Polarization Transfer in Wide-Angle Charged Pion Photoproduction (WAPP)

Andrew Puckett (contact), University of Connecticut, on behalf of:

John Arrington (spokesperson), Argonne National Lab,

Arun Tadepalli (spokesperson), Jefferson Lab,

Bogdan Wojtsekhowski (spokesperson), Jefferson Lab,

and the WAPP Collaboration

The spokespeople

John Arrington

Argonne NATIONAL LABORATORY

Andrew Puckett

UCONN UNIVERSITY OF CONNECTICUT

Arun Tadepalli

Jefferson Lab

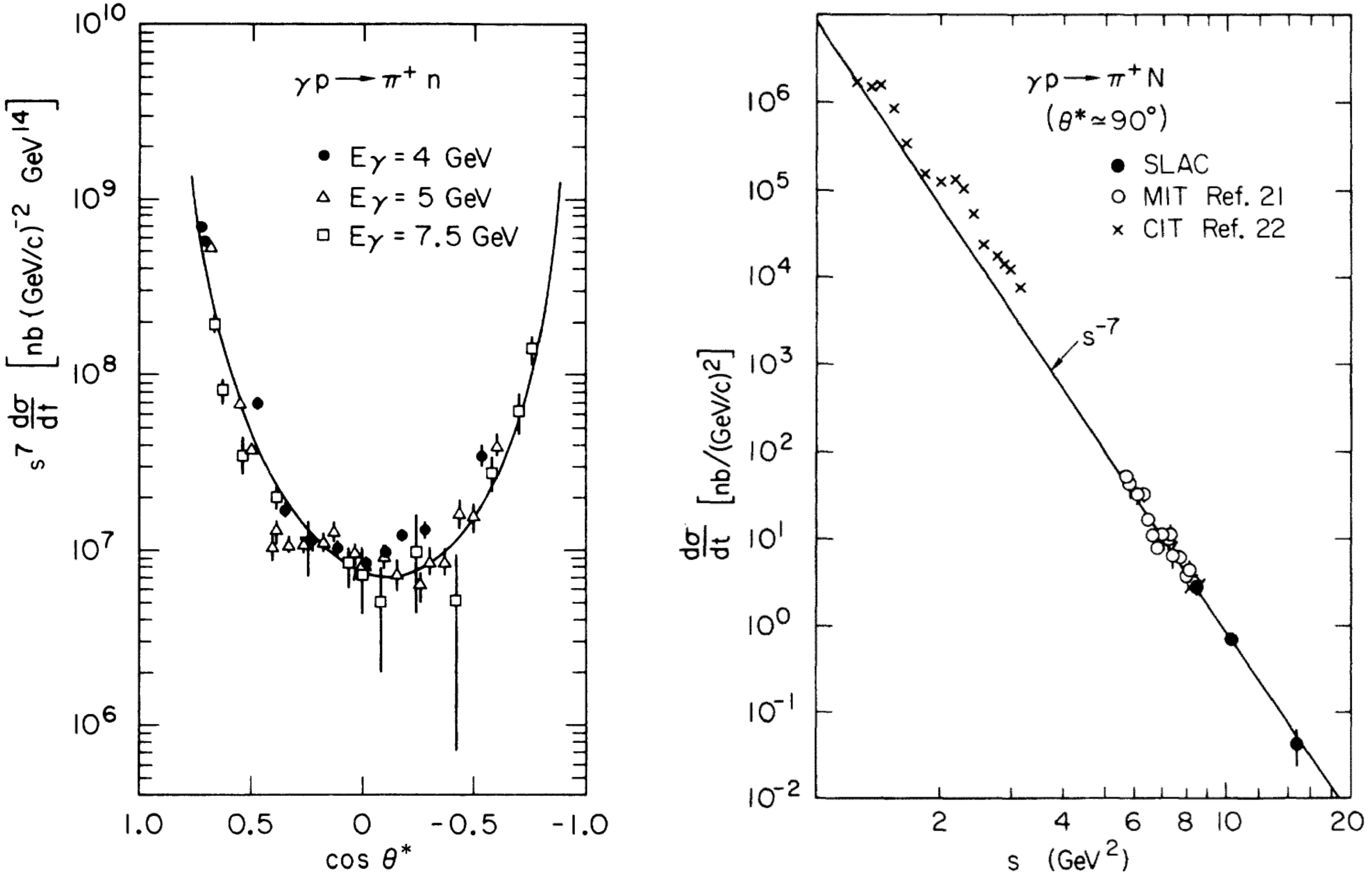
Bogdan Wojtsekhowski

Jefferson Lab

WAPP Collaboration: ~60 Collaborators from ~20 institutions

Introduction—Pseudoscalar Meson Photoproduction

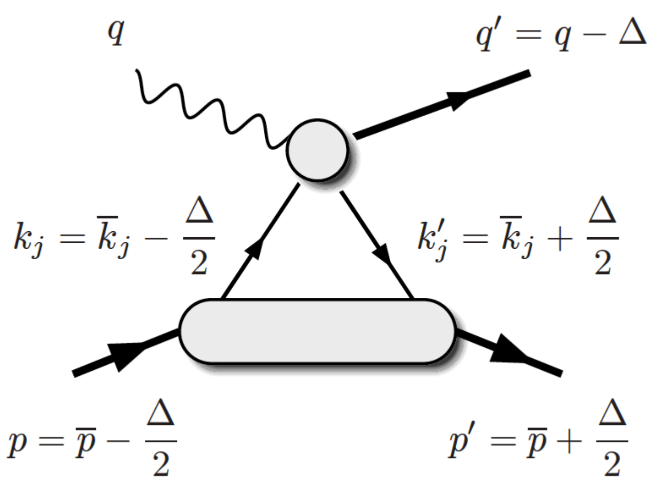
- Arguably the simplest inelastic hadronic process—production of the lightest meson from the lightest baryon:
  - $\gamma N \rightarrow \pi N$
- Cross sections extensively studied from threshold up to the nucleon resonance region
- Limited data exist above the resonance region, including:
  - **SLAC**: R. L. Anderson *et al.*, PRD **14**, 679 (1976)
  - **Hall A**: L. Y. Zhu *et al.,* PRL **91** (2003) 022003, and PRC **71** (2005) 044603
  - **CLAS**: M. C. Kunkel *et al.*, PRC **98**, 015207 (2018) and W. C. Chen *et al.*, PRL **103**, 012301 (2009)
  - And many others…
- Cross section at fixed CM angle exhibits approximate s^{-7} scaling over a wide range of energies, consistent with "constituent counting rules" based on pQCD
- Cross section knowledge necessary but not sufficient for understanding of reaction mechanism

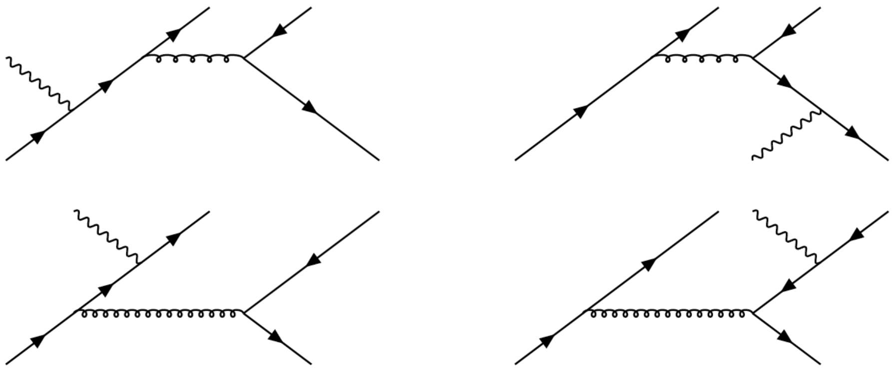


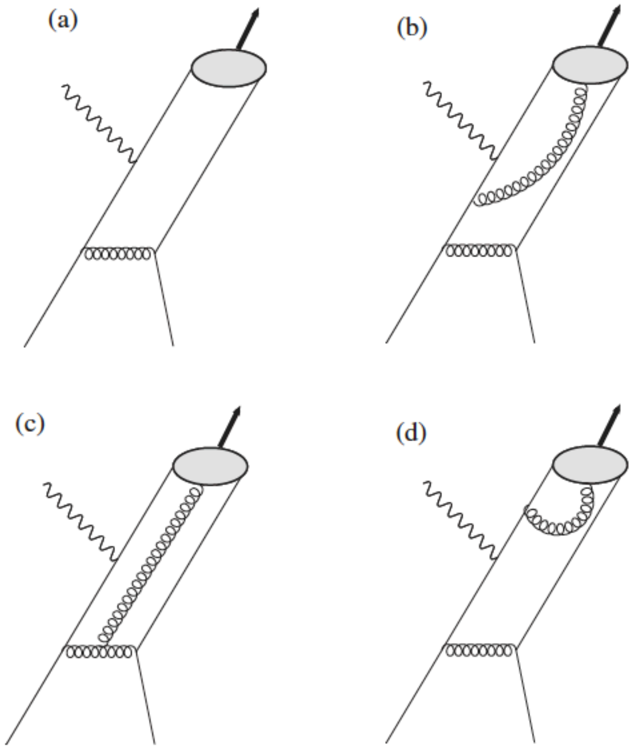
SLAC cross section data for $\gamma p \rightarrow \pi^+ n$ vs s and $\cos\theta_{CM}$

- Underlying reaction mechanism at high energies still not clearly understood after ~5+ decades' experimental and theoretical efforts.

WAPP in the GPD framework—Handbag Mechanism







$s, -t, -u \gtrsim 2.5\ \mathrm{GeV}^2$

Schematically:

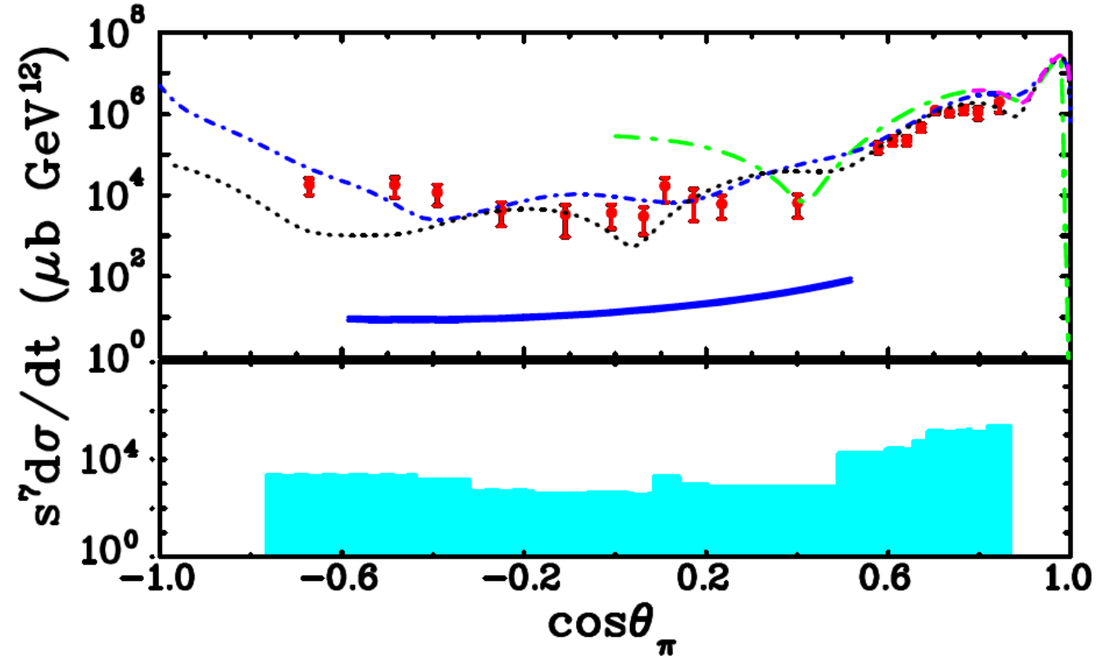
- One active parton from the initial and final nucleon participate in the hard scattering
- Perturbatively calculable hard subprocess folded with overlap of soft wave functions (GPDs)
- Extra hadron in the final state adds additional nonperturbative “soft” factors (DAs), complicating the analysis

- Above: Leading-twist one-hard-gluon exchange diagrams for the ”hard” parton level subprocess $\gamma^{(*)}q \rightarrow Mq$ in handbag mechanism (M is pseudoscalar meson)
- Right: typical leading-order Feynman diagrams including two- and three-particle Fock components of the meson

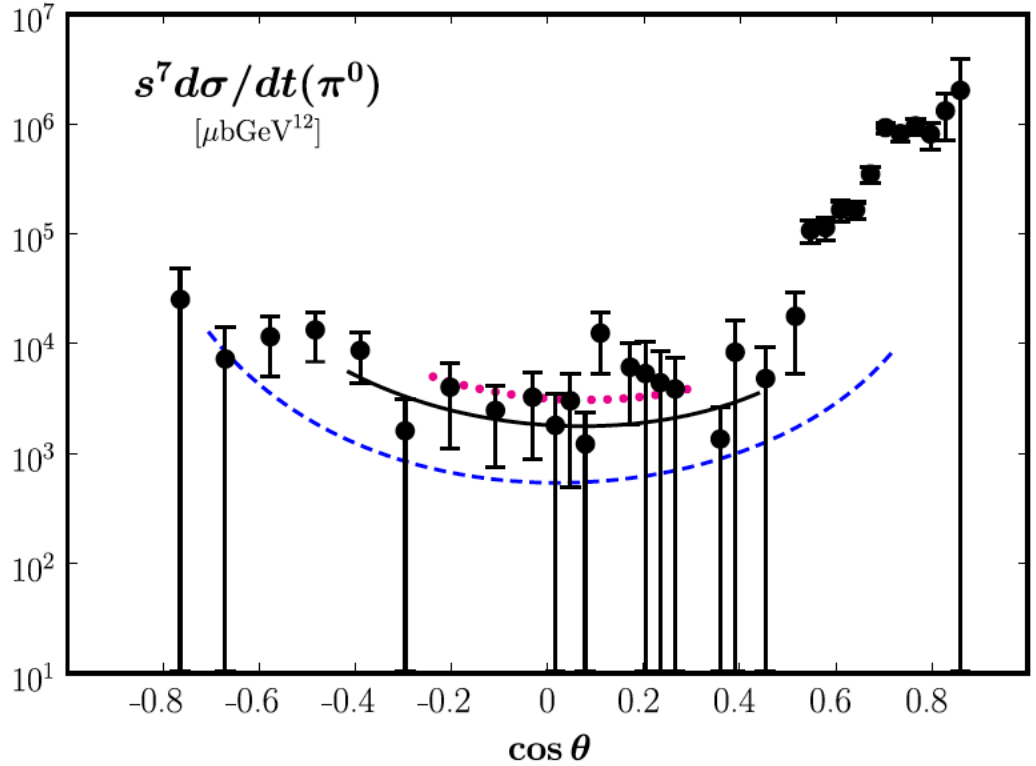
Kroll et al., PRD 97, 074023 (2018):

- Twist-2 calculation fails for meson photoproduction cross section
- Full twist 3 amplitude including three-particle ($q\bar{q}g$) contributions can explain large cross sections in the regime of large $s, -t, -u$
- Leading-twist calculations also fail badly in exclusive pion electroproduction!

Handbag calculations and pion photoproduction cross sections



$\gamma p \rightarrow \pi^0 p$ cross sections from CLAS: Kunkel *et al.,* PRC **98**, 015207 (2018)



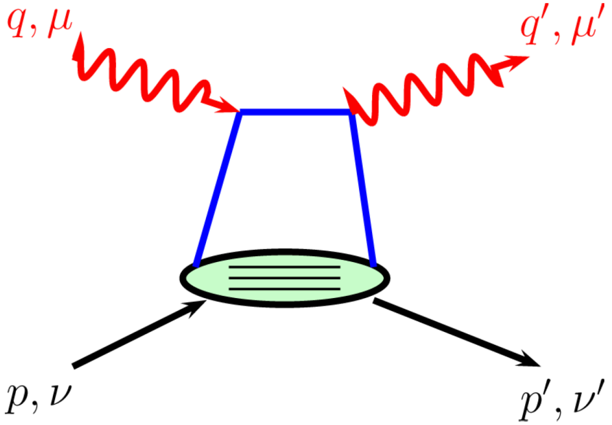
Huang *et al.,* Eur. Phys. J. **C 33**, 91 (2004):

- Calculation including only twist-2 amplitudes underpredicts CLAS data by >2 orders of magnitude (blue solid curve above)

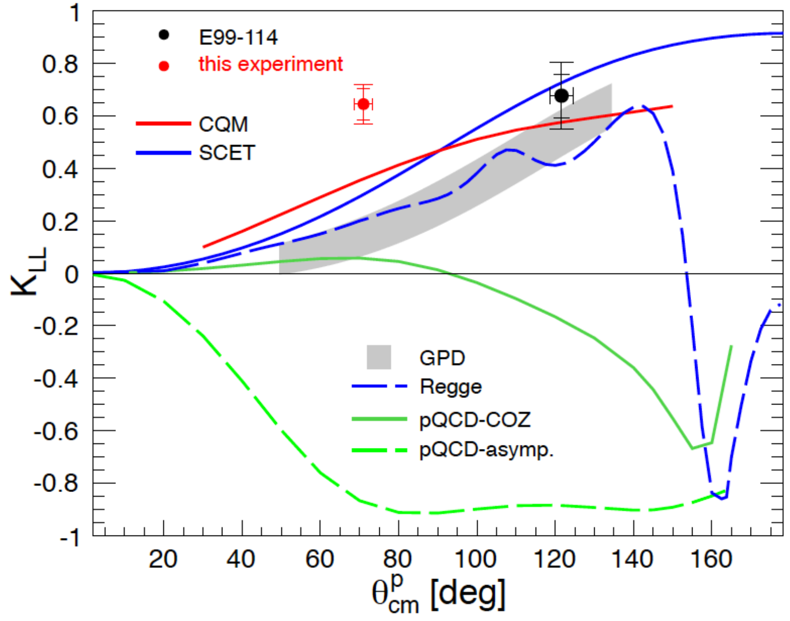
Kroll *et al.,* Phys. Rev. **D 97**, 074023 (2018):

- Updated calculation including twist-3 contributions agrees well with CLAS π^0 data
- Diagrams including 3-particle twist-3 contributions ($\bar{q}qg$) found to be important (dominant, in fact)

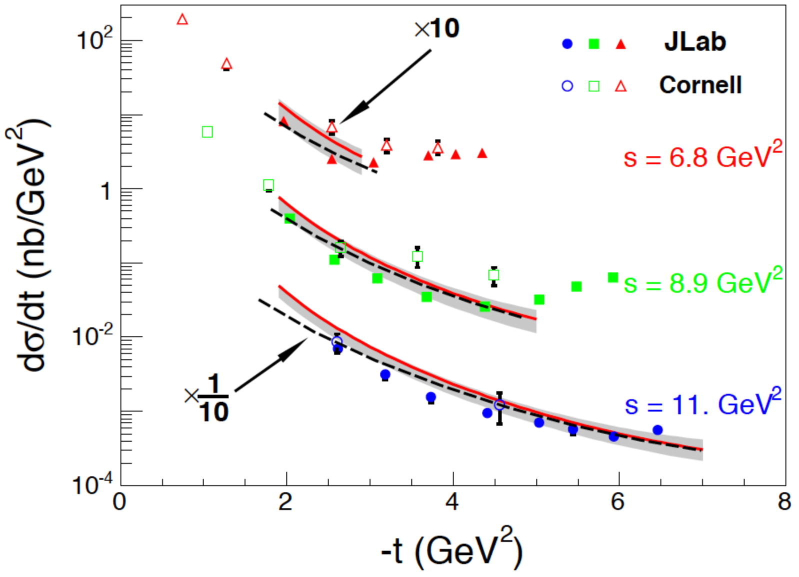
Real Compton Scattering (RCS)



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



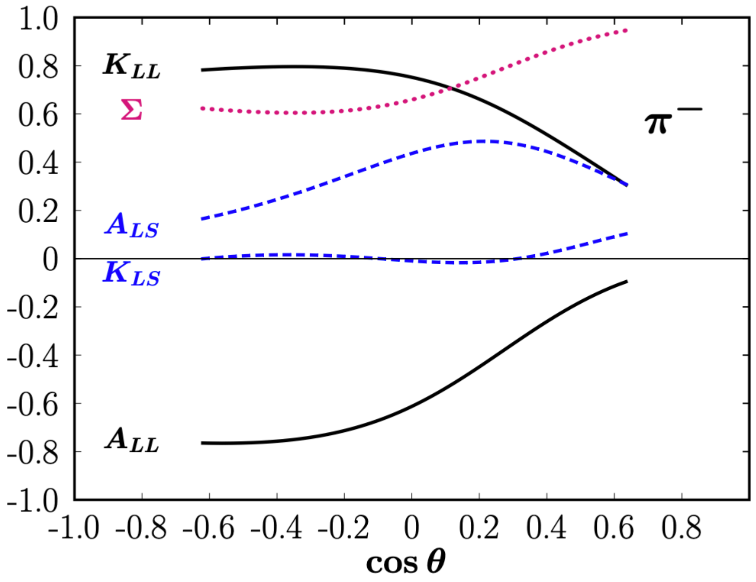
RCS K_{LL}: Fanelli *et al.*, Phys. Rev. Lett. **115**, 152001 (2015) and Hamilton *et al.,* Phys. Rev. Lett. **94**, 242001 (2005)

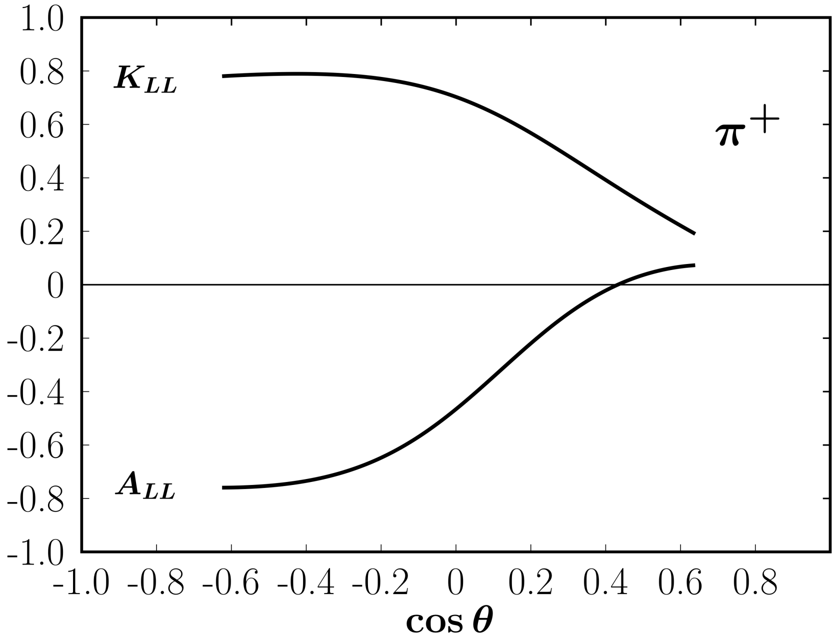


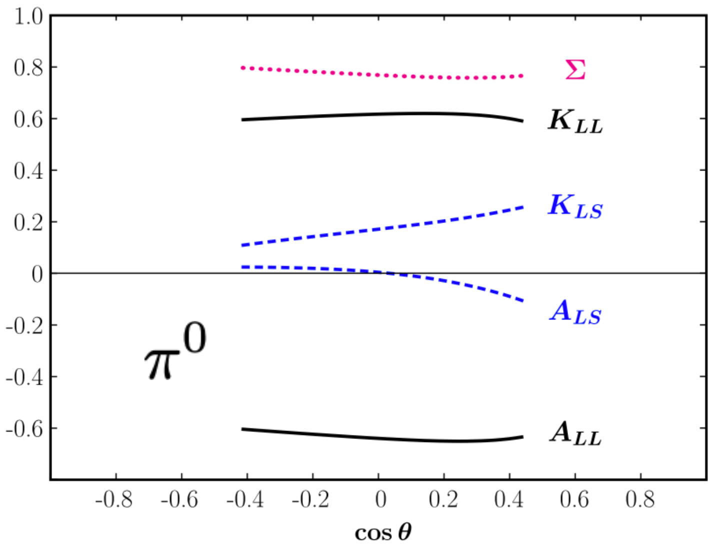
RCS cross sections: A. Danagoulian *et al.*, PRL **98**, 152001 (2007), compared to GPD-based calculations

- 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 $\widetilde{H}$

Handbag predictions for WAPP spin observables







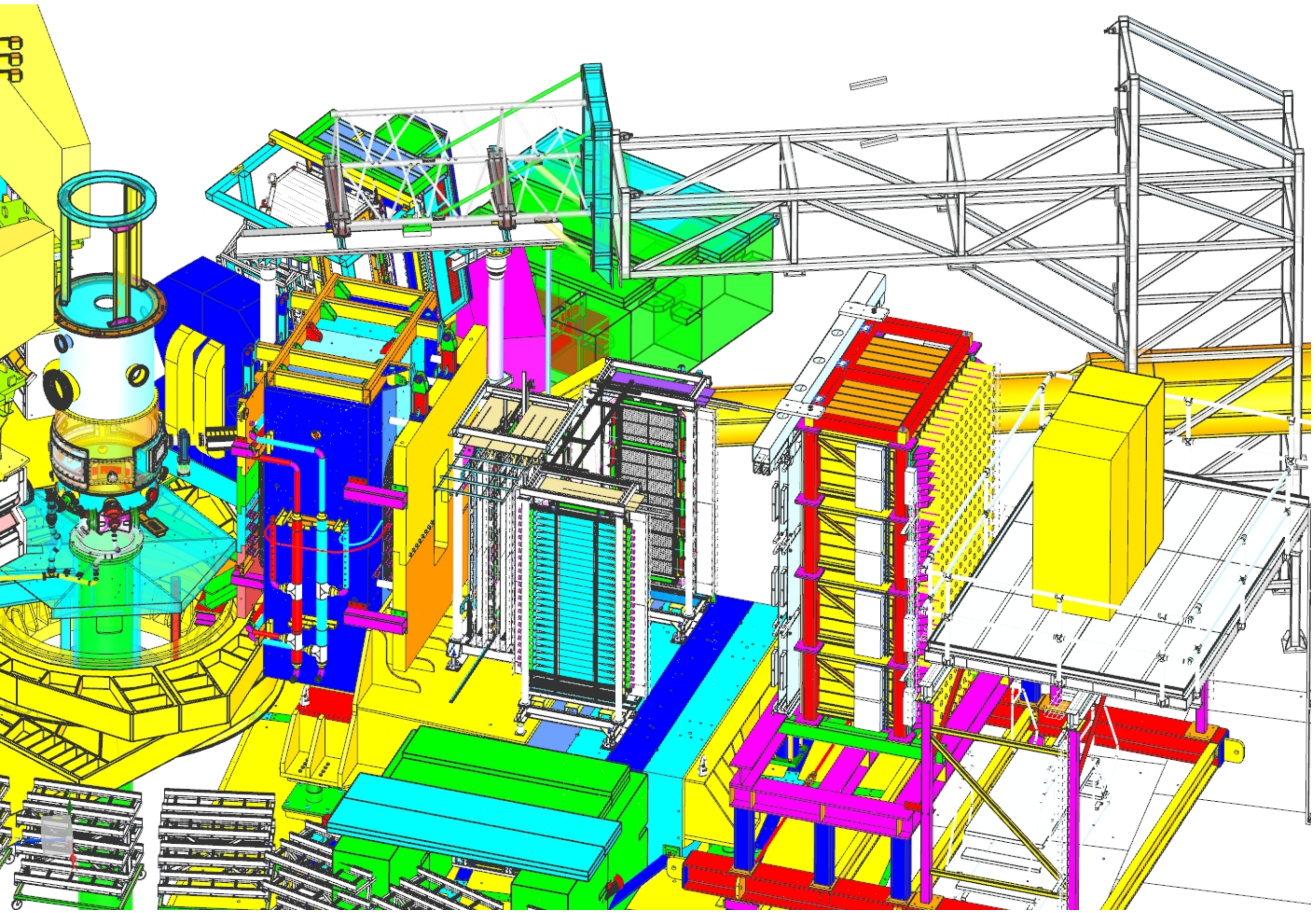
- Curves from calculations by Kroll and Passek-Kumericki, Phys. Rev. **D 97**, 074023 (2018) (charged pion calculations from private communication)
- **Never measured before for charged pions in wide-angle regime!**

$$
\begin{aligned}
A_{LL}^{(\text{Twist }2)} &= K_{LL}^{(\text{Twist }2)} \\
A_{LL}^{(\text{Twist }3)} &= -K_{LL}^{(\text{Twist }3)}
\end{aligned}
$$

Theoretical motivation for this proposal

- 2015 NSAC Long-Range Plan: 3D spatial imaging of the nucleon's parton structure via GPDs is one of the major motivations for the JLab 12 GeV Upgrade and the planned Electron-Ion Collider
- The elephant in the room: failure of leading-twist handbag calculations for wide-angle meson photoproduction by more than two orders of magnitude
  - The good news: inclusion of twist-3 amplitude, with 3-particle ($\bar{q}qg$) contribution, appears to account for much of the "missing" cross section
  - This leads to unambiguous predictions for helicity correlations A_{LL}, K_{LL} → Not tested before in relevant kinematics!
- Goal of this proposal: first measurement of K_{LL} for high-energy, wide-angle charged pion photoproduction (WAPP); to be coupled with future A_{LL} measurement on polarized ^{3}He (if this proposal is approved)
  - Unambiguous test of twist-3 handbag calculations
  - Important constraints for GPD modeling and other theoretical approaches.
- Inexpensive, opportunistic, timely measurements would provide useful information, and *could* lead to a wider program, depending on the results and their interpretation

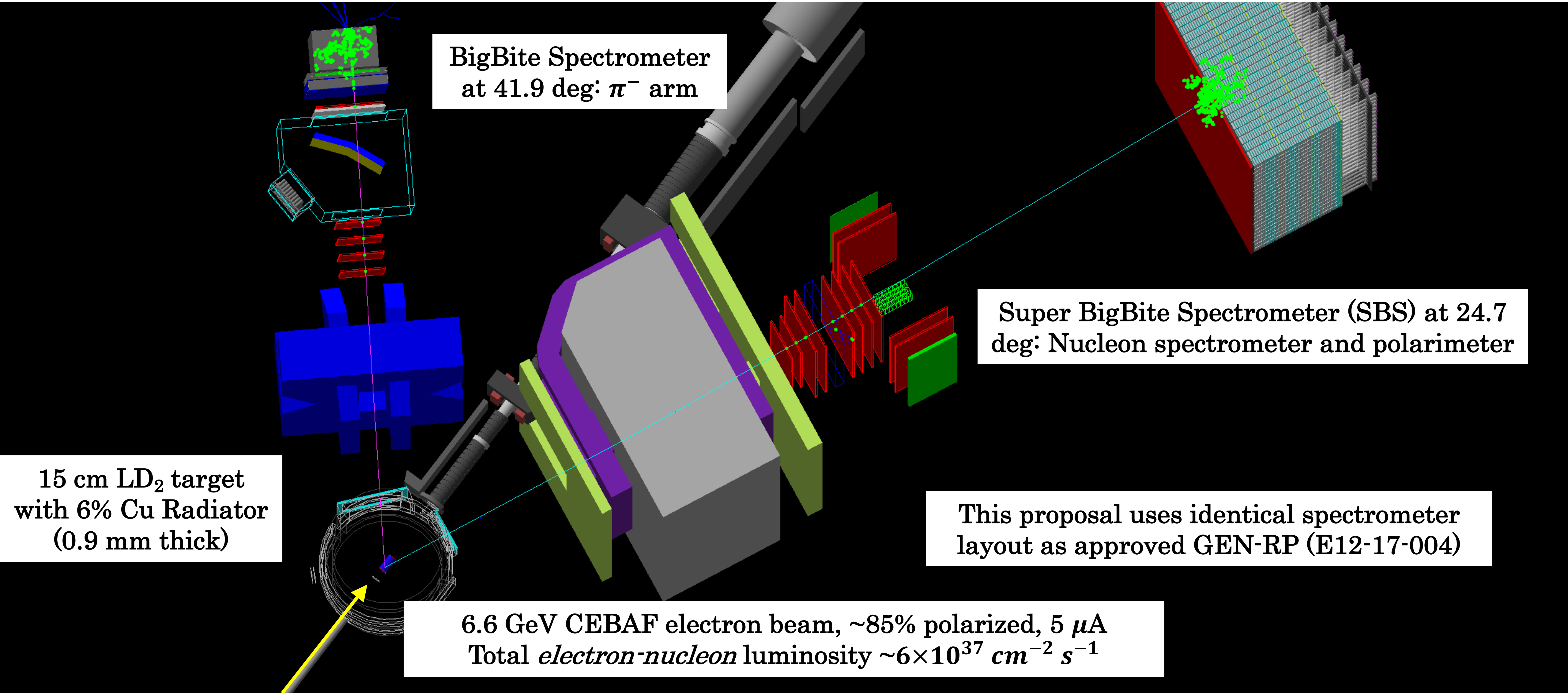
PR12-20-008: a one-time opportunity for first K_{LL} measurement in $\vec{\gamma} n \to \pi^- \vec{p}$



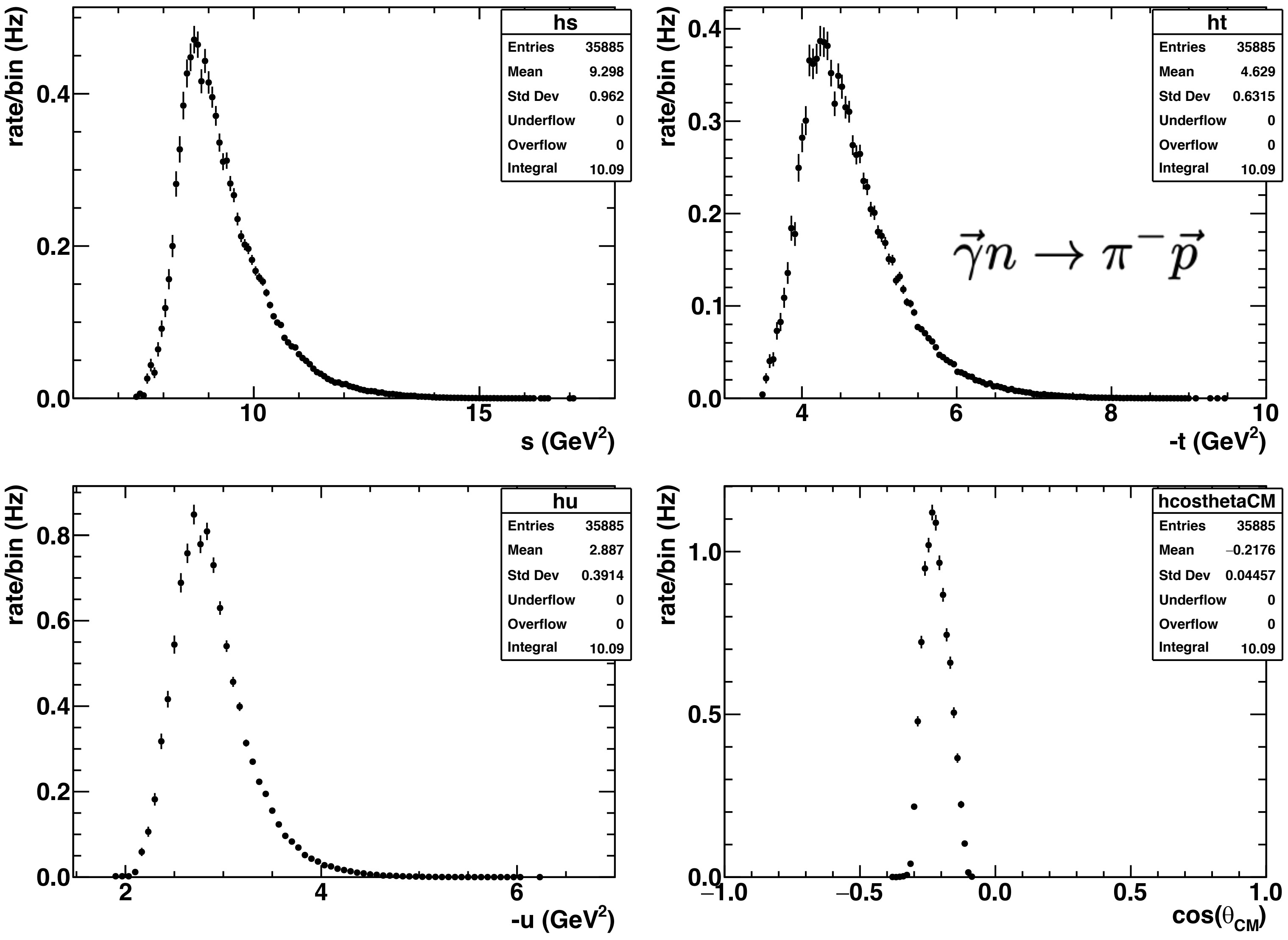
GEN-RP in the Hall A CAD model

- GEN-RP (E12-17-004) approved for 5 days by PAC45 to measure neutron form factor ratio G_E^n/G_M^n at Q^2 = 4.5 GeV^2 using the polarization transfer method—first use of charge-exchange neutron polarimetry in a form factor measurement!
- GEN-RP setup can also be used to measure WAPP K_{LL} , K_{LS} in identical kinematics
- **GEN-RP will likely run in 2021—presenting a one-time opportunity to achieve measurements of WAPP spin observables that would otherwise be very difficult, requiring significant new beam time and/or resources**
- Differences between PR12-20-008 and GEN-RP:
    - Beam energy 6.6 GeV instead of 4.4
    - 5 μA electron beam current instead of 30
    - 6% Cu radiator upstream of the deuterium target
    - Modified BigBite trigger logic (using existing electronics) to enhance sensitivity to charged pions, suppress high-energy electrons and photons

A simulated WAPP ($\vec{\gamma} n \to \pi^- \vec{p}$) event in the GEN-RP setup



WAPP Kinematic distributions within GEN-RP acceptance

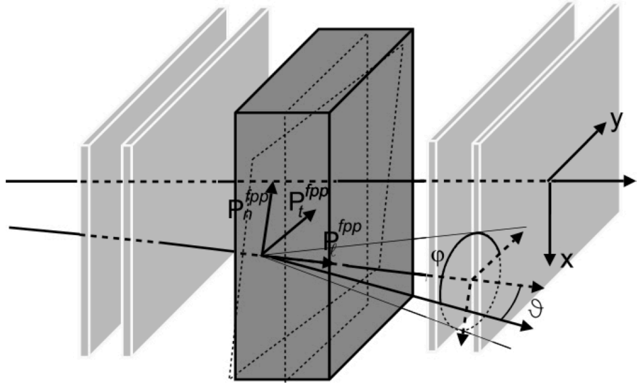


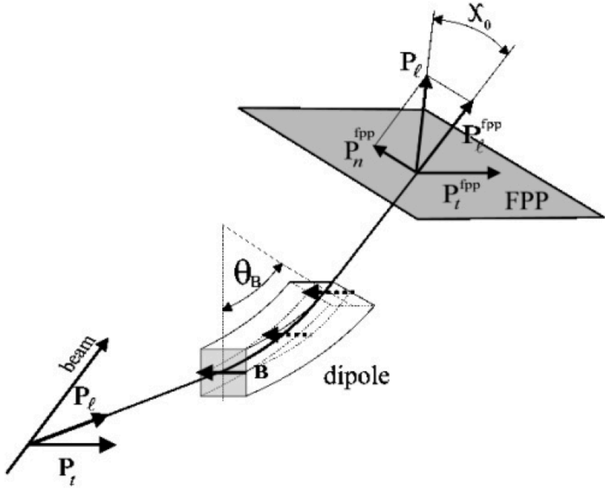
$$4.0 \leq E_\gamma \text{ (GeV)} \leq 6.6$$

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

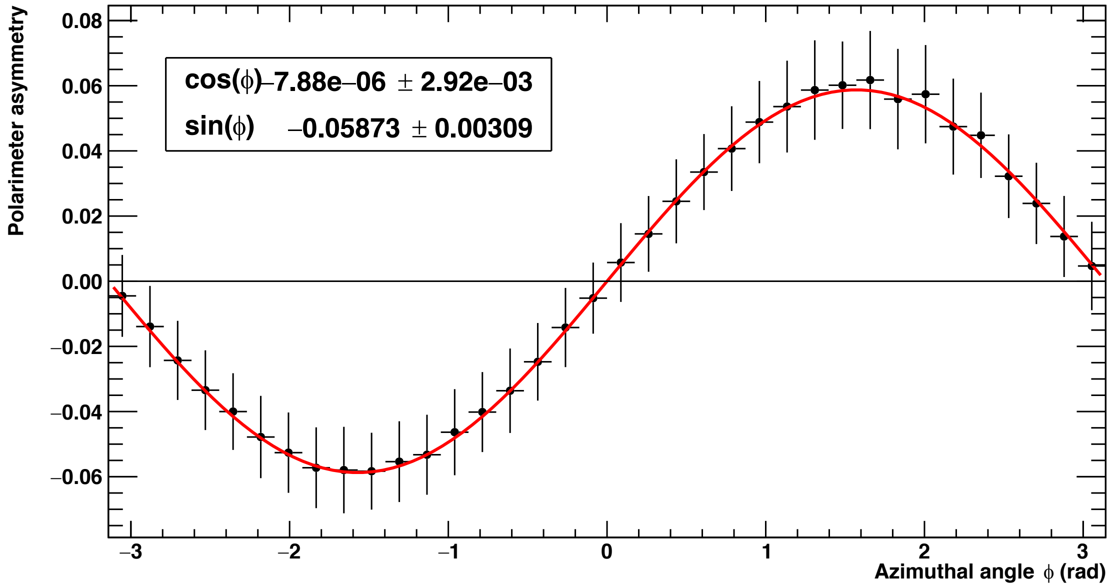
- With 6.6 GeV beam energy (3rd pass), and a minimum photon energy cut of 4 GeV, the cross section-weighted, acceptance-averaged Mandelstam variables are all sufficiently "large" for applicability of the handbag approach

Recoil Proton Polarimetry





- Spin-orbit coupling in proton-nucleus scattering generates azimuthal asymmetry
- Dipole precesses proton spin



Projected asymmetry uncertainty for two days' running ~5% (relative) assuming $K_{LL} = 0.8$

Polarimeter Performance Parameter	Value
$\varepsilon \equiv \frac{N_{event}}{N_{inc}}$	12.2 %
$\langle A_y \rangle$	11.4%
P_γ	76.5%
$\mathcal{F}$	9.3×10^{-4}
$\langle \sin \chi \rangle$	0.86

Polarimeter figure-of-merit:

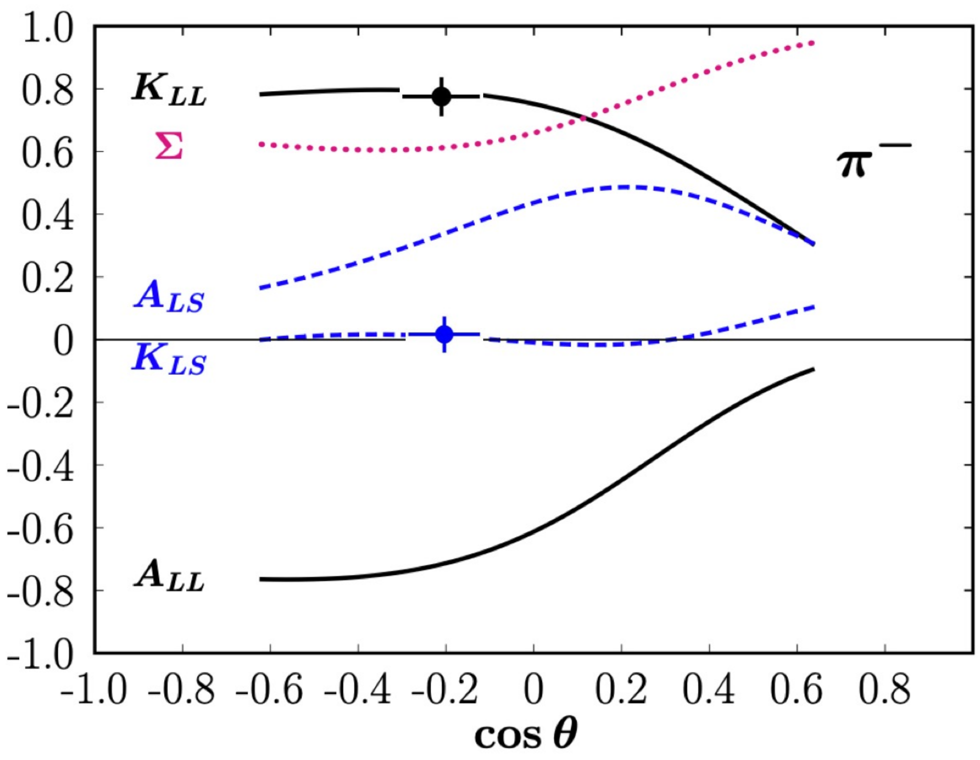
$$\mathcal{F} \equiv \frac{1}{N_{inc}} \sum_{i=1}^{N_{event}} \left(P_\gamma A_y^i(p_p^i, p_T^i)\right)^2$$

$$\begin{aligned} N_{inc} &= \text{\# incident protons} \\ N_{event} &= \text{\# scattered protons} \\ P_\gamma &= \text{Photon polarization} \\ A_y &= \text{Analyzing power} \end{aligned}$$

$$\Delta_{stat}(K_{LL}) \approx \frac{1}{\langle |\sin \chi| \rangle} \sqrt{\frac{2}{N_{inc}\mathcal{F}}}$$

- Estimated figure-of-merit ingredients:
    - Analyzing power from GEp-III data: Puckett *et al.*, PRC 96, 055203 (2017)
    - Scattering efficiency from GEANT4 simulation of GEN-RP polarimeter

Summary of beam time request and projected results



$$\vec{\gamma}n \rightarrow \pi^-\vec{p}:$$
$$\Delta(K_{LL}) = \pm 0.05 \text{ (absolute)}$$
$$\Delta(K_{LS}) = \pm 0.05 \text{ (absolute)}$$

Purpose	Time required
Energy change 4.4 → 6.6 GeV and trigger changeover following GEN-RP	8 hours
BigBite pion trigger commissioning	8 hours
WAPP Production @5 μA (reach 4% absolute statistical uncertainty goal for K_{LL}, K_{LS})	48 hours
Energy change 6.6 → 4.4 GeV	8 hours*
Total	**72 hours**

- In the context of the GMN/GEN-RP run plan, the 2nd energy change can proceed in parallel with the removal of the GEN-RP polarimeter for changeover to GMN; we include it in our request for completeness, but it doesn't add to the total run time of the GMN "run group"
- **We will measure $K_{LS}(\gamma n \rightarrow \pi^- p)$ simultaneously with comparable precision**
- **We will also obtain less precise data for $\gamma p \rightarrow \pi^+ n$ as a byproduct**

Summary/Recap

- Polarization observables never measured before for charged pion photoproduction in the wide-angle, "high-energy" regime where handbag mechanism applicable ("WAPP")
- Cross section calculations in handbag approach strongly suggest twist-3 amplitudes not merely important, but dominant in this process
  - This leads to unambiguous, easily testable predictions for relative sign/magnitude of spin observables
- SBS program starts 2021; GEN-RP (E12-17-004) presents a *one-time* opportunity to achieve such measurements, *very inexpensively*, for WAPP ($\vec{\gamma} n \rightarrow \pi^- \vec{p}$) recoil polarization observables (K_{LL}, K_{LS})
- Planned SBS program with polarized ^{3}He target presents another *one-time* opportunity (2022) to accomplish measurements of the WAPP $\vec{\gamma}\vec{n} \rightarrow \pi^- p$ beam-target asymmetries (A_{LL}, A_{LS}), in similar kinematics, in comparably modest beamtime → a proposal will be submitted to the next PAC if this measurement is approved
- SBS+BB, with its medium solid angle, large momentum bite, and high-luminosity capability, is optimal for the study of two-particle coincidence reactions, especially in hard exclusive and semi-inclusive processes
- Reaction mechanism for (arguably) the simplest inelastic hadronic reaction is still poorly understood above the resonance region
- A timely, inexpensive first look at these observables will provide valuable information, and *could* motivate a larger, more systematic program, depending on the results

Thank you for your time and attention!

Backup slides

Run Plan (July 2020 with TPE &WAPP)

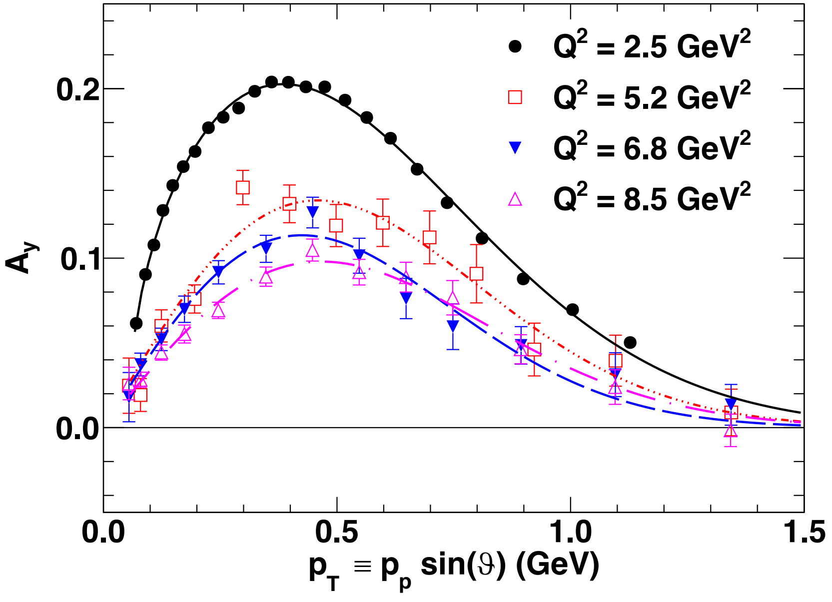
GMN changeover:
→remove polarimeter

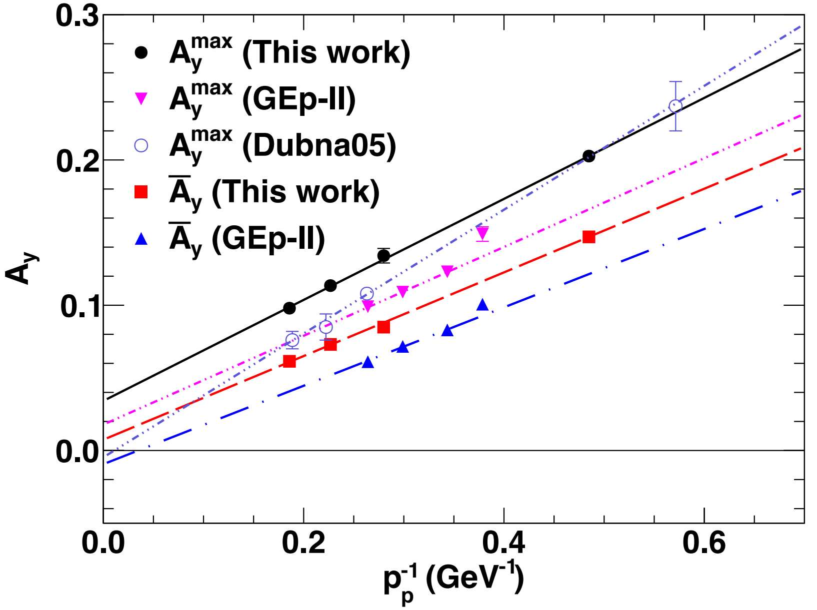
configuration	Q^2 $(GeV/c)^2$	E_{Beam} (GeV)	q_{BB} (deg.)	q_{SBS} (deg.)	d_{BB} (m)	d_{48D48} (m)	48D48 field integral (T-m)	Luminostiy $(10^{38}/A/cm^2/s)$	dHCal (m)
GEN-RP	4.5	4.4	41.9	24.7	1.55	2.25	1.71	2.8	8.5
WAPP		6.6	41.9	24.7	1.55	2.25	1.71	0.6	8.5
2 (&TPE)	4.5	4.4	41.9	24.7	1.55	2.25	1.71	1.4	8.5
3’	**6.1**	**6.6**	**30.5**	**24.7**	**1.85**	**2.25**	**1.71**	**2.8**	**8.5**
TPE	4.5	6.6	23.2	31.1	1.80	2.00			7.2
1	3.5	4.4	32.5	31.1	1.80	2.00	1.71	0.7	7.2
4	8.1	6.6	43.0	17.5	1.55	2.25	1.65	2.8	11
5	10.2	8.8	34.0	17.5	1.75	2.25	1.60	2.8	11
6	12.0	8.8	44.2	13.3	1.55	2.25	1.50	2.8	14
7	13.5	11.0	33.0	14.8	1.55	3.10	0.97	2.8	17
			$\theta_{L\text{-}HRS}$						
8	6.06	4.4	61.1,64.3	14.8		3.10	1.71	0.93	17
			67.5,70.7						
9	4.4	4.4	39.,42.	25.5		3.10	1.71	0.93	17

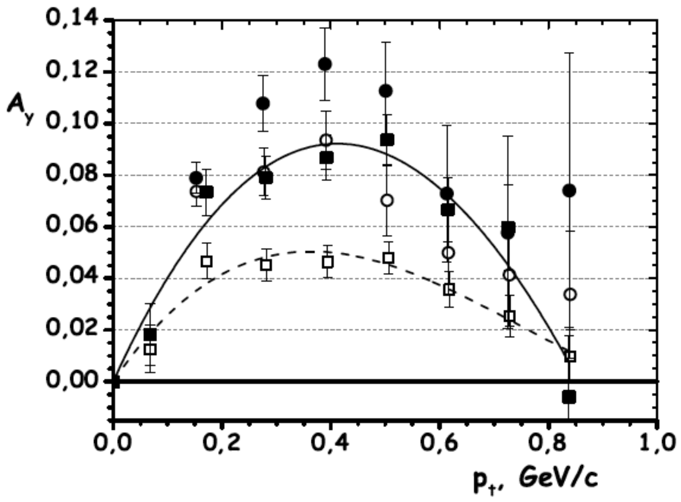
Calibration: Elastic p(e,e’p) (SBS magnet on/off)
$p(\gamma, \pi^+ n)$ near Bremsstrahlung endpoint

Source: Brian Quinn, SBS Collab. Meeting, July 2020

More Details on Analyzing Power







- Puckett *et al.*, PRC 96, 055203 (2017): $\vec{p} + CH_2 \rightarrow$ One charged particle + X analyzing power from GEp-III/GEp-2γ experiments (above, left and center):
  - GEp-III data used in estimating polarimeter figure-of-merit for this proposal
  - **Key difference: in Hall C polarimeter, energy of outgoing particles was not measured, only angles**
- Basilev *et al.*, EPJ A 56, 26 (2020): measurements of analyzing powers for proton and neutron on C, CH, CH_2 and Cu targets in 3-4.2 GeV momentum range (above, right). Key findings:
  - Analyzing power does not depend strongly on target material
  - **Analyzing power for forward elastic (charge-exchange) scattering increases by ~1.3X (~2X) after selecting events with large energy deposit in a hadron calorimeter →** *similar increase might be expected for SBS recoil polarization experiments, but is NOT assumed in our projections*

TAC responses, I:

1. Another current proposal, PR12-20-010 (nTPE), also requests to be considered as part of the GMn/GMn-RP “run group”. Both the current and the nTPE proposal request a beam energy change from 4.4 to 6.6 GeV. Unfortunately, there does not appear to be an easy way to reduce number of required configuration changes when adding these two new proposals. If the run plan were to be arranged such that the beam energy is only changed once, an additional time-consuming SBS/HCal spectrometer move would become necessary. Therefore, no time savings from combining these experiments should be expected. The estimated 16 hours for the beam energy change (from 2 to 3 pass) appear reasonable. (One day is usually scheduled for pass changes.)
   This observation is correct, since the proposed nTPE measurement requires different spectrometer angles. As such, we cannot combine any of the energy changes required by this proposal with those required by nTPE. However, and more importantly, it should be noted that both proposals can be incorporated in the GMN run plan without any increase in the number of SBS/HCAL moves, which are the most time-consuming of configuration changes in the GMN run plan. While the energy changes cannot be avoided, this proposal requires no time-consuming configuration changes, and the required small configuration changes (mainly the trigger) can be accomplished in parallel with the required energy changes.

TAC responses, II:

2. Additional expenditures and time may be necessary for procurement, machining, installation and removal of the 6% copper radiator in front of the target. While the GMn experiment E12-09-019 does call for such a radiator, the present plan is to make it an effectively permanent installation on one of the LH2 cells. By contrast, this proposal requires a radiator to be upstream of the LD2 cell. This will likely have to be a separate device, to be installed during the configuration change immediately preceding this experiment.

We have already begun discussions with the lab and the target group about how this could be implemented; There are several options that will work for this experiment, and a final plan will be developed if the experiment is approved. Options include, but are not limited to:

1. *Addition of a removable radiator upstream of one of the two currently planned large-diameter LD_2 cells*
2. *Replacement of one of the two large-diameter LD_2 cells with two smaller-diameter LD_2 cells, one of which will have a radiator installed upstream.*

TAC responses, III:

3. The 6% Cu radiator will contribute to the overall radiation budget, which will need to be calculated at the appropriate time. This is unlikely to be of concern, however, because of the low requested beam current and run time. Radiation-sensitive equipment downstream of the radiator may benefit from additional shielding.

> *We agree that the radiation budget of this proposal is unlikely to be of concern, given the low beam current and run time. Based on the total electron-nucleon luminosity and run-time of this proposal, we have estimated that this experiment, if approved, would represent a roughly 5% addition to the total radiation budget of the entire GMN running period. We are confident that the detailed radiation budget calculations by the RADCON group will support this.*

TAC responses, IV:

1. Controlling systematic errors from proton spin precession could be an issue as calculating the precession angle depends on the true SBS dipole field, including fringe fields, and the particle trajectory through the field. Accurate field mapping and track reconstruction will be required. Moreover, the proposed steel (iron) analyzer block on the downstream side of the dipole will distort the fringe field and trajectories. Admittedly the spin transport calculation through the simple SBS dipole is far easier than through focusing spectrometers, with which several recoil polarization experiments have been successfully carried out with good systematics, so this is not expected to be an issue of great concern.
   *We agree that the spin precession calculation through the simple SBS dipole will not be an issue of great concern. As part of the commissioning for GMN/GEN-RP, the SBS magnetic field will be mapped within a region sufficient to confirm the validity of existing TOSCA calculations. The calibration of the SBS optics is also part of the commissioning plans for GEN-RP, and will be accomplished using a combination of dedicated multi-foil carbon target runs with sieve slit in BigBite and SBS and coincidence H(e,e'p) elastic scattering, with the electron detected in BigBite and the proton detected in SBS. In the area of the steel analyzer, the fringe field of the SBS magnet is already quite small. The effect of the analyzer on the field integral along the proton trajectory prior to the analyzer itself was evaluated using the SBS TOSCA model, and an increase of approximately 0.06% was found for the central trajectory (and similarly small effects were observed across the acceptance). This represents an essentially negligible effect on the reconstruction of the proton kinematics at the target and the calculation of the spin precession that can be estimated and corrected for. The magnitude of the calculated magnetic field inside the steel plate is approximately 2 kG. This field is small enough that it will have no measurable effect on the scattering asymmetry in the analyzer, as the degree of polarization at room temperature of any polarizable nuclei is negligibly small for a 2 kG field. The field integral transverse to the proton trajectory inside the analyzer is approximately 0.016 T*m, which does not meaningfully affect the proton trajectories, but leads to a small but noticeable extra rotation of the proton spins by 1-2 degrees, which can be calculated and corrected for. As shown in Fig. 19 of the proposal, the spin precession through the SBS dipole is quite simple, as indicated by the small differences between the results of the full GEANT4 spin tracking and the ideal dipole approximation, which only relies on the accurate reconstruction of the trajectory bend angle and the momentum.*

TAC responses, V:

5. The planned change of the BigBite trigger configuration from electron to pion mode is straightforward and easily doable (and reversible) during the planned angle and beam energy changes. It would be prudent to allocate a small amount of trigger commissioning beam time after the configuration change, perhaps up to one shift, because

1. The trigger timing may require fine-tuning.
2. The proposal calls for carefully calibrated threshold levels on the calorimeter signals to be used for trigger formation. These calibrations will likely require live signals with beam.

One should consider pre-commissioning the pion trigger during the initial commissioning of the GMn experiment to minimize the amount of work necessary during the short switchover period.

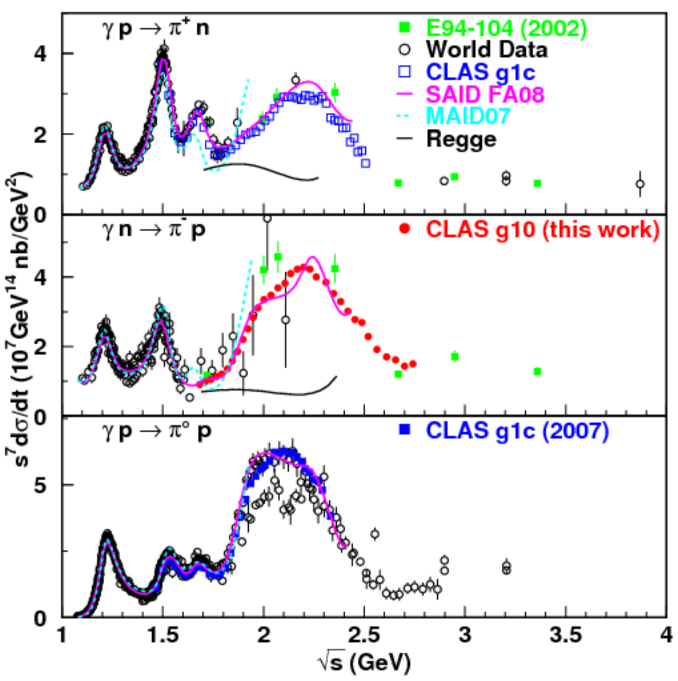
We agree with this assessment, and we note that most of the work required for the pion trigger commissioning can happen during the initial commissioning of BigBite without requiring any extra commissioning time. Part of the commissioning procedure for the BigBite calorimeters involves the calibration and gain matching of the preshower and shower PMTs, and the pion peak in the preshower signal distribution will already be visible in the commissioning data. This will accomplish a large part of the calibration of the threshold levels needed for the pion trigger. Even if the pion trigger is "pre-commissioned" during the initial commissioning phase of GMN, it will still need to be re-tested and possibly fine-tuned with beam after the configuration change, in order to verify that it is working properly. It is reasonable to assume that this will require up to one shift with beam. ***As such, we have decided to expand our total request from 2.66 days (64 hours) to 3 days (72 hours) to accommodate up to one shift to verify the proper functioning of the pion trigger with beam, and make any fine adjustments to the timing and/or threshold levels that might prove necessary.***

TAC responses, VI:

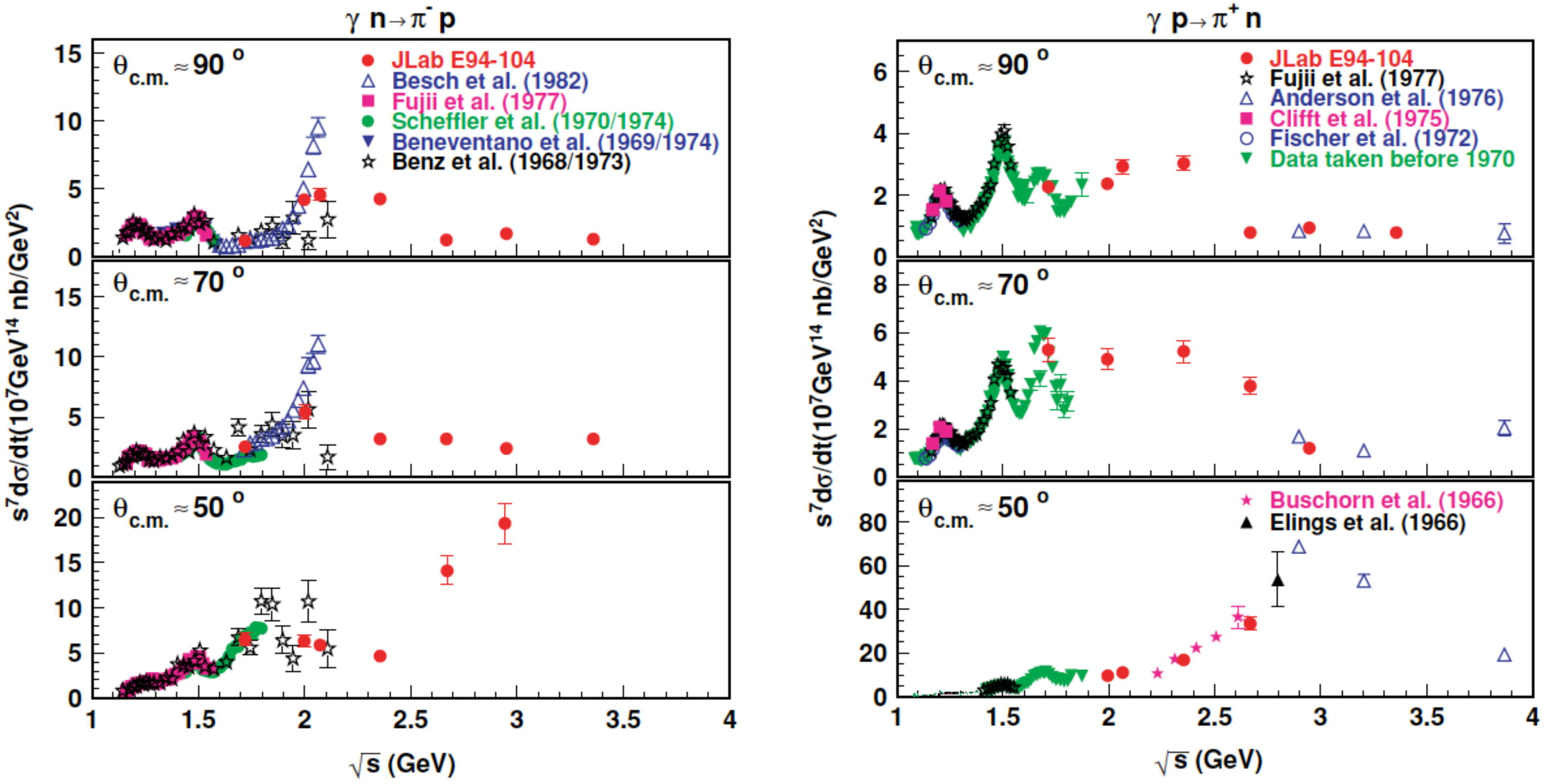
6. The recoil polarization analyzer in the SBS arm is an 8.9 cm (5 X_0) thick steel block. What is the effect of showers, caused by high-energy electrons and photons striking this material, on the rear GEM trackers? The steel is too thin to be a total absorber.

The steel analyzer is not intended to be a total absorber for high-energy electrons and photons, as these kinds of interactions do not contribute significantly to the total background rate in the GEMs. As in all the SBS experiments, the background rates in the GEMs are dominated by the interactions of soft (~1 MeV) photons with the materials of the GEMs themselves. This is a consequence of the GEMs having direct line of sight to the target. The steel analyzer is actually highly effective at attenuating soft photon backgrounds in the rear GEM trackers, as the estimated background rates in the rear GEMs are 3-4 times lower than the rates in the front GEMs (for both the GEN-RP experiment and for this proposal). For this proposal, the average raw occupancies of the front GEMs in the SBS polarimeter are approximately 7-10%, posing no significant problems for GEM operation or track reconstruction. The projected occupancies of the rear GEMs are even lower at about 2%.

Charged pion cross section measurements (representative)



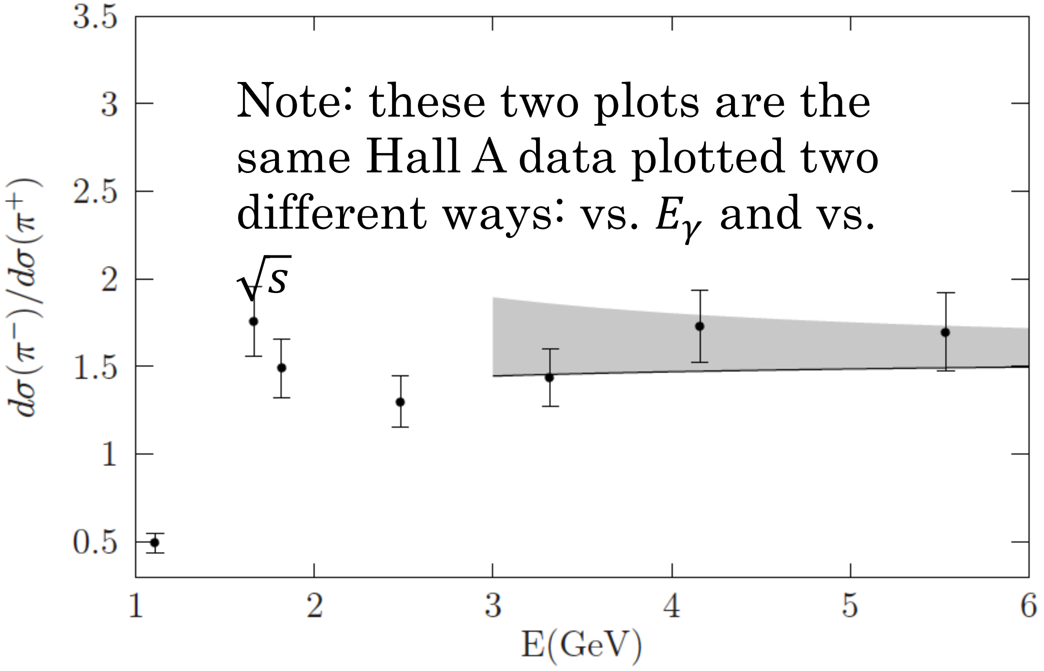
CLAS g10 data: Chen *et al.*, PRL 2009

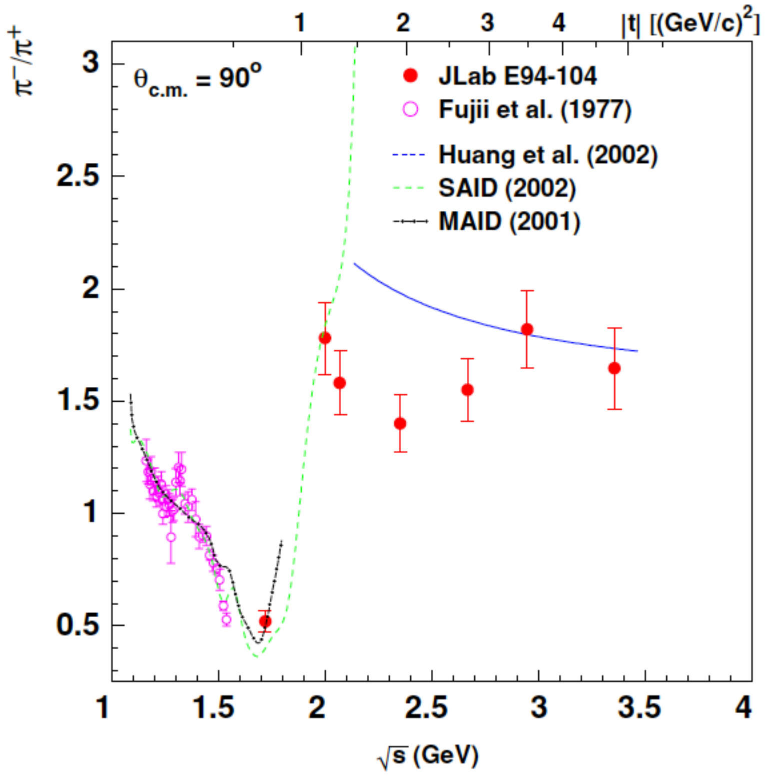


Hall A data: L. Y. Zhu *et al.*, PRC 2005

- Scaled charged pion cross sections $s^7 \frac{d\sigma}{dt}$ show significant structure below about 3 GeV, but then become relatively flat
- Broad enhancement between 2-3 GeV has several plausible, non-mutually-exclusive explanations: overlapping resonances, crossing strangeness production threshold, etc.
- pQCD known not to be applicable in the currently accessible energy range, but what then is the explanation for the s^{-7} scaling behavior of the cross section?

Charged pion cross section ratios





$$\frac{\frac{d\sigma}{dt}(\gamma n \to \pi^- p)}{\frac{d\sigma}{dt}(\gamma p \to \pi^+ n)} \approx \left(\frac{ue_d + se_u}{ue_u + se_d}\right)^2$$

- One-hard-gluon-exchange diagrams, computed within handbag approach, give a simple prediction for the charged pion cross section ratio (Huang *et al.,* 2004)

L. Y. Zhu *et al.,* Phys. Rev. **C71** (2005) 044603:

- Measured *ratios* from Hall A in reasonable agreement with *leading-twist* handbag calculation—contradiction or coincidence?

Polarization Observables in Pion Photoproduction

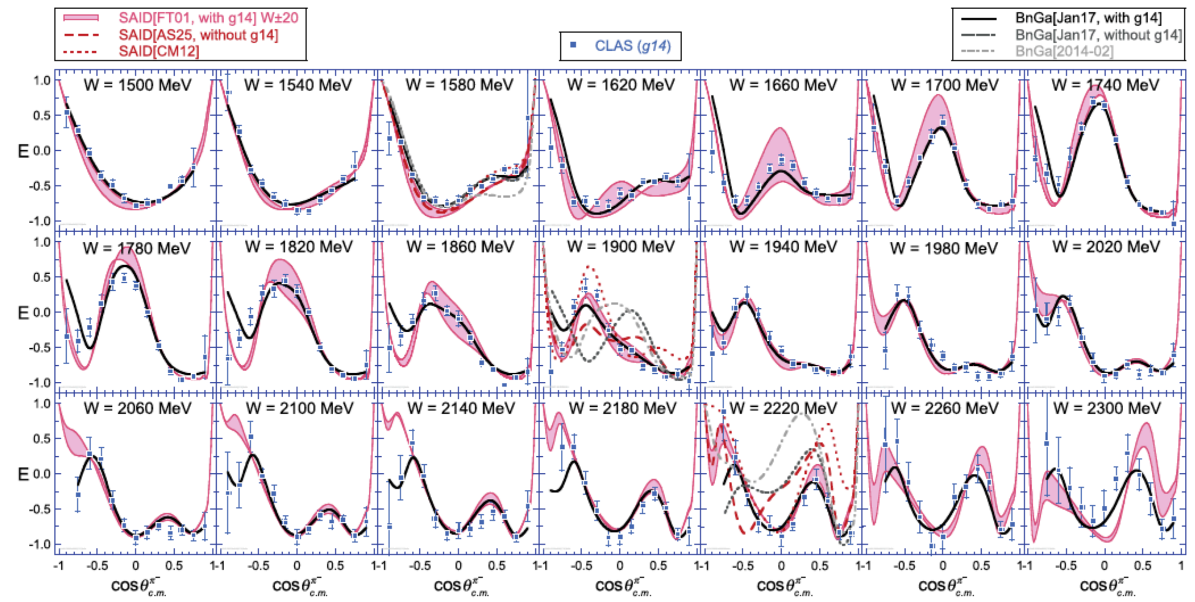


FIG. 4. E asymmetries for $\vec{\gamma}\vec{n} \to \pi^- p$ (blue squares), grouped in ± 20 MeV invariant mass (W) bins, shown with recent PWA fits that include these data: solid red curves from SAID [24], with shaded bands indicating variations across the energy bin, solid black lines from BnGa [25]. Also plotted at three W values (1580, 1900, and 2220 MeV) are previous PWA solutions that did not include the present data set in the multipole search: red-dotted curves from SAID [CM12], based on all data up to 2012 [26], red-dashed curves from SAID [AS25], including all previously published data; grey dot-dashed curves from BnGa [2014-02], based on all data up to 2014 [27], black short-dashed curves from a BnGa PWA using all previously published data.

Ho *et al.* (CLAS Collaboration). PRL **118**, 242002 (2017)

- Beam-target helicity asymmetry E for $\vec{\gamma}\vec{n} \to \pi^- p$ measured in the resonance region with photon energies 0.7-2.4 GeV
- Largely consistent with PWA fits (SAID and BnGa) available at the time

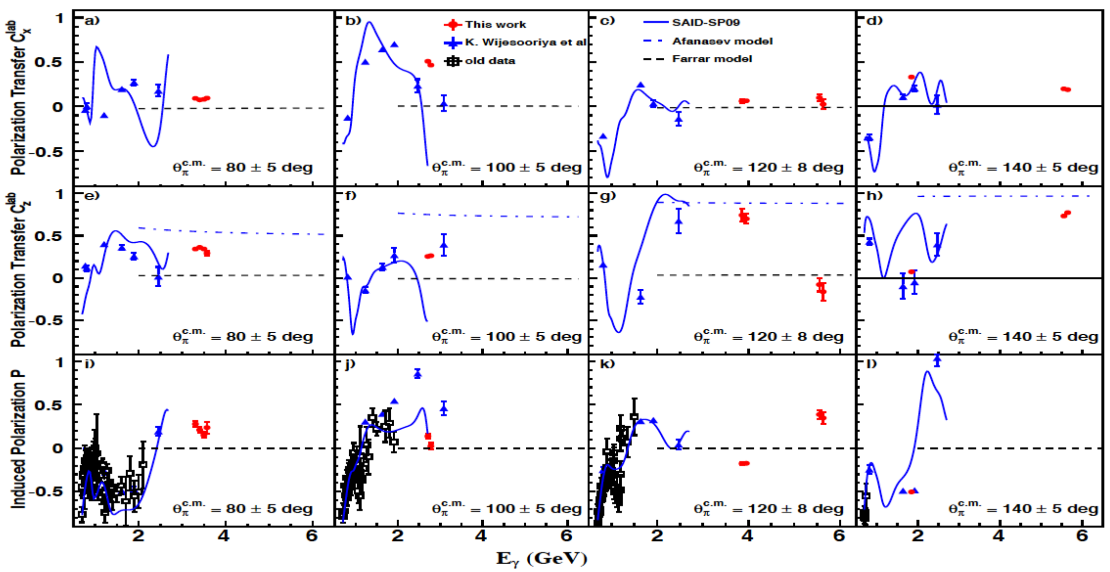
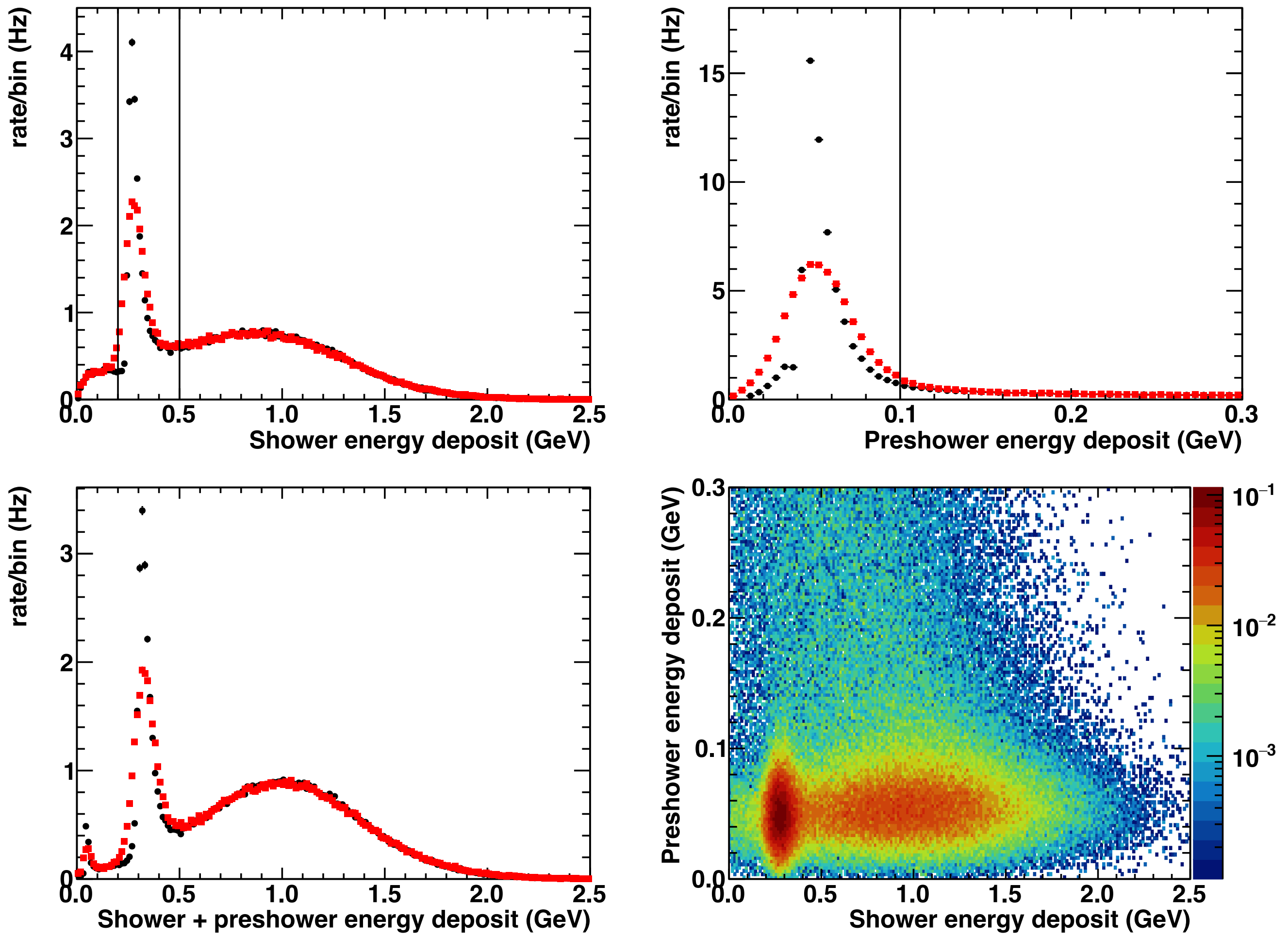


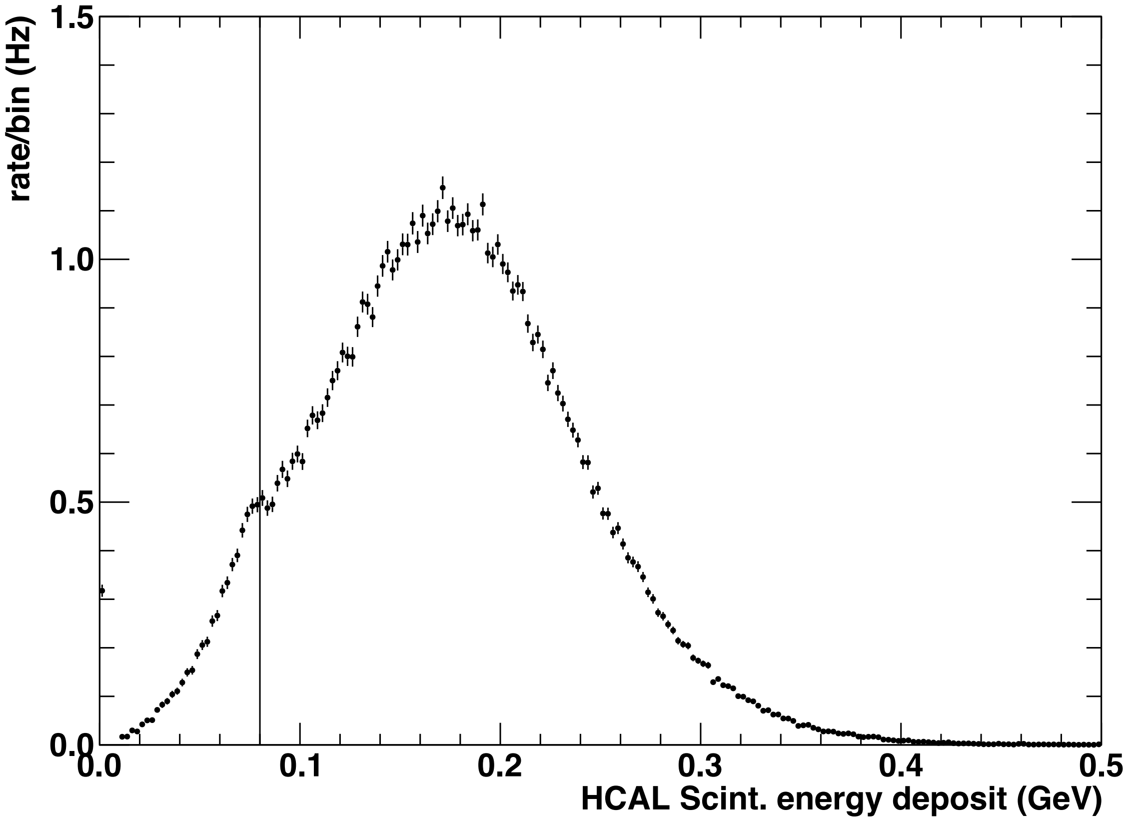
FIG. 2: Top to bottom: polarization transfer C_x^{lab}, C_z^{lab}, and induced polarization P in the lab frame. Left to right: different angles of π^0 in c.m. frame. The "old data" could be found in the SAID data base [23]. The three curves labeled Afanasev model [25], Farrar model [26] and SAID SP09 [27] are described in the text. Only the statistical uncertainties are shown.

Luo *et al.*, PRL **108**, 222004 (2012) and K. Wijesooriya *et al.*, PRC **66**, 034614 (2002)

- Polarization transfer in $\vec{\gamma}p \to \pi^0\vec{p}$. Photon energies 1.8-5.6 GeV (Hall C), up to 4 GeV (Hall A)
- Rapid variation of transferred polarizations with energy, CM angle.
- Not fully explained by any theoretical model so far

Single-arm triggers: BigBite (π^-, π^+) and HCAL (p, n)





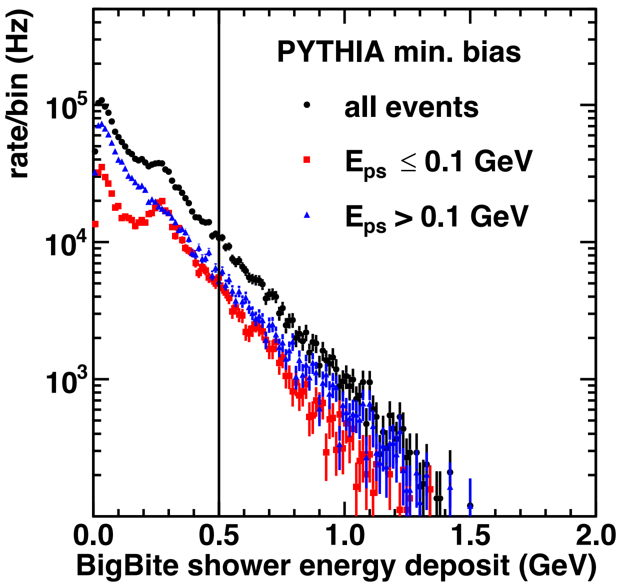
- BigBite charged pion trigger: use pre-shower as a "veto" for electrons/photons (keeps ~80% of signal π^-), shower energy > 0.5 GeV (keeps ~60% of signal π^-) for total efficiency ~48%
- HCAL nucleon trigger: threshold 80 MeV in active scintillator, efficiency 92% for the events of interest for polarimetry
- NOTE: precise knowledge of detection efficiency not important for recoil polarization measurement!

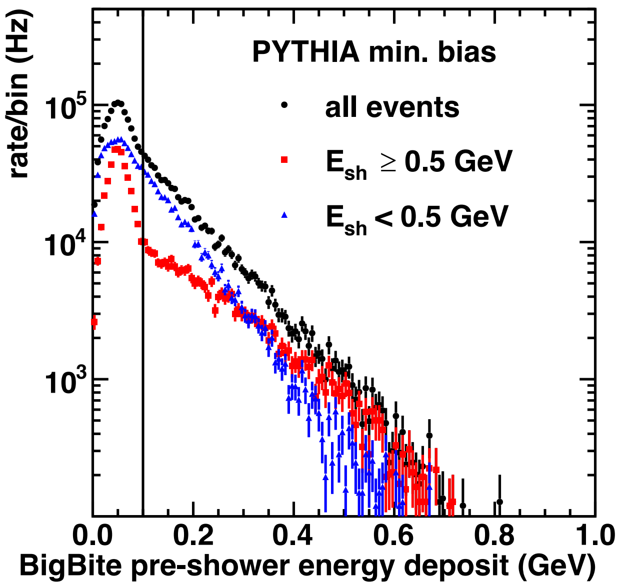
Coincidence trigger and estimated rates (PYTHIA)

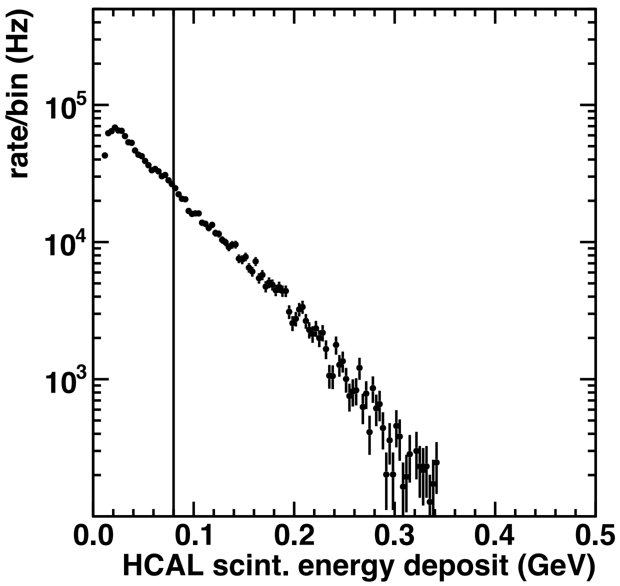
Table 1: Estimated single arm and coincidence trigger rates from PYTHIA, assuming 5 μA on 15-cm LD_2 target with 6% Cu radiator. The "Pion" logic consists of requiring the preshower signal to be *less than* 100 MeV and applying the indicated threshold on the *shower*. The "Electron" logic consists of 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	"Pion"	"Pion"	"Electron"	"Electron"
Threshold (GeV)	0.2	0.5	0.2	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

- Expected GEN-RP DAQ rate capability ~5 kHz*
- Given the low trigger thresholds, a coincidence trigger is required to keep rates manageable
- Trigger rate estimates for such low thresholds are uncertain, but we have headroom to optimize thresholds/beam currents/DAQ rates/etc. (see note below)
- "Signal" event rate ~10 Hz @5 μA (for $E_\gamma \geq 4\ GeV$)







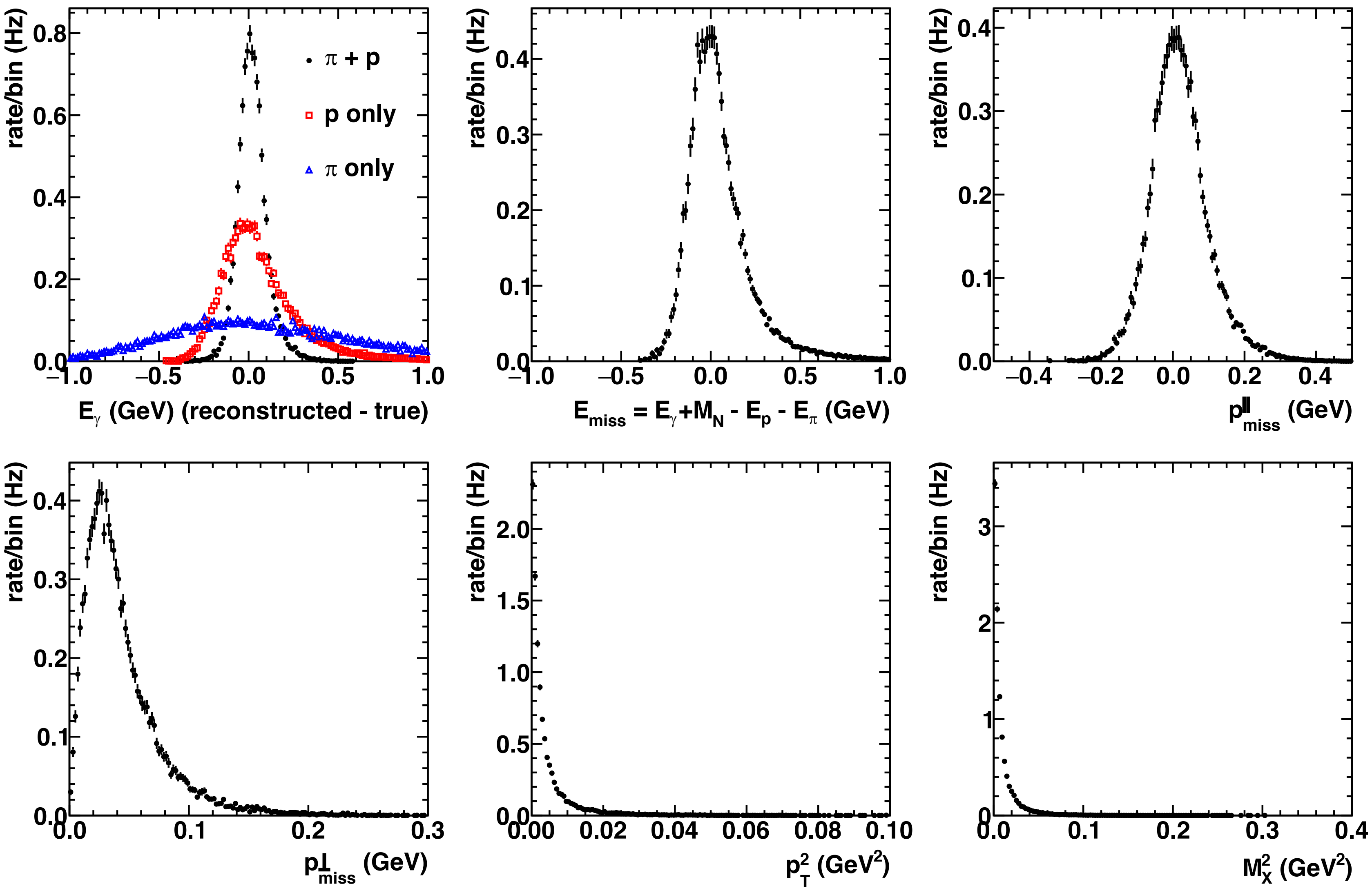
** Note: 5 kHz DAQ rate limit is based on GEN-RP GEM occupancies that are 3-4 times higher than this proposal—it is likely that this experiment can tolerate higher DAQ rate/higher beam current, but we assume 5 kHz limit to be conservative*

Exclusivity cuts and incident photon energy reconstruction

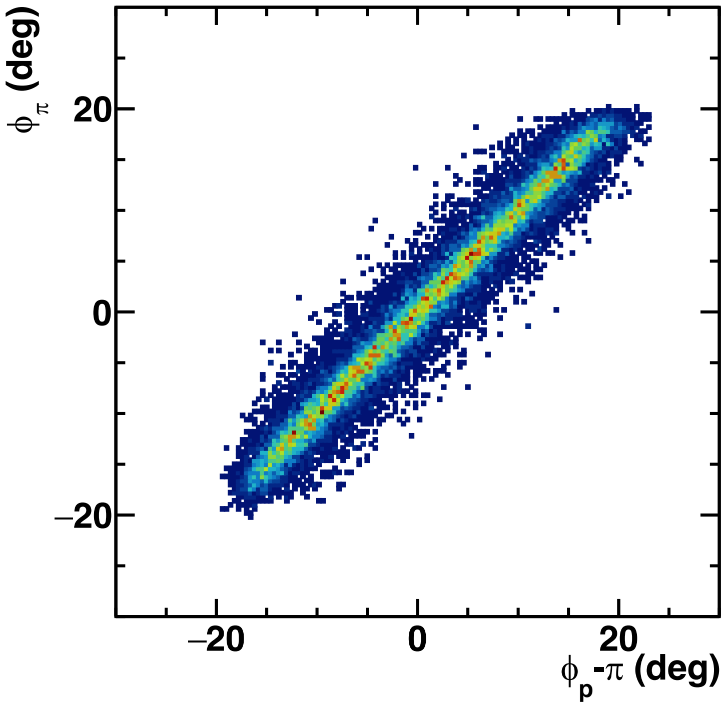
- Event selection for the $\vec{\gamma} n \to \pi^- \vec{p}$ channel is expected to be very clean due to the two charged particles in the final state with full kinematic reconstruction
- Accurate photon energy reconstruction from combined pion+proton kinematics:

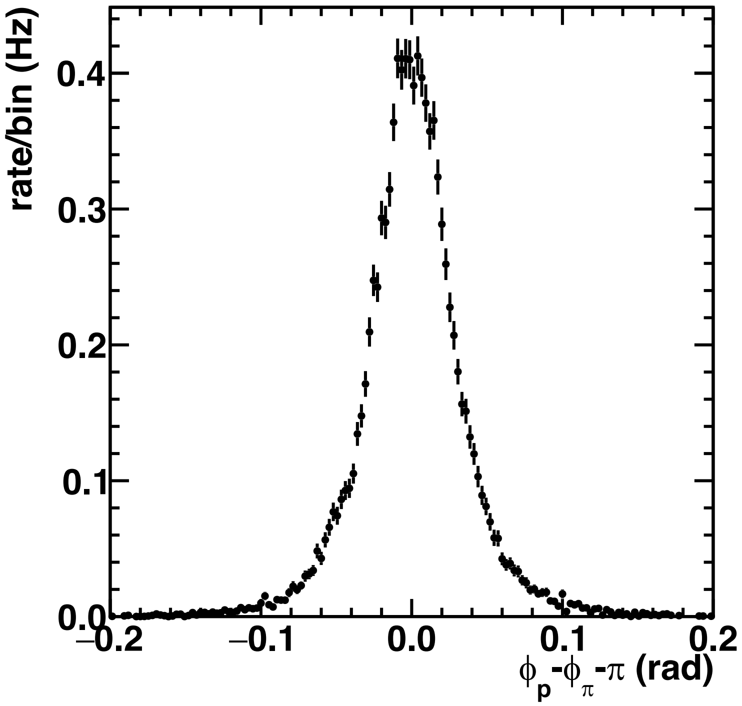
$$
\begin{aligned}
E_\gamma &= \frac{s_{p\pi} - m_n^2}{2(E_\pi + E_p - p_\pi \cos\theta_\pi - p_p \cos\theta_p)}, \\
s_{p\pi} &= (E_p + E_\pi)^2 - (\mathbf{p}_p + \mathbf{p}_\pi)^2
\end{aligned}
$$

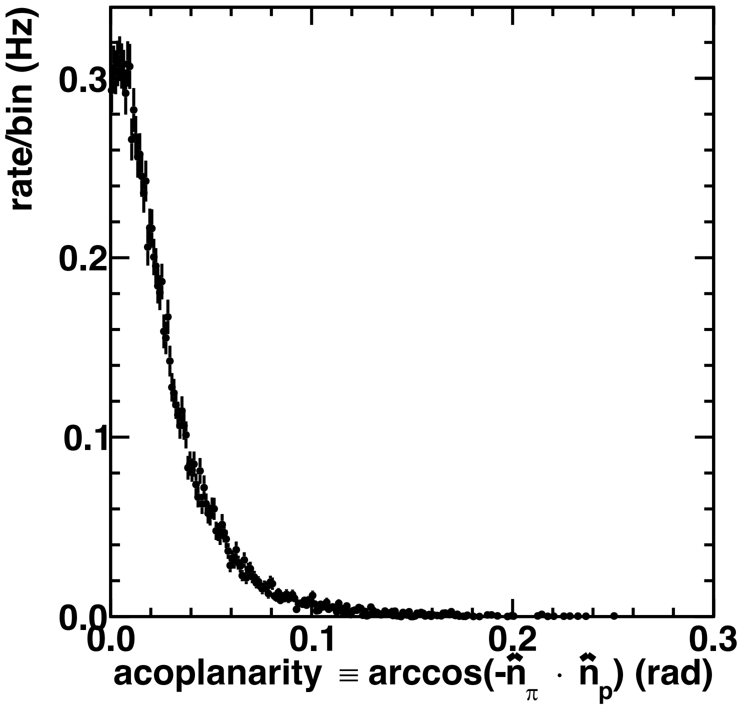
- Exclusivity cuts include:
  - Missing energy
  - Missing parallel and perp. momenta
  - Transverse momentum
  - Missing mass
  - Vertex correlation (suppress accidentals)
  - Coplanarity (next slide)
- Resolution typically dominated by Fermi motion



Coplanarity







- Coplanarity (azimuthal angle correlation) of outgoing particles is a powerful constraint for selection of exclusive channel in the presence of higher-rate non-exclusive backgrounds
- Resolution here is typically dominated by Fermi motion of the initial neutron in the deuteron
- Not all quantities on this and previous slide are independent; some exclusivity cuts are partially or wholly redundant with others.