POLARIZATION TRANSFER IN WIDE ANGLE CHARGED PION PHOTOPRODUCTION

K_{LL} (AND A_{LL})

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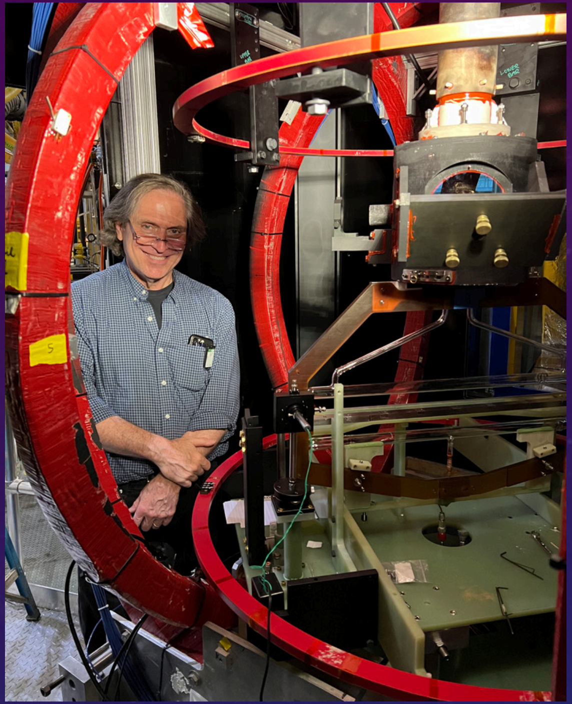

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WAPP Collaboration: ~65 Collaborators from ~20 institutions

CONTENTS

- Field of Meson Photoproduction
- Observed yet unexplained cross sections
- Theoretical calculations fall short!
- Possible solution: Polarization tests of handbag mechanism
- Status of experiments and analyses
- Future ideas

MESON PHOTO- AND ELECTROPRODUCTION

PHYSICAL REVIEW VOLUME 102, NUMBER 5 JUNE 1, 1956

Pion Production by Inelastic Scattering of Electrons in Hydrogen*

W. K. H. Panofsky, W. M. Woodward,† and G. B. Yodh
High-Energy Physics Laboratory and Department of Physics, Stanford University, Stanford, California

(Received February 27, 1956)

- Has been around for quite some time!
- Early measurements at SLAC conducted to study the ratio of the pions produced due to electro and photo production

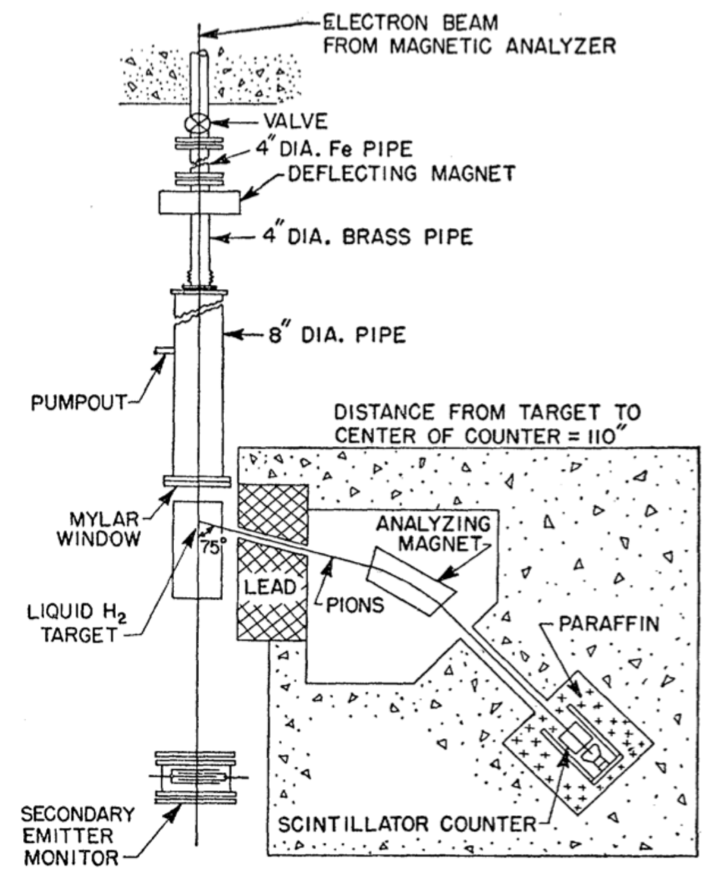
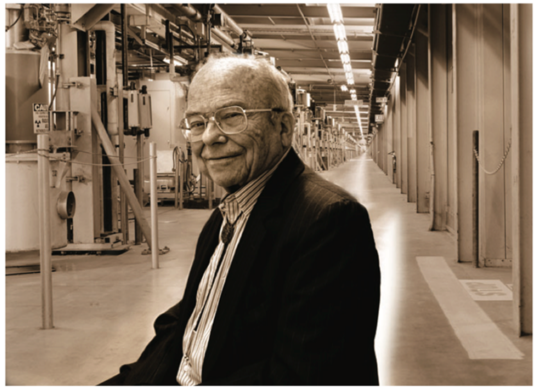


Fig. 3. Meson detection geometry.



Wolfgang K.H. Panofsky

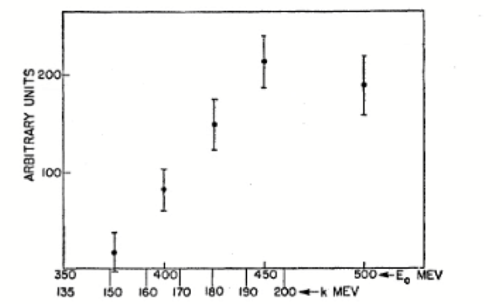
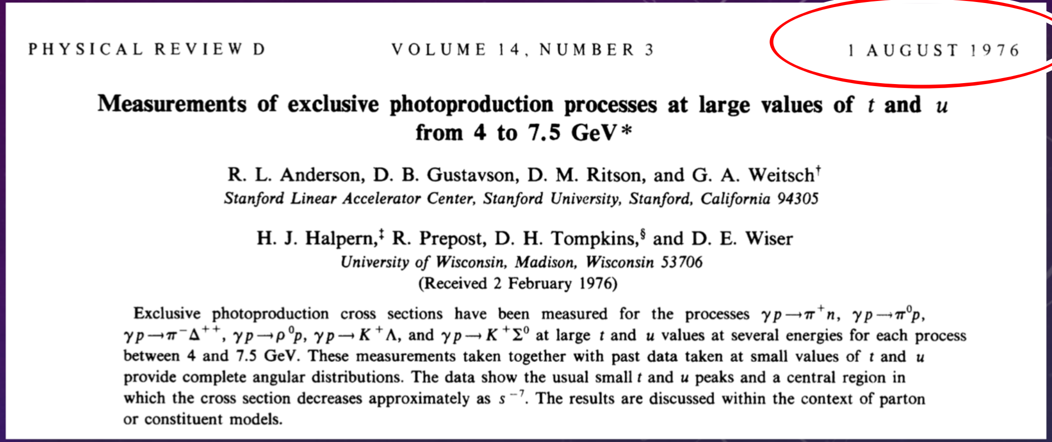


Fig. 5. Excitation function for 170-Mev pions from hydrogen. pion energy uncertainty is estimated from the curve to be ±15 Mev.

MEASUREMENTS OF EXCLUSIVE PHOTO PRODUCTION


PHYSICAL REVIEW D VOLUME 14, NUMBER 3 1 AUGUST 1976

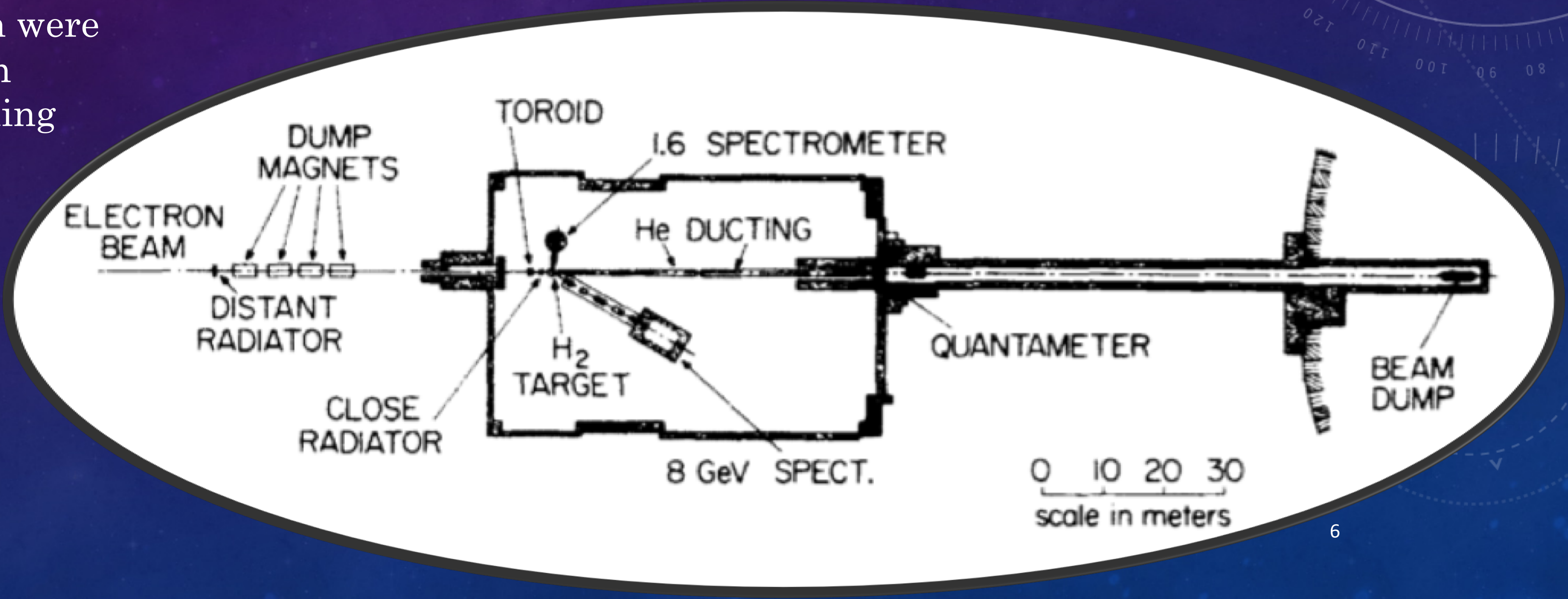
Measurements of exclusive photoproduction processes at large values of t and u from 4 to 7.5 GeV*

R. L. Anderson, D. B. Gustavson, D. M. Ritson, and G. A. Weitsch†
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

H. J. Halpern,‡ R. Prepost, D. H. Tompkins,§ and D. E. Wiser
University of Wisconsin, Madison, Wisconsin 53706
(Received 2 February 1976)

Exclusive photoproduction cross sections have been measured for the processes $\gamma p \to \pi^+ n$, $\gamma p \to \pi^0 p$, $\gamma p \to \pi^- \Delta^{++}$, $\gamma p \to \rho^0 p$, $\gamma p \to K^+ \Lambda$, and $\gamma p \to K^+ \Sigma^0$ at large t and u values at several energies for each process between 4 and 7.5 GeV. These measurements taken together with past data taken at small values of t and u provide complete angular distributions. The data show the usual small t and u peaks and a central region in which the cross section decreases approximately as s^{-7}. The results are discussed within the context of parton or constituent models.

- Other measurements of exclusive photoproduction were conducted which revealed intriguing features



MEASUREMENTS CONDUCTED FOR A VARIETY OF PHYSICS PROCESSES

TABLE I. List of reactions and photon energies covered in this experiment.

Process	Energy (GeV)
$\gamma p \to \pi^+ n$	4, 5, 7.5
$\gamma p \to \pi^0 p$	4, 5
$\gamma p \to \pi^- \Delta^{++}$	4, 5
$\gamma p \to \rho^0 p$	4, 6
$\gamma p \to K^+ \Lambda$	4, 6
$\gamma p \to K^+ \Sigma^0$	4, 6

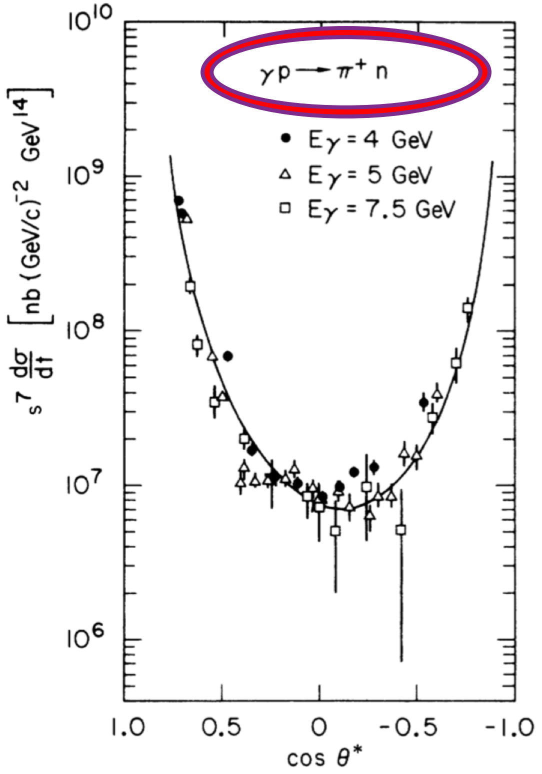


FIG. 6. $s^7 d\sigma/dt$ versus $\cos\theta^*$ for the reaction $\gamma p \to \pi^+ n$. The solid line shows the empirical function $(1-z)^{-5}(1+z)^{-4}$ where $(z = \cos\theta^*)$, which is an empirical fit to the angular distribution.

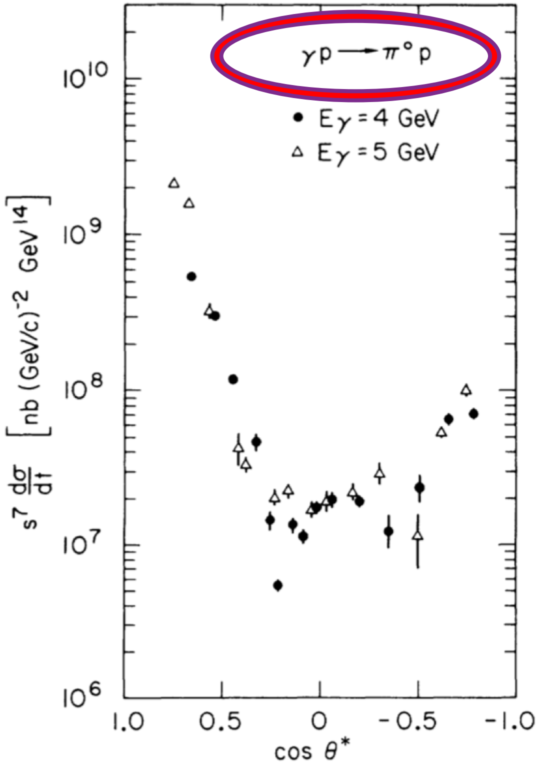


FIG. 9. $s^7 d\sigma/dt$ versus $\cos\theta^*$ for the reaction $\gamma p \to \pi^0 p$.

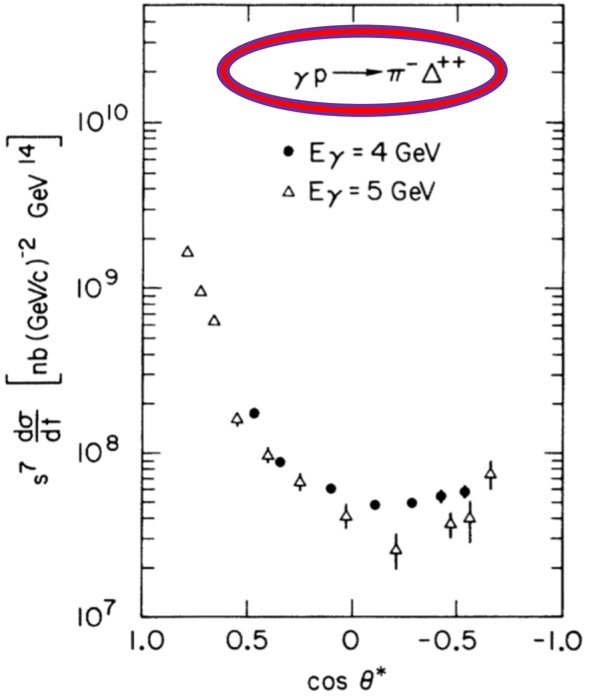


FIG. 12. $s^7 d\sigma/dt$ versus $\cos\theta^*$ for the reaction $\gamma p \to \pi^- \Delta^{++}$.

MECHANISM OF SCALING

- Continuing interest in the features but the cross sections are still unexplained
- Models tried to explain the observed cross sections by considering the number of "active fields" involved in the photoproduction
    - CCR (Constituent Counting Rules)
    - HHC (Hadron Helicity Conservation)
    - pQCD (perturbative QCD)
    - Handbag approach in the GPD framework (Generalized Parton Distributions)

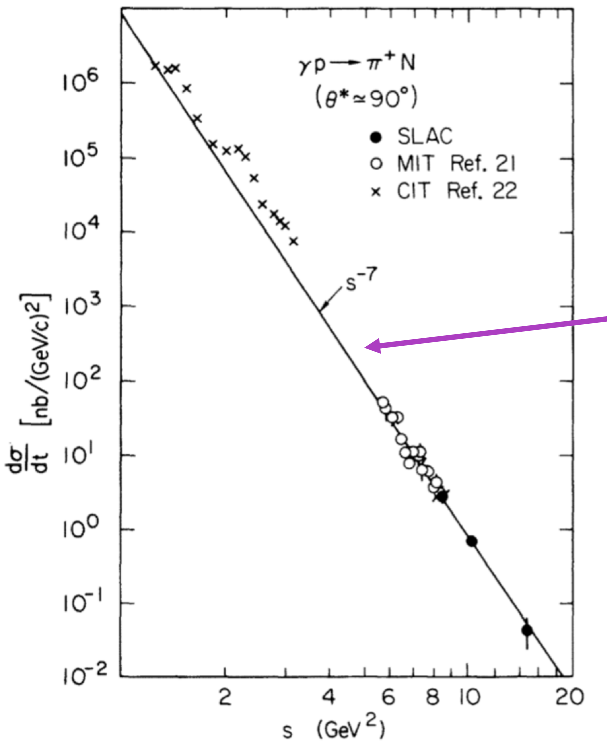


FIG. 20. 90° c.m. values of $d\sigma/dt$ versus s for the process $\gamma p \to \pi^+ n$ from several experiments from E_γ = 700 MeV to E_γ = 7.5 GeV. The solid line shows the function s^{-7} for reference.

The constituent-interchange model of Brodsky, Blankenbecler, and Gunion[5] makes specific predictions for the power dependence of s and the functional dependence of $f(\cos\theta^*)$, but does not predict absolute cross-section values. General dimensional counting arguments of the type of Matveev, Muradyan, and Tavkhelidze,[6] and Brodsky and Farrar[7] also make specific predictions for the s dependence of exclusive processes. Specifically, the s-power fixed-angle behavior for exclusive processes is expected to be

$$\frac{d\sigma}{dt} \sim \frac{1}{s^{N-2}} f(\cos\theta^*),$$

where N is the number of "elementary" fields participating in the reaction. If the photon is assumed to be one elementary field, then the prediction for meson photoproduction is

$$\frac{d\sigma}{dt} \sim \frac{1}{s^7} f(\cos\theta^*).$$

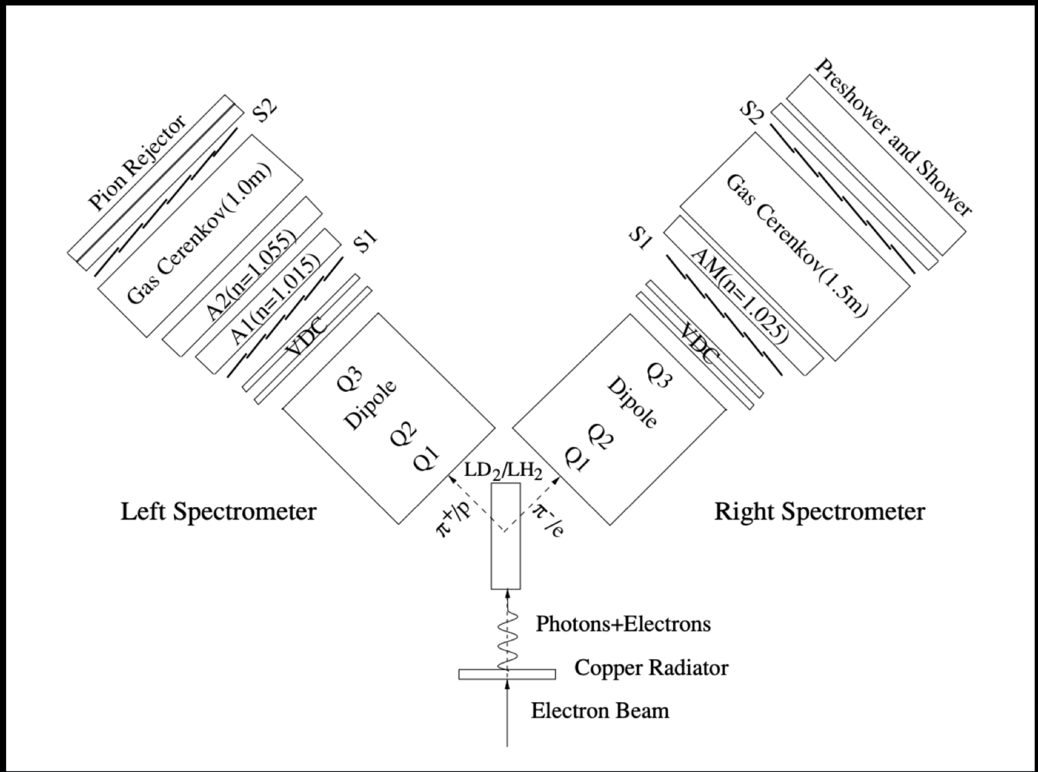
It will be shown that the results of the present experiment are consistent with these predictions in the large-c.m.-angle region.

PHOTOPRODUCTION EXPERIMENTS IN HALL A

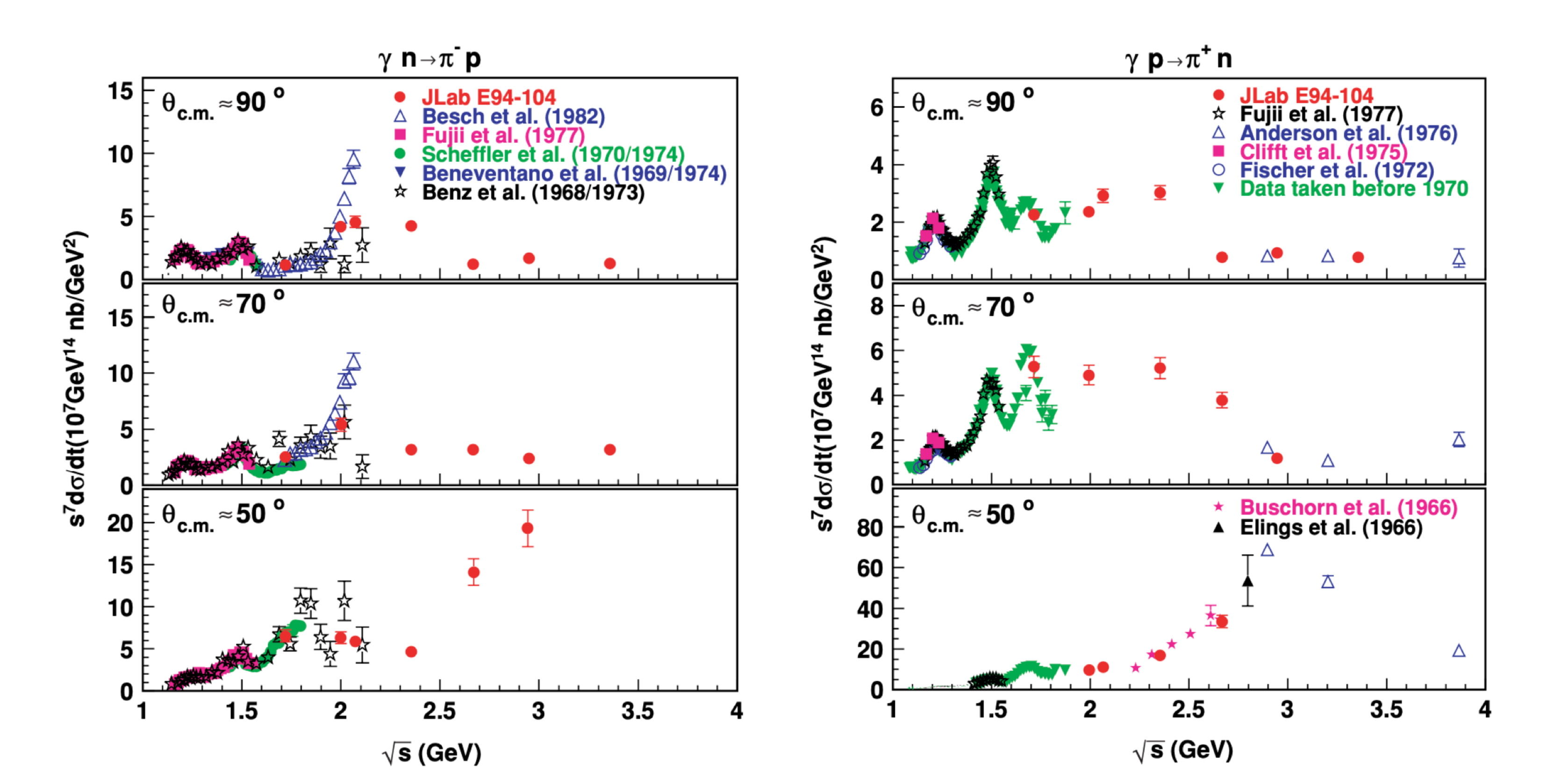
- Photoproduction experiments conducted in Hall A using LHRS and RHRS
- π^+ and π^- cross sections and their ratios studied for a range of s and t
- Many intriguing features that still have continued interest at Jefferson Lab

PHYSICAL REVIEW C **71**, 044603 (2005)

Cross section measurements of charged pion photoproduction in hydrogen and deuterium from 1.1 to 5.5 GeV



RESULTS FROM E94-104



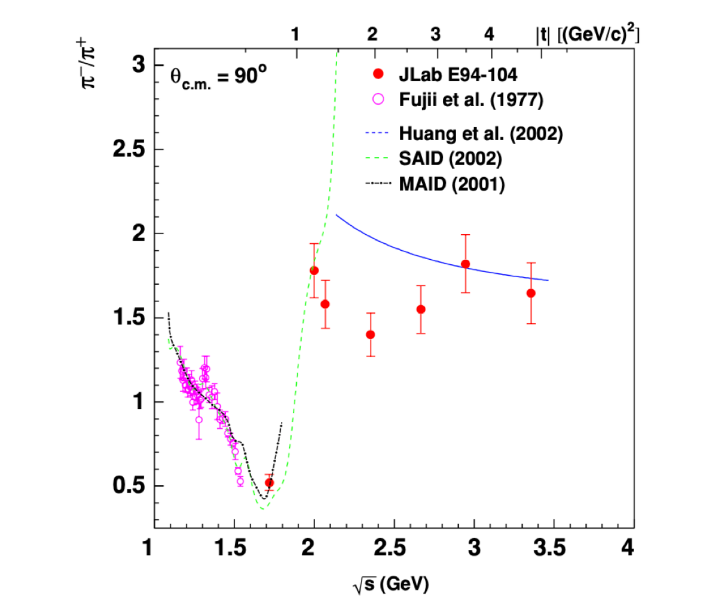


FIG. 18. (Color online). Exclusive charged pion ratio $d\sigma/dt(\gamma n \to \pi^- p)/d\sigma/dt(\gamma p \to \pi^+ n)$ versus center-of-mass energy $\sqrt{s}$ and momentum transfer squre $|t|$ at pion center-of-mass angle $\theta_{c.m.} = 90^\circ$ from JLab E94-104 and previous world data [48], together with the SAID [66], MAID [67], and one-hard-gluon-exchange calculation [44,45].

LEADING ORDER CALCULATIONS GET THE RATIO RIGHT

Signatures of the handbag mechanism in wide-angle photoproduction of pseudoscalar mesons

H.W. Huang[1], R. Jakob[2], P. Kroll[2], K. Passek-Kumerički[3]

[1] Department of Physics, University of Colorado, Boulder, CO 80309-0390, USA
[2] Fachbereich Physik, Universität Wuppertal, 42097 Wuppertal, Germany
[3] Theoretical Physics Division, Rudjer Bošković Institute, 10002 Zagreb, Croatia

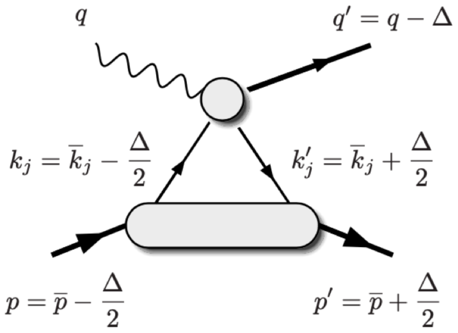
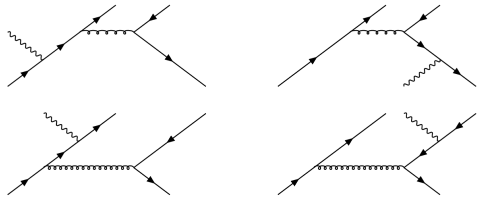
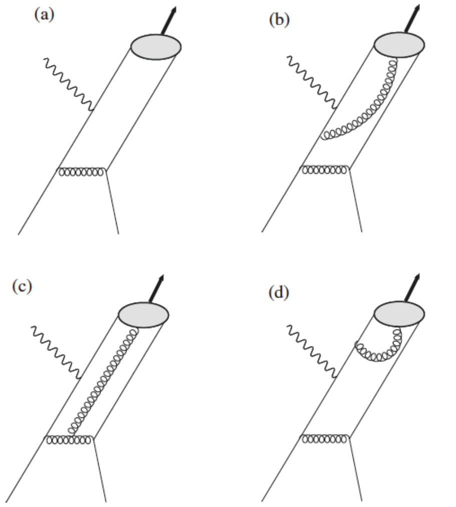


Fig. 1. The handbag diagram for photo- and electroproduction of mesons. The large blob represents a baryon GPD, while the small one stands for meson photo- and electroproduction off partons. The momenta of the various particles are indicated



Leading-twist one-hard-gluon exchange diagrams for the "hard" parton level subprocess $\gamma^{(*)} q \rightarrow Mq$



Feynman diagrams including two- and three-particle Fock components of the meson

$$\frac{d\sigma(\gamma n \rightarrow \pi^- p)}{d\sigma(\gamma p \rightarrow \pi^+ n)} \approx \left(\frac{e_u s + e_d u}{e_u u + e_d s}\right)^2$$

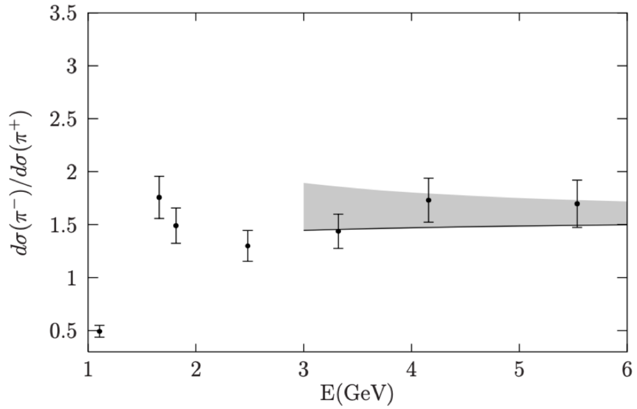


Fig. 4. The ratio of the $\gamma n \rightarrow \pi^- p$ and $\gamma p \rightarrow \pi^+ n$ cross sections versus photon beam energy E, at a CMS scattering angle of 90°. Data are taken from [31]. The solid line is the handbag prediction with the identification (48). The uncertainties due to target mass corrections [30] are indicated by the shaded band

π^0 PHOTOPRODUCTION EXPERIMENTS IN HALL B

- Calculations using the Handbag approach that includes only twist-2 fall short by more than two orders of magnitude
- Missing some crucial information in the amplitude used in calculations
- Figuring that out will shed light on the interaction mechanism responsible for these cross sections

Exclusive photoproduction of π^0 up to large values of Mandelstam variables s, t, and u with CLAS

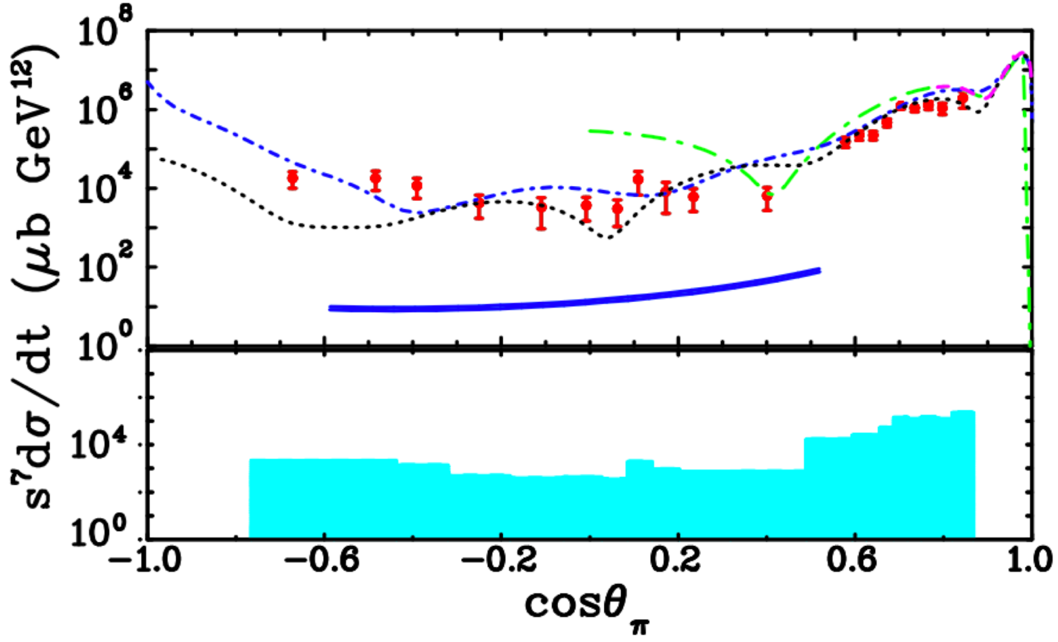


FIG. 5. Differential cross section of π^0 photoproduction. The CLAS experimental data at $s = 11$ GeV^2 are from the current experiment (red solid circles). The plotted uncertainties are statistical. The systematic uncertainties are presented as a shaded area in the subpanel. The theoretical curves for the Regge fits are the same as in Fig. 4 and the Handbag model by Kroll *et al.* [12] (blue double solid line).

CALCULATIONS WITH HIGHER TWISTS

- Calculations with twist 2 and twist 3 contributions performed for π^0 are not only important but dominant

- They are in reasonable agreement (black curve) with CLAS data

- Polarization test of the handbag mechanism is necessary and timely

Twist-3 contributions to wide-angle photoproduction of pions

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Fachbereich Physik, Universität Wuppertal, D-42097 Wuppertal, Germany

K. Passek-Kumerički

Theoretical Physics Division, Rudjer Bošković Institute, HR-10002 Zagreb, Croatia

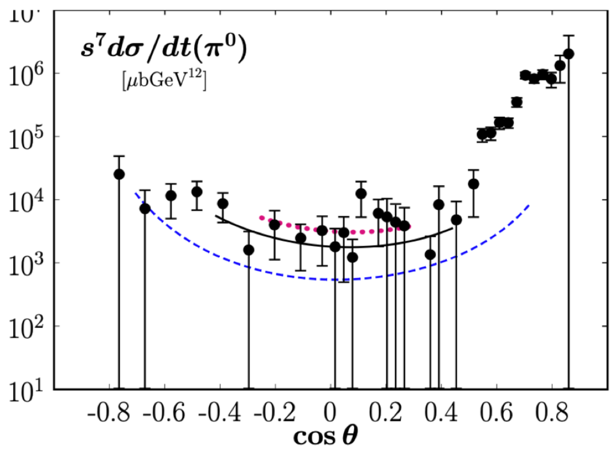


Figure 3: Results for the cross section of π^0 photoproduction versus the cosine of the c.m.s. scattering angle, θ. The solid (dashed, dotted) curves represent our results at $s = 11.06\,(20, 9)$ GeV^2. The data at $s = 11.06$ GeV^2 are taken from CLAS [34]. The cross sections are multiplied by s^7 and the theoretical results are only shown for $-t$ and $-u$ larger than 2.5 GeV^2.

HELICITY CORRELATION OBSERVABLES

- Helicity correlations A_{LL} and K_{LL} provide tests of the handbag mechanism
- Twist 3 contribution dominates twist 2
- Predictions made for π^0 and π^- by Kroll et. al.

$$A_{LL}^{twist-2} = K_{LL}^{twist-2}$$

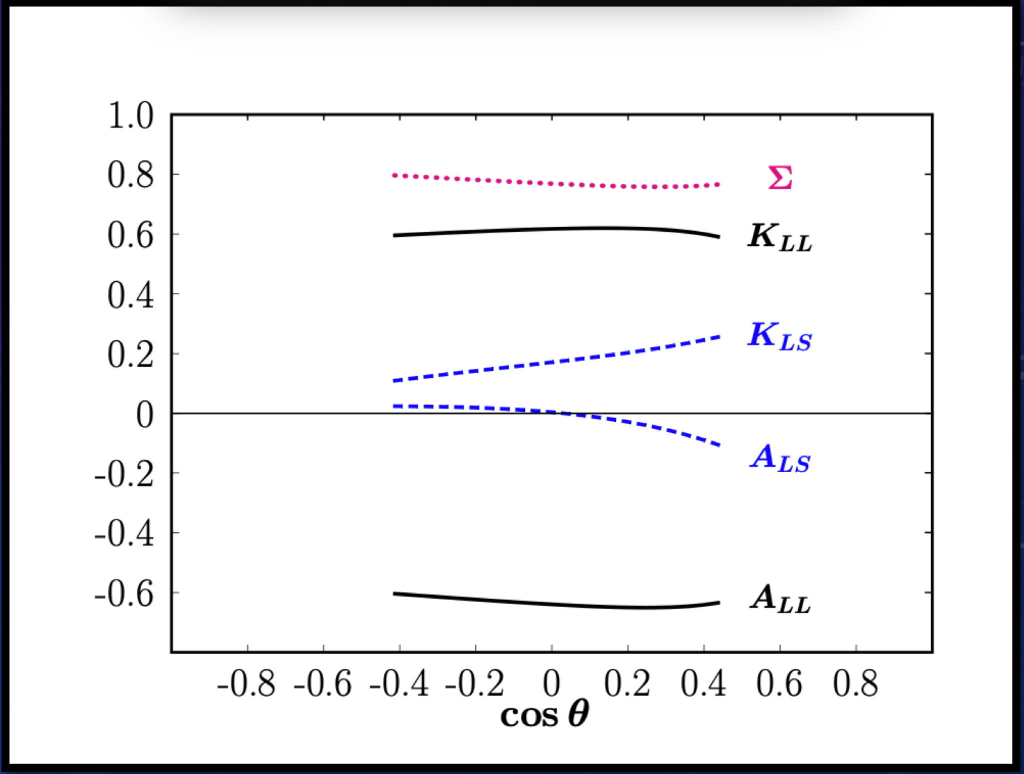
$$A_{LL}^{twist-3} = -K_{LL}^{twist-3}$$

Photon helicity

Target polarization

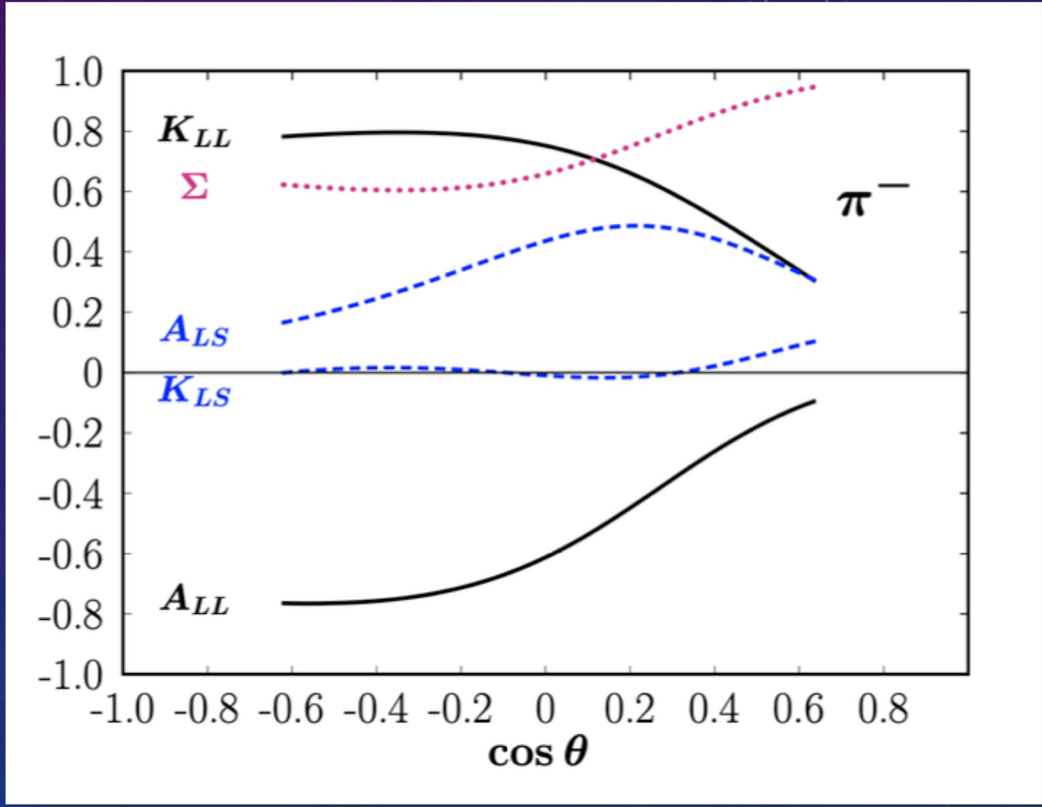
$$K_{LL} = \frac{d\sigma(+,\rightarrow) - d\sigma(-,\rightarrow)}{d\sigma(+,\rightarrow) + d\sigma(-,\rightarrow)}$$

$$A_{LL} = \frac{d\sigma(+\rightarrow) - d\sigma(-\rightarrow)}{d\sigma(+\rightarrow) + d\sigma(-\rightarrow)}$$



PREDICTIONS FOR π^-

- Measurements have been conducted for WACS for π^0 which show good agreement with handbag mechanism
- Calculations made by Kroll et al for WAPP π^- case
- Measurement will test the calculations as well as provide constraints for other models
- This measurement is fundamental, important and the first of its kind in the wide angle regime!



PHYSICS GOALS

The goal for the pioneering measurement of the polarization transfer observable A_{LL} for single π^- photoproduction in the wide-angle regime is to address the following questions:

- What is the nature of the interaction mechanism of meson photoproduction from the nucleon at $s, -t, -u \gg \Lambda^2_{QCD}$?
- Does the twist-3 contribution dominate the twist-2 contribution in the wide angle regime, as suggested by the updated handbag mechanism cross section calculations?

We propose to measure A_{LL} for negatively charged pion photoproduction in the wide angle regime by using the SBS as the proton arm and BB as the pion arm. There, three aspects will be tested:

1. Does A_{LL} equal -K_{LL}?
2. Does A_{LL} have any dependence on cm. angle at $s = 9$ GeV^2 and large $-u$, $-t$?
3. Does A_{LL} have any s dependence at $s > 9$ GeV^2?

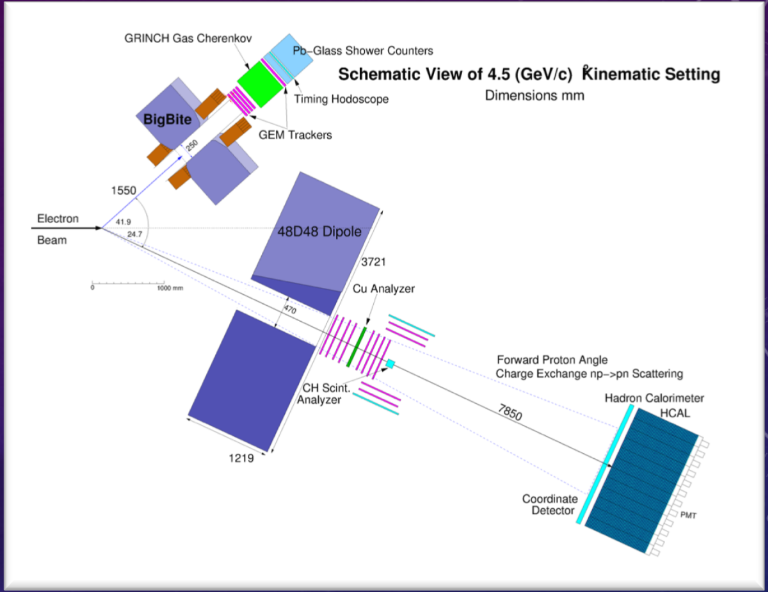
EXPERIMENTAL SETUP

- Beam
  - K_{LL} - 6.6 GeV electron beam (photons in the range 4.0 – 6.0 GeV) for WAPP-I
  - A_{LL} - 6.6, 8,8, 11.0 GeV electron beam for WAPP-II

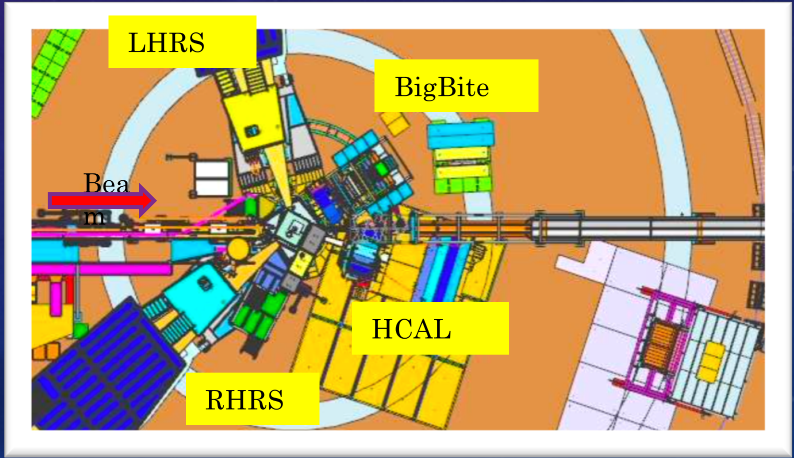
- Target
  - K_{LL} - LD2 target with 6% Cu radiator upstream
  - A_{LL} - He3 target or NH3

- Beam current
  - K_{LL} - 5 micro amps for WAPP-I
  - A_{LL} - 10 micro amps beam for WAPP-II

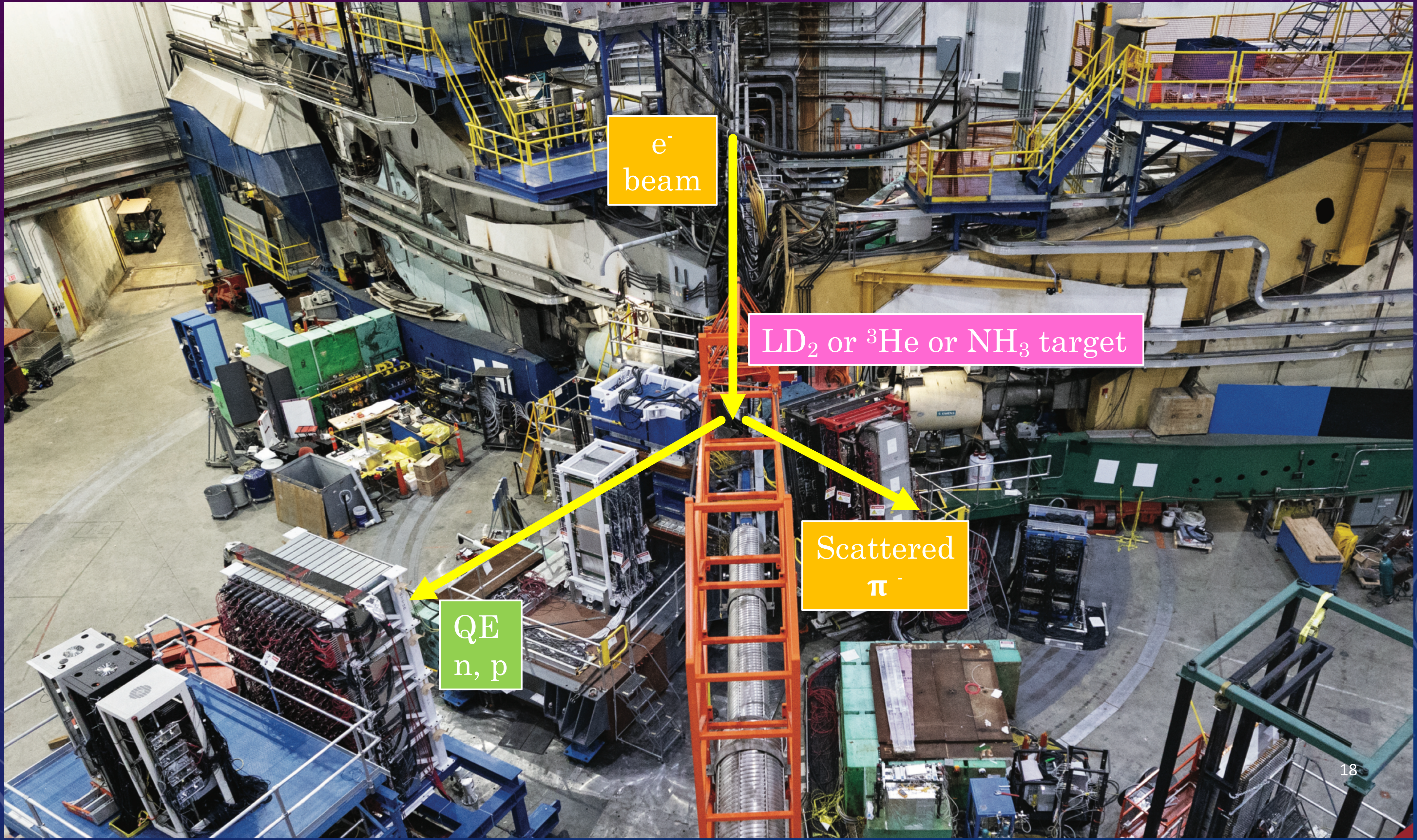
- BigBite as the pion arm and SBS as the nucleon arm



WAPP-I

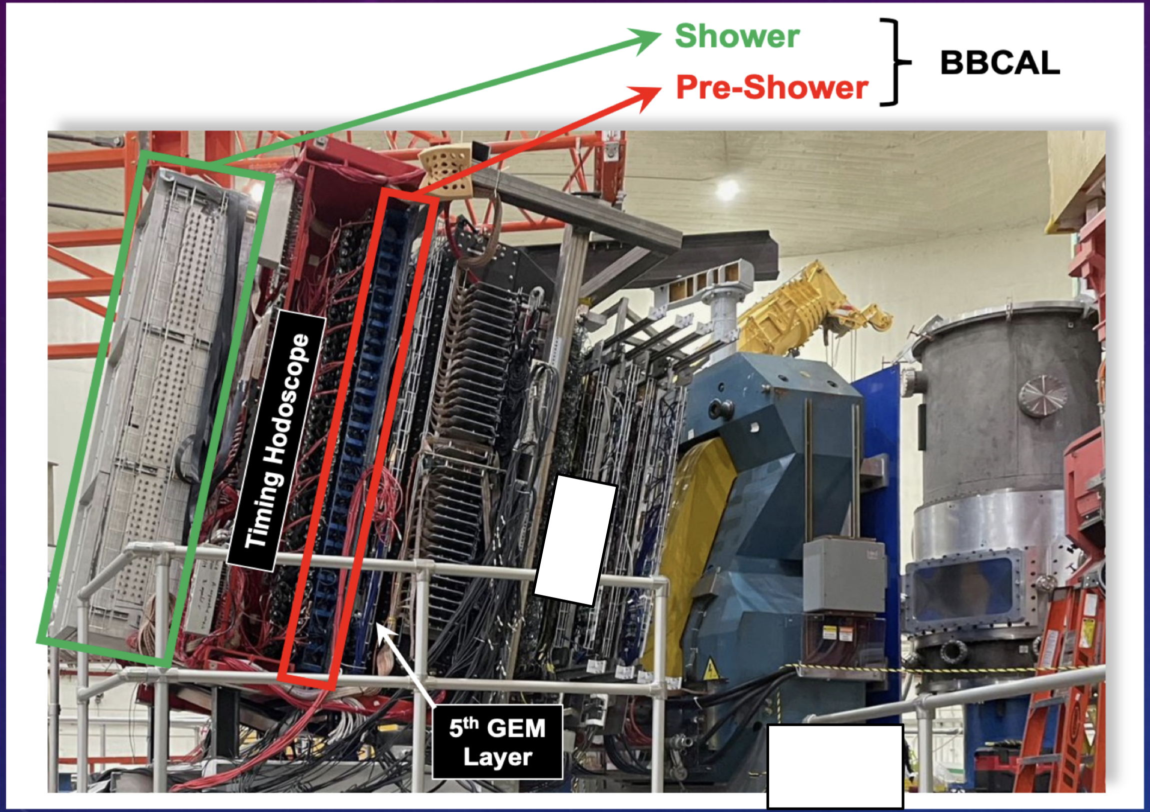


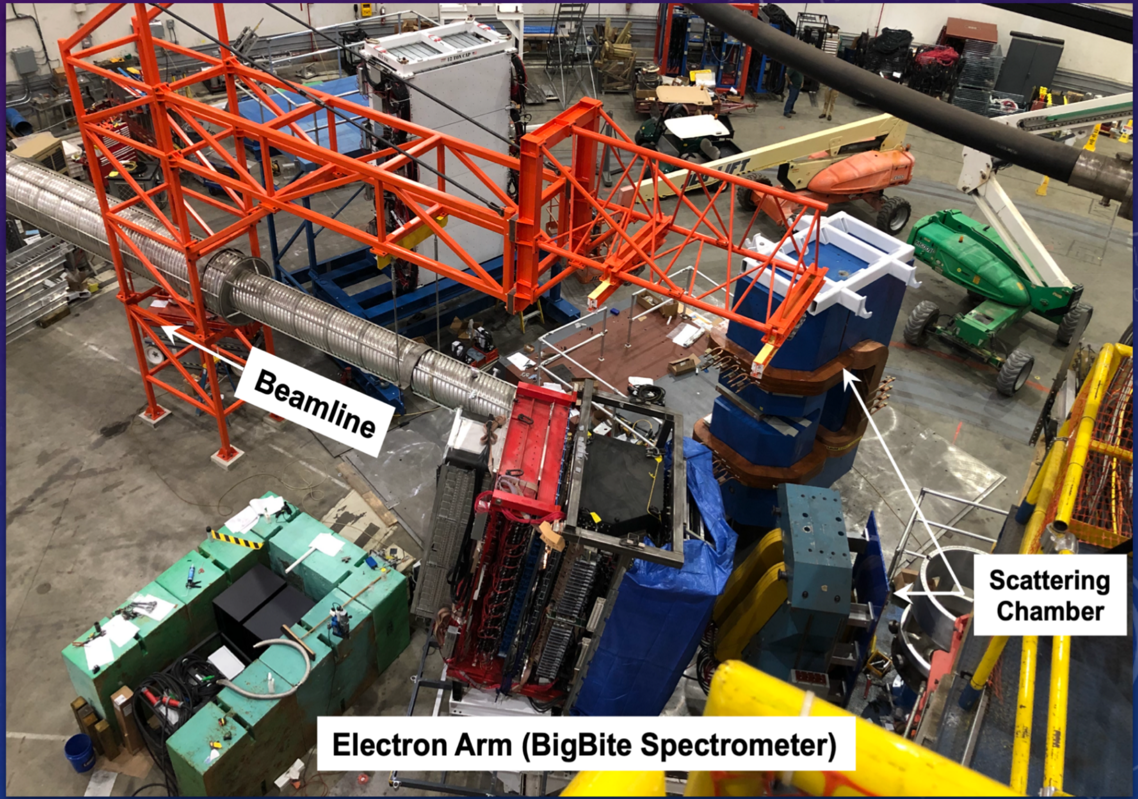
WAPP-II



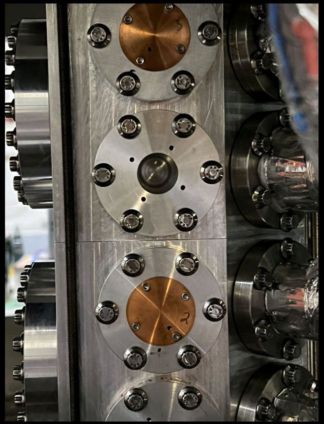
e^- beam
LD_2 or ^3He or NH_3 target
QE n, p
Scattered π^-

SPECTROMETER LAYOUT

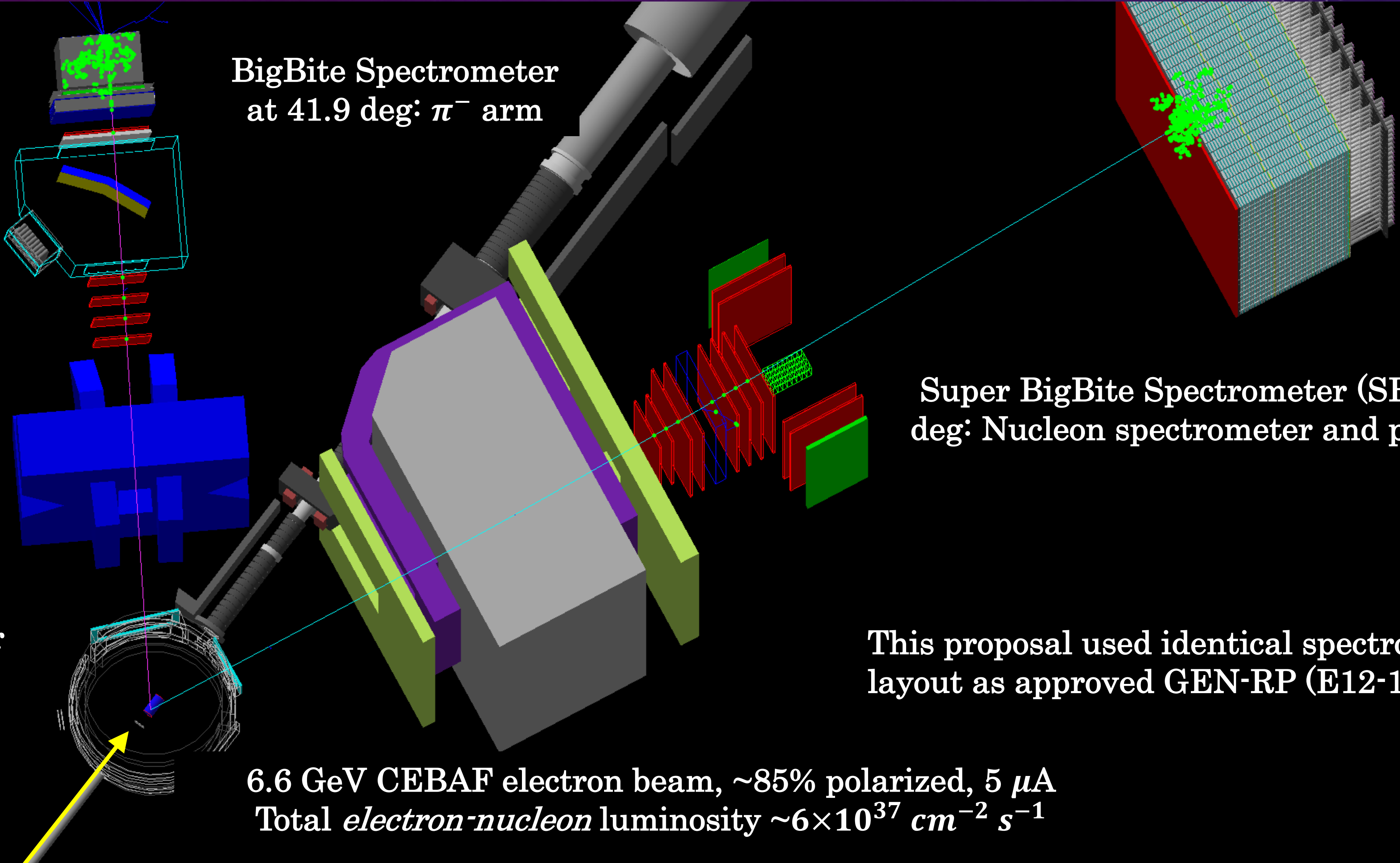




A SIMULATED WAPP ($\vec{\gamma} n \to \pi^- \vec{p}$) EVENT



15 cm LD_2 target
with 6% Cu Radiator
(0.9 mm thick)



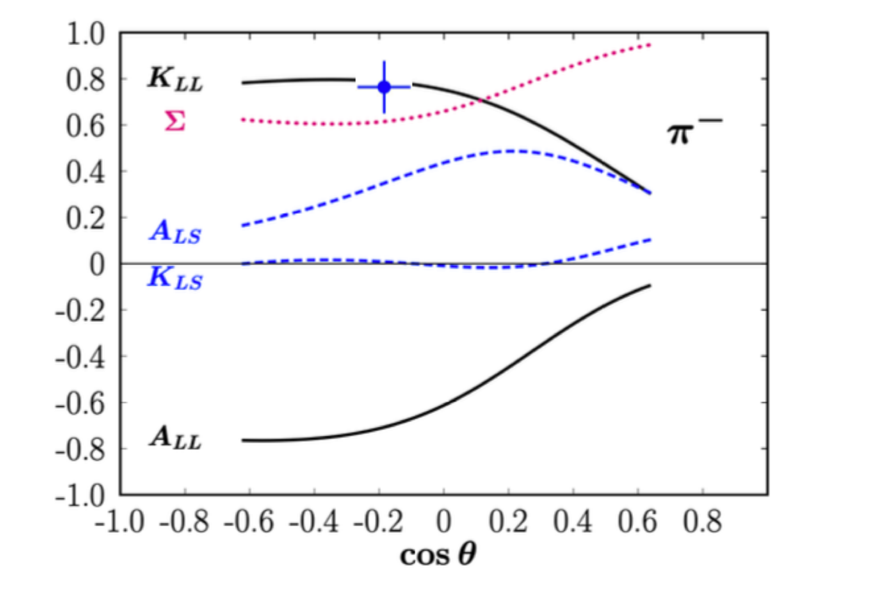
BigBite Spectrometer
at 41.9 deg: π^- arm

Super BigBite Spectrometer (SBS) at 24.7
deg: Nucleon spectrometer and polarimeter

This proposal used identical spectrometer
layout as approved GEN-RP (E12-17-004)

6.6 GeV CEBAF electron beam, ~85% polarized, 5 μA
Total *electron-nucleon* luminosity ~$6 \times 10^{37}\ cm^{-2}\ s^{-1}$

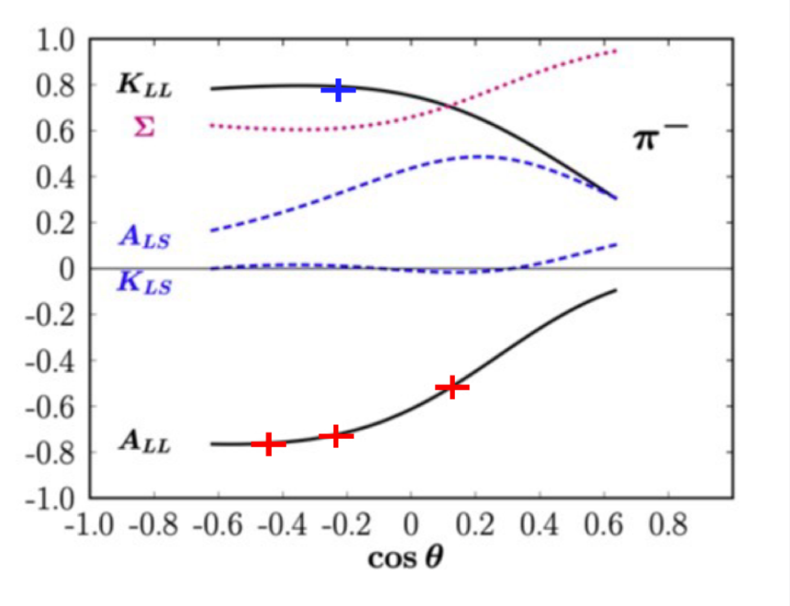
K_{LL}



E_γ	$< s >$	$< -t >$	$< -u >$	K_{LL}	K_{LS}
GeV	$(GeV/c)^2$	$(GeV/c)^2$	$(GeV/c)^2$	accuracy	accuracy
4.5-5.5	9.3	4.6	2.9	±0.05	±0.05

Experiment completed in May 2024 (14th – 19th)

A_{LL}



E_{beam}	$< s >$	$< -t >$	$< -u >$	$\cos\theta_{CM}$	Beam on	Time	ΔA_{LL}
[GeV]	$[(GeV/c)^2]$	$[(GeV/c)^2]$	$[(GeV/c)^2]$		target [hour]	[hour]	accuracy
6.6	9.3	4.7	2.9	-0.23	6	37	±0.05
6.6	9.3	3.3	4.3	+0.14	8	27	±0.05
6.6	9.3	5.5	2.1	-0.44	8	27	±0.05
8.8	12.1	6.4	4.0	-0.23	16	47	±0.05
11.0	15.0	8.1	5.2	-0.23	60	98	±0.05

Experiment cancelled in Oct 2023 due to Hall A beam dump failure

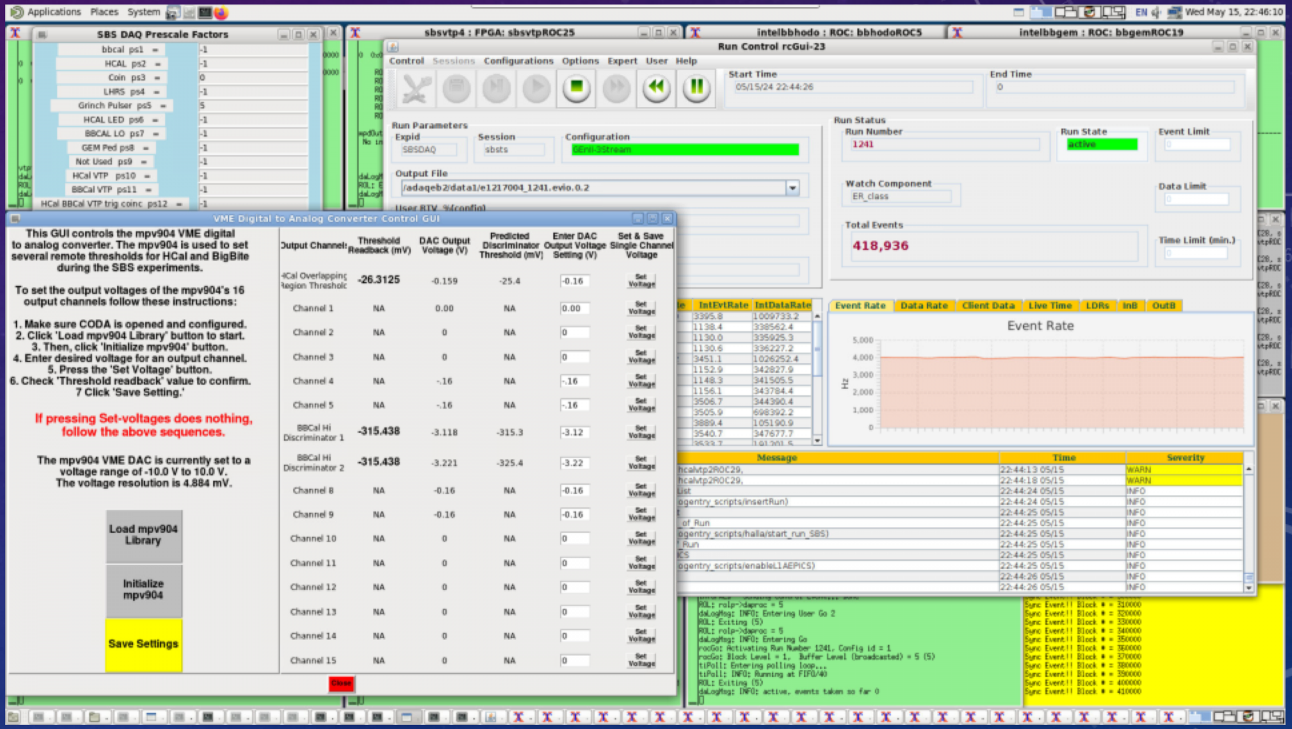
COLLECTED DATA

- Total beam charge on 15-cm LD_2 target with 6% Cu radiator: 0.5 C (not all with equivalent data quality)
- Beam energy 6.37 GeV
- BigBite angle 42.5 degrees, target-magnet distance 1.55 m
- SBS angle 24.7 degrees, target-magnet distance 2.25 m
- HCAL distance 9 m

RUNNING CONDITIONS, ISSUES, CHALLENGES

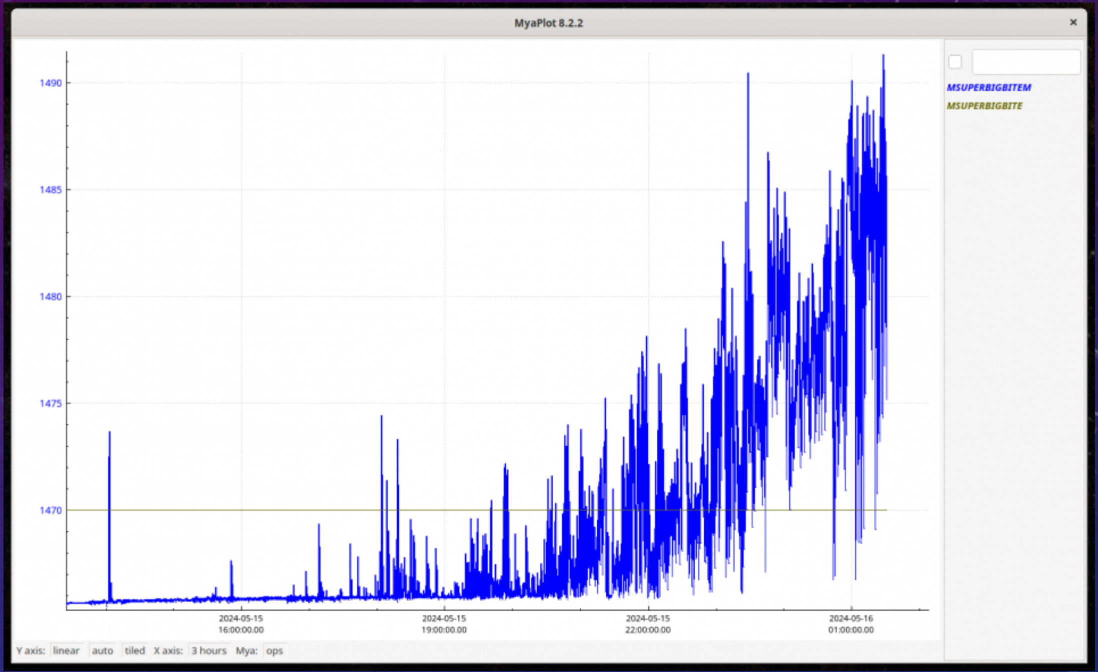
- K_{LL} running was limited to ~half of proposal beam current due to trigger/DAQ, NOT by GEM occupancy. Experiment proposed for 5 uA but saw 4 kHz DAQ rate at 3 uA with 80% livetime.

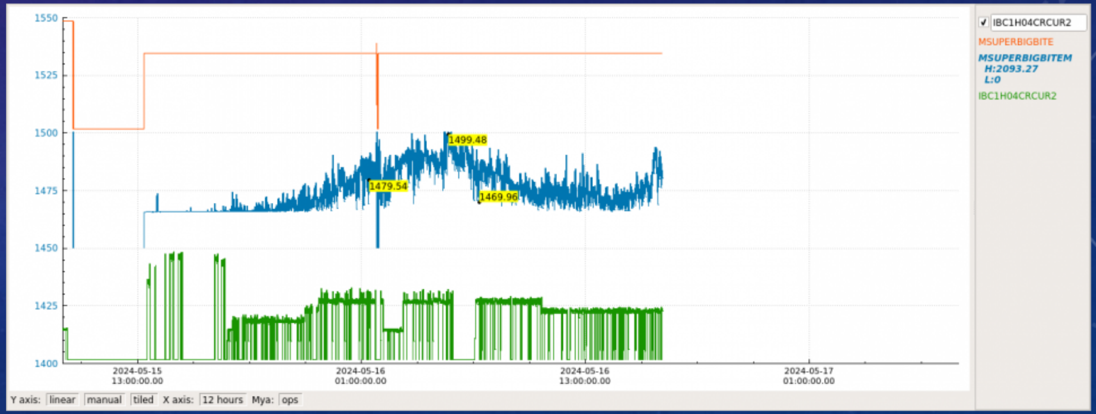
- Standard BigBite trigger logic, threshold significantly higher than proposal (due to higher-than-expected rate in HCAL, which we believe to be attributable to relatively poor hardware-level gain matching in analog trigger).



SBS MAGNETIC FIELD INSTABILITIES

- Data collected include a mix of SBS 100%, SBS 70%, and SBS 65% field.
- SBS magnet current instability (at 2-3% level) when set to 70% may affect data quality, make analysis of that subset of the data much more difficult





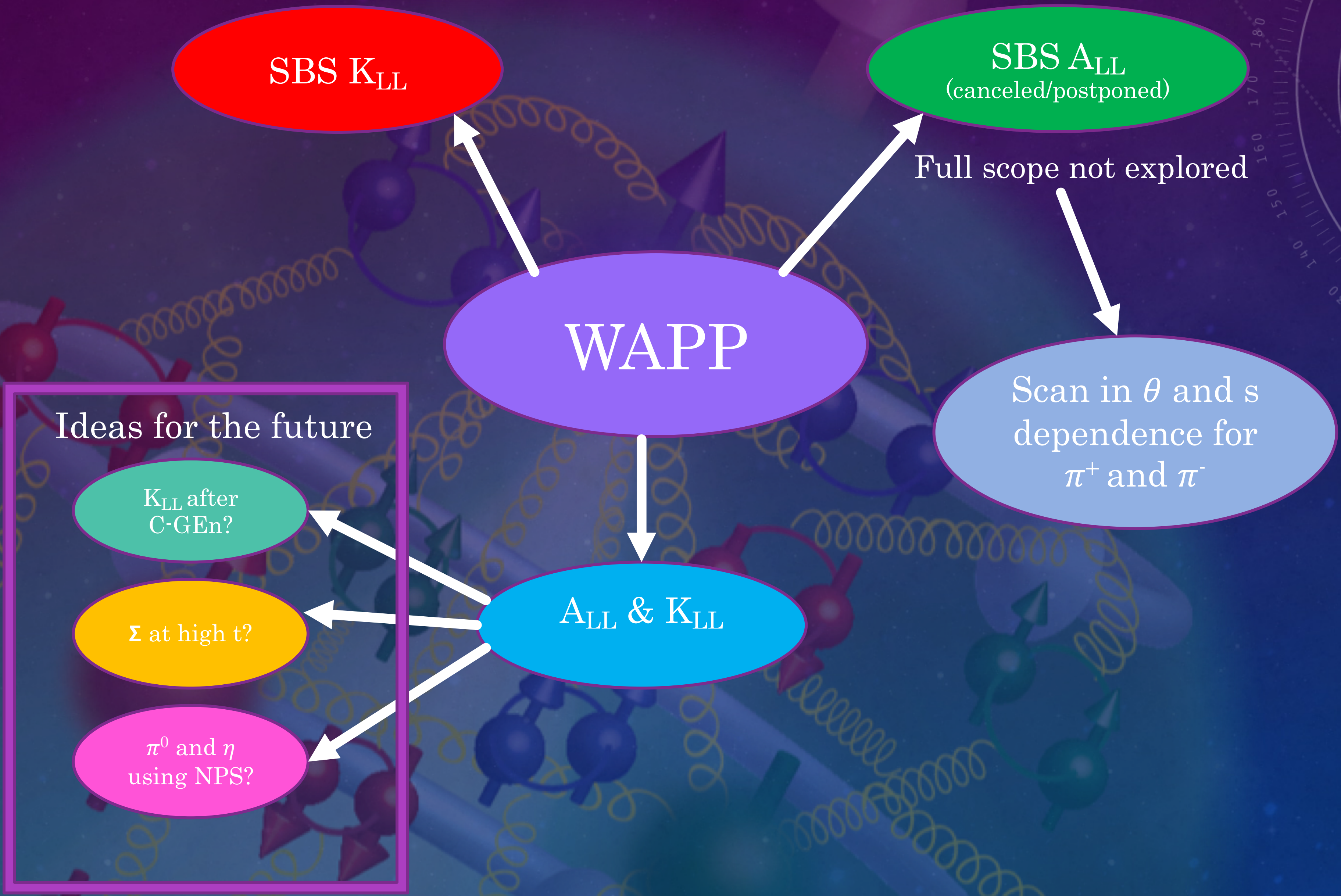
https://logbooks.jlab.org/entry/4306884

CURRENT STATUS OF ANALYSIS

- Understanding working of various detector sub-systems and coincidence trigger in progress (for other experiments) very helpful
- No active student working on this project currently but plans to crank up efforts after other experiment results obtained
- Best current estimate of statistical precision (based purely on beam charge) is about 10.5% (relative, with twist-3 prediction from P. Kroll).
- This could get significantly worse to the extent our assumptions about triggering and/or reconstruction efficiencies.
- This dataset is still likely to produce a statistically significant and publishable physics result.

SUMMARY

- Wide angle pion photoproduction is an interesting and a powerful tool to study the interaction mechanism in the wide angle regime
- Calculations show that twist-3 is not only important but dominate the Wide Angle regime
- A solution (handbag approach in the framework of GPDs) has been proposed and an independent test of the polarization observables is essential
- K_{LL} experiment completed data taking while A_{LL} waiting for another opportunity
- Understanding of detectors from other SBS analyses

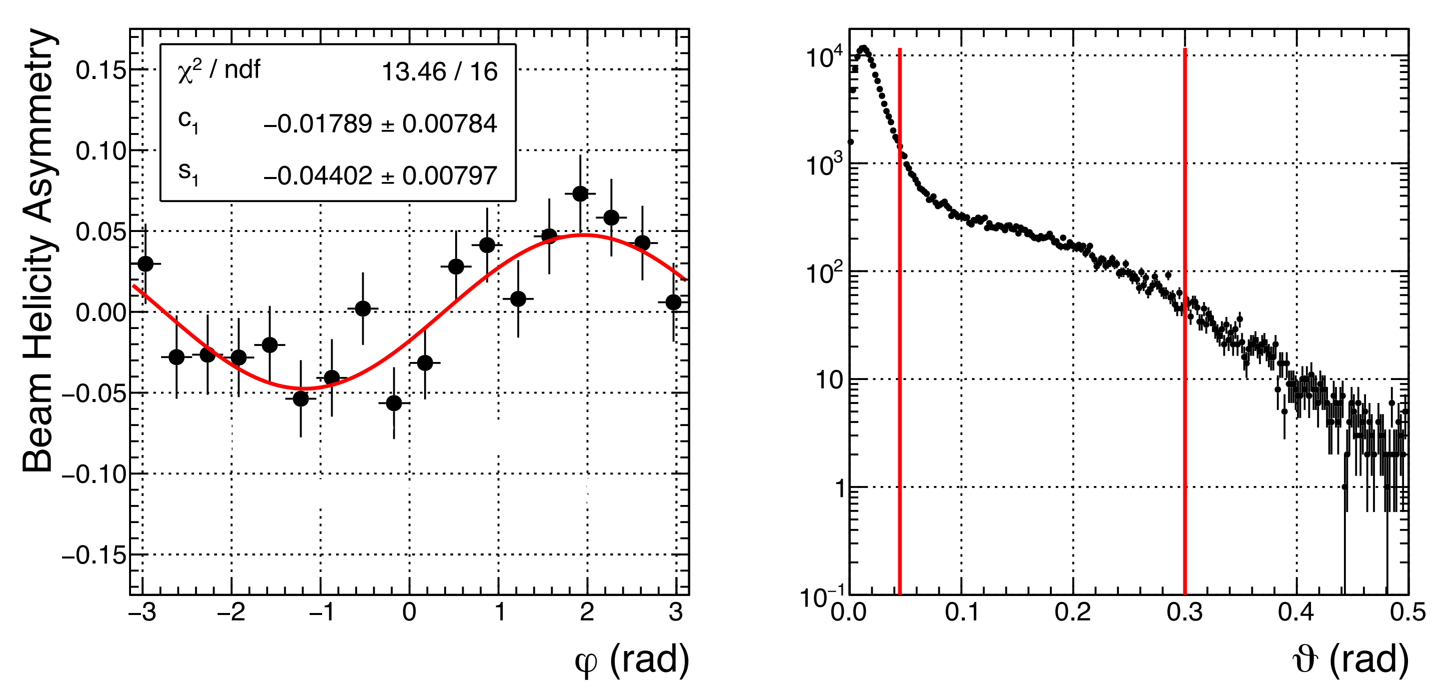

SBS K_{LL}
SBS A_{LL}
(canceled/postponed)
Full scope not explored
WAPP
Scan in θ and s dependence for π^+ and π^-
A_{LL} & K_{LL}
Ideas for the future
K_{LL} after C-GEn?
Σ at high t?
π^0 and η using NPS?

Thank you!

NAÏVE ESTIMATE OF $\gamma n \rightarrow \pi^- p$ STATISTICS

- According to the pion photoproduction event generator in *g4sbs,* with trigger thresholds set to what we believe they approximately were during KLL running (big assumption), we expect about 1.74M exclusive events per Coulomb of beam charge surviving the trigger cuts. This implies that we *should* have about 0.87M exclusive events in the entire K_LL dataset (this estimate doesn't account for the fraction of the data taken at SBS 100% field, which would reduce the statistics somewhat due to lower acceptance, but also increase the precession angle, making the asymmetry larger). This estimate comes with a large uncertainty due to HCAL and BBCAL threshold calibrations
- Expected polarimeter efficiency is 13.5% (fraction of protons scattered in useful p_T range for polarimetry.
- Assuming 85% beam polarization and same analyzing power as GEp-III (interpolated to the proton momentum for this experiment), I project an 8.4% absolute (~10.5% relative) statistical uncertainty for the K_{LL} observable (about twice as big as the proposal)
- Reconstruction inefficiency will reduce statistics further, as will trigger inefficiency (to the extent our estimates of the BBCAL and HCAL thresholds are too optimistic.)

ANALYZING POWER CALIBRATION WITH LH_2 ELASTIC DATA FROM GEN-RP



- Analyzing power for protons in steel seems qualitatively consistent with GEp-III baseline for p+CH_2. But relative stat. uncertainty with ~80% of all LH2 data taken during GEN-RP is about 20%.
- We hope that with improved reconstruction efficiency after calibrations/etc, the LH2 data from GEN-RP will give us a roughly ~10-15% level analyzing power calibration (matched to projected statistics of K_{LL})
- For this analysis, we don't actually use the SBS front GEM data, we use the BigBite information to predict the front track information for polarimetry

<MANDELSTAM VARIABLES>

$$4.0 \leq E_\gamma \text{ (GeV)} \leq 6.6$$

$$\begin{aligned} E_e &= 6.6 \text{ GeV} \\ \langle s \rangle &= 9.3 \text{ GeV}^2 \\ \langle -t \rangle &= 4.6 \text{ GeV}^2 \\ \langle -u \rangle &= 2.9 \text{ GeV}^2 \\ \langle \cos(\theta_{CM}) \rangle &= -0.22 \end{aligned}$$

- Acceptance-averaged Mandelstam variables are all sufficiently “large” for applicability of the handbag approach

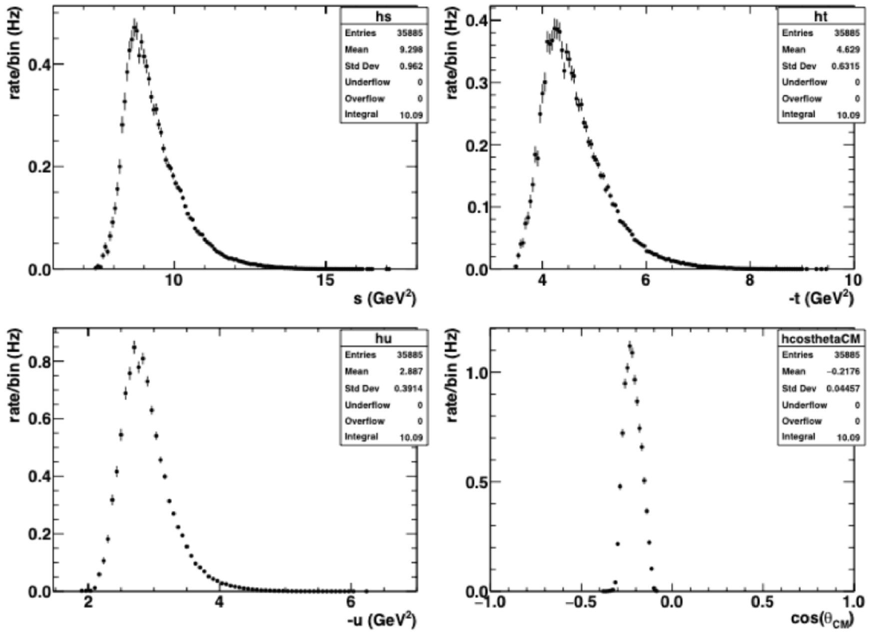
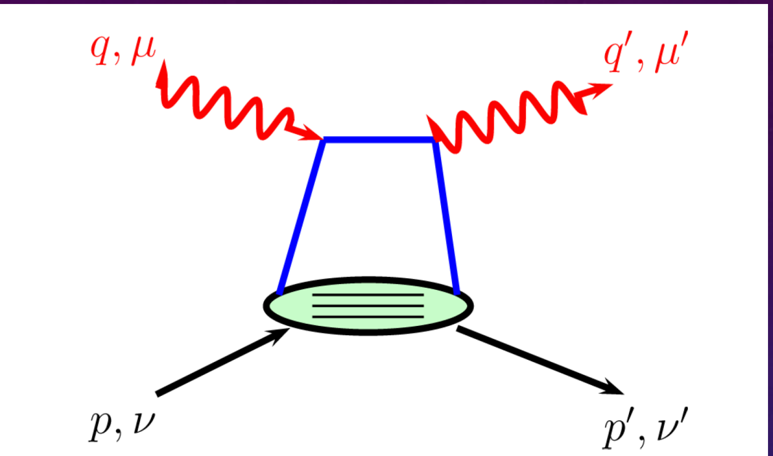
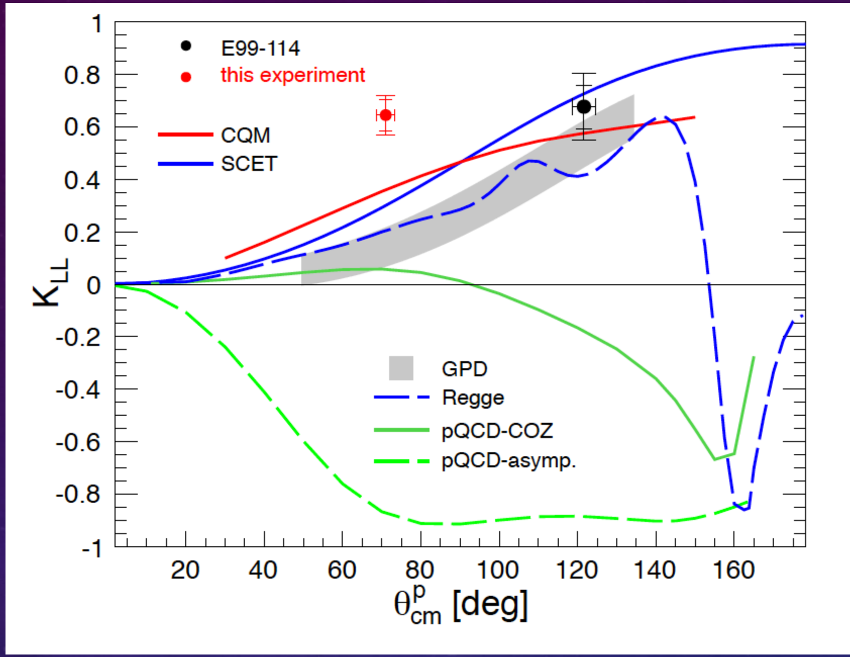


Figure 11: Distributions of s, $-t$, $-u$, and $\cos\theta_{CM}$ within the combined BigBite-SBS acceptance, from *g4sbs*, the SBS GEANT4-based Monte Carlo simulation package. See text for details.

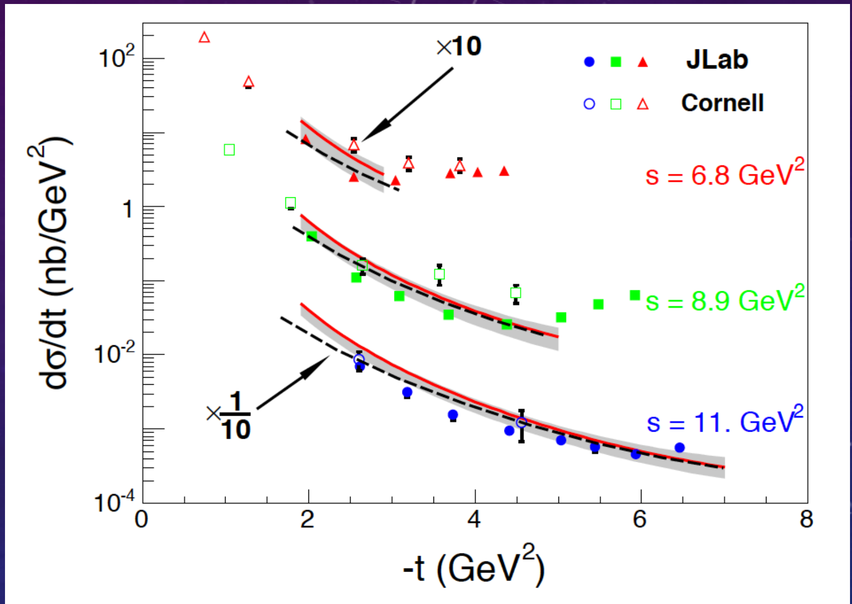
REAL COMPTON SCATTERING (RCS)



Handbag diagram for RCS: Kroll, EPJ A, 53, 130 (2017)



RCS K_{LL}: Fanelli *et al.*, Phys. Rev. Lett. **115**, 152001 (2015) and Hamilton *et al.,* Phys. Rev. Lett. **94**, 242001 (2005)



RCS cross sections: A. Danagoulian *et al.*, PRL **98**, 152001 (2007), compared to GPD-based calculations

- RCS cross sections from Hall A in reasonable agreement with *leading-twist* GPD/handbag predictions
- Polarization transfer K_{LL} for RCS measured in Halls A and C.
  - Hall A result (2005) consistent with pre-existing GPD-based prediction
  - Hall C result (2015) not consistent with any calculation available at the time.
- Updated GPD calculations (Kroll, Eur. Phys. J. A **53** (2017) 6, 130) consistent with Hall C WACS K_{LL} result after improved modeling of poorly known axial GPD $\widetilde{H}$

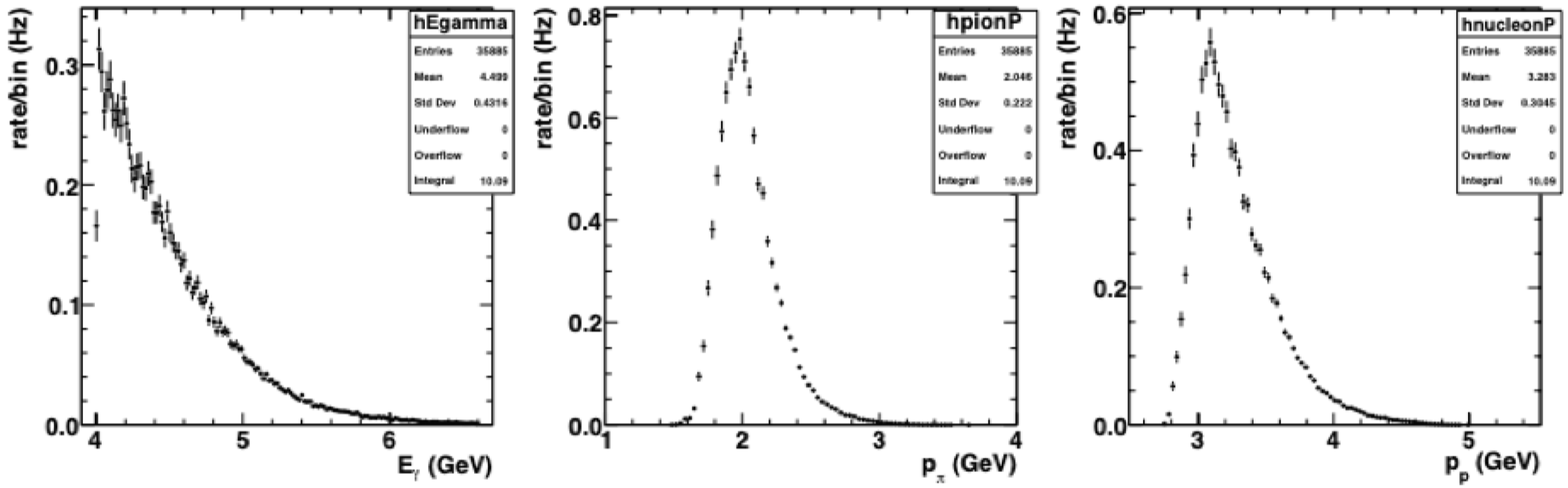


Figure 12: Distributions of E_γ, the incident photon energy, p_π, the π^- momentum in BigBite, and p_p, the proton momentum in SBS. Note that 4 GeV was the lower limit placed on E_γ for "signal" event generation.

$$s^7 \frac{d\sigma}{dt}(\gamma p \to \pi^+ n) \quad = \quad 0.828 \times 10^7 (1-z)^{-5} (1+z)^{-4} \;\; (\mathrm{nb/GeV^2 \cdot GeV^{14}})$$

SINGLE ARM AND COINCIDENCE RATES

Table 1: Estimated single arm and coincidence trigger rates from PYTHIA, assuming 5 μA on 15-cm LD_2 target with 6% Cu radiator. The "Pion" logic consists of requiring the preshower signal to be *less than* 100 MeV and applying the indicated threshold on the *shower*. The "Electron" logic consists of applying the indicated threshold on the sum of preshower and shower signals. The coincidence timing window is assumed to be 30 ns wide for the accidental rate estimate.

Trigger Logic Threshold (GeV)	"Pion" 0.2	"Pion" 0.5	"Electron" 0.2	"Electron" 0.5
"Signal" pion efficiency	75%	49%	97%	71%
BigBite singles rate (kHz)	422	91	976	289
HCAL singles rate (kHz)	416	416	416	416
Accidental coin. rate (kHz)	5.3	1.1	12.2	3.6
Real coin. rate (kHz)	6.2	2.5	14.3	6.5
Total coin. rate (kHz)	11.5	3.6	26.5	9.8
Physics signal rate ($\gamma n \to \pi^- p$, Hz)	16.3	10.4	23.5	17.2

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