Massachusetts Institute of Technology

Laboratory for Nuclear Science

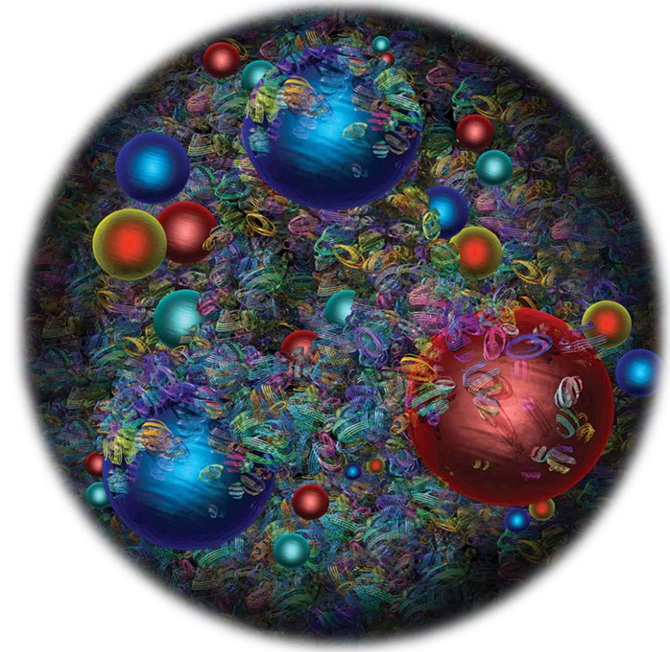
Proton structure studies at the future Electron-Ion Collider

Igor Korover

4th International Workshop on Quantitative Challenges in Short-Range Correlations (SRC) and the EMC Effect Research

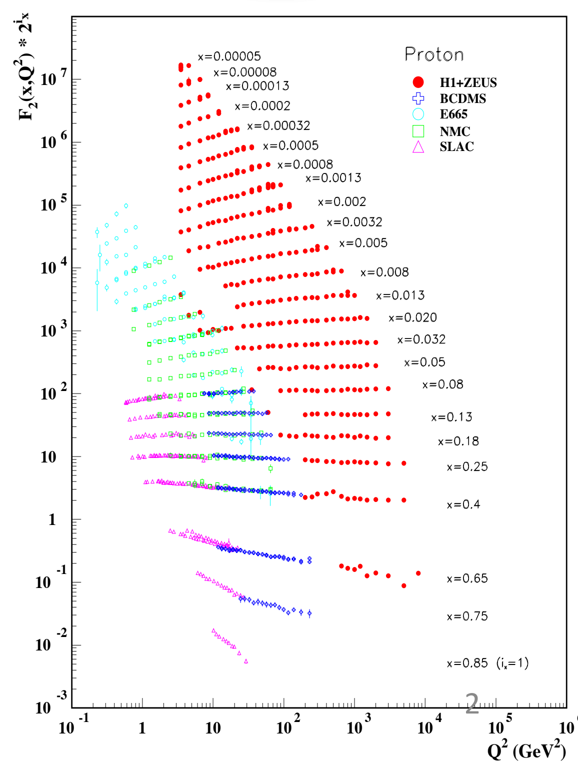
February 3rd 2023

Proton: Simple Building Block of the Visible Universe

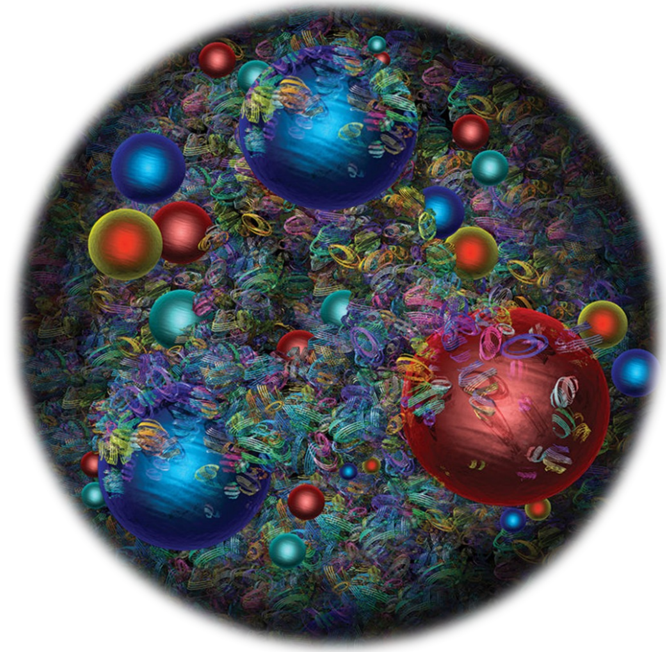


>70 years of electron scattering provided insights to the structure of the proton

- ✓ Charge +1
- ✓ Mass 938 MeV/c^2
- ✓ Spin ½
- ✓ Longitudinal structure, including flavor decomposition.
- ✓ Fundamental building block of nuclei

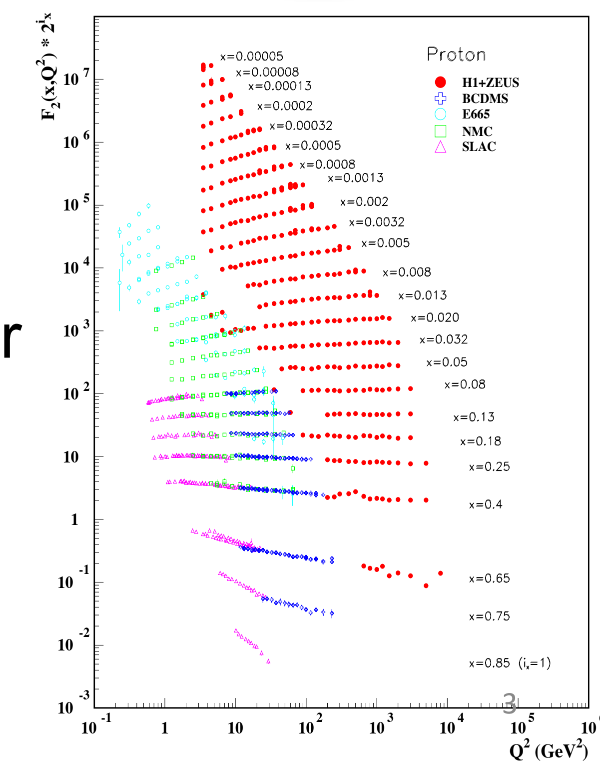


Proton: ~~Simple~~ Building Block of the Visible Universe

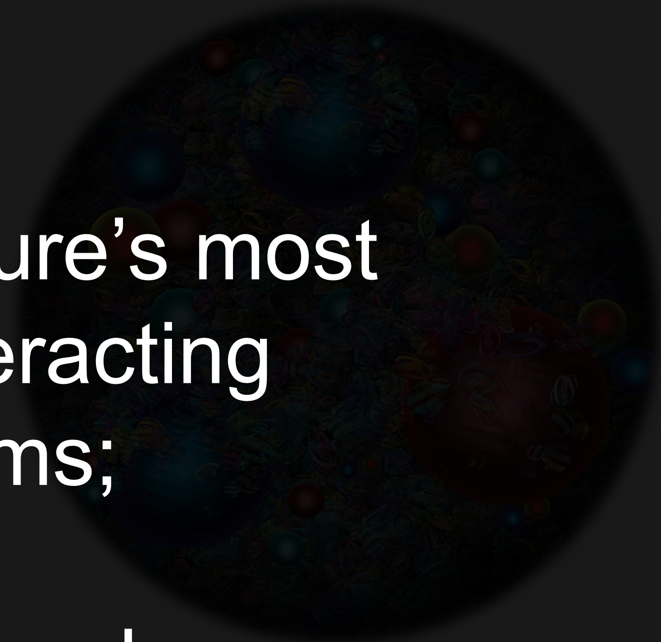


How well do we <u>understand</u> the <u>origin</u> of these properties?

- ✓ Charge +1
- ✓ Mass 938 MeV/c^2
  - X Mass decomposition
- X Spin ½
- ✓ Longitudinal structure, including flavor decomposition.
  - X Transverse structure
- ✓ Fundamental building block of nuclei
  - X Modification inside nuclei



Proton: Simple Building Block of the Visible Universe

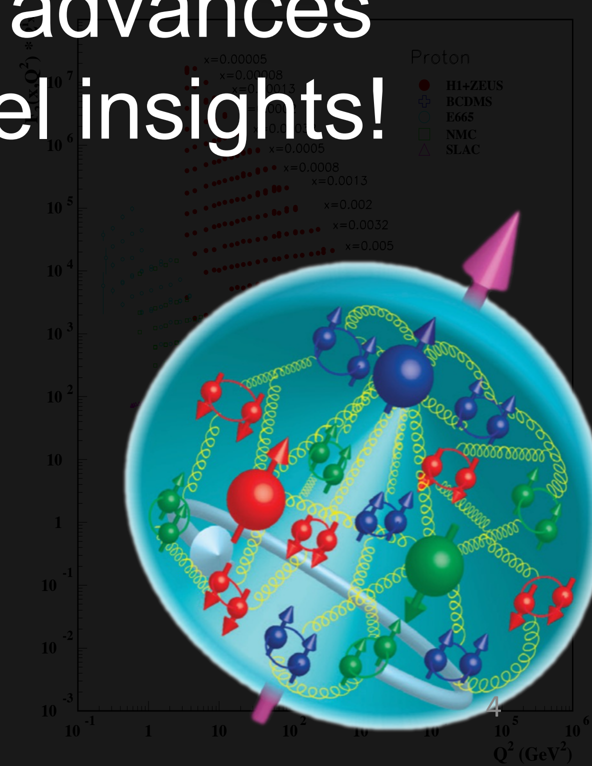


The Proton is one of nature's most intriguing strongly-interacting many-body systems;

➔ Experiment and theory advances required to provide novel insights!

How well do we understand the origin of the structure of the proton?

- ✓ Charge
- ✓ Mass
  - X Mass decomposition
- X Spin ½
- ✓ Longitudinal structure, including flavor decomposition.
  - X Transverse structure
- ✓ Fundamental building block of nuclei
  - X Modification inside nuclei

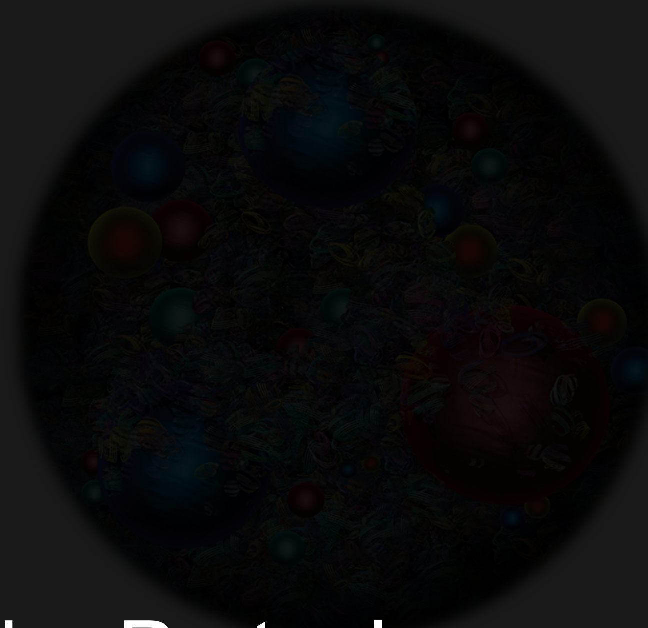


Today:

1. Proton Spin puzzle and the Proton's Generalized Parton Distributions

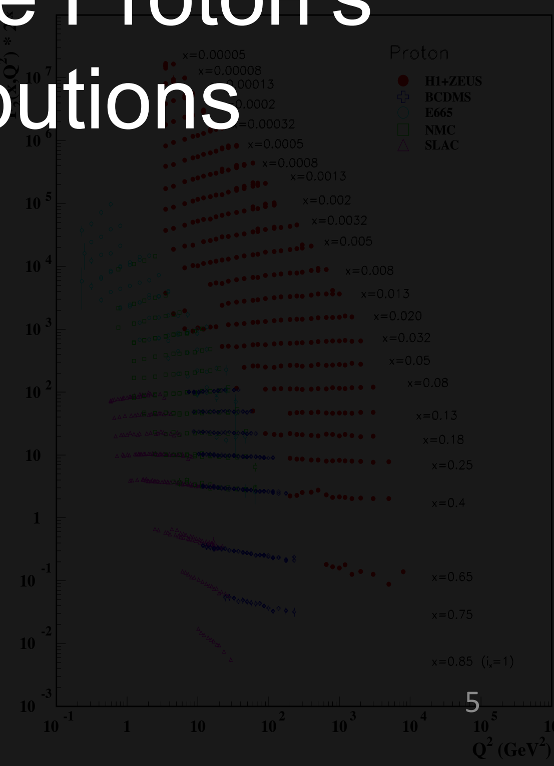
2. The Electron-Ion Collider

Proton: Simple Building Block of the Visible Universe



How well do we understand the origin of the structure of the proton?

- ✓ Charge
- ✓ Mass
  - X Mass decomposition
- X Spin $\frac{1}{2}$
- ✓ Longitudinal structure, including flavor decomposition.
  - X Transverse structure
- ✓ Fundamental building block of nuclei
  - X Modification inside nuclei



Proton Spin – Trivial Expectation

- 3 spin ½ valance quarks couple to produce a spin ½ system.
- No orbital AM contribution.
- No need for sea / glue contribution.

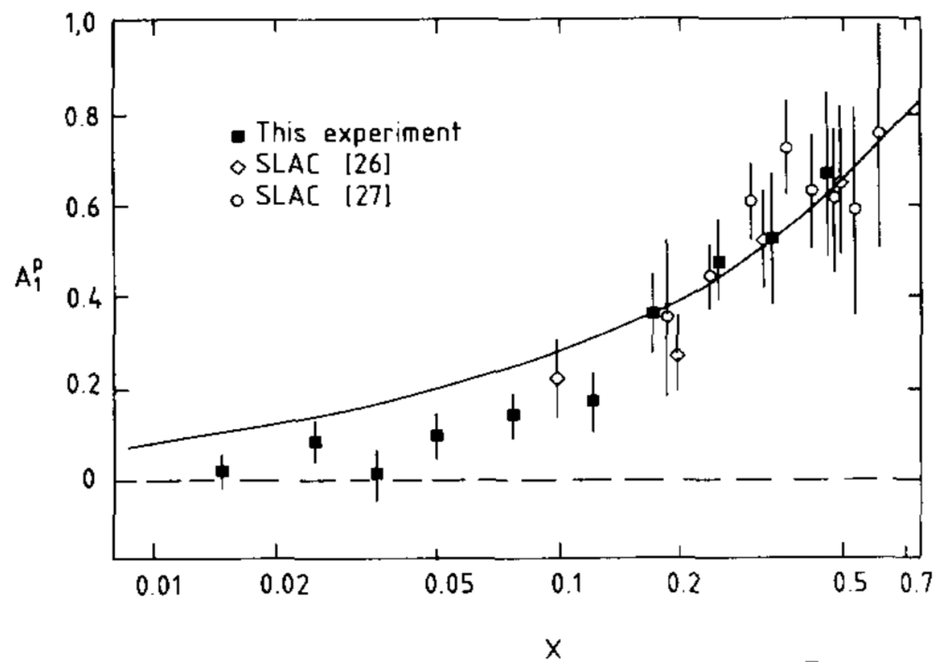
Proton Spin – Reality

Polarized lepton-nucleon DIS asymmetries probe $g_1(x)$

$$A = \frac{d\sigma^{\uparrow\downarrow} - d\sigma^{\uparrow\uparrow}}{d\sigma^{\uparrow\downarrow} + d\sigma^{\uparrow\uparrow}} \Rightarrow g_1 \approx \frac{F_2 A}{2x(1+R)} = \frac{1}{2}\Sigma e_i^2 [q_i^+(x) - q_i^-(x)]$$

$g_1(x)$ integral indicate quarks contribute ~ 14% to the total proton spin

➔ A Spin puzzle is born!

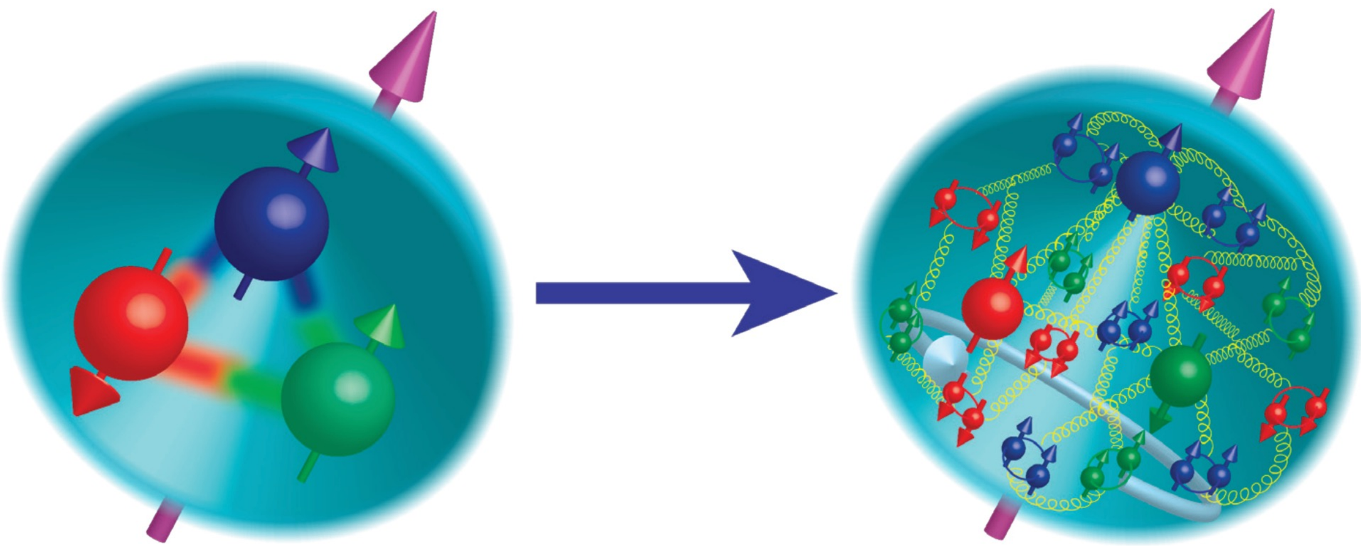


PLB 206, 364 (1988)

Spin Sum rule

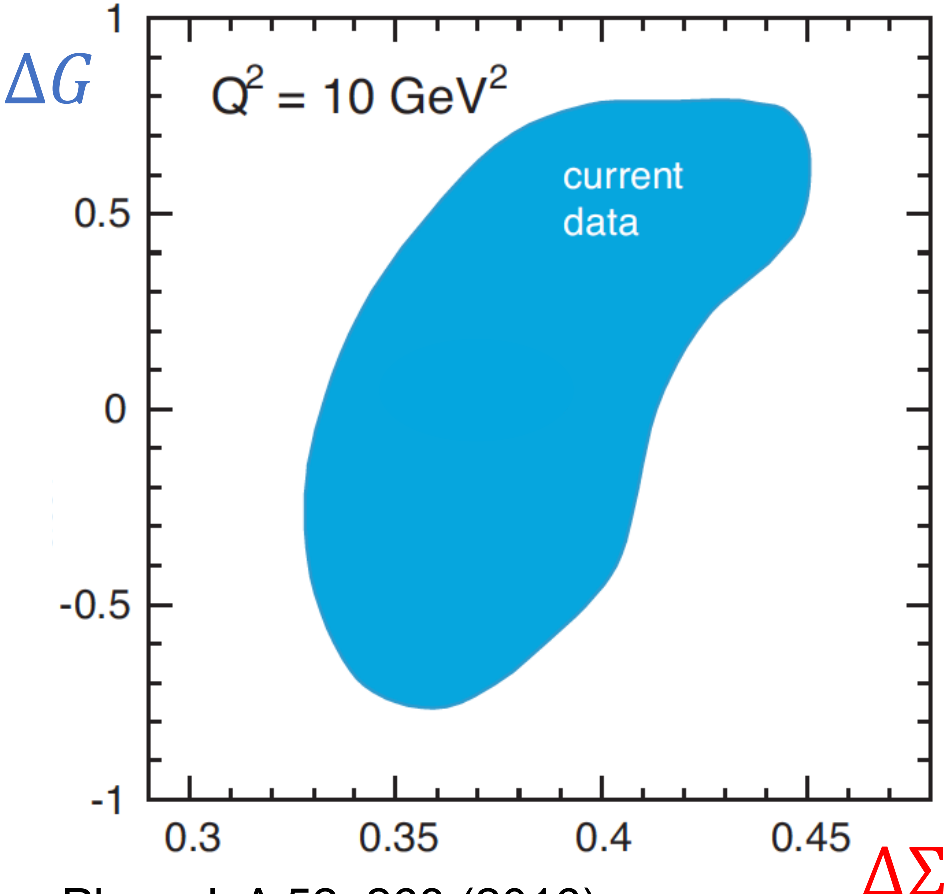
$$\frac{1}{2}\Delta\Sigma \quad + \quad \Delta G \quad + \quad L_q + L_g = \frac{1}{2}$$

Quark spin Gluon spin Orbital AM

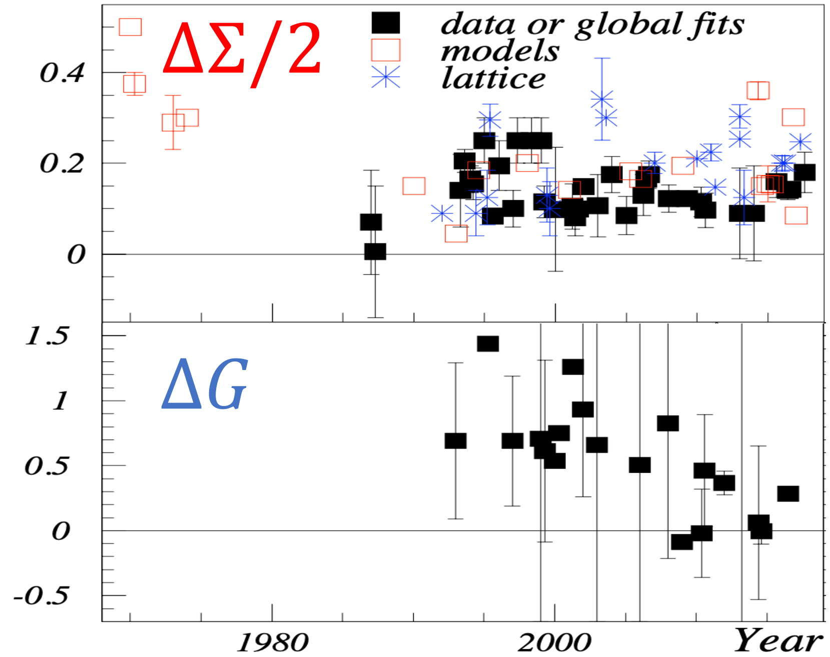


Current status: (1) Large uncertainties from low-x_B

$$\frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g = \frac{1}{2}$$

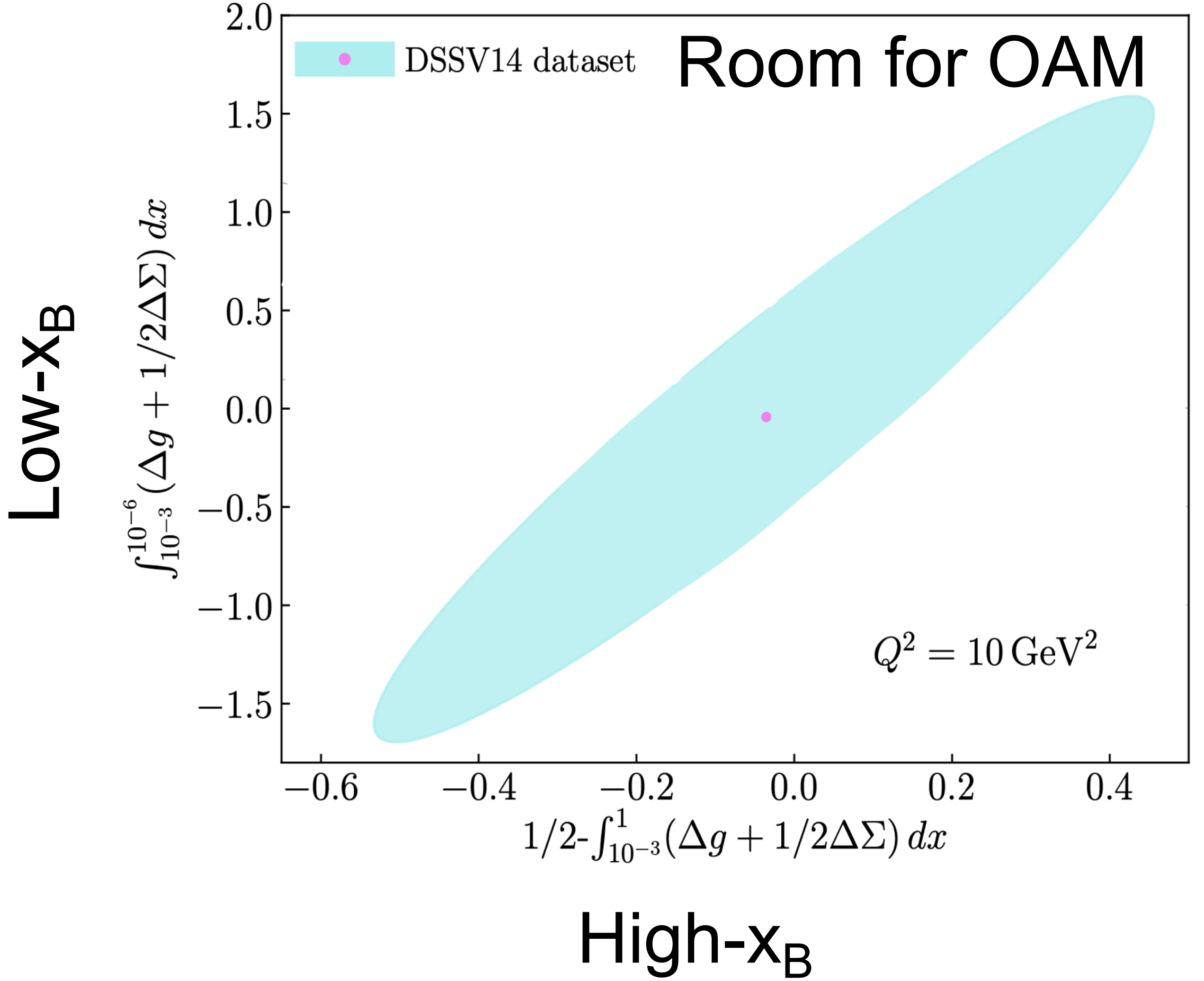


Eur. Phys. J. A 52, 268 (2016)
Phys Rev Lett 113, 012001 (2014)



Rep. Prog. Phys. **82** 076201 (2019)

Current status: (2) Unknown OAM contribution



arXiv:2103.05419v3

Path Forward?

1. Low-x_B measurements

2. OAM measurements

Probing the proton's OAM?

OAM = Going Transverse

Transverse = Form Factors*

*Not Electromagnetic Form Factors

➔ QCD Energy Momentum Tensor Form Factors

EM Form-Factors Example

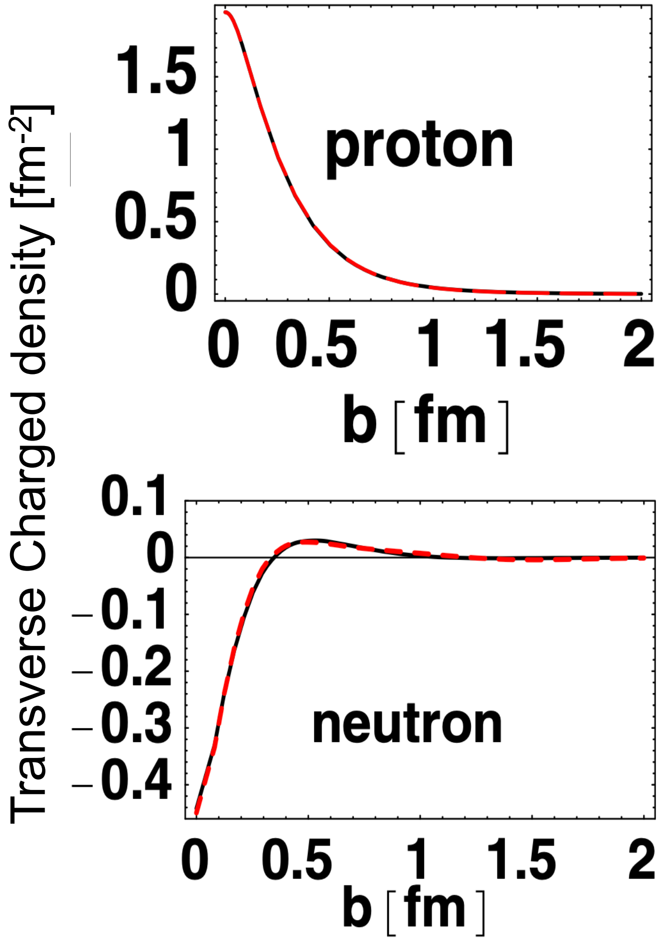
$$\langle P'|j^{\mu}|P\rangle =$$

$$\bar{U}(P')\left[F_1(q^2)\gamma^{\mu} + F_2(q^2)\frac{i\sigma^{\mu\nu}q_{\nu}}{2M}\right]U(P)$$

spatial moment of the electromagnetic current

Magnetic moment:

$$\mu = \left(F_1(0) + F_2(0)\right)\mu_N$$



PRL **99,** 112001 (2007)

QCD EMT Form-Factors

$$\langle P'|T^{\mu\upsilon}|P\rangle =$$
$$\bar{U}(P')\left[A(t)\gamma^{(\mu}\bar{P}^{\upsilon)} + B(t)\frac{\bar{P}^{(\mu}i\sigma^{\upsilon)\alpha}\Delta_\alpha}{2M} + C(t)\frac{\Delta^{(\mu}\Delta^{\upsilon)}}{M}\right]U(P)$$

Matrix elements of the quark and gluon momentum density

Total angular momentum:

$$J_{q,g} = \frac{1}{2}[A_{q,g}(0) + B_{q,g}(0)]$$

(No direct momentum density probe)

QCD EMT Form-Factors

$$\langle P'|T^{0i}|P\rangle =$$
$$\bar{u}(P')\left[A(q^2)\gamma^{\{0}\bar{P}^{i\}} + B(q^2)\frac{\bar{P}^{\{0}i\sigma^{i\}\alpha}q_\alpha}{2M} + C(q^2)\frac{q^0q^i}{M}\right]u(P)$$

How can we access the QCD EMT Form Factors Experimentally?

Matrix elements of the quark and gluon momentum density

➔Through Deeply Virtual Exclusive Processes (DVEP)

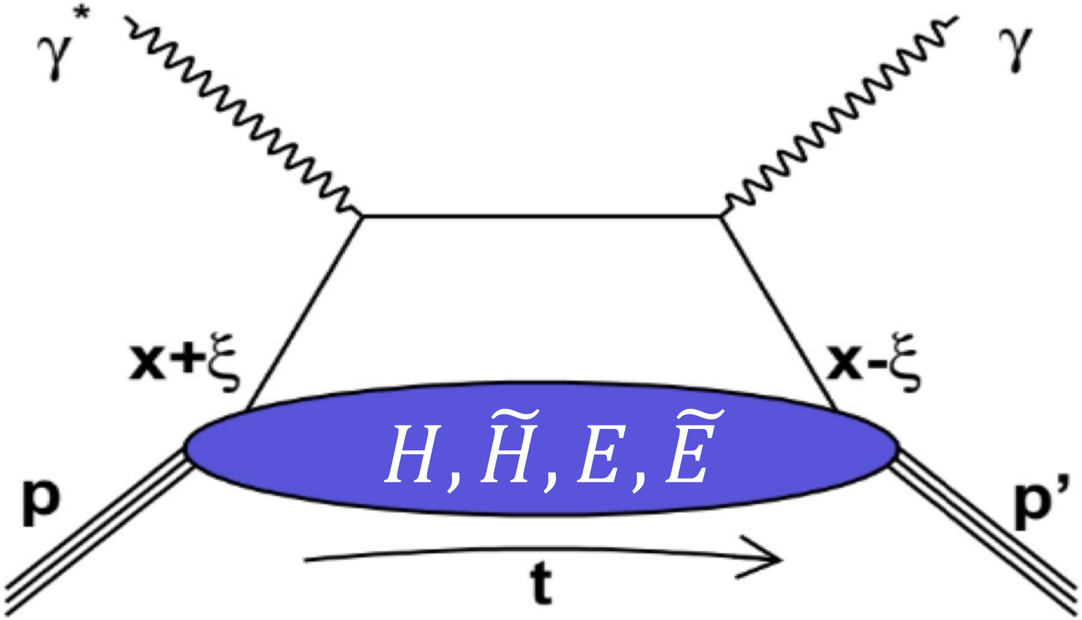
OAM:

$$J_{q,g} = \frac{1}{2}[A_{q,g}(0) + B_{q,g}(0)]$$ (No a direct momentum density probe)

"…, there is very little hope of learning anything about the detailed mechanical structure of a particle, because of the extreme weakness of the gravitational interaction"

H. Pagels, Phys. Rev. 144, 1250 (1966)

Deeply **V**irtual **C**ompton **S**cattering (**DVCS**)

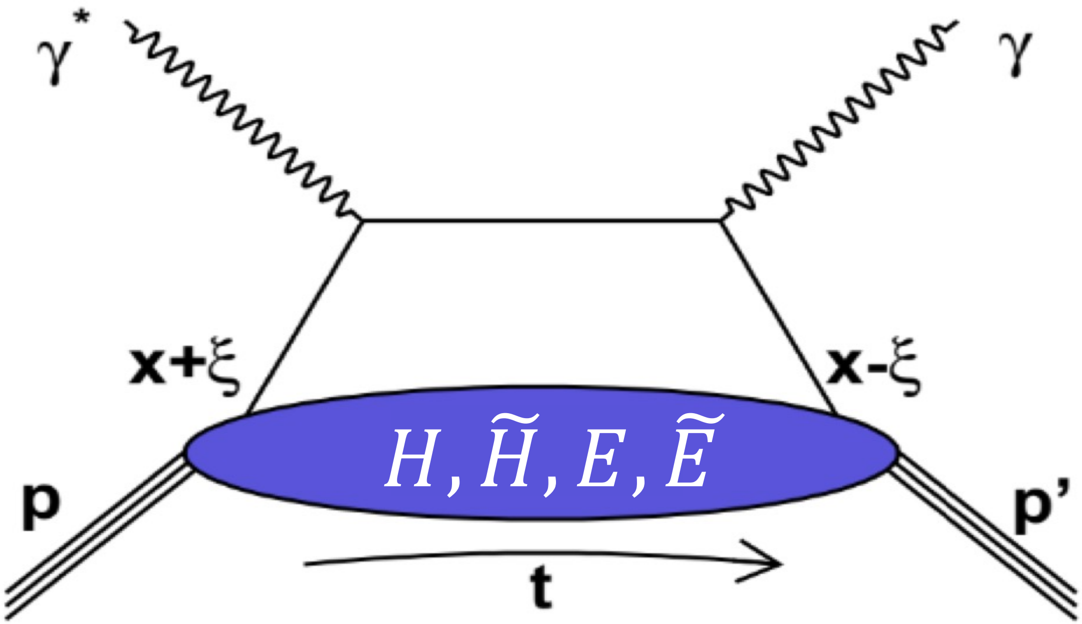


x – longitudinal quark momentum fraction

2ξ – longitudinal momentum transfer

t – Fourier conjugate to transverse impact parameter

Deeply Virtual Compton Scattering (DVCS)



x – longitudinal quark momentum fraction

2ξ – longitudinal momentum transfer

t – Fourier conjugate to transverse impact parameter

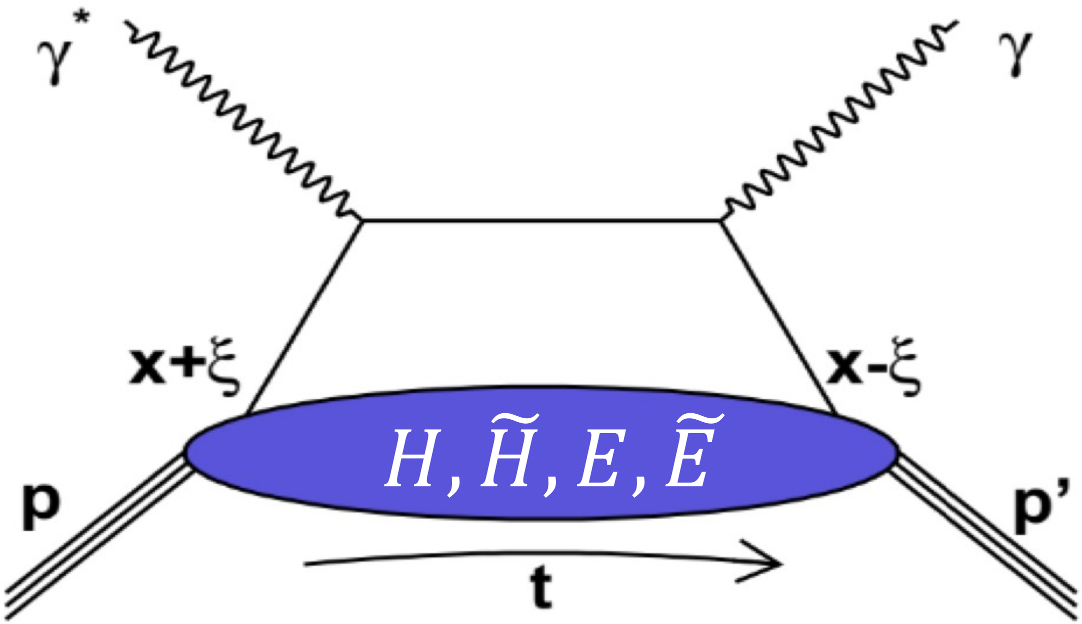
Amplitude is given by four GPDs:

$$i\mathcal{M} = -i\sum_q (|e|Q_q)^2 \epsilon^*_\mu \epsilon_\nu \Big\{$$

$$(p_1^\mu p_2^\nu + p_1^\nu p_2^\mu - g_\perp^{\mu\nu}) \int_{-1}^{1} dx \left[\frac{1}{x-\xi+i\epsilon} + \frac{1}{x+\xi-i\epsilon}\right] \times \frac{1}{2P^+}\left[H^q(x,\xi,t)\bar{u}(p')\gamma^+ u(p) + E^q(x,\xi,t)\bar{u}(p') i\sigma^{+\alpha}\frac{\Delta_\alpha}{2m_N}u(p)\right]$$

$$+i\epsilon^{\mu\nu+-}\int_{-1}^{1} dx \left[\frac{1}{x+\xi-i\epsilon} - \frac{1}{x-\xi+i\epsilon}\right] \times \frac{1}{2P^+}\left[\tilde{H}^q(x,\xi,t)\bar{u}(p')\gamma^+\gamma_5 u(p) + \tilde{E}^q(x,\xi,t)\bar{u}(p')\gamma_5\frac{\Delta^+}{2m_N}u(p)\right]\Big\}$$

Deeply Virtual Compton Scattering (DVCS)



x – longitudinal quark momentum fraction

2ξ – longitudinal momentum transfer

t – Fourier conjugate to transverse impact parameter

Amplitude is given by four GPDs:

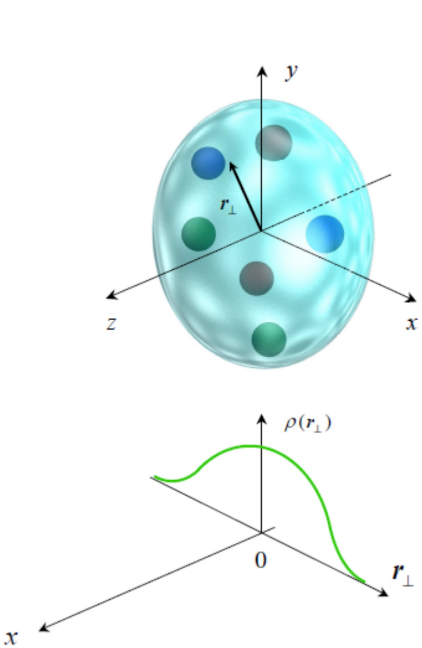
GPDs depend on 3 kinematic variables, e.g. *(x, ξ, t)*, that describe the internal nucleon dynamics.

$$i\mathcal{M} = -i\sum_q (|e|Q_q)^2 \epsilon^*_\mu \epsilon_\nu \Bigg\{$$

$$(p_1^\mu p_2^\nu + p_1^\nu p_2^\mu - g_\perp^{\mu\nu}) \int_{-1}^{1} dx \left[\frac{1}{x-\xi+i\epsilon} + \frac{1}{x+\xi-i\epsilon}\right] \times \frac{1}{2P^+} \left[H^q(x,\xi,t)\bar{u}(p')\gamma^+ u(p) + E^q(x,\xi,t)\bar{u}(p') i\sigma^{+\alpha}\frac{\Delta_\alpha}{2m_N}u(p)\right]$$

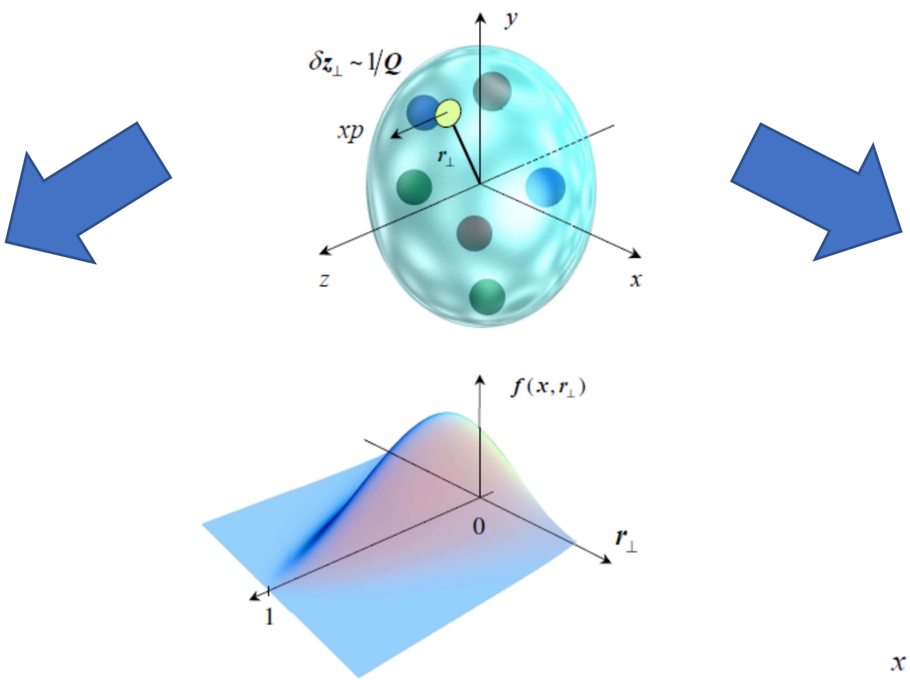
$$+ i\epsilon^{\mu\nu+-} \int_{-1}^{1} dx \left[\frac{1}{x+\xi-i\epsilon} - \frac{1}{x-\xi+i\epsilon}\right] \times \frac{1}{2P^+} \left[\tilde{H}^q(x,\xi,t)\bar{u}(p')\gamma^+\gamma_5 u(p) + \tilde{E}^q(x,\xi,t)\bar{u}(p')\gamma_5\frac{\Delta^+}{2m_N}u(p)\right]\Bigg\}$$

3D nucleon structure and more…

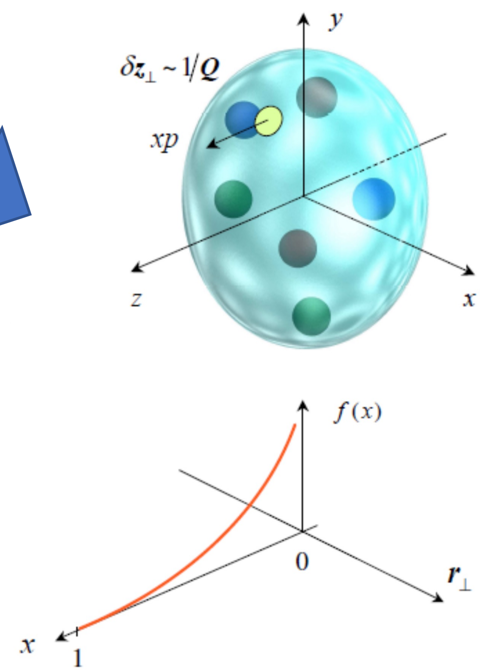


Proton size & structure.
Form factors,
transverse charge &
current distributions

Nobel prize 1961-
R. Hofstadter



GPDs connect quark distribution in transverse space & longitudinal momentum



Quark-gluon constituents.
longitudinal momentum
& helicity distributions
Nobel prize 1990 - J. Friedman,
H. Kendall, R. Taylor

Back to Angular Momentum

GPDs access the proton's AM:

$$\int_{-1}^{1} dxx[H(x,\xi,\Delta^2)+E(x,\xi,\Delta^2)]=A(\Delta^2)+B(\Delta^2)$$

$$J_q=\frac{1}{2}\Delta\Sigma+L_q= \frac{1}{2}[A_{q,g}(0)+B_{q,g}(0)]$$

X. Ji, Phys. Rev. Lett. 78, 610 (1997)

X. Ji, Phys. Rev. Lett. 74, 1071 (1995)

Back to Angular Momentum

GPDs access the proton's AM:

$$\int_{-1}^{1} dx x [H(x,\xi,\Delta^2) + E(x,\xi,\Delta^2)] = A(\Delta^2) + B(\Delta^2)$$

$$J_q = \frac{1}{2}\Delta\Sigma + L_q = \frac{1}{2}[A_{q,g}(0) + B_{q,g}(0)]$$

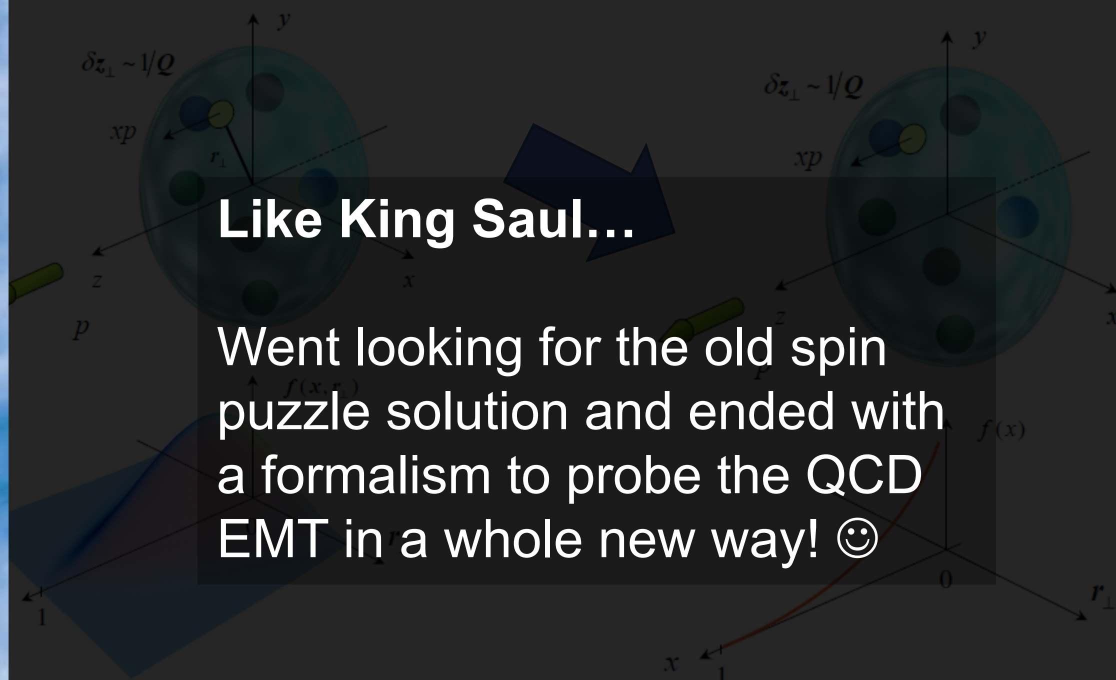
Bonus: access mass (M_2) and
Force and Pressure distribution (d_1):

$$M_2^q(t) + \frac{4}{5} d_1(t)\xi^2 = \frac{1}{2}\int_{-1}^{1} dx x H^q(x,\xi,t)$$

X. Ji, Phys. Rev. Lett. 78, 610 (1997)

X. Ji, Phys. Rev. Lett. 74, 1071 (1995)

GPDs are a unique probe of the QCD EMT FFs and therefore of mass distributions, OAM, 3D ...n structure and more…



Like King Saul…

Went looking for the old spin puzzle solution and ended with a formalism to probe the QCD EMT in a whole new way! ☺

R. Hofstadter

...PDs connect quark distribution in ...ansverse space & longitudinal momentum

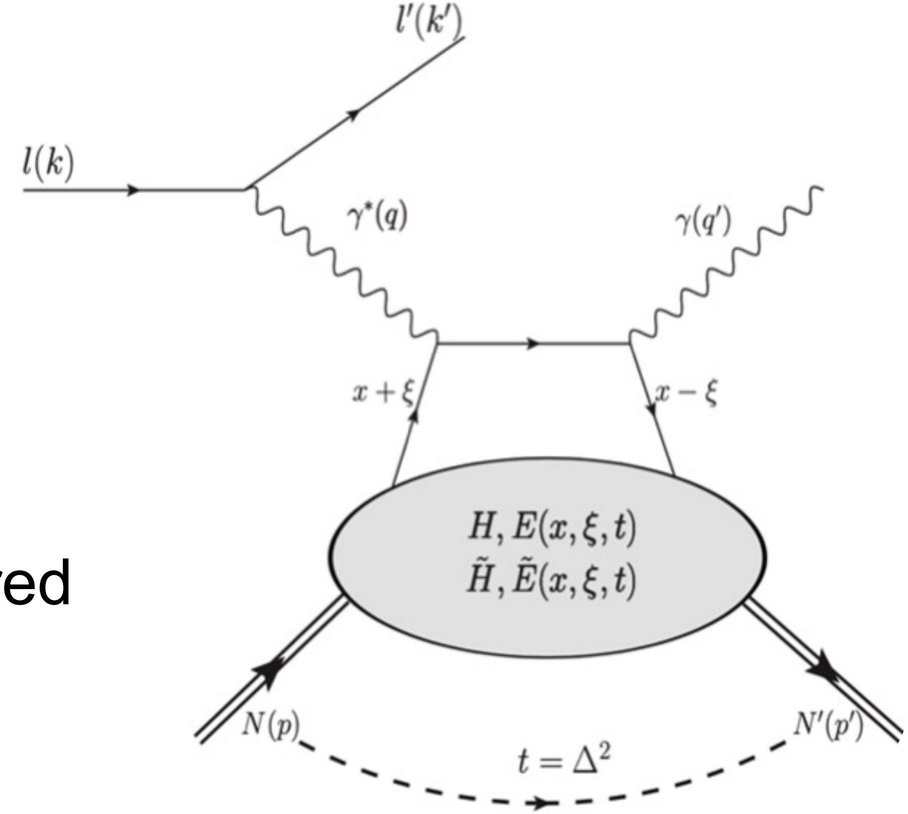
Quark-gluon constituents. longitudinal momentum & helicity distributions
Nobel prize 1990 - J. Friedman, H. Kendall, R. Taylor

DVCS Measurements $e + p \rightarrow e' + p' + \gamma$

Smilingly simple reaction… but:

- Low cross-section
- Large non-DVCS background
- Exclusivity requirement
- 4-dimentional extraction required

➔ Ideally suited for a high-luminosity, high-resolution, large acceptance experimental setup (i.e. Jefferson Lab)



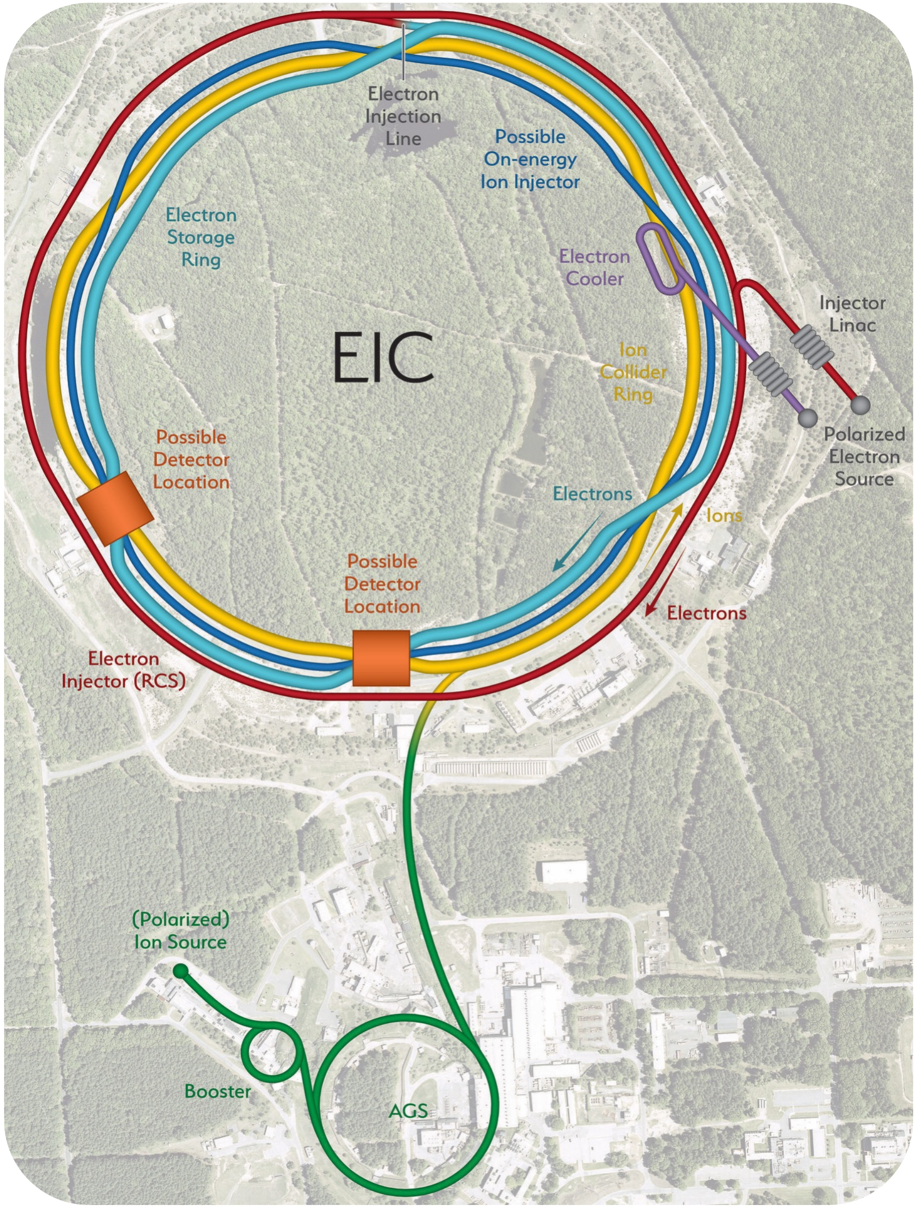
Electron-Ion collider

Polarized ep (eA) collider located at Brookhaven National Lab

DOE project, set to revolutionize our understanding of QCD

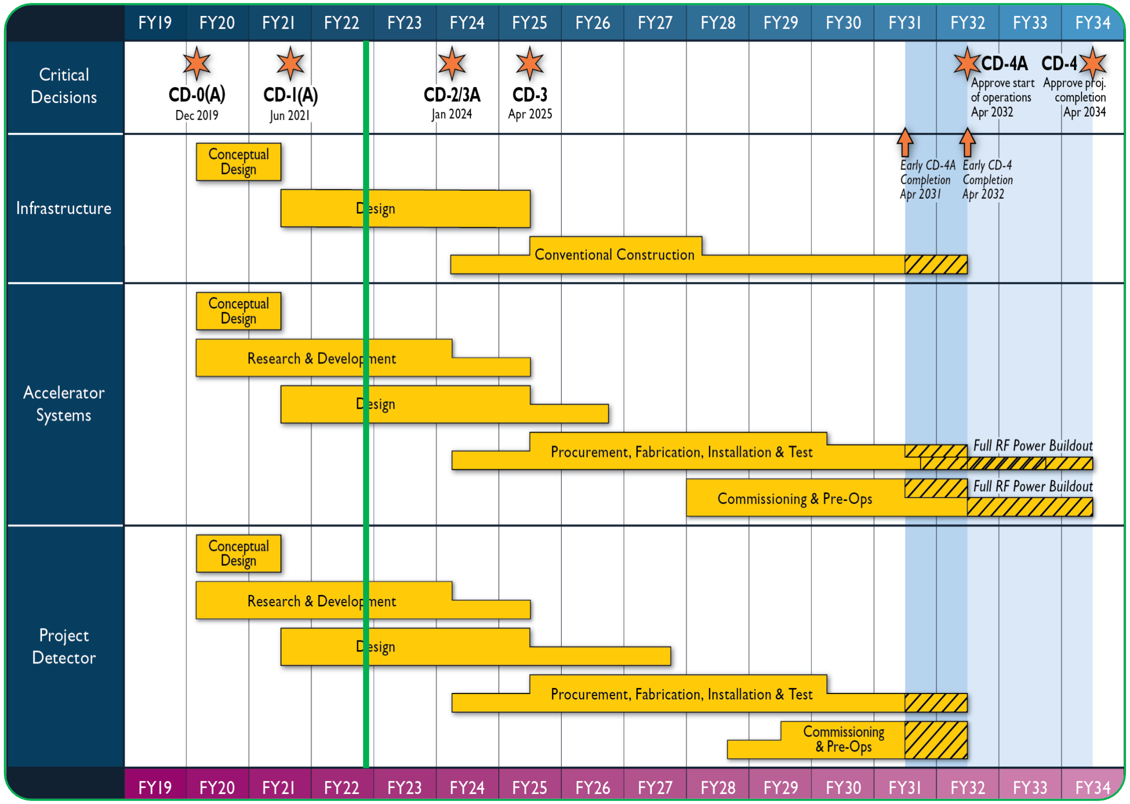
p: 40 – 275 GeV
e: 2.5 – 18 GeV

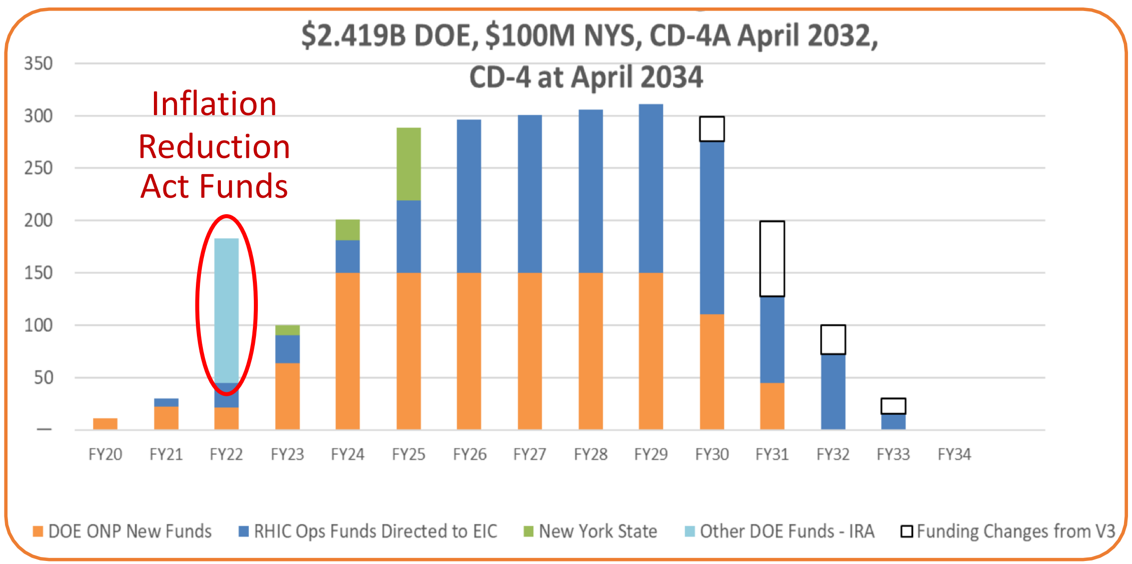
Data taking starting 2031/32



Timeframe

- CD-3 Funding secured (construction start)
- Initial operations planned for 2031/32

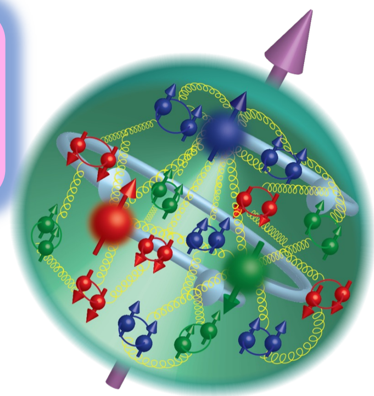




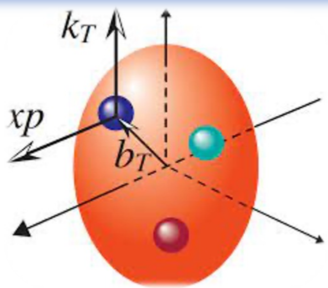
We're reducing inflation! ☺

EIC Core Science

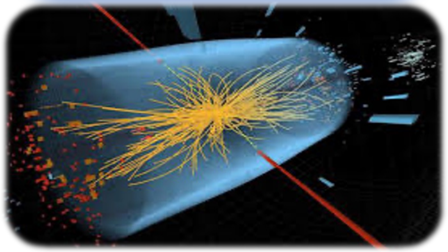
Origin of Spin



Femtography

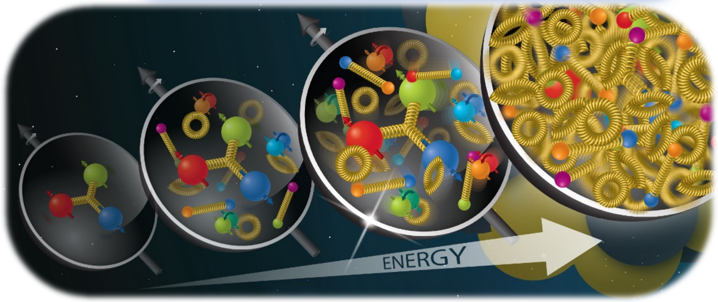


Standard Model

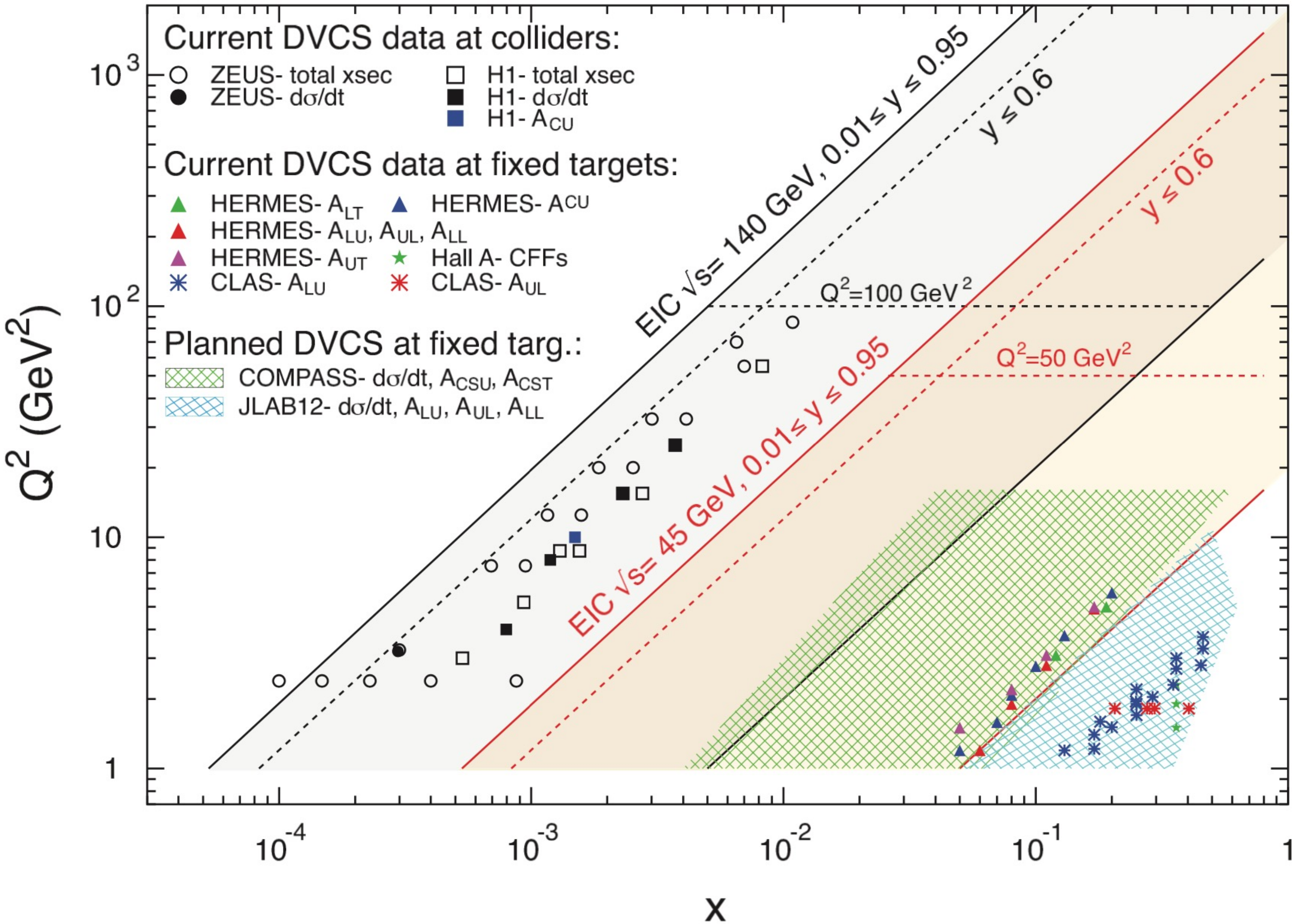


Origin of Mass

Dense Gluons



Precision era for exclusive processes

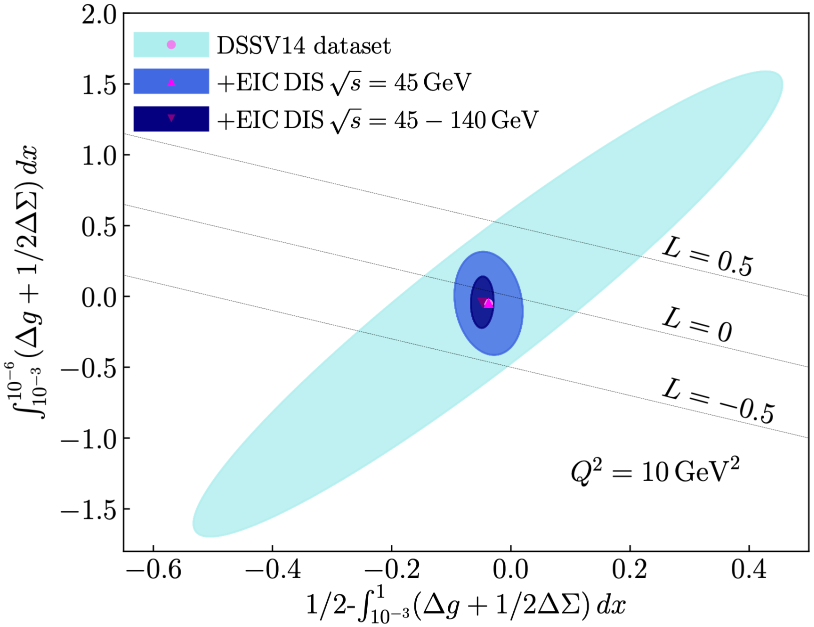


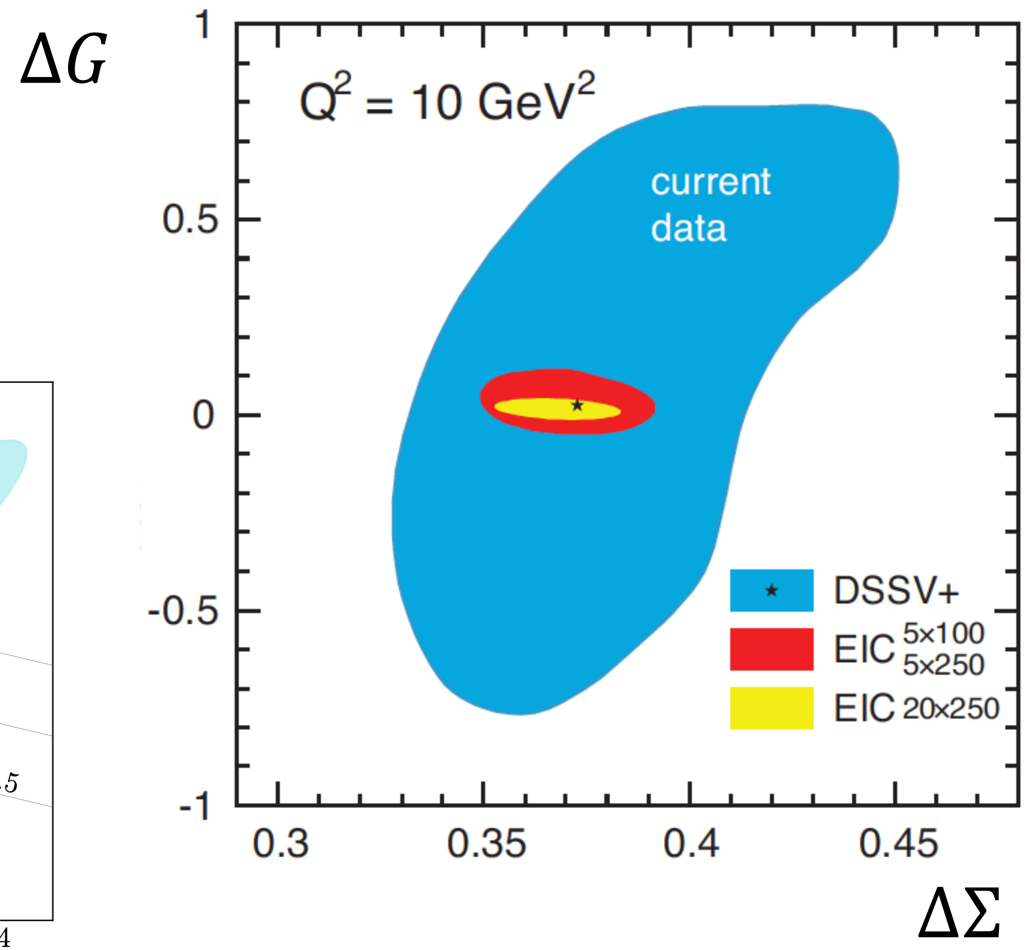
J. High Energ. Phys. **2013**, 93 (2013)

Spin at EIC

$$\int_{-1}^{1} dx x [H(x,\xi,\Delta^2) + E(x,\xi,\Delta^2)] = A(\Delta^2) + B(\Delta^2)$$

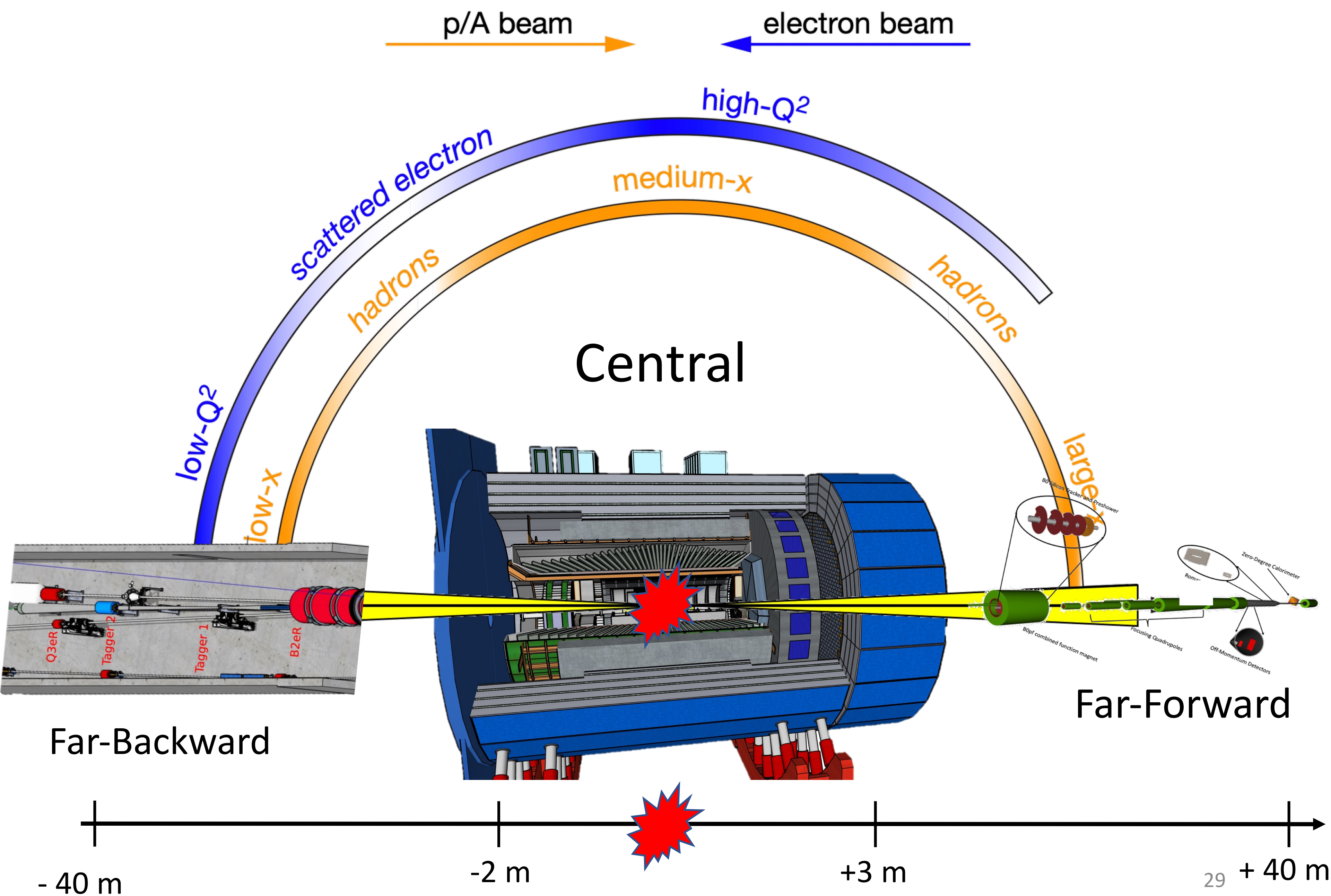
$$J_q = \frac{1}{2}\Delta\Sigma + L_q$$



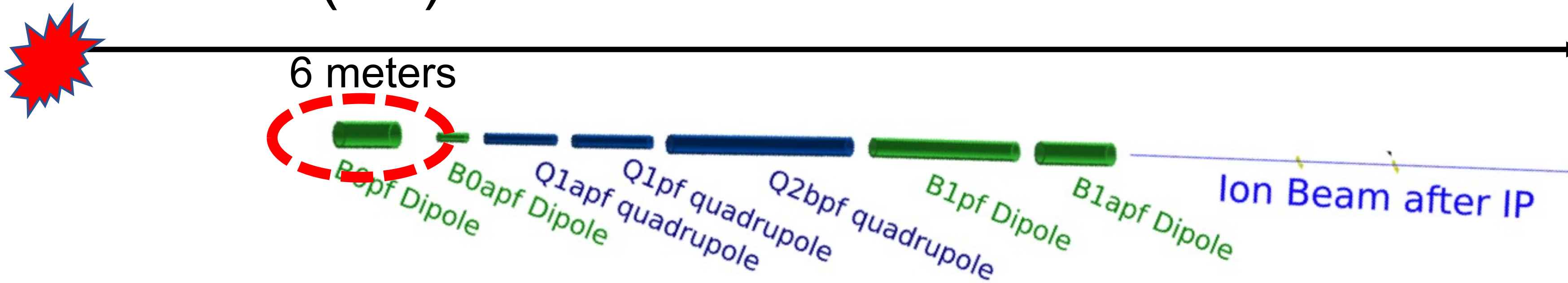


arXiv:2103.05419v3

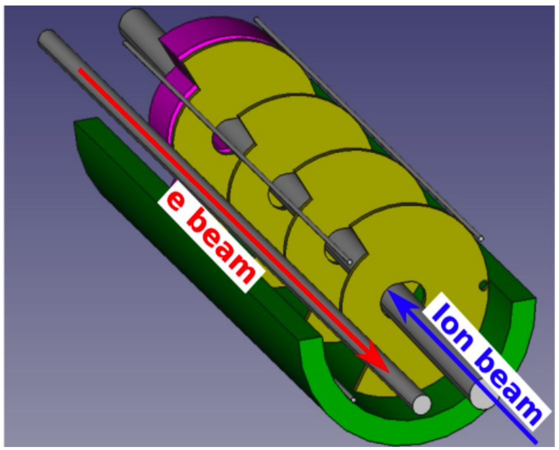
Three Detection Systems



Far Forward (FF)

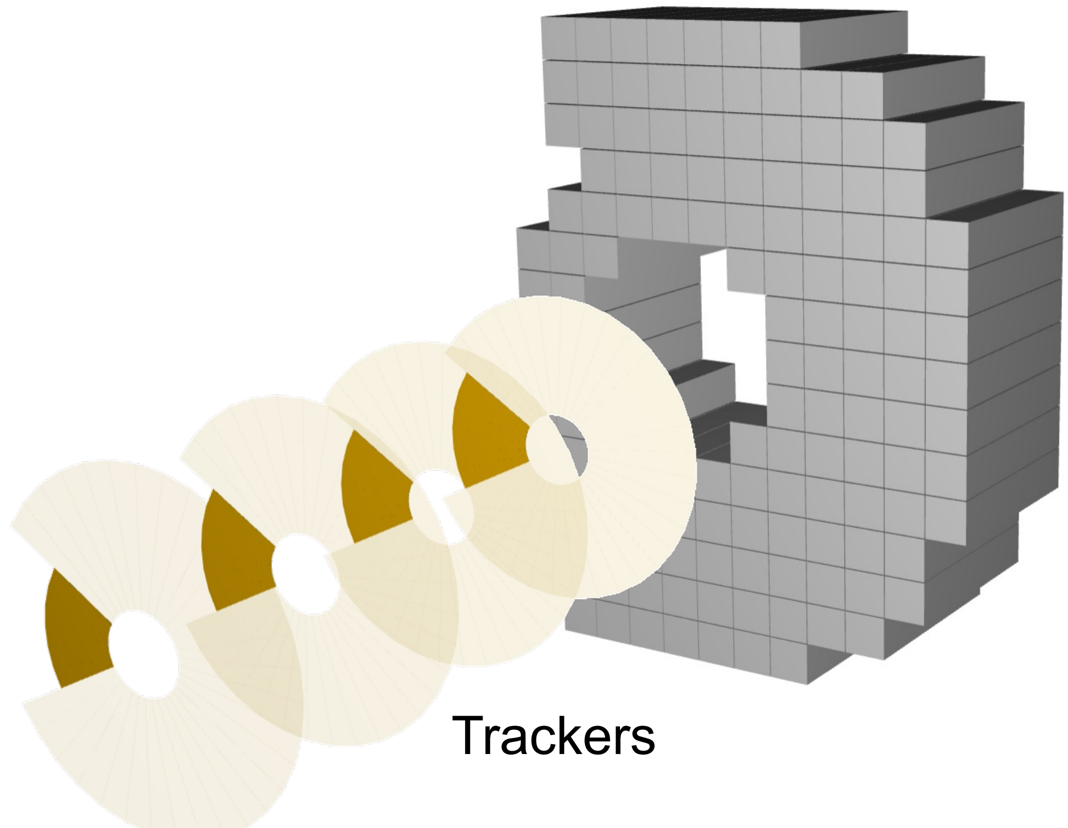


B0 – spectrometer



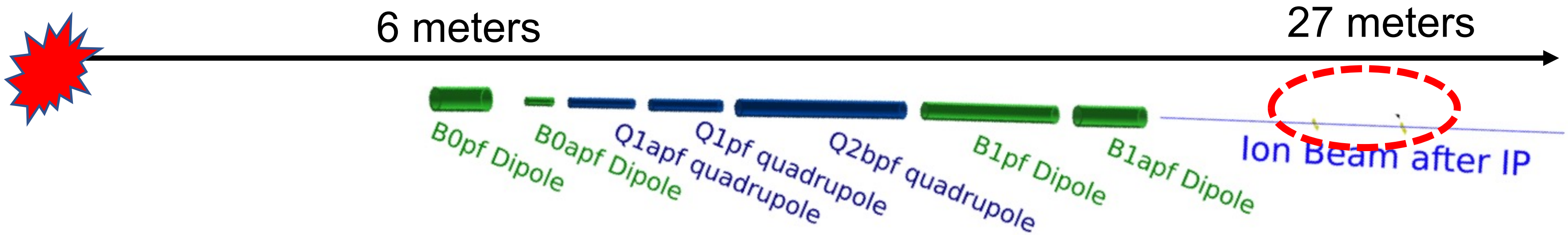
~6 meters from IP

<u>Calorimeter</u> PbWO$_4$ - crystals



Complicated mechanical access!

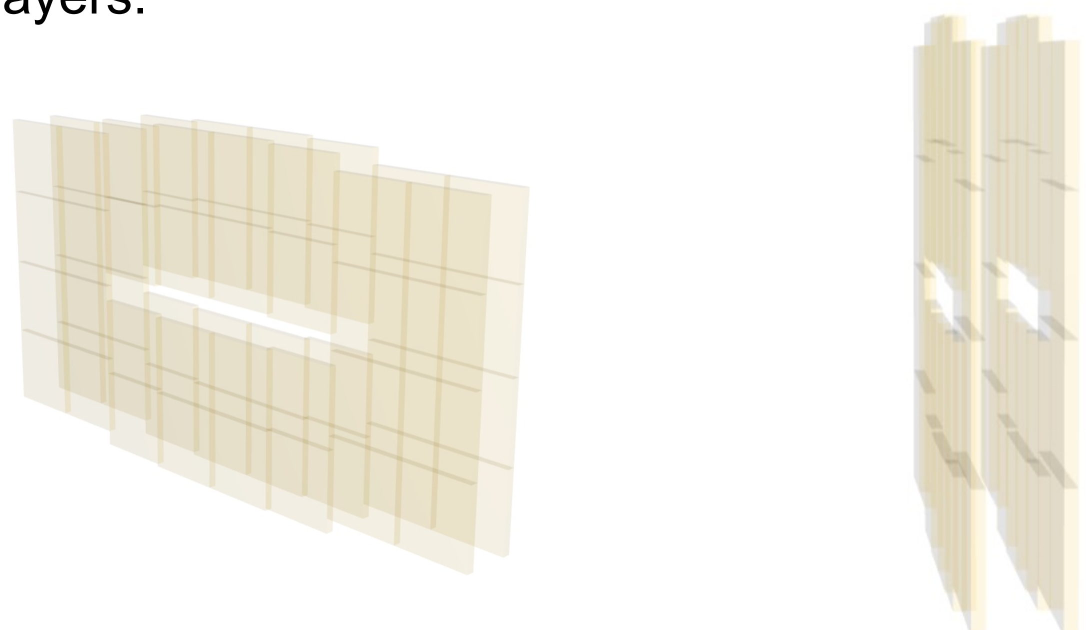
Far Forward (FF)



Roman Pots: 2 stations 26 and 28 meters from IP

25 x 12 cm^2

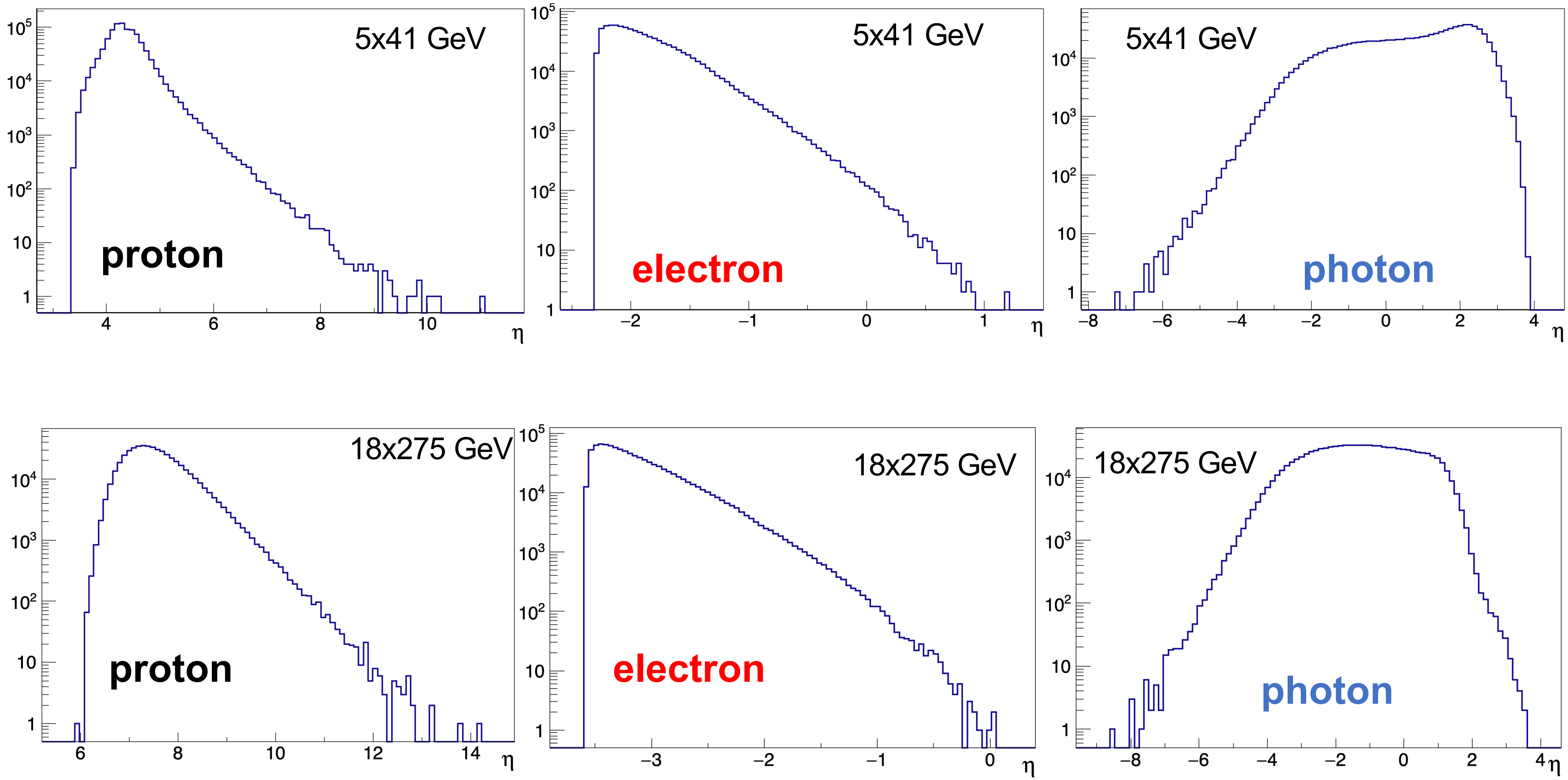
4 tracking layers.



Main challenge: Detectors inside beam pipe!

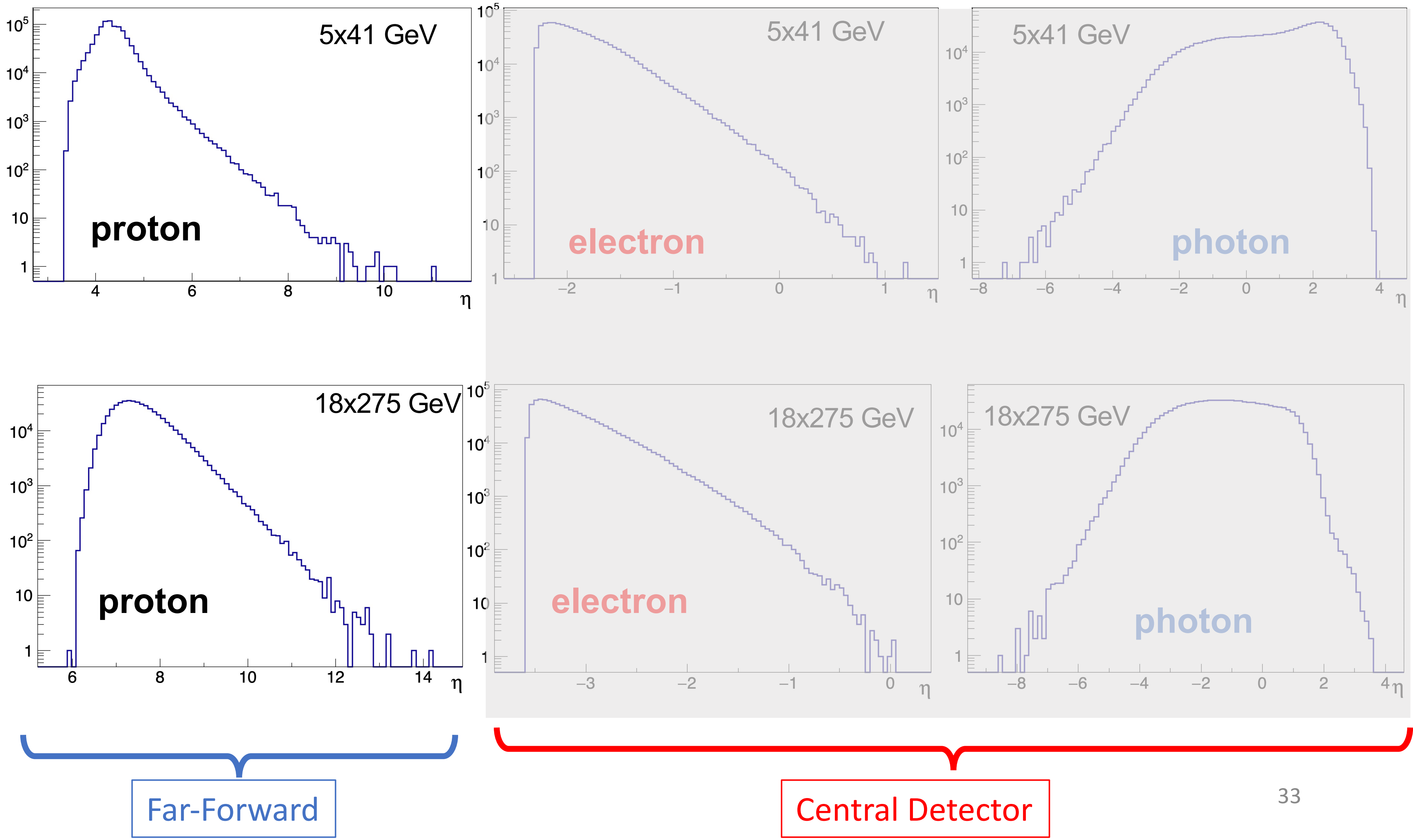
Far Forward region requirement

Angular distributions for DVCS



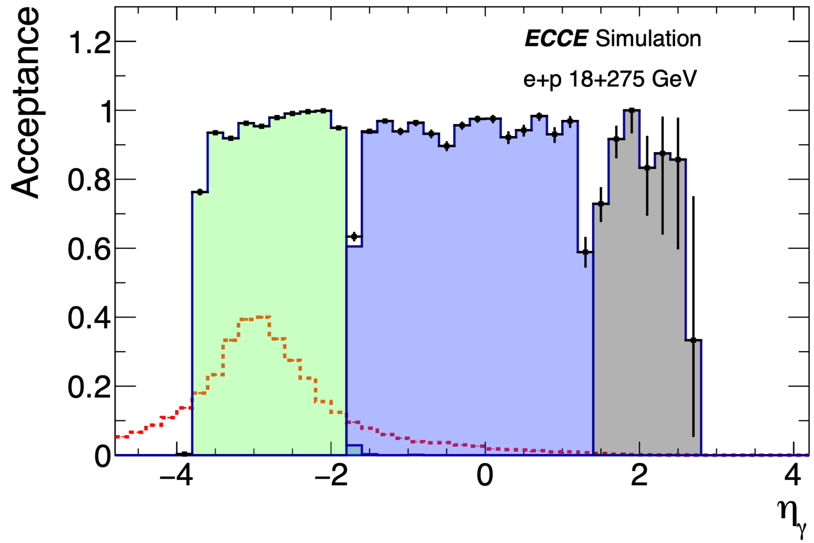
Far Forward region requirement

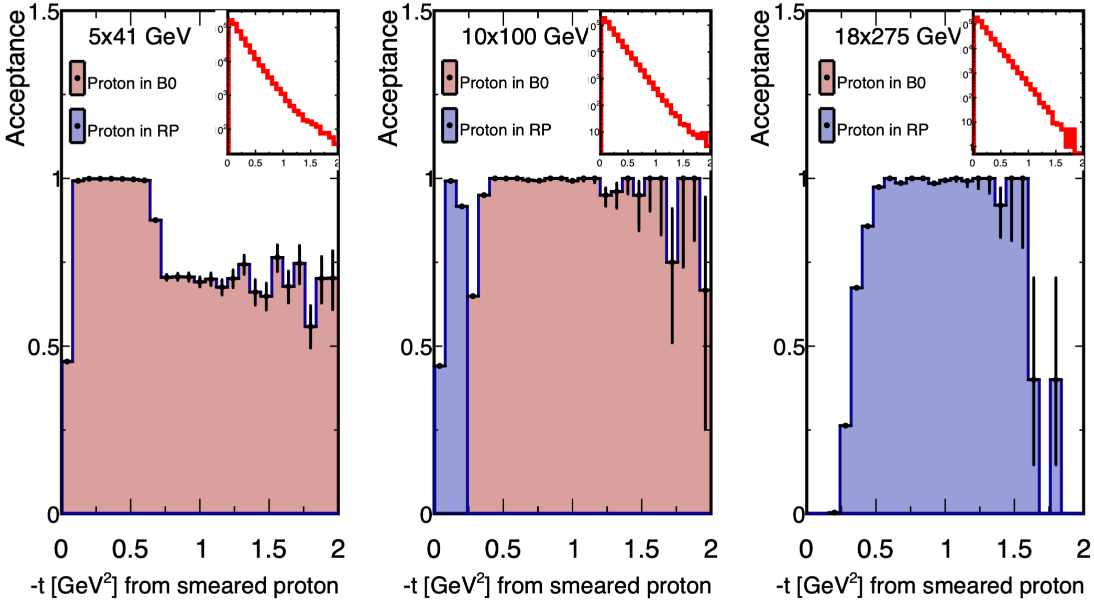
Angular distributions for DVCS



DVCS study for EIC (ECCE)

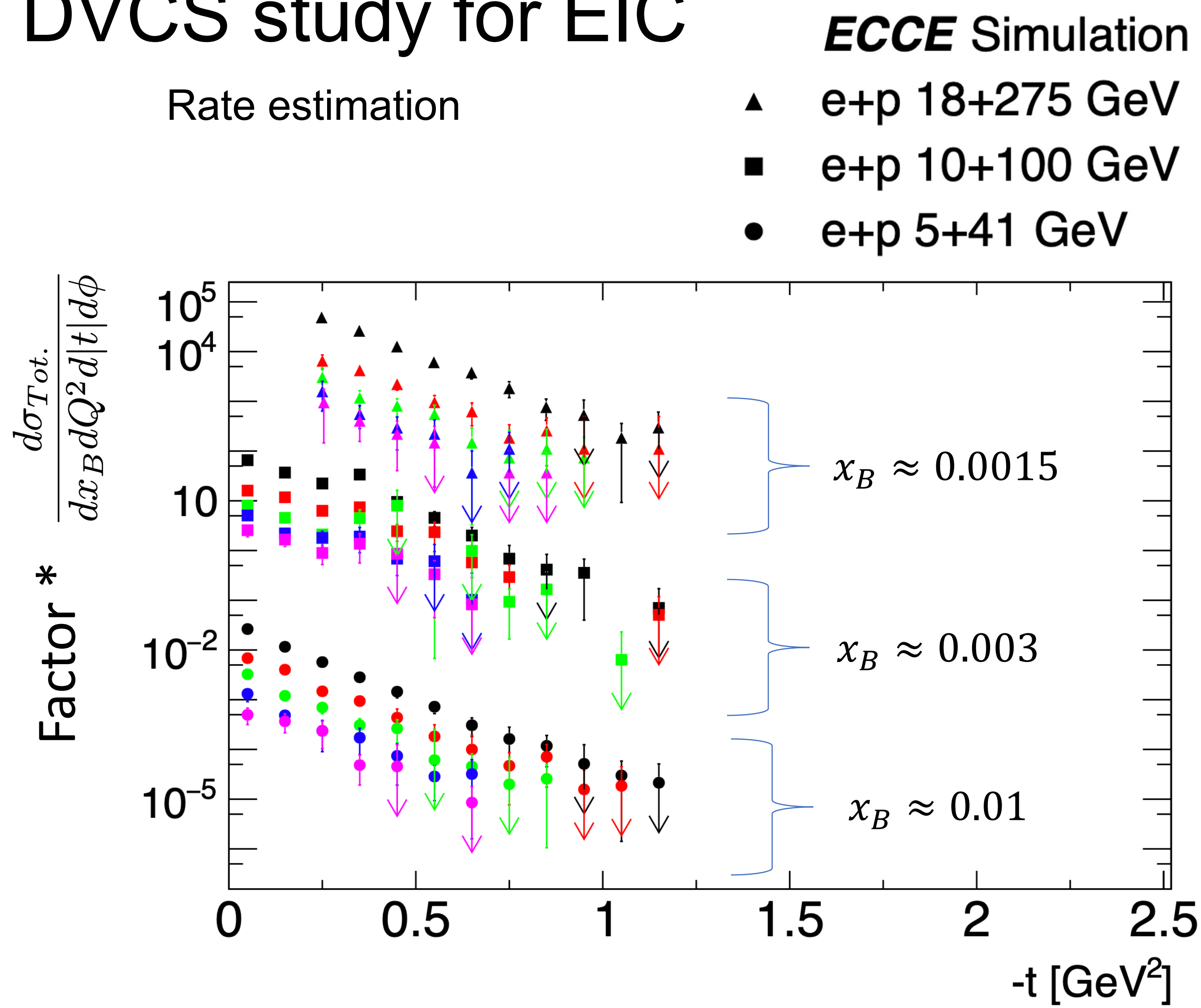
- Simulation
- Realistic reconstruction of all particles
- Pseudo-data analysis
- Acceptance study





DVCS study for EIC

Rate estimation



<u>Q^2 range:</u>

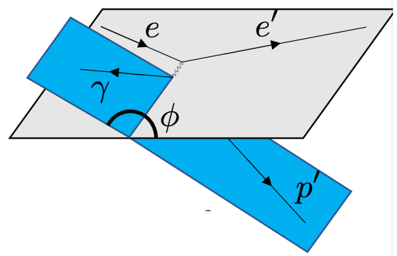
2-10 (GeV/c)^2

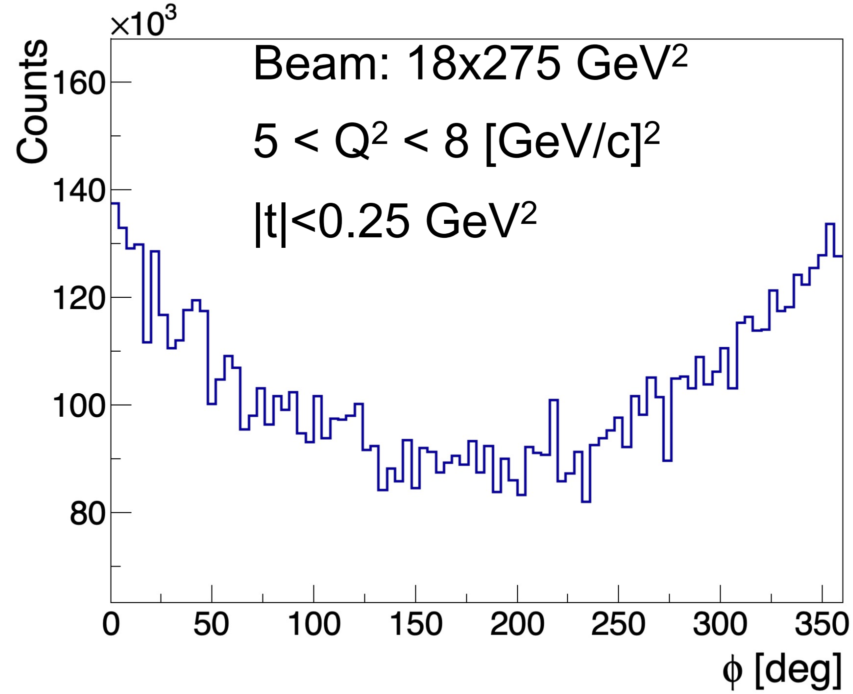
Statistical uncertainties:
$\mathcal{L}$ =10 fb^{-1}
(at each beam energy)

DVCS study for EIC

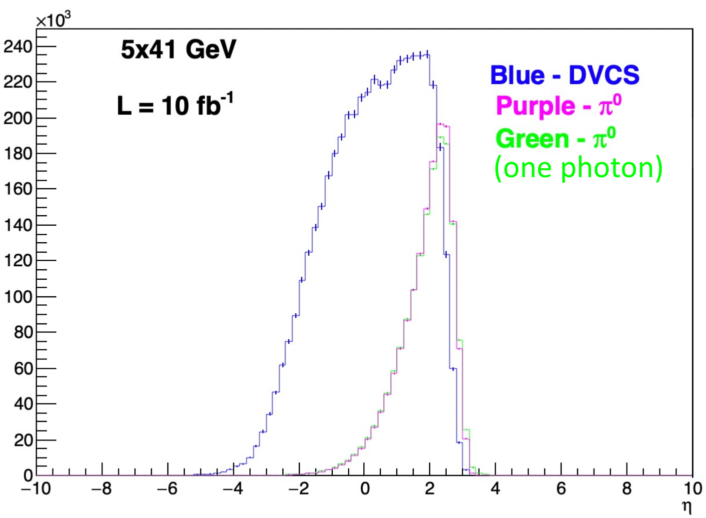
(work in progress)

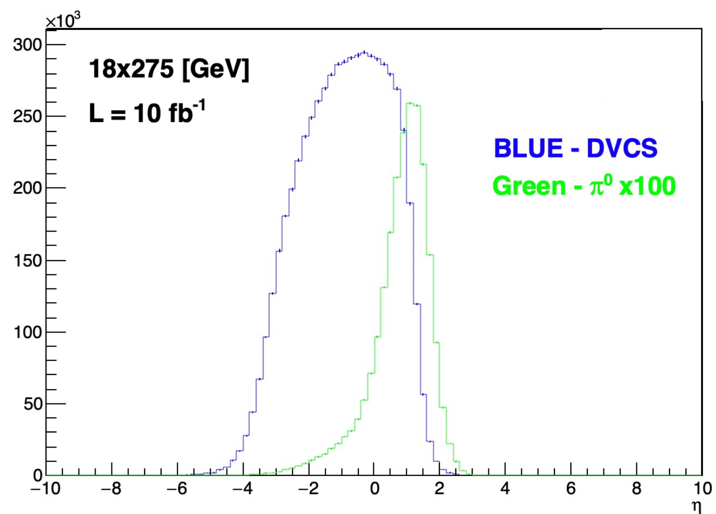
- Asymmetry study





- Contamination due to DV$\pi°$



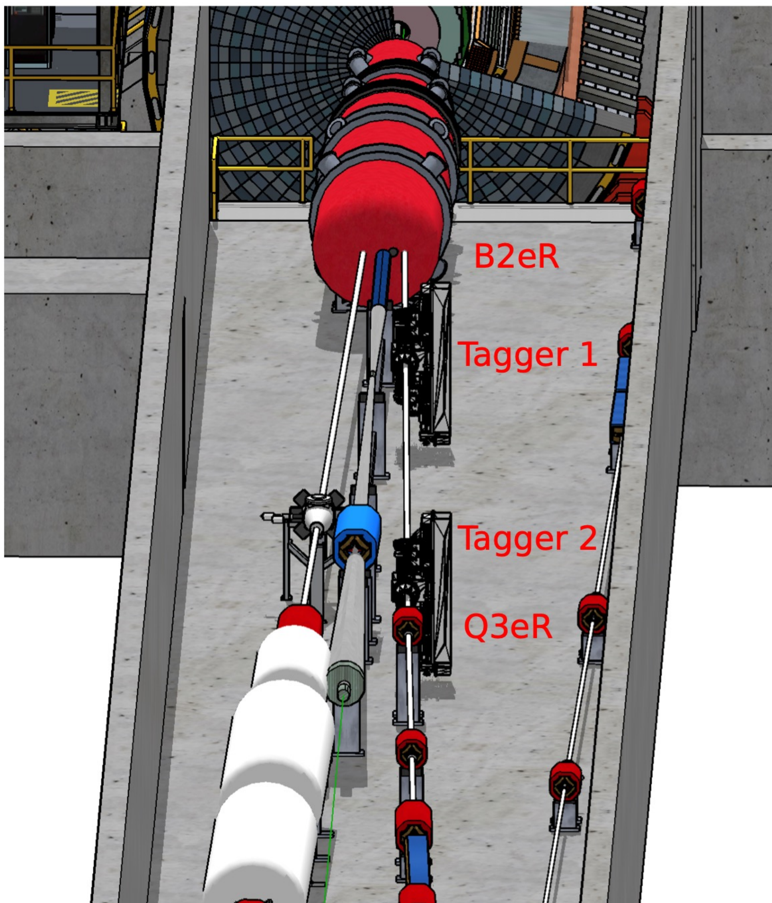


- Simulation with realistic background

Far Backward (FB)

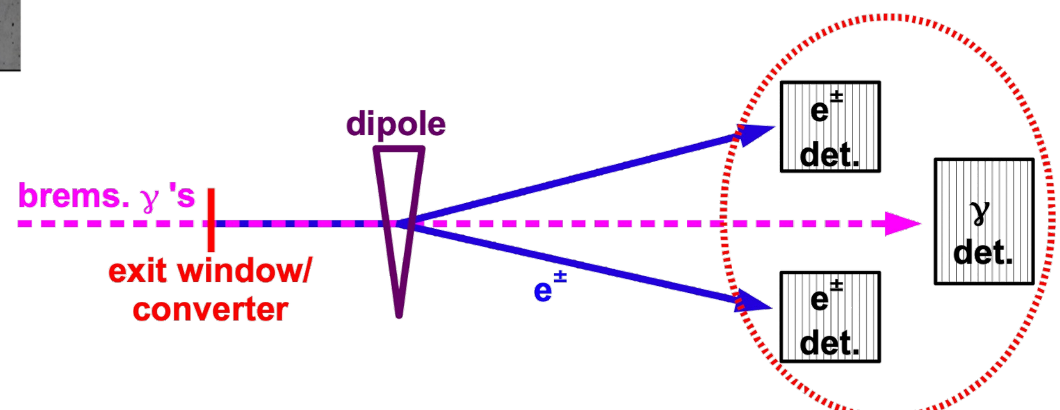
The luminosity measurement provides the required normalization for all physics studies.

Must for absolute cross sections measurements.



Bethe-Heitler: $ep \rightarrow e'p\gamma$

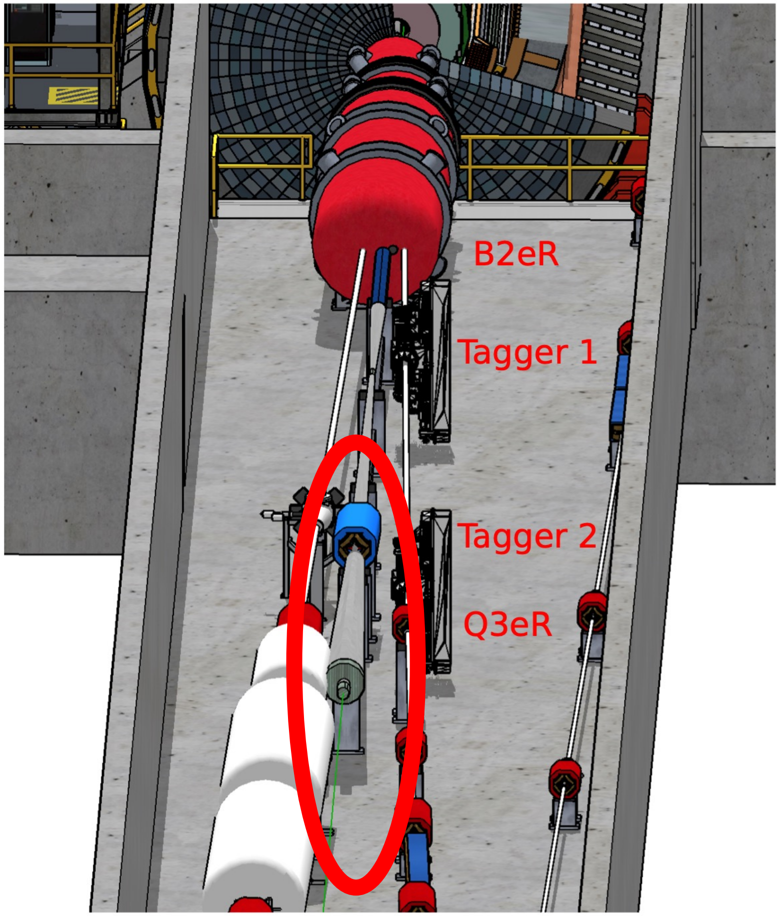
Crucial for DVCS measurement



Luminosity Monitors

EIC luminosity of 10^{33} cm^{-2} s^{-1}

Complicated beam profile

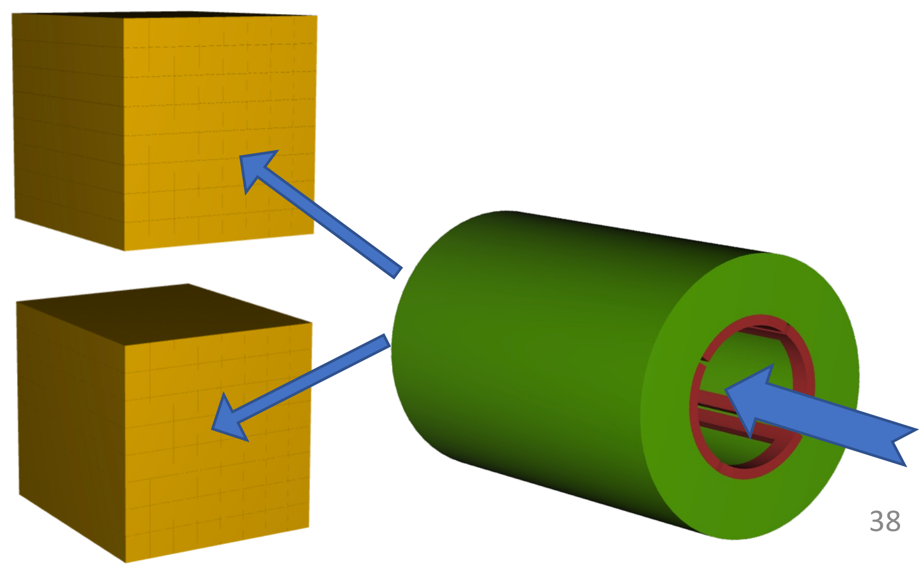


Multiple subsystems:

- **Luminosity Direct Photon Detector**
  - **Calorimeter**
- **Luminosity Pair Spectrometer**
  - **Calorimeter**
  - **Trackers**

$PbWO_4$ 2x2x20 cm^3

Total area ~ 16x16 cm^2 (each)

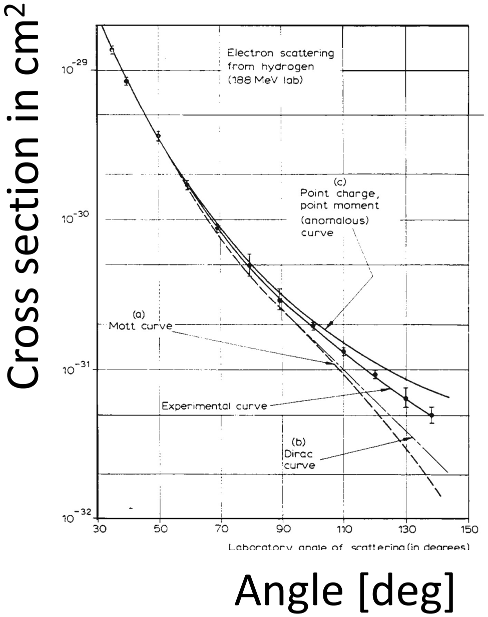


Many Extensive Studies…

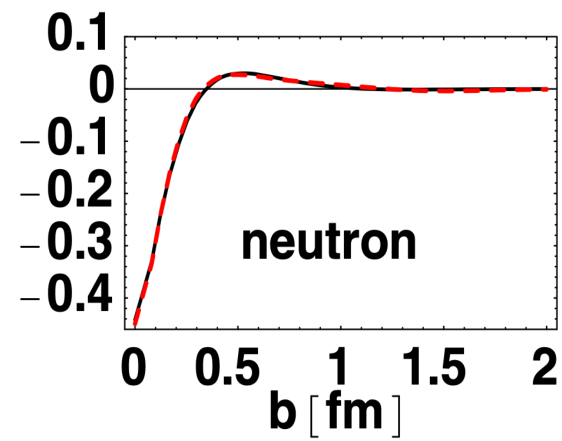
NIM-A special issue on "Detectors for the Electron-Ion Collider":

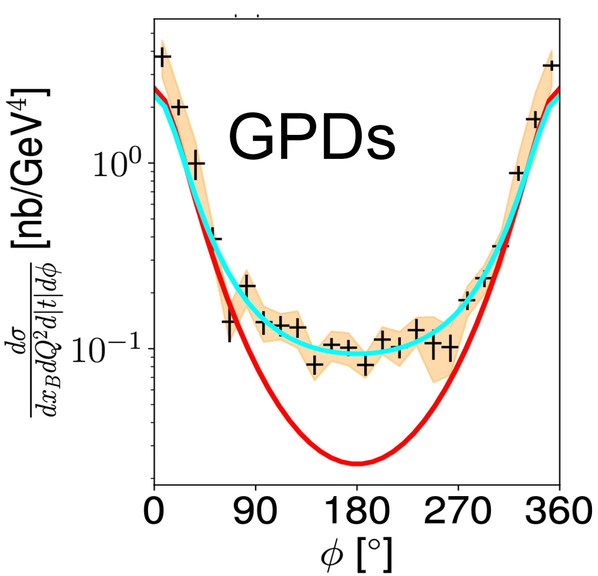
[arXiv: 2209.02580] "Design of the ECCE Detector for the Electron Ion Collider"
[arXiv: 2208.14575] "Detector Requirements and Simulation Results for the EIC Exclusive, Diffractive and Tagging Physics Program using the ECCE Detector Concept"
[arXiv: 2207.09437] "Design and Simulated Performance of Calorimetry Systems for the ECCE Detector at the Electron Ion Collider"
[arXiv: 2205.09185] "AI-assisted Optimization of the ECCE Tracking System at the Electron Ion Collider"
[arXiv: 2207.09437] "Open Heavy Flavor Studies with the ECCE Detector at the Electron Ion Collider"
[arXiv: 2207.10356] "Exclusive J/ψ detection and physics with ECCE"
[arXiv: 2207.10890] "ECCE Sensitivity Studies for Single Hadron Transverse Single Spin Asymmetry Measurements"
[arXiv: 2207.10261] "Search for $e \rightarrow \tau$ Charged Lepton Flavor Violation at the EIC with the ECCE Detector"
[arXiv: 2207.10893] "ECCE unpolarized TMD measurements"
[arXiv: 2205.08607] "Scientific Computing Plan for the ECCE Detector at the Electron Ion Collider"

EM Form Factors
Nobel Lecture, December 11, 1961

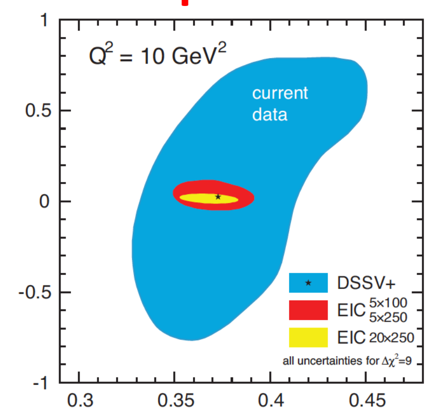


Transverse Charged density [fm^{-2}]

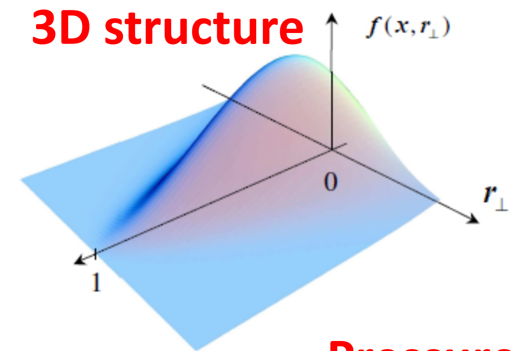




Spin

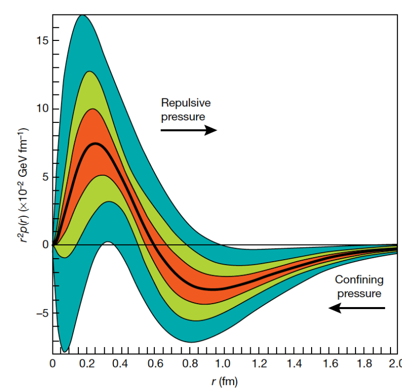


3D structure



Mass

Pressure



Thank you