

Deep Exclusive Reactions

Lecture 1: Nucleon structure studies with the electromagnetic probe

- Elastic scattering: form factors
- DIS: structure function
- Exclusive reactions: Generalized Parton Distributions

Lecture 2: Deeply Virtual Compton Scattering

- GPDs and DVCS
- DVCS on the proton with JLab@6 GeV
- Extraction of GPDs from data
- Proton tomography and forces in the proton

Lecture 3: DVCS and beyond

- DVMP
- New DVCS experiments@12 GeV
- TCS

Lecture 4: Perspectives

- Upgrades at JLab
- GPDs at the EIC

Lecture 5: Tutorial

- Data analysis techniques for exclusive reactions



Silvia Niccolai, IJClab Orsay & CLAS Collaboration
PROBES Annual Meeting, Pisa (Italy), November 2025



Recap: what have we learned so far on GPDs

- $Im\mathcal{H}$ well constrained, in CLAS (and now CLAS12) kinematics $\rightarrow$ proton tomography
- $Re\mathcal{H}$ constrained mainly by Hall A measurements in selected kinematics; important for D-term and distribution of forces
- Initial constraints on $\tilde{\mathcal{H}}$ from longitudinally polarized target experiments, more data coming soon
- Potential of TCS for $Re\mathcal{H}$, D-term, universality of GPDs
- Importance of nDVCS for $\mathcal{E}_n$ sensitivity and flavor separation, but low statistics
- pDVCS on transverse target is vital to constrain $\mathcal{E}_p$
- Still no information on x dependence of GPDs
- DVMP: only pseudo-scalars had until now a « succesful » GPD interpretation (transversity) $\rightarrow$ higher Q^2 may be necessary

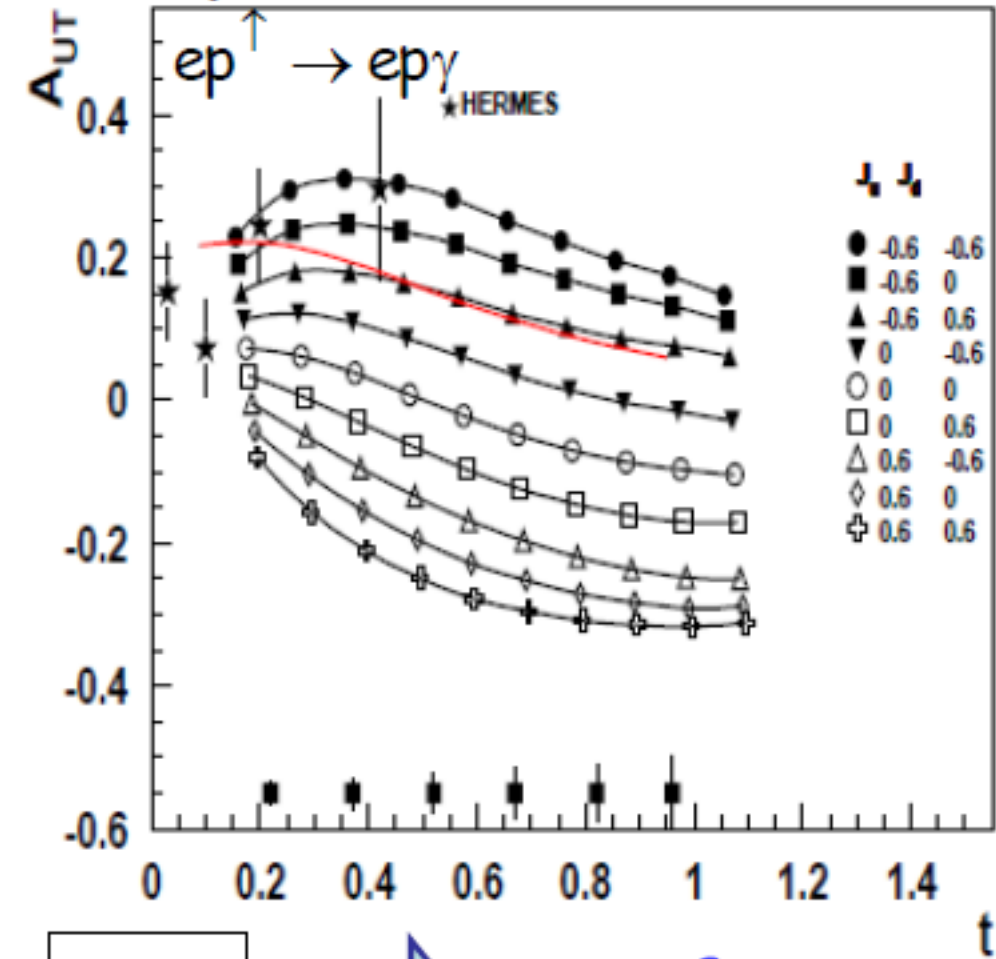
Perspectives for the next few years

- **DVCS on transversely polarized protons at CLAS12**
- **Upgrades for JLab** under discussion:
 - ✓ Higher luminosity for CLAS12
 - ✓ Polarized positrons beam
 - ✓ Double CEBAF beam energy
- **Electron-Ion Collider (EIC)**

CLAS12: p-DVCS *transverse* target-spin asymmetry

100 days of beam time; Beam pol. = 80% ; **target pol. = 60%** ; Luminosity = $5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

Projections for $Q^2 = 2.5 \text{ GeV}^2$, $x_B = 0.2$



$$\Delta\sigma_{UT} \rightarrow \text{Im}\{\mathcal{H}_p, \mathcal{E}_p\}$$

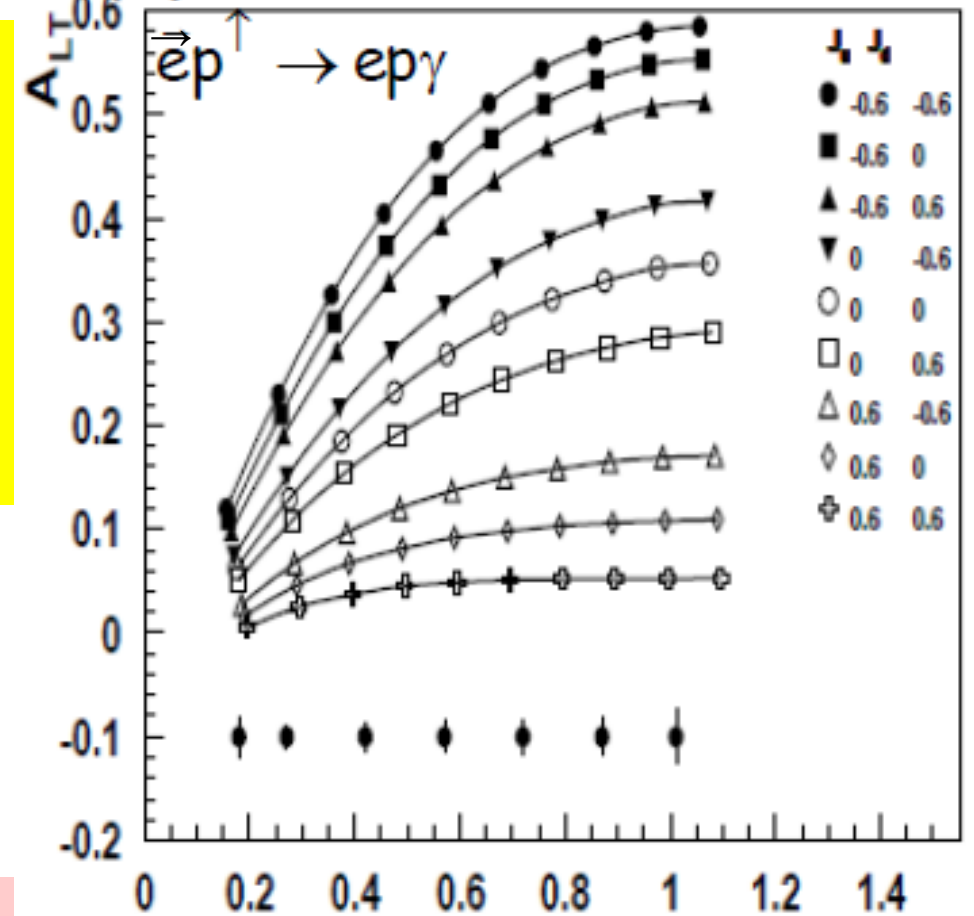
The transverse-target spin asymmetry for pDVCS is **highly sensitive** to $E \rightarrow$ the **u-quark contributions** to the proton spin.

So far, only low-statistics data from HERMES exist

JLab PAC: **high-impact** experiment

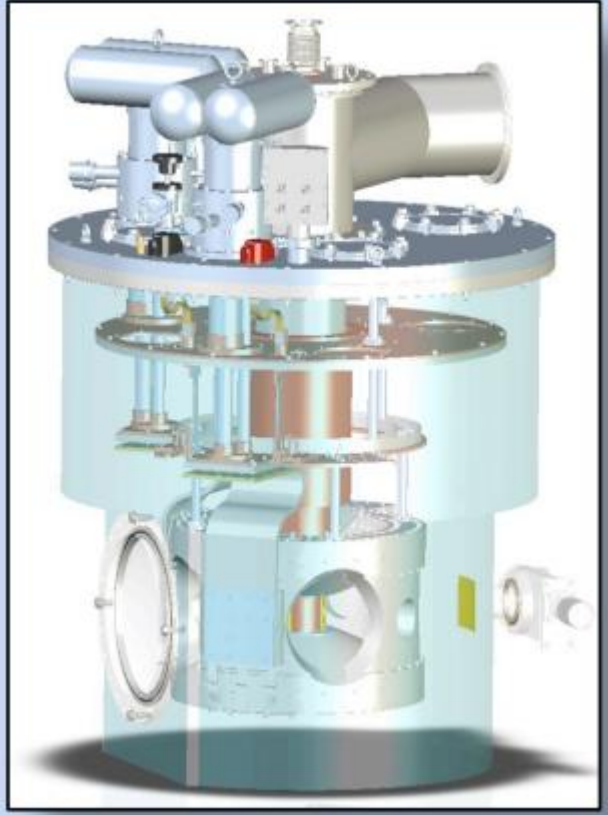
Conditionally approved by PAC39

Projections for $Q^2 = 2.5 \text{ GeV}^2$, $x_B = 0.2$



$$\Delta\sigma_{LT} \rightarrow \text{Re}\{\mathcal{H}_p, \mathcal{E}_p\}$$

Transverse target for CLAS12: an experimental challenge

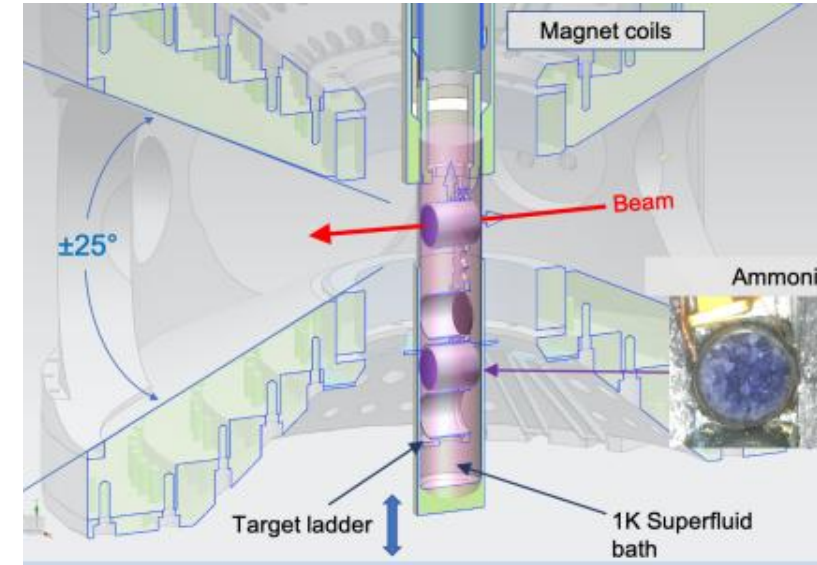


HD-ICE (project was discontinued):

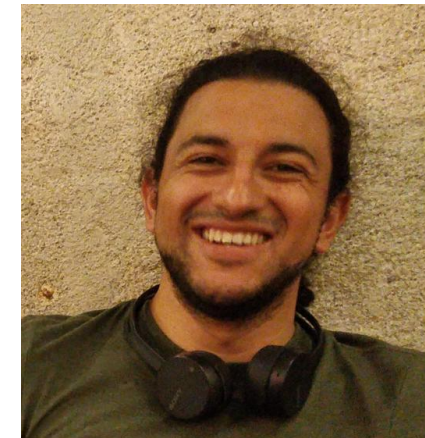
- pros: minimize the dilution and nuclear background (due to not-polarizable material) pros: maximize acceptance (thanks to the light magnetic system)
- cons: beam heating and radiation damage – polarization wouldn't hold in electron beam
- cons: long preparation time

Dynamically polarized NH₃:

- pros: consolidated technology and infrastructure at JLab
- cons: increased systematic effect (nuclear effects, non uniform target density)
- cons: impact on the experimental setup (massive magnet of strong field and reduced acceptance): incompatible with the CLAS12 central detector; limited acceptance $\pm 25^\circ$ forward

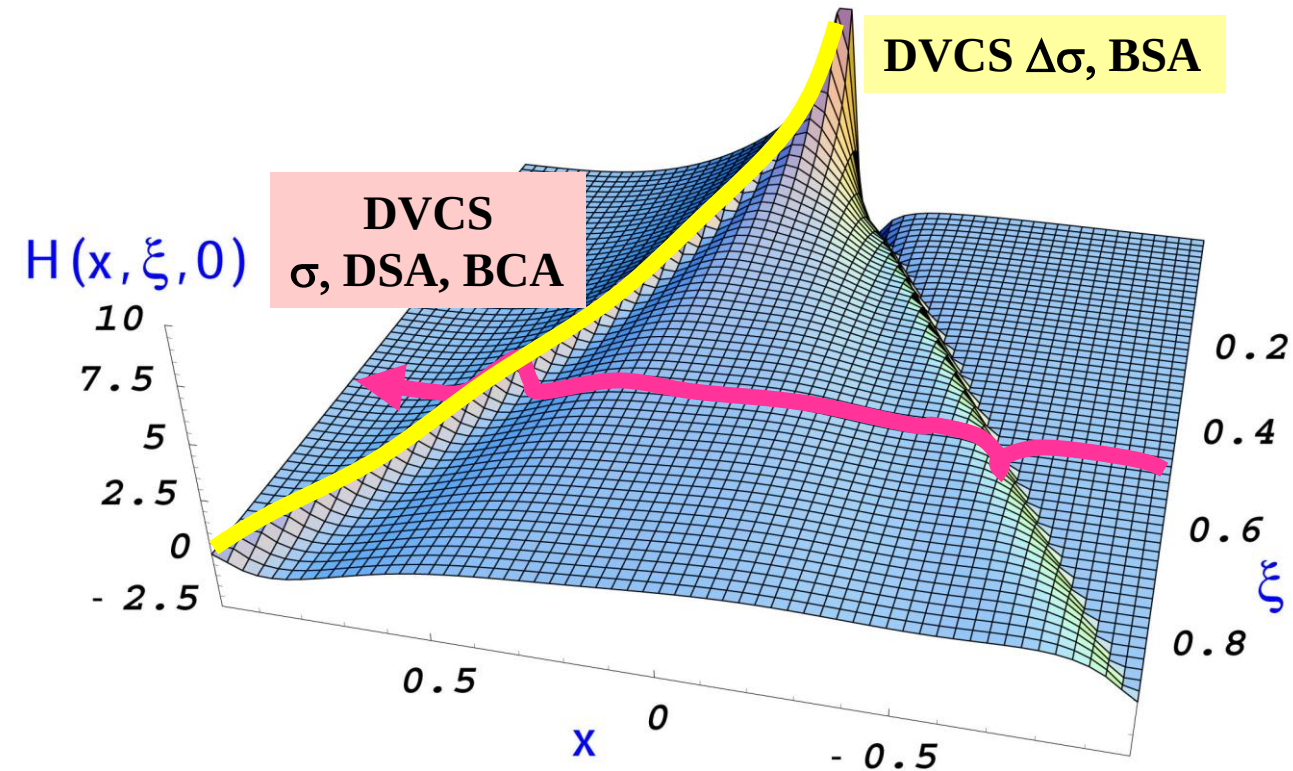
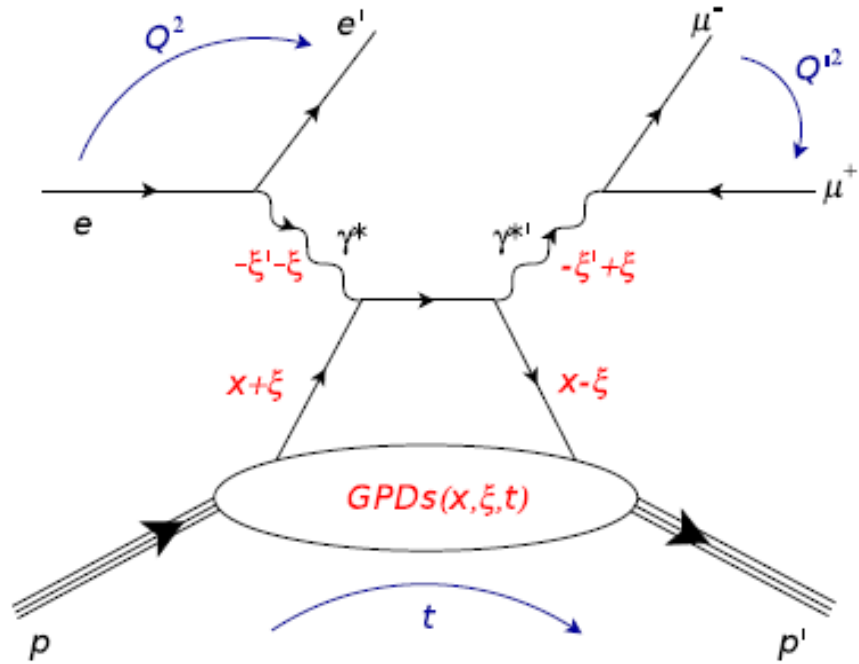


- Feasibility studies for pDVCS with limited acceptance are ongoing
- R&D studies on possible alternative target solutions are also ongoing



**Juan
Sebastian
Alvarado**

DDVCS: the gateway to the full kinematic mapping of GPDs



Thanks to the virtuality of the final photon, Q'^2 , **DDVCS** allows a unique direct access to GPDs at $x \neq \pm\xi$ (within $0 < 2\xi' - \xi < \xi$), which is fundamental for their modeling

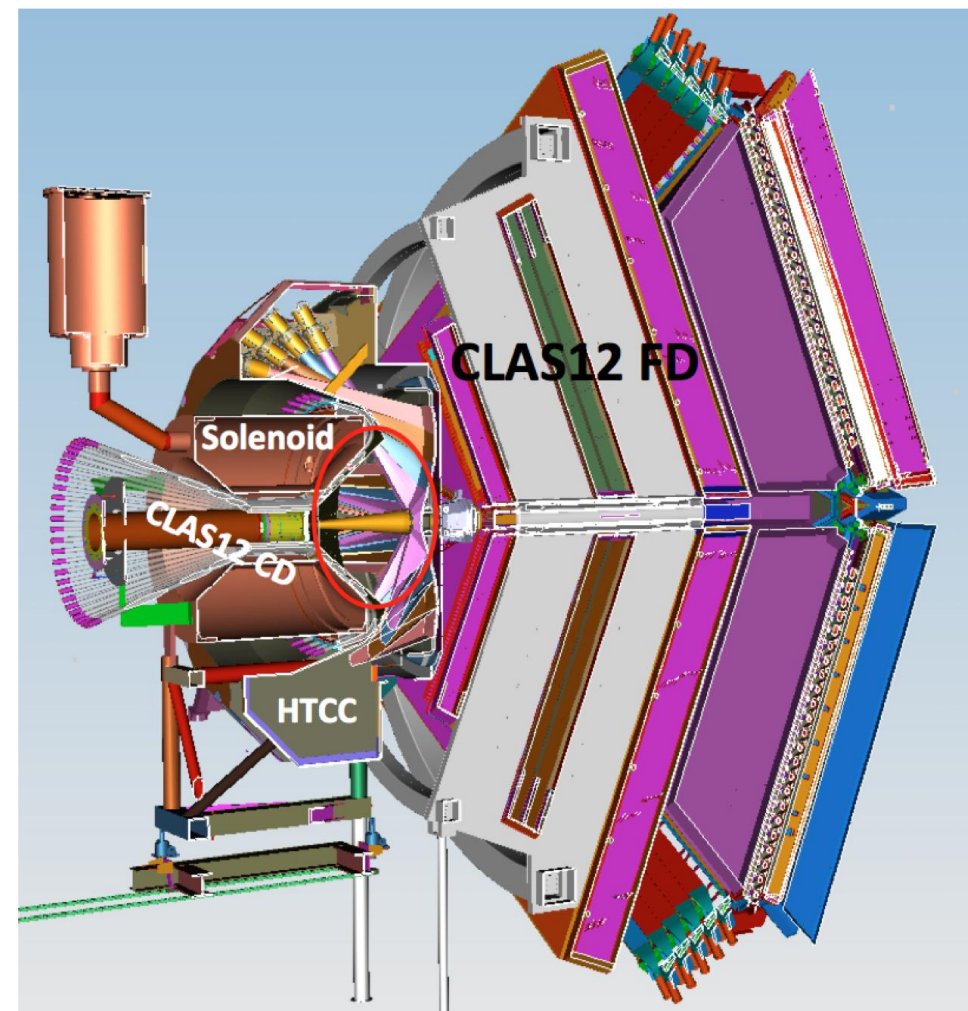
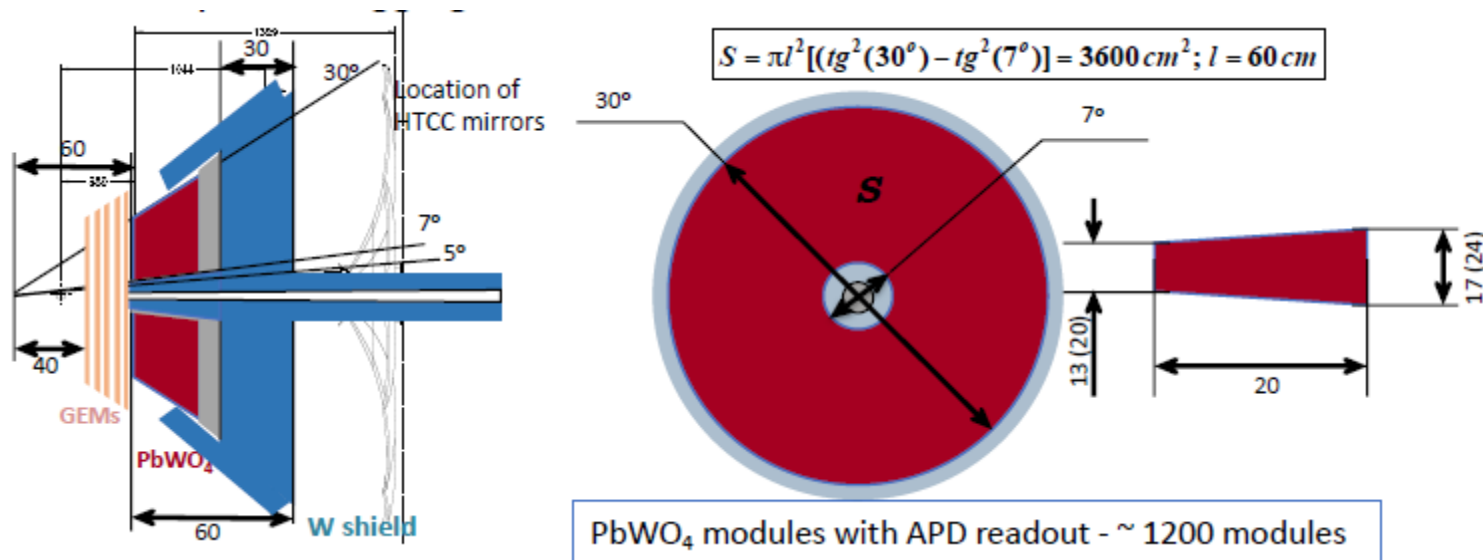
Experimental challenges:

- Small cross section (300 times less than DVCS)
- Need to detect muons

μ CLAS12 for DDVCS and J/psi

$ep \rightarrow e'p'\mu^+\mu^-$ at $L \sim 10^{37} \text{ cm}^{-2}\text{s}^{-1}$

- Remove HTCC and install in the region of active volume of HTCC
 - a new Moller cone that extends up to 7°
 - a new PbWO₄ calorimeter that covers 7° to 30° polar angular range with 2π azimuthal coverage.
- Behind the calorimeter, a 30-cm-thick tungsten shield covers the whole acceptance of the CLAS12 FD
- MPGD tracker in front of the calorimeter for vertexing and inside the solenoid for recoil proton tagging



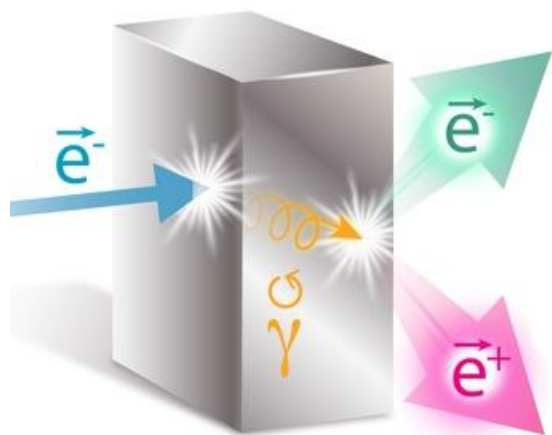
S. Stepanyan, LOI12-16-004

DDVCS project also for SOLID

Polarized positrons beam for Jefferson Lab

Physics Motivations:

- Two-photon physics
- **Generalized parton distributions**
- Neutral and charged current DIS
- Charm production
- Neutral electroweak coupling
- Light Dark Matter search
- Charged Lepton Flavor Violation



PePPO: proof-of-principle for a polarized positron beam
PRL 116 (2016)

- Publication of the **EPJ A Topical Issue about "An experimental program with positron beams at Jefferson lab"** gathering about 250 physicists from 75 institutions around a several-years-long experimental program.
- Two DVCS-based proposals were submitted to JLab PAC48 and were Conditionally Approved

An Experimental Program with Positron Beams at Jefferson Lab

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- The ongoing **R&D** aims to identify the most appropriate implementation of **PEPPO** at **CEBAF**, taking into account the many constraints and technological challenges towards the development of a **prototype** and a **CDR**
- **Possible timeline? Discussions ongoing at JLab**

DVCS with polarized positrons beam at JLab

The importance of beam-charge asymmetry for DVCS was highlighted by the pioneering HERMES experiment

Disposing of a polarized positron/electron beams at JLab → new observables = different sensitivities to GPDs

Beam Charge Asymmetries proposed to be measured at CLAS12:

- The unpolarized beam charge asymmetry A_C^{UU} , which is sensitive to the real part of the CFF → D-term, forces in the proton
- The polarized beam charge asymmetry A_C^{LU} , which is sensitive to the imaginary part of the CFF
- The neutral beam spin asymmetry A_0^{LU} , which is sensitive to higher twist effects

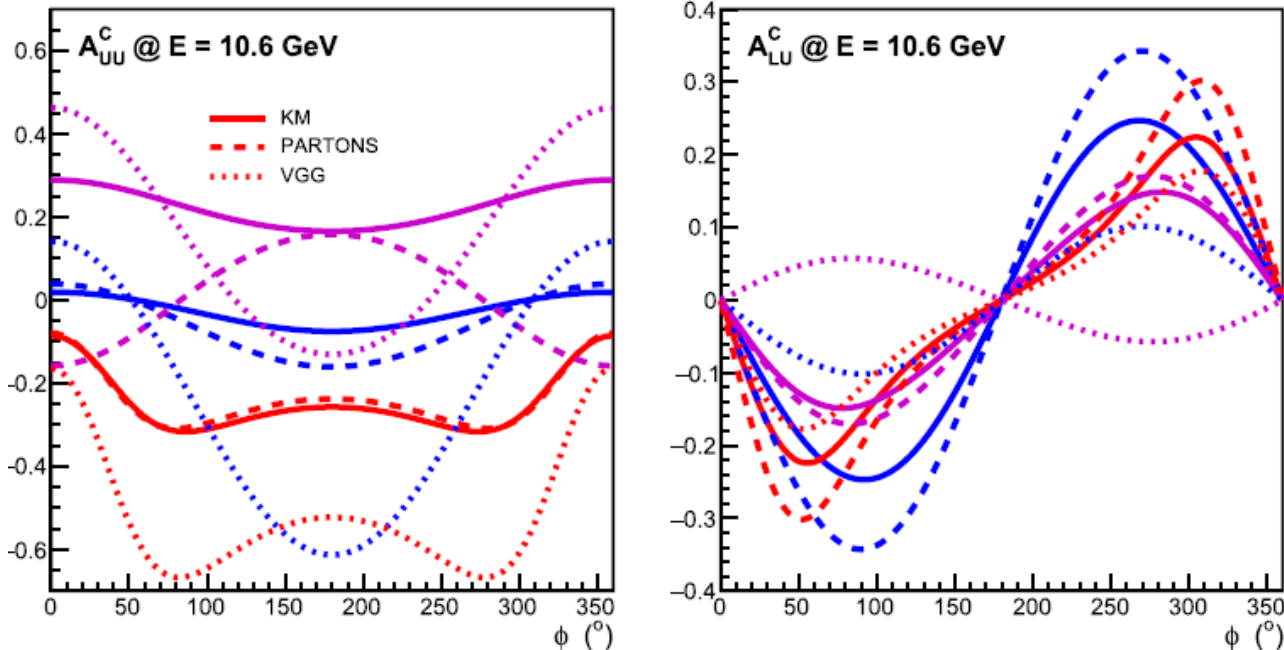
**New GPD
Observables
@ JLab**

$$A_{UU}^C = \frac{(Y_+^+ + Y_-^+) - (Y_+^- + Y_-^-)}{Y_+^+ + Y_-^+ + Y_+^- + Y_-^-}$$
$$= \frac{\sigma_{INT}}{\sigma_{BH} + \sigma_{DVCS}}$$

$$A_{LU}^C = \frac{(Y_+^+ - Y_-^+) - (Y_+^- - Y_-^-)}{Y_+^+ + Y_-^+ + Y_+^- + Y_-^-}$$
$$= \frac{\tilde{\sigma}_{INT}}{\sigma_{BH} + \sigma_{DVCS}}$$

$$A_{LU}^0 = \frac{(Y_+^+ + Y_+^-) - (Y_-^+ + Y_-^-)}{Y_+^+ + Y_-^+ + Y_+^- + Y_-^-}$$
$$= \frac{\tilde{\sigma}_{DVCS}}{\sigma_{BH} + \sigma_{DVCS}}$$

pDVCS and nDVCS with polarized positrons beam at CLAS



Model predictions for 2 out of the 3 proposed pDVCS observables

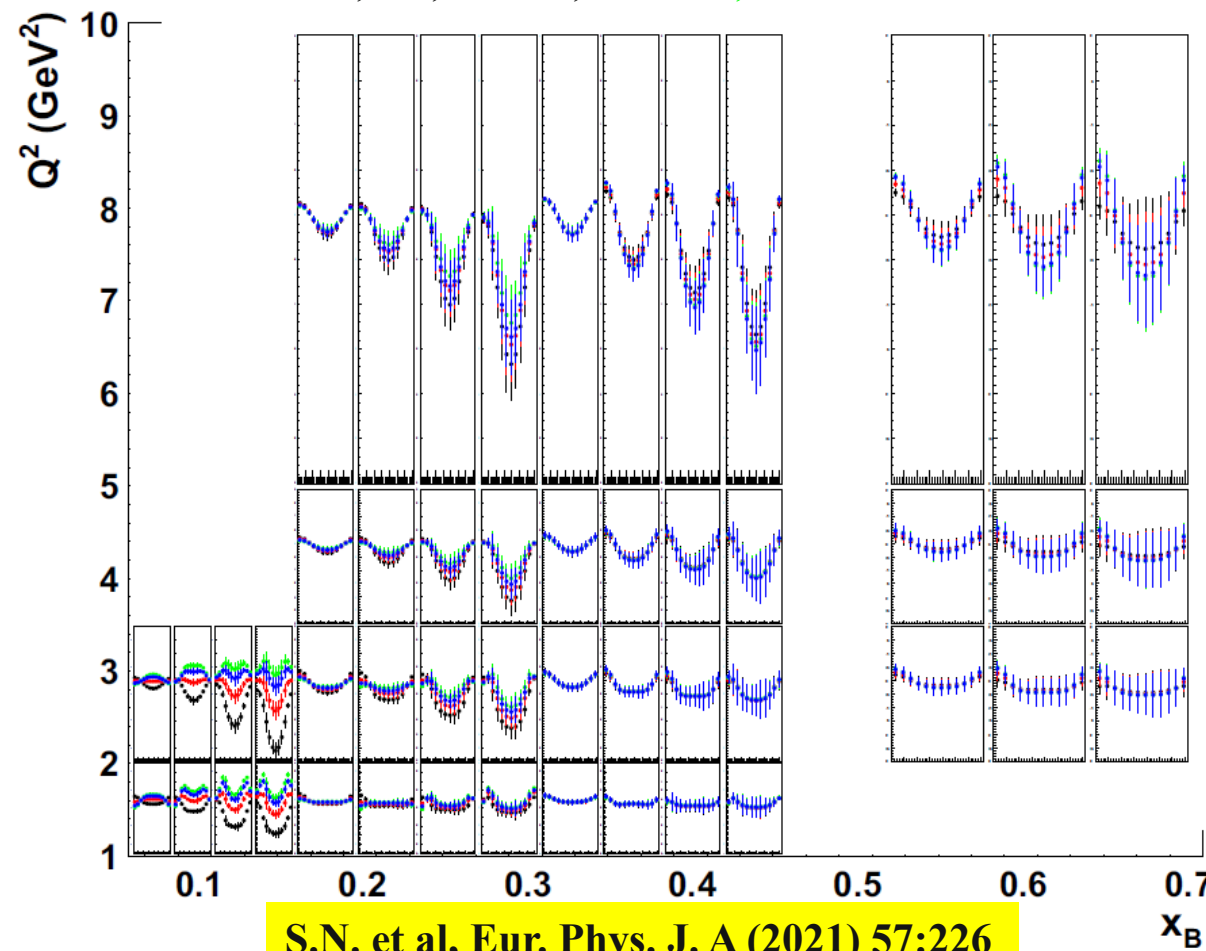
Impact of positron pDVCS projected data on the extraction of $\text{Re}E$ via global fits: major reduction of relative uncertainties, especially at low $-t$

nDVCS Beam-charge asymmetry (BCA):

This observable has a strong impact on the extraction of $\text{Re}E$. This was verified via local fits to the projections of approved CLAS12 nDVCS measurements **with** and **without** BCA

Projections (VGG) for the BCA, for various values of J_u , J_d

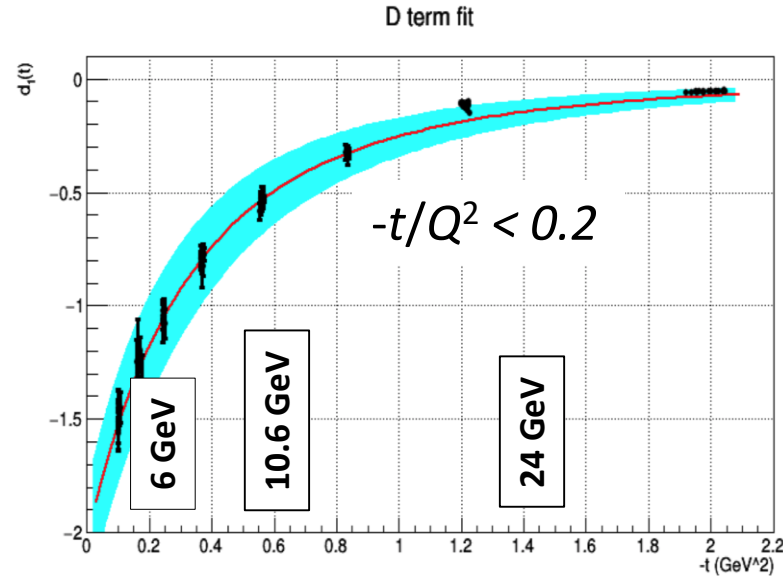
0.3, 0.1; **0.2/0.0**; **0.1/-0.1**; 0.3/-0.1



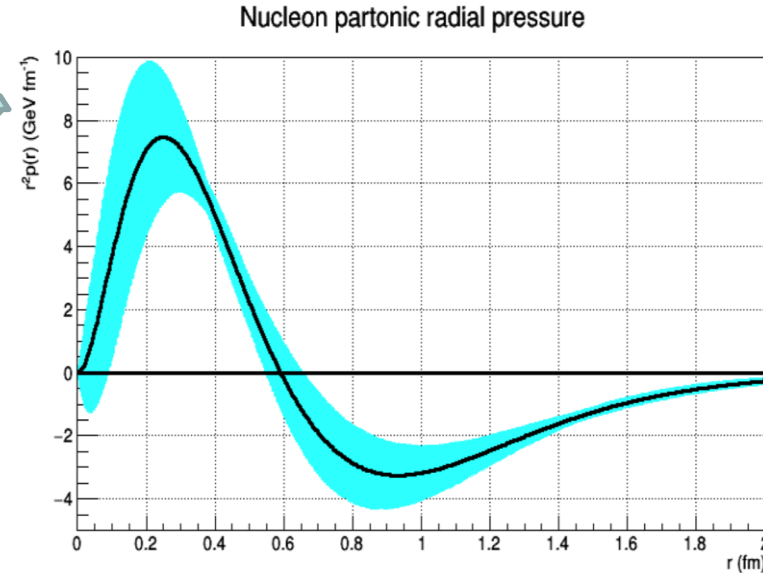
V. Burkert et al., Eur. Phys. J. A (2021) 57

S.N. et al, Eur. Phys. J. A (2021) 57:226

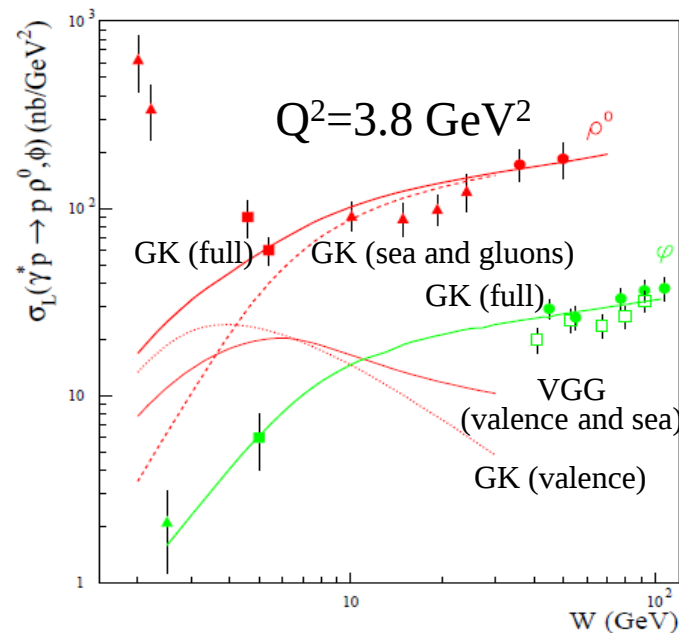
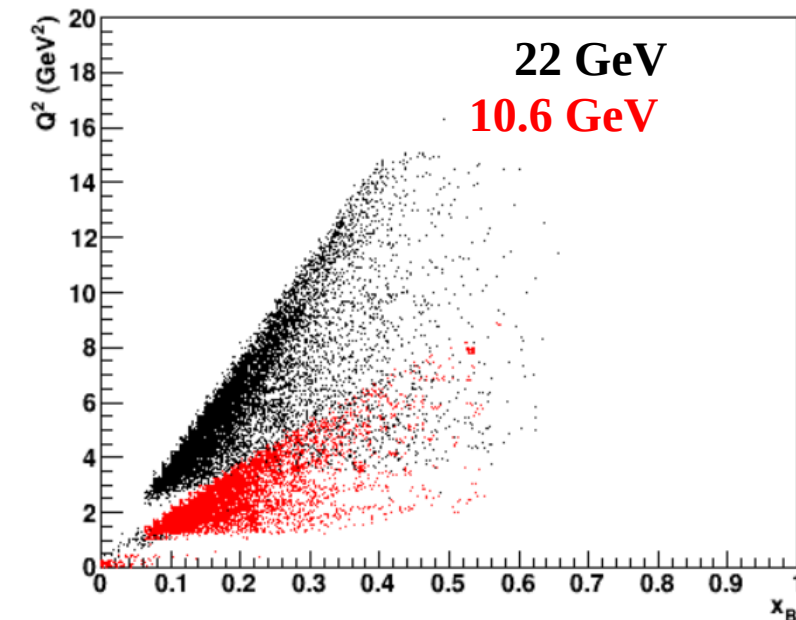
JLab 22 GeV upgrade



Fourier transform



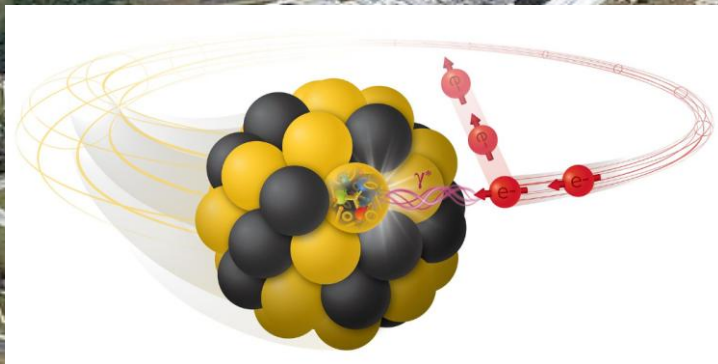
DVCS: 22 GeV required to cover sufficient range in t for the extraction of mechanical properties.



DVMP:

- Existing DVMP CLAS data for vector mesons are in a region in which the leading-twist handbag doesn't apply: GPD predictions work only at very small values of x_B , and Q^2 larger than about 50 GeV^2
- At 20+ GeV energy and luminosity upgrade, one could go to higher Q^2 (assuming sufficient luminosity) at moderate x , to be in the GPD regime for the valence quarks

The Electron-Ion Collider (EIC)

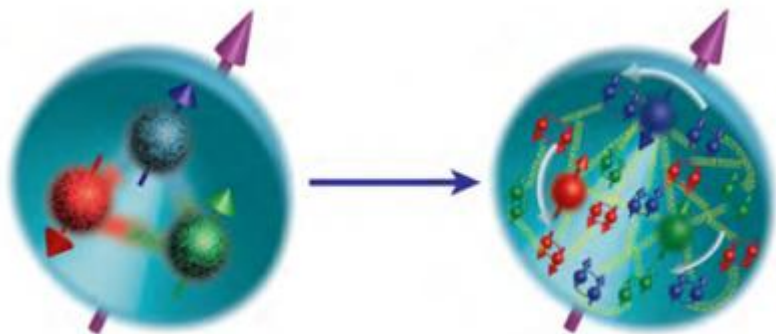
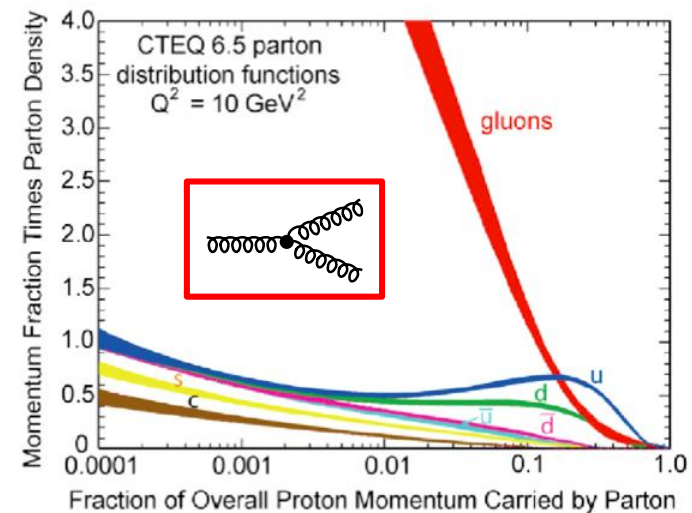


EIC: the answer to many open questions in QCD

Saturation: a new state of hadronic matter?

What happens to the **gluon density** in nuclei at high energies? It cannot grow infinitely...

Is there a **saturation** in some sort of gluonic matter with universal properties (« color glass condensate »)?



Exploring the partonic structure of nucleons and nuclei

How do the **spin** and the **mass** of the nucleon emerge from the dynamics of its constituents?

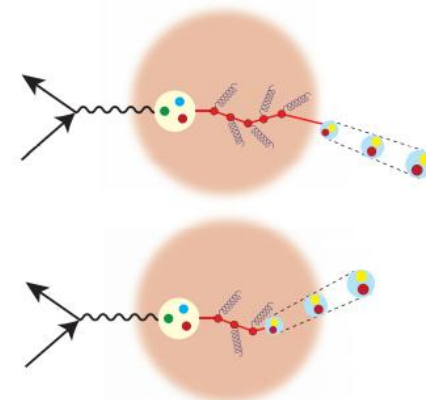
What are the position, momentum and spin distributions of **sea quarks and gluons** in the nucleon and in light nuclei?

What is the role of orbital momentum?

The role of gluons in nuclear medium

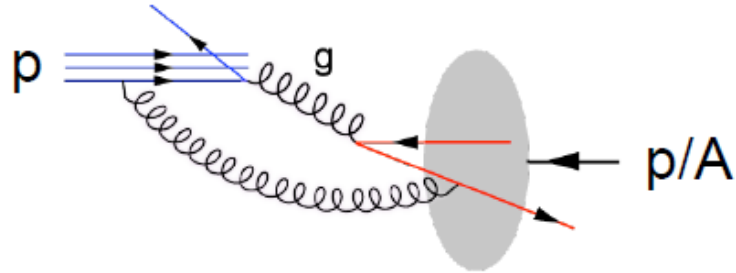
How do gluons and sea quarks contribute to nucleon-nucleon force? How does nuclear matter react when a colored charge passes through it?

How does nuclear matter affect quark and gluon distributions and their interactions in nuclei?



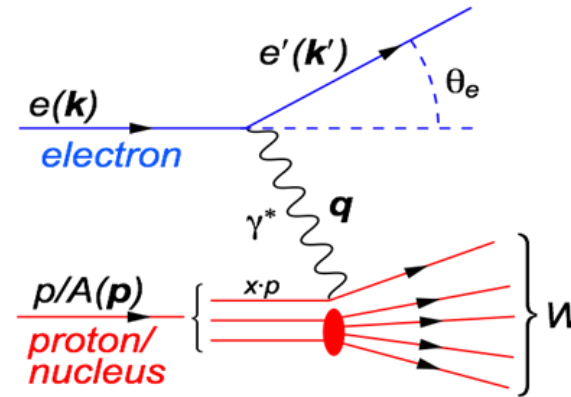
Why do we need an electron-ion collider?

Hadron-hadron



Probe and target have a complex structure
 Soft interactions before collisions
 can destroy factorization
 Kinematics imprecisely determined

Electron-hadron (DIS)



Point-like probe
 No initial-state soft interactions,
 factorization preserved
 Kinematics precisely determined

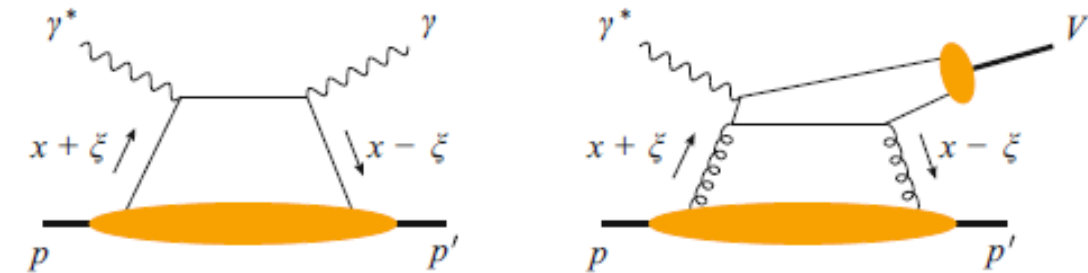
Kinematic variables:
 $Q^2 = -(\mathbf{k} - \mathbf{k}')^2$ (Resolution)
 $x = Q^2 / 2M\nu = Q^2 / (2pq)$
 (mom. fraction)
 $\nu = E_e - E_{e'}$
 $s = (\mathbf{p} + \mathbf{k})^2 = 4E_e E_p$

An EIC, with **high luminosity**, versatile beam **species** and beam **polarizations**, covering $0.1 < Q^2 < 1000 \text{ GeV}^2$, $10^{-4} < x < 10^{-1}$ is needed to:

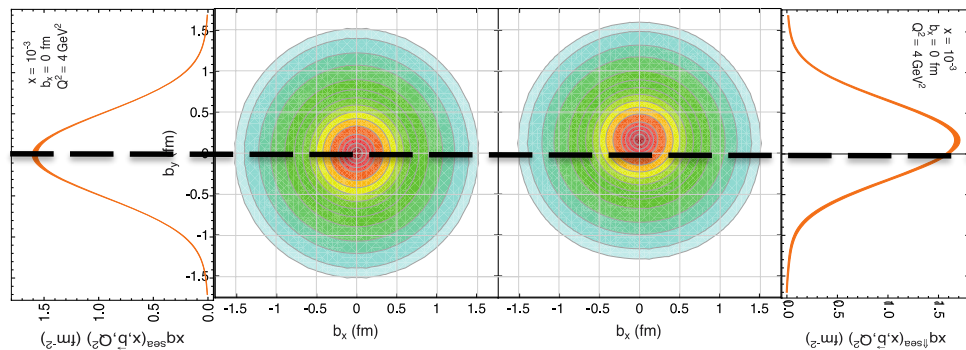
- explore both the region of **non-perturbative** effects and the **gluon dominated** region
- precisely image the **sea quarks and gluons** in nucleons and nuclei
- resolve outstanding issues in understanding nucleons and nuclei in terms of fundamental building blocks of QCD

Multi-D partonic image of the nucleon with the EIC

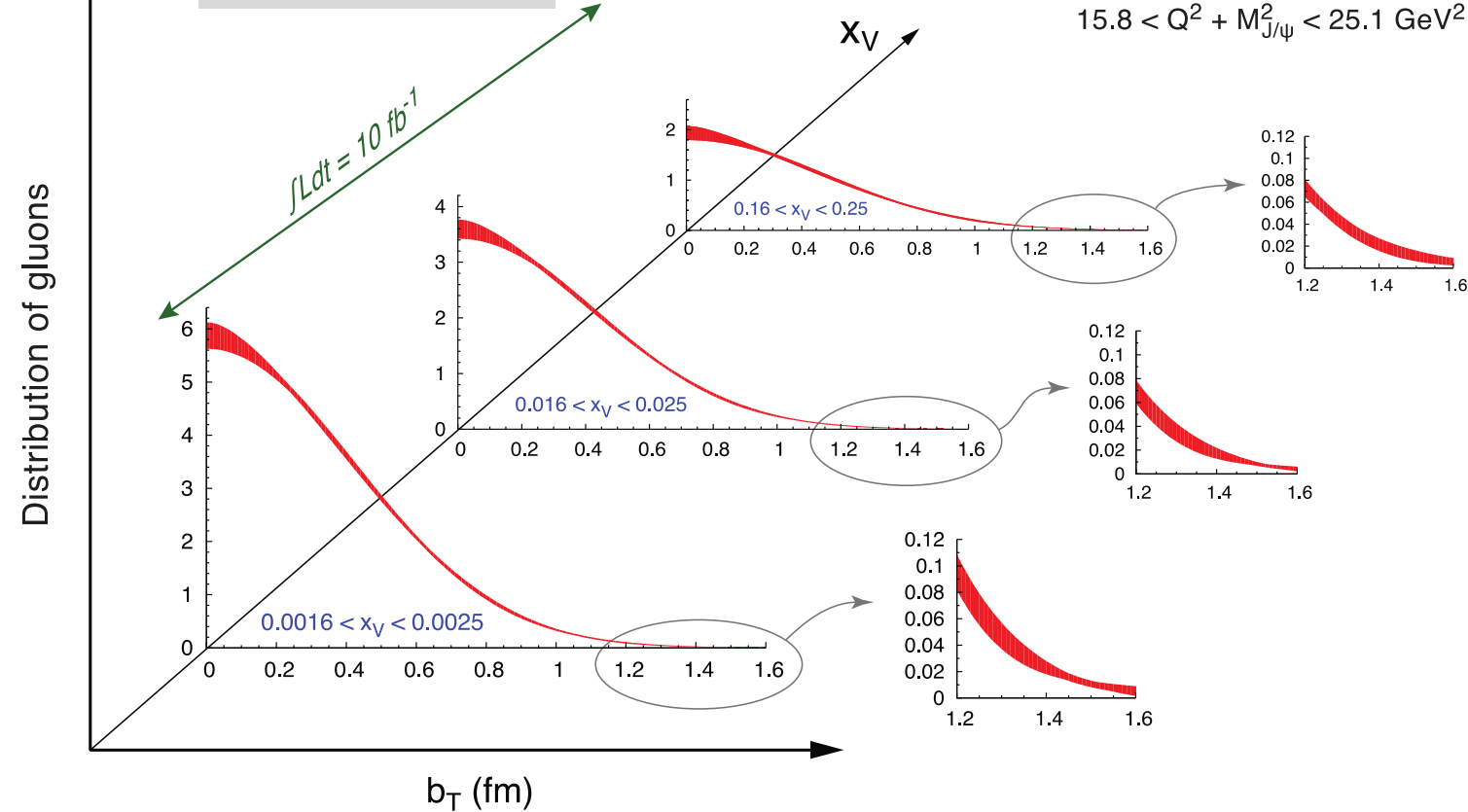
Generalized Parton Distributions



Sea quarks
unpolarized polarized

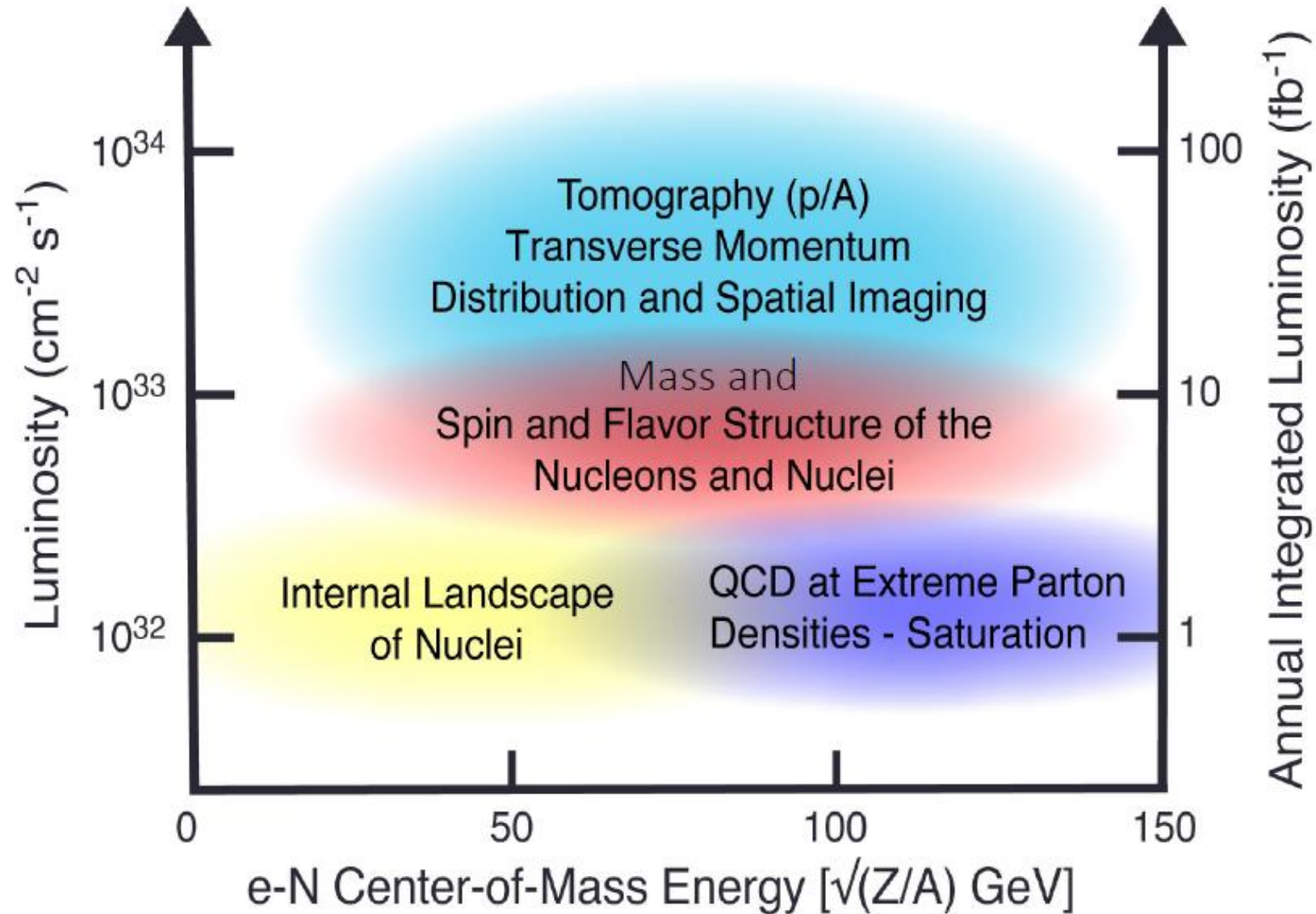


Gluon tomography

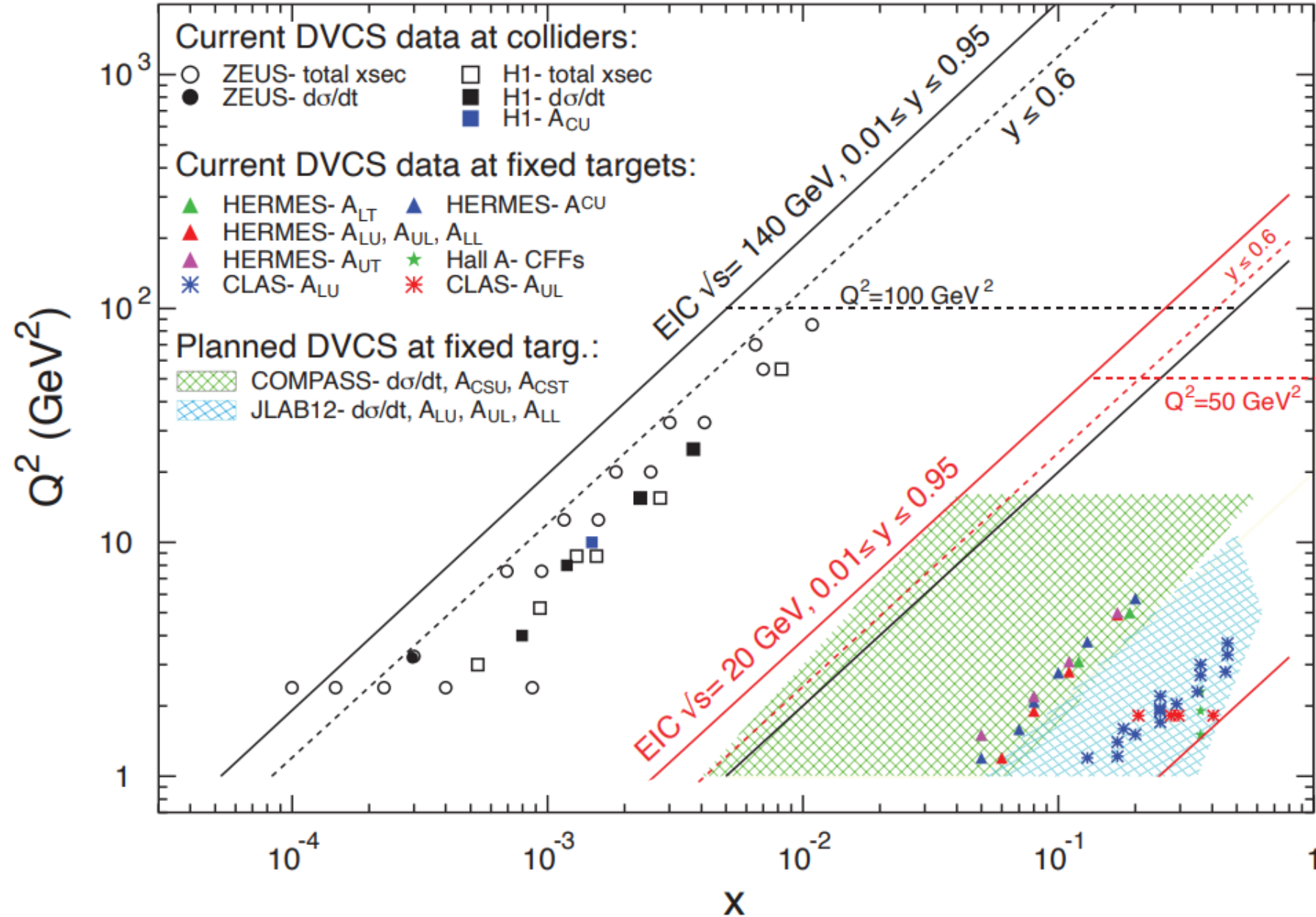


$e + p \rightarrow e + p + J/\psi$
 $15.8 < Q^2 + M_{J/\psi}^2 < 25.1 \text{ GeV}^2$

EIC: Luminosity and physics goals



EIC kinematic reach: DVCS

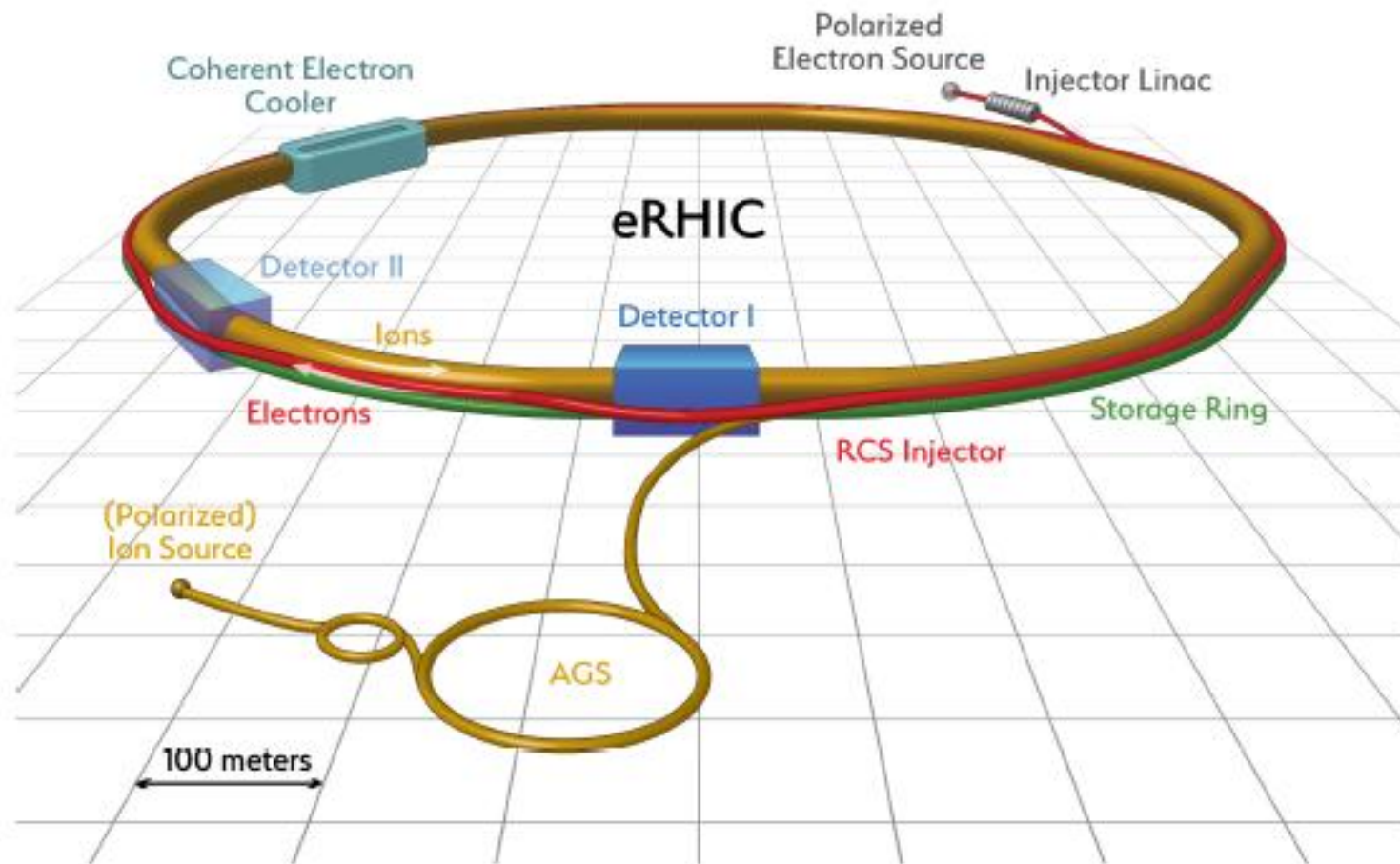


EIC facility @ BNL

The EIC will be built at BNL by adding an electron storage ring to the existing RHIC facility:

- Highly polarized electron / Highly polarized proton and light ions / Unpolarized heavy ions
- CME: $\sim 20 - 100$ GeV
- Luminosity: $\sim 10^{33-34} \text{cm}^{-2}\text{s}^{-1}$

- ❑ Polarized electron source and 400 MeV injector linac
- ❑ 2 detector interaction points capability in the design



Project status:

- Awarded CD-0, CD-1 and site selection
- Lots of recent and future activities towards CD-2/3
- EIC facility completion in roughly a decade from now

General requirements of the EIC detector

Vertex detector → Identify primary and secondary vertices,
Low material budget: 0.05% X/X_0 per layer;
High spatial resolution: 10 mm pitch CMOS Monolithic Active Pixel Sensor

Central tracker → Measure charged track momenta
MAPS – tracking layers in combination with micro pattern gas detectors
MPGD: μ RWell or MicroMegas

Electron and hadron endcap tracker → Measure charged track momenta
MAPS – disks in combination with micro pattern gas detectors

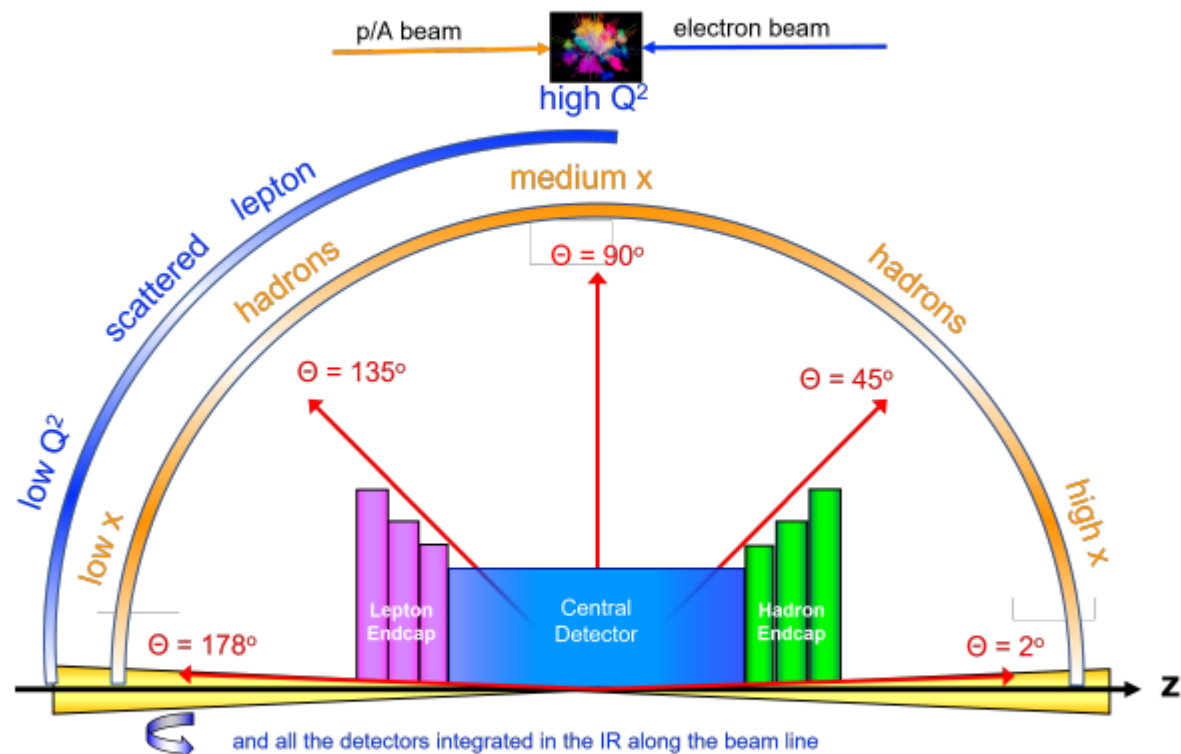
Particle Identification → pion, kaon, proton separation on track level
 RICH detectors (modular and dual radiator RICH, DIRC) & Time-of-Flight
 high resolution timing detectors (LAPPDs, LGAD) 10 – 30 ps
 novel photon sensors: MCP-PMT / LAPPD

Electromagnetic calorimeter → Measure photons (E, angle), identify electrons
PbWO₄ Crystals (backward), W/SciFi Spacal (forward)
Barrel: Pb/SciFi+imaging part or new Scintillating glass

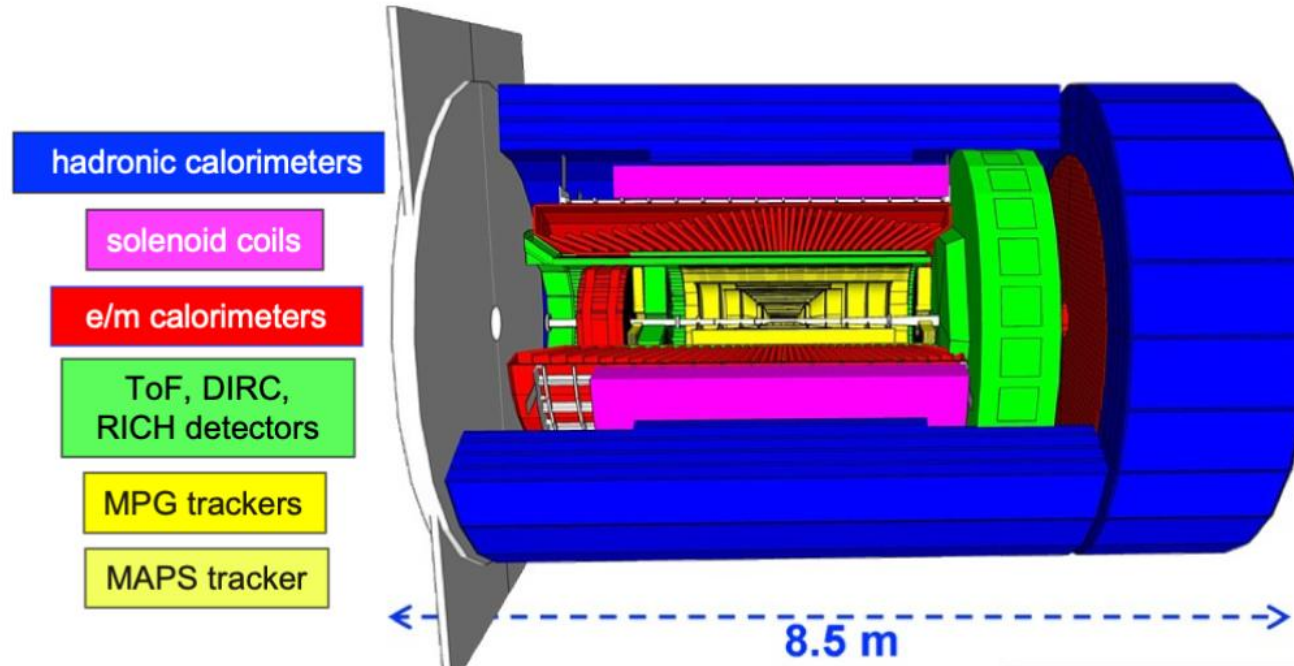
Hadron calorimeter → Measure charged hadrons, neutrons and K_L^0
challenge achieve $\sim 50\%/ \sqrt{E} + 10\%$ for low E hadrons ($\langle E \rangle \sim 20$ GeV)
Fe/Sc sandwich with longitudinal segmentation

DAQ & Readout Electronics: trigger-less / streaming DAQ
Integrate AI into DAQ → cognizant Detector

- Very forward and backward detectors → scattered particles under very small angles
- Silicon tracking layers in lepton and hadron beam vacuum
- Zero – degree high resolution electromagnetic and hadronic calorimeter



The ePIC detector (« Detector 1 »)



Tracking:

- New 1.7T solenoid
- Si MAPS Tracker
- MPGDs (μ RWELL/ μ Megas)

PID:

- hpDIRC
- mRICH/pfRICH
- dRICH
- AC-LGAD (~ 30 ps TOF)

Calorimetry:

- Barrel EMCal
- PbWO₄ EMCal in backward direction
- Finely segmented EMCal +HCal in forward direction
- Outer HCal (sPHENIX re-use)
- Backwards HCal (tail-catcher)

Conclusions/summary

- ✓ GPDs are a unique tool to explore **the structure of the nucleon**:
 - **3D** quark/gluon **imaging** of the nucleon
 - **orbital angular** momentum carried by quarks
 - **pressure** distribution
- ✓ Fitting methods allow to **extract CFFs (→ GPDs) from DVCS** observables → several **p-DVCS** and **n-DVCS observables** are needed, covering a **wide phase space**
- ✓ A lot of **recent results** on DVCS observables were obtained from **CLAS** and **Hall-A** at 6 GeV
 - First **tomographic interpretations** of the quarks in the **proton** from DVCS
- ✓ JLab@12 GeV is **the optimal facility** to perform GPD experiments **in the valence region**
 - DVCS and DVMP experiments on both **proton** and **neutron** (pol. and unpol.) are ongoing in **3 of the 4 Halls at JLab@12 GeV: quarks' spatial densities, flavor separation, quarks' orbital angular momentum, ...**
 - JLab upgrade perspectives (positron beam, higher luminosity and energy) pave the road to the completion of the GPD program in the valence regime
 - **Longer-term future: EIC, to study the gluonic structure of the nucleon and gluon GPDs**