Exclusive π^0 with Jlab HallC

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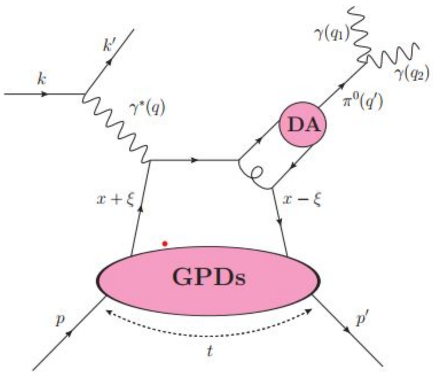
NPS Run Group 1a (Sept 2023 - May 2024)

- **E12-13-010**: Exclusive Deeply Virtual Compton and Neutral Pion Cross-Section Measurements in Hall C
- **E12-13-007**: Measurement of Semi-Inclusive π^0 Production as Validation of Factorization
- **E12-22-006**: Deeply Virtual Compton Scattering off the neutron with the Neutral Particle Spectrometer in Hall C
- **E12-23-014**: Measurements of the Ratio R = σ_L/σ_T, p/d ratios, Pt dependence, and azimuthal asymmetries in Semi-Inclusive DIS π^0 production form proton and deuteron targets using the NPS in Hall C

E12-13-010: Exclusive Deeply Virtual Compton and Neutral Pion Cross-Section Measurements in Hall C

Complement the kinematic settings of Hall A, by one or two conjugate setting. Increases the Q^2 reach to even higher values at fixed x_B. Expands the kinematic coverage to smaller values of x_B.

- π^0 electroproduction complements other channels for studying the nucleon structure:
  - **No diffractive ρ contributions**: Cleaner signal, reducing complications from vector mesons.
  - **No exclusive pole contributions**: Focuses the analysis purely on the production mechanisms without interference.
  - **Reduced resonance contributions**: Resonances play a smaller role, allowing access to more fundamental processes.

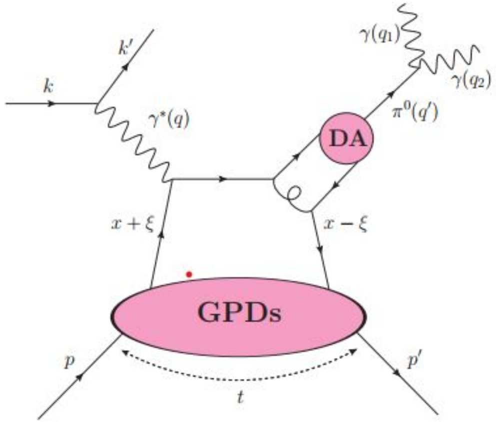


- PhysRevLett.117.262001

- Motivation for π^0 electroproduction towards GPDs:
  - Sensitive to transversity GPDs (H_T, E_T), which are less accessible in vector meson production.
  - Offers insights into parton helicity flipping (chiral-odd GPDs).
  - No need for polarized targets or beams to access these polarized distributions.

Physics Motivation: Exclusive π^0 Electroproduction

- **Measurements** of exclusive π^0 electroproduction in the valence region have been performed by **Hall A** [1] and the **CLAS Collaboration** [3,4].
- Hall A results suggest **dominant contributions from transversely polarized virtual photons** (σ_T).
- **Significant LT and TT interference terms** were also observed, highlighting the complex structure of the reaction mechanism.
- Measuring **longitudinal-transverse (L/T) separated cross sections** offers a **clean probe of transversity effects** in pion electroproduction.
- L/T-separated π^0 predictions above the resonance region remain uncertain, with **limited experimental data available**.
- If a **large** σ_T is confirmed at higher Q^2 and W, it could open the door to a **detailed study of transversity GPDs**—an essential but elusive piece of the nucleon structure puzzle.
- Meanwhile, the **longitudinal cross section** σ_L , if isolated, could provide a **unique channel to access the usual chiral-even GPDs** via **neutral pion production**.



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Previous Hall A Results: π⁰ Electroproduction at Moderate Q^2

- Hall A experiment E07-007 [1] measured exclusive π^0 electroproduction cross sections at x_B=0.36 and Q^2=1.5, 1.75, 2.0 GeV^2.
- Achieved L/T separation of the differential cross section $d\sigma/dt$.
- Longitudinal component $d\sigma_L/dt$ was found to be small or consistent with zero, but compatible with leading-twist chiral-even GPD models.
- Theoretical models including transversity GPDs are also in agreement with the data, particularly at higher Q^2.
- Supports theoretical predictions involving chirally enhanced helicity-flip pion distribution amplitudes.
- Provides strong motivation to pursue π^0 studies at higher Q^2 and W to further explore transversity GPDs.

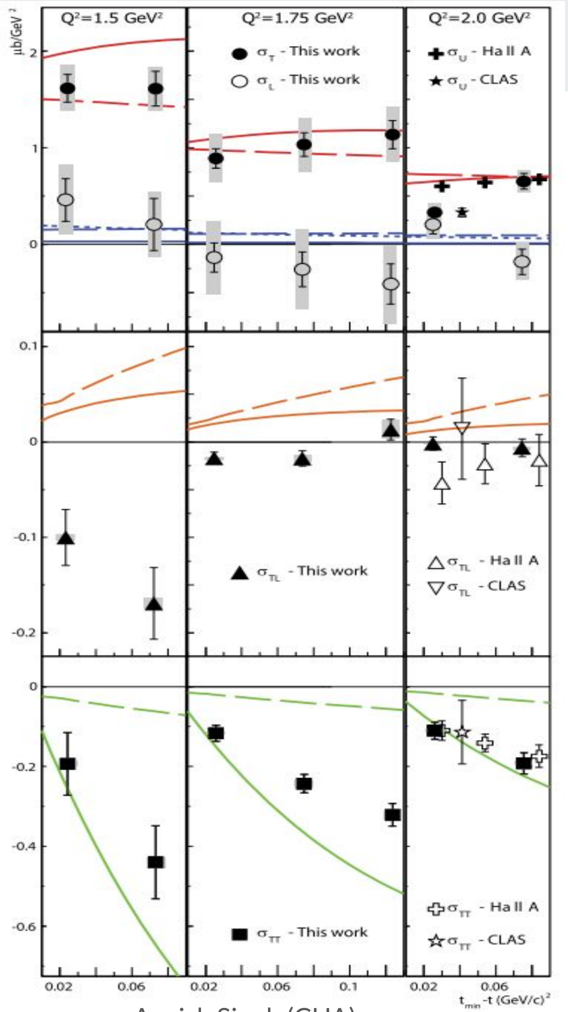
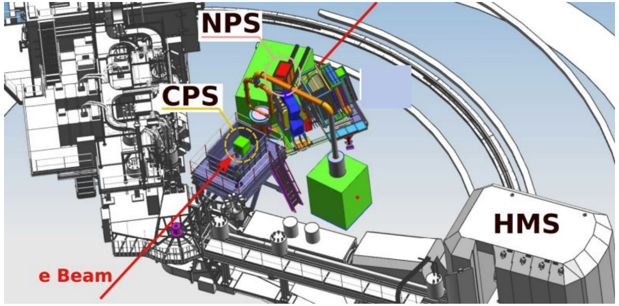
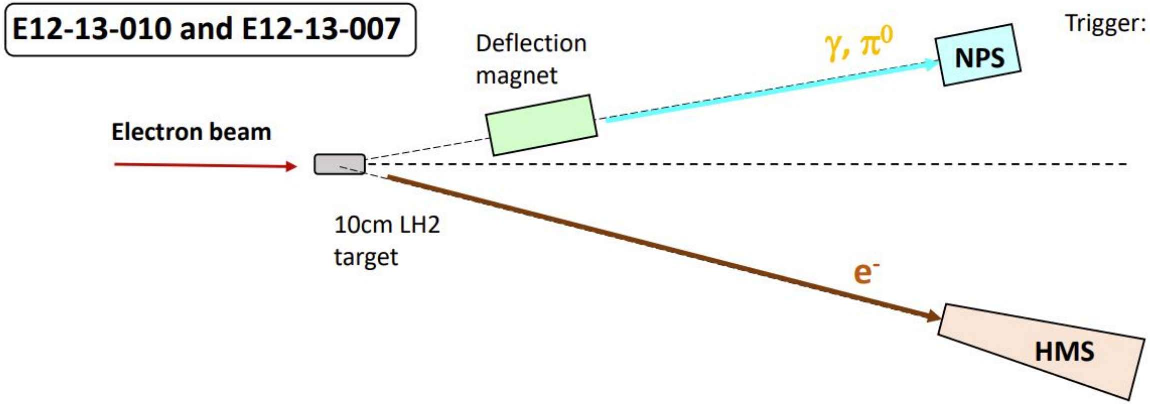


Figure: PhysRevLett.117.262001
The full lines are predictions from Ref. [5] and the long-dashed lines from Ref. [6]. The short-dashed line show the VGG model [7] for $d\sigma_L$.

Neutral Particle Spectrometer in Hall C - Overview

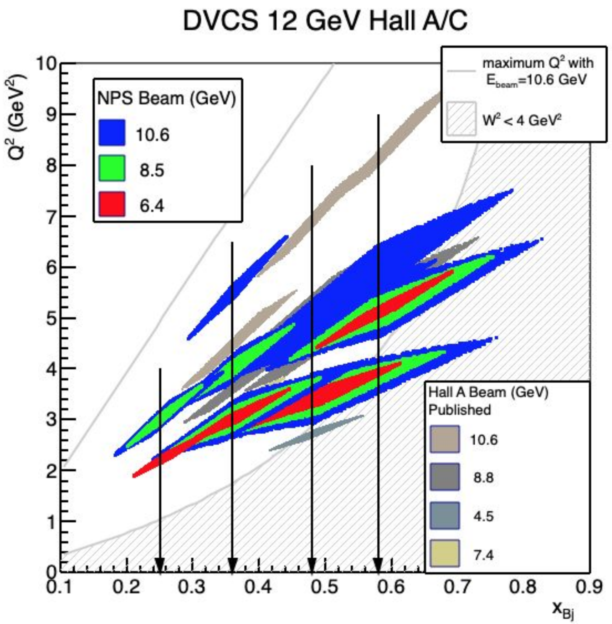
- Neutral Particle Spectrometer replaces one of the Hall C focussing spectrometers in the experiments
  - Angle reach between 5.5 and 60 degrees.
  - HMS has been recommissioned for 12 GeV
- Small angle, precision cross-sections, LT separation, high luminosity
- 1080 PbWO4 blocks.
- Radiation hard and temperature controlled frame.





Trigger: HMS, HMS+NPS

Hall C kinematic complements earlier experiments



- Courtesy Charles Hyde and Julie Roche

Kinematic Setting	Beam Pass	Coulomb Goal Per Target	LH2 % of Goal	LD2 % of Goal
KinC_x36_1	3	1.2	119.33%	134.08%
KinC_x36_2	4	1.1	37.12%	20.67%
KinC_x36_2'	4	1.1	44.78%	25.22%
KinC_x36_2''	4	1.1	34.77%	25.17%
KinC_x36_3	5	0.6	107.21%	119.06%
KinC_x36_4	4	2.7	36.67%	19.16%
KinC_x36_5	5	1.4	121.88%	88.58%
KinC_x36_5'	5	0.5	137.28%	106.98%
KinC_x36_6	5	4.3	43.95%	36.85%
KinC_x50_0a	3	2	55.18%	48.35%
KinC_x50_0b	3	2	40.73%	47.39%
KinC_x50_1	4	1.9	100.14%	81.01%
KinC_x50_1'	4	1.9	94.84%	80.17%
KinC_x50_2	5	2.05	121.33%	89.67%
KinC_x50_2'	5	0.57	109.81%	90.19%
KinC_x50_2''	5	0.61	94.90%	104.86%
KinC_x50_3	5	4.85	117.56%	86.04%
KinC_x50_3'	5	0.68	80.86%	119.14%
KinC_x50_3''	5	0.7	88.31%	111.69%
KinC_x60_1	3	10	32.48%	29.36%
KinC_x60_2	4	4.75	24.59%	22.70%
KinC_x60_2'	4	4.75	18.67%	20.05%
KinC_x60_3	5	3.17	112.50%	99.41%
KinC_x60_3'	5	1.26	85.76%	114.24%
KinC_x60_3a	5	1.83	57.62%	82.17%
KinC_x60_3b	5	1.83	83.94%	72.65%
KinC_x60_4a	5	3.88	85.56%	77.40%
KinC_x60_4b	5	3.88	83.39%	77.13%
KinC_x25_1	3	0.5	53.14%	34.10%
KinC_x25_3	4	2.6	27.73%	18.02%
KinC_x25_4	5	2.6	41.78%	33.59%

x_b	Q^2 (GeV^2)	Energy (MeV)
0.24	2.1	6600
0.26	3.0	8800
0.26	3.1	11000
0.36	3.0	6600
0.36	3.0	8800
0.36	3.0	11000
0.36	4.0	8800
0.36	4.0	11000
0.36	5.5	11000
0.48	3.3	6600
0.48	3.4	8800
0.46	3.3	11000
0.48	4.8	11000
0.58	5.1	6600
0.58	5.1	4400
0.58	5.1	6600
0.58	6.0	8800

Current Analysis Workflow Overview:

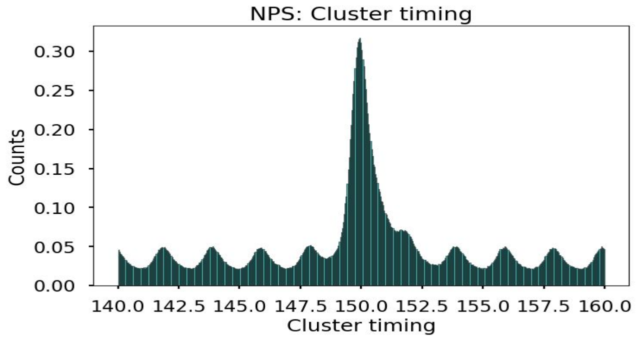
Note: NPS calorimeter calibrations are ongoing; the analysis workflow may be updated as calibrations are finalized.

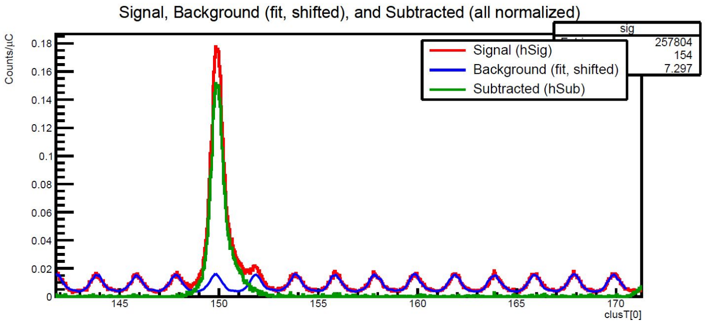
- ✓ HCANA decoding → ROOT ntuples
  - Ingesting skimmed root files for analysis.
- ✓ Event cuts (HMS/NPS) in C++/ROOT
  - Working cuts based on known good acceptances, detailed study to be done.
- ✓ Random-timing & ∅-cluster background
  - Spline fit/Non-gaussian distribution background is shifted under the main coincidence peak and then subtracted to remove accidentals.
- ✓ Dummy LH_2/LD_2 subtraction
  - Taking the Dummy target contribution for the setting and using the charge normalization to subtract.
- ✓ BCM charge Normalization & live-time scaling
  - Applying overall charge normalizations (some done in previous steps) and also introducing the necessary efficiency scaling
- ❑ Extraction of experimental yield (in progress)
  - Comparison of the observed data with the Hall C simulation framework SIMC.
  - Optimization of neutral pion cross section and spectrometer models.
- ❑ Outlook
  - Extraction of the **unseparated and separated cross-section** (multi-dimensional binning), cross-section **systematic uncertainties**, study of the **t-/Q2-dependence of the cross section**

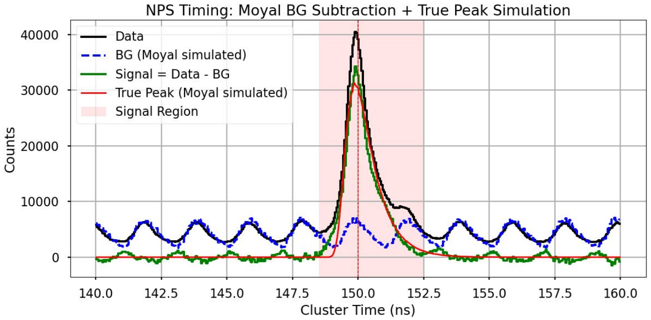
\- Slide by J P Crafts (CUA)

Background Subtraction for π^0 Reconstruction

- Timing resolution precise enough to observe the 2ns beam bunching.
- Background arises from accidental photon pairs, misidentified clusters, and non-exclusive processes.
- We employ complementary approaches to model and subtract background beneath the π^0 peak:
- Spline fit method:
    - A data-driven, non-parametric approach using smooth cubic splines to trace the background shape.
    - Effective at modeling subtle variations not easily captured by analytic functions.
- Non-Gaussian (Moyal) distribution fit (in progress):
    - Captures asymmetric, Landau-like tails typical of calorimetric (energy) background.
    - Provides an analytic form that smoothly transitions across the spectrum.

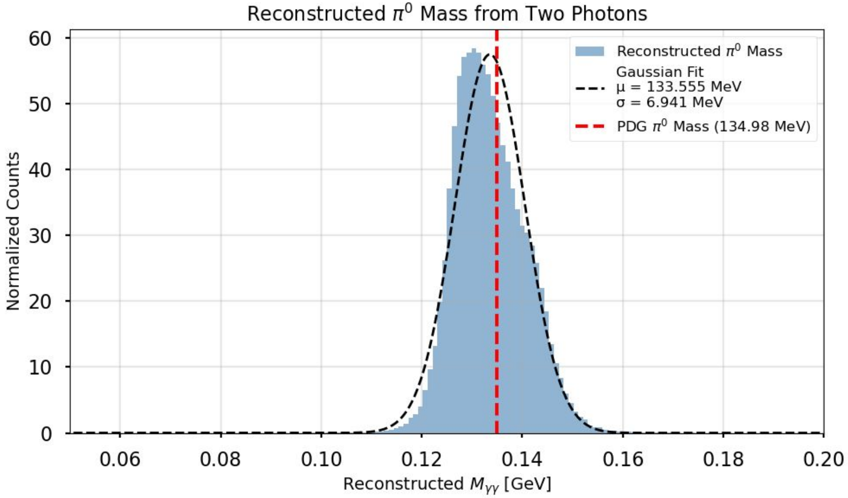






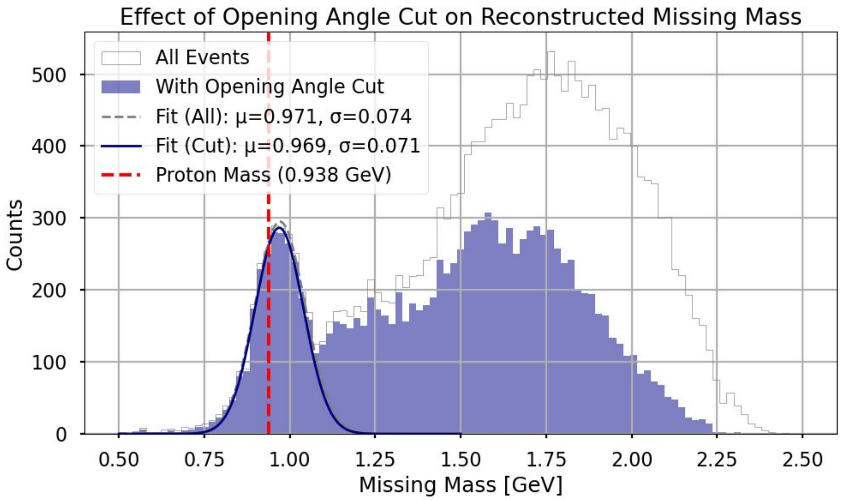
π^0 Reconstruction via Invariant Mass

- Reconstructed π^0 from two-photon invariant mass using cluster energies and opening angle from NPS.
- Invariant mass distribution shows a clear peak near 135 MeV, consistent with the neutral pion mass.
- Demonstrates successful identification of π^0 candidates in the exclusive channel.
- Demonstrated high signal-to-background ratio, ensuring clean event selection for cross section extraction.



Exclusive Channel Identification: Missing Mass off the Proton

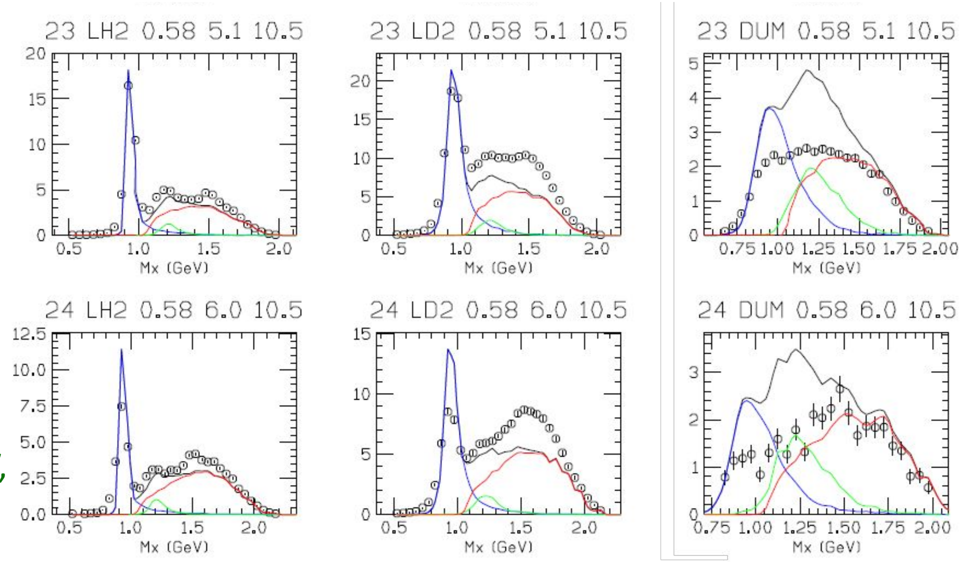
- Use measured scattered electron (HMS) and reconstructed π^0 (from NPS) to compute missing mass:
  $M_X^2 = \left(e + p - e' - \pi^0\right)^2$
- Expect a peak near proton mass (~0.938 GeV) for exclusive $ep \to e'\pi^0 p'$ events.
- Missing mass spectrum shows clear signal, confirming exclusivity of selected events.
- Background includes:
  - Non-exclusive events (e.g., multipion production).
  - Mis-reconstructed clusters or mis-identified photons.
- Clean exclusive region used for final event selection in cross section analysis.

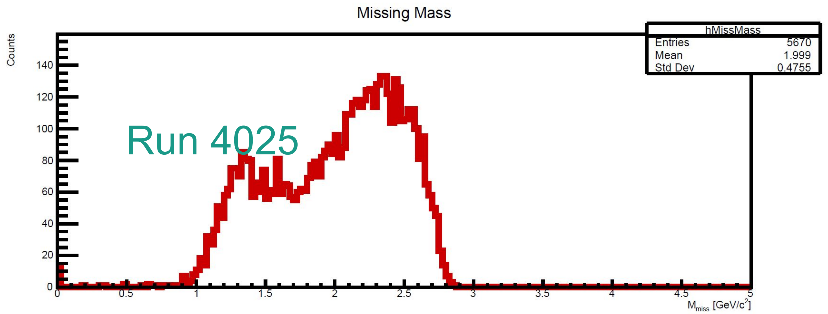


Monte Carlo Status

- HallC uses the simulation framework called SIMC.
- Several models are available for PEEPI
  - **Valery Kubarovsky (VK)** GPD inspired fit for "deep" π^0 (default when doing_pizero=.TRUE.).
  - **param-04 (By Blok)** / **param-3000 (By T. Horn)** / **param-2021 (By P. Bosted)** for wider W,Q^2, latest phenomenological fit of global data by Peter B.
  - MAID 2007 multipole amplitudes below W≈2.2 GeV.
  - Historic (1970s) Blok/Brauel fit.
- The code chooses which one to call based on W, Q^2 and the pion charge (π^+, π^-, π^0).
- Takes a Monte-Carlo event, boosts it to the photon–nucleon CM, evaluates the appropriate $\gamma N \to \pi N$ model cross-section there,
- Then multiplies Jacobian × virtual photon flux, and hands SIMC the fully-differential electron pion coincidence cross-section in the lab.

Credit to Peter B.





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Projected Uncertainties

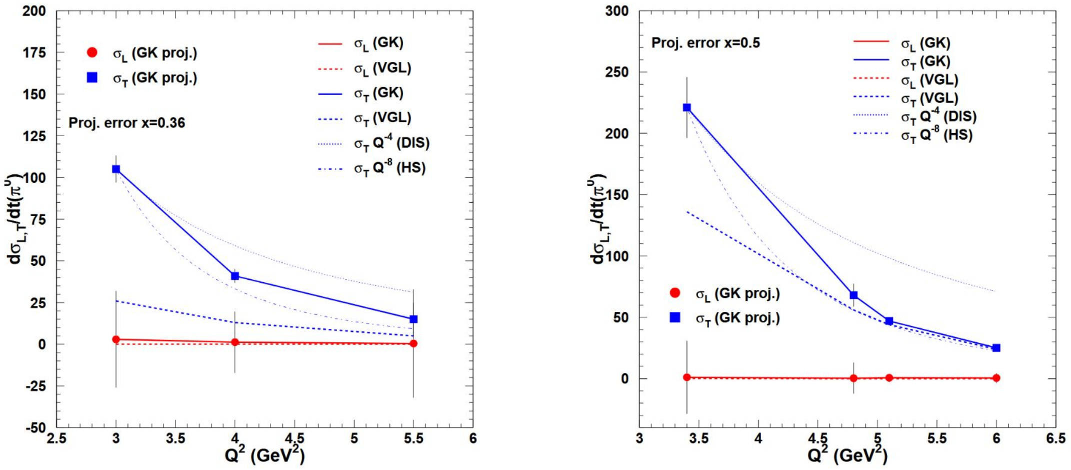

FIG. 3: Projected uncertainties for the Q^2 dependence of σ_L and σ_T at fixed x_B=0.36, 0.5. The points are plotted assuming the GK model predictions. Also shown are the hard scattering (HS, $R=\sigma_L/\sigma_T$ $1/Q^{-2}$) and the DIS (DIS, R $1/Q^2$) expectation, and the model predictions of the VGL (Regge) model. The points at Q^2=5.1 and 6.0 GeV^2 in the right panel are scaled from the x_B=0.6 setting in Table III and include events from the Hall A DVCS experiment [28] for the low beam energy in the L/T separation where appropriate. The point at Q^2=5.5 GeV^2 also includes events from the Hall A experiment for the low beam energy in the L/T separation.

- JLab Hall C proposal PR12-13-010

Closing Remarks

- Successfully reconstructed **π⁰ invariant mass** from NPS photon pairs and achieved **clean missing mass off the proton**, validating exclusive $ep \rightarrow e'\pi^0 p'$ event selection.
- Implemented and cross-validated **background subtraction methods** (Moyal + spline) to isolate clean π^0 signals across kinematics.
- Currently working on:
  - **Extracting experimental yields** in bins of Q^2, x_B, -t.
  - **Comparison with SIMC simulations** to correct for acceptance and radiative effects
- Next step: **Optimize pion production model in SIMC** for neutral pion channels
  - improves agreement between data and simulation and enables reliable cross section extraction.
- Goal: Perform **L/T separation** of the cross section:
- Access σ_T **and** σ_L, and interference terms (σ_{LT} and σ_{TT}).
- Essential for probing **transversity GPDs (** σ_T **)** and **chiral-even GPDs (** σ_L **).**
- This work contributes to the **next generation of hadron structure studies** using exclusive π^0 production with the NPS in Hall C.

References

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