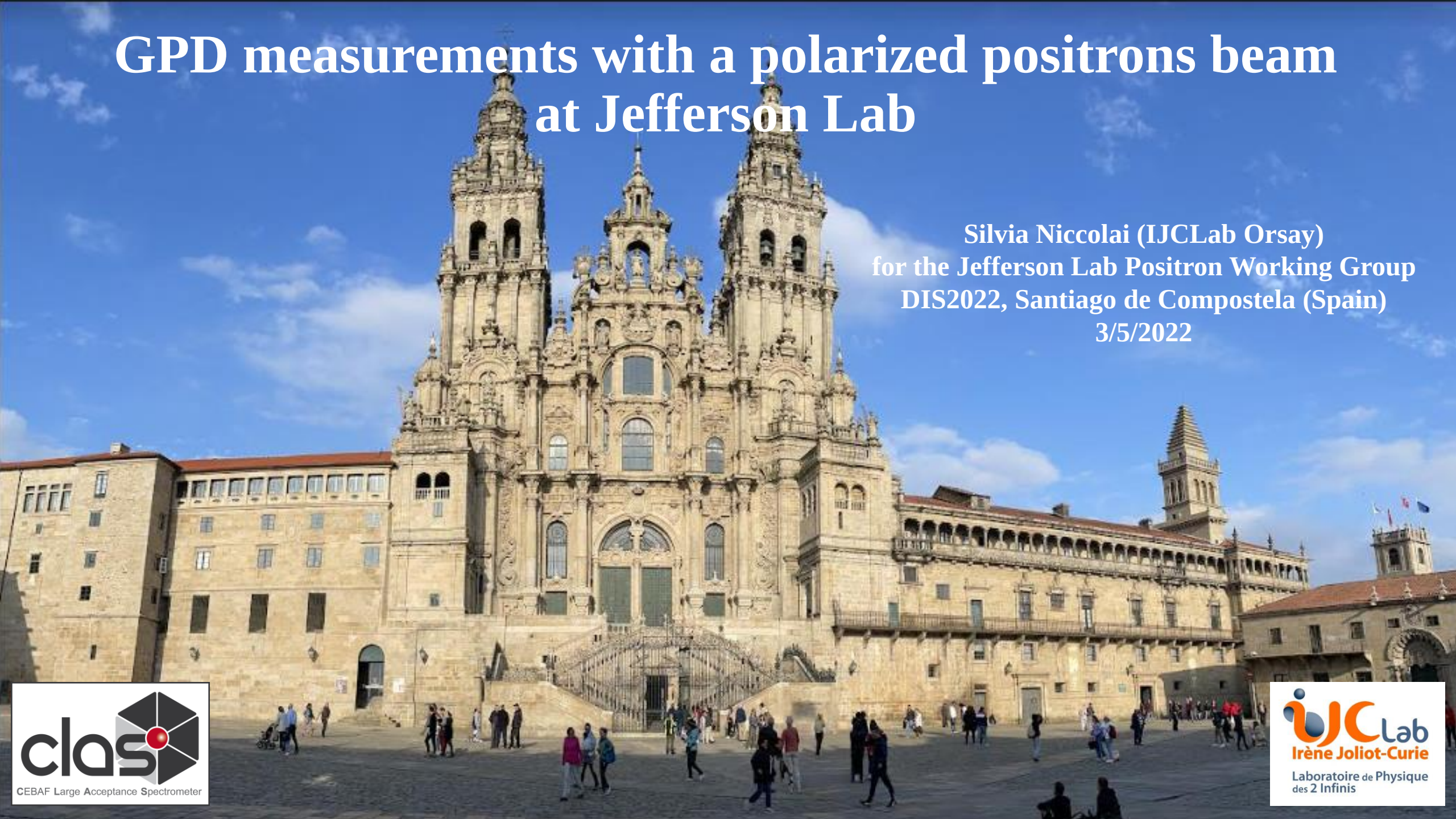
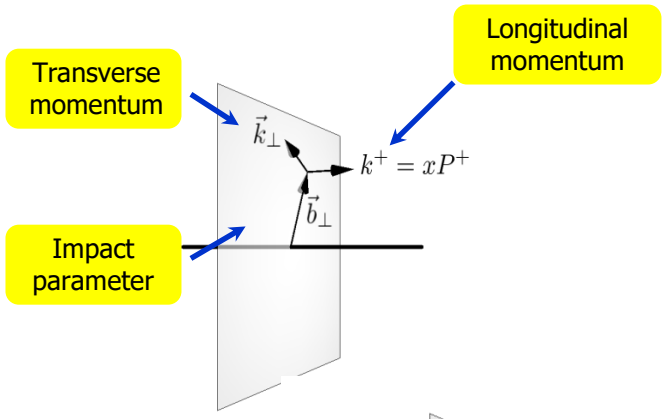
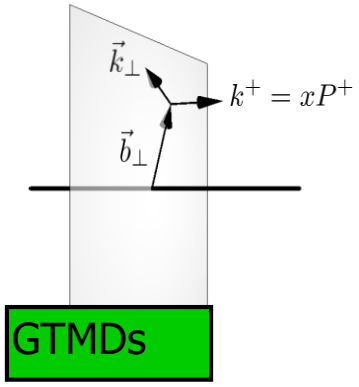
GPD measurements with a polarized positrons beam at Jefferson Lab

Silvia Niccolai (IJCLab Orsay)
for the Jefferson Lab Positron Working Group
DIS2022, Santiago de Compostela (Spain)
3/5/2022



Multi-dimensional mapping of the nucleon





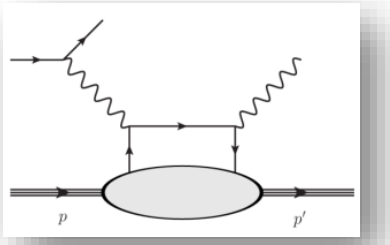
GTMDs

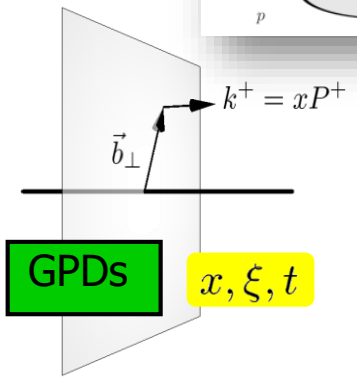
$x, \xi, k_\perp^2, \vec{k}_\perp \cdot \vec{\Delta}_\perp, t$

$\int \mathrm{d}^2\vec{k}_\perp$

$\int \mathrm{d}^2\vec{b}_\perp$

DVCS et al.

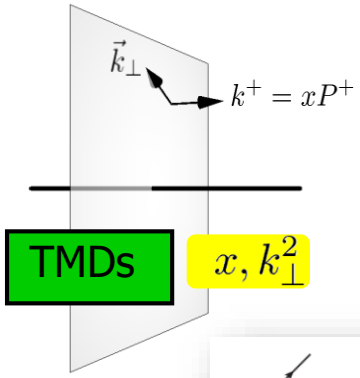




GPDs x, ξ, t

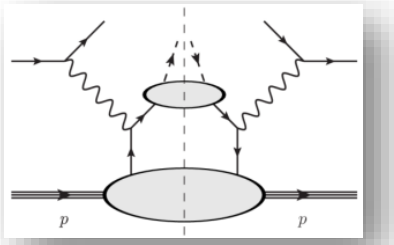
$\int \mathrm{d}x$

$\int \mathrm{d}^2\vec{b}_\perp$



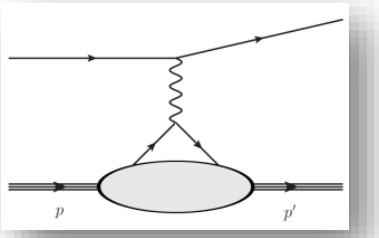
TMDs $x, k_\perp^2$

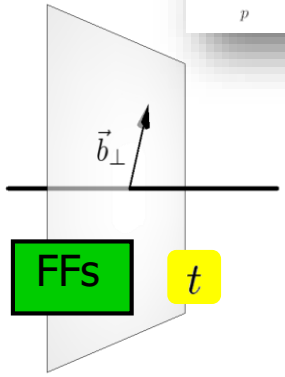
$\int \mathrm{d}^2\vec{k}_\perp$



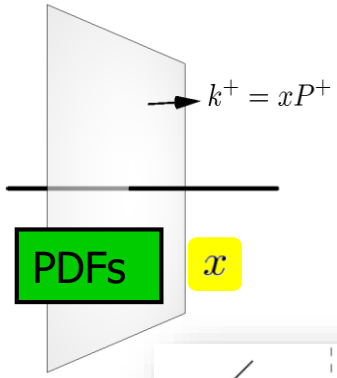
SIDIS

Elastic Scattering

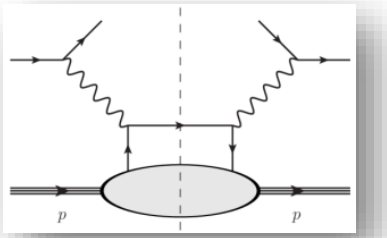




FFs t



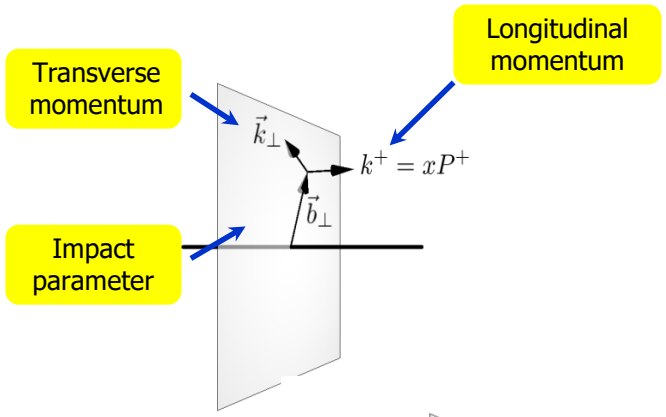
PDFs x

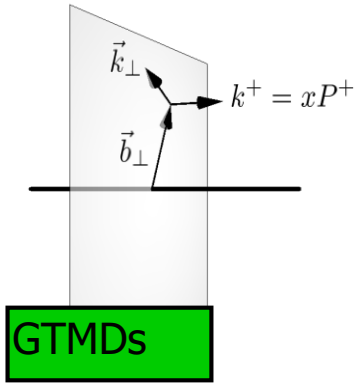


DIS

A complete picture of nucleon structure requires the measurement of all these distributions

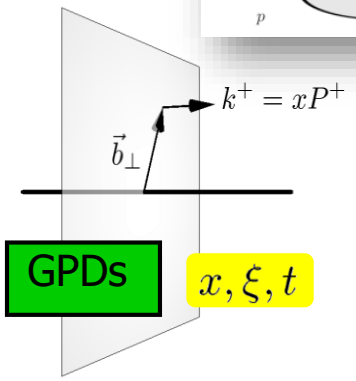
Multi-dimensional mapping of the nucleon





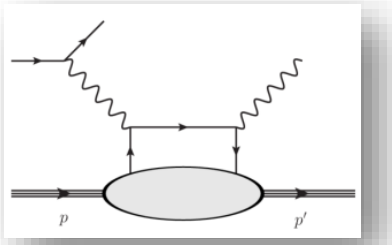
$x, \xi, k_\perp^2, \vec{k}_\perp \cdot \vec{\Delta}_\perp, t$

$\int \mathrm{d}^2\vec{k}_\perp$



x, ξ, t

DVCS et al.



Nucleon tomography

$$q(x,\mathrm{b}_\perp) = \int_0^\infty \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp \mathrm{b}_\perp} H(x,0,-\Delta_\perp^2)$$

$$\Delta q(x,\mathrm{b}_\perp) = \int_0^\infty \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp \mathrm{b}_\perp} \tilde{H}(x,0,-\Delta_\perp^2)$$

Generalized Parton Distributions:

✓fully correlated parton distributions in both **coordinate** and **longitudinal momentum** space

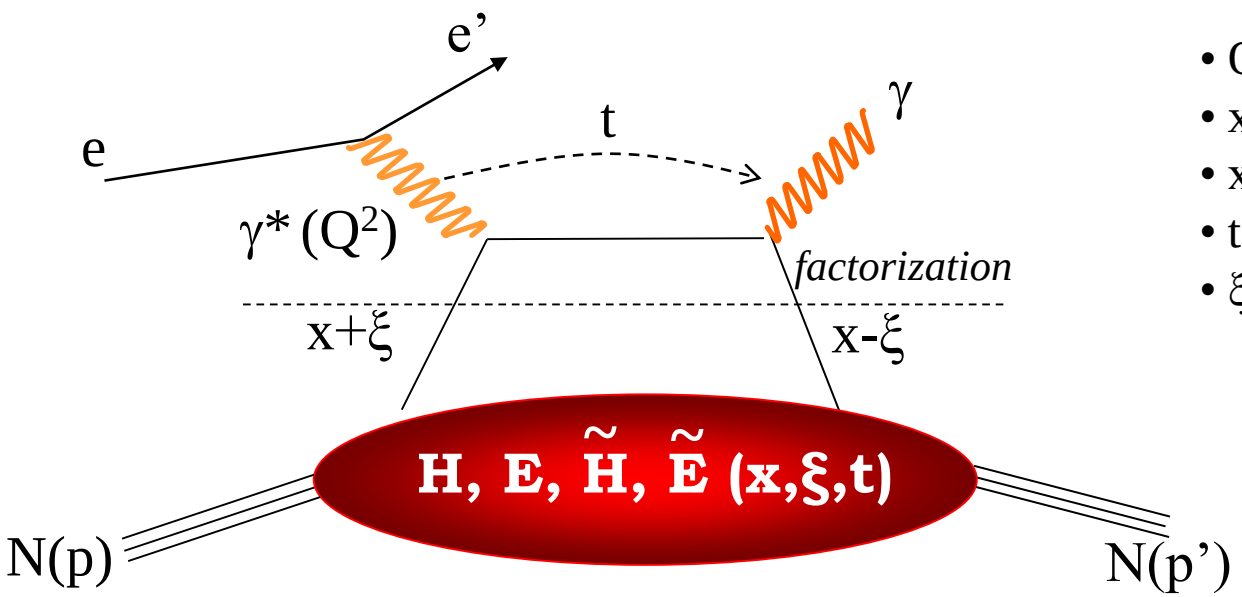
✓ linked to **FFs** and **PDFs**

✓**Accessible in exclusive reactions**

Quark angular momentum (Ji's sum rule)

$$\frac{1}{2}\int_{-1}^{1} x dx (H(x,\xi,t=0) + E(x,\xi,t=0)) = J = \frac{1}{2}\Delta\Sigma + \Delta L$$

Deeply Virtual Compton Scattering and GPDs



- $Q^2 = -(e-e')^2$
- $x_B = Q^2/2M\nu$ $\nu = E_e - E_{e'}$
- $x+\xi$, $x-\xi$ longitudinal momentum fractions
- $t = \Delta^2 = (p-p')^2$
- $\xi \cong x_B/(2-x_B)$

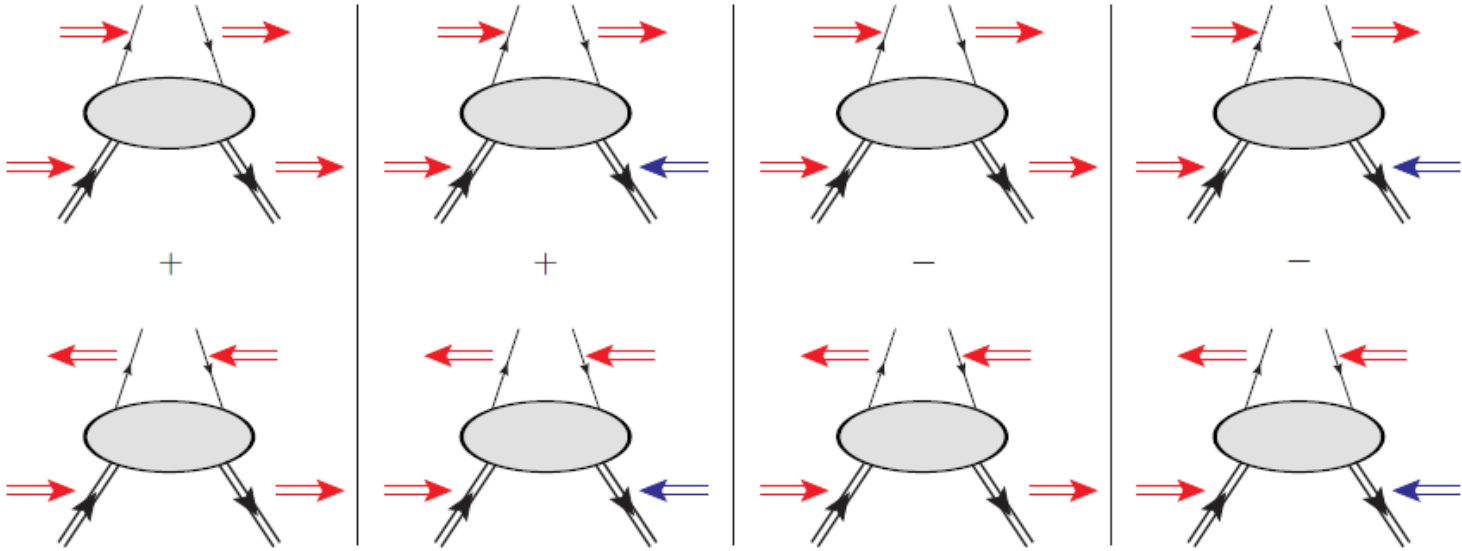
« Handbag » factorization, valid in the **Bjorken regime** (**high Q^2** and **ν**, fixed x_B), **$t \ll Q^2$**

*GPDs: Fourier transforms of **non-local**, **non-diagonal** QCD operators*

4 GPDs for each quark flavor
(leading-order, leading twist, quark-helicity conservation)

conserve nucleon spin

flip nucleon spin



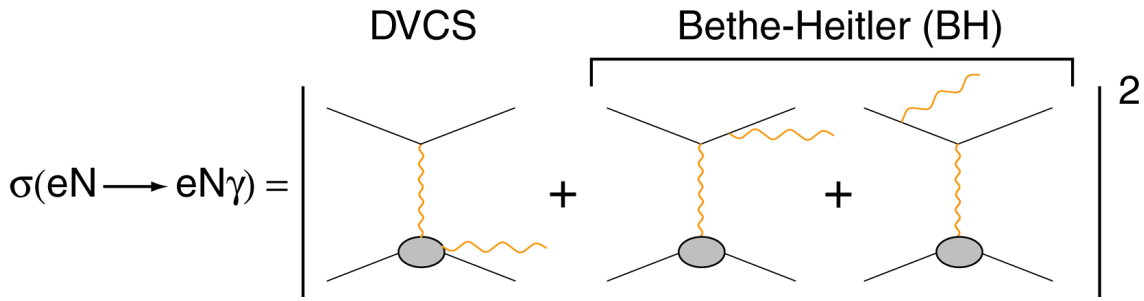
Vector **Tensor** **Axial-vector** **Ps.scalar**

Accessing GPDs through DVCS

$$T^{DVCS} \sim P\int_{-1}^{+1} \frac{GPDs(x,\xi,t)}{x \pm \xi} dx \pm i\pi GPDs(\pm\xi,\xi,t) + \ldots$$

$$Re\mathcal{H}_q = e_q^2 P \int_0^{+1} \left(H^q(x,\xi,t) - H^q(-x,\xi,t)\right)\left[\frac{1}{\xi - x} + \frac{1}{\xi + x}\right] dx$$

$$Im\mathcal{H}_q = \pi e_q^2 \left[H^q(\xi,\xi,t) - H^q(-\xi,\xi,t)\right]$$



Polarized beam, unpolarized target:

$\Delta\sigma_{LU} \sim \sin\phi\ \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E} + \ldots\}$

Unpolarized beam, longitudinal target:

$\Delta\sigma_{UL} \sim \sin\phi\,\mathrm{Im}\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi kF_2\tilde{\mathcal{E}}\}$

Polarized beam, longitudinal target:

$\Delta\sigma_{LL} \sim (A + B\cos\phi)\mathrm{Re}\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) + \ldots\}$

Unpolarized beam, transverse target:

$\Delta\sigma_{UT} \sim \cos\phi\sin(\phi_s - \phi)\mathrm{Im}\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}$

Unpolarized beam and target, different lepton charges:

$\Delta\sigma_C \sim \cos\phi\ \mathrm{Re}\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E} + \ldots\}$

Proton Neutron

$Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$
$Im\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n\}$

$Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$
$Im\{\mathcal{H}_n, \mathcal{E}_n\}$

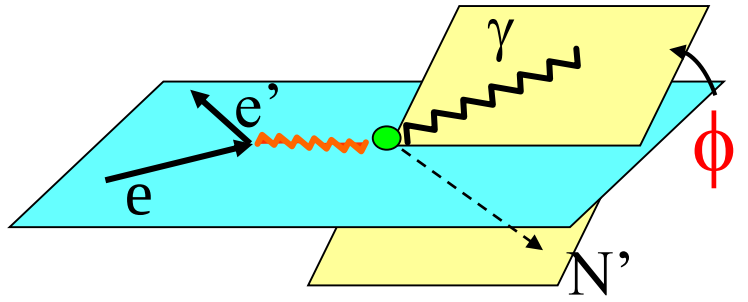
$Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$
$Re\{\mathcal{H}_n, \mathcal{E}_n\}$

$Im\{\mathcal{H}_p, \mathcal{E}_p\}$
$Im\{\mathcal{H}_n\}$

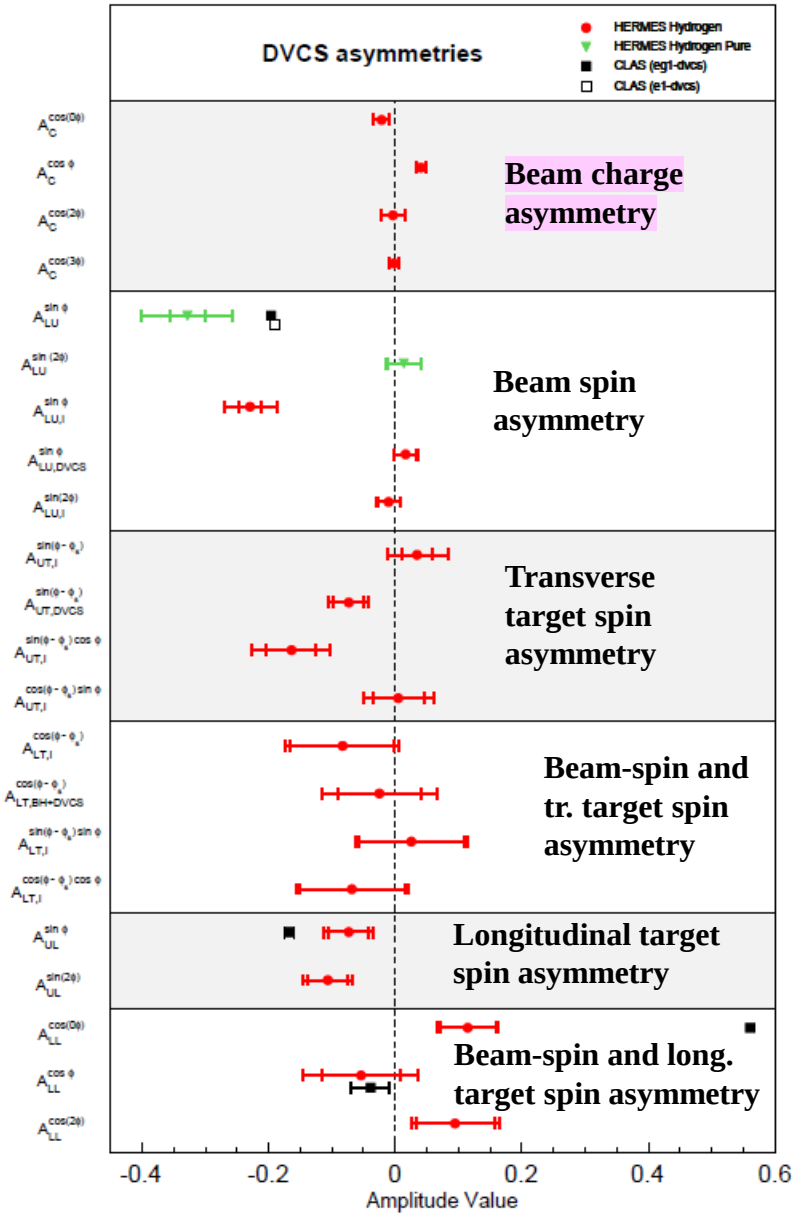
$Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$
$Re\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n\}$

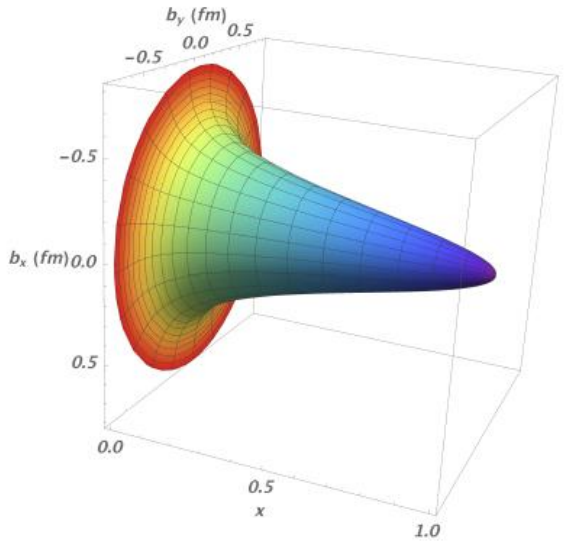
$$\sigma \sim \left|T^{DVCS} + T^{BH}\right|^2$$

$$\Delta\sigma = \sigma^+ - \sigma^- \propto I\left(DVCS \cdot BH\right)$$



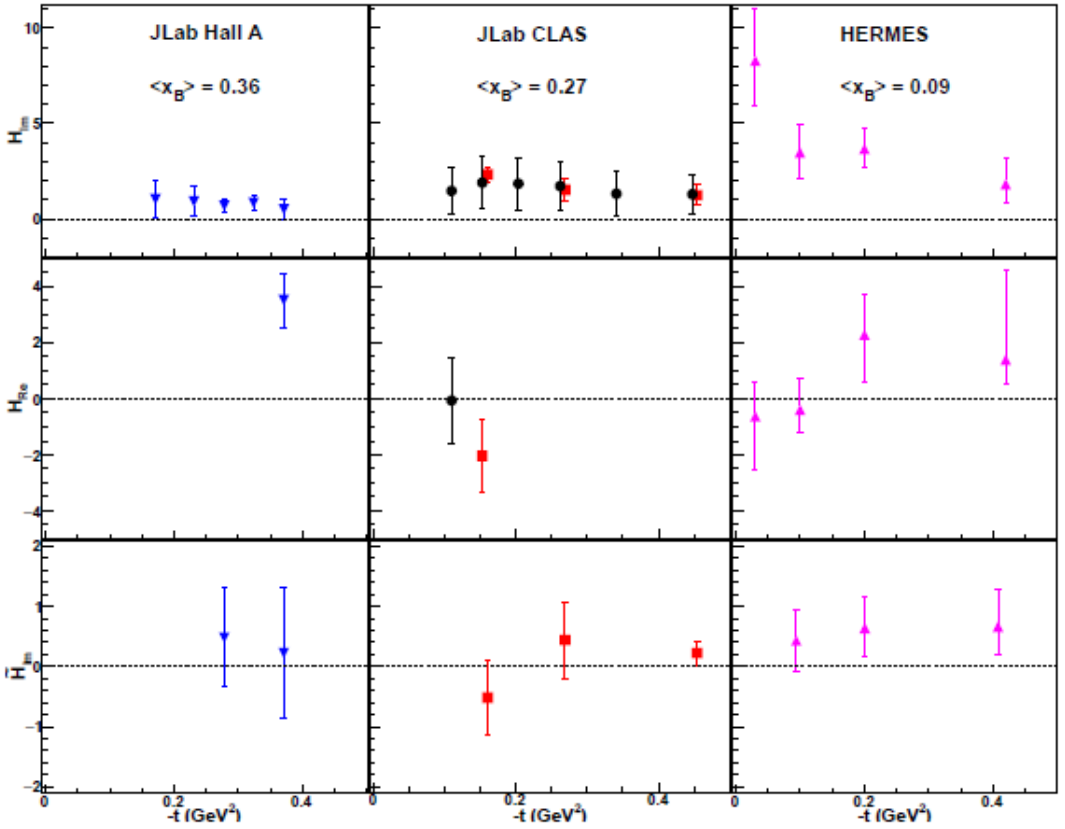
Measured p-DVCS observables and constraints on GPDs





Proton tomography obtained from *local fits* to HERMES, CLAS, and Hall-A data (Im$\mathcal{H}$ + model dependent assumptions for x dependence)

R. Dupré, M. Guidal, M.Vanderhaeghen, PRD95, 011501 (2017)



Hall A (2015)

CLAS C.S.
CLAS C.S. +TSA+DSA

HERMES

Beam Charge Asymmetry: strong constraint for H_{Re}

N. d'Hose, S.N., A. Rostomyan, EPJA 52, 151 (2016)

Distribution of forces in the proton

$$\int xH(x,\xi,t)\,dx = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$$

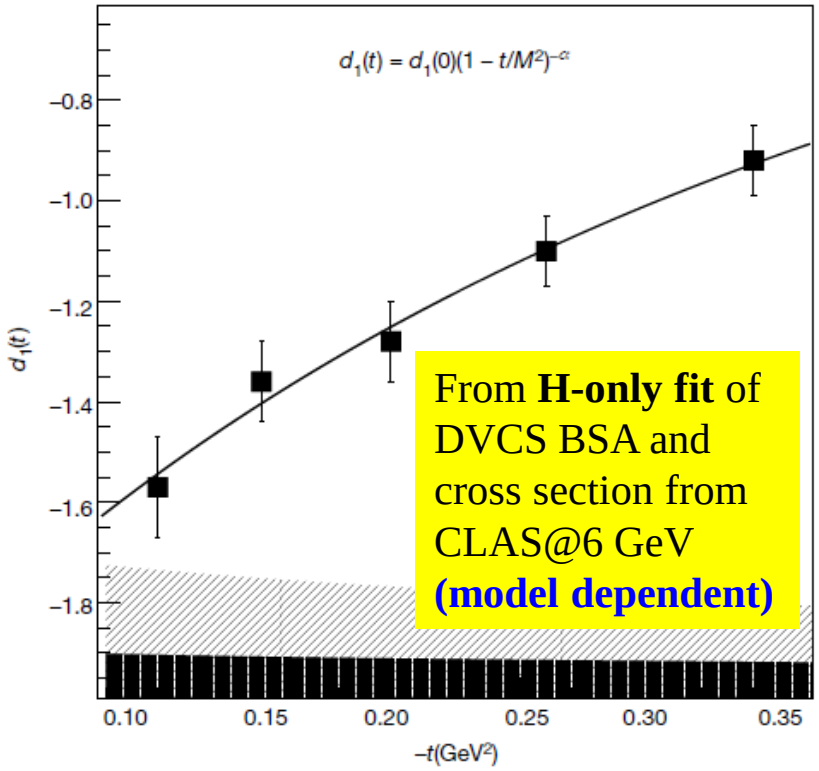
Second Mellin moment of H in x: **gravitational form factor** → shear forces and pressure (d_1)

$$\mathrm{Re}\mathcal{H}(\xi,t) + i\,\mathrm{Im}\mathcal{H}(\xi,t) = \int_{-1}^{1} dx \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right) H(x,\xi,t) \quad (1)$$

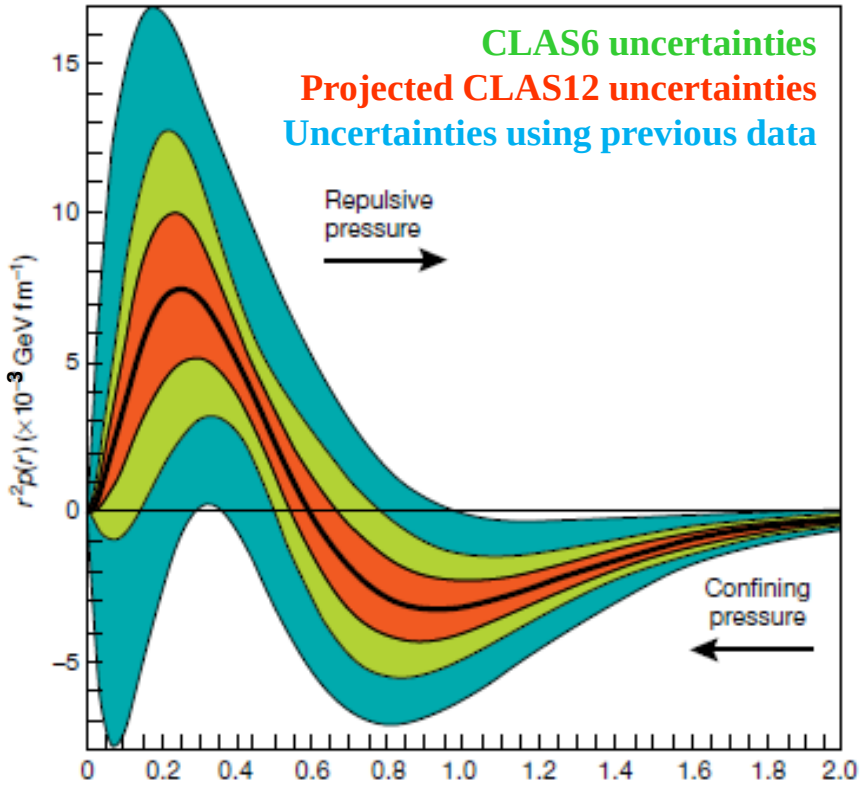
$$\mathrm{Re}\mathcal{H}(\xi,t) \overset{\text{lo}}{=} D(t) + \mathcal{P}\int_{-1}^{1} dx \left(\frac{1}{\xi - x} - \frac{1}{\xi + x}\right) \mathrm{Im}\mathcal{H}(x,t)$$

$$D(t) = \frac{1}{2}\int_{-1}^{1} \frac{D(z,t)}{1-z} dz \qquad D(z,t) = (1-z^2)\left[d_1(t) C_1^{3/2}(z) + \cdots\right]$$

$$d_1(t) \propto \int \frac{j_0(r\sqrt{-t})}{2t} p(r)\, d^3r$$



From **H-only fit** of DVCS BSA and cross section from CLAS@6 GeV **(model dependent)**



V. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557, 396-399 (2018)

JLab@12 GeV DVCS program

Observable (target)	**12-GeV experiments**	**CFF sensitivity**	**Status**
σ, $\Delta\sigma_{beam}(p)$	Hall A CLAS12 Hall C	Re$\mathcal{H}(p)$, Im$\mathcal{H}(p)$	Hall A: data taken in 2016; e-Print: 2201.03714 [hep-ph] CLAS12: data taken in 2018-2019; CS analysis in progress Hall C: experiment planned for 2023-2024
BSA(p)	CLAS12	Im$\mathcal{H}(p)$	BSA publication in Ad Hoc review stage ***M. Defurne's talk, WG5, Tuesday 3PM***
lTSA(p), lDSA(p)	CLAS12	Im$\tilde{\mathcal{H}}(p)$, Im$\mathcal{H}(p)$, Re$\tilde{\mathcal{H}}(p)$, Re$\mathcal{H}(p)$	Experiment will start in June 2022 (6 months)
tTSA(p)	CLAS12	Im$\mathcal{H}(p)$, Im$\mathcal{E}(p)$	Experiment foreseen for ~2025
BSA(n)	CLAS12	Im$\mathcal{E}(n)$	Data taken in 2019-2020, BSA analysis undergoing CLAS review
lTSA(n), lDSA(n)	CLAS12	Im$\mathcal{H}(n)$, Re$\mathcal{H}(n)$	Experiment will start in June 2022 (6 months)

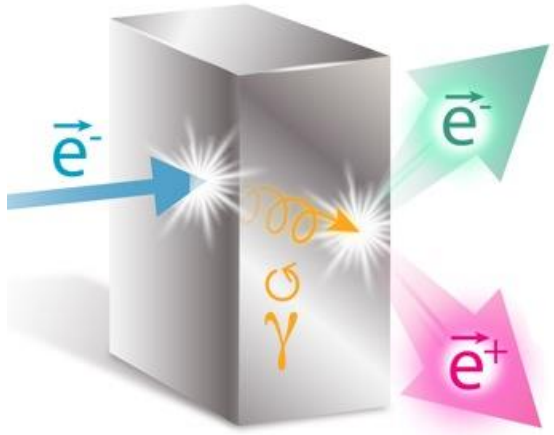
Complementarity of the experimental setups in the JLab Halls A/C and B

- Hall A/C: high luminosity → precision, small kinematic coverage, eγ topology
- Hall B (CLAS12): lower luminosity, large kinematic coverage, fully exclusive final state

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 ***(X. Zheng's talk, Wed 6:10PM)***



PePPO: proof-of-principle for a polarized positron beam
PRL 116 (2016) 214801

Reza Kazimi's talk, Tuesday 10:40AM

- 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 (target heating, collection system, emittance filter, injection into CEBAF, radiation environment, civil construction, cost…) towards the development of a prototype and a CDR.

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 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**

σ: polarization independent CS
σ̃: polarization dependent CS

Physics goal: beam-charge asymmetry for **DVCS** with polarised electrons and positrons **→ separation of DVCS and DVCS-BH interference amplitudes, sensitivity to real part of GPDs**

$$A^{C}_{UU} = \frac{(Y^{+}_{+} + Y^{+}_{-}) - (Y^{-}_{+} + Y^{-}_{-})}{Y^{+}_{+} + Y^{+}_{-} + Y^{-}_{+} + Y^{-}_{-}} = \frac{\sigma_{INT}}{\sigma_{BH} + \sigma_{DVCS}}$$

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

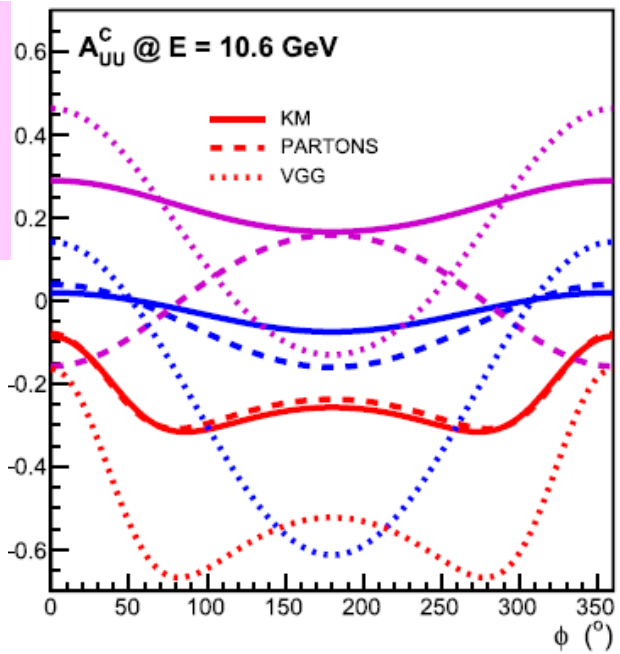
$$A^{0}_{LU} = \frac{(Y^{+}_{+} + Y^{-}_{+}) - (Y^{+}_{-} + Y^{-}_{-})}{Y^{+}_{+} + Y^{+}_{-} + Y^{-}_{+} + Y^{-}_{-}} = \frac{\tilde{\sigma}_{DVCS}}{\sigma_{BH} + \sigma_{DVCS}}$$

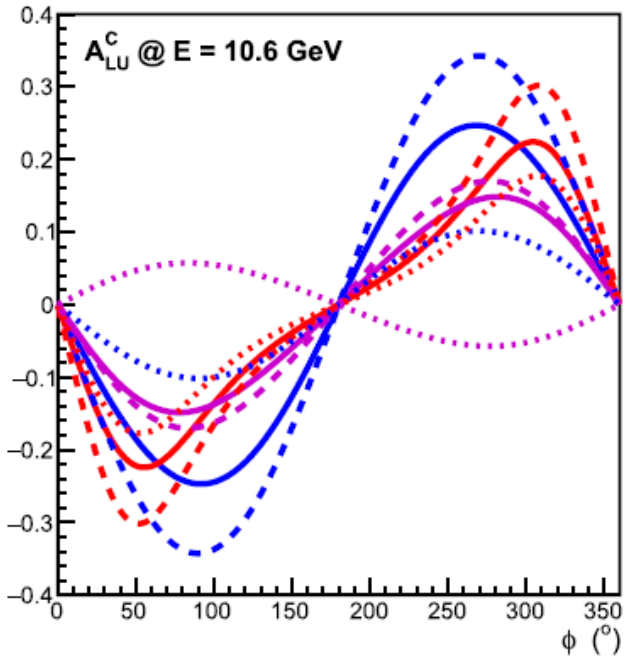
$$\text{☛}\quad A^{C}_{LU} \neq A^{\pm}_{LU} = \frac{\pm(\tilde{\sigma}_{INT} \pm \tilde{\sigma}_{DVCS})}{\sigma_{BH} + \sigma_{DVCS} \pm \sigma_{INT}}$$

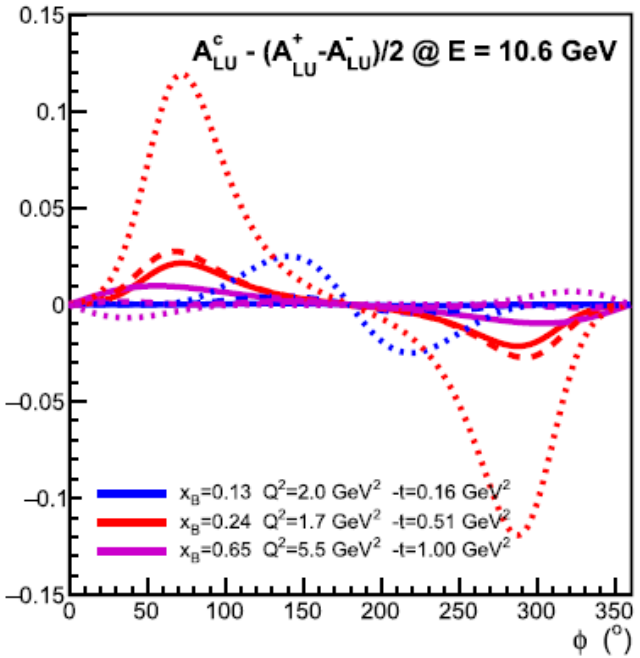
pDVCS with polarized positrons beam at CLAS12

PR12-20-009
V. Burkert, L. Elouadrhiri, F.X. Girod, S. N., E. Voutier *et al.*
Conditionally approved

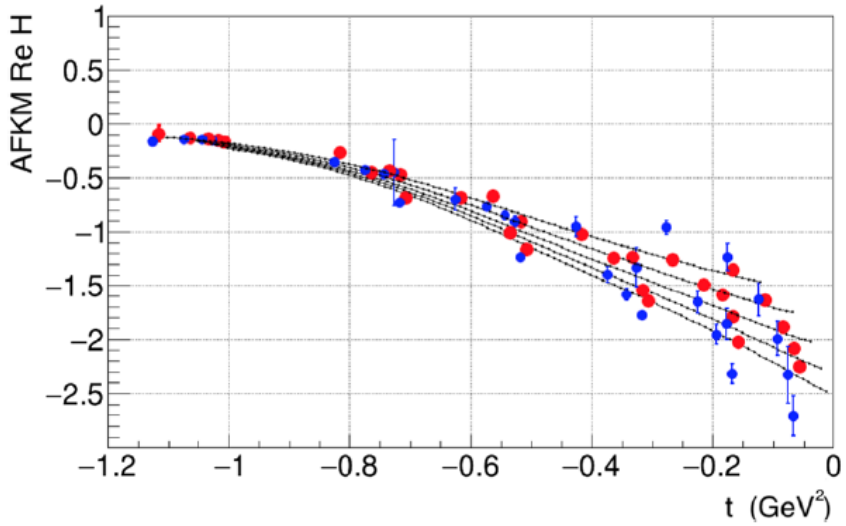
Model predictions for the three observables

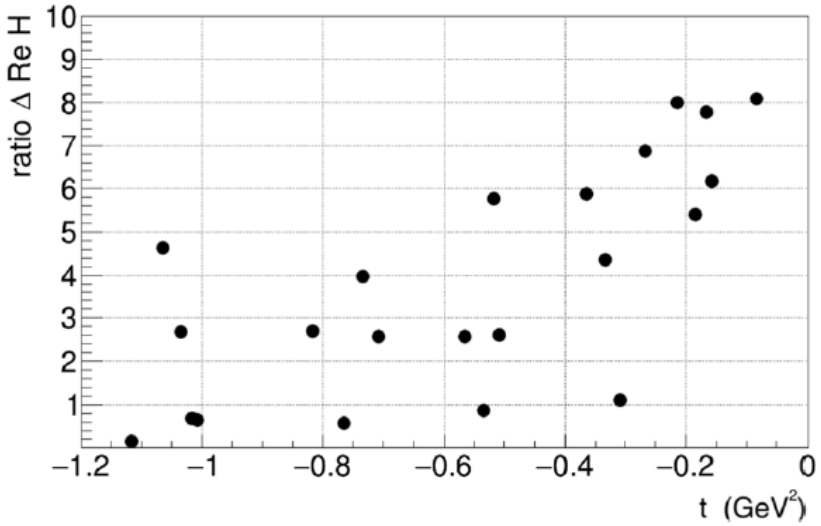






Impact of positron projected data on the extraction of Re$\mathcal{H}$ via global fits, model dependent ($\mathcal{H}$ and $\widetilde{\mathcal{H}}$ only):
→ major reduction of relative uncertainties, especially at low -t



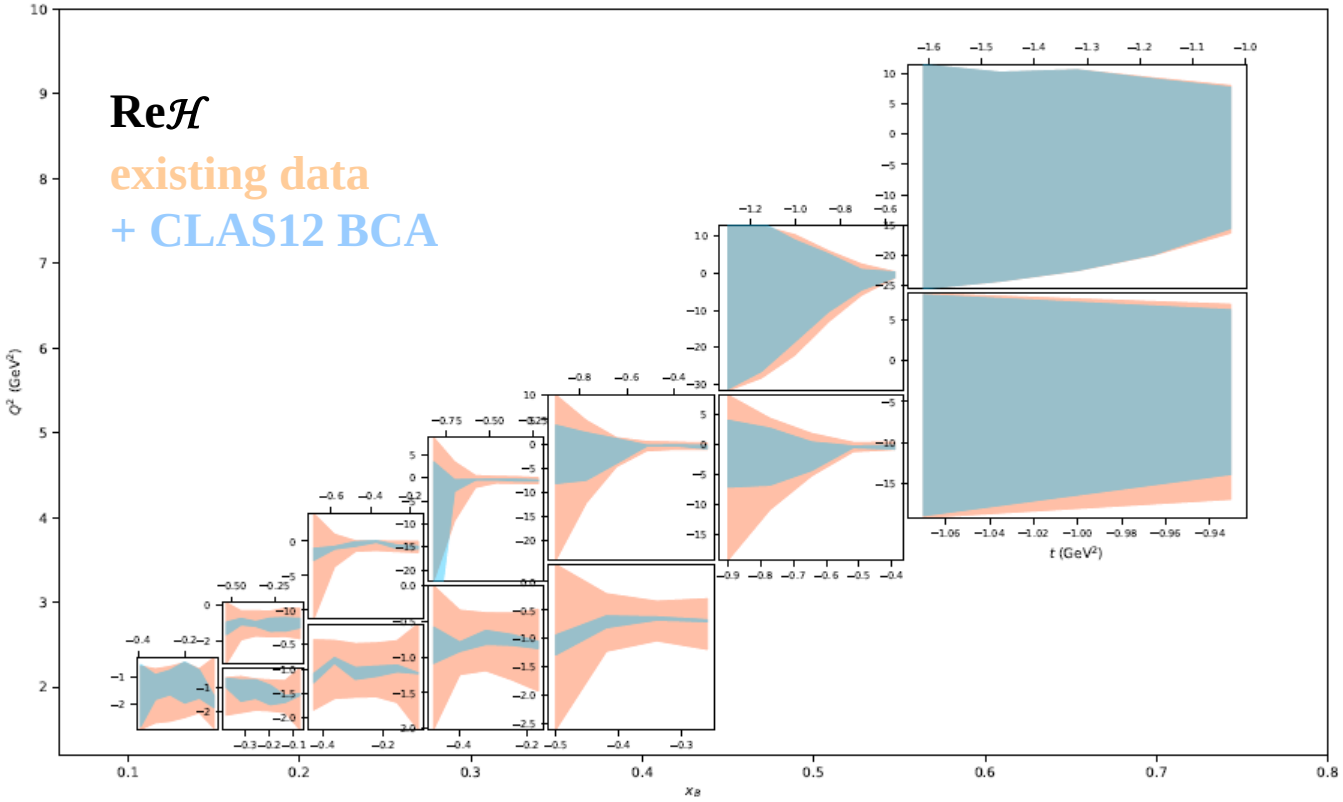


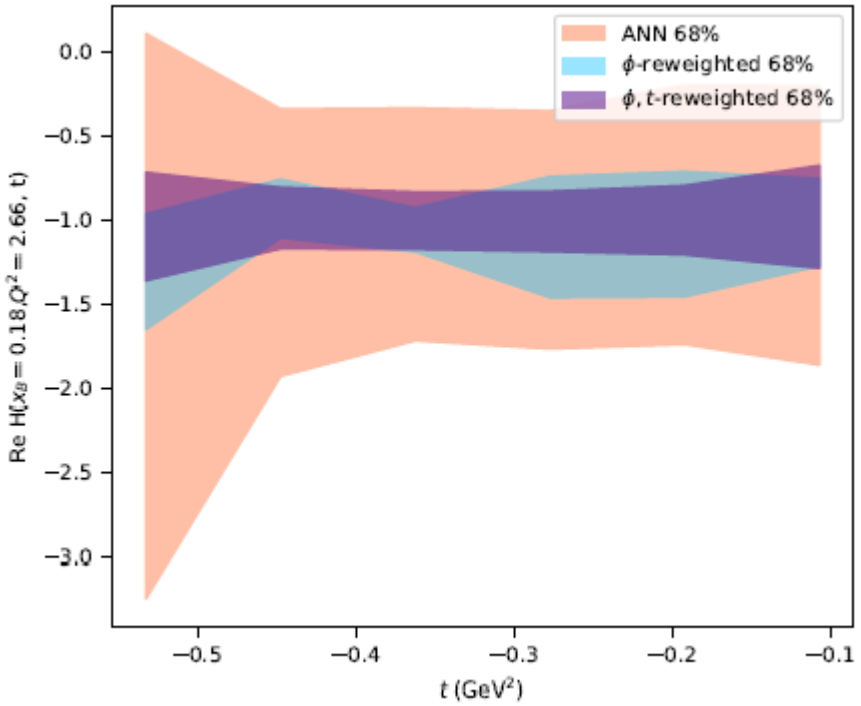
V. Burkert et al., Eur. Phys. J. A 57 (2021) 57, 186

Impact study of CLAS12 pDVCS BCAs on CFF fits

- Artificial neural network (ANN)-based **extractions of DVCS CFFs in a global analysis** of experimental data collected with proton targets: ~30 DVCS observables measured in >2600 kinematic points by Hall-A, CLAS, HERMES, COMPASS, ZEUS and H1, over a wide phase-space.

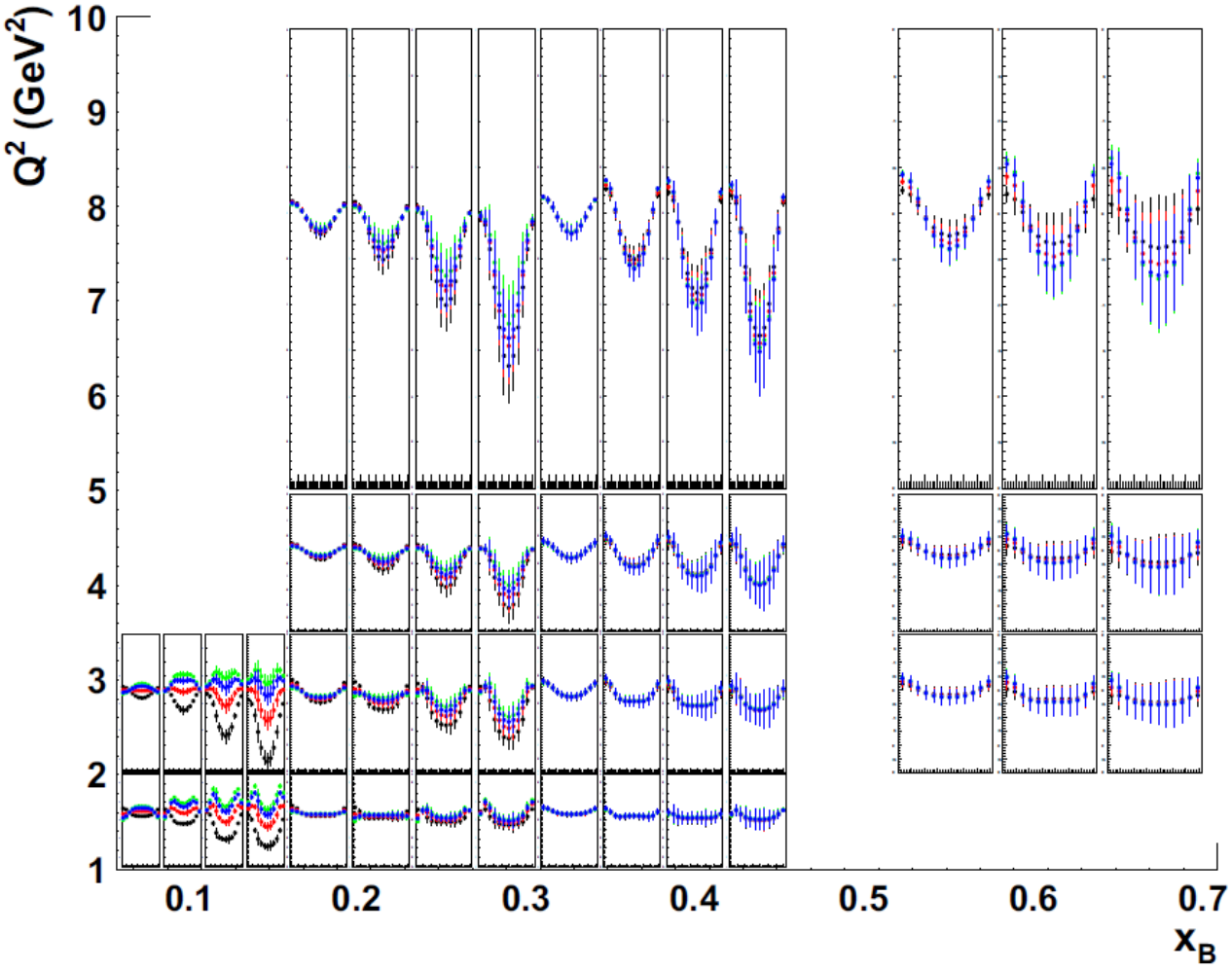
- **Bayesian reweighting analysis** to evaluate how the projected **CLAS12 beam-charge asymmetries** would improve the determination of the CFFs obtained from the global fit with ANNs





V. Dutrieux, V. Bertone, H. Moutarde, P. Sznajder, Eur. Phys. J. A 57 (2021) 8, 250

nDVCS with polarized positrons beam at CLAS12

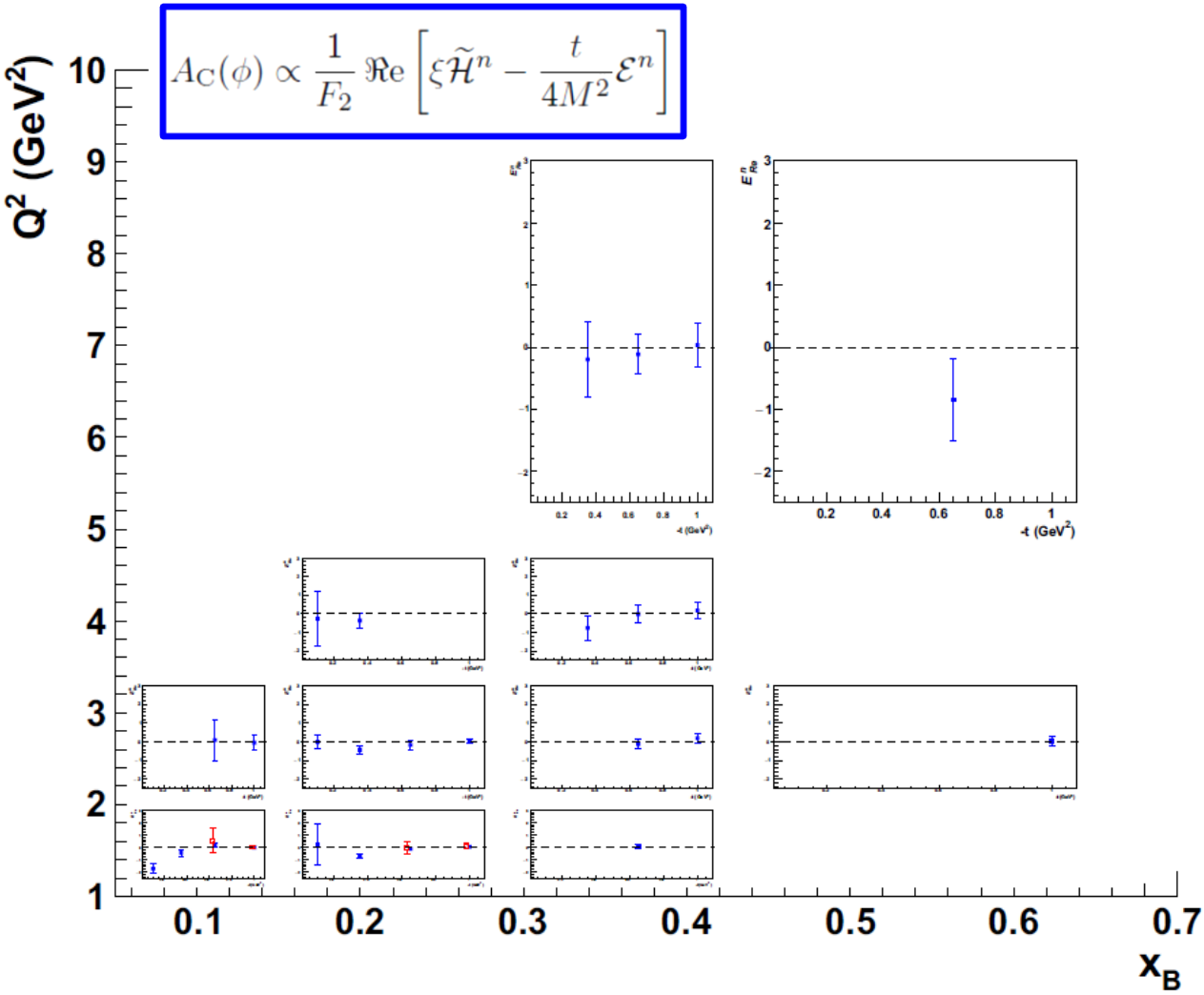


Projections (VGG) for the BCA, for various values of J_u, J_d

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

$$A_C(\phi) \propto \frac{1}{F_2} \Re e \left[\xi \widetilde{\mathcal{H}}^n - \frac{t}{4M^2} \mathcal{E}^n \right]$$



Impact on the extraction of $Re\mathcal{E}$ using local fits, fitting the projections of all approved CLAS12 nDVCS measurements with and without BCA

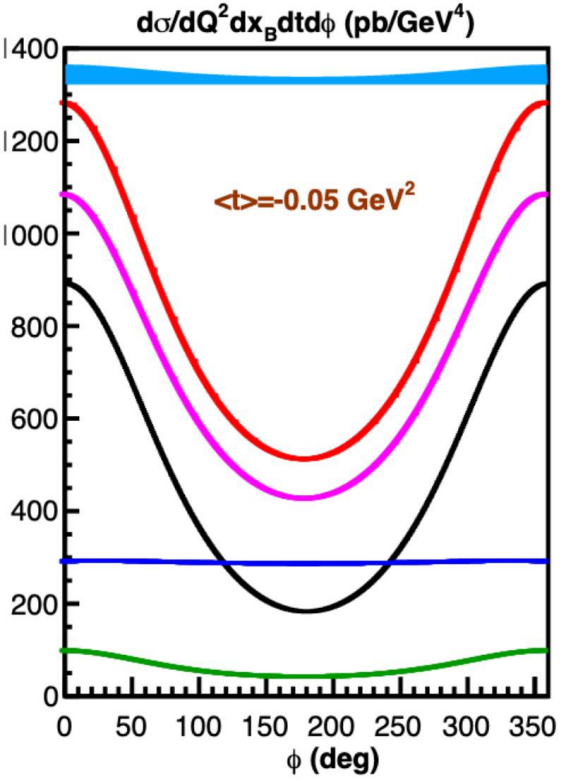
pDVCS with polarized positrons beam in Hall C

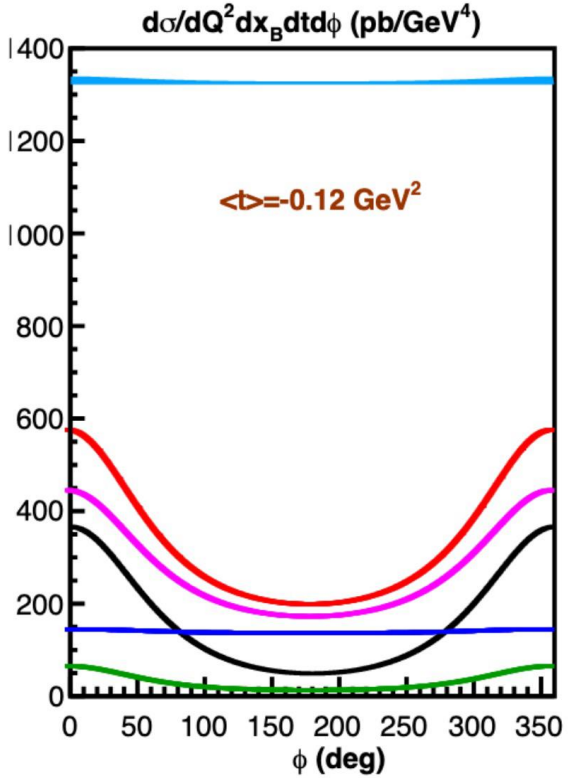
Combining the HMS and the NPS spectrometers, precise DVCS cross section measurements with unpolarized positron beam will be performed at selected kinematics where electron beam data will soon be accumulated.

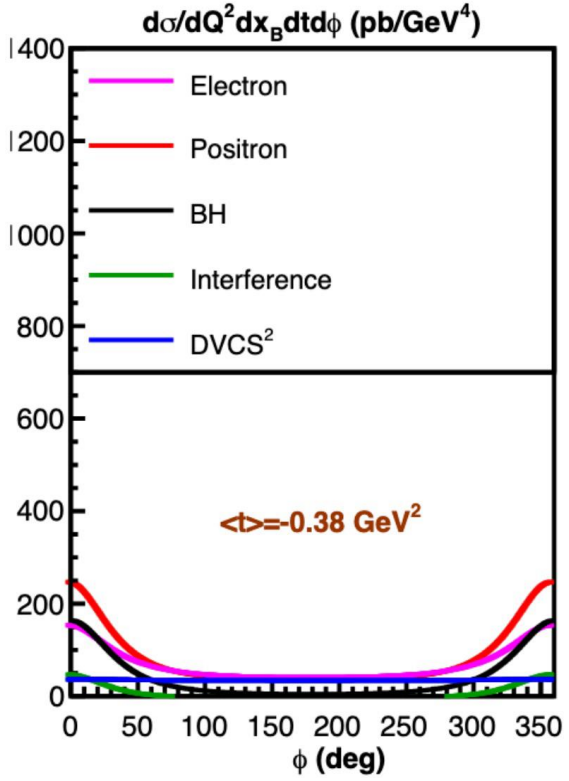
PR12-20-012
J. Grames, M. Mazouz, C. Muñoz Camacho et al.
Conditionally approved

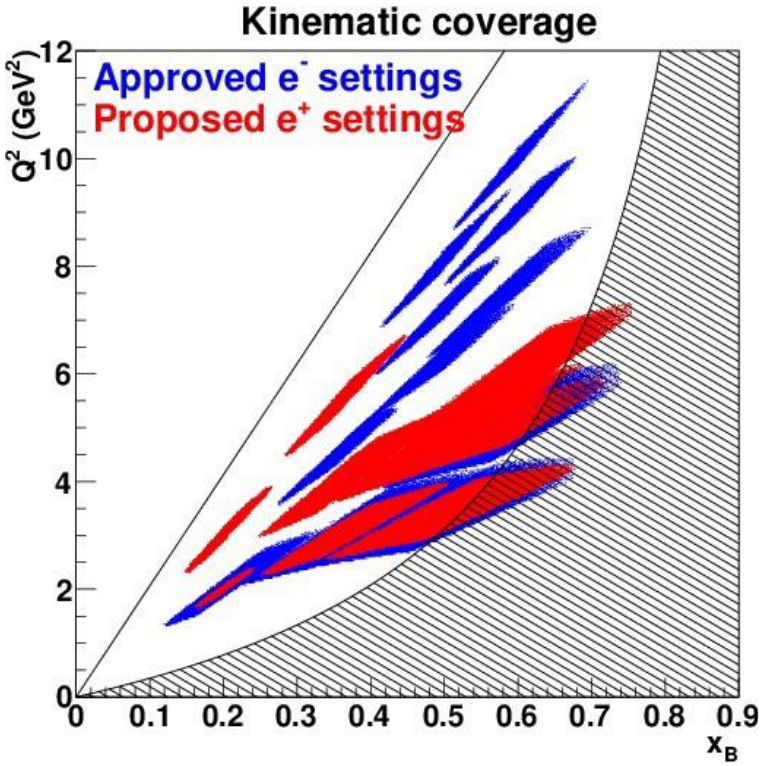
x_B = 0.5 Q^2 = 3.4 GeV^2

A. Afanasev et al, Eur. Phys. J. A 57 (2021) 10, 300

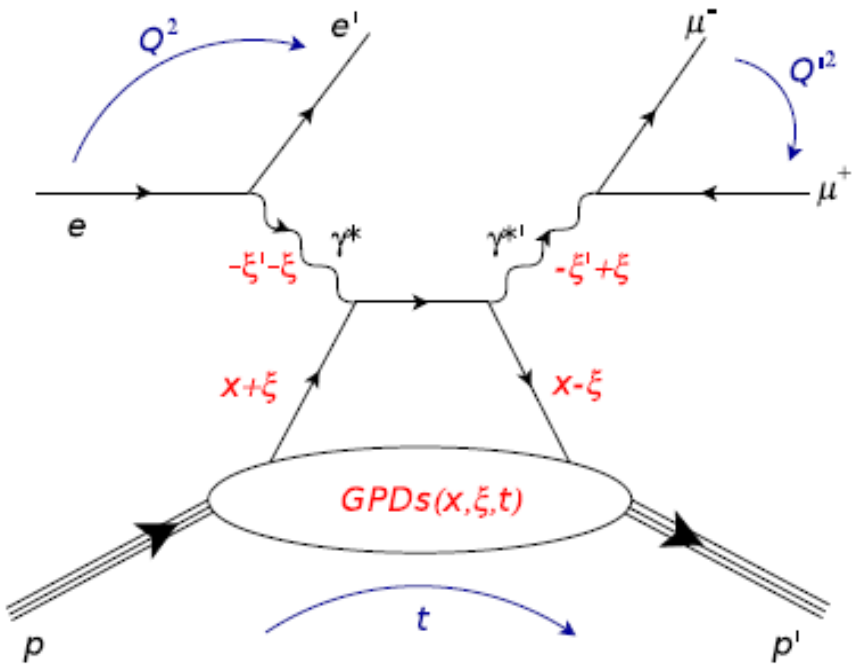


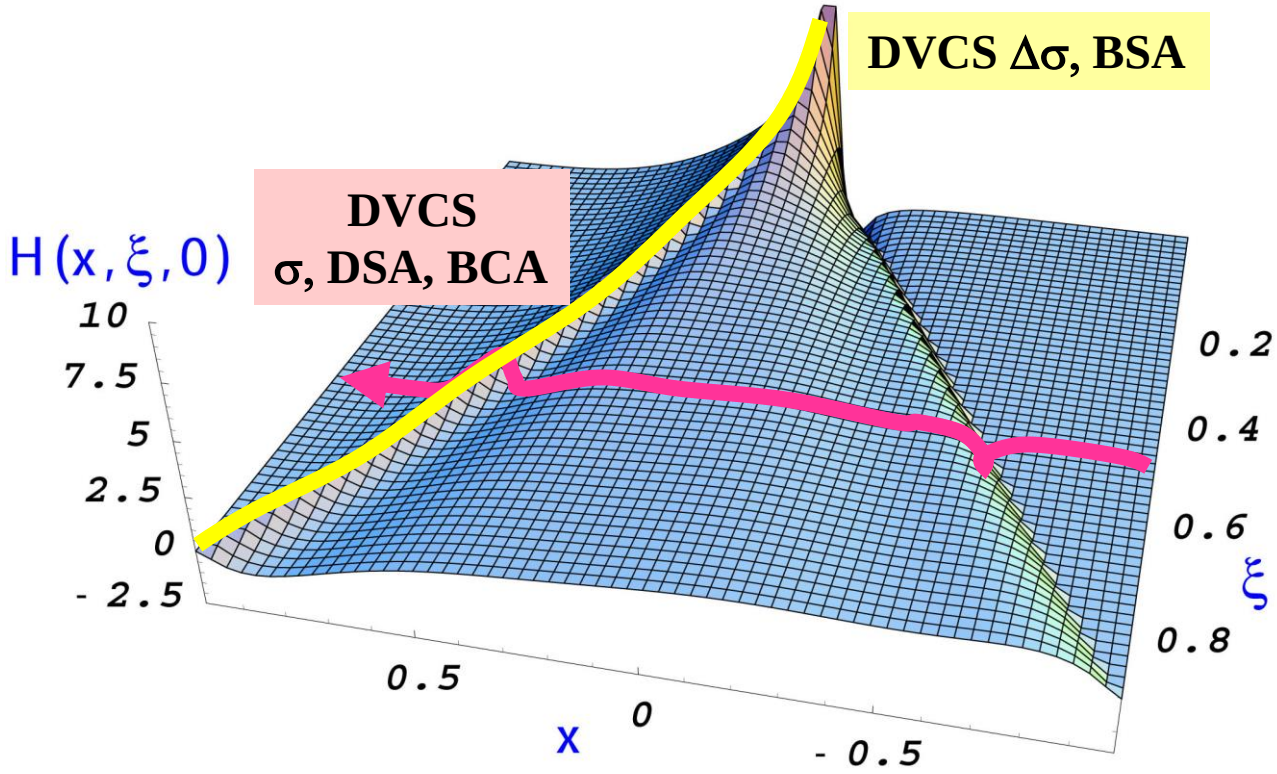






DDVCS: the gateway to the full kinematic mapping of GPDs





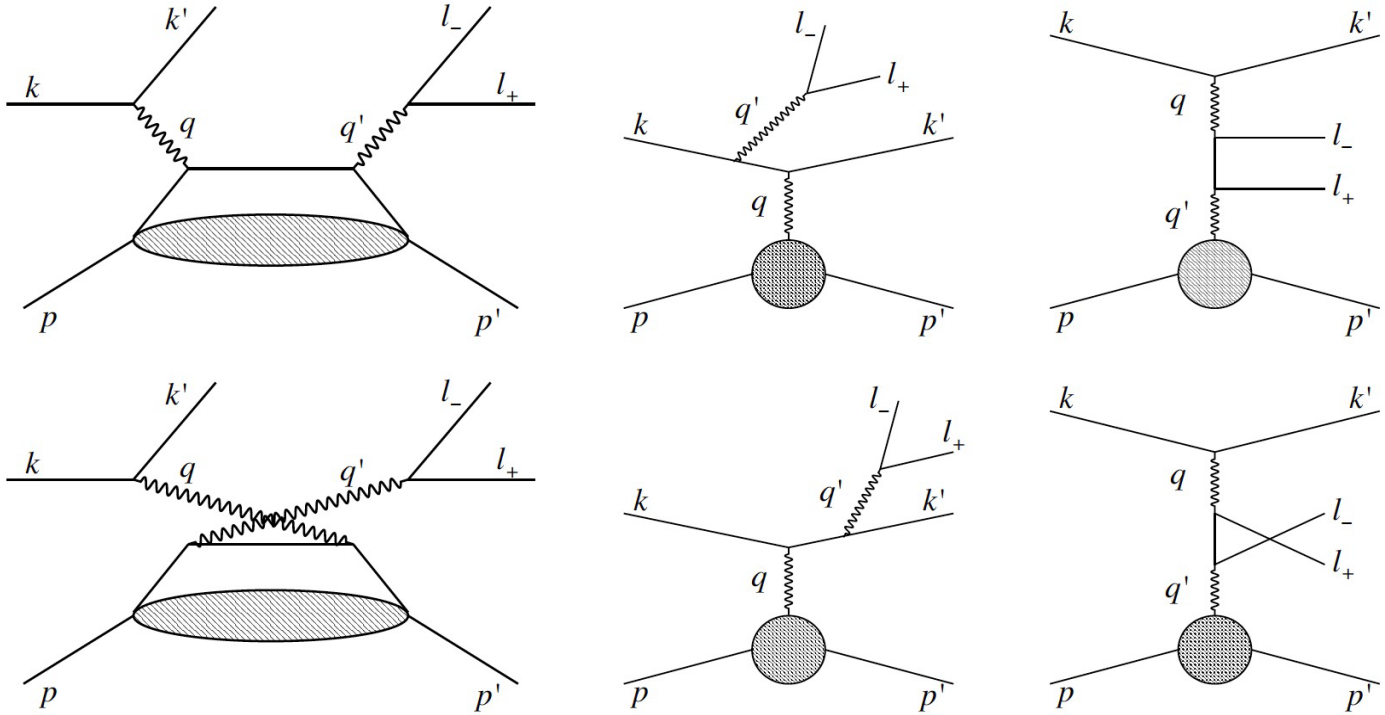
Thanks to the virtuality of the final photon, Q'^{2}, **DDVCS** allows a unique direct access to GPDs at $x \neq \pm\xi$ (within $0 < 2\xi' - \xi < \xi$), which is fundamental for their modeling

Experimental challenges:

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

N(e,e′l^+l^-N) differential cross section

The lepto-production of a lepton-pair off the nucleon involves one additional Bethe- Heitler like mechanism. Integrating over the lepton-pair angles provides a beam charge and polarization dependence similar to DVCS, and INT_2 and BH_{12} terms vanish.

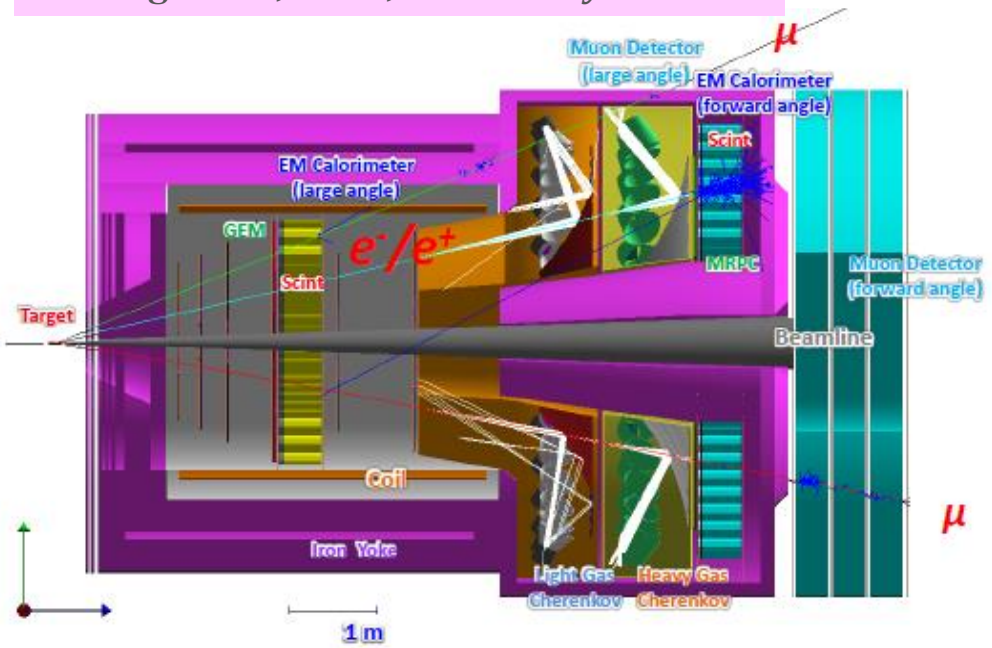


$$d^7\sigma_P^e = d^7\sigma_{BH_1} + d^7\sigma_{BH_2} + d^7\sigma_{DDVCS} + \mathrm{P}\, d^7\tilde{\sigma}_{DDVCS} - e\left[d^7\sigma_{BH_{12}} + d^7\sigma_{INT_1} + \mathrm{P}\, d^7\tilde{\sigma}_{INT_1}\right] + d^7\sigma_{INT_2} + \mathrm{P}\, d^7\tilde{\sigma}_{INT_2}$$

$$d^5\sigma_P^e = d^5\sigma_{BH_1} + d^5\sigma_{BH_2} + d^5\sigma_{DDVCS} + \mathrm{P}\, d^5\tilde{\sigma}_{DDVCS} - e\left[d^5\sigma_{INT_1} + \mathrm{P}\, d^5\tilde{\sigma}_{INT_1}\right]$$

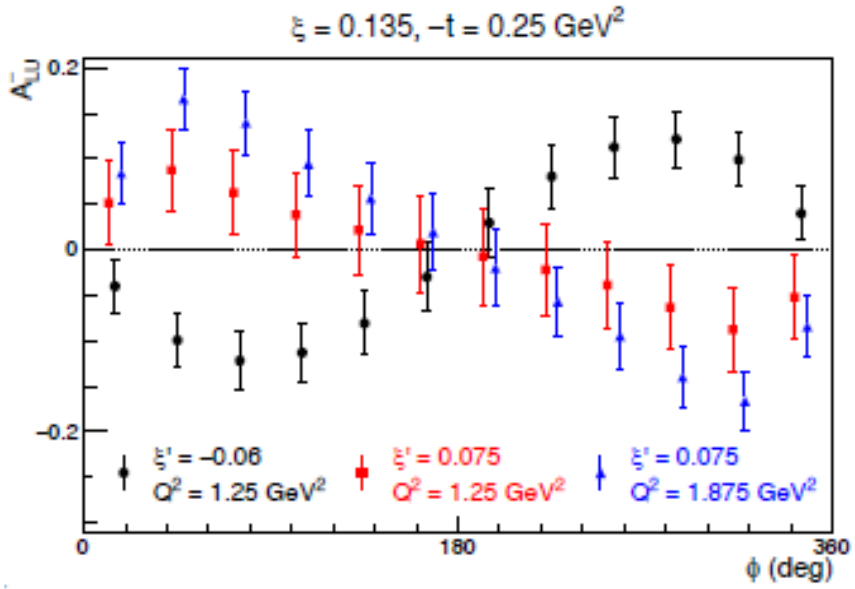
DDVCS with the SOLID detector

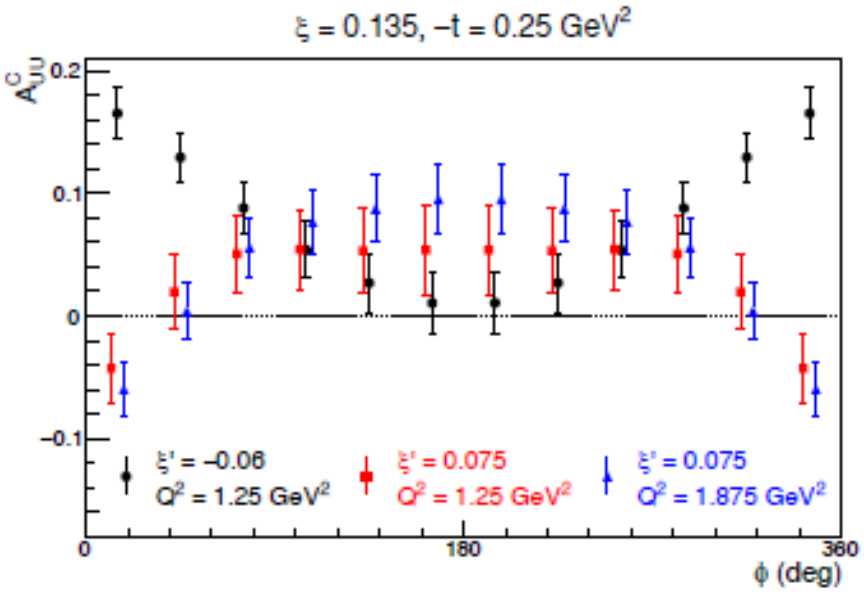
C. Peng's talk, WG6, Wednesday 5:50PM



S. Zhao et al., Eur. Phys. J.A 57 (2021) 7, 240

- The SoLID apparatus completed with muon detectors at large and forward angles, would allow DDVCS measurements with both polarized electron and polarized positron beams.
- The initial LoI discussed electron BSA measurements over a 50 days run parasitic to the J/ψ approved experiment.
- Completing this program with a 50 days positron beam run would provide unpolarized BCA data.

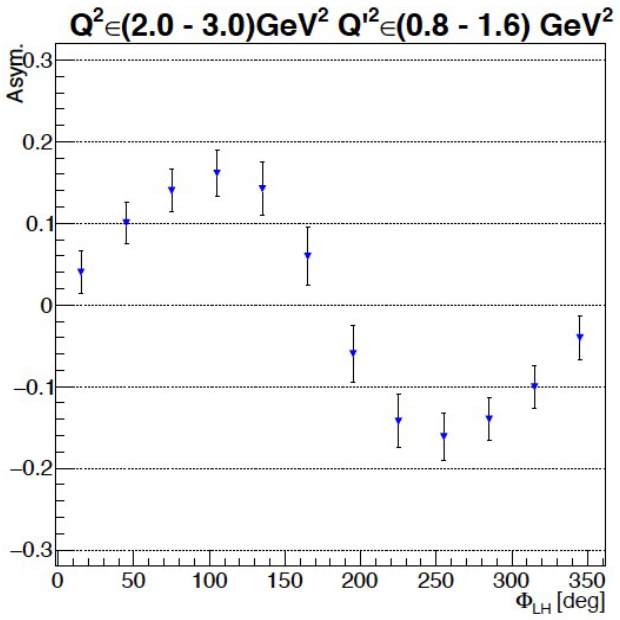


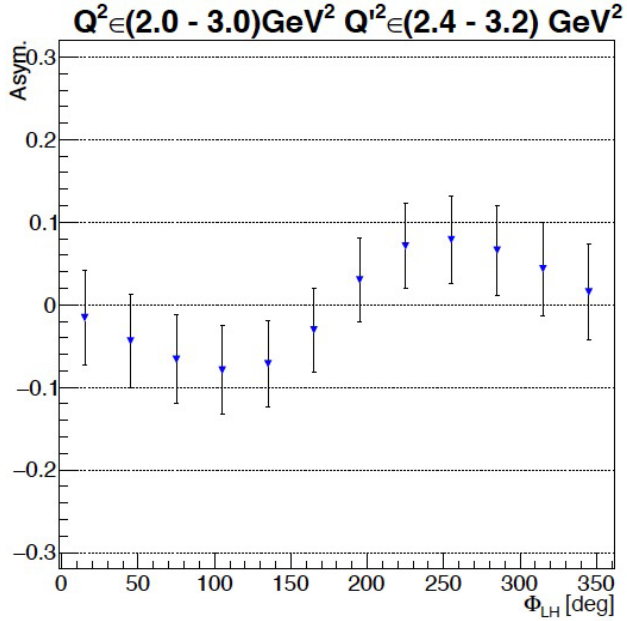


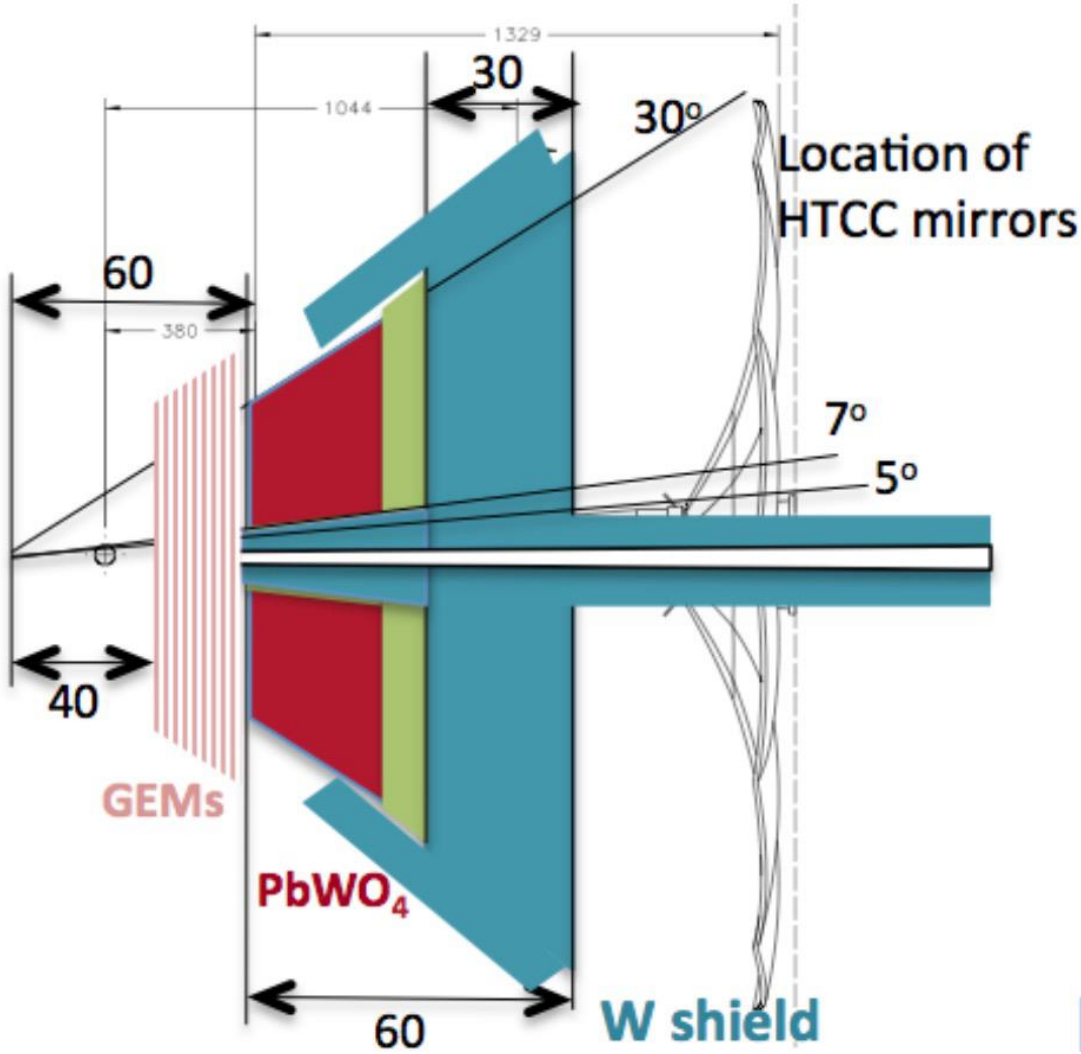
μCLAS12 for DDVCS and J/psi (LOI12-16-004)

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

- A modified CLAS12 spectrometer with a new tracker, a new calorimeter and a tungsten shield in the HTCC working volume would allow to increase CLAS12 luminosity up to $10^{37} cm^{-2}\ s^{-1}$.
- The new detection system will serve electron identification.
- The CLAS12 forward detector will act as a muon detector.
- This reconfigured CLAS12 spectrometer would measure DDVCS and J/ψ electroproduction over a 100 days run.







S. Stepanyan's talk, WG6, Wednesday 5:10PM

Conclusions

A rich and high-impact experimental program to study nucleon structure by means of Generalized Parton Distributions has been developed, requiring a polarized-positrons beam at JLab

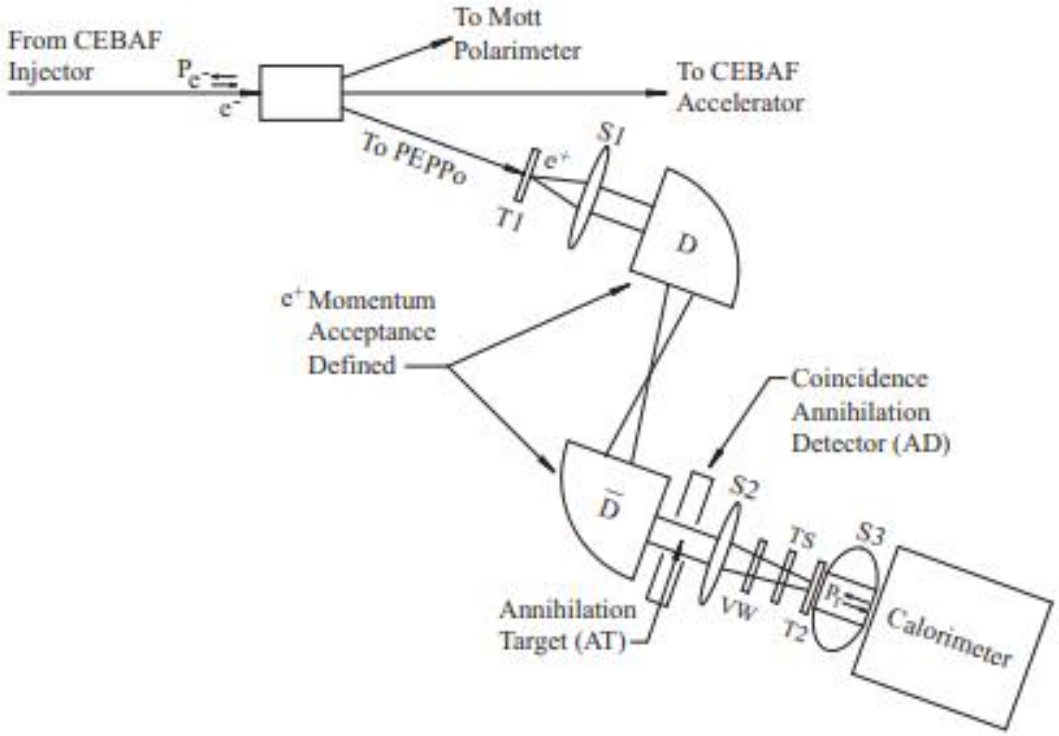
e^+@JLab Topical Issue of EPJ A just published

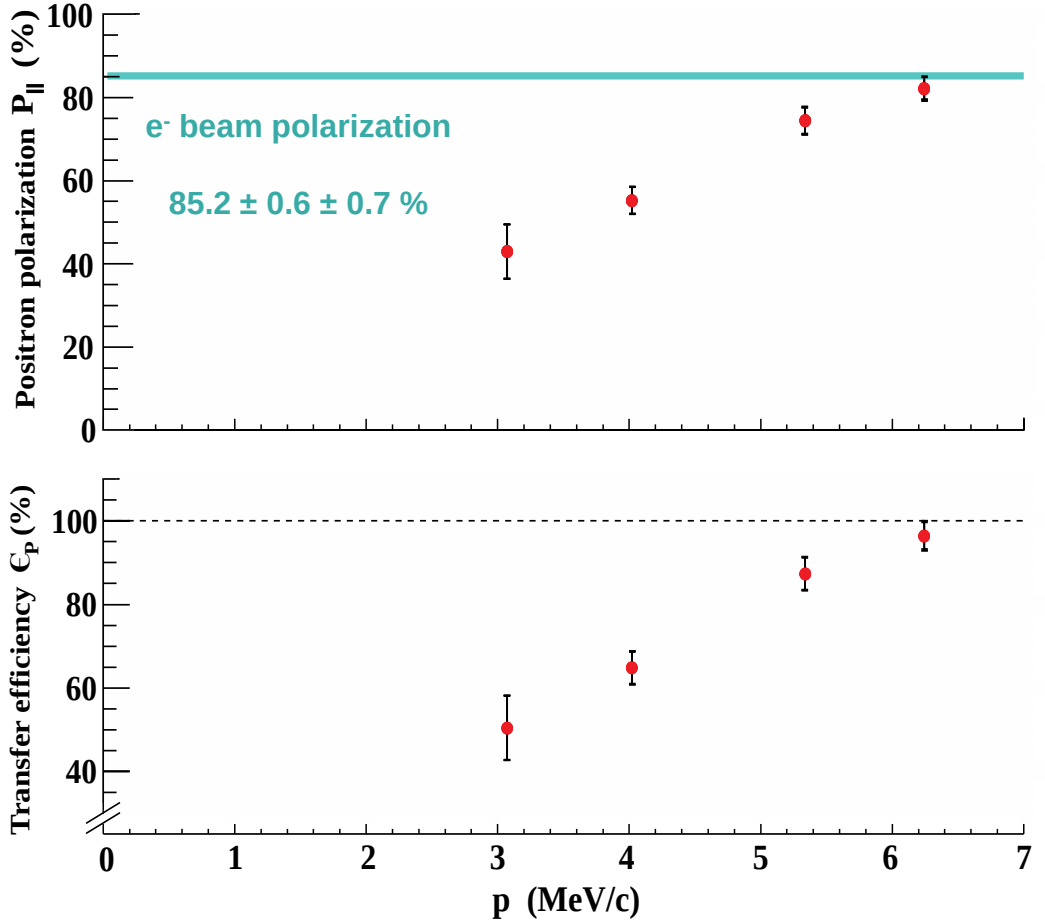
- In the DVCS and DDVCS channels, e^+ beams enable:
  - an undisputable separation of the INT amplitudes
  - a direct access to the real part of CFFs
  - a window to study HT and NLO effects.

Back-up slides

PEPPo: Polarized Electrons for Polarized Positrons

The PEPPo experiment at the CEBAF injector has shown an effective polarization transfer between electrons and positrons. It opens the possibility to produce polarized positrons with accelerators ~MeV

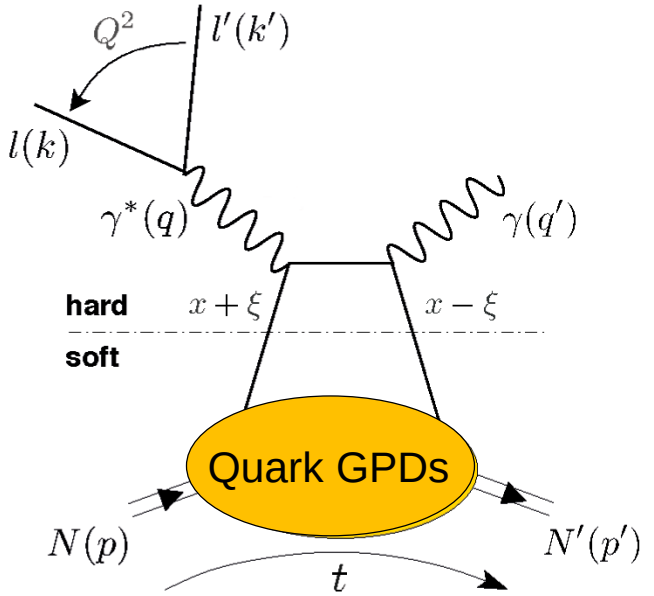




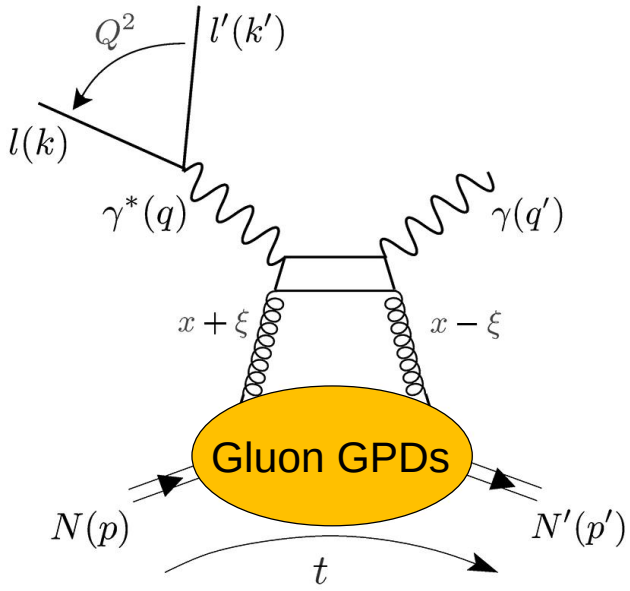
D. Abbott et al., PRL 116 (2016) 214801

Editor's choice, Physics Focus

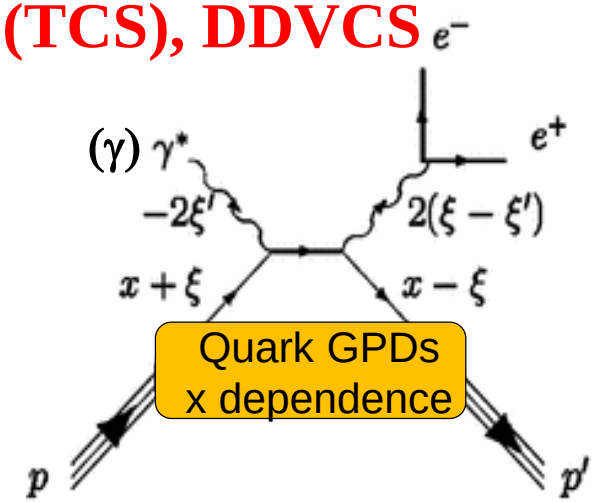
Exclusive reactions giving access to GPDs

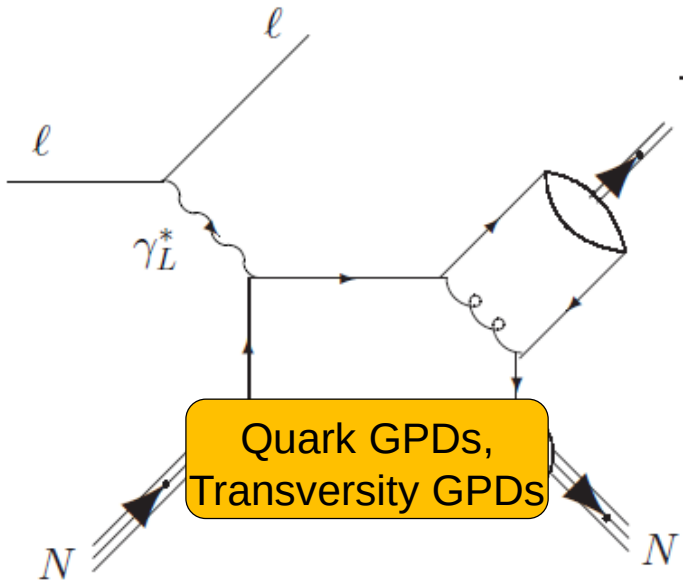


DVCS



(TCS), DDVCS





DVMP