Workshop: Precision QCD Predictions for ep Physics at the EIC (II)

Sep 18 – 22, 2023
CFNS, Stony Brook University

Explore Proton's Quark/Gluon Structure at the EIC without Breaking it

- **Challenges:**

  QCD at femto-scale (0.1fm-10fm) – Seeing quarks and gluons inside a proton without breaking it

- **Factorization:**

  Extracting the proton's internal distributions of quarks and gluons from data of lepton-hadron collisions

- **Nuclear femtography:**

  Pixelating the spatial distribution of quarks and gluons inside a proton in slices of the momentum fraction x

- **Summary and Outlook**

In collaboration with Zhite Yu, Nobuo Sato, … and the QuantOm Collaboration (a SciDAC project)

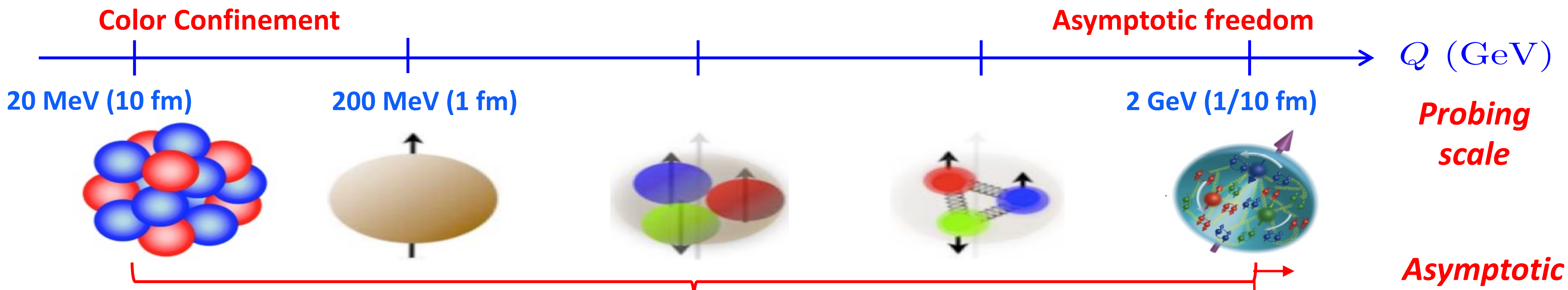
Jianwei Qiu
Jefferson Lab, Theory Center

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

QCD Landscape of Nucleons and Nuclei



QCD at the Fermi Scale: Femto-science (0.1-10 fm)

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

Asymptotic regime PQCD works beautifully!

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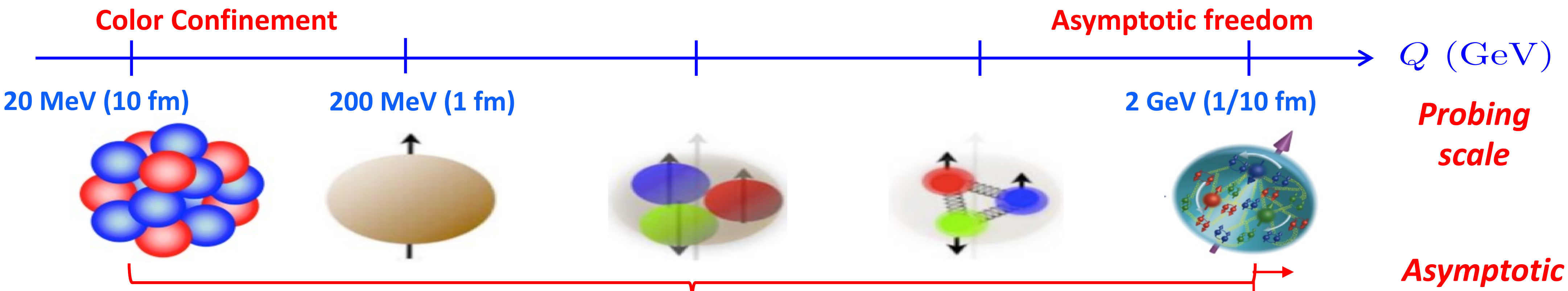

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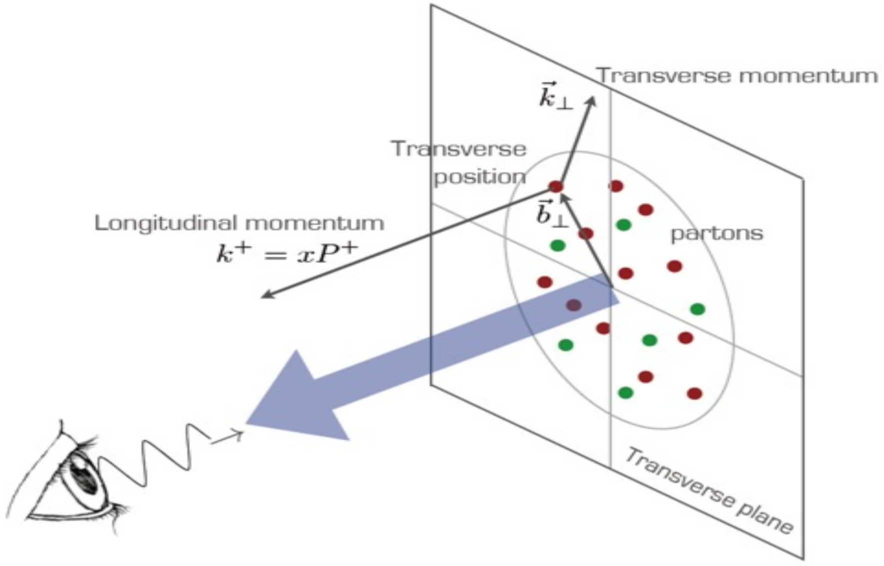
❑ Need new observables with two distinctive scales:

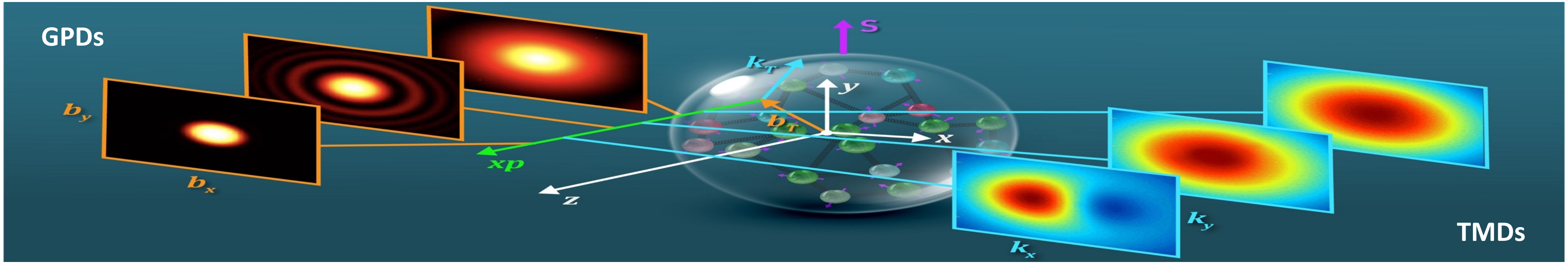
$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\text{QCD}}$$

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



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

❑ 3D hadron structure:



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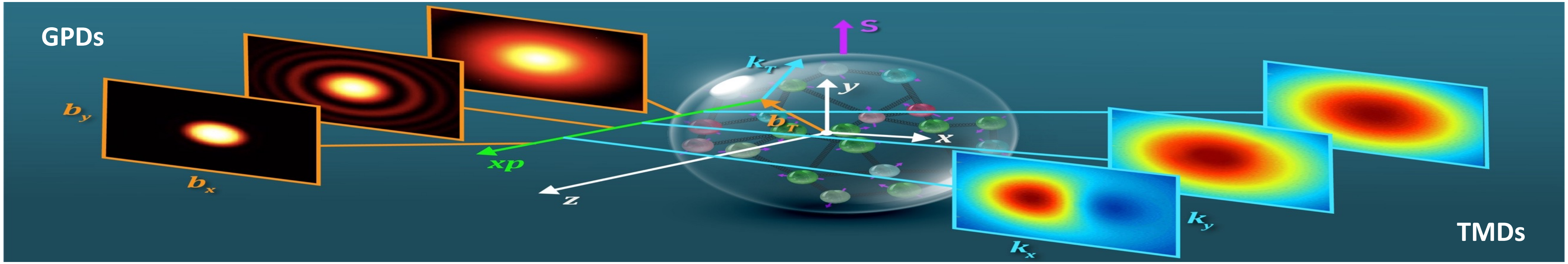

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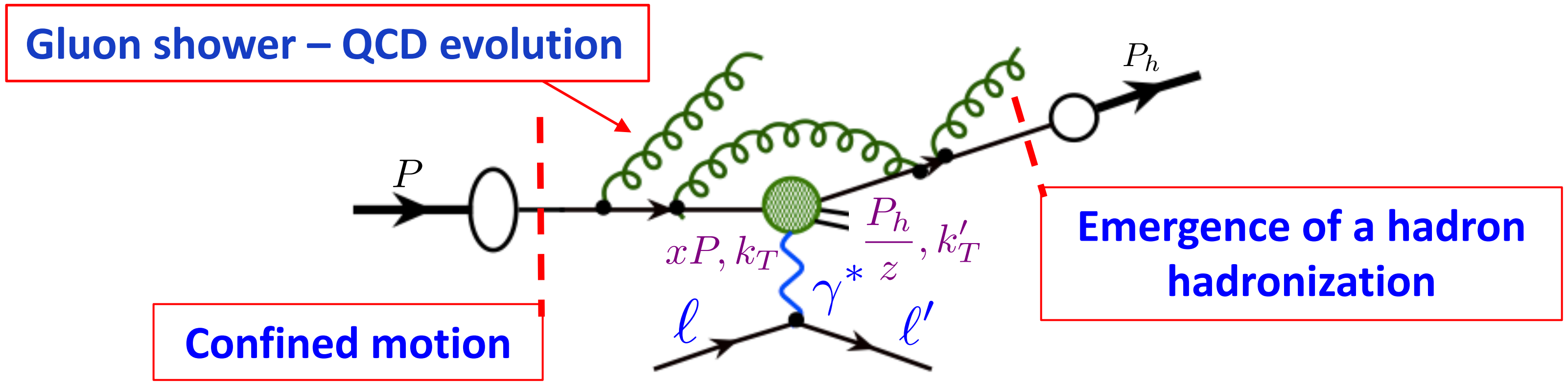

- *Measured k_T is NOT the same as k_T of the confined motion!*
- *Too larger Q^2 could weaken our precision to probe the true hadron structure!*

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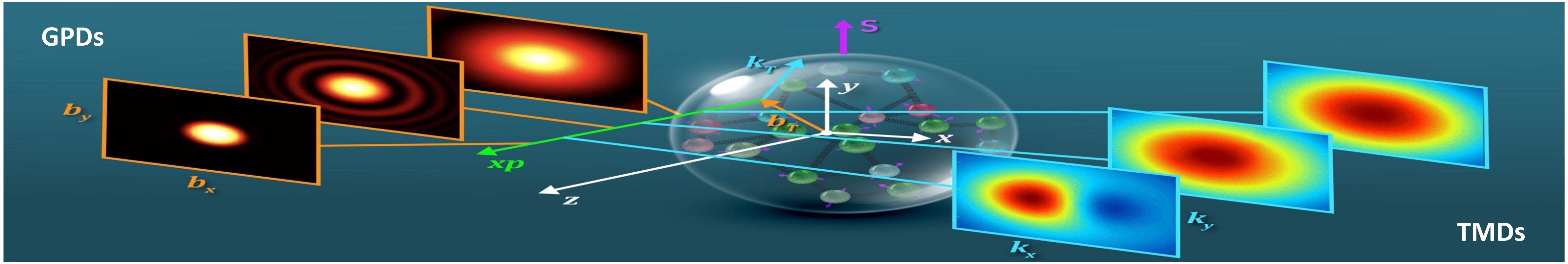

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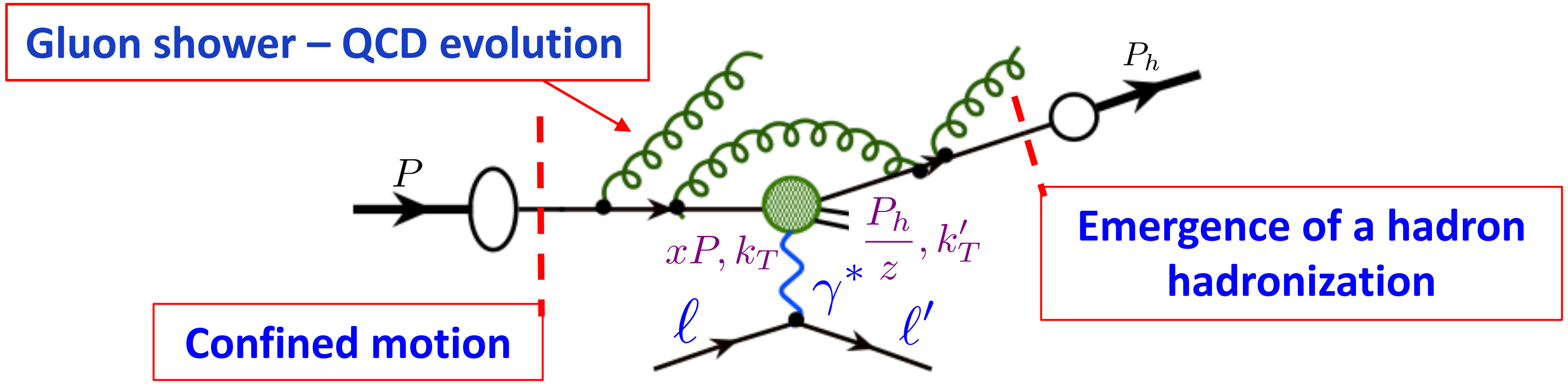


Transverse momentum Broadening from the shower:

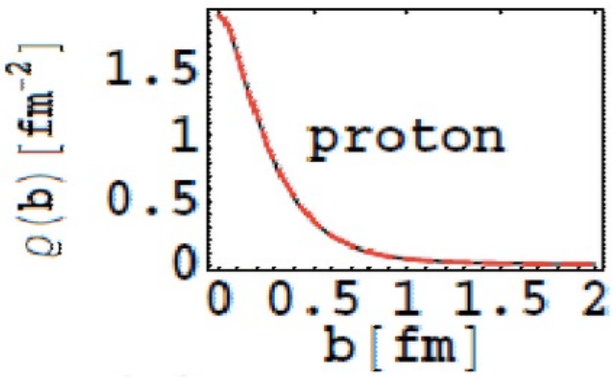
$$\Delta k_T^2 \propto \Lambda_{\rm QCD}^2 \times \alpha_s(C_F, C_A) \times \log(Q^2/\Lambda_{\rm QCD}^2) \times \log(s/Q^2) \quad \Big\} \gtrsim 1$$

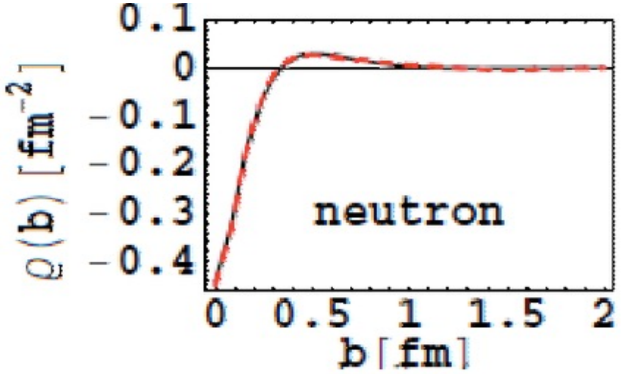
Structure information can be diluted by the collision induced shower!

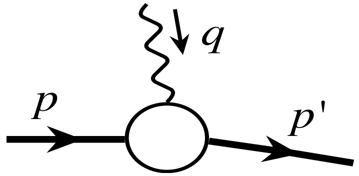
- *Measured k_T is NOT the same as k_T of the confined motion!*
- *Too larger Q^2 could weaken our precision to probe the true hadron structure!*

Challenges for Exploring Internal Structure of Hadron without Breaking it

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

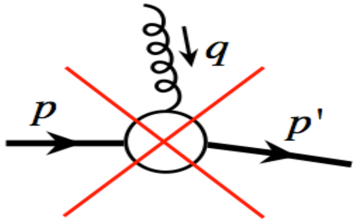






Proton "Radius"
in EM charge distribution

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



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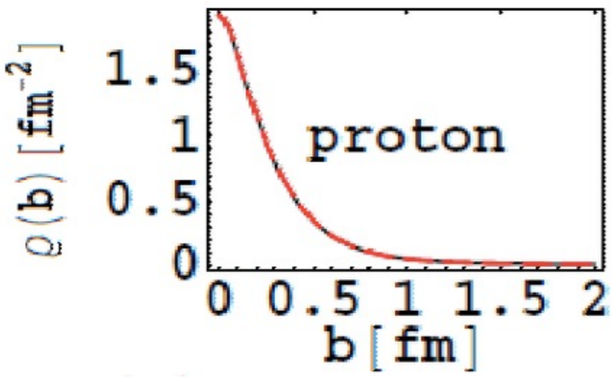

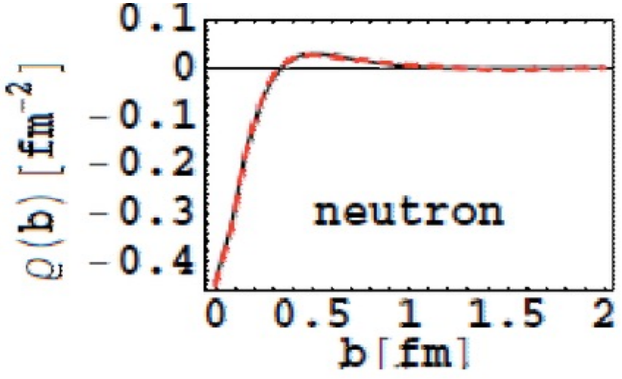

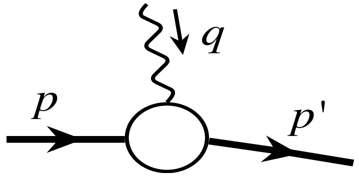

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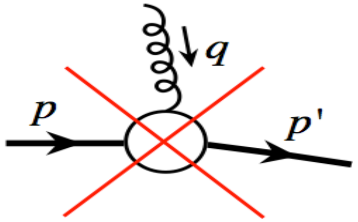

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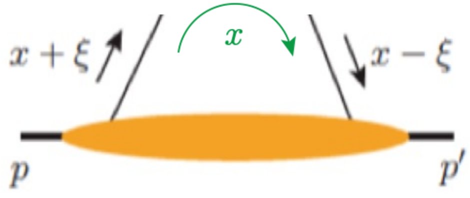
- **3D hadron tomography:**

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

Generalized PDFs (GPDs) – without breaking the proton

$$F_{q/h}(x,\xi,t) \qquad \text{skewness} \quad \xi = \frac{(p-p')^+}{(p+p')^+} \quad t = (p-p')^2$$



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

F.T. to get spatial distribution of quark/gluon density, quark/gluon correlations, …

Generalized Parton Distributions (GPDs)

D. Müller, D. Robaschik, B. Geyer, F.-M. Dittes, J. Hořejši, *Fortsch. Phys.* 42 (1994) 101

❑ Definition:

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

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

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

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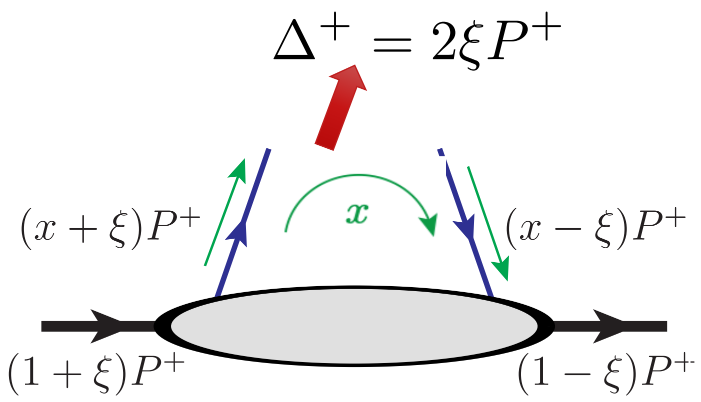

$$P^+ = \frac{p^+ + p'^+}{2}$$

$$\Delta = p - p' \qquad t = \Delta^2$$

Similar definition for gluon GPDs

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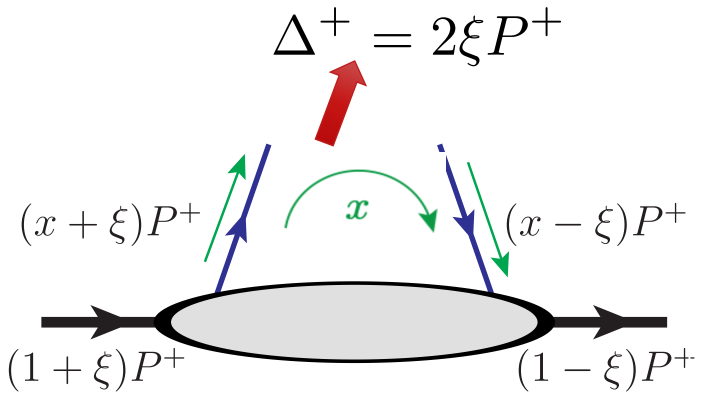

$$P^+ = \frac{p^+ + p'^+}{2}$$

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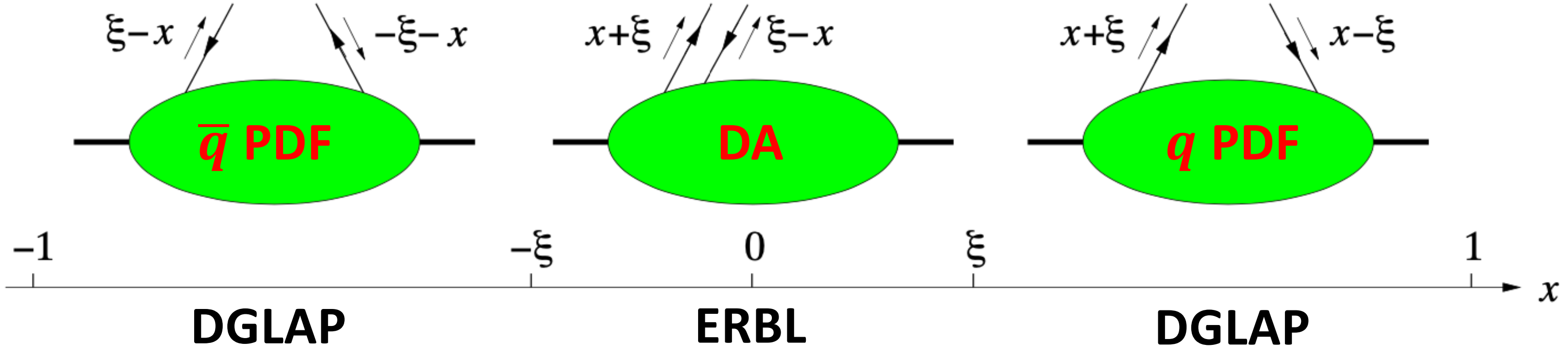
Similar definition for gluon GPDs

❑ 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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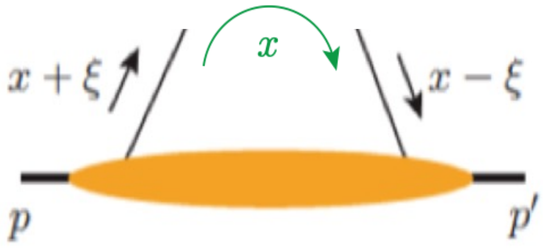
Properties of GPDs - I

❑ **Impact parameter dependent parton density distribution:**

$$q(x, b_\perp, Q) = \int d^2\Delta_\perp e^{-i\Delta_\perp \cdot b_\perp} H_q(x, \xi = 0, t = -\Delta_\perp^2, Q)$$

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



Measurement of p' fixes (t, ξ)

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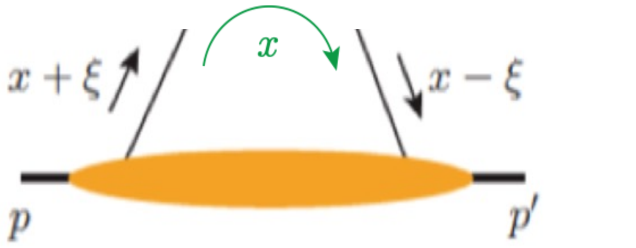

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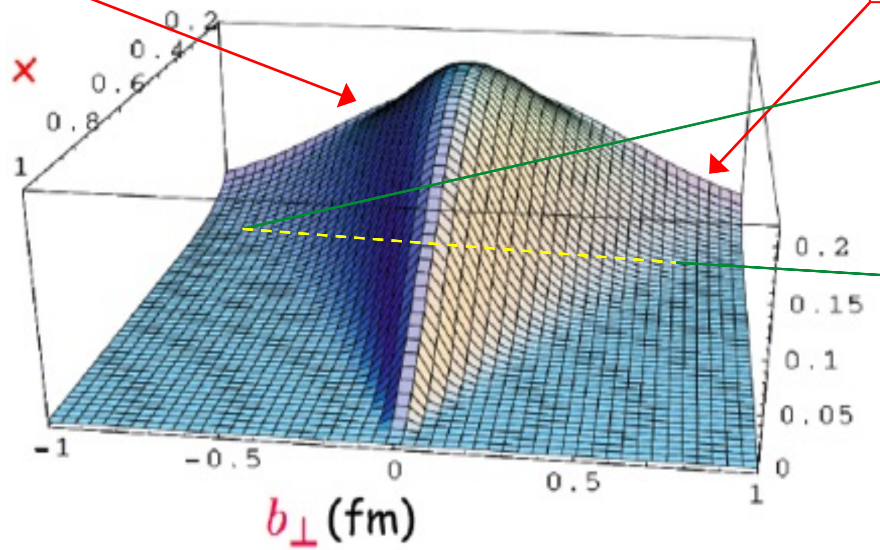
How fast does glue density fall?

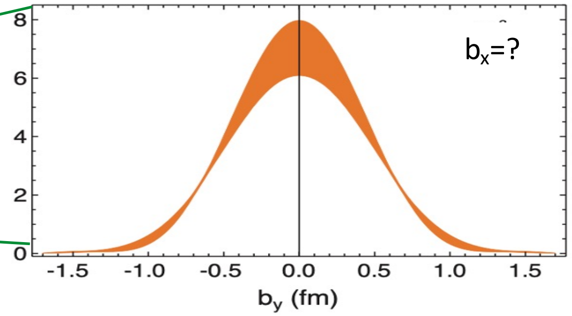
Tomographic image of hadron in slice of x

How far does glue density spread?

➡



Modeled by M. Burkdart, PRD 2000



Slice in (x,Q)

$$\langle q_\perp^N \rangle \equiv \int db_\perp b_\perp^N \, q(x, b_\perp, Q)$$

➡ **Proton radii from quark and gluon spatial density distribution,** $r_q(x)$ **&** $r_g(x)$

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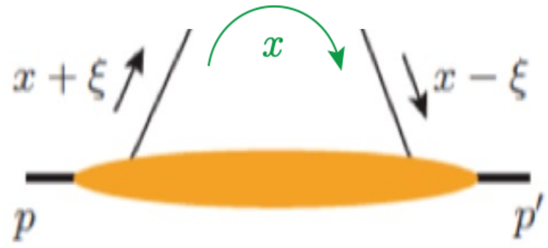

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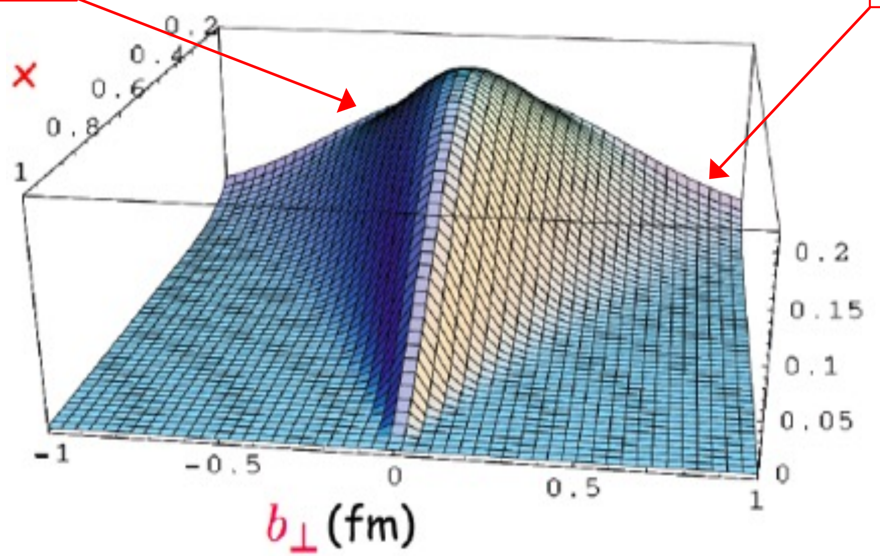

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➡ **Proton radii from quark and gluon spatial density distribution, $r_q(x)$ & $r_g(x)$**

- **Should $r_q(x)$ > $r_g(x)$, or vice versa?**
- **Could $r_g(x)$ saturates as $x \to 0$**
- **How do they compare with known radius (EM charge radius, mass radius, …), & why?**
- **How the image correlate to hadron spin, … ?**
- …

Properties of GPDs - II

❑ QCD energy-momentum tensor:

Ji, PRL78, 1997

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

❑ "Gravitational" form factors:

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

❑ Connection to GPD moments:

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

$C_i(t) \leftrightarrow D_i(t)/4$

Related to pressure & stress force inside h

Polyakov, schweitzer, Inntt. J. Mod. Phys. A33, 1830025 (2018)
Burkert, Elouadrhiri , Girod Nature 557, 396 (2018)

❑ Angular momentum sum rule:

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

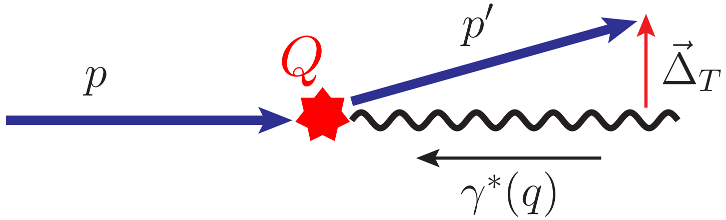
$i = q, g$

➡ **3D tomography**
Relation to GFF
Angular Momentum ➡ ***x*-dependence of GPDs!**

Need to know the x-dependence of GPDs to construct the proper moments!

Exclusive Diffractive Processes for Extracting GPDs

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



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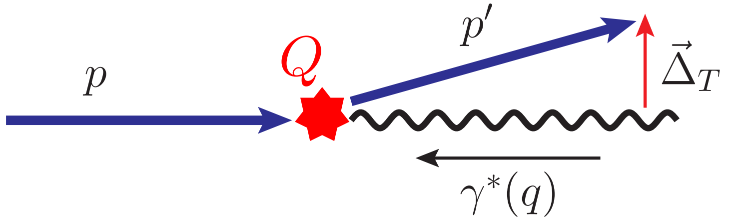

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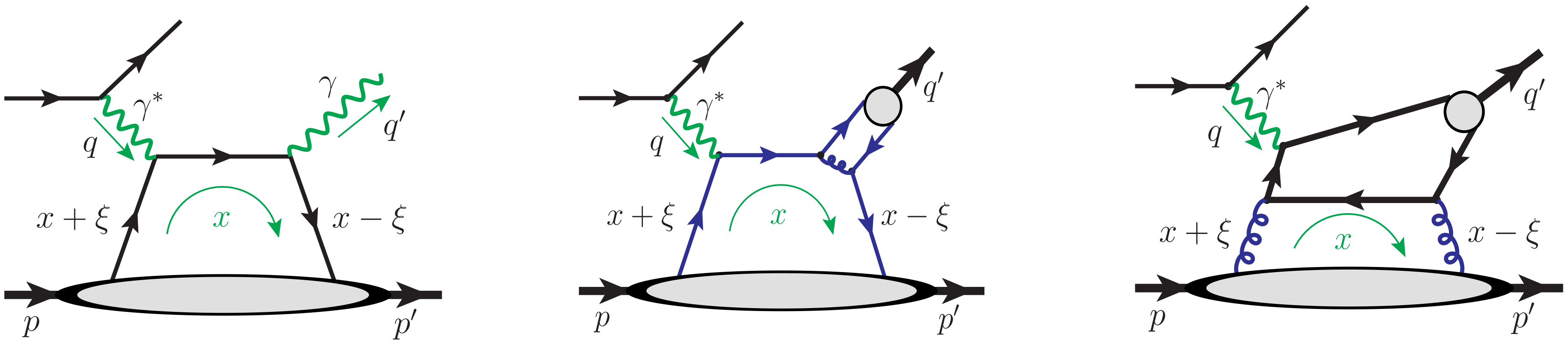
- ❑ **Known exclusive processes for extracting GPDs:**



DVCS: Q^2 >> |t| **DVMP** **DVQP**

+ DDVCS, …

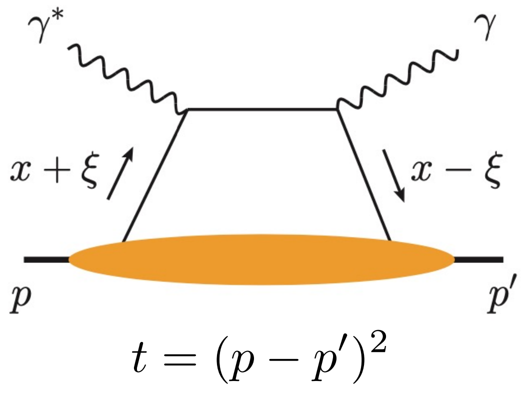
Feature: Two-scale observables $Q^2 \gg |t|$ $t = (p - p')^2$

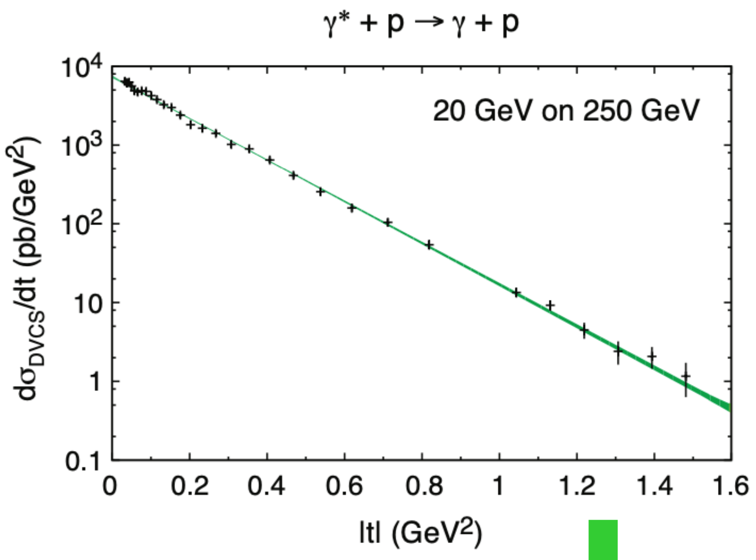
- **Hard scale Q: allows pQCD, factorization**
- **Low scale t: probes non-pert. hadron structure**

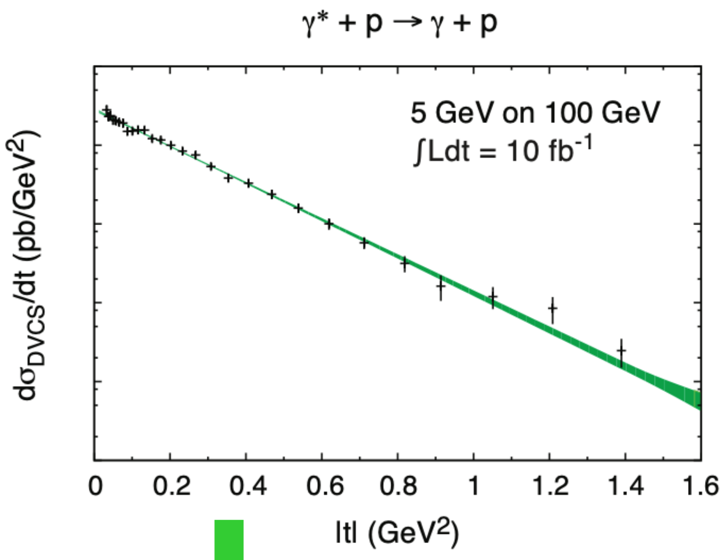
Factorization → **GPDs:** $f_{i/h}(x, \xi, t; \mu)$

Imaging the quarks at a Future EIC (White Paper)

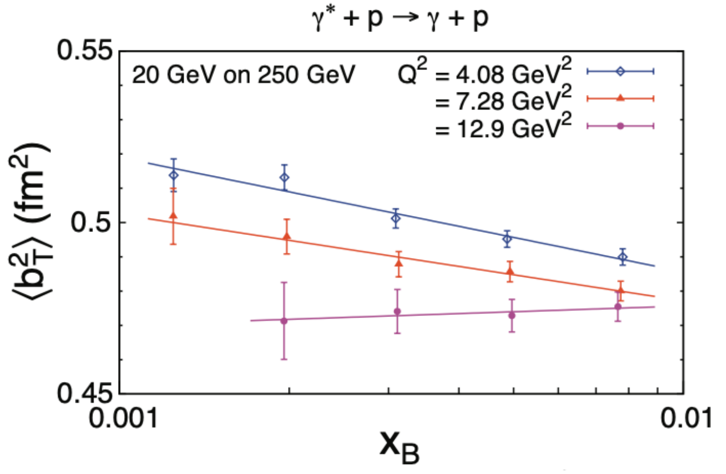
DVCS Cross Sections:

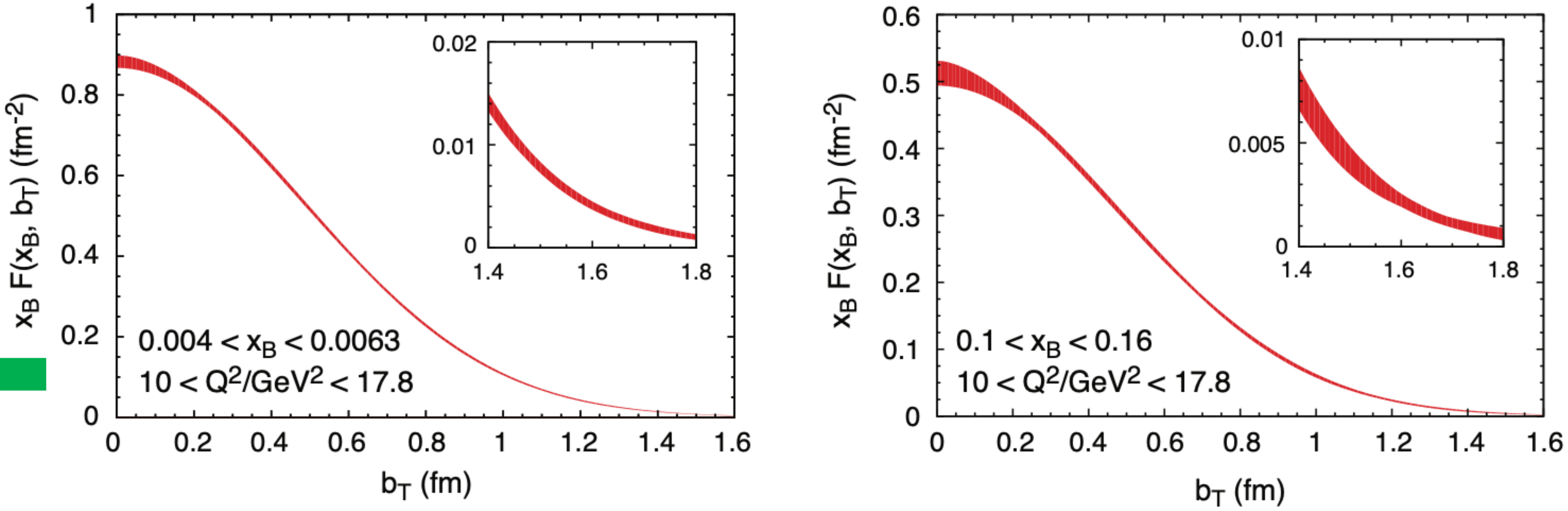






Spatial distributions:

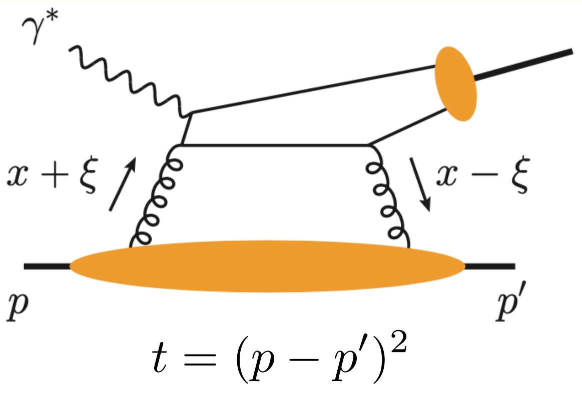


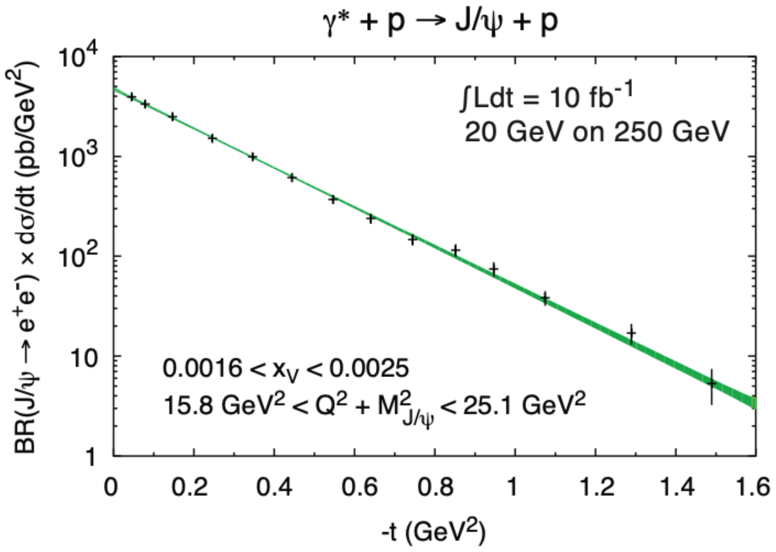


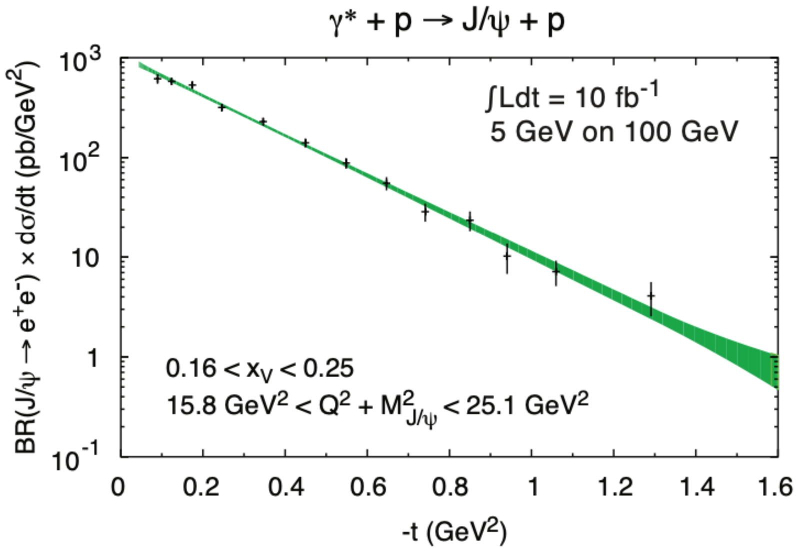
Effective "proton radius" in terms of quark distributions as a function of x_B

Imaging the gluons at the EIC (White Paper)

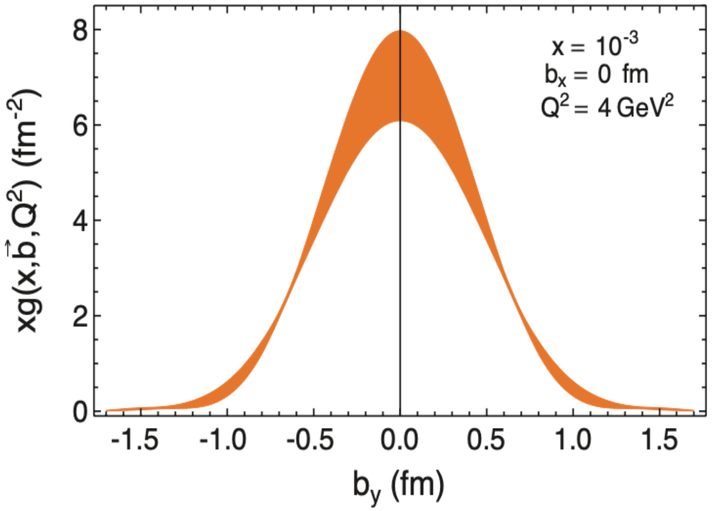
❑ Exclusive vector meson production:

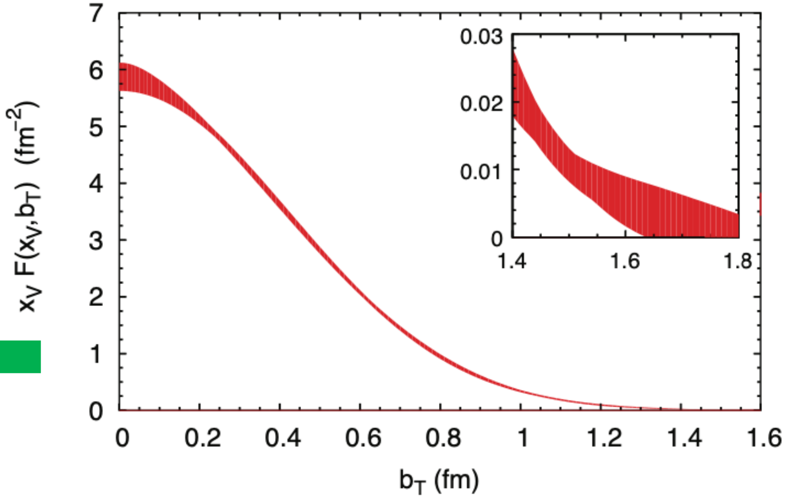


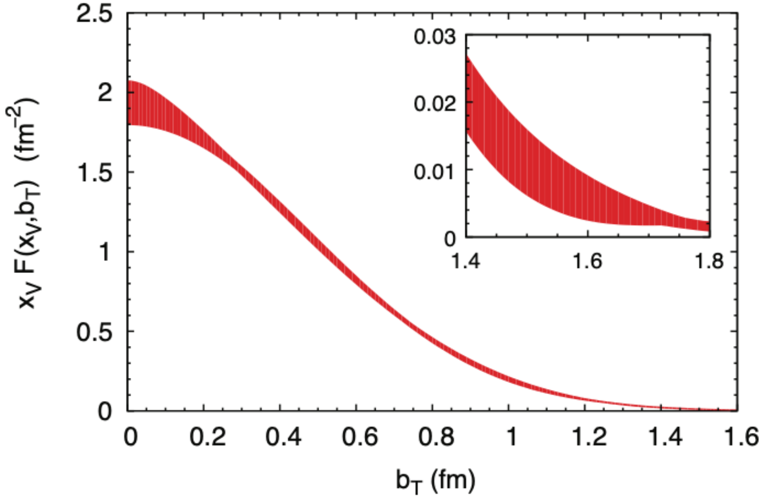




❑ Spatial distributions:







The b_T space density for gluons → "proton radius" in terms of distribution of gluons

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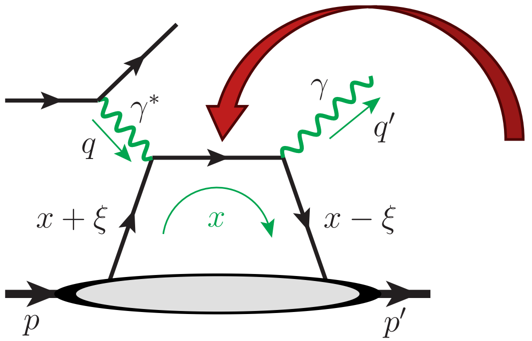
How well can we infer the (x,ξ,t) dependence of GPDs from the EIC data?

- **Amplitude nature:** $x \sim$ **loop momentum**



DVCS

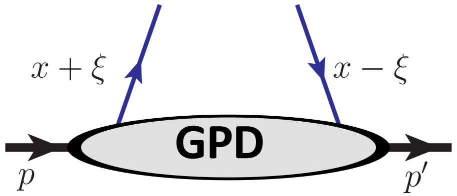
Smaller propagator = bigger amplitude

$$\propto \frac{1}{x - \xi + i\varepsilon}$$

PRD56 (1997) 5524
PRD58 (1998) 094018
PRD59 (1999) 074009

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

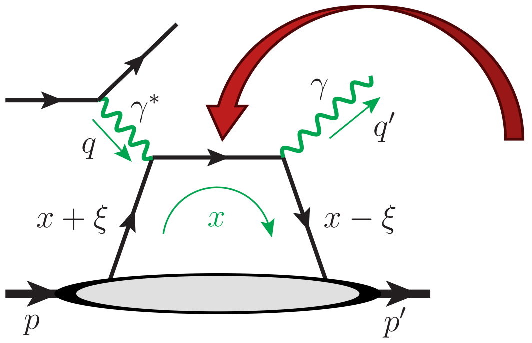
- **also true for most other processes**
- ***x*-dependence is only constrained by a “moment”**
- ***x*-integration decouples from external Q^2**

⇒ 

NO full *x*-dependence for given t and ξ

How well can we infer the (x,ξ,t) dependence of GPDs from the EIC data?

❑ Amplitude nature: $x \sim$ loop momentum



DVCS

Smaller propagator
= bigger amplitude

$$\propto \frac{1}{x-\xi+i\varepsilon}$$

PRD56 (1997) 5524
PRD58 (1998) 094018
PRD59 (1999) 074009

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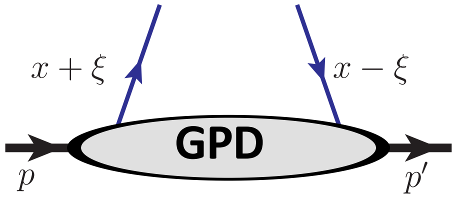


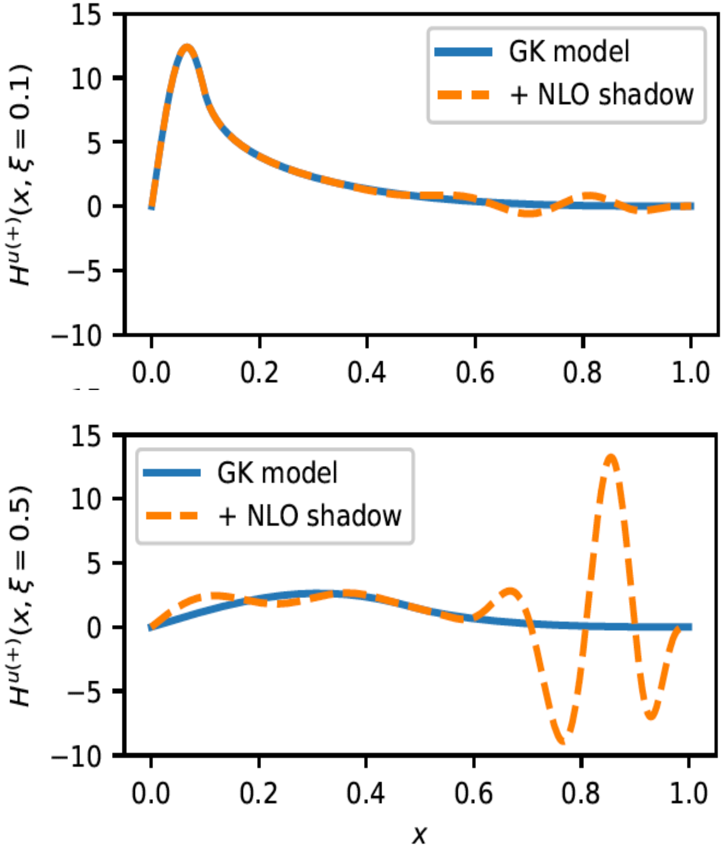
NO full x-dependence
for given t and ξ

❑ “Shadow GPDs”

PRD103 (2021) 114019

$$F(x,\xi,t) \to F(x,\xi,t) + S(x,\xi,t)$$

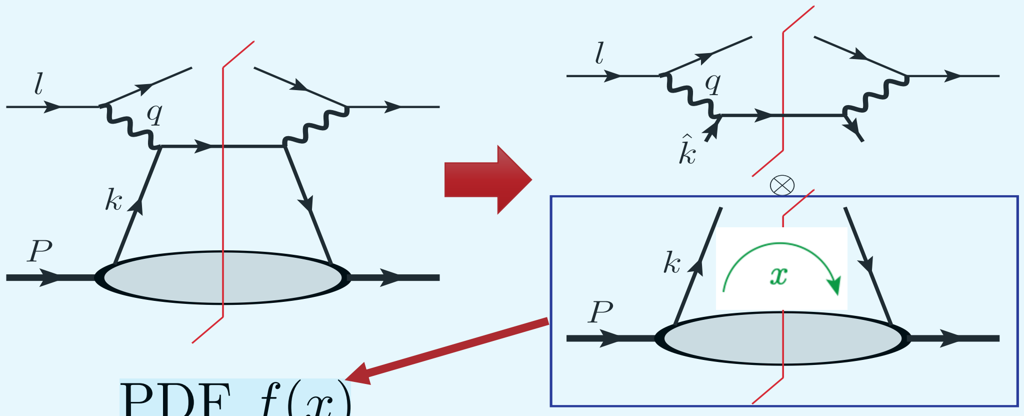
with $$\int_{-1}^{1} \mathrm{d}x \, \frac{S(x,\xi,t)}{x-\xi+i\varepsilon} = 0$$



Blue and dashed
Fit the same CFFs !

Inclusive Process vs. Exclusive Process

❑ Deeply Inelastic Scattering (DIS):



PDF $f(x)$

$x = k^+/P^+$

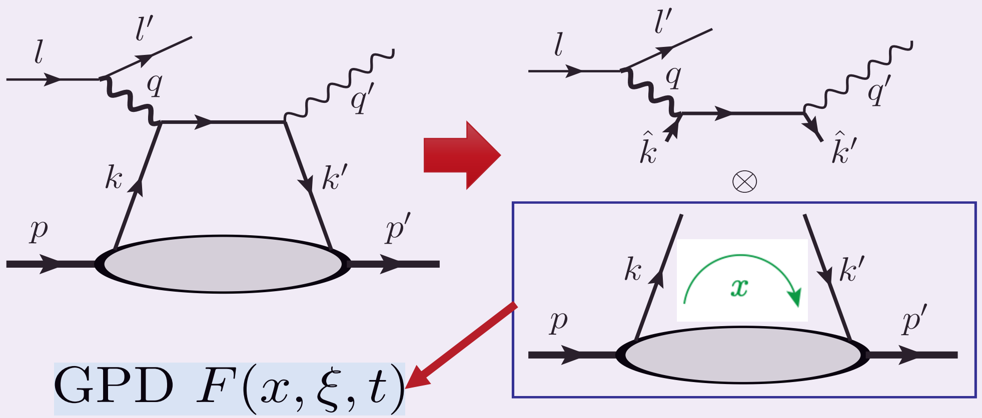
Cross section: Cut diagrams

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

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

x-dependence: Part of measurement

❑ Deeply Virtual Compton Scattering (DVCS)



GPD $F(x, \xi, t)$

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

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

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

Amplitude: Uncut diagrams

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

$$\propto \frac{1}{x - \xi + i\varepsilon}$$

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

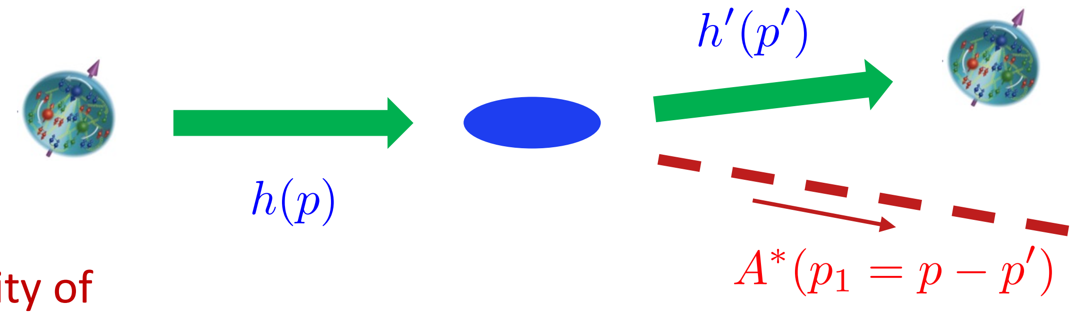
x-dependence: Hard to measure

Single-Diffractive Hard Exclusive Processes (SDHEP)

Qiu & Yu, JHEP 08 (2022) 103,
PRD 107 (2023) 1
2305.15397 (PRL in press)

- **Two-stage diffractive $2 \to 3$ hard exclusive processes:**
  - **Single diffractive – keep the hadron intact:**

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



Virtuality of
exchanged state: $t = (p - p')^2 \equiv p_1^2$

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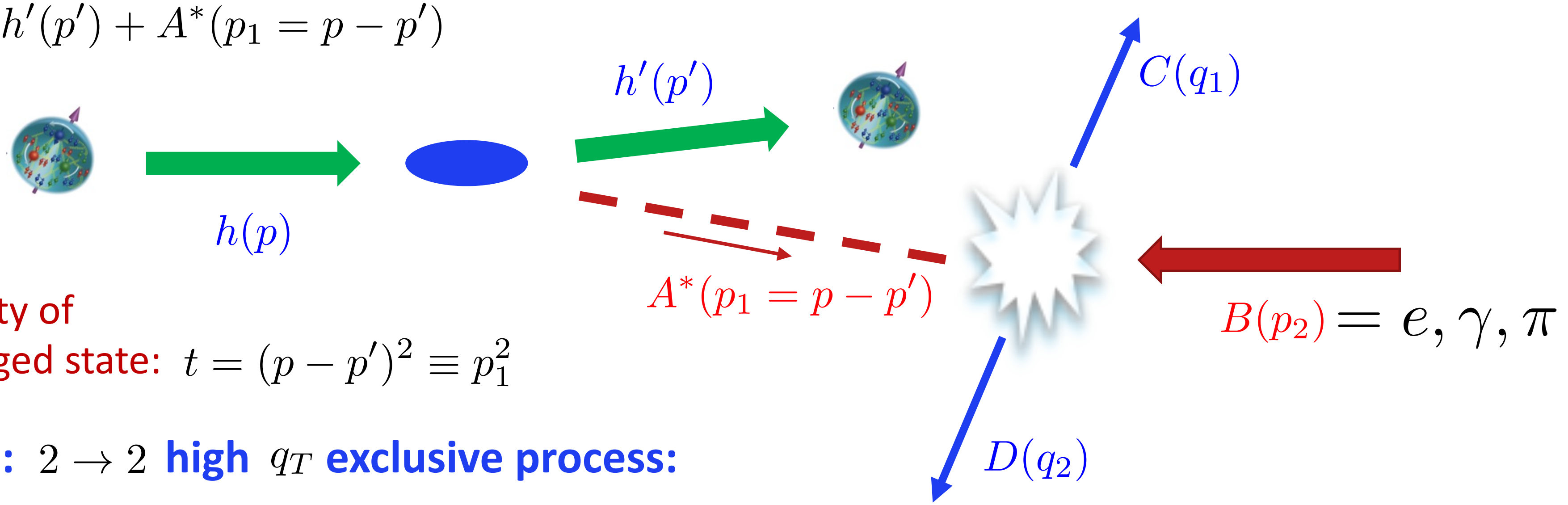

Virtuality of
exchanged state: $t = (p - p')^2 \equiv p_1^2$

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

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

Probing time: $\sim 1/|q_{1T}| \approx 1/|q_{2T}|$

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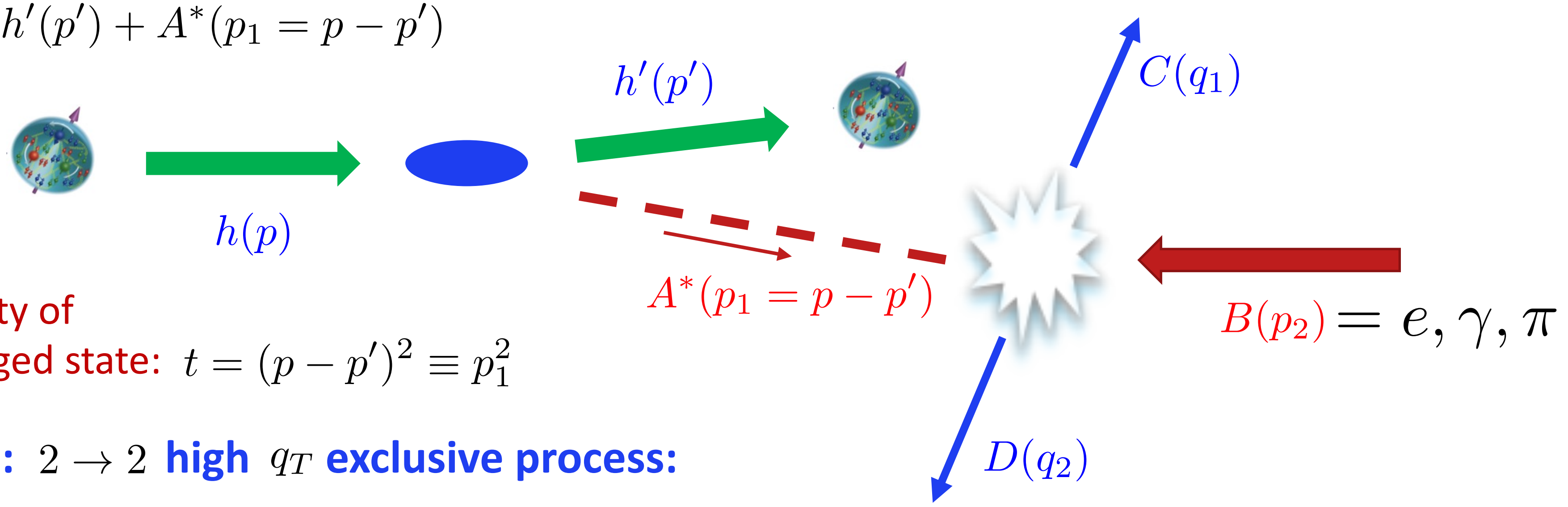

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Probing time: $\sim 1/|q_{1T}| \approx 1/|q_{2T}|$

  - **Necessary condition for QCD factorization:**

Lifetime of $A^*(p_1)$ is much longer than collision time of the probe! ➡ $|q_{1_T}| = |q_{2_T}| \gg \sqrt{-t}$

Not necessarily sufficient!

➡ **The single diffractive $2 \to 3$ exclusive hard processes (SDHEP):**

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

A 2-scale observable!

Single-Diffractive Hard Exclusive Processes (SDHEP)

❑ The exchange virtual state and the power expansion:

Qiu & Yu, JHEP 08 (2022) 103,
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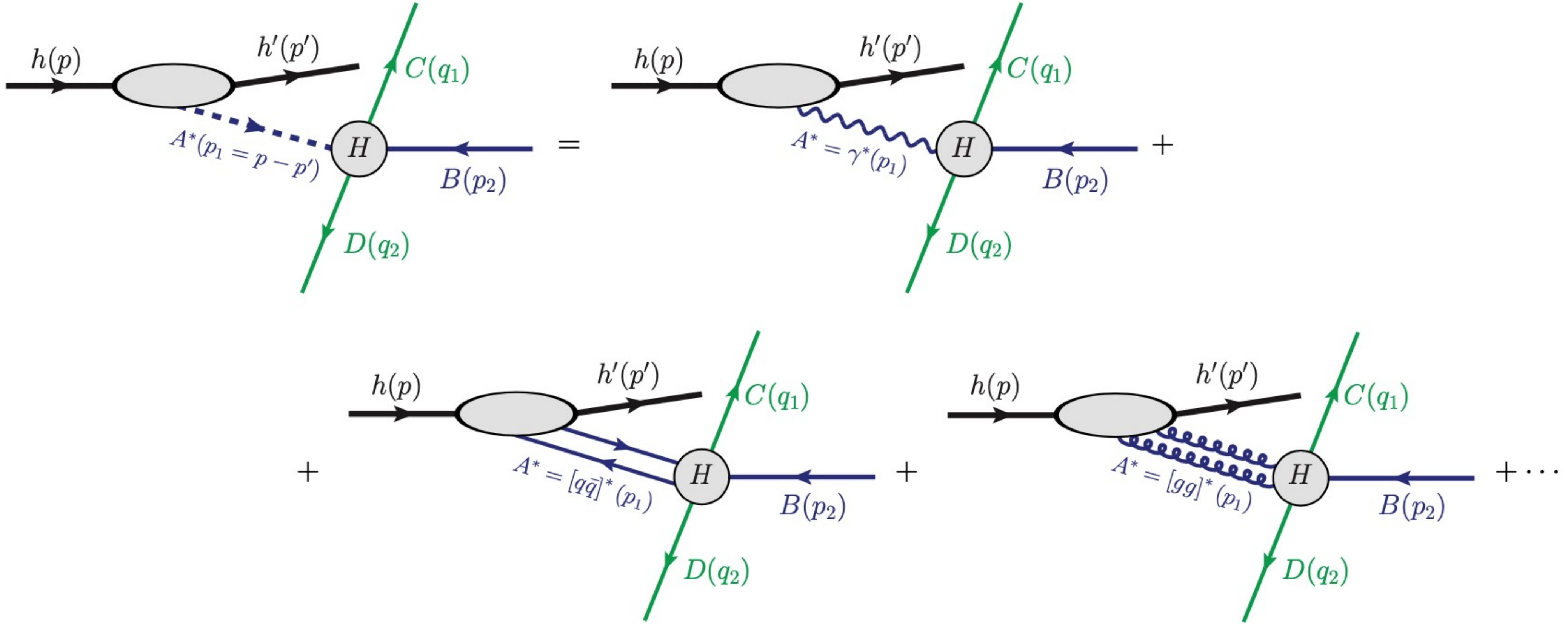

The exchanged state $A^*(p\text{-}p')$ is a sum of all possible partonic states, $\sum_{n=1,2,..}$, allowed by

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

Single-Diffractive Hard Exclusive Processes (SDHEP)

Qiu & Yu, JHEP 08 (2022) 103,
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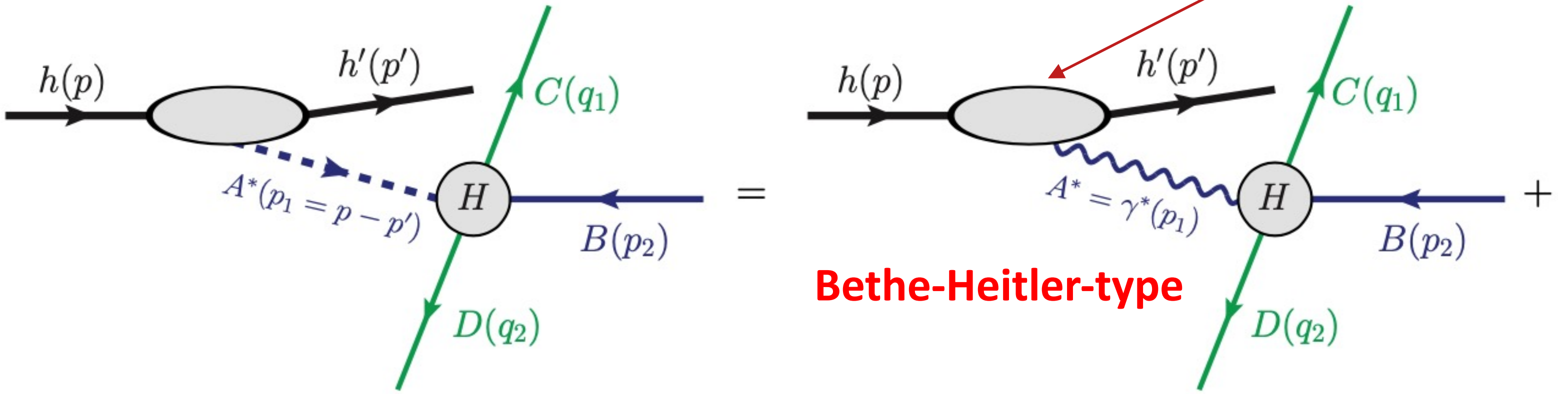
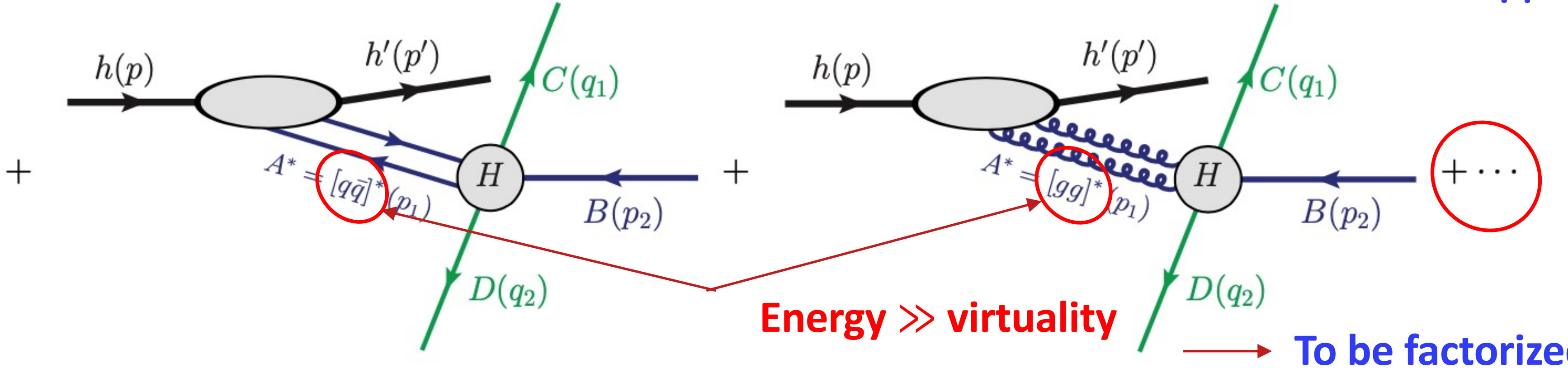
- The exchange virtual state and the power expansion:

EM form factor



Bethe-Heitler-type

$\geq$ 3 parton connection:
Power suppressed



Energy $\gg$ virtuality

→ To be factorized into GPD

The exchanged state $A^*(p\text{-}p')$ 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*

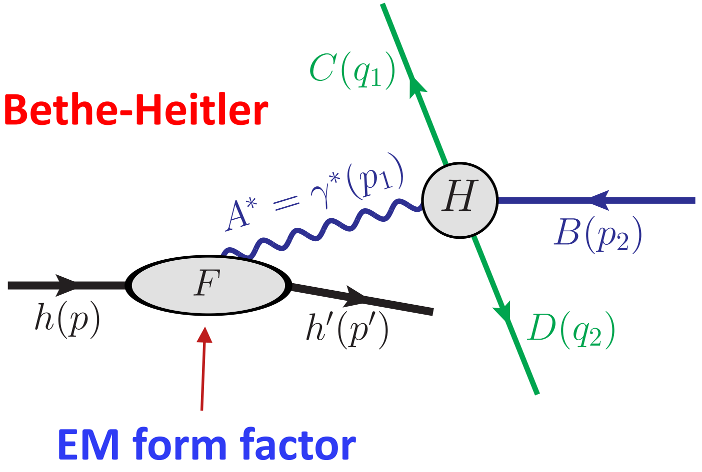
Need entanglement between q_T and loop momentum for the sensitivity on the x-dependence of GPDs!

Jefferson Lab

General Discussion on n=1 state: γ*

Qiu & Yu, PRD 107 (2023) 1

❑ Exchange of a virtual photon – "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

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

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

Jefferson Lab

General Discussion on n=1 state: γ^*

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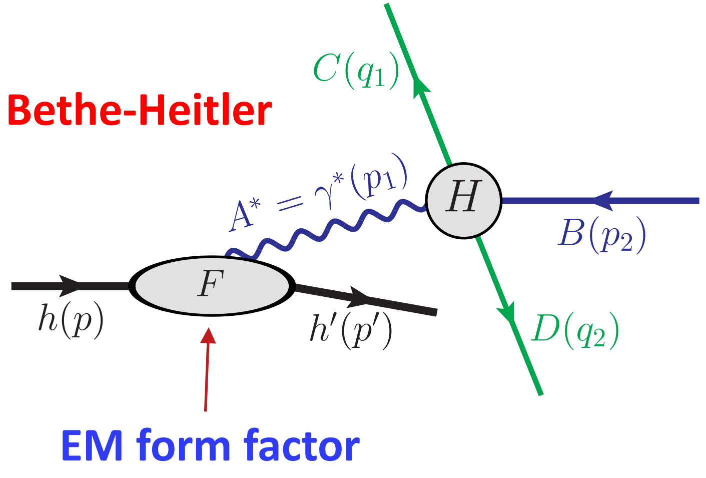
Qiu & Yu, PRD 107 (2023) 1



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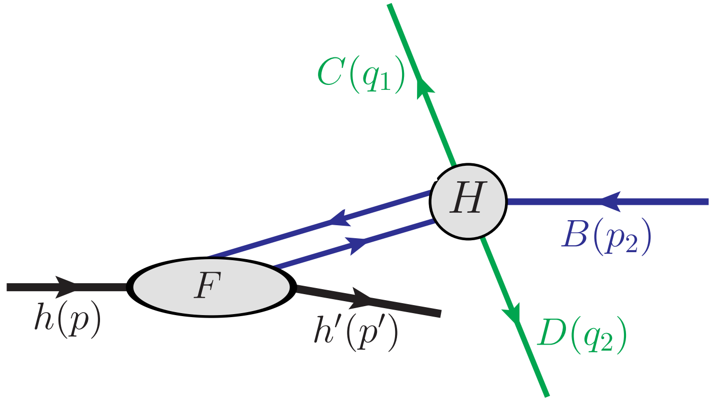
$$\mathcal{M}^{(1)} \sim \mathcal{O}(1/\sqrt{|t|})$$

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

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



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

Extract GPDs from SDHEP with controllable approximation - Factorization

50 years of QCD
2212.11107

❑ QCD Facts:

- **Any scattering cross section with identified hadron(s) cannot be calculated fully in QCD perturbation theory**

Extract GPDs from SDHEP with controllable approximation - Factorization

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2212.11107

QCD Facts:

- Any scattering cross section with identified hadron(s) cannot be calculated fully in QCD perturbation theory
- QCD factorization is a controllable approximation with following 3 key features:
  - All process-dependent nonperturbative contributions to factorizable cross sections are suppressed by powers of 1/(RQ), which could be neglected if the hard scale Q is sufficiently large;
  - All factorizable nonperturbative contributions are process independent, representing the characteristics of identified hadron(s); and
  - Process dependence of factorizable contributions is perturbatively calculable from partonic scattering at the short-distance.
- Predictions follow when cross sections with different hard scatterings but the same nonperturbative long-distance effect of identified hadron are compared

Extract GPDs from SDHEP with controllable approximation - Factorization

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2212.11107

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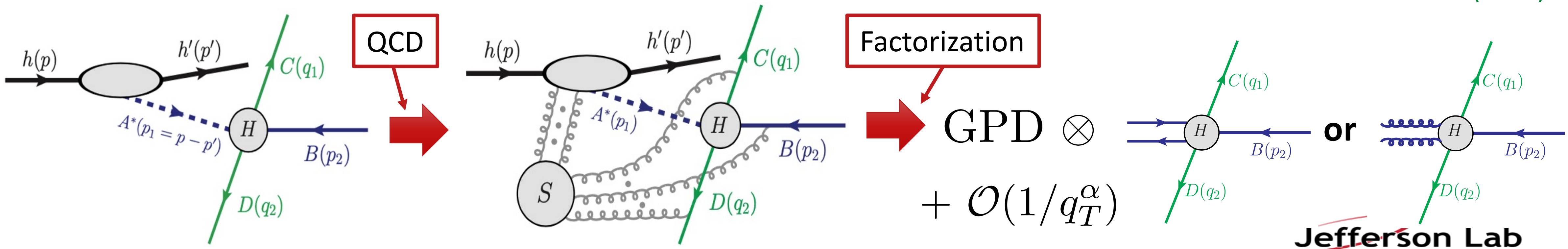
❑ Factorization for 2-parton channels – Very nontrivial:

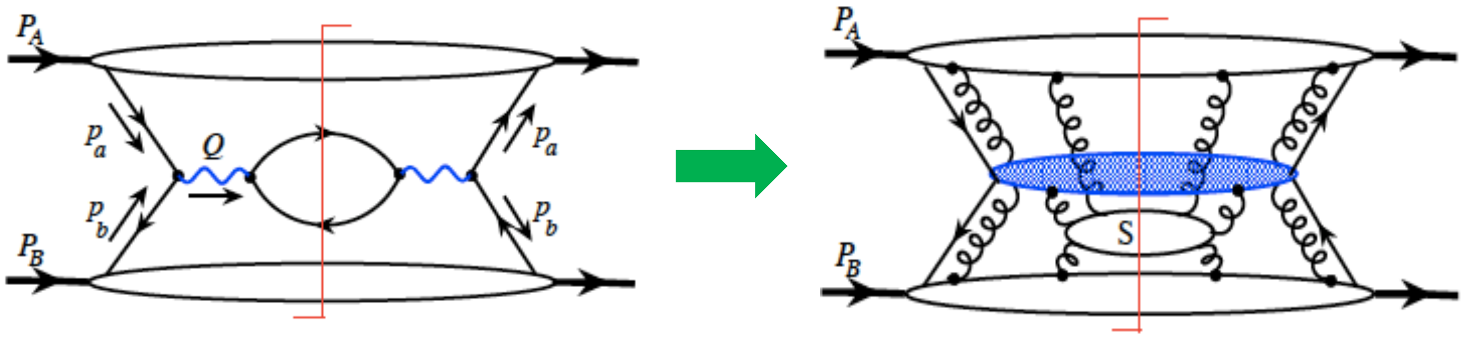
Qiu & Yu, JHEP 08 (2022) 103,
PRD 107 (2023) 1



Extract GPDs from SDHEP with controllable approximation - Factorization

❑ Lessons learned from QCD factorization for hadronic collisions (e.g., Drell-Yan):

Collins, Soper, Sterman 1989



Leading pinch surface

Hard: all lines off-shell by Q

Collinear:

✧ lines collinear to A and B
✧ One "physical parton" per hadron

Soft: all components are soft

Extract GPDs from SDHEP with controllable approximation - Factorization

Collins, Soper, Sterman 1989

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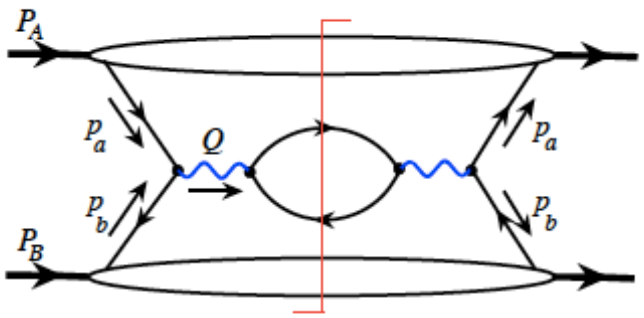

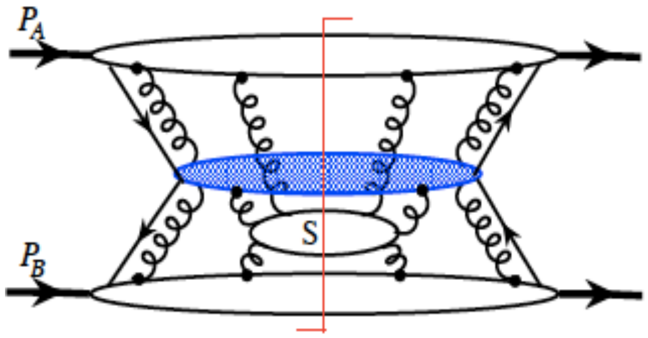

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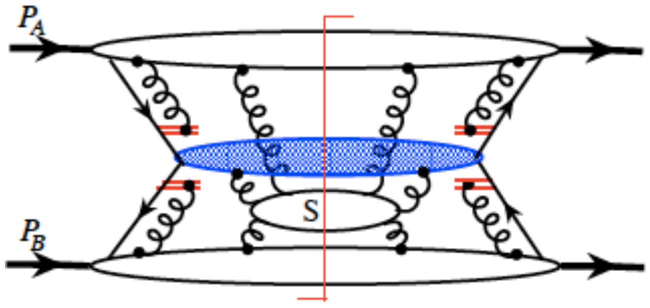
- **Collinear and longitudinally polarized gluons:**

  Easy to factorize:

  - Apply Ward Identity to decouple them from the hard part
  - Reconnect them the gauge links



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Collins, Soper, Sterman 1989

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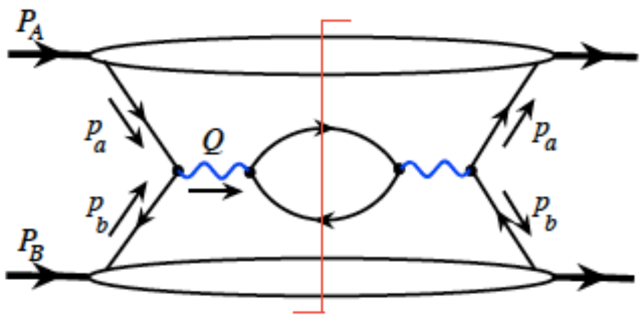

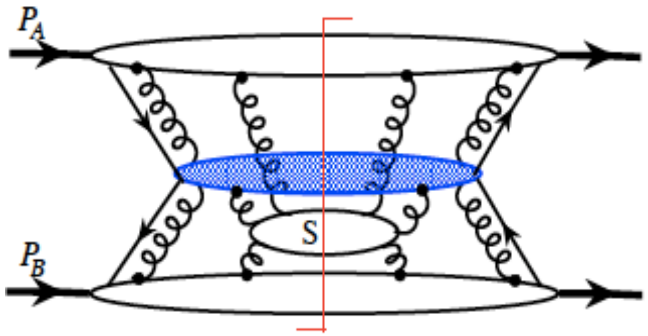

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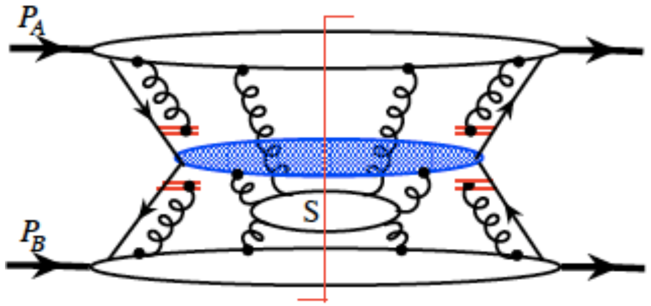
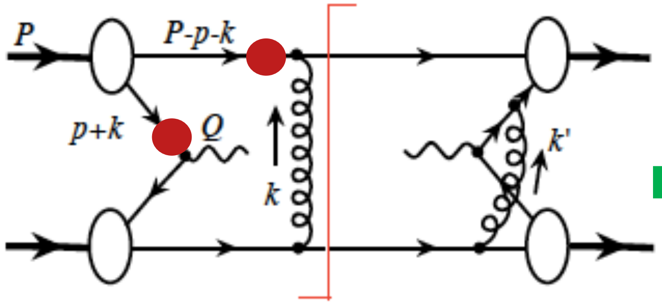


❑ Trouble with the soft gluons:



$$(xp+k)^2 + i\epsilon \propto k^- + i\epsilon$$
$$((1-x)p-k)^2 + i\epsilon \propto k^- - i\epsilon$$

$$k \to (\lambda^2, \lambda^2, \lambda) \quad \lambda \sim \frac{\Lambda_{\rm QCD}}{Q}$$

Pinched in Glauber regime

Solution:

- Sum over all final states,
- Cancelation of all poles in one-half plane (remove pinches)

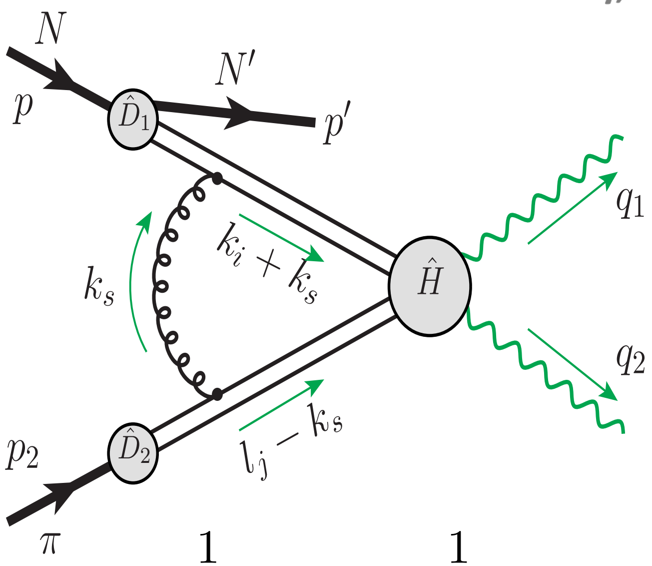
Difficulty for exclusive processes:

No final-states to sum!

Extract GPDs from SDHEP with controllable approximation - Factorization

- **Glauber pinch for SDHEP, e.g.** $\pi^-(p_\pi) + P(p) \to \gamma(q_1) + \gamma(q_2) + N(p')$

ERBL region (Efremov, Radyushkin, Brodsky, Lepage)



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

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

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

No pinch!

Extract GPDs from SDHEP with controllable approximation - Factorization

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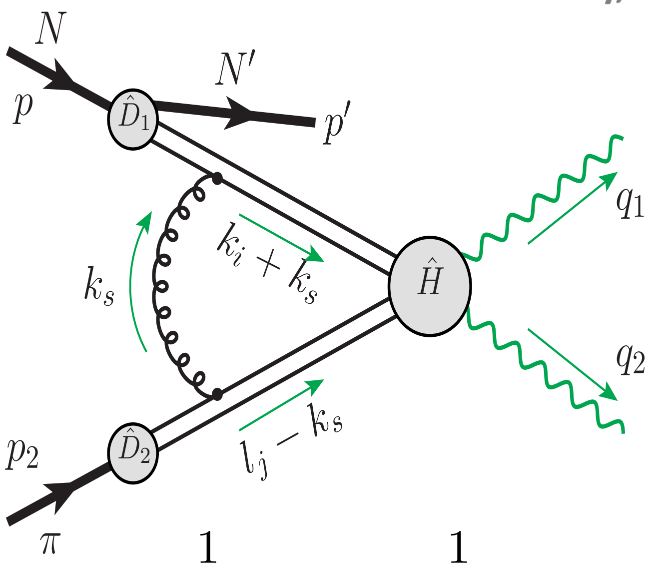

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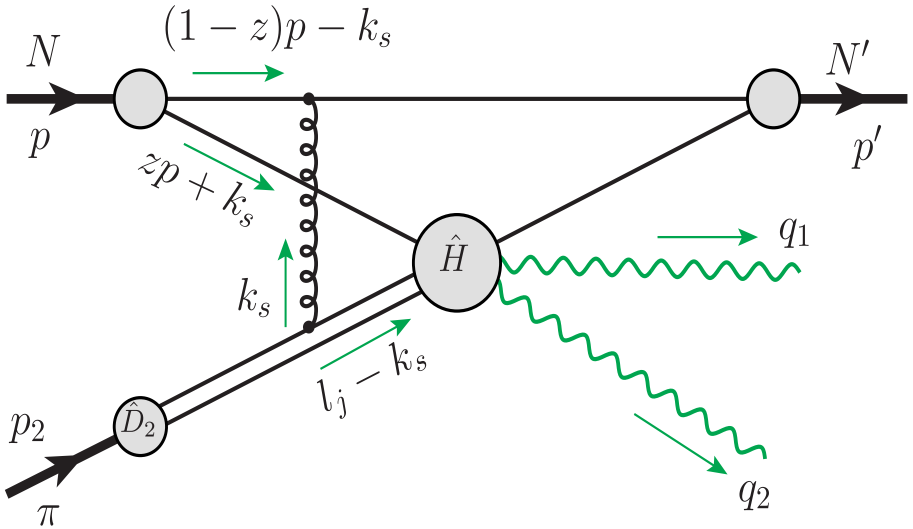
No pinch!

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'!

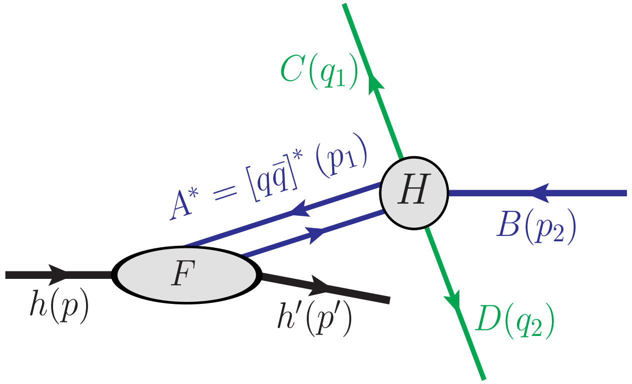
Gluons pinched in the Glauber region: $k_s = (\lambda^2, \lambda^2, \lambda)\, Q$

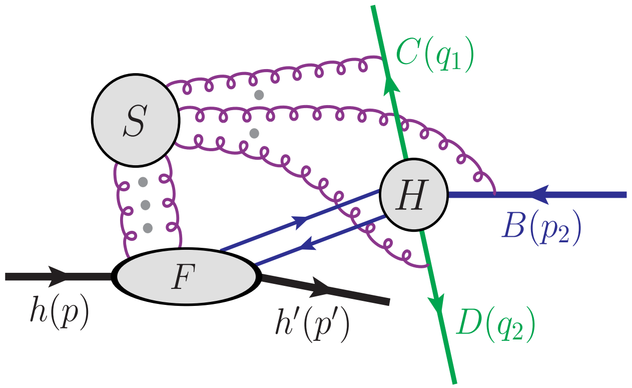
Transverse component contribute to the leading region!

Factorization for SDHEP in the Two-stage Paradigm

Qiu & Yu, JHEP 08 (2022) 103,
PRD 107 (2023) 1

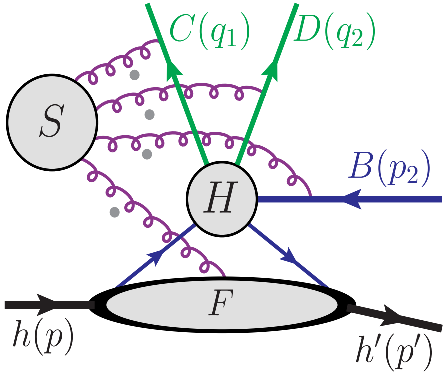
- **Factorization for 2-parton channels (CO gluons are easy to factorize):**





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

+



DGLAP region: Glauber pinch

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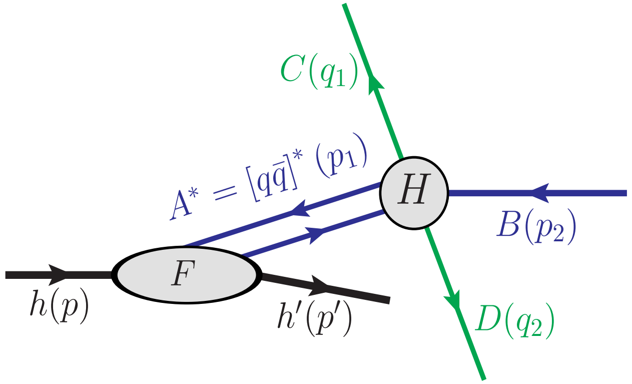

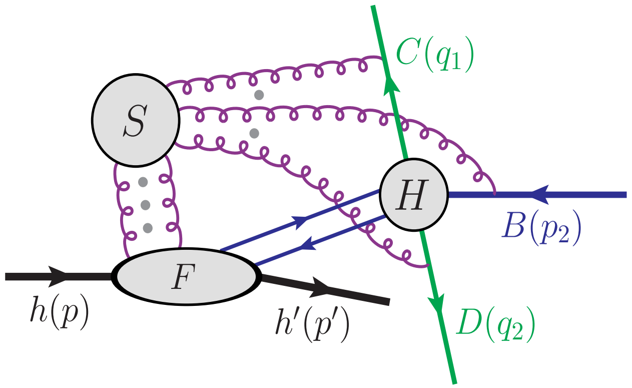

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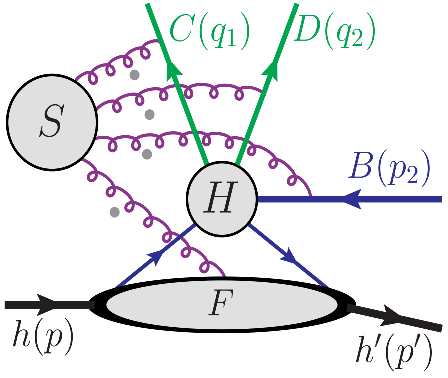
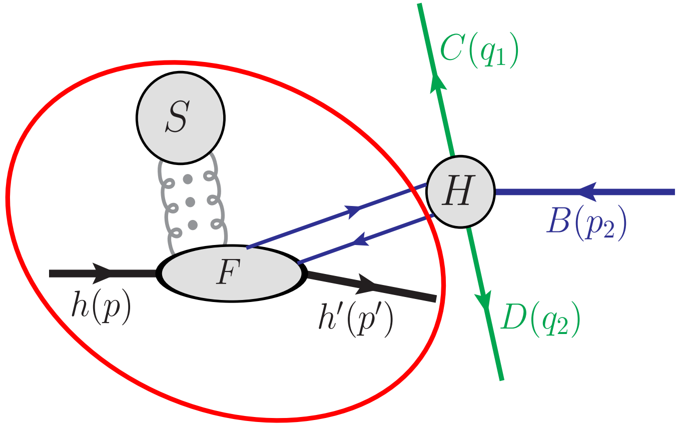


ERBL region: $[q\bar{q}'] \sim$ meson **DGLAP region: Glauber pinch**

- **Soft gluons cancel when coupling to color neutral hadrons:**

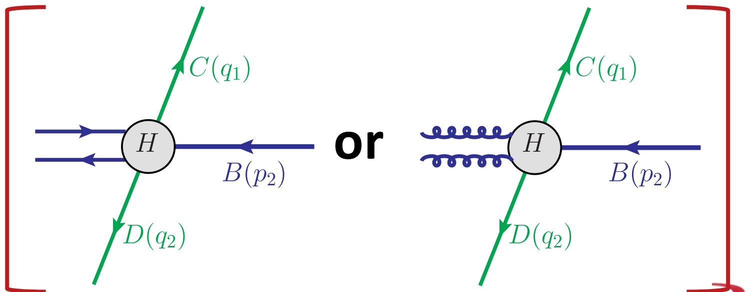


Glauber gluons of SDHEP (*only* k_s^- is pinched in Glauber region):

$$k_s^+ \mapsto k_s^+ \pm i\mathcal{O}(Q) \quad \Rightarrow \quad k_s = (\lambda^2, \lambda^2, \lambda) \ \rightarrow \ (1, \lambda^2, \lambda)$$

CO gluons

$$\text{GPD} \otimes$$



Hard probes

No factorization for double diffractive scattering! Soper, 1997

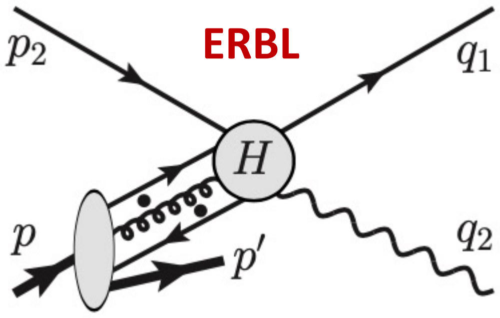
SDHEP with a Lepton Beam – JLab, EIC

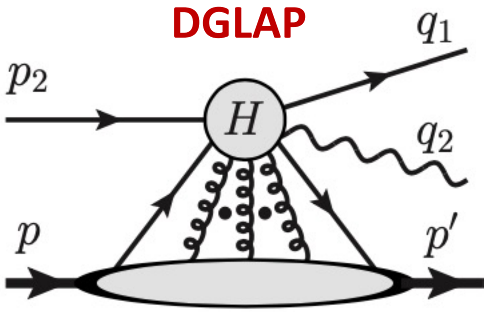
PRD56 (1997) 5524; PRD58 (1998) 094018; PRD59 (1999) 074009

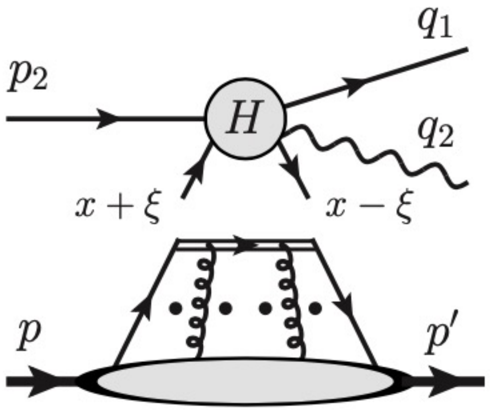
DVCS:

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

Leading pinch region:







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

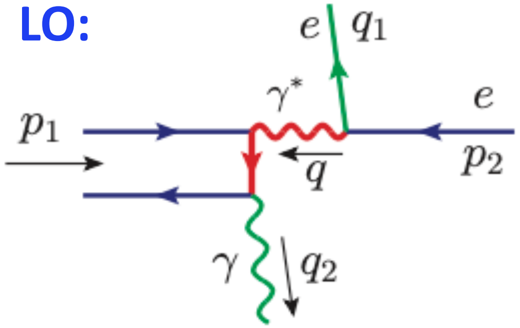
$$\xi = \frac{(p-p')^+}{(p+p')^+}$$

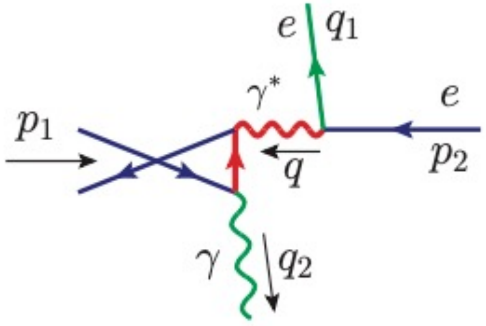
Factorization formula:

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

$$C^{(0)} \propto \frac{1}{x-\xi+i\varepsilon} - \frac{1}{x+\xi-i\varepsilon}$$

LO:





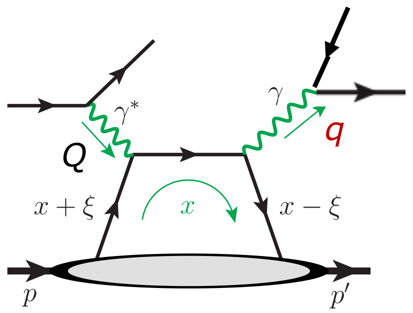
The x-integration is NOT sensitive to externally measured hard scale, q_T or Q^2!

What kind of process/observable could be sensitive to the x-dependence?

- **Create an entanglement between the internal x and an externally measured variable?**

$$i\mathcal{M} \propto \int_{-1}^{1} \mathrm{d}x \frac{F(x,\xi,t)}{x - x_p(\xi,q) + i\varepsilon}$$

Change external *q* to sample different part of x.



- **Double DVCS (two scales):**

$$x_p(\xi,q) = \xi\left(\frac{1-q^2/Q^2}{1+q^2/Q^2}\right) \to \xi \quad \text{same as} \quad \text{DVCS} \quad \text{if } q \to 0$$

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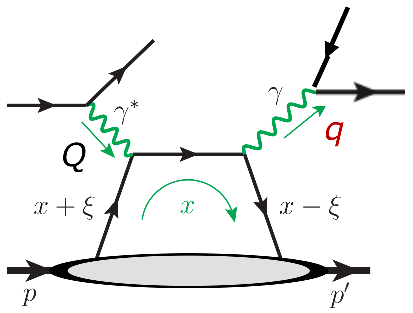

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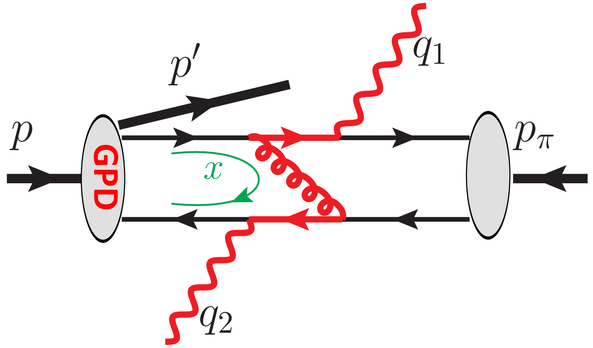
- **Production of two back-to-back high pT particles (say, two photons):**

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

Qiu & Yu
JHEP 08 (2022) 103

Hard scale: $q_T \gg \Lambda_{\mathrm{QCD}}$ **Soft scale:** $t \sim \Lambda^2_{\mathrm{QCD}}$



- **Factorization:**

[*suppressing pion DA factor*]

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

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

q_T distribution is "conjugate" to x distribution

$$x \leftrightarrow q_T$$

GPD Models for Testing the x-dependence

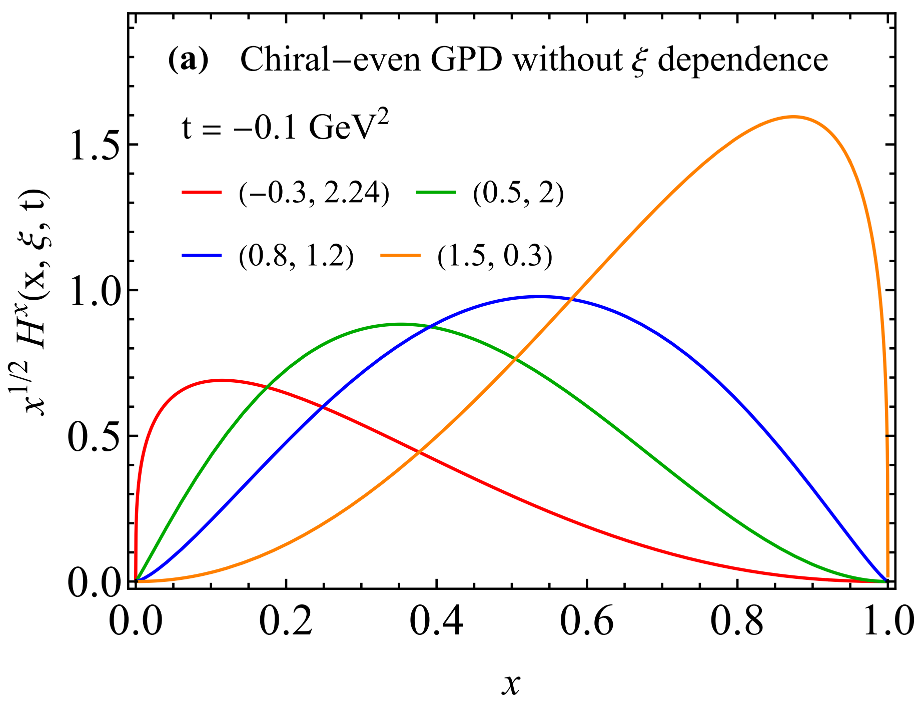
❑ Simplified GK models:

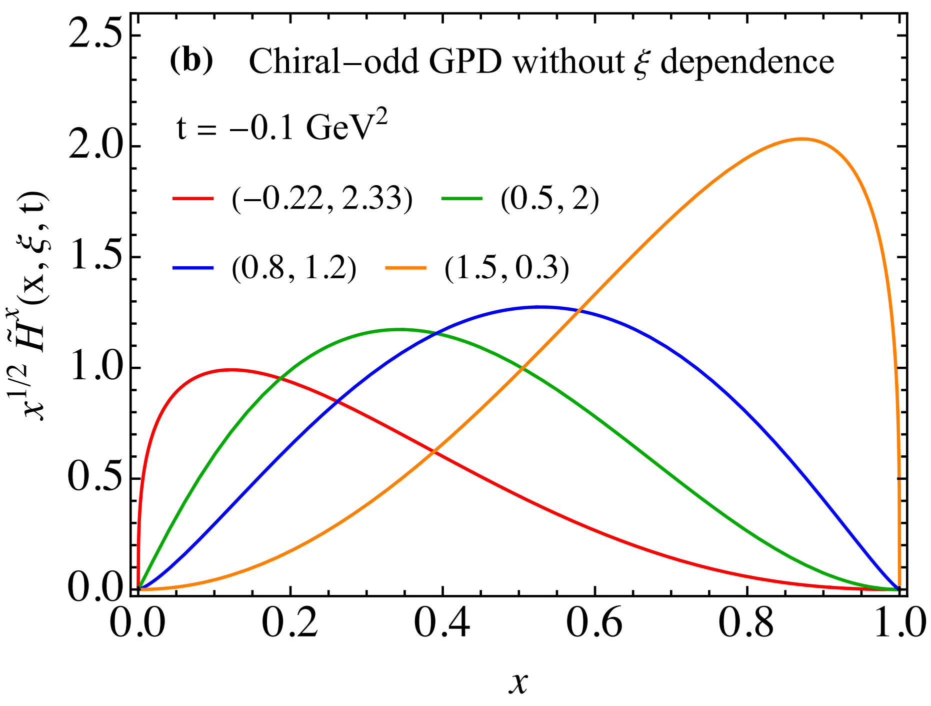
Goloskokov, Kroll
hep-ph/0501242
arXiv: 0708.3569
arXiv: 0906.0460
Qiu & Yu,
arXiv:2305.15397

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

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

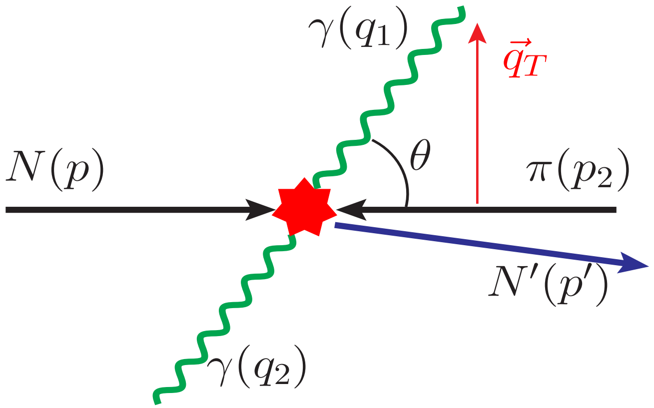
- Neglect $E, \widetilde{E}$. Neglect evolution effect.
- Tune (ρ, τ) to control x shape.
- Fix DA: $D(z) = N\, z^{0.63}(1-z)^{0.63}$





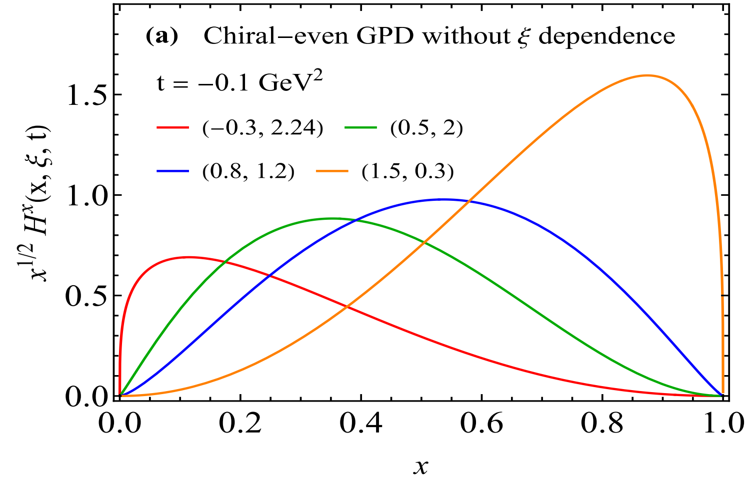
Enhanced Sensitivity on x-dependence of GPDs

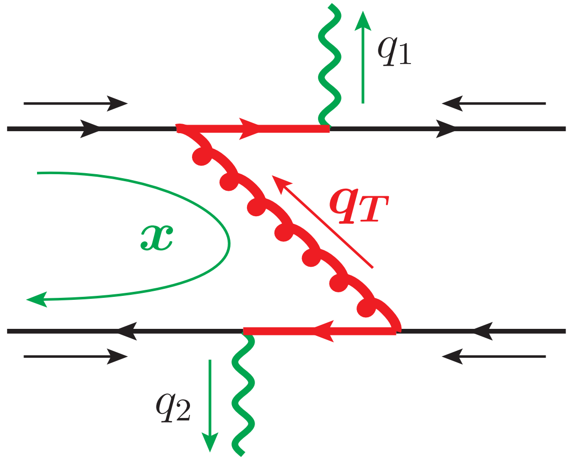
❑ **Two-photon production:** $\pi^-(p_\pi) + P(p) \to \gamma(q_1) + \gamma(q_2) + N(p')$ **J-PARC, COMPASS** Qiu & Yu, JHEP 08 (2022) 103

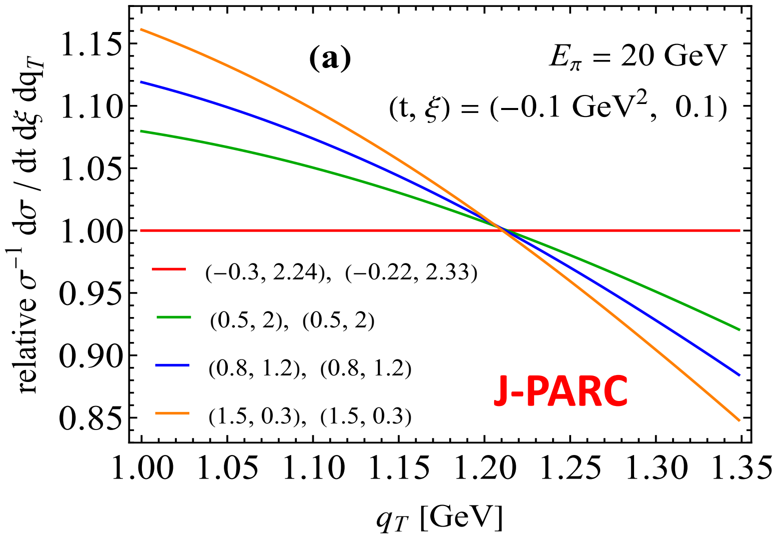


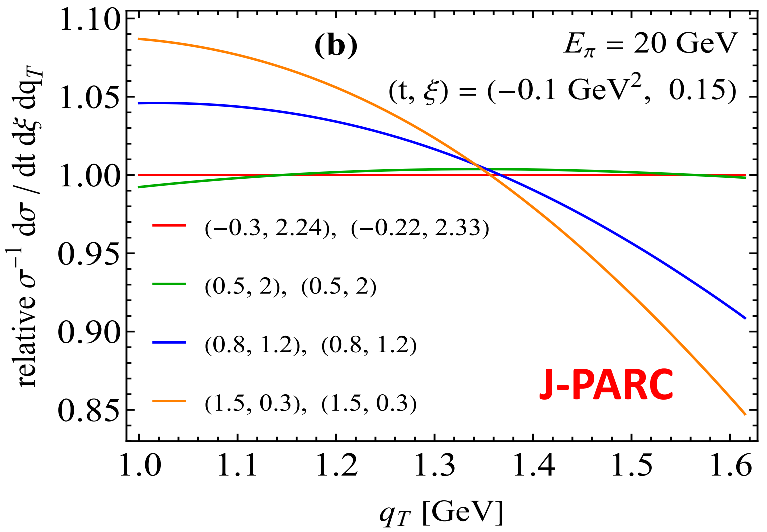
Vary GPD x shapes

Different q_T shapes





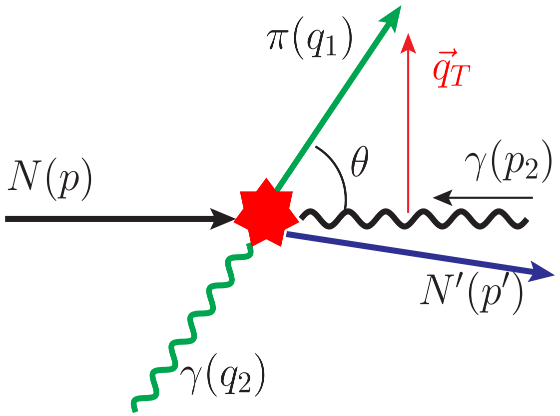




Enhanced Sensitivity on x-dependence of GPDs

❑ **Pion-photon production:** $\gamma(p_\gamma) + h(p) \to \pi^\pm(q_1) + \gamma(q_2) + h'(p')$

JLab-Hall D, other Halls & EIC with a quasi-photon beam

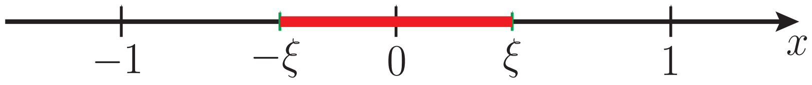


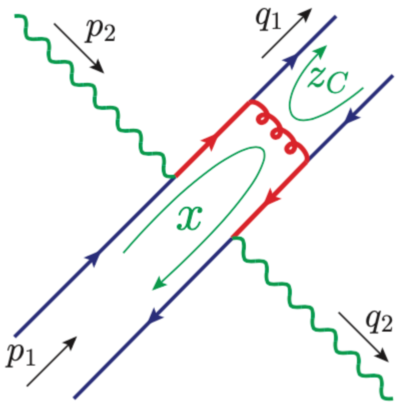
$i\mathcal{M}$ **contains the entanglement between x and qT**

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

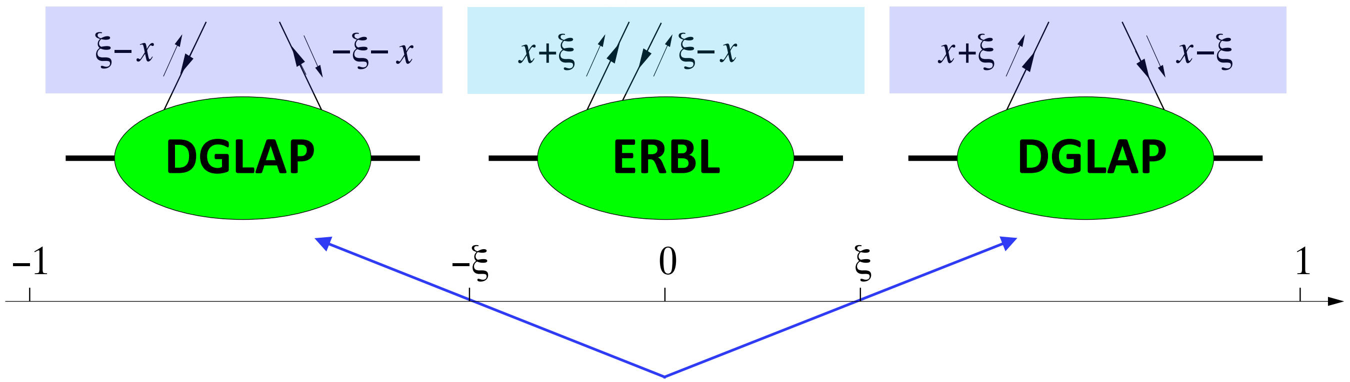
Qiu & Yu, arXiv:2305.15397
PRL (in press)

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





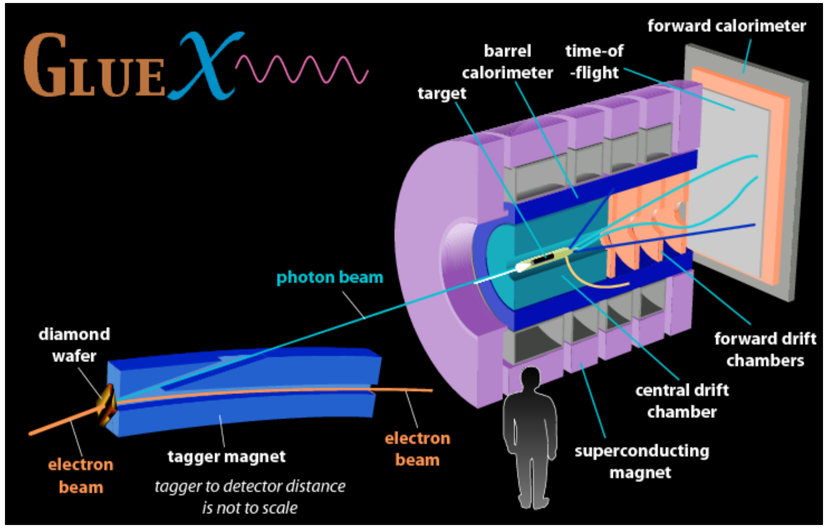
Complementary sensitivity:



N π → N′ γ γ

Exclusive Photo-Production of a π γ Pair – Hall D at JLab

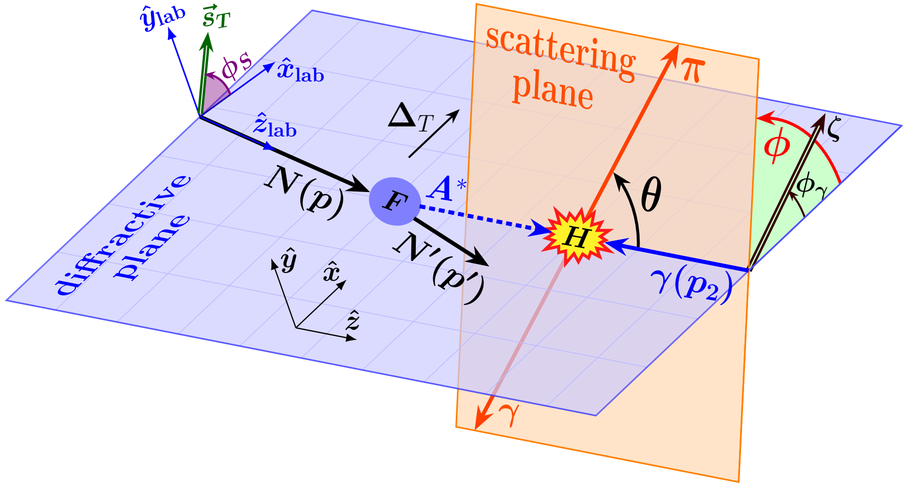
Qiu & Yu, arXiv:2305.15397
PRL (in press)



❑ Polarization asymmetries

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

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



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

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

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

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

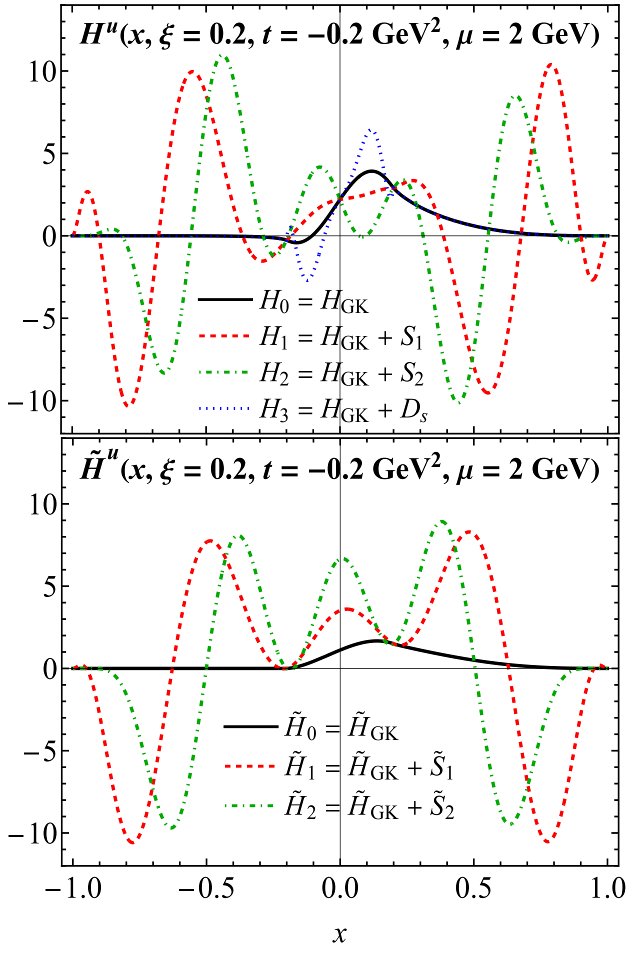
Exclusive Photo-Production of a π γ Pair – Hall D at JLab

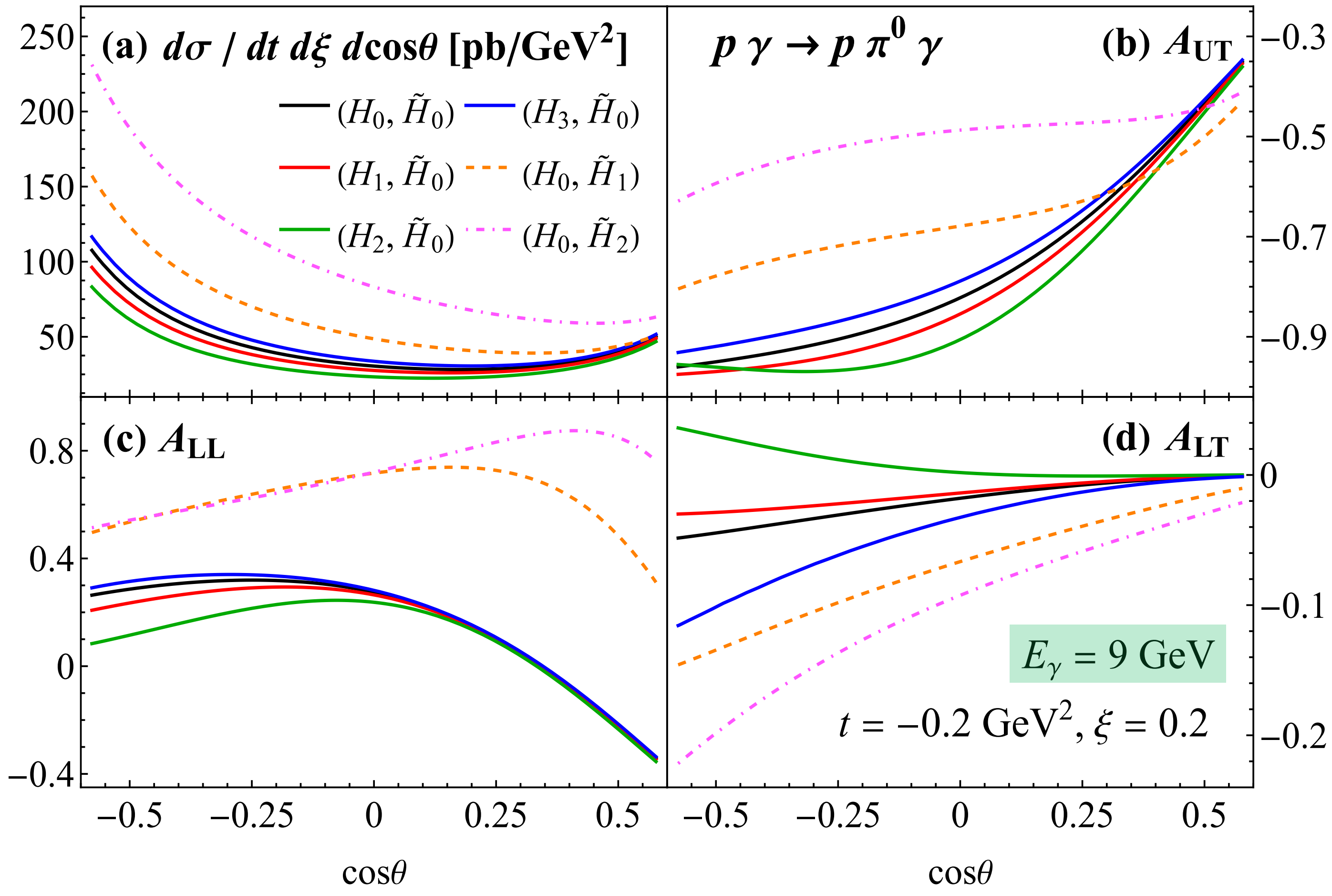
Goloskokov, Kroll, `05, `07, `09
Bertone et al. `21
Moffat et al. `23
Qiu & Yu, arXiv:2305.15397
PRL (in press)

- **GPD Models:**

  = GK model + shadow GPDs

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





Jefferson Lab

Exclusive Photo-Production of a $\pi\gamma$ Pair – Hall D at JLab

Goloskokov, Kroll, \`05, \`07, \`09
Bertone et al. \`21
Moffat et al. \`23
Qiu & Yu, arXiv:2305.15397
PRL (in press)

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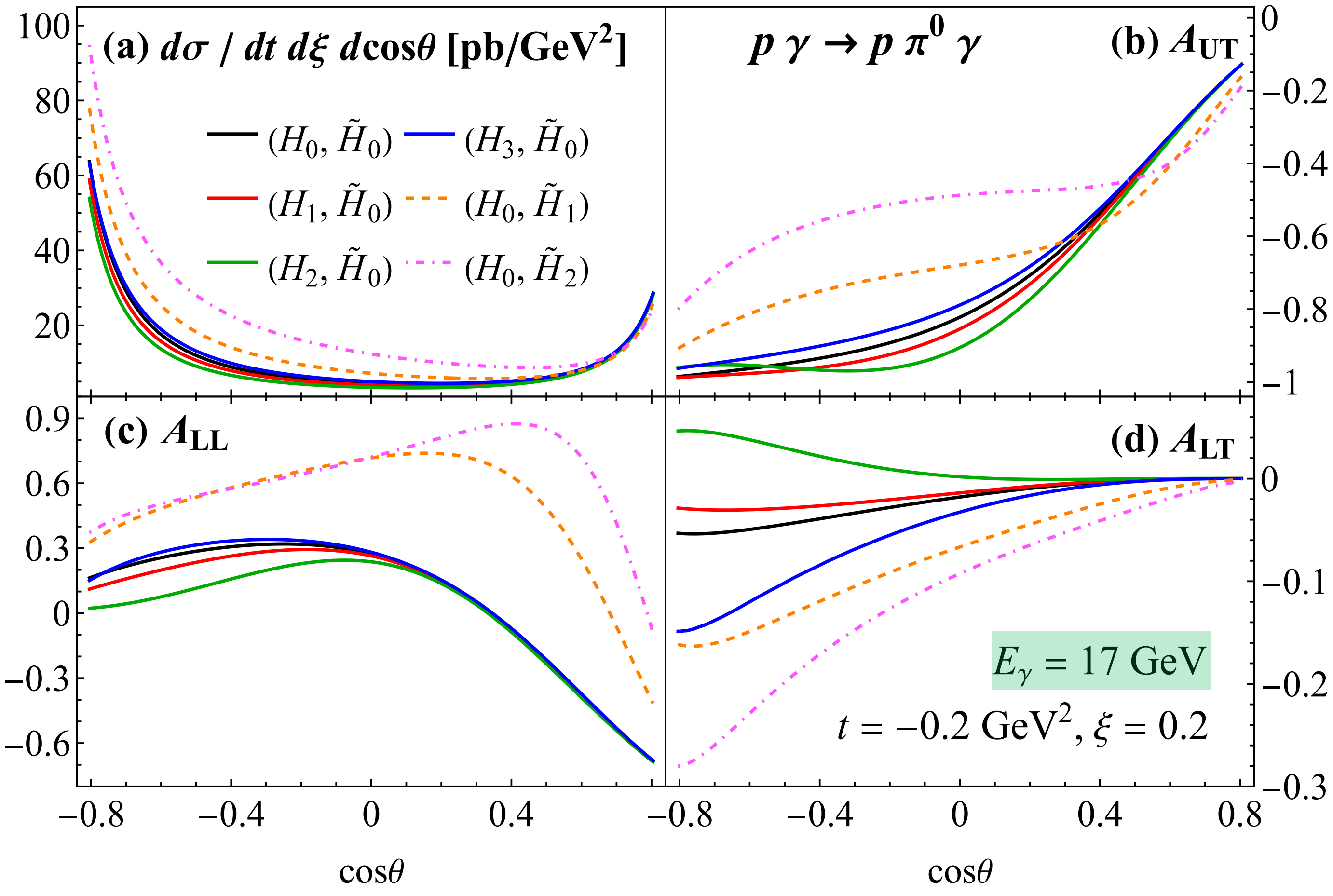
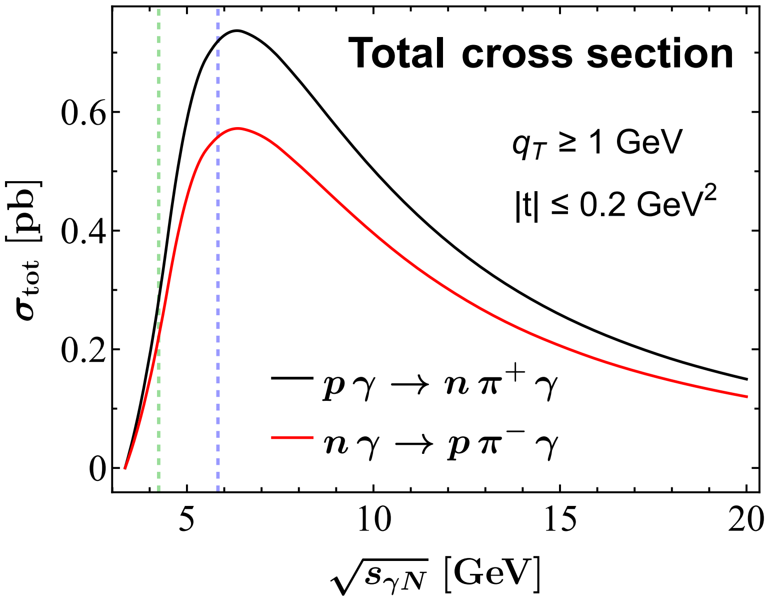
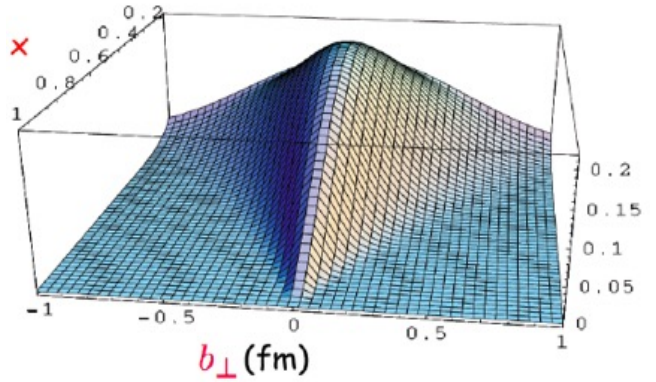






Extracting GPDs is a challenging inverse problem! $\sigma \propto [\mathcal{F} \otimes C]^2$

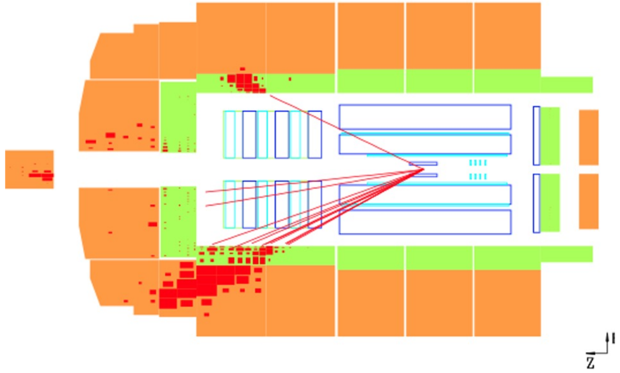
From cross sections to parton correlation functions (PDFs, TMDs, GPDs, …)

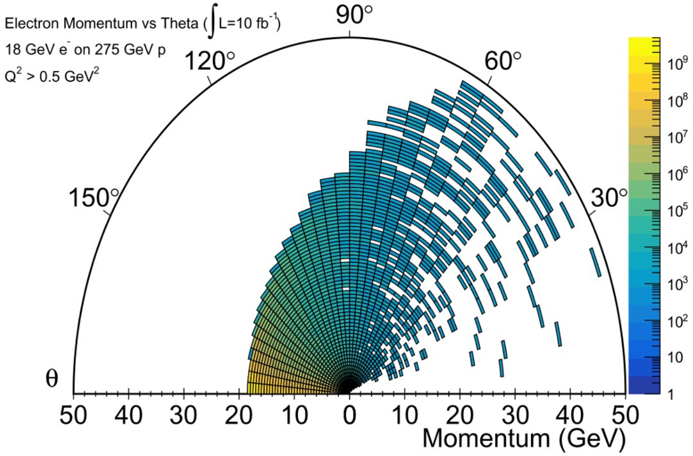
❑ Existing paradigm – histogram approach:

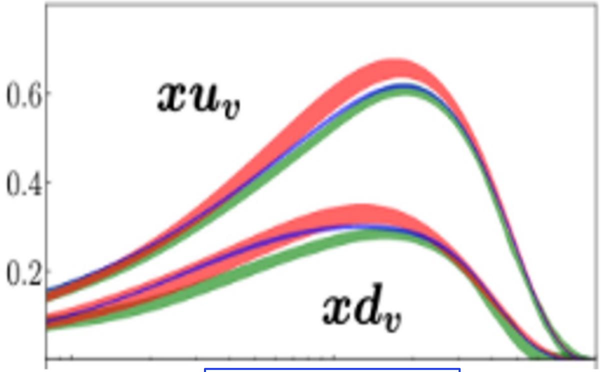
Inverse problem

Inverse problem

Detector level events → Detector level histograms → Unfolded histograms → Deconvolution "femtography"



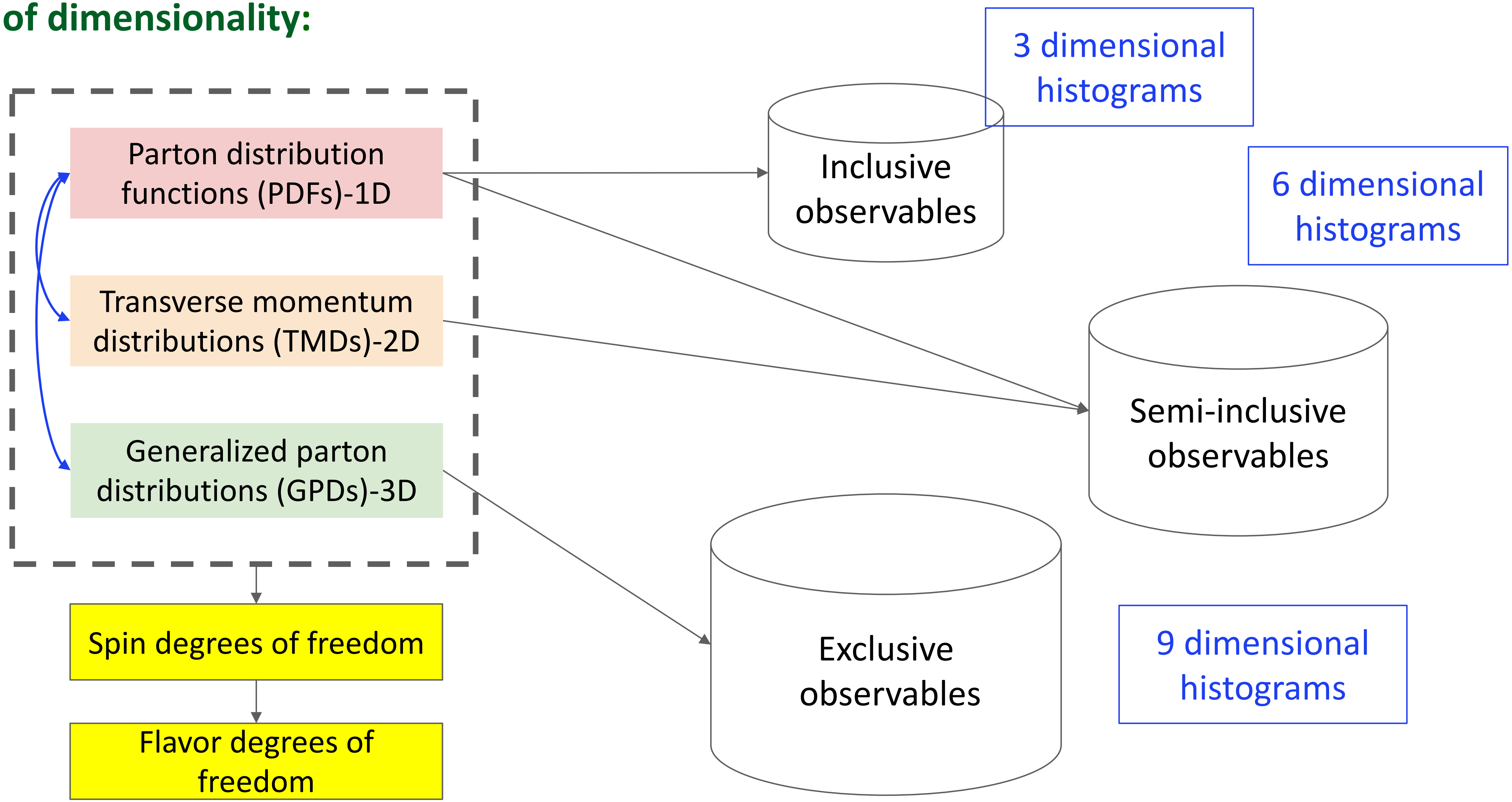




1D PDFs

From cross sections to parton correlation functions (PDFs, TMDs, GPDs, …)

❑ Curse of dimensionality:



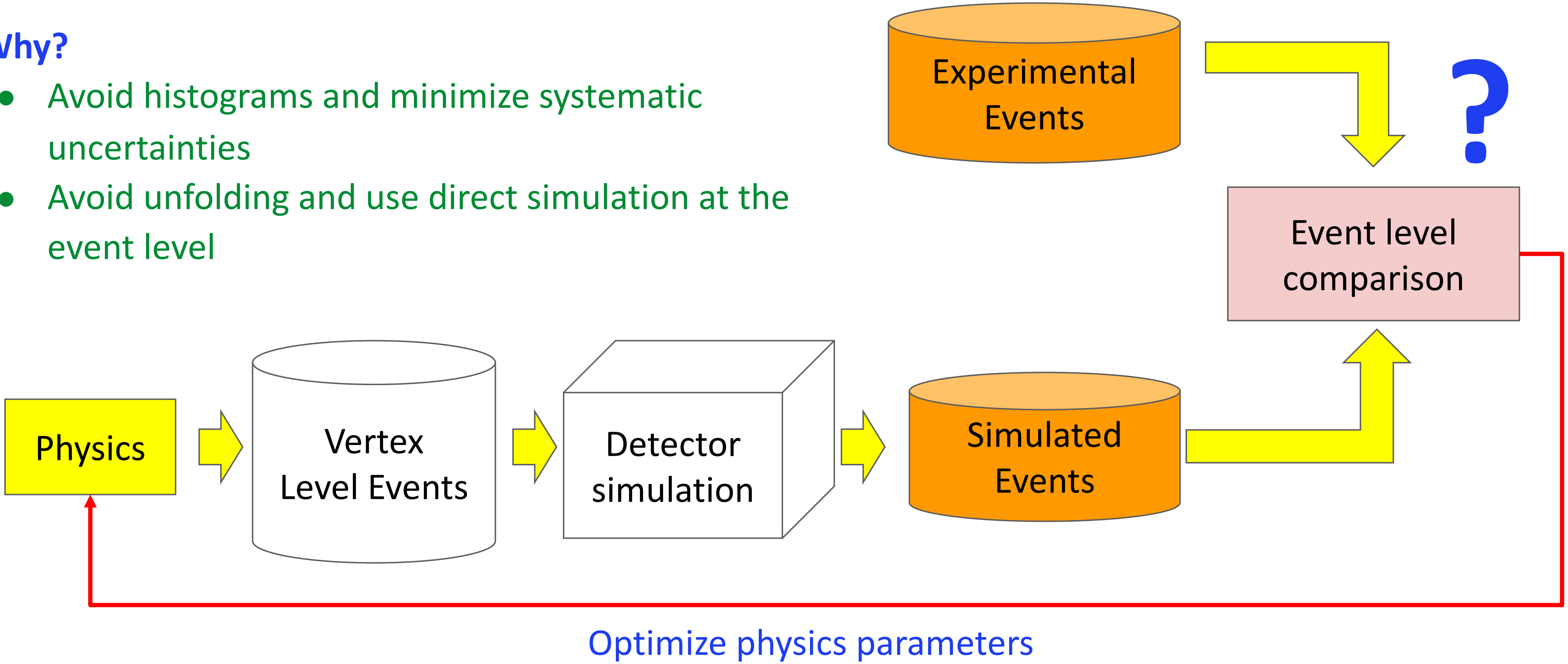
From cross sections to parton correlation functions (PDFs, TMDs, GPDs, ...)

❑ Event-based analysis?

Can we compare real vs synthetic events?

Why?

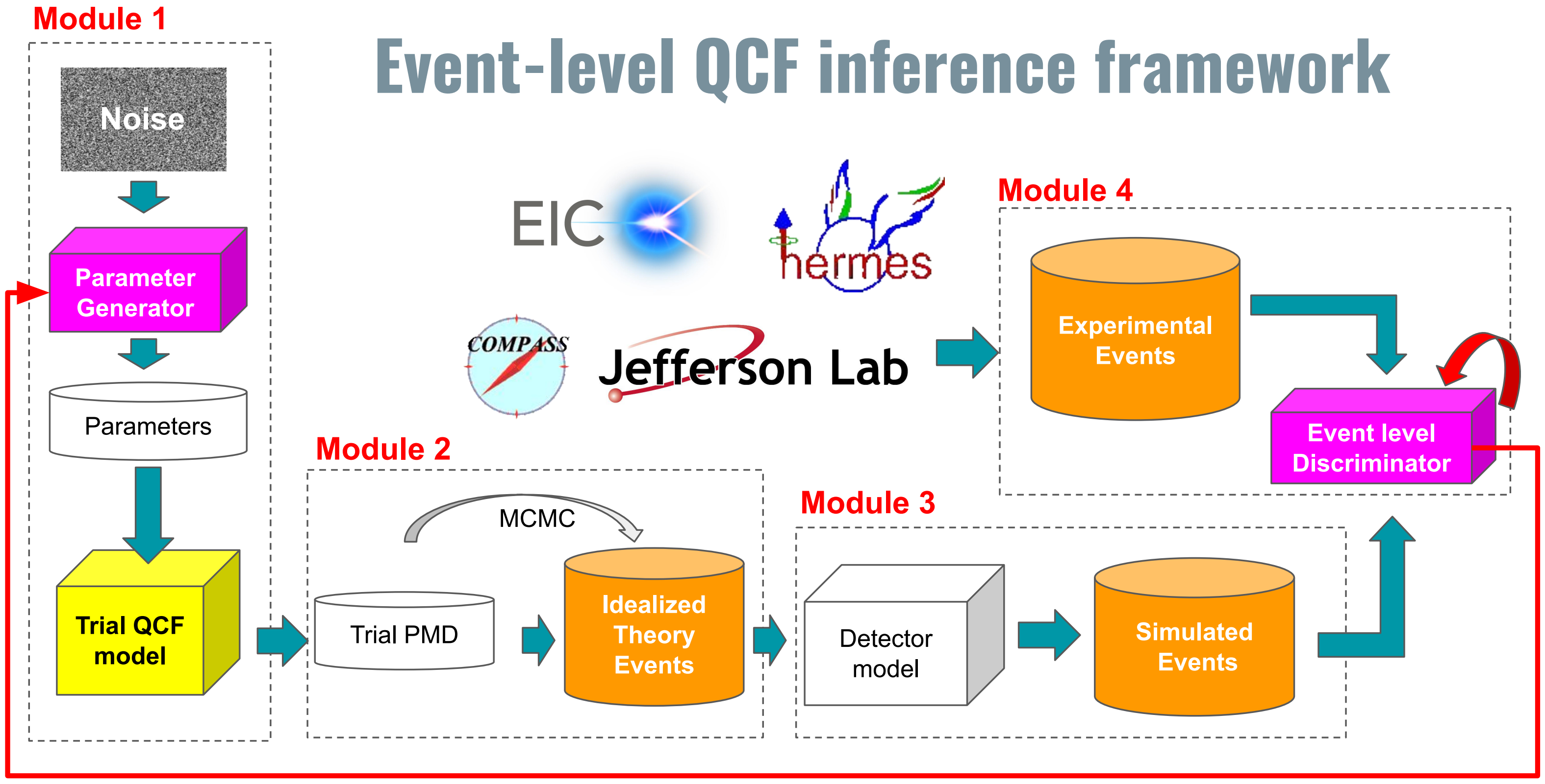
- Avoid histograms and minimize systematic uncertainties
- Avoid unfolding and use direct simulation at the event level



QuantOm Collaboration – a 5-year SciDAC project

❑ Femtoscale Imaging of Nuclei using Exascale Platforms:

Pixelating hadron in terms of probabilities to find quarks and gluons in slices of the momentum fraction x



Optimize QCF parameters (or pixelated images)

PMD: Particle Momentum Distribution - Observables
QCF: Quantum Correlation Functions: PDFs, TMDs, GPDs, …

QuantOm Collaboration

NP: ANL(Lead), JLab, ODU, VT
ASCR: FASTMath, RAPIDs

Exp Events (PMD):

- **DIS:**
  1 particle inclusive
- **SIDIS:**
  2 particle inclusive
- **SDHEP:**
  3 particle exclusive

Generated Events:

Many templates from trial QCFs & trusted theory

Inference:

Optimized QCFs or pixelated images in trusted phase space

New regimes:

Go beyond the trusted phase space

Summary and Outlook

- **GPDs are fundamental parton correlation functions of an "unbroken" hadron:**
  - **Carry rich information on emergent hadron properties (mass, spin, …) from QCD/parton dynamics**
  - **Are responsible for the tomographic images of confined quarks and gluons inside a bound hadron**
  - **Provide the much needed hints on how confined quarks/gluons respond to the probing scale, …**

Extracting their x-dependence from experimental observable(s) is non-trivial, but, full of opportunities, …

- **SDHEP provides a reliable way to explore tomography of a hadron without breaking them:**
  - **Covered all existing/known processes for extracting GPDs, plus ideas for new observables, …**
  - **Introduced new SDHEPs that could be more sensitive to the x-dependence of GPDs**
  - **Angular modulation between diffractive plane and hard scattering plane could provide unique opportunity to separate various GPDs (similar to the separation of TMDs in SIDIS)**
  - **Exclusive photoproduction at JLab and quasi-photoproduction at the EIC could provide excellent opportunities for extracting GPDs & their x-dependence, …**

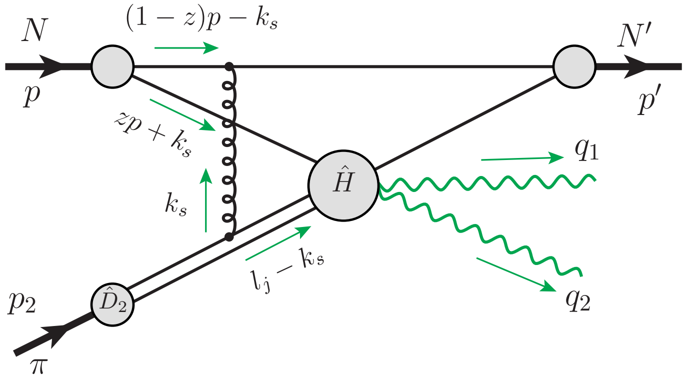
Exclusive processes provide opportunities for exploring the GPDs and the confined phenomena of QCD

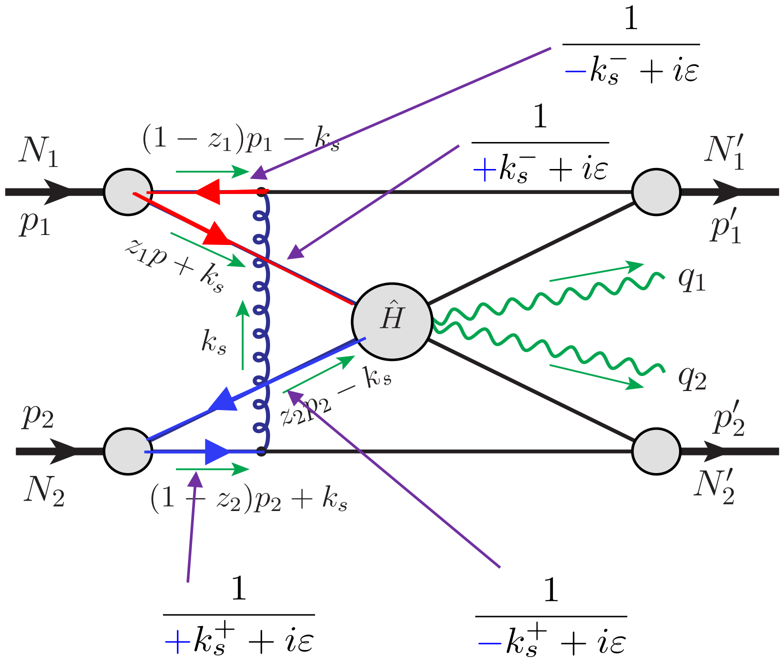
Thanks!

Why *single* diffractive?

- Double diffractive process

  Glauber pinch for diffractive scattering



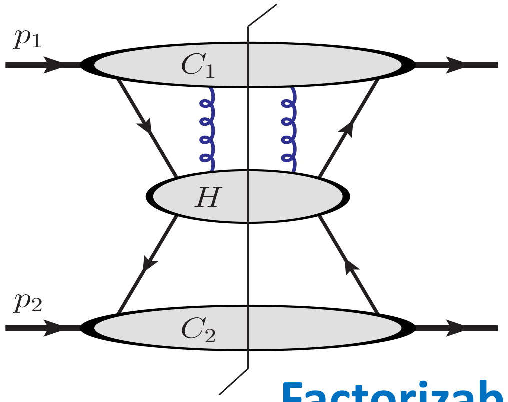


Factorizable if all pion momentum flows into hard part

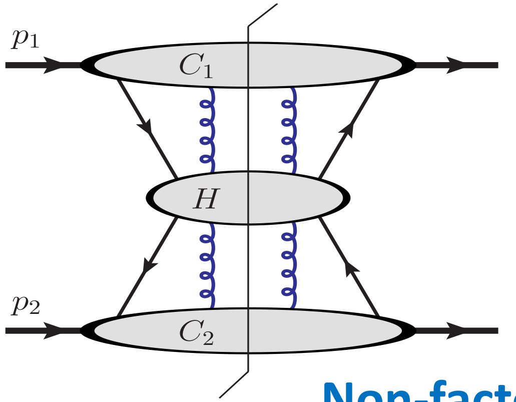
Both k_s^+ and k_s^- are pinched in Glauber region!

Break of factorization

- Compare: Drell-Yan process at high twist:



Factorizable



Non-factorizable

Only the 1st sub-leading twist is factorizable!

Qiu & Sterman, NPB, 1991

Jefferson Lab