# Nuclear Femtography
through
# Deep-Exclusive Processes

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CENTER *for* NUCLEAR FEMTOGRAPHY

IR2@EIC: Science and Instrumentation of the 2nd IR for the EIC (Joint Argonne and CFNS Workshop)

Argonne NATIONAL LABORATORY

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Center for Frontiers in Nuclear Science

# Outline

- Nature of deep exclusive processes
- Nuclear femtography with GPDs

  Solving inverse problem with

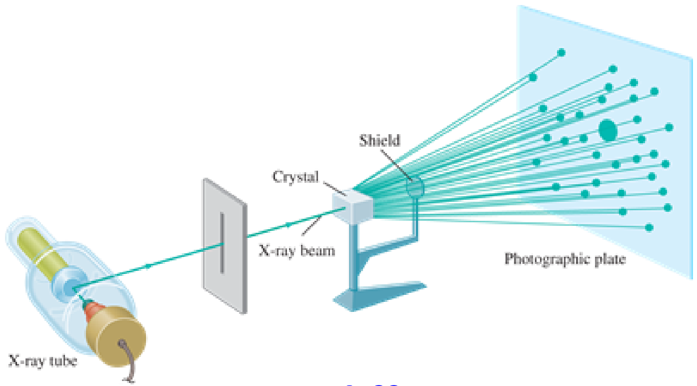
  data, models, AI/ML, & lattice QCD simulations
- Physics of proton from femtography

  Proton mass, spin, and pressure …
- Summary

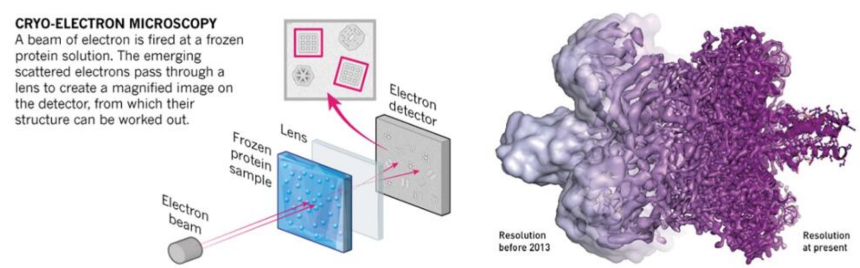
# Nature of Deep-Exclusive Processes

# Diffractive imaging

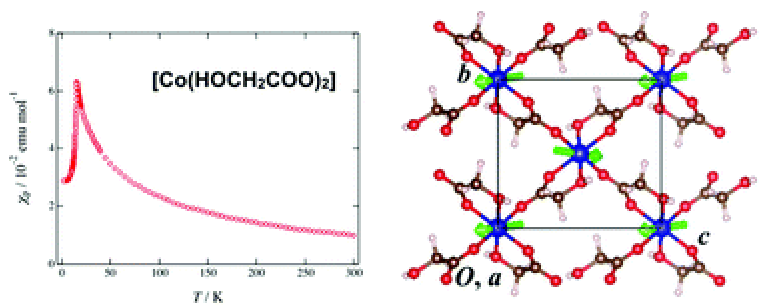
- Diffraction has long known being a best method to image the microscopic structure of matter




X-ray diffraction on crystals




Electron diffraction on protein

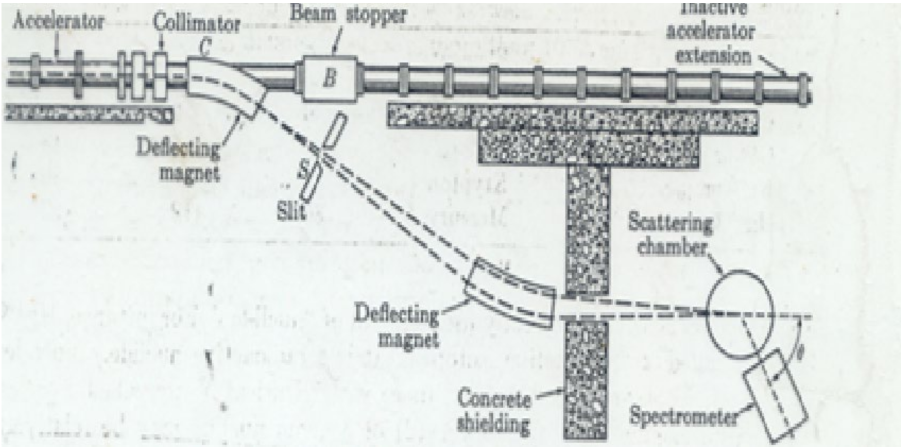


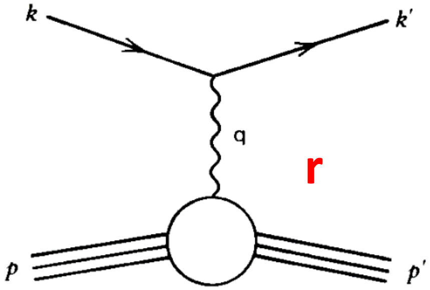

Neutron diffraction on complex chemicals

# Electron diffraction on the proton

## Hofstadter ~1955

- Diffraction with momentum transfer q




- Form factor and charge distribution: Inverse problem

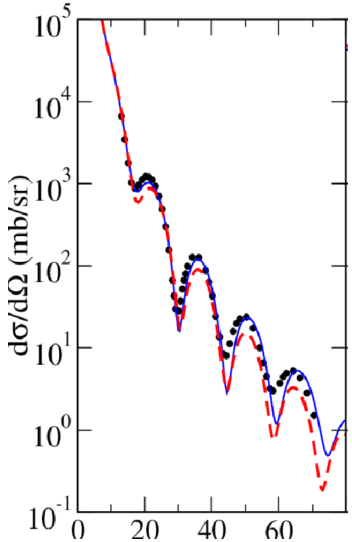
$$F(\Delta p/\hbar) = \frac{1}{Z}\int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi}\int_{r=0}^{\infty}\rho(r)e^{-i\Delta\vec{p}.\vec{r}/\hbar}dV = \frac{2\pi}{Z}\int_0^{\pi}\int_0^{\infty}\rho(r).r^2 dr\sin\alpha.e^{-i\Delta p.r\cos\alpha/\hbar}d\alpha$$

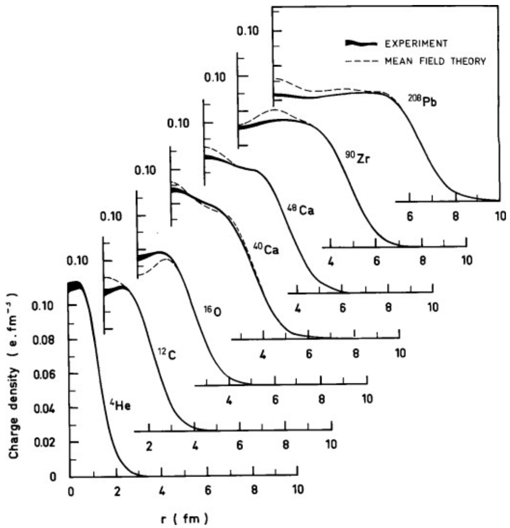
# Challenges for imaging the proton

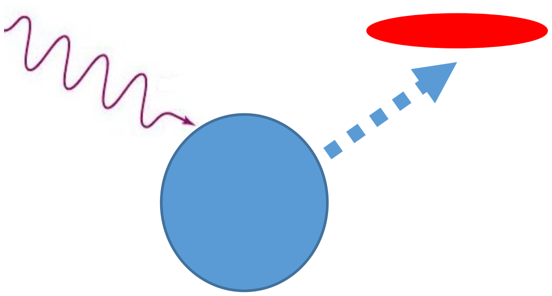
Momentum & energy transfer (q, $\omega$) ~ $M$

**Coherence**: Imaging efficiency goes down very quickly if high resolution is needed ($\sigma$ ~ small)

**Recoil**: It is difficult to relate the diffraction pattern to the spatial distributions



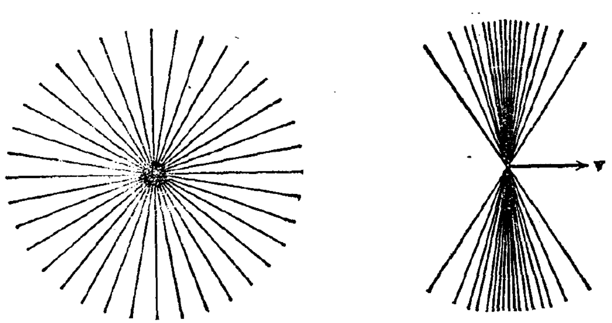



# Recoiling problem:

- Because the boost operator is **dynamical**, the internal states are different at different momenta!

$$|p'\rangle = U(L)|p\rangle$$

where $|p'\rangle$ is different from $|p\rangle$ dynamically!
  - The electromagnetic fields of a moving charge depends on its velocity or $\beta = v/c$



# Solution: Infinite momentum frame

- Experimental "solution"
  - Fixing the proton with a 5th force? ("Mossbauer effect")
- Theory solution: (Soper'77, Miller'07)
  - Let the system travel at the speed of light

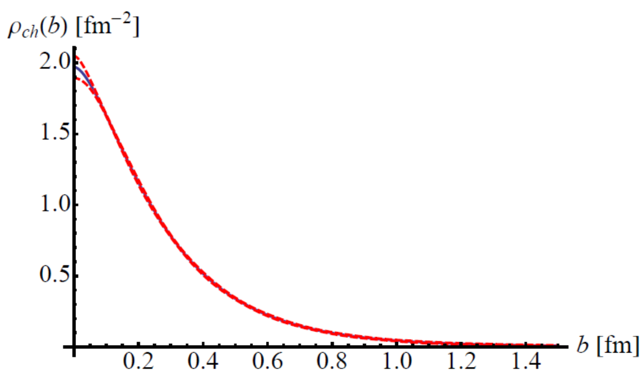
    $M_{eff} = \gamma M \rightarrow \infty$ fixing the transverse position
  - $\vec{Q}$ is applied in transverse direction $\vec{Q}_{\perp}$

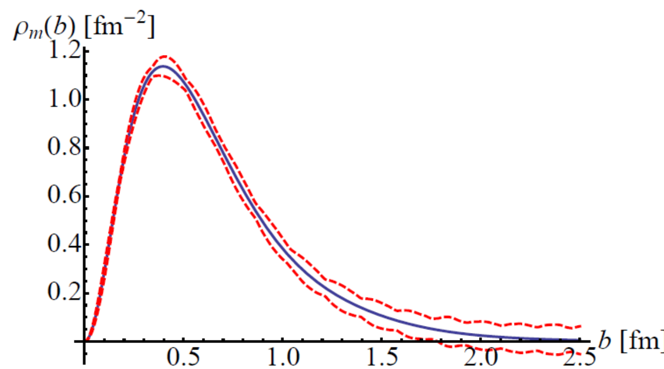
  Imaging in 2D transverse space! (sacrificing 1D)
- When the proton travels at the speed of light, all constituents have $k^z = \infty$, and the densities as probed in form factors must be related to partons'.

# Charge and magnetization densities of the proton

$$\rho(b) = \frac{1}{(2\pi^2)}\int d^2q e^{-i\mathbf{q}\cdot\mathbf{b}}\, F(Q^2=\mathbf{q}^2) = \frac{1}{2\pi}\int QdQJ_0(Qb)F(Q^2),$$

$$\rho_m(b) = -b\frac{d}{db}\rho_2(b) = \frac{b}{2\pi}\int Q^2dQJ_1(Qb)F_2(Q^2).$$

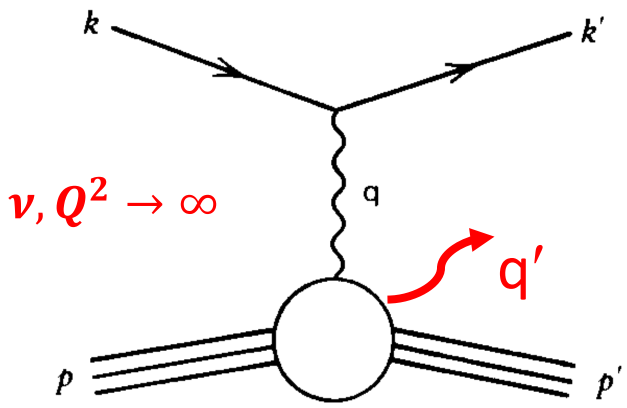



Miller, PRL’07; ARNPS’10
Venkat et al, PRC’09…
Other Approach: Lorce, PRL’20…

# Coherence: diffraction with emission

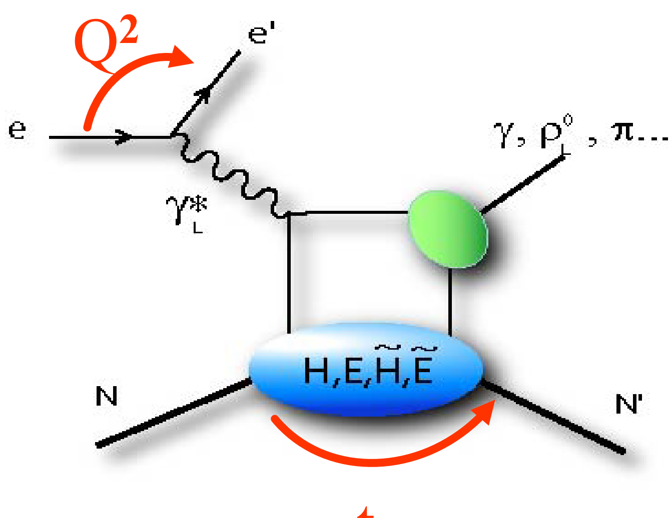
- Deeply-virtual photon diffraction (DVCS) Ji '96

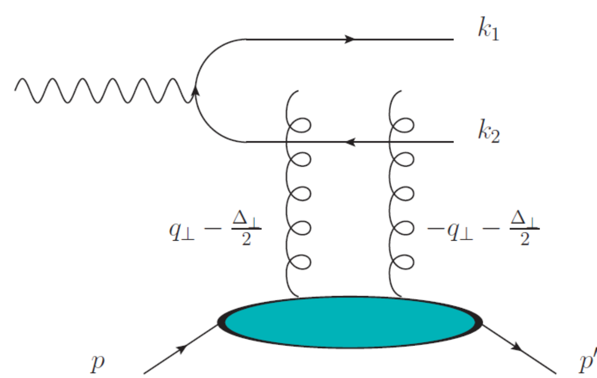



- Two more kinematic variables are now in the play.
- Photon emission can be replaced by other mesons or even jets. (Radyushkin '96, K. Golec-Biernat, Kwiecinski, Martin, '98)

# Handbag diagram mechanism

- In the Bjorken limit $Q^2 \to \infty$, $\nu \to \infty$, $Q^2/\nu$ =finite, the emission mechanism becomes very simple, single-quark & gluon (Compton-ish) scattering



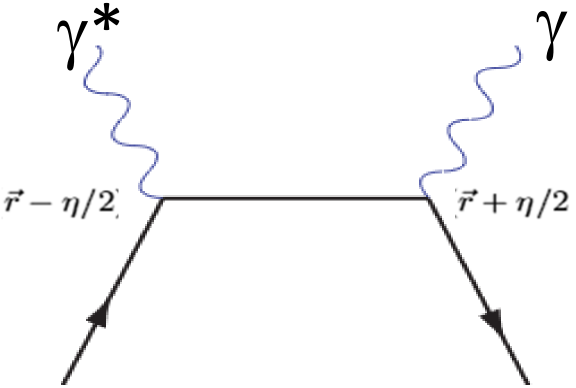




- One probes generalized parton distributions

(Mueller et al '94, Ji'96)

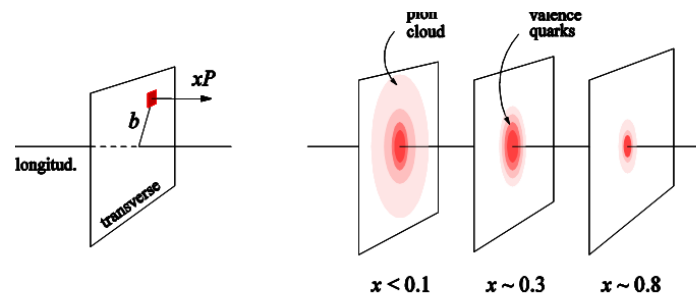
# GPDs: A type of Wigner function

- Displacement between absorption and radiation provides valuable information about parton's long. mom. x GPDs contain both x and transverse $b_\perp$



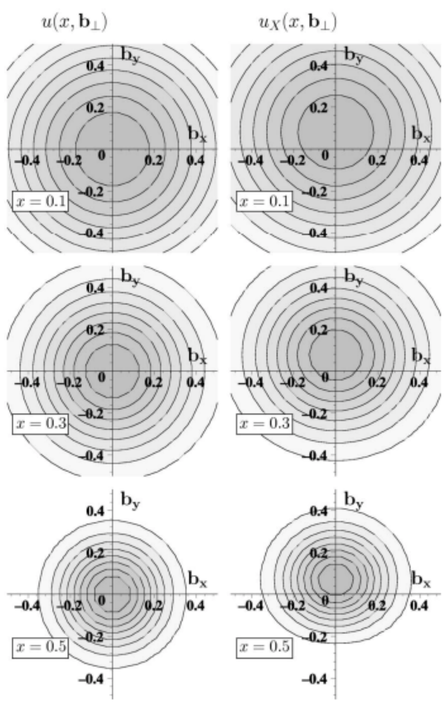

- Extending Hofstadter's imaging to individual partons of fixed long. momentum.

# GPD imaging



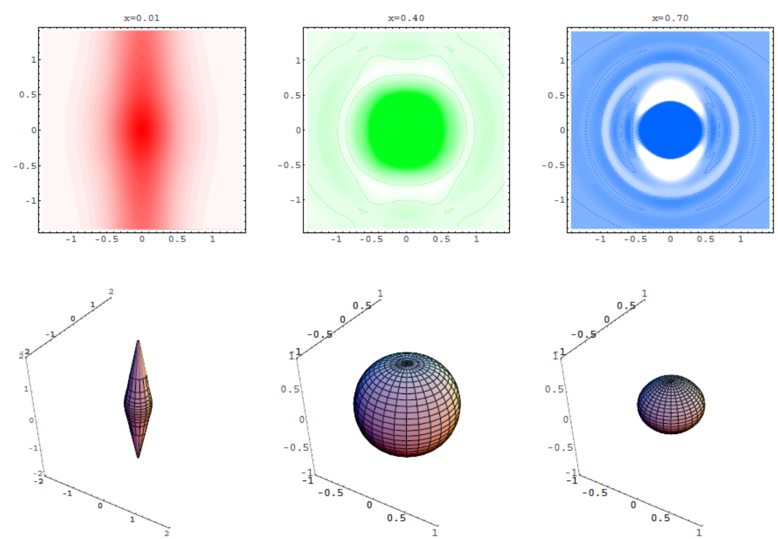

- Parton transverse space density imaging

(M. Buarkart, '00, '02)




- Reduced Wigner distribution imaging

(Belitsky, Ji & Yuan, '04)

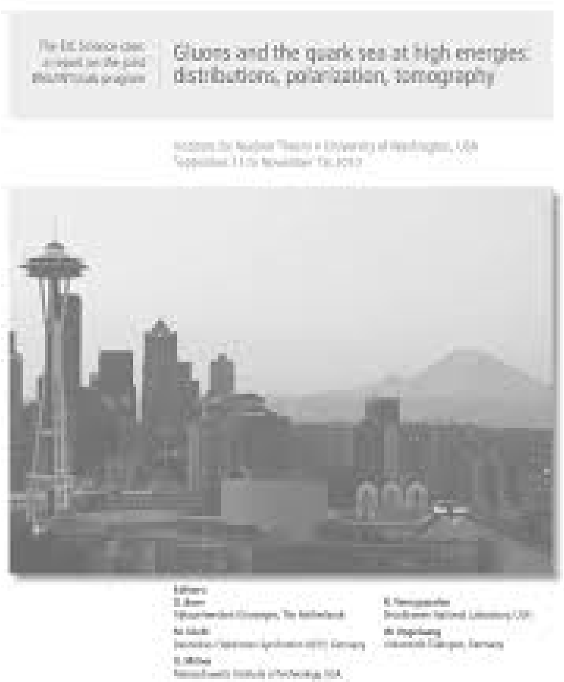


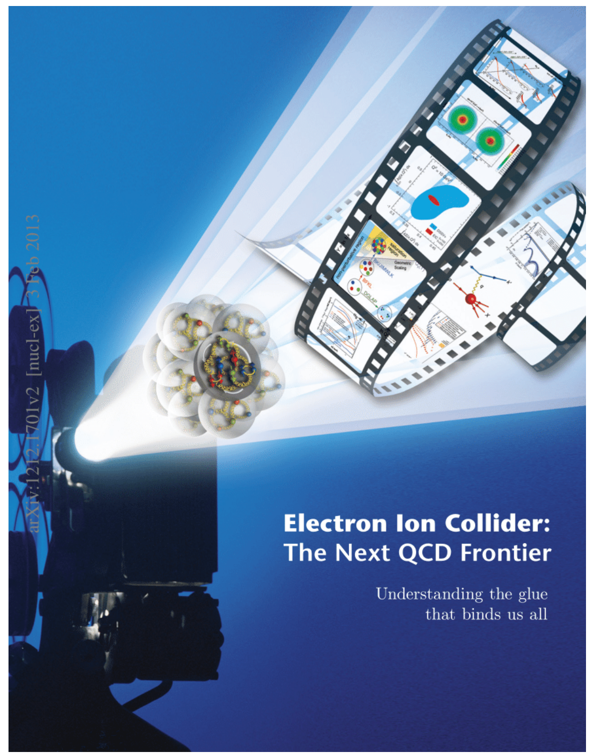
# Nuclear Femtography with GPDs

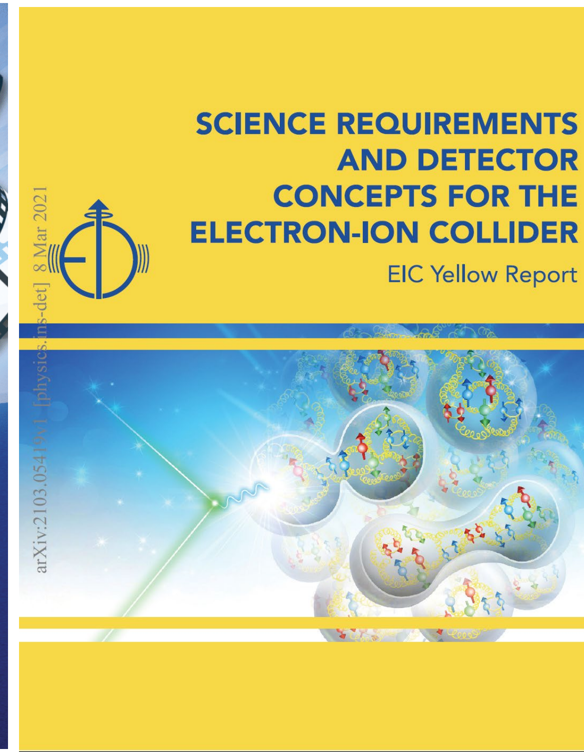
## Solving inverse problem with data, models, AI/ML, & QCD-simulations

# Community studies related to EIC

INT Report on EIC Science




- Aschenauer, Burkardt, Deshpande, Diehl, Fazio, Horn, Goldstein, Guzey, Kroll, Kumericki, Liuti, Metz, Meziani, Miller, Moutarde, Muller, Pasquini, Qiu, Radyushkin, Sabatie, Weiss, ….

# DVCS data


Current DVCS data at colliders:

- ○ ZEUS- total xsec
- ● ZEUS- $d\sigma/dt$
- □ H1- total xsec
- ■ H1- $d\sigma/dt$
- ■ H1- $A_{CU}$

Current DVCS data at fixed targets:

- ▲ HERMES- $A_{LT}$
- ▲ HERMES- $A_{CU}$
- ▲ HERMES- $A_{LU}$, $A_{UL}$, $A_{LL}$
- ▲ HERMES- $A_{UT}$
- ★ Hall A- CFFs
- ✳ CLAS- $A_{LU}$
- ✳ CLAS- $A_{UL}$

Planned DVCS at fixed targ…

- COMPASS- $d\sigma/dt$, $A_{CSU}$, $A_{CST}$
- JLAB12- $d\sigma/dt$, $A_{LU}$, $A_{UL}$, $A_{LL}$

# Key measurements at EIC

- Findings from the EIC whitepaper

<table>
<tr><th>Deliverables</th><th>Observables</th><th>What we learn</th><th>Requirements</th></tr>
<tr><td>GPDs of sea quarks and gluons</td><td>DVCS and $J/\Psi, \rho^0, \phi$ production cross-section and polarization asymmetries</td><td>transverse spatial distrib. of sea quarks and gluons; total angular momentum and spin-orbit correlations</td><td rowspan="2">$\int dt\, L \sim 10$ to $100\,\mathrm{fb}^{-1}$;<br>leading proton detection;<br>polarized $e^-$ and $p$ beams;<br>wide range of $x$ and $Q^2$;<br>range of beam energies;<br>$e^+$ beam<br>valuable for DVCS</td></tr>
<tr><td>GPDs of valence and sea quarks</td><td>electro-production of $\pi^+, K$ and $\rho^+, K^*$</td><td>dependence on quark flavor and polarization</td></tr>
</table>

Table 2.3: Key measurements for imaging partons in the transverse plane. With an EIC running at lower energies, one can investigate the transition from the valence to the sea quark regime and measure the processes in the lower block, while an EIC with higher energies provides access to a wide region dominated by sea quarks and gluons.

# Beam requirements for DEP

- Run at variable energy ($E_{cm} = 25 \sim 65\ GeV$)
  - Fixed $Q^2$, scanning through x, and vice versa
- Luminosity has to be on the order of $10^{34}$ or >
  - Cross section scales, but small fraction of DIS
  - Multi-variable binning
  - Most of the simulation studies have been made with $\int Ldt = 10 \sim 100$ fb$^{-1}$

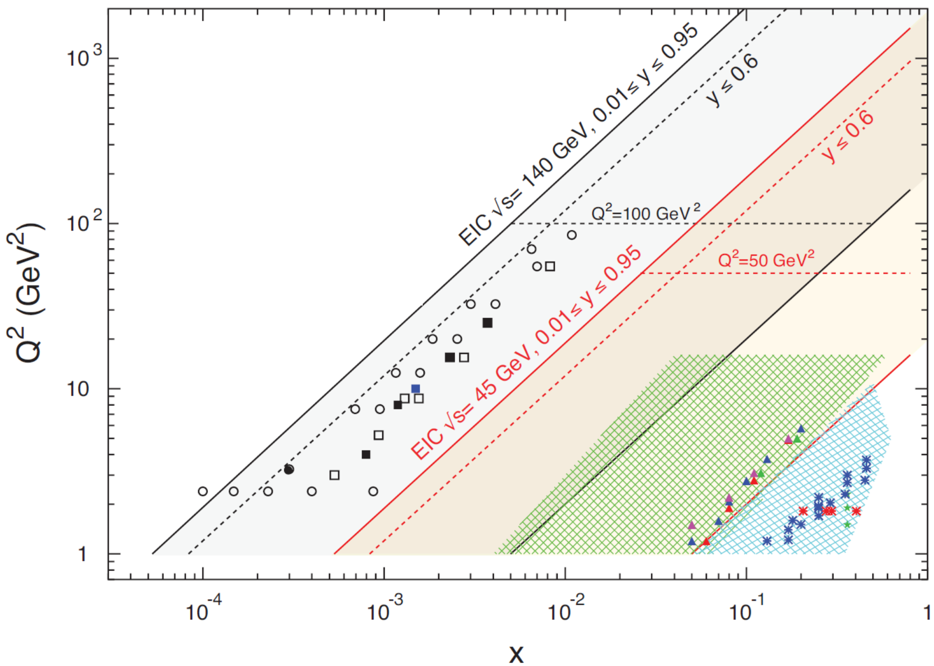
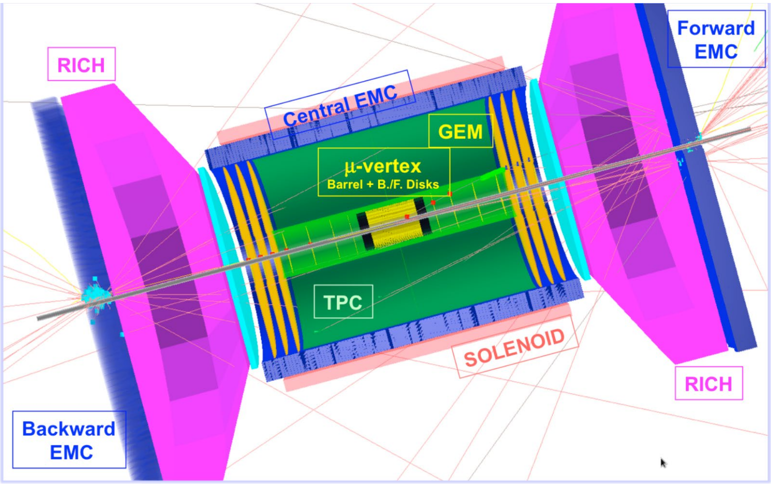


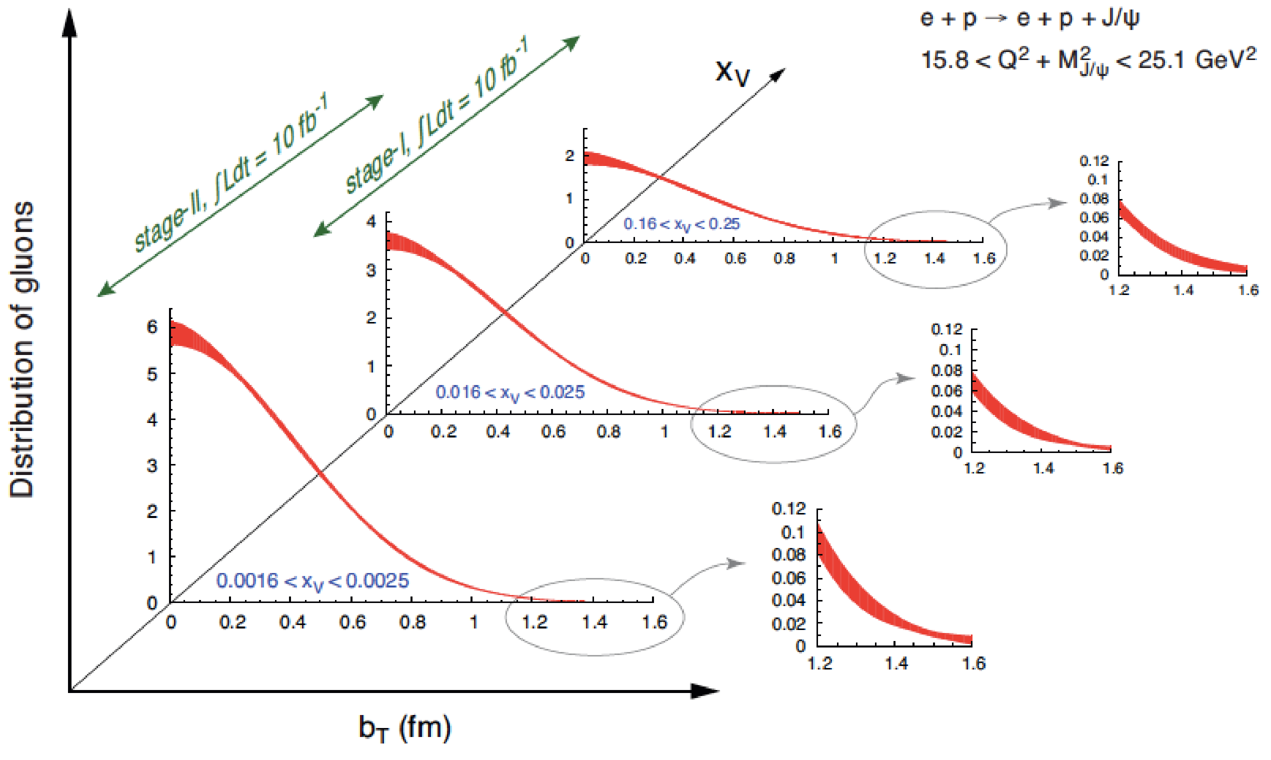

Figure 2.19: An overview of existing and planned measurements of DVCS in the $x, Q^2$ plane.

# Detector requirements




- Detecting all particles
  - Particularly the proton recoil
  - Small t
- Good Particle ID
- J/ψ detection: mass resolution
- Polarized targets: transverse or longitudinal
- Energy & momentum resolution

# Gluon tomography at small x




From EIC whitepaper

# Solving the inverse problem

- All imaging problems eventually reduce to an inverse problem ⇨

From the momentum-space observables, looking for the coordinate-space distributions!

# Challenge: dimensional reduction

- GPDs are function of three variables (ignoring RG scale, $\mu$)

$$|x| \leq 1$$

$$0 \leq \xi \leq \xi_{max}$$

$$0 \leq t \leq \infty$$

- However, most of the DEPs generates form factors which depends on only two kinematic variables,

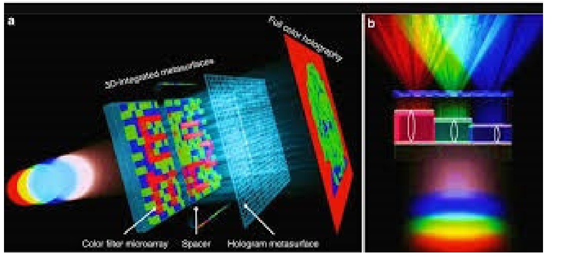
$$0 \leq x_B \; or \; x_V \leq 1$$

$$0 \leq t \leq \infty$$

Parton longitudinal momentum are "averaged over"

Solutions are highly non-unique?

(holography?)



# Center for Nuclear Femtography

- A Southeastern Universities Research Associate (SURA, Washington DC) center. https://www.femtocenter.org/

  (Ji, Elouadrhiri, Richards)

The mission of the Center for Nuclear Femtography is to coalesce the expertise in nuclear physics, computational science, mathematics and visualization to establish the world-leading center for three-dimensional imaging of nucleons and nuclei.

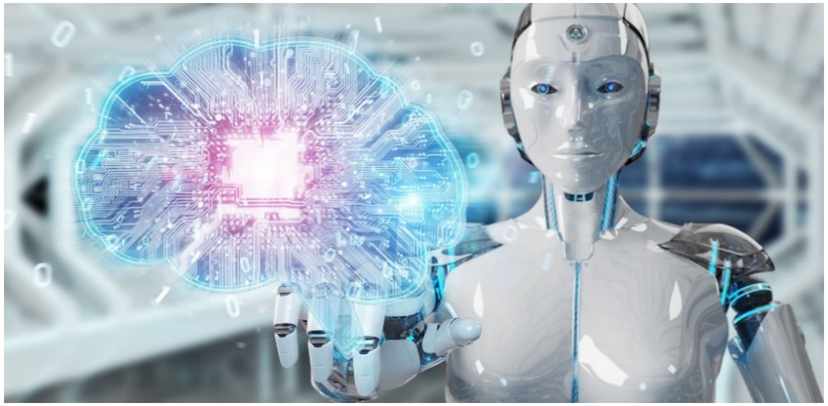
# CNF strategy

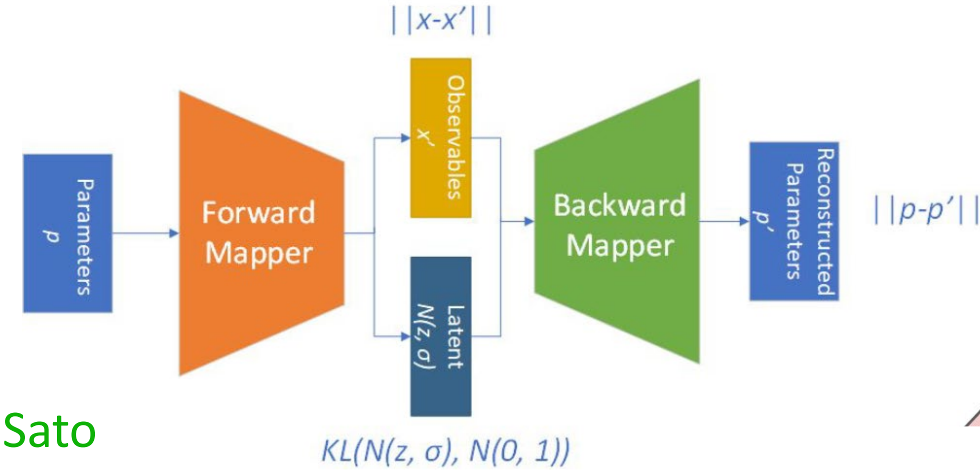
1. Actively involving in experimental programs: Jlab 12 GeV and EIC
    1. Ensure to get the best data and analysis
    2. Expanding in channels and dimension through new measurements (J/ψ, jets, DDVCS, e+)
2. Building realistic GPD models
3. Advanced Inverse problem solutions, including Artificial Intelligence/Machine Learning
4. Promoting first principles lattice QCD calculations

Mini-workshops, S. Liuti, M. Burkardt, …

# AI/ML for computing tomography

- Efficient detector simulations
- AI/ML techniques for searching the optimized solutions
- Advanced data science & algorithms
- Smart visualization





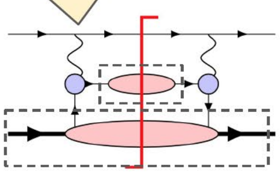

N.Sato

# The ML workforce

Jefferson Lab

co-PI

QCD Theory



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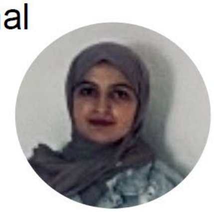

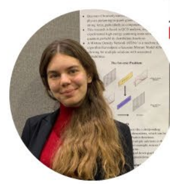

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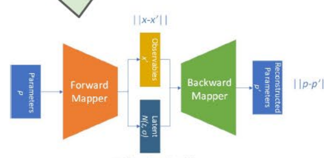
DAVIDSON

Inverse mappers

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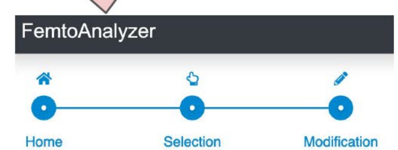
Web-interface




Raghu
DAVIDSON

Annabel
DAVIDSON

# Lattice QCD calculations

Moments: Hagler et al,08
Detmold & Shanahan,'19

- Using large-momentum effective theory, providing important insights on dependence on multiple variables.

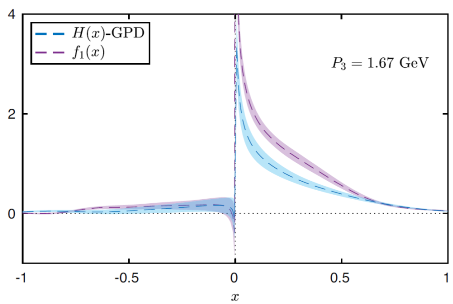
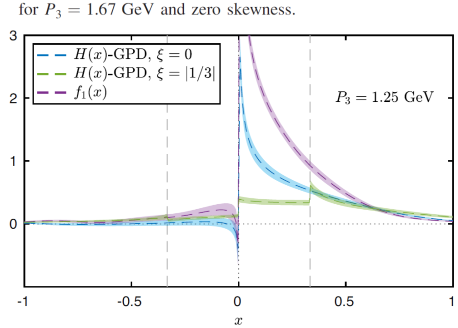



FIG. 1. $H$ GPD (blue band) and unpolarized PDF (violet band) for $P_3 = 1.67$ GeV and zero skewness.




ETMC, PRL125 (2020)

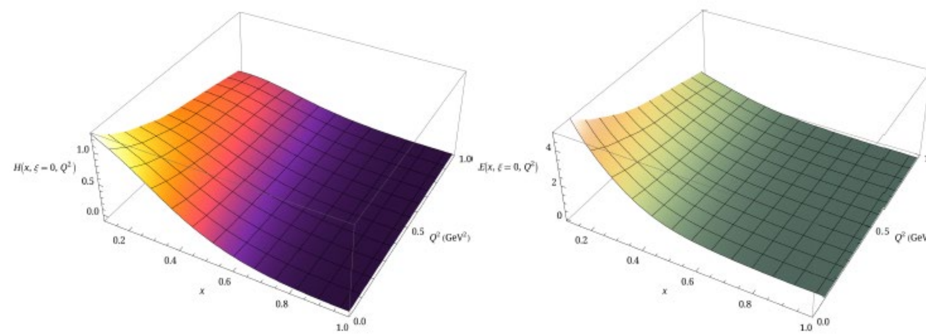
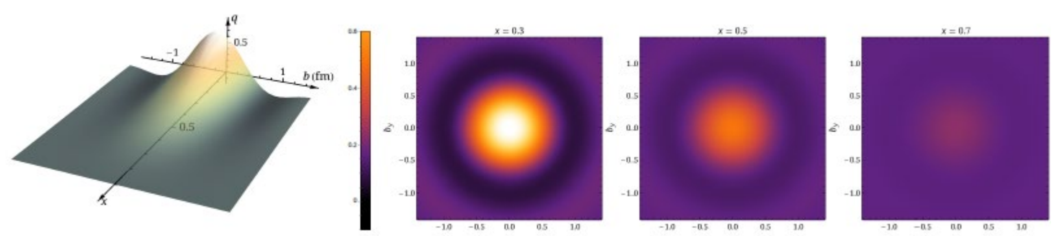



FIG. 4: $H$ and $E$ GPDs at $\xi = 0$ as functions of $x$ and momentum transfer $Q^2$.



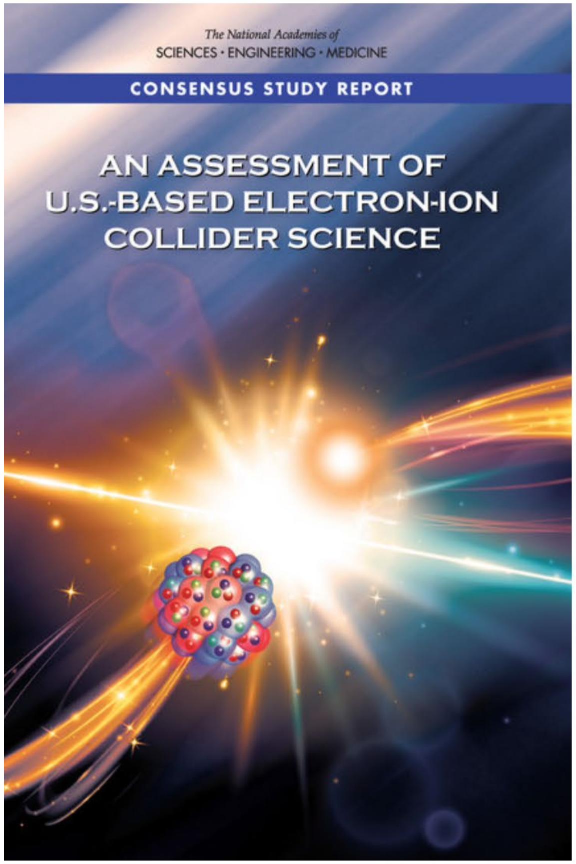

H. W. Lin, 2008.12474

# QCD simulations in exa-scale era

# Physics of proton from femtography:

proton mass, spin, pressure…

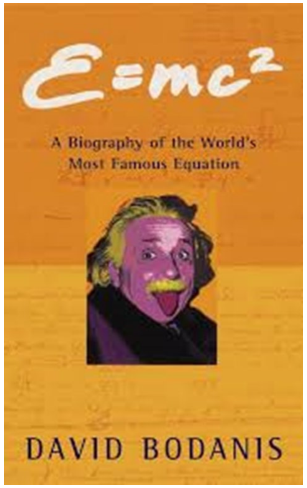
# EIC Science Assessment by NAS




## Finding 1:

An EIC can uniquely address three profound questions about nucleons—neutrons and protons-and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?




# Origin of the proton mass

- According to Einstein, mass is internal energy.

$$H_{\mathrm{QCD}} = H_q + H_m + H_g + H_a \,.$$

- The proton mass has an unusual contribution: quantum anomalous energy (Ji '95, Ji & Liu, '21)

$$H_a = \frac{1}{4}\int d^3\vec{x}\left(\frac{\beta(g_0)}{2g_0}F^2 + m_0\gamma_m\bar{\psi}\psi\right)$$

Scalar field response in the presence of the quarks, corresponding the MIT bag constant, B.

A matrix element related the energy-momentum tensor-> GPDs

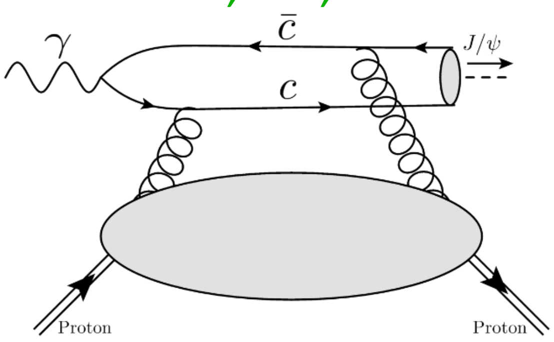
# Proton mass distribution

- The proton mass distribution is related to the EM form factors

Mass form factor

$$G_m(Q^2) = \left[ M A(Q^2) - B(Q^2)\frac{Q^2}{4M} + C(Q^2)\frac{Q^2}{M} \right]$$

Kharzeev, '96 '99 '21
Meziani, '12,'19




Mass radius

$$\langle r^2 \rangle_m = -6\frac{dA(Q^2)}{dQ^2} - 6\frac{C(0)}{M^2},$$

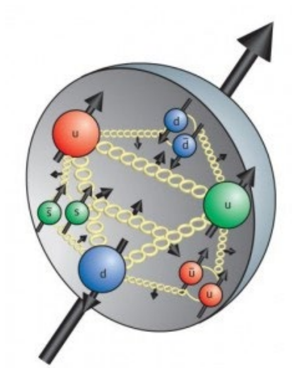
Hatta el al, Zahed et al, '20,'21,
Ivanov et al '04, Guo et al, '21

$$\mathcal{M}(\varepsilon_V, \varepsilon) = \frac{2\sqrt{2}g^2}{M_V^2}\phi(0)G(t,\xi)(\varepsilon \cdot \varepsilon_V)$$

$$G(t,\xi) = \frac{1}{2\xi(\bar{P}^+)^2}\int_{-1}^{1} \mathrm{d}x \mathcal{A}(x,\xi)F_g(x,\xi,t).$$

# Spin structure of the nucleon

- All spin sum rules are related to GPDs. (original motivation for introducing GPDs!)
- The simplest picture for the proton spin (twist-2) is the parton AM densities in $\vec{S}_\perp$ state (Ji & Yuan '12,'20)



$$J_\perp^{2q}(x) = x\left[q(x) + E_q(x)\right]/2,$$

$$J_\perp^{2g}(x) = x\left[g(x) + E_g(x)\right]/2,$$

The integrals over x provide a frame-independent and pol. independent spin sum rule (Ji '97)

# Spin structure of the nucleon

- Longitudinal spin sum rule

Jaffe & Manohar, '90

$$\frac{1}{2} = \frac{1}{2}\ \Delta\Sigma + \Delta G + \ell_q^z + \ell_g^z$$

OAM density involves twist-3 GPDs

- Similar twist-3 sum rule for transverse pol.

Guo, Ji, & Shiells, '21

$$\int \mathrm{d}x \left( \frac{1}{2} g_T(x) + \Delta G_T(x) + l_q^{x(3)}(x) + l_g^{x(3)}(x) \right) = \frac{\hbar}{2}$$

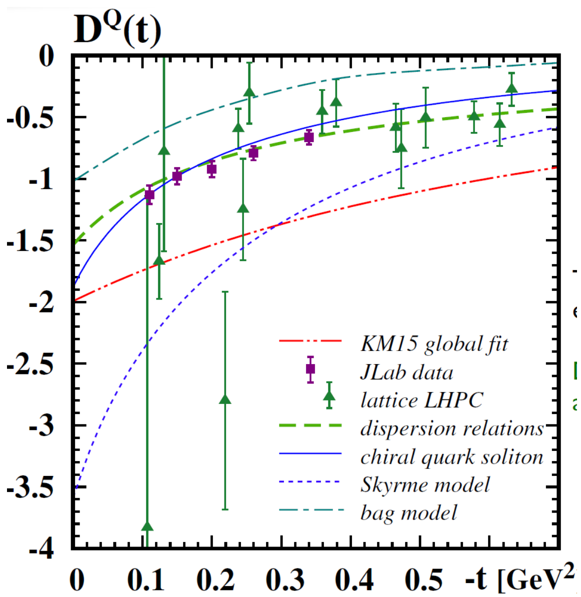
Twist-3 GPDs: needs polarizations and low-Q.

# Mechanical pressure tomography

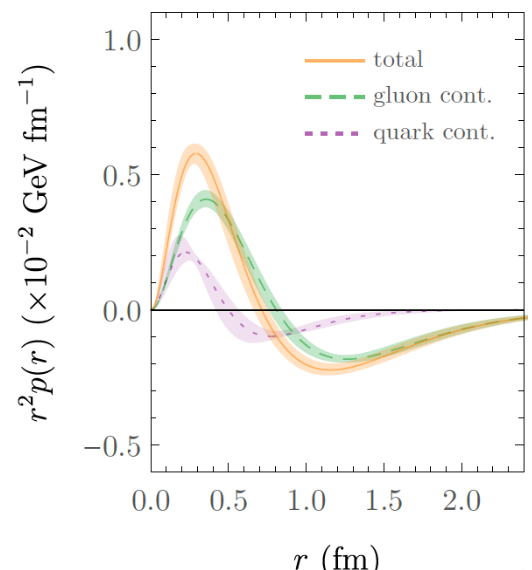
Schweitzer & Polyakov, 1805.06596

- Energy-momentum information from Femtography allows studying the pressure distributions (Polyakov '03)

$$s^a(r) = -\frac{1}{4M_N}\, r\frac{d}{dr}\frac{1}{r}\frac{d}{dr}\widetilde{D}^a(r), \quad p^a(r) = \frac{1}{6M_N}\frac{1}{r^2}\frac{d}{dr}r^2\frac{d}{dr}\widetilde{D^a}(r)$$




Burkert, Elouadrhiri, Girod, '18




Shanahan&Detmold, '19

Gluon?

# Summary

- It is critically important that EIC will have high-luminosity, varied energy beams, and high precision hermitic detectors.
- Femtography requires high-quality data, good GPD models, AL/ML, first-principles QCD simulations.
- Femtography allows us to understand the fundamental properties of the nucleon, such as mass and spin, at a deep level.