Hadron Spectroscopy Working Group Report

Bryan McKinnon
University of Glasgow

Friday, November 15, 2019

Agenda

08:30 - 10:00 Hadron Spectroscopy Working Group

https://bluejeans.com/870559854

Convener: Dr. Bryan McKinnon (University of Glasgow)

Location: L102

08:30 **HSWG Business** *10'*
Speaker: Dr. Bryan McKinnon (University of Glasgow)
Material: **Slides**

08:40 **JPAC Update** *30'*
Speaker: Dr. Lukasz Bibrzycki (Pedagogical University of Cracow)
Material: **Slides**

09:10 **g12 Trigger Efficiency** *20'*
Speaker: Ken Hicks (Ohio University)
Material: **Slides**

09:30 **Photoproduction of Lambda*** *15'*
Speaker: Utsav Shrestha (Ohio University)
Material: **Slides**

09:45 **Update on Lambda-Nucleon Scattering** *15'*
Speaker: Mr. Joey Rowley (Ohio University)
Material: **Slides**

10:30 - 12:00 Hadron Spectroscopy Working Group

https://bluejeans.com/870559854

Convener: Dr. Bryan McKinnon (University of Glasgow)

Location: L102

10:30 **Beam Spin Asymmetries from ep->eppi(0) in the resonance region** *20'*
Speaker: Dr. Evgeny Isupov (Moscow State University)
Material: **Slides**

10:50 **Helicity Asymmetry E for gammp->pi(0)p from FROST** *15'*
Speaker: Mr. Chan Kim (GWU)
Material: **Slides**

11:05 **Polarization observables P, C(x), and C(z) for the reaction K(0)Sigma(+) from g12 plus XSec issues** *20'*
Speakers: Mr. Frank Gonzalez (FSU), Prof. Volker Crede (Florida State University)
Material: **Slides**

11:25 **Analysis of K(0)Sigma(+) photoproduction off the proton** *15'*
Speaker: Mrs. Louise Clark (University of Glasgow)
Material: **Slides**

11:40 **HSWG Business** *20'*
Speaker: Dr. Bryan McKinnon (University of Glasgow)
Material: **Slides**

- Busy agenda

Business Updates

- Busy start

- Since the last meeting:
  - JPAC-HS meeting (future support planning) September
  - DNP approvals October
    - See HSWG wiki for presentations from both and DNP release notes
  - “wiki in the wild” has been tamed and is now behind CUE
  - Reviews (more later)
  - FROST run group meeting to review Chan Kim analysis
    - CLAS(6) run-groups are not disbanded (more later)

Business Updates

- Busy future

- HSWG conference calls to start-up again
- Reviews require run group approval including CLAS(6)
- Early oversight of analyses – Let's start this
- Analysis list updates

- First (or soon after) publication: review and process
  – We need to get organised

Analysis Review Status Updates

- Complete
  - **G Double-Polarization 4 Observable for the Reaction gamma p -> pi+ n and gamma p -> pi0 p from g9 (Frost) Data**
    - **Nicholas Zachariou**
    - **RC:** Steffen Strauch (Chair), Daria Sokhan , Philip Cole
    - **June – October 2019**

    drafting
  - **Analysis of the reaction gamma p -> p eta pi0 from g12 data set**
    - **Andrea Celentano**
    - **RC:** Lei Guo (Chair), Nicholas Zachariou , Eugene Pasyuk
    - **July – October 2019**

    drafting
  - **Photoproduction of 3pi with CLAS g12**
    - **Paul Eugenio**
    - **RC:** Derek Glazier (Chair), Alessandra Filippi , Michael Dugger
    - **April 2017 – July 2019**

    paper out
- New
  - **Quasi-free cross section measurements for the pi+ pi- electroproduction off the proton in deuterium**
    - **Iuliia Skorodumina**
    - **RC:** Douglas MacGregor (Chair), Nikolay Markov , James Ritman
    - **September 2019**

Analysis Review Status Updates

- In Progress
  - **Polarization observables H and P from the reaction gamma p -> pi+ n**
    - **Michael Dugger**
    - **RC:** Annalisa D’Angelo (Chair), Mikhail Bashkanov , Evgeny Golovach
    - **April 2019 – Committee working on response - soon**
  - **Exclusive pi- Electroproduction off the Neutron in Deuterium in the Resonance Region**
    - **Ye Tian**
    - **RC:** Nikolay Markov (Chair), Mikhail Bashkanov , Eugene Isupov
    - **April 2017 ??**
  - **Dalitz Plot Analysis of eta' to eta pi+ pi− from CLAS g12 Data Set**
    - **Sudeep Ghosh**
    - **RC:** Volker Crede (Chair), Alessandro Rizzo , Eugene Pasyuk
    - **July 2017 – Sudeep indicates to continue – provide updated note in a short time**

HWSG Updates

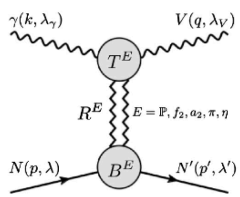
JPAC update

ŁUKASZ BIBRZYCKI

JEFFERSON LABORATORY / INDIANA UNIVERSITY, BLOOMINGTON / PEDAGOGICAL UNIVERSITY OF KRAKÓW

FOR JPAC COLLABORATION

- At forward direction the amplitude is dominated by Reggeon exchange

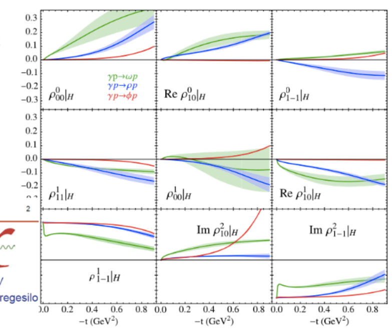


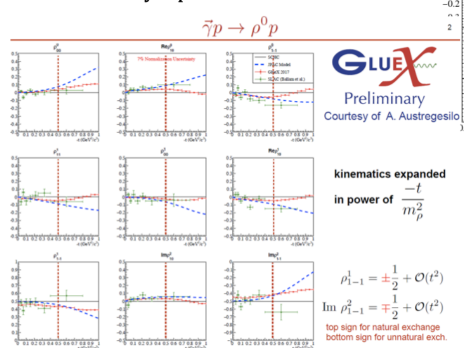
- Quantum numbers describing trajectory:
  - Isospin *I*, naturality $\eta=P(-1)^J$, signature $\tau=(-1)^J$, charge conjugation *C*, *G*-parity $C(-1)^I$
- Model includes both natural (IP, f_2, a_2) and unnatural (π,η) exchanges
- Residue factorisation enables the independent parametrization of helicity dependence in beam and target vertices
- Parity conservation reduces the number of helicity components in each vertex

Vector meson photoproduction with linearly polarized photons

V. Mathieu et al. PRD 97 (2018)

- Motivation:
  - Testing the mechanisms of production (dominanace of natural exchanges like IP, f_2, a_2)
  - Testing models of residues (couplings, helicity dependence)
  - Confronting model with experimental spin density matrix elements (SDME)
  - Description of the CLAS12 and GlueX data
- Immediate purpose: description of the ρ, ω and φ photoproduction at Eγ=8.5 GeV
- Observations
  - For ω and ρ photoproduction small f_2 exchange double helicity flip contribution required along with dominant single halicity flip
  - For isovector a_2 exchange only sigle helicity flip occurs





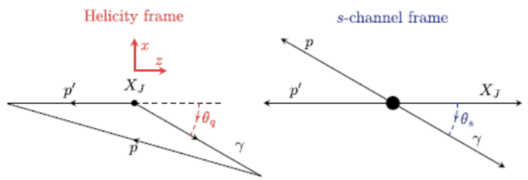
HWSG Updates

Moments and beam asymmetries in ηπ photoproduction at GlueX

V. Mathieu et al. PRD 100 (2019)

- Motivation
  - Searching for exotic hybrids in the $\eta^{(\prime)}\pi$ channels
  - Description of data to be taken at JLab
  - Testing the sensitivity of the observables to the exotic P-wave
  - Testing the s-channel helicity conservation

- Frames used:



- s-channel frame is obtained from helicity frame by boosting the $\pi\eta$ system along the z-axis (which is directed opposite to recoil momentum)
- Cross section:

$$I(\Omega,\Phi) \equiv \frac{d\sigma}{dt\, dm_{\eta\pi^0}\, d\Omega\, d\Phi} = \kappa \sum_{\substack{\lambda\lambda' \\ \lambda_1\lambda_2}} A_{\lambda;\lambda_1\lambda_2}(\Omega)\rho^{\gamma}_{\lambda\lambda'}(\Phi)A^{*}_{\lambda';\lambda_1\lambda_2}(\Omega),$$

- Explicit form:

$$I(\Omega,\Phi) = I^0(\Omega) - P_\gamma I^1(\Omega)\cos 2\Phi - P_\gamma I^2(\Omega)\sin 2\Phi,$$

- Resonances included in the model: $\mathbf{a_0(980)}$, $\mathbf{\pi_1(1600)}$, $\mathbf{a_2(1320)}$ and $\mathbf{a'_2(1700)}$
- They are parametrized by Breit-Wigners: $\Delta_R(m_{\eta\pi}) = \frac{m_R\Gamma_R}{m_R^2 - m_{\eta\pi}^2 - i m_R\Gamma_R}$

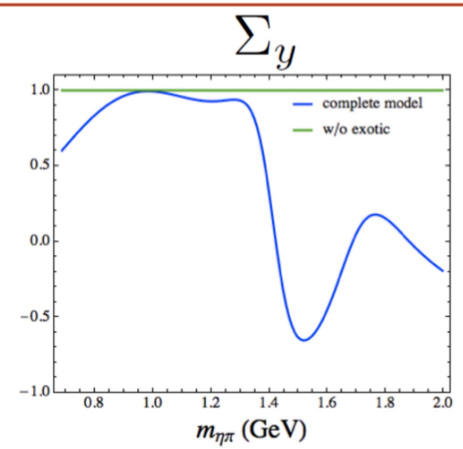
Beam Asymmetries

VM et al (JPAC), PRD100 (2019) 4

$$\Sigma_y = \frac{1}{P_\gamma}\frac{I(\Omega_y,0) - I(\Omega_y,\frac{\pi}{2})}{I(\Omega_y,0) + I(\Omega_y,\frac{\pi}{2})} = -\frac{I^1(\Omega_y)}{I^0(\Omega_y)}$$

Intensities can be computed from moments:

$$I^0(\Omega_y) = H^0(00) - \frac{5}{2}H^0(20) - 5\sqrt{\frac{3}{2}}H^0(22) + \frac{27}{8}H^0(40) + \frac{9}{2}\sqrt{\frac{5}{2}}H^0(42) + \frac{9}{4}\sqrt{\frac{35}{2}}H^0(44)$$



HWSG Updates

N* in inclusive electron scattering

A. N. Hiller Blin et al. PRC 100 (2019)

- Motivation
  - Evaluating the resonant contributions to the inclusive electron-proton scattering observables
  - Employing the $\gamma_v pN^*$ electrocouplings obtained in exclusive reaction studies in CLAS
  - Obtaining virtual photon and electron scattering cross sections and F_2 structure function
- Resonances included in the analysis

N^*	M_r (MeV)	Γ_r (MeV)	L_r	$\beta_{\pi N}$	$\beta_{\eta N}$	$\beta_{r.}$	X (GeV)
$\Delta(1232)\,3/2^+$	1232	117	1	1.00	0	0	
$N(1440)\,1/2^+$	1430	350	1	0.65	0	0.35	0.3
$N(1520)\,3/2^-$	1515	115	2	0.60	0	0.40	0.1
$N(1535)\,1/2^-$	1535	150	0	0.45	0.42	0.13	0.5
$\Delta(1620)\,1/2^-$	1630	140	0	0.25	0	0.75	0.5
$N(1650)\,1/2^-$	1655	140	0	0.60	0.18	0.22	0.5
$N(1675)\,5/2^-$	1675	150	2	0.40	0	0.60	0.5
$N(1680)\,5/2^+$	1685	130	3	0.68	0	0.32	0.2
$\Delta(1700)\,3/2^-$	1700	293	2	0.10	0	0.90	0.22
$N(1710)\,1/2^+$	1710	100	1	0.13	0.30	0.57	0.5
$N(1720)\,3/2^+$	1748	114	1	0.14	0.04	0.82	0.5
$N'(1720)\,3/2^+$	1725	120	1	0.38	0	0.62	0.5

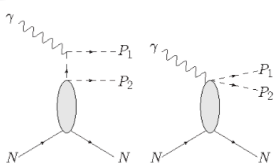
Polarization in P_c photoproduction

D. Winney et al. PRD 100 (2019)

- Motivation
  - Observation a resonance like structures $P_c(4380)$, $P_c(4449)$ in the $J/\psi pK^-$ channel of Λ^0_b decay
  - The prospect to observed these structures in photoproduction experiments at CLAS12 and GlueX
  - Photoproduction is especially advantageous environment for studying the J/ψ p system because:
    - Background is supposed to be smaller that in hadronic decays
    - There is no "third particle"
  - Test of spin parity assignments: $3/2^-$ for the lighter and $5/2^+$ for the heavier resonance

Photoproduction of pseudoscalar pairs

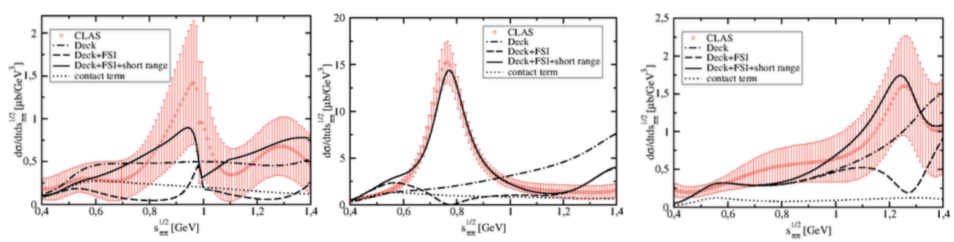
Ł. Bibrzycki et al. Phys. Lett. B 789 (2019)



- Deck + „short range" approach to P_1P_2N photoproduction
- Photon dissociates to $\pi+\pi$-. One π in a pair is on shell, other one is brought on shell by scattering of N
- πp scattering is described in terms SAID PWA
- P_1P_2N can be: π+ π-p, π+ π0n (in theory also K+K-p,… but we don't have reliable KN PW amplitudes)
- General form of unitary amplitude: $M = M_{diffuse} e^{i\delta_{\pi\pi}} \cos\delta_{\pi\pi} + M_{compact} e^{i\delta_{\pi\pi}} \sin\delta_{\pi\pi}$
- Charge πp amplitudes constructed from isospin SAID partial waves

  $A(\pi^+p)=A(3/2)$ $A(\pi^-p)=1/2[A(3/2)+2A(1/2)]$

- Partial wave mass distributions for π+π- photoproduction



- Similar analysis for $\pi^+ \pi^0$ n final state is underway

HWSG Updates

Studies of the g12 trigger efficiency

Ken Hicks, Utsav Shrestha, Joey Rowley (Ohio U.)

CLAS Collaboration Meeting

November 14, 2019

Overview

- The g12 trigger was complicated. Many reactions (2-prong, 3-prong, leptons, etc) were programmed to trigger DAQ.
  - Similar to g11 and other experiments
- The trigger efficiency is needed for cross sections, but how to calculate this efficiency is not straight-forward
  - CLAS publications by g11 included a ~16% correction for trigger efficiency
  - The g12 procedures document did NOT give an approved algorithm
  - Several approaches are known: Johann, MK, FSU
  - This needs to be documented, approved, and added to the g12 procedures
- Here, we start with the FSU procedure and improve upon it.

What was the g12 trigger? It changed.

Part 1: runs < 56650

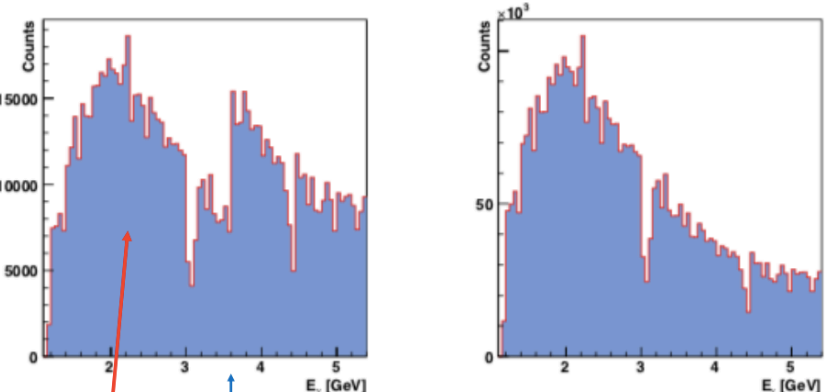
g12 runs 56363–56594, 56608–56647			
bit	definition	L2 multiplicity	prescale
1	MORA·$(ST\times TOF)_1$·(ST×TOF)	–	1
2	MORA·$(ST\times TOF)_2$·(ST×TOF)	–	1
3	MORA·$(ST\times TOF)_3$·(ST×TOF)	–	1
4	MORA·$(ST\times TOF)_4$·(ST×TOF)	–	1
5	MORA·$(ST\times TOF)_5$·(ST×TOF)	–	1
6	MORA·$(ST\times TOF)_6$·(ST×TOF)	–	1
7	ST×TOF	–	1
8	MORA·(ST×TOF)×2	–	1
11[a]	MORB·(ST×TOF)×2	–	1
12	(ST×TOF)×3	–	1

Part 2: runs > 56650

g12 runs 56595–56607, 56648–57323			
bit	definition	L2 multiplicity[a]	prescale
1	MORA·(ST×TOF)	1	1000/300[b]
2	MORA·(ST×TOF)×2	2/–[c]	1
3	MORB·(ST×TOF)×2	2	1
4	ST×TOF	1	1000/300
5	(ST×TOF)·ECP×2	1	1
6	(ST×TOF)·(EC×CC)	2	1
7	MORA·(ST×TOF)·(EC×CC)	–	1
8	MORA·(ST×TOF)×2	–	1
11	(EC×CC)×2	–	1
12	(ST×TOF)×3	–	1

Trigger bit 11 starting with run 56519: MORA = “Master OR of tagger, range A” = tagger $E\gamma$ > 3.6 GeV (before 56519)
Master OR split into two halves starting with 56519.

Compare: 2-prong and 3-prong events (g12)

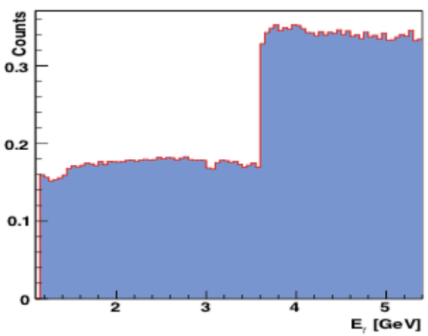


Why are there ANY events < 3.6?

Discontinuity at 3.6 GeV for 2-sector events (due to trigger)

HWSG Updates

Ratio of 2-sector to 3-sector triggers: FSU



This ratio is only for the reaction:
$\gamma p \to p \pi^+\pi^-$

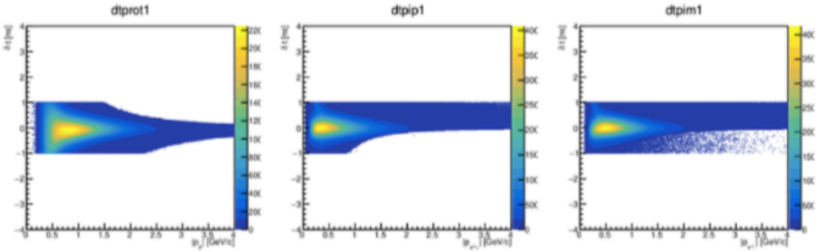
We will see that this ratio depends on the final state particles.

The problem with complicated triggers

- Due to the high luminosity, and a broad (~150 ns) tagger coincidence window, there were 10-20 tagger hits per event
- Accidental coincidences between two-sector hits (associated with a photon BELOW 3.6 GeV) and a chance photon ABOVE 3.6 GeV.
  - The trigger efficiency for two-sector events with $E\gamma$ < 3.6 GeV can be determined empirically for a nearly-constant beam current.
  - Some 3-prong events have 2-prongs in one sector -> trigger is 2-sector
- Bottom line: by following careful procedures, the trigger correction can be done.

Trigger Map $p\pi^+\pi^-$

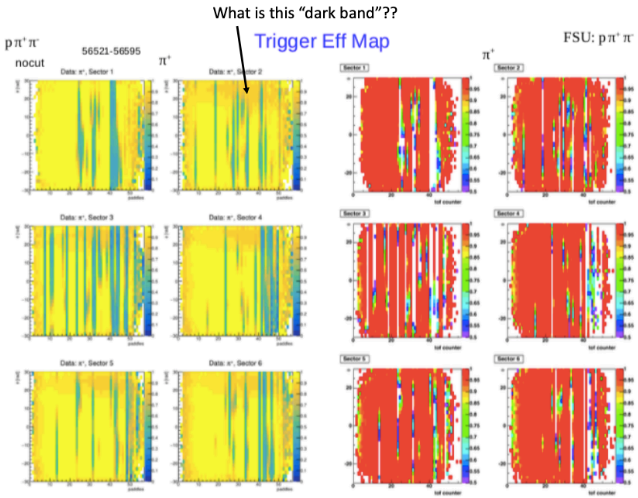
- Photon selection → 1 photon case
- PID → p, π^+, π^-. Straight cuts of 1 ns on Momentum Vs Timing plots were made for particle identification (Shown below).
- The run number selected were 56521 – 56595, same trigger set up.
- Trigger total and Trigger Hit was obtained.
- Trigger efficiency map was plotted as the ratio of the hit to total.
- Egam ratio of 2-sec to 3-sec was obtained for pid cut and pidfidn-cut.



The problem with TOF counters

- A common discriminator level was used as the trigger threshold for all TOF counters.
  - These detectors were not perfectly gain-matched.
  - PROBLEM: some TOF counters showed an inefficiency for triggering.
  - SOLUTION: develop a trigger efficiency map, apply this to the Monte Carlo
- In the data analysis, where there are clearly three tracks that can be matched to an exclusive reaction, the trigger didn't always fire!
  - This is due to one particle hitting a "weak" TOF counter
  - With enough statistics, one can create a MAP of efficiency per TOF vs. ϕ.
  - Maps depend on particle type! (protons deposit more energy than pions)

HWSG Updates

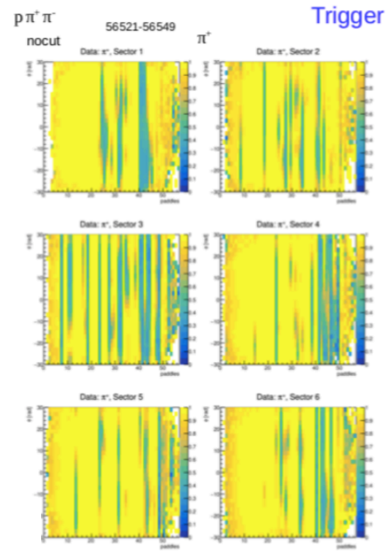


Left side: Ohio
Right side: FSU

Same reaction
Same g12 runs
Different plotting
(color scale)

→We could reproduce maps (with much help from Zulkaida!)

Similar for π^-, p

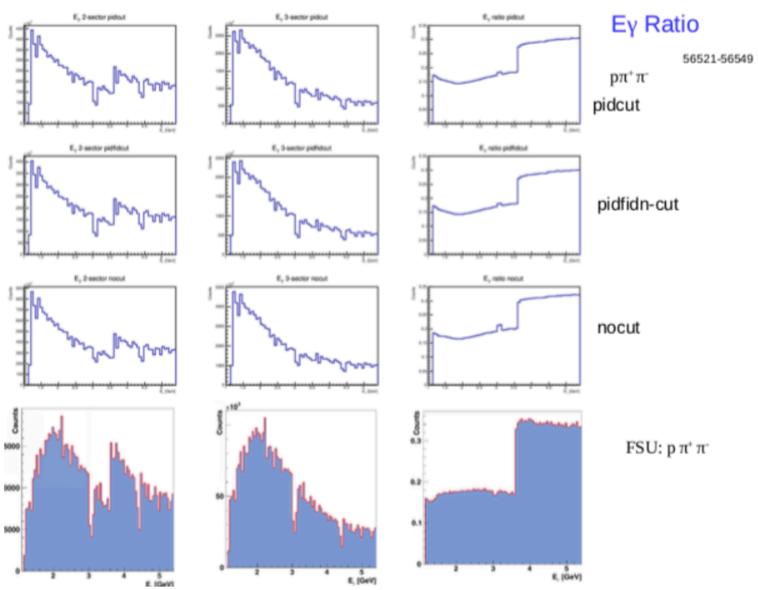


Change the range of runs:
56521 – 56549
"dark band" is gone!?

Something strange happened to the trigger efficiency in sectors 2-6 for runs > 56550

From the g12 analysis note by Andreas Celantano (under review) where a single-charged particle was detected: mismatch between the ST-SC track match done by the FPGA. Runs 56573-56747 only!

This effect would be taken into account by the trigger efficiency method used by FSU & Ohio.



2-sector/3-sector ratio depends on the cuts!

We get almost the same results as FSU, but not exact. To get exact, we need the same cuts.

Next step: study other reactions

- Utsav Shrestha: $\gamma p \to K^+ \pi^+ \pi^-$ (n).
- Joey Rowley: $\gamma p \to K^+ \Lambda$, followed by $\Lambda N \to \Lambda N$ (final state: $pp\pi^-$).
- Kevin Ward (& Will Phelps): $\gamma p \to$ p p anti-p.

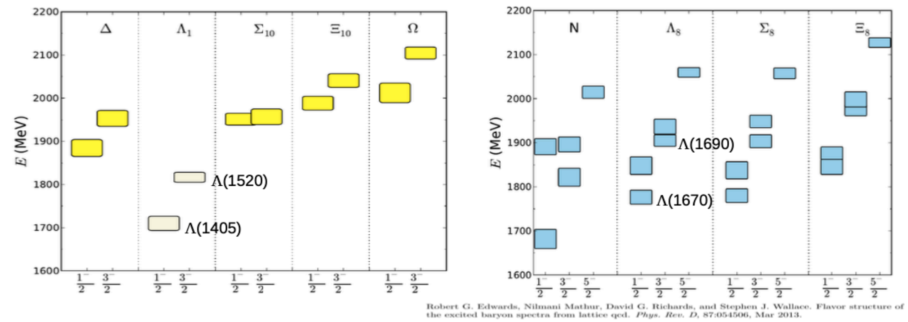
- All above reactions have 3-particle final states.
  - Each case needs its own trigger efficiency map & 2-sector/3-sector ratio.
  - Same procedures followed in each case.

Photoproduction of Λ* Resonances at CLAS

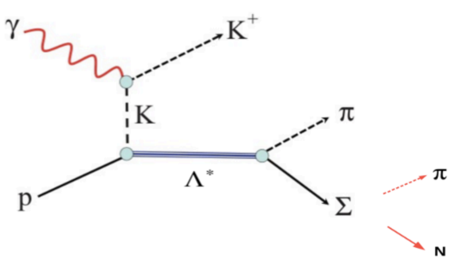
CLAS Collaboration Meeting
November October 12 – 15, 2019

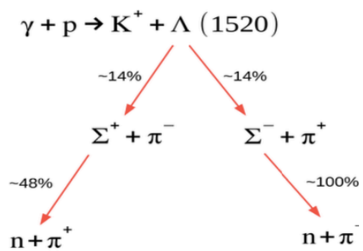
Utsav Shrestha and Ken Hicks
Ohio University

Baryon Spectra from Lattice QCD



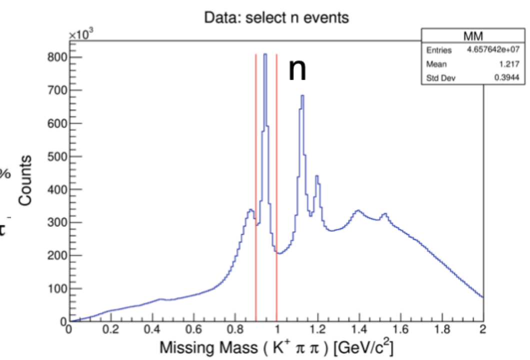
- Missing baryon resonances play important role to explore the fundamental degrees of freedom inside hadrons.
- Study of quark dynamics to determine properties of hadrons that are responsible for spectrum of hadrons.





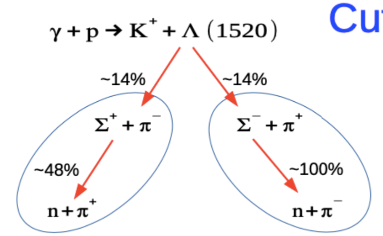
$\gamma + p \rightarrow K^+ + \Lambda^*$ $\Lambda^* \rightarrow \Sigma^+ + \pi^-$ $\Lambda^* \rightarrow \Sigma^- + \pi^+$

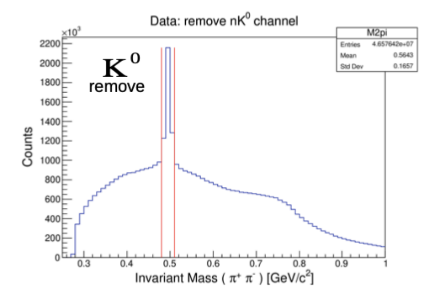
- Photo-prodution off a proton creates a K^+-meson and a Λ^*.
- Λ^* decays by $\Sigma\pi$ channel. Σ^+ gives off a n & π^+, Σ- gives off a n & π^-.
- The final particles detected are K^+, π^+ & π^-.



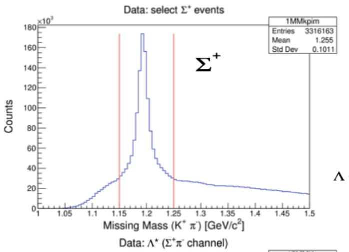
$0.9 < MM(K^+\pi\pi) < 1.0$ [GeV]

Cuts

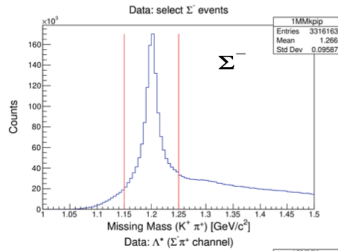




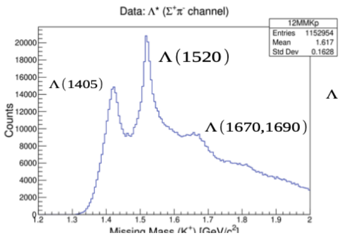
HWSG Updates



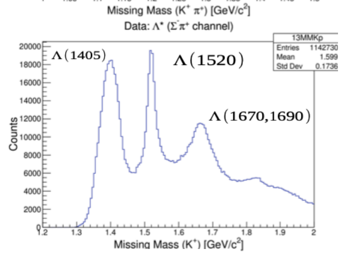
$\Lambda(1520) \rightarrow \Sigma^{+} + \pi^{-}$

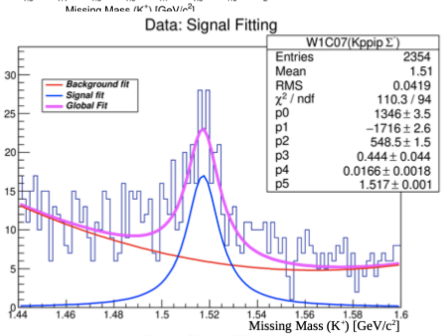


Cuts



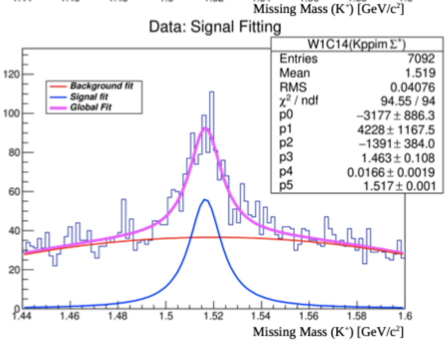
$\Lambda(1520) \rightarrow \Sigma^{-} + \pi^{+}$



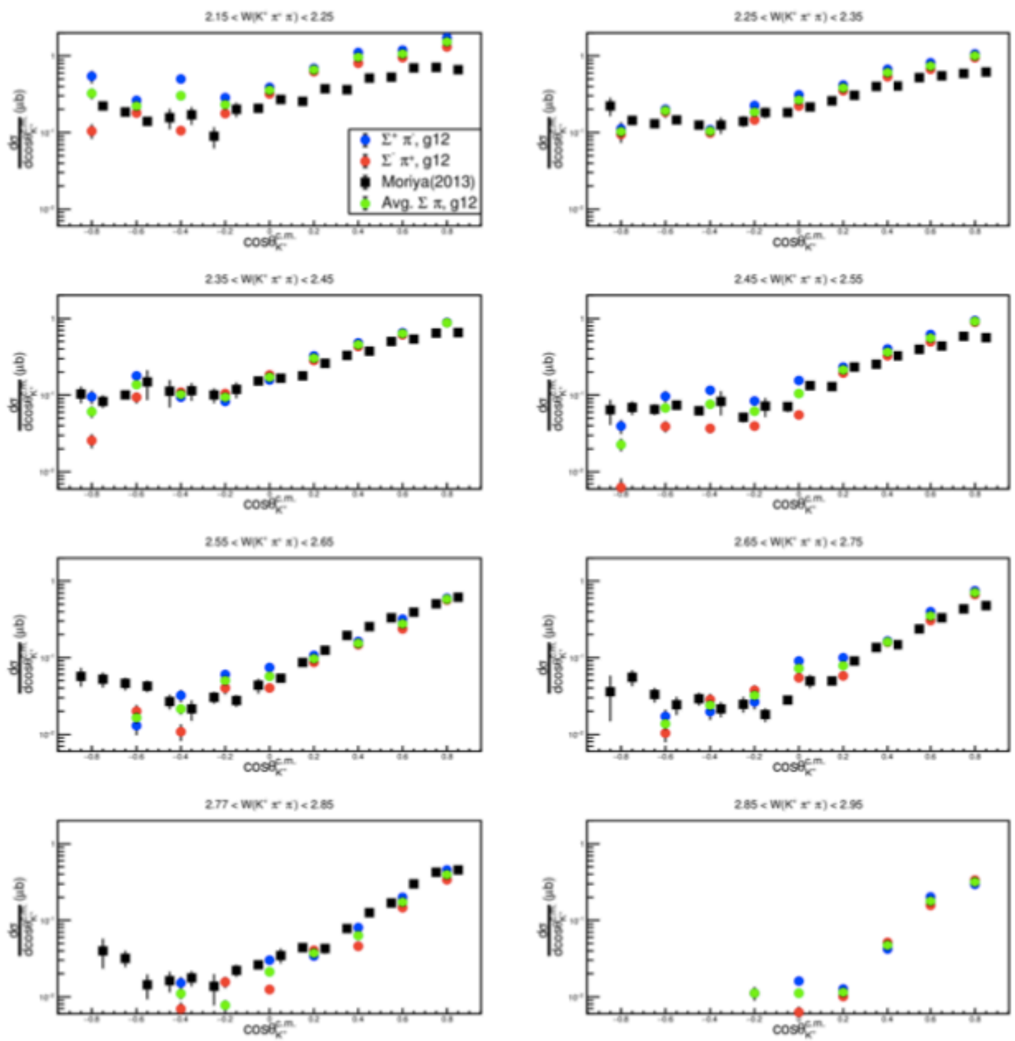


$\Lambda(1520) \rightarrow \Sigma^{-} + \pi^{+}$

Λ(1520): Yield & Acceptance



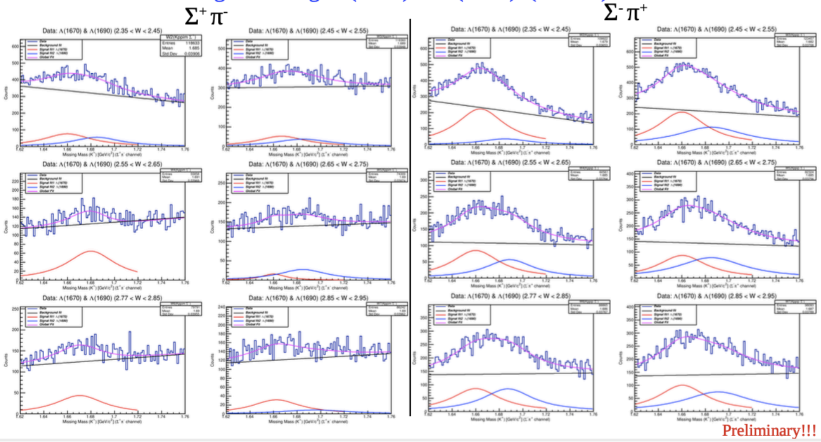
$\Lambda(1520) \rightarrow \Sigma^{+} + \pi^{-}$



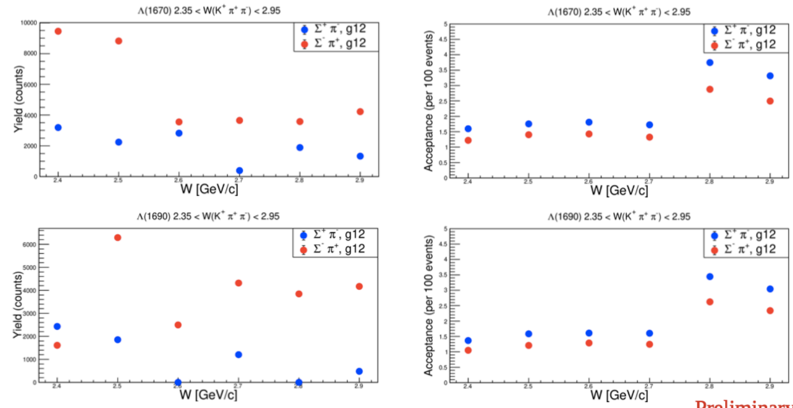
HWSG Updates

Signal Fitting: Λ(1670) & Λ(1690) (W bins)

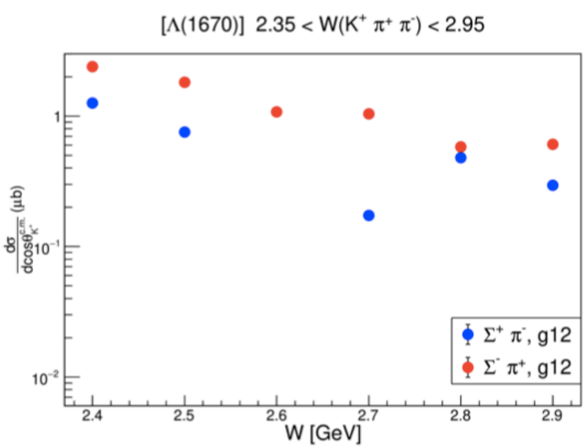
$\Sigma^+\pi^-$ $\Sigma^-\pi^+$

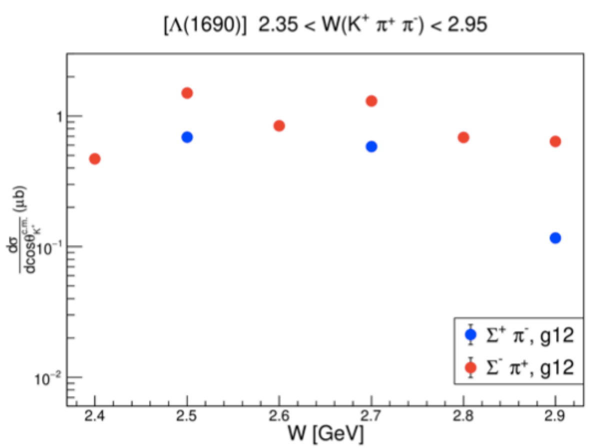


Yield & Acceptance: Λ(1670) & Λ(1690) (W bins)

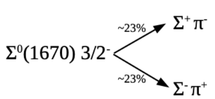


Differential Cross-section: Λ(1670) & Λ(1690) (W bins)





- The Λ(1520) cross section matches with the CLAS g11 data.
- Λ(1520) cross sections for higher W value will be obtained.
- First attempt at Λ(1670) & Λ(1690) peaks are shown.
- We believe that there is an asymmetry to the branching ratio of the two channels due to some interference of other resonances.



Preliminary!!!

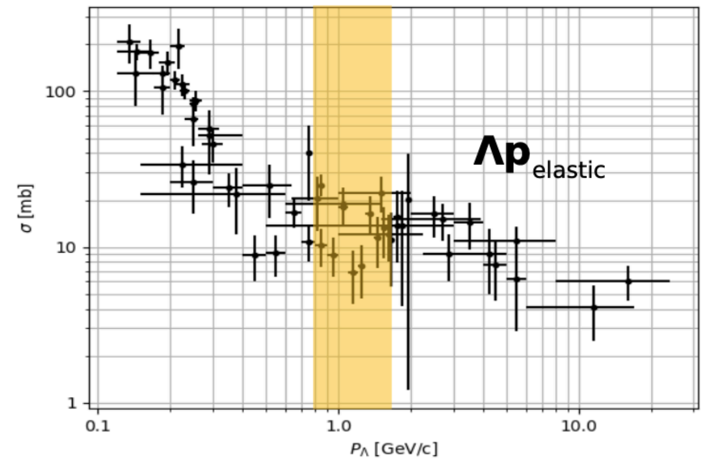
A Study of Λ-N Scattering using the g12 experiment

CLAS Collaboration

Joey Rowley, Ken Hicks (Ohio University)

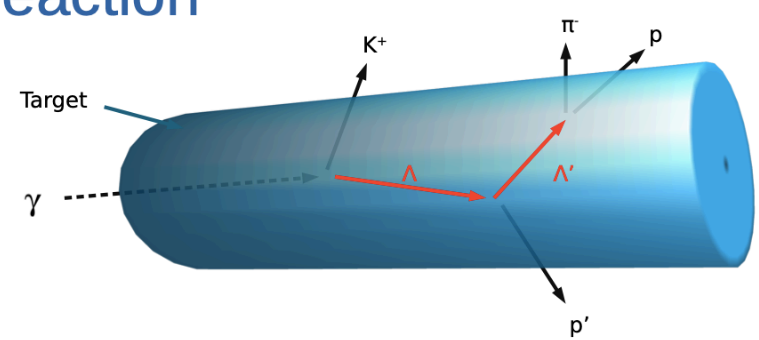
Motivation

- Currently very little data for ΛN
  < 1300 events
- Entirely from Bubble Chamber
- ΛN scattering is important to understand the interior of neutron stars. (Haidenbauer and Meissner, PRC 72, 044005 (2005).)



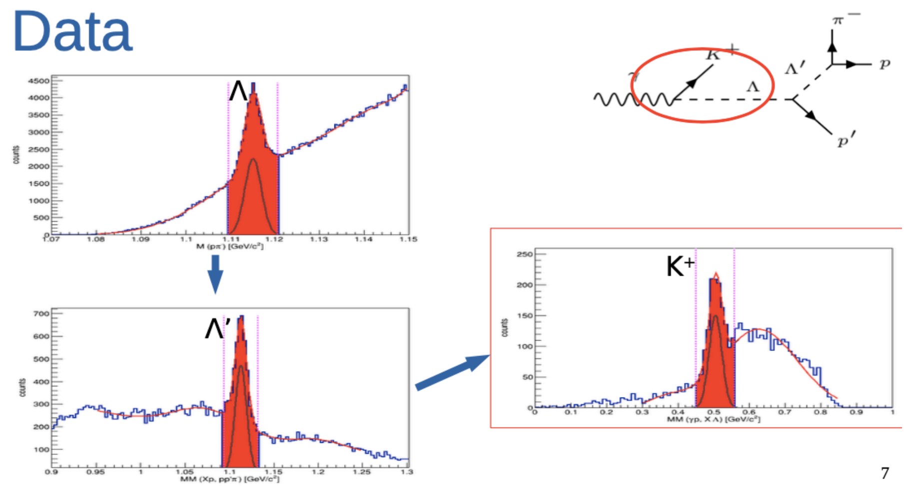
2

Reaction



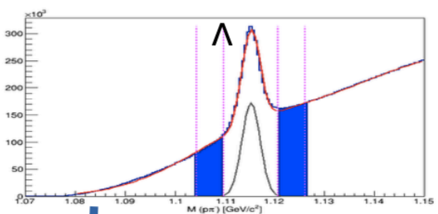
- Liquid Hydrogen Target
- p, p', π^- detected
- Λp scatter elastically

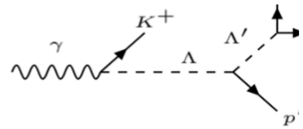
Data

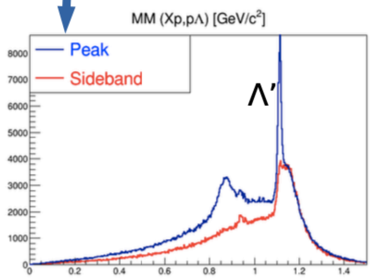


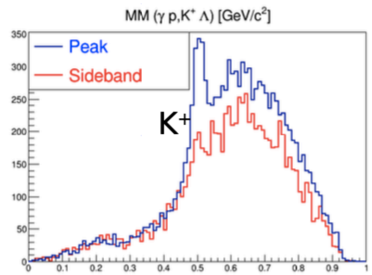
7

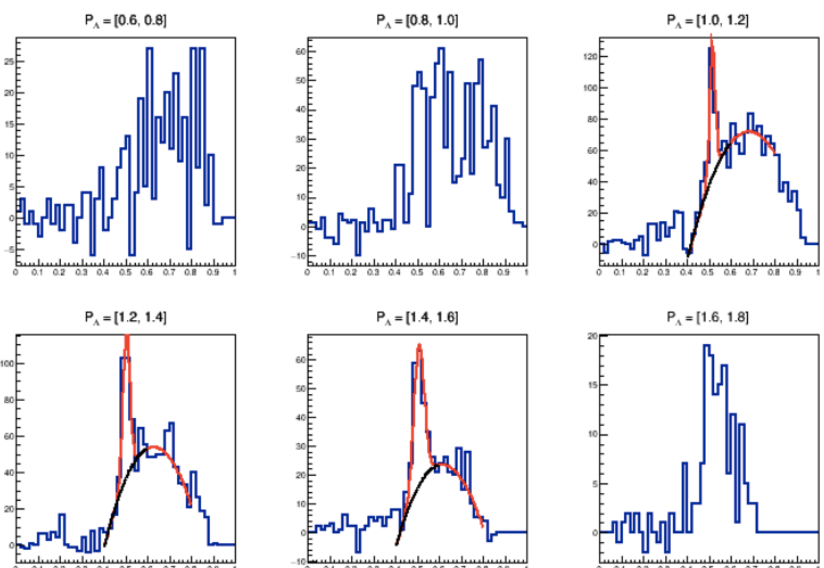
HWSG Updates



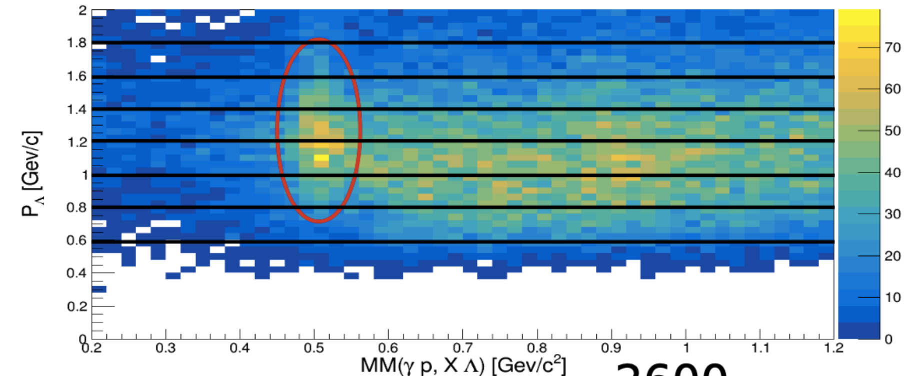






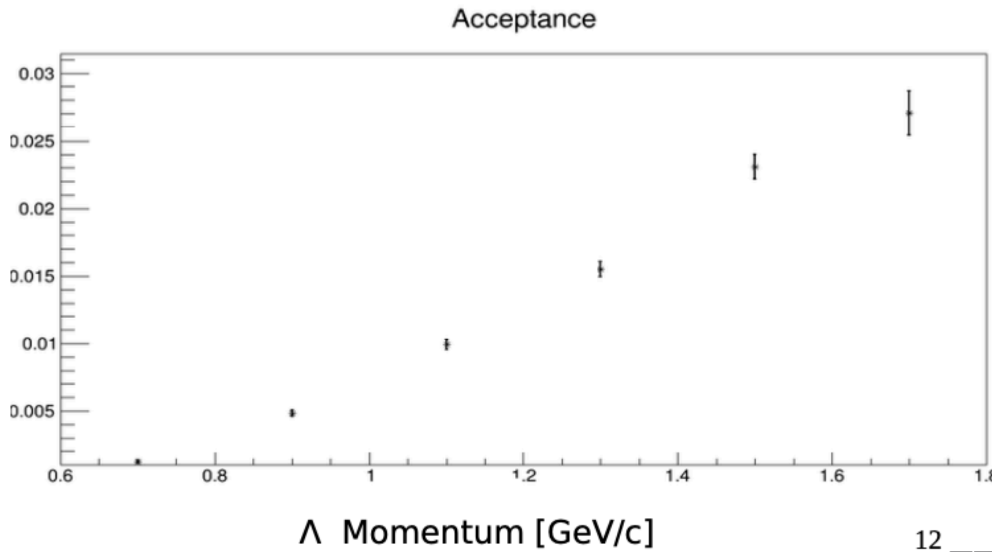


Yield



~2600 events

10



12

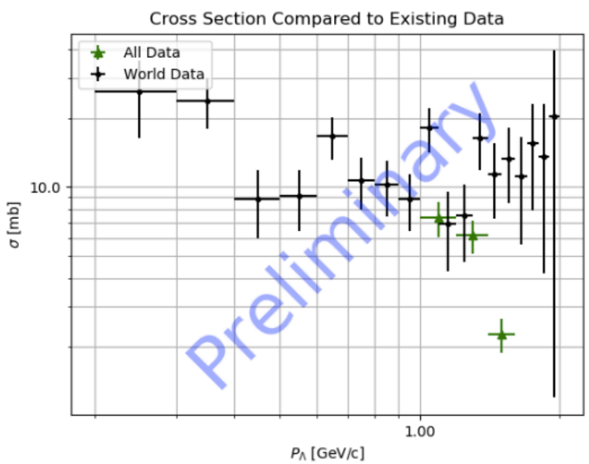
HWSG Updates

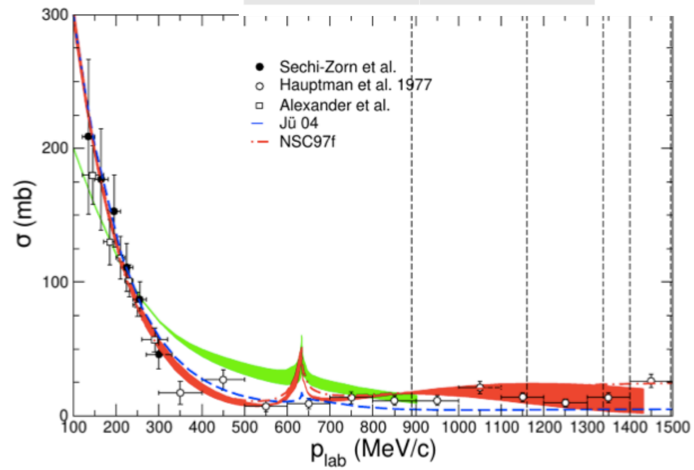
$$L_\Lambda(E_\Lambda) = \frac{\rho_T * N_A * l}{M} * N_\Lambda(E_\Lambda)$$

- ρ_T: density of the target
- N_A: Avogadro's number
- M: molar mass of Hydrogen
- l: travel distance of Λ
- $N_\Lambda(E_\Lambda)$: yield in a certain energy range

Cuts	Error (%)
Vertex	2.8
M (p π⁻)	10.4
MM (Xp, Λp)	8.1
PID	0.2
pp events	8.7
Fit Function	12.0

Total Systematic: ~20%

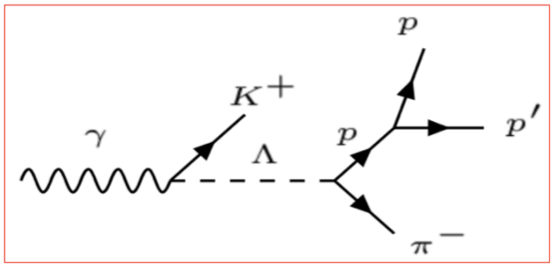


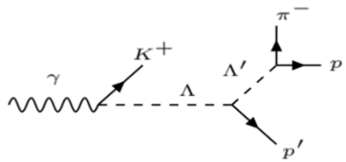


Theoretical prediction from Haidenbauer extended to our momentum range (unpublished). 15

HWSG Updates

Why Low Cross Section? pp → pp scattering





- pp → pp events can also result in the same final state.

Summary

- Double the statistics as previous experiments
- Previous data could be excluding pp-scattering events
  - evidence to suggest that it does
- There is some agreement to theory but more work needs to be done.
- Results are still preliminary.

HWSG Updates

Beam Spin Asymmetries from ep->epπ⁰ in the resonance region

Evgeny Isupov (MSU), Nick Markov (JLab)
Kyungseon Joo (UConn), Victor Mokeev (JLab)

Insight into the Strong QCD from the Synergy between Experiment, Phenomenology, and Theory

Experiment | **Theory**

Observables from the Experiments with the EM Probes:

- Differential cross sections
- Beam asymmetry
- Target asymmetries
- Recoil asymmetries
- Combinations of 2-fold and 3-fold asymmetries

Phenomenology:

- Amplitude analyses
- Reaction models

Elastic/Transition form factors
PDFs, PDA,TMD-functions
Compton form factors
Projection of GPD to observables

Strong QCD underlying the hadron generation $\alpha_s \sim 1$

QCD Lagrangian:

$$\mathcal{L}_{QCD} = \bar{\psi}(i \not{D}_a T_a - m)\psi - \frac{1}{4} F_a^{\mu\nu} F_{\mu\nu,a}$$

- Covariant derivative, gluon field tensor

$$D_a^\mu = \partial^\mu + i g A_a^\mu$$
$$F_a^{\mu\nu} = \partial^\mu A_a^\nu - \partial^\nu A_a^\mu - g f_{abc} A_b^\mu A_c^\nu$$

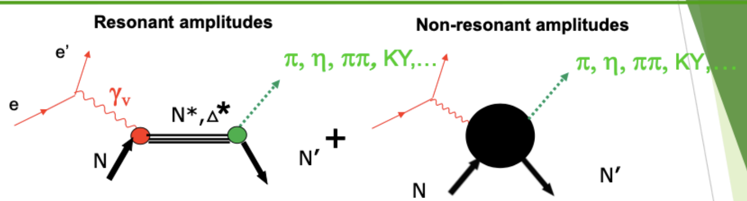
- Color matrices and structure constants

$$[T_a^{(F)}, T_b^{(F)}] = i f_{abc} T_c^{(F)}, \quad (T_a^{(A)})_{bc} = -i f_{abc}$$

- Lattice QCD
- Continuum QCD

Light front quark models
AdS/CFT approaches
χ Quark-Soliton models
Hypercentral quark model
Covariant quark models
....

Extraction of $\gamma_v NN^*$ Electrocouplings from Exclusive Meson Electroproduction off Nucleons



Definition of N* photo-/electrocouplings employed in the CLAS data analyses:

- Real $A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$, $S_{1/2}(Q^2)$

I.G. Aznauryan and V.D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012)

$$\Gamma_\gamma = \frac{k_{\gamma_{N^*}}^2}{\pi} \frac{2M_N}{(2J_r+1)M_{N^*}} \left[|A_{1/2}|^2 + |A_{3/2}|^2 \right]$$

- Consistent results on $\gamma_v pN^*$ electrocouplings from different meson electroproduction channels are critical in order to validate reliable extraction of these quantities.

Single meson electroproduction in the resonance region from Hall-B

		Q^2	W	
JLab/Hall B	$\frac{d\sigma}{d\Omega}(\pi^0 p, \pi^+ n)$	0.16–0.36	1.1–1.38	[8]
	$\frac{d\sigma}{d\Omega}(\pi^0 p)$	0.4–1.8	1.1–1.68	[9]
	$\frac{d\sigma}{d\Omega}(\pi^0 p)$	3.0–6.0	1.1–1.39	[10]
	$A_{LT'}(\pi^0 p)$	0.4, 0.65	1.1–1.66	[11]
	$A_t, A_{et}(\pi^0 p)$	0.252, 0.385, 0.611	1.12–1.55	[12]
	$\frac{d\sigma}{d\Omega}(\pi^+ n)$	0.3–0.6	1.1–1.55	[13]
	$\frac{d\sigma}{d\Omega}, A_{LT'}(\pi^+ n)$	1.7–4.5	1.11–1.69	[14]
	$A_{LT'}(\pi^+ n)$	0.4, 0.65	1.1–1.66	[15]
	$\frac{d\sigma}{d\Omega}(\eta p)$	0.375–1.385	1.5–1.86	[16]
	$\frac{d\sigma}{d\Omega}(\eta p)$	0.17–3.1	1.5–2.3	[17]

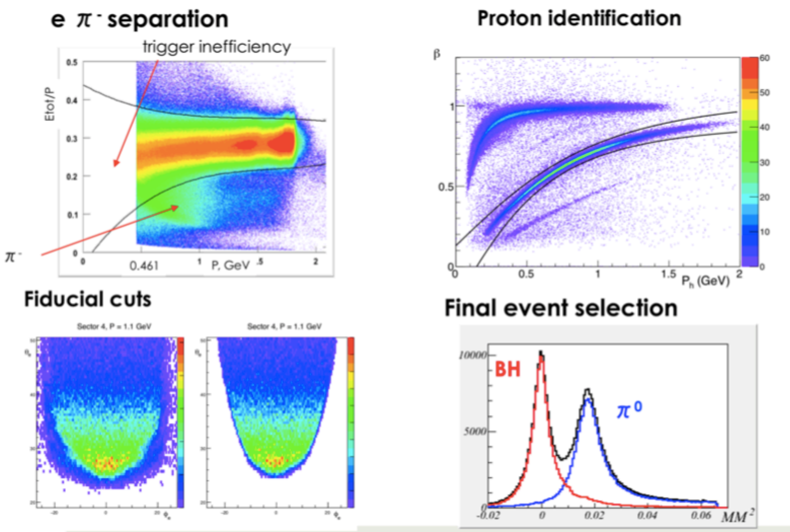
Progress in Particle and Nuclear Physics 67 (2012) 1
I.G. Aznauryan, V.D. Burkert

Exclusive $\pi^0 p$ electroproduction off protons in the resonance region at photon virtualities 0.4 GeV² ≤ Q^2 ≤ 1 GeV²

N. Markov,[8,36,*] K. Joo,[8] V.D. Burkert,[36] V.I. Mokeev,[36] L. C. Smith,[41] M. Ungaro,[36] S. Adhikari,[11]

Same data (E1E) 1.1 < W < 1.8 GeV
Access to second and third N* regions!

HWSG Updates



Polarized Structure Function $\sigma_{LT'}$

$$\frac{d^2\sigma^h}{d\Omega_\pi^*} = \frac{p_\pi^*}{k_\gamma^*}[\sigma_0 + h\sqrt{2\epsilon_L(1-\epsilon)}\ \sigma_{LT'}\ \sin\theta_\pi^*\ \sin\phi_\pi^*]$$

$$A_{LT'} = \frac{d^2\sigma^+ - d^2\sigma^-}{d^2\sigma^+ + d^2\sigma^-} = \frac{\sqrt{2\epsilon_L(1-\epsilon)}\ \sigma_{LT'}\ \sin\theta_\pi^*\ \sin\phi_\pi^*}{\sigma_0}$$

$$A_{LT'} = \frac{A_m}{P_e},$$

$$A_m = \frac{N_\pi^+ - N_\pi^-}{N_\pi^+ + N_\pi^-}$$

We have unpolarized cross sections from the same data.

Polarized Structure Function $\sigma_{LT'}$

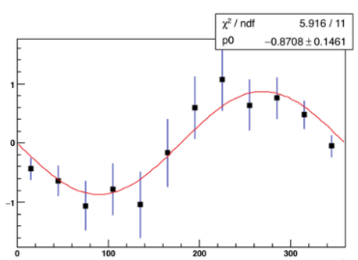
Binning:

28 W-bins from 1.1 to 1.8 GeV, width = 25 MeV
2 Q^2-bins [0.4-0.6] and [0.6-1.0] GeV^2
10 Cos(θ)-bins [-1,1] width = 0.2
12 Φ-bins [0,360] width = 30°

W = 1.66 GeV

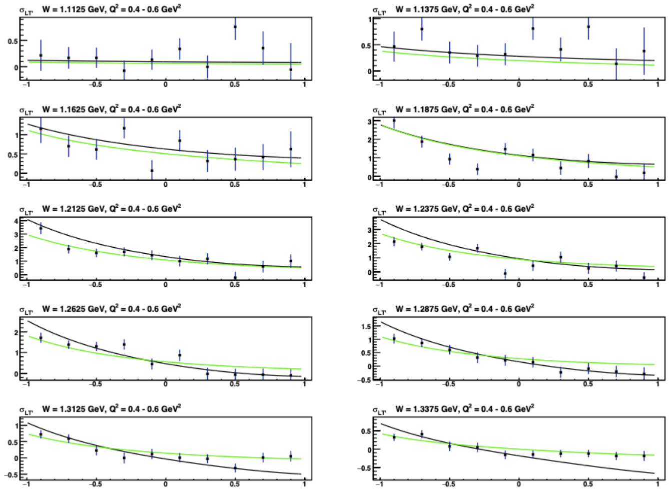
$0.4<Q^2<0.6$ GeV^2

Cos(θ)=-0.9

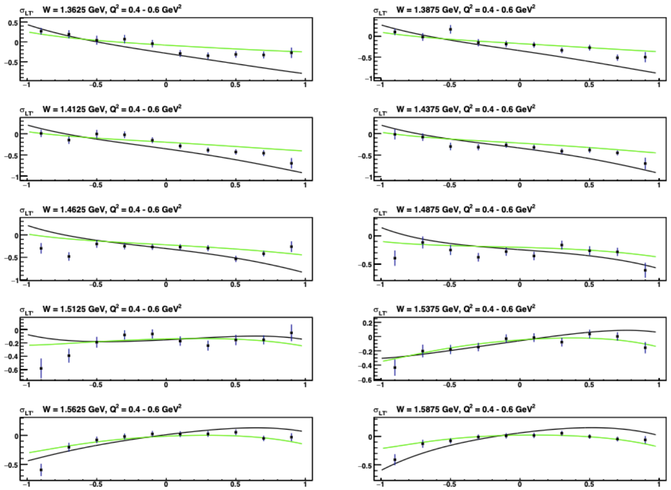


HWSG Updates

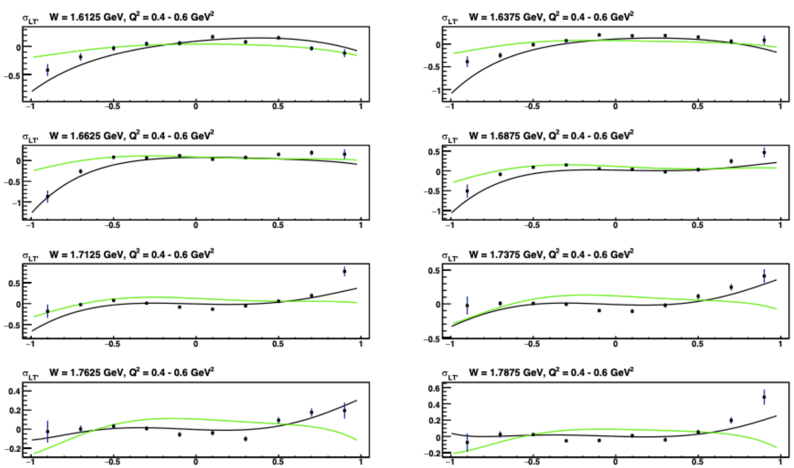
$\sigma_{LT'}$, $0.4<Q^2<0.6$ GeV^2 green-MAID2007, black-UIM



$\sigma_{LT'}$, $0.4<Q^2<0.6$ GeV^2 green-MAID2007, black-UIM

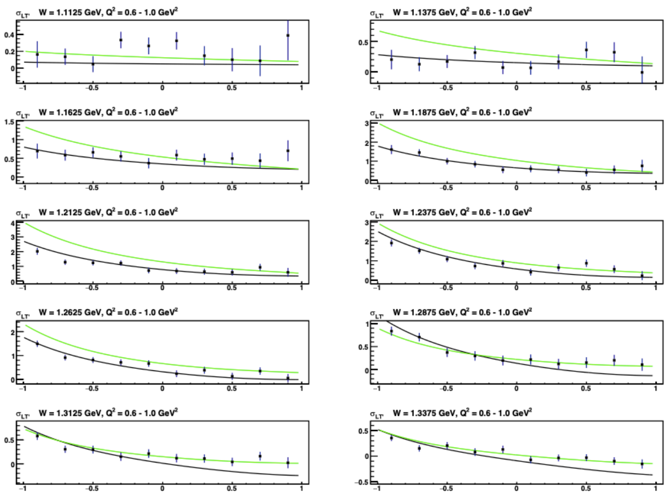


$\sigma_{LT'}$, $0.4<Q^2<0.6$ GeV^2 green-MAID2007, black-UIM

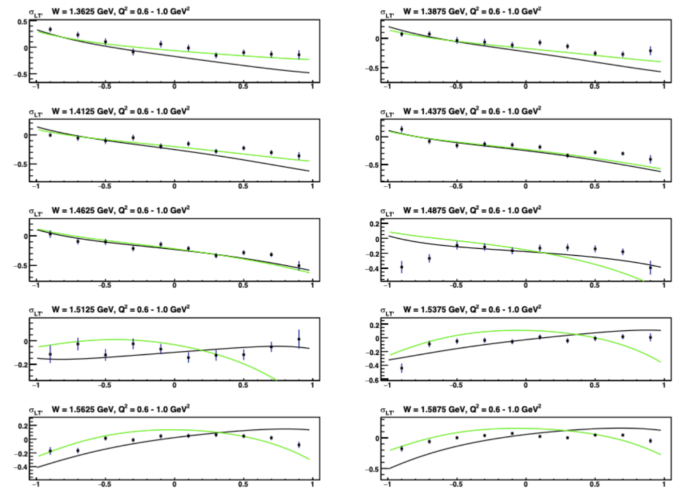


HWSG Updates

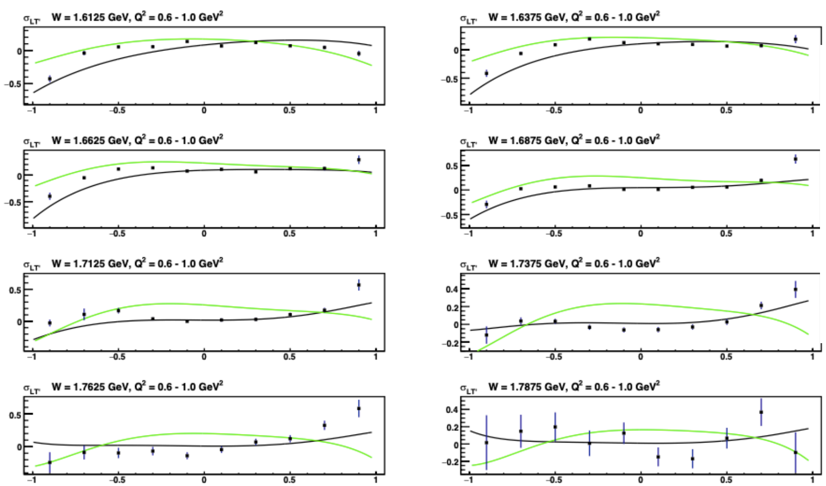
$\sigma_{LT'}$ $0.6<Q^2<1.0$ GeV^2 green-MAID2007, black-UIM



$\sigma_{LT'}$ $0.6<Q^2<1.0$ GeV^2 green-MAID2007, black-UIM



$\sigma_{LT'}$ $0.6<Q^2<1.0$ GeV^2 green-MAID2007, black-UIM



- LP analysis and overall check on the data
- The polarized structure function $\sigma_{LT'}$ was extracted from the CLAS E1E data in the kinematical region

  $0.4 < Q^2 < 1$ GeV^2

  $1.1 < W < 1.8$ GeV
- The combined analysis of polarized and unpolarized data will give us information on electroexcitation amplitudes with focus on the second and third resonance regions.

HWSG Updates

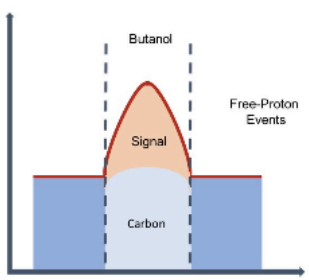
Helicity Asymmetry E for $\gamma p \rightarrow \pi^0 p$ from FROST

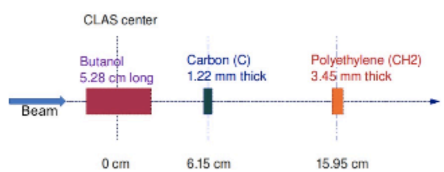
Chan Kim

Igor Strakovsky, William Briscoe, Stuart Fegan

The George Washington University

Butanol & Carbon Targets





- Butanol target (C_4H_9OH) consists of polarized hydrogen (free-nucleons) & unpolarized carbon and oxygen (bound-nucleons)
- Fermi motion of bound-nucleons → negative missing mass M_{π^0}
- Carbon target consists of unpolarized bound-nucleon
- Scale carbon target events & subtract from butanol target events

Helicity Asymmetry E

- Double polarization observable E is the helicity asymmetry of the cross section:

$$E = \frac{\sigma_{3/2} - \sigma_{1/2}}{\sigma_{3/2} + \sigma_{1/2}} \quad \text{for } \frac{3}{2} \; \& \; \frac{1}{2} \text{ are total helicty states}$$

- $\frac{d\sigma}{d\Omega}$ of polarized beam & polarized target for E (theo. & exp.):

$$\left(\frac{d\sigma}{d\Omega}\right)_{\frac{1}{2},\frac{3}{2}} = \frac{d\sigma_0}{d\Omega}(1 \mp (P_z P_\lambda)_{\frac{1}{2},\frac{3}{2}} E) \qquad \left(\frac{d\sigma}{d\Omega}\right)_{\frac{1}{2},\frac{3}{2}} = \frac{N_{\frac{1}{2},\frac{3}{2}}}{A \cdot F \cdot \rho \cdot \Delta x_i}$$

- E is measured via:

$$E = \left[\frac{1}{D_f}\right]\left[\frac{1}{P_z P_\lambda}\right]\left[\frac{N_{\frac{3}{2}} - N_{\frac{1}{2}}}{N_{\frac{3}{2}} + N_{\frac{1}{2}}}\right]$$

D_f = dilution factor

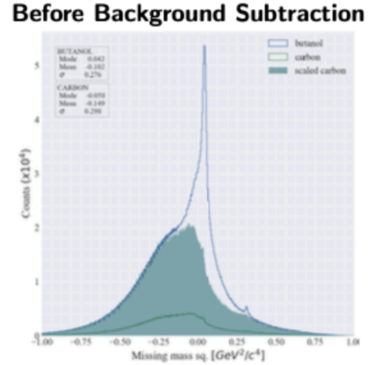
P_z = Polarization of target in $\hat{z}$

P_λ = Polarization of beam

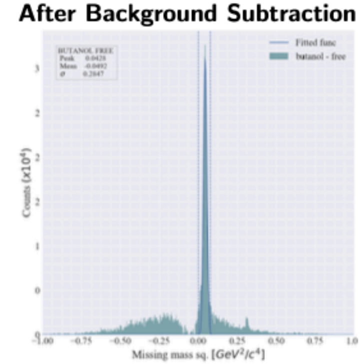
$N_{\frac{3}{2},\frac{1}{2}}$ = # of events

Missing Mass Sq. Selection

Before Background Subtraction



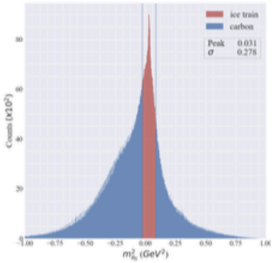
After Background Subtraction

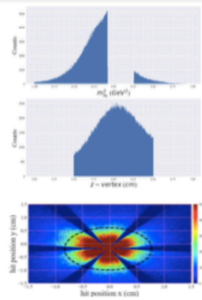


- $M_X^2 = (E_\gamma + m_{p_i} - E_{p_f})^2 - (\mathbf{p}_\gamma - \mathbf{p}_{P_2})^2$
- Butanol free-nucleon region by subtracting scaled carbon from total butanol events
- Select events within $M_X \leq M_{\pi^0} \pm 3\sigma$
- Will perform separate mmsq selection for each E_γ&$\cos\theta_{cm}$ bins

HWSG Updates

Training Data for Hydrogen Contamination





- Tight cut on the $m^2_{\pi_0}$ peak on g9a-Carbon data (or MC sim) as ice
  - Bound-nucleon (fermi p) $\rightarrow$ broader m^2 distribution
  - Sharper peaks from free-nucleon (ice) & Broad background from bound-nucleon (carbon)
- Randomly select events within three criterion:
  - Classified carbon from initial target classification
  - Missing mass squared $\notin [-\sigma, \sigma]$
  - Z-vertex position $\in [5.5, 6.5]$
  - Events within target cup (r=7.5mm)

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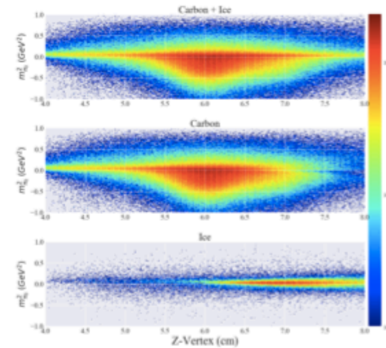
Final Result of ML: ICE vs CARBON



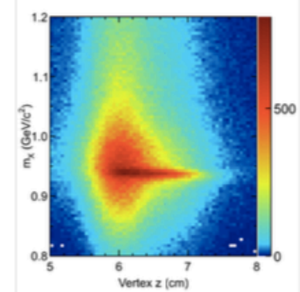
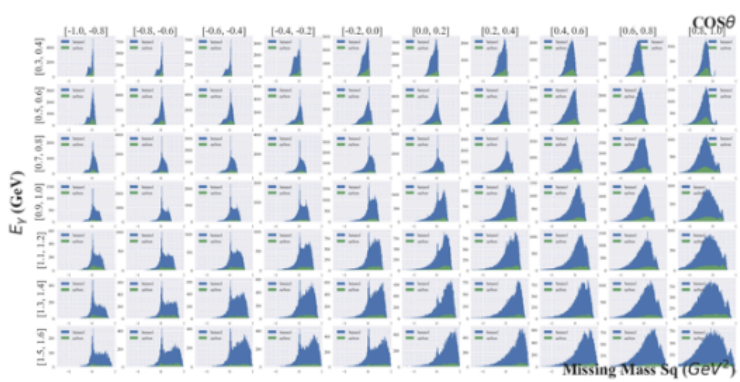


Figure 3: Missing-mass distribution as a function of the MVRT z vertex of the π+. The shape of the missing-mass distribution strongly changes with z. Event selection: $p_\pi > 0.2$ GeV/c and $\theta_\pi > 20°$.

[Result from USC for $\gamma p \rightarrow \pi^+ n$]

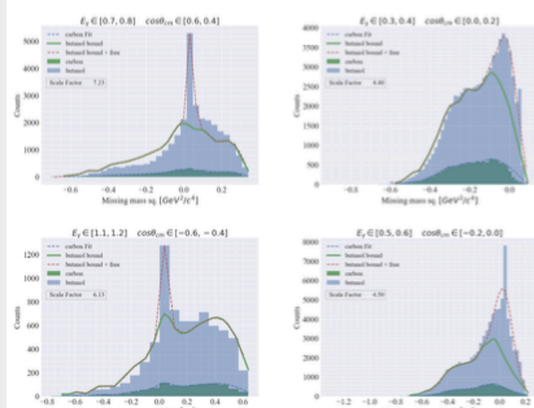
- Classified ice events from Carbon target in z-vertex $\in$ [6.0, 7.5]cm
- It is likely that ice was formed in 20 K heat shield in between Carbon and Polythene targets.

Scale Factor ($\frac{N_{C_4H_9OH}}{N_C}$) & Dilution Factor



- As $E_\gamma \uparrow$, more interactions in butanol target than carbon
- $D_f\big|_{\text{low lim}} = \frac{\text{free H in butanol}}{\text{total nucleon in butanol}} = \frac{10}{74} \cong 0.135$
- $D_f(E_\gamma, \theta_{cm}) = \frac{N_{B,f}}{N_{B,tot}} \cong 1 - \frac{s(E_\gamma) \times N_C(E_\gamma, \theta_{cm})}{N_{B,tot}(E_\gamma, \theta_{cm})}$

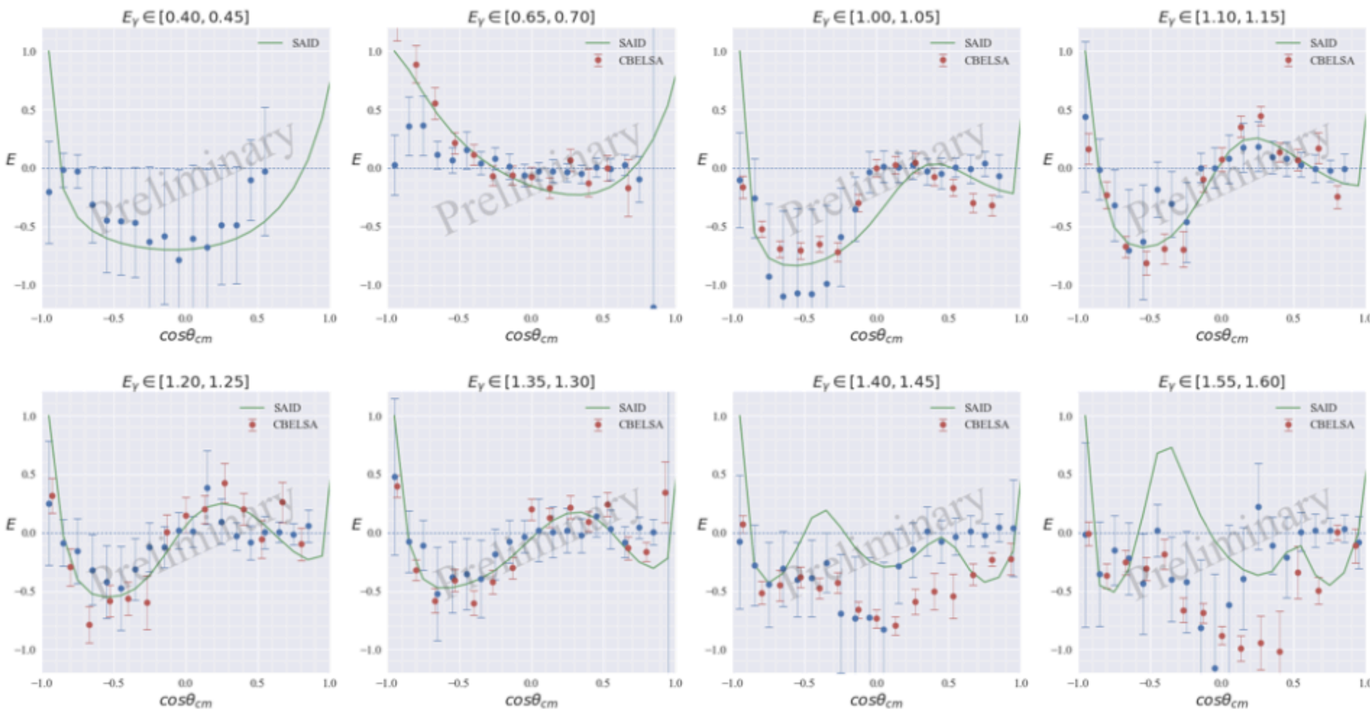
Scale Factor ($\frac{N_{C_4H_9OH}}{N_C}$)



- Fit carbon with splines polynomials
- Splines + Gaussian to fit butanol
- Extract scale factor

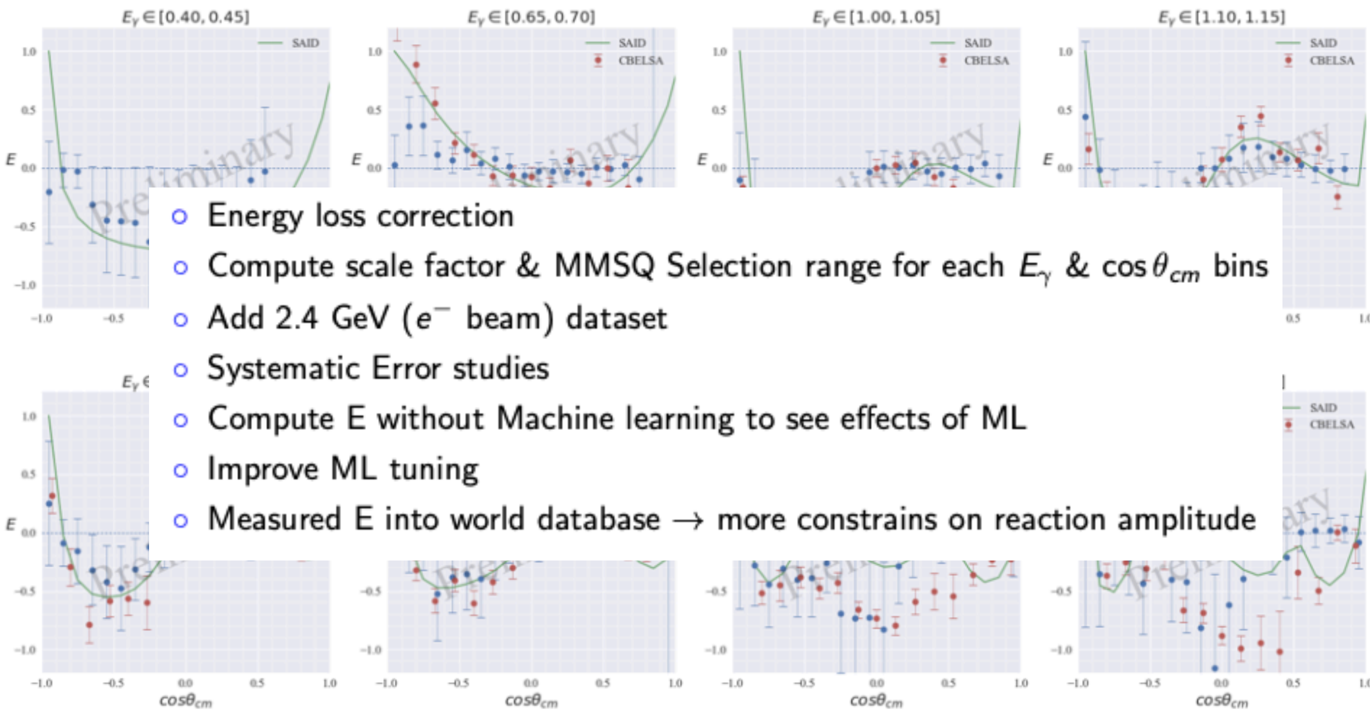
$$B(x) = \alpha C(x) + S(x)$$
$$C(x) = p_2(x_0, \cdots, x_i)$$
$$S(x) = A \exp\left[-\frac{(x - m_0^2)^2}{2\sigma^2}\right]$$

HWSG Updates



- $E = \left[\frac{1}{D_f}\right] \left[\frac{1}{P_\gamma P_T}\right] \left[\frac{N_{\frac{3}{2}} - N_{\frac{1}{2}}}{N_{\frac{3}{2}} + N_{\frac{1}{2}}}\right]$
- Measured E comparison to SAID Partial Wave Analysis predictions & CBELSA measurements
- Large error from low photon polarization (20% - 83%) & incomplete scale factor calculation

HWSG Updates



- Energy loss correction
- Compute scale factor & MMSQ Selection range for each E_γ & $\cos\theta_{cm}$ bins
- Add 2.4 GeV (e^- beam) dataset
- Systematic Error studies
- Compute E without Machine learning to see effects of ML
- Improve ML tuning
- Measured E into world database $\rightarrow$ more constrains on reaction amplitude

- $E = \left[\frac{1}{D_f}\right]\left[\frac{1}{P_\gamma P_T}\right]\left[\frac{N_{\frac{3}{2}} - N_{\frac{1}{2}}}{N_{\frac{3}{2}} + N_{\frac{1}{2}}}\right]$
- Measured E comparison to SAID Partial Wave Analysis predictions & CBELSA measurements
- Large error from low photon polarization (20% - 83%) & incomplete scale factor calculation

HWSG Updates

Measurement of Polarization Observables for the reaction $\gamma p \to K^0\Sigma^+$

Frank Gonzalez

Florida State University, Tallahassee, FL

- The C_x and C_z double polarization observables allow for a characterization of the transferred polarization from incident beam to recoiling hyperon along the orthonormal axes in the scattering plane.

Spin-Dependent Cross-Section for $K^0\Sigma^+$ Photoproduction

$$\rho_Y \frac{d\sigma}{d\Omega_{K^+}} = \frac{d\sigma}{d\Omega_{K^+}}\bigg|_{\text{unpol}} \{1 + \sigma_y P + P_\odot(C_x\sigma_x + C_z\sigma_z)\}$$

$$\rho_Y = (1 + \vec{\sigma} \cdot \vec{P}_Y)$$

Polarization Components

$$P_{\Sigma_x^+} = P_\odot C_x$$
$$P_{\Sigma_y^+} = P$$
$$P_{\Sigma_z^+} = P_\odot C_z$$

- Transverse (induced) polarization $P_{\Sigma_y^+}$ is equivalent to P observable.
- The $\hat{x}$ and $\hat{z}$ components of hyperon polarization are proportional to C_x, C_z via degree of beam polarization $P_\odot$.

Extraction Methods for the C_x & C_z Observables

- Double polarization observables C_x and C_z have not been extracted for $\gamma p \to K^0\Sigma^+$ reaction.
- Furthermore, beam polarization g12 data has not been used for the extraction of these observables; new addition to the analysis of $K^0\Sigma^+$.
- Asymmetry is calculated for proton angle bin ($\cos\theta_p$) recording number of events as $N_\pm$ for positive/negative helicity states.
- Implemented two strategies in order to extract double polarization observables:
  - **One-dimensional fit:** Individually yields C_x or C_z.
  - **Maximum-likelihood fit:** Simultaneous extraction of all observables P, C_x and C_z.

HWSG Updates

$\gamma p \rightarrow K^0\Sigma^+$: Q-factor

- Considered two different mass cuts before applying the background subtraction:
  - Strangeness conserved in EM and strong interactions. Applied a narrow cut of 30 MeV around K^0 mass of 500 MeV to enhance Σ^+ peak of q-values.
  - Dominant reaction contributing to $p\pi^+\pi^-\pi^0$ is ω. Applied mass cut to remove contributions from ω: $m_{\pi^+\pi^-\pi^0} < 752$ MeV and $m_{\pi^+\pi^-\pi^0} < 812$ MeV.
- **Q-factor method:** Removal of background underneath signal peak. Event-based method.
- Q-factor used as event weight in order to determine signal contribution to physical distributions.
- Due to $K^0 \rightarrow \pi^+\pi^-$ and $\Sigma^+ \rightarrow p\pi^0$ correlation, reference quantity can be either invariant mass.

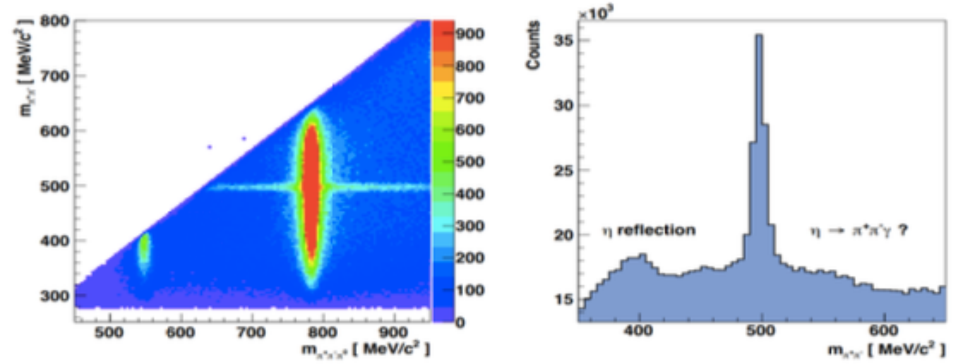
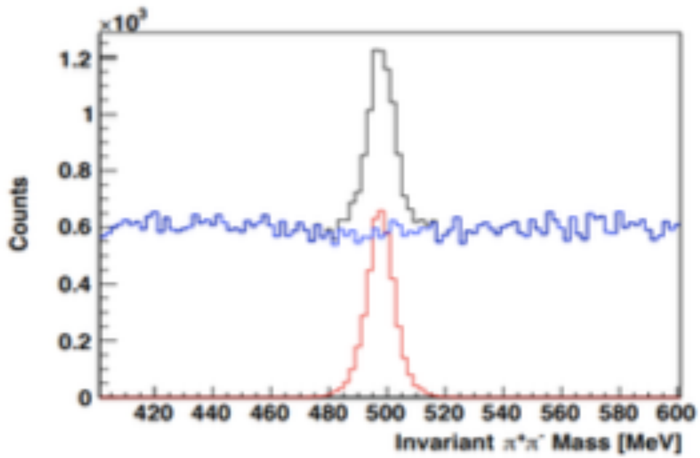
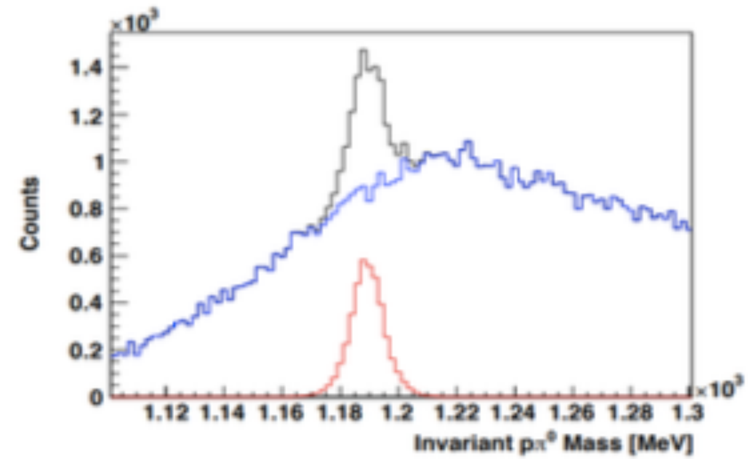


Figure 5: **Left:** Invariant $\pi^+\pi^-\pi^0$ mass vs. $\pi^+\pi^-$ mass for all g12 $\pi^+\pi^-\pi^0$ events. **Right:** Same invariant $\pi^+\pi^-$ mass distribution after the ω and Σ^+ mass-cuts.





HWSG Updates

One-Dimensional Fit

- For g12 experiment, electron-beam helicity flipped at 30 Hz rate.
- If beam helicity $P_\odot$ can be flipped, one can thus obtain C_i asymmetry as a function of proton angle $\cos\theta_p$. Asymmetry is related to angular distribution of proton as

$$A(\cos\theta^p_{x/z}) = \frac{N_+ - N_-}{N_+ + N_-} = \alpha P_\odot C_{x/z} \cos\theta^p_{x/z}.$$

Maximum-Likelihood Method

- Binning of data could hide some asymmetry features.
- Maximum-likelihood method is an event-by-event method, requiring no binning and therefore preventing the possible loss of information and allowing simultaneous extraction of polarization observables.
- Likelihood $\mathbb{L}$ (joint-probability density) for obtaining set of observed values in experiment, given specific set of polarization observables, is given by the product of probability density $\mathcal{P}_i$ for observing individual events.

Likelihood Function

$$\mathbb{L} = \prod_{i=1}^{N} \mathcal{P}_i$$

Single Event Probability Distribution Function

$$\mathcal{P}(\cos\theta^p_x, \cos\theta^p_z, \cos\theta^p_y | C_x, C_z, P) =$$
$$1 \pm P_\odot \alpha (C_x \cos\theta^p_x + C_z \cos\theta^p_z) + \alpha P \cos\theta^p_y$$

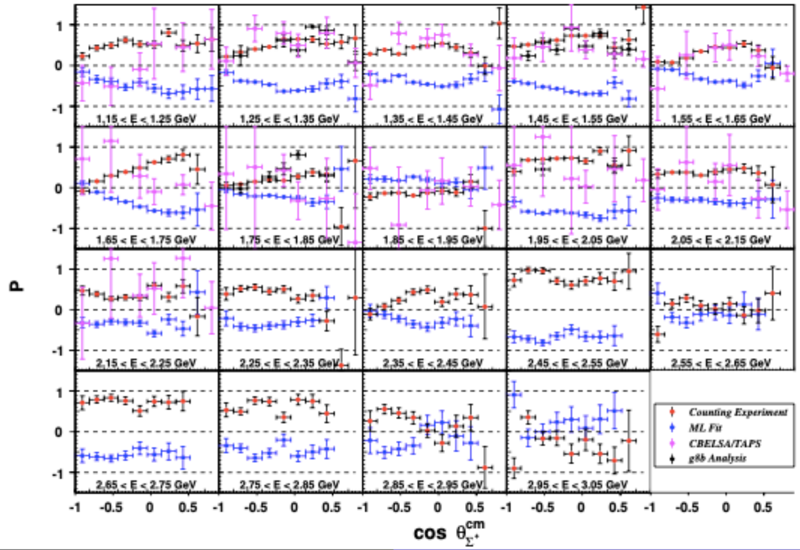
- Each given event has its own weight w_i, calculated via Q-factor method.
- Computationally, it is convenient to minimize negative log-likelihood function as opposed to maximazing it.

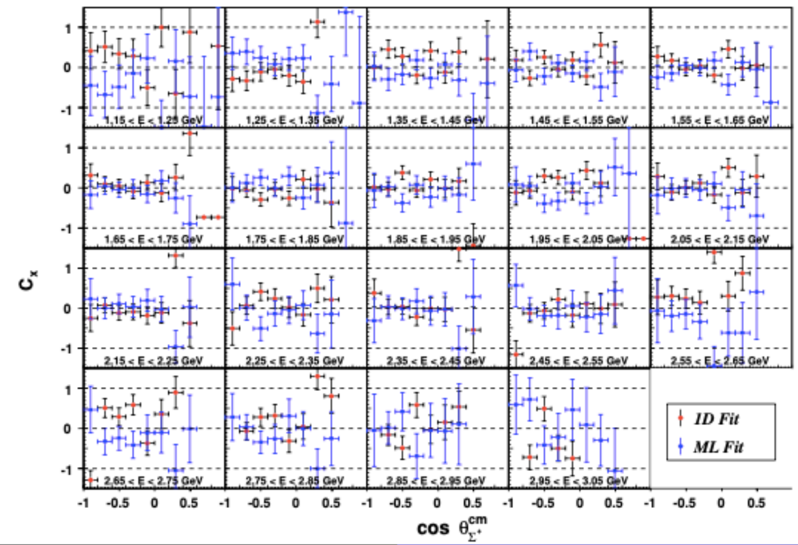
Probability Distribution Function

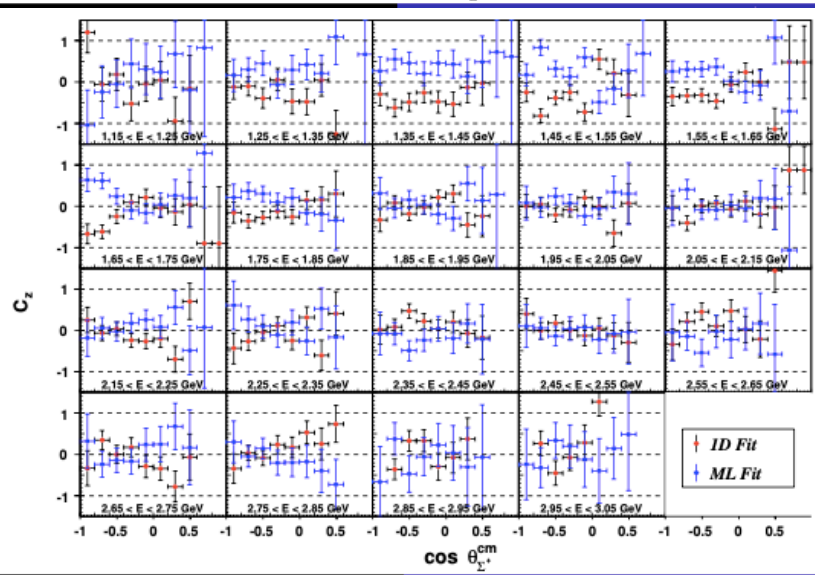
$$-\log\mathbb{L} = -\sum_{i=1}^{N} w_i \log(\mathcal{P}_i)$$

$$-\log\mathbb{L} = -\sum_{i=1}^{N} w_i \log(1 \pm P_\odot \alpha (C_x \cos\theta^p_x + C_z \cos\theta^p_z) + \alpha P \cos\theta^p_y)$$

HWSG Updates







- The photoproduction of $K^0\Sigma^+$ is an unexplored and important channel to study due to its parity violation, allowing for the construction of an asymmetry, thus allowing for measurement of polarization observables.
- Polarization observables allow for the disentanglement of N^* and Δ^* resonances.
- Determination of observables leads an understanding of the intermediate steps involved in the reaction of interest.
- Double polarization observables C_x and C_z have never measured for the $K^0\Sigma^+$ channel.
- Current issue lies with the ML fit error bars; C_x/C_z observables appear to be consistent with zero. We seek to address what becomes of this "missing" polarization.

HWSG Updates

Analysis of $K^0\Sigma^+$ photoproduction off the proton from g8b

Louise Clark
Hadron Spectroscopy Working Group

Analysis method

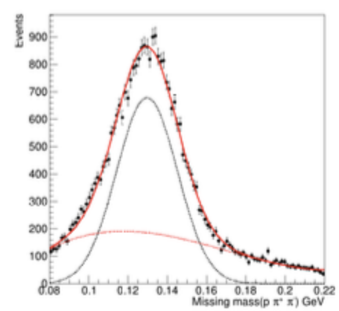
- Identify final state $p\ \pi^+\ \pi^-\ (\pi^0)$
- Identify reaction channel using sPlots to obtain signal and background weights
  - M. Pivk and F. R. Le Diberder. splot: a statistical tool to unfold data distributions.arXiv preprint physics/0402083
- Simulation of phase space $\gamma p \rightarrow K^0\Sigma^+$ used for acceptance corrections in likelihood calculations
  - Event generation with https://github.com/lorenzozana/EdGenedgen-event-generator
  - g8b simulation and reconstruction
- Likelihood sampling with MCMC using pdf as follows

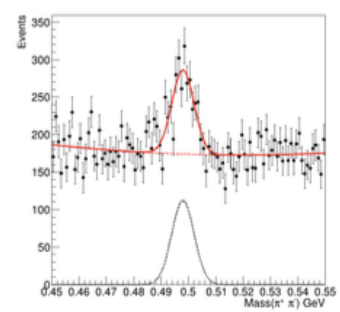
$$\frac{d\sigma}{d\Omega} \equiv \sigma(\phi, \cos\theta_x, \cos\theta_y, \cos\theta_z) = \sigma_0 \{1 - P^\gamma \Sigma \cos 2\phi - \alpha \cos\theta_x P^\gamma O_x \sin 2\phi + \alpha \cos\theta_y P - \alpha \cos\theta_y P^\gamma T \cos 2\phi - \alpha \cos\theta_z P^\gamma O_z \sin 2\phi\},$$

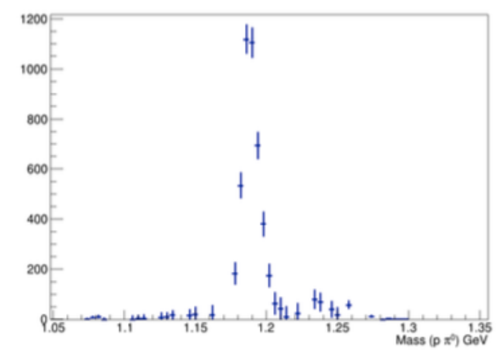
- Preliminary results quoted here are the mean $\pm\ \sigma$ of the resulting posterior distribution for each observable
- sPlots fits and MCMC studies performed using the HaSpect framework: Derek Glazier talk this afternoon 17:00

Objectives and status of analysis

- Objective: Extraction of linear polarisation observables Σ, P, T, O_x, and O_z for the reaction $\gamma p \rightarrow K^0\Sigma^+$ using g8b data
- Status of analysis:
  - Preliminary results have been extracted using simultaneous fit of all 5 observables
  - Beginning validation and systematic studies
- Comparisons to previous work
  - CBELSA/TAPS: R. Ewald et al. Measurement of polarisation observables in $K^0_S\Sigma^+$ photoproduction off the proton. *Physics Letters B*, 738:268 – 273, 2014
  - CLAS: C.S. Nepali et al. Transverse polarization of $\Sigma^+(1189)$ in photoproduction on a hydrogen target in clas. *Phys. Rev. C*, 87:045206, Apr 2013
- Current FSU g12 analysis, F. Gonzalez, V. Crede (previous talk)

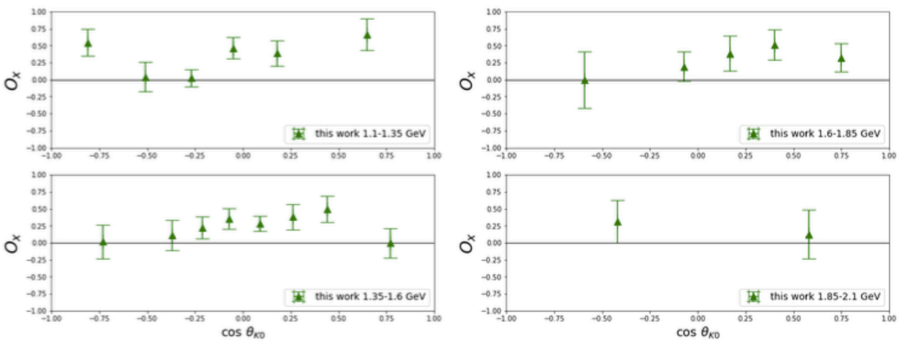


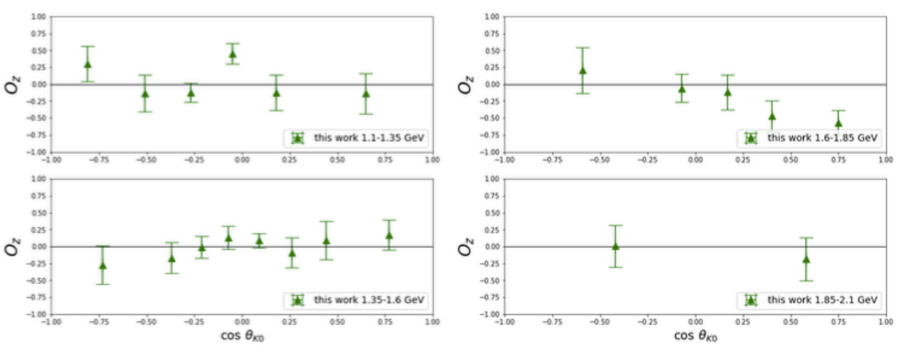


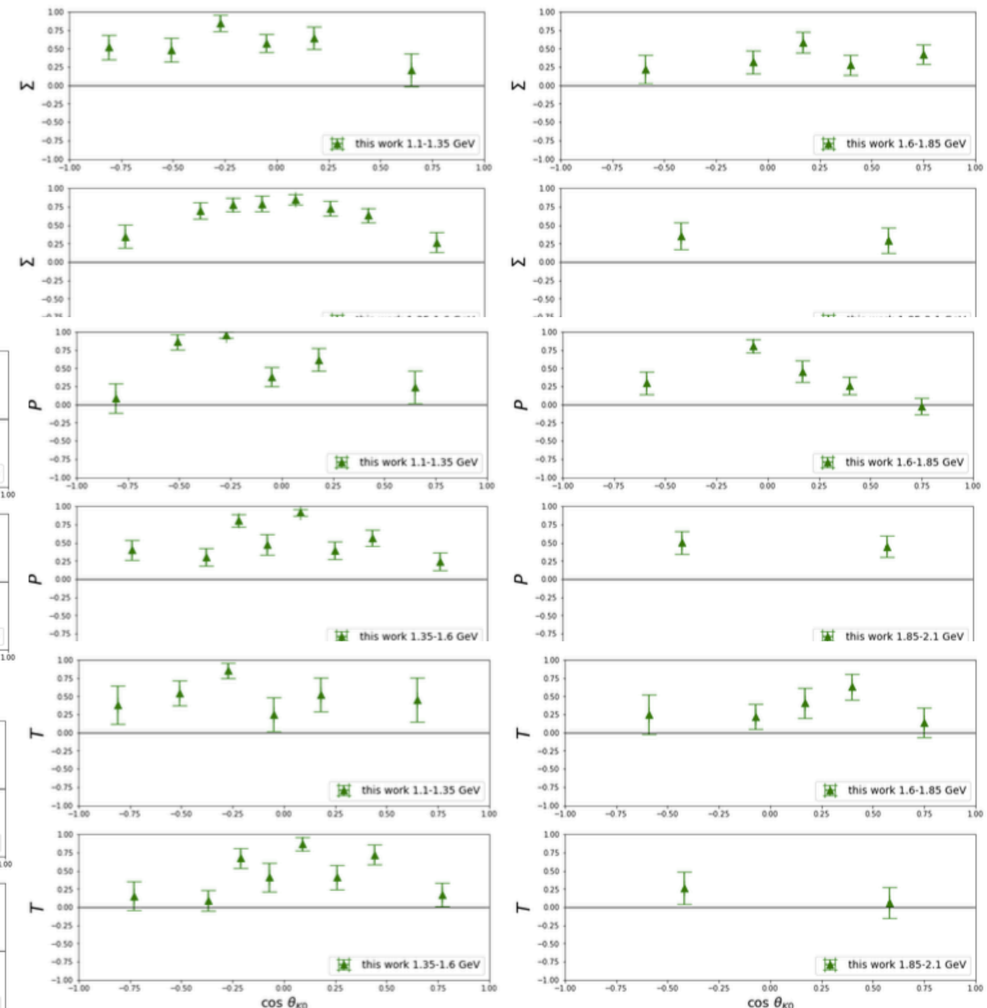


HWSG Updates

- Preliminary results have been extracted for Σ, P, T, O_x, and O_z
- Current binning
  - 4 energy bins 1.1 GeV - 2.1 GeV
  - Variable width bins in $cos\ \theta_{K_0}$ to produce integrated signal weight of approximately 1000 per bin
  - 21 bins in total



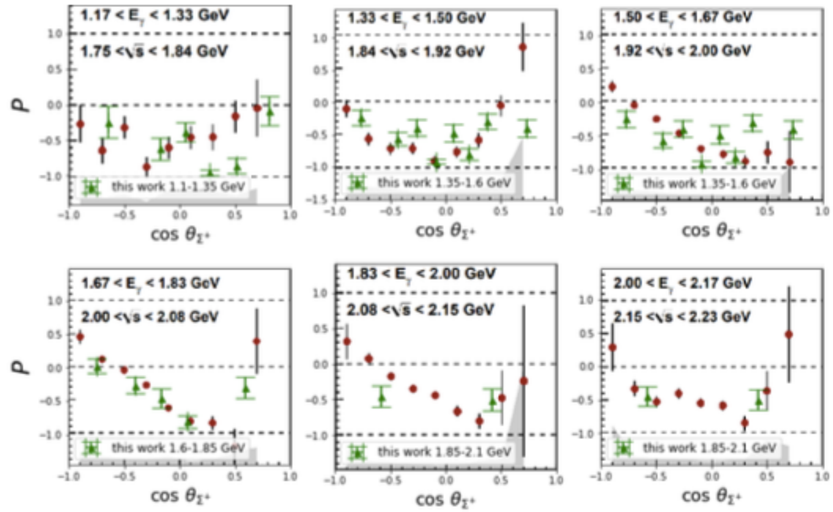


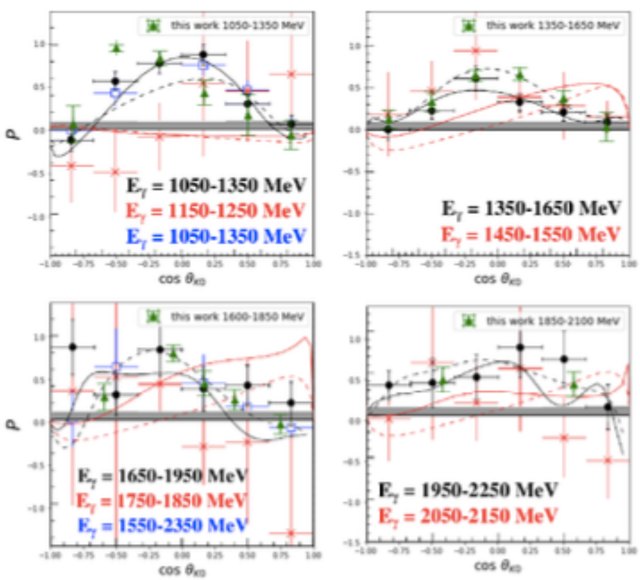


HWSG Updates

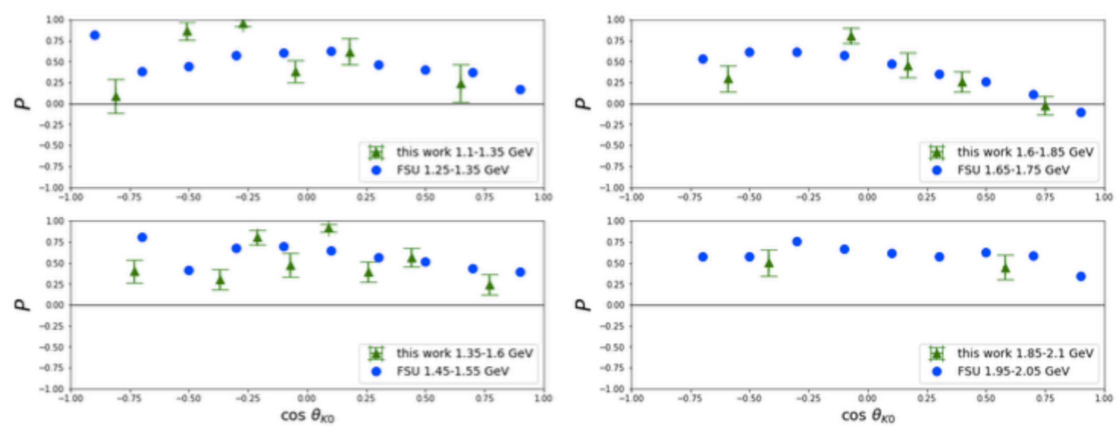
Comparison to previous work and current analysis

Experiment	Measurements	$E\gamma$	Notes
CLAS g11	P	1.0–3.5 GeV	Difference in frame means different sign is extracted Some agreement with this work
CBELSA/TAPS	Σ P	1.15-1.65 GeV 1.05-2.25 GeV	Σ extracted using cross sections P results agree, but Σ do not
FSU analysis	P C_x, C_z	1.15-3.05 GeV	Results agree (subject to checking sign)
CLAS g8b	Σ, P, T, O_x, O_z	1.1-2.1 GeV	This work



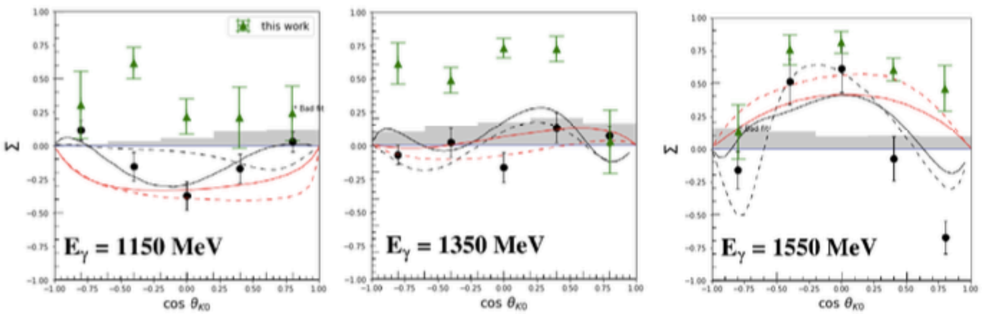


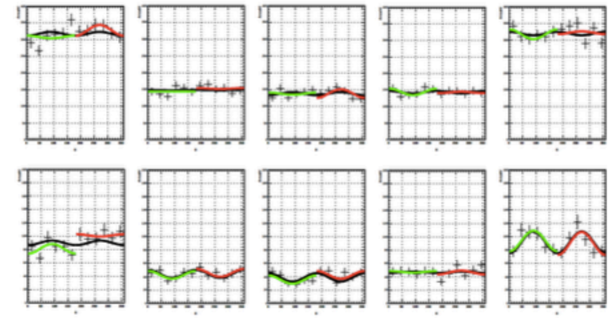
Recoil polarisation - comparison with FSU



HWSG Updates

Beam asymmetry - comparison with Ewald





- Fits are made to the modulation of the cross section
- $0 - 180°$ and $180 - 360°$ fitted separately and average taken
- Thesis (in German): http://hss.ulb.uni-bonn.de/2010/2044/2044.pdf

- Preliminary results have been obtained from g8b data for Σ, P, T, O_x, and O_z for $\gamma p \to K^0\Sigma^+$
- These are first measurements of T, O_x, and O_z
- Comparison to previous measurements of P from CLAS and CBELSA/TAPS show agreement
- Comparison to previous measurement of Σ from CBELSA/TAPS show discrepancy
- Next steps
  - Systematic studies
  - Toy MC studies
  - Improvements to simulation

CLAS Collaboration Meeting November 2019

Hadron Spectroscopy Working Group Report

Bryan McKinnon
University of Glasgow

Friday, November 15, 2019