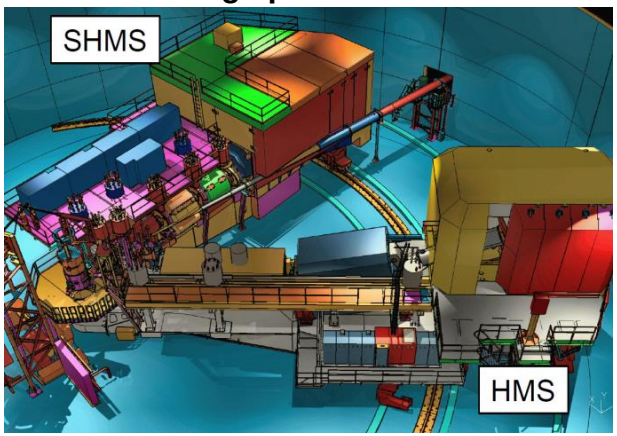
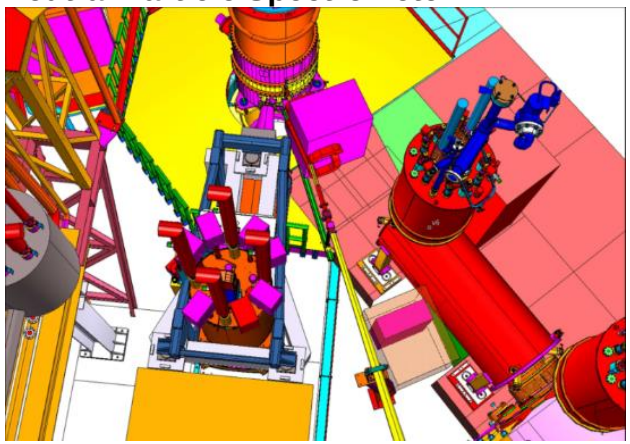
Precision Cross Section Measurements in Hall C

Hall C focusing spectrometers



Neutral Particle Spectrometer



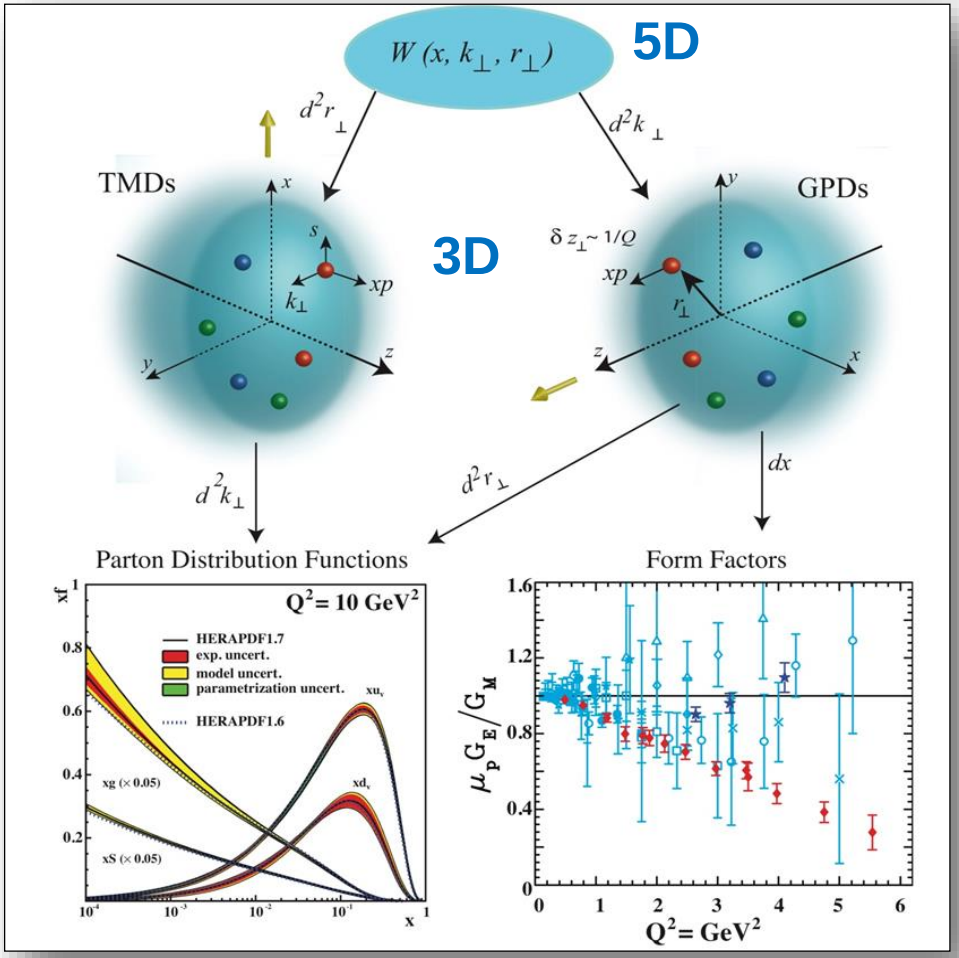
Tanja Horn

The Catholic University of America

Jefferson Lab
Thomas Jefferson National Accelerator Facility

The 3D Nucleon Structure

Generalized 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
  - Polarized beams and targets

Major new capability with JLab12

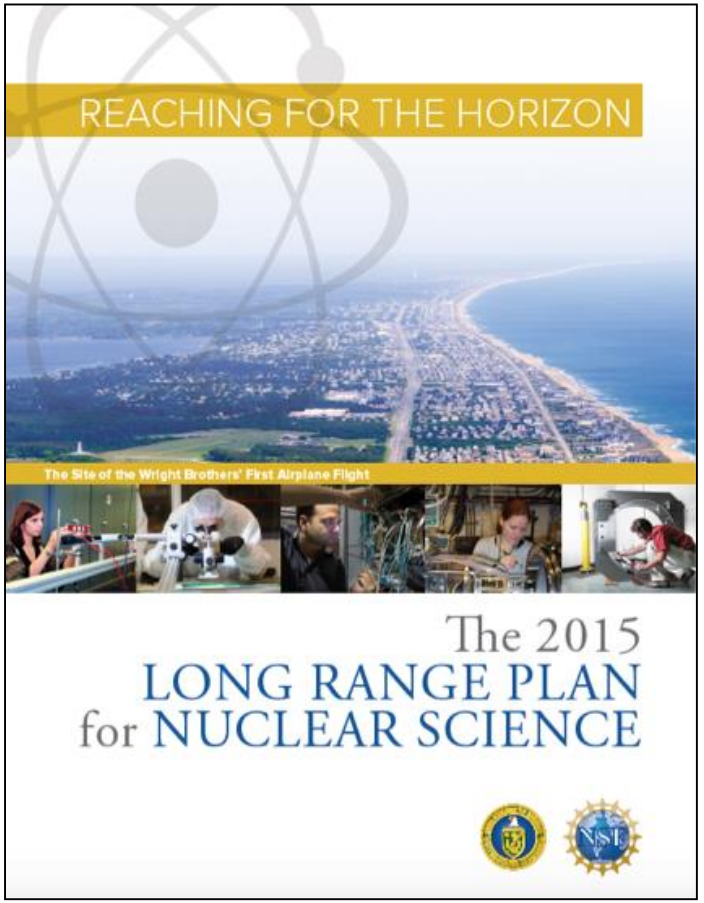
NSAC 2015 Long Range Plan

- "Precision measurements in semi-inclusive pion and kaon production from unpolarized, as well as longitudinally and transversely polarized proton … targets in the JLab 12 GeV era will allow access to both flavor and spin dependent transverse momentum distributions in the valence quark region."

- "Multiple instruments bring essential elements to this campaign: … HMS-SHMS and the … NPS"

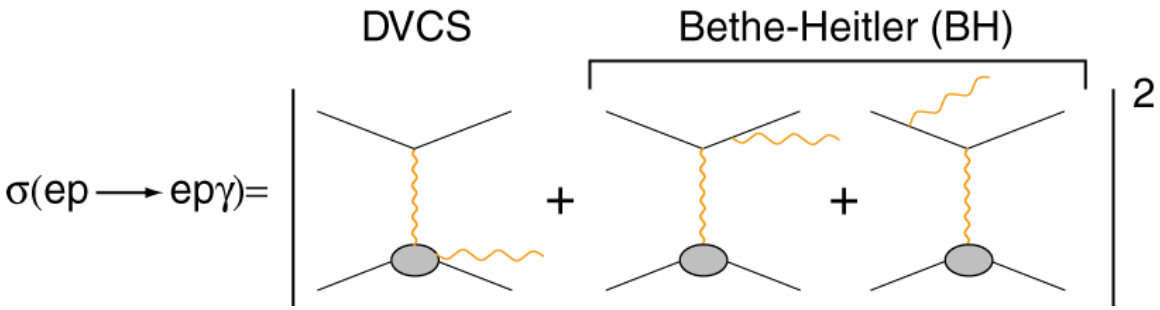
- "Some of the most important tools for describing hadrons are Generalized Parton Distributions, [which] can be investigated through the analysis of hard exclusive processes"

- "The HMS-SHMS …[and] the NPS will allow …refined high resolution imaging of the nucleon's internal landscape…"



Experimental Access to GPDs: DVCS

See also talks by, e.g. F-X Girod, C. Hyde



Cleanest way to probe GPDs

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

At leading twist:

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

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

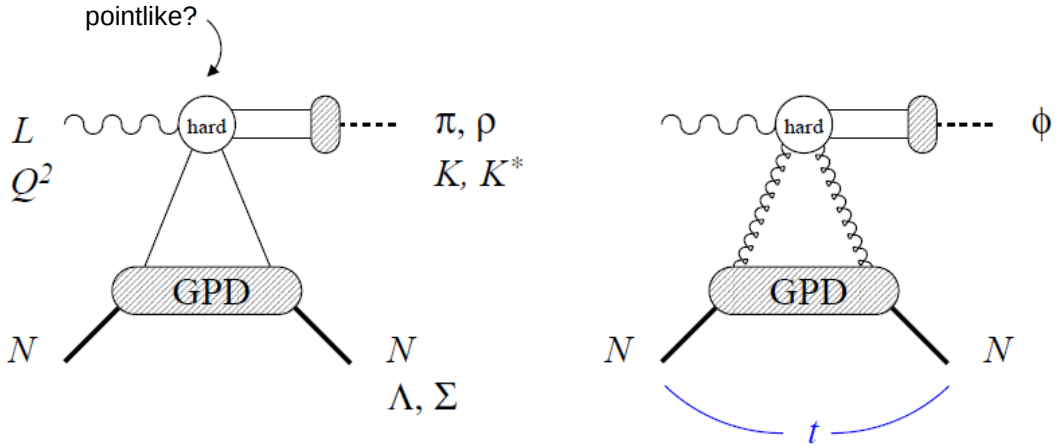
$$\underbrace{\mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi}}_{\text{Access in helicity-independent cross section}} - \underbrace{i\pi\, H(x=\xi,\xi,t)}_{\text{Access in helicity-dependent cross-section}} + \ldots$$

Towards spin-flavor separation: DVMP

See also talks by, e.g. F-X Girod, C. Hyde

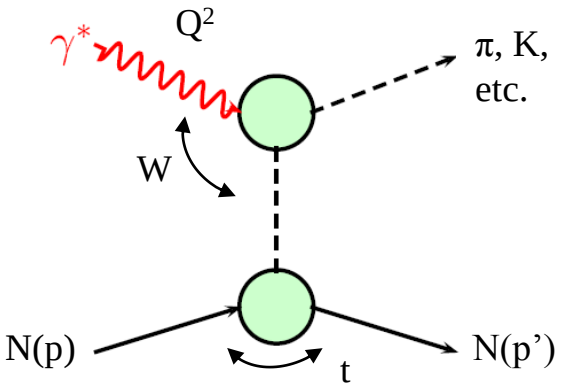
Deep Virtual Meson Production (DVMP)

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



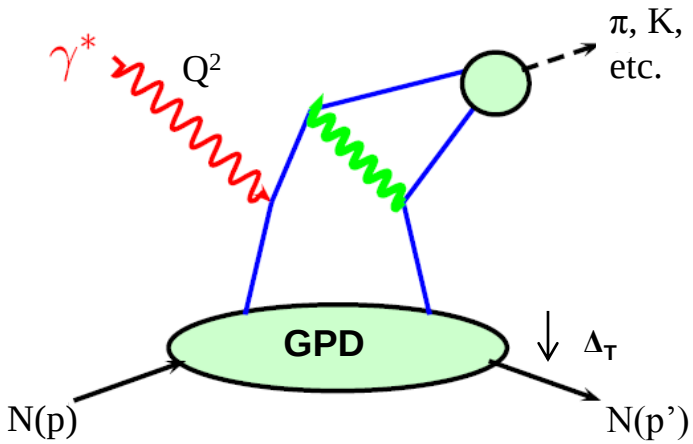
- Nucleon structure described by 4 (helicity non-flip) GPDs:
  - *H, E* (unpolarized), $\tilde{H}, \tilde{E}$ (polarized)
- Quantum numbers in DVMP probe individual GPD components selectively
  - Vector : $\rho^o/\rho+/K^*$ select *H, E*
  - **Pseudoscalar: π,η,K select the polarized GPDs, $\tilde{H}$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

QCD Factorization in Deep Exclusive Meson Electroproduction



t-channel process

- In the limit of small –*t*, meson production can be described by the *t*-channel meson exchange (pole term)
  - Spatial distribution described by form factor

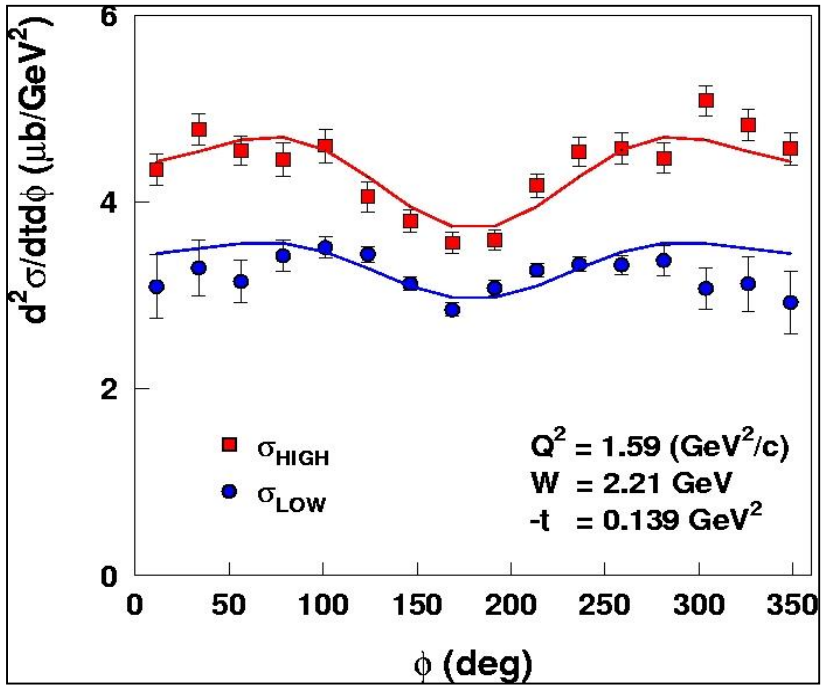


Handbag diagram

- 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
    - Shown to factorize from QCD perturbative processes for longitudinal photons *[Collins, Frankfurt, Strikman, 1997]*

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

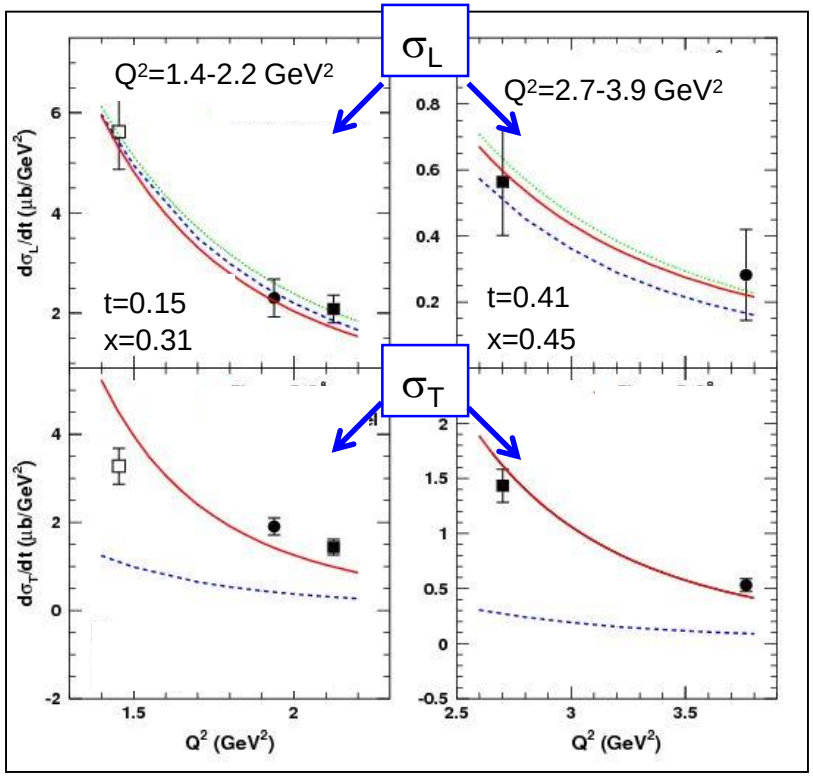


$$2\pi\frac{d^2\sigma}{dtd\phi} = \varepsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

σ_L for testing QCD factorization

Relative L/T contribution to the meson cross section

Important for nucleon structure studies

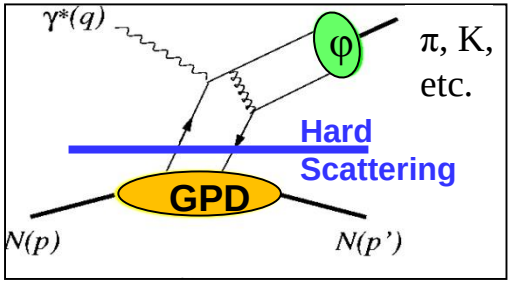


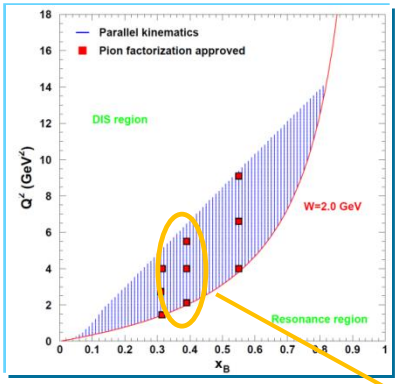
- Data from Jlab 6 GeV demonstrated the technique of measuring the Q^2 dependence of L/T separated cross sections at fixed x and t

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

- For nucleon transverse spatial structure studies need to know:
  - Relative contribution of σ_L and σ_T
  - t/Q^2 dependence of σ_L and σ_T

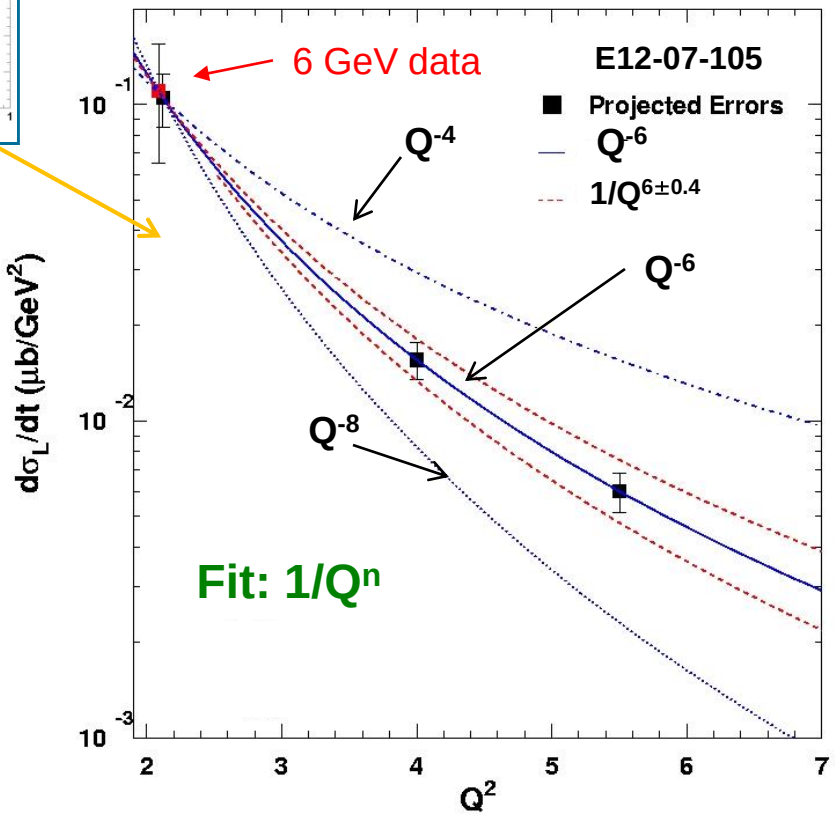
JLab12: confirming potential for nucleon structure studies with pion production





- E12-07-105: Measure the Q^2 dependence of the π electro production cross section at fixed x and -t
  - Factorization theorem predicts σ_L scales to leading order as Q^{-6}
- Derivation of this theorem assumes the asymptotic form of the pion DA – synergy with pion form factor measurements

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

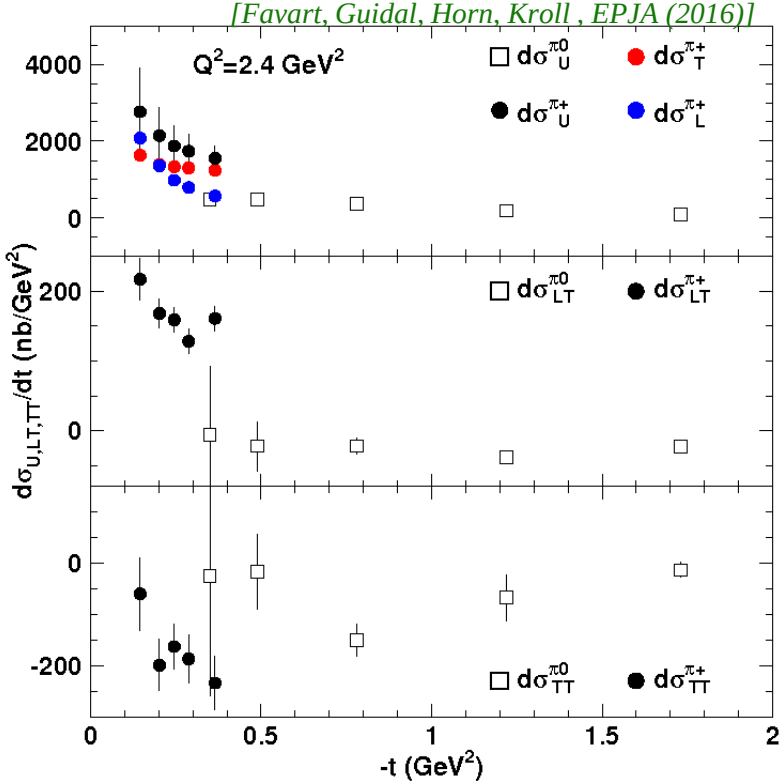


Transverse Contributions in meson electroproduction

- Recent data suggest that transversely polarized photons play an important role in charged and neutral pion electroproduction
  - *HALL C π^+:* σ_T magnitude is large even at Q^2=2.5 GeV^2
  - CLAS: π^o data show substantial fraction of σ_{TT} in the *unseparated* cross section for t > 0.2 GeV^2

*[*Bedlinskiy et al, PRL**109**, **(2012)** *109; arXiv:1405.0988* ***(2014)****]*

[Favart, Guidal, Horn, Kroll , EPJA (2016)]



Measurements of relative σ_L and σ_T contributions to the π cross section to higher Q^2 planned for JLab 12 may shed light on this

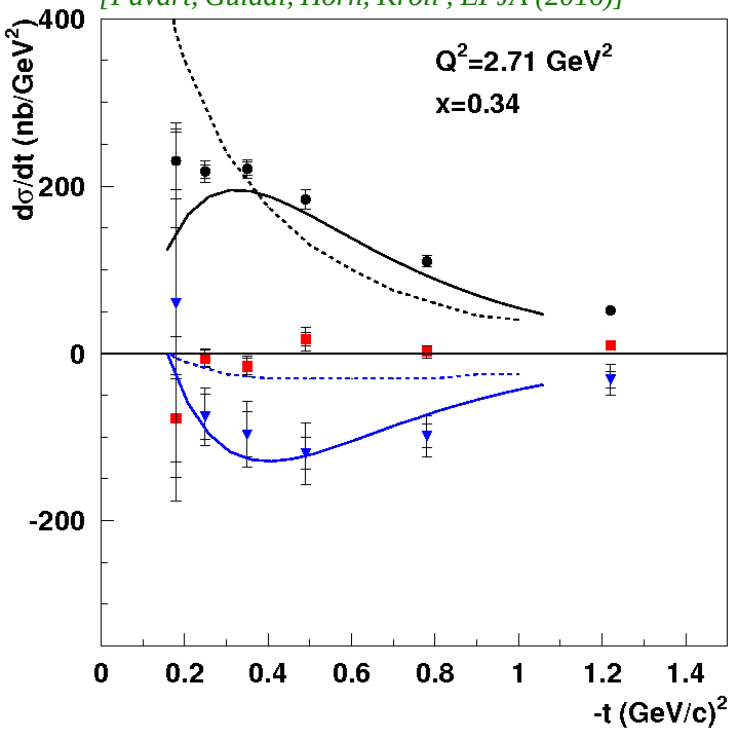
- Exclusive π^o data may also be helpful for constraining non-pole contributions in F_π extraction

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

*E12-**13**-010 spokespersons: C. Munoz-Camacho, T. Horn, C. Hyde, R. Paremuzyan, J. Roche; E12-**06**-101: K. Joo et al.*

Transverse Contributions may allow for probing a new set of GPDs

[Favart, Guidal, Horn, Kroll , EPJA (2016)]



Goloskokov, Kroll, EPJ C65, 137 (2010); EPJ A45, 112 (2011)

*[Ahmad, Goldstein, Liuti, PRD **79 (2009)**]*

*[Goldstein, Gonzalez Hernandez, Liuti, J. Phys. G **39 (2012)** 115001]*

- To access transversity GPDs need transverse photons to dominate
  - Separated precision charged pion data confirmed a large contribution of transverse photons up to Q^2=2.45 GeV^2
  - Model predictions based on handbag in good agreement with data
- For pion and kaon production the relative contribution of longitudinal and transverse photons in JLab 12 GeV kinematics has to be verified
- A large transverse cross section in meson production may allow for accessing helicity flip GPDs

JLab12: confirming potential for nucleon structure studies with kaon production

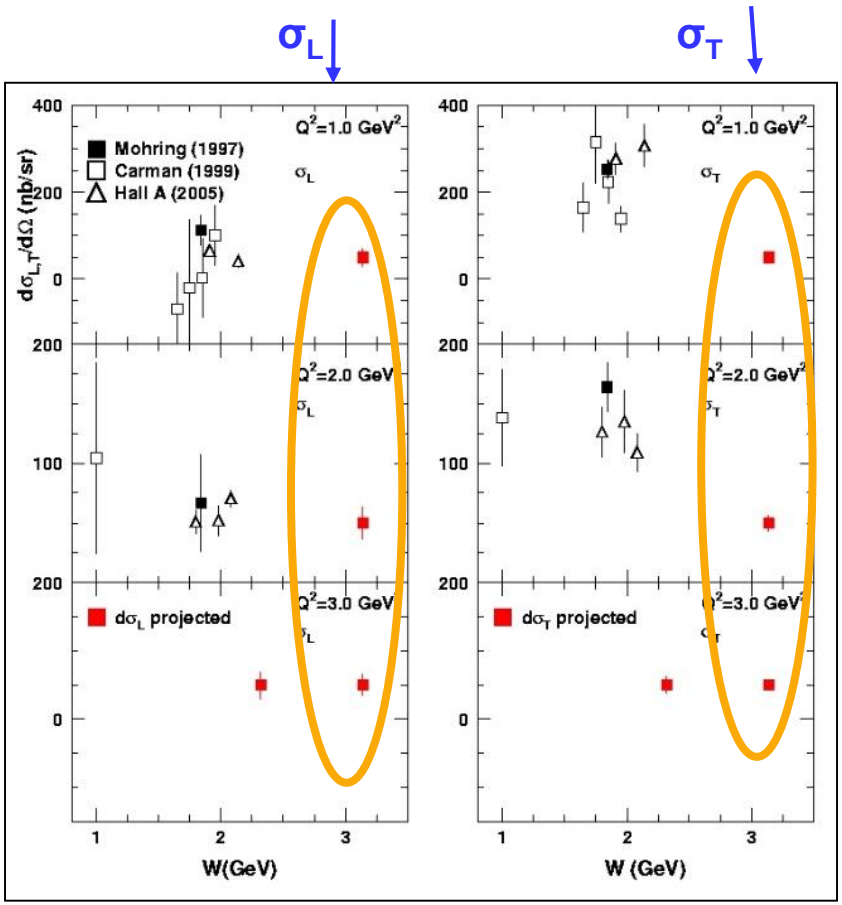
- **E12-09-011**: Separated L/T/LT/TT cross section over a wide range of Q^2 and t

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

JLab 12 GeV Kaon Program features:

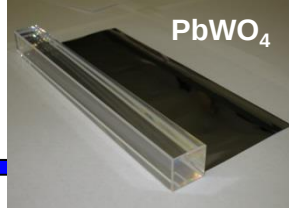
- First cross section data for Q^2 scaling tests with kaons
- Highest Q^2 for L/T separated kaon electroproduction cross section
- First separated kaon cross section measurement above W=2.2 GeV

approved for 40 PAC days and **scheduled to run in 2017/18**



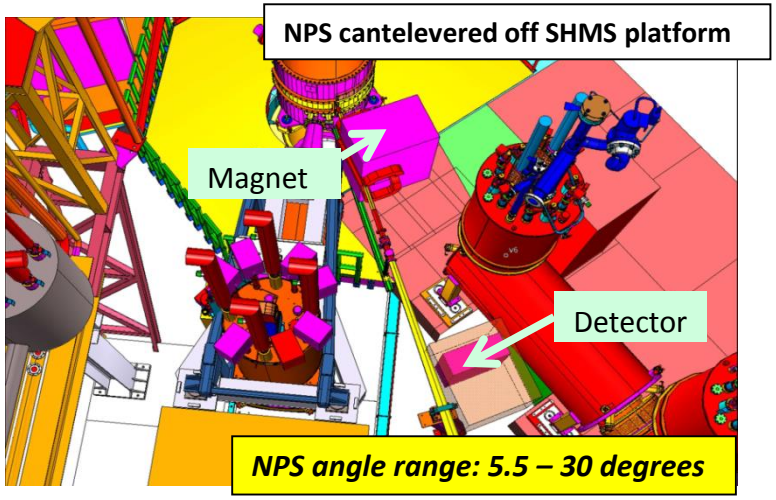
x	Q^2 (GeV²)	W (GeV)	-t (GeV/c)²
0.1-0.2	0.4-3.0	2.5-3.1	0.06-0.2
0.25	1.7-3.5	2.5-3.4	0.2
0.40	3.0-5.5	2.3-3.0	0.5

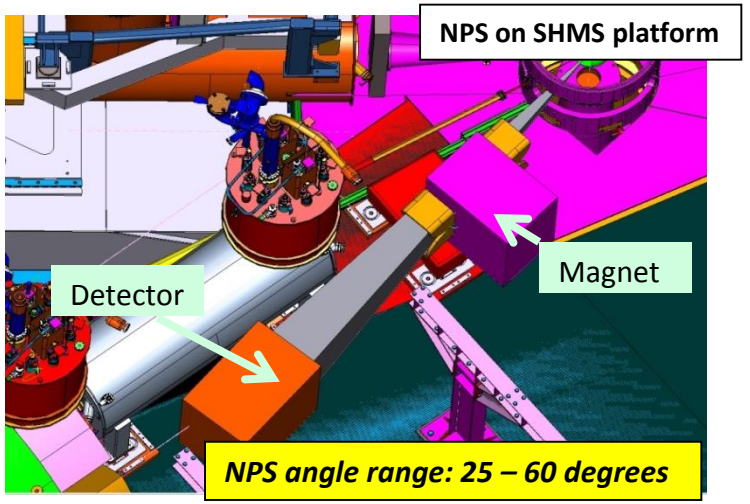
The Neutral-Particle Spectrometer



NSF MRI PHY-1530874

- The NPS is envisioned as a 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).





- Global design of a neutral-particle spectrometer between 5.5 and 60 degrees consists of a highly segmented EM calorimeter preceded by a sweeping magnet

Overview Scientific Program

- 5 experiments approved by PAC (40, 42) to date
  - E12-13-007: Measurement of Semi-inclusive π^0 production as Validation of Factorization
  - 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
  - E12-14-006 – Initial State Helicity Correlation in Wide-Angle Compton Scattering

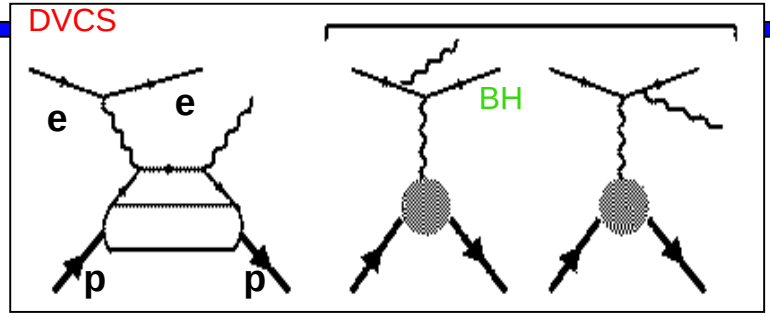
- 1 LOI and one proposal submitted to PAC43
  - LOI12-15-007 – Timelike Compton Scattering with transverse target
  - PR12-15-003 – Double Polarization Observables in WACS at Photon Energies up to 8 GeV

- Ideas exist for future experiments and new scientific directions taking advantage of the compatibility of NPS with Hall infrastructure
  - Experiments with polarized targets
  - High-Intensity Photon Source
  - Exploring possibilities for correlation experiments

E12-13-010: precision DVCS cross sections

See also talk by C. Hyde

Simplest process **e + p → e' + p + γ (DVCS)**



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

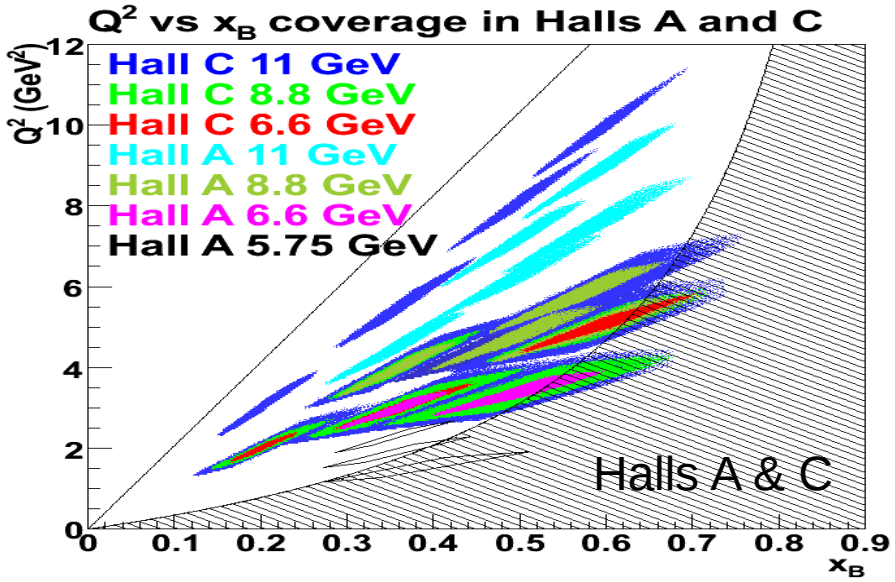
- Scaling of the Compton Form Factor
- Rosenbluth-like separation of DVCS:

$$\sigma = |BH|^2 + \mathrm{Re}\left[DVCS^{\perp}\ BH\right] + |DVCS|^2$$

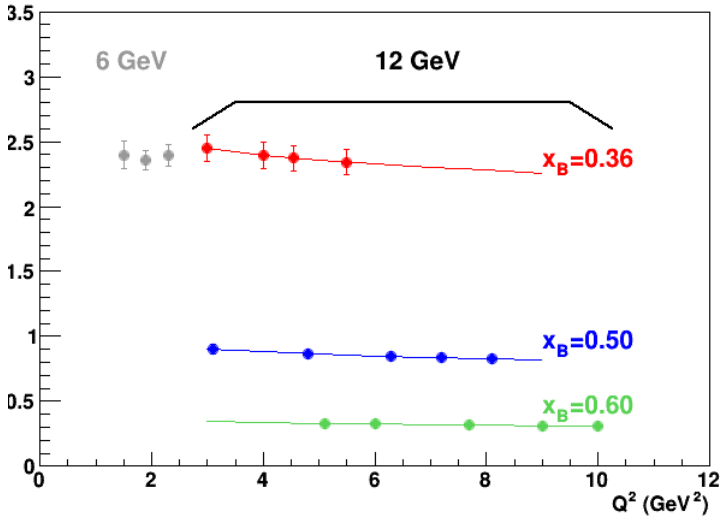
($\sim E_{beam}^2$ for the interference term, $\sim E_{beam}^3$ for $|DVCS|^2$)

- L/T separation of π^0 production

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



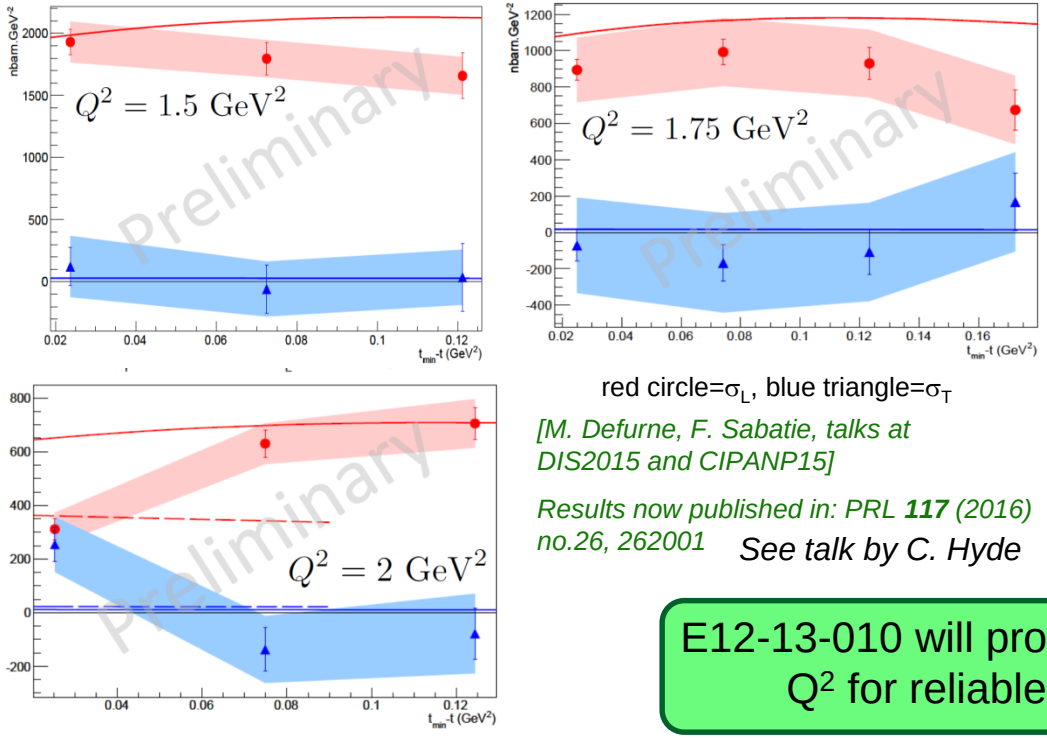
12 GeV projections: confirm formalism



Extracting the real part of CFFs from DVCS requires measuring the cross section at multiple beam energies (DVCS²−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
- Preliminary results from Hall A at 6 GeV Jlab suggest that the longitudinal cross section in π^0 production is non-zero at Q^2~2GeV^2
- Q^2/t dependence complicates final conclusion on dominance of σ_T



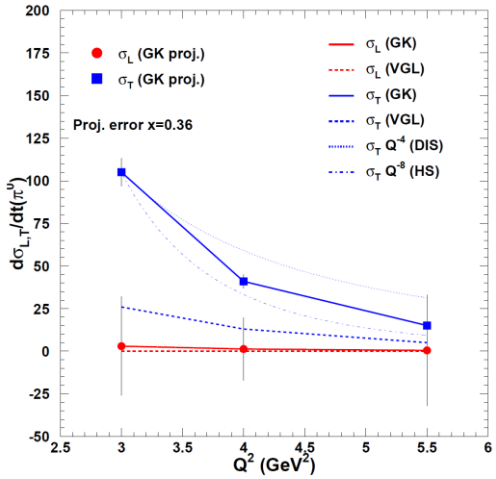
red circle=σ_L, blue triangle=σ_T

[M. Defurne, F. Sabatie, talks at DIS2015 and CIPANP15]

*Results now published in: PRL **117** (2016) no.26, 262001*

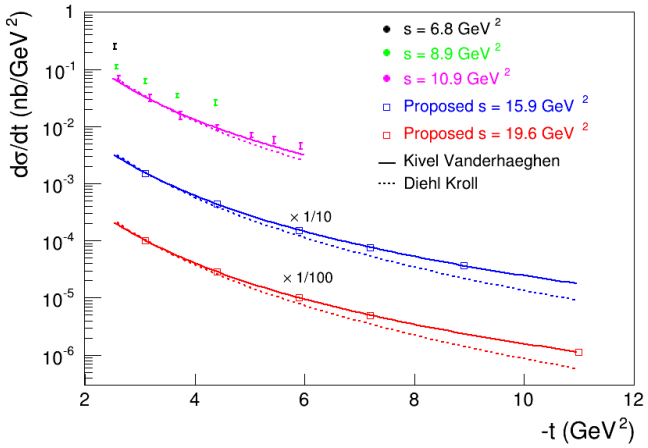
See talk by C. Hyde

[E12-13-010 projections]

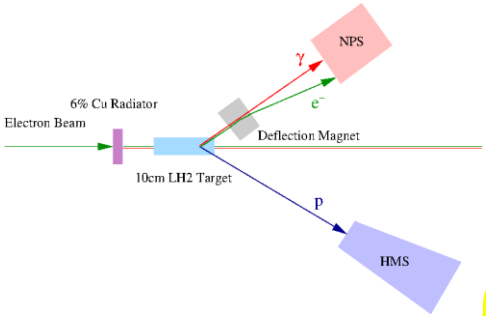


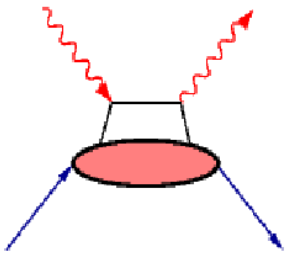
E12-13-010 will provide essential data on σ_T and σ_L at higher Q^2 for reliable interpretation of 12 GeV GPD data!

E12-14-003: exploring factorization in Wide-Angle Compton Scattering (WACS)



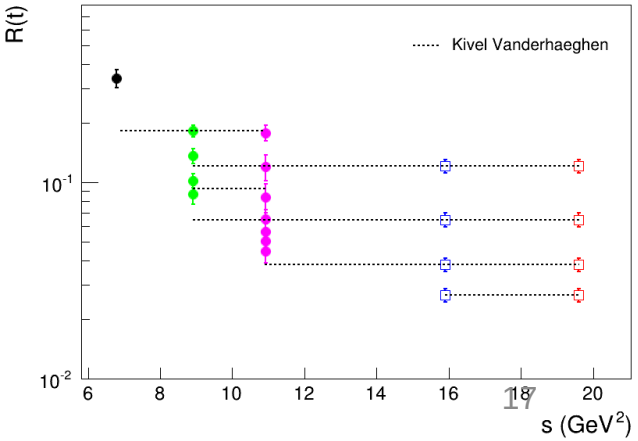
- WACS is a powerful probe of nucleon structure -several theoretical approaches developed in recent years.
  - Developments within the Soft Collinear Effective Theory (SCET) demonstrated importance of future data for interpretation of a wide variety of hard exclusive reactions.
- JLab Hall A data suggest factorization into hard and soft-collinear parts (but limited in -t).
- E12-14-003 will use the Hall C HMS and the new **Neutral Particle Spectrometer** to measure the differential cross section up to s~20 GeV^2!





E12-14-003

- Four fixed -t scans
- The t-dependence of the Compton form factor will allow for gaining valuable insights into proton structure at high momentum transfer.

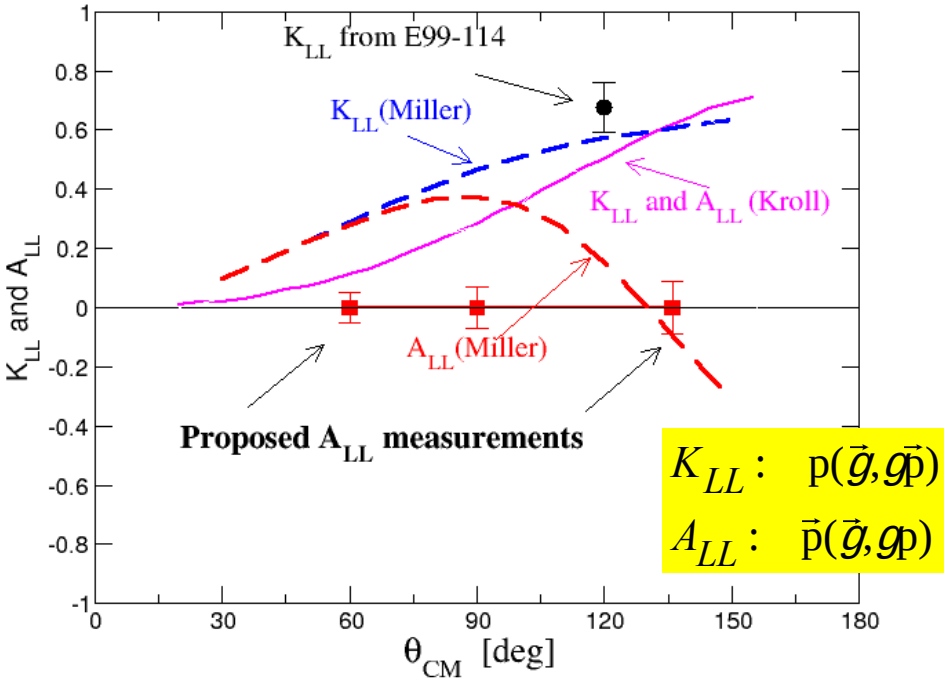


Polarization observables in Wide-Angle Compton Scattering

- Polarized WACS allows for studies of the size of *power-suppressed corrections* in the reaction mechanism due to, e.g., quark mass effects in a constituent quark model framework or to dressed-quark mass effects

- Jlab data on recoil obervable K_{LL} indicate partonic mechanism

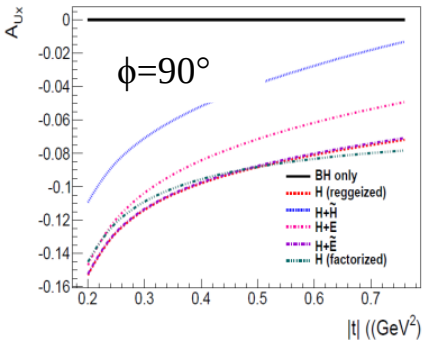
- Theoretical models do not describe the data well
  - GK: Elementary quarks, x ~ 1 kinematic approx.
  - Miller: Constituent qqq wave function; Good fit to Elastic G_E, G_M

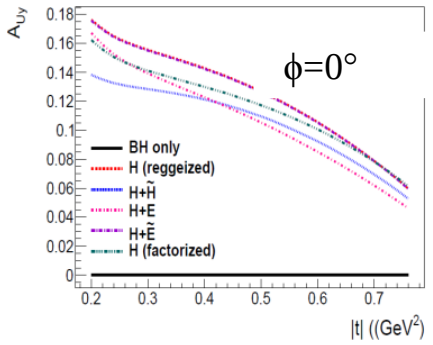


E12-14-006: measurements of target polarization observable A_{LL}. Any difference between A_{LL} and the recoil observable K_{LL} is indicative of the scale at which one approaches the leading order partonic mechanism

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

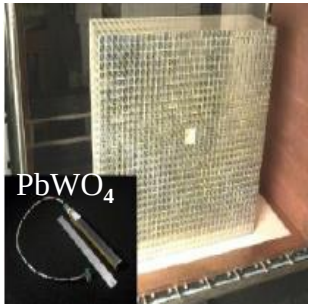
- Features of TCS measurements with transversely polarized target
  - Theoretical calculations show that transverse asymmetries are very sensitive to GPDs
    [M. Boer, M. Guidal, arXiv:1412.2036]
  - Asymmetries for the BH the main background for TCS is zero!
  - Predictions for asymmetries with different assumption of GPDs vary up to 20%

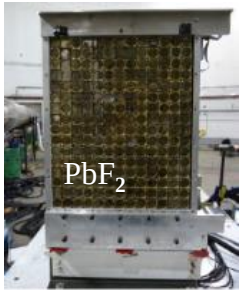


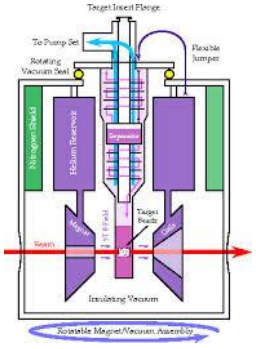


- TCS event detection with NPS
  - Lepton pair will be detected by pair of NPS
  - Recoil detection by combination of tracking and TOF

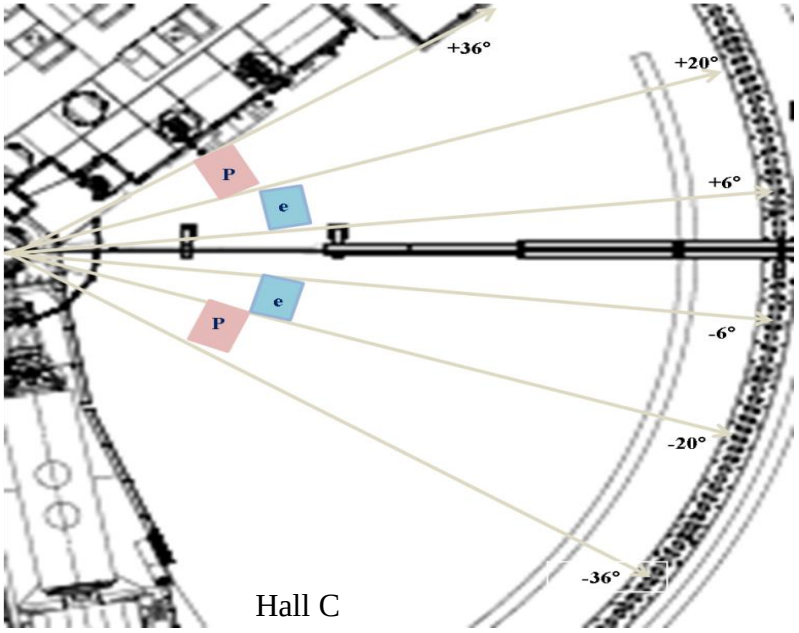
TCS measurements with transversally polarized target open interesting opportunities for probing GPD E







NH_3 Target



Hall C

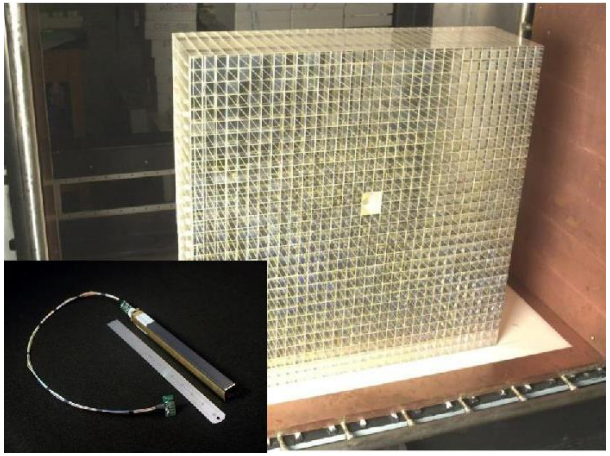
- Encouraging feedback from TAC43 Theory:

extraction of nucleon GPD's. This is a solid experimental idea well allied with the JLAB nucleon structure studies program. The proposed experiment has the potential to explore nucleon GPD's in a novel kinematical region where parton knockout is followed by $q\bar{q}$ formation. Given the diffractive nature of

NPS General Design Concept

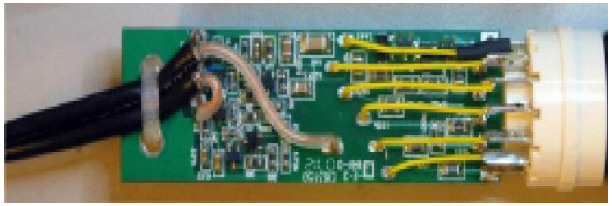
NSF MRI PHY-1530874

- a ~25 msr neutral particle detector consisting of up to 1116 **$PbWO_4$ crystals** in a temperature-controlled frame including gain monitoring and curing systems



- HV distribution bases with built-in amplifiers for operation in a high-rate environment

- Essentially deadtime-less digitizing electronics to independently sample the entire pulse form for each crystal – JLab-developed Flash ADCs

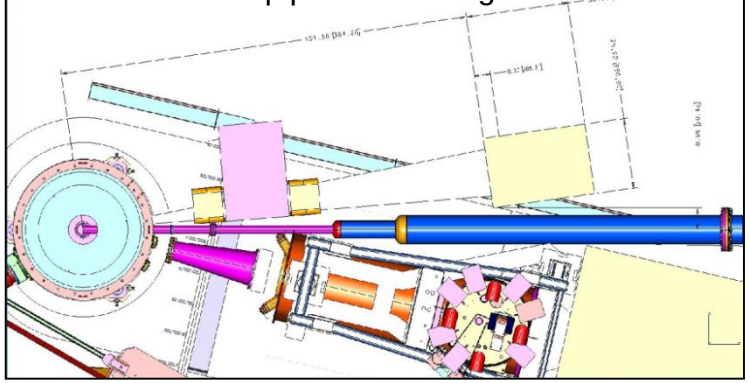


- A new 0.3Tm sweeping magnet allowing for small-angle and large angle operation at 0.6 TM. The magnet is compatible with existing JLab power supplies.

- Cantelevered platforms off the SHMS carriage to allow for remote rotation (in the small angle range), and platforms to be on the SHMS carriage (in the large angle range) – new

- A beam pipe with as large critical angle as possible to reduce beamline-associated backgrounds – further study showed only a small section needs modification (JLab/Hall C)

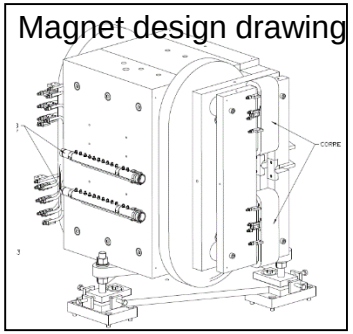
Modified beam pipe: critical angle 13.5 mr

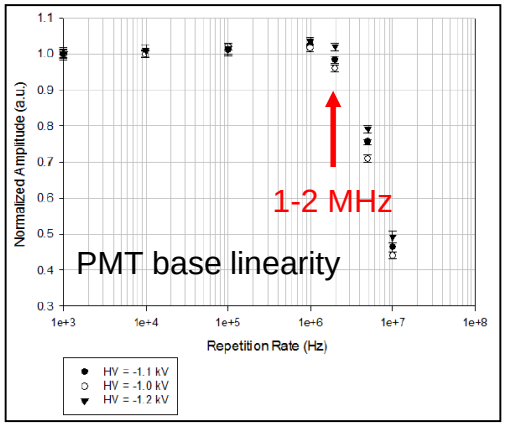


NPS Project Status

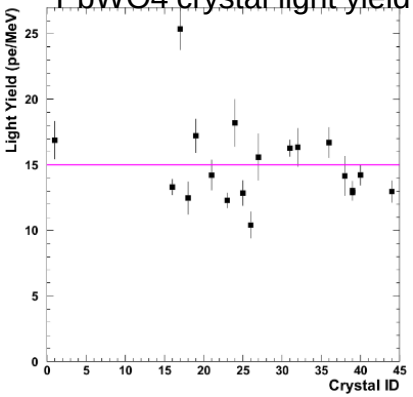
The Catholic University of America

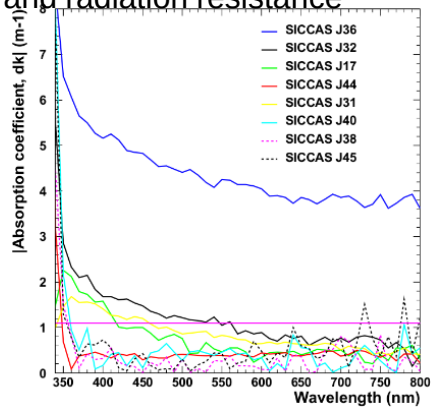
- Magnet: design drawings finalized, procurement of main and corrector coil awarded, yoke ongoing
- PMT and HV bases: design drawings final, vendor selection ongoing, linearity test complete, magnetic shielding concept selected
- Frame and integrated systems: initial design drawings completed, specifications for Light Monitoring System and curing system ongoing
- Crystals: characterization of systematic dependencies, irradiation studies, chemical analysis and crystal growing in collaboration with the Vitreous State Laboratory (VSL), synergy with EIC crystal calorimeter R&D





PbWO4 crystal light yield and radiation resistance





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Editors: T. Horn, C. Keppel, C. Munoz-Camacho, and I. Strakovsky

Summary and Outlook

- Precision cross section measurements are essential for the GPD/TMD program at 12 GeV JLab
  - Validate applicability of hard-soft factorization in exclusive processes required for accessing GPDs

- The neutral particle physics program in Hall C plays an important role in the GPD/TMD program

- The Neutral Particle Spectrometer gives unique opportunity for coincidence precision cross section measurements with neutral particles
  - Preparations for NPS design/construction underway