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

CEBAF Large Acceptance Spectrometer

Silvia Niccolai, IJClab Orsay & CLAS Collaboration
HUGS, JLab, June 2023

IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

Recap: what have we learned so far on GPDs

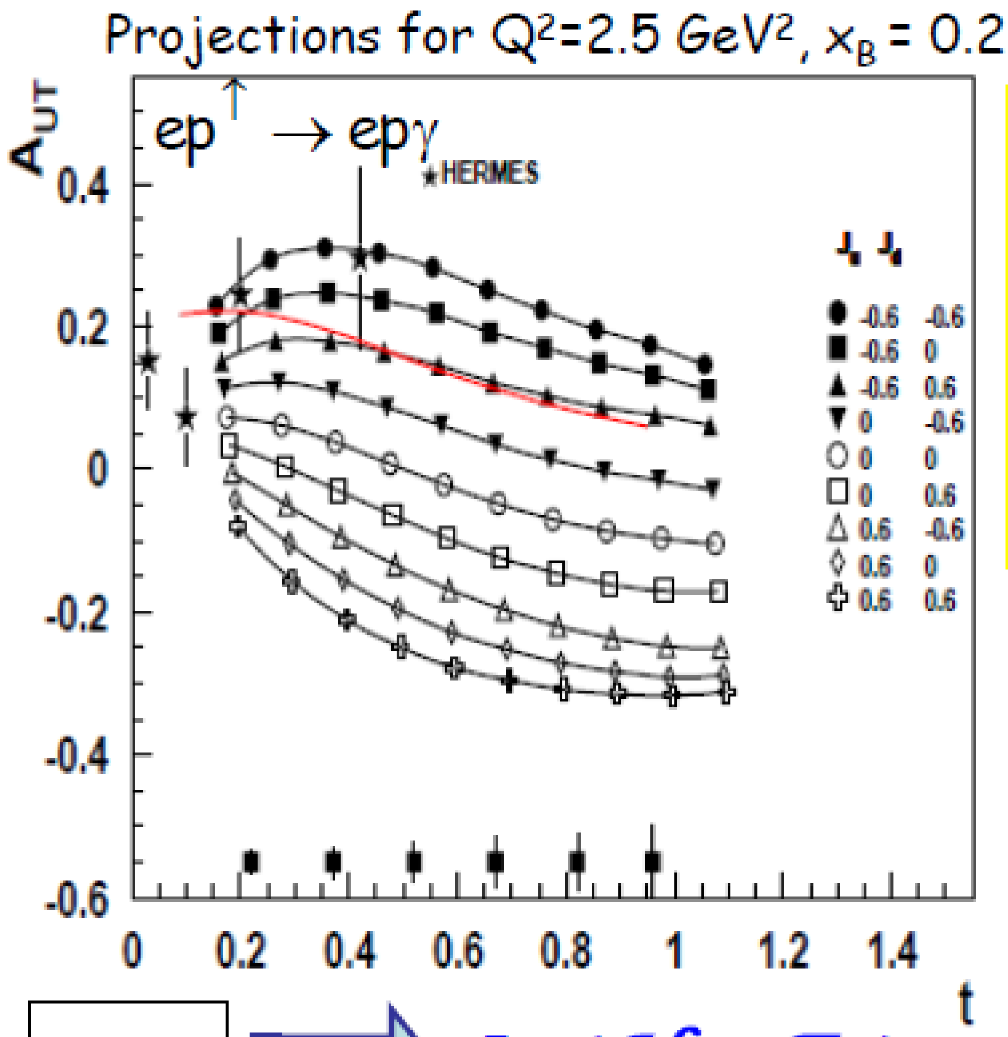
- *Im*$\mathcal{H}$ well constrained, in CLAS (and now CLAS12) kinematics → proton tomography
- *Re*$\mathcal{H}$ constrained mainly by Hall A measurements in selected kinematics; important for D-term and distribution of forces
- Initial constraints on $\tilde{\mathcal{H}}$ from longitudinally polarized 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) → 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

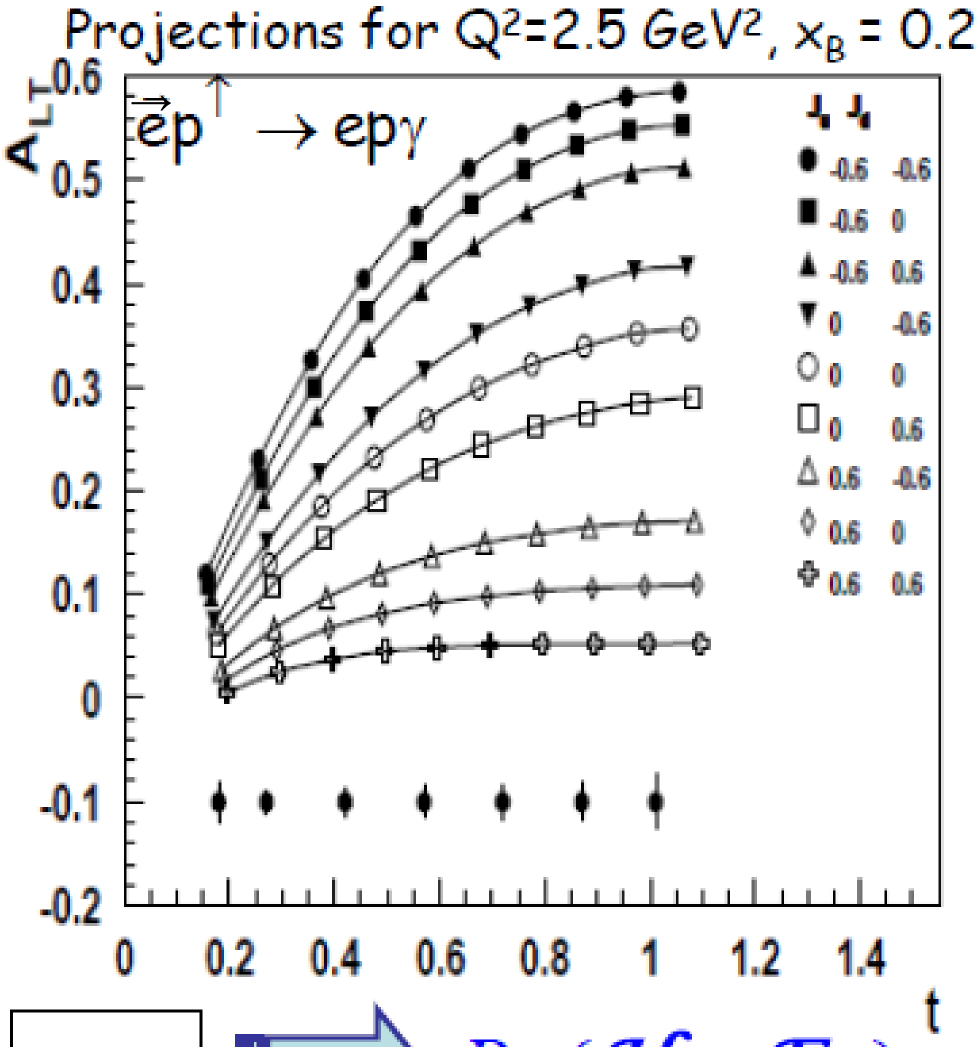
100 days of beam time; Beam pol. = 80% ; **target pol. = 60%** ; Luminosity = 5×10^{33} $cm^{-2}s^{-1}$



The transverse-target spin asymmetry for pDVCS is **highly sensitive** to E → the **u-quark contributions** to the proton spin.
So far, only low-statistics data from HERMES exist

JLab PAC: **high-impact experiment**

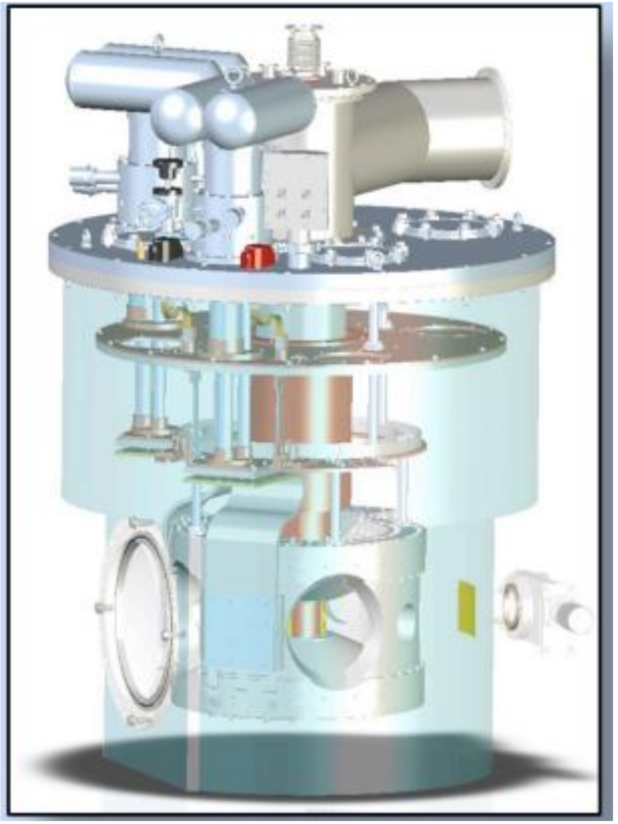
Conditionally approved by PAC39



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

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

Transverse target for CLAS12: an experimental challenge

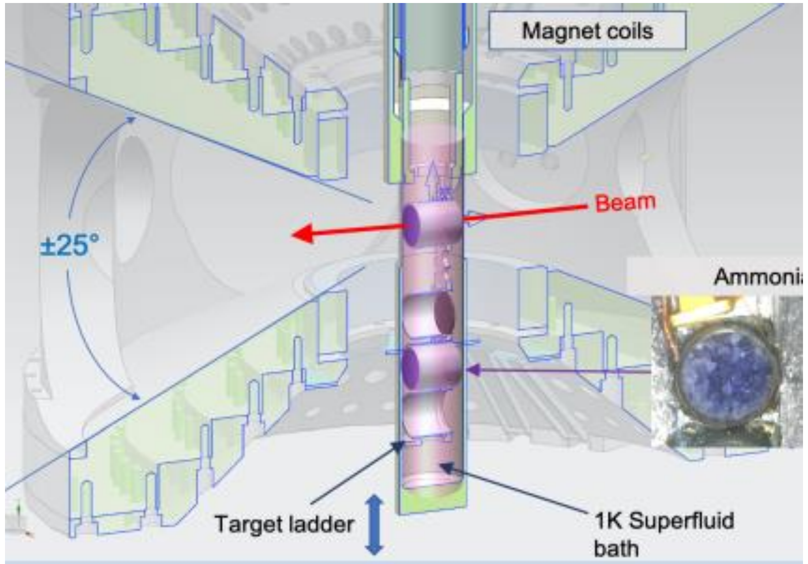


HD-ICE (project was discontinued):

- 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:

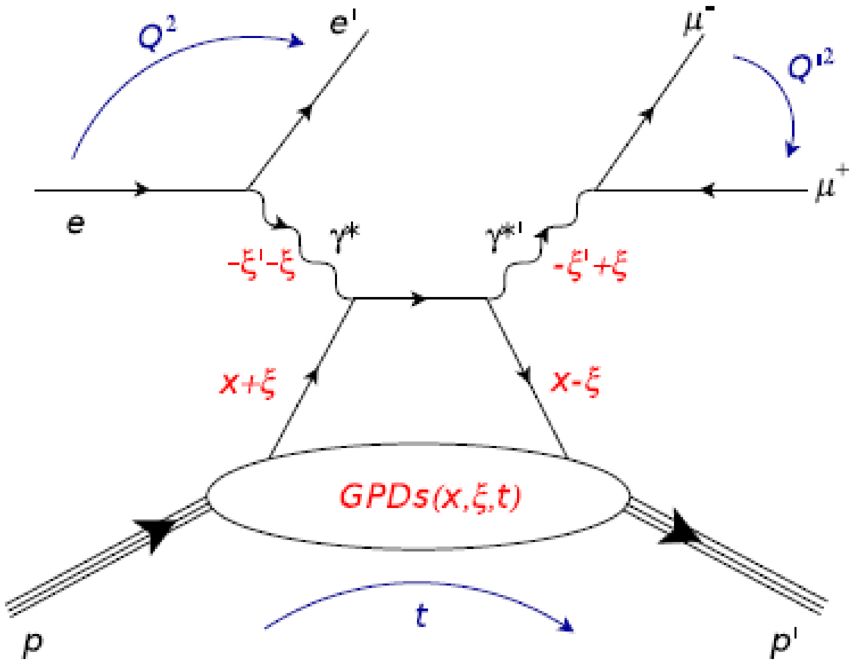
- pros: consolidated technology and infrastructure at JLab
- cons: increased systematic effect (nuclear effects, non uniform target density)
- cons: impact on the experimental setup (massive magnet of strong field and reduced acceptance): incompatible with the CLAS12 central detector; limited acceptance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

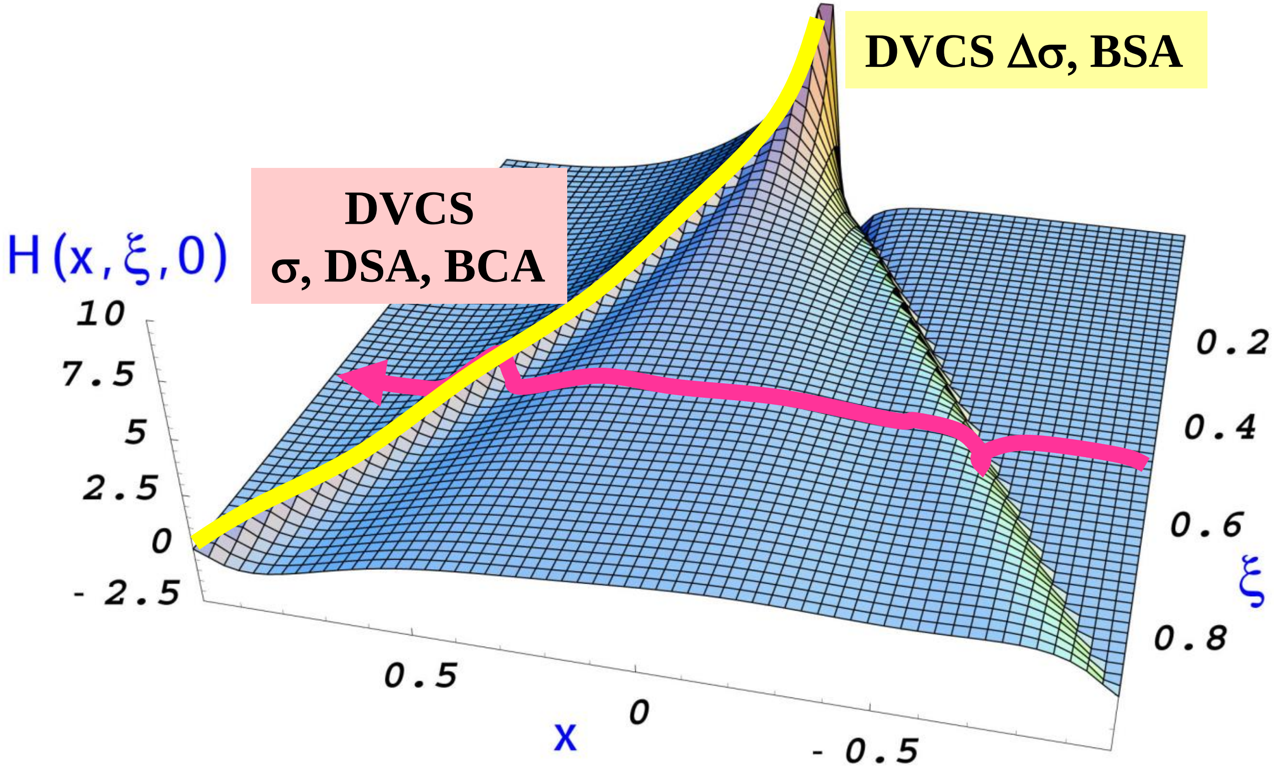


- ➢ Feasibility studies for pDVCS with limited acceptance are ongoing
- ➢ R&D studies on possible alternative target solutions are also ongoing

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

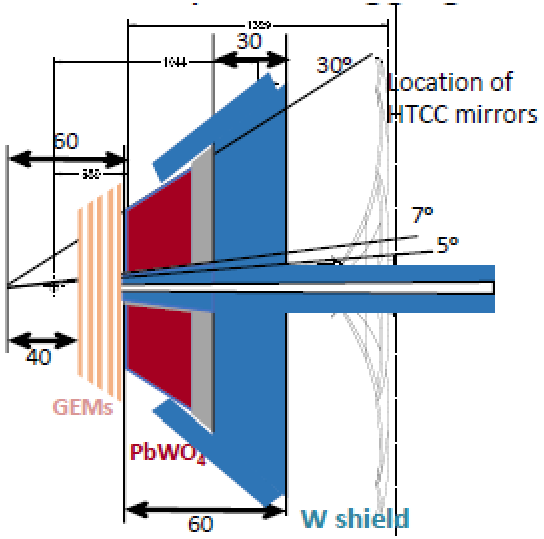
μCLAS12 for DDVCS and J/psi

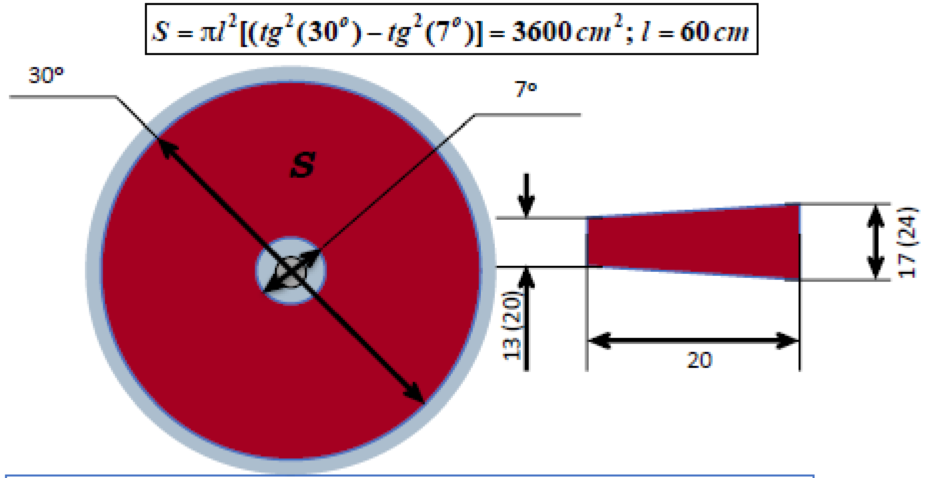
$ep \to e'p'\mu^+\mu^-$ at $L \sim 10^{37}\ cm^{-2}s^{-1}$

• 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.

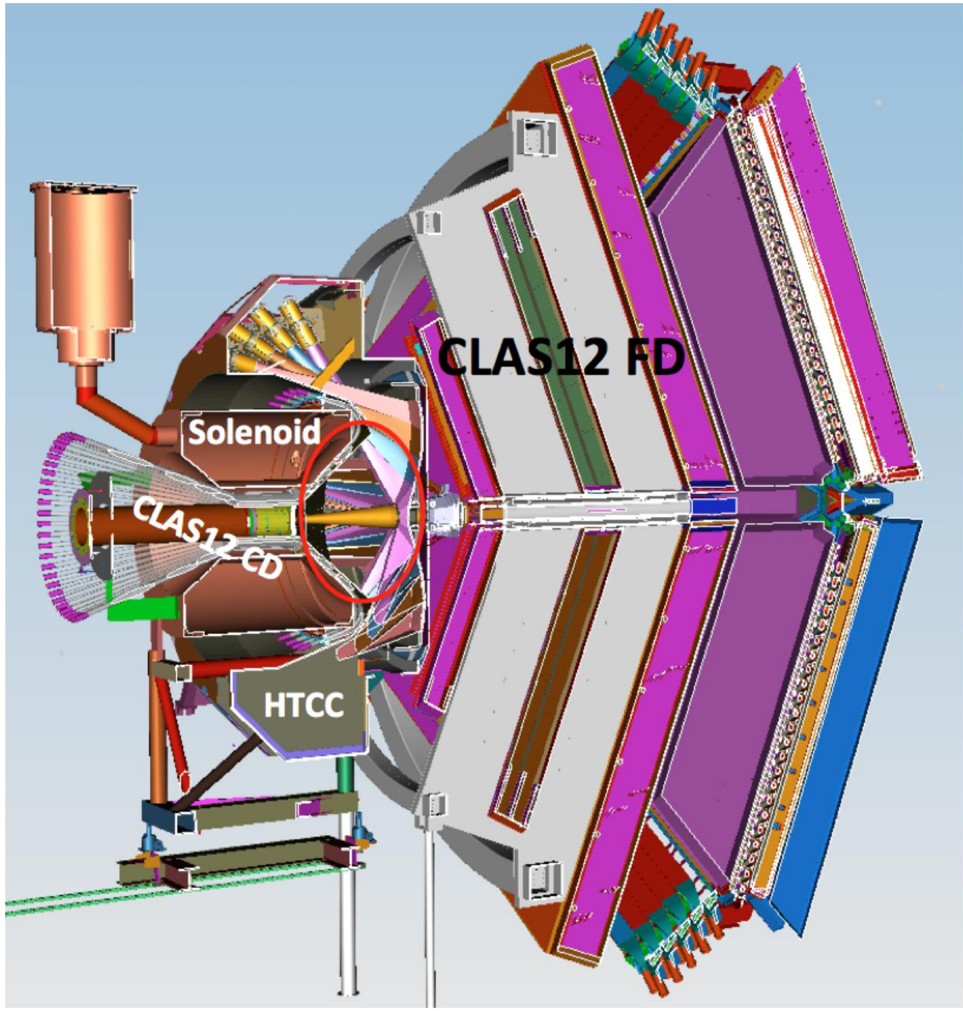
• Behind the calorimeter, a 30-cm-thick tungsten shield covers the whole acceptance of the CLAS12 FD

• MPGD tracker in front of the calorimeter for vertexing and inside the solenoid for recoil proton tagging





$PbWO_4$ modules with APD readout - ~ 1200 modules

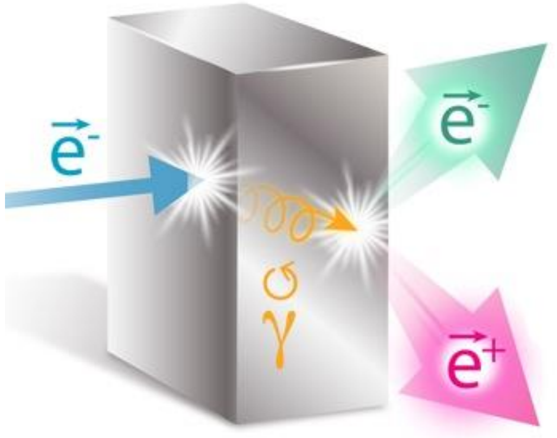


S. Stepanyan, LOI12-16-004

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

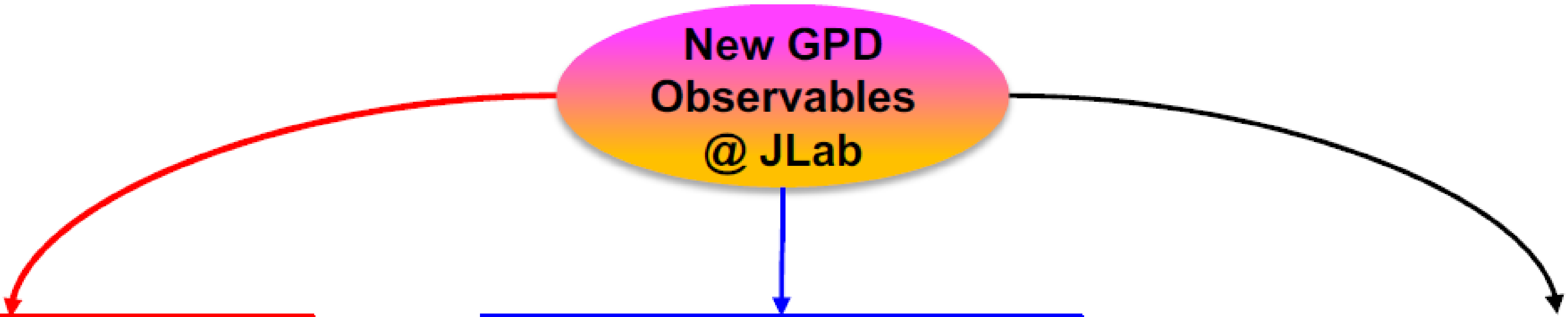
Eur. Phys. J. A 58 (2022) 3, 45

- 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 important 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 $\mathbf{A_C^{UU}}$, which is sensitive to the real part of the CFF → D-term, forces in the proton
- The polarized beam charge asymmetry $\mathbf{A_C^{LU}}$, 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

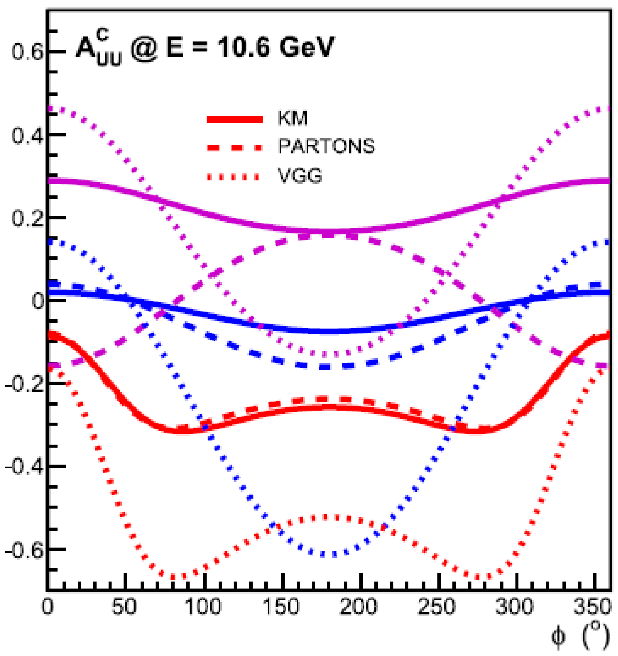


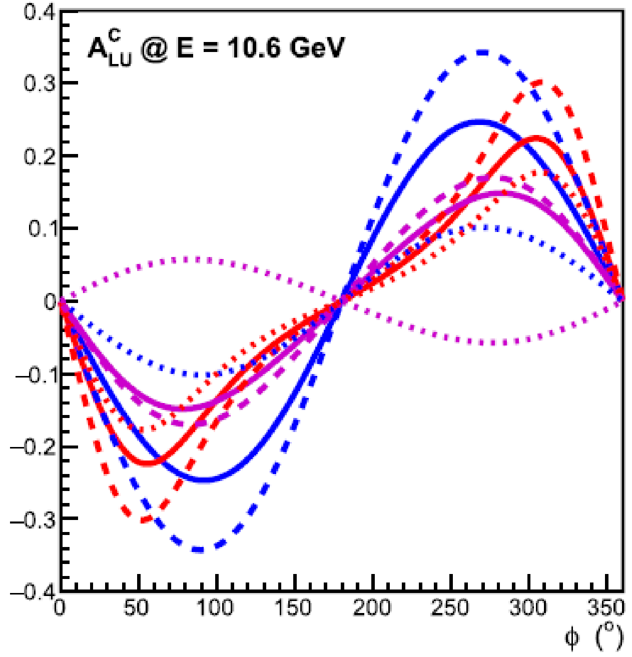
$$A^C_{UU} = \frac{(Y_+^+ + Y_-^+) - (Y_+^- + Y_-^-)}{Y_+^+ + Y_-^+ + Y_+^- + Y_-^-} = \frac{\sigma_{INT}}{\sigma_{BH} + \sigma_{DVCS}}$$

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

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

pDVCS and nDVCS with polarized positrons beam at CLAS





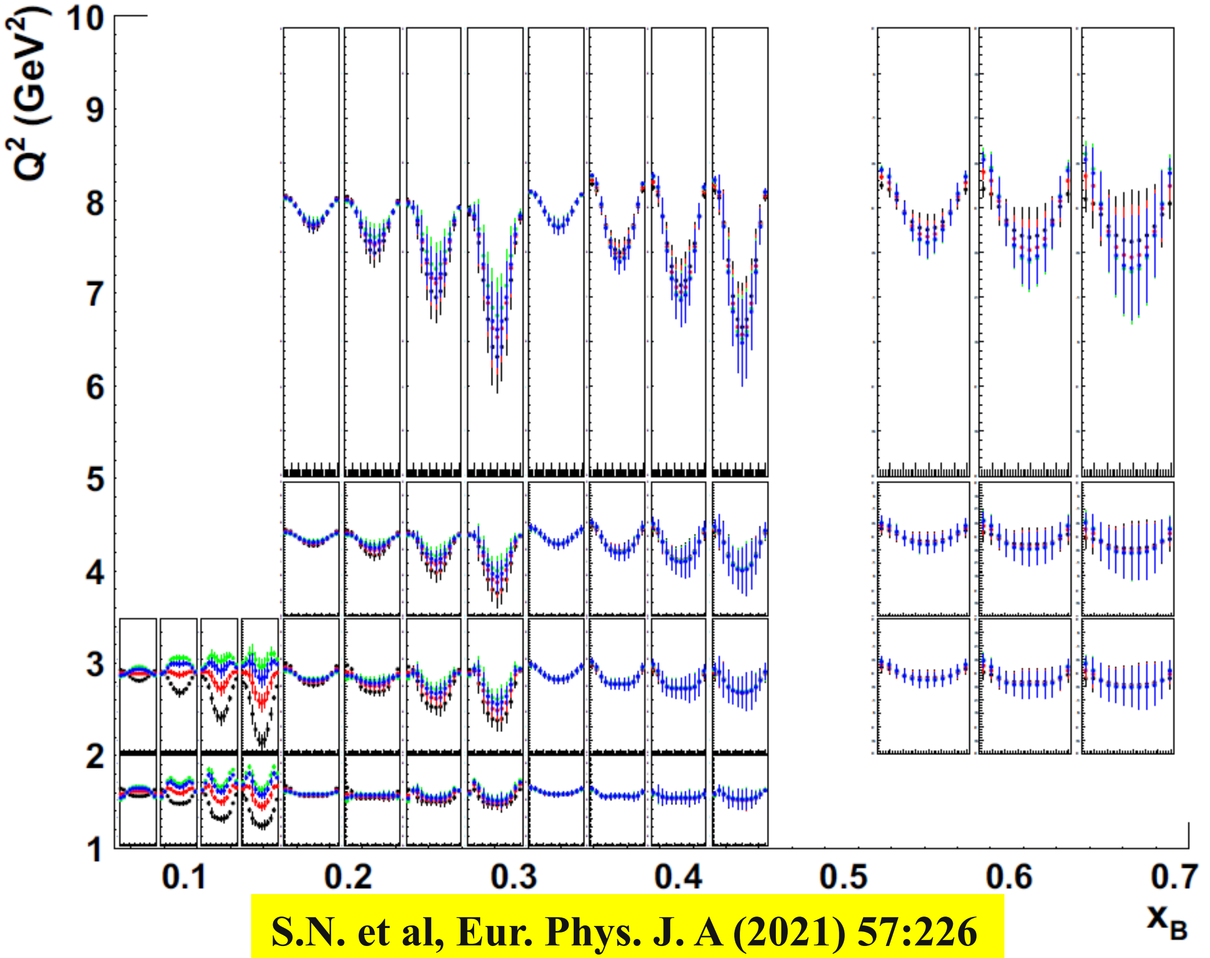
Model predictions for 2 out of the 3 proposed pDVCS observables

Impact of positron pDVCS projected data on the extraction of ReH via global fits: major reduction of relative uncertainties, especially at low -t

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

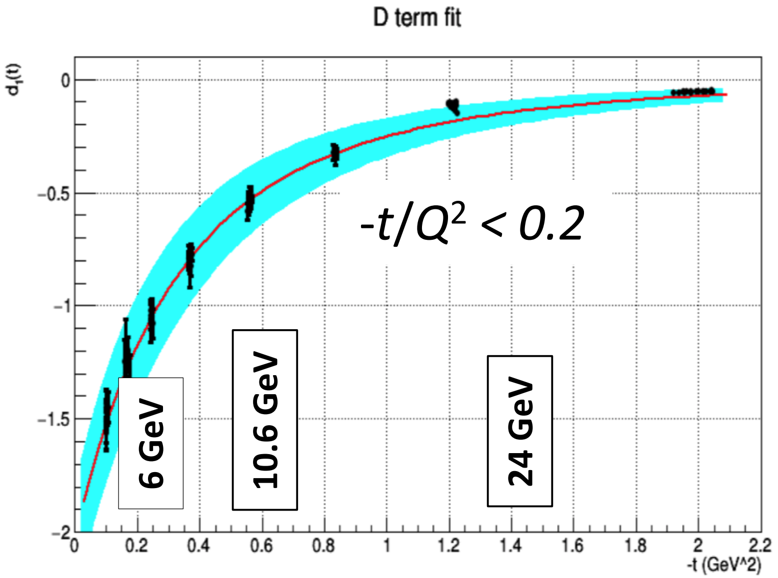
nDVCS Beam-charge asymmetry (BCA):
This observables has a strong impact on the extraction of Re$\mathcal{E}$. This was verified via local fits to the projections of approved CLAS12 nDVCS measurements with and without BCA

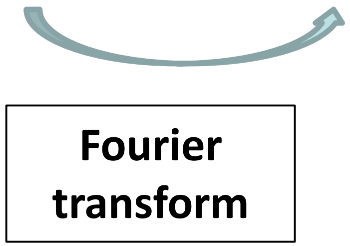
Projections (VGG) for the BCA, for various values of J_u, J_d
0.3, 0.1; 0.2/0.0; 0.1/−0.1; 0.3/−0.1

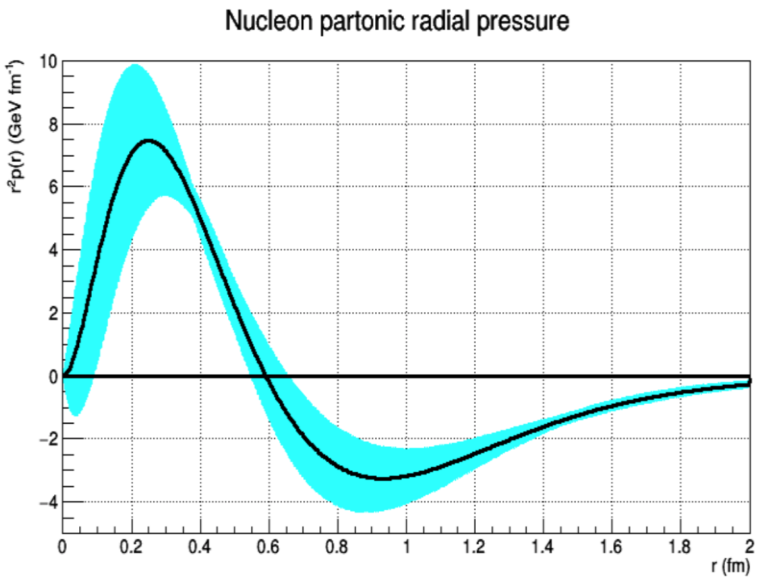


S.N. et al, Eur. Phys. J. A (2021) 57:226

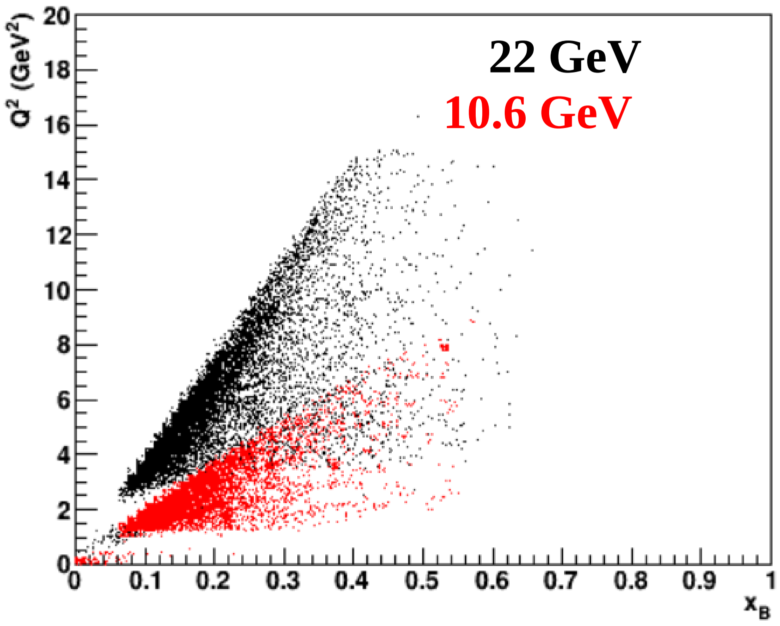
JLab 22 GeV upgrade

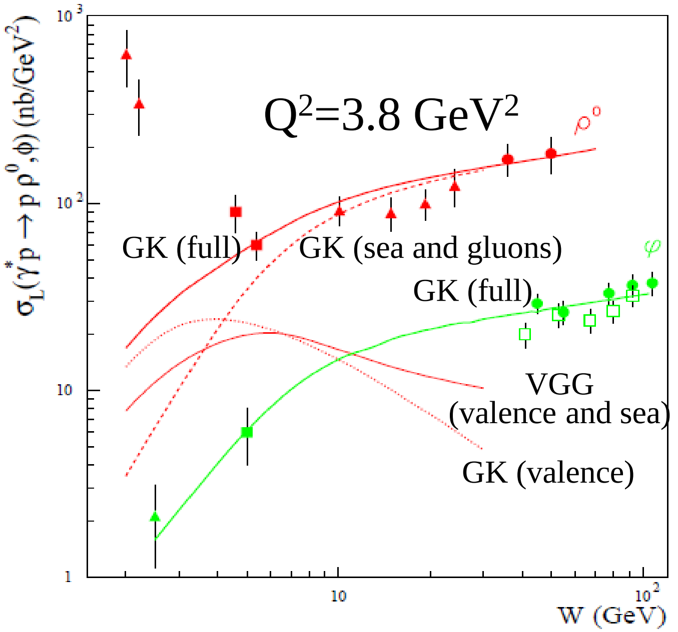






DVCS: 22 GeV required to cover sufficient range in t for the extraction of mechanical properties.

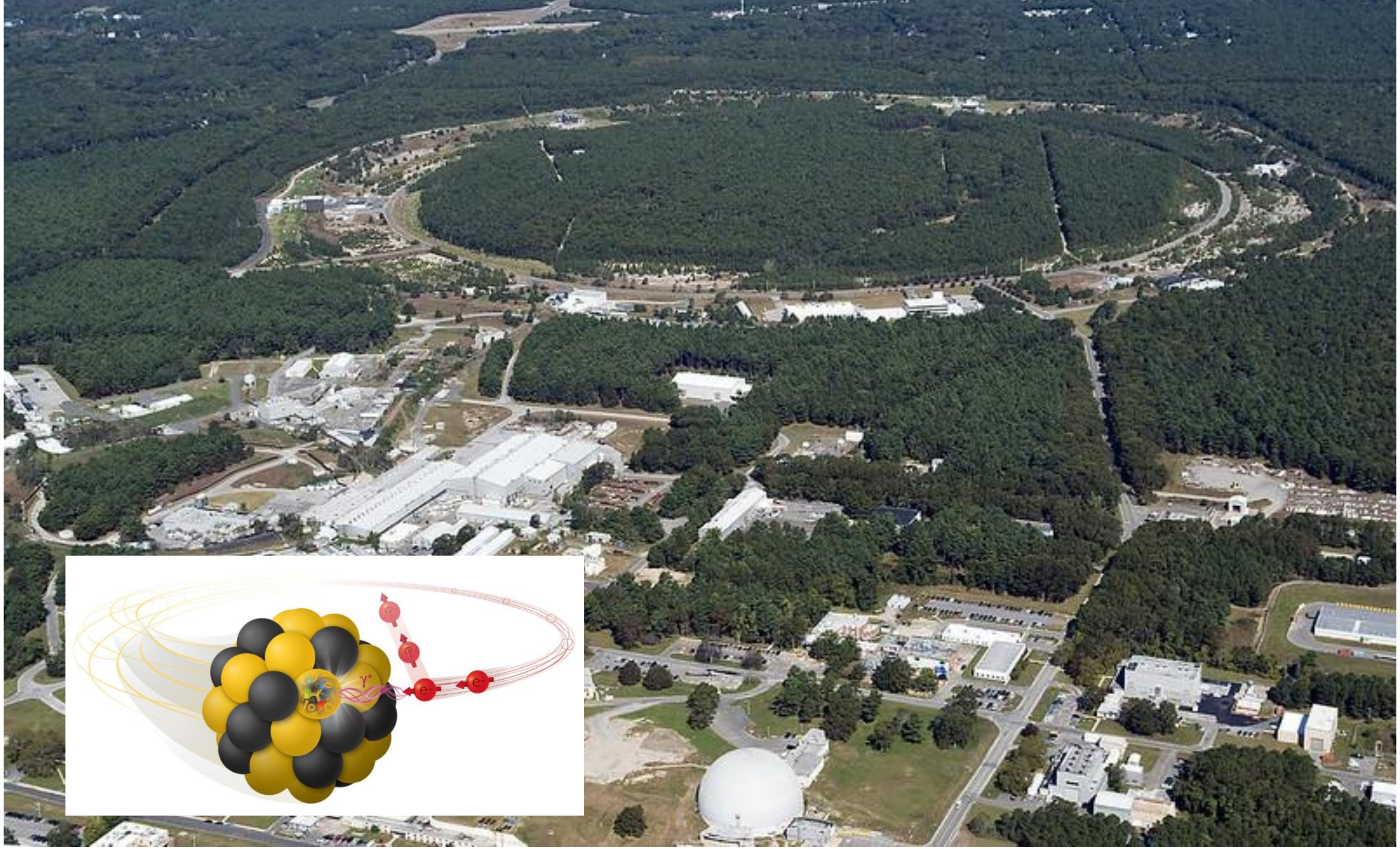




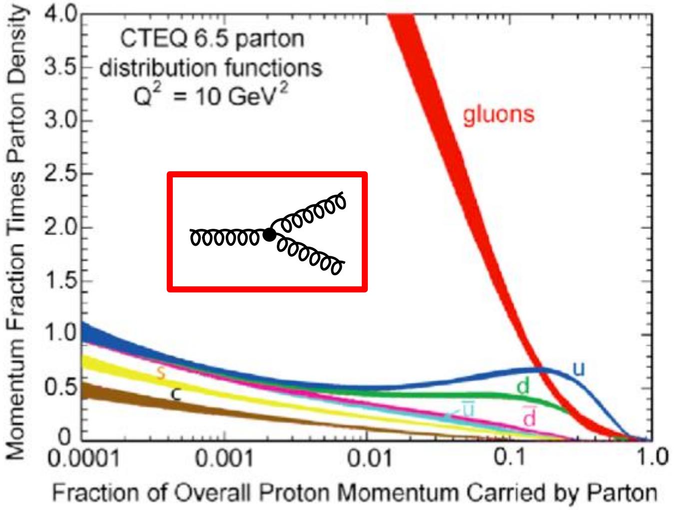
DVMP:

- 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 Q2 (assuming sufficient luminosity) at moderate x, to be in the GPD regime for the valence quarks

The Electron-Ion Collider (EIC)

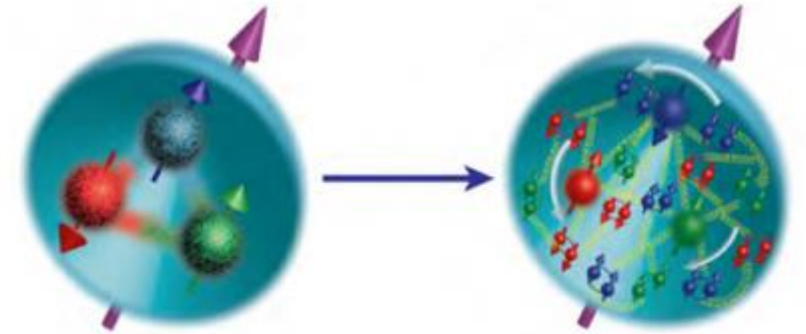


EIC: the answer to many open questions in QCD



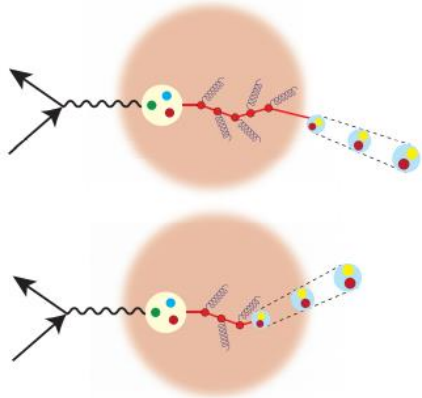
Saturation: a new state of hadronic matter?

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

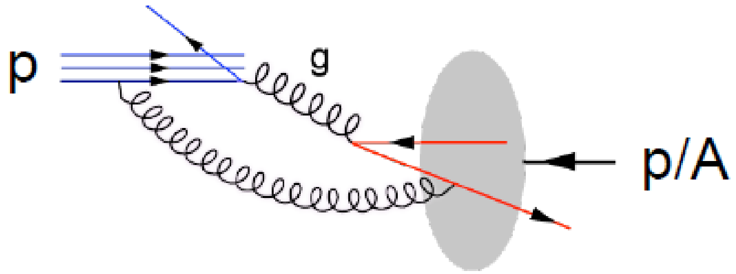


The role of gluons in nuclear medium

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?

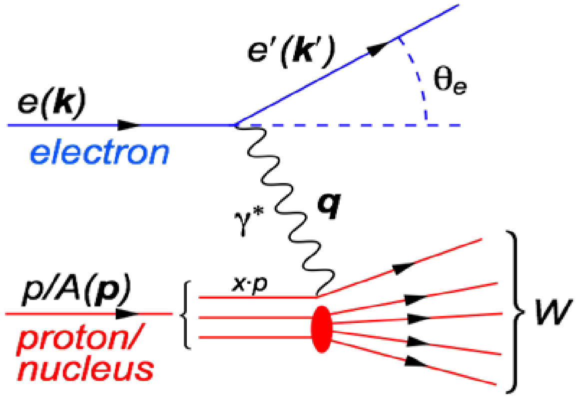
Why do we need an electron-ion collider?

Hadron-hadron



Probe and target have a complex strucure
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

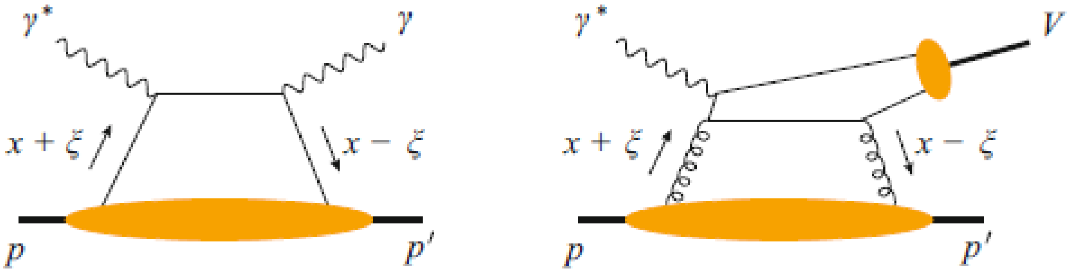
Kinematic variables:
$Q^2 = -(k-k')^2$ (Resolution)
$x = Q^2/2M\nu = Q^2/(2pq)$
(mom. fraction)
$\nu = E_e - E_{e'}$
$s = (p+k)^2 = 4E_eE_p$

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

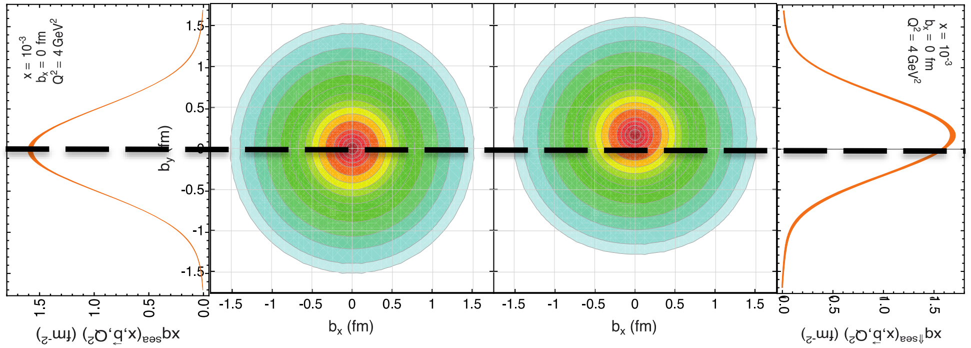
- explore both the region of **non-perturbative** effects and the **gluon dominated** region
- precisely image the **sea quarks and gluons** in nucleons and nuclei
- resolve outstanding issues in understanding nucleons and nuclei in terms of fundamental building blocks of QCD

Multi-D partonic image of the nucleon with the EIC

Generalized Parton Distributions



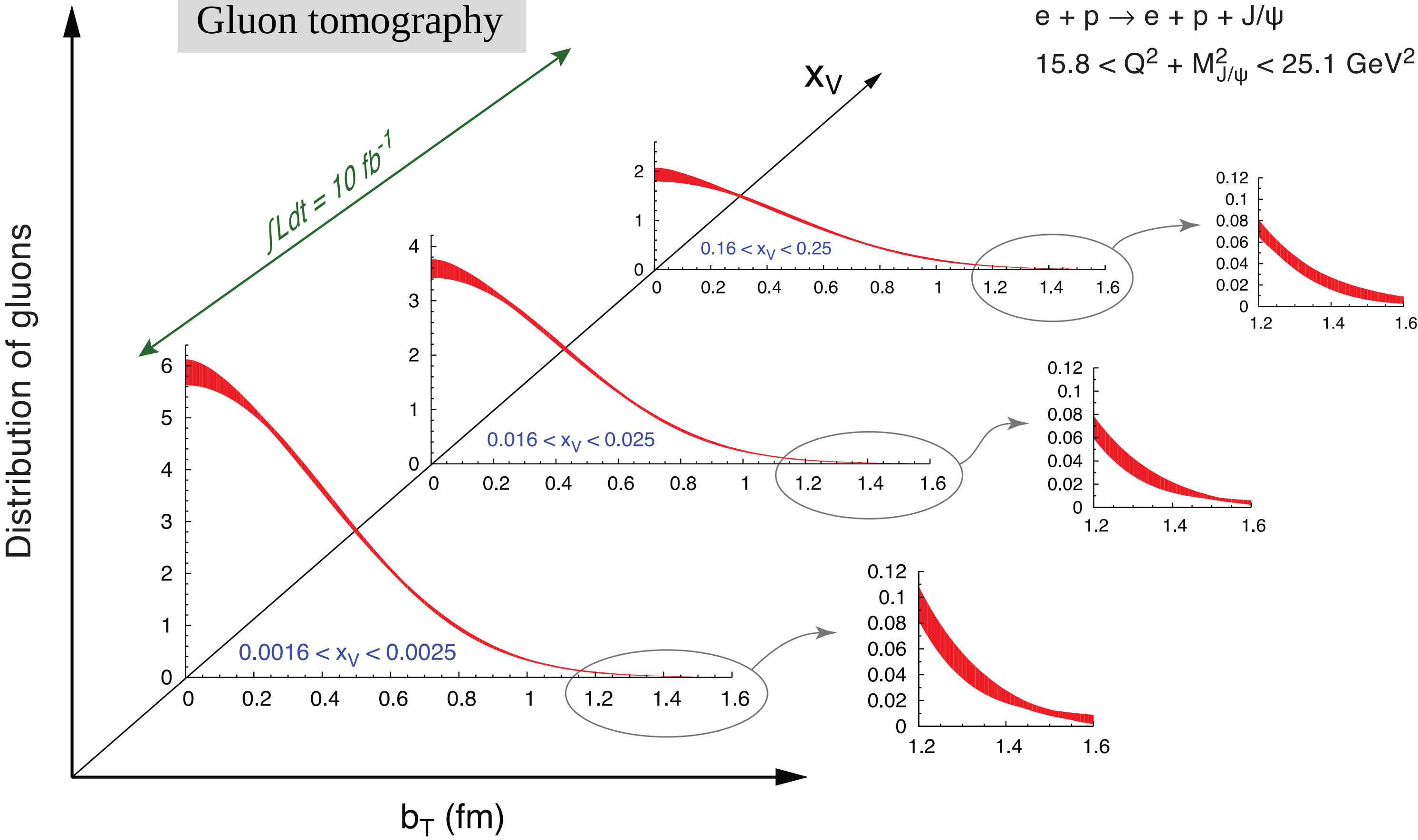
Sea quarks
unpolarized polarized



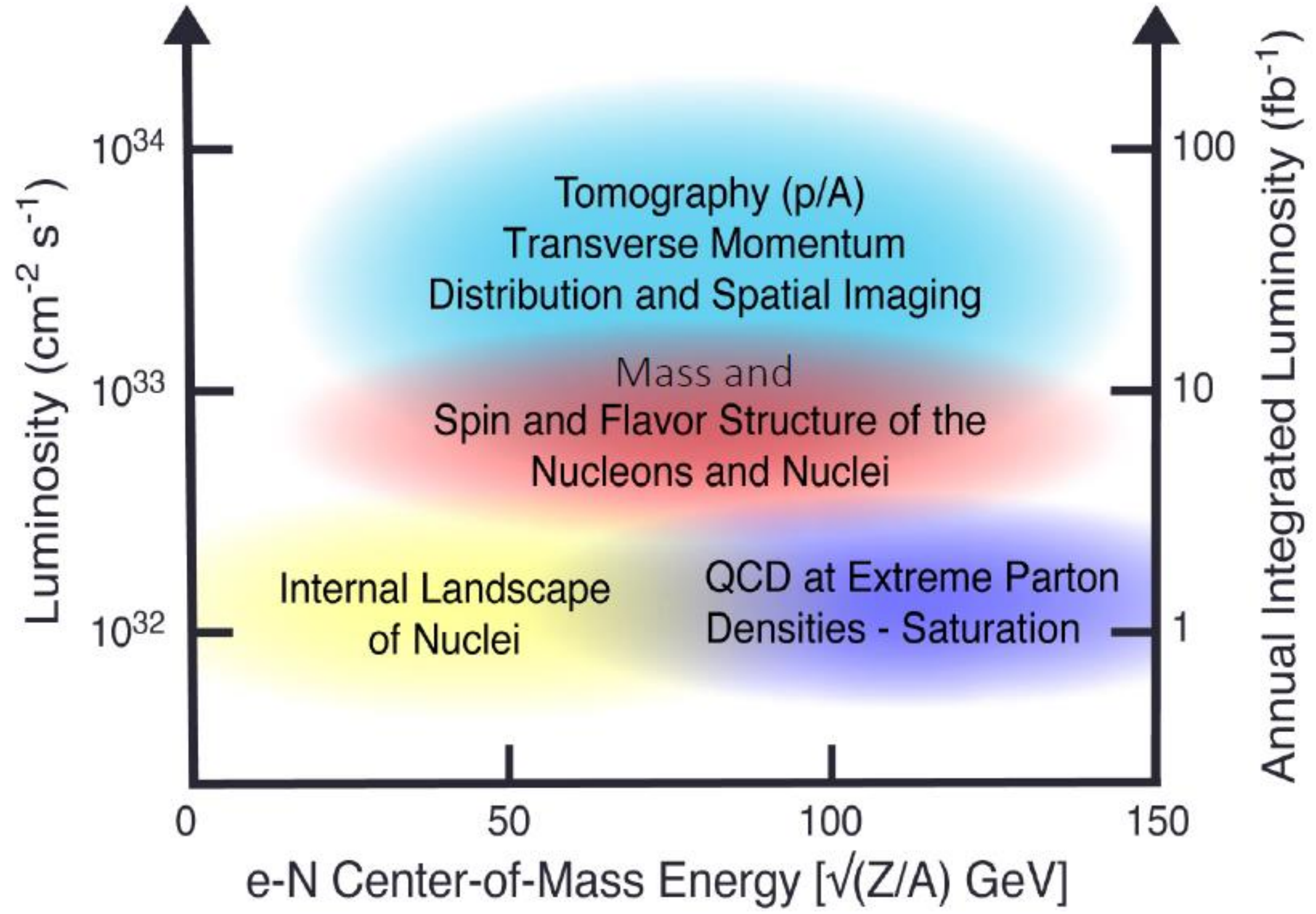
Gluon tomography

$e + p \rightarrow e + p + J/\psi$

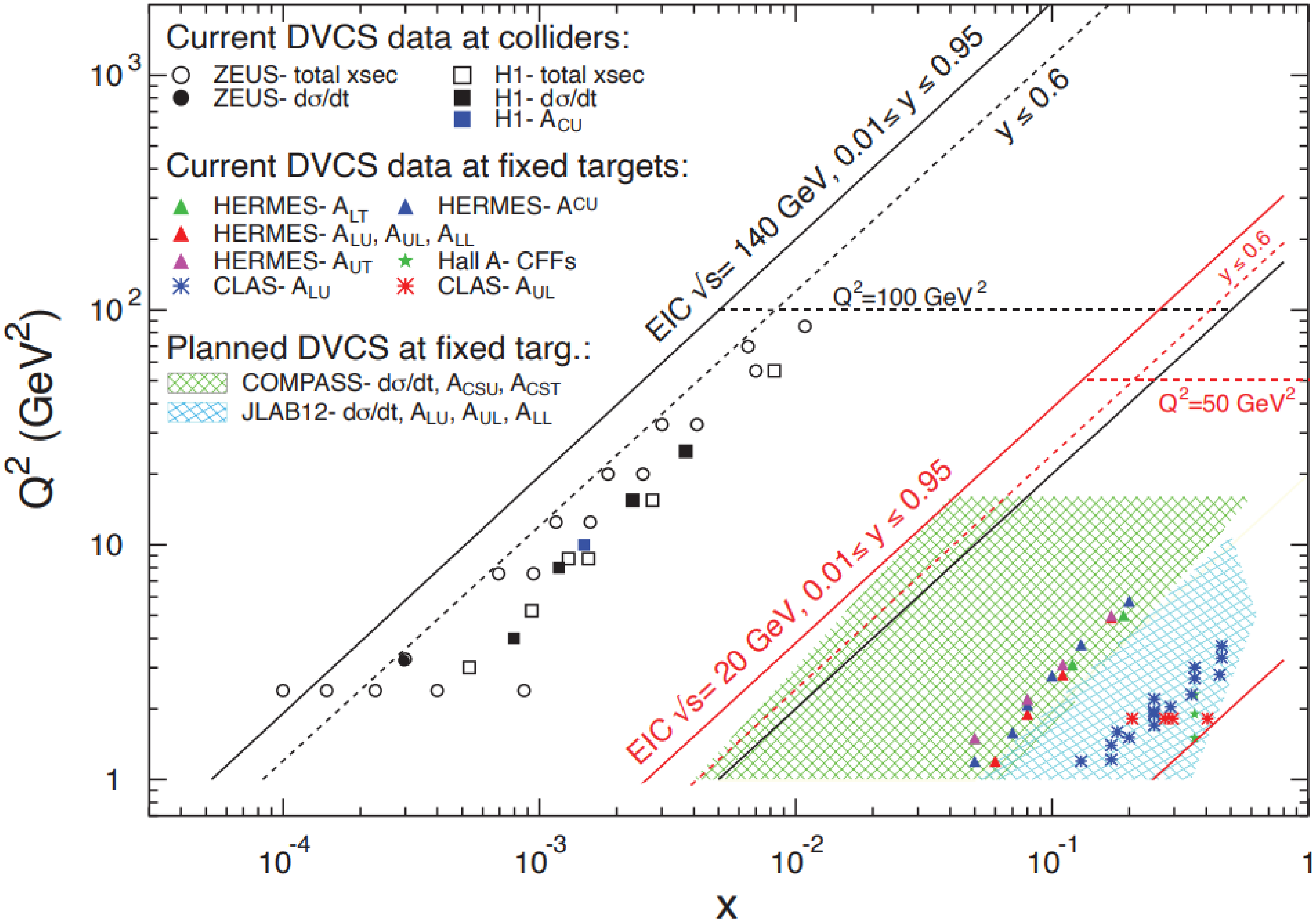
$15.8 < Q^2 + M^2_{J/\psi} < 25.1\ \text{GeV}^2$



EIC: Luminosity and physics goals



EIC kinematic reach: DVCS

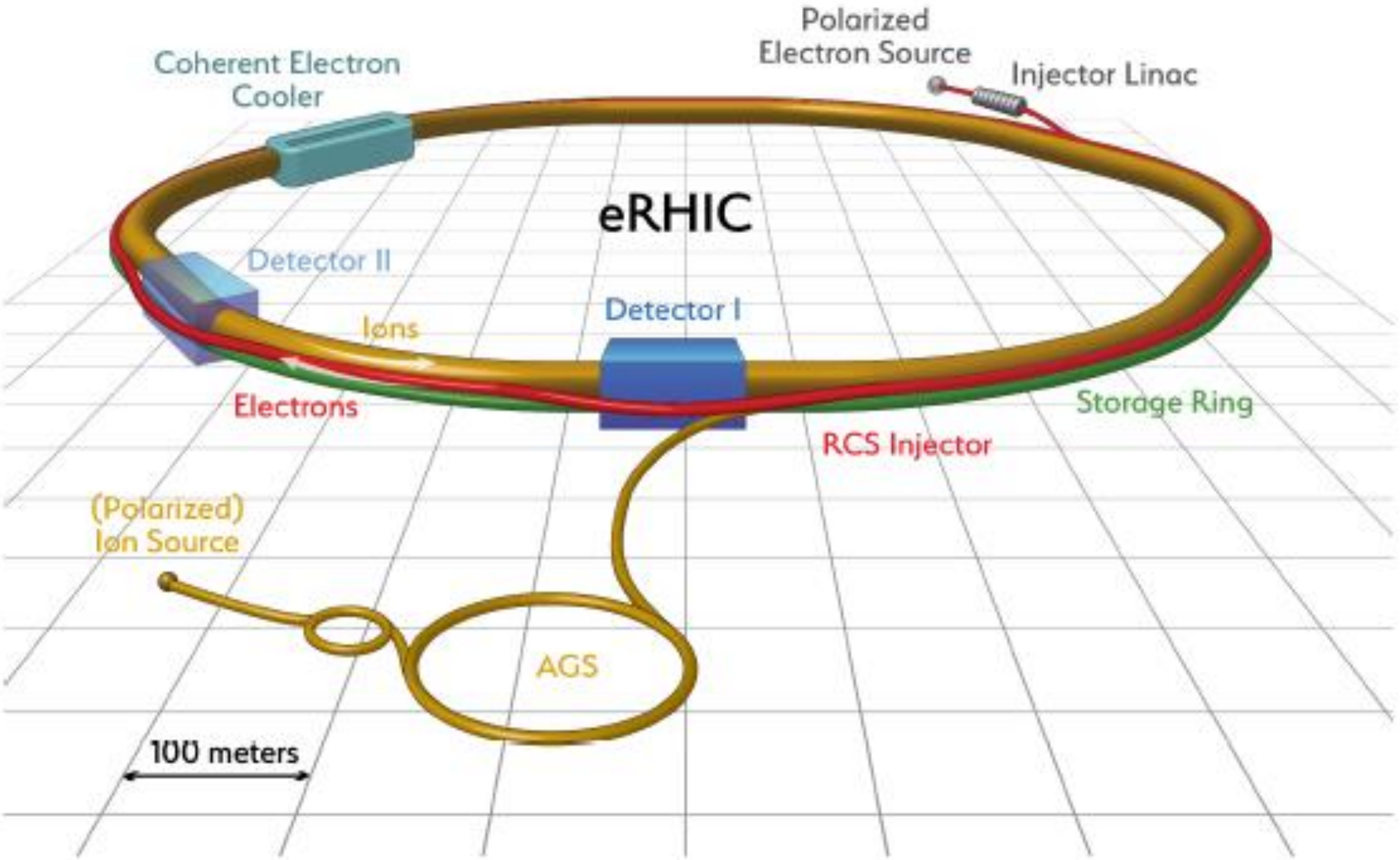


EIC facility @ BNL

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 lights ions / Unpolarized heavy ions
- CME: ~ 20 – 100 GeV
- Luminosity: ~ $10^{33\text{-}34}\text{cm}^{-2}\text{s}^{-1}$

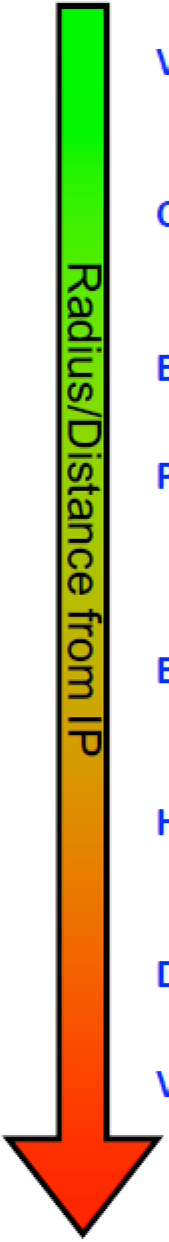
- Polarized electron source and 400 MeV injector linac
- 2 detector interaction points capability in the design



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: µRWell or MicroMegas

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

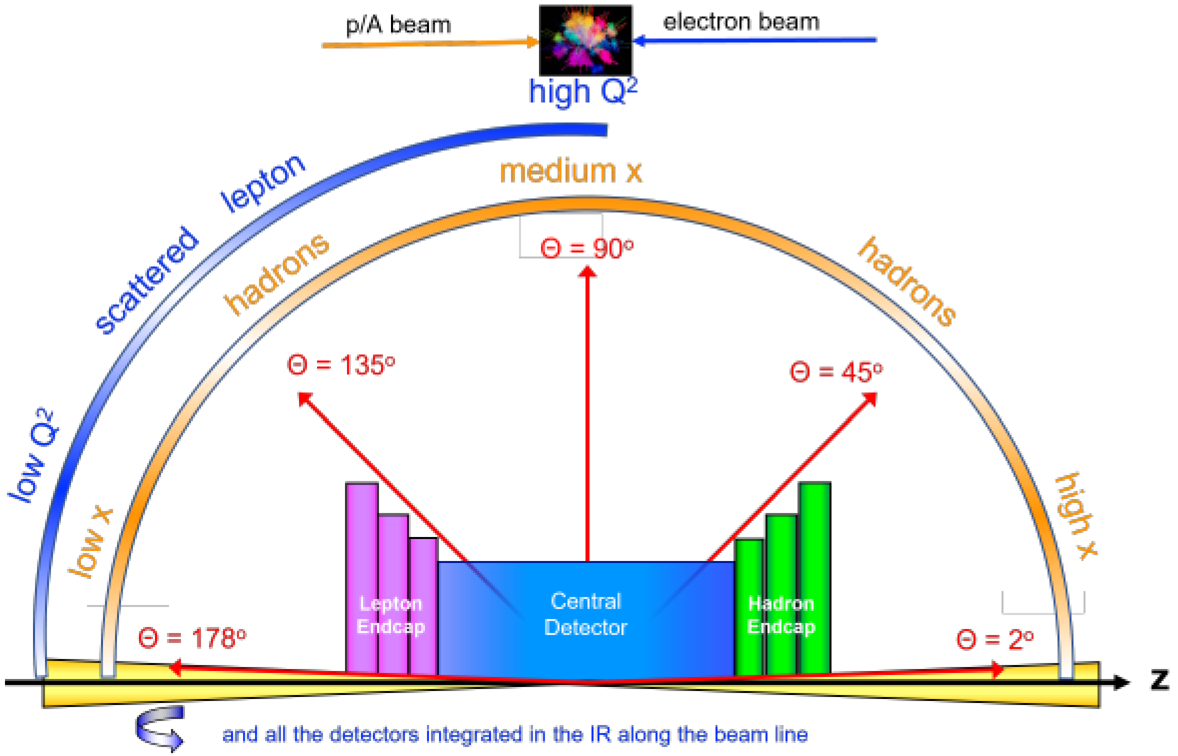
Particle Identification → pion, kaon, proton separation on track level
RICH detectors (modular and dual radiator RICH, DIRC) & Time-of-Flight
high resolution timing detectors (LAPPDs, LGAD) 10 – 30 ps
novel photon sensors: MCP-PMT / LAPPD

Electromagnetic calorimeter → Measure photons (E, angle), identify electrons
$PbWO_4$ Crystals (backward), W/SciFi Spacal (forward)
Barrel: Pb/SciFi+imaging part or new Scintillating glass

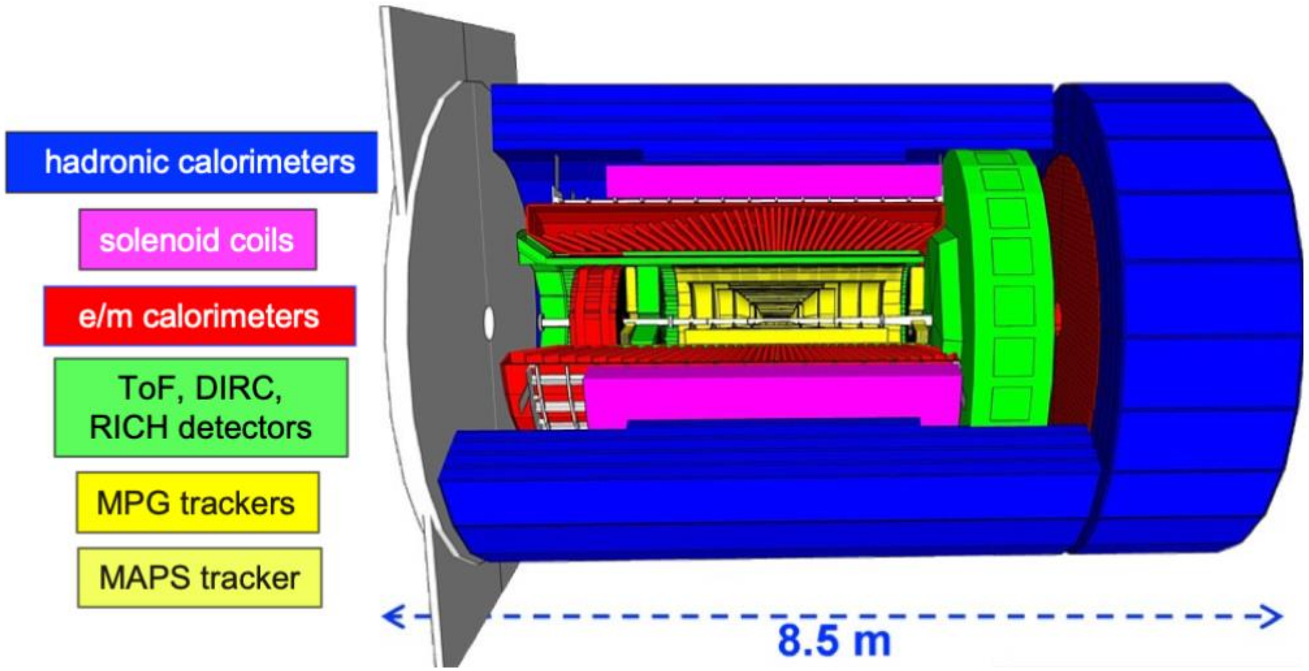
Hadron calorimeter → Measure charged hadrons, neutrons and K_L^0
challenge achieve ~50%/√E + 10% for low E hadrons (<E> ~ 20 GeV)
Fe/Sc sandwich with longitudinal segmentation

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 »)



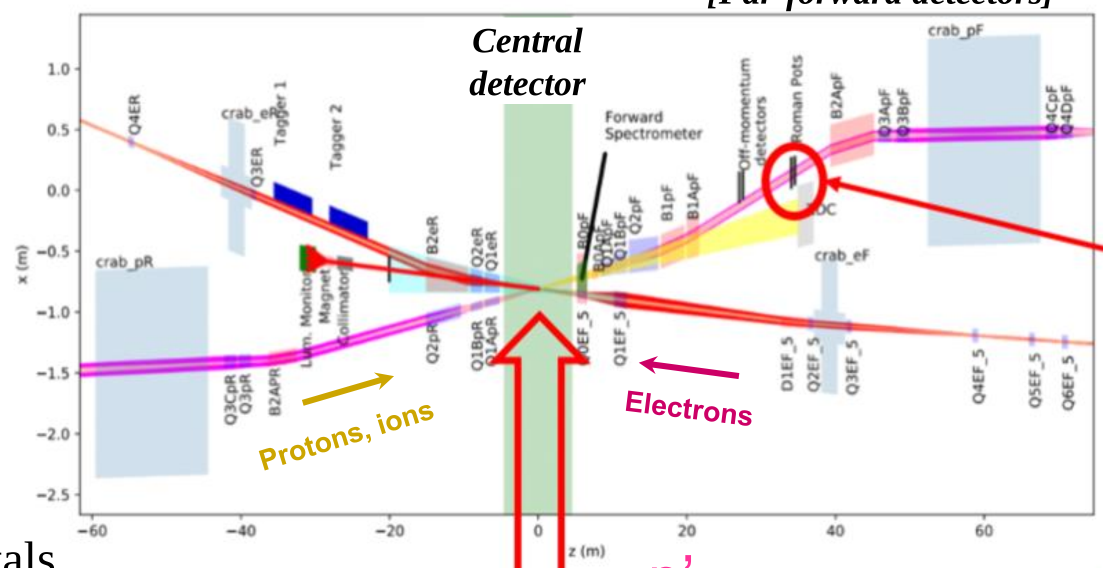
Tracking:
- New 1.7T solenoid
- Si MAPS Tracker
- MPGDs (μRWELL/μMegas)

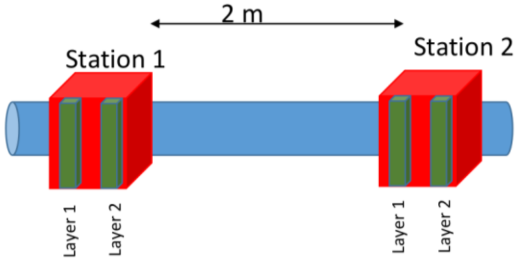
PID:
- hpDIRC
- mRICH/pfRICH
- dRICH
- AC-LGAD (~30ps TOF)

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

How to measure DVCS at EIC: EMCal, Roman Pots

[Far-forward detectors]





Roman Pots

protons / ions

Momentum & Timing

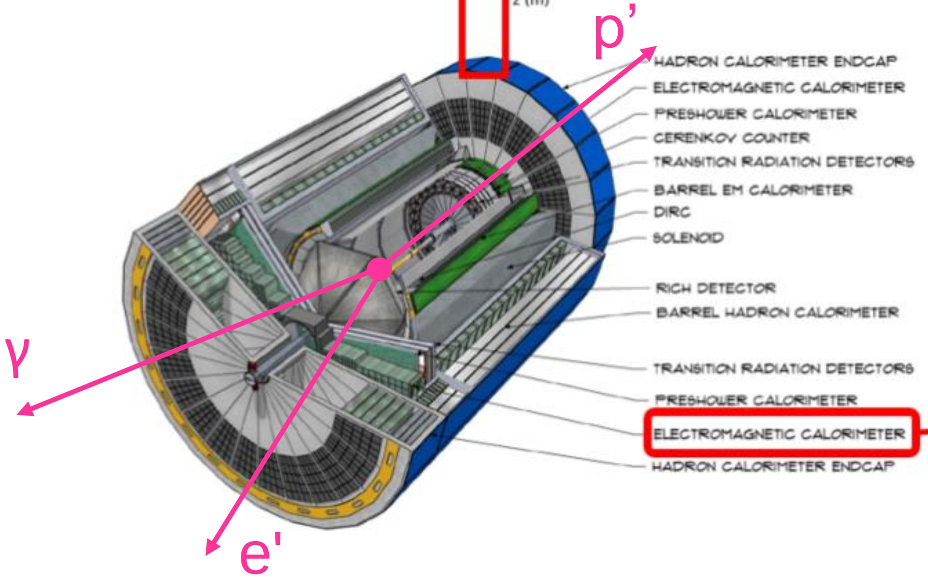
(25 – 30 m from IP)

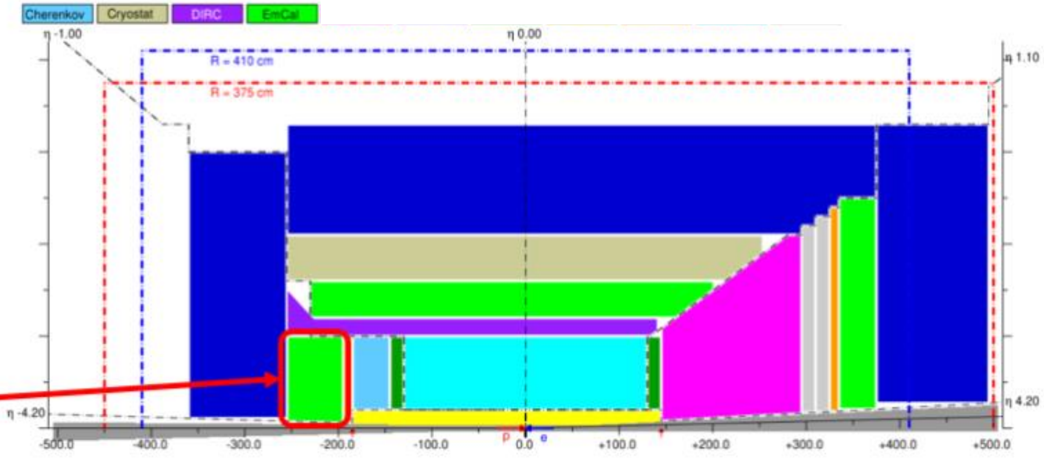
Technology :

- Ultra-fast silicon detectors (AC-LGADs)
- Readout ASIC to be developed

Technology :

- PbWO4 crystals
- SiPM readout (or APDs)





Calo. EM, e-End-Cap

Noémie Pilleux

These are the R&D projects ongoing in my lab, IJCLab Orsay ☺

IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

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**