Exploring the hadron structure at Jefferson Laboratory
Part I

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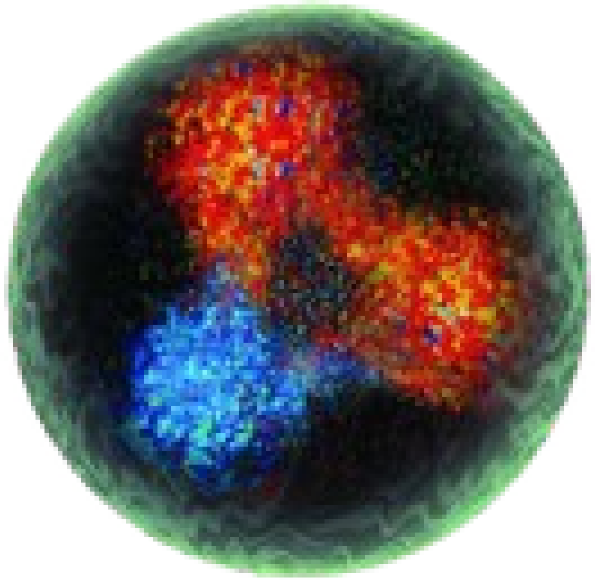
CSTD du DPhN, Orme des merisiers, June 12th 2024

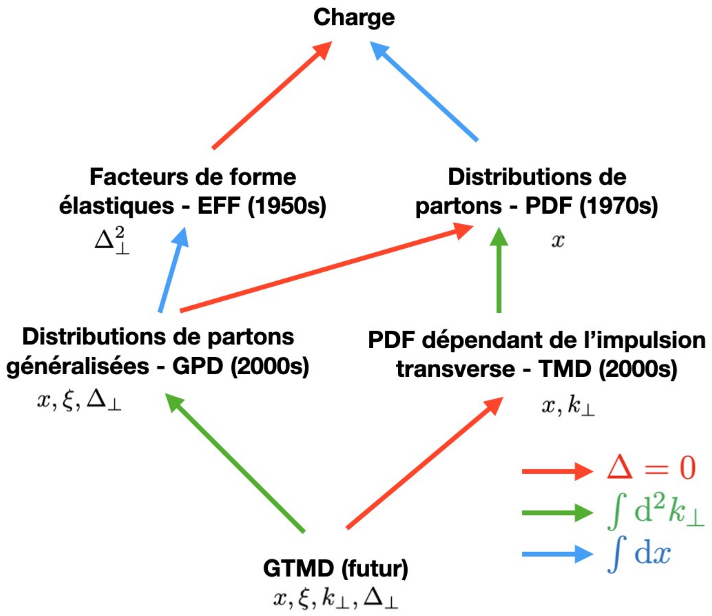
Motivation

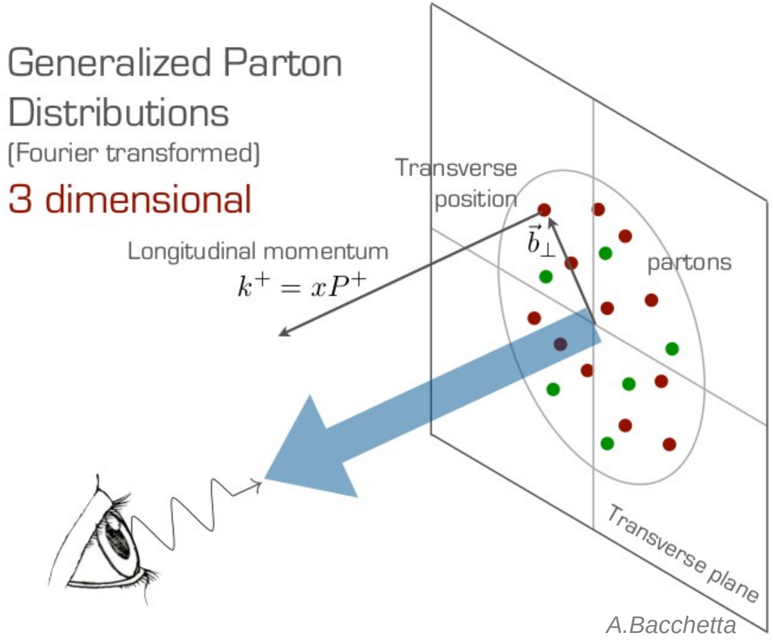
- Hadrons make up most of the visible matter in the universe
- Hundred years of research and yet are not fully understood
- Quarks and gluons are bond together into hadrons in the non-perturbative QCD regime
- Open questions:
  - How quarks and gluons are distributed in space and momentum
  - How properties of hadrons such as the mass and the spin arise from quarks and gluons distributions and interactions



Deep inelastic scattering is the cleanest way to probe its internal structure

Introduction





- GPDs encode the correlation between the longitudinal momentum fraction (x) and the transverse position ($b_\perp \leftrightarrow \Delta$)of partons inside hadrons
- The number of GPDs needed to describe the structure of a hadron depends on its spin
- For the proton: four chiral-even (H, $\tilde{H}$, E, $\tilde{E}$) and four chiral-odd GPDs

Properties of GPDs of the nucleon

Forward limit: GPDs become PDFs

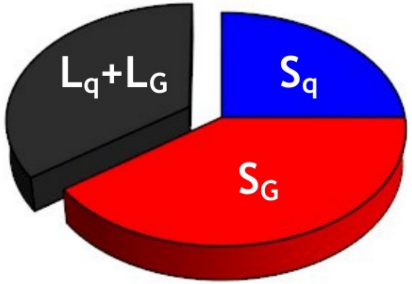
$$H(x,0,0) \to q(x)\ ,\ \widetilde{H}(x,0,0) \to \Delta q(x)$$

Sum rules: link to Form Factors

$$\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t) \text{ and } \int_{-1}^{1} dx E^q(x,\xi,t) = F_2^q(t).$$

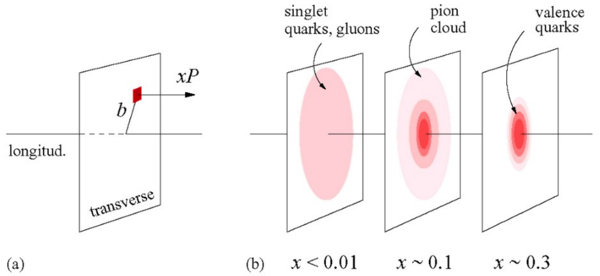
Ji's sum rule: link to spin decomposition

$$\int_{-1}^{1} x \left[H^f(x,\xi,t) + E^f(x,\xi,t)\right] \, dx = J(t)^f$$



Probabilistic interpretation in the transverse plane

$$GPD(x,\xi=0,t) \leftrightarrow \rho(x,b_\perp)$$



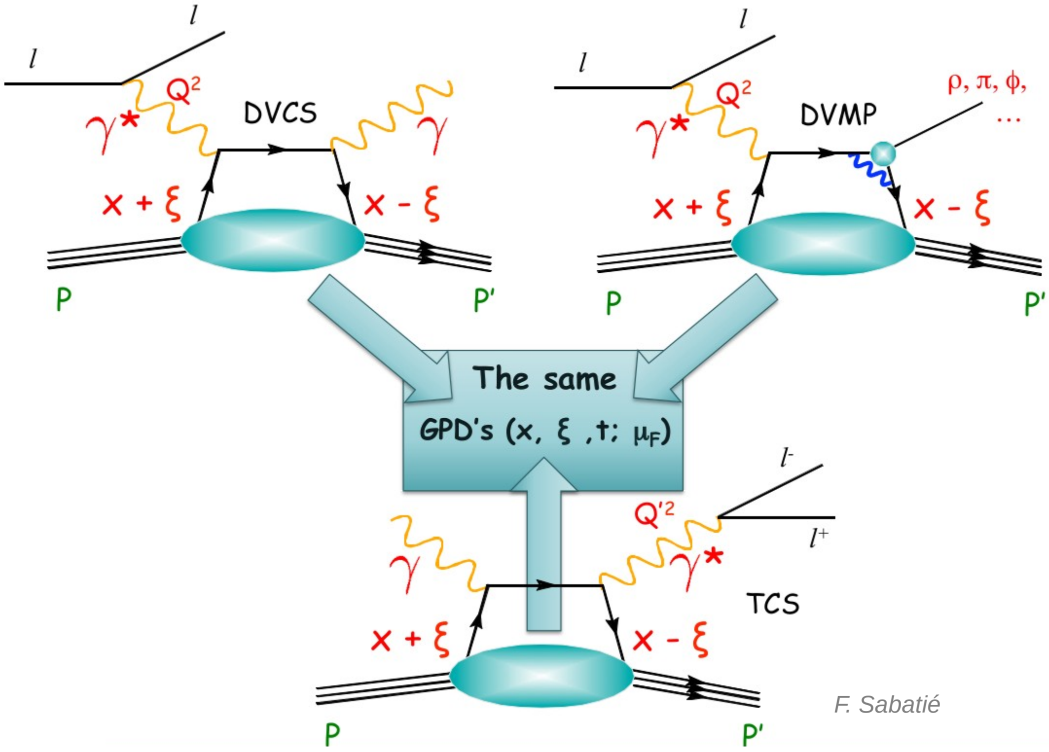
C. Weiss

Energy momentum tensor: mass distribution and forces

$$\int_{-1}^{1} x H^f(x,\xi,t) \, dx = M_2^f(t) + \tfrac{4}{5}\xi^2 d_1^f(t) \qquad \forall \xi$$

How to access GPDs

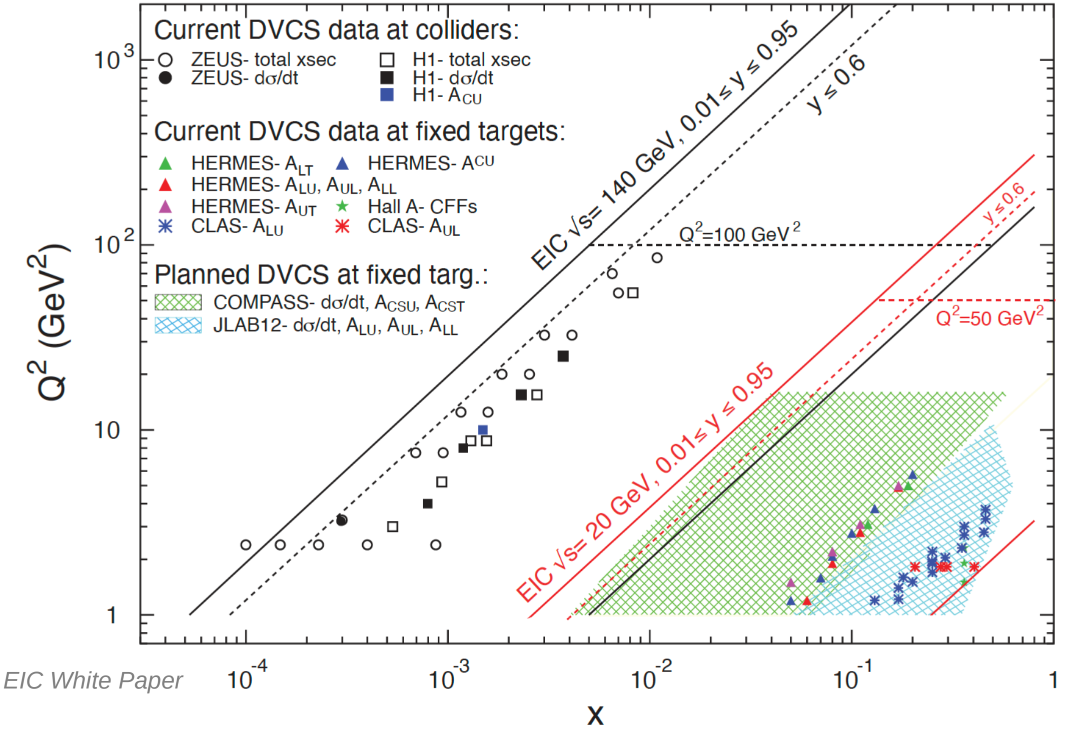
- Exclusive processes give access to GPDs
  - Deeply virtual Compton scattering
  - Deeply virtual meson production
  - Time-like Compton Scattering
- In the Bjorken regime, at high Q^2 and large W,
  - factorization theorem: amplitude = hard scattering ⊗ non-perturbative parts
- GPDs are universal, but not directly accessible: they enter via convolution integrals with hard kernels



F. Sabatié

$$\mathcal{F}(\xi, t, \mu_F, Q^2) = \int_{-1}^{1} dx\, C\left(x, \xi, \alpha_S(\mu_F), \frac{Q}{\mu_F}\right) F(x, \xi, t, \mu_F)$$

Where to study GPDs



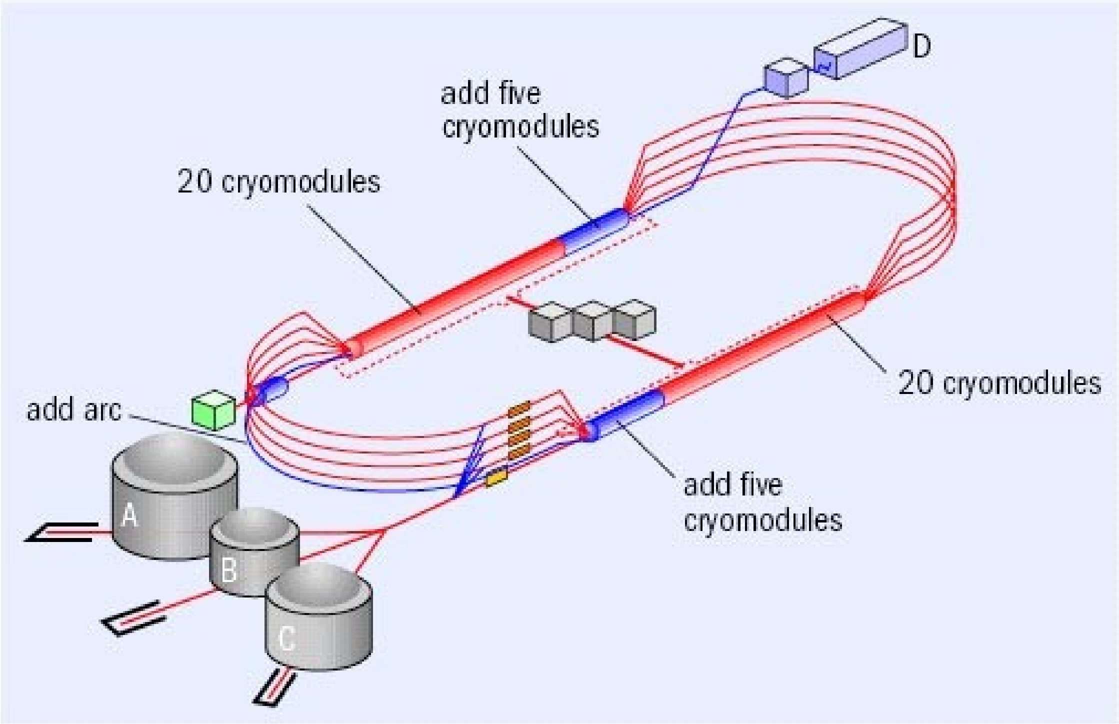
EIC White Paper

JLab	Valence	10^{38}Hz/cm^2
Hermes/ Compass	Sea	10^{32}Hz/cm^2
HERA	Small-x	10^{31}Hz/cm^2
EIC	From small-x to valence	10^{34}Hz/cm^2

JLab offers the access to the **valence** region $0.1 < x_B < 0.7$ with **high luminosity**

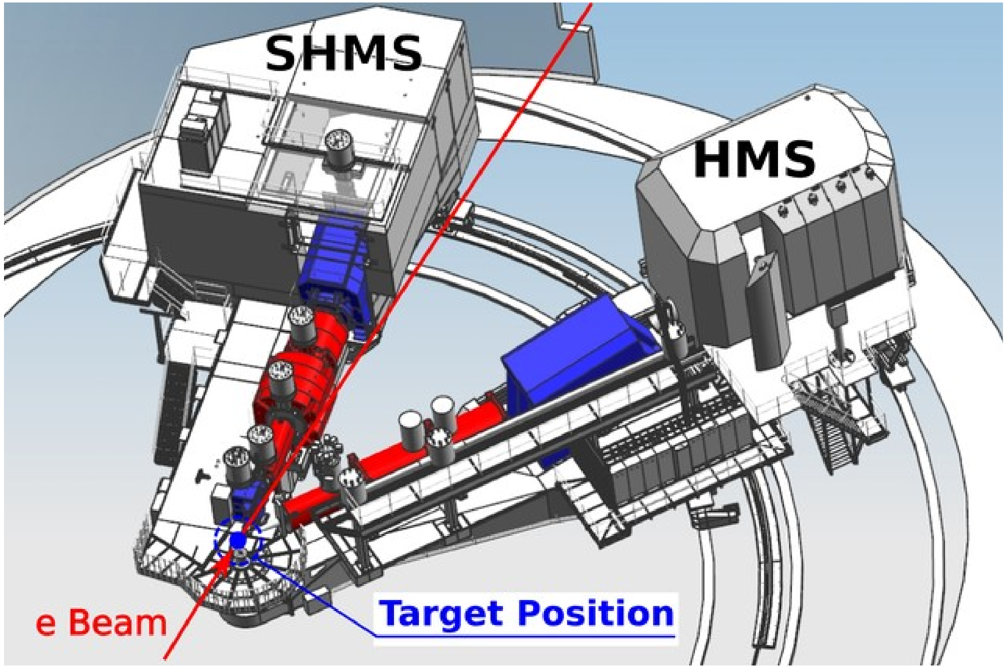
Jefferson Lab

- CEBAF upgraded to 12 GeV
- In operation since 2014
- Unique features:
  - Beam polarization > 85%
  - Four experimental halls
  - Currents up to 85 µA



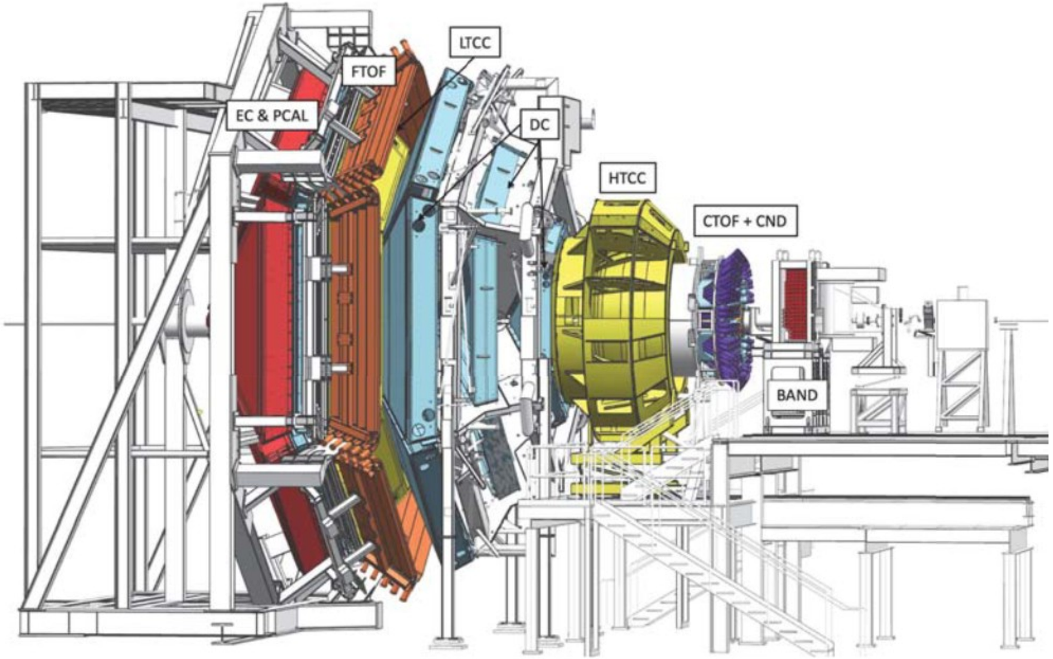
Hall C

- Equipped with two small acceptance spectrometers
- It can reach luminosities of 10^{37} Hz/cm^2
- The High Momentum Spectrometer (HMS) :
  - 8.1 msr acceptance
  - 0.1 % momentum resolution
- The Super High Momentum Spectrometer (SHMS) :
  - 2 to 4 msr acceptance
  - 0.2 % momentum resolution
- Additional detectors can be added for specific measurements.
- The Neutral Particle Spectrometer, designed for DVCS measurements:
  - A sweeping magnet
  - A $PbWO_4$ calorimeter



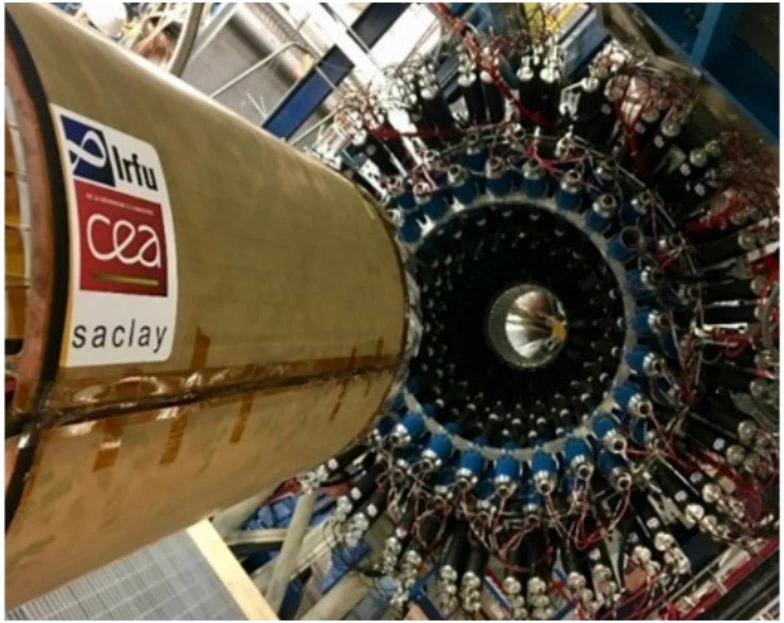
Hall B - CLAS12

- A large acceptance spectrometer
- Luminosities up to 10^{35} Hz/cm^2
- Forward detector, [5,35] deg
  - in a toroidal magnetic field,
  - fully equipped for tracking and particle identification (drift chambers, calorimetry, time of flight, Cherenkov detectors)
- Central detector, [40, 120] deg,
  - in a 5 T solenoid
  - tracking and TOF detectors
- Forward tagger, [2,5] deg,
  - hodoscope and a calorimeter
  - small angle electron and photon reconstruction

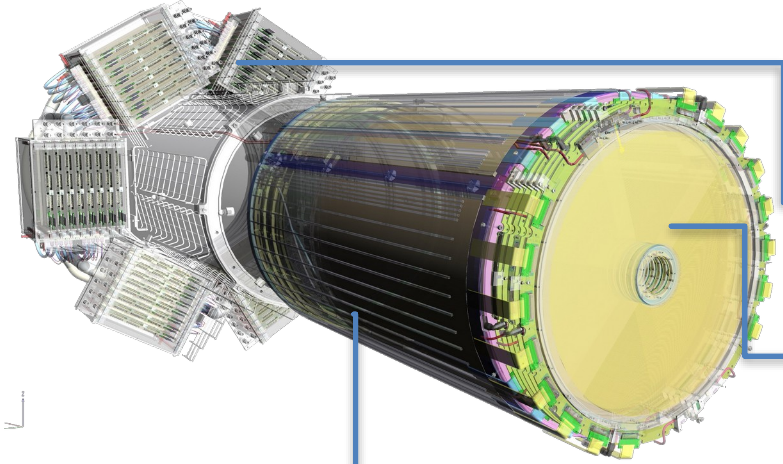


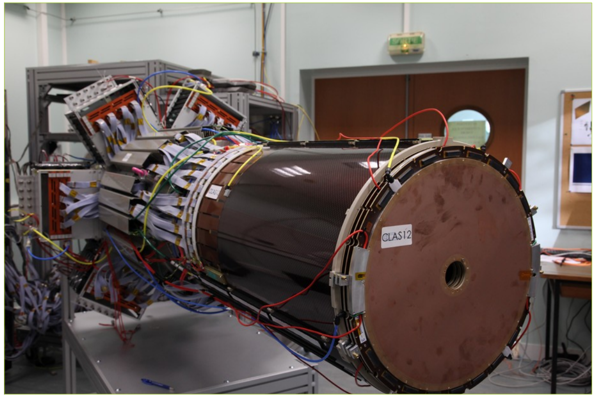
CLAS12 – DPhN-DEDIP involvement

- Experimental program on DVCS with CLAS12 proposed in 2006
- Design and development of the Micromegas Vertex Tracker and the DREAM ASIC for the signal readout
- Installation in 2017, taking data since.
- Involved in the simulation and reconstruction software for the Micromegas
- Convenorship of the Deep Process WG (M. Defurne)
- Leading group in the DVCS analysis both on unpolarized and polarized targets



CLAS12 – Micromegas Vertex Tracker



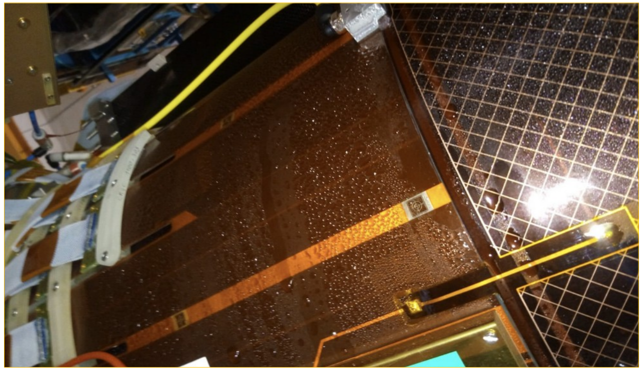


4 m² of resistive Micromegas detectors designed, assembled and installed by Saclay in 2017

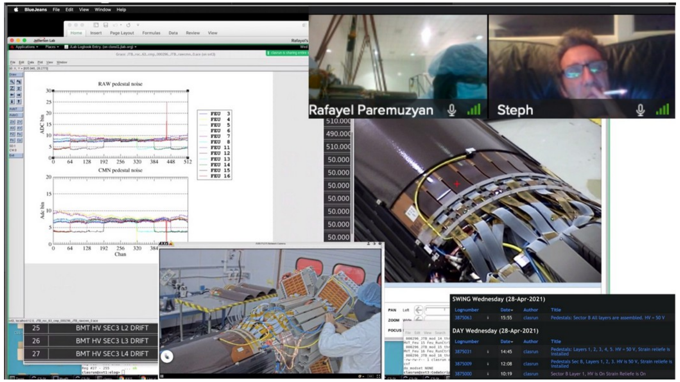
- **DREAM** based Front-End Electronics
- Remote off-detector frontend electronics connected with 2m micro-coaxial cables
- Forward Detectors
  - High particle rate (30MHz) => Fast detectors
  - Dimensions: 6x 430 mm diameter disk with a 50 mm diameter hole at the center
- Cylindrical Barrel
  - Low momentum particles => Light Detectors
  - Limited space of ~10 cm for 6 layers
  - High magnetic field (5T)
  - 6 Layers (18 modules) of resistive Micromegas

CLAS12 – Micromegas Vertex Tracker

- **Taking data since 2017!**
- Up to now, MVT has integrated more than 20 Coulomb of charge per module, (more than foreseen). **Data taking with several different targets.**
- After installation, maintenance needed in several occasions
- Also issues with **unforeseen ambient conditions** (water condensation on modules, now solved) and higher background rates, mainly with nuclear targets
- **Strong involvement of DPhN and DEDIP** in maintenance, training of JLab staff and support all along, even during Covid.
- Few modules failed and had to be replaced with spares and for some layers, there are no more spares
- In view of restarting operations in 2026 with higher luminosities (x2-x5), Hall B inquired with Saclay about the possibility to produce new spares
- Studies are ongoing at DEDIP to refurbish the production chain and to understand the origin of the failures
- **The CLAS12 MVT is the base technology for the Cylindrical Micromegas Barrel Tracker of the EIC detector**



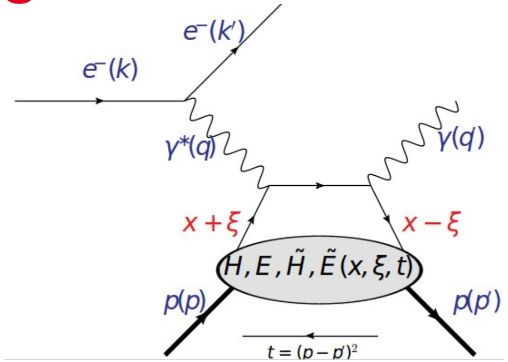
Water condensation on MVT tiles in Hall B



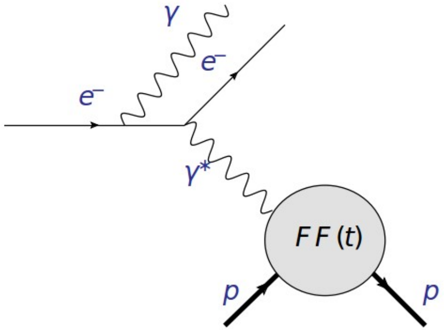
Remote support during Covid

Deeply Virtual Compton Scattering

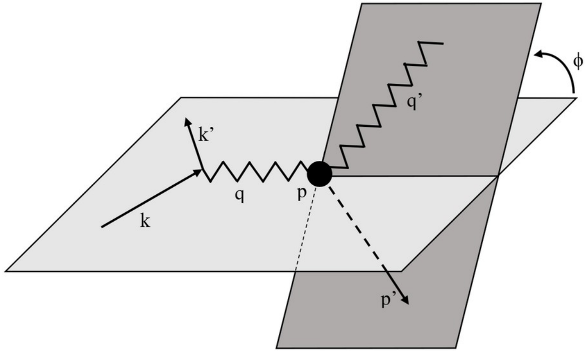
- Experimentally: photon lepto-production
- Two interfering processes:
  - DVCS
  - Bethe-Heitler
- Modulation of the cross section with the angle between the lepton and gamma-proton planes
- GPD enter the DVCS amplitude through complex integrals, the Compton Form Factors
- The interference term helps accessing the real and imaginary parts of CFFs
- Asymmetries with respect to the beam or target polarizations allow one to select specific CFF combinations



DVCS



BH



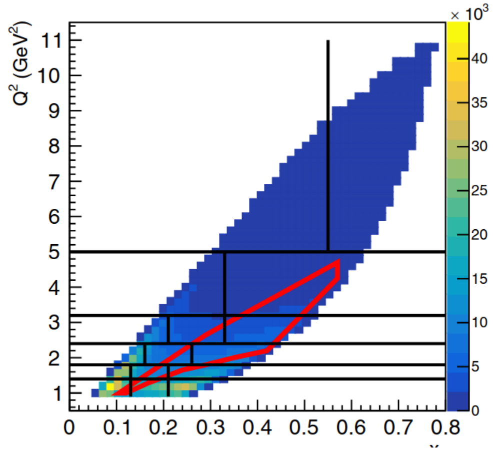
$$\frac{d^4\sigma(\lambda, \pm e)}{dQ^2 dx_B dt d\phi} = \frac{d^2\sigma_0}{dQ^2 dx_B} \frac{2\pi}{e^6} \times \left[\left|\mathcal{T}^{BH}\right|^2 + \left|\mathcal{T}^{DVCS}\right|^2 \mp \mathcal{I} \right]$$

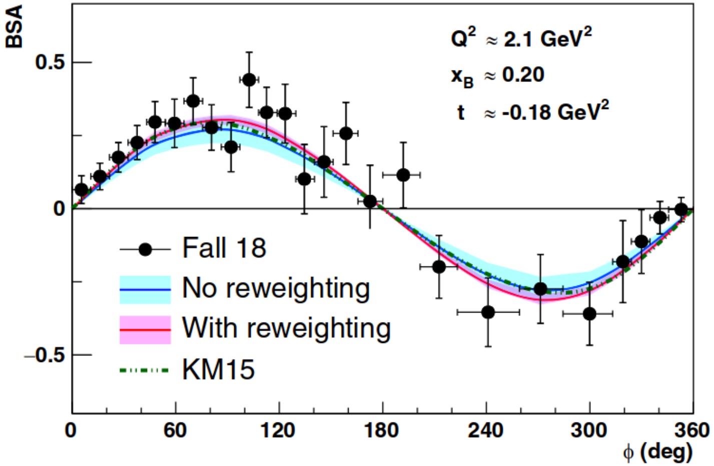
DVCS in CLAS12 – unpolarized LH2 target

- Flagship measurement for upgraded CLAS detector
- Saclay among the spokespersons of the experiment
- Beam Spin Asymmetry (BSA) sensitive to the imaginary part of GPD H

$$A_{LU} = \frac{d\sigma^{\rightarrow} - d\sigma^{\leftarrow}}{d\sigma^{\rightarrow} + d\sigma^{\leftarrow}} \Rightarrow \Im\mathrm{m}\left[F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}\right]$$

- Data taking in 2018-2019 for the first 50% of the allotted time
- The very first experiment run with CLAS12
- DPhN heavily involved in the development of reconstruction code for the central detector
- Leading role in the data analysis

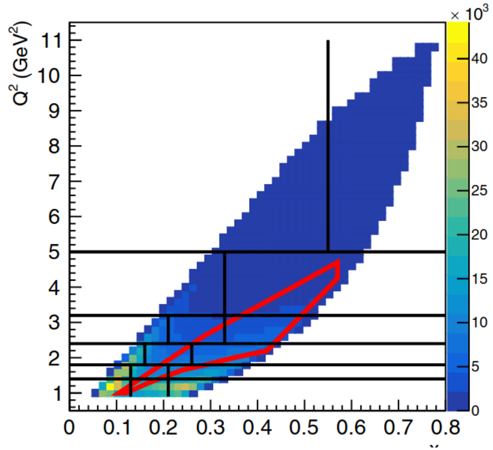


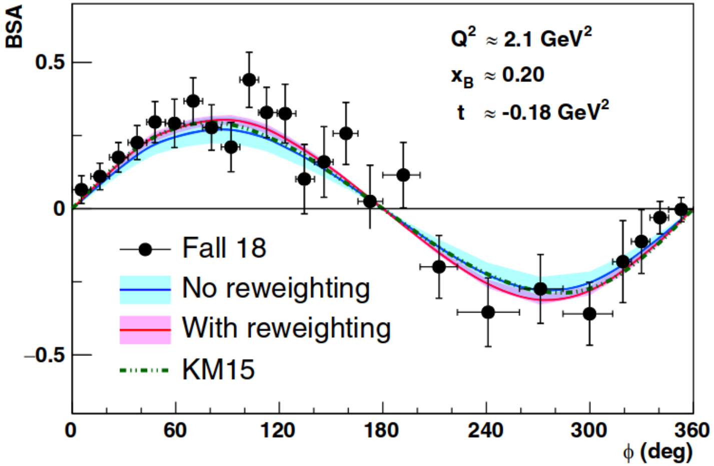


PRL 130, 211902 (2023)

DVCS in CLAS12 – unpolarized LH2 target

- Main analysis performed by one student (G. Christiaens, PhD in 2020)
- Finalized at DPhN (M.Defurne) for **publication in PRL in 2023**
- Analysis of **only 25 % of the allocated beam-time**
- Largely extends beyond the 6 GeV data
- New data show already the potential to refine GPD extraction
  - Phenomenology using PARTONS software co-developed at DPhN
- Exploring new ML algorithms for background rejection
  - Focus of a thesis (N. Cherrier, PhD in 2020)
- **More data will come:**
  - 25 % of the data is currently being calibrated
  - The second half of data will be collected in 2026





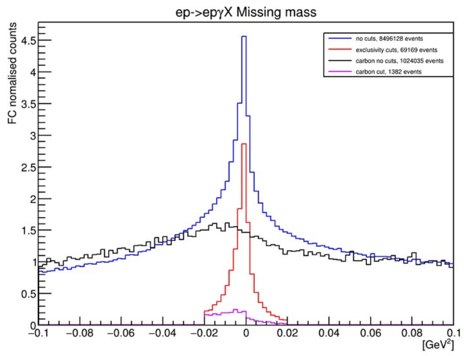
PRL 130, 211902 (2023)

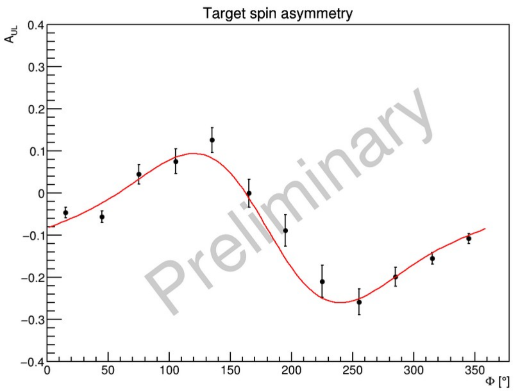
DVCS in CLAS12 – longitudinal polarized NH3 target

- DVCS on a longitudinal polarized protons gives access (mainly) to the imaginary part of H̃-tilde

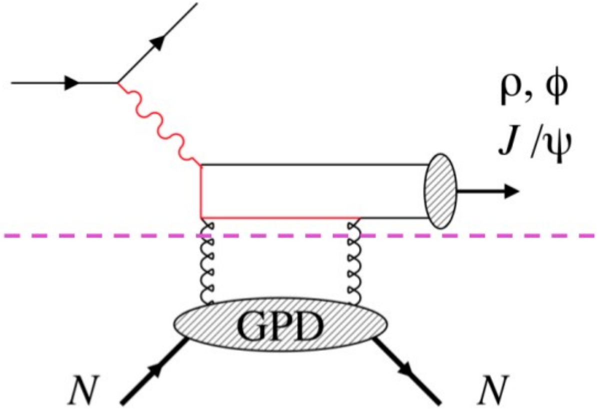
$$A_{UL}(\phi, e_\ell) \equiv \frac{d\sigma^{\Rightarrow} - d\sigma^{\Leftarrow}}{d\sigma^{\Rightarrow} + d\sigma^{\Leftarrow}} \quad \Rightarrow \quad \propto \Im\mathrm{m}\left[F_1 \widetilde{\mathcal{H}} + \xi(F_1 + F_2)\left(\mathcal{H} + \frac{x_B}{2}\mathcal{E}\right) - \xi\left(\frac{x_B}{2}F_1 + \frac{t}{4M^2}F_2\right)\widetilde{\mathcal{E}}\right].$$

- Data taking in 2022-2023, 2/3 of the data have being collected, target polarization up to 90%
- Analysis ongoing by a PhD student at DPhN (S. Polcher Rafael)
- Challenges of the analysis:
  - Complex NH3 target, with time varying polarization
  - Background from nuclear events
- Preliminary results of the Target Spin Asymmetry A_{UL} shows a clear signal



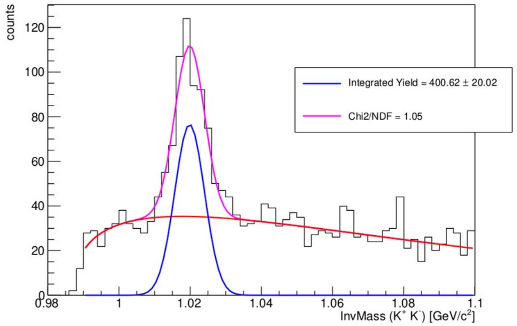


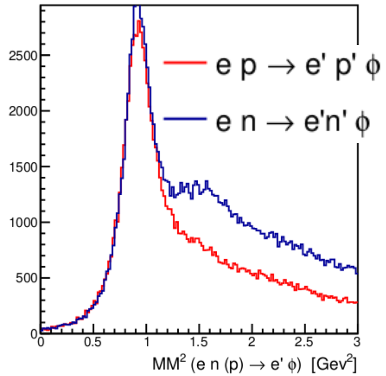
DVMP with CLAS12



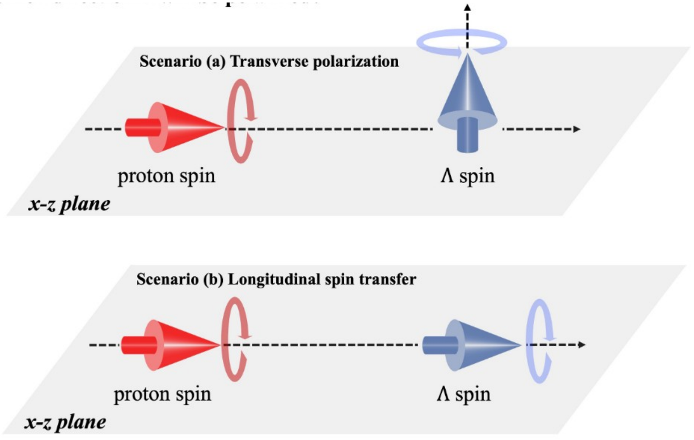
ϕ-meson electroproduction on neutron

- Motivation:
  - exclusive vector mesons production gives access to valence gluons
  - Test for neutron-proton possible differences
- Analysis of BSA on data taken with LD2 target, carried out during a 2-years post-doc (N. Ramasubramanian)
- Challenging neutron detection and scarce statistics limit the possible output of this analysis
- Possible outlook: focus on t-dependence



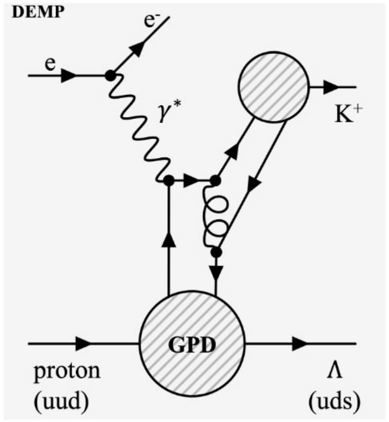


DVMP with CLAS12



Exclusive K-Λ electroproduction

- Motivation:
  - Long standing Λ polarization puzzle
  - Exclusive reactions give full control on the process
  - Polarization transfer from the target to the hyperon, possible hint to solve the puzzle
  - Based recent publication Phys.Rev.C 109 (2024) 5, 055205
  - Also, access to transition GPDs
- Partnered with Z. Tu on an BNL-LDRD proposal, unfortunately unsuccessful
- Challenging measurement with the longitudinal polarized target. A thesis subject has been opened



Summary

- Jefferson Lab is a versatile facility dedicated to the hadron structure studies
- DPhN is among the leaders in DVCS physics
- The DVCS program in CLAS12 has been the driver for the development and production of the cylindrical resistive Micromegas technology and its readout electronics.
- The large acceptance and multipurpose design of CLAS12 has the potential to explore several measurements
- At DPhN, currently only two permanent staff work on JLab topics.
  - On average, one PhD student
  - Shared post-doctoral researchers funded through EIC related sources
- In Fall, a new staff member (P. Chatagnon) will join the group bringing his expertise, in particular on TCS and J/psi production
- On the long term, opportunities at high-luminosity or with the positron beam will be considered

Backups

GPDs

- Maxtrix elements of bi-local twist-2 operators
- In analogy with the PDF definition

$$F^q = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle p' \left| \bar{q}\left(-\frac{z}{2}\right)\gamma^+ q\left(\frac{z}{2}\right)\right| p\rangle_{z^+=0, z_\perp=0}$$

$$= \frac{1}{2P^+}\left[H^q \bar{u}(p')\gamma^+ u(p) + E^q \bar{u}(p') \frac{i\sigma^{+\alpha}\Delta_\alpha}{2M} u(p)\right]$$

$$\tilde{F}^q = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle p' \left| \bar{q}\left(-\frac{z}{2}\right)\gamma^+\gamma_5 q\left(\frac{z}{2}\right)\right| p\rangle_{z^+=0, z_\perp=0}$$

$$= \frac{1}{2P^+}\left[\tilde{H}^q \bar{u}(p')\gamma^+\gamma_5 u(p) + \tilde{E}^q \bar{u}(p') \frac{\gamma^5\Delta^+}{2M} u(p)\right]$$