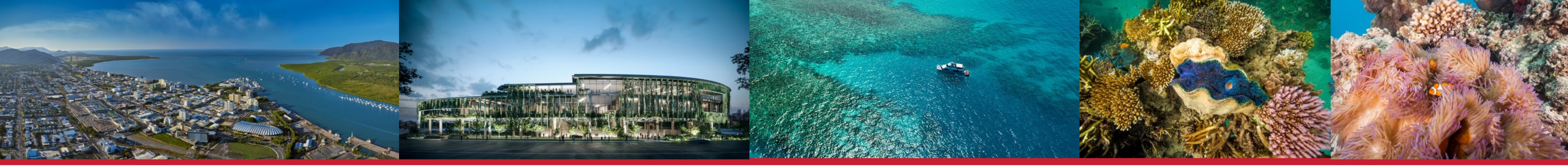


The Current JLab 12 GeV and Future EIC Research Programs

– in 25 minutes?

- Focus on opportunities and challenges
- QCD confinement, hadron spectroscopy & structure, and emergence of hadrons
- JLab 12 GeV & future EIC research programs
- Summary and Outlook

See also Plenary Round Table 2:
Precision QCD: What we know, what we want to know
Wednesday (8/21/2024) at 12:00-13:00

Jianwei Qiu
Theory Center, Jefferson Lab

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

QCD and QCD Confinement

- **QCD Confinement – Phenomenologically:**
  - **How quarks and gluons are confined inside the hadron?**
    - 3D quark/gluon spatial and momentum distributions (PDFs, GPDs, TMDs, …) ?
    - All quantum correlation functions (QCFs) of quarks and gluons ?

  But,

  None of these QCFs (= hadron matrix elements of quark/gluon correlators) is a direct physical observable!

  Limitation of LQCD for calculating nonlocal QCFs (Euclidean formulation) – Quantum Computer ?

  Need to match partonic dynamics to hadronic observables with controllable approximations!

  Factorization of PQCD, NRQCD, SCET, …, or EFTs in general, or QCD inspired models

  - **How hadrons and their properties are emerged from quarks, gluons and their dynamics?**
    - Fragmentation functions do not address how color or quark flavor is neutralized – soft/strong physics ?
    - Cannot be calculated in LQCD (sum of all final hadronic states) – Quantum Computer ?
    - Can we get hints from event shape, jet sub-structure, … ?

- **JLab 12 GeV (possible 22 GeV upgrade) & future EIC are much needed QCD facilities:**

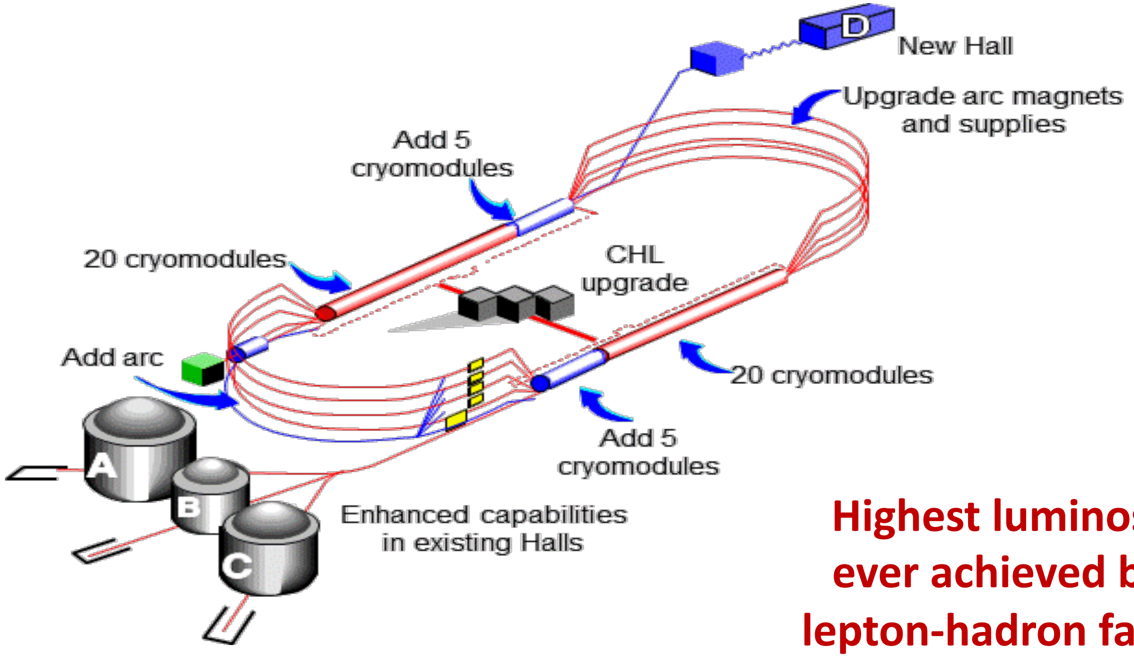
  JLab/CEBAF – Luminosity frontier ($10^{38\text{-}39}$ $cm^{-2}s^{-1}$) BNL/EIC – Energy frontier ($10^{33\text{-}34}$ $cm^{-2}s^{-1}$)

  Plus Compass/Amber, JPARC, EICC, …, & facilities around the world

CEBAF @ 12 GeV at Jefferson Lab

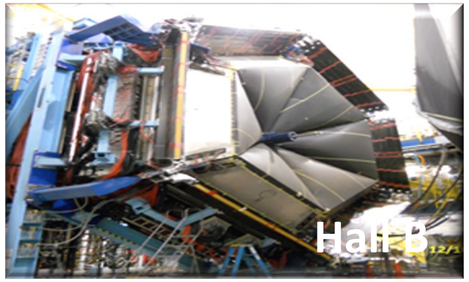
- Only Lepton-Hadron facility in the US now – Luminosity Frontier:

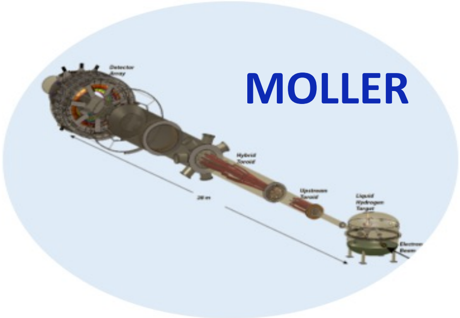
  12 GeV CEBAF Upgrade Project was just complete, on-time and on-budget!



Highest luminosity ever achieved by a lepton-hadron facility
10^{38} ($cm^{-2}\,s^{-1}$)

- Search for exotic hadrons, …
- Explore for hadron properties and 3D structures, …
- Search for dark matter, dark photon, …
- Advance accelerator technology, …
- …





Future: SoLID Detector

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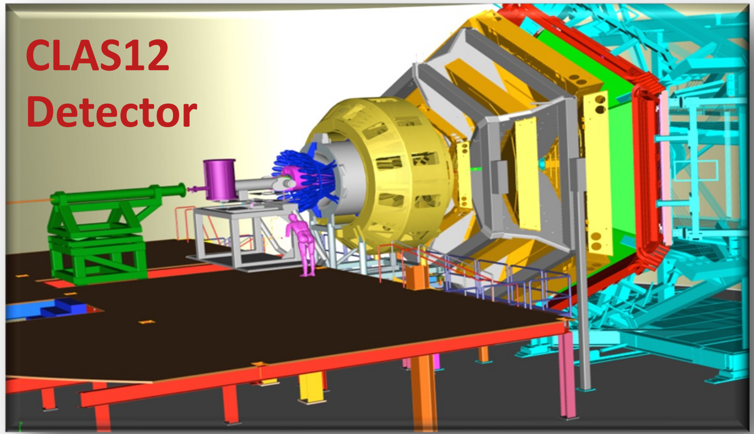
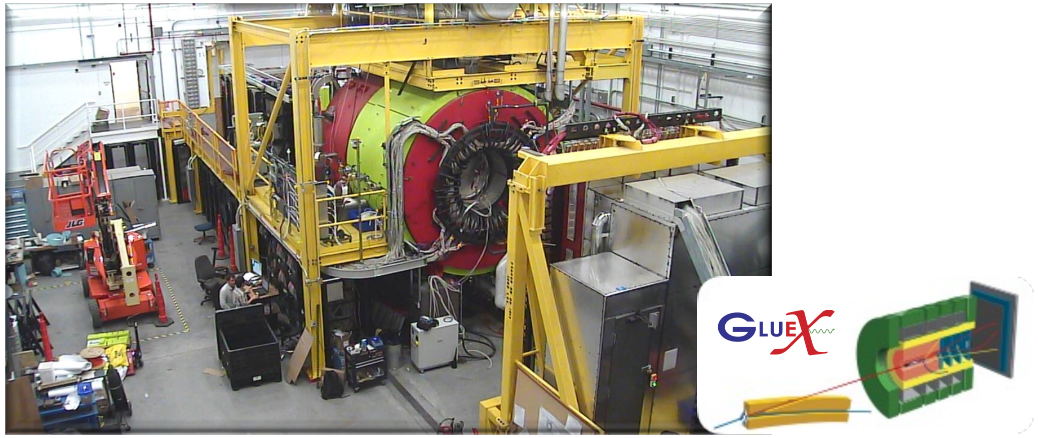
Detectors in 4 Halls = Scientific Capabilities and Opportunities

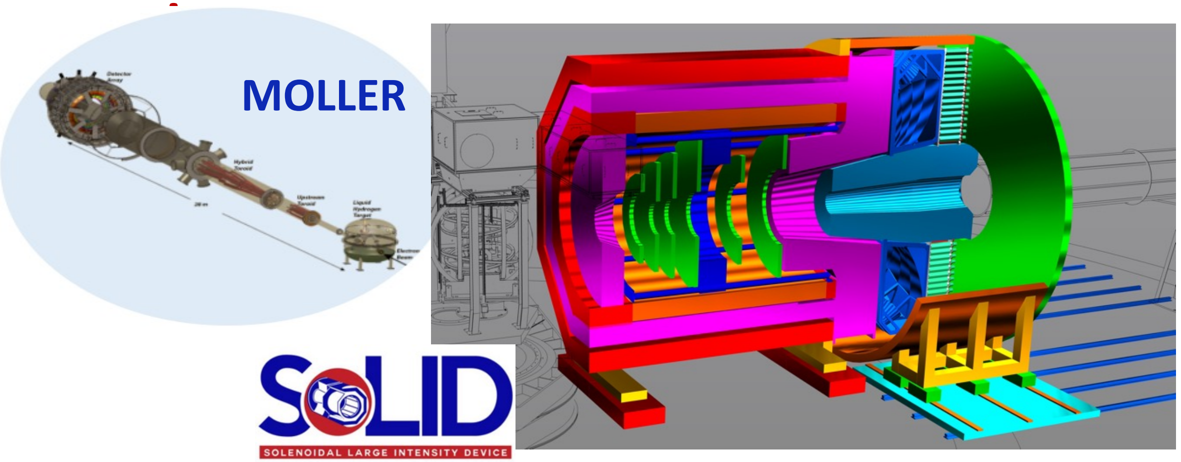
- **Hall B – understanding nucleon structure via 3D imaging**



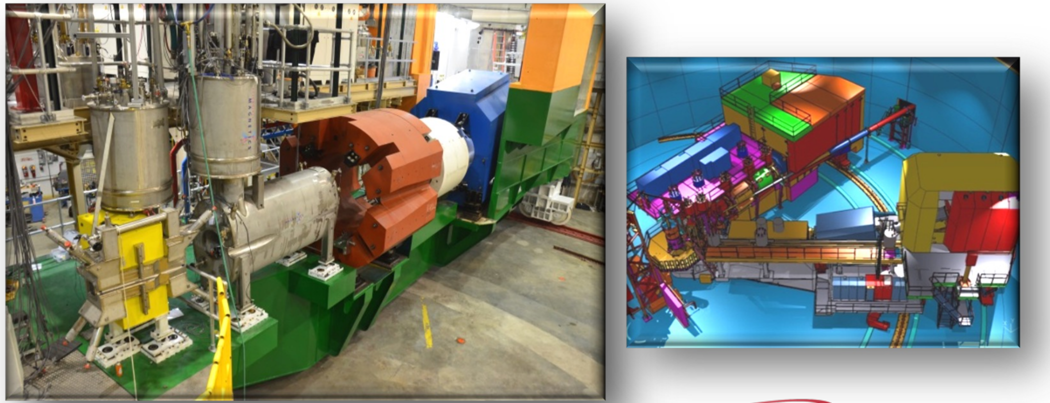
- **Hall D – discovering and exploring exotic mesons & charm near threshold**



- **Hall A – Form factors, Moller experiment: A_{pv} + future SoLID**



- **Hall C – precision determination of quark properties in nucleons/nuclei**

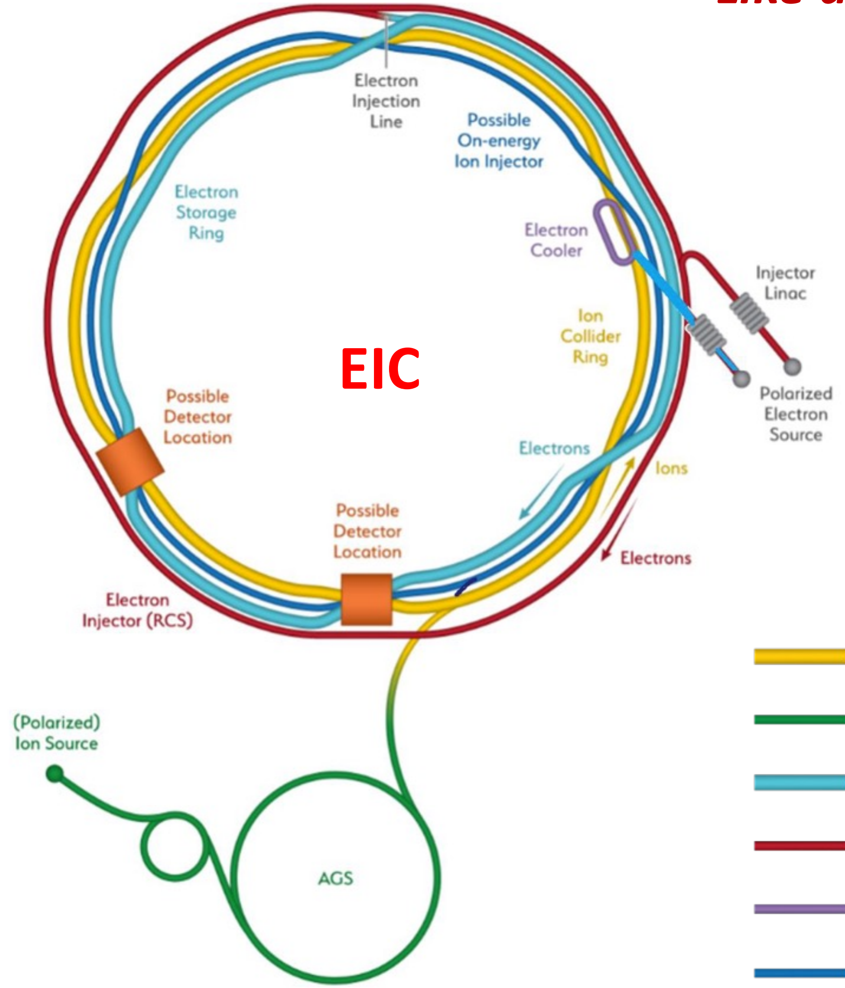


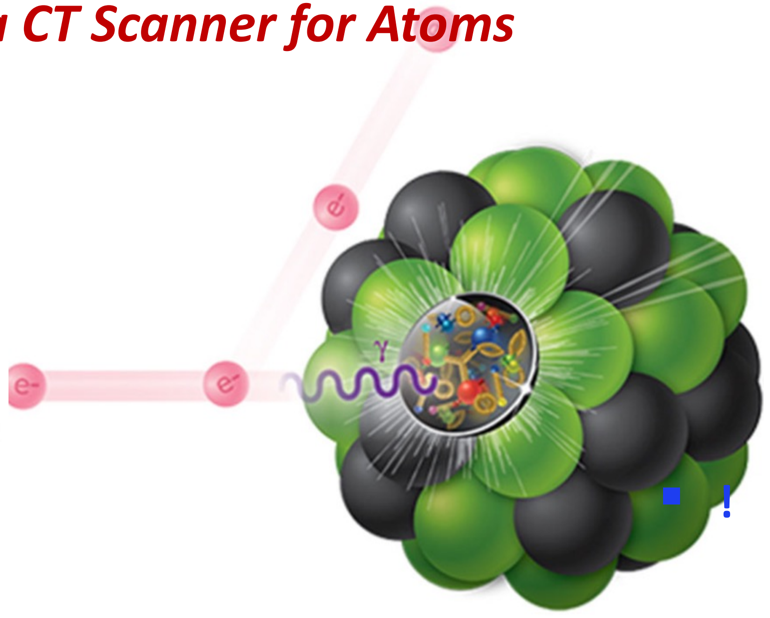
U.S. - based Electron-Ion Collider (EIC)

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

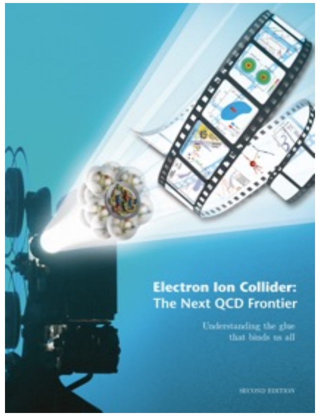
A machine that will unlock the secrets of the strongest force in Nature

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

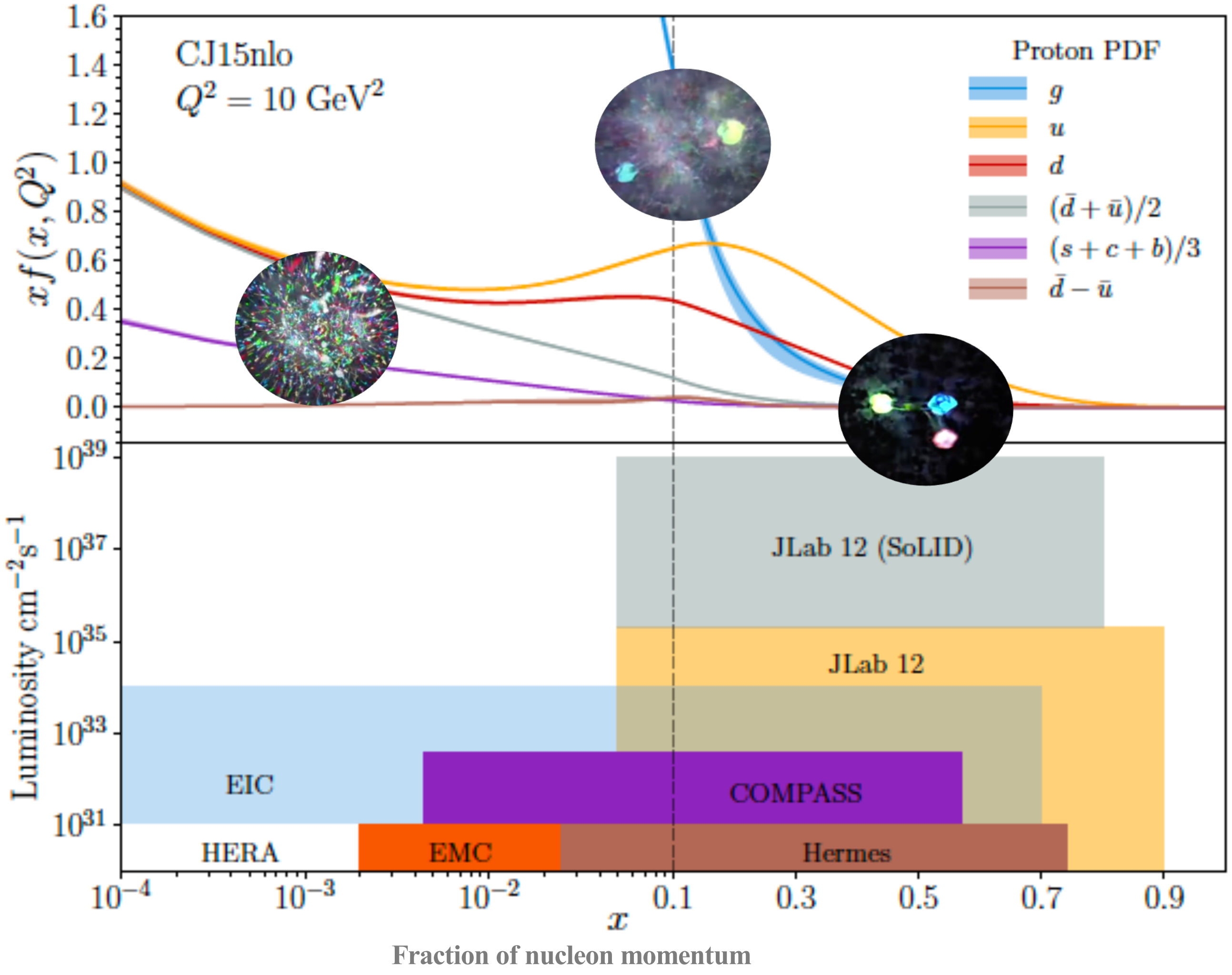
- Center of Mass Energies:
  20 GeV – 141 GeV
- Required Luminosity:
  10^{33} - 10^{34} $cm^{-2}s^{-1}$
- Hadron Beam Polarization:
  80%
- Electron Beam Polarization:
  80%
- Ion Species Range:
  p to Uranium
- Number of interaction regions:
  up to two

EPIC Detector for EIC at IP6

Complementarity of JLab 12 and Future EIC

❑ Covering different kinematic regimes:

Prog. Part. Nucl. Phys. 127 (2022) 103985



See also Keppel's talk

❑ High luminosity – JLab12:

- Excess to valence region of QCD

  Sensitive to hadron properties, baryon #, …
- Scattering without breaking the hadron!
  - All kind of Form Factors
  - Spatial imaging

    Proton radius of EM charge,
    matter distribution, quark density, …
- Excess to BSM from A_{PV} & PVDIS, …

❑ High Energy – EIC:

- Excess to the gluon sector of QCD !
  - Role of glue to hadron mass, spin, …
  - Spatial imaging of glue
- Excess to the small-x gluons in nucleon/nuclei

  Gluon saturation phenomena, …

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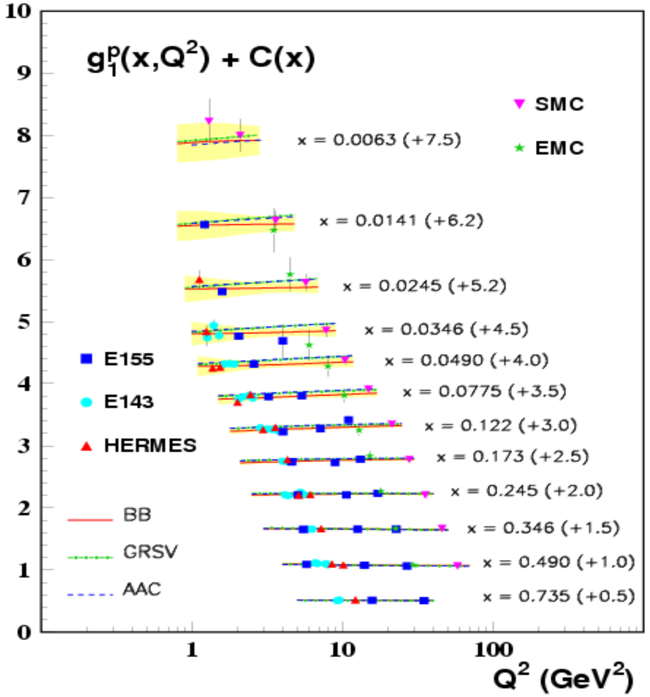
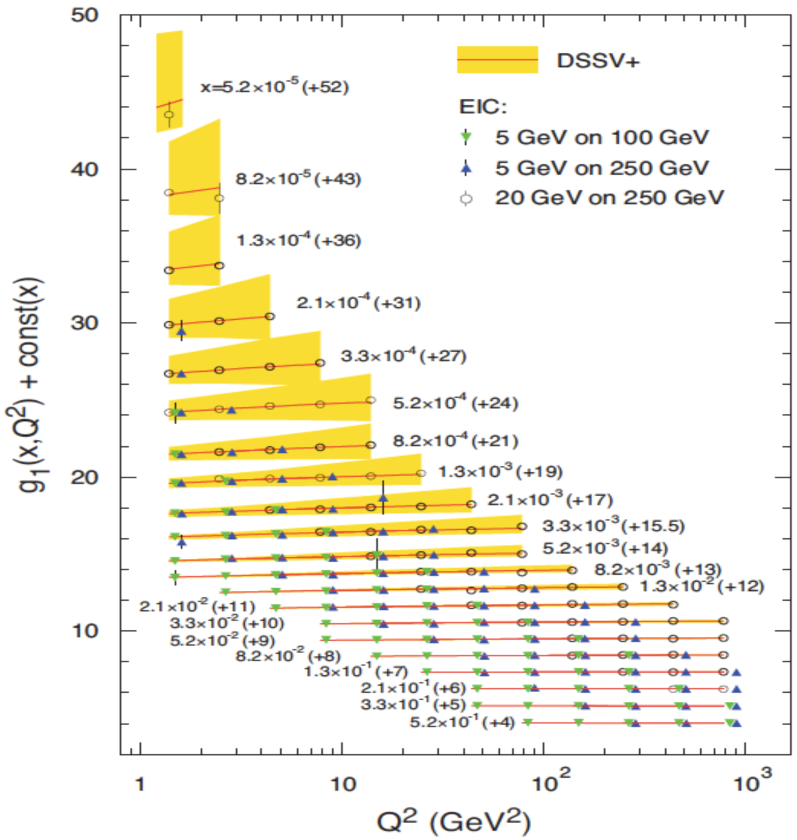
The Proton Spin: from JLab12 to EIC

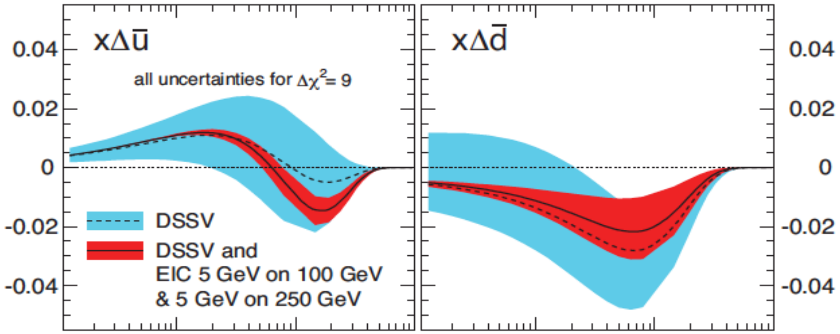
❑ The power & precision of EIC:

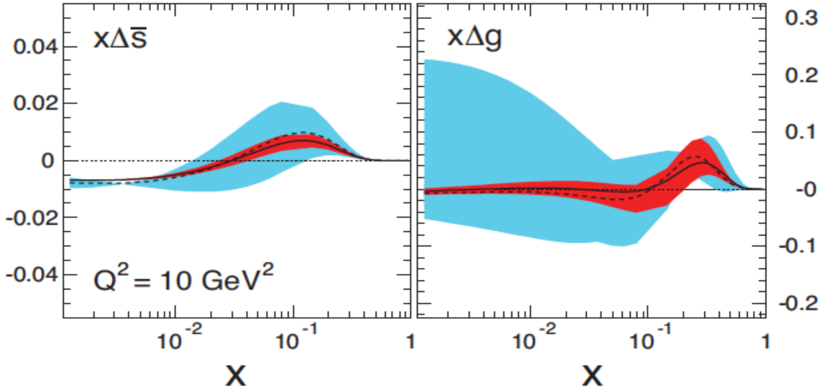


Polarized DIS at EIC



❑ What an EIC could help:





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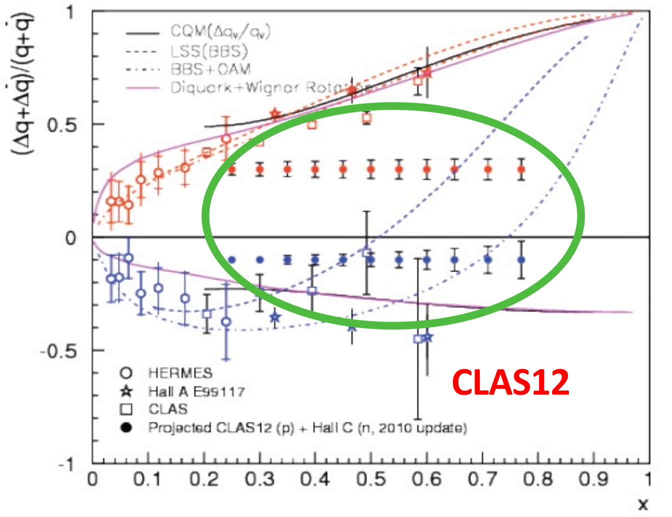
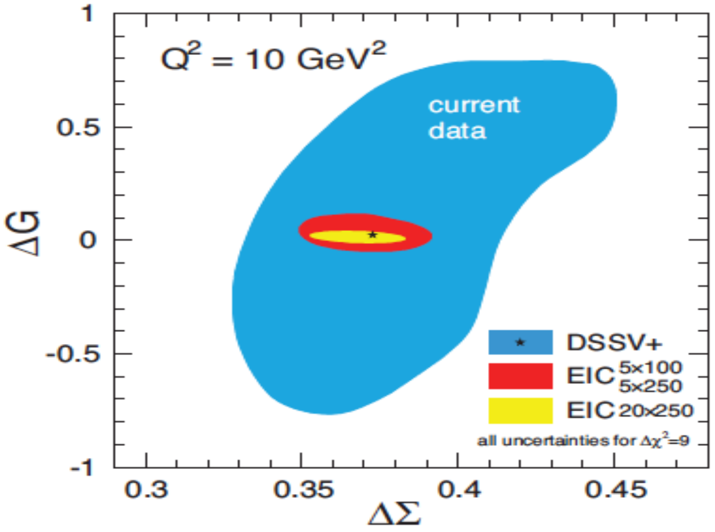
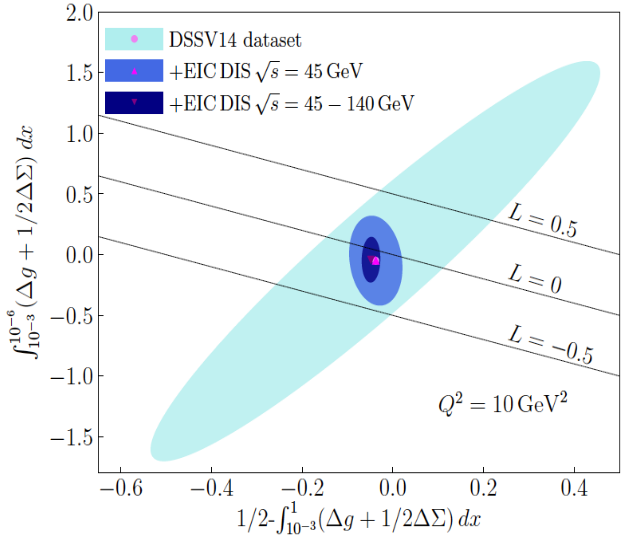
The Proton Spin: from JLab12 to EIC

❑ Complementary between JLab12 and EIC – White Paper:

arXiv:2103.05419

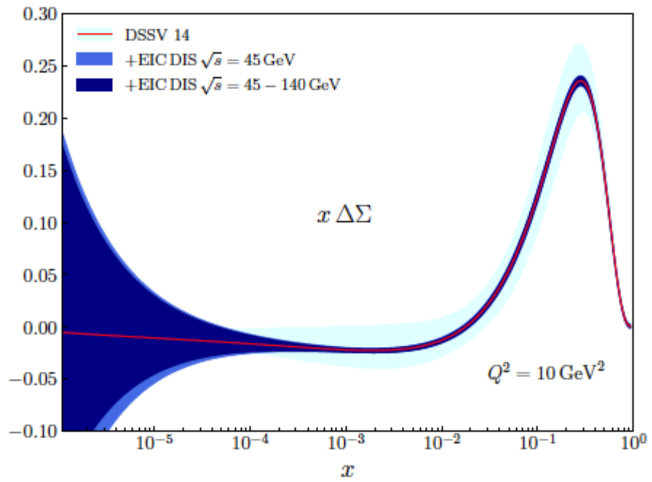


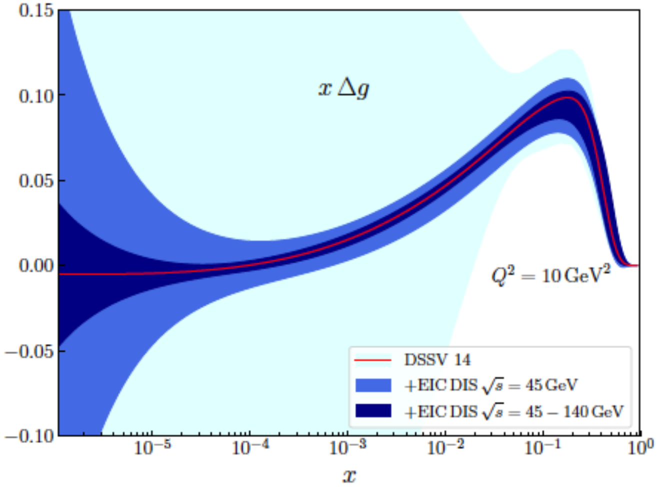


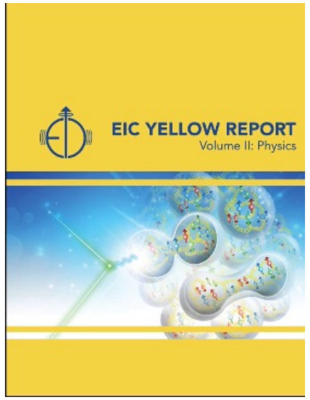


Room for orbital momentum

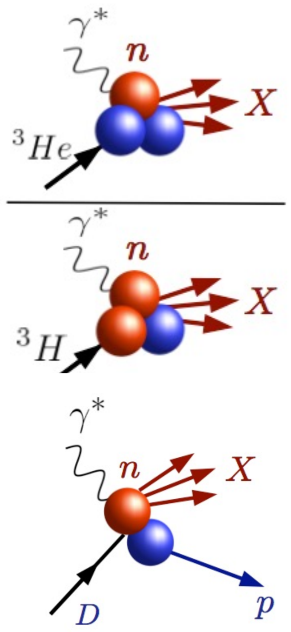
❑ What the EIC could do/help – EIC Yellow Report:

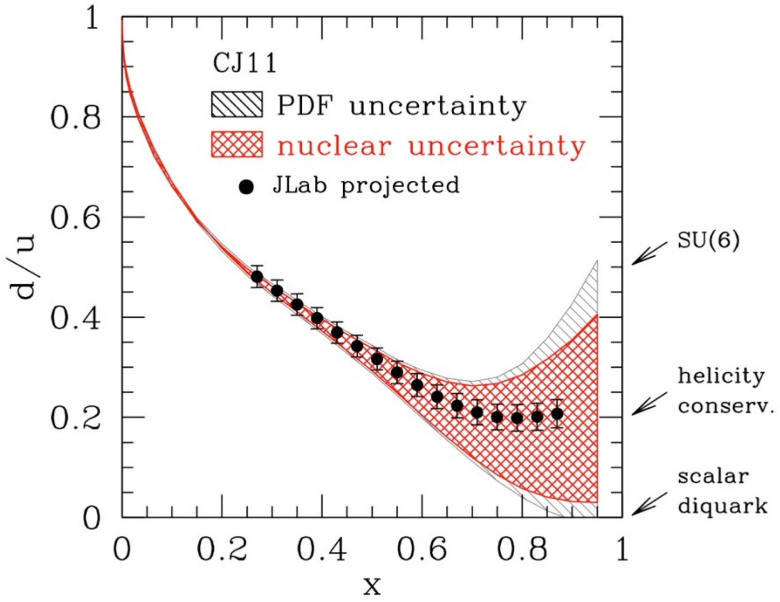




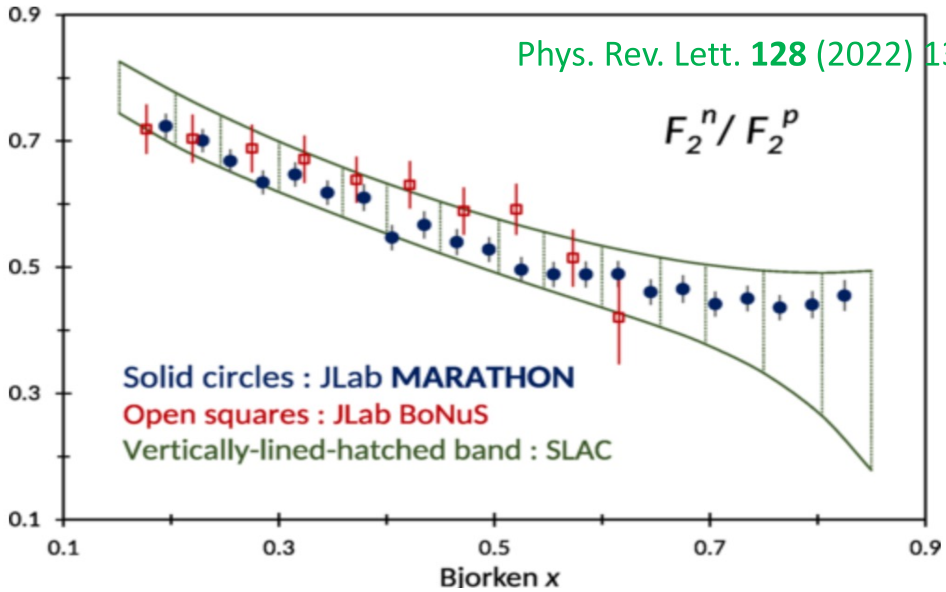


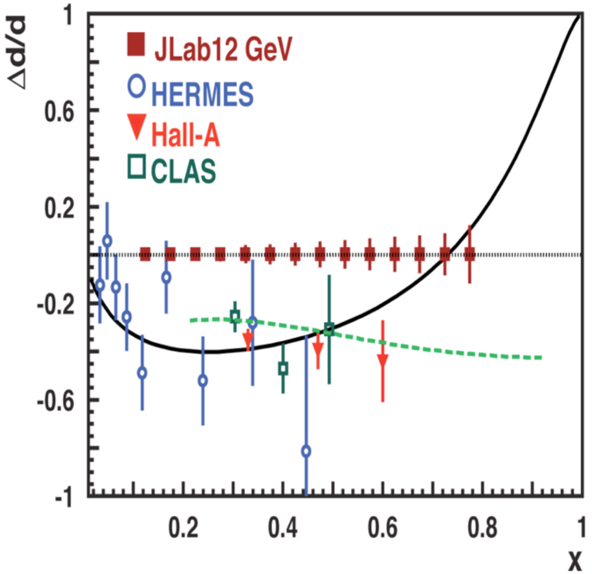
Excess to Unprecedented Large-x Structure Functions – JLab12

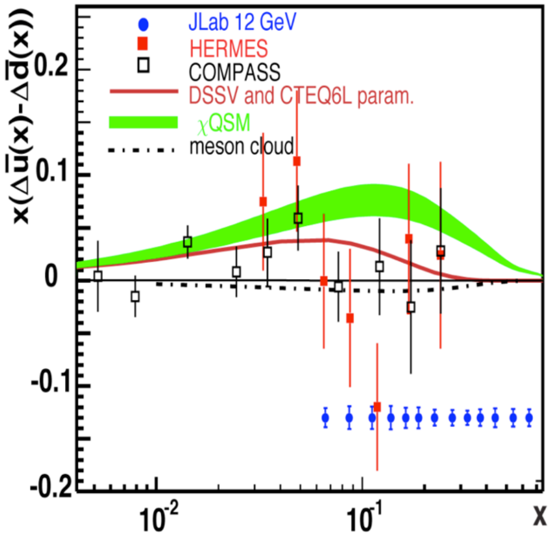


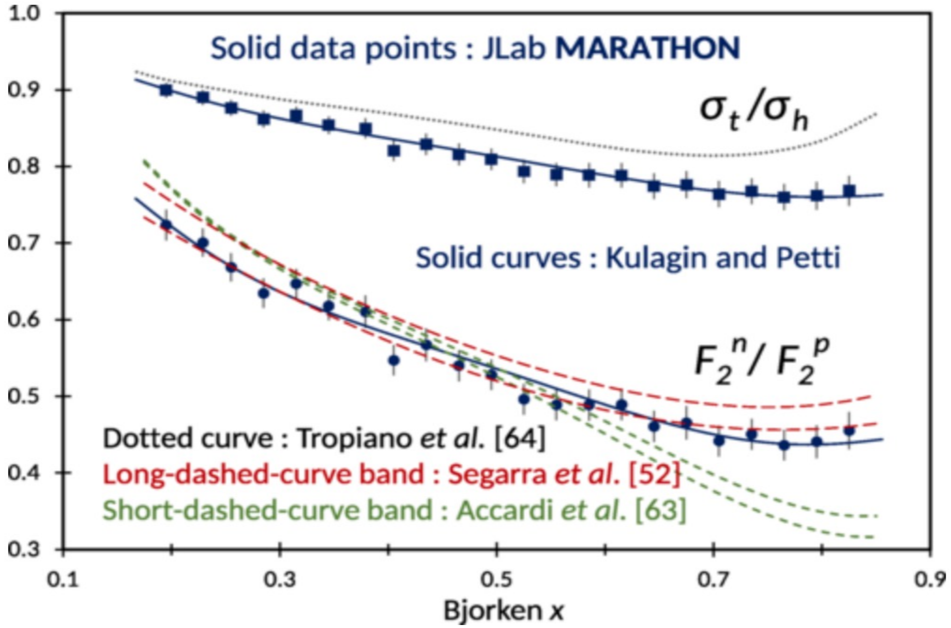


Phys. Rev. Lett. **128** (2022) 132003





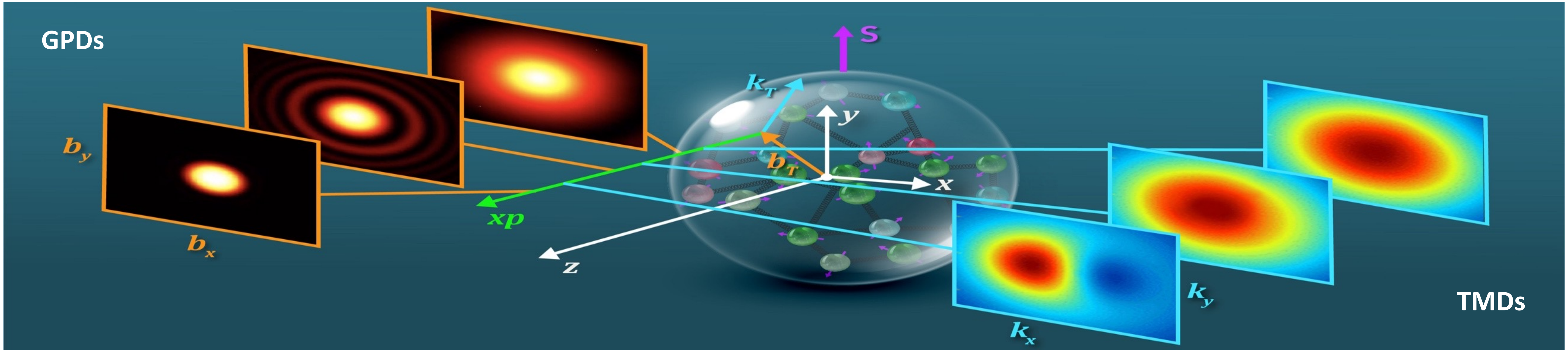




Exploring Hadron's 3D Partonic Structure

- **3D hadron structure:**

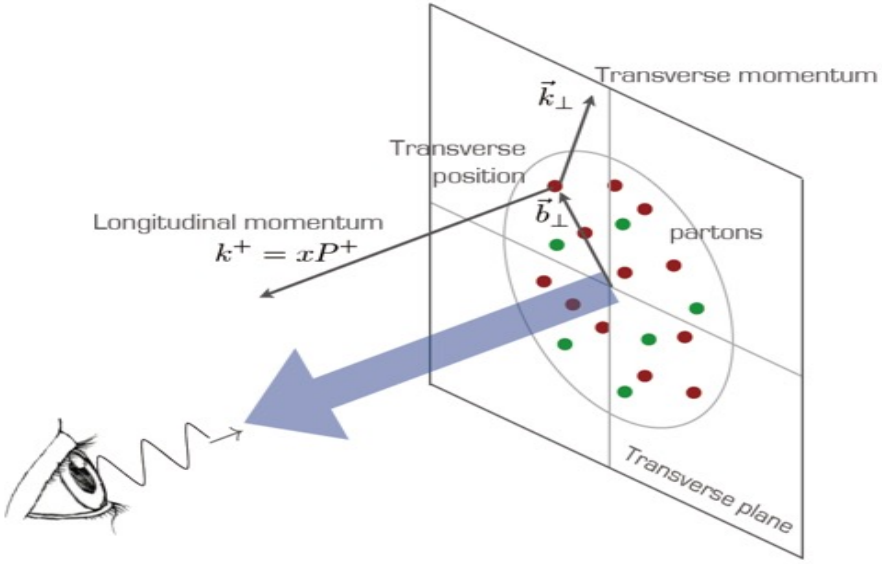
NO quarks and gluons can be seen in isolation!



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

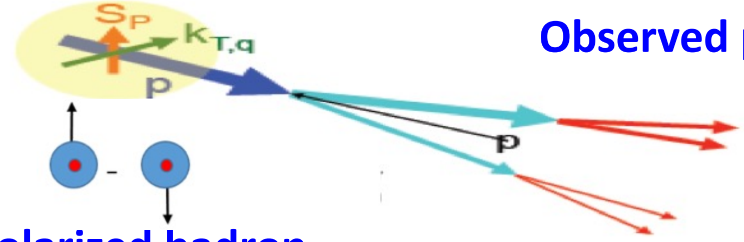
$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\mathrm{QCD}}$$

- **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



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

- Quantum correlation between hadron spin and parton motion:



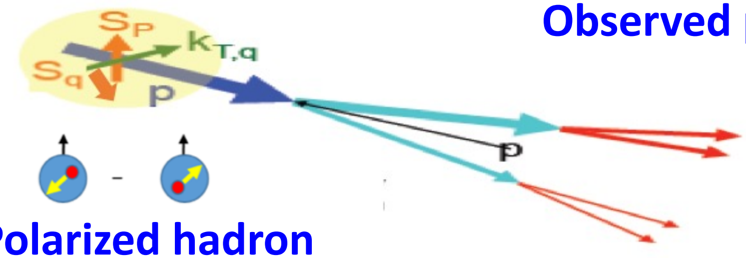
Observed particle

Polarized hadron

Sivers effect – Sivers function

Hadron spin influences
parton's transverse motion

- Quantum correlation between hadron spin and parton spin:



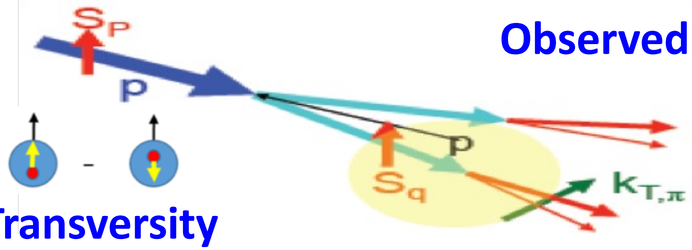
Observed particle

Polarized hadron

Pretzelosity – model OAM

Hadron spin and parton spin
influence
parton's transverse motion

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



Observed particle

Transversity

Polarized hadron

Collins effect – Collins function

Parton's transverse polarization
influences its hadronization

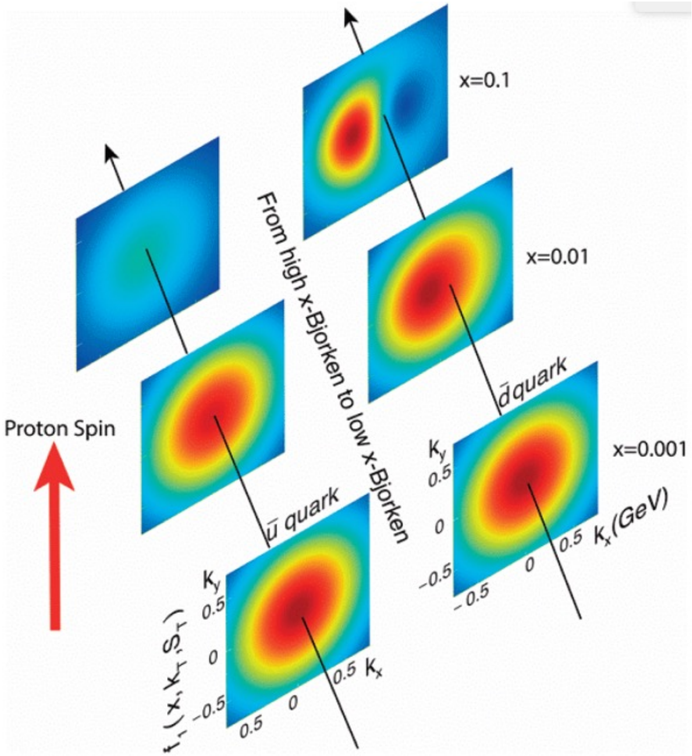


Fig. 2.7 NAS Report

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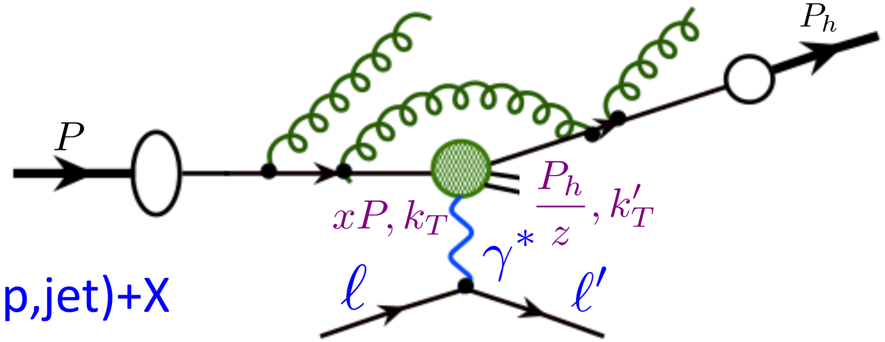
Lepton-Hadron Semi-Inclusive Deep Inelastic Scattering (DIS)

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

e+p/A → e'+h(p,K,p,jet)+X



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

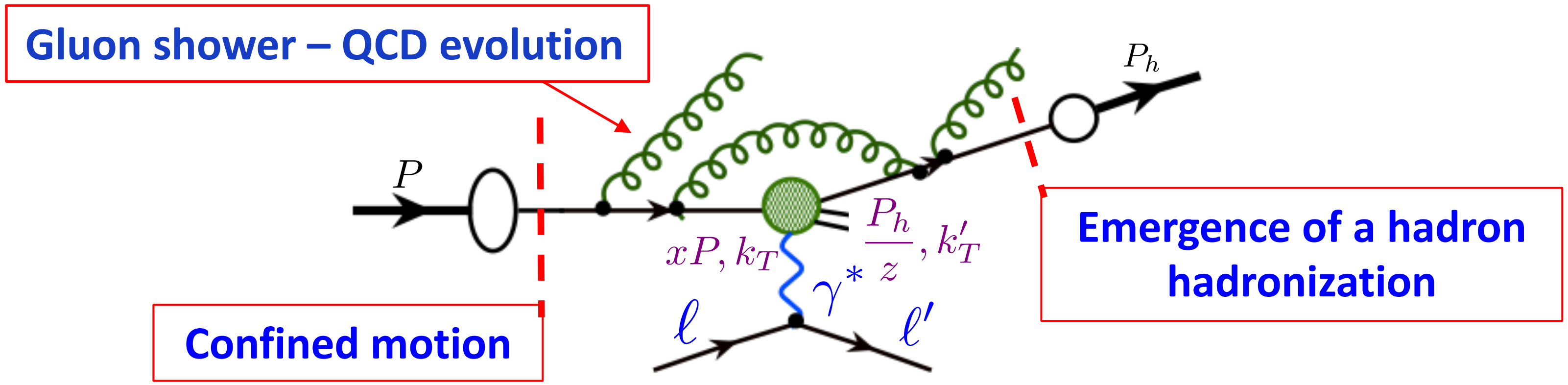
$Q_2: \quad |\vec{P}_{h_T} + \vec{\ell}'_T| \ll |\vec{P}_{h_T}| \sim Q_1$

Naturally sensitive to parton transverse motion

TMDs

See also TMD Handbook [2304.03302]

- But, once the proton is broken, …



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

Transverse momentum broadening:

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

Structure information is diluted by the collision induced shower!

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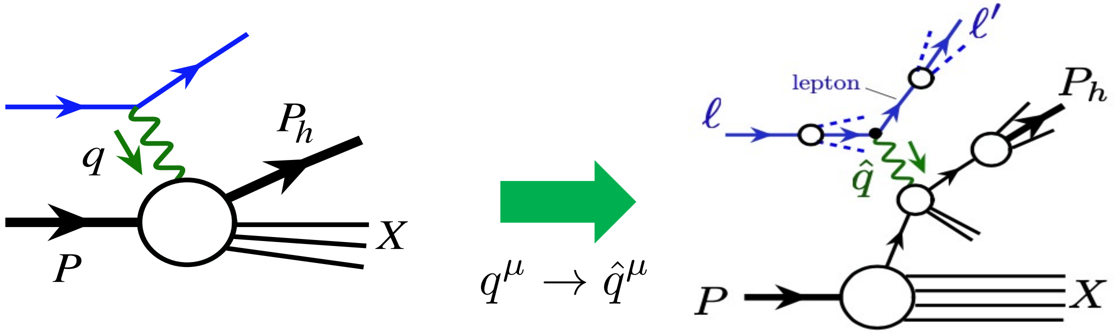
Collision-Induced QED Radiation to SIDIS – Major Challenge

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



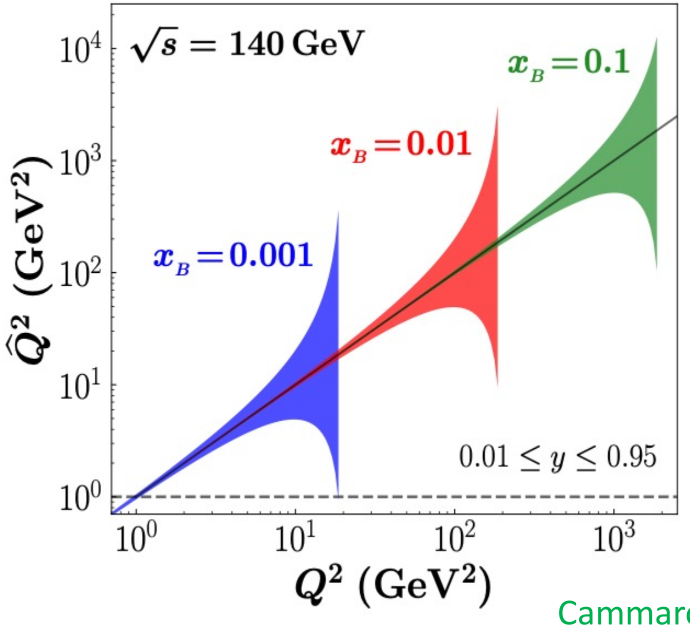
- **Prevents a well-defined "photon-hadron" frame**
- **Radiation is IR sensitive as** $m_e/Q \to 0$

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

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

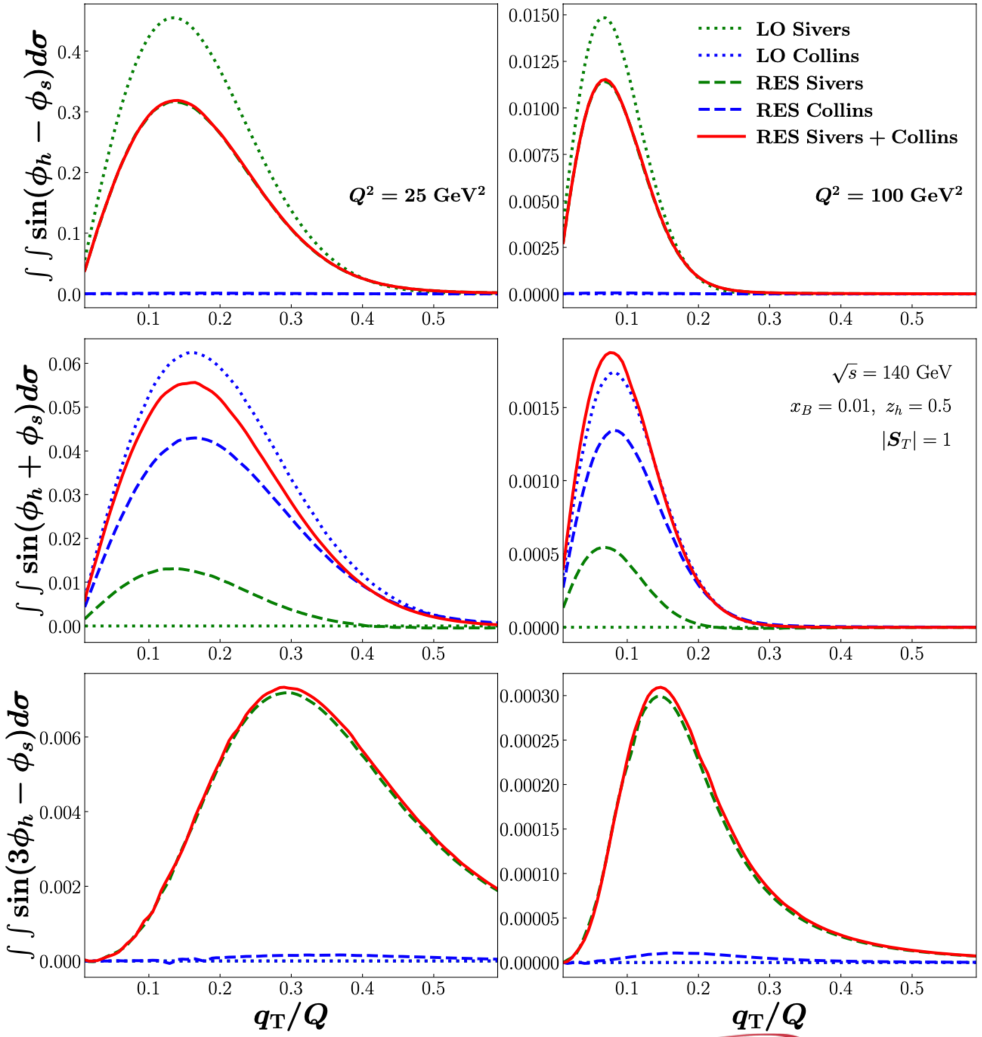
$$\widehat{Q}^2_{\text{min}} = Q^2 \frac{(1-y)}{(1-x_B\, y)} \le Q^2$$

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



Liu, Melnitchouk, Qiu, Sato
2008.02895, 2108.13371

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



Cammarota, Qiu, Watanabe, Zhang, arXiv:2408.08377

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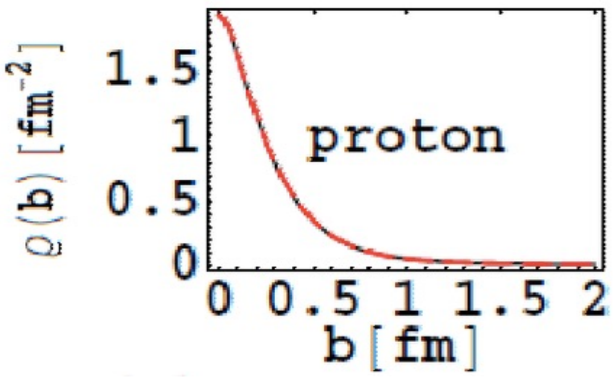
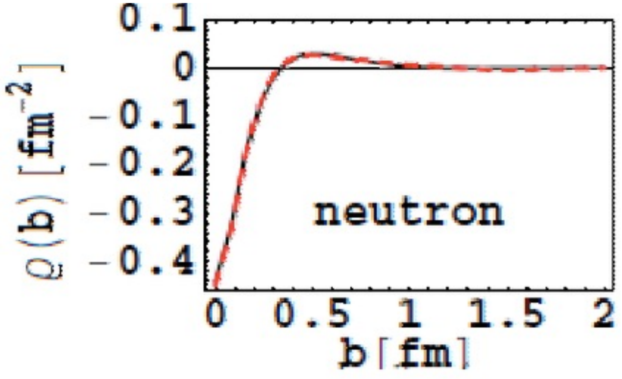
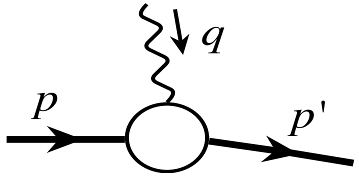
How to Explore Internal Structure of Hadron without Breaking it?

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



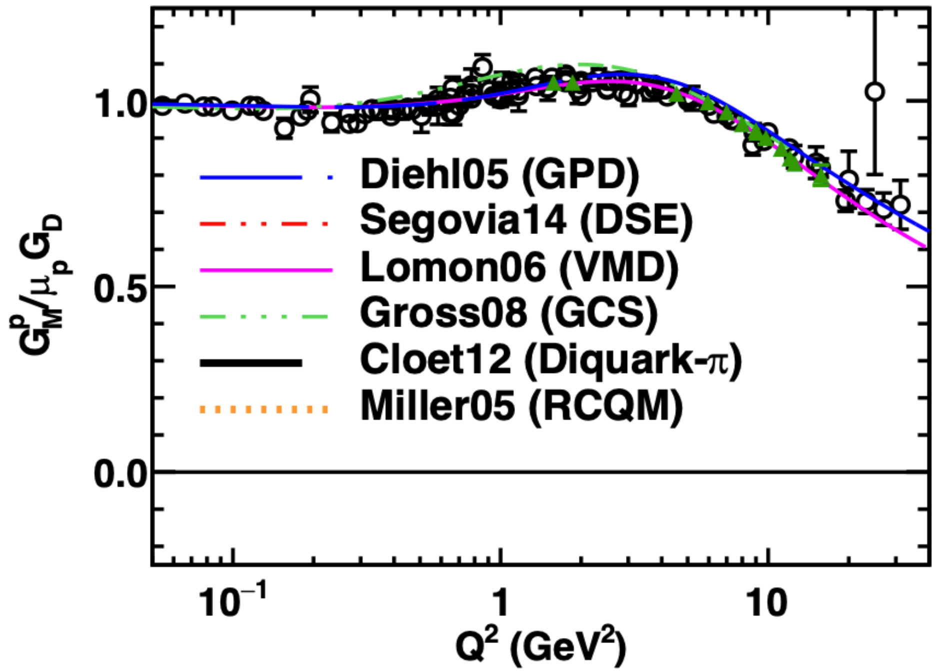


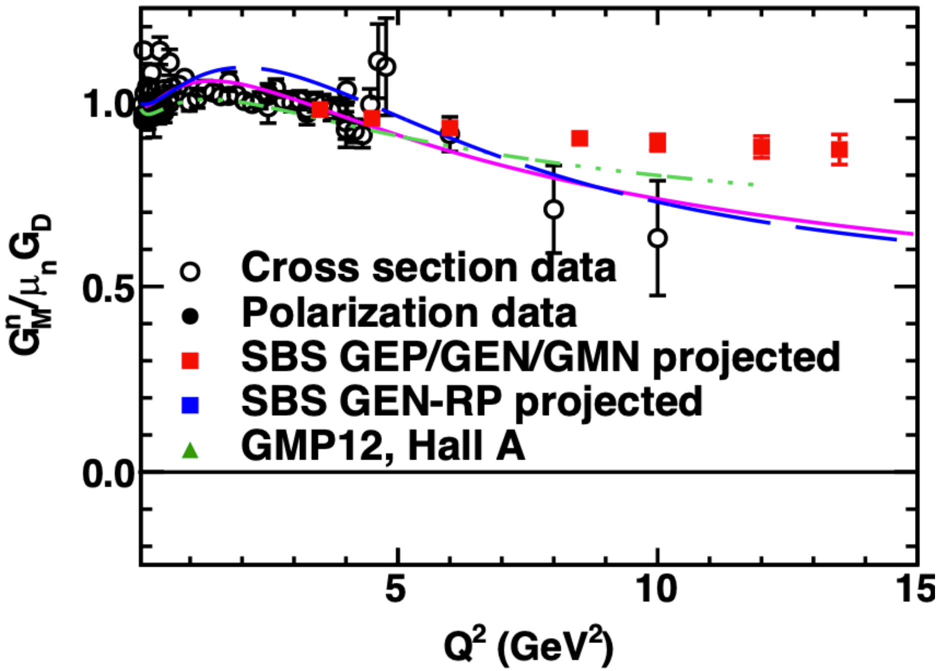


Proton "Radius"
in EM charge distribution

Imaging of the nucleon charge
and magnetization densities

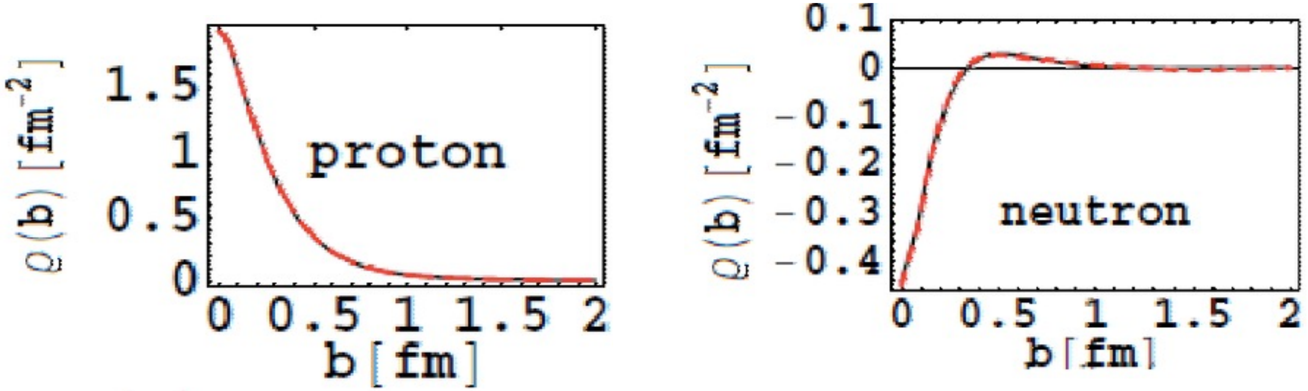
- **JLab has Unprecedented access to all nucleon form factors at high Q^2:**

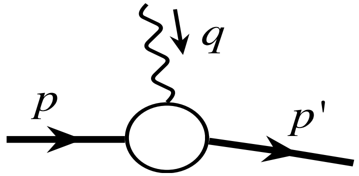




How to Explore Internal Structure of Hadron without Breaking it?

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





→ Proton "Radius" in EM charge distribution

Imaging of the nucleon charge and magnetization densities

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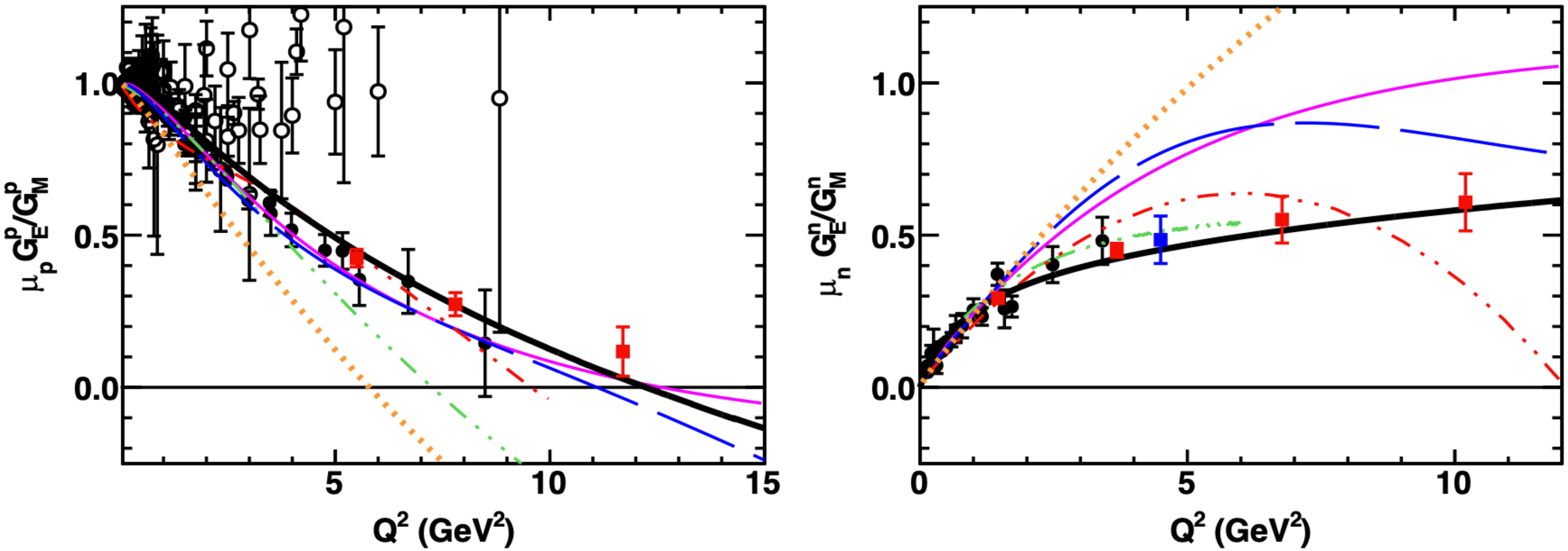
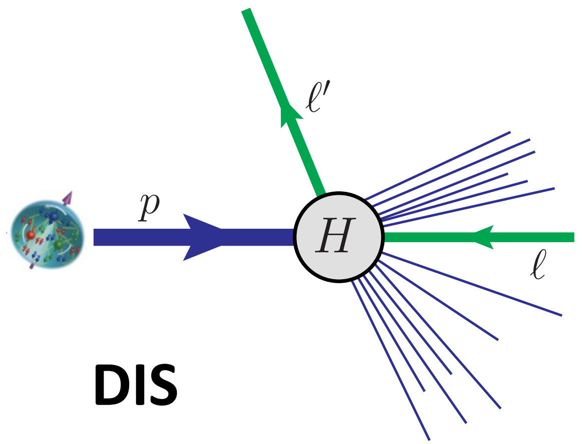
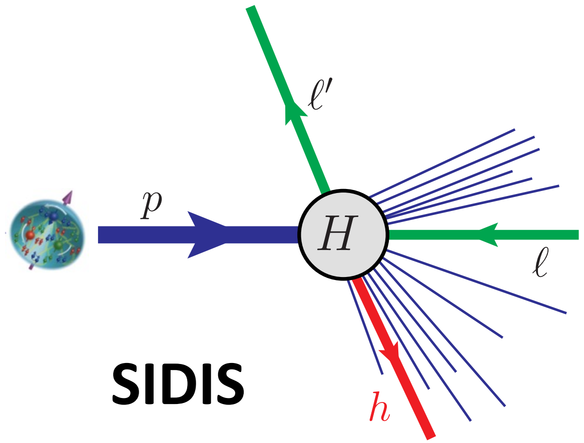


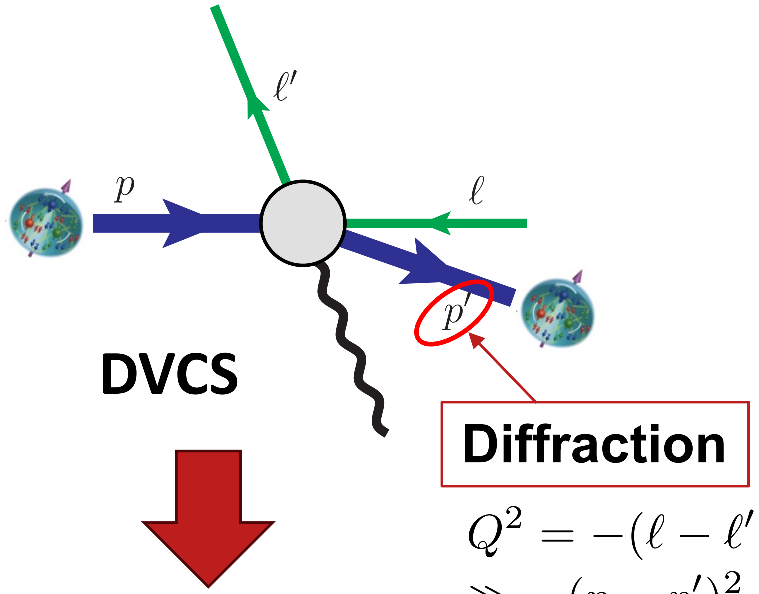
Inclusive vs. Exclusive – Partonic Structure without Breaking the Hadron!

Inclusive scattering





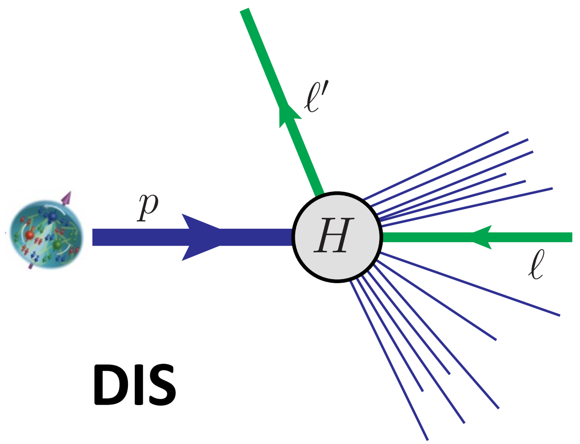
Exclusive diffraction

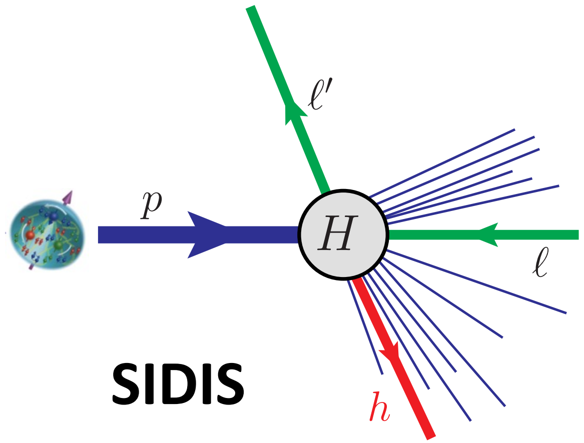


$$Q^2 = -(\ell - \ell')^2$$
$$\gg -(p - p')^2 = -t$$

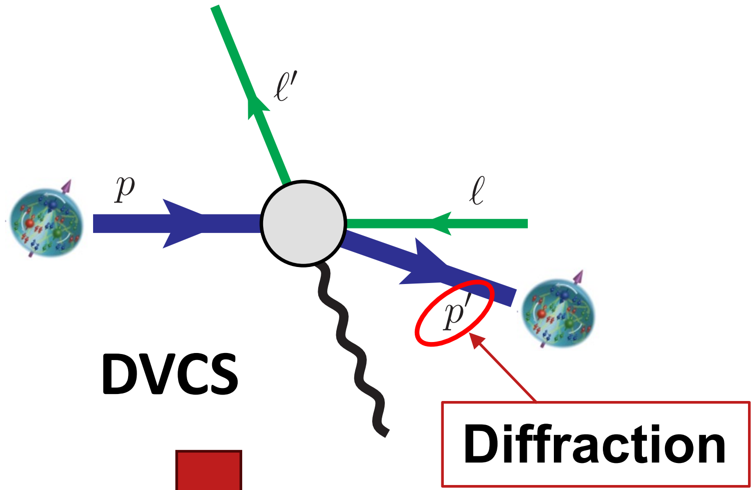
Inclusive vs. Exclusive – Partonic Structure without Breaking the Hadron!

Inclusive scattering





Exclusive diffraction

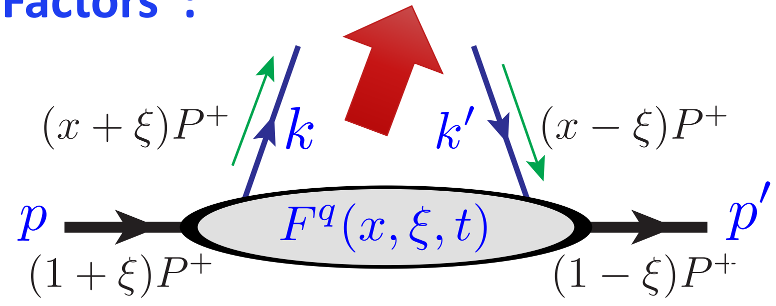


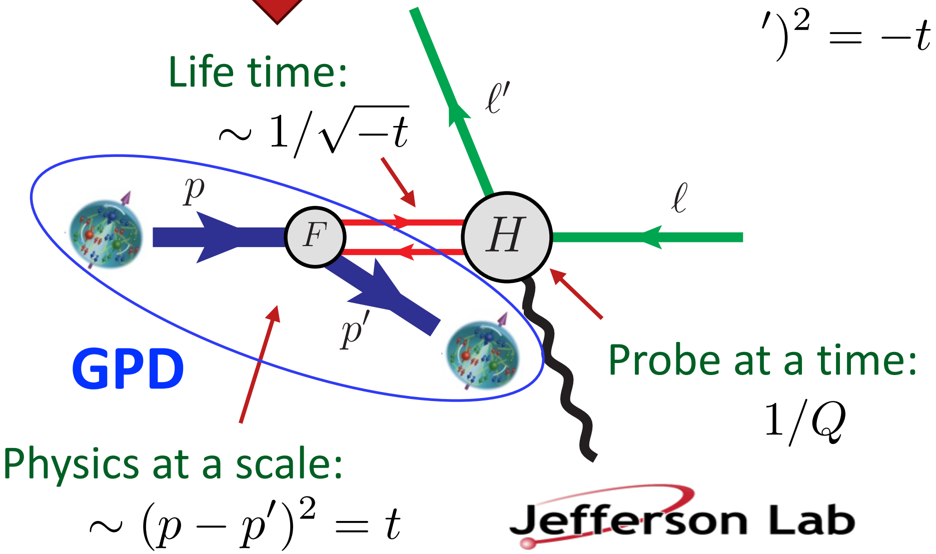
$Q^2 = -(\ell - \ell')^2$

$')^2 = -t$

GPDs as "Form Factors":

$\Delta^+ = 2\xi P^+$





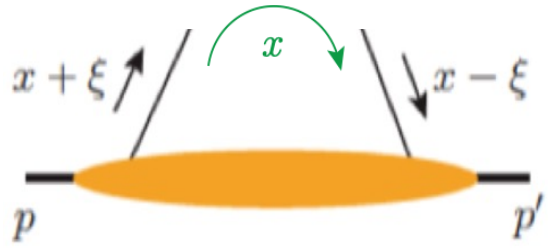
$$F^q(x,\xi,t) = \int \frac{\mathrm{d}z^-}{4\pi} e^{-ixP^+z^-} \langle p' | \bar{q}(z^-/2)\gamma^+ q(-z^-/2)|p\rangle$$

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

Properties of GPDs – Partonic

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

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



Measurement of p' fixes (t, ξ)

x = momentum flow between the pair

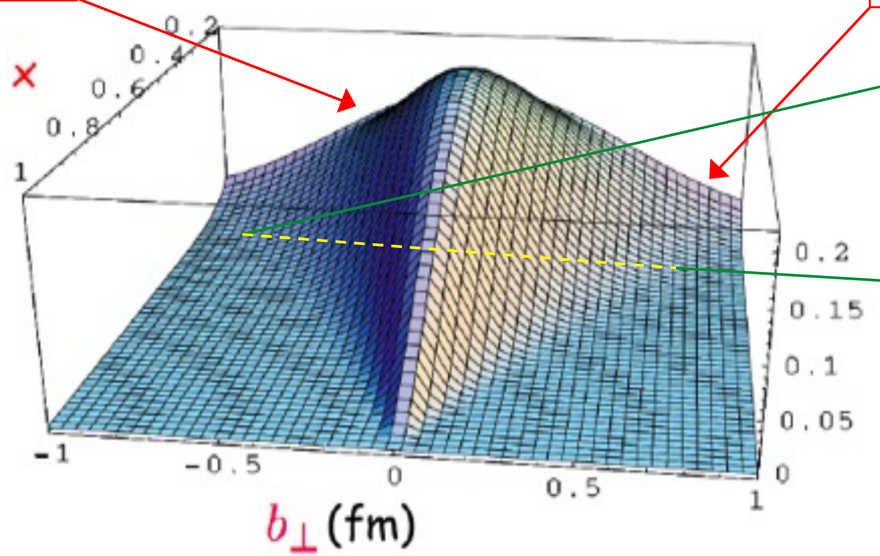
➡ **Quark density in** $\mathrm{d}x\,\mathrm{d}^2\boldsymbol{b}_T$

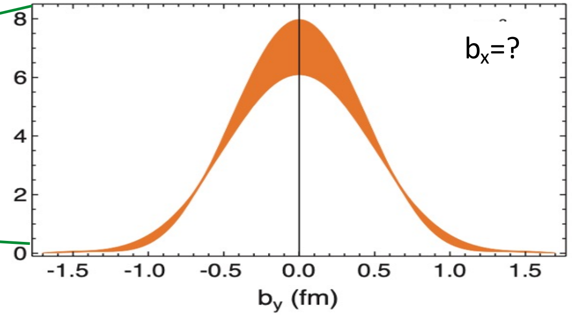
How fast does glue density fall?

Tomographic image of hadron in slice of x

How far does glue density spread?

➡





Slice in (x,Q)

Modeled by M. Burkdart, PRD 2000

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

- **Should $r_q(x)$ > $r_g(x)$, or vice versa?**
- **How do they compare with known radius (EM charge radius, mass radius, …) & why?**

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

Properties of GPDs – Hadronic = Moments of GPDs

Ji, PRL78, 1997
V. D. Burkert, et al. RMP 95 (2023) 041002

- **QCD energy-momentum tensor:**

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

- **"Gravitational" form factors:**

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

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

Related to pressure & stress force inside h

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

- **Connection to GPD moments:**

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

- **Angular momentum sum rule:**

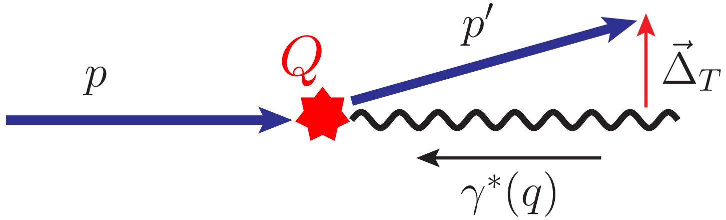
$$J_i = \lim_{t \to 0} \int_{-1}^{1} dx \, x \left[H_i(x,\xi,t) + E_i(x,\xi,t) \right] \qquad i = q, g$$

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

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

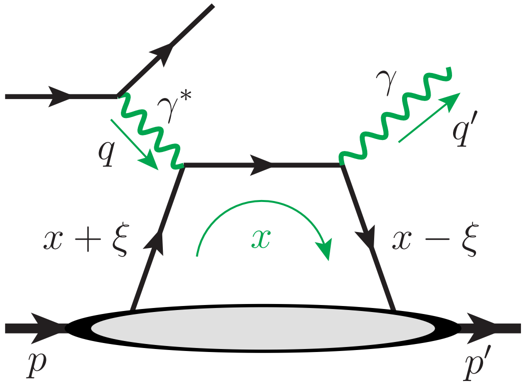
Known Physical Processes for Extracting GPDs

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

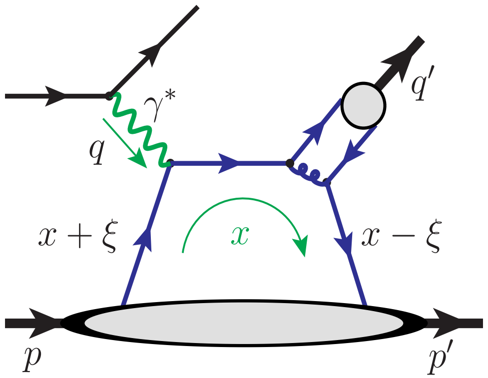


HERA discovery:
~ 10-15% of HERA events with the Proton stayed intact

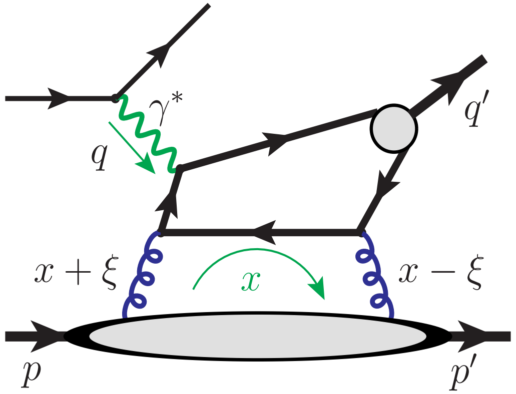
- Known exclusive processes for extracting GPDs:



DVCS: Q^2 >> |t|



DVMP



DVQP

+ DDVCS, …

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

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

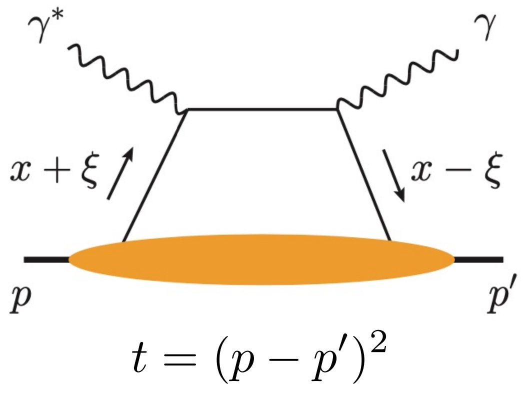
Factorization

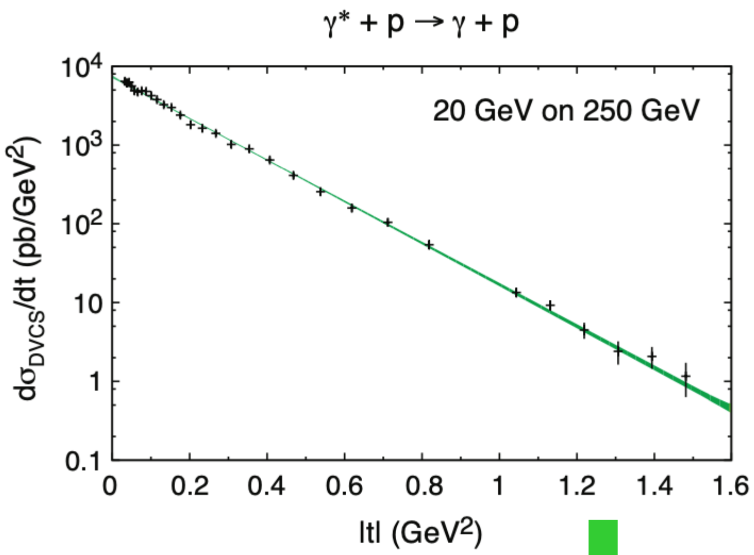
GPDs: $f_{i/h}(x,\xi,t;\mu)$

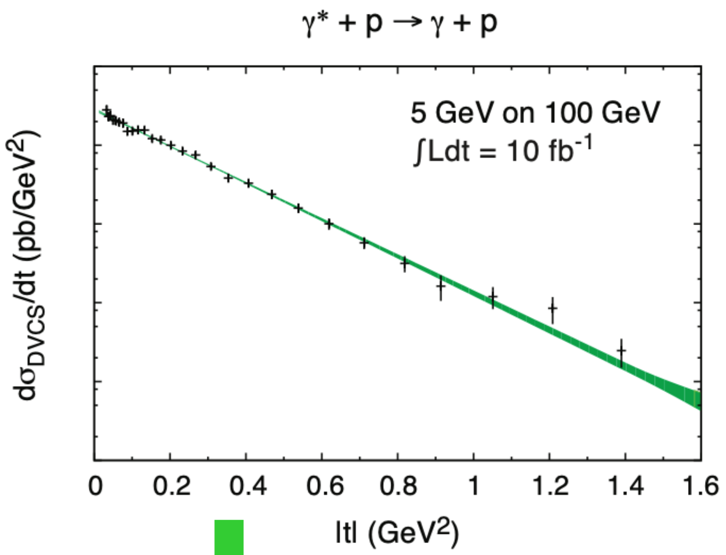
Jefferson Lab

DVCS at a Future EIC (White Paper)

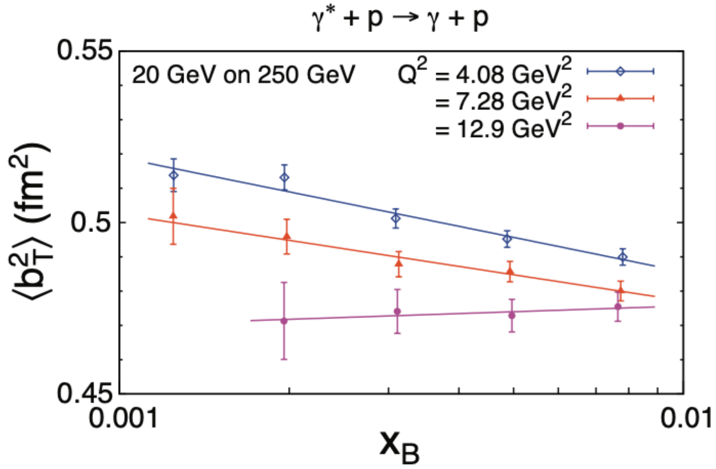
- **Cross Sections:**

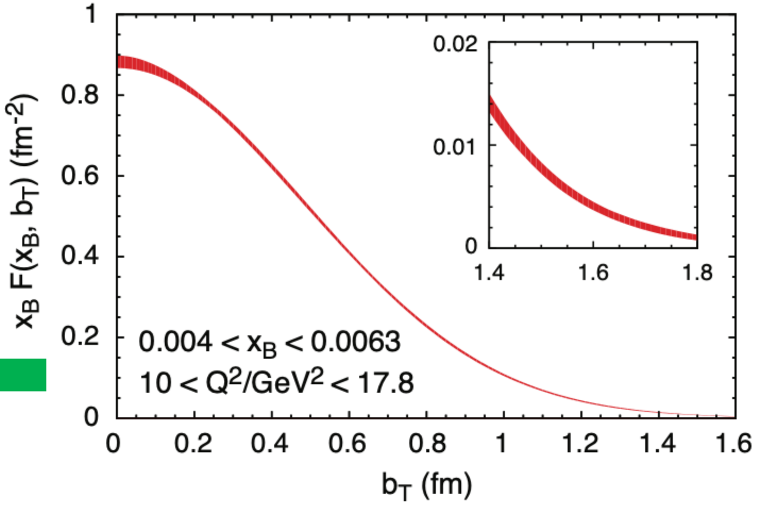


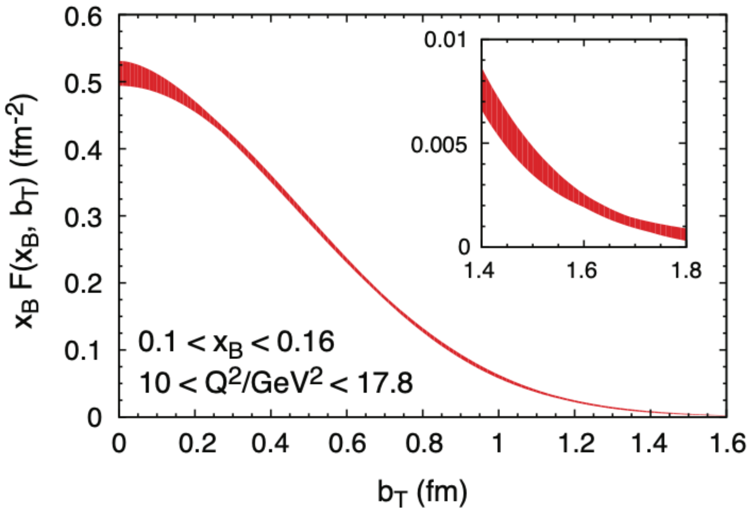




- **Spatial distributions:**



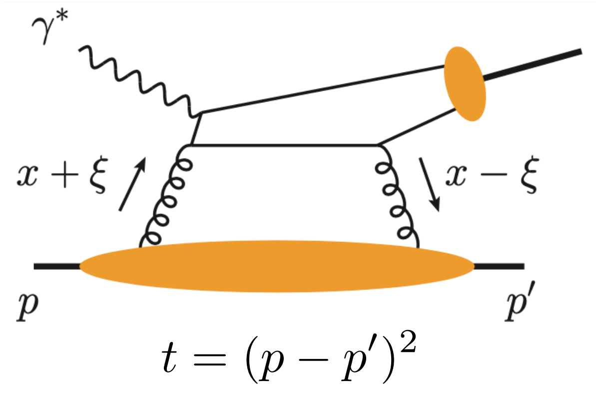


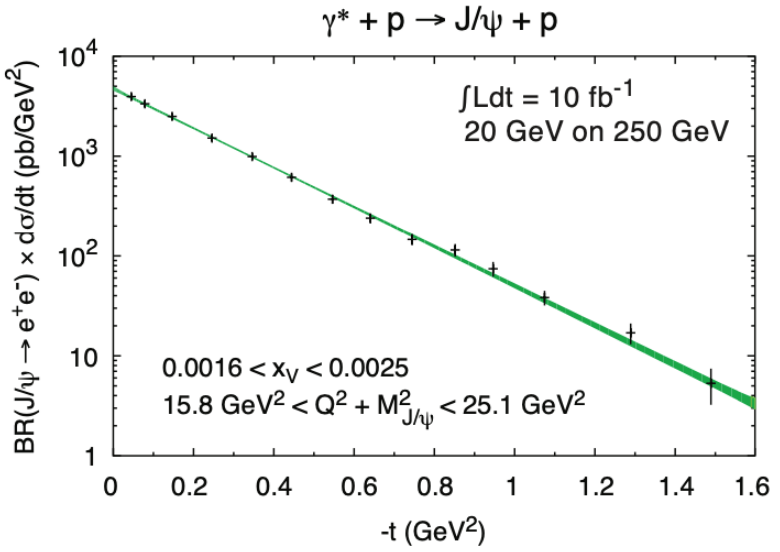


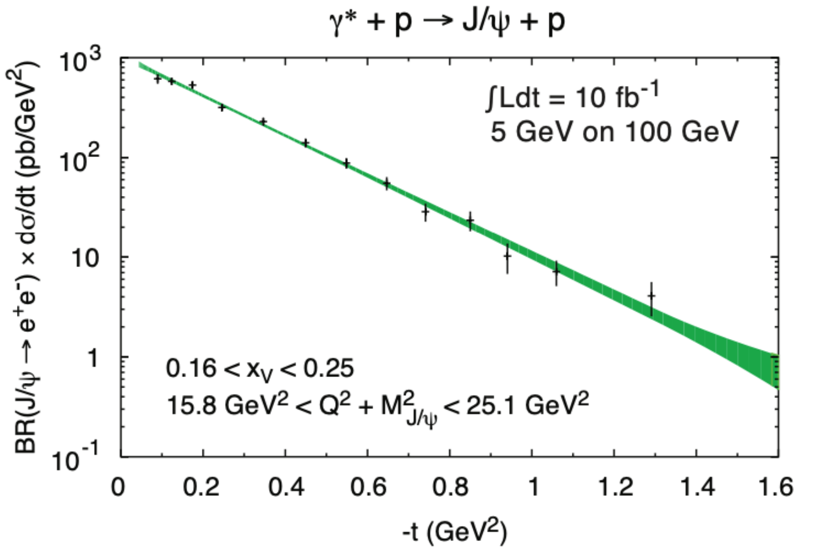
Effective "proton radius" in terms of quarks as a function of x_B

Imaging the Gluon at the EIC (White Paper)

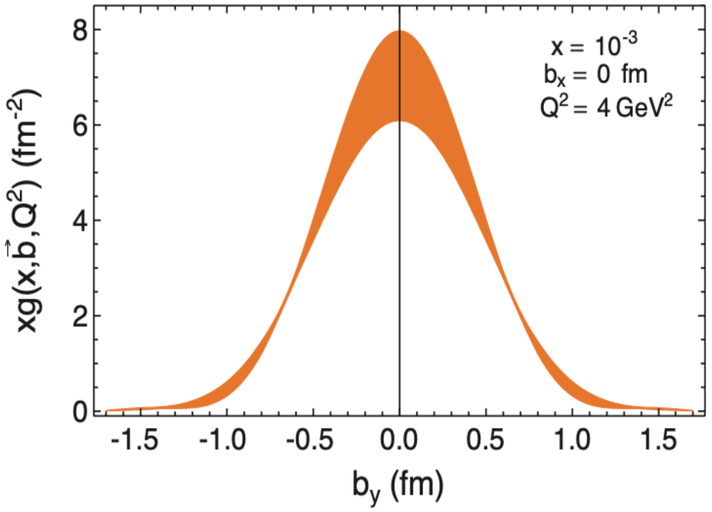
❑ Exclusive vector meson production:

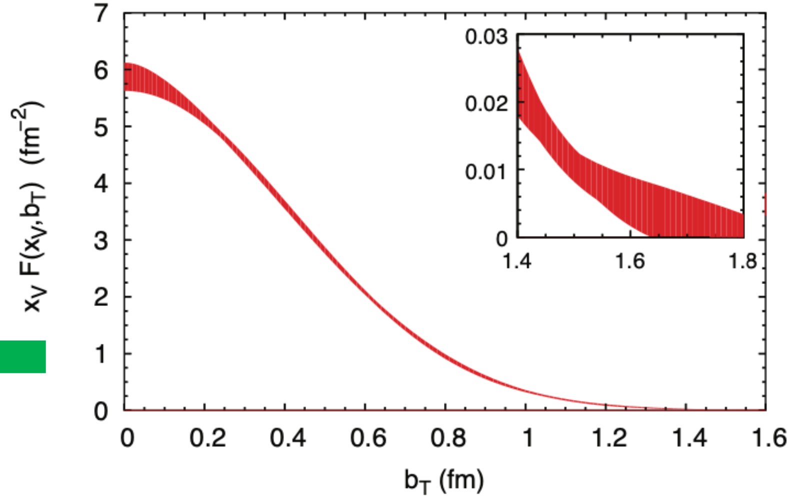


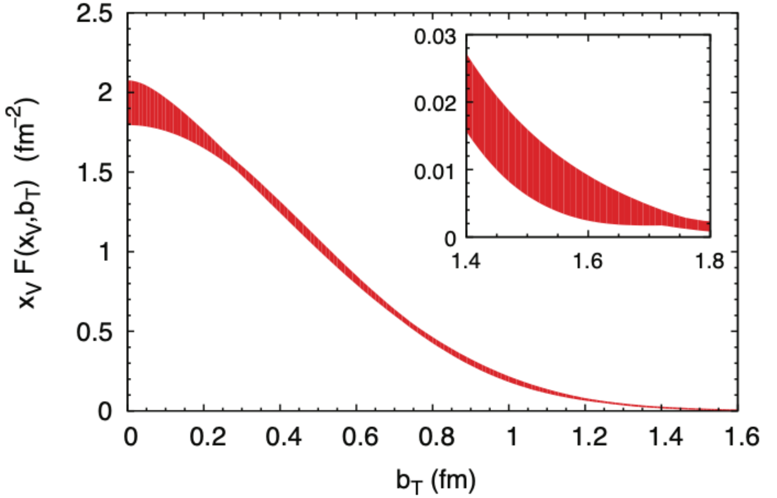




❑ Spatial distributions:





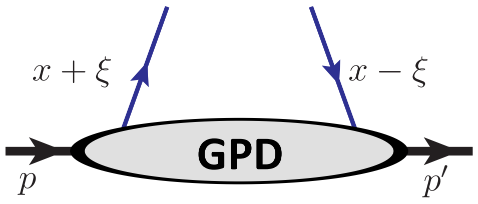


The b_T space density for gluons ➡ **Effective "proton radius" in terms of gluons**

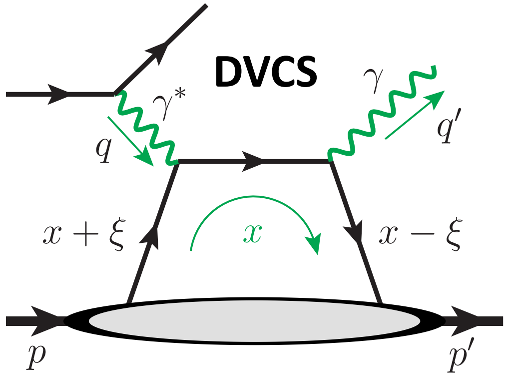
Jefferson Lab

Why is the GPD's *x*-dependence so *difficult* to measure?

❑ Amplitude nature: exclusive processes



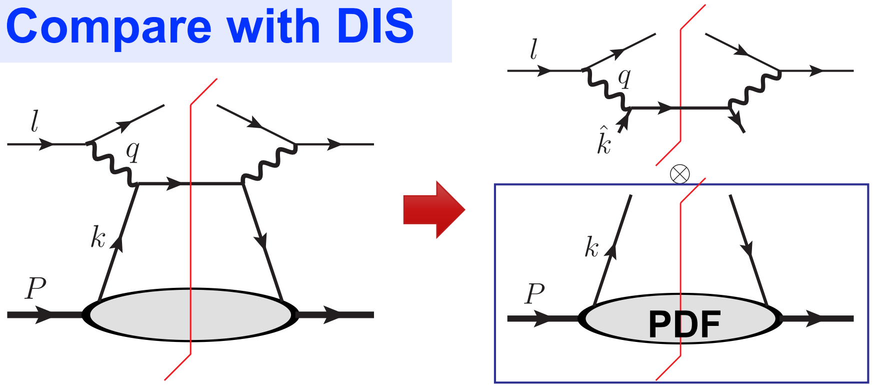
x ~ loop momentum



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

Full range of x, including $x=0;\quad x=\pm\xi$

Compare with DIS



***cross section*: cut diagram**

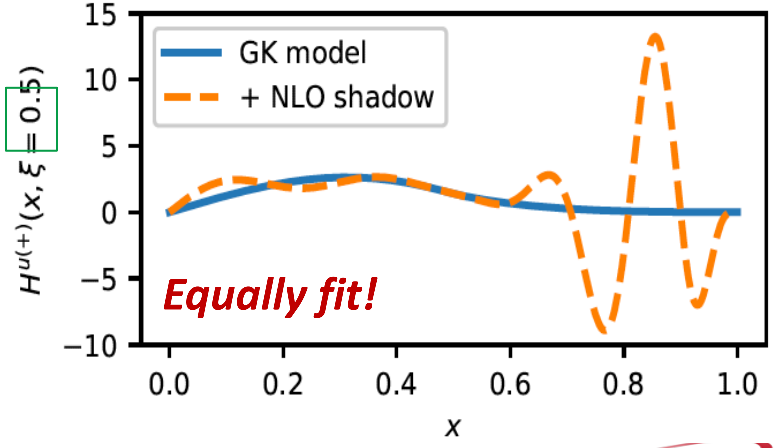
$$\sigma_{\rm DIS} \simeq \int_{x_B}^{1} \mathrm{d}x\, f(x)\,\hat{\sigma}(x/x_B)$$

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

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

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

“moment”



[Bertone et al. PRD `21]

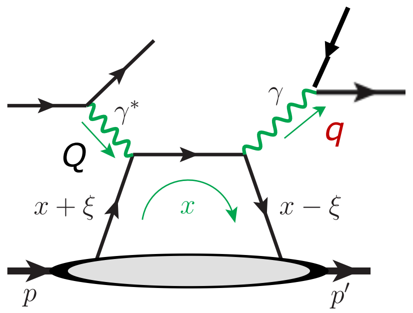
Jefferson Lab

Process/Observable could be Sensitive to the x-Dependence of GPDs?

- **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):**

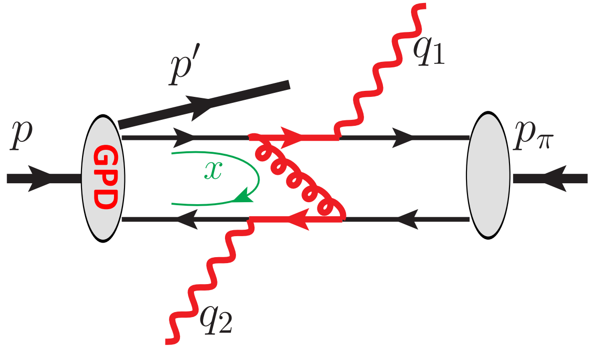
$$x_p(\xi,q) = \xi\left(\frac{1-q^2/Q^2}{1+q^2/Q^2}\right) \rightarrow \xi \quad \text{same as} \quad \text{DVCS} \quad \text{if } q \rightarrow 0$$

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

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

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*]

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

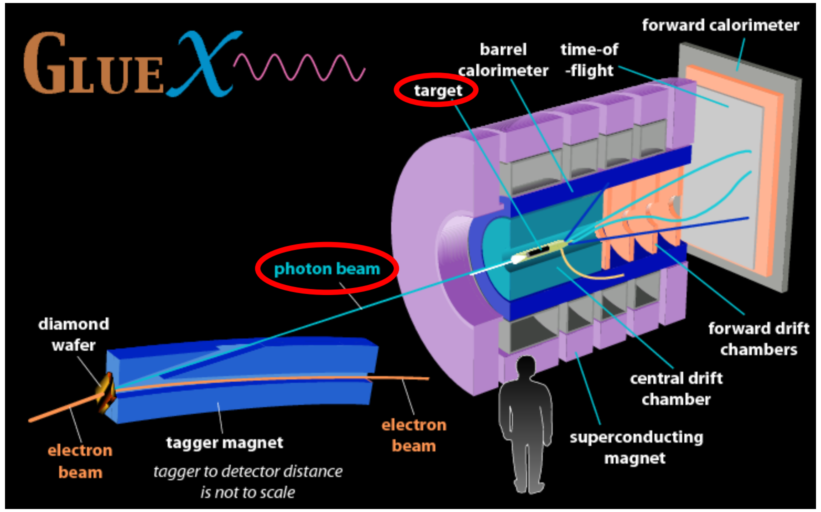
$$\frac{\mathrm{d}\sigma}{\mathrm{d}t\;\mathrm{d}\xi\;\mathrm{d}q_T} \sim |\mathcal{M}(t,\xi,q_T)|^2$$

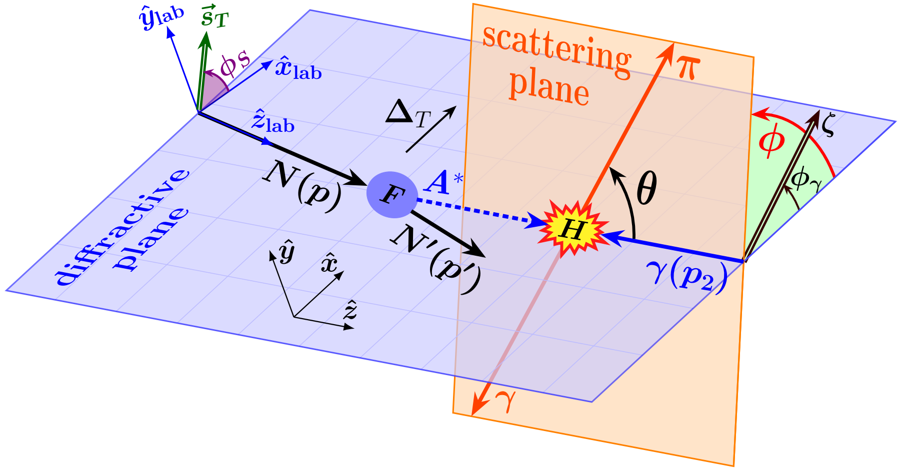
q_T distribution is "conjugate" to x distribution

$$x \leftrightarrow q_T$$

Enhanced x-Sensitivity: γ-π Pair Photoproduction (at JLab Hall D)

Qiu & Yu, PRL 131 (2023), 161902





❑ Polarization asymmetries:

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

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

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

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

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

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

Neglecting: (1) E and $\widetilde{E}$; (2) gluon channel

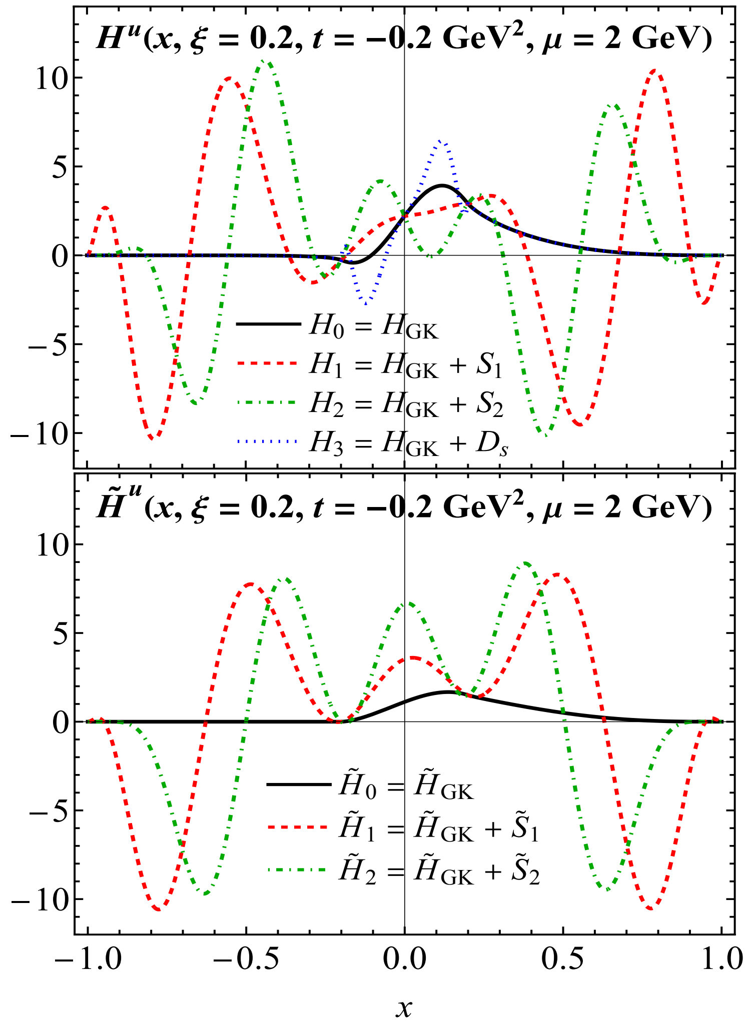
24

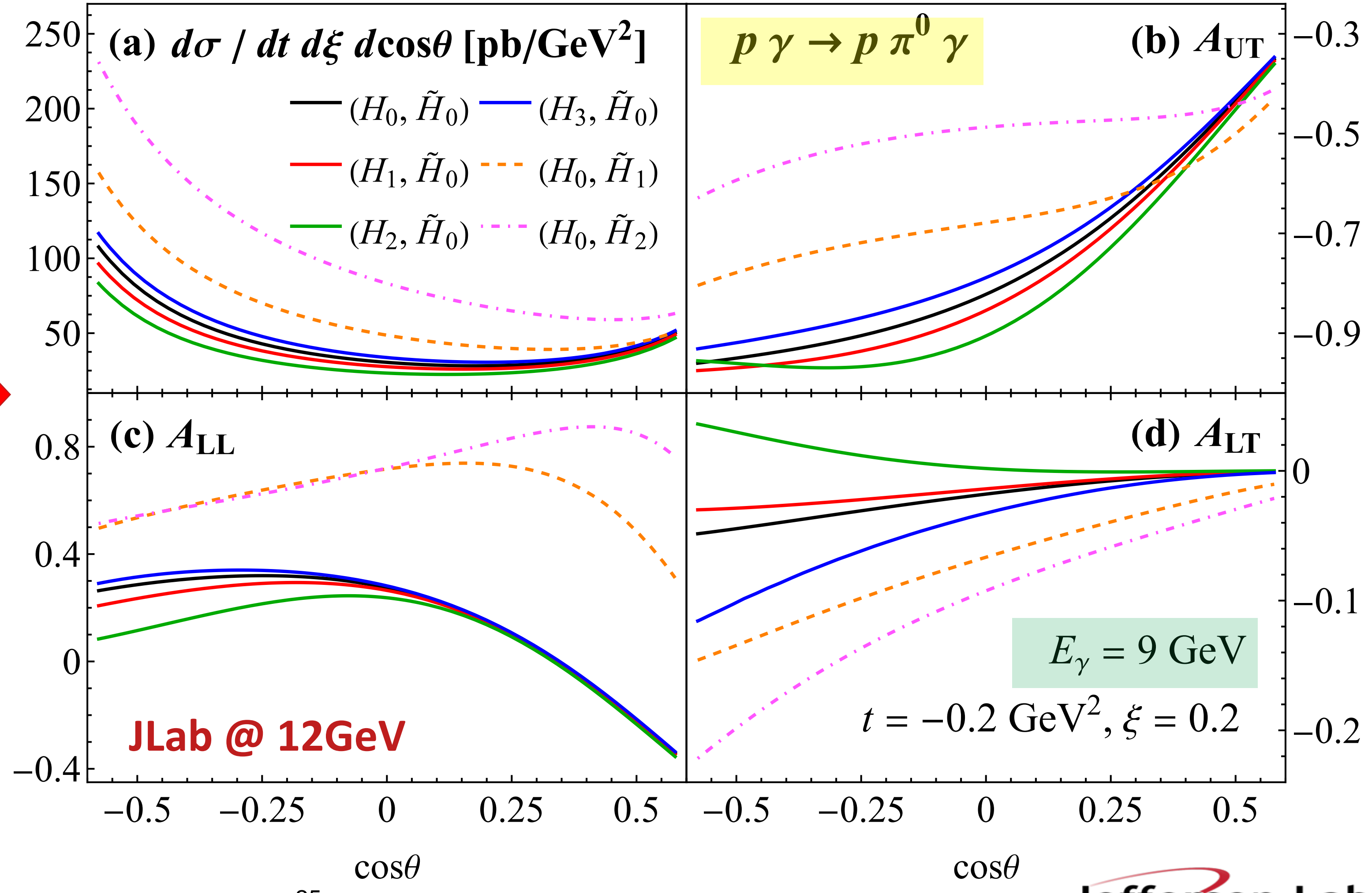
Enhanced x-Sensitivity: γ-π Pair Photoproduction (at JLab Hall D)

GPD models = GK model + shadow GPDs

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

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





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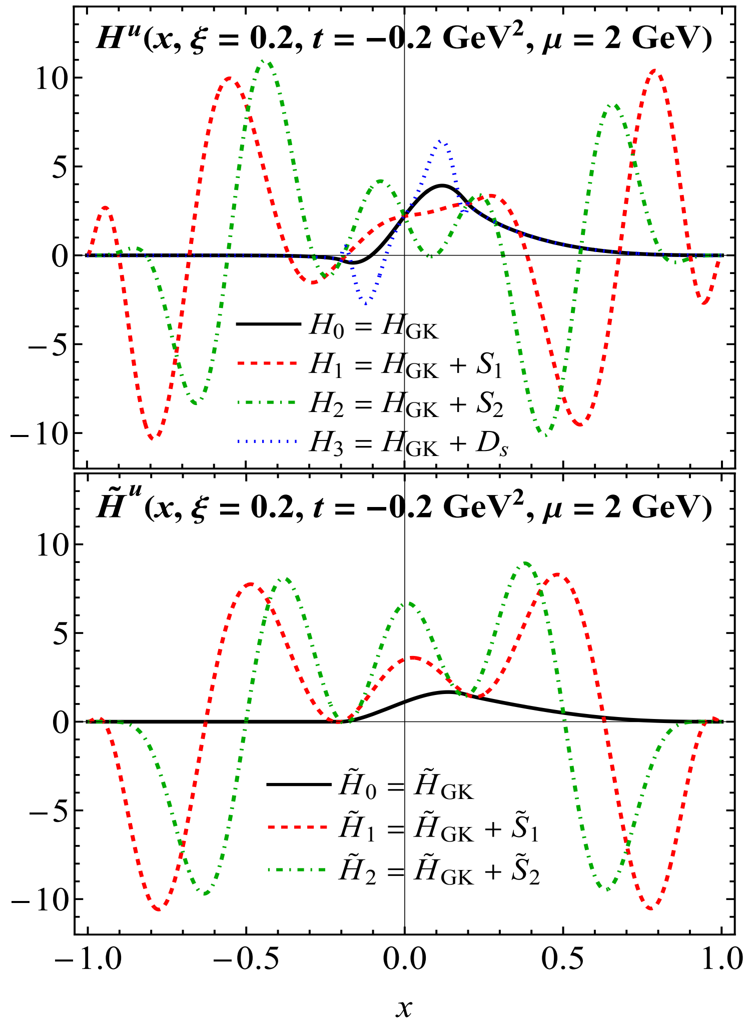
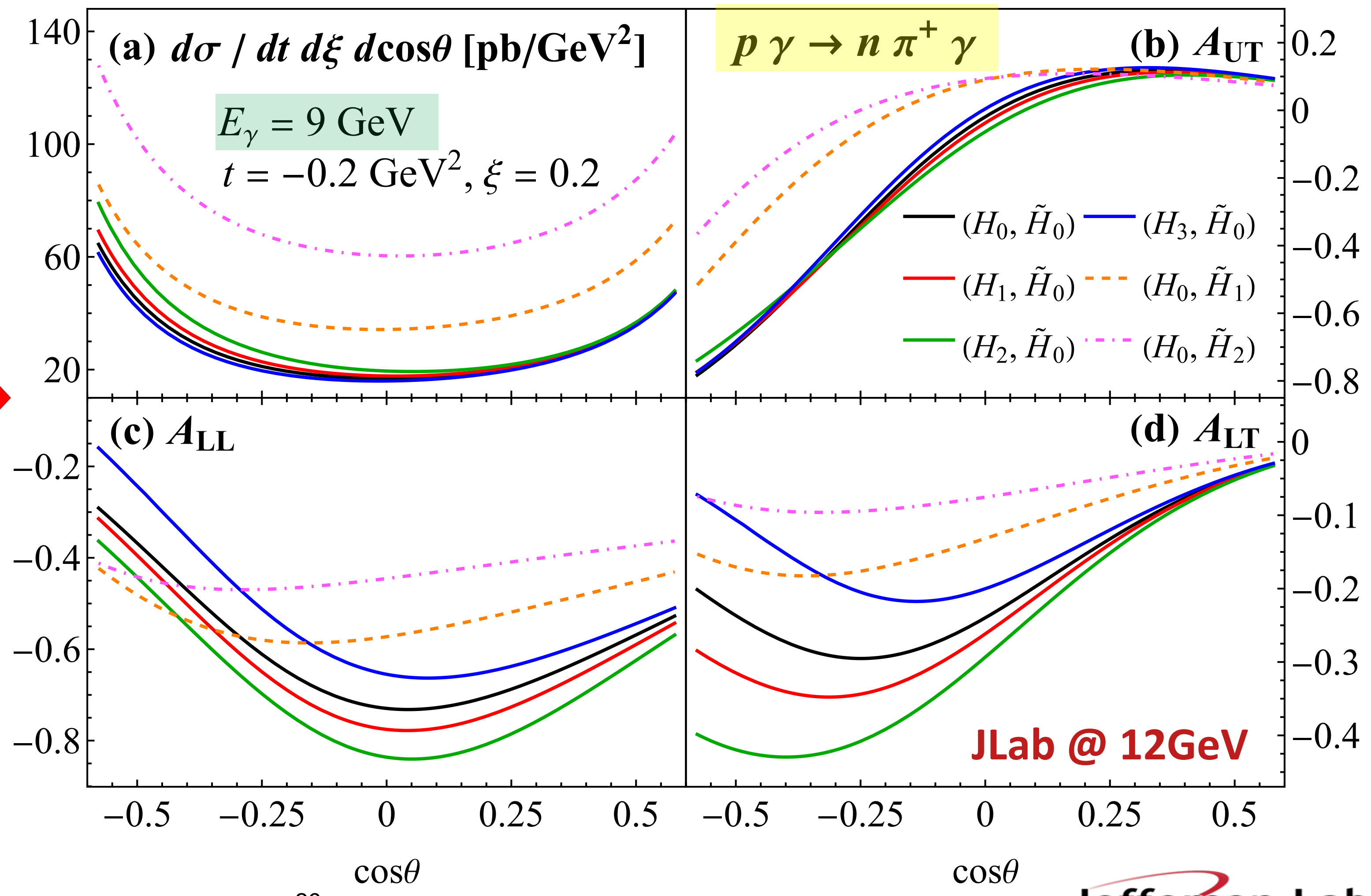
Enhanced x-Sensitivity: γ-π Pair Photoproduction (at JLab Hall D)

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

GPD models = GK model + shadow GPDs ⟵

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



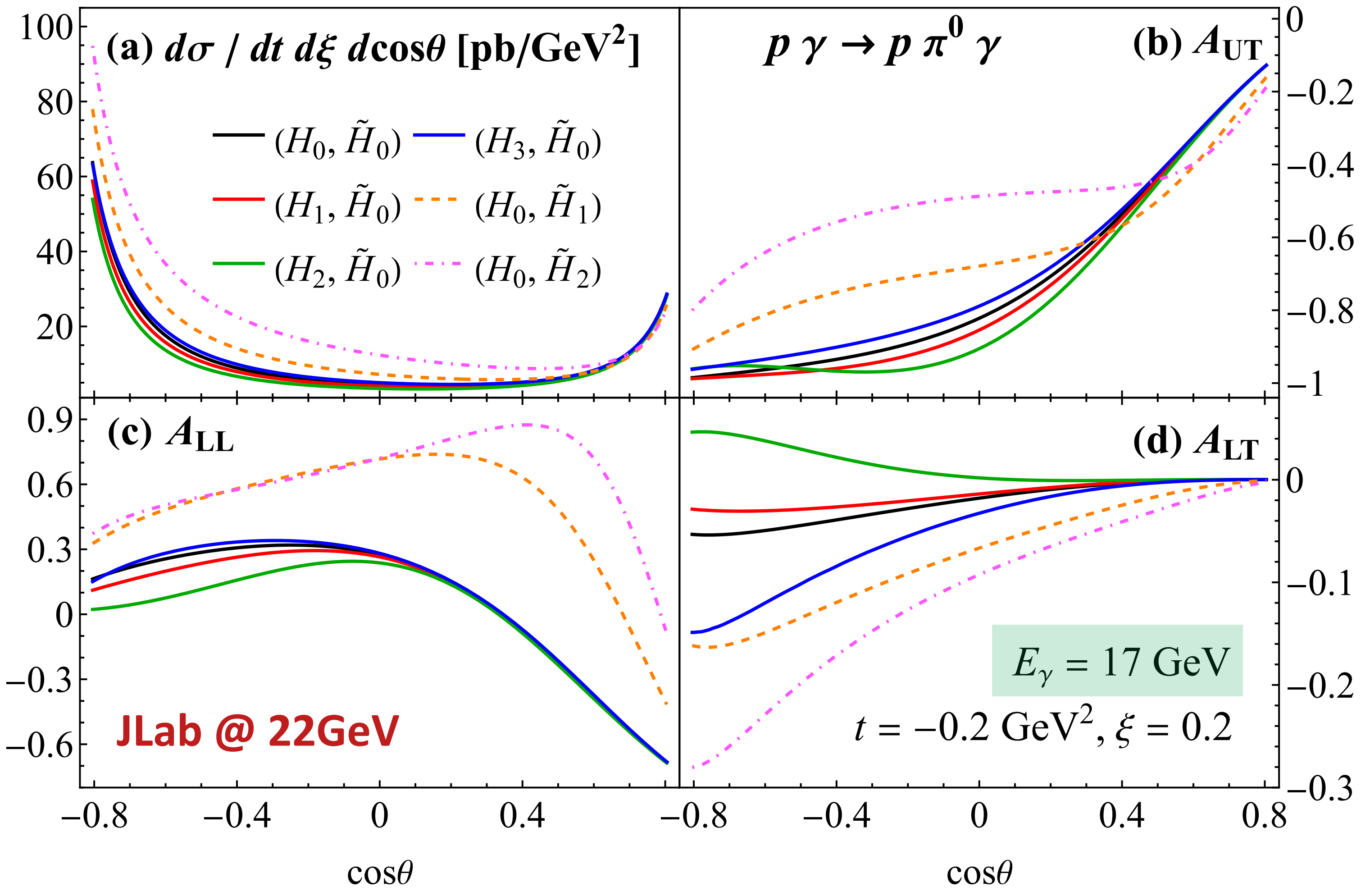


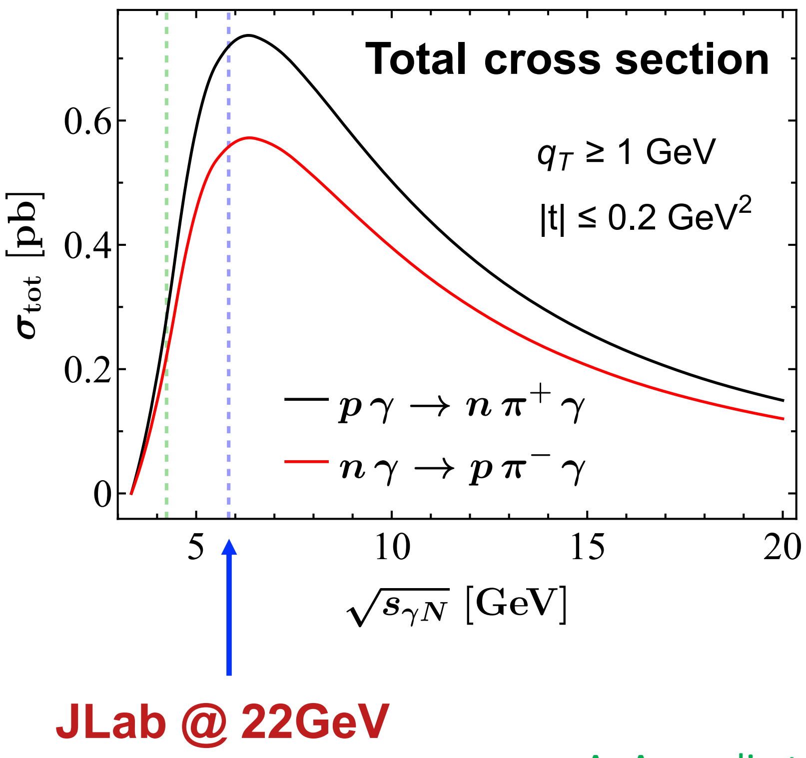
Jefferson Lab

Enhanced x-Sensitivity: γ-π Pair Photoproduction (at upgraded energy)

Goloskokov, Kroll, `05, `07, `09
Bertone et al. `21
Moffat et al. `23
Qiu & Yu, `23

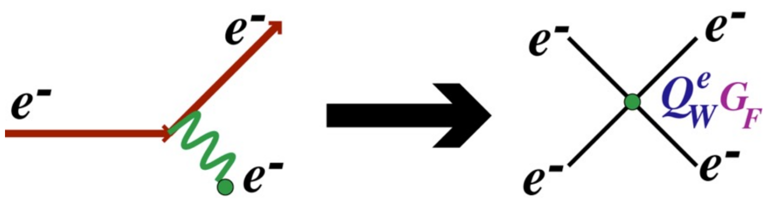
GPD models = GK model + shadow GPDs ⟵ $\int_{-1}^{1} \frac{dx\, S(x,\xi)}{x-\xi \pm i\epsilon} = 0$



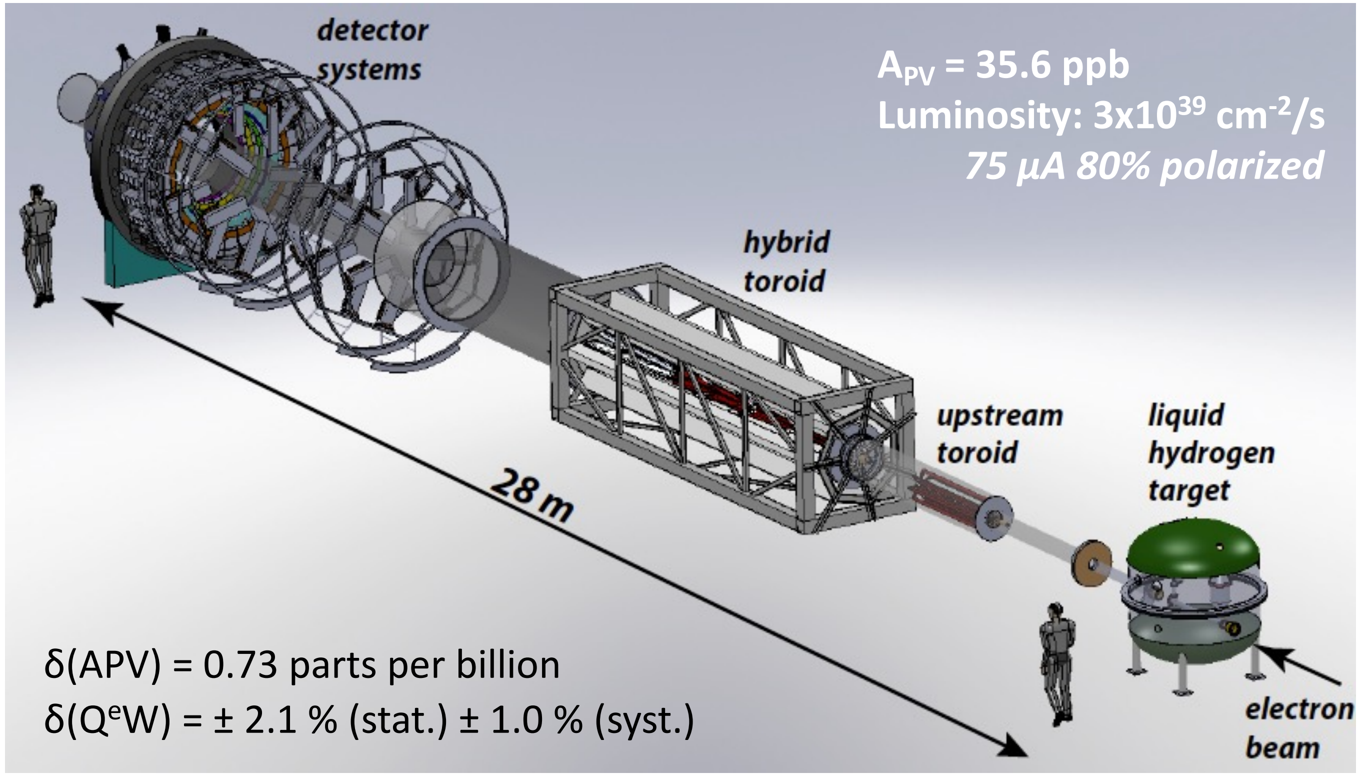


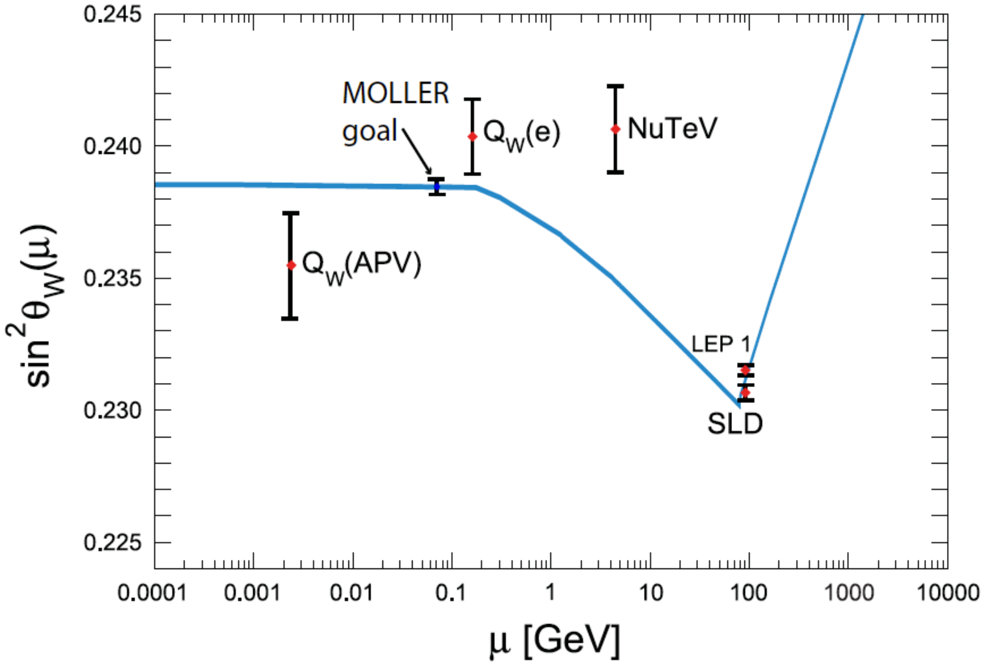
A. Accardi et al. [arXiv:2306.09360]

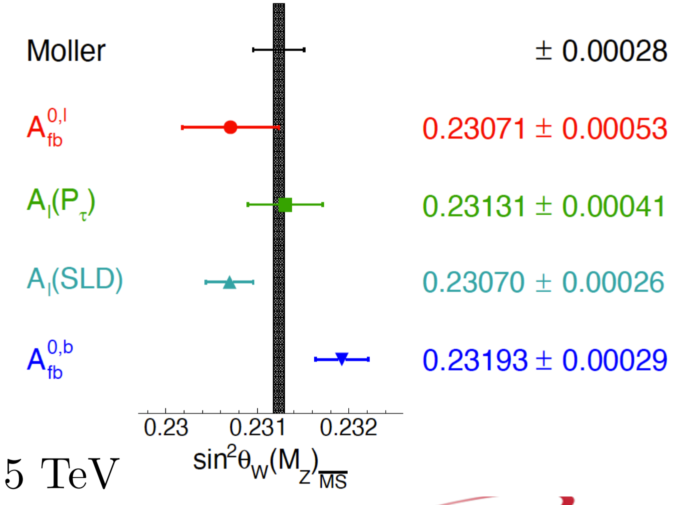
The Moller Experiment at JLab12



with 11 GeV electron beam







Sensitivity to new 4-electron contact interaction:

$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = \frac{1}{\sqrt{\sqrt{2}G_F|\Delta Q_W^e|}} \simeq \frac{246.22\ \mathrm{GeV}}{\sqrt{0.023 Q_W^e}} = 7.5\ \mathrm{TeV}$$

$$\Rightarrow \Lambda = \sqrt{|g_{RR}^2 - g_{LL}^2|} \times 7.5\ \mathrm{TeV}$$

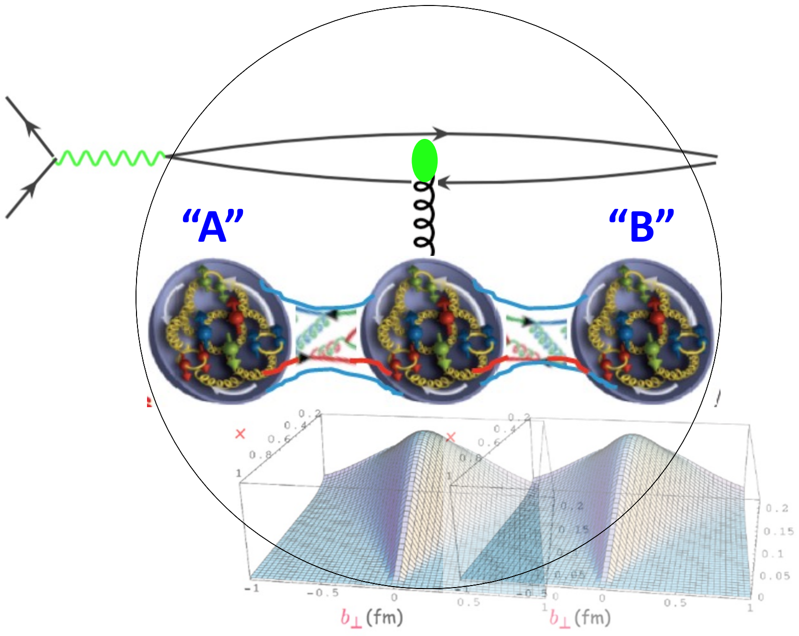
Jefferson Lab

Internal Nuclear Landscape at Small-x

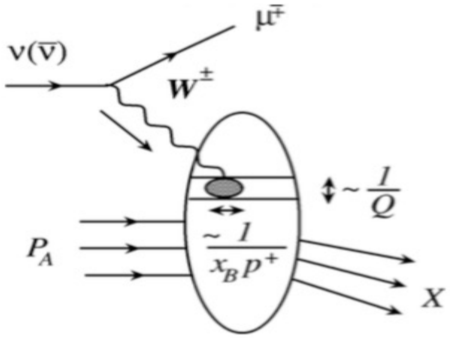
- **A simple, but fundamental, question:**

  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 !***

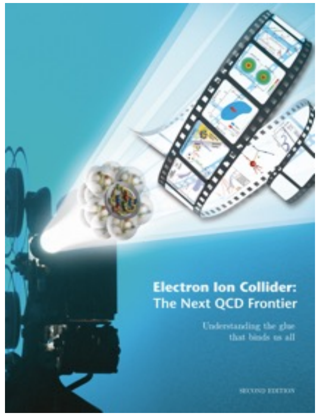
Jefferson Lab

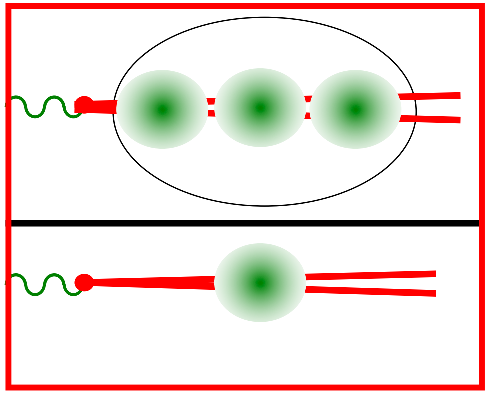
Coherent Length of the Color

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

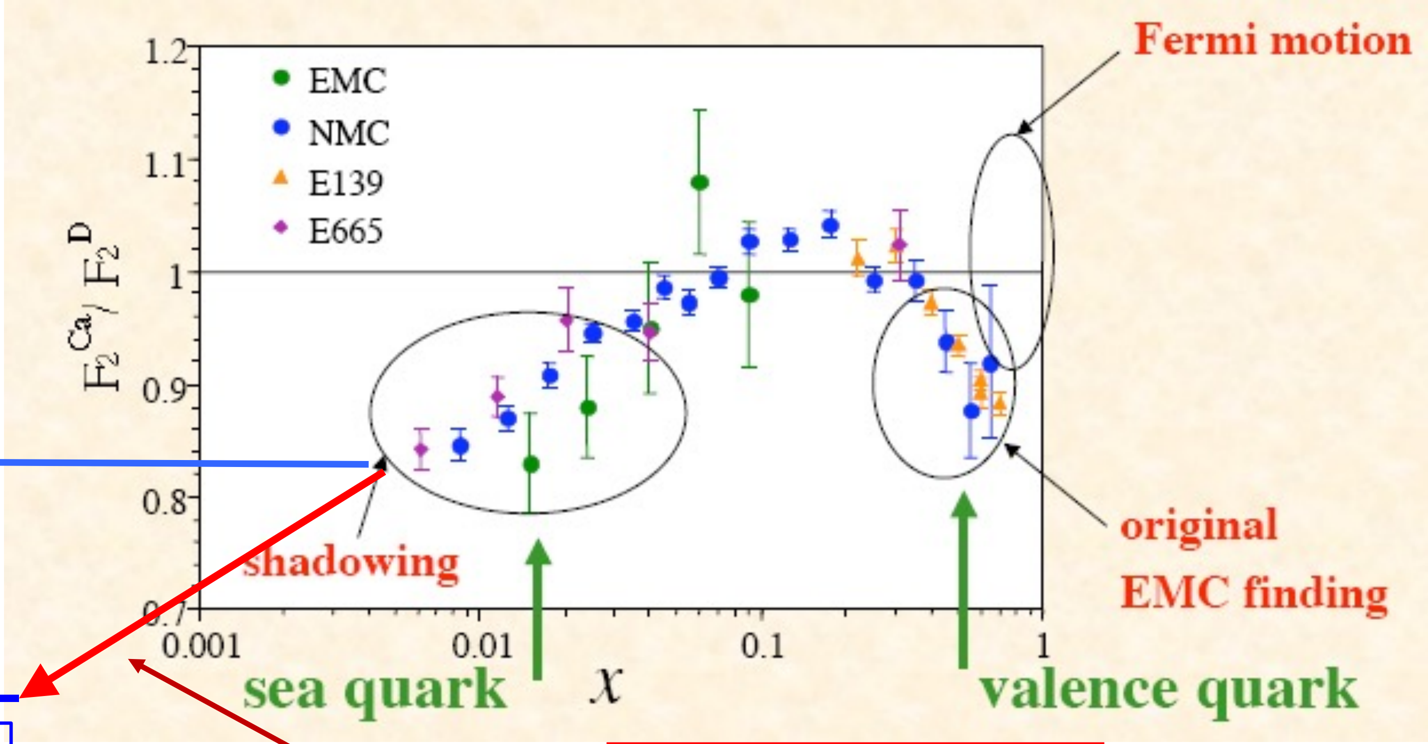
  Will the nuclear shadowing continue to fall as x decreases?

EIC White Paper



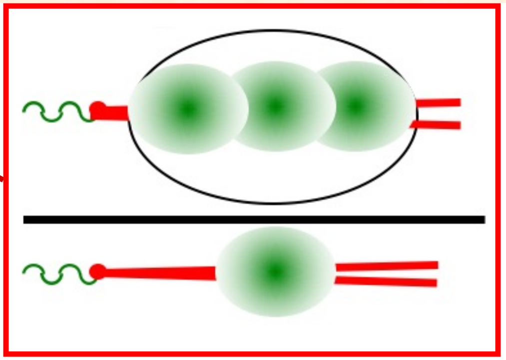


Color localized
Inside nucleons



Nucleus as a
bigger proton

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



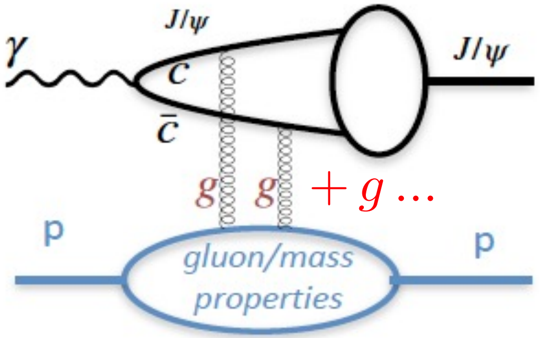
EIC can tell !

Theory Meets Experiments

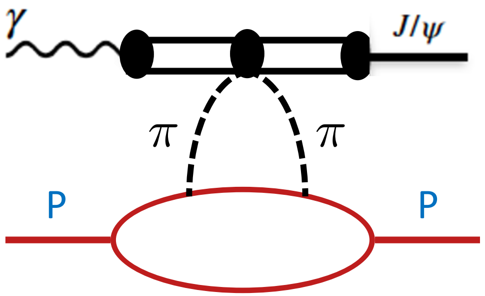
❑ Dual representation of QCD and strong interaction phenomena:

- Represented by colored quarks, gluons and their interactions in QCD
- Represented by color neutral mesons, baryons and their effective interactions (e.g., Hatsuda's talk)

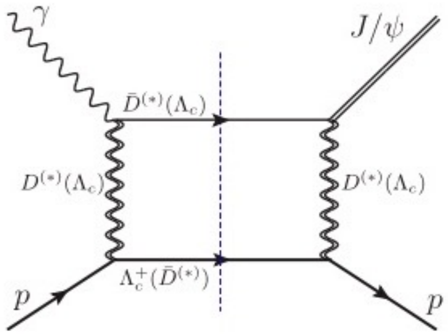
JLab Hall D: $\gamma + p \to J/\psi + p$ **All depend on the energy transfer of the scattering, …** GlueX: Phys. Rev. C 108 (2023) 025201



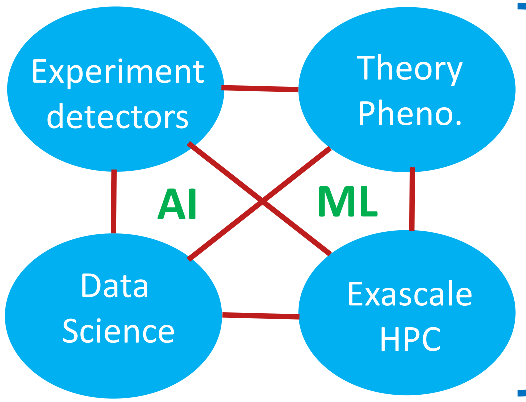
vs.



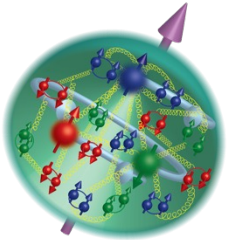
vs.



❑ Develop advanced tools to "see" quarks, gluons & their quantum correlations:



QuantOm Collaboration



3D Hadron Structure at Femtoscale → Pixelated images of proton

Synergy by physicists & computational scientists

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, femto-meter sized detectors, …
    - Relationship between the particle and wave nature of quarks and gluons, …

- ❑ **JLab12 & EIC are complementary QCD facilities, capable of discovering and exploring the emergent phenomena of QCD, and the role of color and glue, …**

- ❑ **Owing to QCD confinement, it is a challenge to probe and explore the dynamics of quarks and gluons without seeing them directly. Need collaboration between theorists, experimenters, and computational scientists**

Thanks!