Studies of GPDs (and Time-like Compton Scattering) at Jefferson Lab

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Jefferson Lab
Thomas Jefferson National Accelerator Facility

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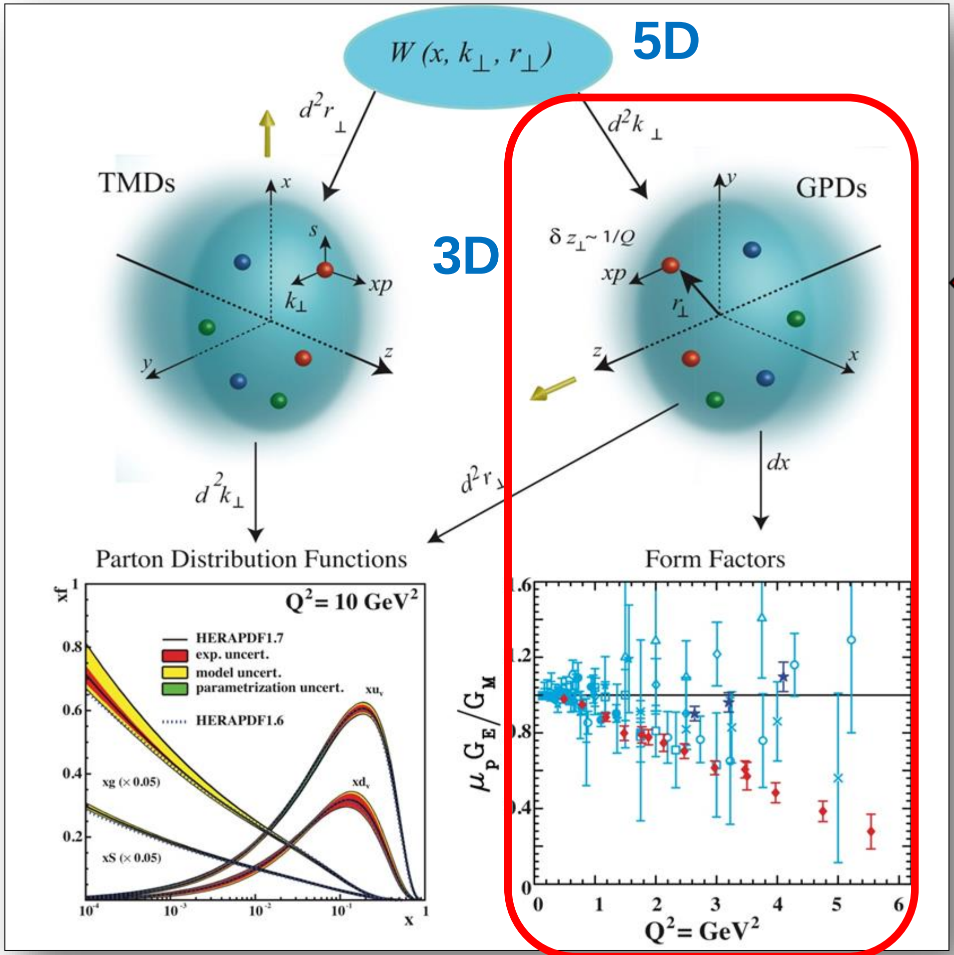
The 3D Nucleon Structure

Generalised Parton and Transverse Momentum Distributions are essential for our understanding of internal hadron structure and the dynamics that bind the most basic elements of Nuclear Physics



- TMDs
  - Confined motion in a nucleon (semi-inclusive DIS)

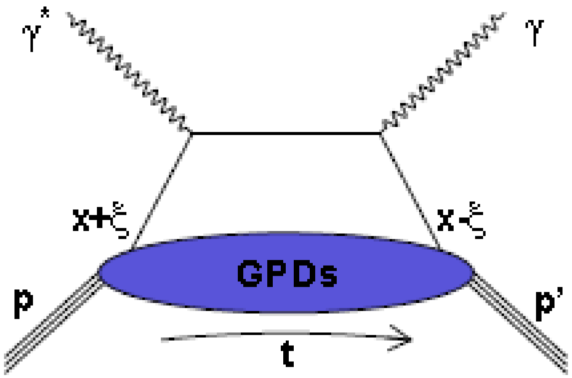
- GPDs
  - Spatial imaging (exclusive DIS)

- Requires
  - High luminosity
  - Polarised beams and targets
  - Sophisticated detectors

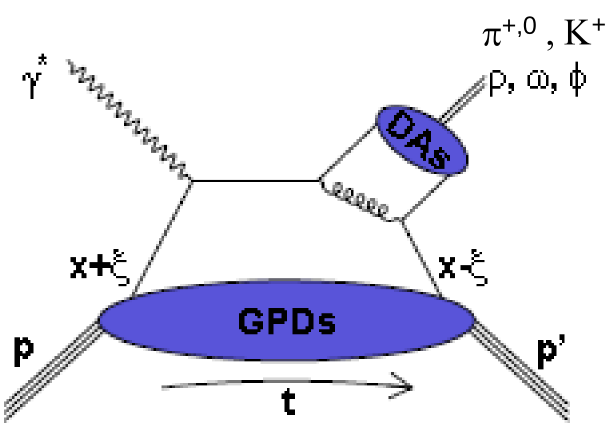
Major new capability with JLab12

QCD Factorisation in Deep Exclusive Processes

The key to extracting GPDs from experiment are QCD factorisation theorems



- At sufficiently high Q^2, the process should be understandable in terms of the "handbag" diagram – can be verified experimentally
  - The non-perturbative (soft) physics is represented by the GPDs



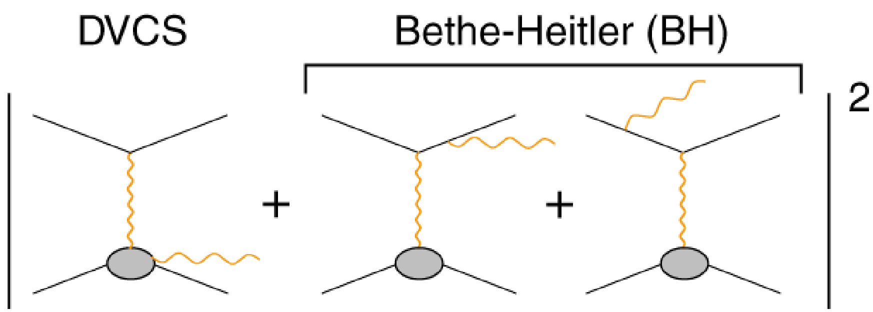
Handbag diagram

- DVMP: Shown to factorise from QCD perturbative processes for longitudinal photons *[Collins, Frankfurt, Strikman, 1997]*
  - Factorisation theorem predicts σ_L scales in this regime as Q^{-6}

Experimental Access to GPDs: DVCS

Deep Virtual Compton Scattering (DVCS)

$\sigma(ep \longrightarrow ep\gamma) =$



DVCS is the cleanest way to probe GPDs

- As the DVCS process interferes with BH one can access the DVCS amplitudes

At leading twist: (L/T interference gives specific cos/sin ϕ-dependence)

$$d^5 \overrightarrow{\sigma} - d^5 \overleftarrow{\sigma} = \Im m \left(T^{BH} \cdot T^{DVCS}\right)$$

$$d^5 \overrightarrow{\sigma} + d^5 \overleftarrow{\sigma} = |BH|^2 + \Re e \left(T^{BH} \cdot T^{DVCS}\right) + |DVCS|^2$$

- GPDs show up in integrals – definitions are related to helicity of quarks/gluons

$$T^{DVCS} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x - \xi + i\epsilon} + \dots =$$

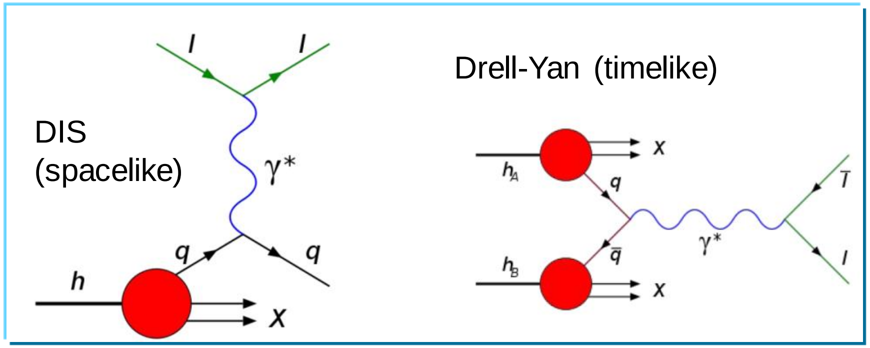
$$\underbrace{\mathcal{P} \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x - \xi}} \quad - \quad \underbrace{i\pi \, H(x=\xi,\xi,t)} \quad + \dots$$

Access in helicity-independent cross section

Access in helicity-dependent cross-section

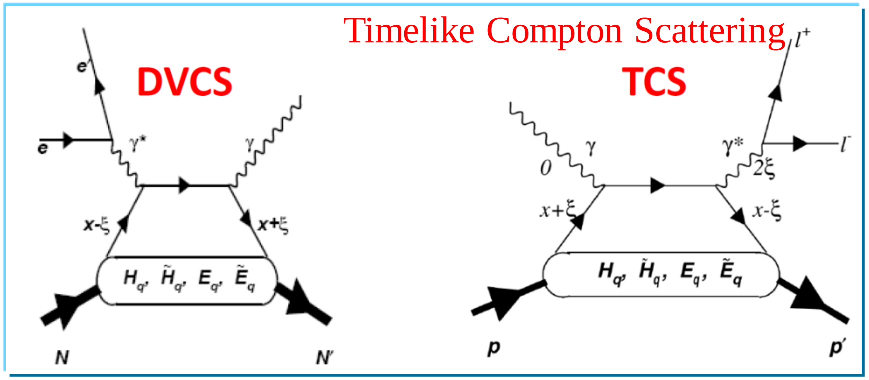
Testing Universality of GPDs: TCS

- Spacelike DIS and timelike Drell-Yan processes both factorise into partonic cross section and a Parton Distribution Function (PDF)
  - Measurement of both demonstrated the universality of PDFs



- For DVCS there is a similar factorisation at the amplitude level into a perturbative coefficient function and a Generalised Parton Distribution (GPD)
  - Amplitudes are related, but differ significantly at next to leading order

[H.Moutarde et al., PRD87 (2013) no.5, 054029]



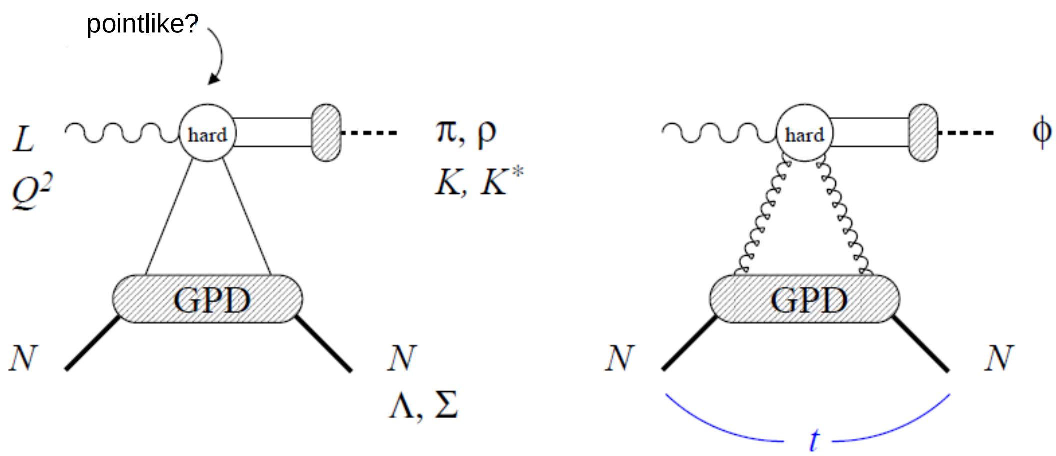
$Q'^2 = M^2_{e^+e^-}$ is in TCS the virtuality of the outgoing photon, which gives the hard scale

Timelike and spacelike cases are complementary - their differences deserve special attention

Towards spin-flavor separation: DVMP

Deep Virtual Meson Production (DVMP)

Exclusive Reactions: $\gamma^* N \rightarrow M + B$



- Nucleon structure described by 4 (helicity non-flip) GPDs:
  - *H, E* (unpolarised), $\tilde{H}, \tilde{E}$ (polarised)
- Quantum numbers in DVMP probe individual GPD components selectively
  - Vector : ρ°/ρ+/*K** select *H, E*
  - **Pseudoscalar: π,η,*K* select the polarised GPDs, $\tilde{H}$ and $\tilde{E}$**
- Need good understanding of reaction mechanism
  - QCD factorisation for mesons is complex (additional interaction of the produced meson)
  - **L/T separated cross sections to test QCD Factorisation**

Nucleon Imaging at JLab - Strategy

Nucleon Imaging Studies through deep exclusive processes with unique capabilities and complementarity of three experimental halls

- **Hall A:** small acceptance, high resolution spectrometer to define kinematic variables very precisely, extremely high luminosity allowing very accurate tests of the kinematic dependences of the observables *See talk by J. Roche…*
  - ***Precision tests of the absolute cross section and Q^2-dependence***
- **Hall B:** large acceptance CLAS12, coverage and hermeticity *See talk by K. Joo*
  - ***Experiments with all combinations of beam and target spin measurements***
- **Hall C:** high luminosity, high resolution spectrometer also allowing momentum reach to 11 GeV/c, compact photon source
  - ***Precision cross sections to highest Q^2***
  - ***Rigid connection to pivot allows for L/T separations – a unique feature***

DVCS with CLAS12

E12-06-119: Unpolarised liquid H_2 target

Beam-spin asymmetry → $Im(H_p)$

First experiment with CLAS12! Autumn '17

- $P_{beam} = 85\%$
- $L = 10^{35}\ cm^{-2}s^{-1}$
- $1 < Q^2 < 10\ GeV^2$
- $0.1 < x_B < 0.65$
- $-t_{min} < -t < 2.5\ GeV^2$

E12-16-010: Unpolarised liquid H_2 target

Beam energy: 6.6 GeV, 8.8 GeV ~2018/20

E12-11-003: Unpolarised liquid D_2 target

$$e + d \rightarrow e' + \gamma + n + (p_s)$$

Beam-spin asymmetry in neutron-DVCS → $Im(E_n)$

~2019

E12-12-010: Transversely polarised HD target.

Target-spin asymmetries → $Im(E_p)$

~2021/22

E12-06-109: Longitudinally polarised NH_3 and ND_3 targets

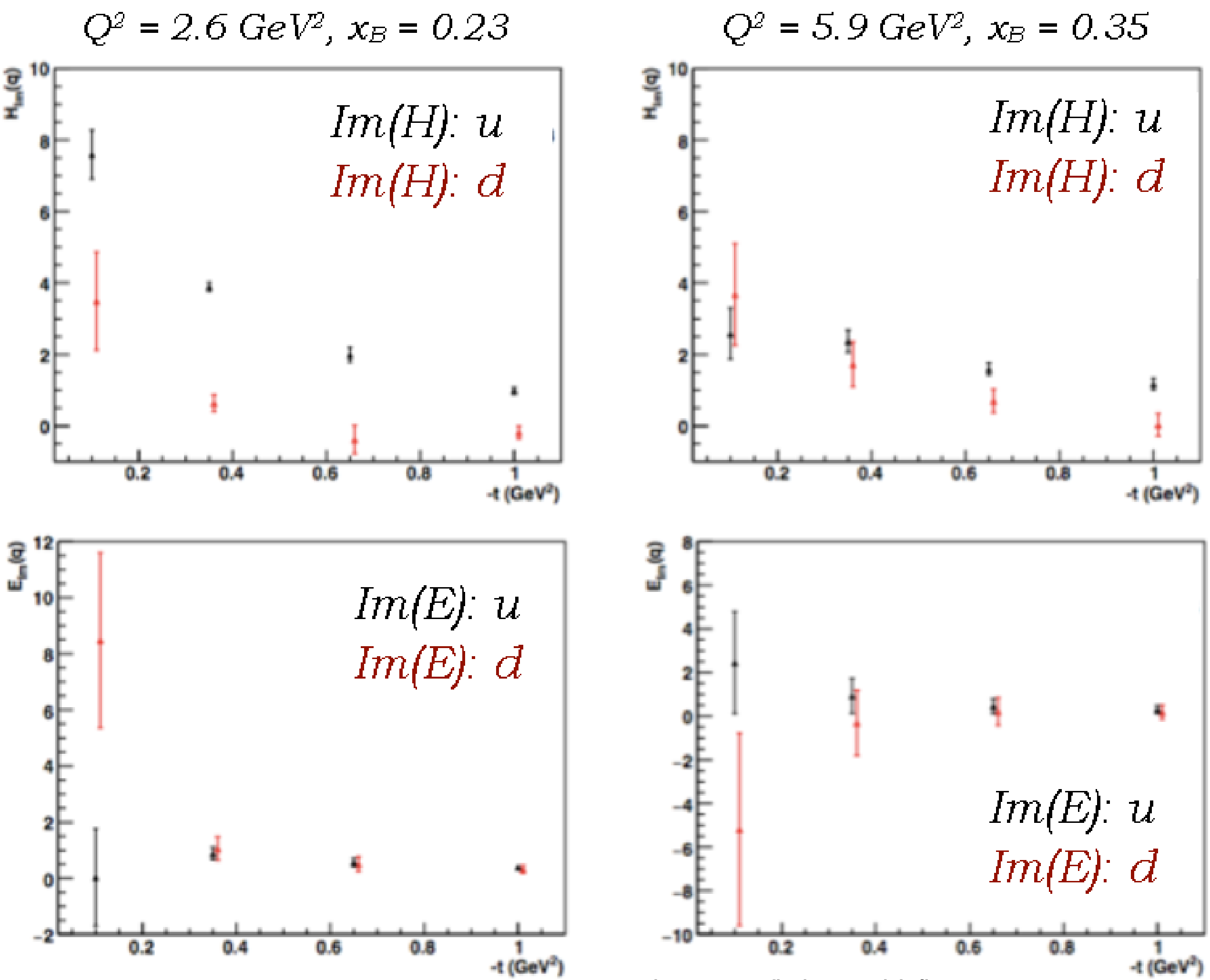
- Dynamic Nuclear Polarisation (DNP) of target material, cooled in a *He* evaporation cryostat.
- $P_{proton} = 80\%$, $P_{deuteron}$ up to 50%

Target-spin asymmetry in proton- and neutron-DVCS → $Im(\tilde{H}_p)$, $Im(H_n)$

~ 2020

Projected Sensitivities: CLAS12

Projections for *Im(H)* and *Im(E)* up and down Compton Form Factors (CFFs) to be extracted from approved CLAS12 experiments



Using VGG fit (M. Guidal)

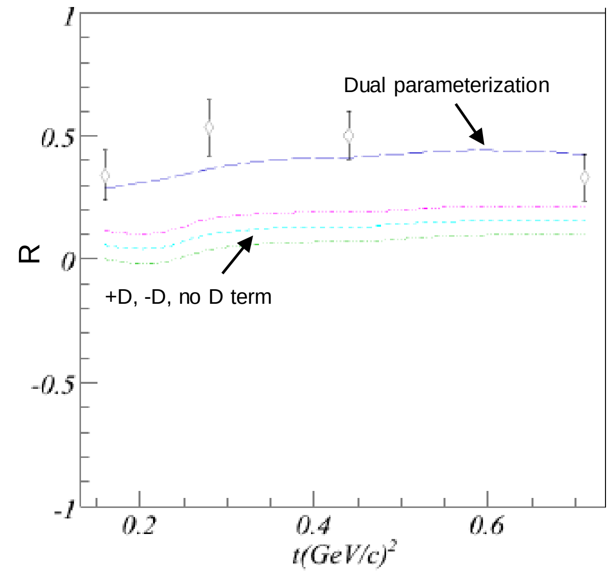
TCS with CLAS12 and SoLID

- Cosine moment of weighted cross sections – *R* can be compared directly with GPD models

$$R = \frac{2\int_0^{2\pi} d\varphi \cos\varphi \frac{dS}{dQ'^2 dt d\varphi}}{\int_0^{2\pi} d\varphi \frac{dS}{dQ'^2 dt d\varphi}}$$

$$\frac{dS}{dQ'^2 dt d\varphi} = \int \frac{L(\theta,\varphi)}{L_0(\theta)} \frac{d\sigma}{dQ'^2 dt d\varphi d\theta} d\theta$$

Comparison of results from e1-6/e1f [Paremuzyan et al.] with calculations by V. Guzey



- 6 GeV data demonstrated feasibility of the procedure, but kinematics limited

- TCS at 12 GeV (E12-12-001 and E12-12-006A)
  - extend *s* to 20 GeV^2
  - M_{e+e-} ~3.5 GeV allowing access to resonance free region > 2 GeV
  - higher luminosity for multi-dimensional binning

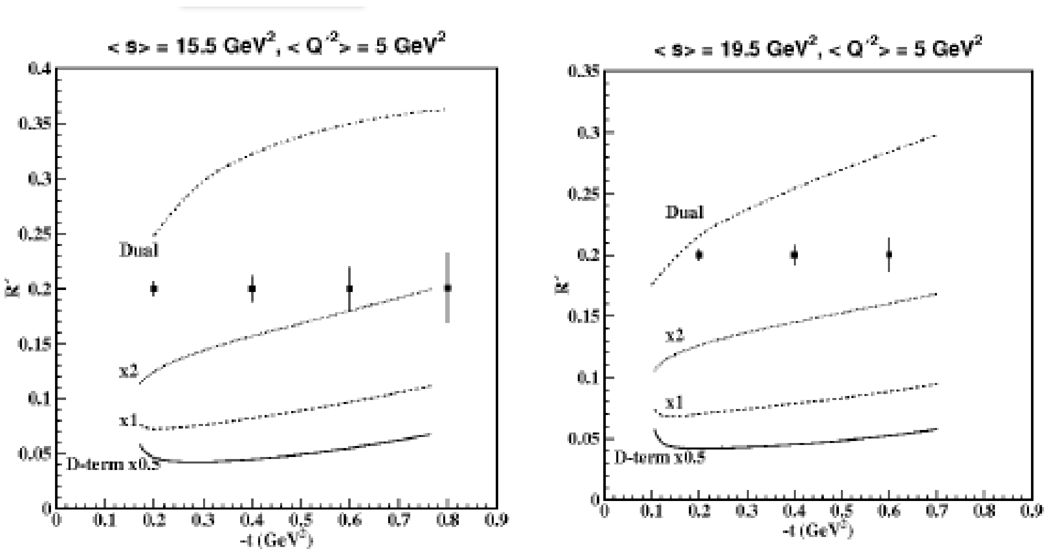
	CLAS12	SoLID
e^+, e^- coverage	θ: 5°-36° ϕ: ~80% asymmetric	θ: 8°-17°, 18°-28° ϕ: 100% symmetric
Proton coverage	θ: 5°-36°, 38°-125° ϕ: ~80%	θ: 8°-17°, 18°-28° ϕ: 100%
Luminosity	10^{35}/cm^2/s	10^{37}/cm^2/s

Acceptance important for cross section

Different angular acceptance

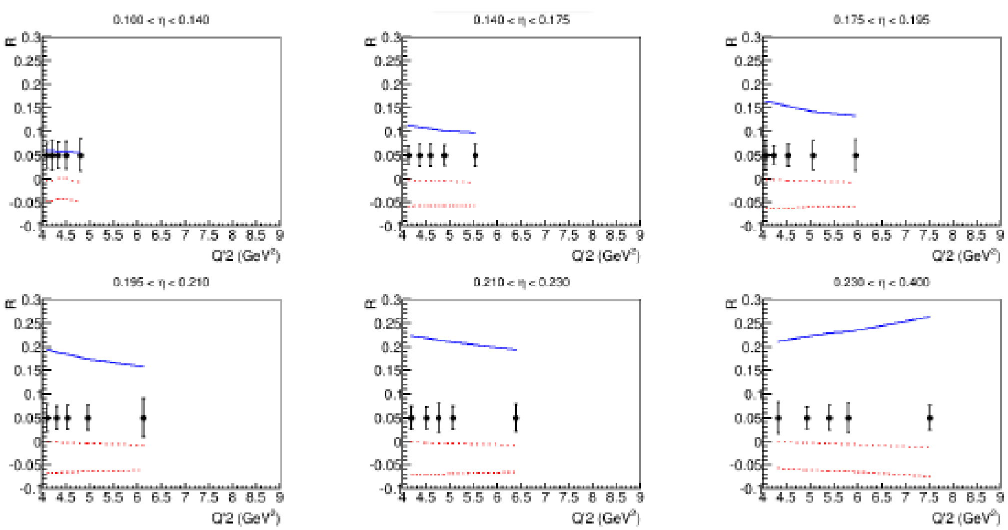
Projected Sensitivities with CLAS12 and SoLID

CLAS12



E12-12-001 also measures J/Psi on proton near threshold – possibly verify existence of charmed pentaquark

SoLID



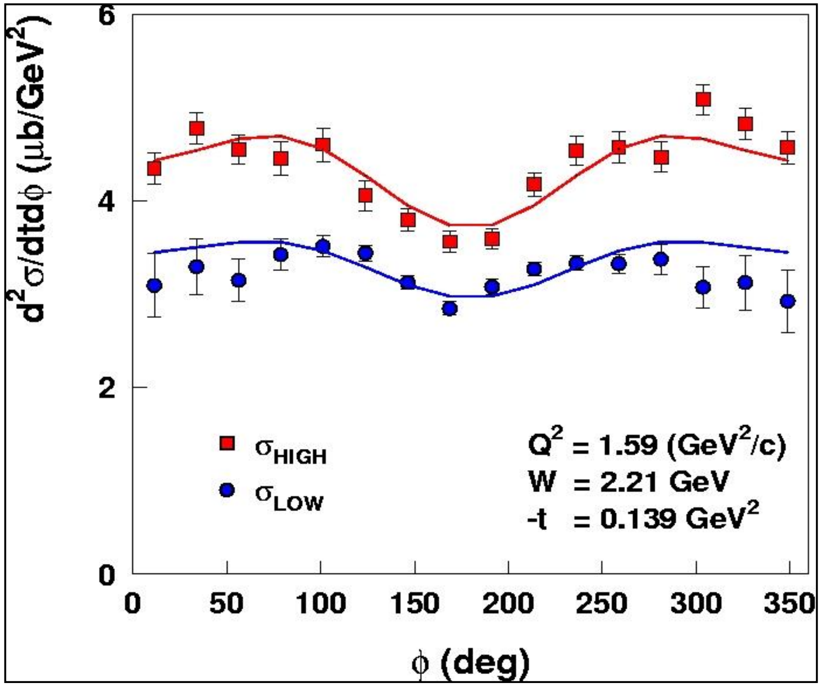
SOLID projection with x10 more data allows for kinematic exploration

Hall C: Cross Section L/T Separation Example

- σ_L is isolated using the Rosenbluth separation technique
  - Measure the cross section at two beam energies and fixed W, Q^2, -t
  - Simultaneous fit using the measured azimuthal angle (ϕ_π) allows for extracting L, T, LT, and TT

- Careful evaluation of the systematic uncertainties is important due to the $1/\varepsilon$ amplification in the σ_L extraction
  - Spectrometer acceptance, kinematics, and efficiencies

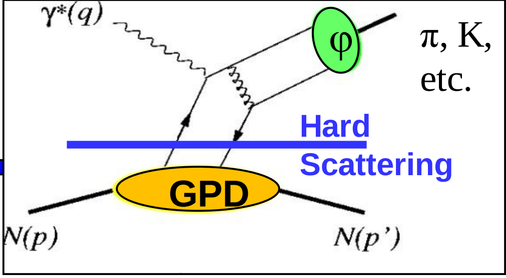
- Magnetic spectrometers a must for such precision cross section measurements
  - This is only possible in Hall C at JLab



$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\,\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

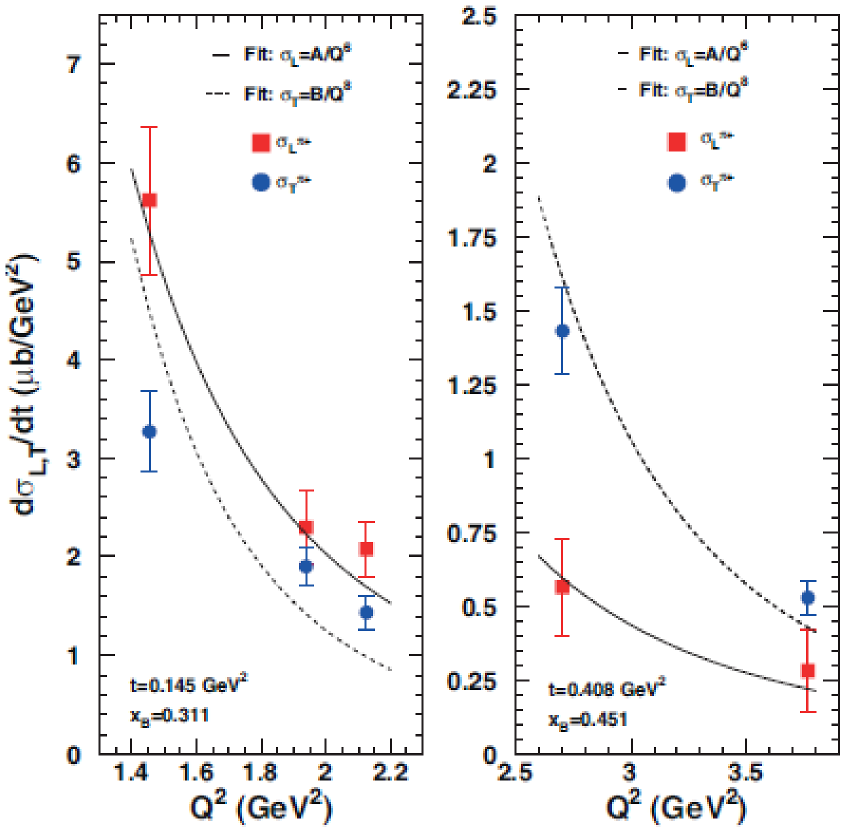
σ_L for testing QCD factorisation

Relative L/T contribution to the Pion cross section



Important for nucleon structure studies

[L. Favart, M. Guidal, T. Horn, P. Kroll, Eur. Phys. J A 52 (2016) no.6, 158]



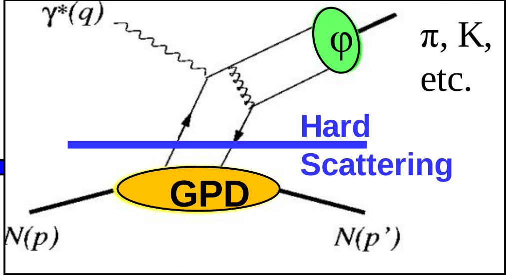
- ❑ Data from JLab 6 GeV demonstrated the technique of measuring the Q^2 dependence of L/T separated cross sections at fixed x/t

  *[T. Horn et al., Phys. Rev. C **78**, 058201 **(2008)**]*

- ❑ Separated cross sections over a large range in Q^2 are essential for:
  - ➢ testing factorisation required for studies of transverse spatial structure
  - ➢ understanding dynamical effects in both Q^2 and –t kinematics
  - ➢ interpretation of non-perturbative contributions in experimentally accessible kinematics

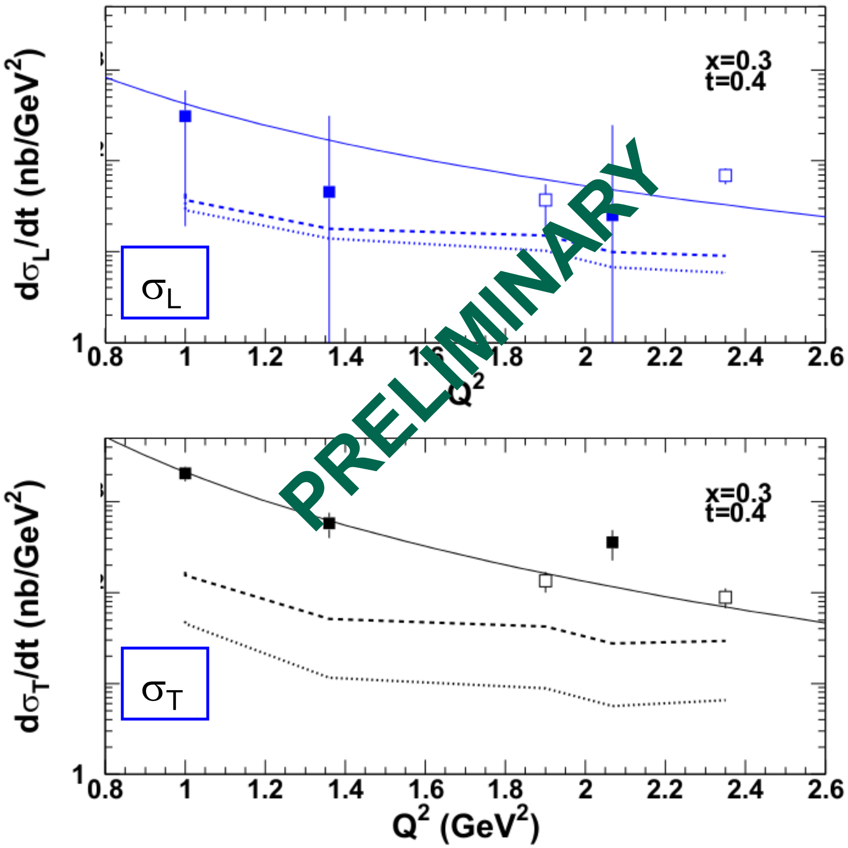
Q^2 dependence of σ_L relevant towards an interpretation in a GPD-based framework

Relative L/T contribution to the Kaon cross section



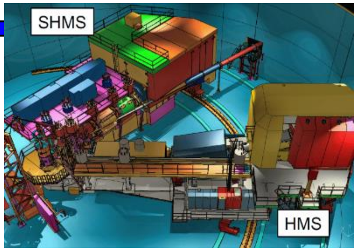
Much less known…

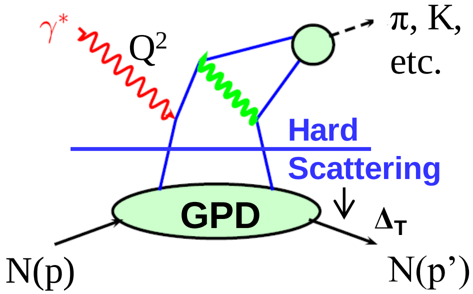
$$Fit = \frac{A}{Q^b}$$

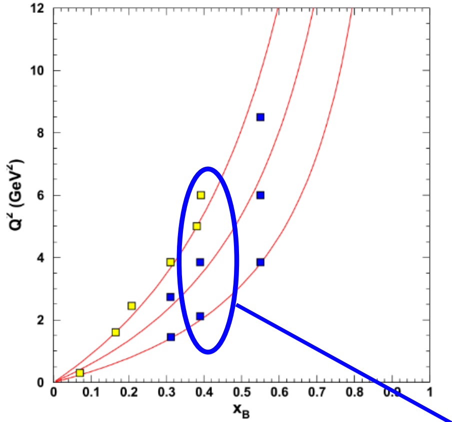


6 GeV JLab cross section data appear to be consistent with expected scaling, but small Q^2 lever arm and relatively large uncertainties

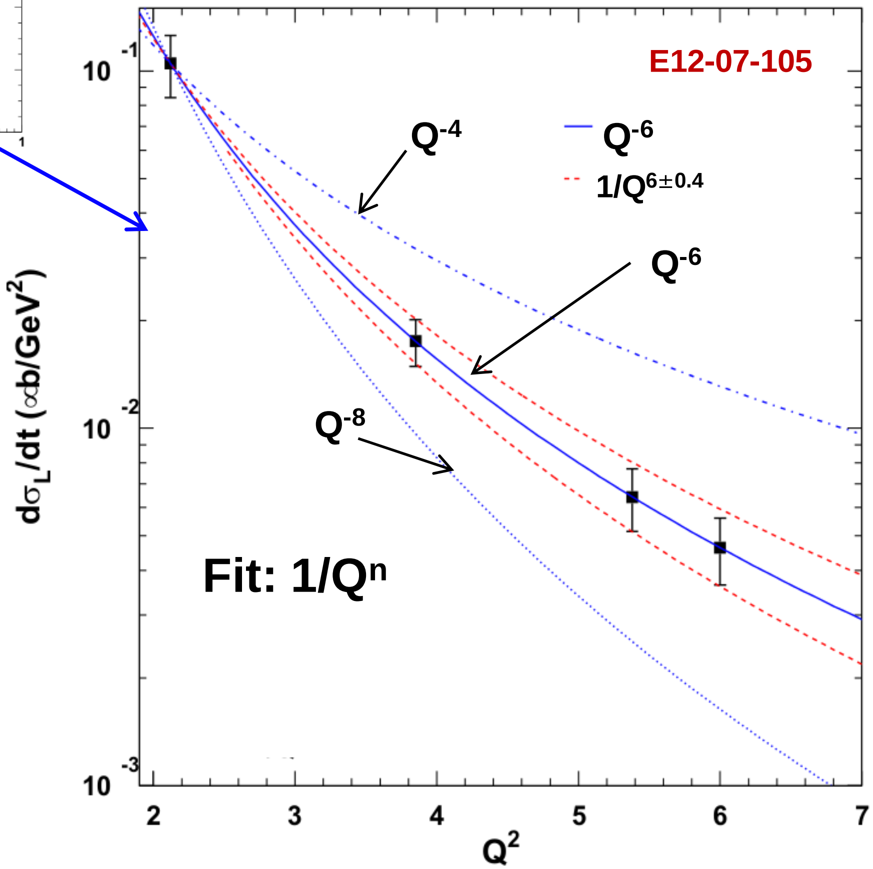
JLab12: confirming potential for nucleon structure studies with pion production







*E12-**07**-105 spokespersons: T. Horn, G. Huber*

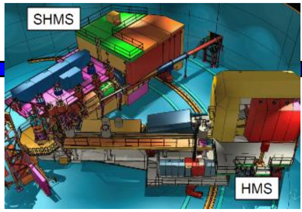


- **E12-07-105 (P12):** Measure the Q^2 dependence of the π electro production cross section at fixed x and -t
  - Factorisation theorem predicts σ_L scales to leading order as Q^{-6}

x	Q^2 (GeV^2)	W (GeV)	-t $(GeV/c)^2$
0.3	1.5-2.7	2.0-2.6	0.1
0.4	2.1-6.0	2.0-3.2	0.2
0.5	3.9-8.5	2.0-2.8	0.5

Considered for running **in 2019**

JLab12: confirming potential for nucleon structure studies with kaon production



- **E12-09-011**: Separated L/T/LT/TT cross section over a wide range of Q^2 and t

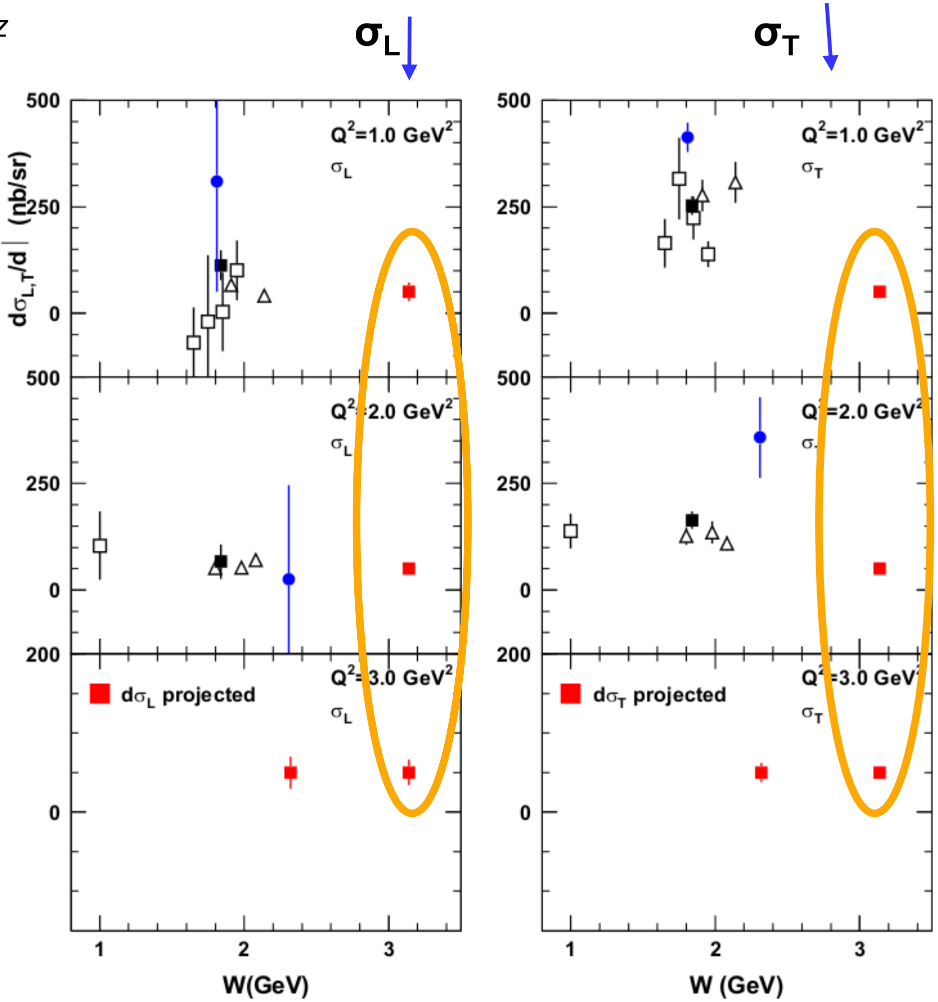
*E12-**09**-011 spokespersons: T. Horn, G. Huber, P. Markowitz*

JLab 12 GeV Kaon Program features:

- First cross section data for Q^2 scaling tests with kaons
- Highest Q^2 for L/T separated kaon electroproduction cross section
- First separated kaon cross section measurement above W=2.2 GeV

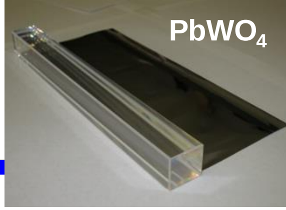
approved for 40 PAC days and **scheduled to run in 2018/19**

x	Q^2 (GeV^2)	W (GeV)	-t $(GeV/c)^2$
0.1-0.2	0.4-3.0	2.5-3.1	0.06-0.2
0.25	1.7-3.5	2.5-3.4	0.2
0.40	3.0-5.5	2.3-3.0	0.5



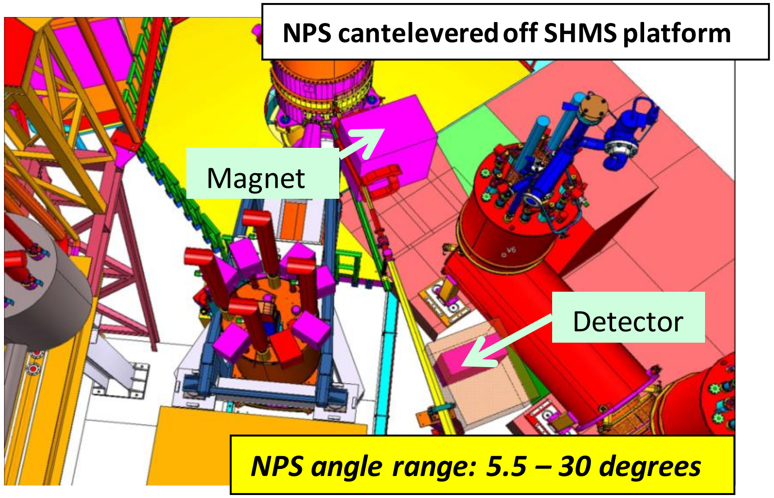
*[blue points from M. Carmignotto, PhD thesis **(2017)**]*

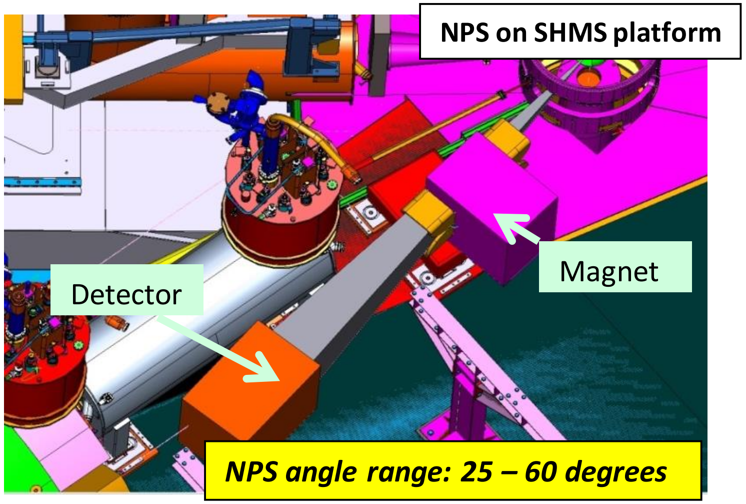
New Opportunities with the Neutral-Particle Spectrometer



NSF MRI PHY-1530874

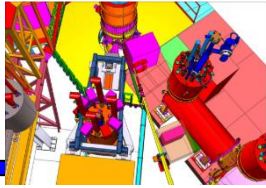
- The NPS is envisioned as a $PbWO_4$-based facility in Hall C, utilizing the well-understood HMS and the SHMS infrastructure, to allow for precision (coincidence) cross section measurements of neutral particles (γ and π^0).





- Scientific program: 5 experiments approved by PAC to date
  - E12-13-007: Measurement of Semi-inclusive π^0 production as Validation of Factorisation
  - E12-13-010 – Exclusive Deeply Virtual Compton and π^0 Cross Section Measurements in Hall C
  - E12-14-003 – Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies
  - E12-14-005 – Wide Angle Exclusive Photoproduction of π^0 Mesons
  - C12-17-008 – Polarisation Observables in Wide Angle Compton Scattering

E12-13-010: precision DVCS cross sections



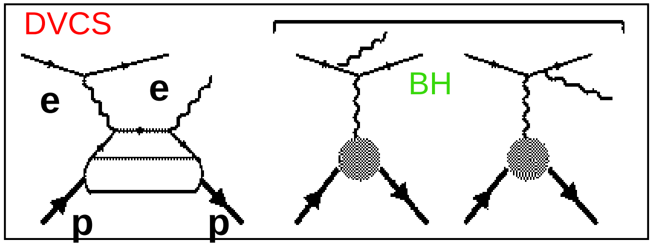
Simplest process **$e + p \rightarrow e' + p + \gamma$ (DVCS)**

E12-13-010 DVCS measurements follow up on measurements in Hall A:

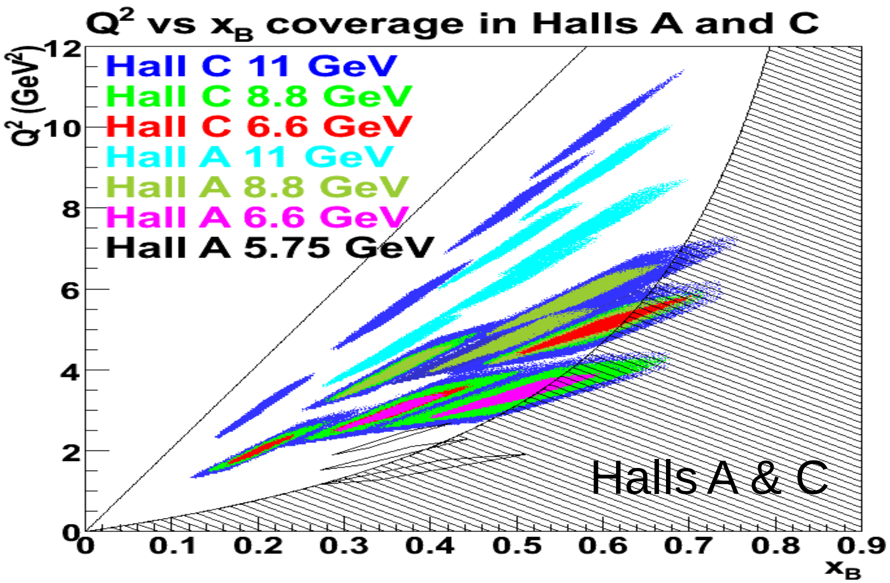
- Scaling of the Compton Form Factor
- Rosenbluth-like separation of DVCS:

$$\sigma = |BH|^2 + \mathrm{Re}\left[\underbrace{DVCS^{\perp}\ BH}_{\sim E_{beam}^2}\right] + \underbrace{|DVCS|^2}_{\sim E_{beam}^3}$$

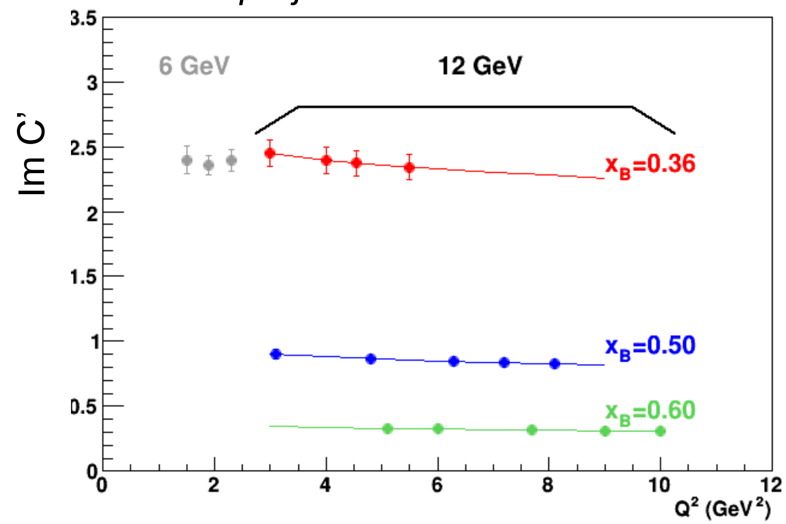
- L/T separation of π^0 production



Hall A data for Compton form factor (over *limited* Q^2 range) agree with hard-scattering

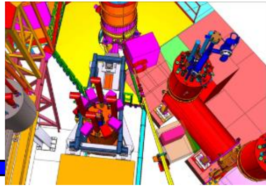


12 GeV projections: confirm formalism

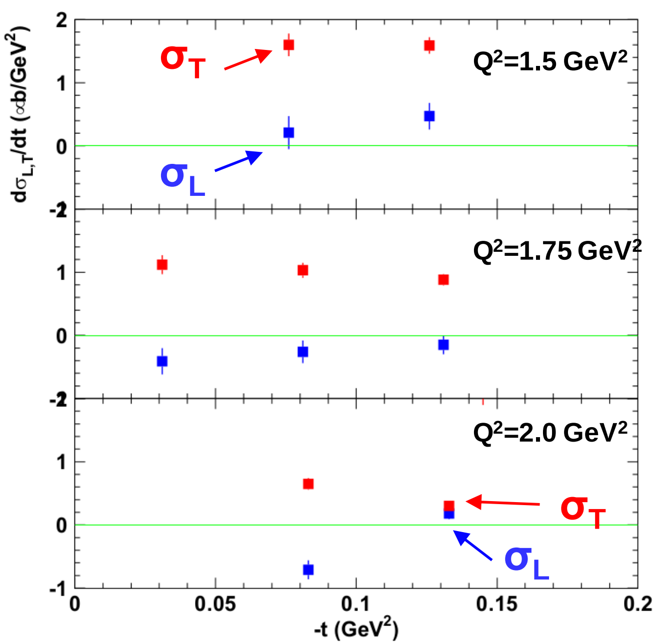


Extracting the real part of CFFs from DVCS requires measuring the cross section at multiple beam energies (DVCS^2−Interference separation)

E12-13-010: exclusive π^0 cross section

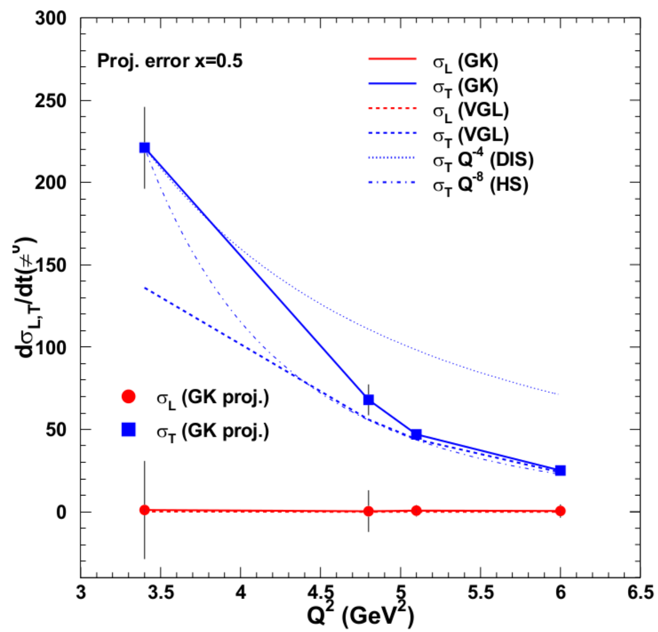


- Relative L/T contribution to π^0 cross section important in probing transversity
  - If σ_T large: access to transversity GPDs
- Results from Hall A at 6 GeV Jlab suggest that the longitudinal cross section in π^0 production is non-zero up to Q^2=2 GeV^2
- Need to understand Q^2/t dependence for final conclusion on dominance of σ_T



*M. Defurne et al, PRL **117** (**2016**) no.26, 262001*

E12-13-010 projections



E12-13-010 will provide essential data on σ_T and σ_L at higher Q^2 for reliable interpretation of 12 GeV GPD data

New Opportunities with NPS and a Compact Photon Source (CPS)

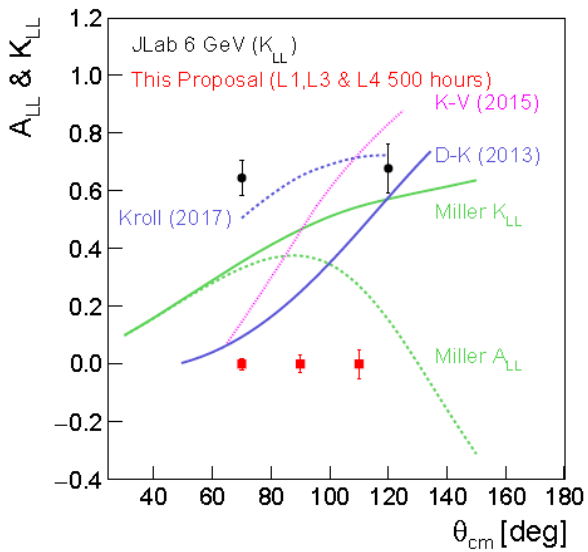
The Catholic University of America

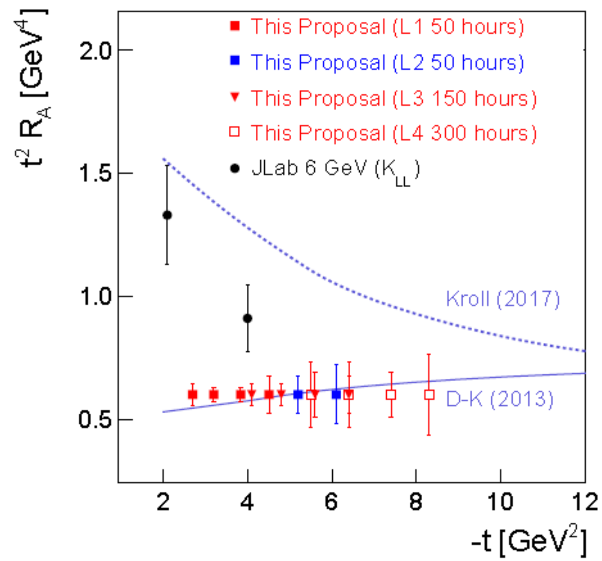
6-7 February 2017 High-Intensity Photon Sources Workshop (CUA)

https://www.jlab.org/conferences/HIPS2017/

Example: Impact of the photon source for polarised WACS:

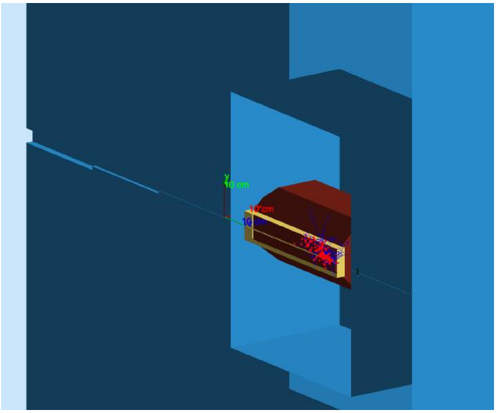
- **The experiment productivity is improved x30 times** due to higher target polarisation averaged over the experiment, and reduced overhead time for the target annealing procedure.

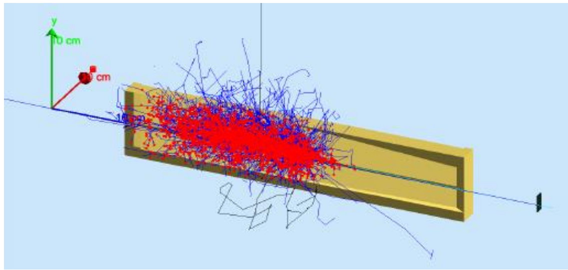




Compact Photon Source (CPS) – Concept

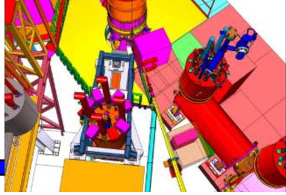
- Strong magnet after radiator deflects exiting electrons
- Long-bore collimator lets photon beam through
- No need in tagging photons, so the design could be compact as opposed to a Tagger Magnet concept
- The magnet itself is the electron beam dump
- Water-cooled W-Cu core for better heat dissipation
- Hermetic shielding all around and close to the source to limit prompt radiation and activation
- High Z and high density material for bulk shielding
- Boron outer layer for slowing, thermalising, and absorbing fast neutrons still exiting the bulk shielding



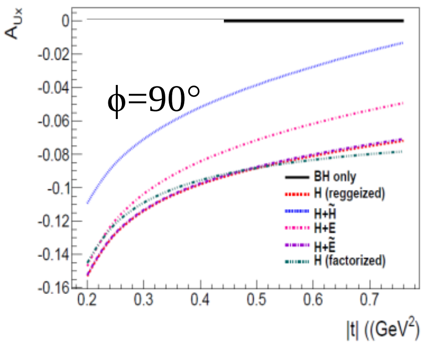


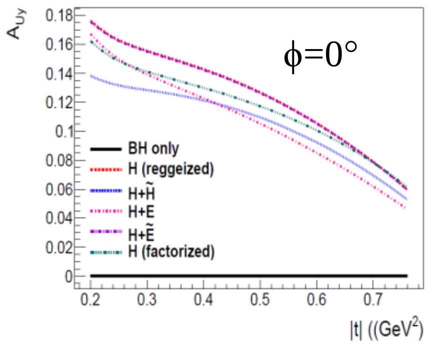
CPS is a novel concept allowing for ***high photon intensity*** (equivalent photon flux: ~10^{12} photons/s) and ***low radiation*** (low activation: <1mrem/h after one hour) in the hall

LOI12-15-007: Timelike Compton Scattering with Transverse targets

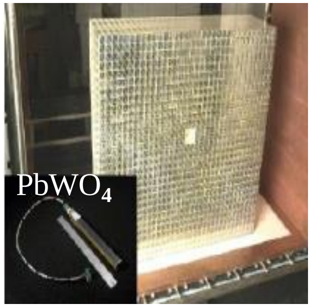


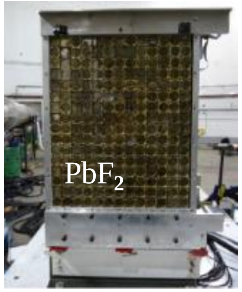
- Features of TCS measurements with transversely polarised target
  - Theoretical calculations show that transverse asymmetries are very sensitive to GPDs
    [M. Boer, M. Guidal, arXiv:1501:00270]
  - Asymmetries for the BH, the main background for TCS, is zero
  - Predictions for asymmetries with different assumption of GPDs vary up to 20%

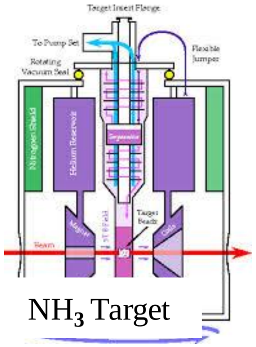


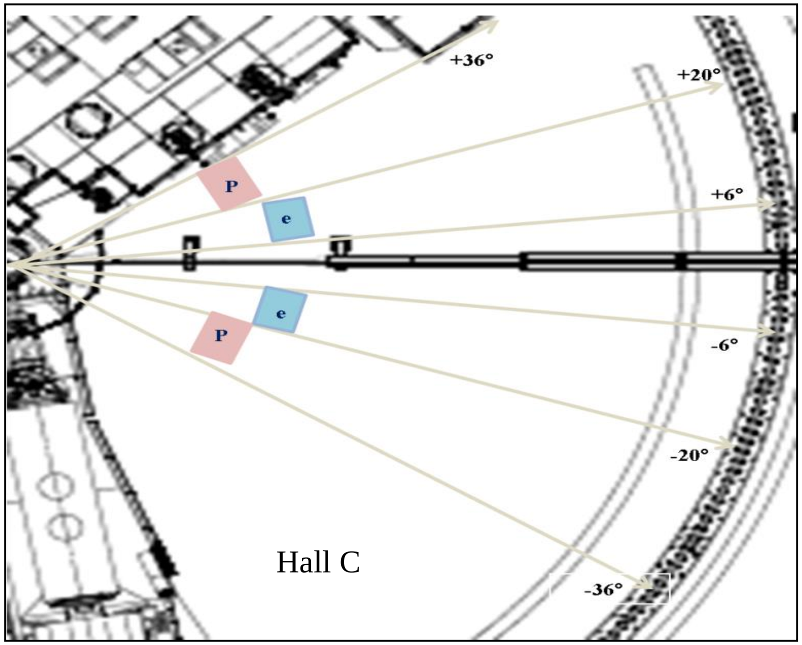


- TCS event detection with NPS
  - Lepton pair will be detected by pair of NPS
  - Recoil detection by combination of tracking and TOF









TCS measurements with transversally polarised target open interesting opportunities for probing GPD E

Summary and Outlook

- A comprehensive GPD program is enabled by 12 GeV JLab – combines the unique strengths of three experimental halls (A, B, C)

- Validation of QCD factorisation in exclusive processes is key for accessing GPDs – requires precision cross sections

- Comparison of spacelike (DVCS) and timelike (TCS) Compton Scattering allows for testing universality of GPDs

- Progress towards flavour separation made possible through measurements of meson production – L/T separations are crucial for pions and kaons

- A Neutral Particle Spectrometer and a Compact Photon Source enable precision cross section measurements with neutral particles - the design/construction of both is underway in Hall C