



Single Diffractive Hard Exclusive Processes for the Study of Generalized Parton Distributions

Zhite Yu

(Michigan State University)

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

1. JHEP 08 (2022) 103
2. PRD 107 (2023), 014007

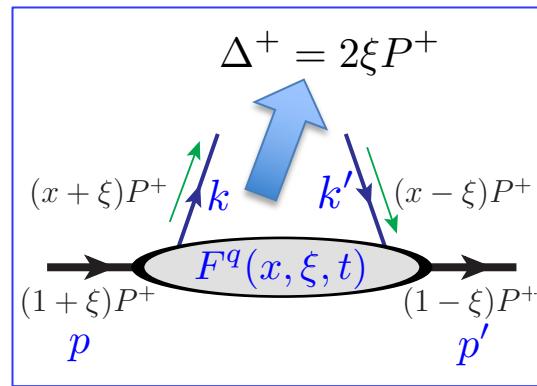
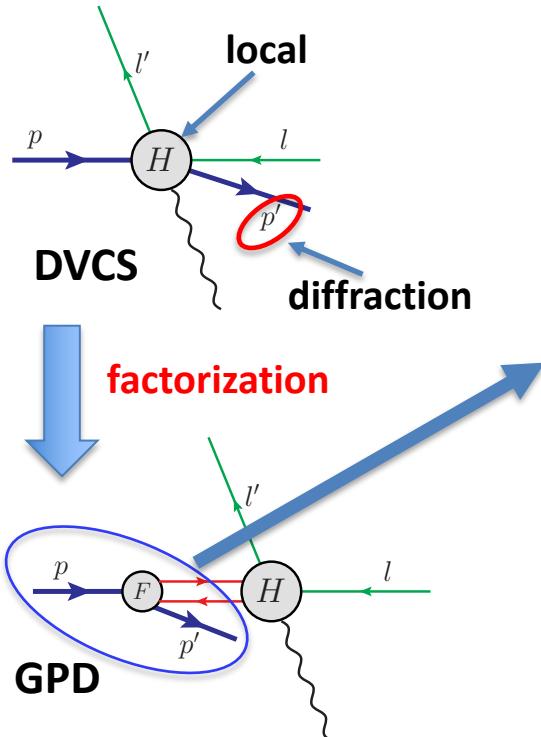
DIS 2023 @ MSU
Mar/28/2023



<https://pa.msu.edu/conf/DIS2023>

Generalized parton distribution (GPD)

□ From factorization of exclusive diffractive process



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

$$\Delta = p - p'$$

$$t = \Delta^2$$

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

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

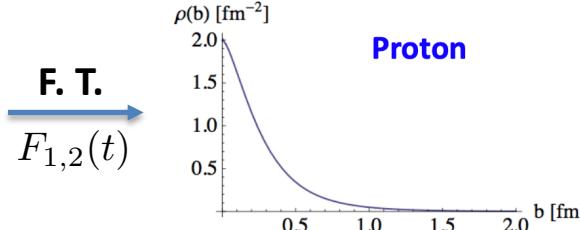
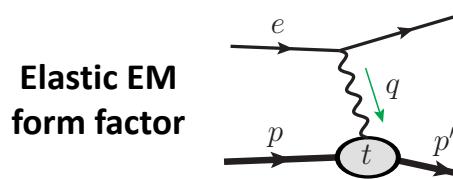
Hadron diffraction
 $p \rightarrow p'$

parton momentum

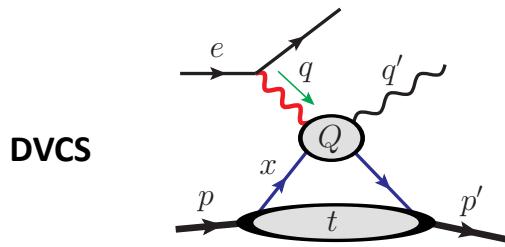
$$\begin{aligned} F^q(x, \xi, t) &= \int \frac{dz^-}{4\pi} e^{-ixP^+z^-} \langle p' | \bar{q}(z^-/2) \gamma^+ q(-z^-/2) | p \rangle \\ &= \frac{1}{2P^+} \left[H^q(x, \xi, t) \bar{u}(p') \gamma^+ u(p) - E^q(x, \xi, t) \bar{u}(p') \frac{i\sigma^{+\alpha} \Delta_\alpha}{2m} u(p) \right] \end{aligned}$$

GPD properties: 3D image

Controllable soft scale t and 3D tomography



- Flavor, color blind
 - EM charge radius
 - No color elastic form factor
- no color radius

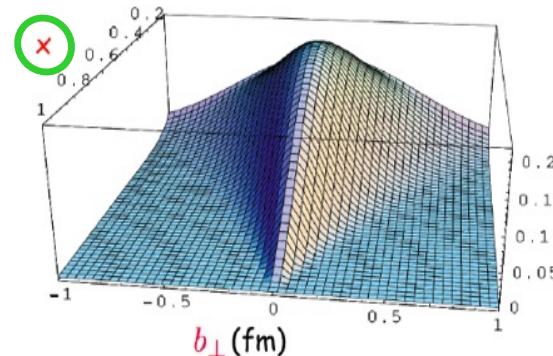


$$f_i(x, \mathbf{b}_T) = \int d^2 \Delta_T e^{i \Delta_T \cdot \mathbf{b}_T} F_i(x, 0, -\Delta_T^2)$$

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

- Two distinct scales at the same time
- Hard Q : see partons (with x)
 - Low t : probe the confined motion (\mathbf{b}_T)

3D image



“Color” density
↓
confinement;
nuclear force;
color radius...

GPD properties: gravitational form factor

□ QCD energy-momentum tensor

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

□ Gravitational form factor

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

□ Connection to GPD moments

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

□ Angular momentum sum rule

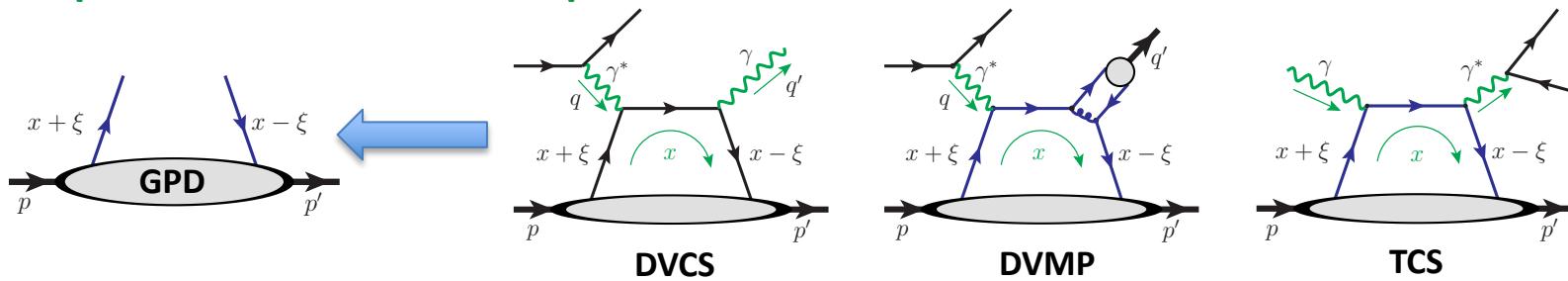
$$J_i = \lim_{t \rightarrow 0} \int_{-1}^1 dx x [H_i(x, \xi, t) + E_i(x, \xi, t)]$$

$$i = q, g$$

- 3D tomography
 - relations to GFF
 - angular momentum
 - ...
- 
- x-dependence!**

However, the x -dependence of GPD is hard to measure

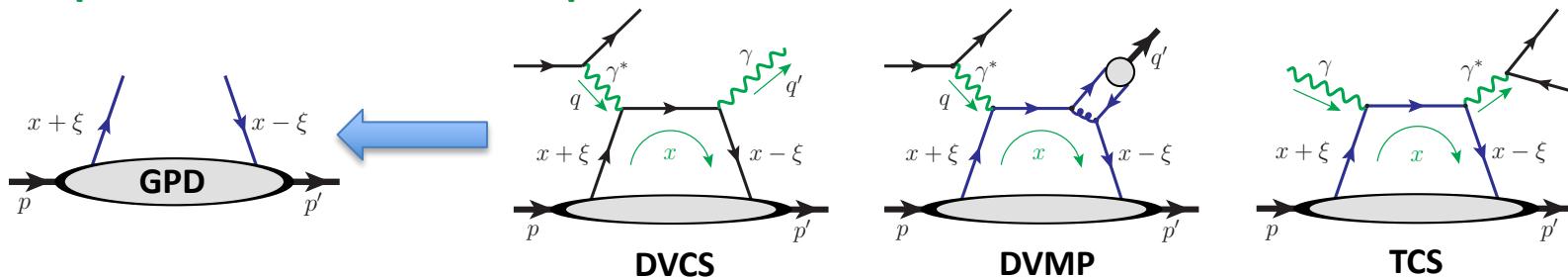
❑ Amplitude nature: exclusive processes



$x \sim \text{loop momentum}$ $i\mathcal{M} \sim \int_{-1}^1 dx F(\textcolor{red}{x}, \xi, t) \cdot C(\textcolor{red}{x}, \xi; Q/\mu)$ never pin down to some x

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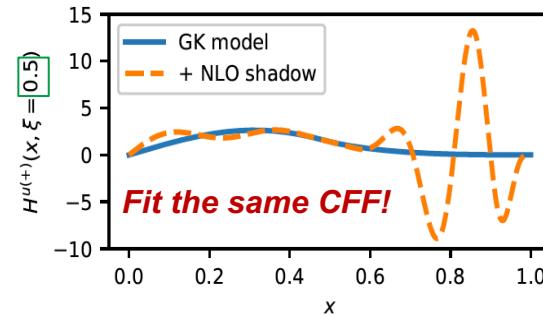
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- Sensitivity to x comes from $C(x, \xi; Q/\mu)$

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

DVCS

→ $i\mathcal{M} \propto \int_{-1}^1 dx \frac{F(\textcolor{red}{x}, \xi, t)}{\textcolor{red}{x} - \xi + i\varepsilon} \equiv "F_0(\xi, t)"$

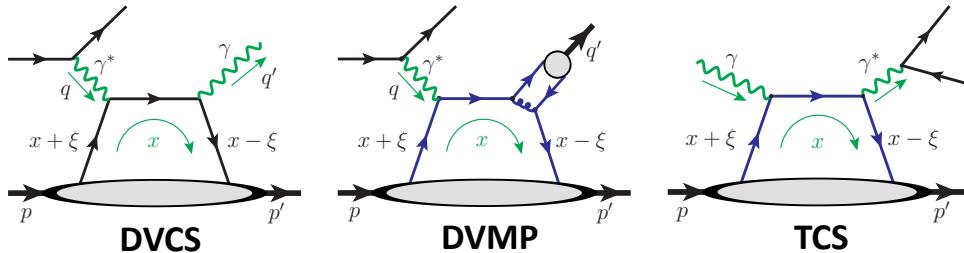


Types of x -sensitivity

☐ Moment-type sensitivity

$$C(\mathbf{x}; \mathbf{Q}) = G(\mathbf{x}) \cdot T(\mathbf{Q})$$

→ $F_G = \int_{-1}^1 d\mathbf{x} G(\mathbf{x}) F(\mathbf{x}, \xi, t)$

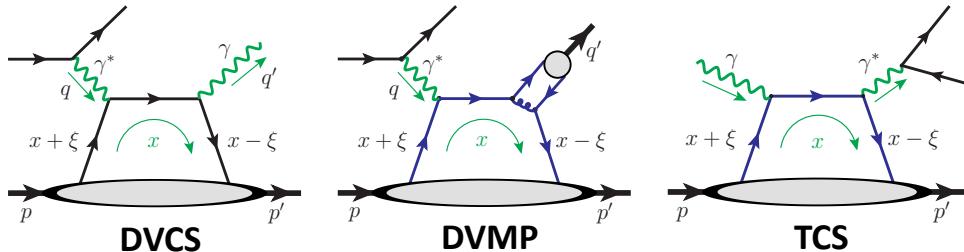


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☐ Enhanced sensitivity

$$C(\mathbf{x}; \mathbf{Q}) \neq G(\mathbf{x}) \cdot T(\mathbf{Q})$$

\mathbf{Q} flow entangles with the \mathbf{x} flow

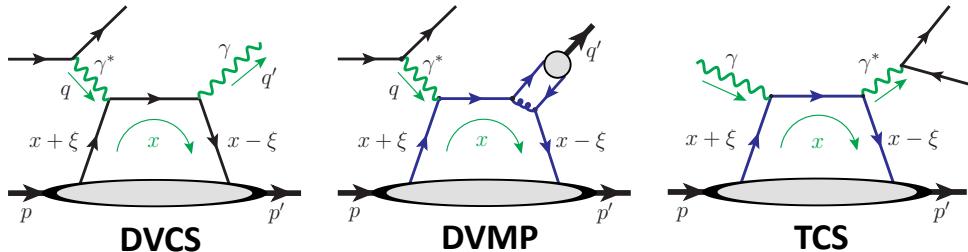
→ $d\sigma/d\mathbf{Q} \sim |C(\mathbf{x}; \mathbf{Q}) \otimes_{\mathbf{x}} F(\mathbf{x}, \xi, t)|^2$ gives extra sensitivity to the \mathbf{x} dependence

Types of x -sensitivity

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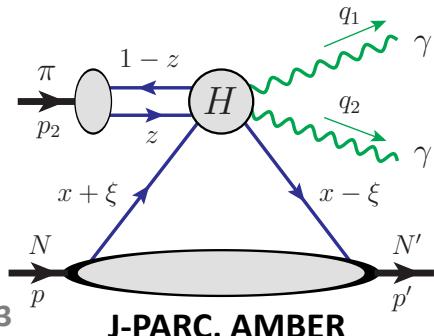


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Q flow entangles with the x flow

$$\rightarrow d\sigma/d\mathbf{Q} \sim |C(\mathbf{x}; \mathbf{Q}) \otimes_{\mathbf{x}} F(\mathbf{x}, \xi, t)|^2 \text{ gives extra sensitivity to the } x \text{ dependence}$$

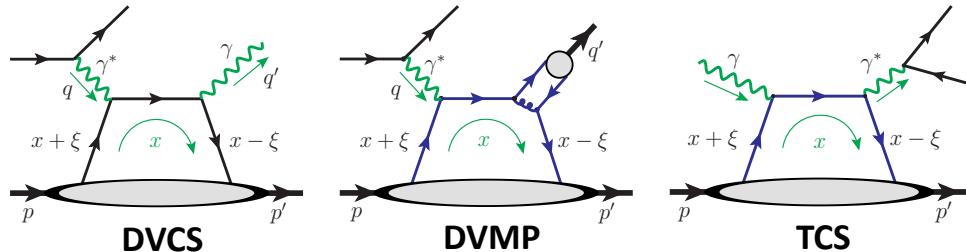


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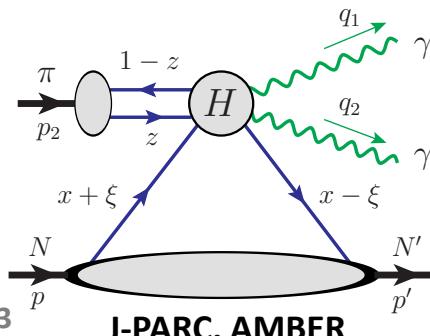


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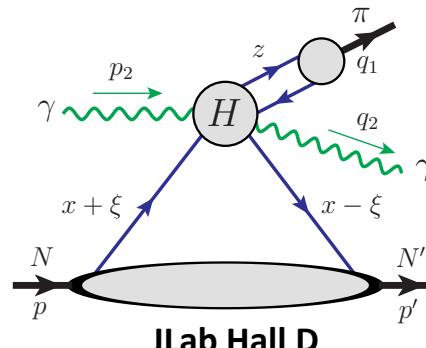
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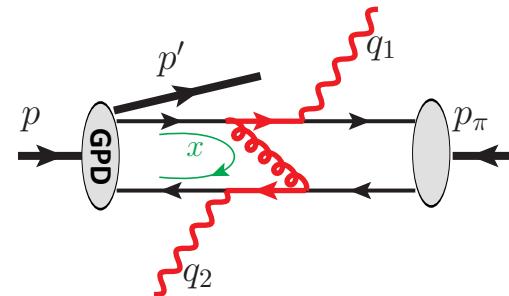
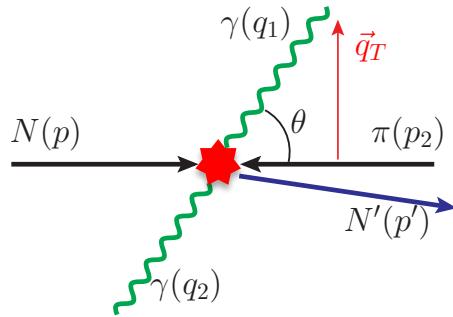
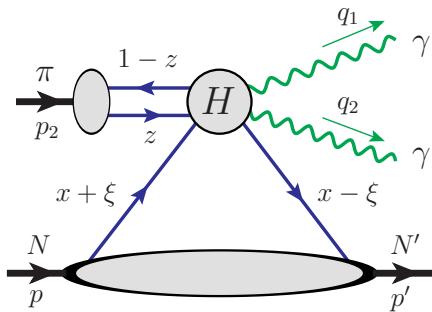
Qiu, Yu,
JHEP 08 (2022) 103



First introduced by
G. Duplancic et al.
JHEP 11 (2018) 179



Exclusive hard diphoton production in πN collision



❑ Kinematical observables: t, ξ, q_T

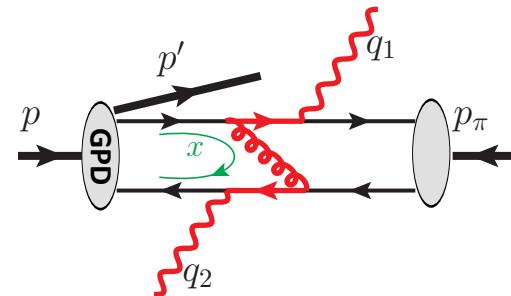
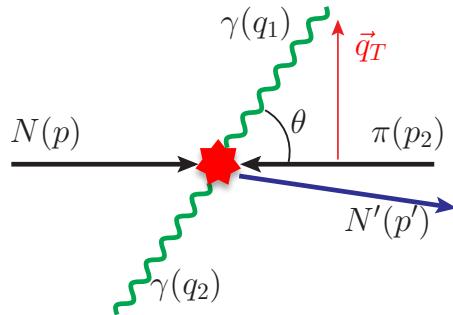
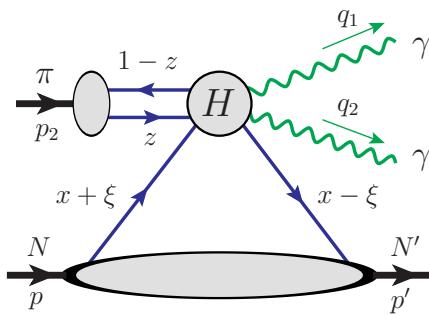
$$t = (p - p')^2$$

$$\xi = (p - p')^+ / (p + p')^+$$

Hard scale: $q_T \gg \Lambda_{\text{QCD}}$

Soft scale: $t \sim \Lambda_{\text{QCD}}^2$

Exclusive hard diphoton production in πN collision



- ❑ Kinematical observables: t, ξ, q_T
- ❑ Factorization

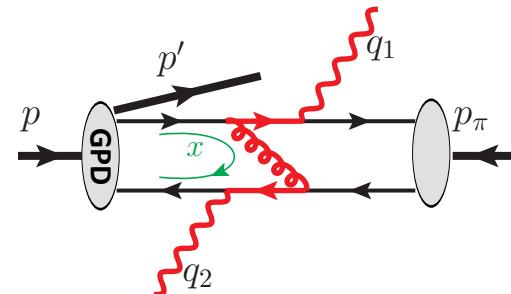
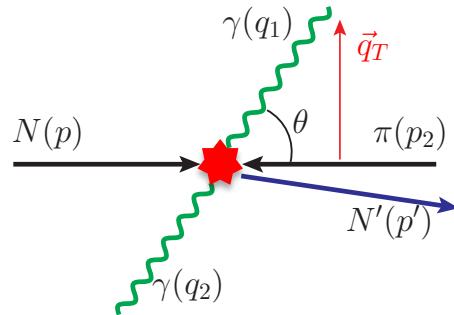
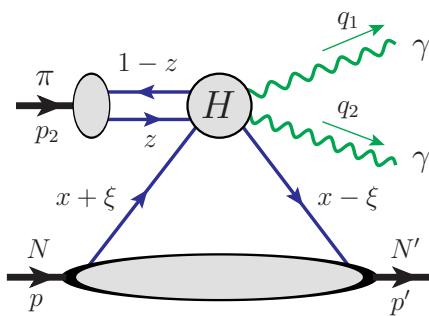
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Hard scale: $q_T \gg \Lambda_{\text{QCD}}$
 Soft scale: $t \sim \Lambda_{\text{QCD}}^2$

$$\mathcal{M}(t, \xi, q_T) = \int_{-1}^1 d\xi F(\xi, \xi, t; \mu) \cdot C(\xi, \xi; q_T/\mu) + \mathcal{O}(\Lambda_{\text{QCD}}/q_T) \quad [\text{suppressing DA factor}]$$

Exclusive hard diphoton production in πN collision



- ❑ Kinematical observables: t, ξ, q_T
- ❑ Factorization

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

t, ξ are directly observed

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

$x \leftrightarrow q_T$

6

Photoproduction of $\gamma\pi$ pair

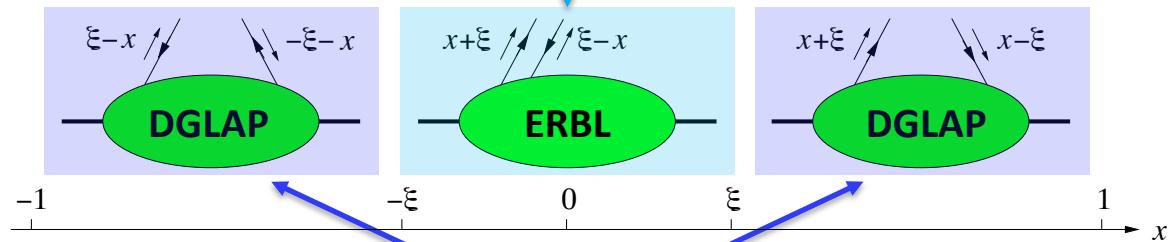
- ❑ Crossed process [Qiu, Yu, in preparation]

$$N(p) + \gamma(p_\gamma) \rightarrow N'(p') + \pi(q_1) + \gamma(q_2)$$

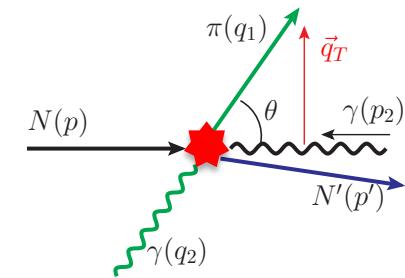
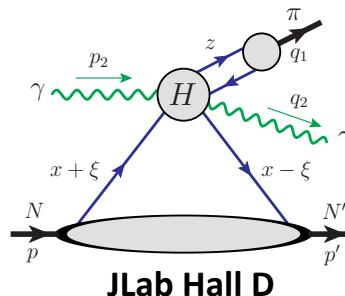
- ❑ Factorization:

$$q_T \gg \sqrt{-t} \simeq \Lambda_{\text{QCD}}$$

- ❑ Complementary sensitivity


 $N \pi \rightarrow N' \gamma \gamma$

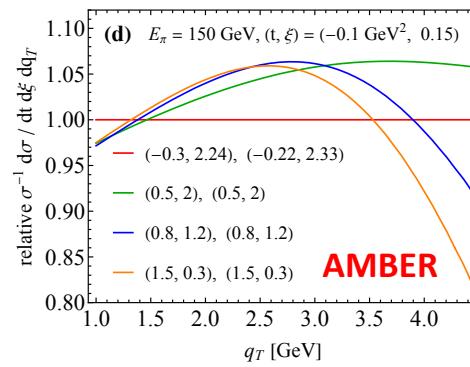
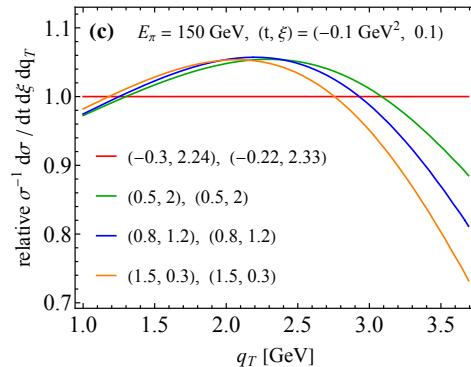
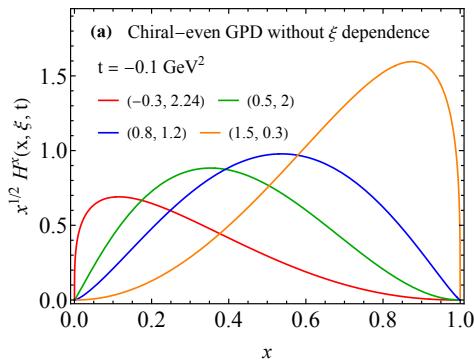
Also sensitive to the *D-term*.



$$\frac{d\sigma}{dt d\xi d\cos\theta} \downarrow F(x, \xi, t)$$

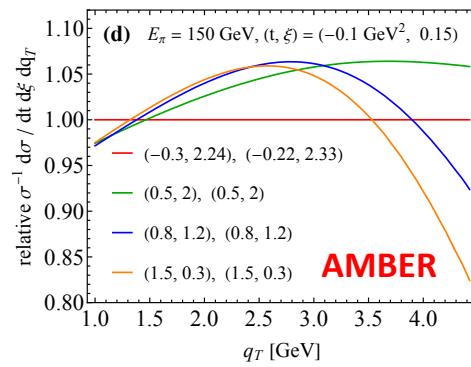
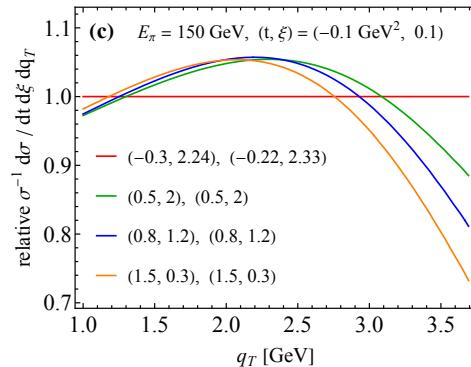
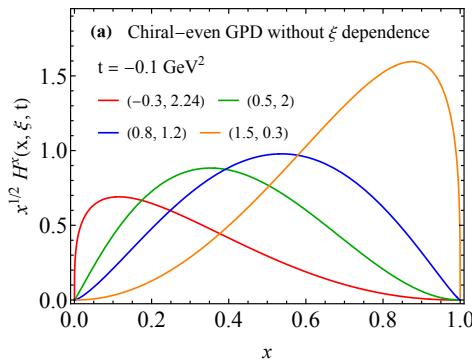
Sensitivity to GPD x

□ $N\pi \rightarrow N'\gamma\gamma$: $q_T \leftrightarrow x$ [Qiu, Yu, JHEP 08 (2022) 103]

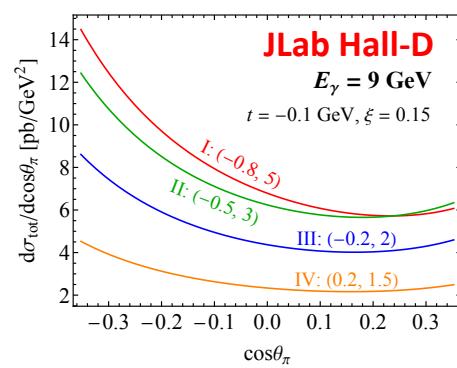
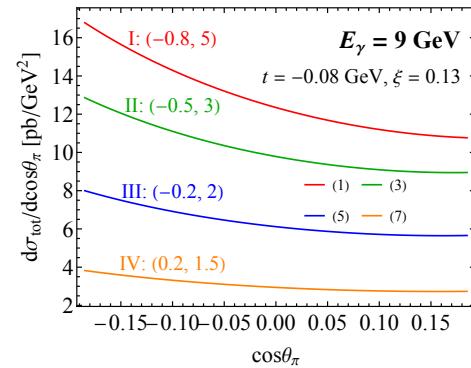
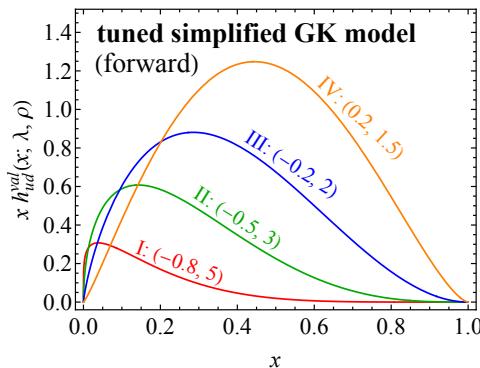


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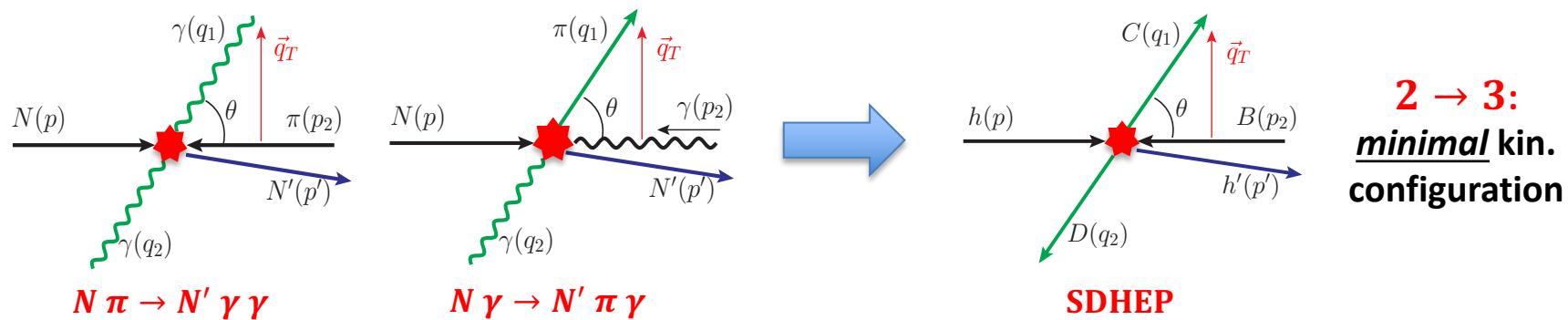
□ $N\gamma \rightarrow N'\pi\gamma$: $\cos\theta \leftrightarrow x$ [Qiu, Yu, in preparation]



Generalize: Single Diffractive Hard Exclusive Process (SDHEP)

❑ Unified kinematic structure

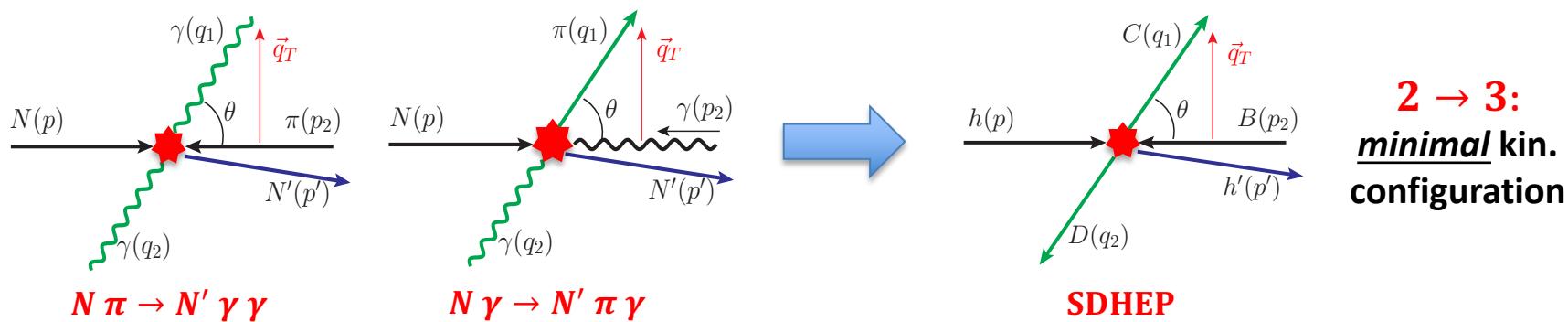
[Qiu, Yu, PRD 107 (2023), 014007]





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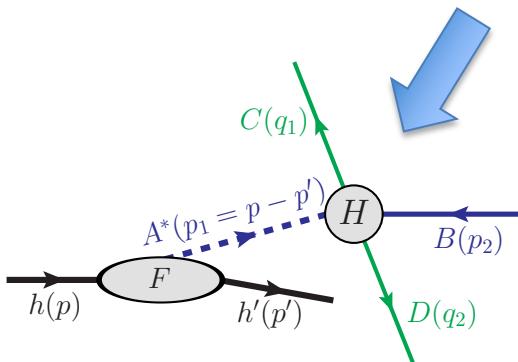


□ Two-stage process paradigm

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

factorize

$$A^*(p_1) + B(p_2) \rightarrow C(p_3) + D(p_4)$$

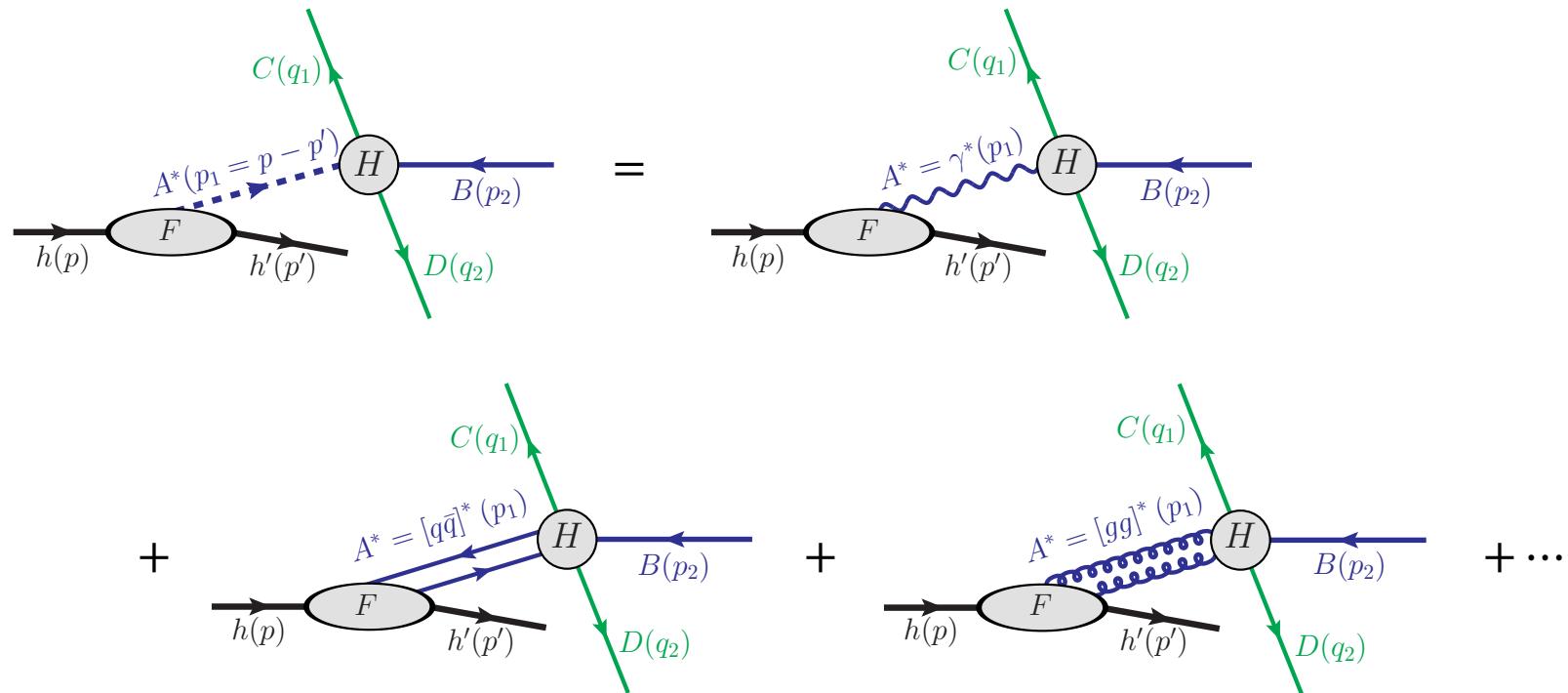


Necessary condition:

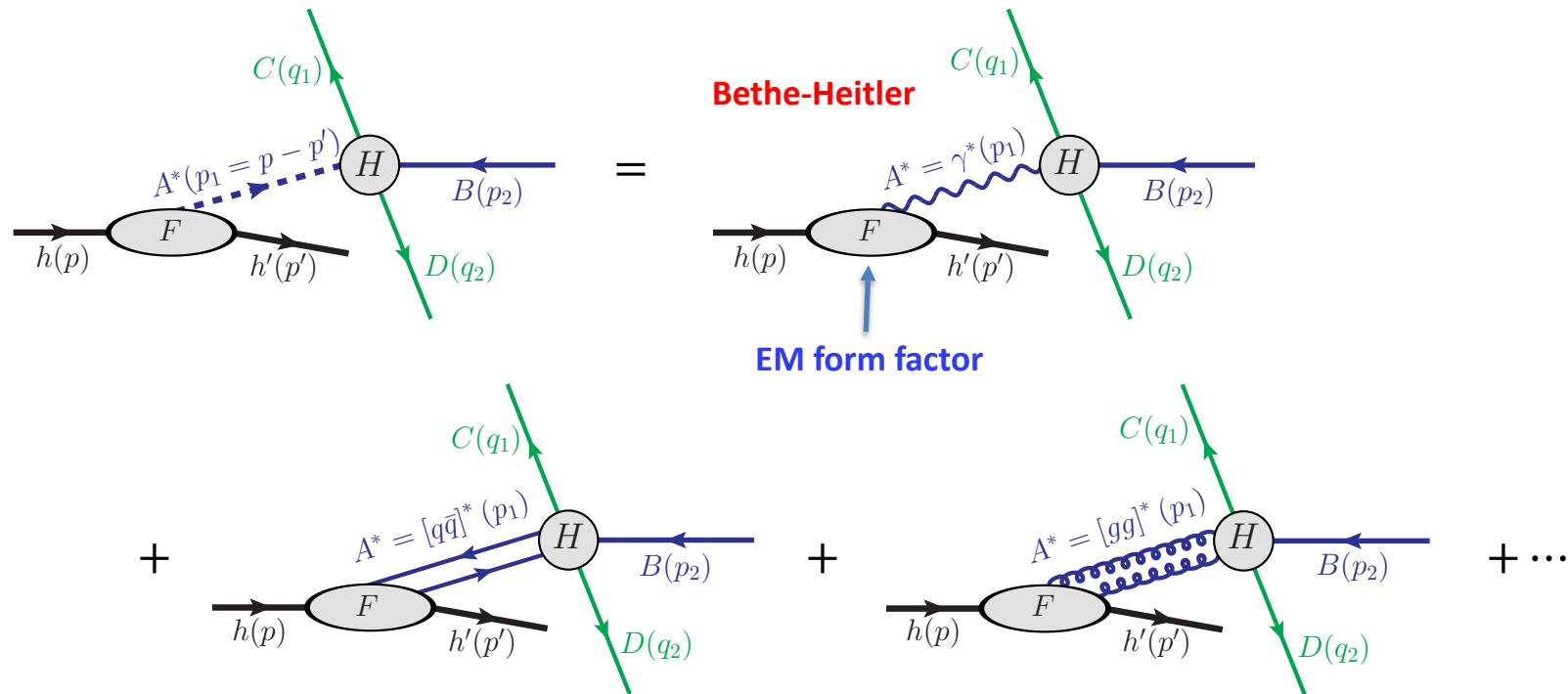
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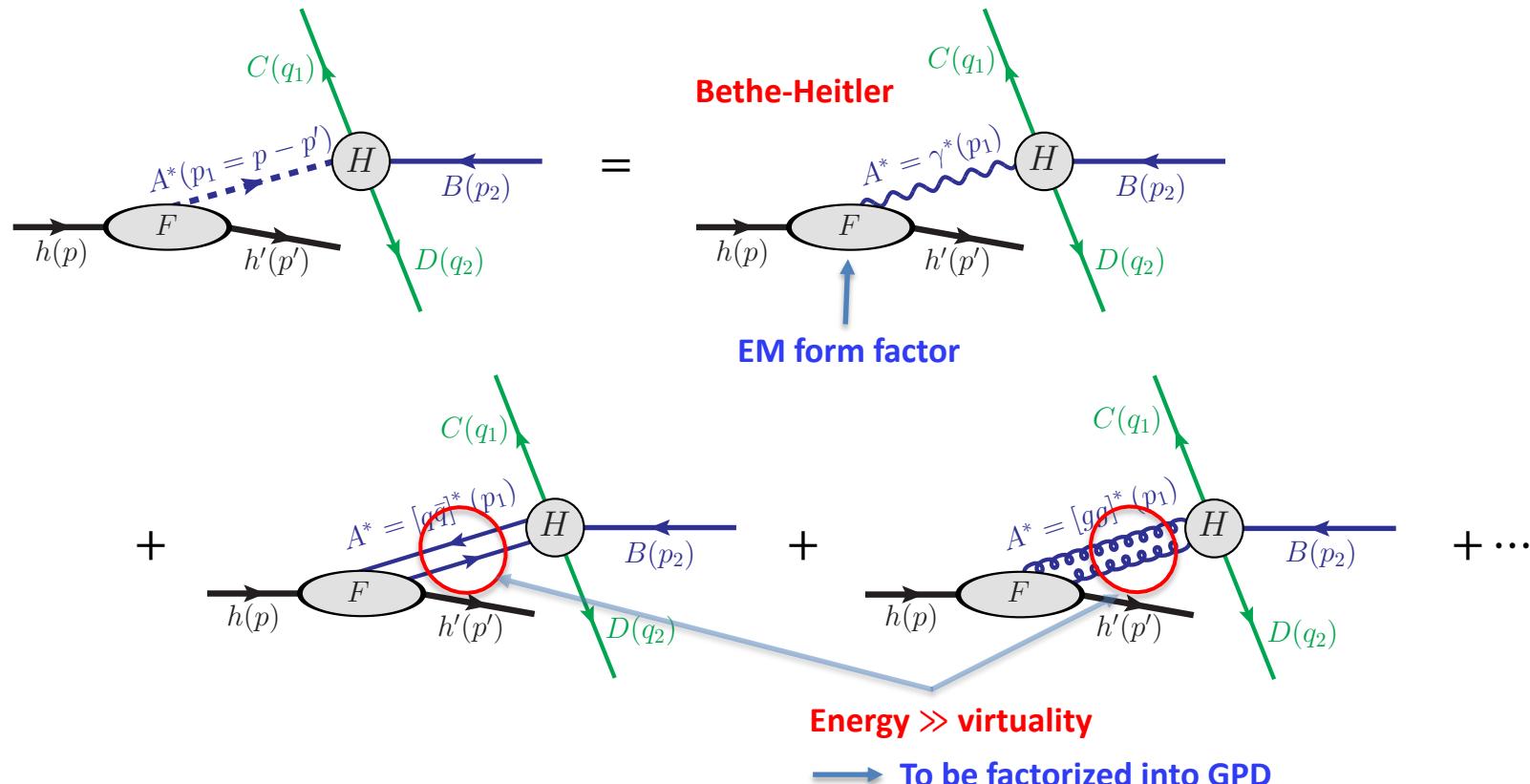
Two-stage paradigm and channel expansion (twist expansion)



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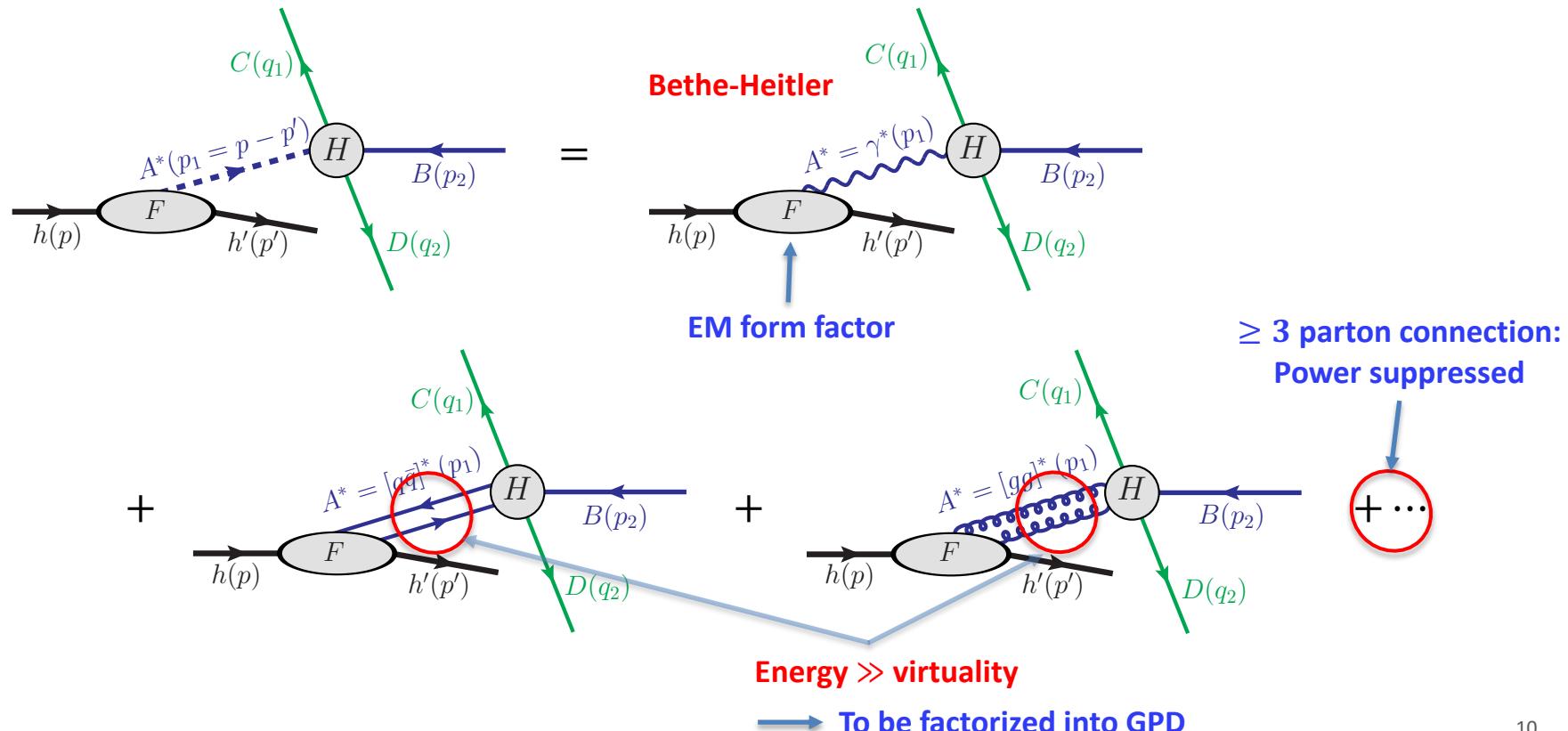


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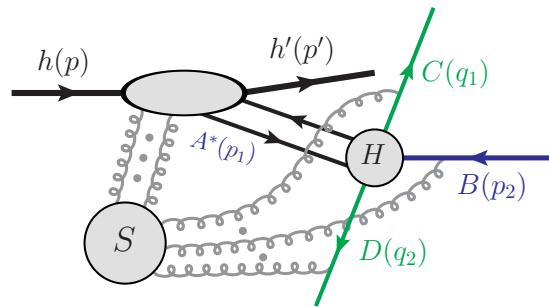


Two-stage paradigm and channel expansion (twist expansion)



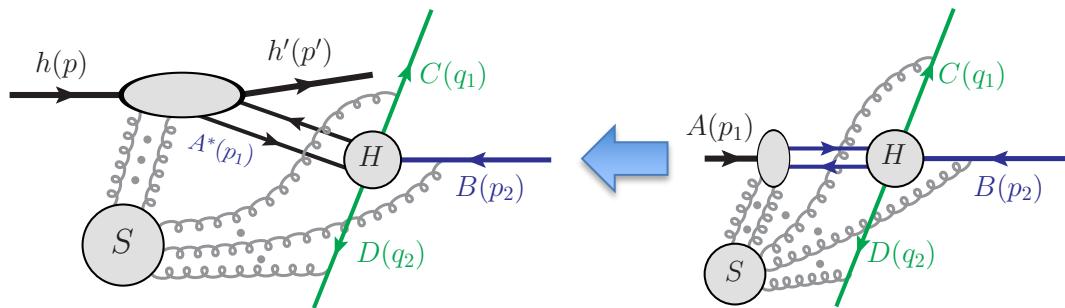
Factorization in the two-stage paradigm

□ Factorization for 2-parton channel



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Only complication:

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

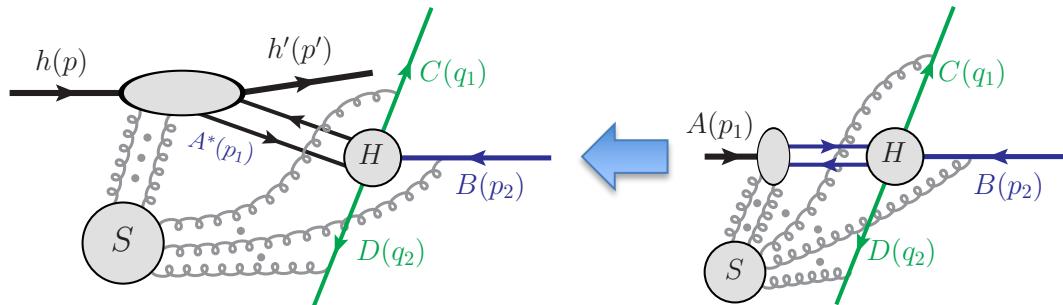


$$k_s^+ \mapsto k_s^+ \pm i\mathcal{O}(Q)$$

Glauber  h -collinear region

Factorization in the two-stage paradigm

□ Factorization for 2-parton channel

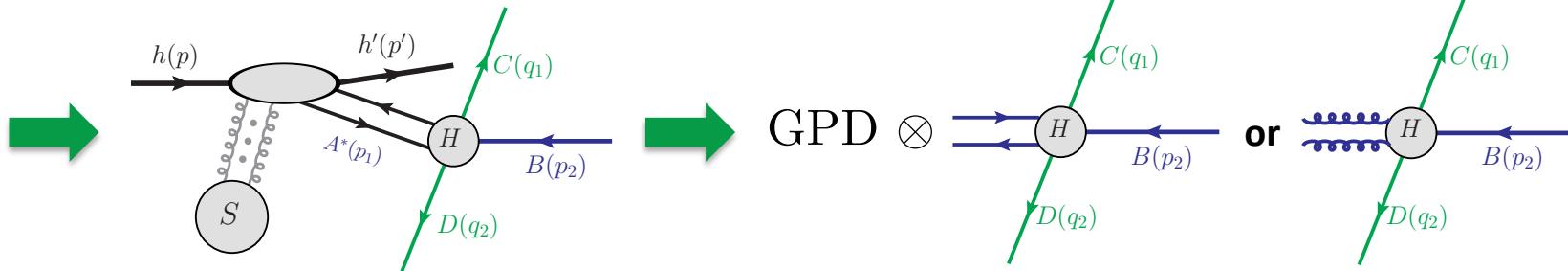


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Glauber \rightarrow h -collinear region

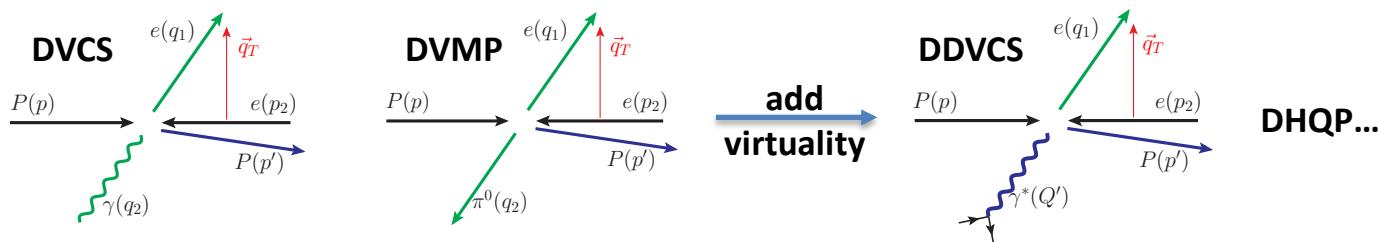
Soft gluons cancel for the meson-initialized process





Classification of GPD processes

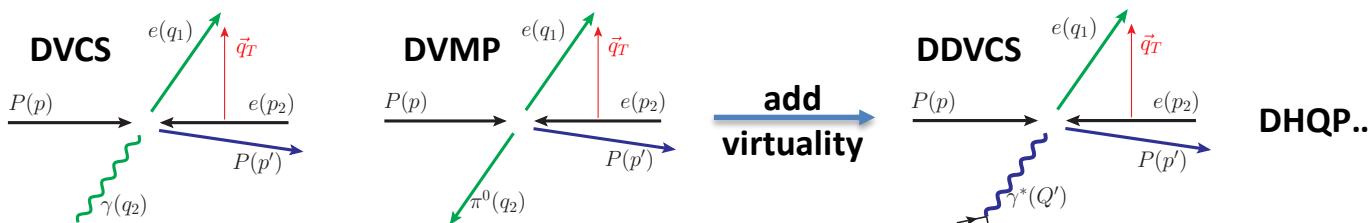
□ Electro-production (JLab, EIC, ...)



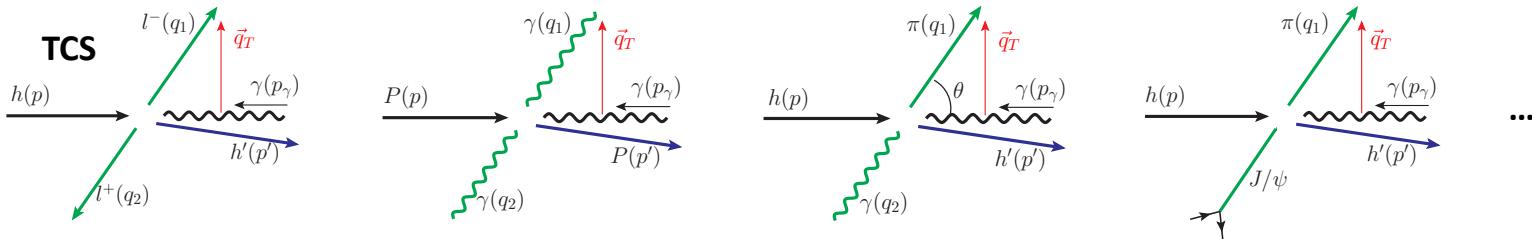


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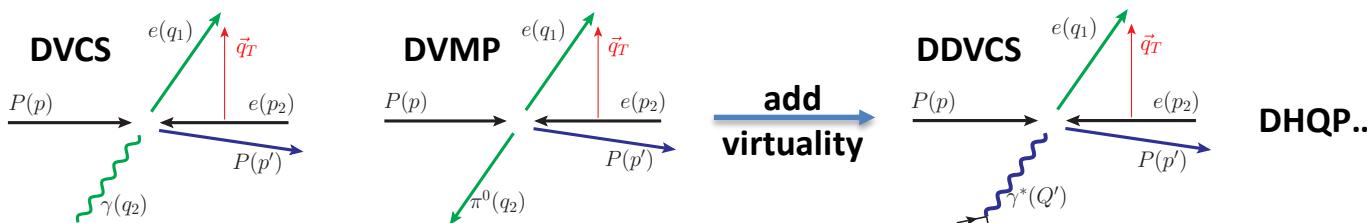


□ Photo-production (JLab Hall-D, ...)

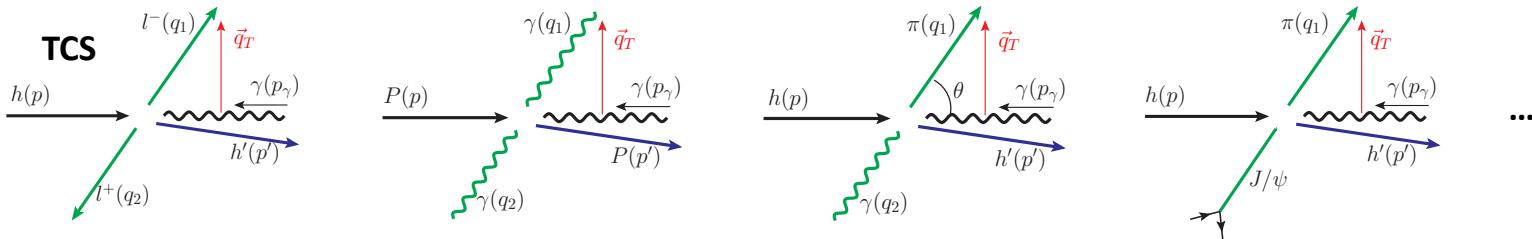


Classification of GPD processes

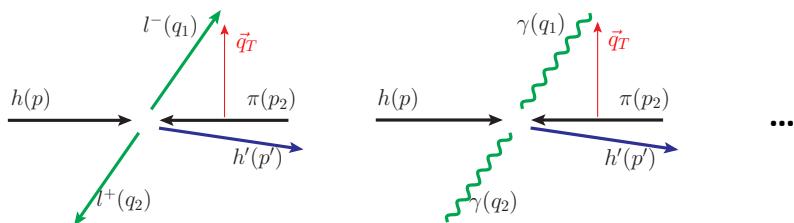
□ Electro-production (JLab, EIC, ...)



□ Photo-production (JLab Hall-D, ...)



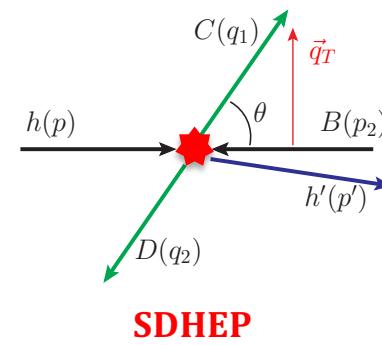
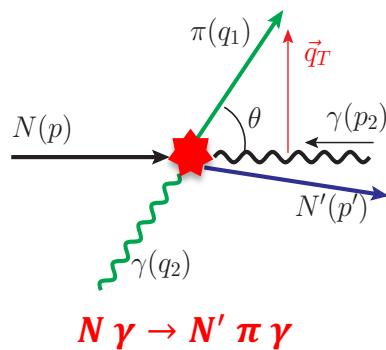
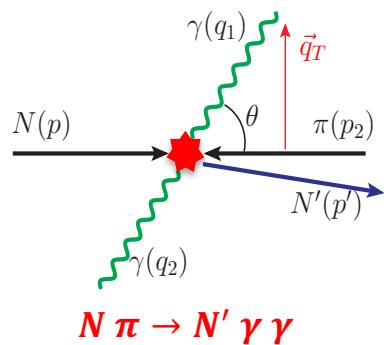
□ Meso-production (AMBER, J-PARC, ...)



Proved factorization generally
[Qiu, Yu, PRD 107 (2023), 014007]

Summary

□ Enhanced sensitivity to x dependence



□ Single Diffractive Hard Exclusive Processes (SDHEP)

- Systematic factorization.
- Roadmap for known and more new processes!

Thank you!



Backup slides

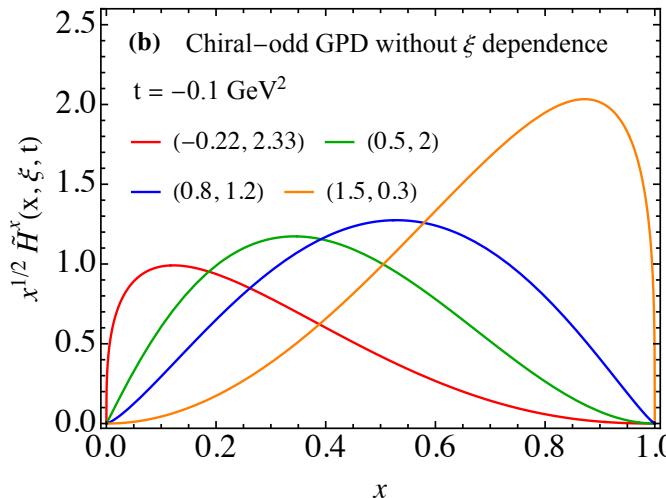
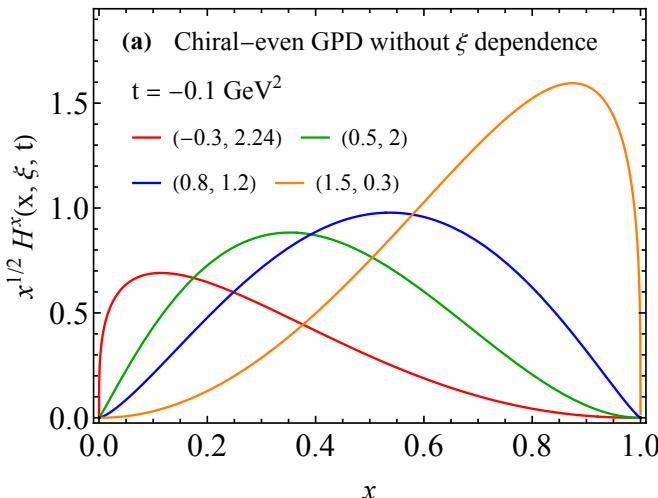
Phenomenology on $\pi^- p \rightarrow n\gamma\gamma$: sensitivity to GPD x

□ GPD models: simplified GK model

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

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

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



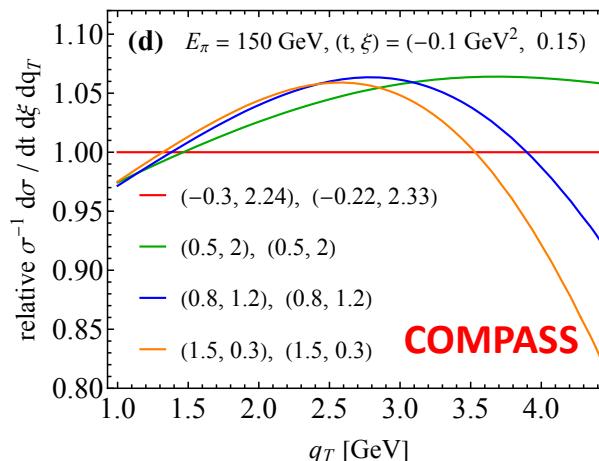
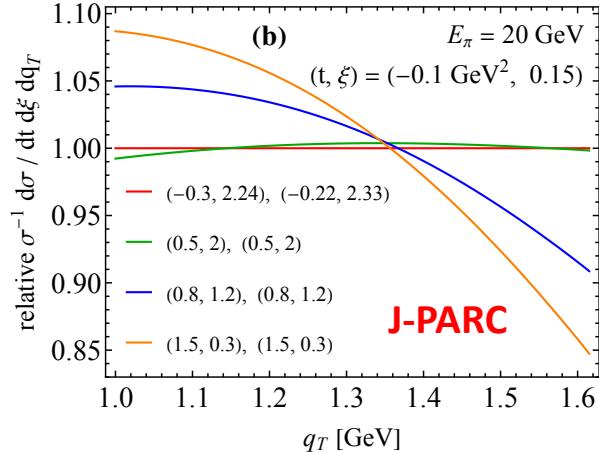
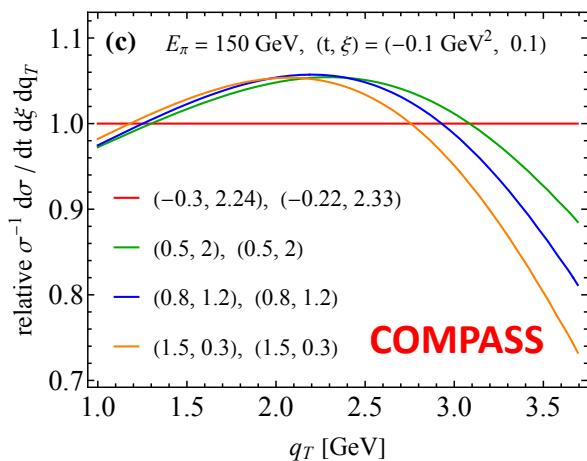
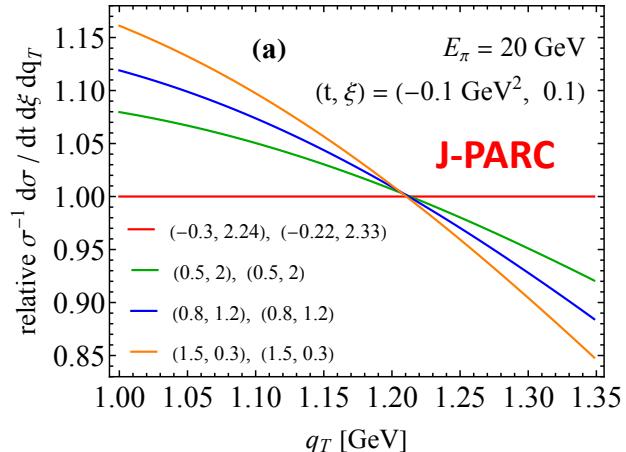
$$\frac{d\sigma}{dt d\xi dq_T} \sim |H(\textcolor{red}{x}, \xi, t)|^2$$



Relative q_T shape

$$\frac{\sigma_{\text{tot}}^{-1} d\sigma/dq_T}{\text{some shape func}}$$

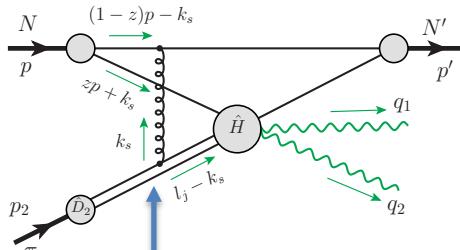
$$\sigma_{\text{tot}} = \int_{1 \text{ GeV}}^{\sqrt{\hat{s}}/2} dq_T \frac{d\sigma}{dt d\xi dq_T}$$



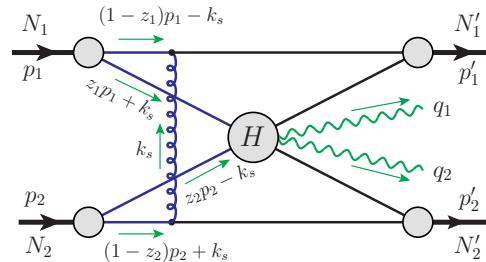
Why single diffractive?

□ Double diffractive process

Glauber pinch for diffractive scattering



Factorizable thanks to pion



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

Non-factorizable even with hard scale

□ Compare: Drell-Yan process at high twist

