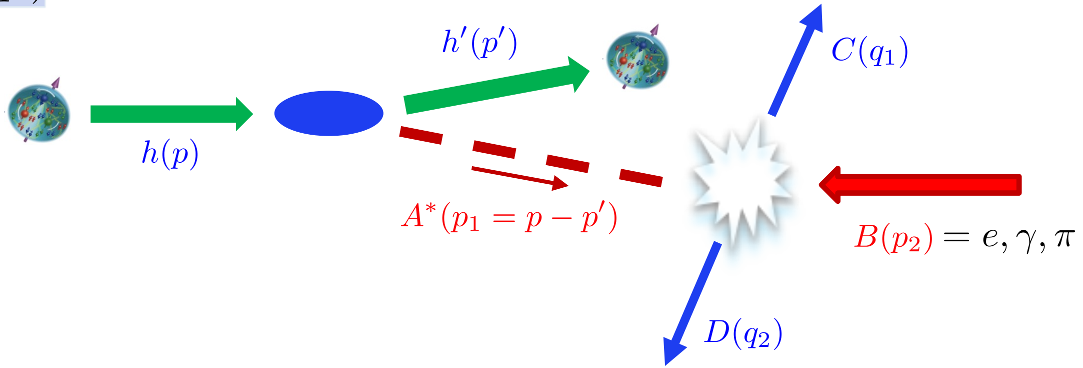

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❑ Two-stage process paradigm

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

↓ **factorize**

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

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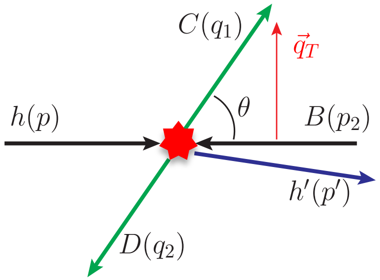

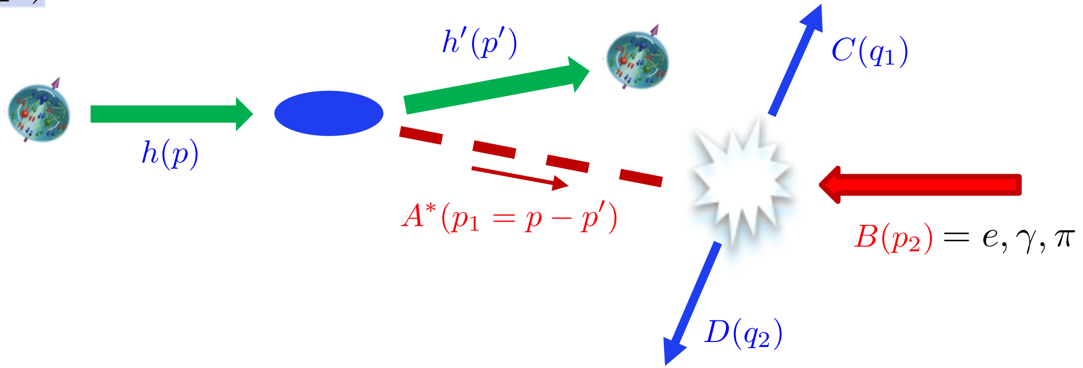

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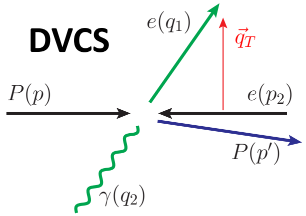
Necessary **condition for factorization:**

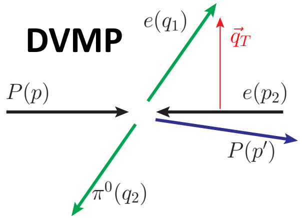
$$q_T \gg \sqrt{-t} \simeq \Lambda_{\rm QCD} \qquad t = (p - p')^2$$

- ***C*, *D* are produced in a hard process *H* ~ q_T**
- **A^* lives much longer than *H***

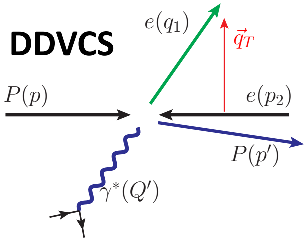
Classification of SDHEPs

- Electro-production (JLab, EIC, …)





add
virtuality



DHQP…

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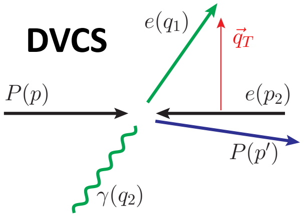
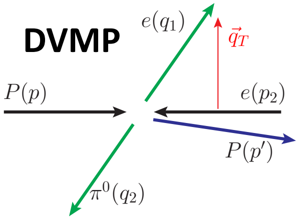
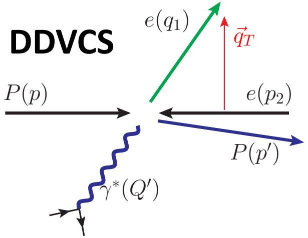


DVMP



add virtuality

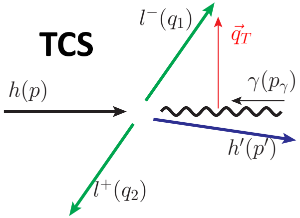
DDVCS

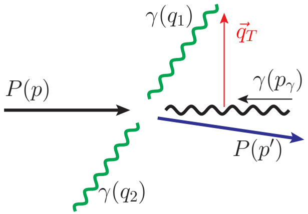


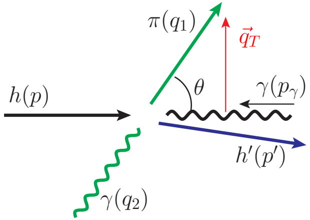
DHQP…

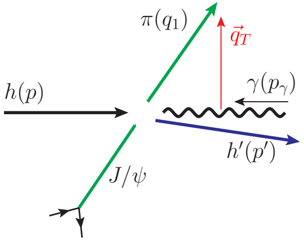
- **Photo-production (JLab, EIC, …)**

TCS









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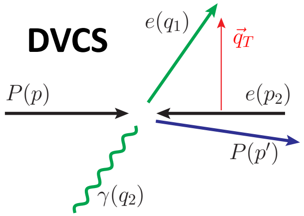

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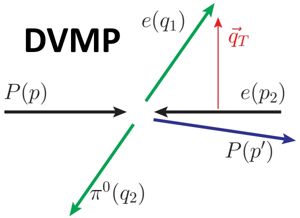

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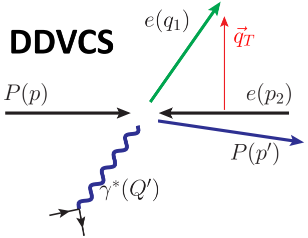

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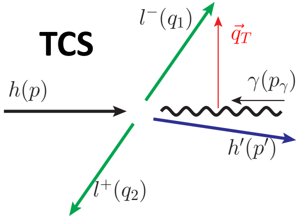
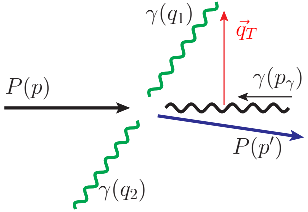
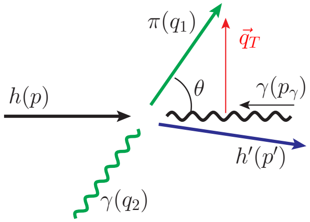
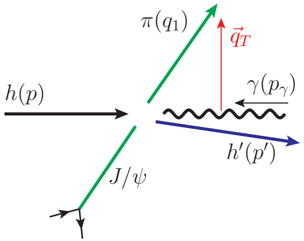


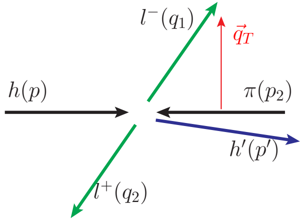


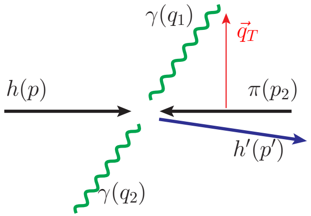




…

- **Meso-production (COMPASS/AMBER, J-PARC, …)**



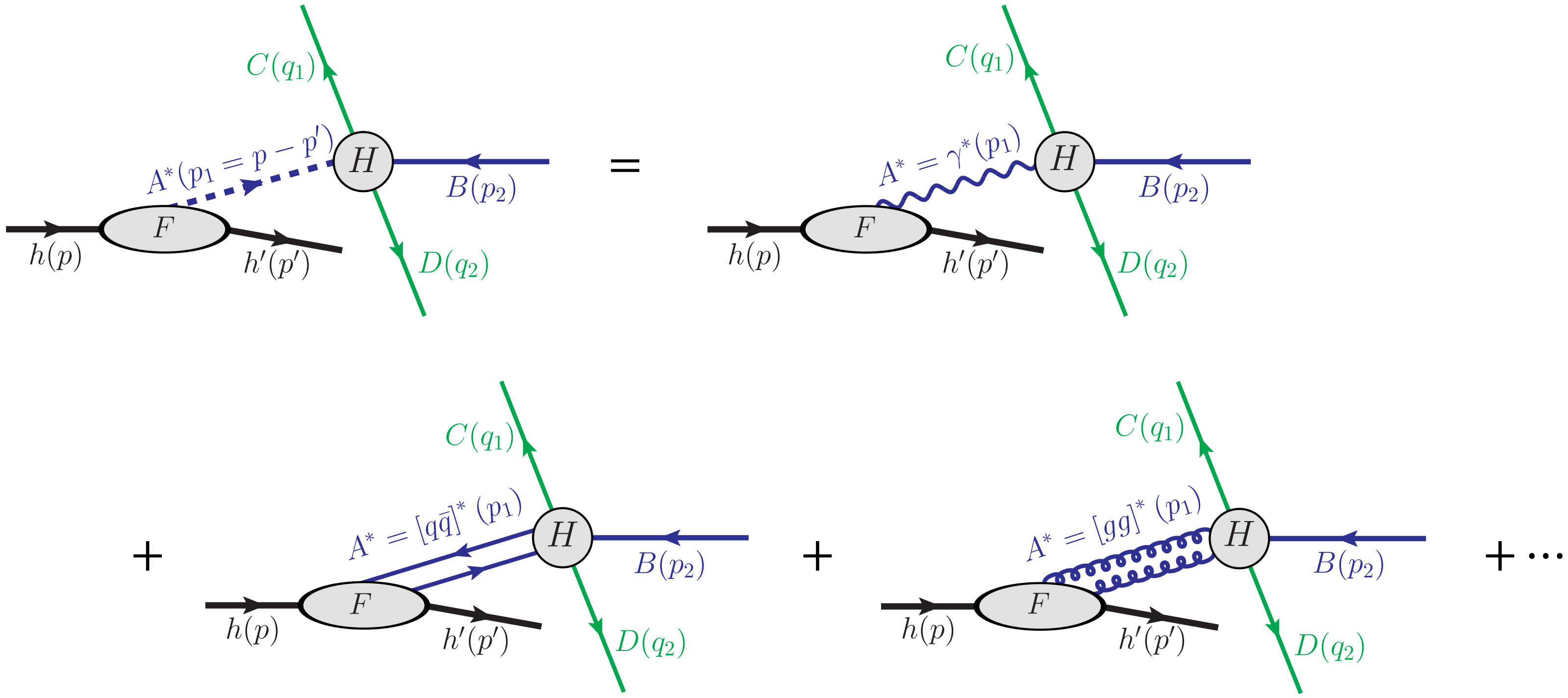


…

Generic discussion

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

Two-stage paradigm and channel expansion



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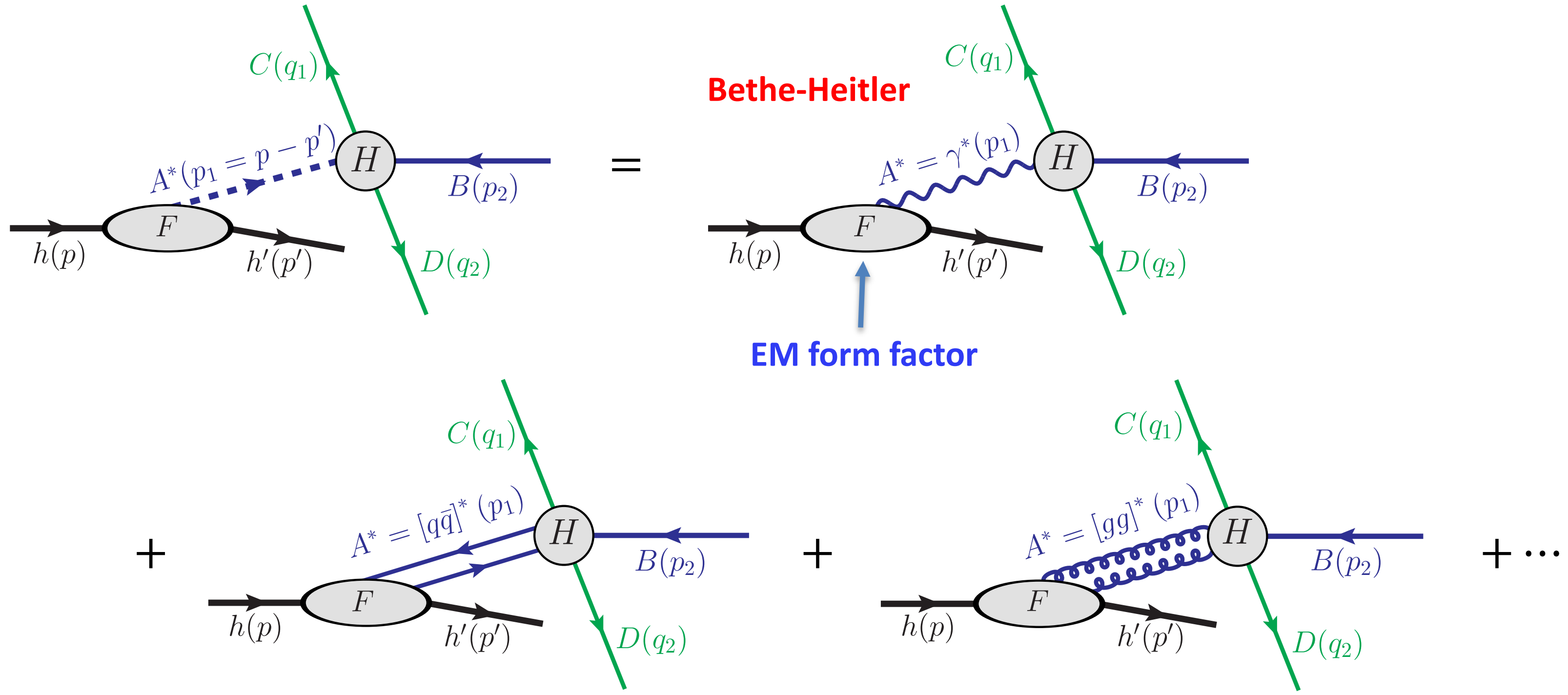

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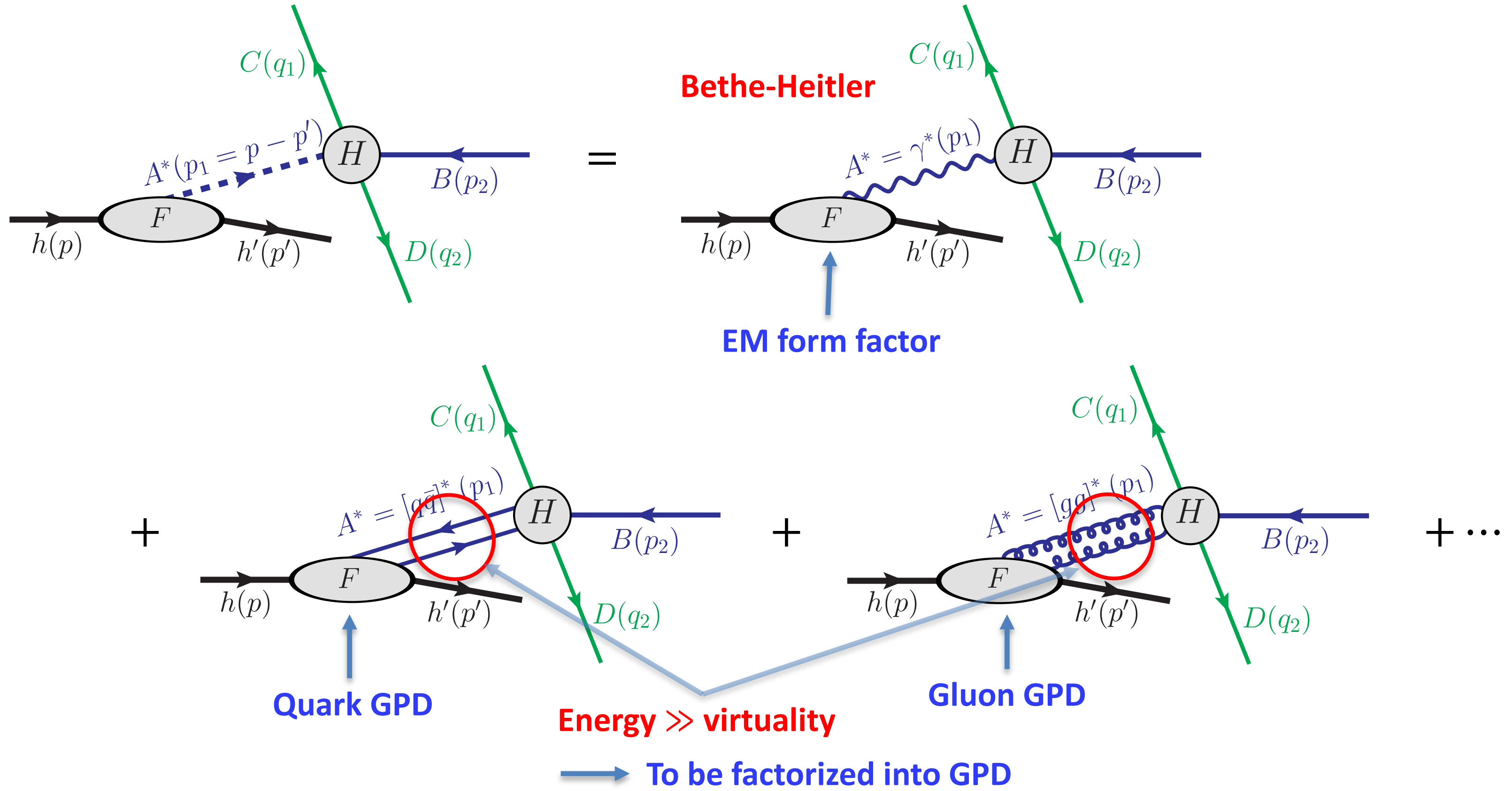
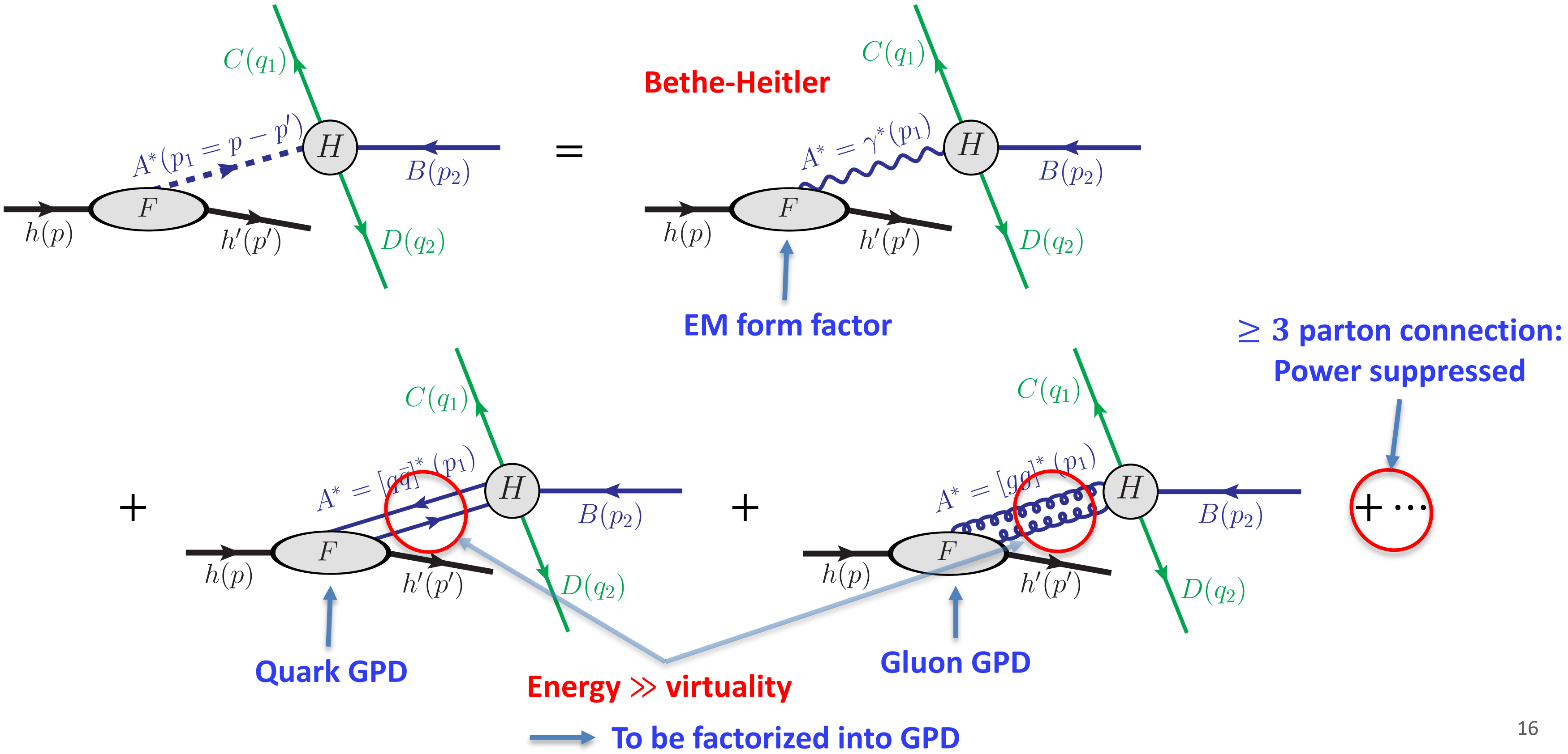
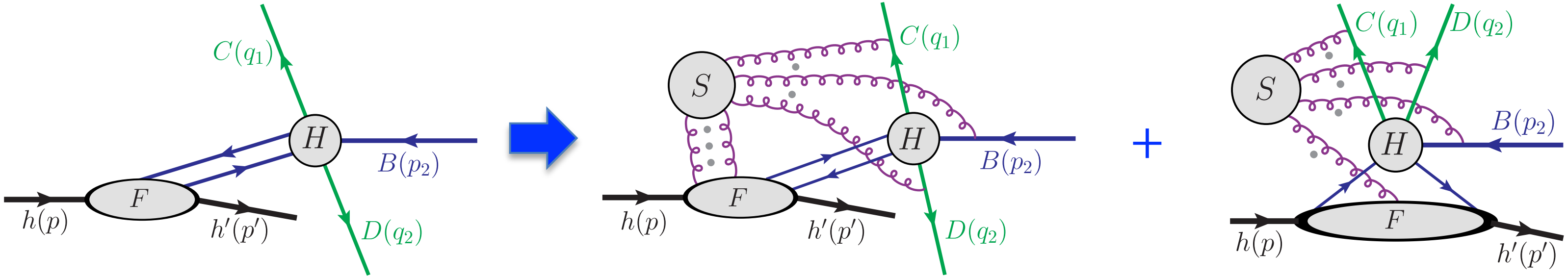


Two-stage paradigm and channel expansion (twist expansion)



Two-parton channel: GPD factorization

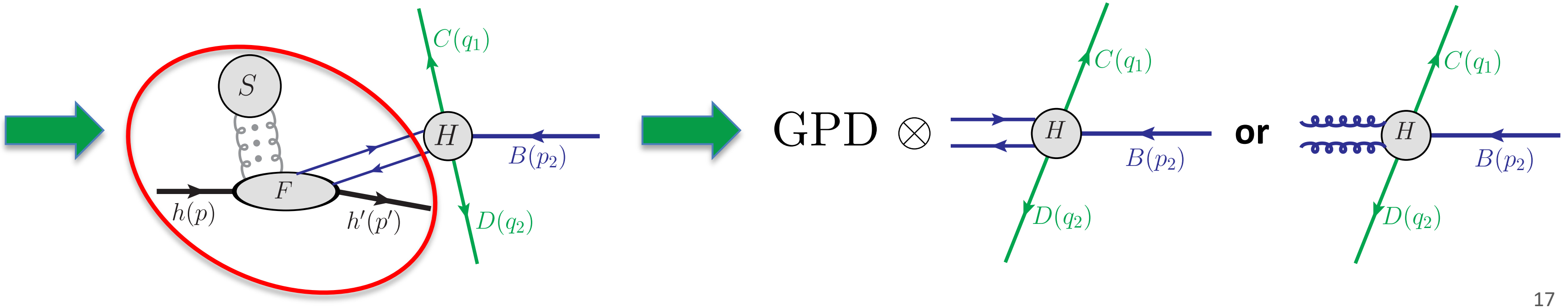
[Qiu & Yu, PRD 107 (2023), 014007]



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

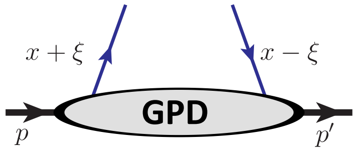
DGLAP region: Glauber pinch

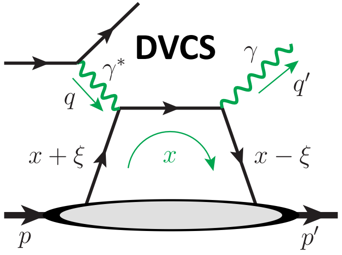
Soft gluons cancel when coupling to (color-neutral) mesons!



Challenge for GPD: x-dependence

❑ ***Amplitude*** **nature: exclusive processes**





x ~ loop momentum

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

never pin down to some x

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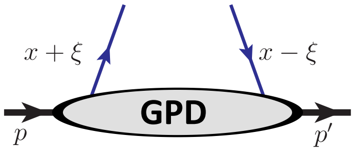

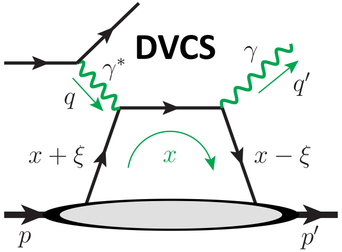

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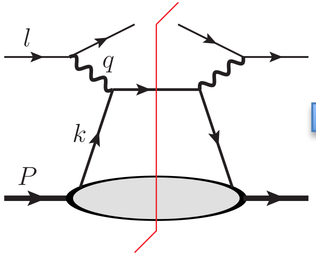
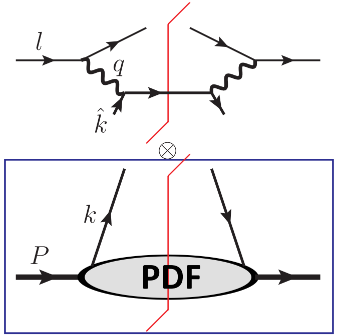
Compare with DIS





cross section**: cut diagram**

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

Challenge for GPD: x-dependence

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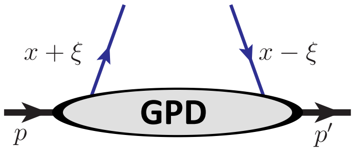

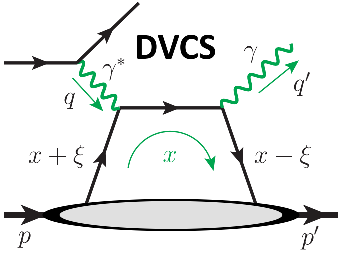

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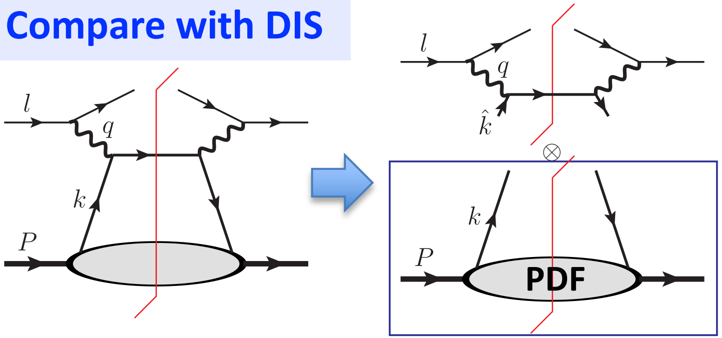


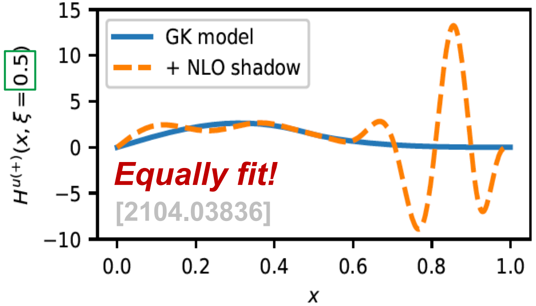
***cross section*: cut diagram**

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

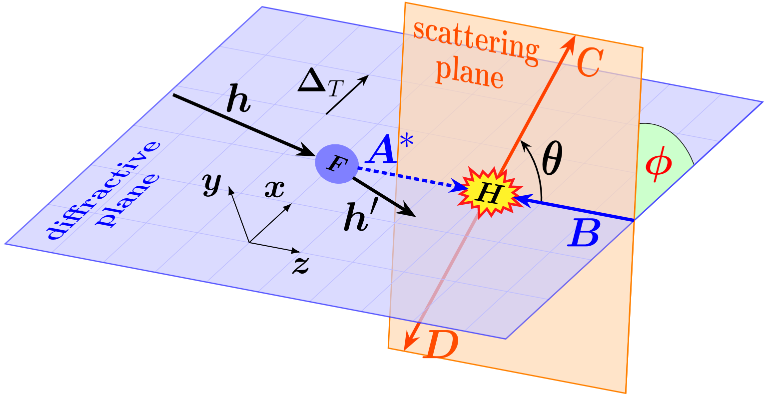
- ***Sensitivity*** **to x: comes from $C(x,\xi;Q/\mu)$**

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

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



Enhanced x-sensitivity



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

Kinematics:

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

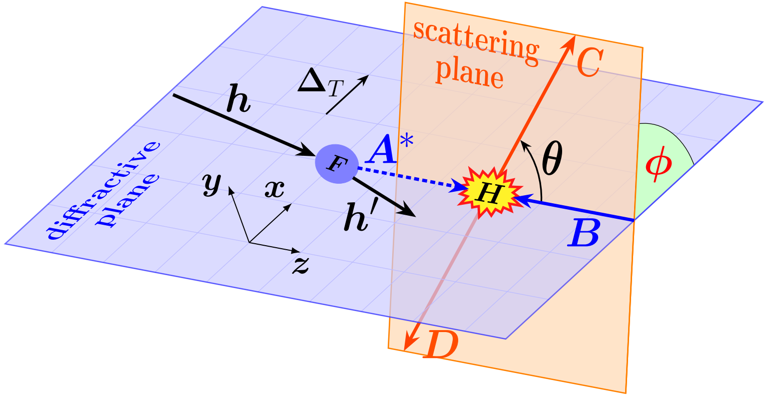
$$\mathcal{M}(Q,\phi) \simeq \sum_A e^{i(\lambda_A-\lambda_B)\phi} \cdot \int_{-1}^{1} dx\, F_A(x)\, C_A(x;Q) \qquad (Q = \theta \text{ or } q_T)$$

[suppressing t and ξ dependence]

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

⟶ **Inversion problem: *shadow GPD*** $S_G = \int_{-1}^{1} dx\, G(x)\, S(x,\xi) = 0$

Enhanced x-sensitivity



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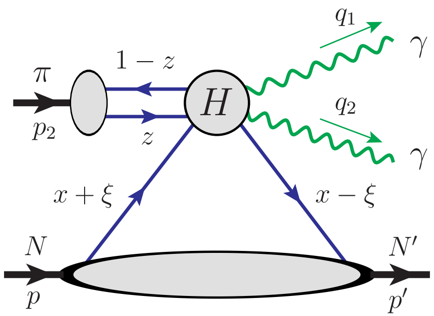
$$\mathcal{M}(Q,\phi) \simeq \sum_A e^{i(\lambda_A-\lambda_B)\phi} \cdot \int_{-1}^{1} dx\, F_A(x)\, C_A(x;Q) \qquad (Q = \theta \text{ or } q_T)$$

[suppressing t and ξ dependence]

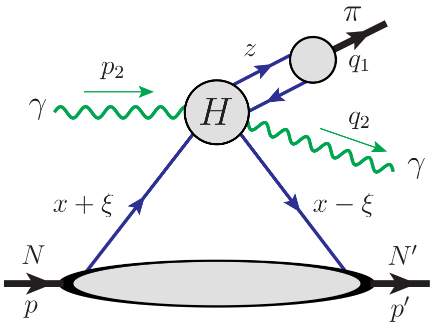
- **Moment-type sensitivity** $C(x;Q) = G(x)\cdot T(Q)$ ⟶ $F_G = \int_{-1}^{1} dx\, G(x)\, F(x,\xi,t)$
- **Enhanced sensitivity** $C(x;Q) \neq G(x)\cdot T(Q)$ ⟶ $d\sigma/dQ \sim \left|C(x;Q) \otimes_x F(x,\xi,t)\right|^2$

Two example processes with enhanced x-sensitivity



J-PARC, AMBER

Qiu, Yu, JHEP 08 (2022) 103

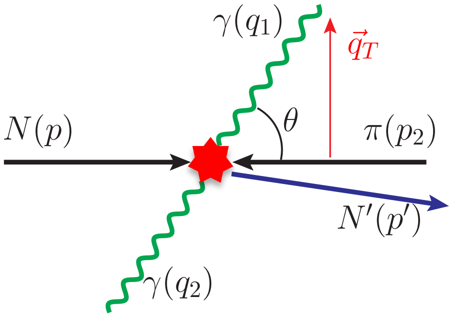


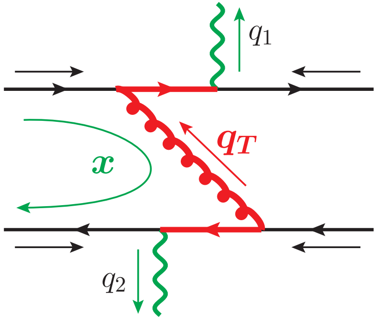
JLab Hall D

G. Duplancic et al., JHEP 11 (2018) 179
Qiu & Yu, PRD 107 (2023), 014007
Qiu & Yu, 2305.15397

Enhanced x-sensitivity: (1) diphoton production

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





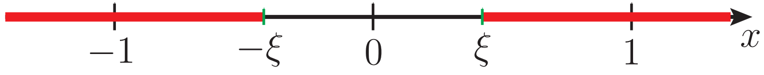
In addition to

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

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

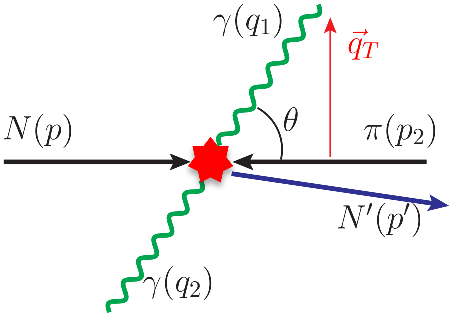
$$I(t,\xi;z,\theta) = \int_{-1}^{1} \frac{dx\, F(x,\xi,t)}{x-\rho(z;\theta)+i\epsilon\,\mathrm{sgn}\left[\cos^2(\theta/2)-z\right]}$$

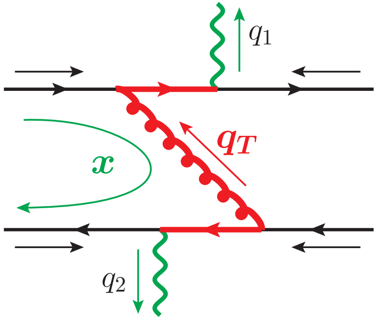
$$\rho(z;\theta) = \xi\cdot\left[\frac{1-z+\tan^2(\theta/2)\,z}{1-z-\tan^2(\theta/2)\,z}\right] \in (-\infty,-\xi]\cup[\xi,\infty)$$



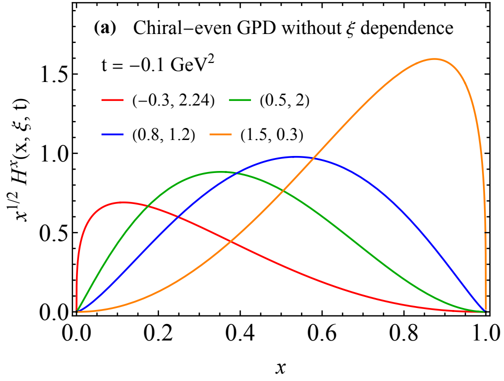
Enhanced x-sensitivity: (1) diphoton production

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

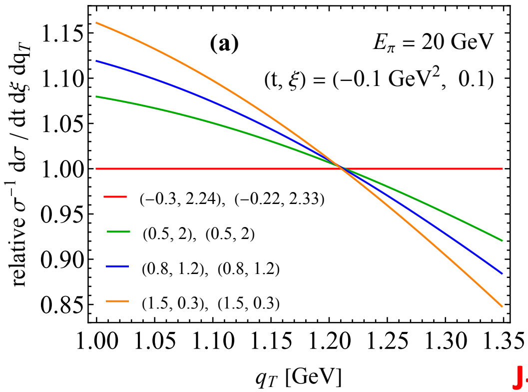


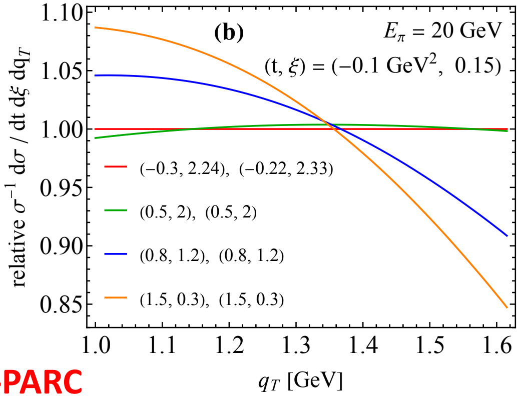


Vary GPD x shapes



Different q_T shapes

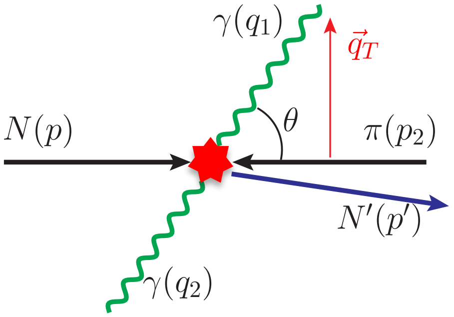


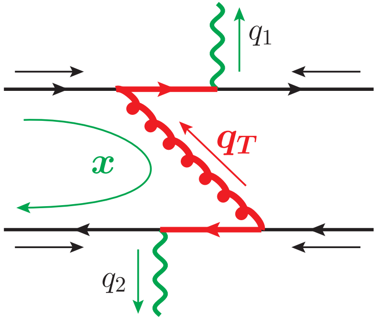


J-PARC

Enhanced x-sensitivity: (1) diphoton production

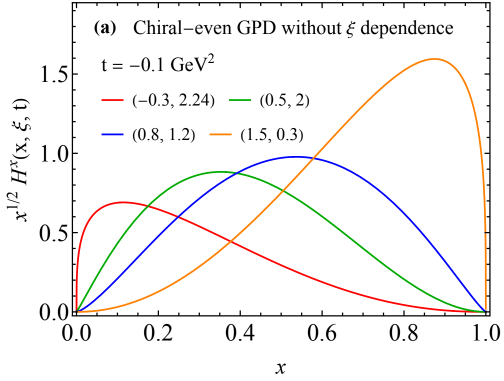
[Qiu & Yu, JHEP 08 (2022) 103]

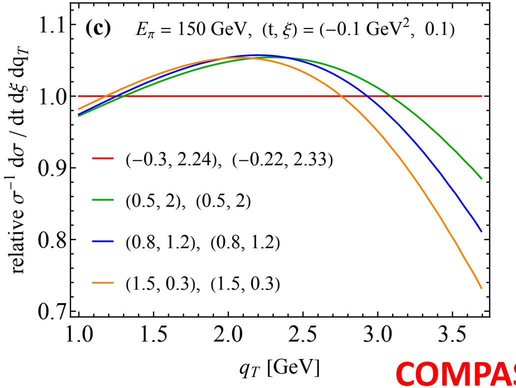


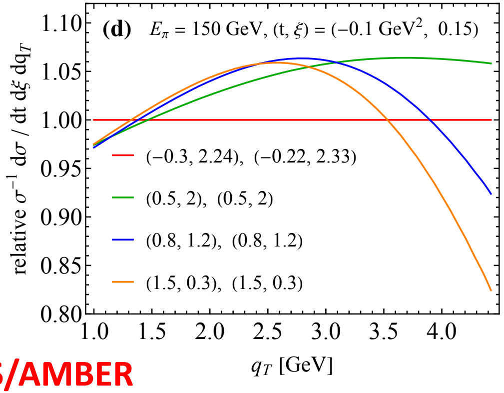


Vary GPD x shapes

Different q_T shapes



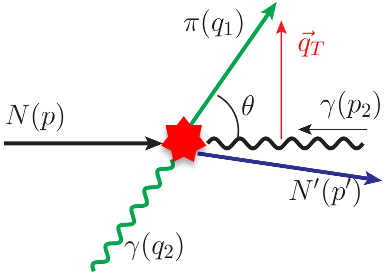




COMPASS/AMBER

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

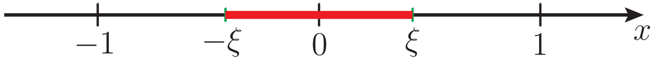
[Qiu & Yu, arXiv:2305.15397]



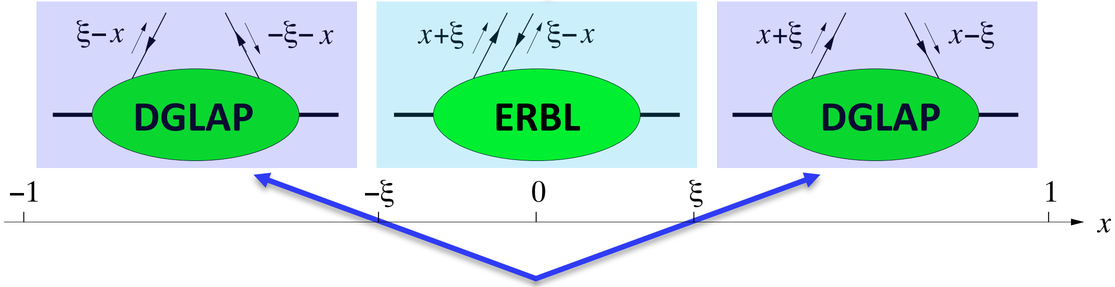
$i\mathcal{M}$ **also contains the special integral**

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

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

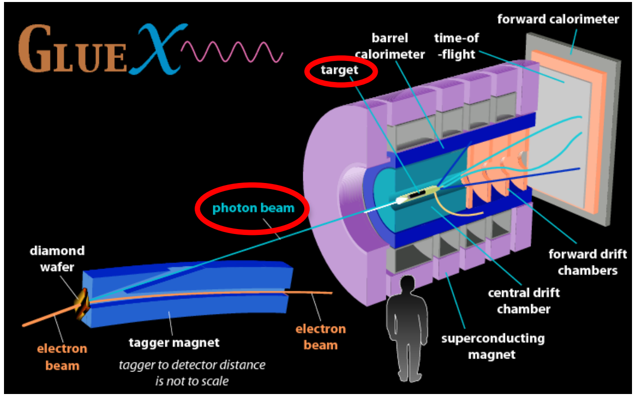


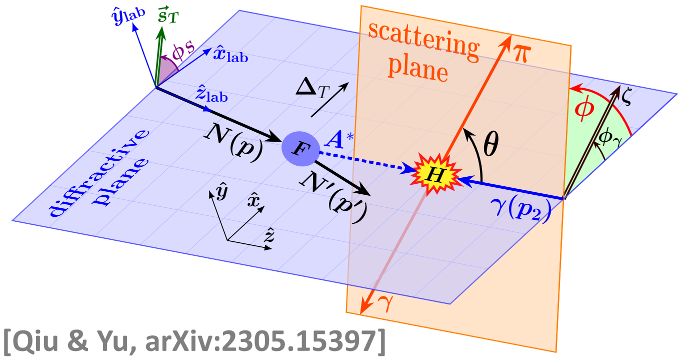
Complementary sensitivity



$\boldsymbol{N\,\pi \to N'\,\gamma\,\gamma}$

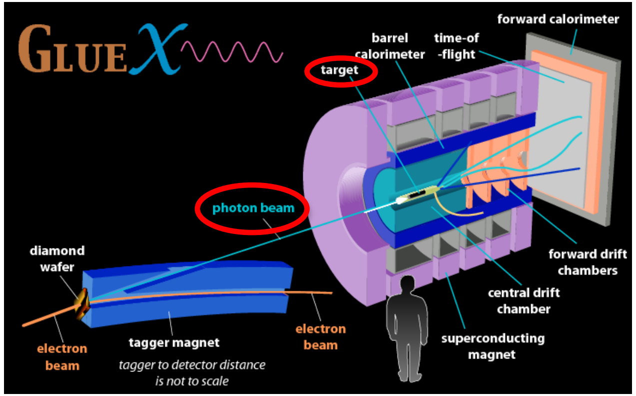
Enhanced x-sensitivity: (2) γ-π pair production

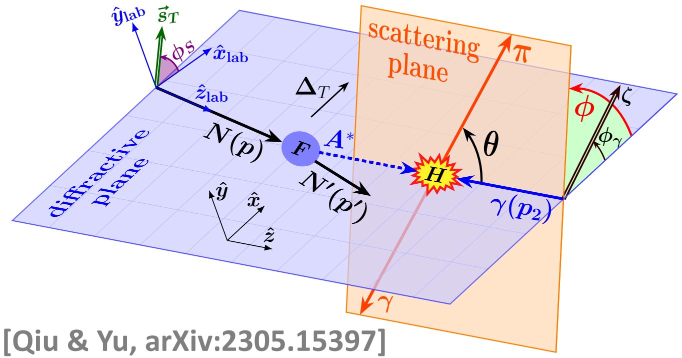




[Qiu & Yu, arXiv:2305.15397]

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





[Qiu & Yu, arXiv:2305.15397]

Polarization asymmetries

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

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

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

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

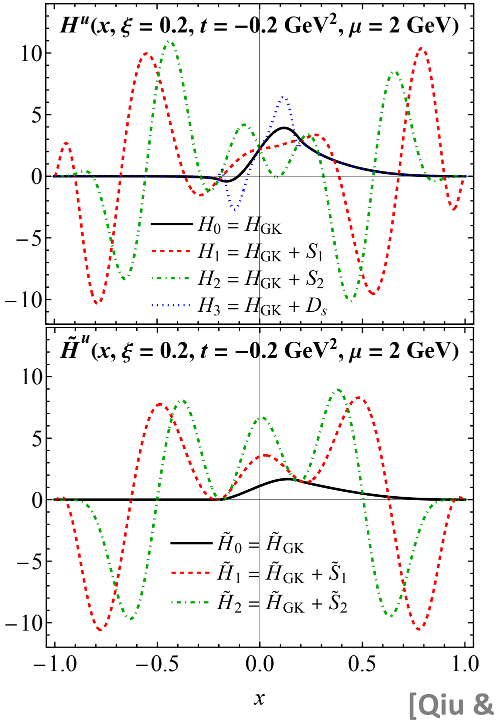
$$A_{UT} = 2\,\Sigma_{UU}^{-1}\,\mathrm{Re}\left[\widetilde{\mathcal{M}}_+^{[H]}\,\widetilde{\mathcal{M}}_-^{[H]*} - \mathcal{M}_+^{[\widetilde{H}]}\,\mathcal{M}_-^{[\widetilde{H}]*}\right],$$

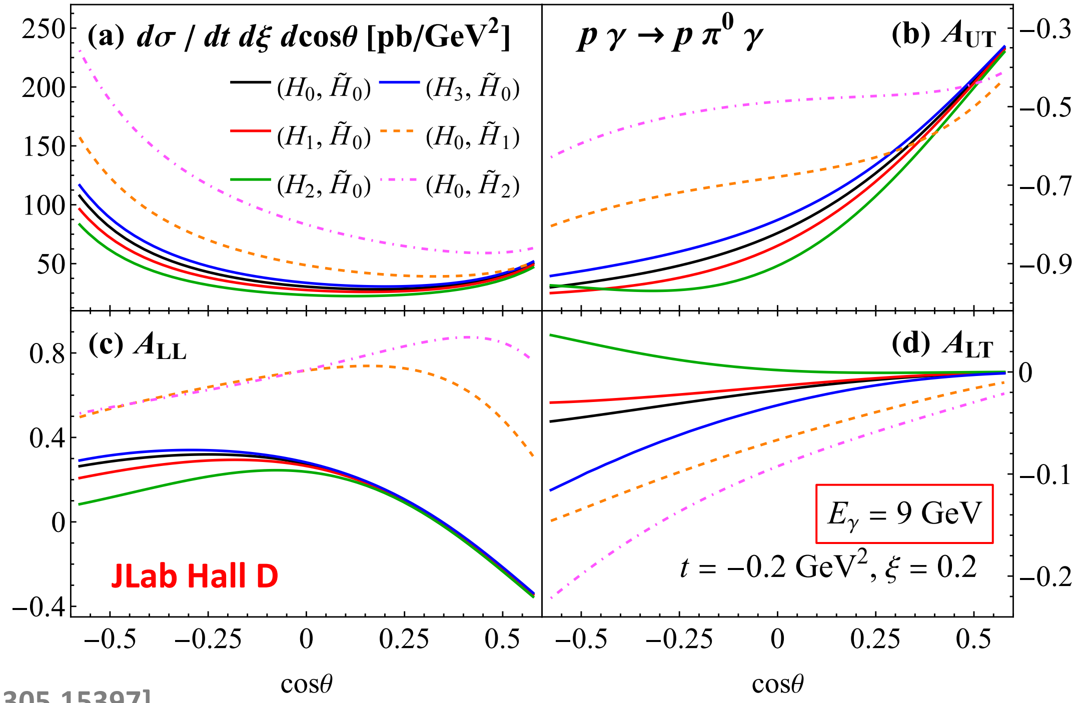
$$A_{LT} = 2\,\Sigma_{UU}^{-1}\,\mathrm{Im}\left[\mathcal{M}_+^{[\widetilde{H}]}\,\widetilde{\mathcal{M}}_-^{[H]*} + \mathcal{M}_-^{[\widetilde{H}]}\,\widetilde{\mathcal{M}}_+^{[H]*}\right].$$

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

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, arXiv:2305.15397]

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

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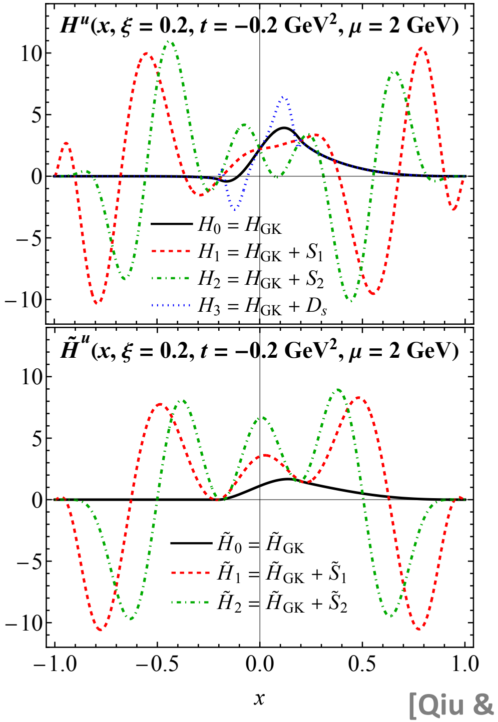
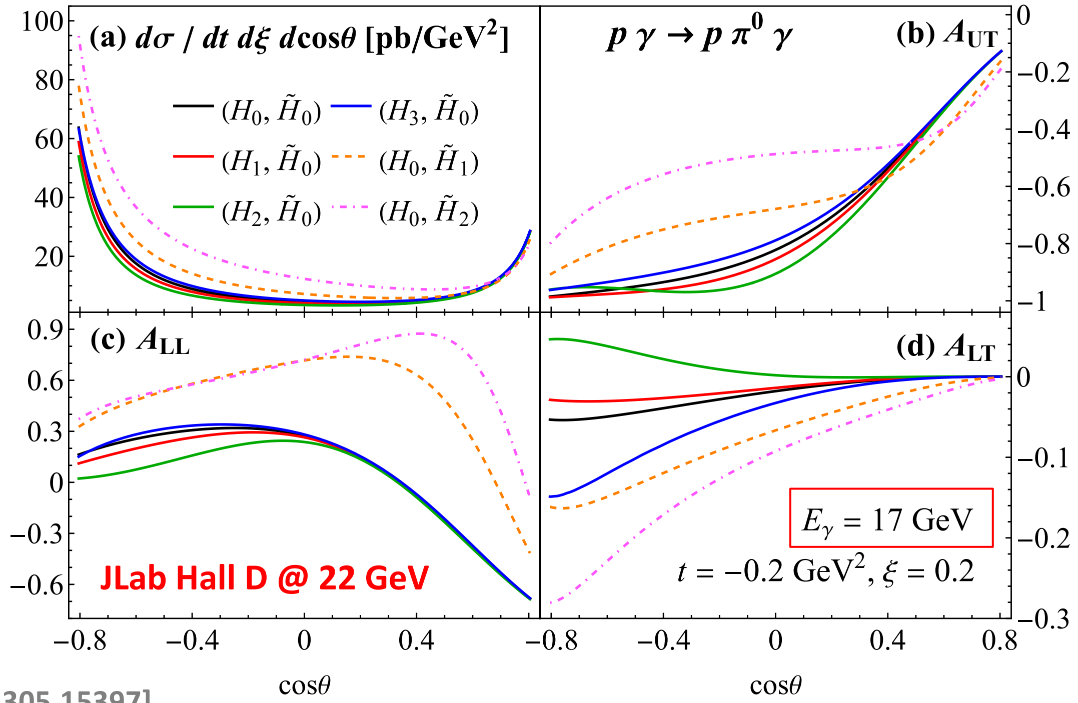
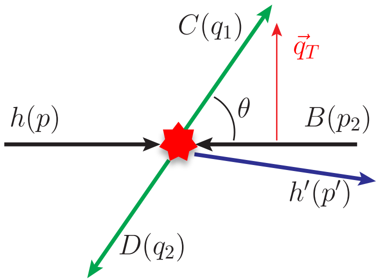




[Qiu & Yu, arXiv:2305.15397]

Summary

- GPD and hadron 3D imaging
- Single Diffractive Hard Exclusive Processes (SDHEP)
  - Systematic factorization.
  - Roadmap for known and more new processes!



SDHEP

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

- ML/AI
- LQCD

Thank you!

Backup slides

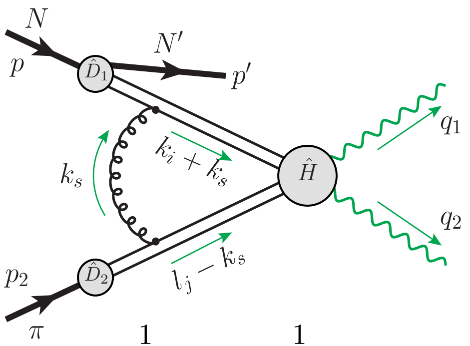
SDHEP: soft gluon and factorization

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

Gluons in the Glauber region: $k_s = (\lambda^2, \lambda^2, \lambda)\, Q$ $\quad \lambda \sim m_\pi/Q, \quad Q \sim q_T$

Transverse component contribute to the leading region!

ERBL region



$$\frac{1}{k_s^2 + i\varepsilon} \to \frac{1}{-\mathbf{k}_s^2 + i\varepsilon}$$

$$\frac{1}{(k_i + k_s)^2 + i\varepsilon} \to \frac{1}{k_s^- + i\varepsilon}$$

$$\frac{1}{(l_j - k_s)^2 + i\varepsilon} \to \frac{1}{-k_s^+ + i\varepsilon}$$

No pinch!

SDHEP: soft gluon and factorization

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

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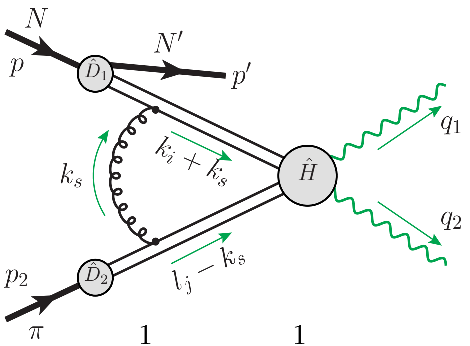
ERBL region



$$\frac{1}{k_s^2 + i\varepsilon} \to \frac{1}{-\mathbf{k}_s^2 + i\varepsilon}$$

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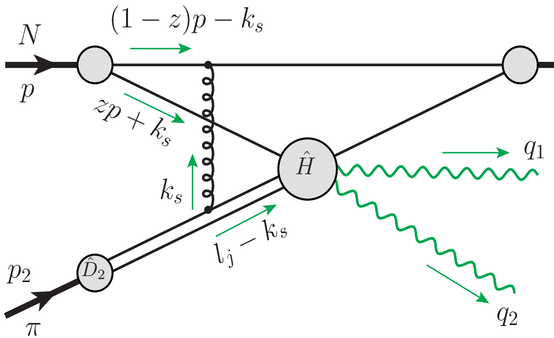
$$\frac{1}{(l_j - k_s)^2 + i\varepsilon} \to \frac{1}{-k_s^+ + i\varepsilon}$$

No pinch!

DGLAP region



$$\frac{1}{((1-z)p - k_s)^2 + i\varepsilon} \to \frac{1}{k_s^- - i\varepsilon}$$

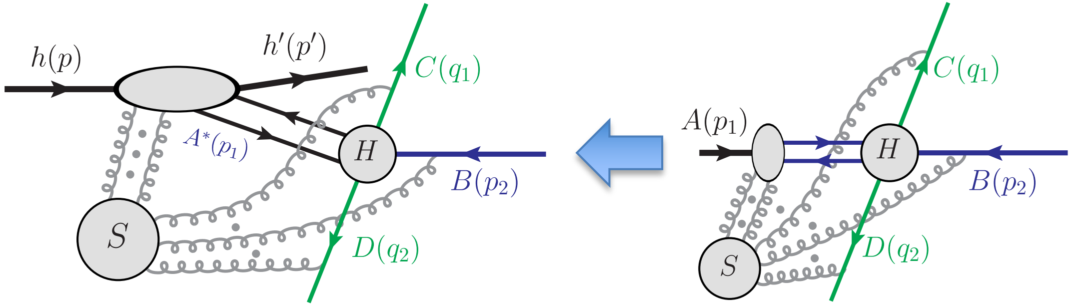
$$\frac{1}{(zp + k_s)^2 + i\varepsilon} \to \frac{1}{k_s^- + i\varepsilon}$$

Pinched!

Same conclusion if k_s flows through N'!

SDHEP: two-stage paradigm and factorization

❑ Factorization for 2-parton channel



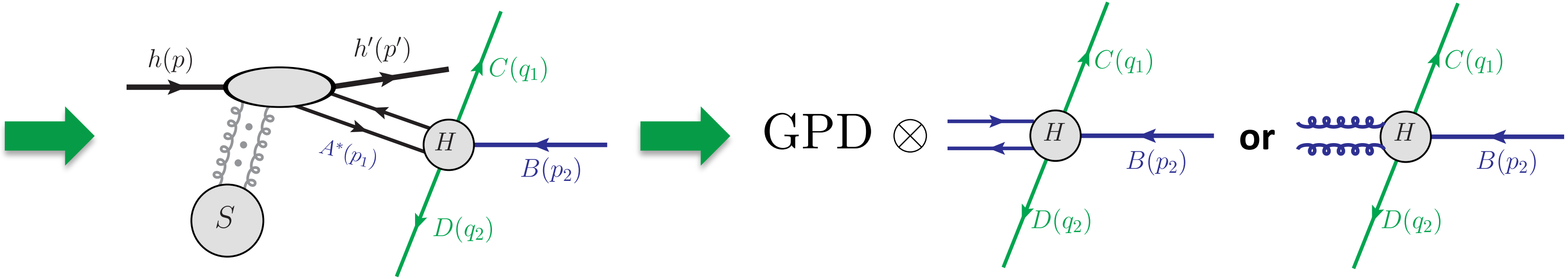
Only complication:

k_s^- is pinched in Glauber region for DGLAP region.

$$k_s^+ \mapsto k_s^+ \pm i\mathcal{O}(Q)$$

Glauber ⇒ ***h*-collinear region**

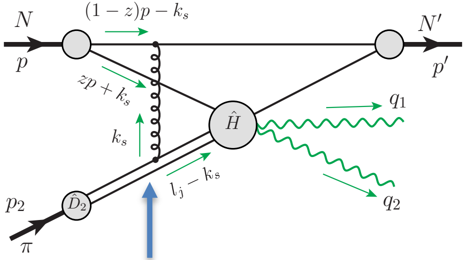
Soft gluons cancel for the meson-initialized process



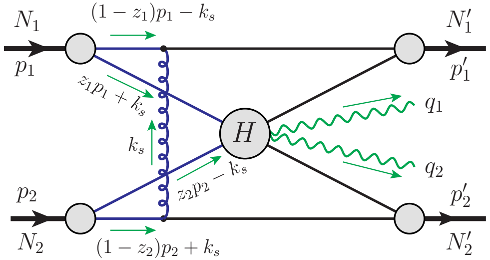
Why *single* diffractive?

❑ Double diffractive process

Glauber pinch for diffractive scattering



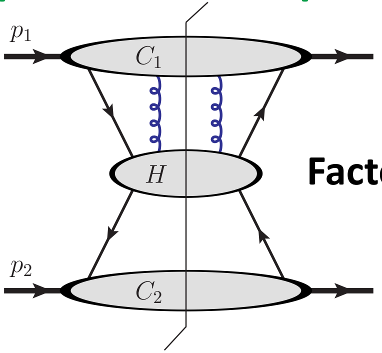
Factorizable thanks to pion



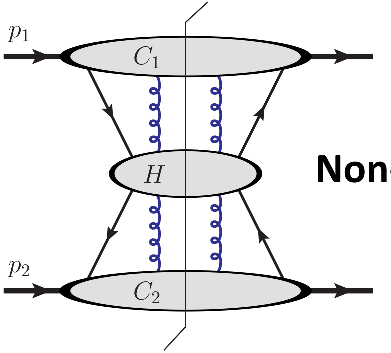
Non-factorizable **even with hard scale**

Both k_s^+ and k_s^- are pinched in Glauber region!

❑ Compare: Drell-Yan process at high twist



Factorizable



Non-factorizable