The 16th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon

October 16-20, 2023
Erbacher Hof, Mainz, Germany

Electron-Ion Collider - A Giant CT Scanner for Nucleons and Nuclei

– Opportunities and Challenges for Theory

- **Nuclear Femtography & Hadron Properties:**
  Need of Two-scale observables
  ➡ Localized probe + sensitivity to structure
- **Particle Nature of Quarks and Gluons**
  ➡ 3D confined hadron structure
- **Wave Nature of Quarks and Gluons**
  ➡ Hard probe at small-x is not localized
- **Summary and outlook**

See talks by S. Fazio & S. Dalla Torre

Jian-Wei Qiu
Jefferson Lab, Theory Center

Frontiers of QCD and Strong Interaction

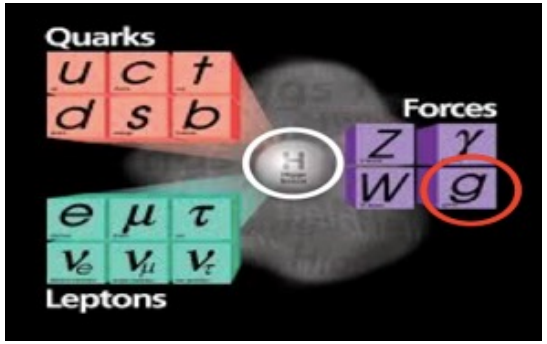
- **Understanding where did we come from?**

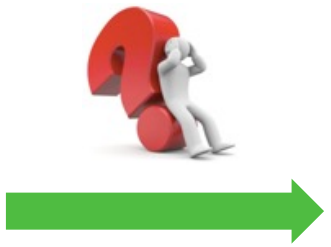
Global Time: →

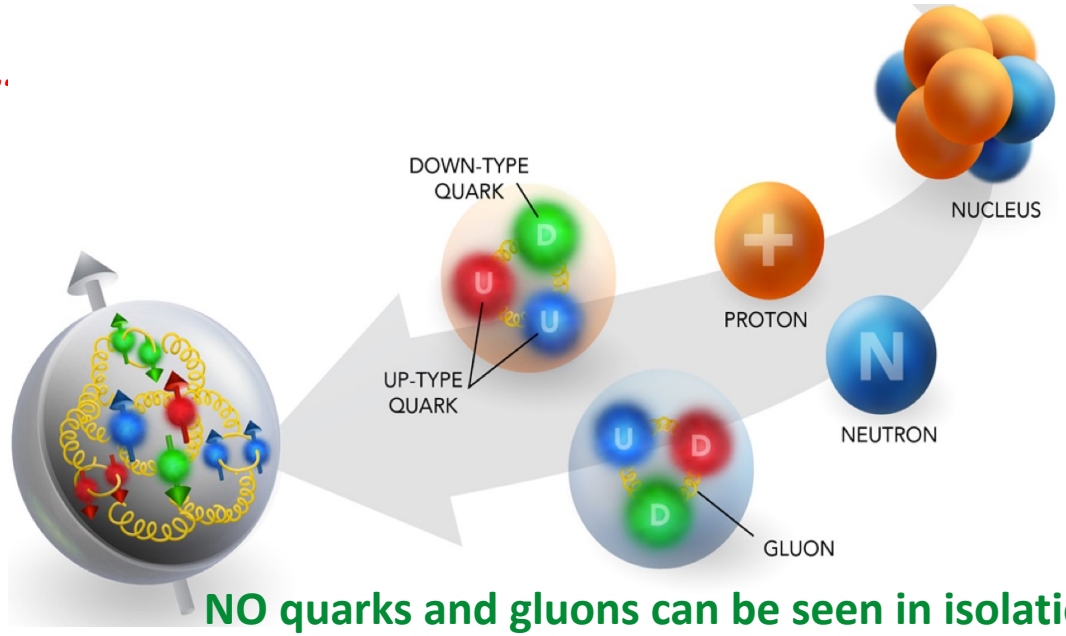
QCD at high temperature, high densities, phase transition, …

Facilities – Relativistic heavy ion collisions: SPS, RHIC, the LHC, ..

- **Understanding what are we made of?**







NO quarks and gluons can be seen in isolation!

- **Try to understand the emergent properties of nucleon and nuclei (elements of the periodic table) in terms of elements of the modern periodic table?**
- **Understanding QCD fully is still beyond the best mind that we have!**

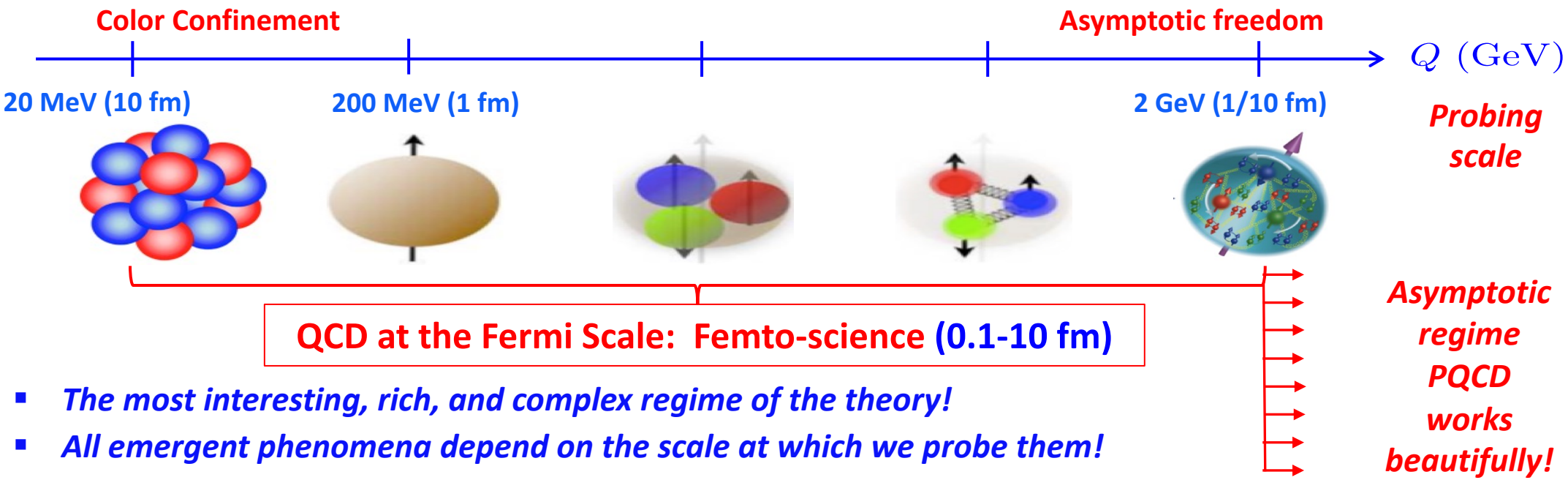
Nuclear Femtography:

Search for answers to these questions at a Fermi scale!

Facilities – CEBAF, EIC, EICC, LHeC, …

Jefferson Lab

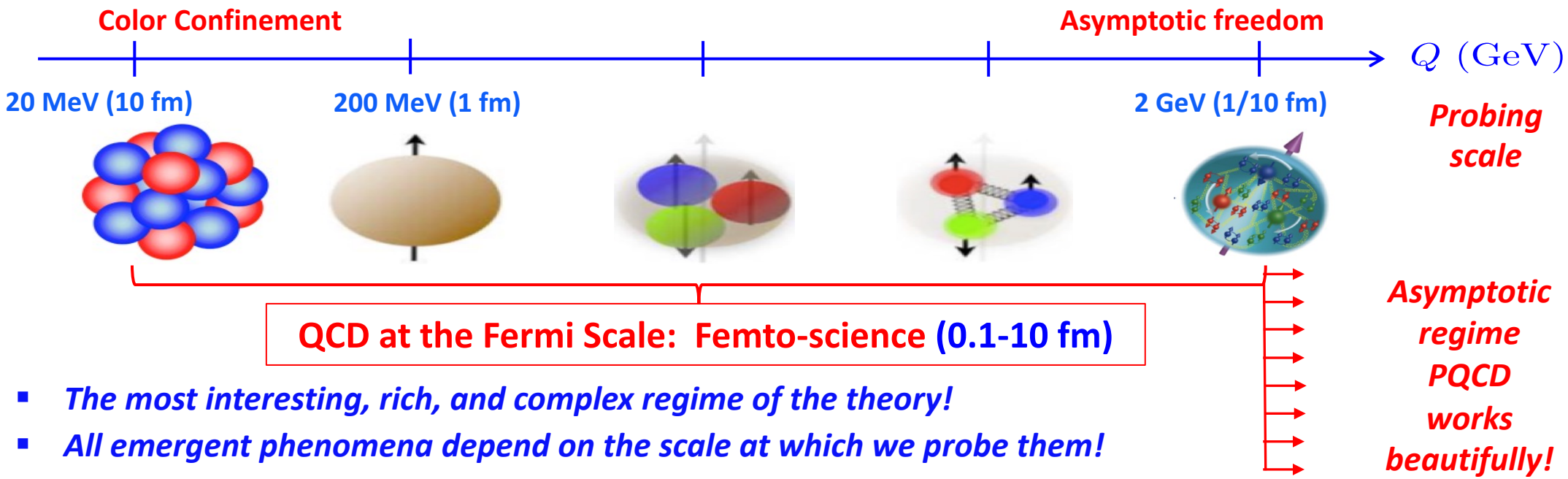
Nuclear Femtography: QCD Dynamics/Phenomena at the Fermi-Scale



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

Jefferson Lab

Nuclear Femtography: QCD Dynamics/Phenomena at the Fermi-Scale

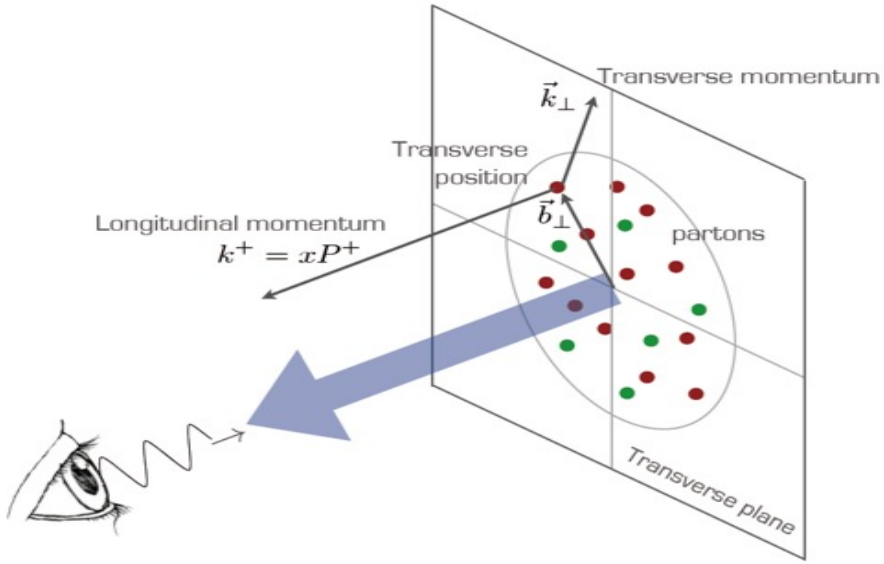


- *The most interesting, rich, and complex regime of the theory!*
- *All emergent phenomena depend on the scale at which we probe them!*

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

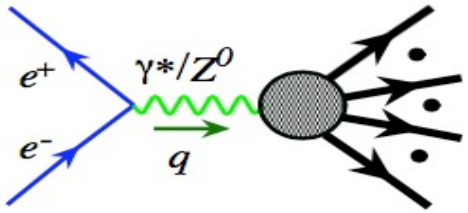
$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\rm QCD}$$

- **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**

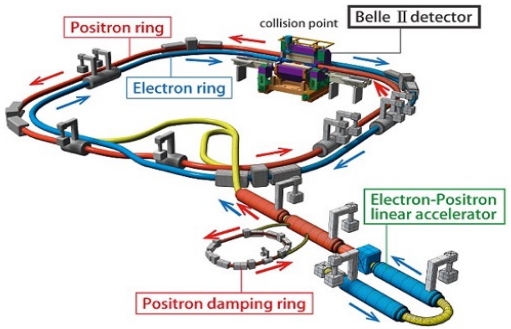


Exploring QCD & Hadron Structure needs Lepton-Hadron Facilities

- **Lepton-lepton colliders (e+e- collisions):**

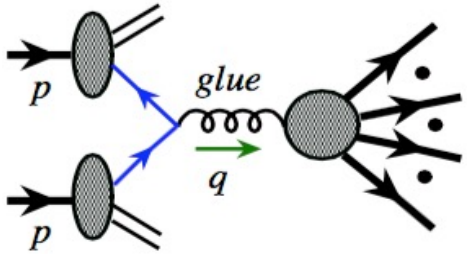


- *No hadron to start with*
- *Hadrons are produced in the collisions*
- *Emergence of hadrons*

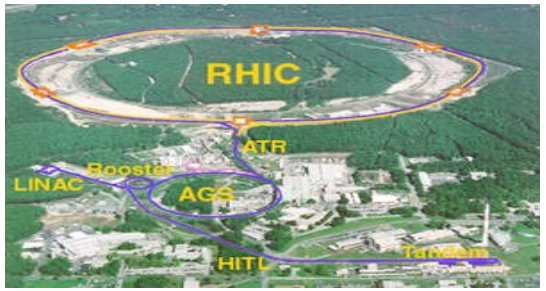


Also BES III

- **Hadron-hadron facilities (hadrons are likely broken in the collisions):**

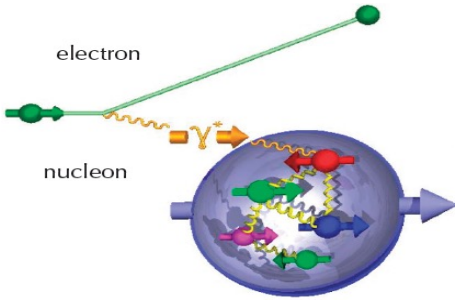


- *Partonic structure mixed with collision effects*
- *Emergence of hadrons*
- *Heavy ion beam(s) – dense medium, QGP*

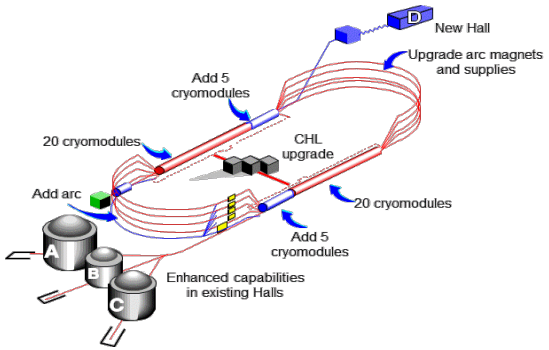


Also the LHC, J-PARC, …

- **Lepton-hadron facilities (HERA discovery: hadron stays intact 10-15% time):**



- *Two-scale observables are natural*
- *Imaging partonic structure without breaking it!*
- *Emergence of hadrons*
- *Heavy ion target or beam*



Also future EIC, COMPASS/Amber, …

Ideal facility for partonic structure of hadron/nuclei !

Jefferson Lab

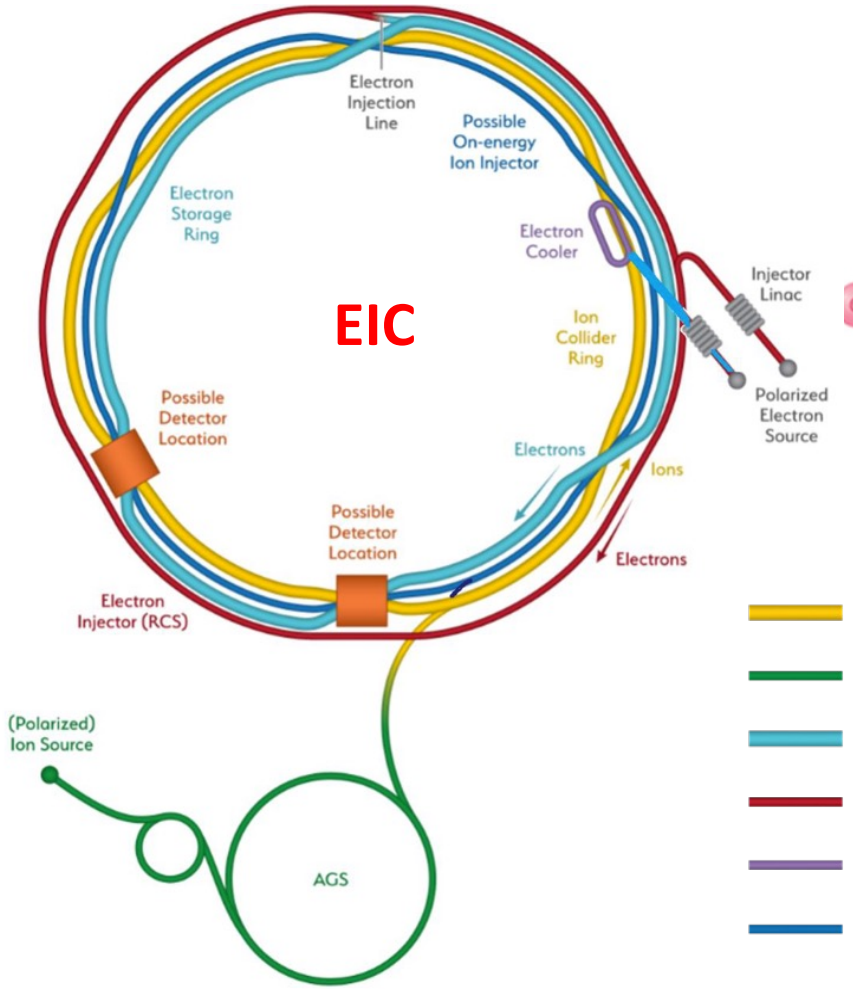
U.S. - based Electron-Ion Collider (EIC)

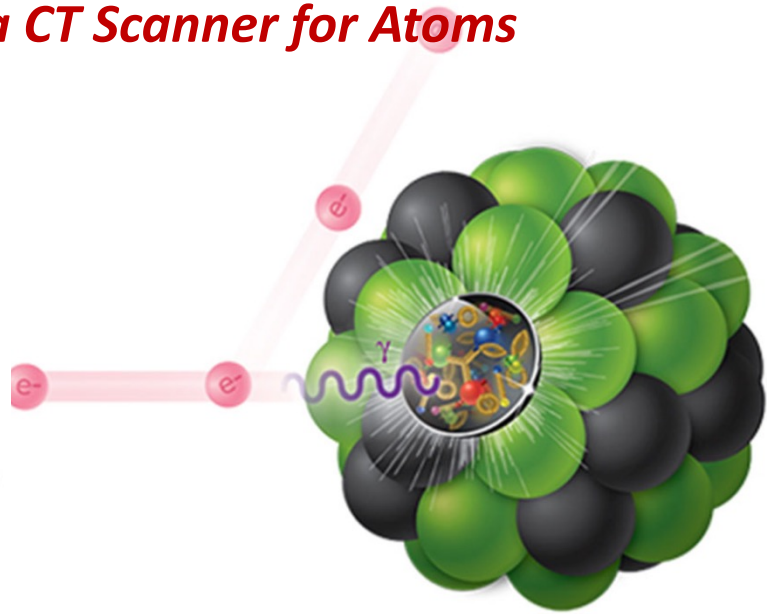
https://www.bnl.gov/eic/

See talks by S. Fazio & S. Dalla Torre

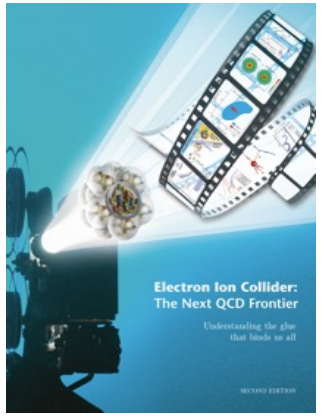
A machine that will unlock the secrets of the strongest force in Nature

Like a CT Scanner for Atoms





- Hadron Storage Ring
- Hadron Injector Complex
- Electron Storage Ring
- Electron Injector Synchrotron
- Electron Cooler
- Possible On-energy Hadron Injector Ring



Basic Tech Requirements

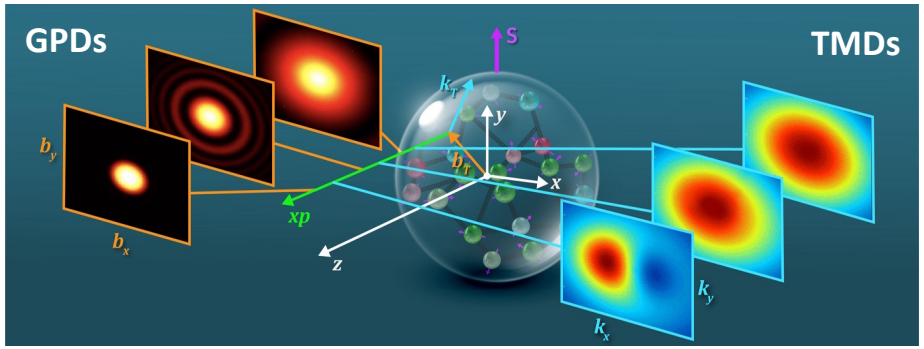
- **Center of Mass Energies:**
  20 GeV – 141 GeV
- **Required Luminosity:**
  10^{33} - 10^{34} $cm^{-2}s^{-1}$
- **Hadron Beam Polarization:**
  80%
- **Electron Beam Polarization:**
  80%
- **Ion Species Range:**
  p to Uranium
- **Number of interaction regions:**
  up to two

Jefferson Lab

US-EIC – can do what HERA could not do

- **Quantum imaging:**
  - **HERA discovered: 10-15% of e-p events is diffractive – Proton not broken!**
  - **US-EIC: 100-1000 times luminosity – *Critical for 3D tomography!***

Large momentum transfer without breaking the proton Luminosity!



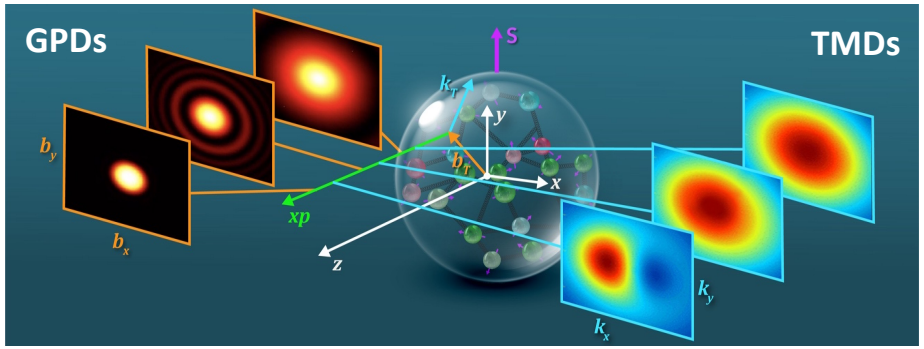
Jefferson Lab

US-EIC – can do what HERA could not do

- **Quantum imaging:**
  - ✧ **HERA discovered: 10-15% of e-p events is diffractive – Proton not broken!**
  - ✧ **US-EIC: 100-1000 times luminosity – *Critical for 3D tomography!***

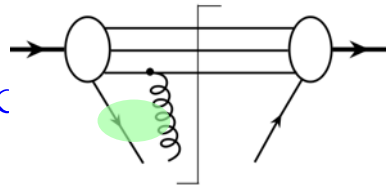
Large momentum transfer without breaking the proton Luminosity!

- **Quantum interference & entanglement:**
  - ✧ **US-EIC: Highly polarized beams – *Origin of hadron property: Spin, …***
    Direct access to chromo-quantum interference!



$$\sigma(Q,\vec{s}) \propto \left| \text{[diagrams: } p,\vec{s};\ k;\ \leftarrow t \sim 1/Q;\ + \text{ diagrams} \right|^2$$

$\sigma(s) - \sigma(-s)$ ➡ **Quantum interference** ➡ $T^{(3)}(x,x) \propto$



No probability interpretation!

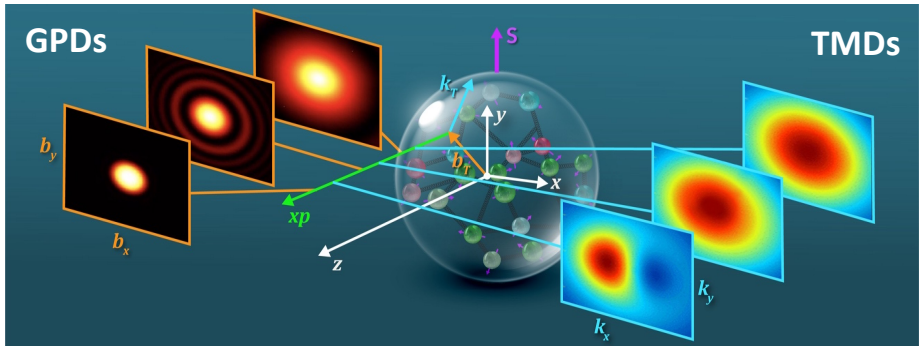
Jefferson Lab

US-EIC – can do what HERA could not do

- **Quantum imaging:**
  - ✧ **HERA discovered: 10-15% of e-p events is diffractive – Proton not broken!**
  - ✧ **US-EIC: 100-1000 times luminosity – *Critical for 3D tomography!***

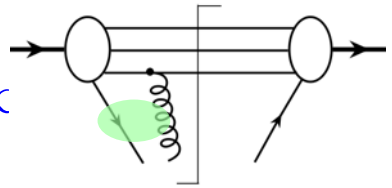
Large momentum transfer without breaking the proton Luminosity!

- **Quantum interference & entanglement:**
  - ✧ **US-EIC: Highly polarized beams – *Origin of hadron property: Spin, …***
    Direct access to chromo-quantum interference!



$$\sigma(Q,\vec{s}) \propto \left| \text{[diagrams: } p,\vec{s};\ k;\ \leftarrow t \sim 1/Q;\ + \text{ diagrams} \right|^2$$

$\sigma(s) - \sigma(-s)$ ➡ **Quantum interference** ➡ $T^{(3)}(x,x) \propto$



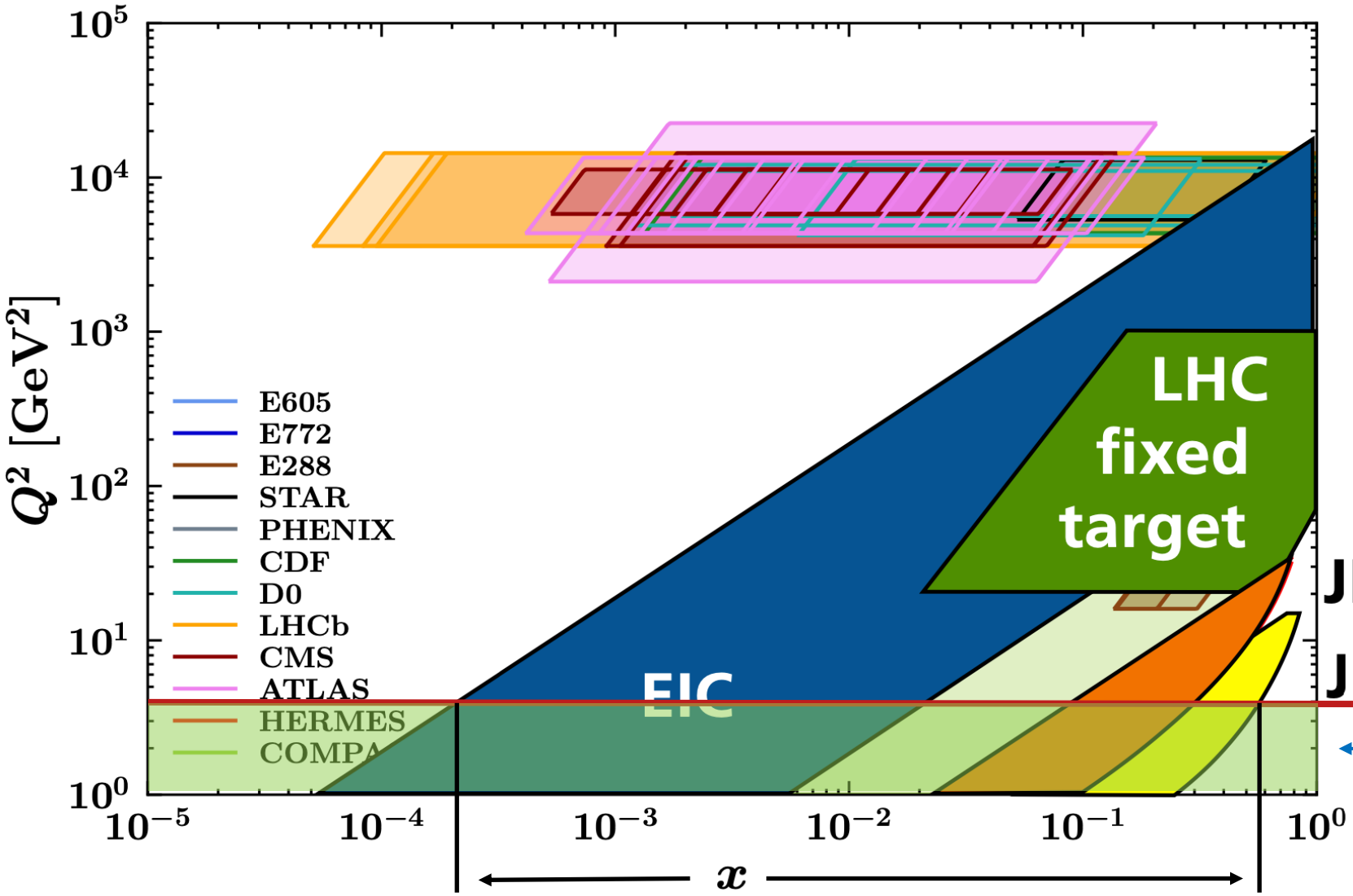
No probability interpretation!

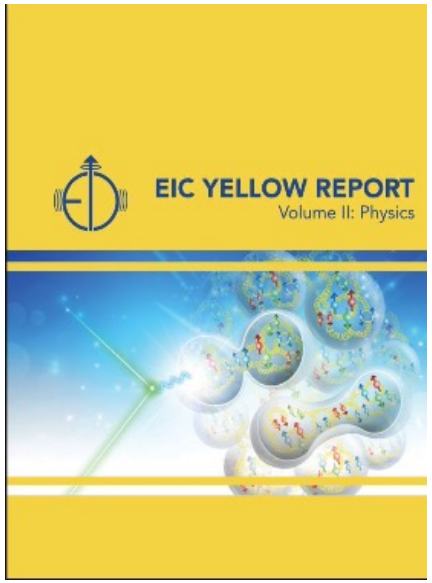
- **Nonlinear quantum dynamics:**
  - ✧ **US-EIC: Light-to-heavy nuclear beams – *Origin of nuclear force, …***
    Catch the transition from chromo-quantum fluctuation to chromo-condensate of gluons, …
    Emergence of hadrons (nuclei as femtometer size detectors!),
    – "a new controllable knob" – Atomic weight of nuclei

Wave nature of quark/gluon field

Jefferson Lab

Phase-Space Coverage by the Facilities around the World:





arXiv:2103.05419

Asymptotic purbative regime PQCD works beautifully!

JLab 22

JLab 12

0.1 fm

Q_1 Lives here

Transition Region

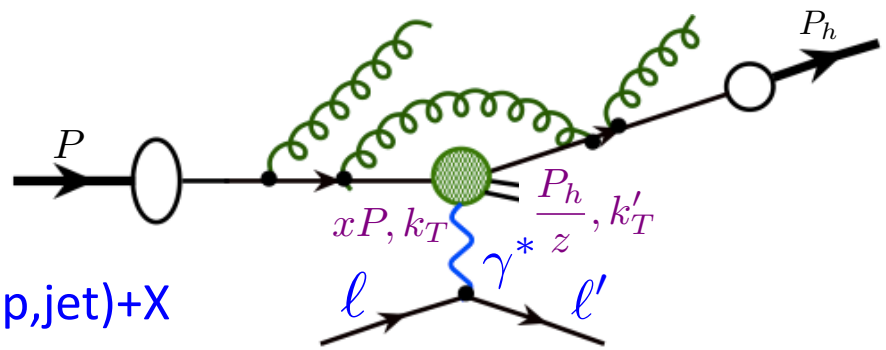
Q_2 Lives here

Jefferson Lab

Lepton-Hadron Semi-Inclusive Deep Inelastic Scattering (DIS)

- SIDIS naturally covers both one-scale and two-scale observables:

See talk by B. Pasquini



e+p/A → e'+h(p,K,p,jet)+X

$$Q_1: \quad P_{h_T} \sim \ell'_T$$ In lepton-hadron frame

$$Q_2: \quad |\vec{P}_{h_T} + \vec{\ell}'_T| \ll |\vec{P}_{h_T}| \sim Q_1$$

Naturally sensitive to parton transverse motion

TMDs

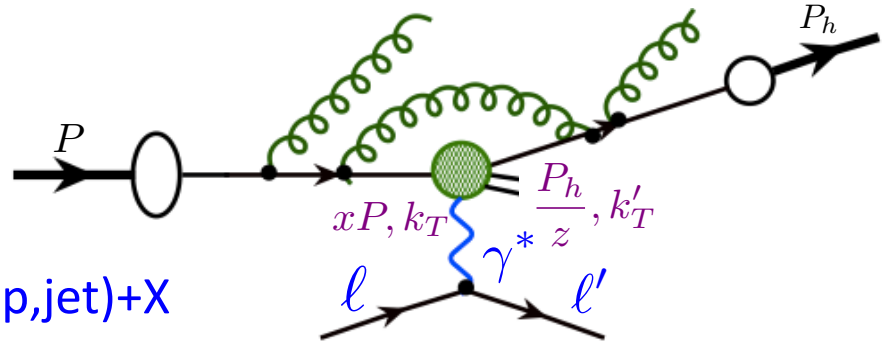
See also TMD Handbook [2304.03302]

Jefferson Lab

Lepton-Hadron Semi-Inclusive Deep Inelastic Scattering (DIS)

- **SIDIS naturally covers both one-scale and two-scale observables:**

See talk by B. Pasquini



e+p/A → e'+h(p,K,p,jet)+X

$$Q_1: \quad P_{h_T} \sim \ell'_T$$ In lepton-hadron frame

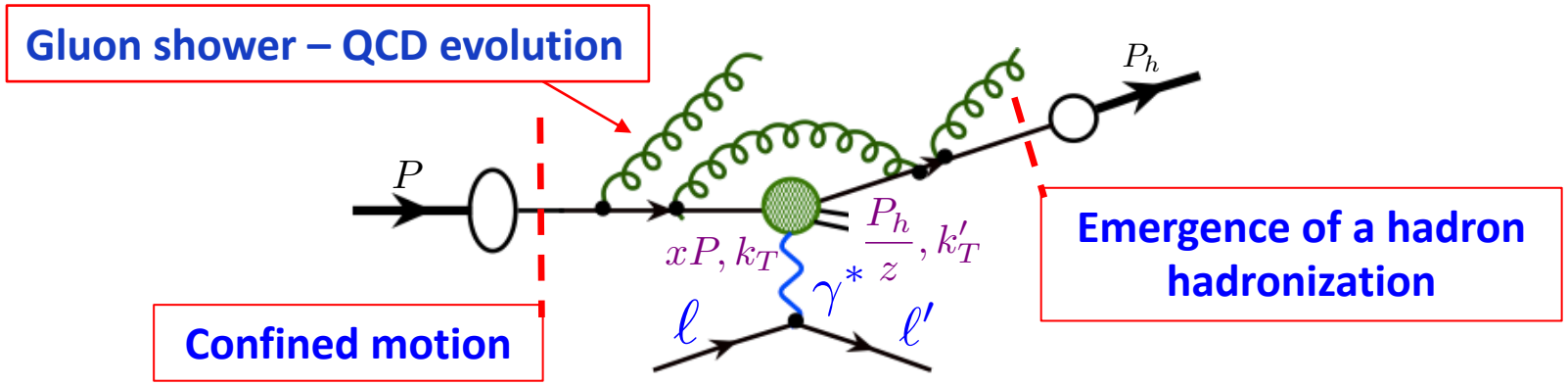
$$Q_2: \quad |\vec{P}_{h_T} + \vec{\ell}'_T| \ll |\vec{P}_{h_T}| \sim Q_1$$

Naturally sensitive to parton transverse motion

TMDs

See also TMD Handbook [2304.03302]

- **But, if the proton is broken, …**



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 is mixed with collision effects!***

Structure information is diluted by the collision induced shower!

Jefferson Lab

Transverse momentum dependent PDFs (TMDs) – Power of SIDIS

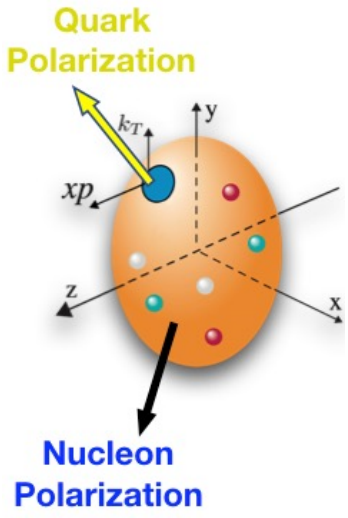
See talk by B. Pasquini

❑ Quark TMDs with polarization:

Nucleon Polarization	Quark Polarization: Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	$f_1(x,k_T^2)$		$h_1^\perp(x,k_T^2)$ Boer-Mulders
L		$g_1(x,k_T^2)$ Helicity	$h_{1L}^\perp(x,k_T^2)$ Long-Transversity
T	$f_1^\perp(x,k_T^2)$ Sivers	$g_{1T}(x,k_T^2)$ Trans-Helicity	$h_1(x,k_T^2)$ Transversity; $h_{1T}^\perp(x,k_T^2)$ Pretzelosity

Analogous tables for:

- **Gluons** $f_1 \to f_1^g$ etc
- **Fragmentation functions**
- **Nuclear targets** $S \neq \frac{1}{2}$



See also TMD Handbook [2304.03302]

Jefferson Lab

Transverse momentum dependent PDFs (TMDs) – Power of SIDIS

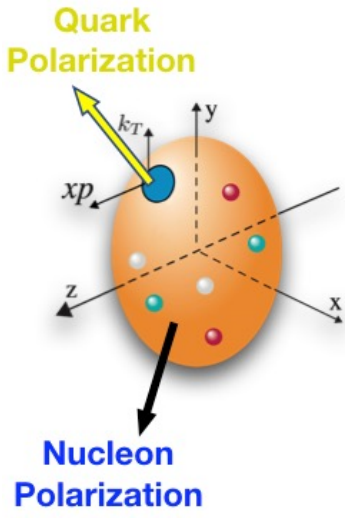
See talk by B. Pasquini

❑ Quark TMDs with polarization:

Nucleon Polarization	Quark Polarization: Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	$f_1(x,k_T^2)$		$h_1^\perp(x,k_T^2)$ Boer-Mulders
L		$g_1(x,k_T^2)$ Helicity	$h_{1L}^\perp(x,k_T^2)$ Long-Transversity
T	$f_1^\perp(x,k_T^2)$ Sivers	$g_{1T}(x,k_T^2)$ Trans-Helicity	$h_1(x,k_T^2)$ Transversity; $h_{1T}^\perp(x,k_T^2)$ Pretzelosity

Analogous tables for:

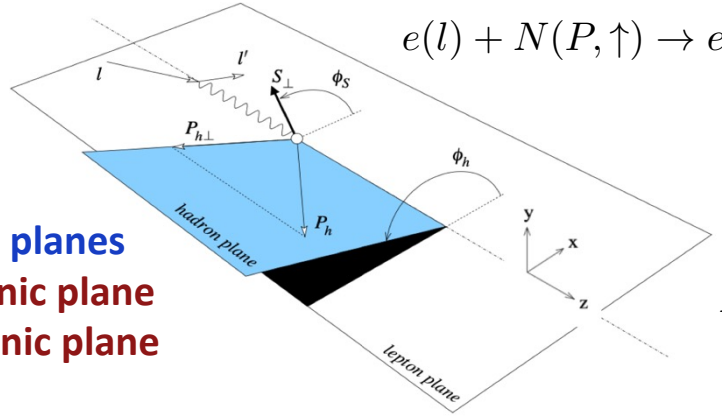
- **Gluons** $f_1 \to f_1^g$ etc
- **Fragmentation functions**
- **Nuclear targets** $S \neq \frac{1}{2}$



See also TMD Handbook [2304.03302]

❑ Polarized SIDIS:

$$e(l) + N(P,\uparrow) \to e(l') + h(P_h) + X$$



Two planes
Leptonic plane
Hadronic plane

Single Transverse-Spin Asymmetry

$$A_{UT} = \frac{1}{P}\frac{\sigma_{lN(\uparrow)} - \sigma_{lN(\downarrow)}}{\sigma_{lN(\uparrow)} + \sigma_{lN(\downarrow)}}$$

In photon-hadron frame:

$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^\perp$$

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^\perp \otimes D_1$$

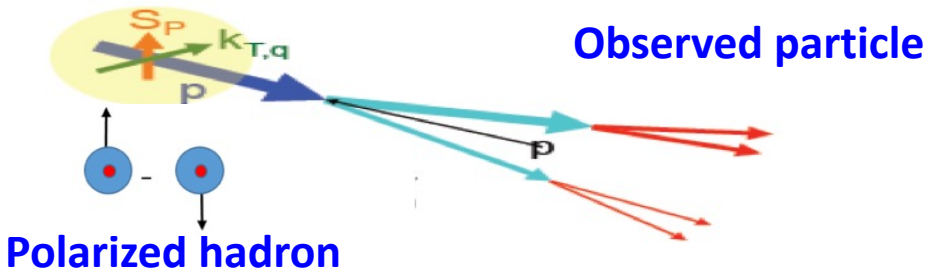
$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^\perp \otimes H_1^\perp$$

Angular modulation provides the best way to separate TMDs

Jefferson Lab

TMDs: Correlation between Hadron Property and Parton Flavor-Spin-Motion

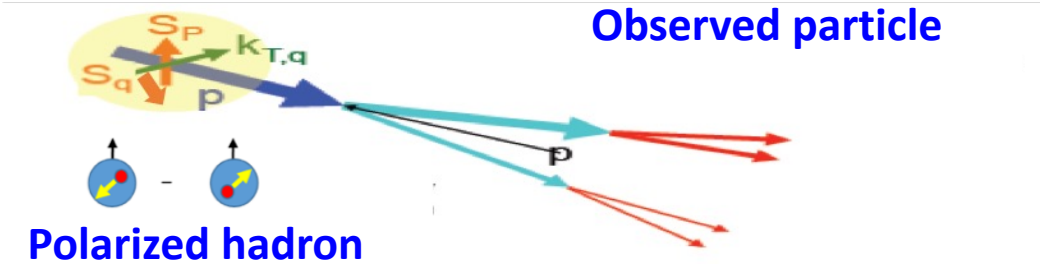
- **Quantum correlation between hadron spin and parton motion:**



Sivers effect – Sivers function

Hadron spin influences parton's transverse motion

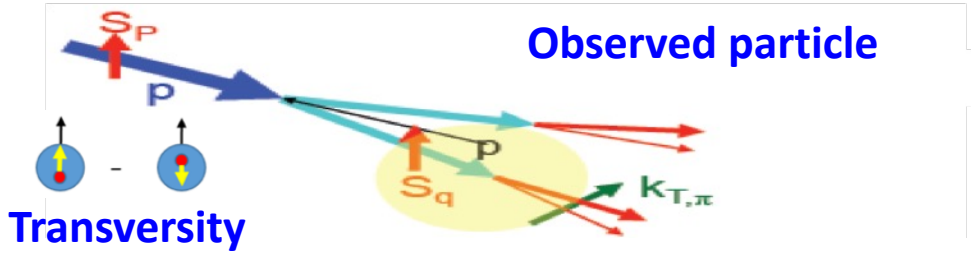
- **Quantum correlation between hadron spin and parton spin:**



Pretzelosity – model OAM

Hadron spin and parton spin influence parton's transverse motion

- **Quantum correlation between parton's spin and its hadronization:**



Collins effect – Collins function

Parton's transverse polarization influences its hadronization

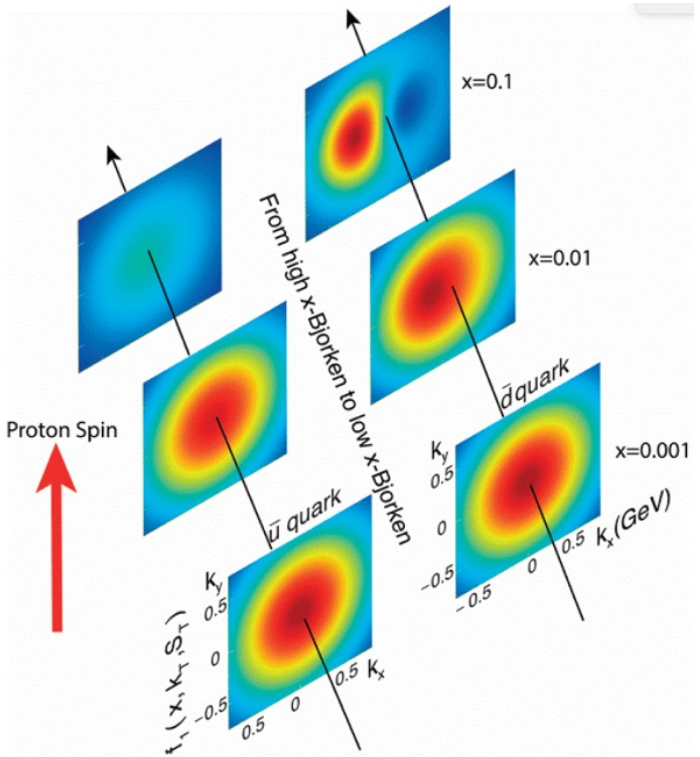
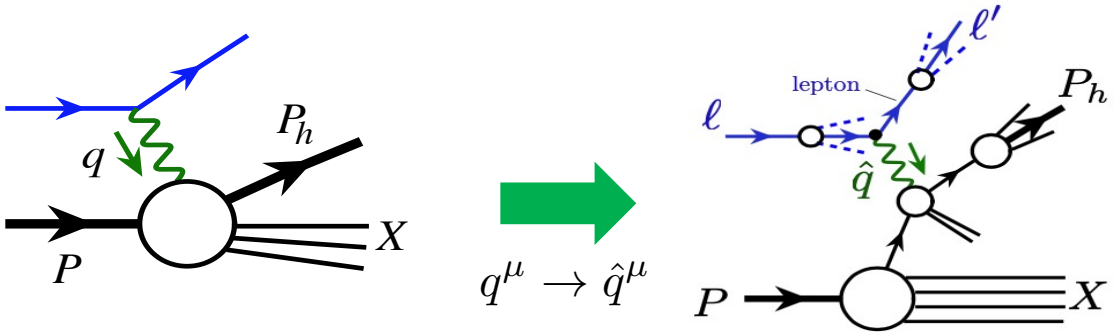


Fig. 2.7 NAS Report

Jefferson Lab

Collision-Induced QED Radiation to SIDIS – Major Challenge

- **QED radiation modifies the probe for the hadron:**



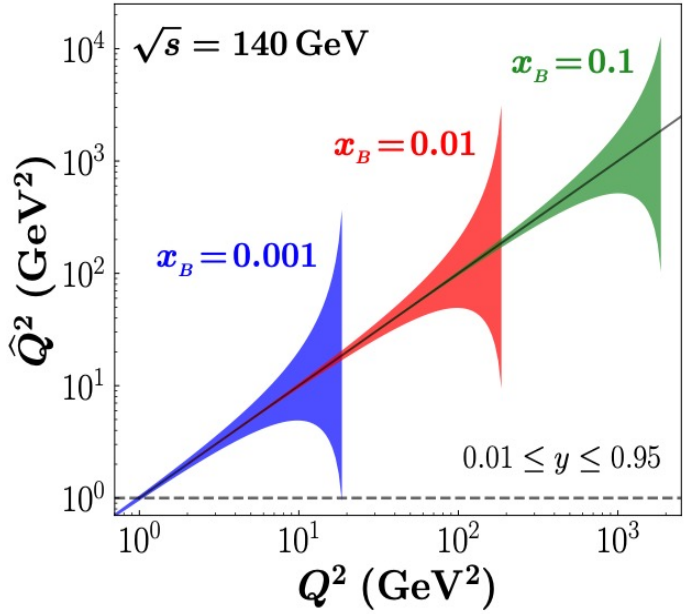
- **Prevents a well-defined "photon-hadron" frame**
- **Radiation is IR sensitive as** $m_e/Q \to 0$

$$(x_B, Q^2) \to (\hat{x}_B, \widehat{Q}^2)$$

$$x_B \to \hat{x}_B \in [x_B, 1]$$

$$\widehat{Q}^2_{\rm min} = Q^2 \frac{(1-y)}{(1-x_B\, y)} \leq Q^2$$

$$\widehat{Q}^2_{\rm max} = Q^2 \frac{1}{(1-y+x_B\, y)}$$

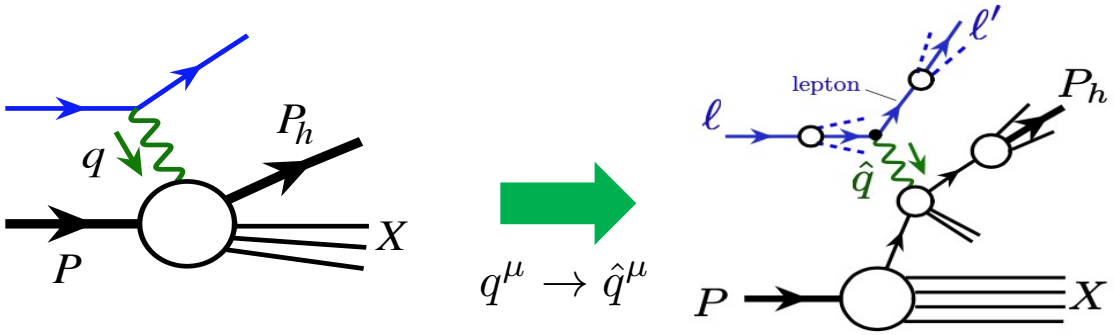


Liu, Melnitchouk, Qiu, Sato
2008.02895, 2108.13371

Jefferson Lab

Collision-Induced QED Radiation to SIDIS – Major Challenge

- **QED radiation modifies the probe for the hadron:**



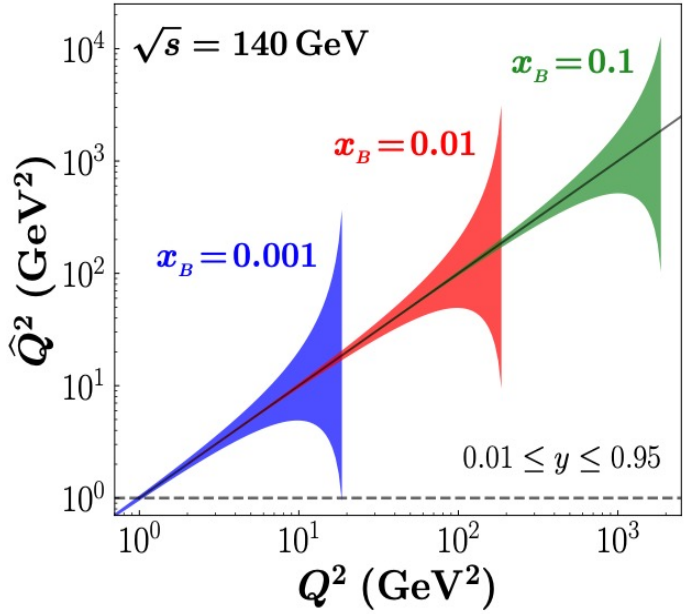
  - **Prevents a well-defined "photon-hadron" frame**
  - **Radiation is IR sensitive as** $m_e/Q \to 0$

$$(x_B, Q^2) \to (\hat{x}_B, \widehat{Q}^2)$$

$$x_B \to \hat{x}_B \in [x_B, 1]$$

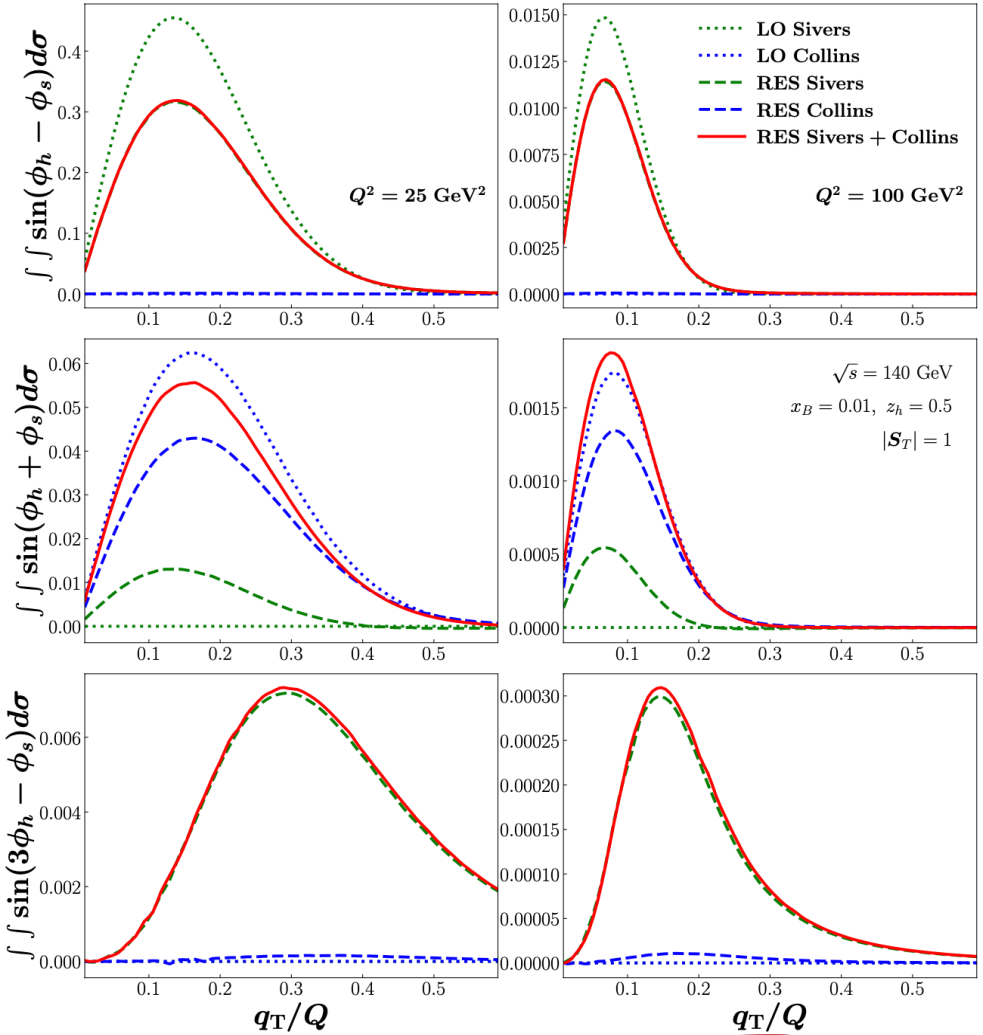
$$\widehat{Q}^2_{\min} = Q^2 \frac{(1-y)}{(1-x_B\, y)} \leq Q^2$$

$$\widehat{Q}^2_{\max} = Q^2 \frac{1}{(1-y+x_B\, y)}$$



Liu, Melnitchouk, Qiu, Sato
2008.02895, 2108.13371

- **Modify the angular modulations between leptonic and hadronic planes – the separation of TMDs ?**



Jefferson Lab

Collision-Induced QED Radiation to SIDIS – Major Challenge

- **QED factorization of collision-induced radiation – treating QED and QCD equally:**
  - Think the colliding lepton as the colliding hadron at the LHC, or RHIC

    DIS = Inclusive production of a high pT lepton: $(p_T, y) \to (x_B, Q^2)$

    SIDIS = Inclusive production of a high pT lepton and a high pT hadron (or a jet): $(\vec{\ell}', \vec{P}_h) \to (x_B, Q^2, z_h, P_{h_T}, \phi)$

$$E_{\ell'} E_{P_h} \frac{\mathrm{d}^6\sigma_{\ell(\lambda_\ell)P(S)\to\ell' P_h X}}{\mathrm{d}^3\ell'\,\mathrm{d}^3P_h} \approx \sum_{ij\lambda_k} \int_{\zeta_{\min}}^1 \frac{\mathrm{d}\zeta}{\zeta^2} D_{e/j}(\zeta) \int_{\xi_{\min}}^1 \mathrm{d}\xi\, f_{i(\lambda_k)/e(\lambda_\ell)}(\xi) \left[E_{k'} E_{P_h} \frac{\mathrm{d}^6\hat{\sigma}_{k(\lambda_k)P(S)\to k' P_h X}}{\mathrm{d}^3k'\,\mathrm{d}^3P_h} \right]_{k=\xi\ell, k'=\ell'/\zeta} + \mathcal{O}\left(\frac{m_e^n}{Q^n}\right)$$

  - Leading power IR sensitive contribution is universal, as $m_e/Q \to 0$, and factorized into universal LDFs and LFFs

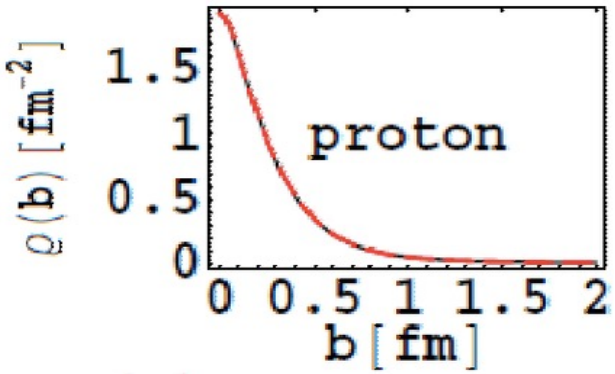
    [global fits of LDFs, LFFs]
  - IR safe contributions are calculated order-by-order in powers of α

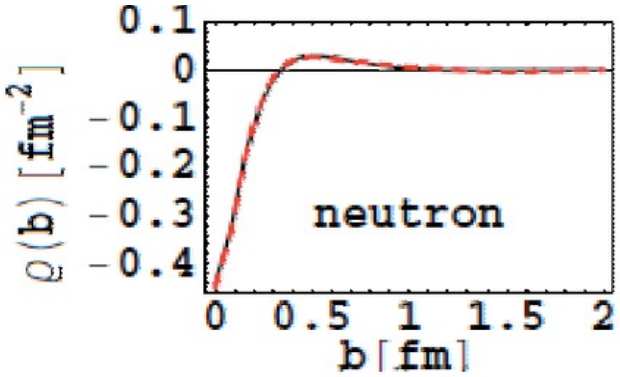
- **Hybrid factorization for the TMD regime:** Colinear for QED & TMD for QCD
  - QED contribution (not correction) to SIDIS can be systematically improved order-by-order in power α!
  - Two photon exchange is naturally included as the loop corrections to the "perturbative" hard parts – no cutoff!

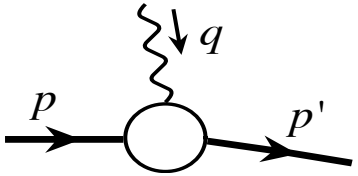
More works are needed for precise 3D in momentum space!

How to Explore Internal Structure of Hadron without Breaking it?

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

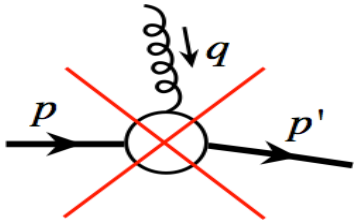






→ **Proton "Radius" in EM charge distribution**

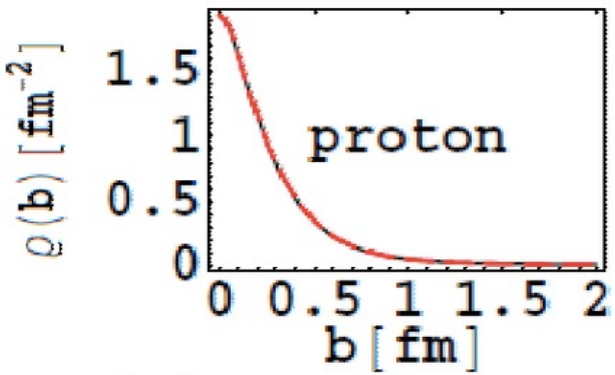
- **But, there is NO elastic "color" form factor!**

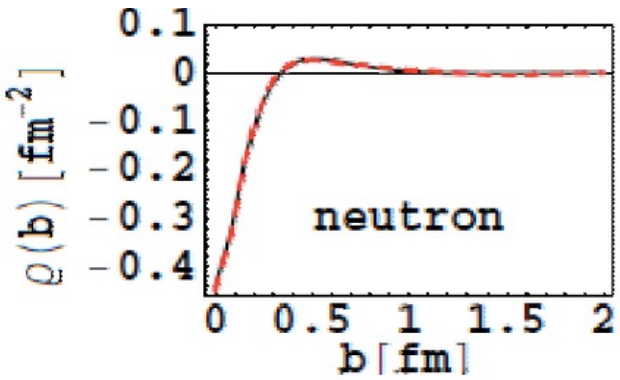


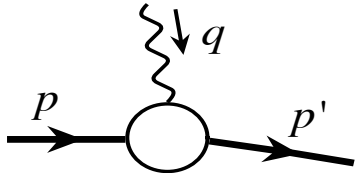
→ **No Proton "Radius" in color charge distribution!**

How to Explore Internal Structure of Hadron without Breaking it?

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

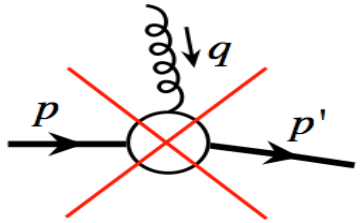






Proton "Radius" in EM charge distribution

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



No Proton "Radius" in color charge distribution!

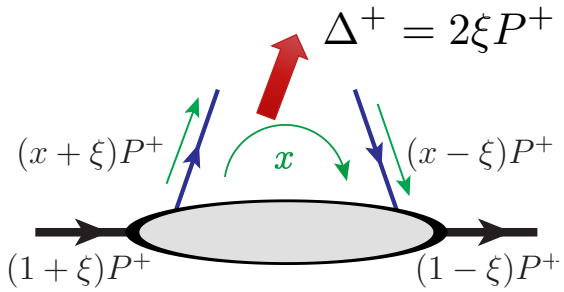
- **Combine PDF and Form Factor – GPDs:**

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

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

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

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



$\Delta = p - p'$

$t = \Delta^2$

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

Similar definition for gluon GPDs

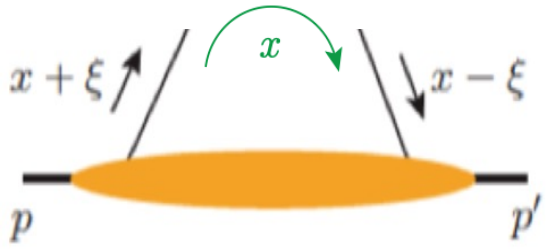
Jefferson Lab

Properties of GPDs – Partonic

- **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)

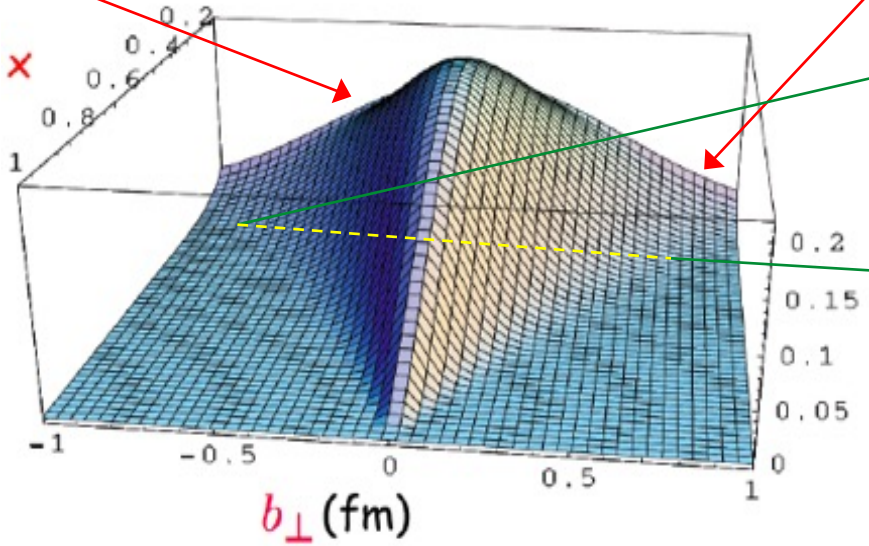
x = momentum flow between the pair

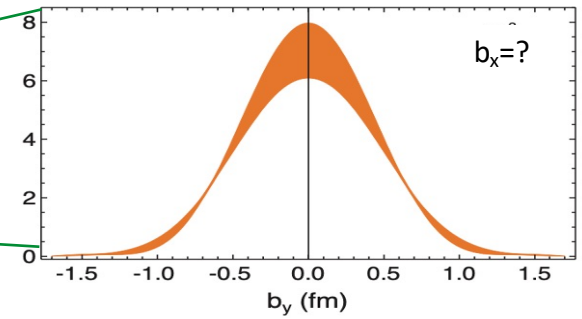
How fast does glue density fall?

Tomographic image of hadron in slice of x

How far does glue density spread?

➡





Slice in (x,Q)

Modeled by M. Burkdart, PRD 2000

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

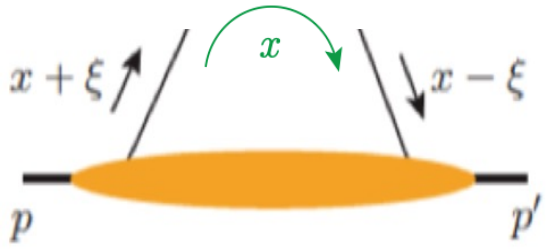
➡ **Proton radii from quark and gluon spatial density distribution,** $r_q(x)$ **&** $r_g(x)$

Properties of GPDs – Partonic

- **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)

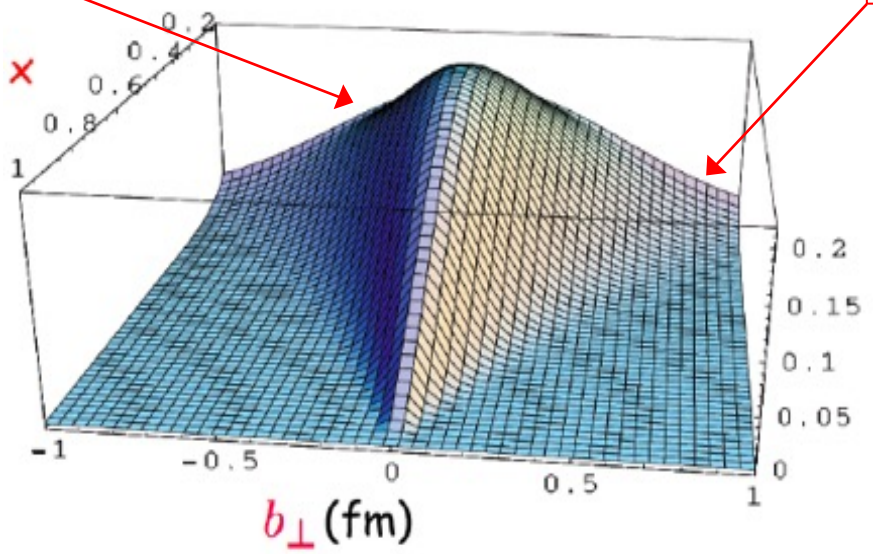
x = momentum flow between the pair

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

- **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, … ?**
- **…**

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

Jefferson Lab

Properties of GPDs – Hadronic

❑ 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:

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

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

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:

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

$$i = q, g$$

➡ **3D tomography**
Relation to GFF
Angular Momentum

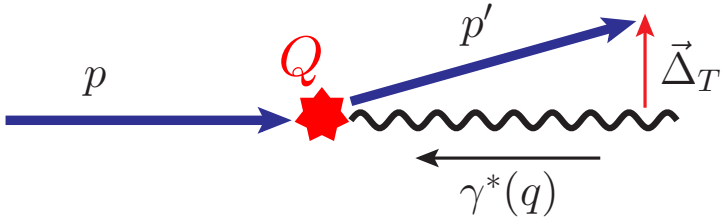
➡ ***x*-dependence of GPDs!**

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

Jefferson Lab

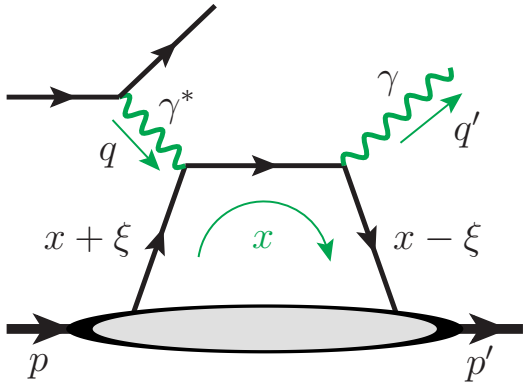
Exclusive Diffractive Processes for Extracting GPDs

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

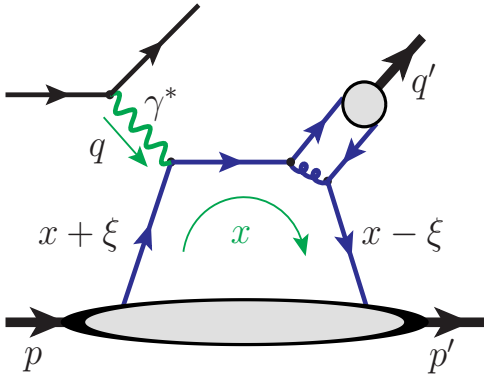


HERA discovery:
~ 10-15% of HERA events with the Proton stayed intact

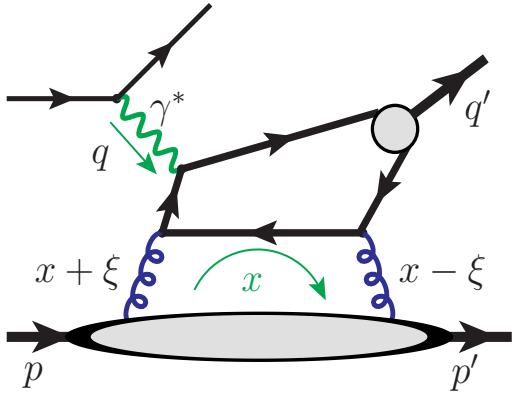
- **Known exclusive processes for extracting GPDs:**



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**

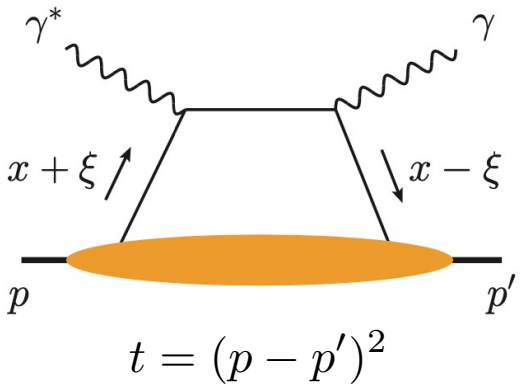
$\Rightarrow$ **Factorization**

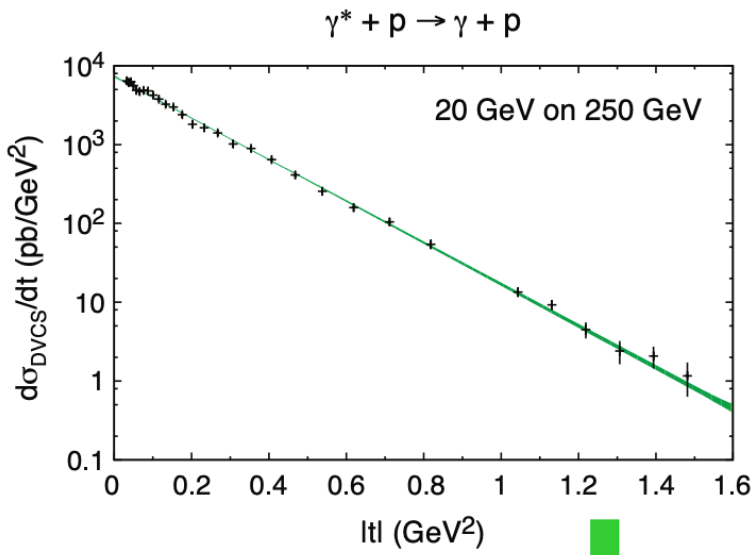
GPDs: $f_{i/h}(x, \xi, t; \mu)$

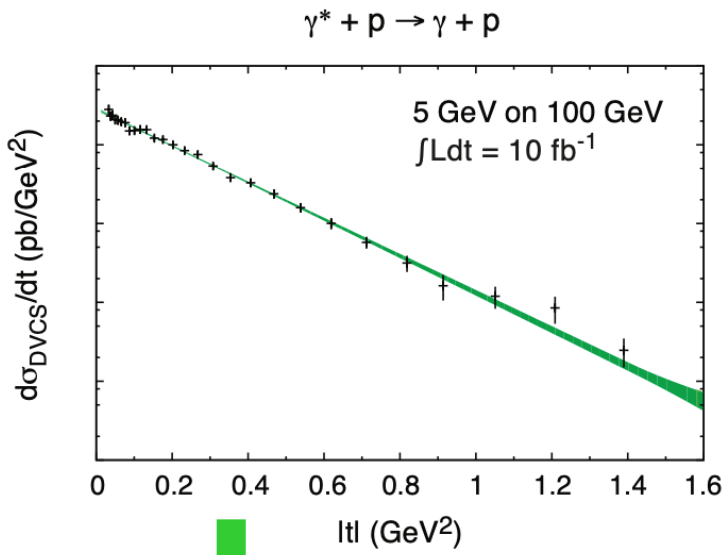
Jefferson Lab

DVCS at a Future EIC (White Paper)

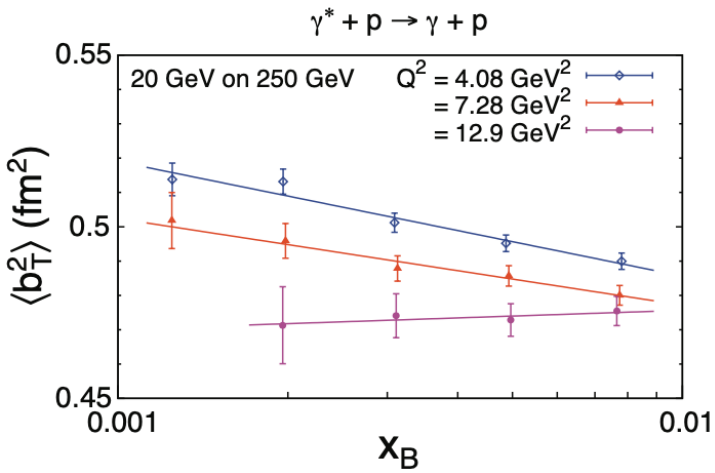
❑ Cross Sections:

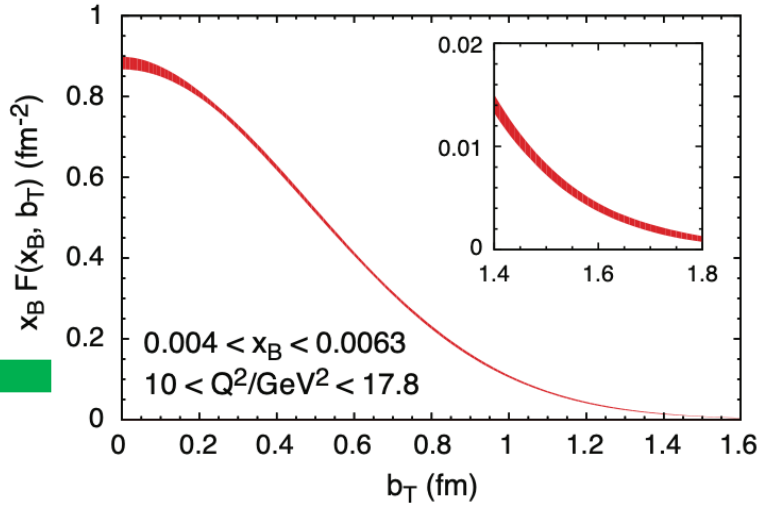


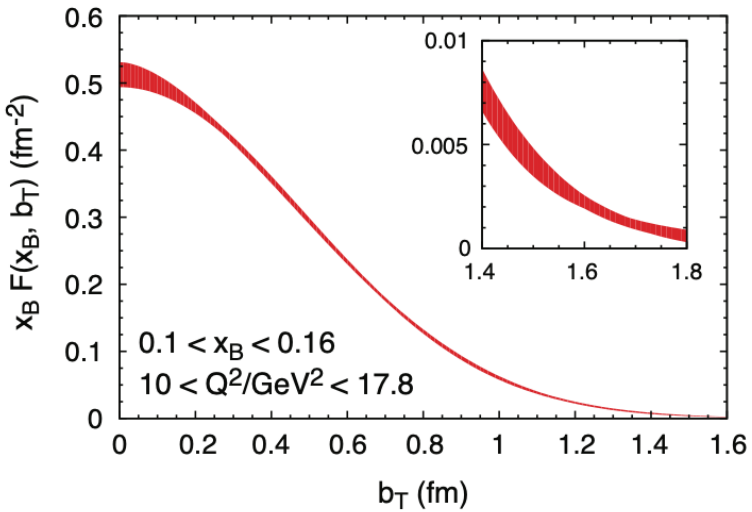




❑ Spatial distributions:





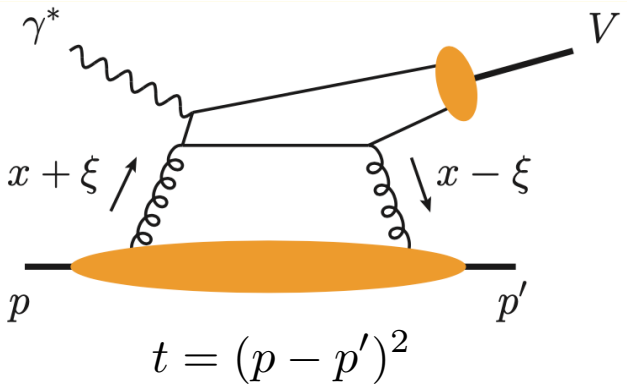


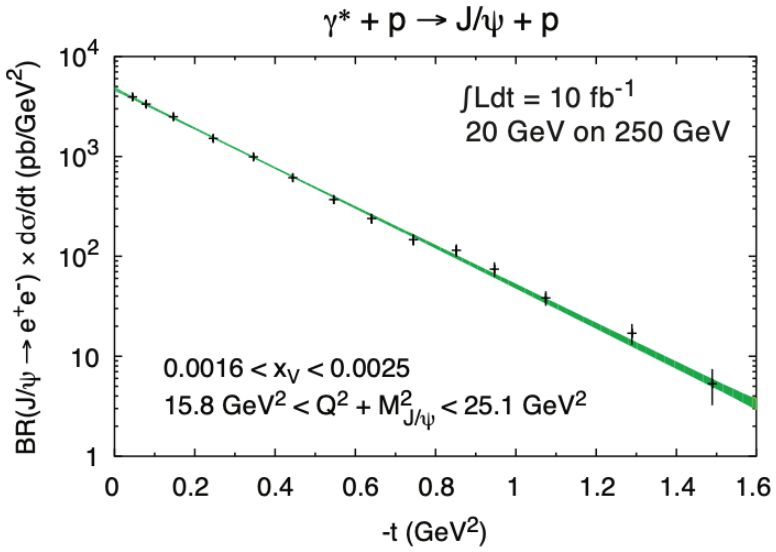
Effective "proton radius" in terms of quarks as a function of x_B

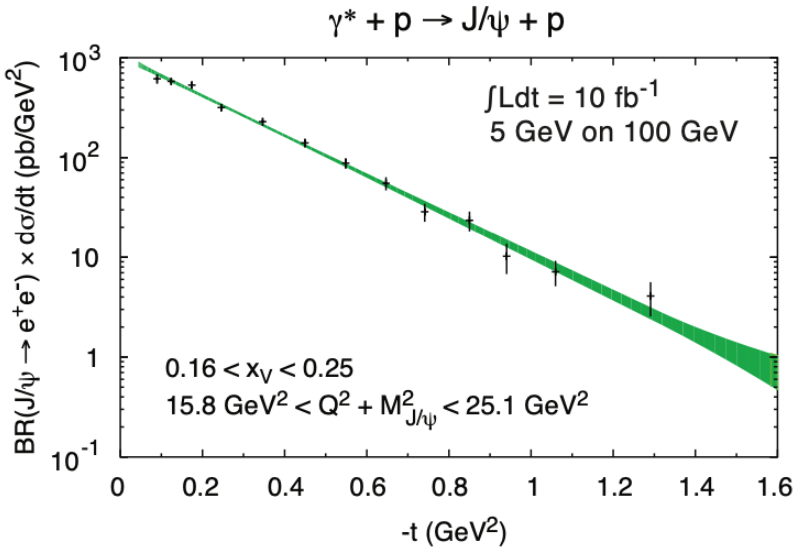
Jefferson Lab

Imaging the Gluon at the EIC (White Paper)

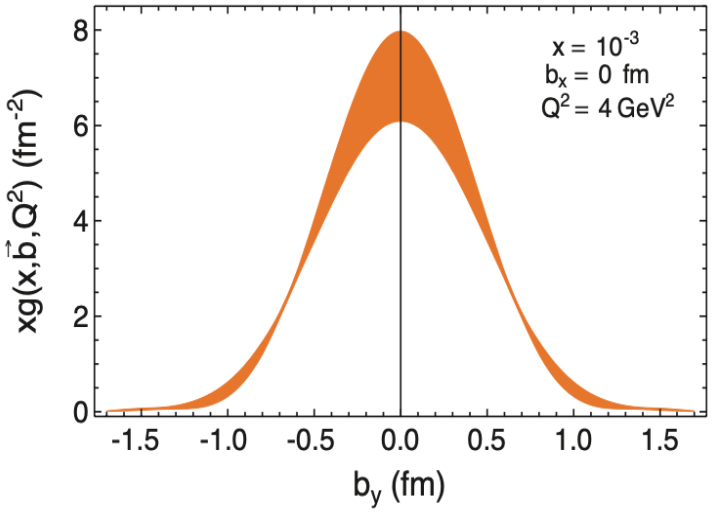
- **Exclusive vector meson production:**

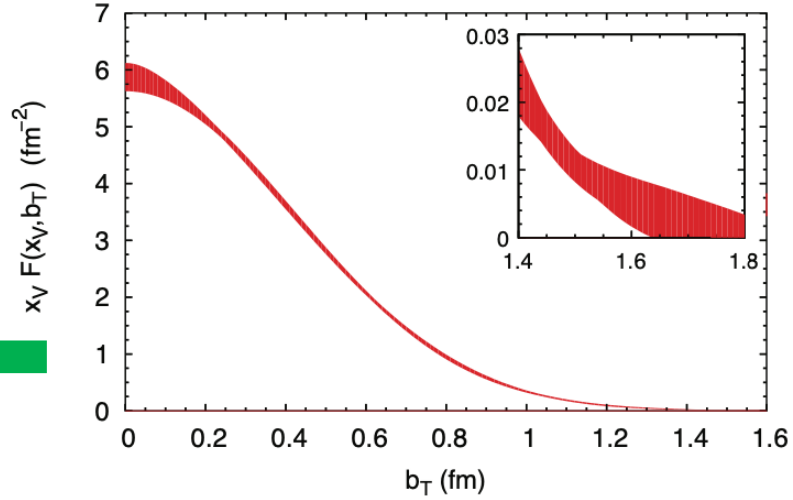


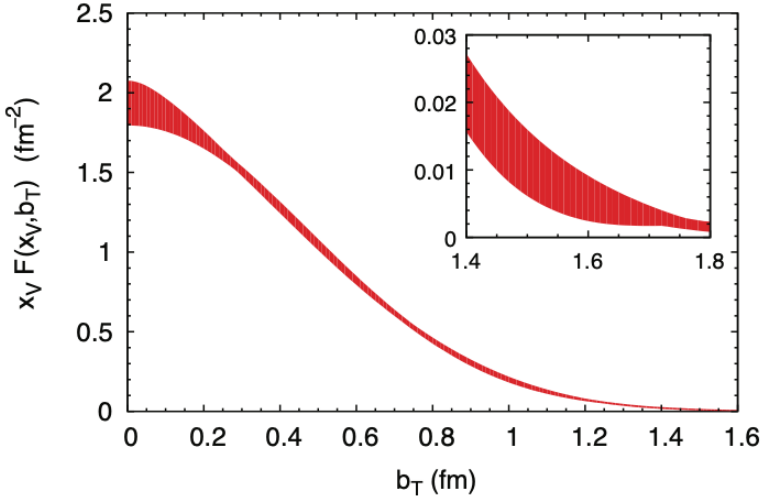




- **Spatial distributions:**





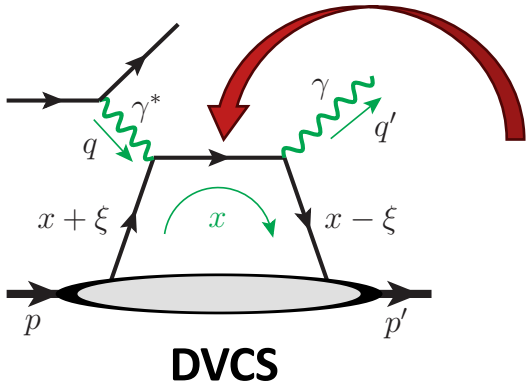


The b_T space density for gluons → **Effective "proton radius" in terms of gluons**

Jefferson Lab

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

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



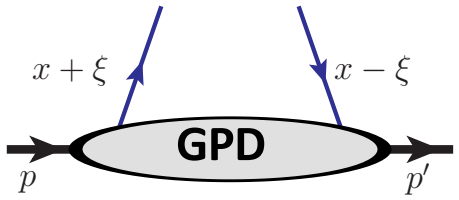
Smaller propagator = bigger amplitude

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

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

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

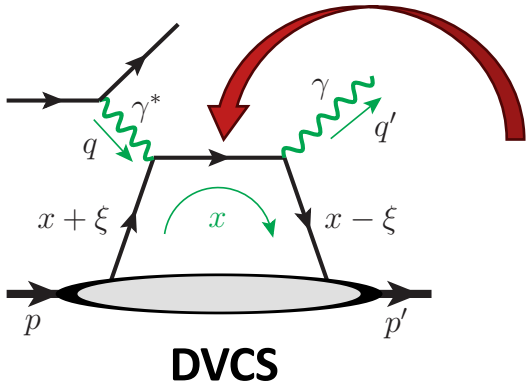
- **also true for most other processes**
- ***x*-dependence is only constrained by a “moment”**
- ***x*-integration decouples from external Q^2**



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



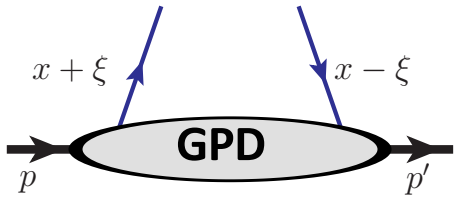
Smaller propagator
= bigger amplitude

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

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

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

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



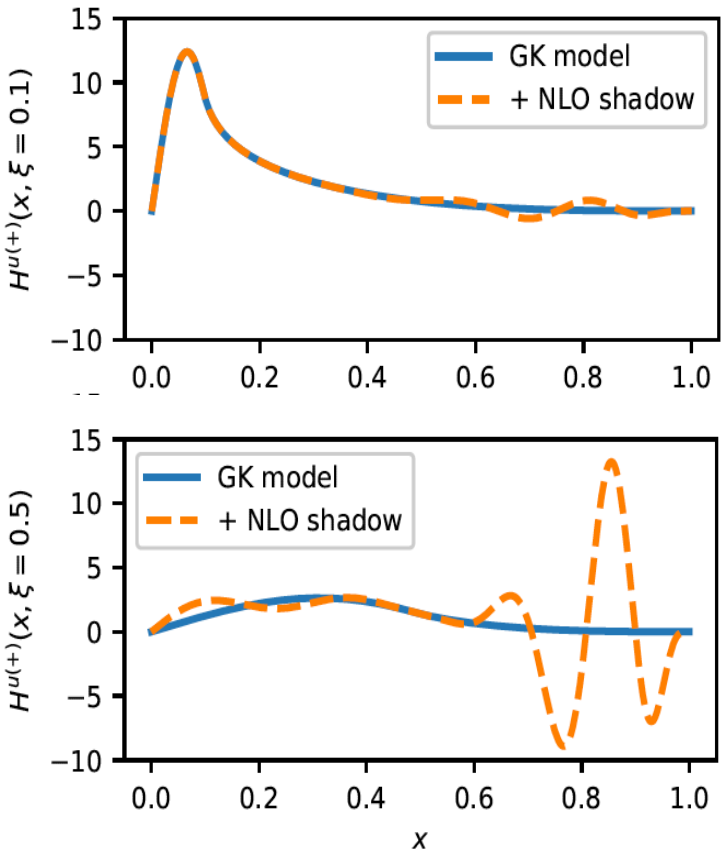
NO full x-dependence
for given t and ξ

❑ “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 !

Jefferson Lab

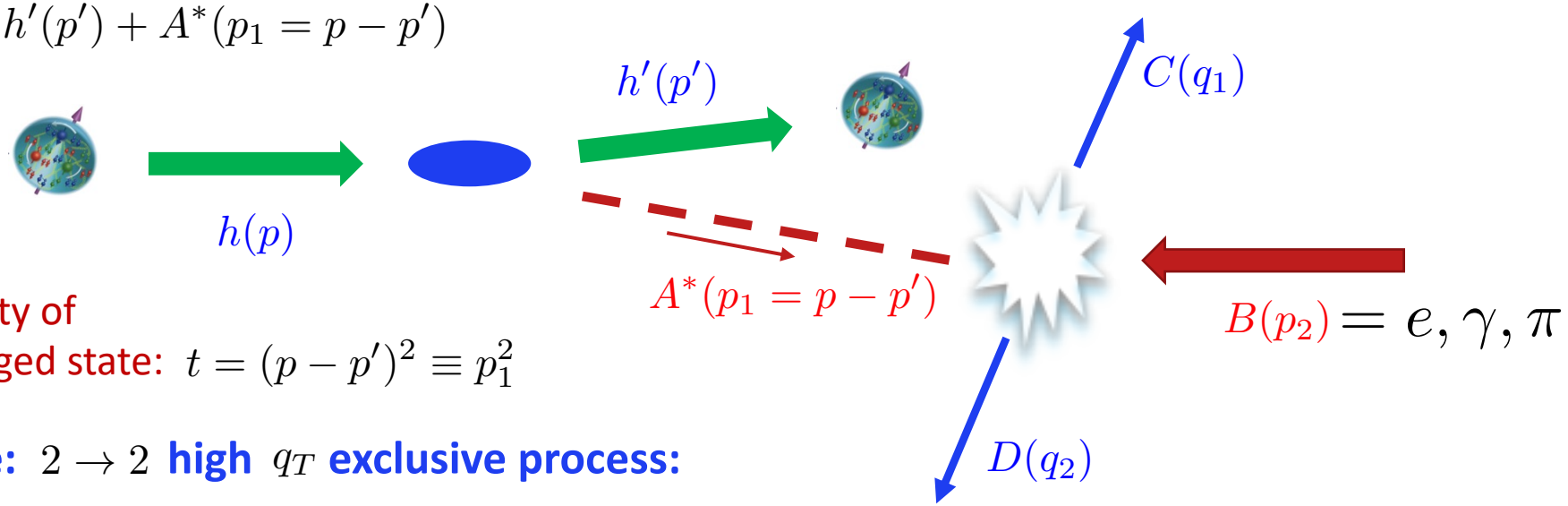
Single-Diffractive Hard Exclusive Processes (SDHEP) – New

Qiu & Yu, JHEP 08 (2022) 103
PRD 107 (2023) 1
PRL 131 (2023)161902

❑ 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: $t = (p - p')^2 \equiv p_1^2$

- **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: $\sim 1/|q_{1T}| \approx 1/|q_{2T}|$

- **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):**

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

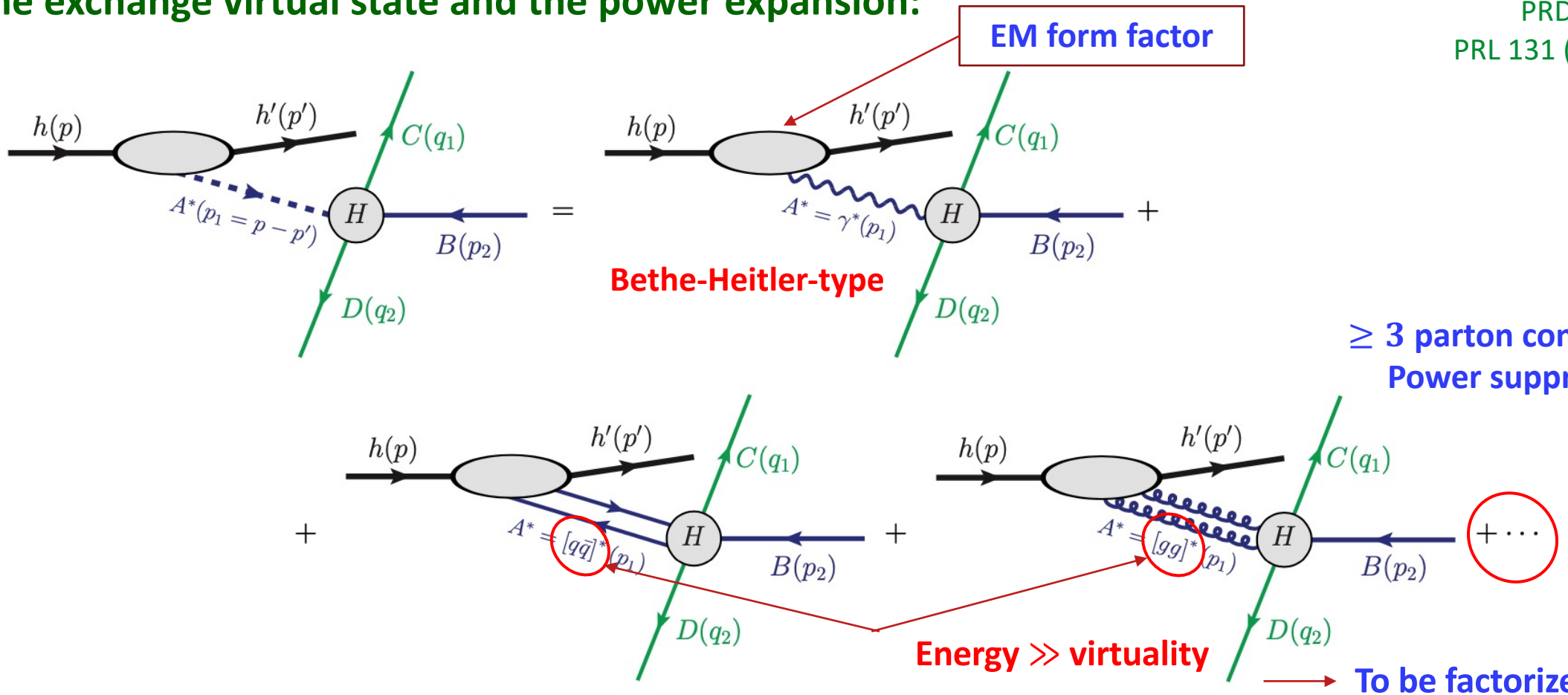
A 2-scale observable!

Jefferson Lab

Single-Diffractive Hard Exclusive Processes (SDHEP) – New

Qiu & Yu, JHEP 08 (2022) 103
PRD 107 (2023) 1
PRL 131 (2023)161902

❑ The exchange virtual state and the power expansion:



$\geq$ 3 parton connection:
Power suppressed

→ 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!

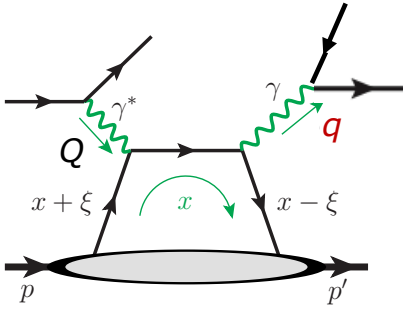
Jefferson Lab

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):**

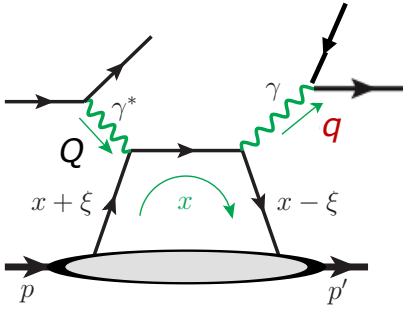
$$x_p(\xi,q) = \xi\left(\frac{1-q^2/Q^2}{1+q^2/Q^2}\right) \to \xi \quad \text{same as} \quad \text{DVCS} \quad \text{if } q \to 0$$

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):**

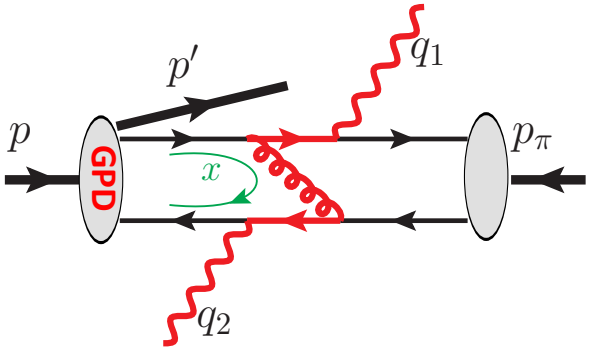
$$x_p(\xi,q) = \xi\left(\frac{1-q^2/Q^2}{1+q^2/Q^2}\right) \to \xi \quad \text{same as} \quad \text{DVCS} \quad \text{if } q \to 0$$

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

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

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

Qiu & Yu
JHEP 08 (2022) 103



- **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

$x \leftrightarrow q_T$

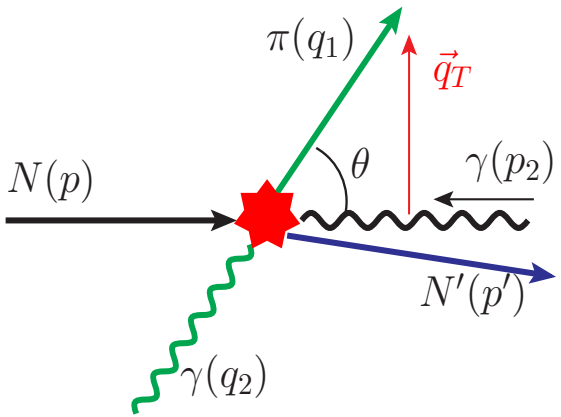
J-PARC, Amber, …

Jefferson Lab

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

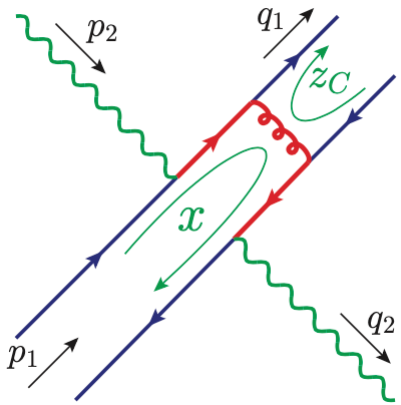


$i\mathcal{M}$ **contains the entanglement between x and qT**

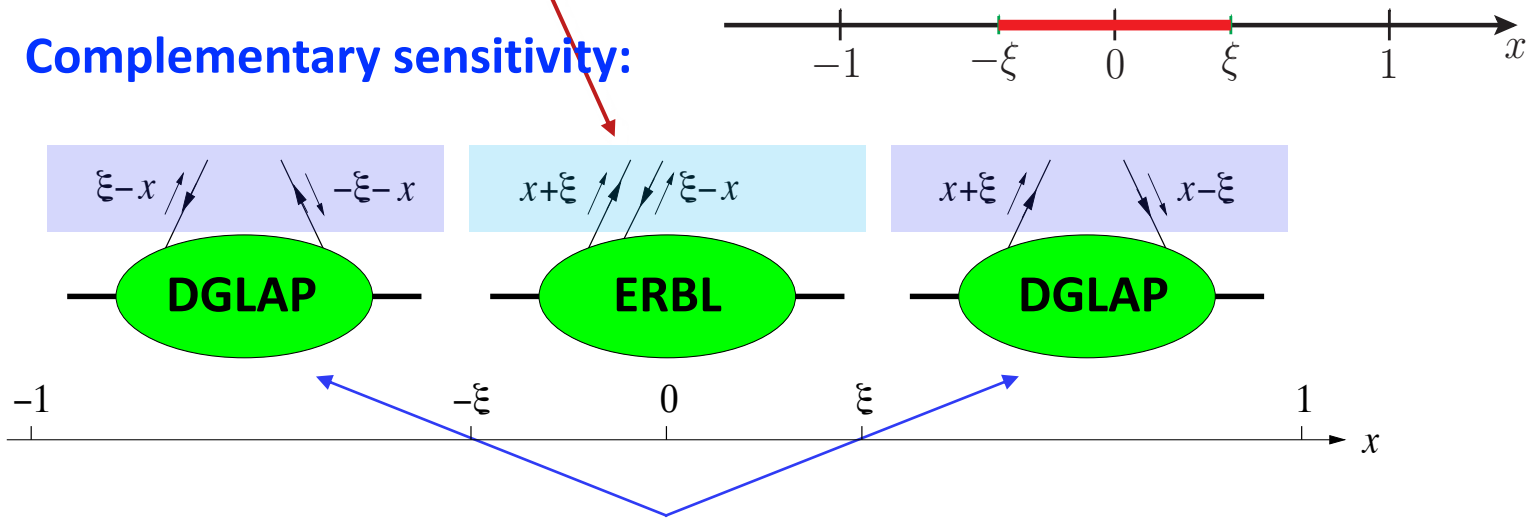
$$I'(t,\xi;z,\theta) = \int_{-1}^{1} \frac{dx\, F(x,\xi,t)}{x - \rho'(z;\theta) + i\epsilon}$$

Qiu & Yu, PRL 131 (2023)161902

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



Complementary sensitivity:

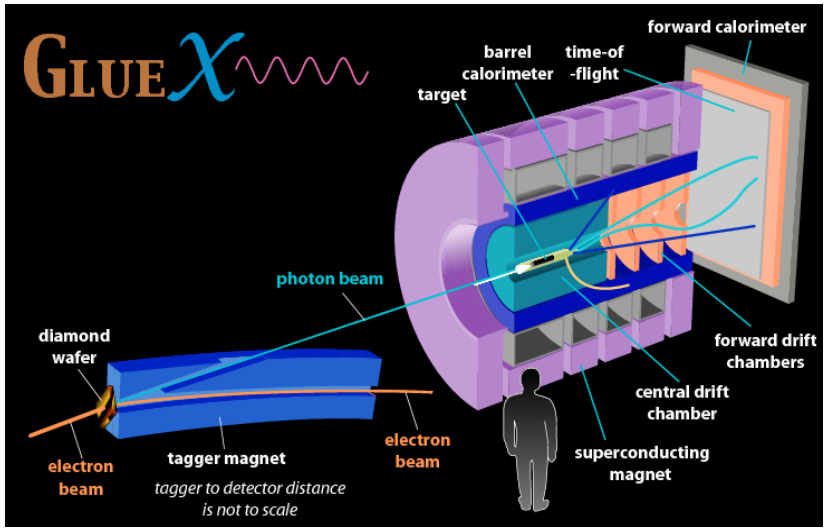


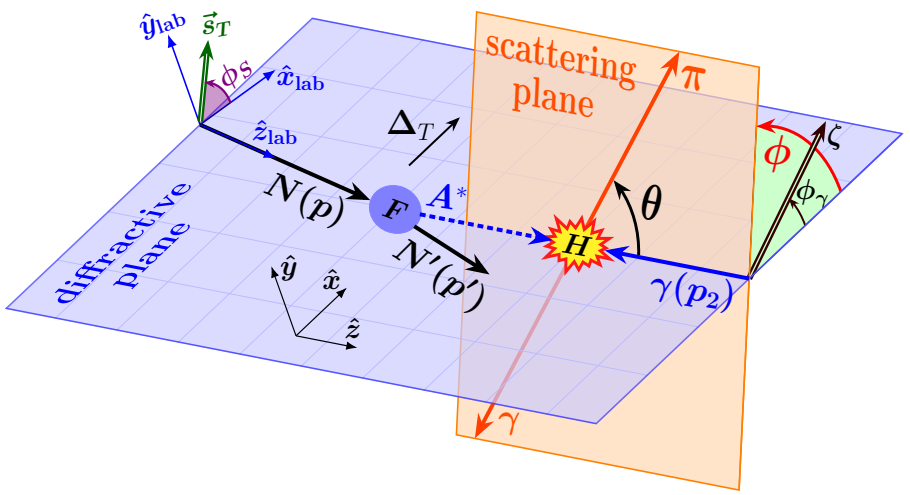
$$N\,\pi \to N'\,\gamma\,\gamma$$

Jefferson Lab

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

Qiu & Yu, PRL 131 (2023)161902





❑ Polarization asymmetries

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

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

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

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

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

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

Jefferson Lab

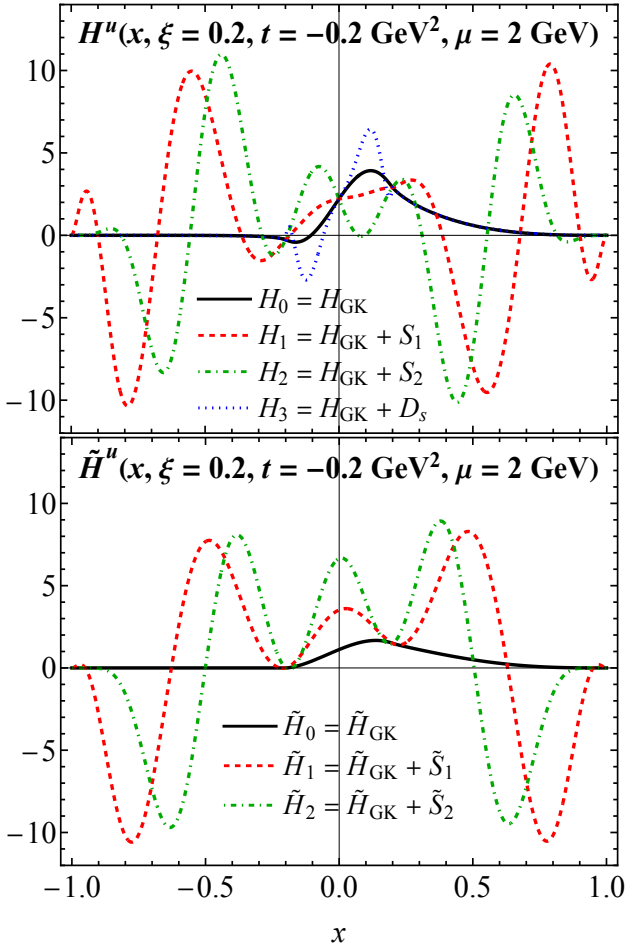
Exclusive Photo-Production of a $\pi\gamma$ Pair – Hall D at JLab

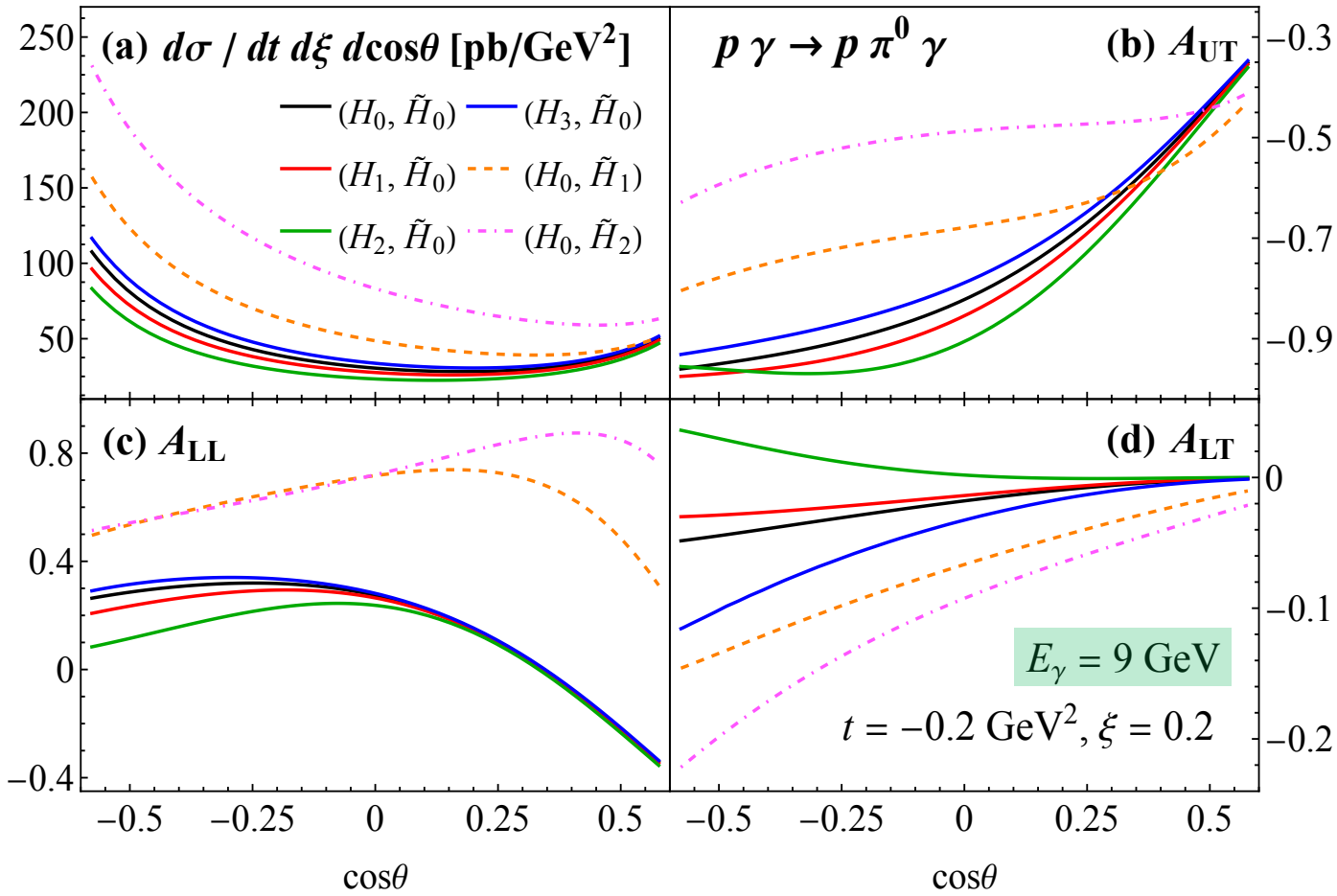
Goloskokov, Kroll, `05, `07, `09
Bertone et al. `21
Moffat et al. `23
Qiu & Yu, PRL 131 (2023)161902

❑ GPD Models:

= GK model + shadow GPDs

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





Jefferson Lab

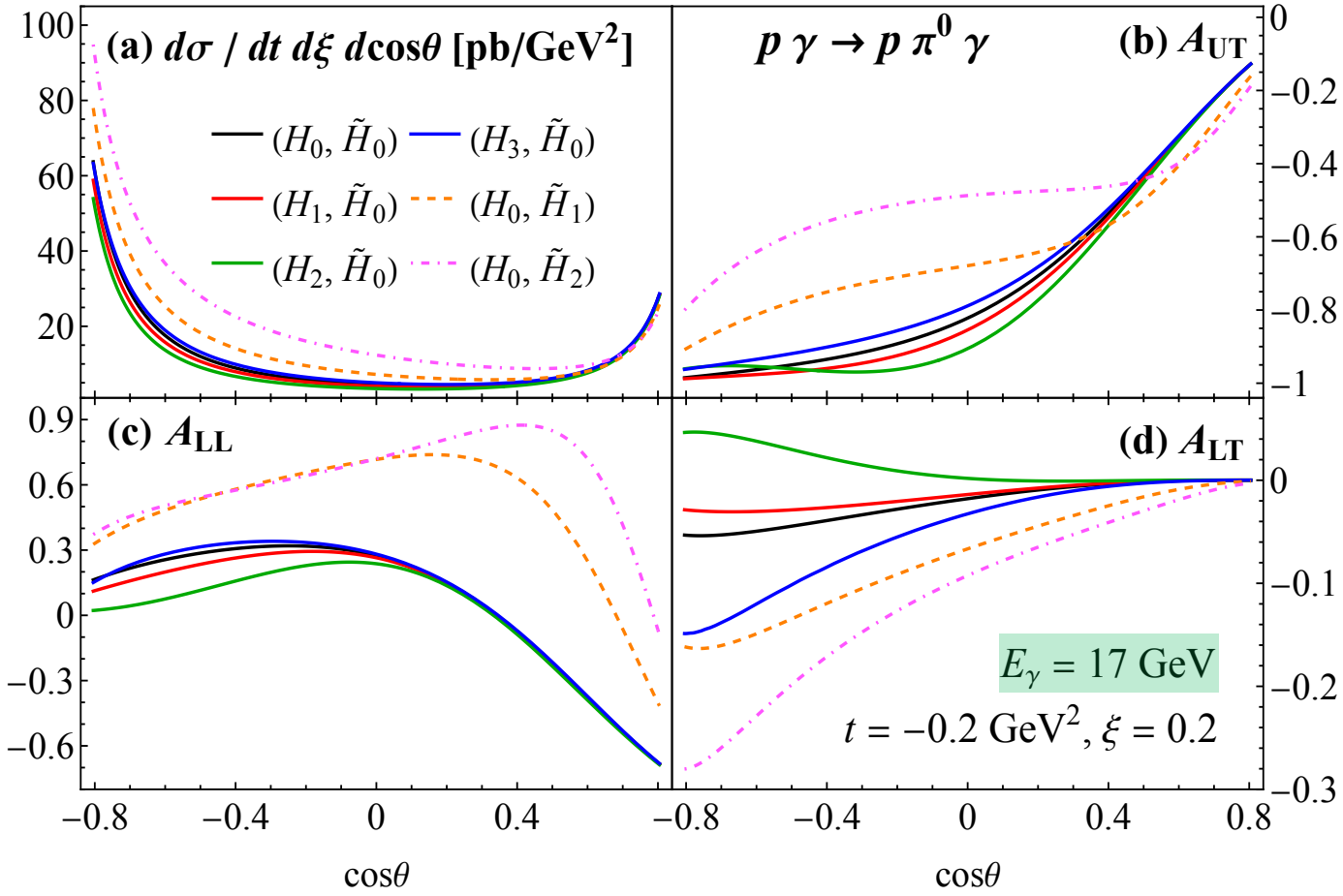
Exclusive Photo-Production of a $\pi\gamma$ Pair – Hall D at JLab

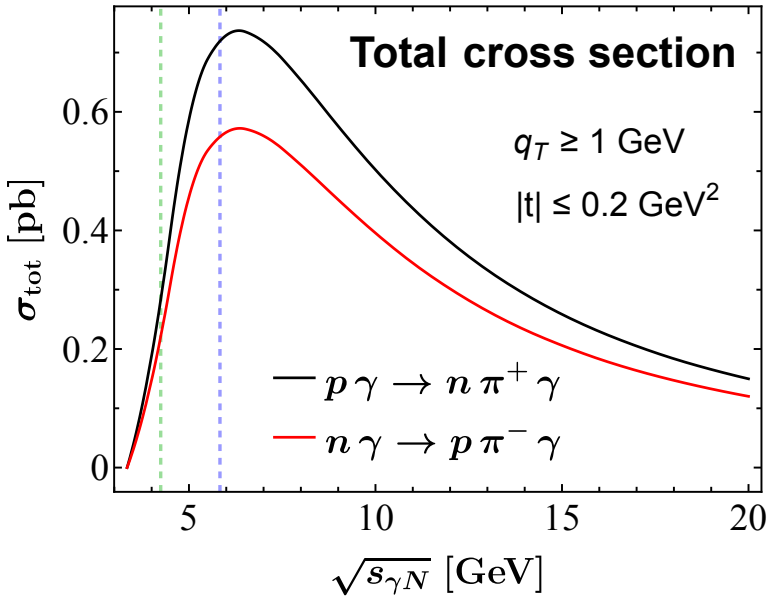
Goloskokov, Kroll, `05, `07, `09
Bertone et al. `21
Moffat et al. `23
Qiu & Yu, PRL 131 (2023)161902

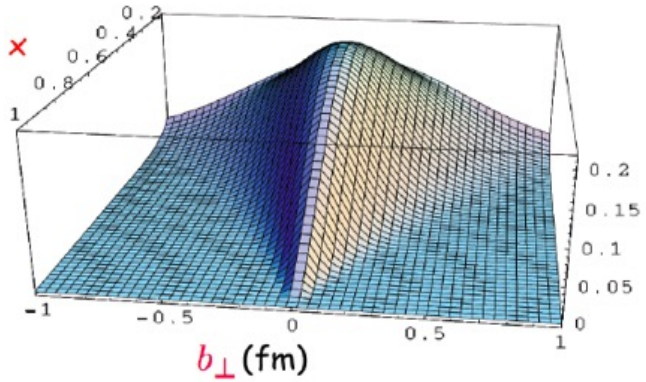
❑ GPD Models:

= GK model + shadow GPDs

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







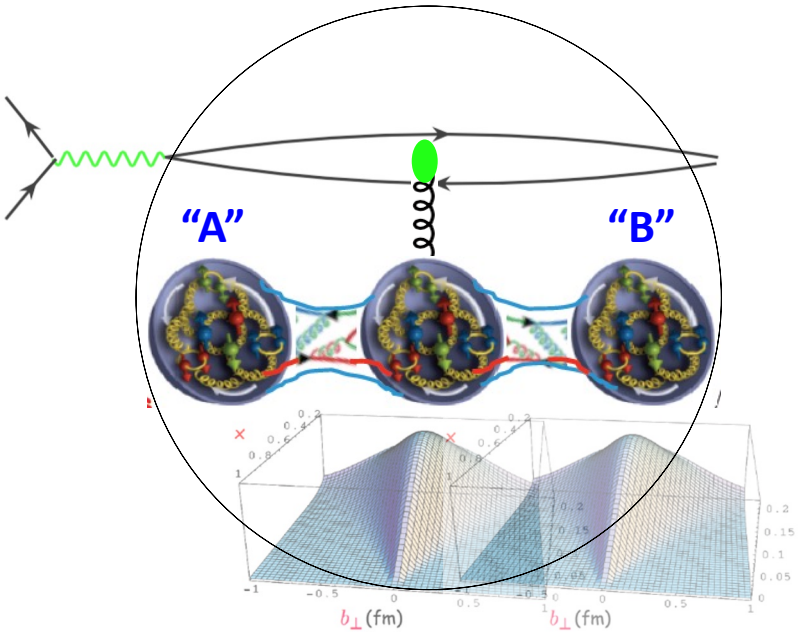
Extracting GPDs is a challenging inverse problem! $\sigma \propto [\mathcal{F} \otimes C]^2$

Internal Nuclear Landscape

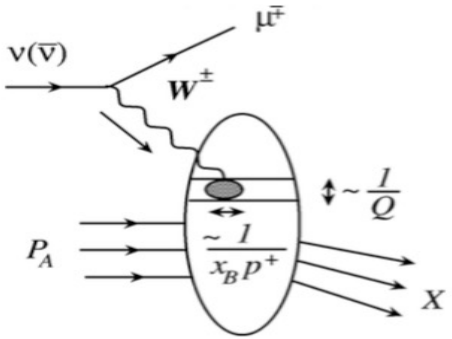
- **A simple, but fundamental, question:**

  What does a nucleus look like *if we only see quarks and gluons ?*

  Need localized hard probes – "see" more particle nature of the "glue"



- **But, a hard probe at small-x is NOT necessarily localized:**



In c.m. frame

Longitudinal probing size

> Lorentz contracted nucleon

if $\frac{1}{xp} > 2R\frac{m}{p}$ or $x < 0.1$

A hard probe at small-x can interact with multiple nucleons (partons from multiple nucleons) at the same impact parameter coherently

- **Another simple, and fundamental, question:**

  Does the color of a parton in nucleon "A" know the color of a parton in nucleon "B"?

  IF YES, Nucleus could act like a bigger proton at small-x (long range of color correlation), and could reaching the saturation much sooner!

  IF NOT, only short-range color correlation, and observed nuclear effect in cross-section at small-x is dominated by coherent collision effect

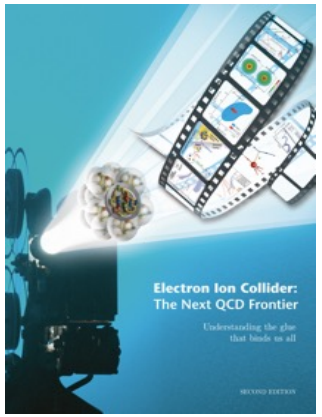
Saturation of gluons is a part of QCD, where to find it? ***EIC can tell !***

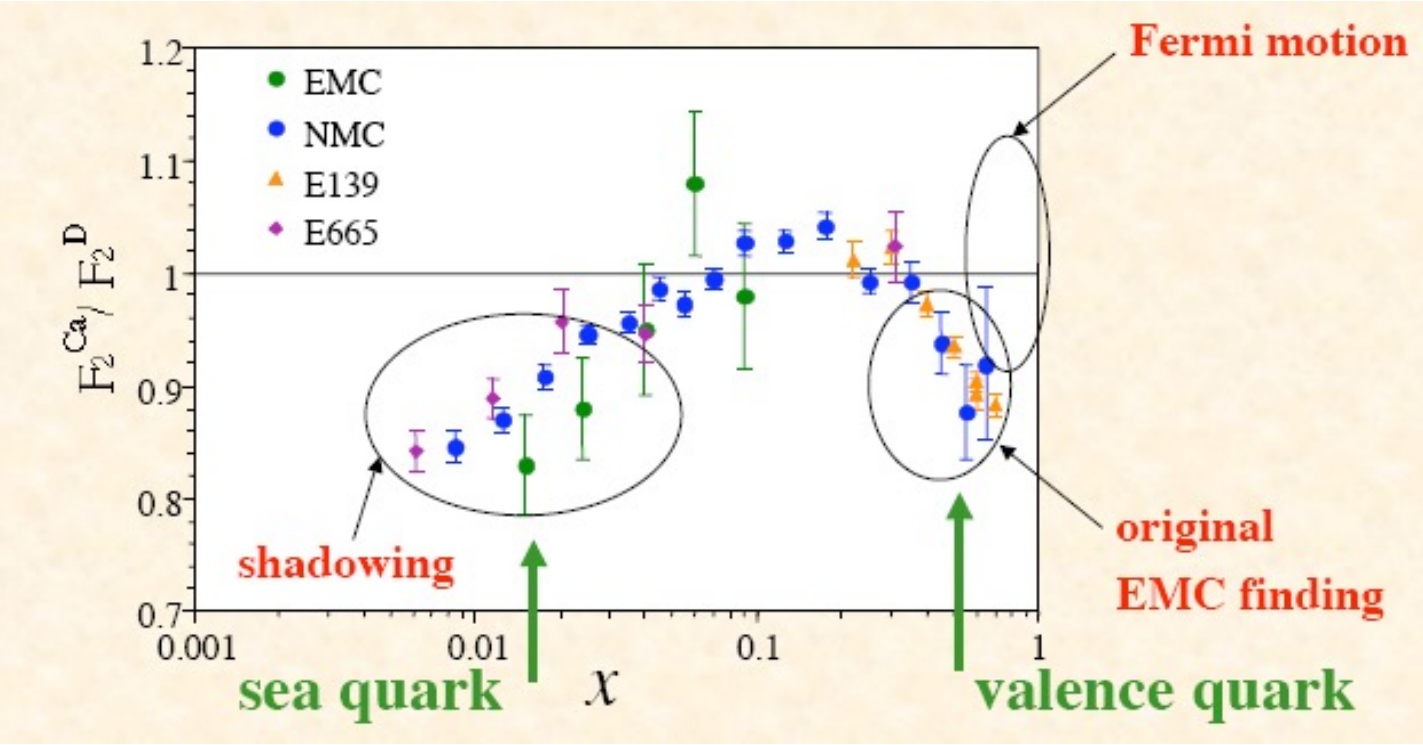
Coherent Length of the Color

- **A simple experiment to address a "simple" question:**

  Will the nuclear shadowing continue to fall as x decreases?

EIC White Paper





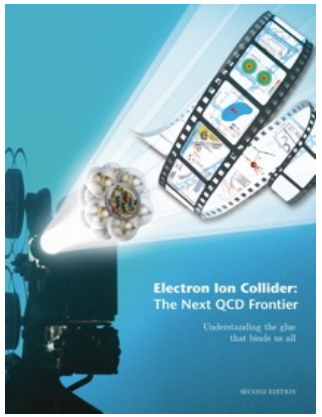
Jefferson Lab

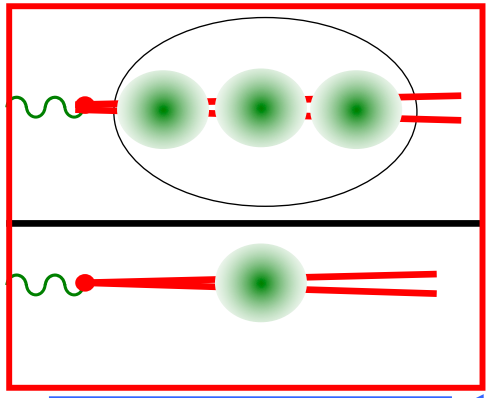
Coherent Length of the Color

- **A simple experiment to address a "simple" question:**

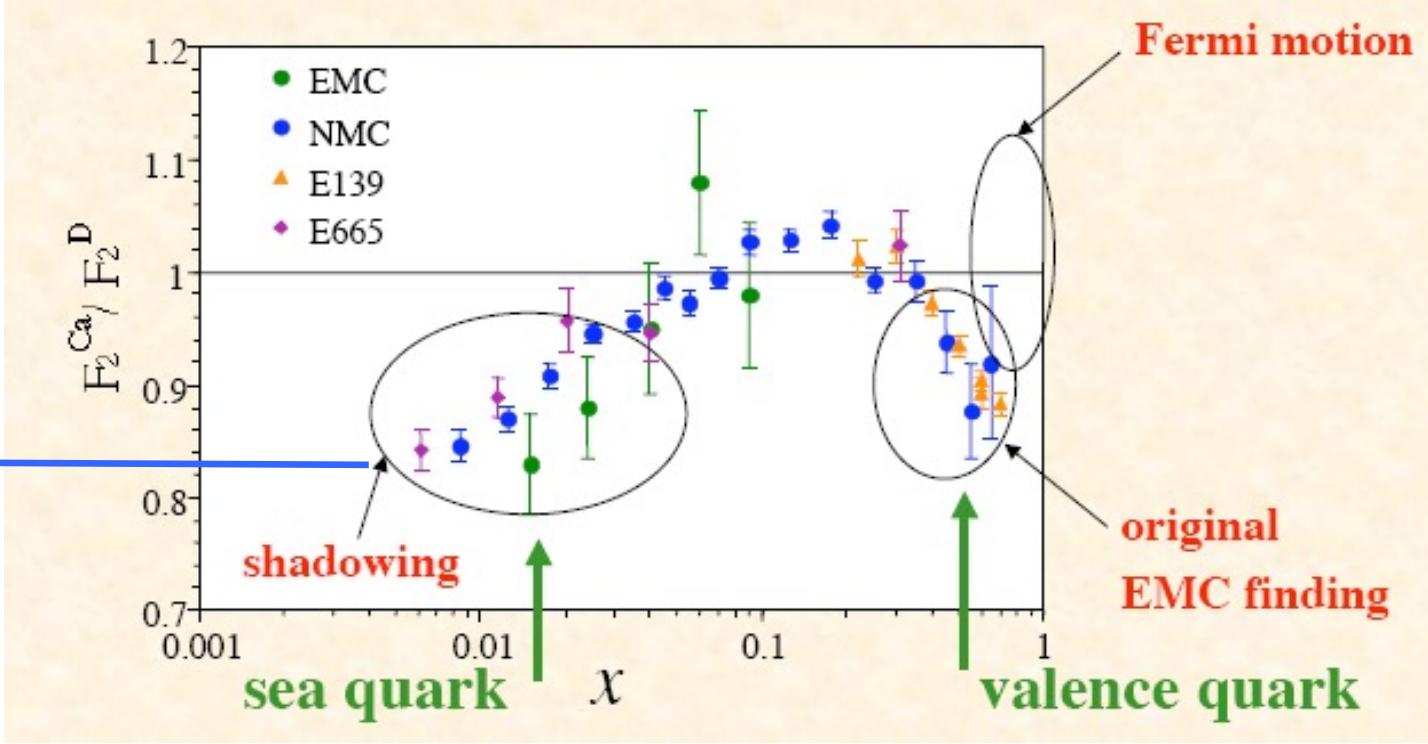
  Will the nuclear shadowing continue to fall as x decreases?

EIC White Paper





Color localized Inside nucleons



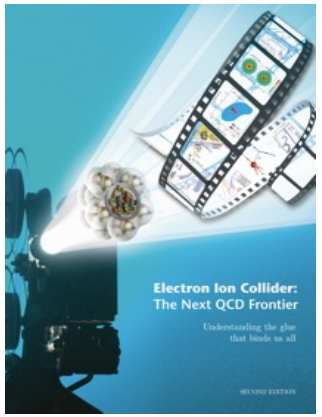
Jefferson Lab

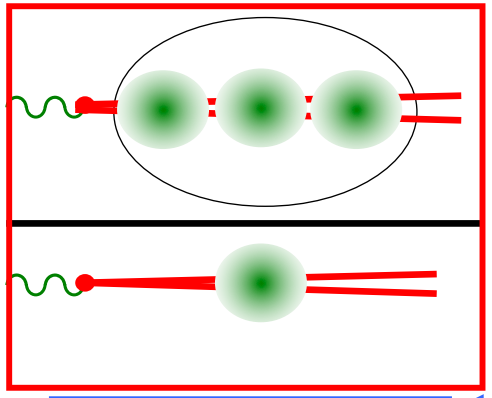
Coherent Length of the Color

- **A simple experiment to address a "simple" question:**

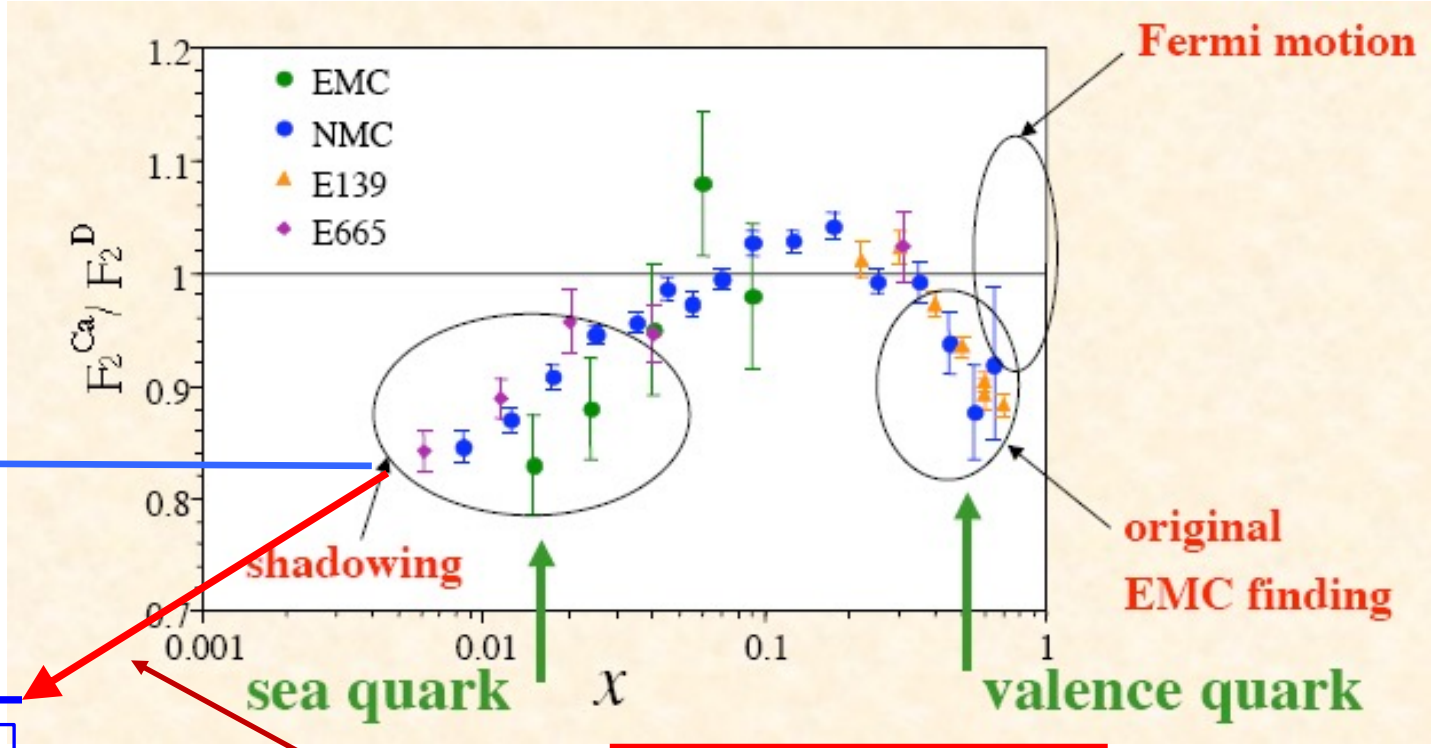
  Will the nuclear shadowing continue to fall as x decreases?

EIC White Paper

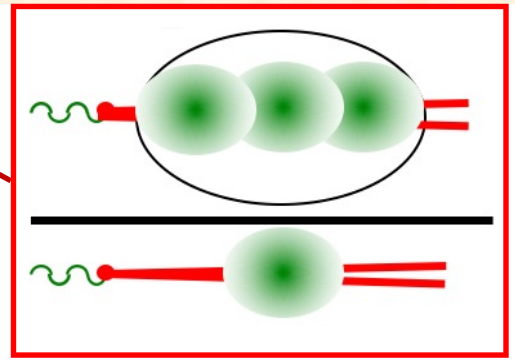




Color localized Inside nucleons



Nucleus as a bigger proton



Color leaks outside nucleons
Proton radius of soft gluon is larger !

EIC can tell !

Jefferson Lab

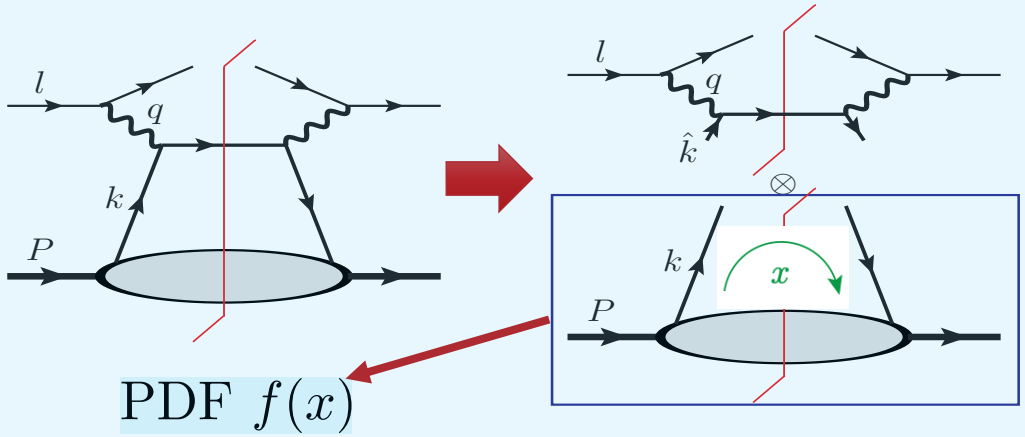
Summary and Outlook

- **We have the right Theory – QCD, but, unprecedented challenges**
  - QCD has been very successful in describing the short-distance dynamics
  - Trying to understand the emergent phenomena of QCD:
    - Hadron properties, such as the mass, spin, …, in the most fundamental way
    - Internal structure and landscape of hadrons, such as confined motion, spatial tomography of nuclei, …
    - Emergence of hadrons from quarks and gluons, neutralization of the color, …
    - Emergence of jet(s) and jet substructure, …, need femto-meter sized detectors!
    - Interplay of the particle and wave nature of quarks and gluons, …
- **EIC is an ultimate QCD machine and a facility, capable of discovering and exploring the emergent phenomena of QCD, and the role of color and glue, …**
- **US-EIC is sitting at a sweet spot for rich QCD dynamics, capable of taking us to the next frontier of QCD and nuclear theory!**

Thanks!

Inclusive Process vs. Exclusive Process

❑ Deeply Inelastic Scattering (DIS):



$x = k^+/P^+$

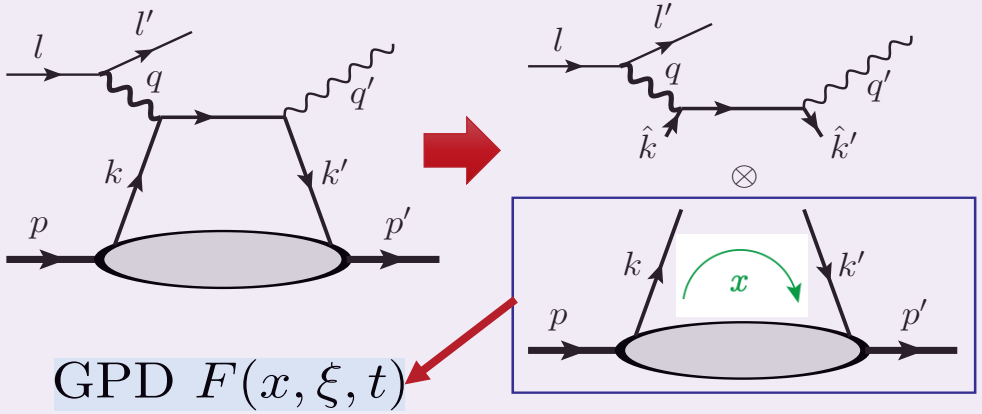
Cross section: **Cut diagrams**

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

- **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**