

# Analysis Progress and Future Plans for the $u$ -Channel Nucleon Structure Program

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Hall A/C Collaboration Meeting 2026

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University  
of Regina



- Motivation

- Previous Results

- **Analysis progress**

... **Alicia's PhD Thesis**

- KaonLT experiment

- Event selection for  $p(e, e' p')\omega^0$

- Rosenbluth separation

- **Future plans**

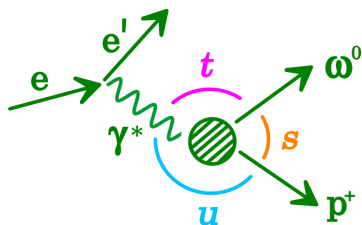
...  **$\nu$ -Channel Physics Opportunities**

- Exclusive  $\pi^0$  production

- Exclusive  $\pi^+ / K^+$  production

- SIDIS

- DVCS



$$t = (\mathbf{p}_{\gamma^*} - \mathbf{p}_{\omega^0})^2$$

$$u = (\mathbf{p}_{\gamma^*} - \mathbf{p}_{p'})^2$$

## **t-channel:**

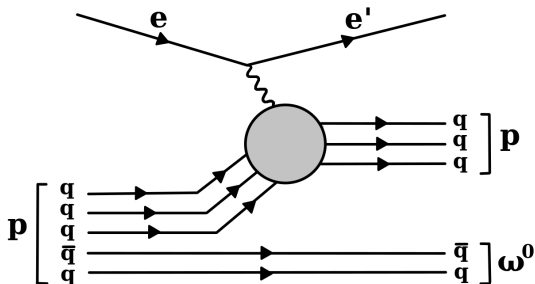
- $-t \lesssim 1 \text{ GeV}^2$
- High momentum forward **meson**
- Larger cross-section
- Well studied

## **u-channel:**

- $-u \lesssim 1 \text{ GeV}^2$
- High momentum forward **baryon**
- Smaller cross-section
- **Mostly unexplored...**



- Unique access to  $qqqq\bar{q}$  part of the proton wavefunction
- Transfer of **baryon number** → sensitive to baryon number distribution
- Backward photoproduction used to estimate proton **baryon number radius**

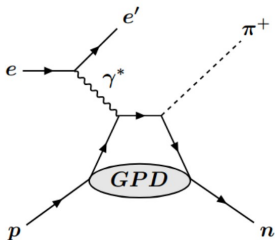


“Knocking a proton out of the proton”

W. B. Li et al. (F $\pi$  Collaboration), *Unique Access to  $u$ -Channel Physics: Exclusive Backward- Angle Omega Meson Electroproduction* Phys. Rev. Lett. 123, 182501 (2019).

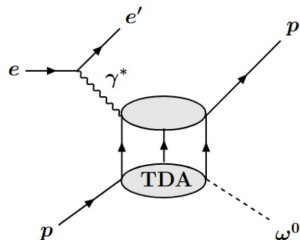
S. R. Klein, M. C. Labonte, Z. Sweger, G. Miller, & R. Vogt, *Imaging baryon number density within the proton*, arXiv:2603.03730v1 [hep-ex] (2026).

# Forward and Backward-Angle Observables



***t*-channel:**

- Access to **Generalized Parton Distribution (GPD)**
- GPDs encode position & momentum of **partons**

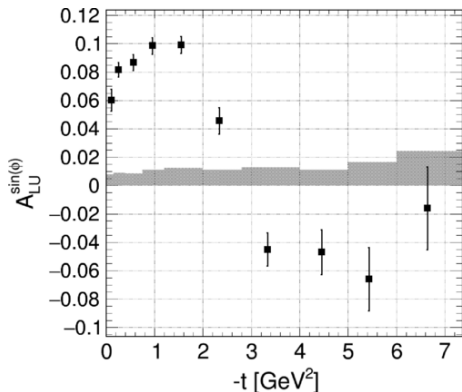


***u*-channel:**

- Access to **Transition Distribution Amplitude (TDA)**
- TDAs encode momentum distribution of **baryon number**

Both GPD & TDA formalism rely on hard/soft **factorization**.

B. Pire, K. Semenov-Tian-Shansky, and L. Szymanowski, *Transition distribution amplitudes and hard exclusive reactions with baryon number transfer*, Phys. Rep, **940** 1 (2021).

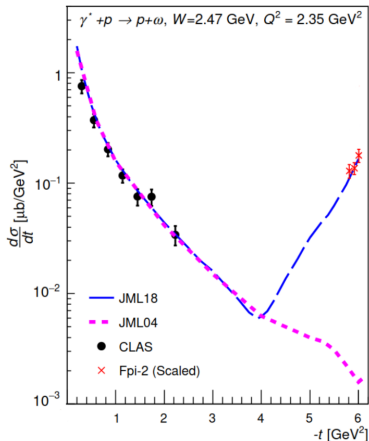


- Beam-Spin Asymmetry measurement of  $\rho(e, e'\pi^+)n$  with CLAS
- Forward (small  $-t$ ) vs backward (large  $-t$ )  $\pi^+$  production
- Sign change of  $A_{LU}$  implies a change in reaction mechanism

$$s + t + u = \Sigma m^2$$
$$\text{large } -t \iff \text{small } -u$$

( $u$ -channel)

S. Diehl et al (CLAS Collaboration), *Extraction of Beam-Spin Asymmetries from the Hard Exclusive  $\pi^+$  Channel off Protons in a Wide Range of Kinematics*, Phys. Rev. Lett. 125, 182001 (2020).



- Measurement of  $p(e, e' p')\omega^0$  in the  $F\pi$ -2 experiment
- Forward (small  $-t$ ) vs backward (large  $-t$ )  $\omega^0$  production
- Surprisingly large  $u$ -channel peak in unseparated cross-section!

$$s + t + u = \Sigma m^2$$

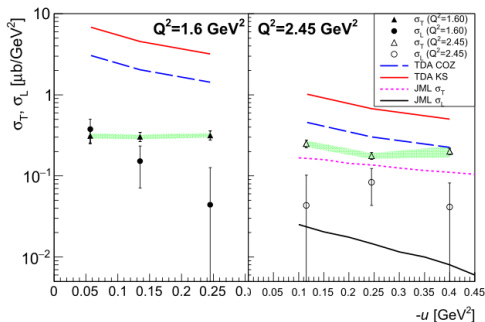
large  $-t \iff$  small  $-u$   
( $u$ -channel)

W. B. Li et al. ( $F\pi$  Collaboration), *Unique Access to  $u$ -Channel Physics: Exclusive Backward-Angle Omega Meson Electroproduction* Phys. Rev. Lett. 123, 182501 (2019).

# Previous Indications of Factorization



Data approaching TDA prediction by  $Q^2 \approx 2.5 \text{ GeV}^2$  in both **Hall C  $\omega^0$**  production and **CLAS  $\pi^+$**  production

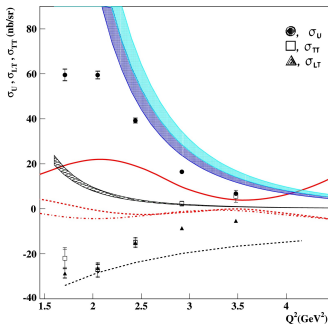


## Hall C $\omega^0$

Agreement between  $\sigma_T$  and **TDA** is poor at  $Q^2 = 1.65 \text{ GeV}^2$ , but decent at  $Q^2 = 2.45 \text{ GeV}^2$

K. Park et al (CLAS Collaboration), *Hard Exclusive Pion Electroproduction at Backward Angles With CLAS*, Phys. Lett. B **780** 340 (2018).

W.B. Li et al ( $F\pi$  Collaboration), Phys. Rev. Lett. **123** 182501 (2019).



## CLAS $\pi^+$

**TDA** predictions approach  $\sigma_U$  at  $Q^2 \approx 2.5 \text{ GeV}^2$

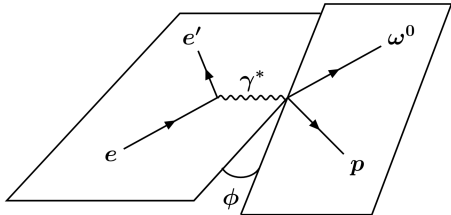
## **ANALYSIS PROGRESS**

**Rosenbluth Separation of  $p(e, e' p)\omega$  in KaonLT**

$$2\pi \frac{d^2\sigma}{dud\phi} = \frac{d\sigma_T}{du} + \epsilon \frac{d\sigma_L}{du} + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{LT}}{du} \cos\phi + \epsilon \frac{d\sigma_{TT}}{du} \cos 2\phi$$

- Separate total cross-section  $\sigma$  into components  $\sigma_L, \sigma_T, \sigma_{LT}, \sigma_{TT}$
- Relies on virtual photon polarization fraction

$$\epsilon = \left(1 + 2 \frac{(E_e - E_{e'})^2 + Q^2}{Q^2} \tan^2 \frac{\theta_{e'}}{2}\right)^{-1}$$



Test of **factorization** in  $u$ -channel:

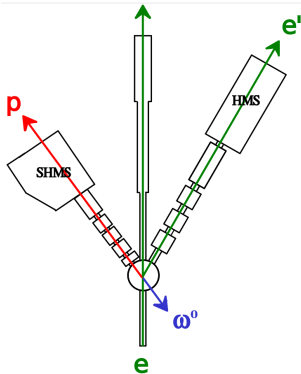
- Dominance of transverse cross-section  $\sigma_T \gg \sigma_L$
- Characteristic scaling  $\sigma_T \propto 1/Q^8$

M. Diehl and S. Sapeta, *On the analysis of lepton scattering on longitudinally or transversely polarized protons*, Eur. Phys. J. C 41, 515–533 (2005).



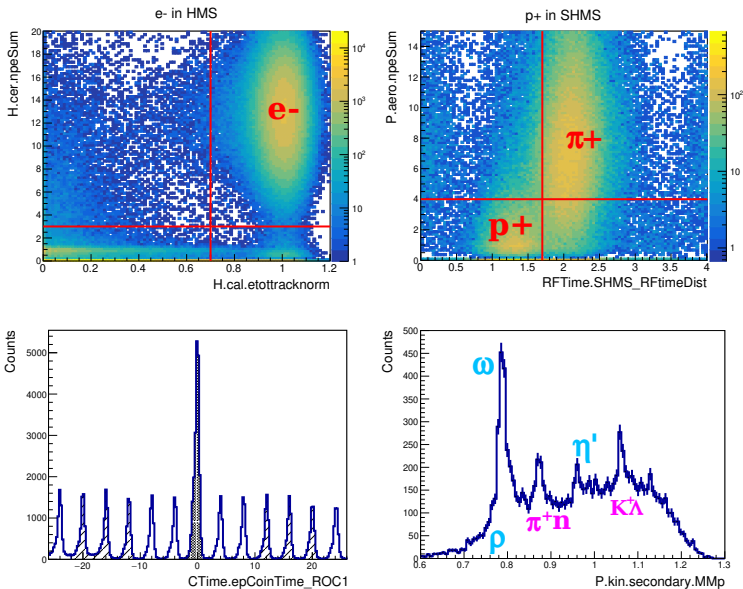
- **Main goal:** LT separation of  $p(e, e' K^+) \Lambda$  for extraction of the **kaon form factor**  $F_K(Q^2)$
- **HMS electron + SHMS hadron:**  $t$ -channel  $\pi^+ / K^+$  &  $u$ -channel **p**
- Data taken at two values of  $\epsilon$  per  $(Q^2, x_B)$  for LT separation
- **This work:** LT separation of  $u$ -channel  $p(e, e' p') \omega^0$

$E$ [GeV]	$Q^2$ [GeV <sup>2</sup> ]	$W$ [GeV]	$\epsilon_{HIGH}/\epsilon_{LOW}$
10.6/8.2	5.5	3.02	0.53/0.18
10.6/8.2	4.4	2.74	0.71/0.48
10.6/8.2	3.0	3.14	0.67/0.39
10.6/6.2	3.0	2.32	0.88/0.57
10.6/6.2	2.1	2.95	0.79/0.25



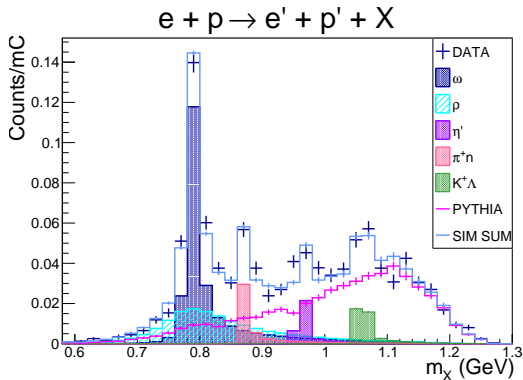
G. Huber, T. Horn, and P. Markowitz, E12-09-011, Jefferson Lab PAC 38 (2009).

# Event Selection $p(e, e'p')\omega^0$

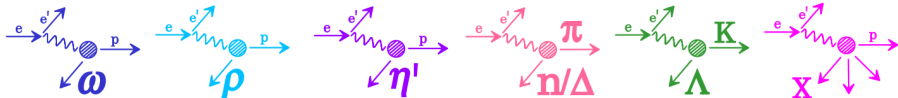


Plots:  $Q^2=3.0 \text{ GeV}^2$ ,  $W=3.14 \text{ GeV}$ , SHMS center, low  $\epsilon$

# Background "Shape" Study



- Individually simulate exclusive processes with SIMC
- SIDIS background simulated with PYTHIA as input to SIMC
- $\pi^+ / K^+$  leakthrough: parametrize with real data sample
- Fit sum of contributions to data

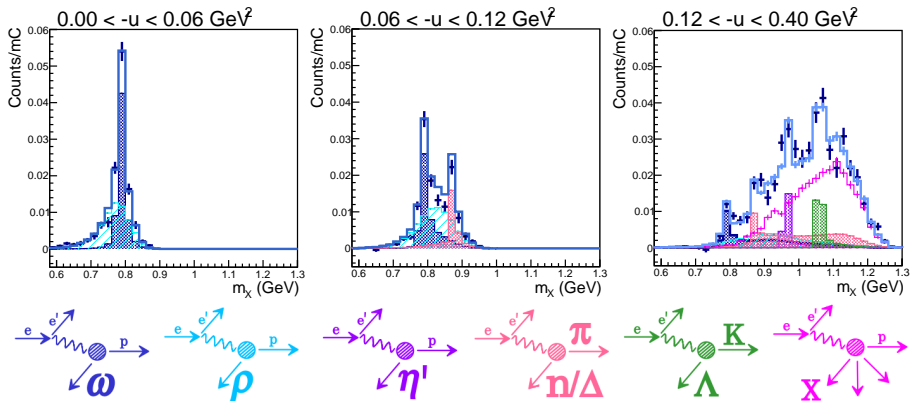


Plot:  $Q^2=3.0 \text{ GeV}^2$ ,  $W=3.14 \text{ GeV}$ , SHMS center, low  $\epsilon$

# Binned Background Study



- Input to Rosenbluth equation is  $d^2\sigma/dud\phi$ : need to bin data in  $u, \phi$
- Higher  $-u$  corresponds to higher available  $m_X$
- Huge  $u$ -dependence in background processes!



Plots:  $Q^2=3.0 \text{ GeV}^2$ ,  $W=3.14 \text{ GeV}$ , SHMS center, low  $\epsilon$

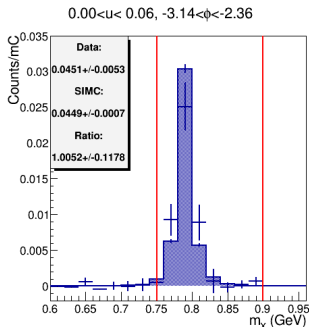


- Subtract all background simulations from data
- Integrate  $\omega$  peak for yield of  $p(e, e'p')\omega^0$  events
- Cross-sections calculated per  $u, \phi$  bin by the ratio method

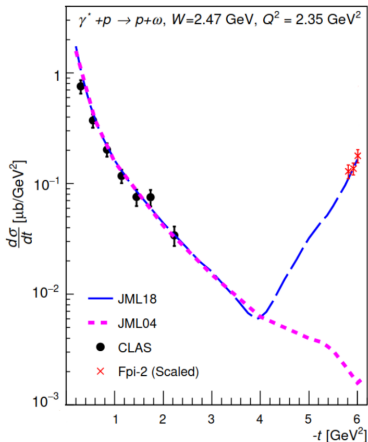
$$\left(\frac{d^2\sigma}{dud\phi}\right)_{EXP} = \left(\frac{Y_{EXP}}{Y_{MC}}\right)\left(\frac{d^2\sigma}{dud\phi}\right)_{MC}$$

## Current Work:

- Finalize all corrections to  $Y_{EXP}$
- Iterative L/T separation procedure



Plot: sample  $u - \phi$  bin,  $Q^2=3.0 \text{ GeV}^2$ ,  $W=3.14 \text{ GeV}$ , SHMS center, low  $\epsilon$



**Fπ-2 2019**

## ■ Unseparated cross-sections

→ Search for  $u$ -channel peak

## ■ Rosenbluth separation

→ Check factorization predictions for feasibility of TDA extraction

$$\sigma_T \gg \sigma_L, \quad \sigma_T \propto 1/Q^8$$

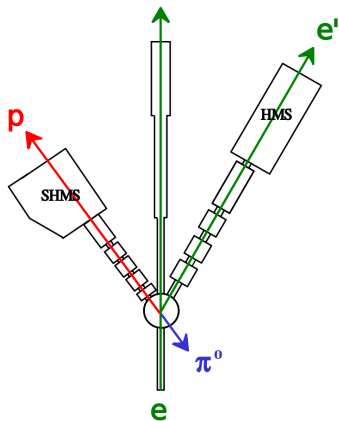
■ KaonLT results [This work] will **triple** existing data and extend  $Q^2$  reach from 2.45 to 4.4  $\text{GeV}^2$

W. B. Li et al (Fπ Collaboration), *Unique Access to  $u$ -Channel Physics: Exclusive Backward-Angle Omega Meson Electroproduction*, Phys. Rev. Lett. **123** 182501 (2019).

## **FUTURE PLANS**

***U*-Channel Physics Opportunities**

- Dedicated  $u$ -channel  $\pi^0$  experiment E12-20-007 (approved PAC 48)
- **Goal:** LT separation of  $\rho(e, e' p')\pi^0$  to verify TDA factorization

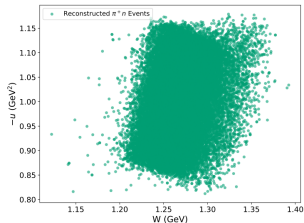
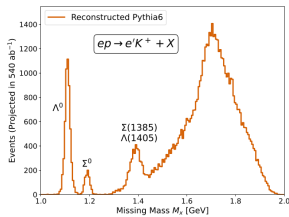
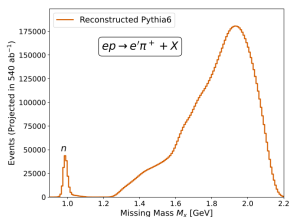


$Q^2$ (GeV <sup>2</sup> )	$W$ (GeV)	$x_B$	$E_{\text{Beam}}$ (GeV)	$\epsilon$
2.0	2.11	0.36	4.4*	0.52*
			10.9*	0.94*
2.0	3.00	0.20	6.60	0.32
			10.90	0.79
3.0	2.49	0.36	6.60	0.54
			10.90	0.86
4.0	2.83	0.36	8.80	0.56
			10.90	0.73
5.0	3.13	0.36	8.80	0.26
			10.90	0.55
6.25	3.46	0.36	10.90	0.27

Expecting 1.5 PAC days in FY27! (As per [Hall A/C Status Update](#))  
Analysis led by MSU students Zakia Tithi and Roman Tkachenko



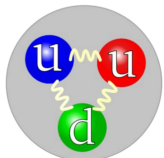
Opportunistic measurement possible with  $\phi$ -007 (E12-25-007, approved PAC 54):



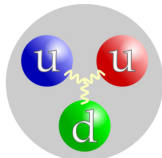
- Nicely complimentary to current Hall C  $u$ -channel data
- **KaonLT**:  $t$ -channel  $\pi^+ / K^+$ ,  $u$ -channel  $p$  ( $u < 0.5$ )
- $\phi$ -007:  $t$ -channel  $p$ ,  $u$ -channel  $\pi^+ / K^+$  ( $u \approx 1$ )
- $K^+$  analysis challenging without refurbishment of the HMS AGC

Plots by Henry Klest (ANL)

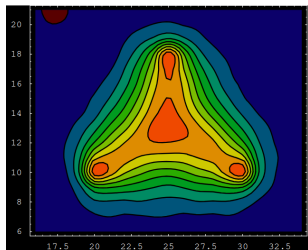
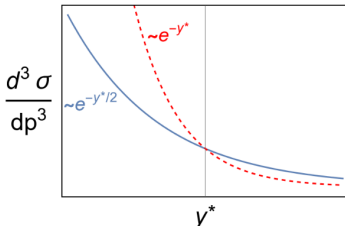
- Is baryon number carried by quarks or gluons?
- Lattice QCD calculations imply existence of gluon junction in the proton “vorton”
- $u$ -channel SIDIS provides more direct access to potential vorton



A



B



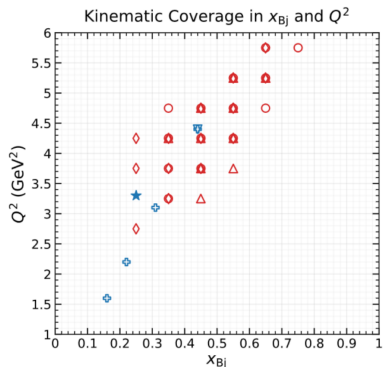
Rapidity of forward baryon:

**RED:** conventional prediction, **BLUE:** with vorton

D. Frenklakh, D.E. Kharzeev, & W.B. Li, *Signatures of baryon junctions in semi-inclusive deep inelastic scattering*, arXiv:2312.15039 [hep-ph] (2023).

H. Suganuma et al, *Lattice QCD Study for the Interquark Force in Three-Quark and Multi-Quark Systems*, AIP Conf. Proc. **756** 0094-243X 123–132 (2005).

- Hall C has abundant SIDIS data, e.g. **R-SIDIS** (E12-09-017) **PionCT** (E12-06-107), etc.
- Primary reaction:  $p(e, e' \pi^+) X$
- Additional data acquired with a high-z proton:  $p(e, e' p) X$
- Similar measurements possible with CLAS12 → Analysis proposal in preparation for RG-A & RG-B (MSU student Preet Mann)

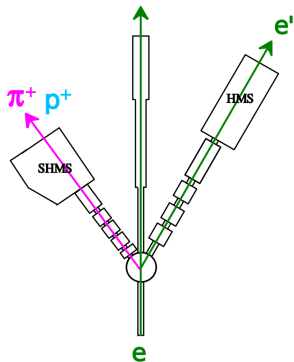


E12-09-002 (CSV)  
 E12-09-017 (pT-SIDIS)  
 E12-06-107 (pion-CT)  
 $\diamond$   $z < 0.6$   
 $\circ$   $0.6 < z < 0.8$   
 $\triangle$   $z > 0.8$

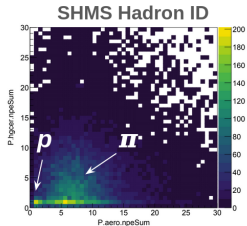
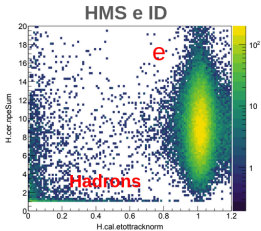
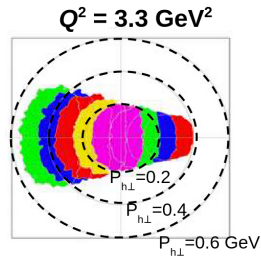
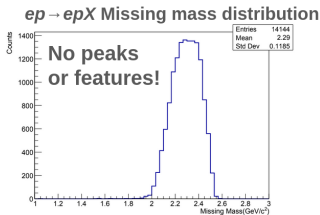
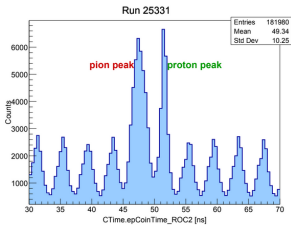
**Devesh Bhattarai**  
 (MSU student)

E12-06-104 (R-SIDIS)  
 $\diamond$   $z < 0.6$   
 $\nabla$   $0.6 < z < 0.8$   
 $\star$  Completed:  $x_{Bj} = 0.25, Q^2 = 3.3$

**Zichen Yin**  
 (MSU student)



# Proton Signature in SIDIS Data



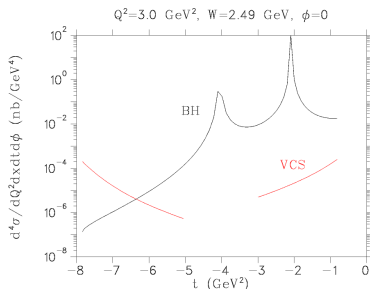
- Example plot from RSIDIS,  $x_b = 0.25$ ,  $Q^2 = 3.3 \text{ GeV}^2$
- End goal is to extract the differential cross section as function of  $p_T$

Slide by Wenliang (Bill) Li & students (MSU).



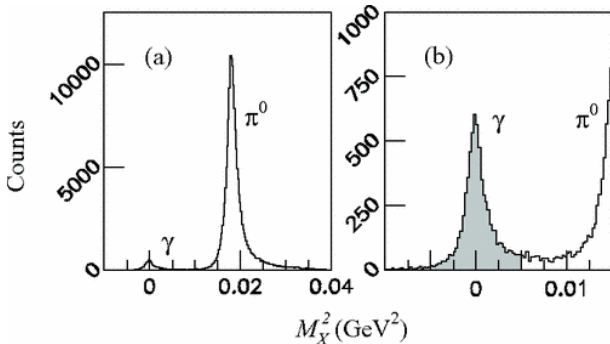
*"Since the study in terms of GPDs of [DVCS] in the forward region has been very fruitful to understand the underlying structure of the hadron, we foresee that the corresponding one with TDAs of the backward region be of equal importance, if not more since it involves the exchange of 3 quarks"*

J.P. Lansberg, B. Pire, and L. Szymanowski,  
*Backward DVCS and Proton to Photon  
Transition Distribution Amplitudes*, Nuclear  
Physics A **782** 16c–23c (2007).



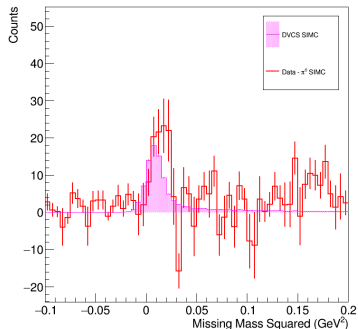
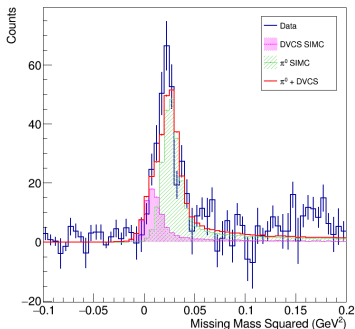
Bethe-Heitler suppressed  
compared to DVCS at large  $t$   
( $u$ -channel)!

→ Experimentally measured cross  
sections will depend bilinearly on  
(proton-to-photon) TDAs



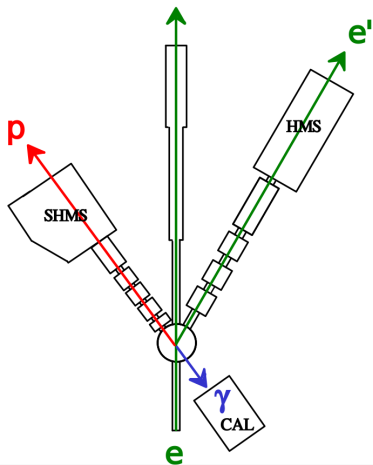
- Backward VCS from  $1.45 < W < 1.6$  GeV,  $0.5 < Q^2 < 2.0$  GeV<sup>2</sup> in E93–050
- $e'$  and  $p'$  detected in HRS,  $\pi^0$  and  $\gamma$  reconstructed from  $M_X^2$
- Similar measurement in Hall C VCS experiment, but wide angle instead of true  $u$ -channel

G. Laveissiere et al. (Hall A Collaboration), *Virtual Compton scattering and neutral pion electroproduction in the resonance region up to the deep inelastic region at backward angles*, Phys. Rev. C **79**, 015201.



- Unexpected signal in KaonLT
- Detect  $e'$  (HMS) and  $p'$  (SHMS), reconstruct  $\pi^0$  and  $\gamma$  from  $M_X^2$
- Mainly  $\pi^0$ , but data suggest a small **DVCS** contribution
- Current work: estimating systematic uncertainties  
→ resolution, radiative effects, offsets...
- Analysis by U. Regina undergraduate student Dex Yadlowski

Plots:  $Q^2=3.0 \text{ GeV}^2$ ,  $W=3.14 \text{ GeV}$ , SHMS center, low  $\epsilon$



- Future experiment opportunity!
- Validate KaonLT signal with results from E12-20-007 for rate estimates
- Triple coincidence: HMS+SHMS+Calorimeter
- Photon tagging to reject  $\pi^0$  background



- Emerging field with lots of new opportunities
- Unique access to **meson cloud** of proton and distribution of **baryon number**
- Rosenbluth separation of  $\rho(e, e' p)\omega^0$  underway in KaonLT
- SIDIS data from R-SIDIS, PionCT, and CLAS12
- Measurement of  $\rho(e, e' p)\pi^0$  running soon!

The  $u$ -channel nucleon structure program:  
DEMP + SIDIS + DVCS

# Acknowledgements



## **KaonLT Working Group:**

Dave Gaskell\*, Nacer Hamdi, Nathan Heinrich,  
Garth Huber\*, Tanja Horn\*, Sameer Jain,  
Muhammad Junaid, Stephen Kay, Vijay Kumar,  
B.C. Manoj, Pete Markowitz\*, Gabriel Niculescu,  
Ioana Niculescu, Alicia Postuma, Kathleen  
Ramage, Julie Roche, Nermin Sadoun, Chi Kin  
Tam, Richard Trotta, Ali Usman, Dex Yadlowski

## **u-Channel Working Group:**

Devesh Bhattarai, Garth Huber, Wenliang (Bill) Li,  
Preet Mann, Alicia Postuma, Zakia Tithi, Roman  
Tkachenko, Dex Yadlowski, Zichen Yin

*This work supported by:*

*NSERC Vanier CGS (A. Postuma)*

*NSERC SAPIN-2026-00043 (G. Huber)*

*NSF PHY 2309976, 2012430, 1714133, 2209199*

*MSU Physics & Astronomy startup funds (W. Li)*



Bourses d'études  
supérieures du Canada

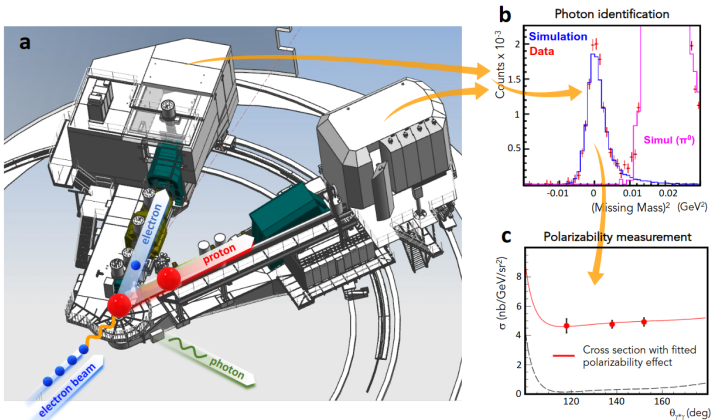
Vanier

Canada Graduate  
Scholarships



**EXTRA SLIDES**

# Wide-Angle VCS in Hall C



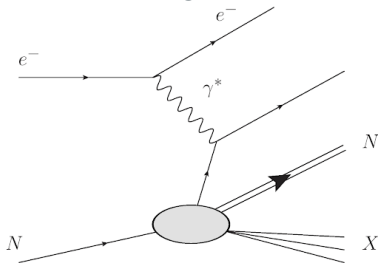
- Wide-angle VCS for  $Q^2 = 0.28, 0.33, 0.40$  GeV $^2$  in E12-15-001
- VCS-II (E12-23-001) to scan  $0.05 < Q^2 < 0.50$  GeV $^2$

R. Li et al., *Measured proton electromagnetic structure deviates from theoretical predictions*, Nature **611**, 265–270 (2022).

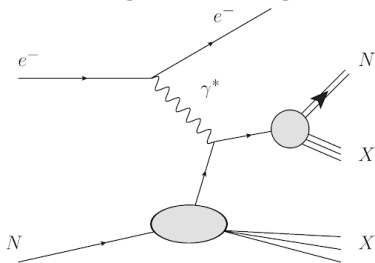
N. Sparveris et al, *Measurement of the Generalized Polarizabilities of the Proton in Virtual Compton Scattering*, JLab Experimental Proposal to PAC 51 (2023).

- A high momentum proton can be generated by multiple mechanisms in SIDIS
- Fracture functions: hybrid between structure and fragmentation functions
- Both fragmentation and fracture functions are uncalculable but measurable and universal

## Parton fragmentation:



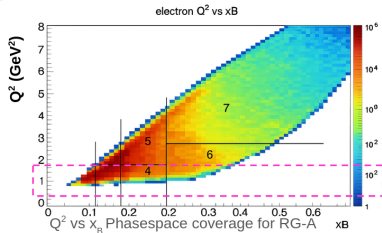
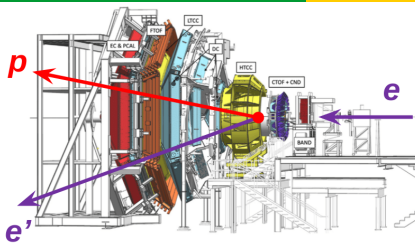
## Target fracturing:



L. Trentadue & G. Veneziano, *Fracture functions: an improved description of inclusive hard processes in QCD*, Phys. Lett. B 323, 201–211, 1994.

Schematics by Bill Li.

# High Momentum Proton in CLAS12



- SIDIS differential cross section at  $Q^2 \sim 1 \text{ GeV}^2$  with proton momentum of 3–8 GeV

→ Extract the Regge slope

- Comparison between  $e + p$  and  $e + d$  events as a function of  $W$ ,  $Q^2$ , and proton momentum

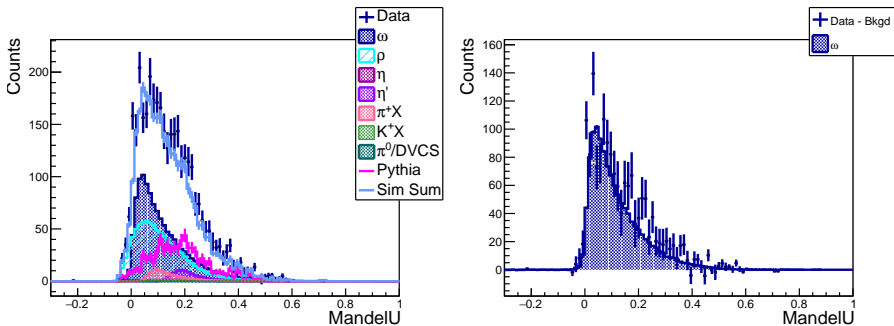
→ Confirm EMC results of flavor independence

**Analysis proposals** for RG-A and RG-B under preparation.

Collaborators: MSU, Kent State, Shandong U, Tsinghua U

Plots from Wenliang (Bill) Li & students (MSU).

- Input to Rosenbluth equation is  $d\sigma^2/dud\phi$ : need to bin data in  $u$ ,  $\phi$
- Apply scaling factors from the  $m_\chi$  shape study to  $u$  distribution
- Subtract all MC except for  $\omega$  and compare with  $\omega$  SIMC
- Use background-subtracted  $u$  spectrum to select bins in  $u$
- *Other variables plotted in the same way to validate shape study*



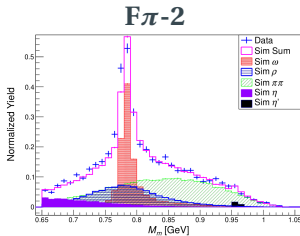
$u$ -bin borders: [0.00, 0.06, 0.12, 0.40] GeV

# Why PYTHIA?

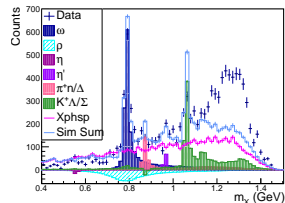


SIMC default phase space model **Xphsp** uses  $2\pi$  production

- Sufficient for 6 GeV, but 12 GeV has more available phase space  $\rightarrow 2\pi$  not sufficient

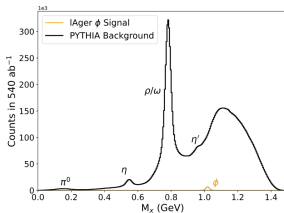


**KaonLT + Xphsp**

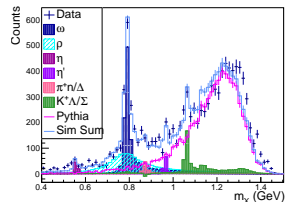


- Very similar  $m_\chi$  distribution in simulations for the  $\phi-007$  proposal with PYTHIA  $\rightarrow$  try this instead

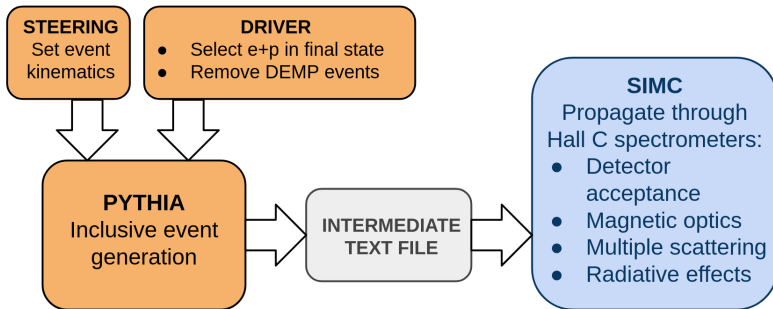
**$\phi-007$  Proposal**



**KaonLT + PYTHIA**



W.B. Li, *Exclusive Backward-Angle Omega Meson Electroproduction*, PhD Thesis, University of Regina (2017).  
 H.T. Klest et al, *Studying the Strangeness D-Term in Hall C via Exclusive  $\phi$  Electroproduction*, JLab Experimental Proposal to PAC 54 (2025).



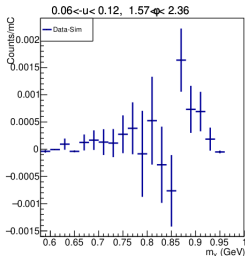
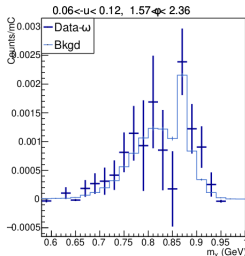
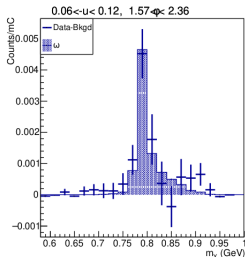
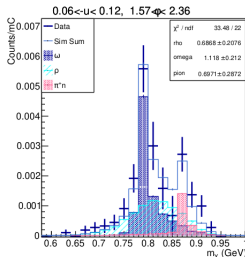
<https://pythia.org>



## Welcome to PYTHIA

**PYTHIA** is a program for the generation of high-energy physics collision events, i.e. for the description of collisions at high energies between electrons, protons, photons and heavy nuclei. It contains theory and models for a number of physics aspects, including hard and soft interactions, parton distributions, initial- and final-state parton showers, multiparton interactions, fragmentation and decay. It is largely based on original research, but also borrows many formulae and other knowledge from the literature. As such it is categorized as a **general-purpose Monte Carlo event generator**.

Based on PYTHIA for EIC, modified from: <https://gitlab.com/henryklest12/pythia-rad-corr-simc/>  
SIMC interfacing modified from: [https://github.com/MarkKJones/simc\\_gfortran/tree/file-input/](https://github.com/MarkKJones/simc_gfortran/tree/file-input/)  
C. Bierlich et al, *A comprehensive guide to the physics and usage of PYTHIA 8.3*, SciPost Phys. Codebases **8** (2022).



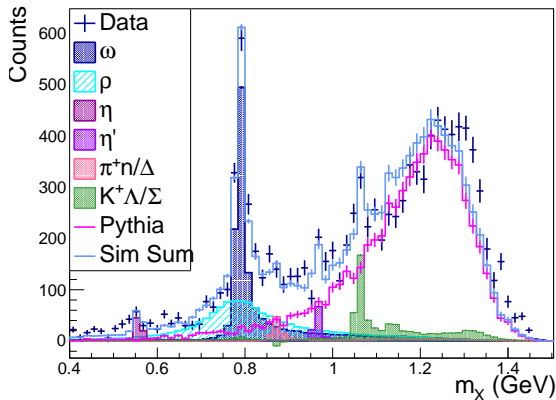
## FITTING CROSS-CHECKS

1. Compare data to sum of simulations
2. Compare (data - background MC) to  $\omega$  MC
3. Compare (data -  $\omega$  MC) to sum of background MC
4. Compare (data - all MC) to zero

# $u$ -Channel Exclusive $\eta/\eta'$ Production



- Potential measurement from KaonLT
- Smaller signal than  $\omega$  production, visible in same data set
- Different  $u$  ranges, but comparison in  $u'$  possible
- Large statistical uncertainty from background subtraction



Extract  
production  
ratios:

$$\eta : \omega$$

$$\eta' : \omega$$

$$\eta : \eta'$$