Single Diffractive Hard Exclusive Process

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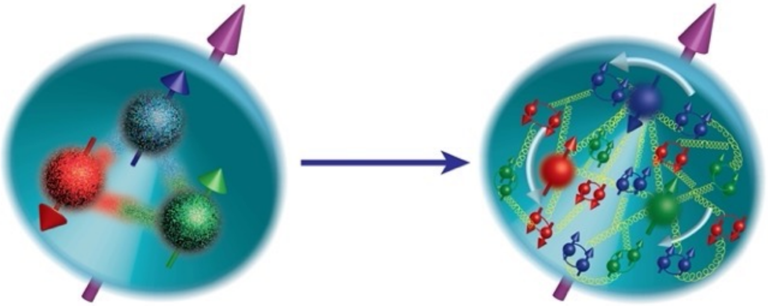
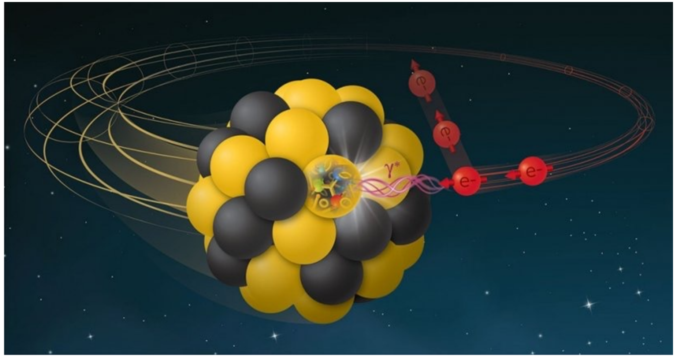
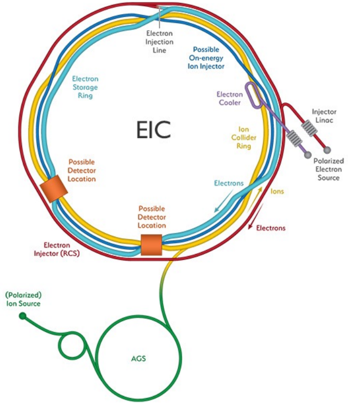
International Workshop on a 2nd Detector for the EIC

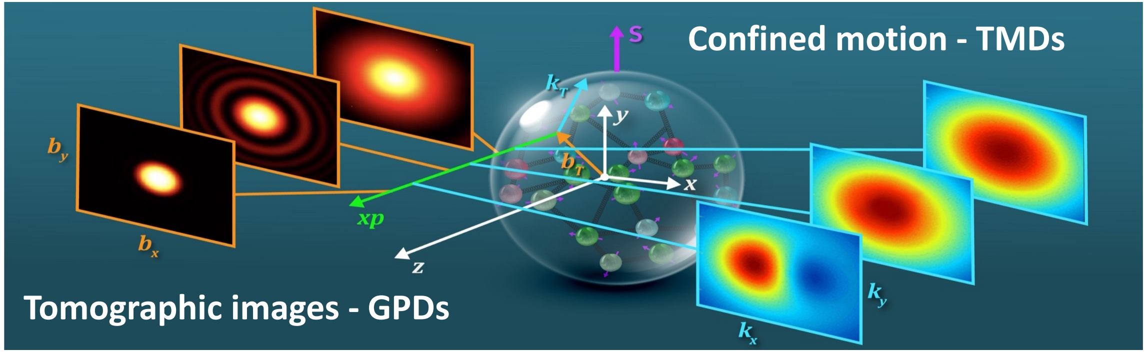
May/19/2023

QCD Femtography --- Central Goal of EIC



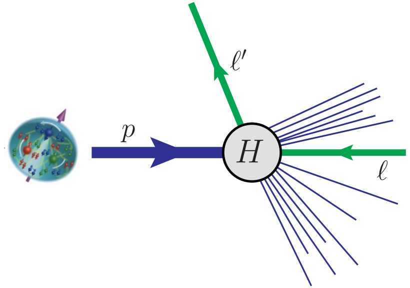






QCD Femtography --- Hard inclusive processes as probes

❑ DIS and PDF



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

QCD Femtography --- Hard inclusive processes as probes

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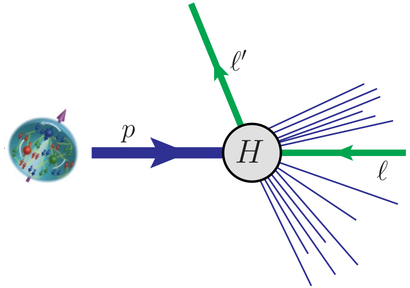
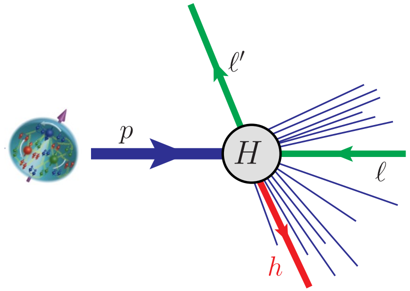
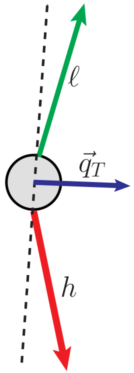


Single scale Q → **One-dim. structure $f_i(x)$**

❑ SIDIS and TMD

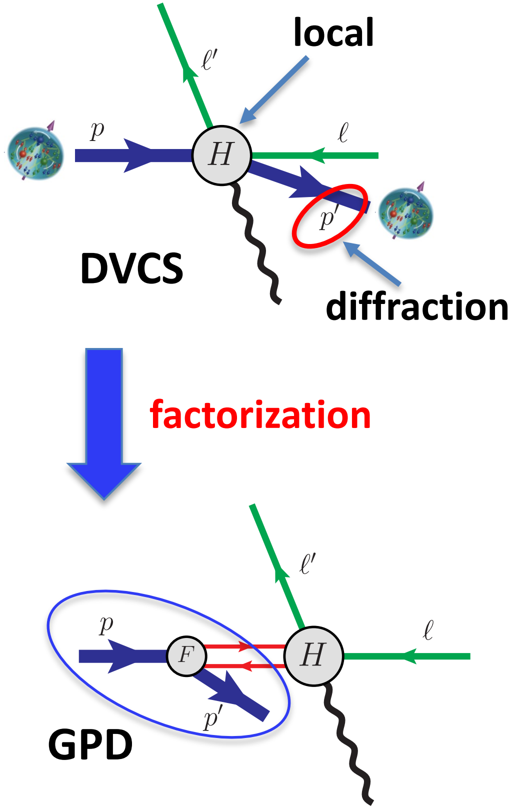




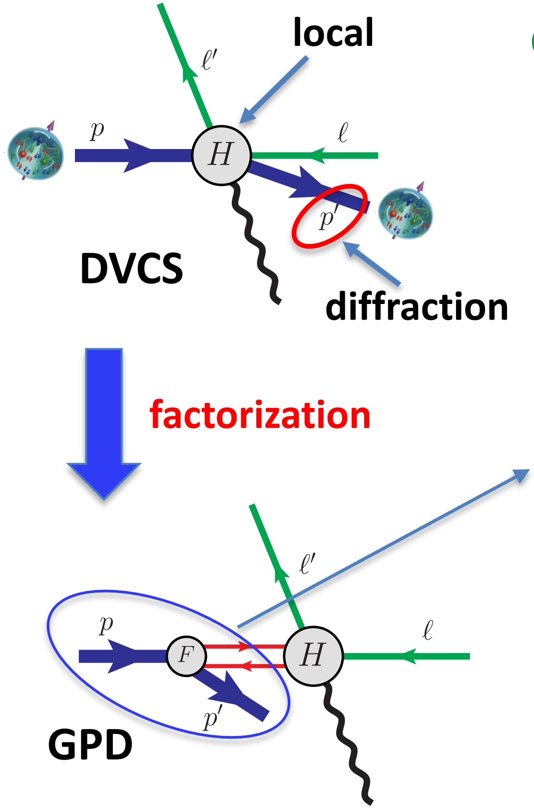
Two scales: $Q \gg q_T \sim \Lambda_{\text{QCD}}$

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

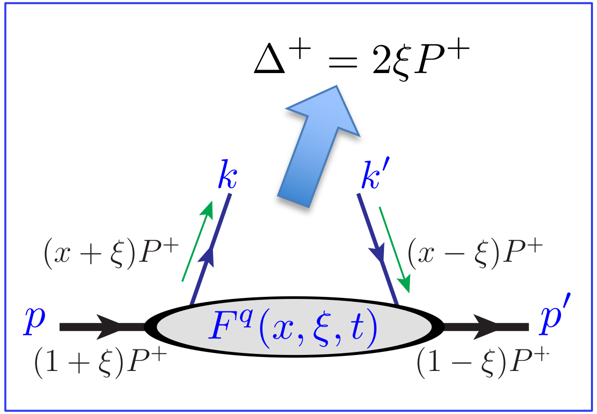
QCD Femtography --- Hard exclusive processes as probes



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 $p \to p'$

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

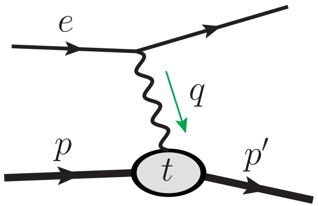
← **parton momentum**

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

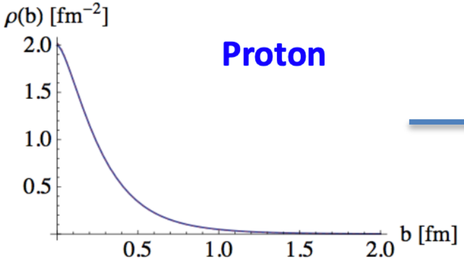
$$= \frac{1}{2P^+}\left[H^q(x,\xi,t)\,\bar{u}(p')\,\gamma^+ u(p) - E^q(x,\xi,t)\,\bar{u}(p')\,\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m}u(p)\right]$$

GPD and 3D tomography

❑ Diffraction probes spatial density



F. T. → $F_{1,2}(t)$

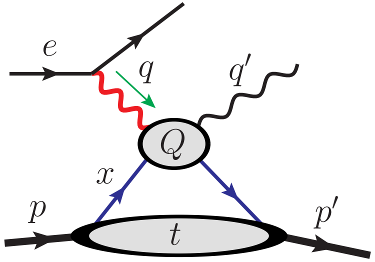


→ Electric charge radius

❑ *Two-scale* diffraction probes 3D tomography

[M. Burkardt, 2000, 2003]

DVCS

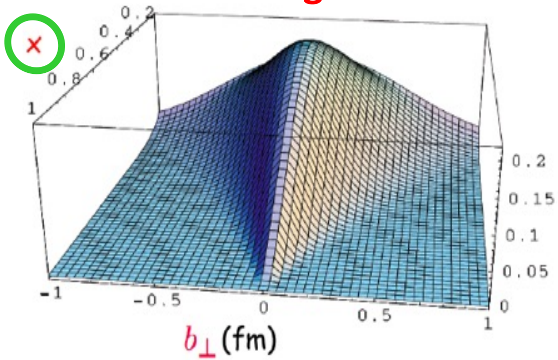


$$f_i(x, \boldsymbol{b}_T) = \int \mathrm{d}^2\boldsymbol{\Delta}_T\, e^{i\boldsymbol{\Delta}_T\cdot\boldsymbol{b}_T} F_i(x, 0, -\Delta_T^2)$$

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

F. T. →

3D image



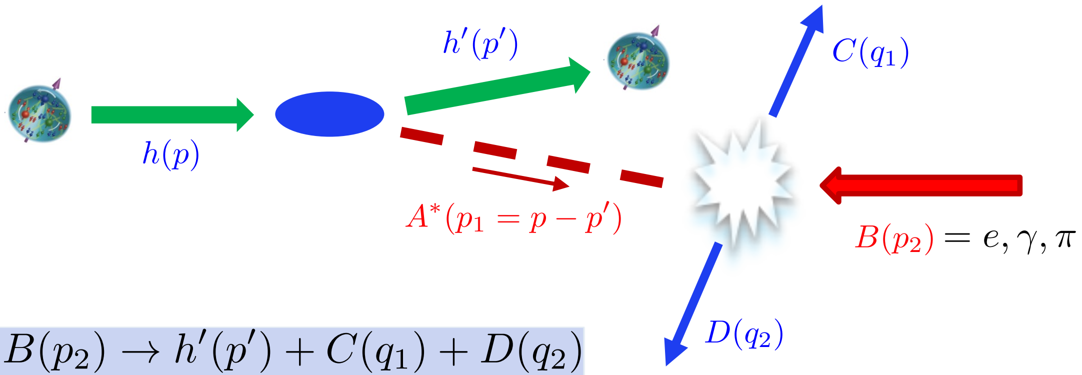
→ "Color" density

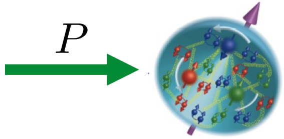
↓

confinement;
nuclear force;
color radius…

Single diffractive hard exclusive process (SDHEP)

Qiu & Yu, PRD 107 (2023) 014007





Probing its structure without breaking it!

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

❑ 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:**

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

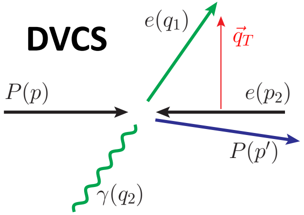
- ***C*, *D* are produced in a hard process *H* ~ q_T**
- **A^* lives much longer than *H***

2 → 3: *minimal* kin. configuration!

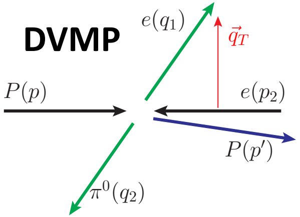
Classification of SDHEPs

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

DVCS

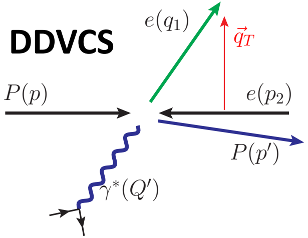


DVMP



add virtuality

DDVCS



DHQP…

…

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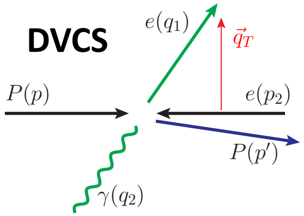

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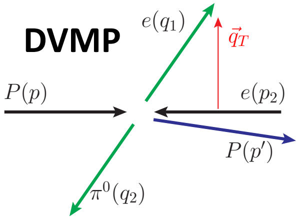
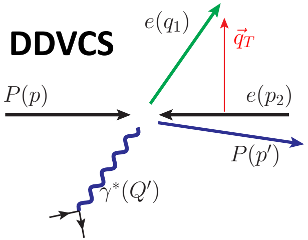


add virtuality

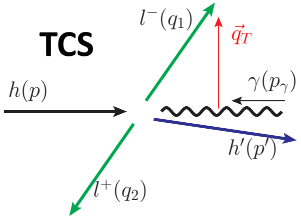
DDVCS

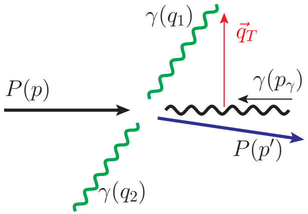


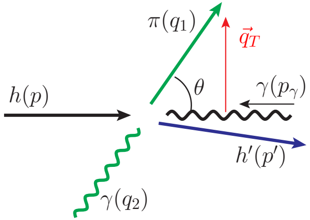
DHQP…

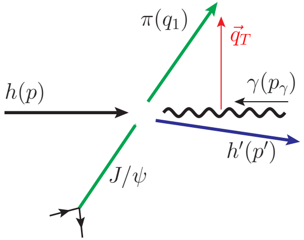
- Photo-production (JLab, EIC, …)

TCS









…

Classification of SDHEPs

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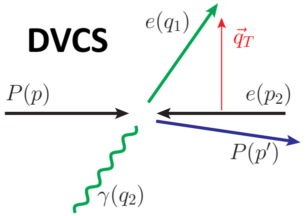

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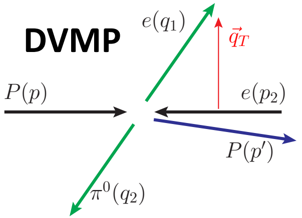

add virtuality

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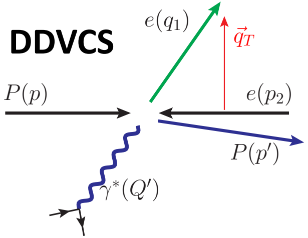

DHQP…

- **Photo-production (JLab, EIC, …)**

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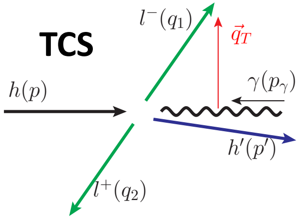
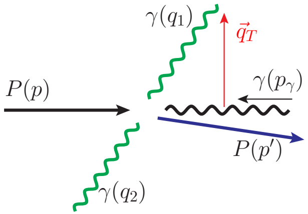
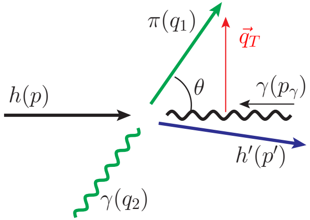
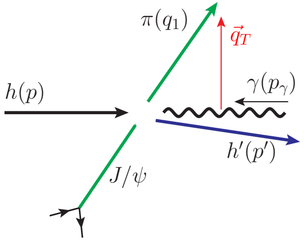


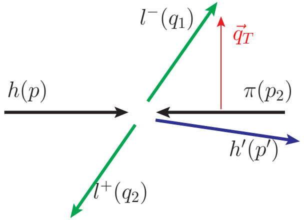


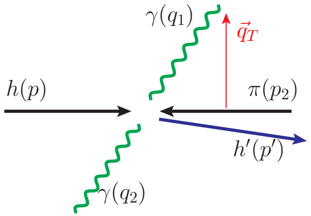




…

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





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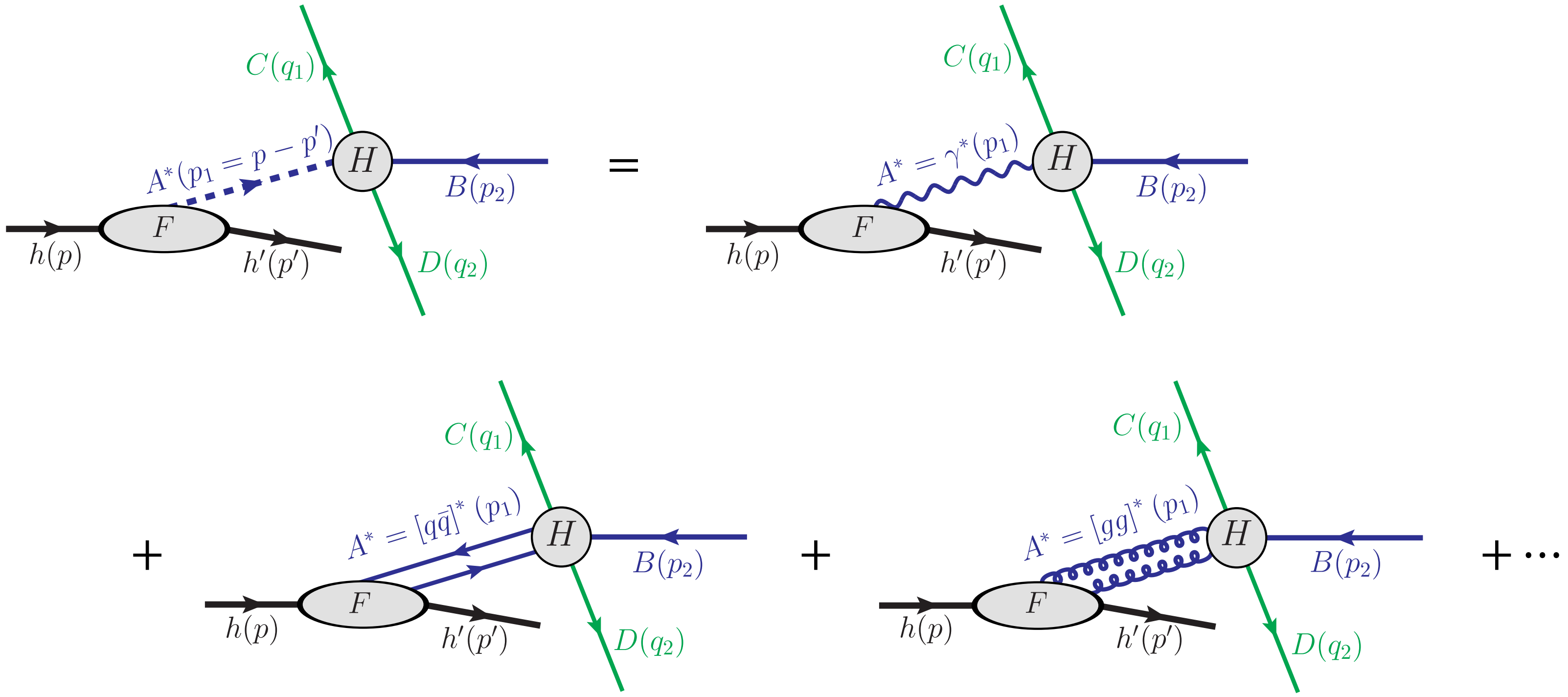
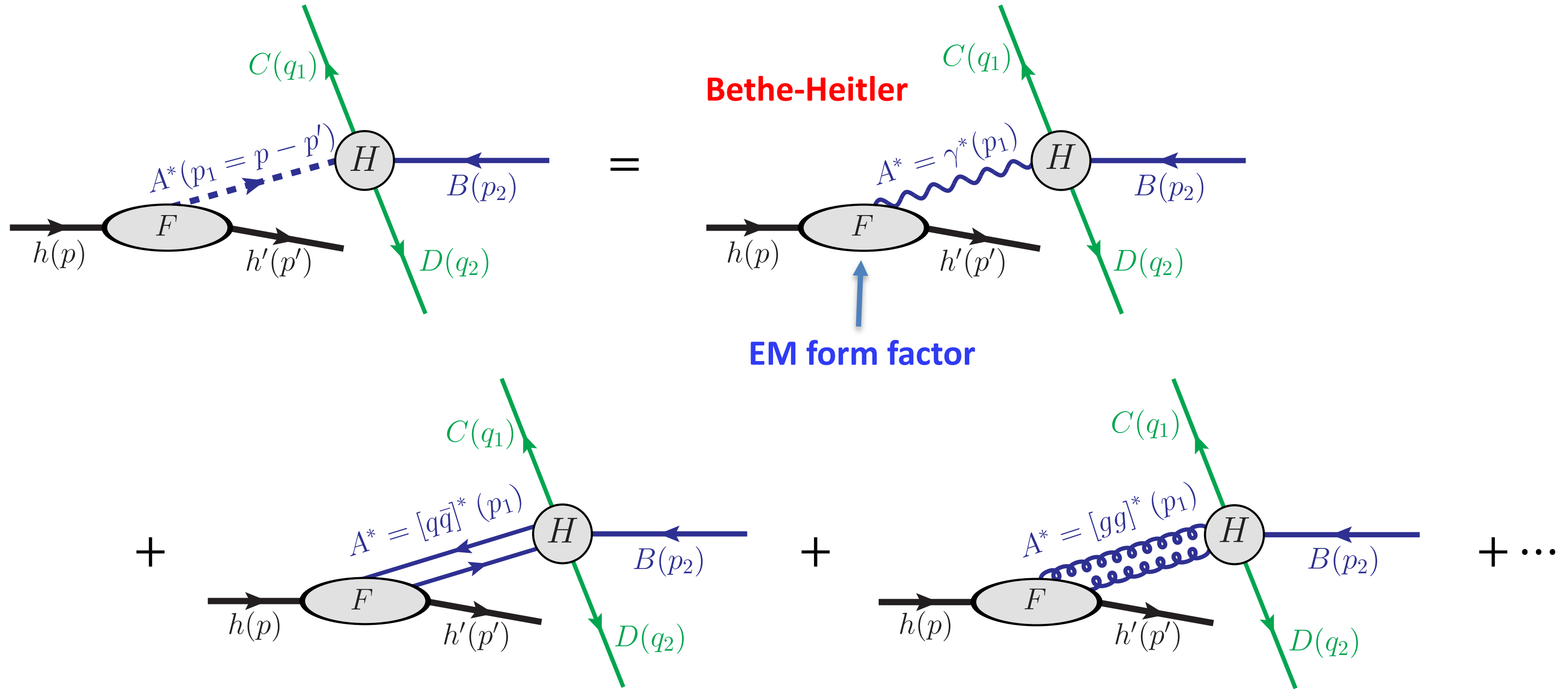
Proved factorization generally

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

Two-stage paradigm and channel expansion



Two-stage paradigm and channel expansion



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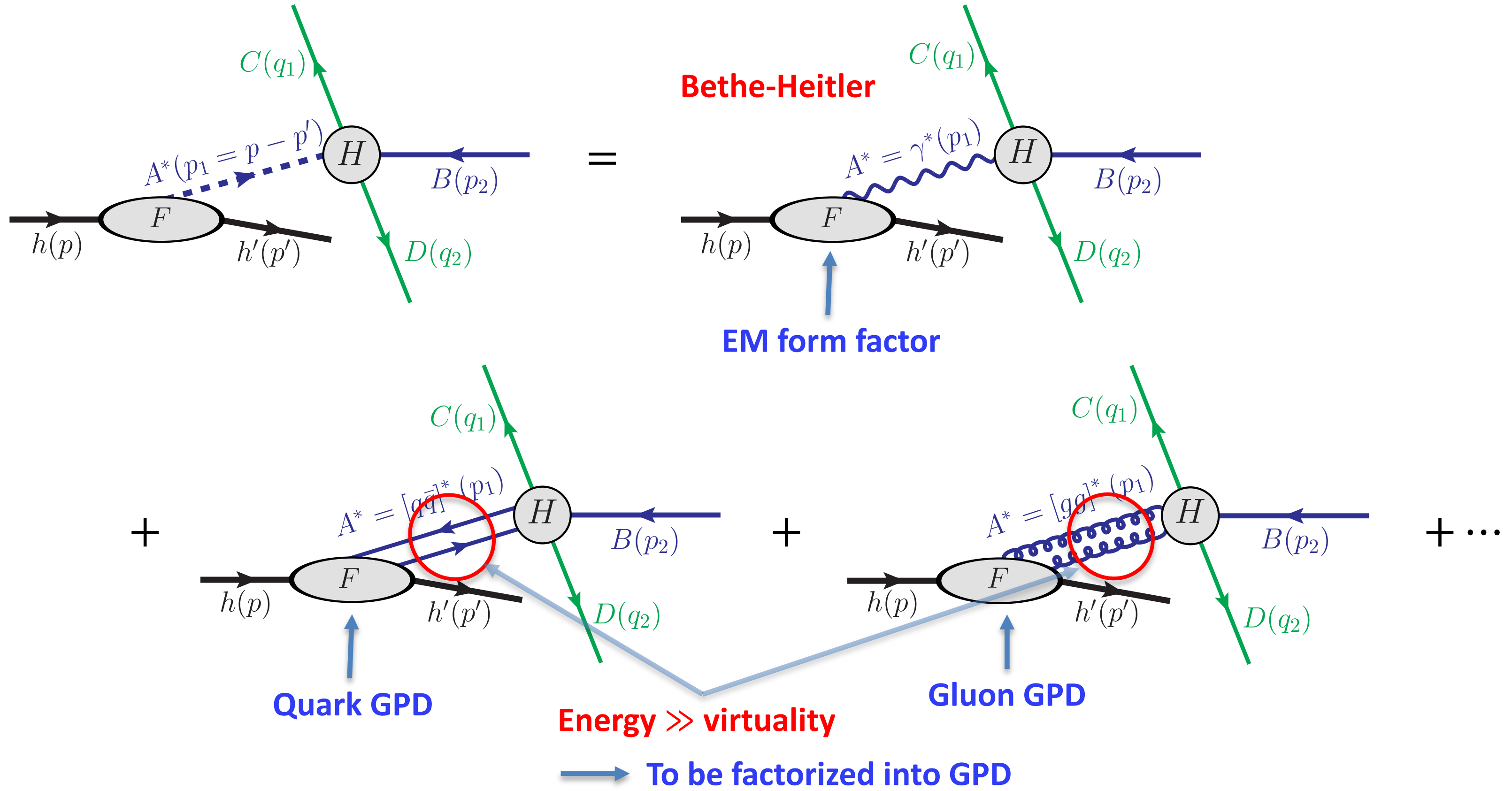
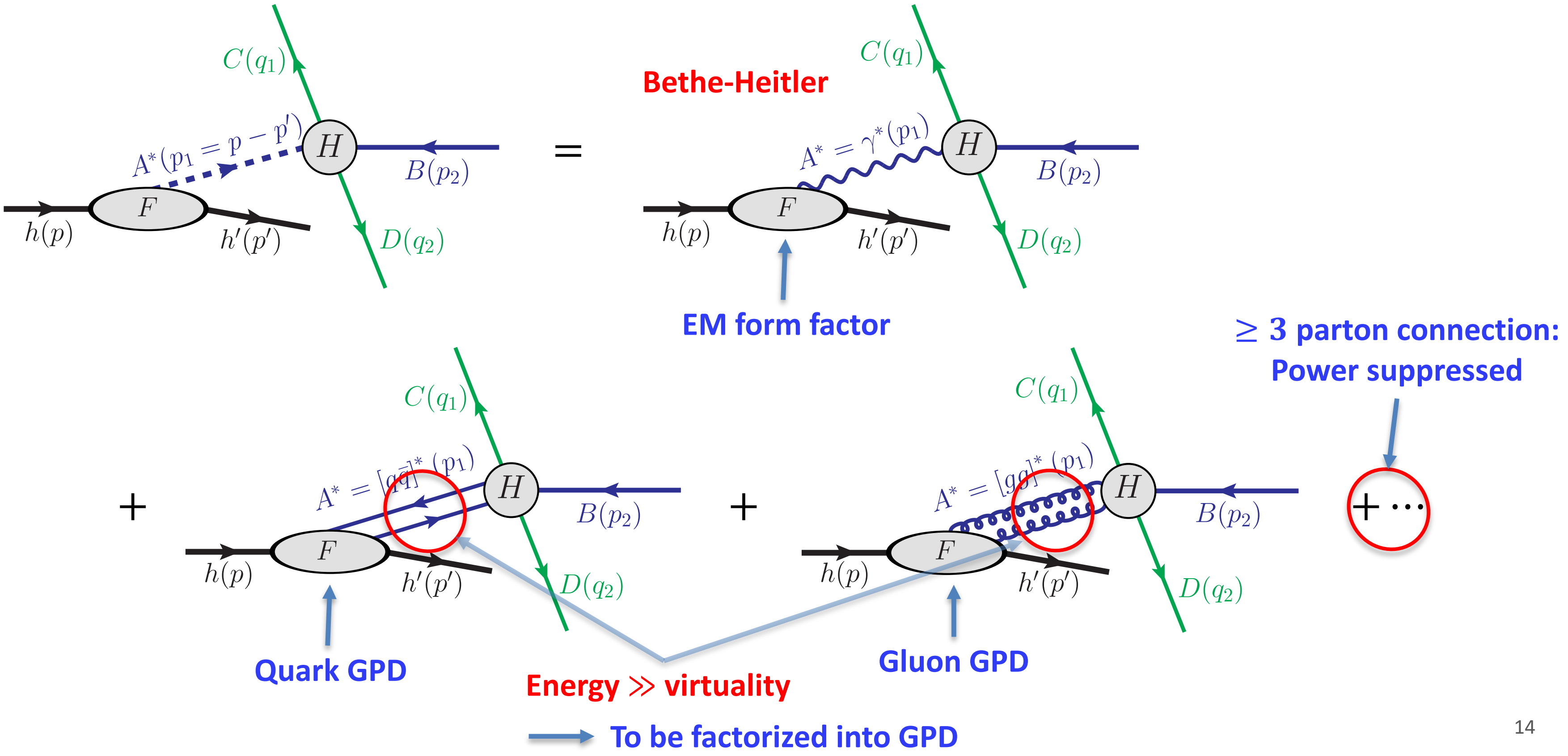


Two-stage paradigm and channel expansion (twist expansion)



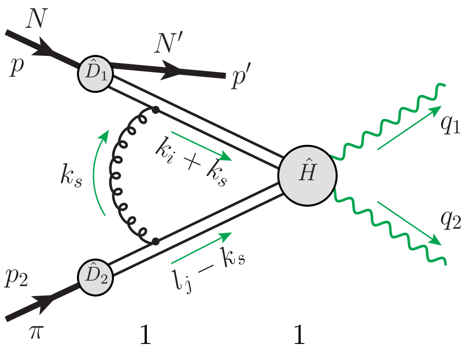
SDHEP: soft gluon and factorization

- **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!

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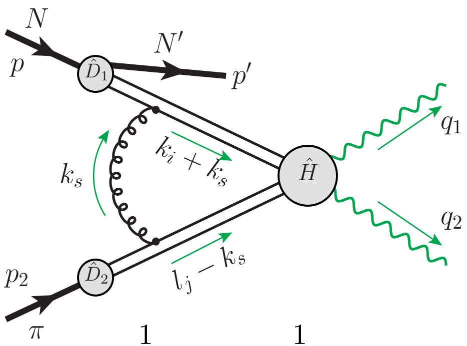

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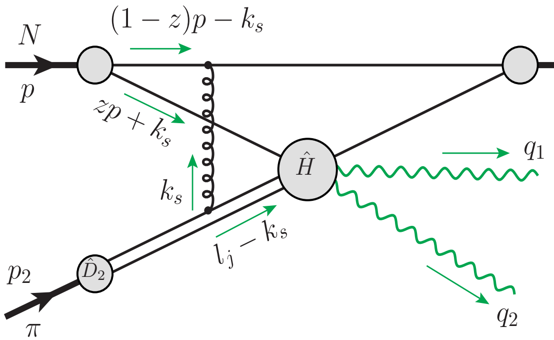
No pinch!

DGLAP region



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

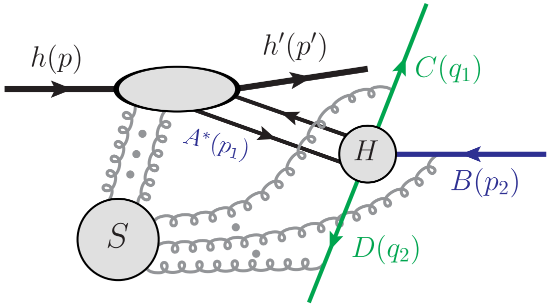
$$\frac{1}{(zp + k_s)^2 + i\varepsilon} \to \frac{1}{k_s^- + i\varepsilon}$$

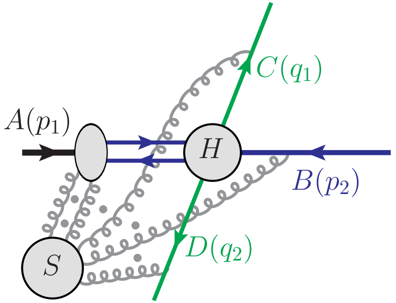
Pinched!

Same conclusion if k_s flows through N'!

SDHEP: two-stage paradigm and factorization

❑ Factorization for 2-parton channel





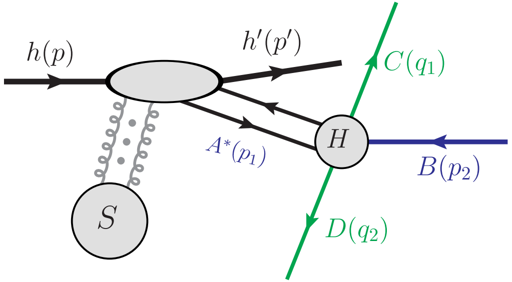
Only complication:

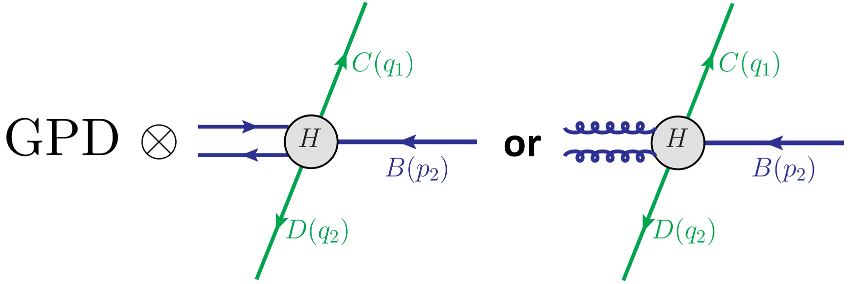
k_s^- is pinched in Glauber region for DGLAP region.

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

Glauber → ***h*-collinear region**

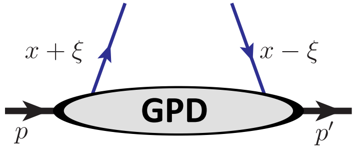
Soft gluons cancel for the meson-initialized process

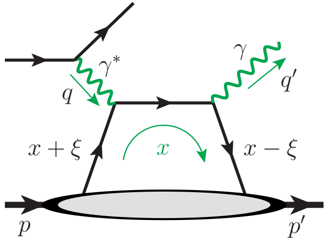




Challenge for GPD: x-dependence

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





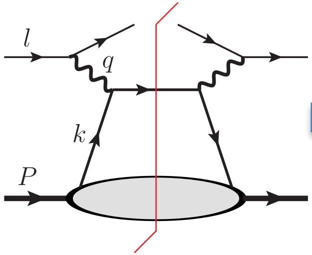
DVCS

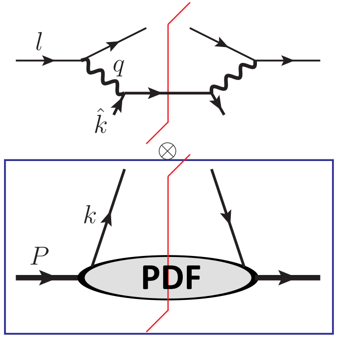
x ~ loop momentum

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

never pin down to some x

Compare with DIS





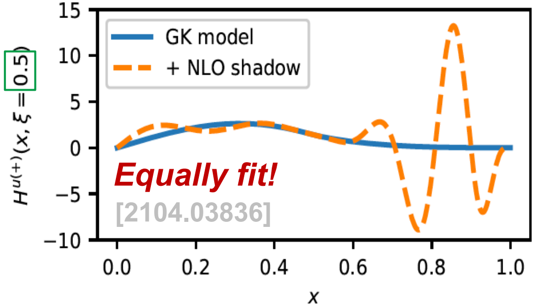
cross section: **cut diagram**

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

❑ 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”**

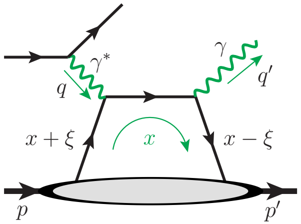


Types of x-sensitivity

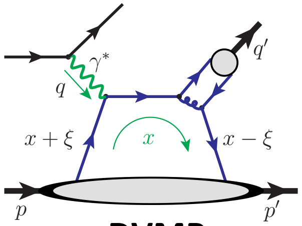
- **Moment-type sensitivity**

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

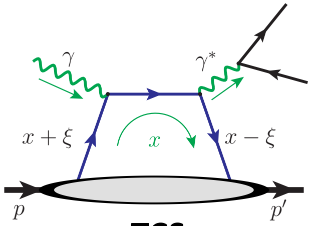
$$\Rightarrow\quad F_G = \int_{-1}^{1} dx\, G(x)\, F(x,\xi,t)$$



DVCS



DVMP



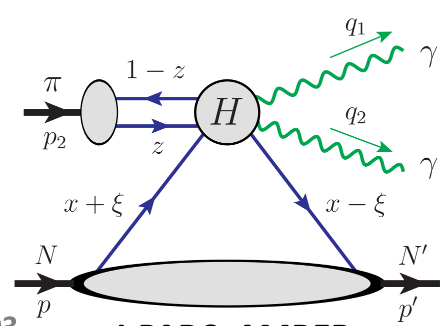
TCS

- ***Enhanced*** **sensitivity**

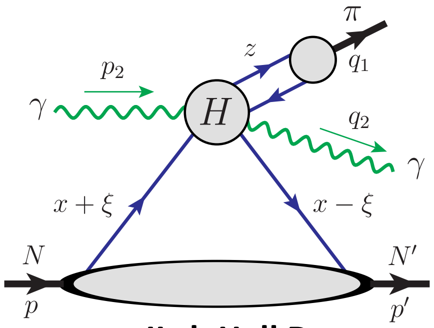
$$C(x;Q) \neq G(x)\cdot T(Q)$$

Q flow entangles with the x flow

$\Rightarrow\quad d\sigma/dQ \sim |C(x;Q)\otimes_x F(x,\xi,t)|^2$ **gives extra sensitivity to the x dependence**



J-PARC, AMBER



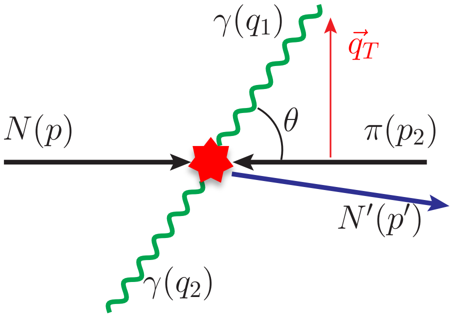
JLab Hall D

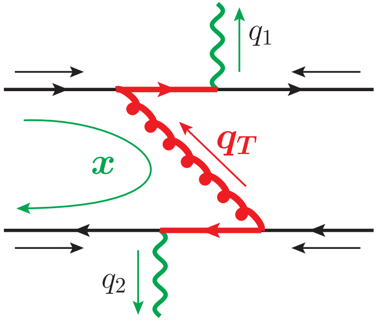
Qiu, Yu,
JHEP 08 (2022) 103

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

Enhanced x-sensitivity: (1) diphoton production

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





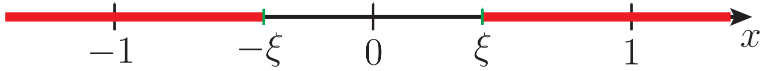
In addition to

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

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

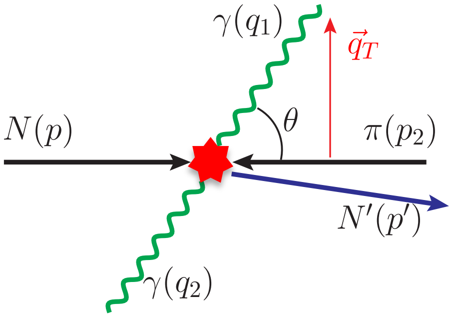
$$I(t, \xi; z, \theta) = \int_{-1}^{1} \frac{dx\, F(x, \xi, t)}{x - \rho(z;\theta) + i\epsilon\, \mathrm{sgn}\left[\cos^2(\theta/2) - z\right]}$$

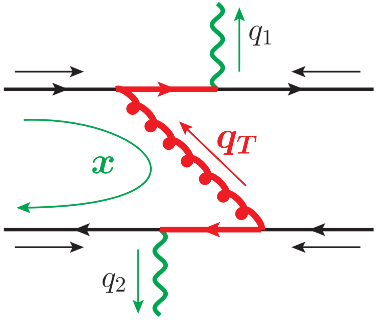
$$\rho(z;\theta) = \xi \cdot \left[\frac{1 - z + \tan^2(\theta/2)\, z}{1 - z - \tan^2(\theta/2)\, z}\right] \in (-\infty, -\xi] \cup [\xi, \infty)$$



Enhanced x-sensitivity: (1) diphoton production

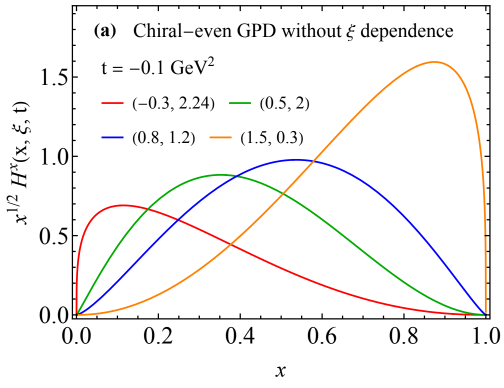
[Qiu & Yu, JHEP 08 (2022) 103]

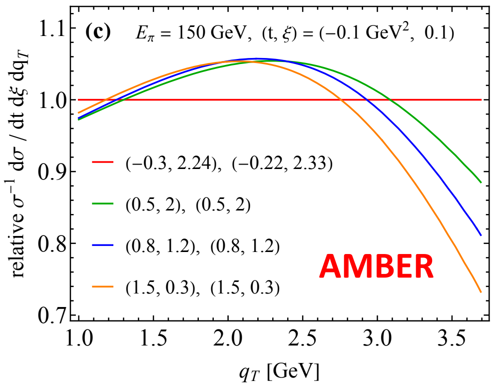


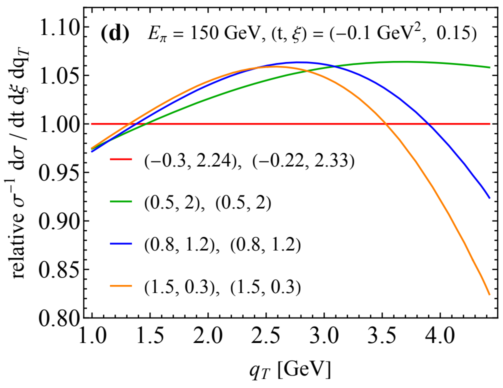


Vary GPD x shapes

Different q_T shapes

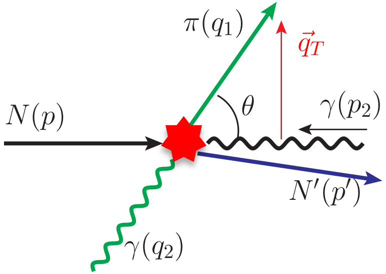






Enhanced x-sensitivity: (2) γ-π pair production

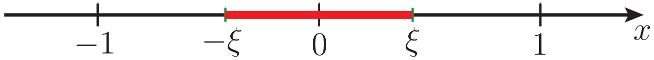
[Qiu & Yu, arXiv:2023.xxxxx]



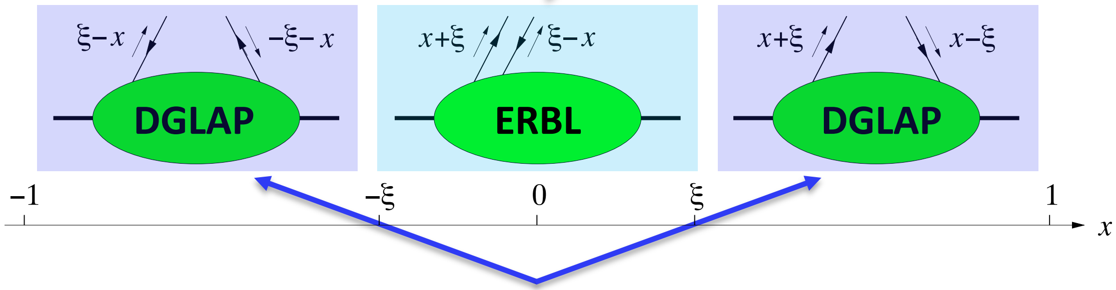
$i\mathcal{M}$ **also contains the special integral**

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

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

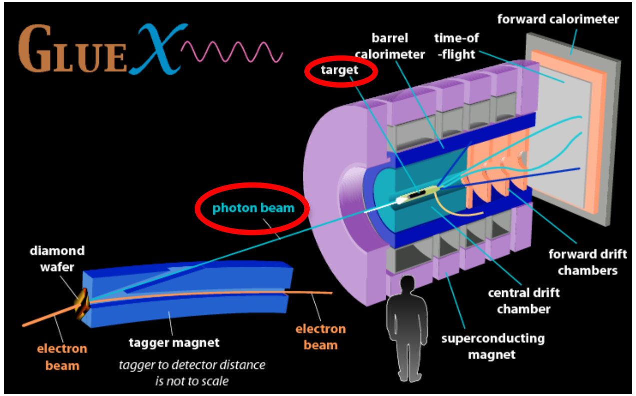


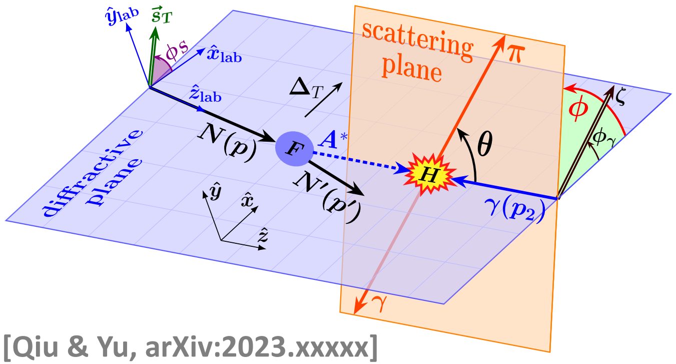
Complementary sensitivity



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

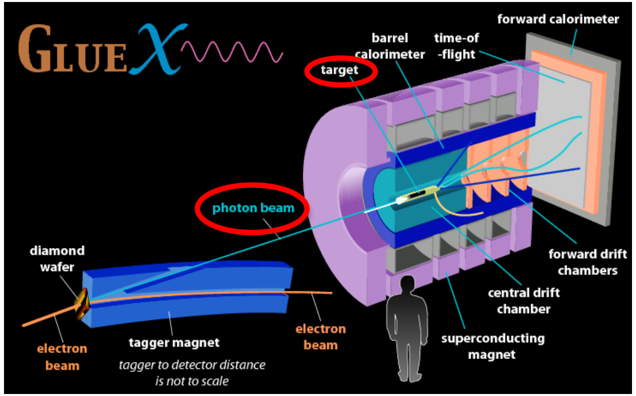
Enhanced x-sensitivity: (2) γ-π pair production

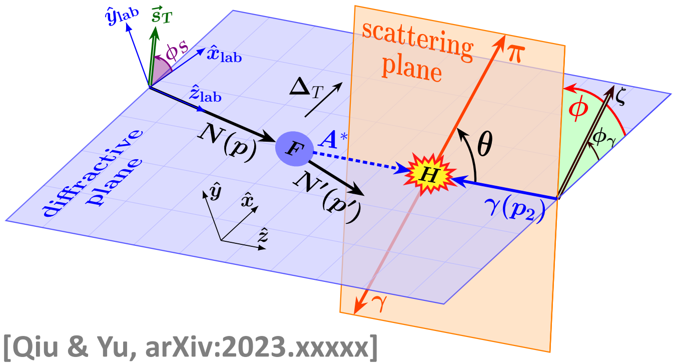




[Qiu & Yu, arXiv:2023.xxxxx]

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





Polarization asymmetries

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

$$\frac{d\sigma}{d|t|\,d\xi\,d\cos\theta} = \frac{N^2\,(1-\xi)}{32\,s\,(2\pi)^3\,(1+\xi)}\Sigma_{UU}$$

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

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

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

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

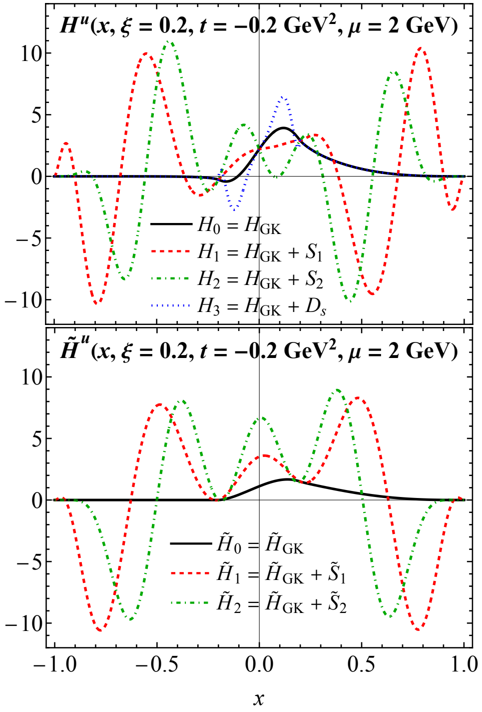
[Qiu & Yu, arXiv:2023.xxxxx]

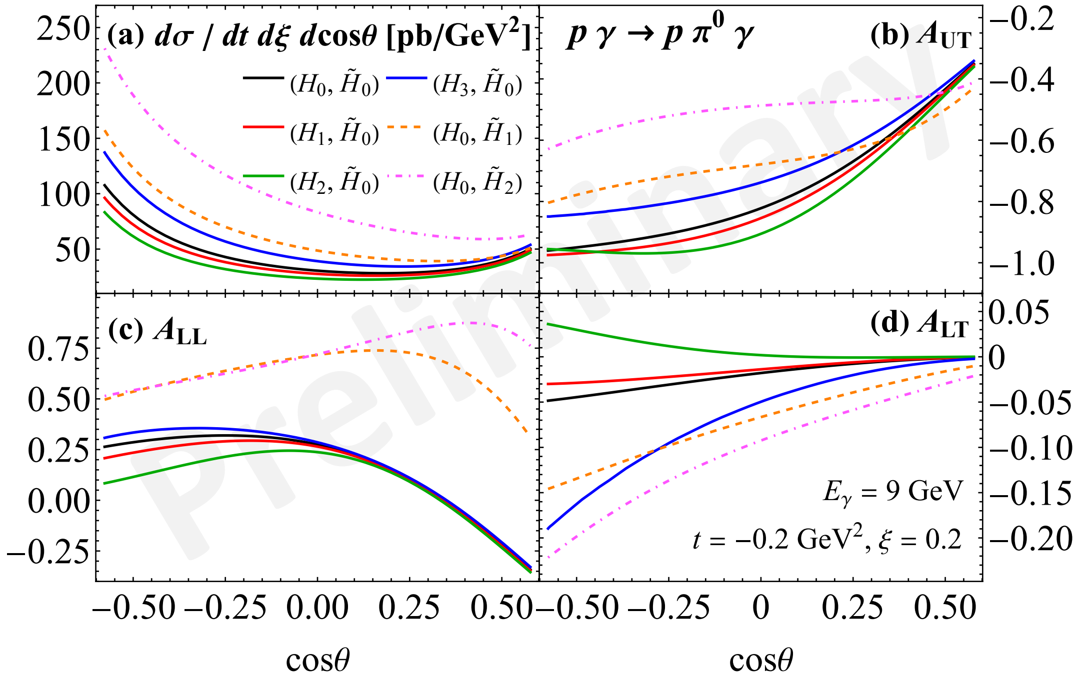
Enhanced x-sensitivity: (2) γ-π pair production

GPD models = GK model + shadow GPDs

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

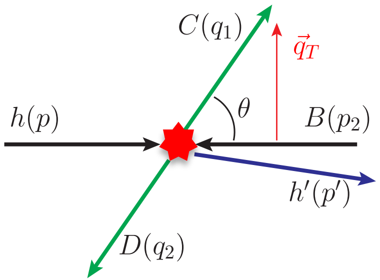
Goloskokov, Kroll, \`05, \`07, \`09
Bertone et al. \`21
Moffat et al. \`23





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

→ Global Analysis ←

- ML/AI
- LQCD

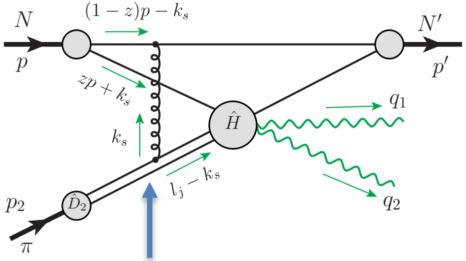
Thank you!

Backup slides

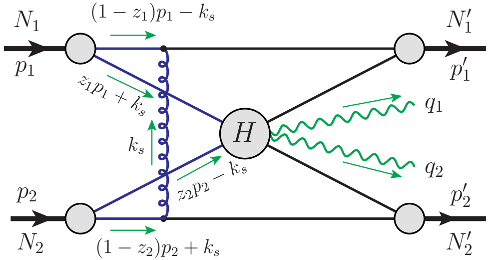
Why *single* diffractive?

❑ Double diffractive process

Glauber pinch for diffractive scattering



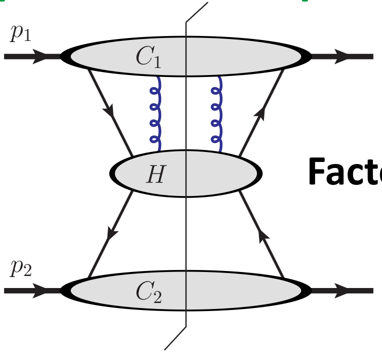
Factorizable thanks to pion



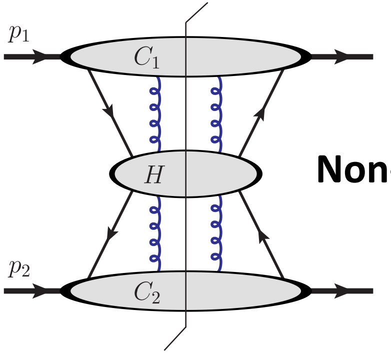
Non-factorizable **even with hard scale**

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

❑ Compare: Drell-Yan process at high twist



Factorizable



Non-factorizable