MICHIGAN STATE UNIVERSITY

Single Diffractive Hard Exclusive Process

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

JHEP 08 (2022) 103, PRD 107 (2023) 014007, arXiv:2305.15397

CNF Generalized Parton Distributions and Global Analysis

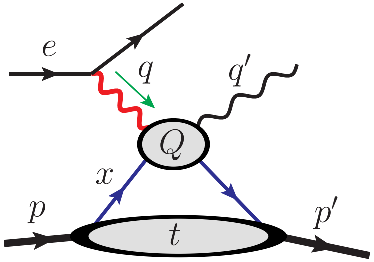
Jun/12/2023

Jefferson Lab

CENTER *for* NUCLEAR FEMTOGRAPHY

GPD and 3D tomography

DVCS

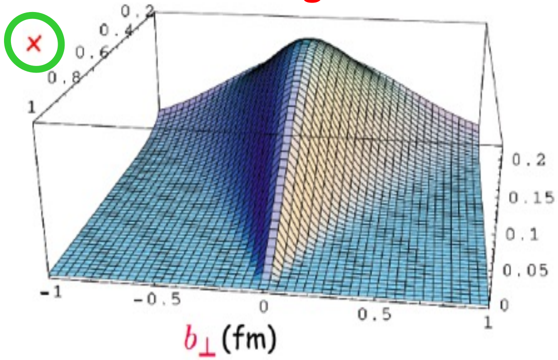


$$f_i(x, \boldsymbol{b}_T) = \int d^2\boldsymbol{\Delta}_T\, e^{i\boldsymbol{\Delta}_T\cdot\boldsymbol{b}_T} F_i(x, 0, -\Delta_T^2)$$

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

F. T.

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



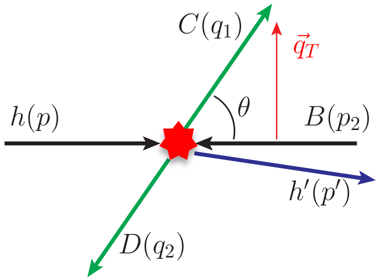
❑ Essential features

- **Hadron is kept intact** → **Amplitude nature: Exclusive process**
- **Parton dynamics** → **Hard scale** Q
- **Extra nonperturbative scale** t → **Diffractive process**

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!

Single diffractive hard exclusive process (SDHEP)

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

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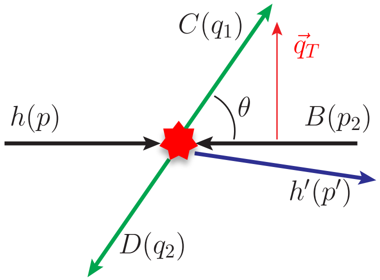

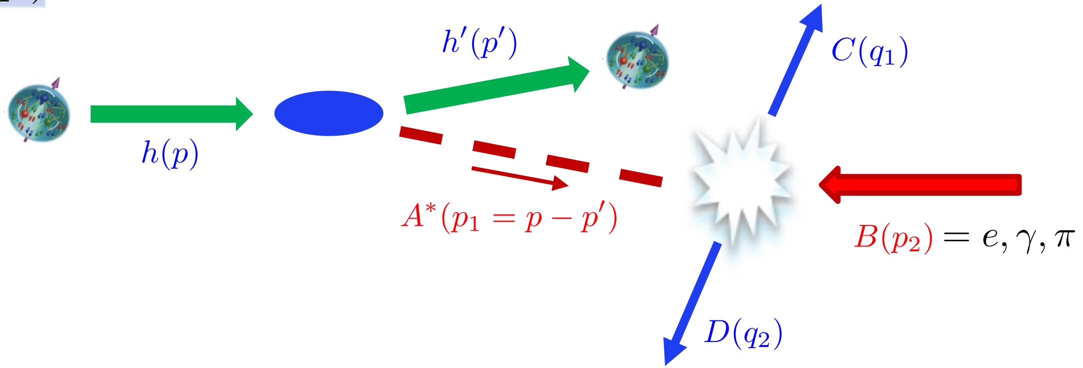

2 → 3: *minimal* kin. configuration!

❑ Two-stage process paradigm

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

factorize

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

Single diffractive hard exclusive process (SDHEP)

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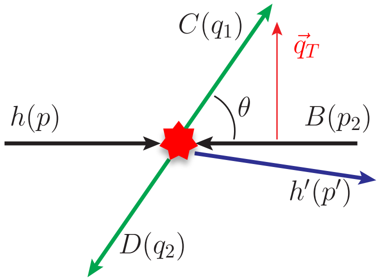
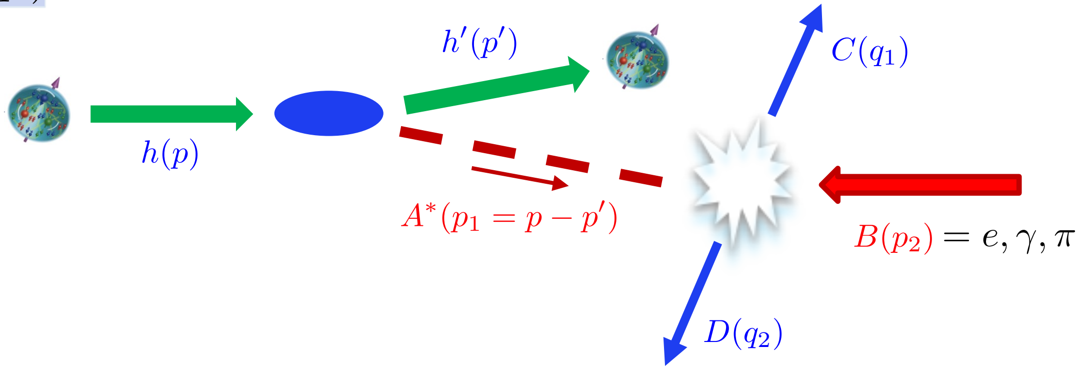




$2 \to 3$: ***minimal*** **kin. configuration!**

❑ Two-stage process paradigm

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

↓ **factorize**

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

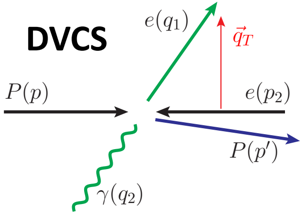
Necessary **condition for factorization:**

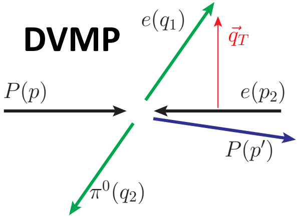
$$q_T \gg \sqrt{-t} \simeq \Lambda_{\rm QCD} \qquad t = (p - p')^2$$

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

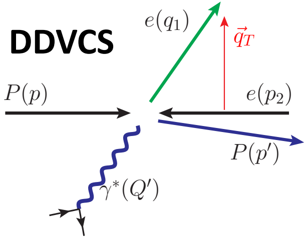
Classification of SDHEPs

- Electro-production (JLab, EIC, …)





add virtuality



DHQP…

Classification of SDHEPs

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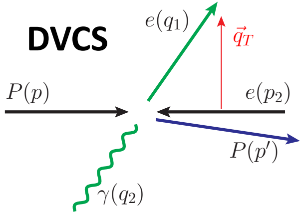
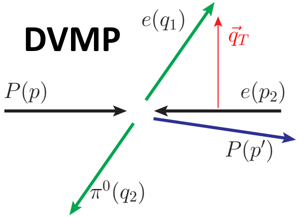
DVCS



DVMP



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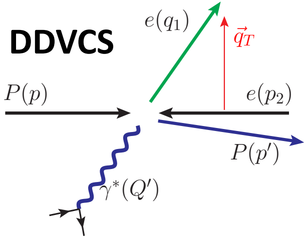
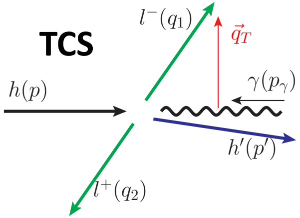
DDVCS

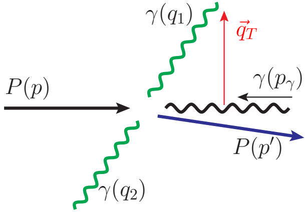


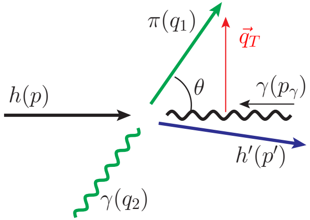
DHQP…

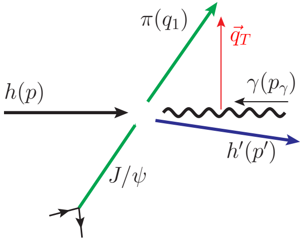
- **Photo-production (JLab, EIC, …)**

TCS









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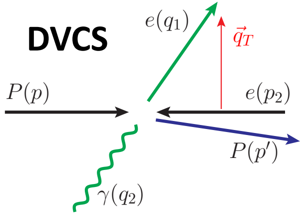

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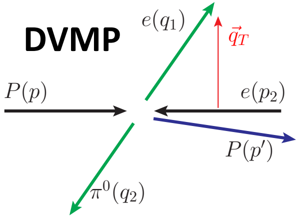

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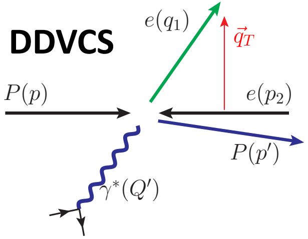

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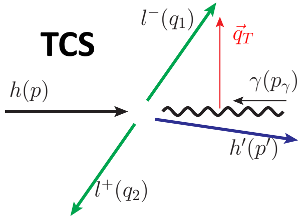

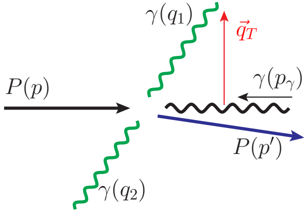

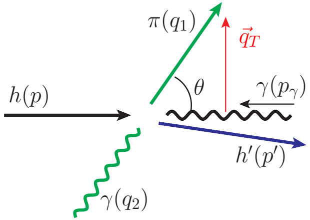

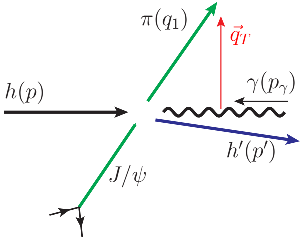

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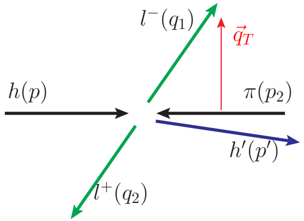
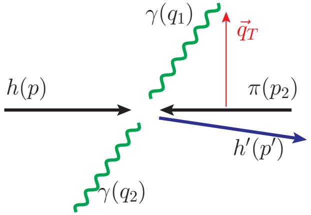
❑ Meso-production (AMBER, J-PARC, …)





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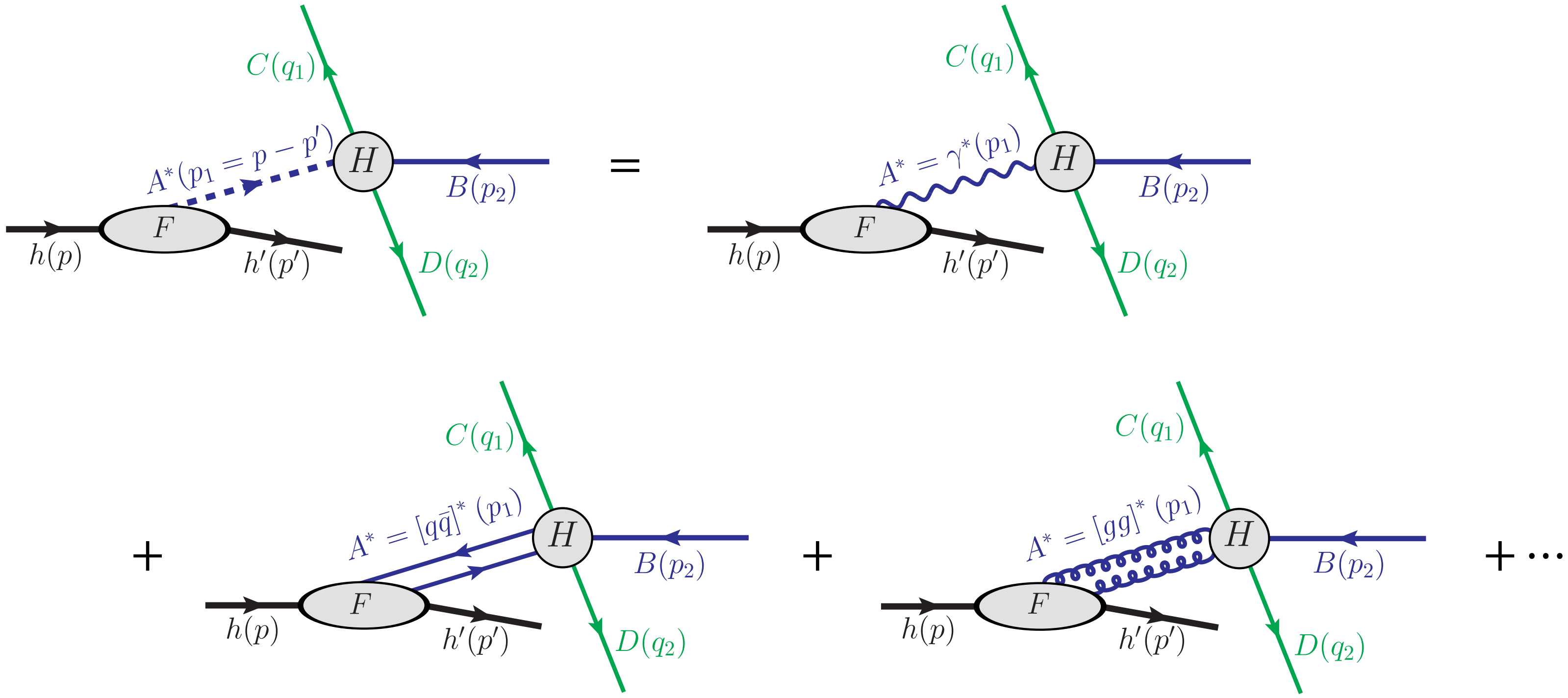
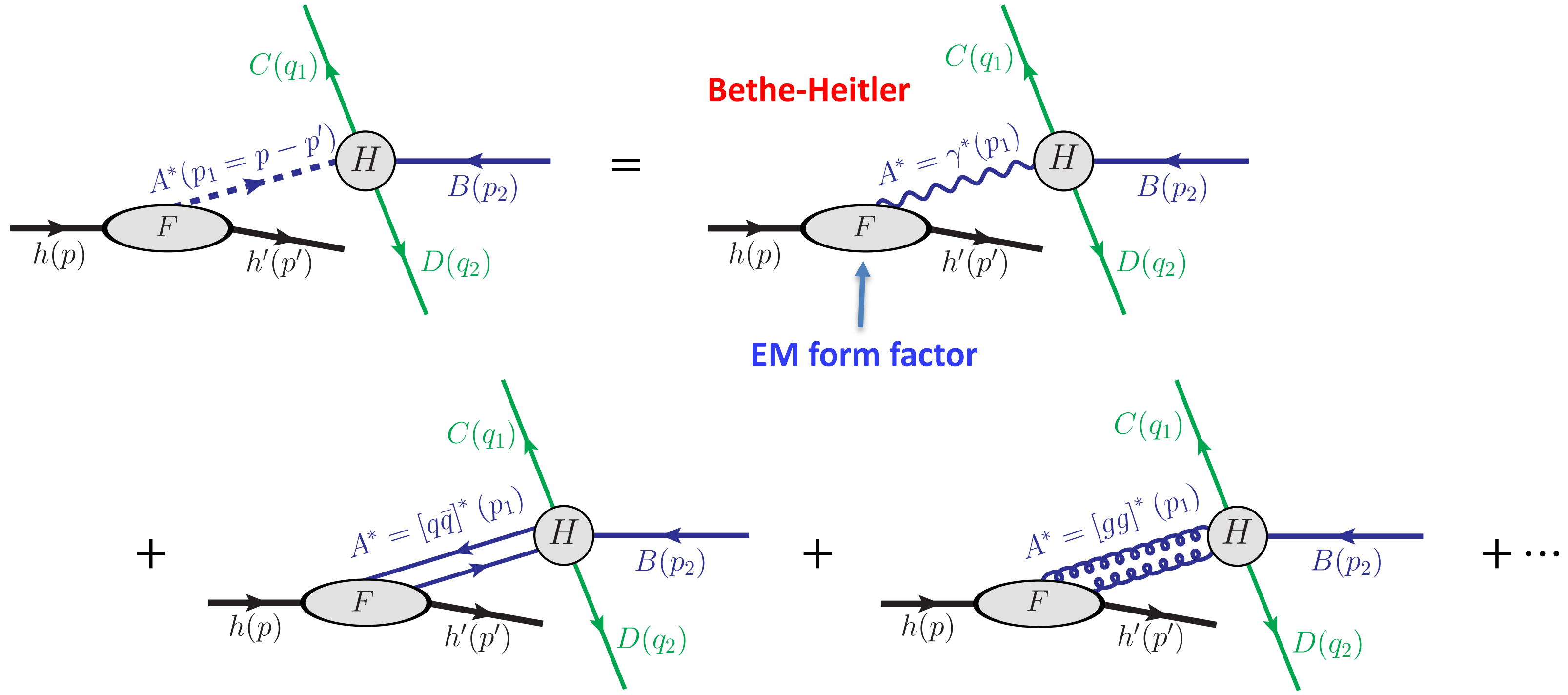
Generic discussion

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

Two-stage paradigm and channel expansion



Two-stage paradigm and channel expansion



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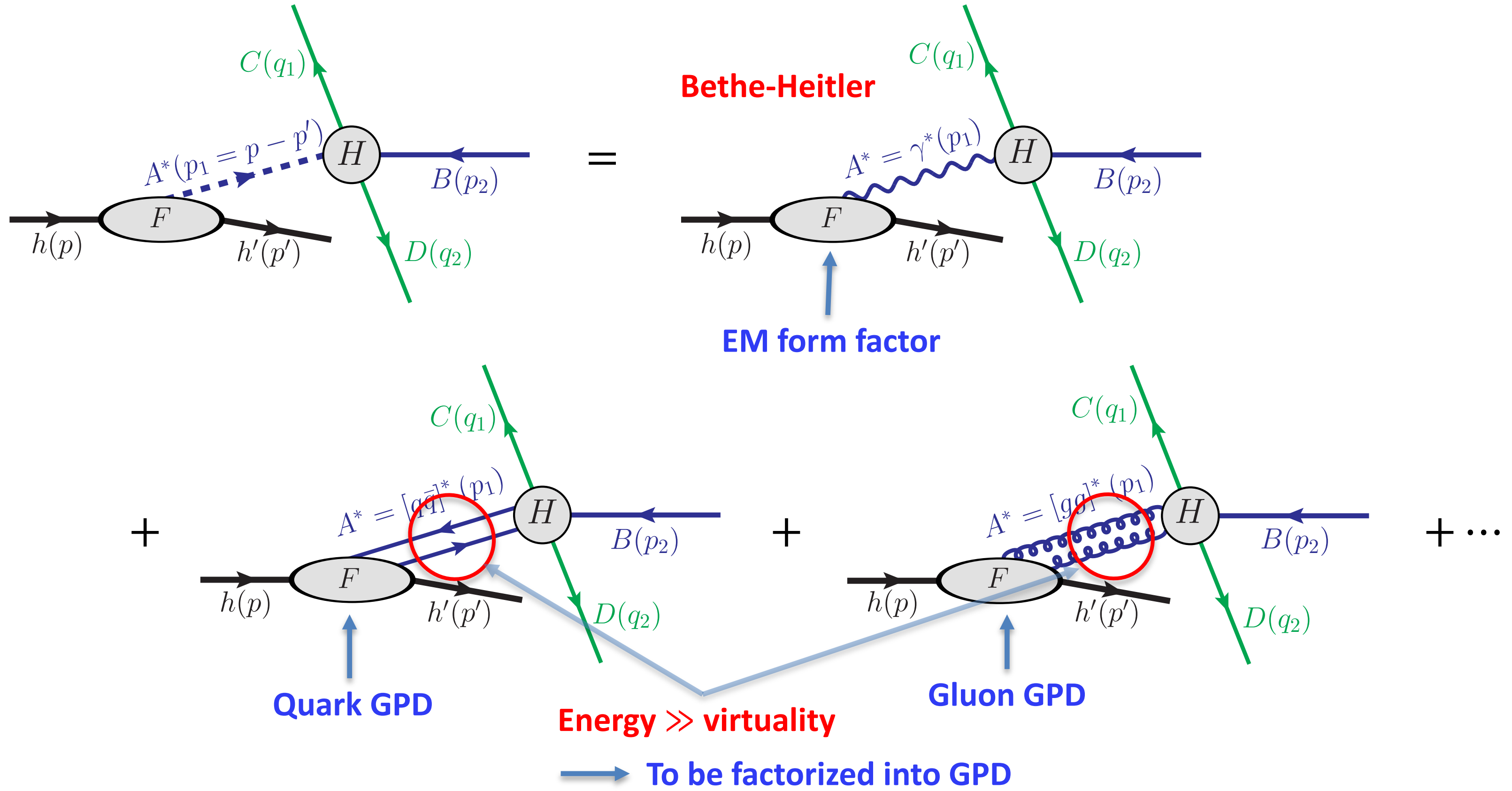
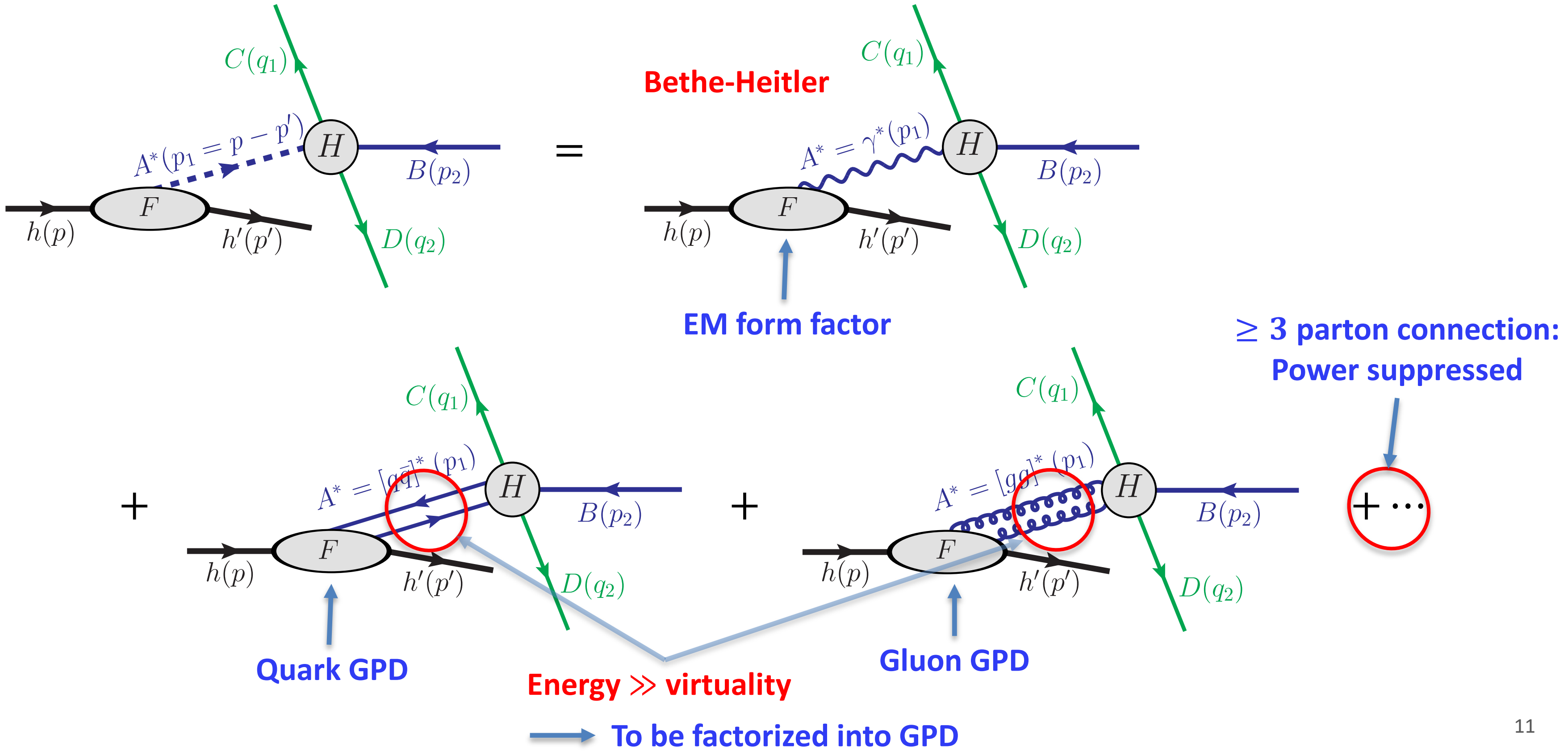
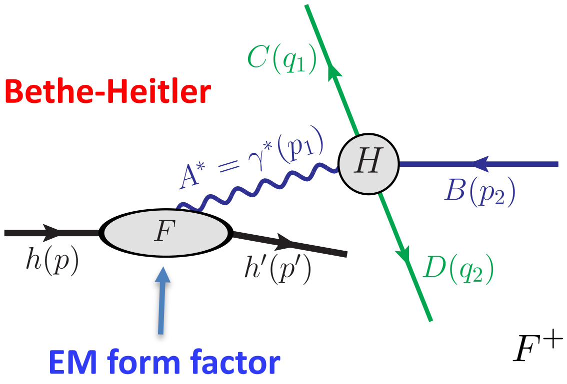


Two-stage paradigm and channel expansion (twist expansion)



Virtual photon channel: "GPD background"



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

$$\equiv \frac{ie^2}{t} F^\mu(p, p') \mathcal{H}_\mu(p_1, p_2, q_1, q_2)$$

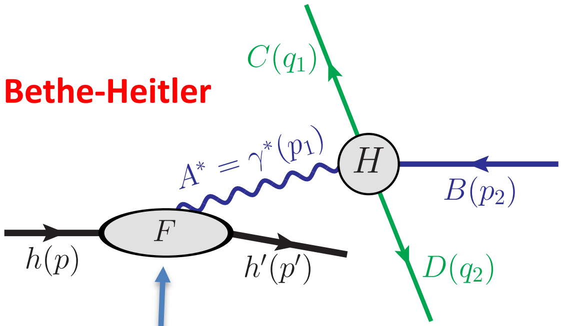
Leading component

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

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

Virtual photon channel: "GPD background"

Bethe-Heitler



EM form factor

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

$$\equiv \frac{ie^2}{t}F^\mu(p,p')\mathcal{H}_\mu(p_1,p_2,q_1,q_2)$$

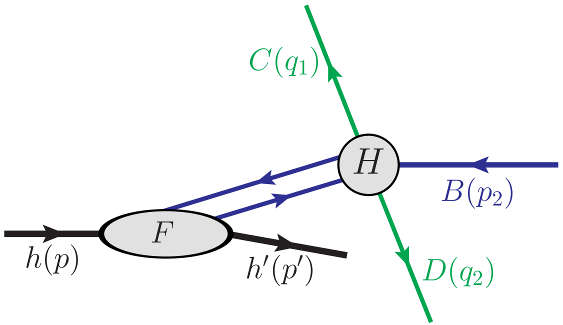
Leading component

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

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

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

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



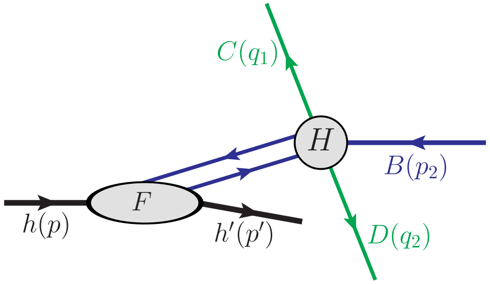
γ^* channel is of a *more leading power* than GPD contribution, but higher power in α_{EM}

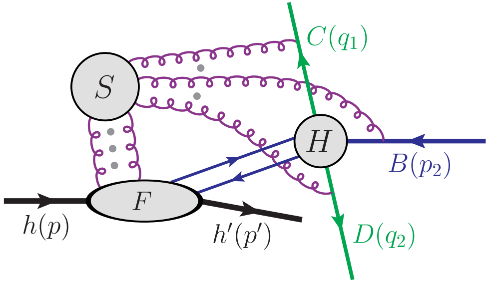
Generally allowed, except

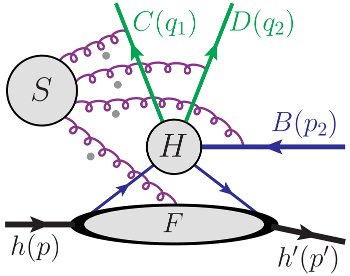
(1) flavor changing ($p \to n, n \to p$, etc.)
(2) forbidden by symmetry in the hard part

Two-parton channel: GPD factorization

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

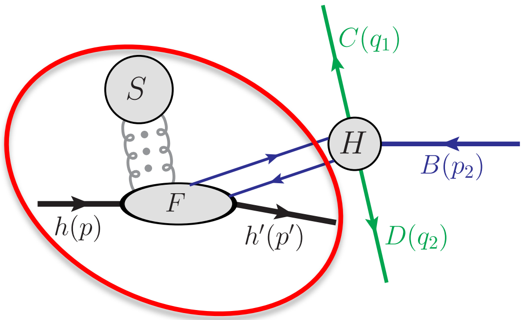




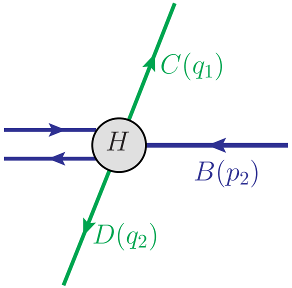


ERBL region: $[q\bar{q}']\sim$ meson **DGLAP region: Glauber pinch**

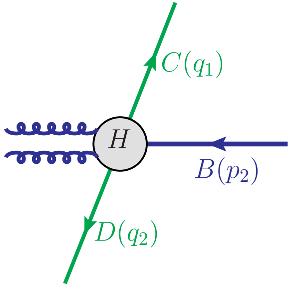
Soft gluons cancel when coupling to (color-neutral) mesons!



$\mathrm{GPD}\otimes$

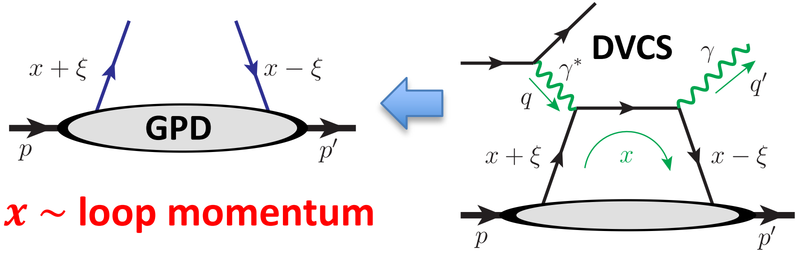


or



Challenge for GPD: *x*-dependence

- ***Amplitude*** **nature: exclusive processes**

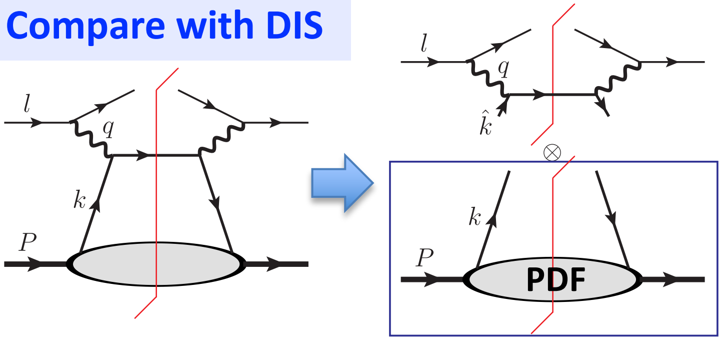


x **~ loop momentum**

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

never pin down to some ***x***

Compare with DIS



cross section**: cut diagram**

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

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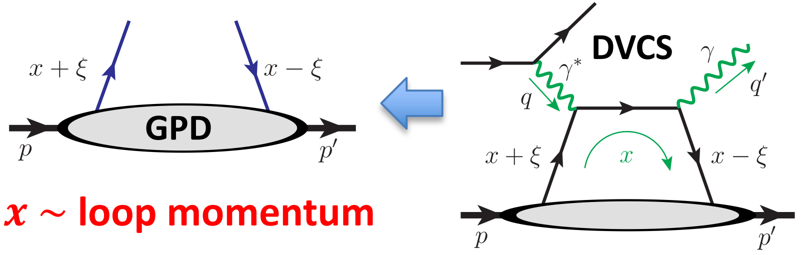

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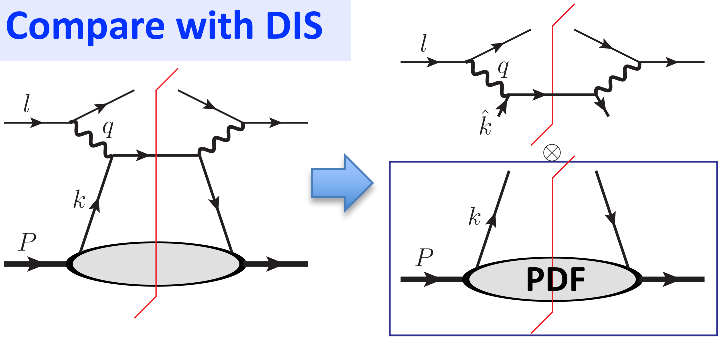


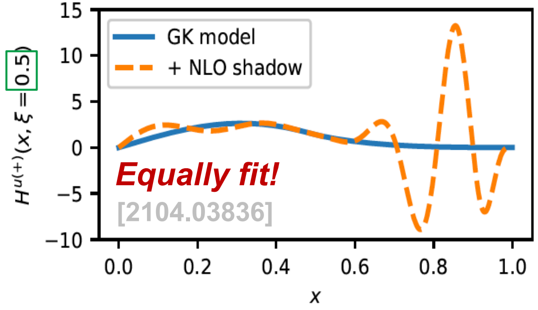
cross section**: cut diagram**

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

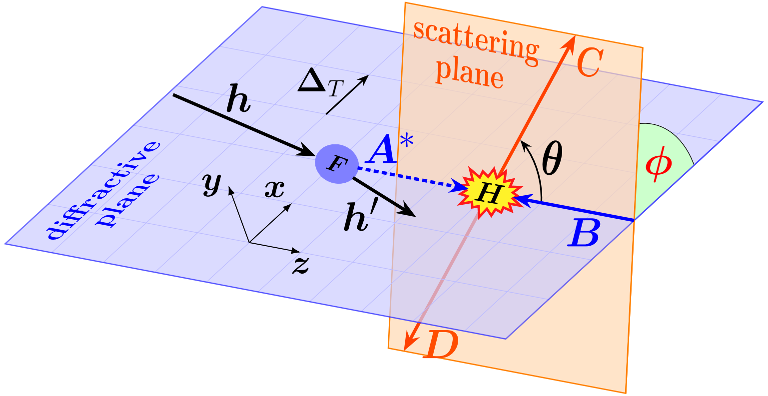
- ***Sensitivity*** **to x: comes from $C(x,\xi;Q/\mu)$**

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

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



Enhanced x-sensitivity



- x-sensitivity ⇔ 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

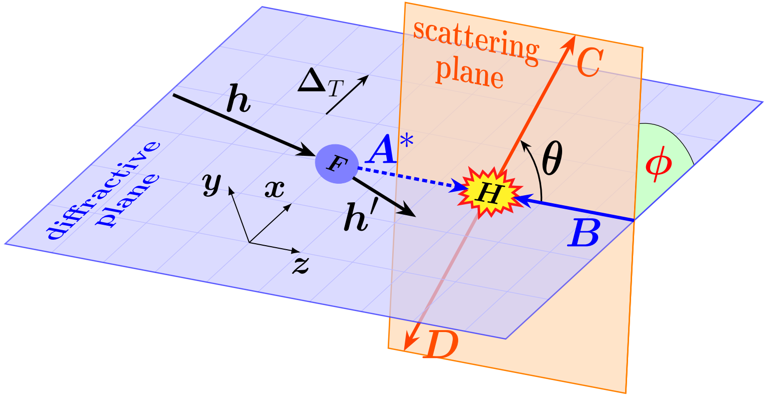
$$\mathcal{M}(Q,\phi) \simeq \sum_A e^{i(\lambda_A - \lambda_B)\phi} \cdot \int_{-1}^{1} dx\, F_A(x)\, C_A(x;Q) \qquad (Q = \theta \text{ or } q_T)$$

[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



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

Kinematics:

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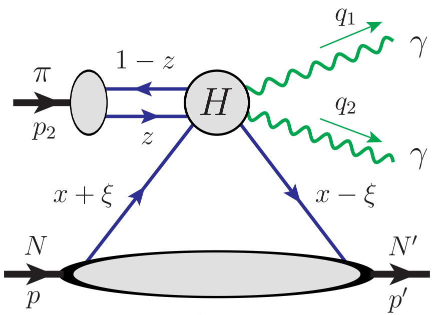
[suppressing t and ξ dependence]

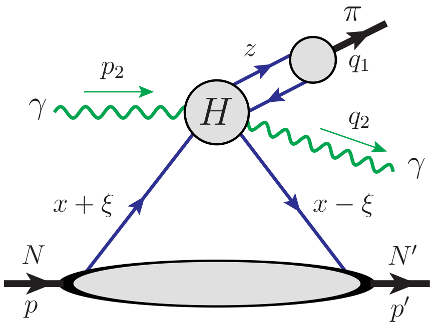
- **Moment-type sensitivity** $C(x;Q) = G(x) \cdot T(Q)$ ⟶ $F_G = \int_{-1}^{1} dx\, G(x)\, F(x,\xi,t)$
- **Enhanced sensitivity** $C(x;Q) \neq G(x) \cdot T(Q)$ ⟶ $d\sigma/dQ \sim \left|C(x;Q) \otimes_x F(x,\xi,t)\right|^2$

Two example processes with enhanced x-sensitivity



J-PARC, AMBER

Qiu, Yu, JHEP 08 (2022) 103

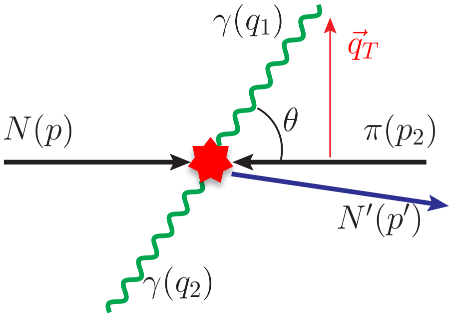


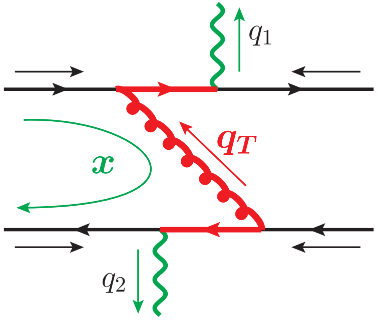
JLab Hall D

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]





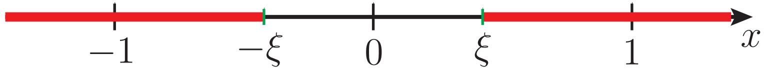
In addition to

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

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

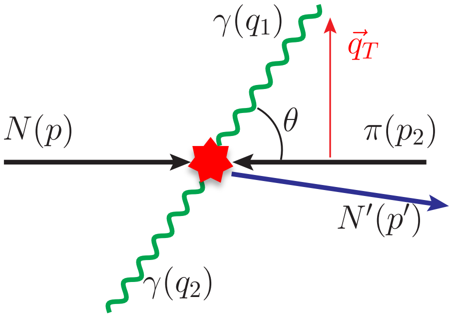
$$I(t, \xi; z, \theta) = \int_{-1}^{1} \frac{dx\, F(x, \xi, t)}{x - \rho(z;\theta) + i\epsilon\, \mathrm{sgn}\left[\cos^2(\theta/2) - z\right]}$$

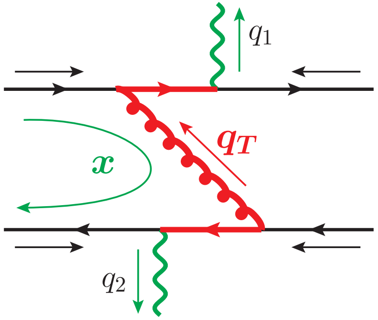
$$\rho(z;\theta) = \xi \cdot \left[\frac{1 - z + \tan^2(\theta/2)\, z}{1 - z - \tan^2(\theta/2)\, z}\right] \in (-\infty, -\xi] \cup [\xi, \infty)$$



Enhanced x-sensitivity: (1) diphoton production

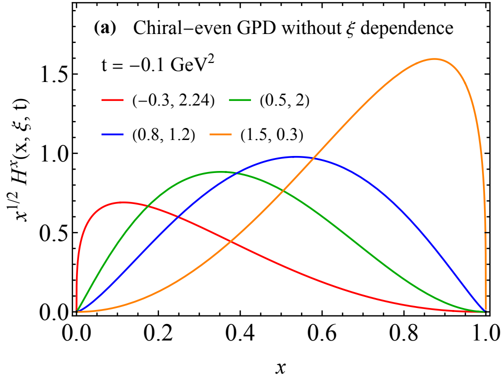
[Qiu & Yu, JHEP 08 (2022) 103]

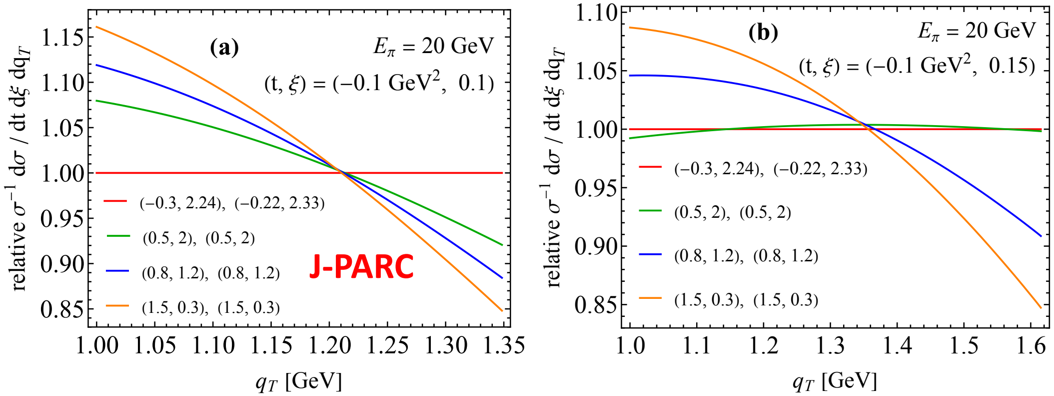




Vary GPD x shapes

Different q_T shapes





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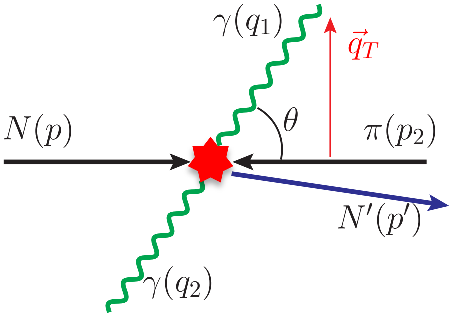

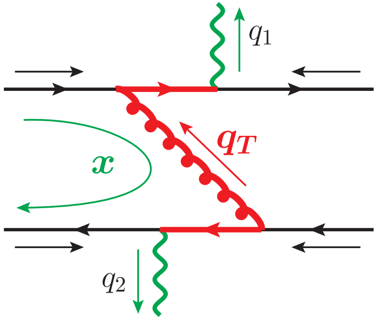

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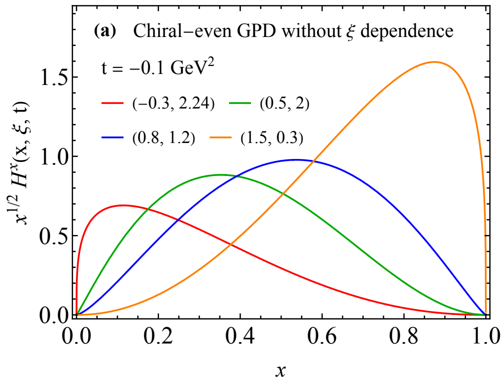
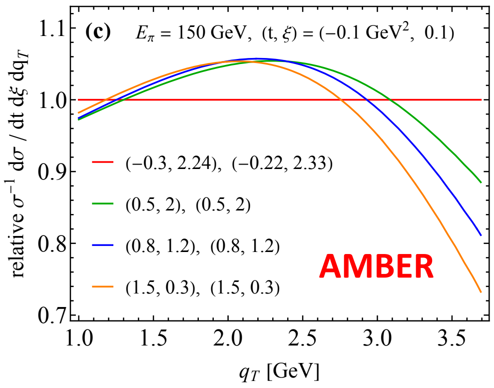
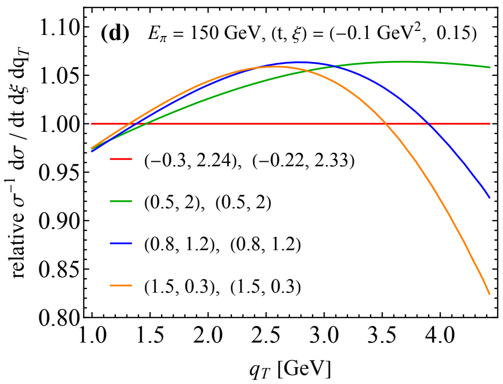
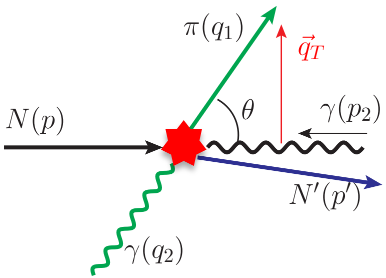






Enhanced x-sensitivity: (2) γ-π pair production

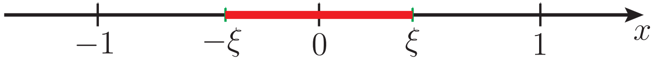
[Qiu & Yu, arXiv:2305.15397]



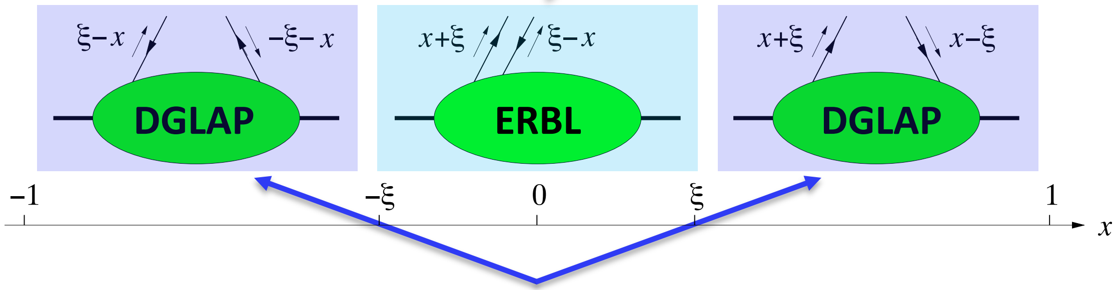
$i\mathcal{M}$ **also contains the special integral**

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

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

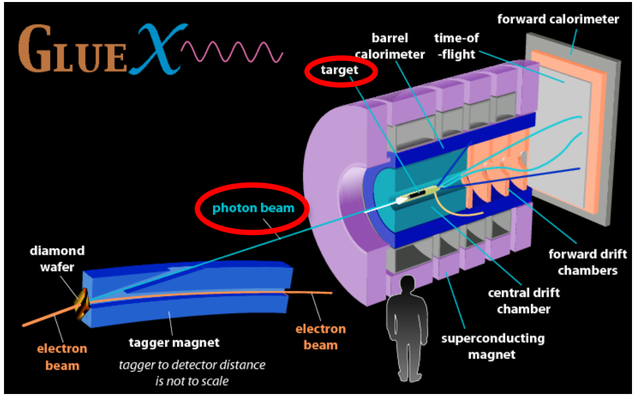


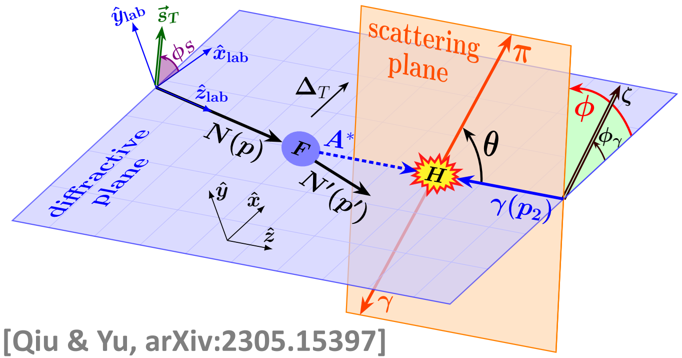
Complementary sensitivity



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

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





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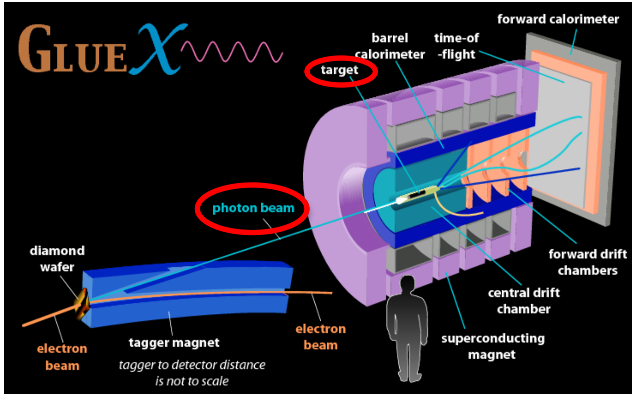
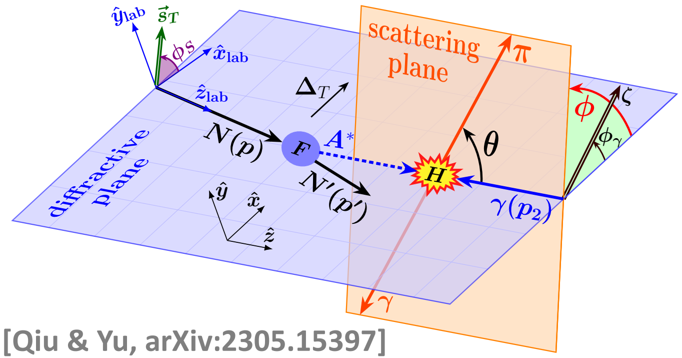
Enhanced x-sensitivity: (2) γ-π pair production





[Qiu & Yu, arXiv:2305.15397]

Polarization asymmetries

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

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

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

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

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

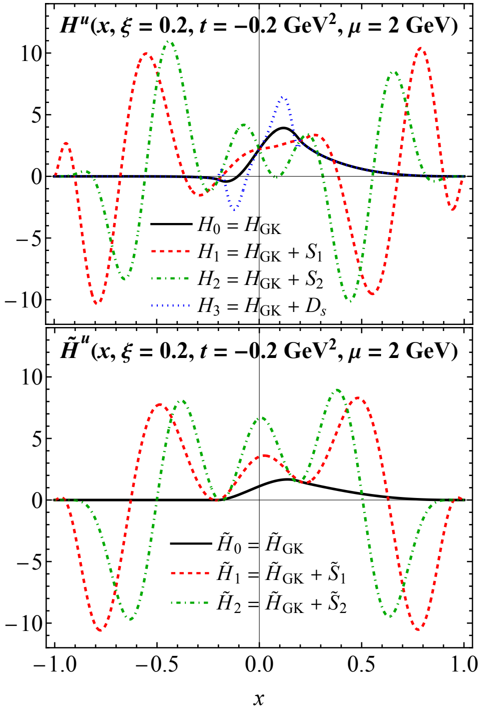
$$A_{LT} = 2\,\Sigma_{UU}^{-1}\,\mathrm{Im}\left[\mathcal{M}_+^{[\widetilde{H}]}\,\widetilde{\mathcal{M}}_-^{[H]*} + \mathcal{M}_-^{[\widetilde{H}]}\,\widetilde{\mathcal{M}}_+^{[H]*}\right].$$

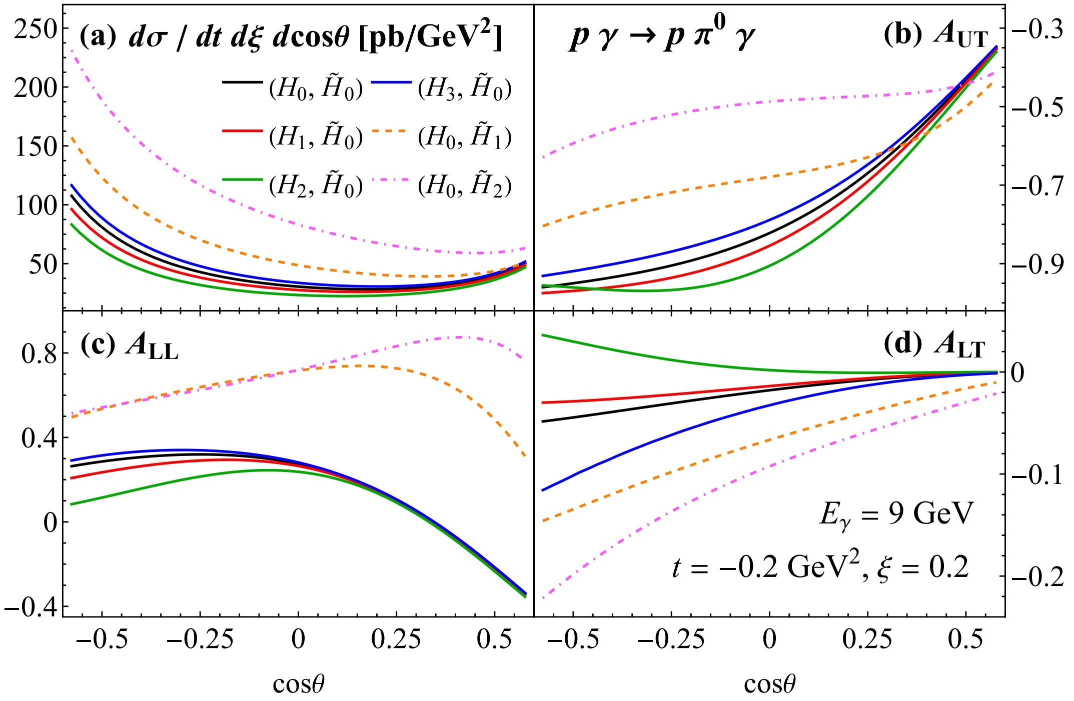
Enhanced x-sensitivity: (2) γ-π pair production

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





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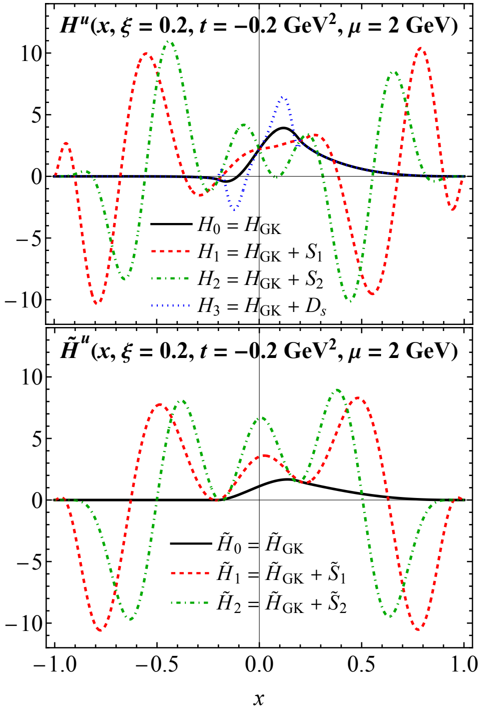
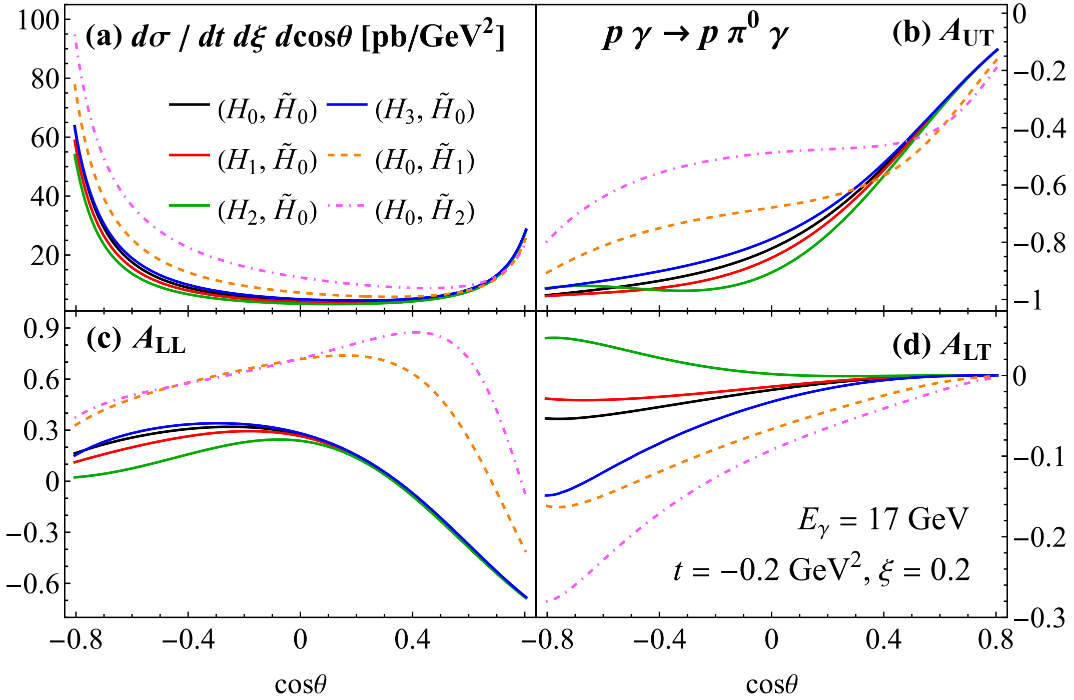
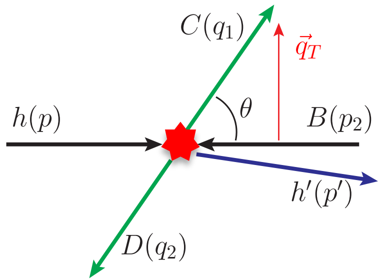




Summary

- 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)

→ Global Analysis ←

- ML/AI
- LQCD

Thank you!

Backup slides

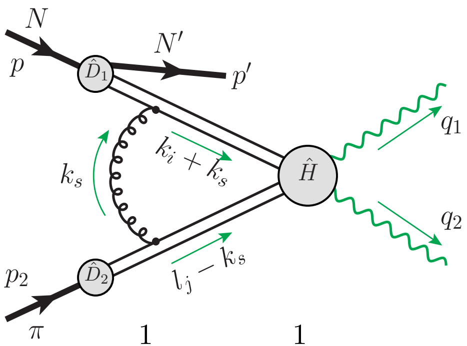
SDHEP: soft gluon and factorization

- **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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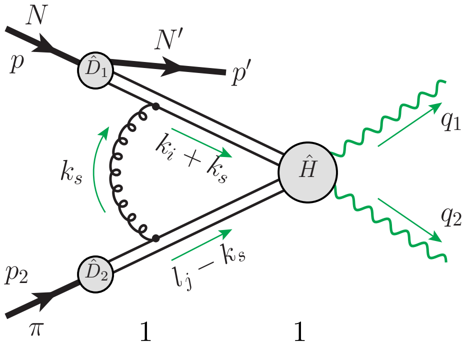

$$\frac{1}{k_s^2 + i\varepsilon} \to \frac{1}{-\mathbf{k}_s^2 + i\varepsilon}$$

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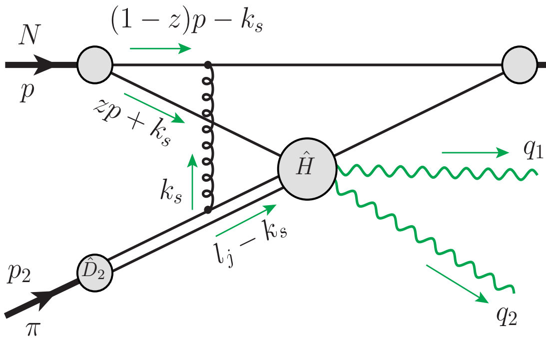
No pinch!

DGLAP region



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

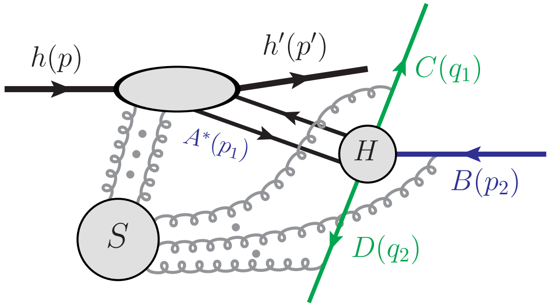
$$\frac{1}{(zp + k_s)^2 + i\varepsilon} \to \frac{1}{k_s^- + i\varepsilon}$$

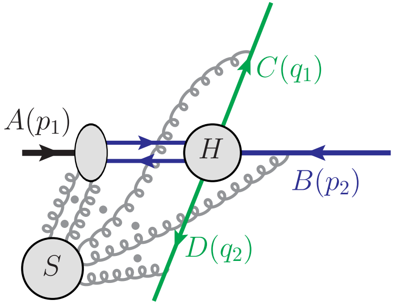
Pinched!

Same conclusion if k_s flows through N′!

SDHEP: two-stage paradigm and factorization

❑ Factorization for 2-parton channel





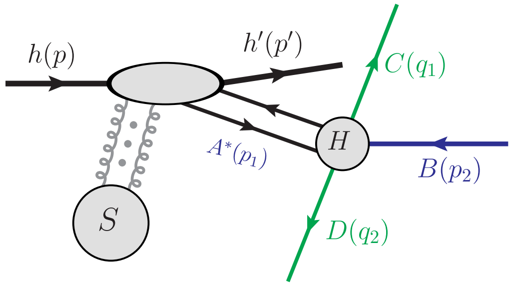
Only complication:

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

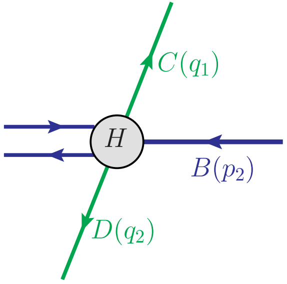
$$k_s^+ \mapsto k_s^+ \pm i\mathcal{O}(Q)$$

Glauber → h-collinear region

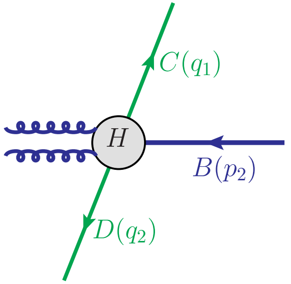
Soft gluons cancel for the meson-initialized process



$\text{GPD} \otimes$



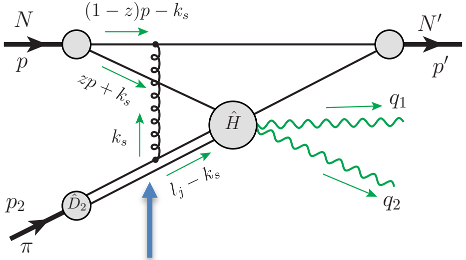
or

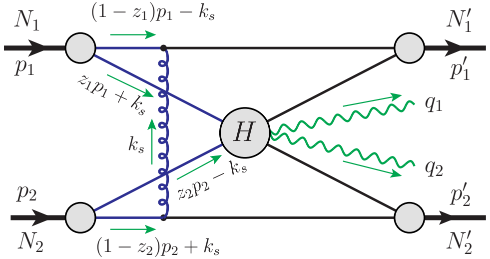


Why *single* diffractive?

❑ Double diffractive process

Glauber pinch for diffractive scattering



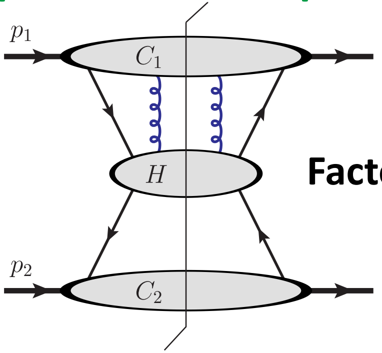


Both k_s^+ and k_s^- are pinched in Glauber region!

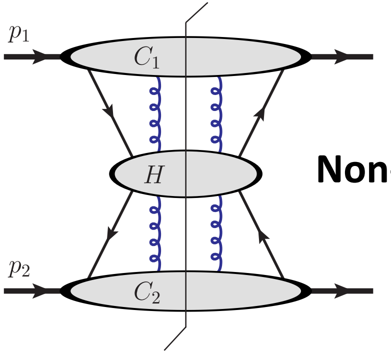
Factorizable thanks to pion

***Non-factorizable* even with hard scale**

❑ Compare: Drell-Yan process at high twist



Factorizable



Non-factorizable