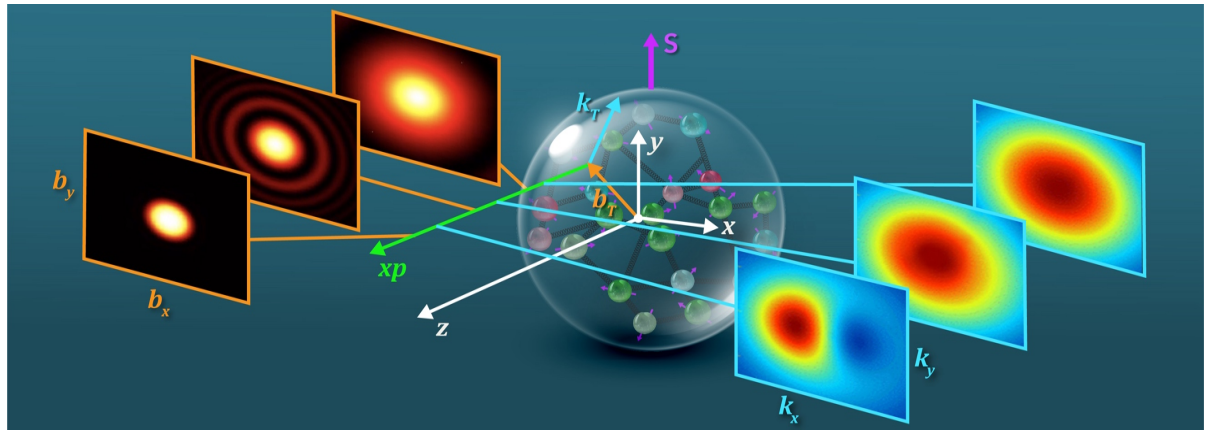
ECT*
EUROPEAN CENTRE
FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREA
FONDAZIONE BRUNO KESSLER

REVEALING EMERGENT MASS THROUGH STUDIES
OF HADRON SPECTRA AND STRUCTURE

12 September 2022 — 16 September 2022

Single Diffractive Hard Exclusive Processes (SDHEP) for the Study of 3D Hadron Structure



Emergent Properties

Dynamical Structure

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In collaboration with Zhite Yu (MSU)

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Jefferson Lab

TMD Collaboration

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Mass of Nucleon?

❑ Nucleon Mass:

$m = E/c^2$ from the A. Einstein's famous equation E = mc²

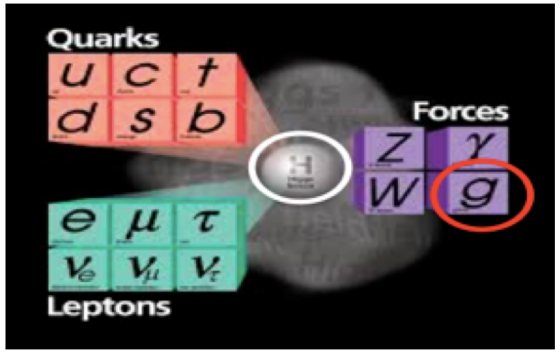
Mass is the Energy of the nucleon when it is at Rest!

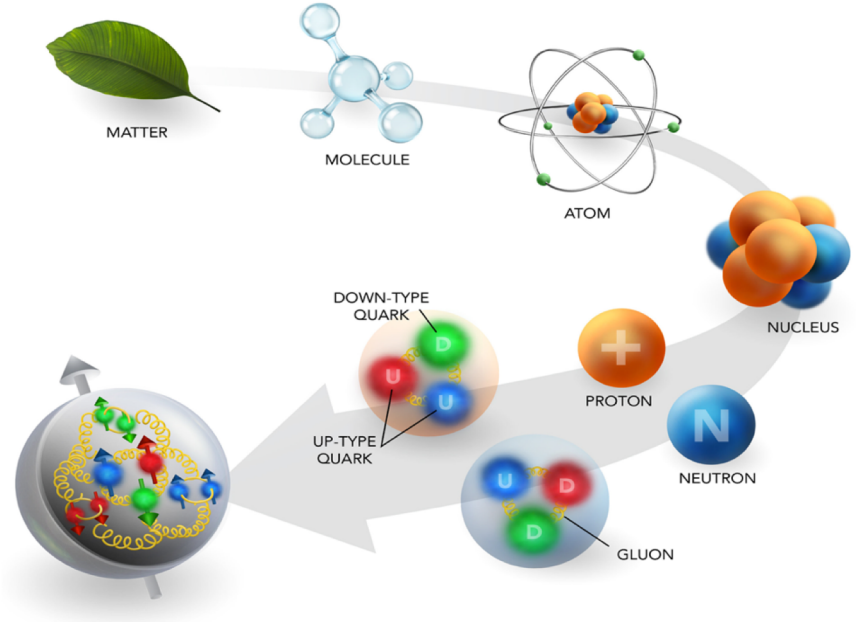
$$M_n = \left.\frac{\langle P|H_{\rm QCD}(\psi, A)|P\rangle}{\langle P|P\rangle}\right|_{\rm at\ rest}$$

❑ Nucleon is not elementary:

Nucleon is a strongly interacting, relativistic bound state of quarks and gluons of QCD

Our understanding of the nucleon has been evolving, and will continue to evolve, …

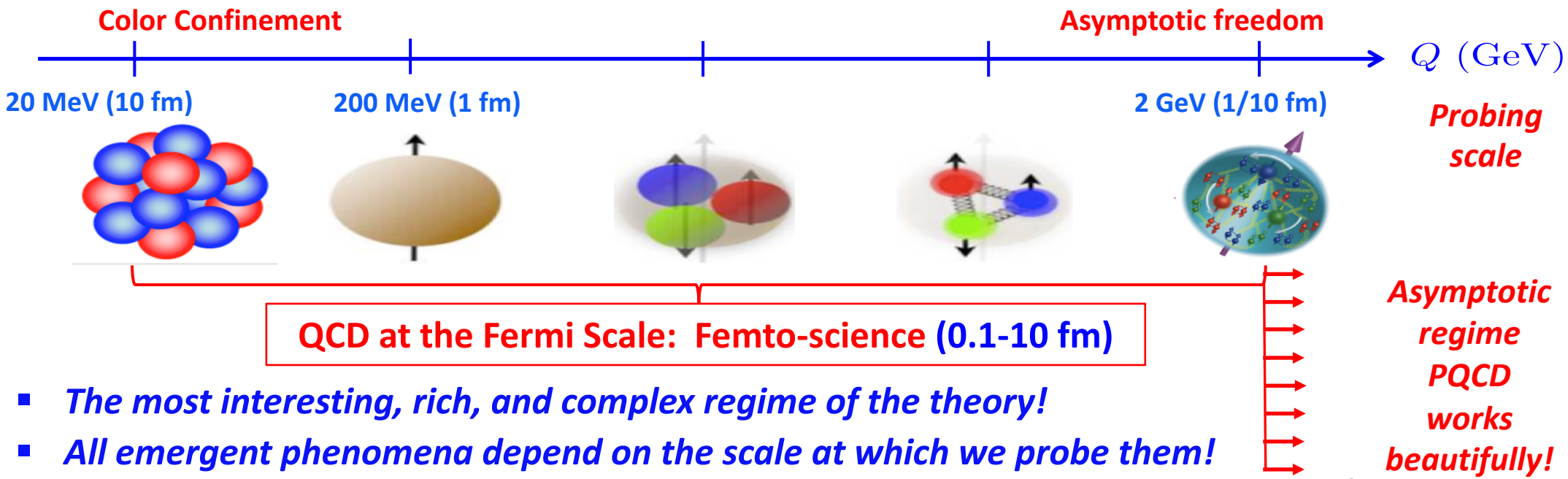




Understanding it fully is still beyond the best mind that we have!

$H_{\rm QCD}(\psi, A)$ **is known, but not** $|P\rangle = ?$

QCD Landscape of Nucleons and Nuclei

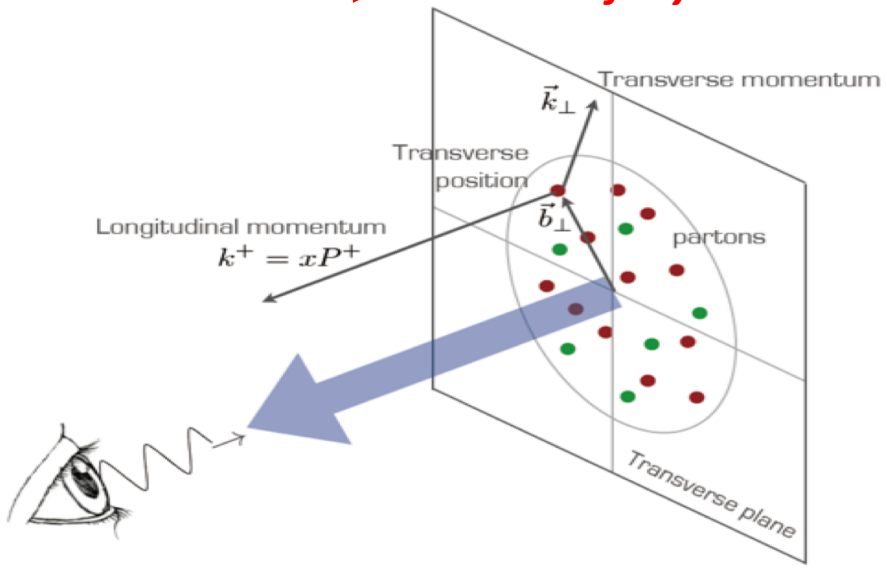


- *The most interesting, rich, and complex regime of the theory!*
- *All emergent phenomena depend on the scale at which we probe them!*

❑ **Need new observables with two distinctive: scales:**

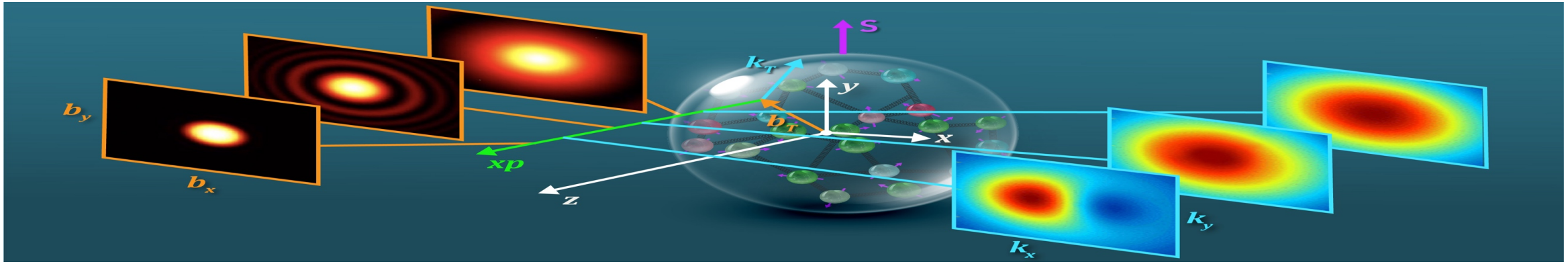
$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\rm QCD}$$

- **Hard scale:** Q_1 **to localize the probe to see the particle nature of quarks/gluons**
- **"Soft" scale:** Q_2 **could be more sensitive to the hadron structure ~ 1/fm**



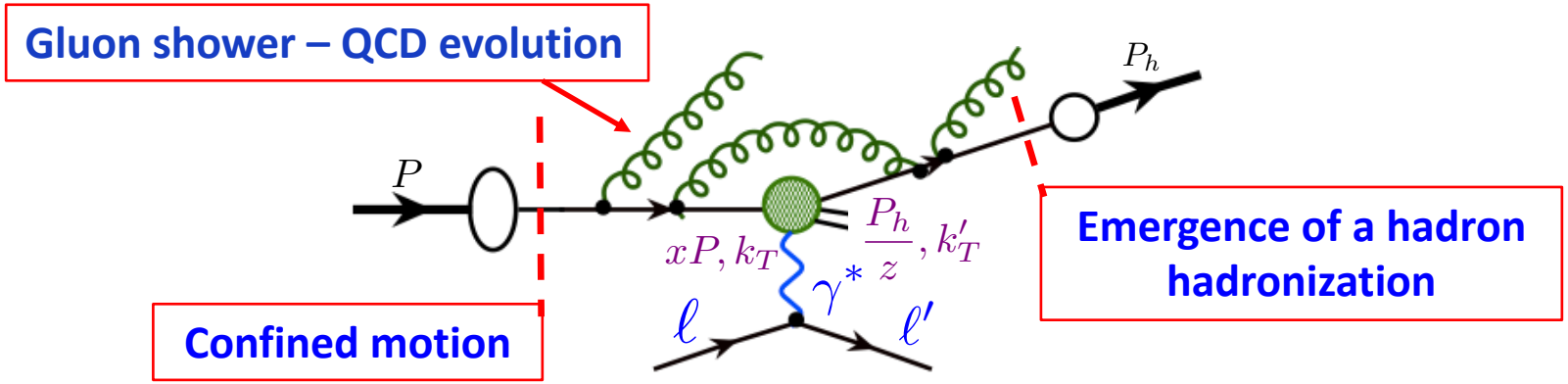
"See" Internal Structure of Hadron without seeing quarks/gluons?

❑ 3D hadron structure:



NO quarks and gluons can be seen in isolation!

❑ If the proton is broken, e.g., in SIDIS, …



Transverse momentum broadening:

$$\Delta k_T^2 \propto \Lambda_{\rm QCD}^2 \times \alpha_s(C_F, C_A) \times \log(Q^2/\Lambda_{\rm QCD}^2) \times \log(s/Q^2) \gtrsim 1$$

- *Measured k_T is NOT the same as k_T of the confined motion!*
- *Structure information vs. collision effects*

Structure information is diluted by the collision induced shower!

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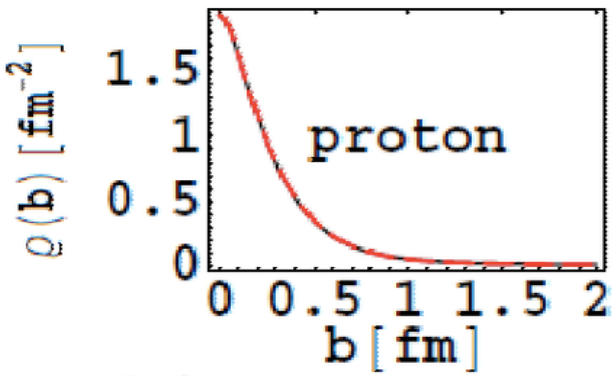
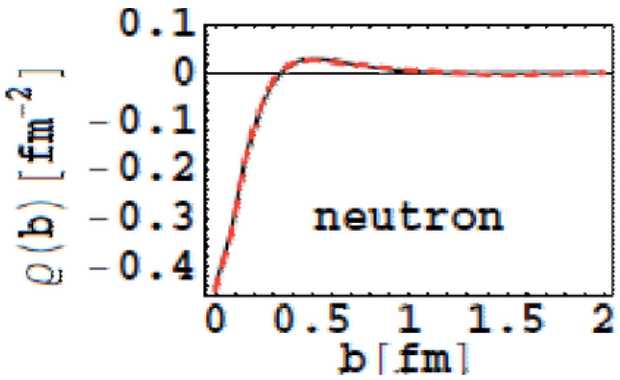
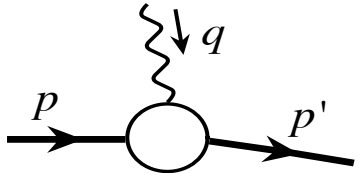
How to Explore Internal Structure of Hadron without Breaking it?

- **Form factors:** Elastic electric form factor → Charge distributions

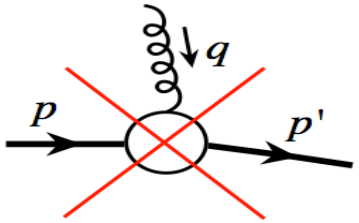






→ Proton "Radius" in EM charge distribution

- **But, there is NO elastic "color" form factor!** →



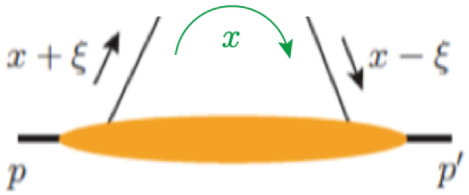
No Proton "Radius" in color charge distribution!

- **3D hadron tomography:**

Generalized "form factor" for quark and gluon "density" distribution

Generalized PDFs (GPDs) – without breaking the proton

$$F_{q/h}(x,\xi,t) \qquad \text{skewness} \qquad \xi = \frac{(P-P')^+}{(P+P')^+}$$



Spatial distribution of quark/gluon density, quark/gluon correlations, …

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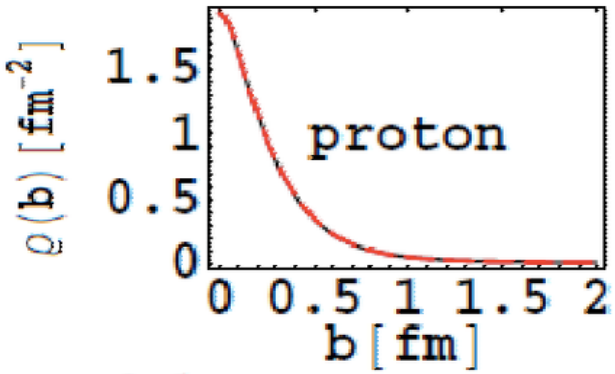

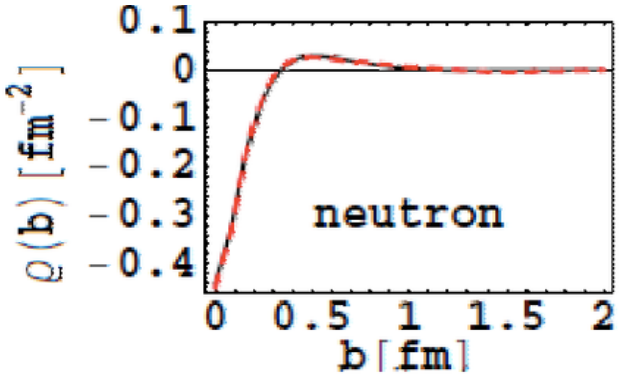

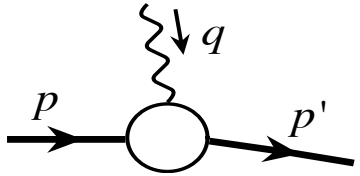

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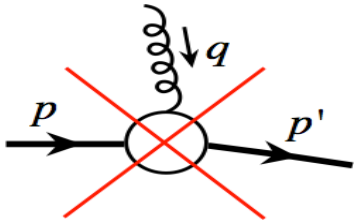


→ No Proton "Radius" in color charge distribution!

- **3D hadron tomography:**

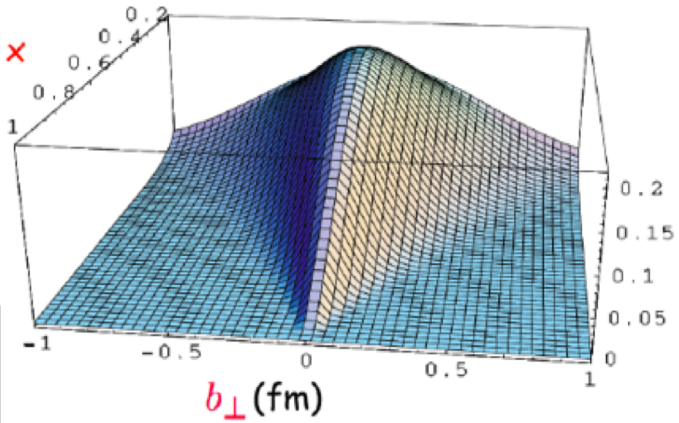
$$t \xrightarrow{\xi \to 0} -\Delta_T^2$$

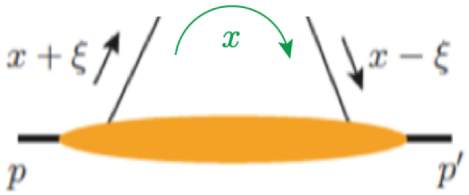
$$F(x,\xi,t) \to F(x,0,-\Delta_T^2)$$

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

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

3D image





→ Proton radii of quark and gluon spatial distribution, $r_q(x)$ & $r_g(x)$

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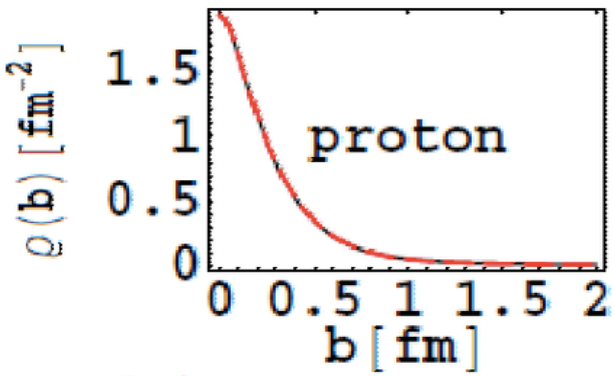

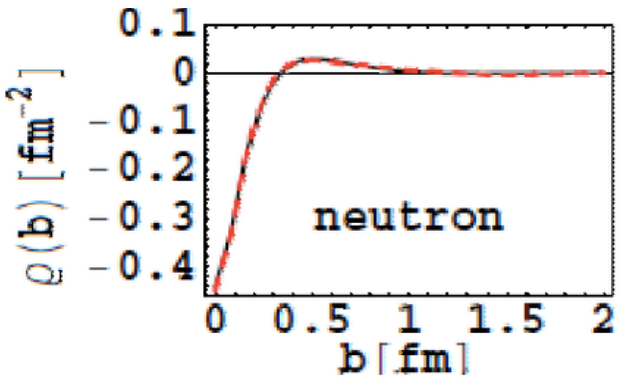

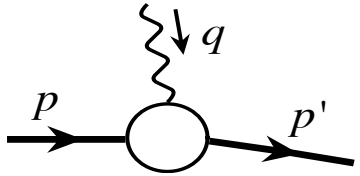

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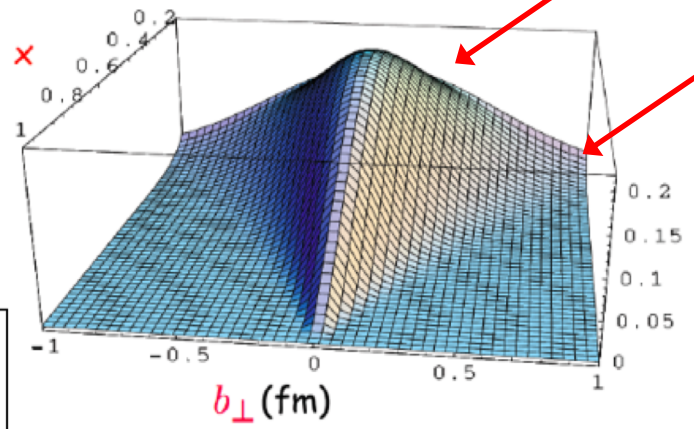
$$t \xrightarrow{\xi \to 0} -\Delta_T^2$$

$$F(x,\xi,t) \to F(x,0,-\Delta_T^2)$$

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

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

3D image



How fast does glue density fall?

How far does glue density spread?

Should $r_q(x) > r_g(x)$, or vice versa?

Could $r_g(x)$ saturates as $x \to 0$?

How do they compare with the "known" proton radius (EM charge, mass, …)? …

→ Proton radii of quark and gluon spatial distribution, $r_q(x)$ & $r_g(x)$

Generalized Parton Distribution (GPD)

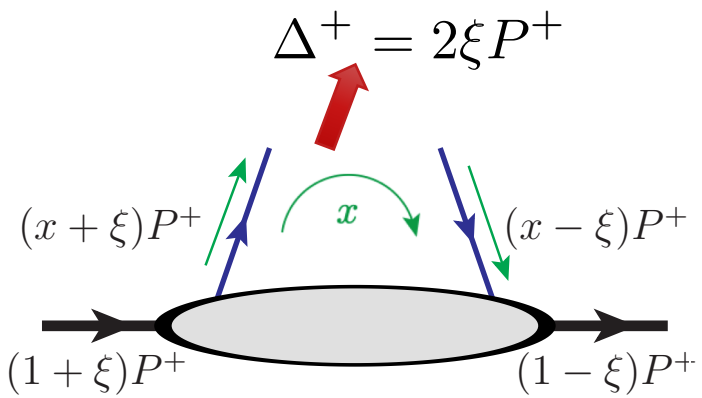
- **Definition:**

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

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

$$\widetilde{F}^q(x,\xi,t) = \int \frac{\mathrm{d}z^-}{4\pi} e^{-ixP^+z^-} \langle p'|\bar{q}(z^-/2)\gamma^+\gamma_5 q(-z^-/2)|p\rangle$$

$$= \frac{1}{2P^+}\left[\widetilde{H}^q(x,\xi,t)\,\bar{u}(p')\,\gamma^+\gamma_5 u(p) - \widetilde{E}^q(x,\xi,t)\,\bar{u}(p')\,\frac{\gamma_5\Delta^+}{2m}u(p)\right].$$

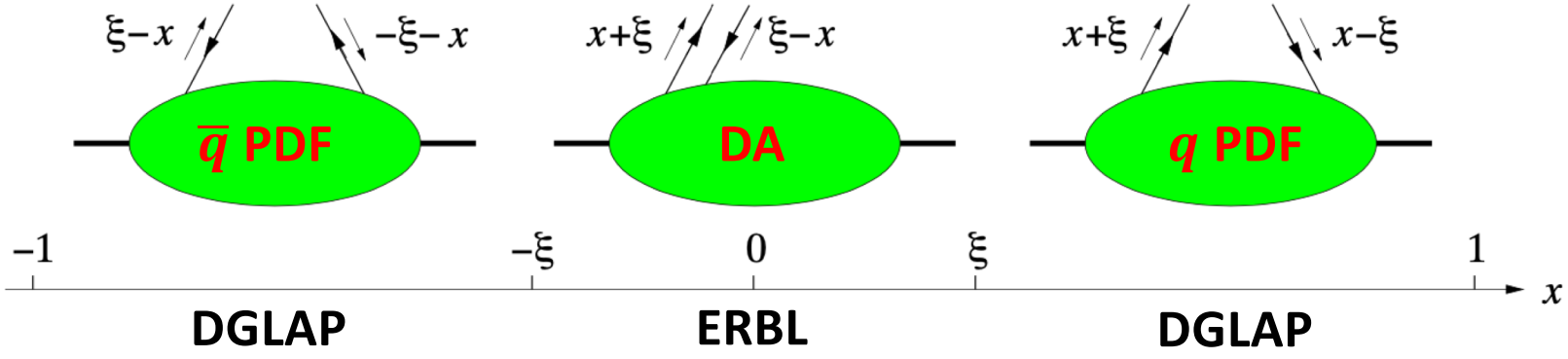


$$P^+ = \frac{p^+ + p'^+}{2}$$

$$\Delta = p - p'$$

- **Combine *PDF* and *Distribution Amplitude (DA):***

Forward limit $\xi = t = 0$ **:** $\quad H^q(x,0,0) = q(x), \quad \tilde{H}^q(x,0,0) = \Delta q(x)$



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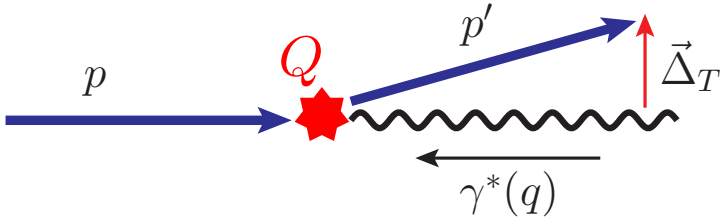
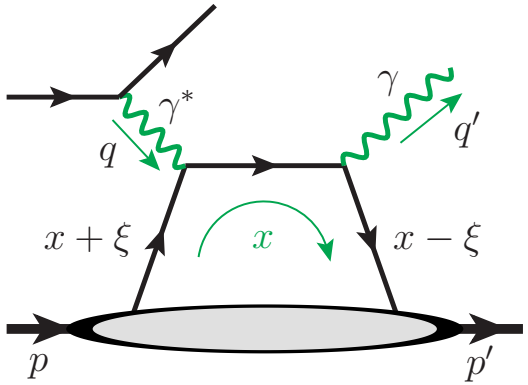
Exclusive Diffractive Process for Extracting GPDs

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

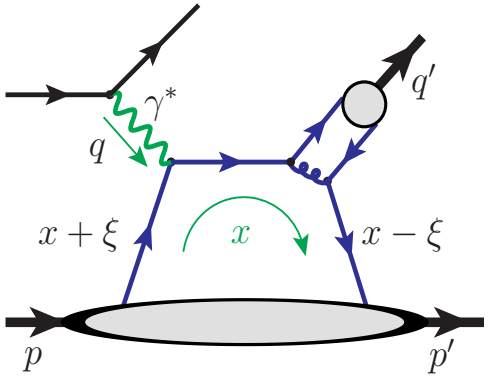


HERA discovery:
~15% of HERA events with the Proton stayed intact

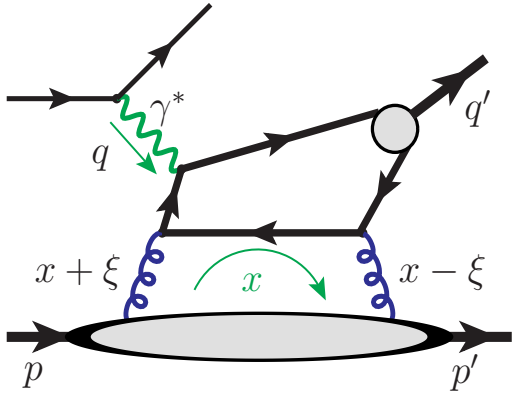
- Known exclusive processes for extracting GPDs:



DVCS: $Q^2 >> |t|$



DVMP



DVQP

+ DDVCS, …

Feature: Two-scale observables $\quad Q^2 \gg |t| \qquad t = (p-p')^2$

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

$\Rightarrow$ **Factorization**

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

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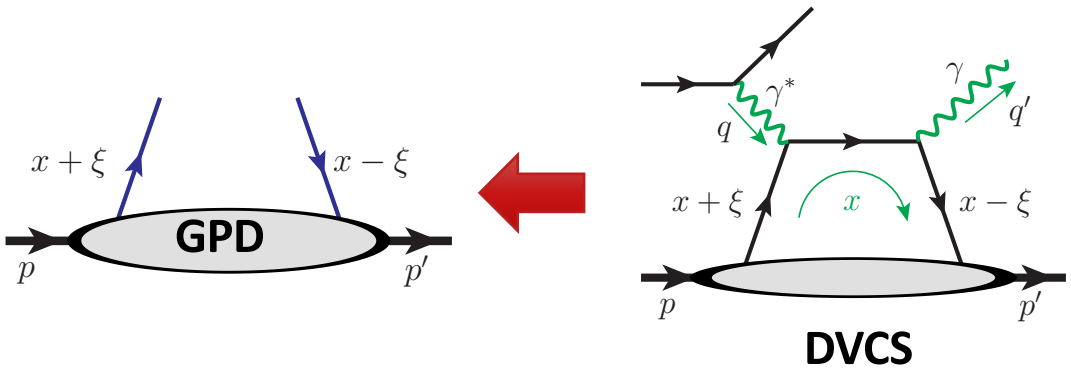
Why it is difficult to extract the x-dependence of GPD?

- **Amplitude nature: exclusive processes**

  $x \sim$ loop momentum

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

  never pin down to some x



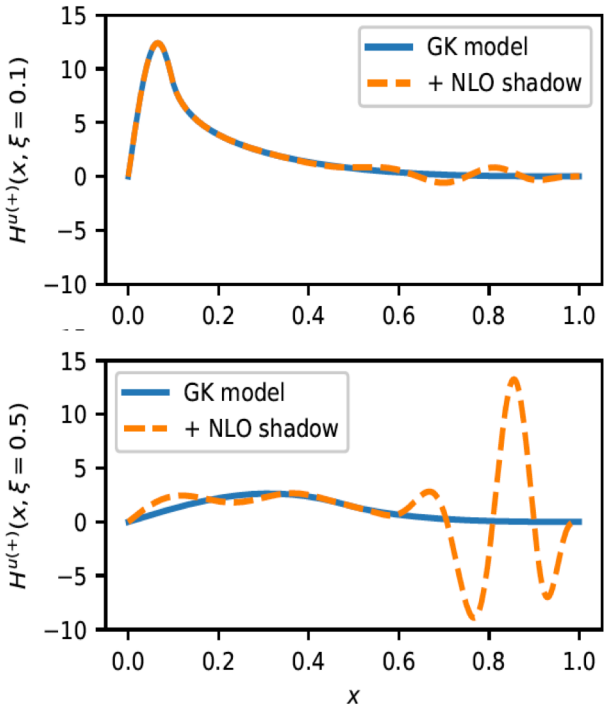
- **Sensitivity to x comes from $C(x,\xi;Q/\mu)$**

  At LO, DVCS hard coefficient factorizes

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

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

- **also true for most other processes**
- **x-dependence is only constrained by a “moment”**
- **easy to fit to the data**



Blue and dashed Fit the same CFFs !

PRD103 (2021) 114019

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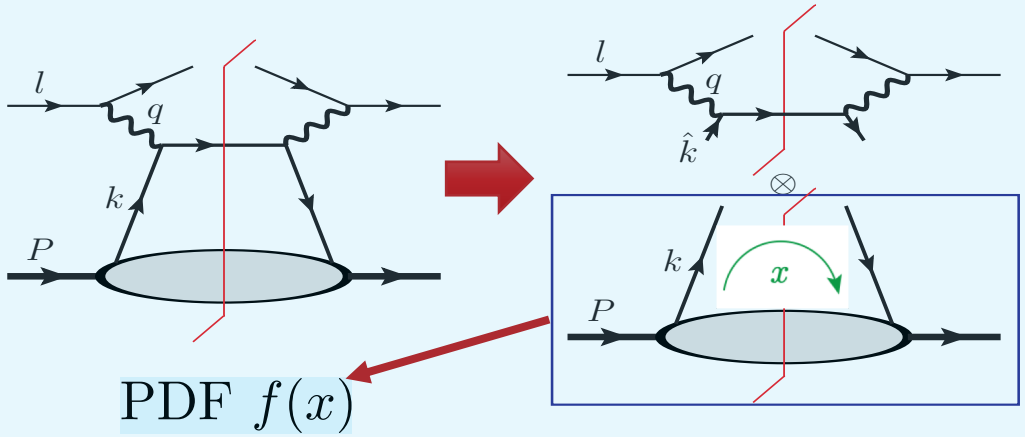
Inclusive Process vs. Exclusive Process

❑ Deeply Inelastic Scattering (DIS):



$x = k^+/P^+$

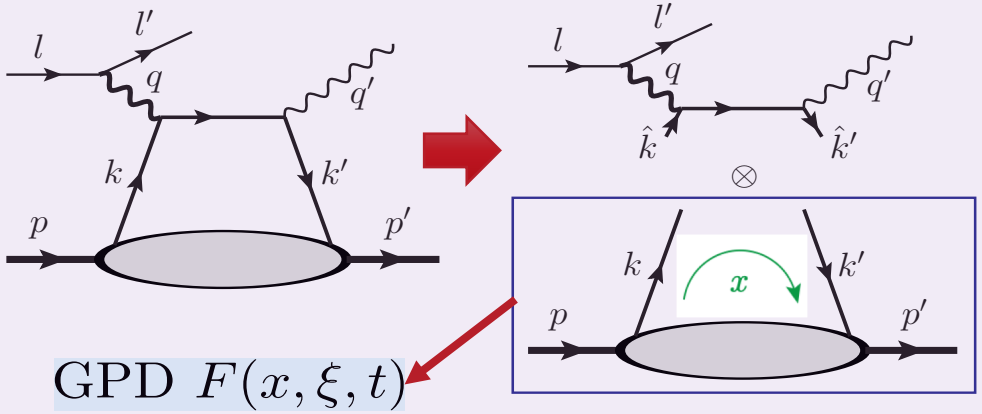
Cross section: **Cut diagrams**

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

- **PDF ~ probability**
- **At LO:** $x = x_B$
- **Beyond LO:** $x \in [x_B, 1]$

x-dependence: **Part of measurement**

❑ Deeply Virtual Compton Scattering (DVCS)



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

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

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

Amplitude: **Uncut diagrams**

$$\mathcal{M}_{\rm DVCS}(\xi,t) \simeq \int_{-1}^{1} \mathrm{d}x\, F(x,\xi,t)\, \hat{\mathcal{M}}(x,\xi)$$

- **GPD ~ amplitude**
- $k^+ = (x+\xi)\, P^+$ **is loop momentum**
- **At any order:** $x \in [-1, 1]$

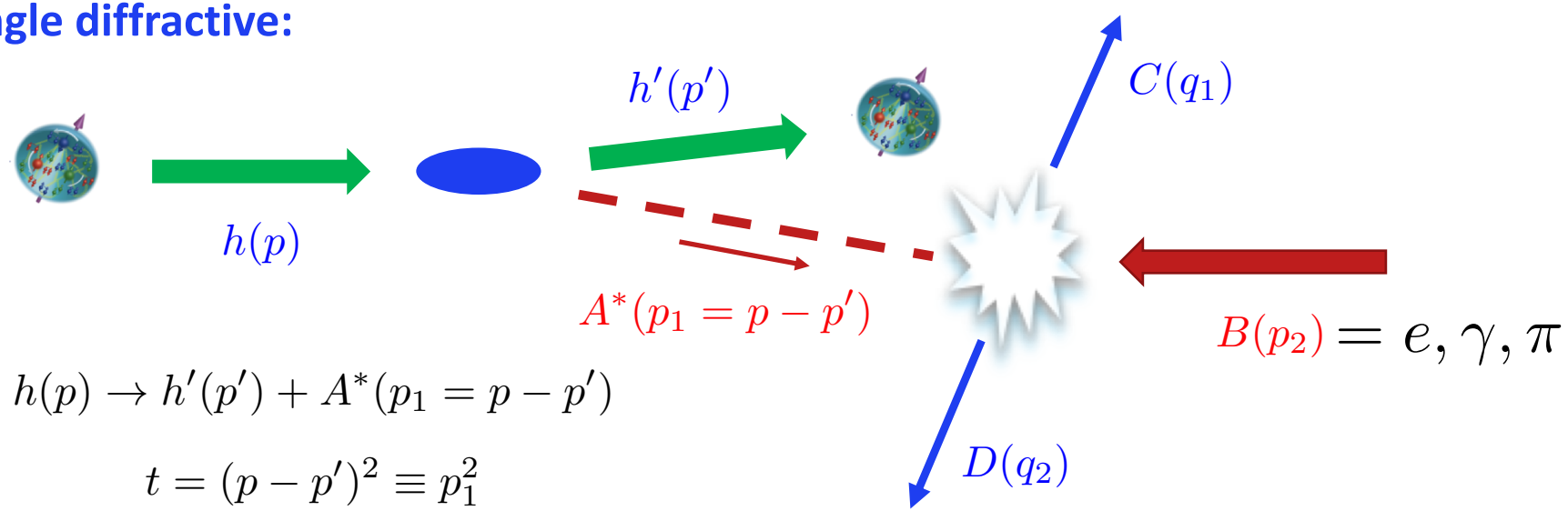
x-dependence: **Hard to measure**

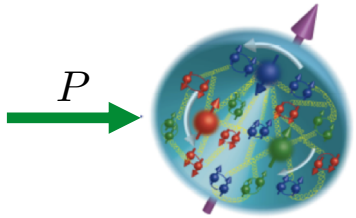
Single-Diffractive Hard Exclusive Processes (SDHEP)

Qiu & Yu, 2022

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

- **Single diffractive:**





Probing its structure without breaking it!

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

$$t = (p - p')^2 \equiv p_1^2$$

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

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

$$(p - p') \cdot n \gg \sqrt{|t|} \quad \Longleftrightarrow \quad |q_{1_T}| = |q_{2_T}| \gg \sqrt{-t}$$

- **The single diffractive $2 \to 3$ exclusive hard processes:**

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

- **Necessary condition for QCD factorization:**

$$|q_{1_T}| = |q_{2_T}| \gg \sqrt{-t}$$

The state $A^*(p_1)$ lives much longer than $2 \to 2$ hard exclusive collision!

Not necessarily sufficient!

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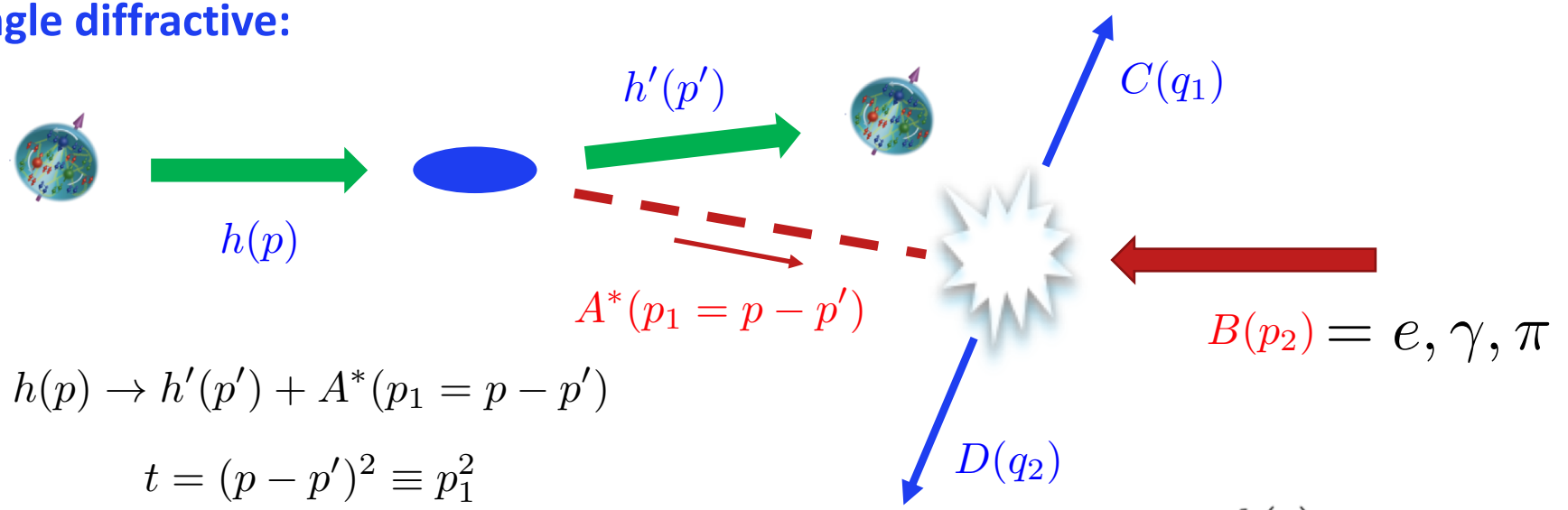
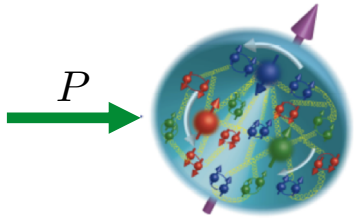
Single-Diffractive Hard Exclusive Processes (SDHEP)

Qiu & Yu, 2022

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

- **Single diffractive:**





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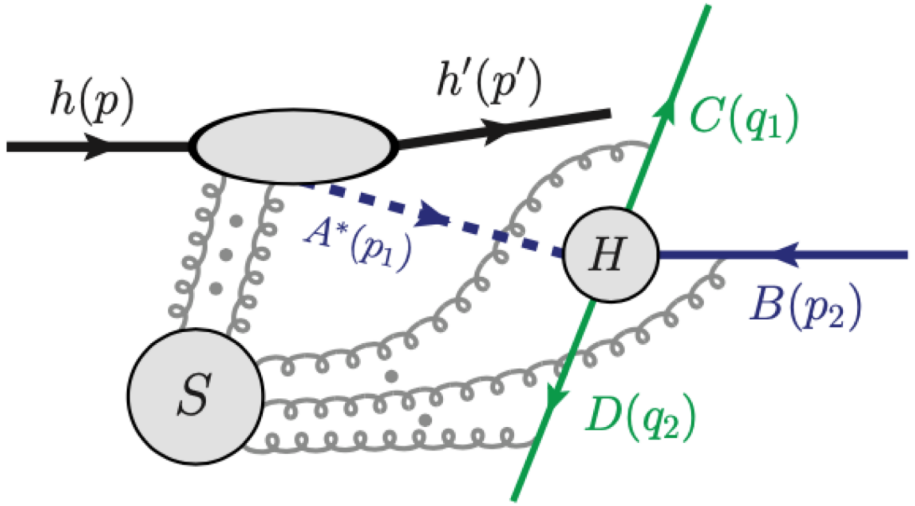

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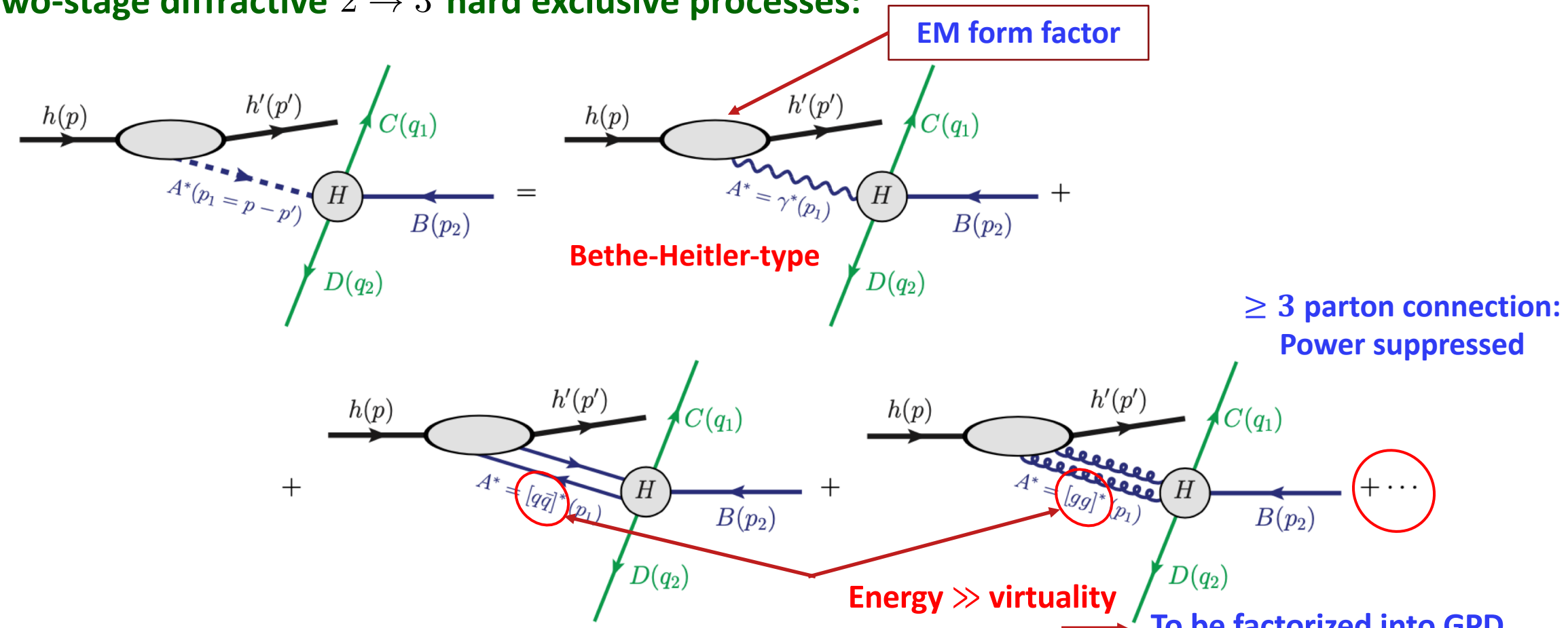
Single-Diffractive Hard Exclusive Processes (SDHEP)

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



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

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

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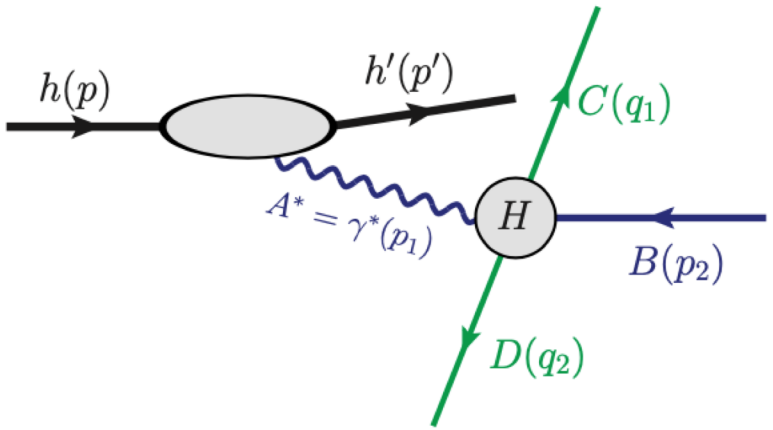
General Discussion on n=1 state: γ^*

❑ Exchange of a virtual photon:

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

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

$$J^\mu = \sum_{i\in q} Q_i\bar{\psi}_i\gamma^\mu\psi_i$$



$$F^\mu(p,p') = \langle h'(p')|J^\mu(0)|h(p)\rangle$$

$$= F_1^h(t)\,\bar{u}(p')\gamma^\mu u(p) + F_2^h(t)\,\bar{u}(p')\frac{i\sigma^{\mu\nu}p_{1\nu}}{2m_h}u(p)$$

Forbidden for $p \to n$ (or $n \to p$) transition GPDs
Or not allowed by H

Has a leading component , $F^+ \propto \mathcal{O}(Q)$, as h-h' fast along "+"

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

Leading power of $F\cdot\mathcal{H}$

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

Higher power than n=2 contribution, but, higher power in power of α_{EM}

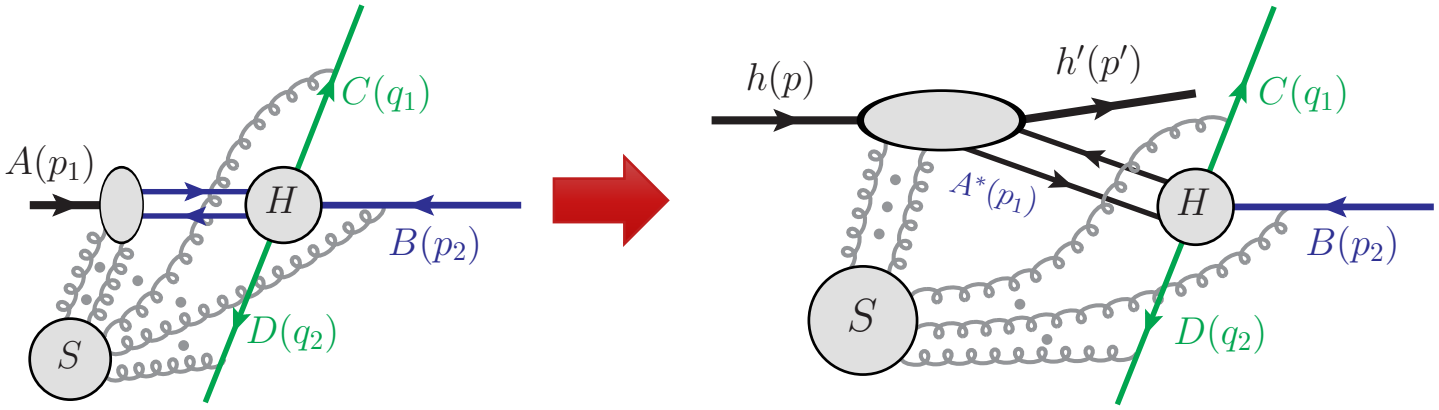
$$\mathcal{M}^{(2)} \sim \mathcal{O}(1/Q) \quad \longrightarrow \quad \mathcal{M}^{(1)}/\mathcal{M}^{(2)} \sim \mathcal{O}(Q/\sqrt{|t|})$$

If we neglect contribution from $n \geq 3$, $\mathcal{M}^{(1+2)}_{\rm SDHEP} \sim$ is up to corrections at $\mathcal{O}(\sqrt{|t|}/Q^2)$

Factorization in the Two-stage Paradigm

Qiu & Yu, 2205.07846 (JHEP in press)

❑ Factorization for 2-parton channel factorization:



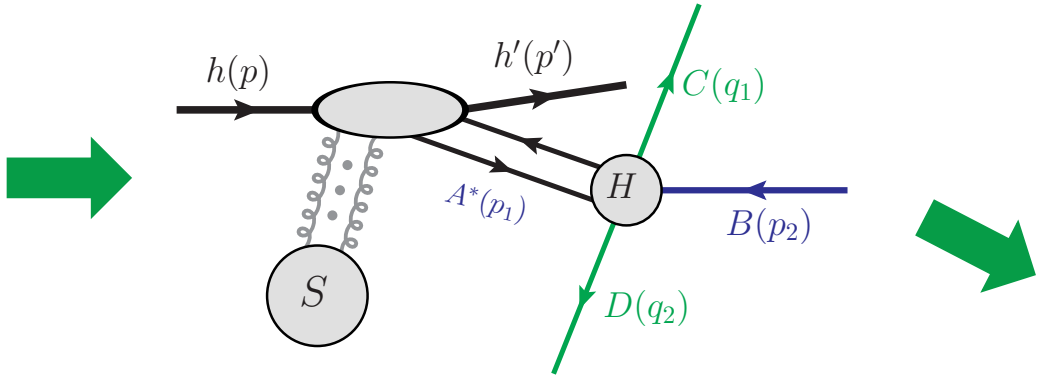
Only complication:

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

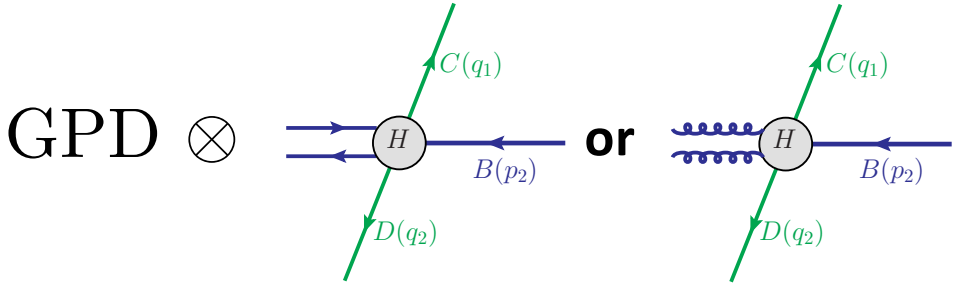
$$k_s^+ \mapsto k_s^+ \pm i\mathcal{O}(Q)$$

Glauber → h-collinear region

❑ Soft gluons cancel for the meson-initialized process if *C* and *D* are mesons:



Soft gluons are no longer pinched and can be deformed into h-collinear region



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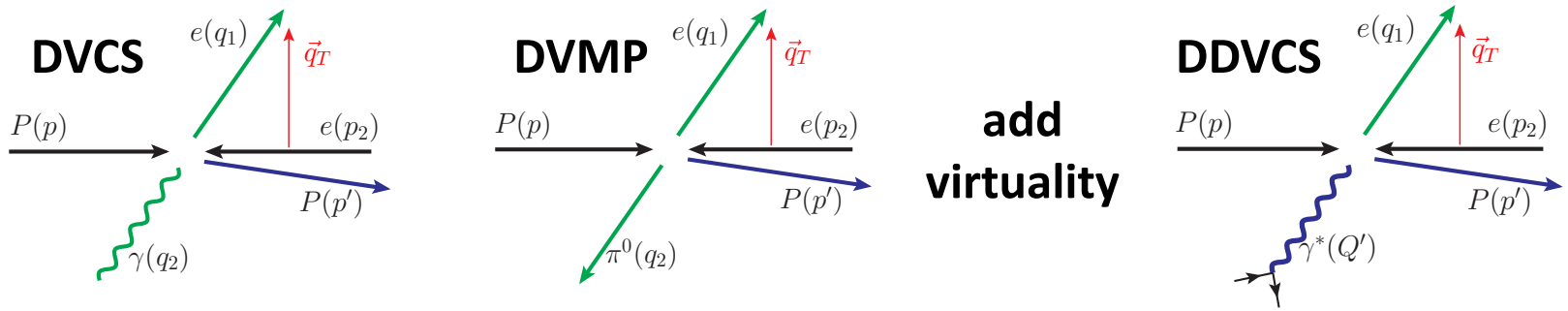
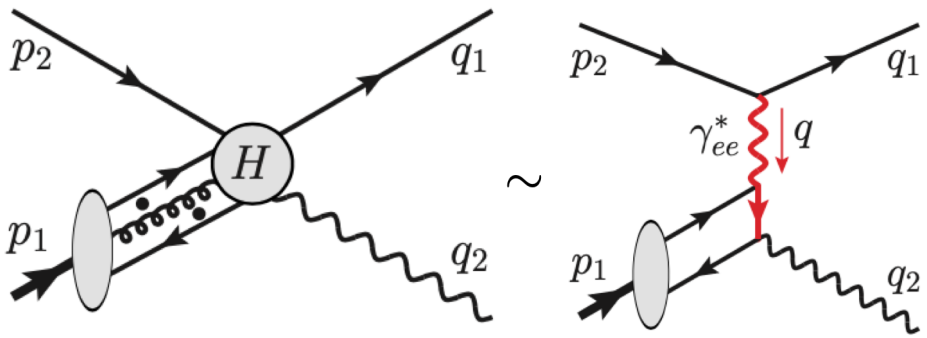
Electroproduction of Single Diffractive Hard Processes

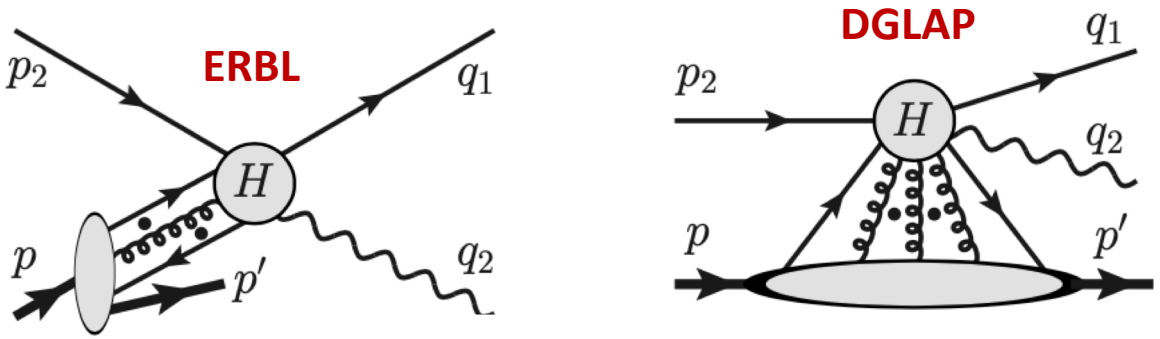
(JLab, EIC, …)



❑ **DVCS:** $h(p) = \text{Proton}(p),\ h'(p') = \text{Proton}(p'),\ B(p_2) = \text{electron}(p_2),\ C(q_1) = \text{electron}(q_1),\ D(q_2) = \text{photon}(q_2)$



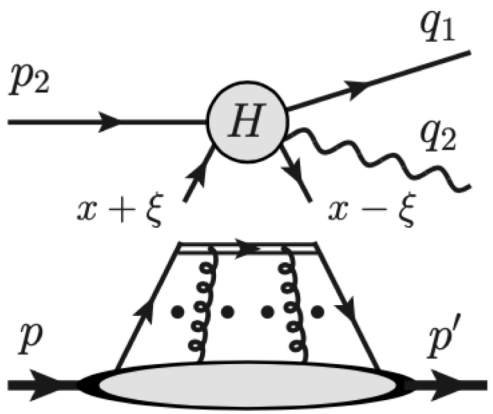
Stage-2:



Stage-1: $2 \to 2$ exclusive process

$$\mathcal{M}_{Me\to e\gamma} = \sum_i \int_0^1 \mathrm{d}z\, D_i(z)\, C_{ie\to e\gamma}(z, q_T)$$

$$\mathcal{M}^{(2)}_{he\to h'e\gamma} = \sum_i \int_{-1}^1 \mathrm{d}x\, F_i^h(x,\xi,t)\, C_{ie\to e\gamma}(x,\xi,q_T),$$



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

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

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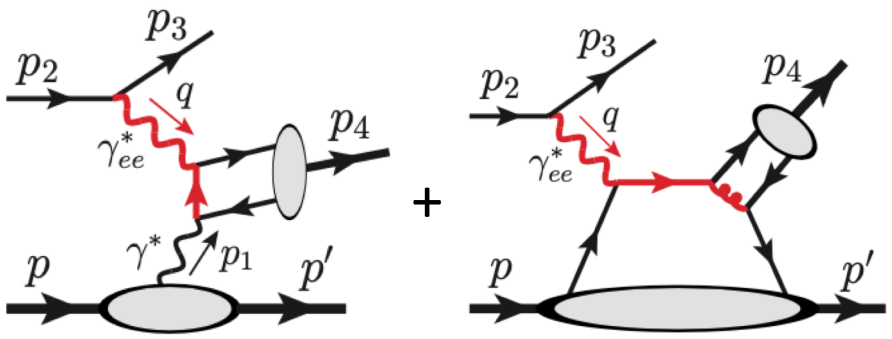
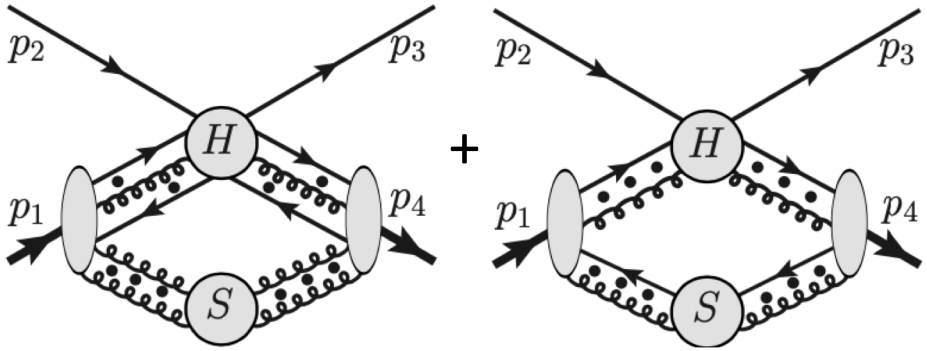
Electroproduction of Single Diffractive Hard Processes

- **DVMP:** $h(p) = \text{Proton}(p),\ h'(p') = \text{Proton}(p'),\ B(p_2) = \text{electron}(p_2),\ C(q_1) = \text{electron}(p_3),\ D(q_2) = \text{Meson}(p_4)$

  - **Leading order diagram:**



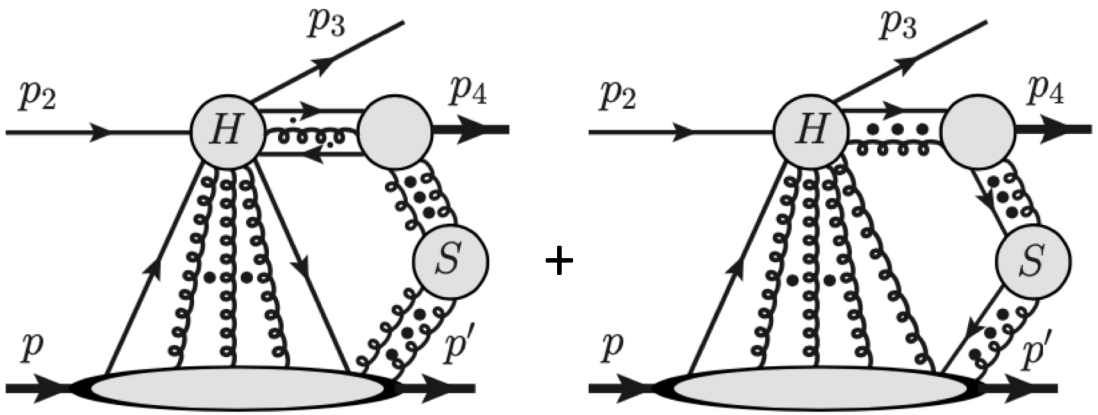
  - **Leading pinch surface:**



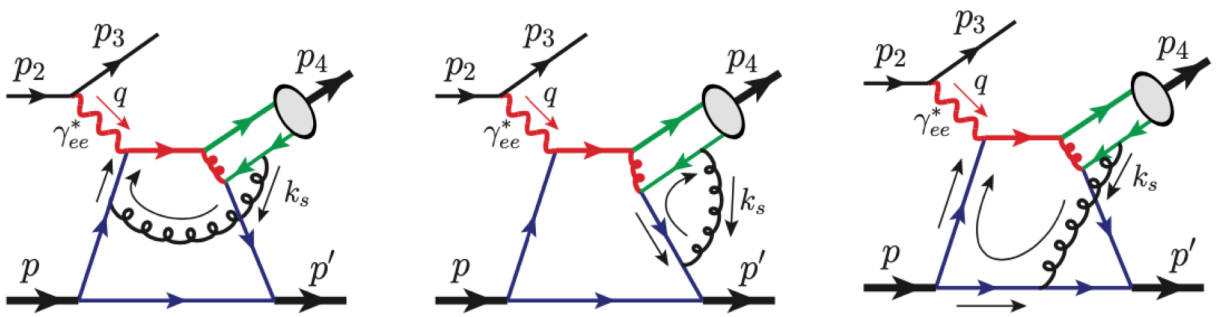
$$\mathcal{M}_{M_A e \to e M_D} = \sum_{i,j} \int_0^1 \mathrm{d}z_1\, \mathrm{d}z_2\, D_{i/A}(z_A) \times$$

$$\times\, C_{ie \to ej}(z_A, z_D, q_T)\, D_{j/D}(z_D)$$

  - **SDHEP – Leading region:**



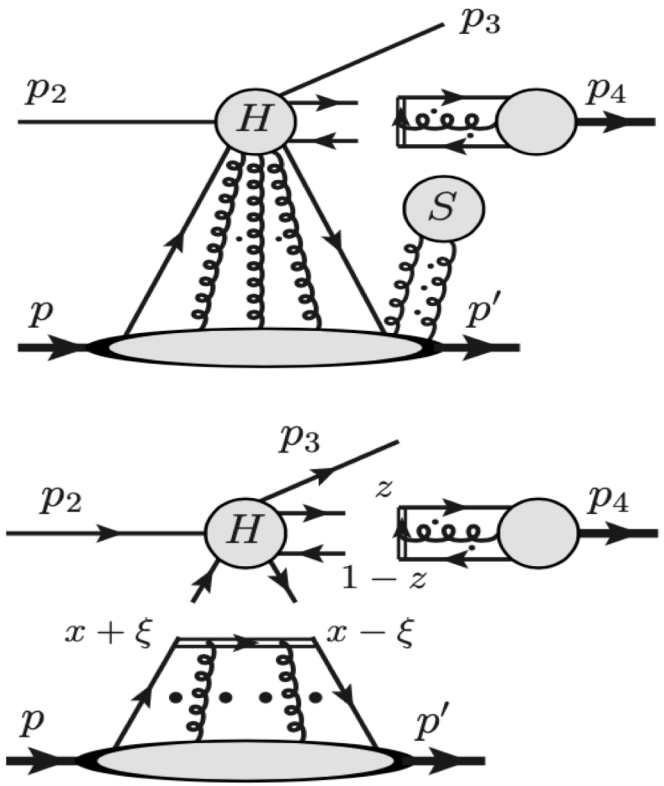
  - **SDHEP – sample diagrams:**



Electroproduction of Single Diffractive Hard Processes

- **DVMP:** $h(p) = \text{Proton}(p),\ h'(p') = \text{Proton}(p'),\ B(p_2) = \text{electron}(p_2),\ C(q_1) = \text{electron}(p_3),\ D(q_2) = \text{Meson}(p_4)$

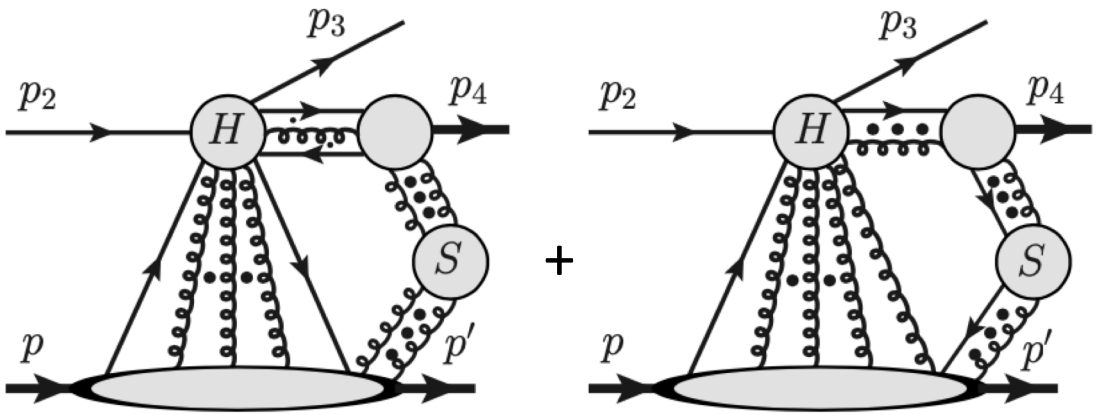
- **Factorization:**



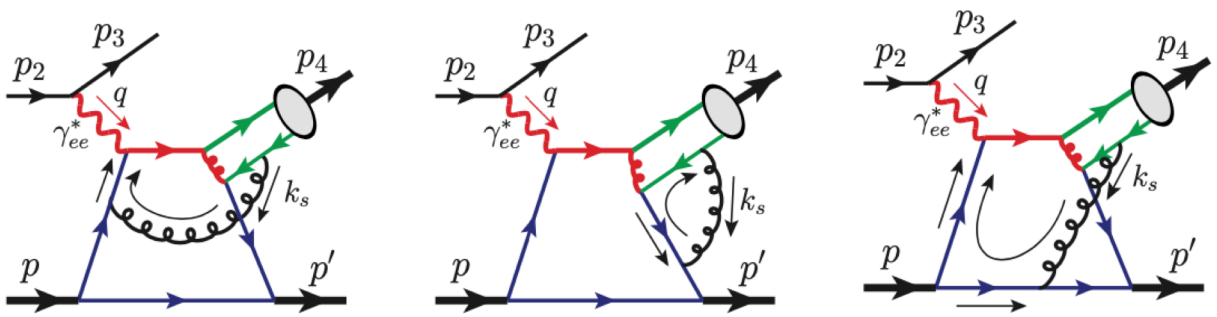
$$\mathcal{M}_{he\to h'eM} = \sum_{i,j} \int_{-1}^{1} \mathrm{d}x \int_{0}^{1} \mathrm{d}z$$

$$\times\, F_i^{hh'}(x,\xi,t)\, C_{ie\to ej}(x,\xi;z_D;q_T)\, D_{j/D}(z_D)$$

- **SDHEP – Leading region:**



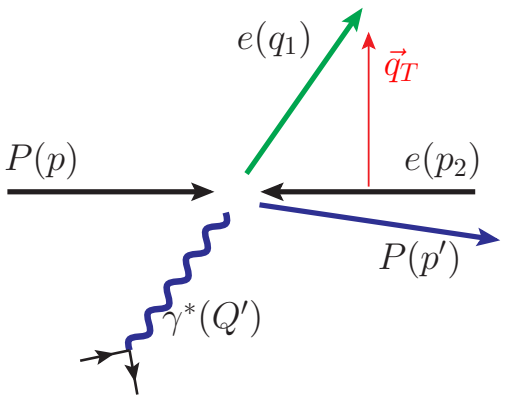
- **SDHEP – sample diagrams:**



Electroproduction of Single Diffractive Hard Processes

❑ DDVCS:

$$h(p) = \text{Proton}(p),\ h'(p') = \text{Proton}(p'),\ B(p_2) = \text{electron}(p_2)$$
$$C(q_1) = \text{electron}(q_1),\ D(q_2) = \gamma^*[\to e^+e^-](q')$$



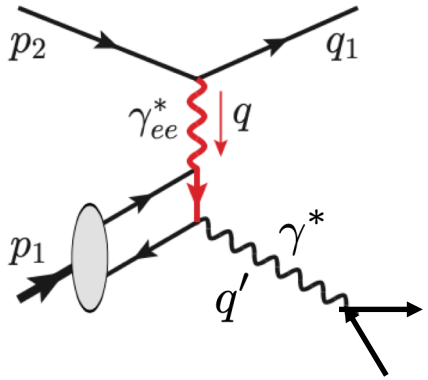
Factorization: Can be factorized in the same way as DVCS!

❑ Heavy meson production (high q_T):

Factorization could be valid if p_T >> m_Q, not sure for other regions.

❑ The x-dependence on GPDs:

As explained earlier, the type of DVCS and DVMP processes only sensitive to: $\int_{-1}^{1} dx \frac{F(x,\xi,t)}{x-\xi \pm i\varepsilon}$

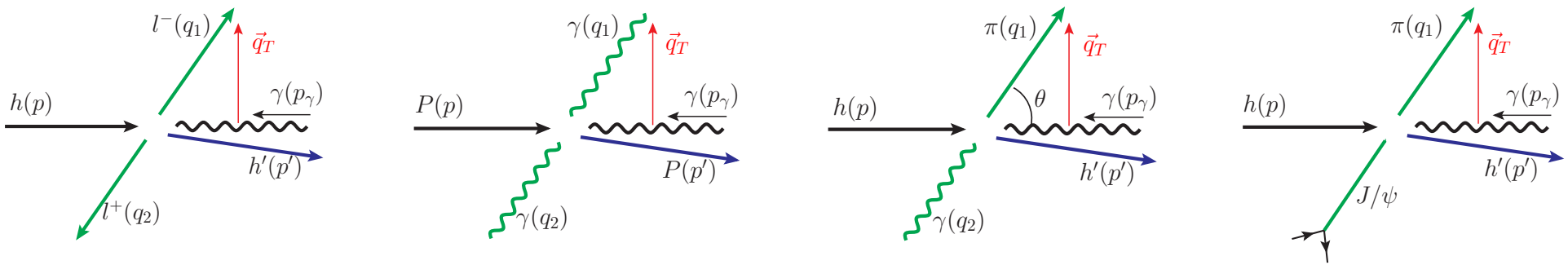


For DDVCS: **Transverse momentum flow from the final-state lepton and the virtual photon is sensitive to the virtuality of the dilepton**

$$Q'^2 \equiv q'^2 = \left(\frac{2\xi}{x_B(1+\xi)} - 1\right)$$

Direct sensitive to external variable, x_B, directly sensitive to q_T

Photoproduction of Single Diffractive Hard Processes



(JLab Hall-D, …)

- **Dilepton & Diphoton production:**

A. Pedrak, et al. Phys.Rev.D96 (2017)074008, …

Both n=1 and n=2 should contribution, and factorizable

- **Real photon + meson production:**

G. Duplancic, et al. JHEP 11 (2018) 179, …

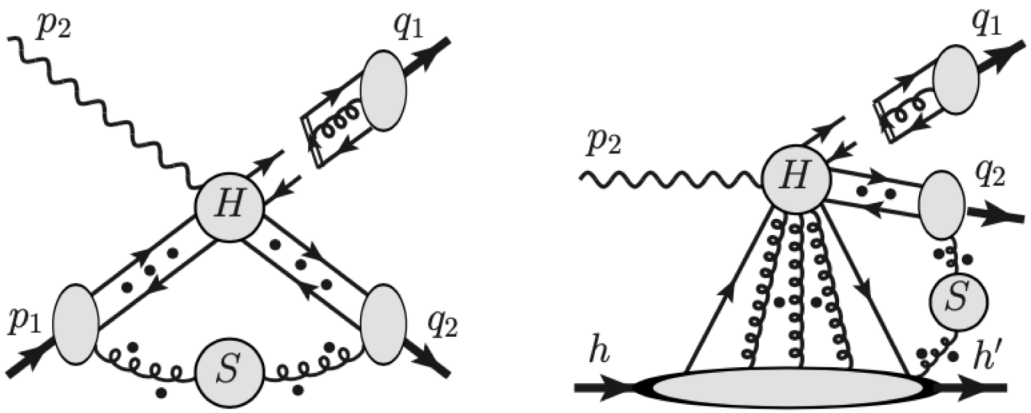
The n=1 channel is forbidden for a charge meson: $\pi^{\pm}$, or transversely polarized vector meson, ρ_T,

but, allowed for the production of a longitudinally polarized vector meson like ρ_L.

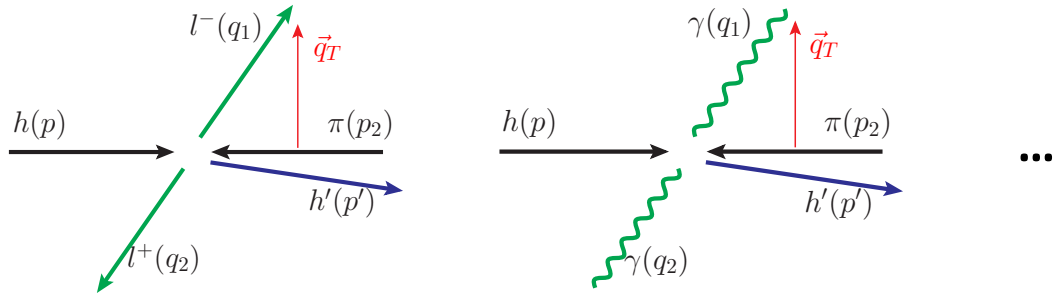
Factorization arguments are the same as that for DVMP.

- **Light meson pair production:**

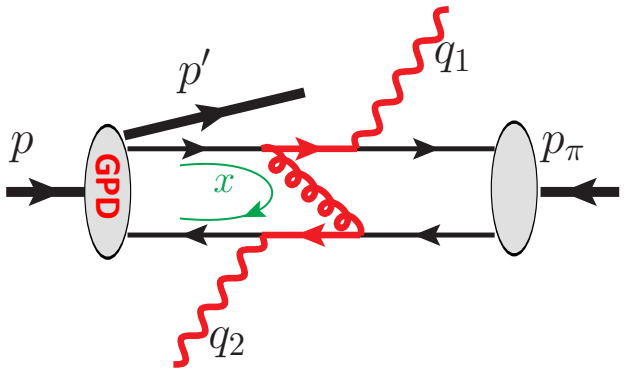
$$\mathcal{M}_{h\gamma\to h' M_C M_D} = \sum_{i,j,k} \int_{-1}^{1} \mathrm{d}x \int_0^1 \mathrm{d}z_C\, \mathrm{d}z_D\; F_i^{hh'}(x,\xi,t) \times C_{i\gamma\to jk}(x,\xi;z_C,z_D;q_T)\, D_{j/C}(z_C)\, D_{k/D}(z_D)$$



Meson-initiated Single Diffractive Hard Processes



(AMBER, J-PARC, ...)



❑ Two-photon production: $\pi^-(p_\pi) + P(p) \to \gamma(q_1) + \gamma(q_2) + N(p')$

- **Kinematical observables:**

t, ξ, q_T

- $t = (p - p')^2$
- $\xi = (p^+ - p'^+)/(p^+ + p'^+)$

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

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

- **Factorization:**

[suppressing DA factor]

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

$x \leftrightarrow q_T$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t\ \mathrm{d}\xi\ \mathrm{d}q_T} \sim |\mathcal{M}(t, \xi, q_T)|^2$$

q_T **distribution is "conjugate" to** x **distribution**

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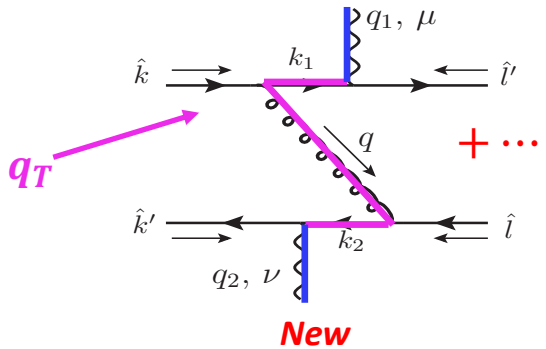
Meson-initiated Single Diffractive Hard Processes

❑ Hard part for A-type:



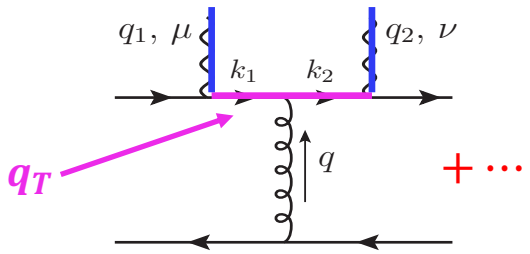
$\kappa = 4\,q_T^2/\hat{s}$

- **Gluon propagator** $$q^2 = -\frac{\hat{s}}{4}\left[\left(2z_1 - 1 - \sqrt{1-\kappa}\right)\left(2z_2 - 1 - \sqrt{1-\kappa}\right) + \kappa\right]$$

$$\Rightarrow \quad \mathcal{M} \propto \int_0^1 \mathrm{d}z_1\,\mathrm{d}z_2\,\frac{\phi(z_1)\phi(z_2)}{(1-z_1)\,(1-z_2)\left[\left(2z_1 - 1 - \sqrt{1-\kappa}\right)\left(2z_2 - 1 - \sqrt{1-\kappa}\right) + \kappa\right]}$$

- **Change q_T changes the z_1-z_2 integral.**
- **$\mathrm{d}\sigma/\mathrm{d}q_T^2$ provides sensitivity to the DA's functional form of z.**

❑ Hard part for B-type:



Like "time-like" form factor

- **Gluon propagator** $$q^2 = z_2(1-z_1)\hat{s}$$

$$\Rightarrow \quad \mathcal{M} \propto \int_0^1 \mathrm{d}z_1\,\mathrm{d}z_1\,\frac{\phi(z_1)\phi(z_2)}{z_1\,(1-z_1)\,z_2\,(1-z_2)} \sim \left[\int_0^1 \mathrm{d}z\,\frac{\phi(z)}{z\,(1-z)}\right]^2$$

- ***Not* sensitive to DA functional form.**
- **Relies on $\phi(z) = 0$ at end points.**
- **Sudakov resummation could suppress the end-point sensitivity.**

Li, Sterman, 1992

Numerical results

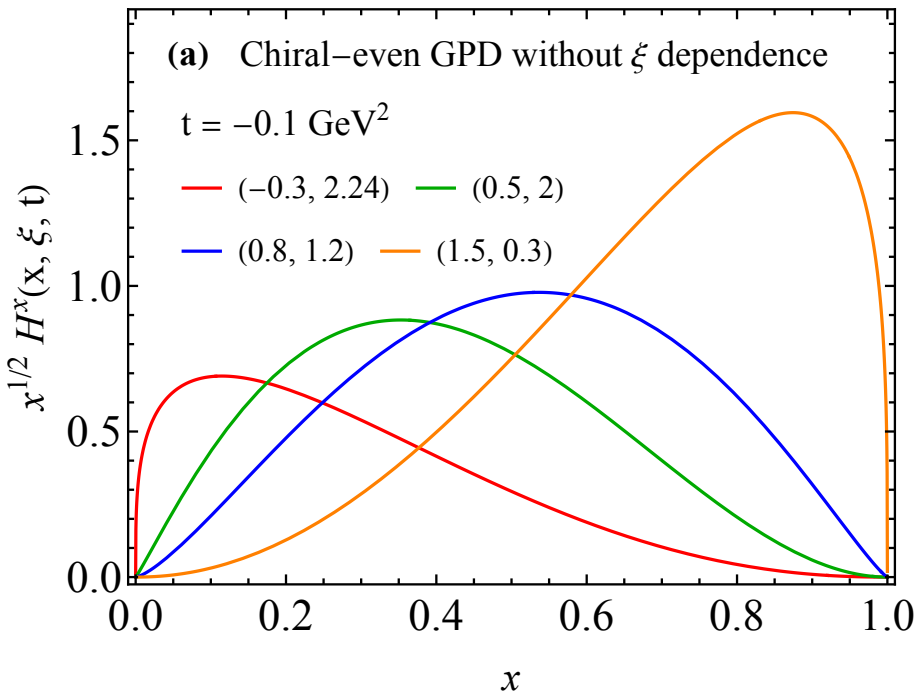
❑ GPD models – simplified GK model:

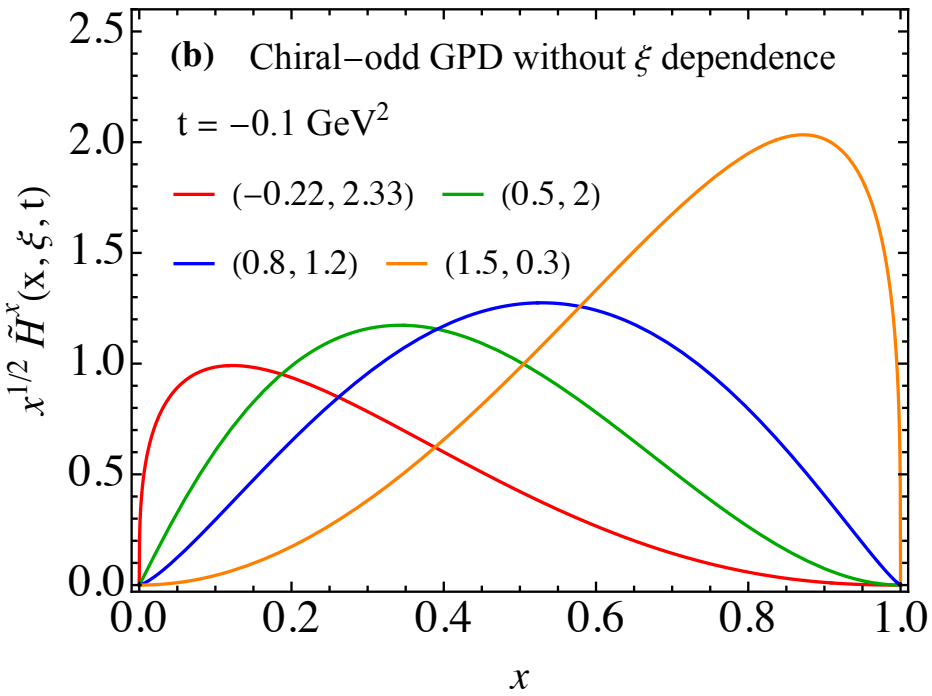
Goloskokov, Kroll
hep-ph/0501242
arXiv: 0708.3569
arXiv: 0906.0460

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

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

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





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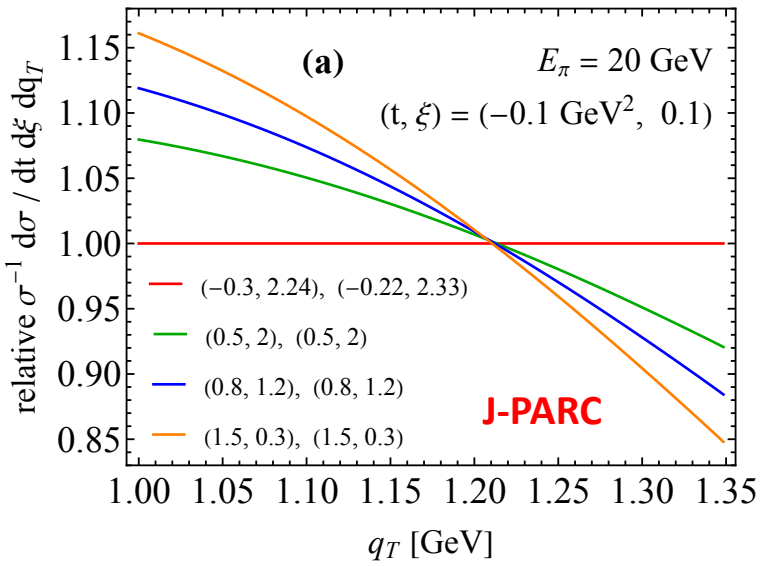
Numerical results

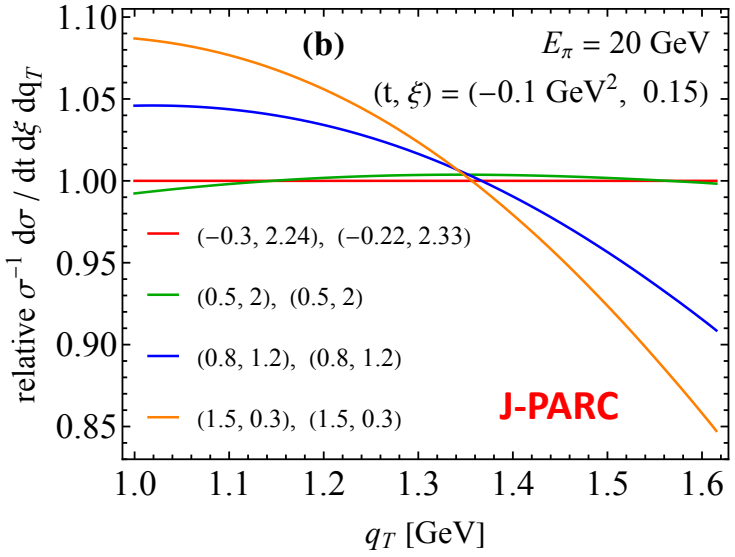
$$\frac{\mathrm{d}\sigma}{\mathrm{d}t\,\mathrm{d}\xi\,\mathrm{d}q_T} \sim |H(x,\xi,t)|^2$$

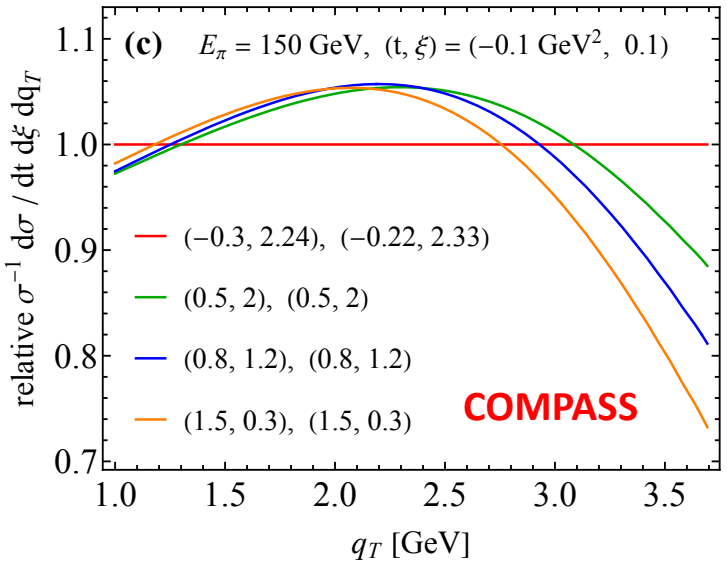
Relative q_T shape

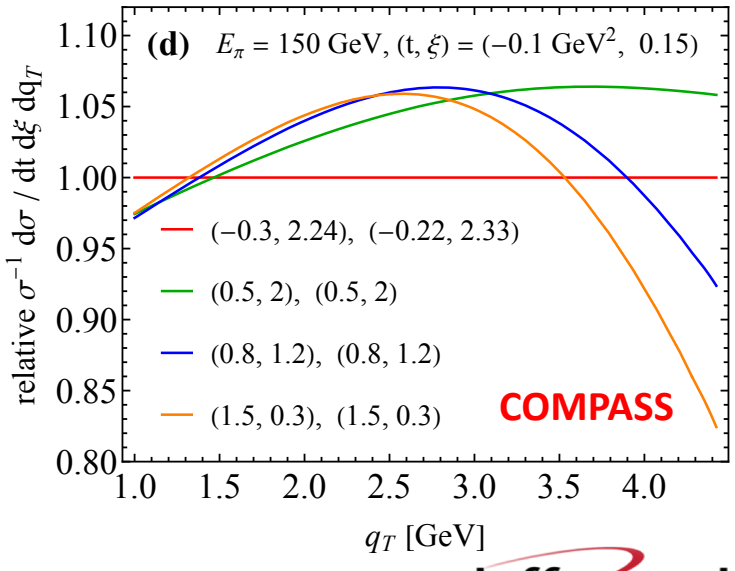
$$\frac{\sigma_{\mathrm{tot}}^{-1}\mathrm{d}\sigma/\mathrm{d}q_T}{\text{some shape func}}$$

$$\sigma_{\mathrm{tot}} = \int_{1\ \mathrm{GeV}}^{\sqrt{\hat{s}}/2} \mathrm{d}q_T \frac{\mathrm{d}\sigma}{\mathrm{d}t\mathrm{d}\xi\mathrm{d}q_T}$$









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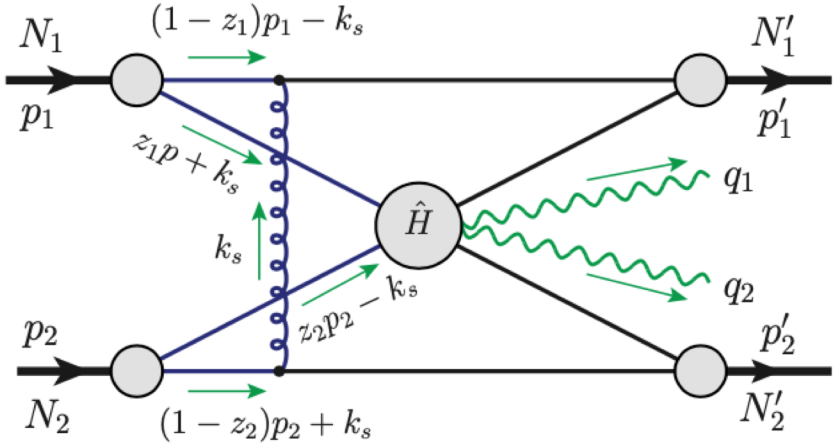
Discussion

❑ Why single-diffractive?

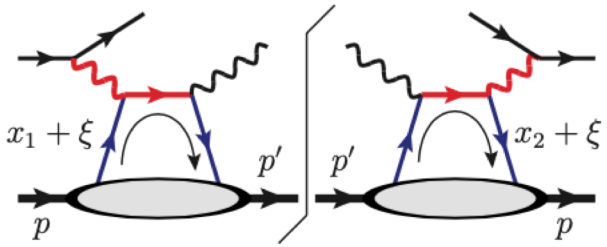
We need diffractive process to keep proton intact.

But, double diffractive process is not factorizable!

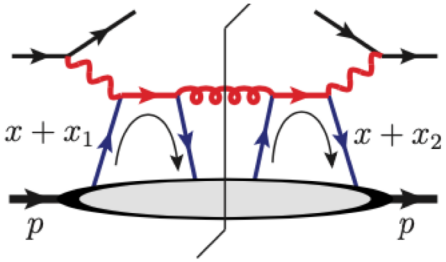


❑ Connection to high-twist inclusive production:

DVCS



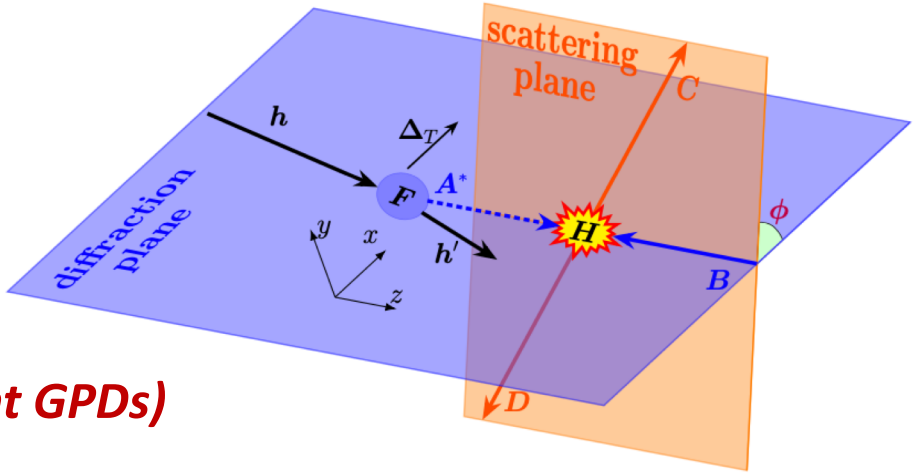
Twist-4 DIS



Not sensitive to the loop momentum fraction: x_i

❑ More opportunities:

- Diffractive plane
- Exclusive hard scattering plane
- Angular modulation between the two planes



➡ *Selection from different exchange state A* (or different GPDs)*

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Summary and Outlook

- **Understanding the emergency of nucleon mass is a challenge:**
  - Mass is closely related to QCD trace anomaly and chiral symmetry breaking
  - Mass decomposition to matrix elements of quark/gluon fields is not unique
  - Single hadron matrix element of quark/gluon field operator is not physical observable

  Extract each of them from experimental observable(s) with controllable approximation - factorization

- **Introduced the diffractive $2 \to 3$ exclusive hard processes for extracting GPDs, …**
  - Provide both necessary and sufficient conditions for leading power factorization
  - Including existing/known processes for extracting GPDs, ..
  - Identify new factorizable exclusive processes for GPDs more sensitive to their x-dependence
  - Angular modulation between diffractive plane and hard scattering plane could provide unique opportunity to separate various GPDs

  Introduce a path forward to identify more factorizable exclusive processes for extracting GPDs, and multi-parton correlations, …

Thanks!