



Polarization observables in double charged pion photo-production with circularly polarized photons off transversely polarized protons (g9b-FROST)

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Research supported in parts by National Science Foundation NSF PHY-1505615

NSTAR 2017, Columbia, SC

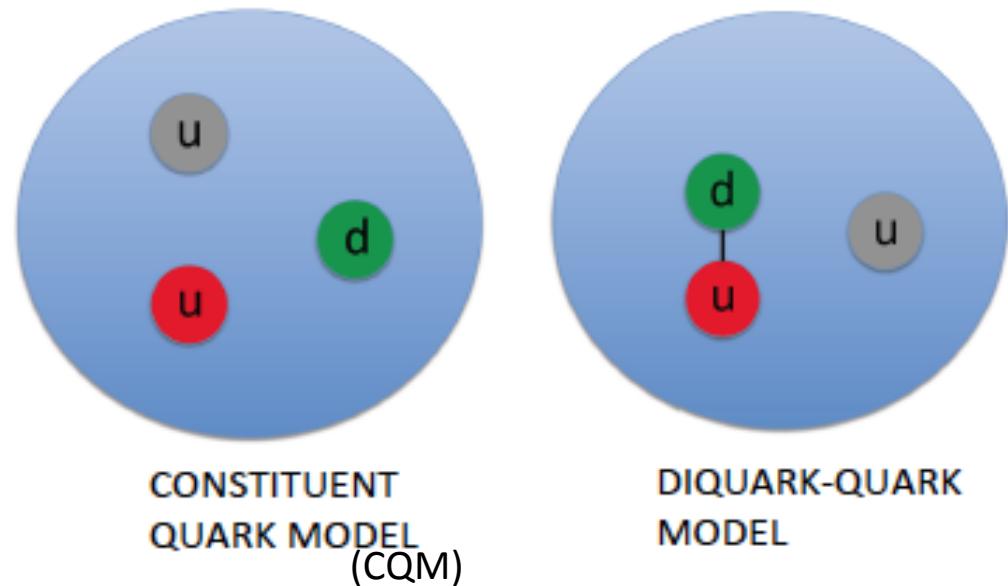
August 22nd, 2017

Outline

- The Theory and the Models
- Double pion channel - Missing Resonances Problem
- FROST Experiment (g9b)
- Analysis: Extraction of polarization observables
- Results for I^\odot , P_x , P_y , P_x^\odot , P_y^\odot
- Summary

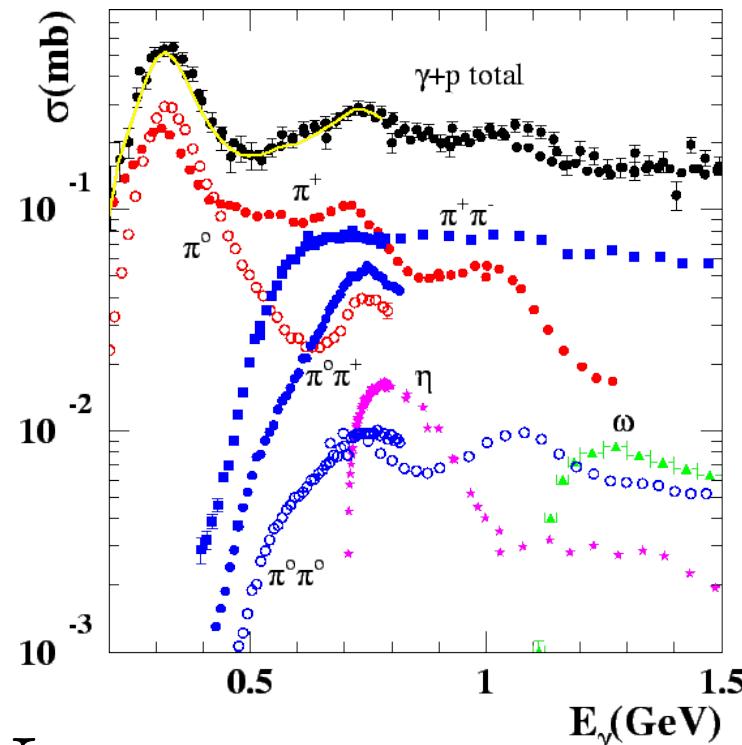
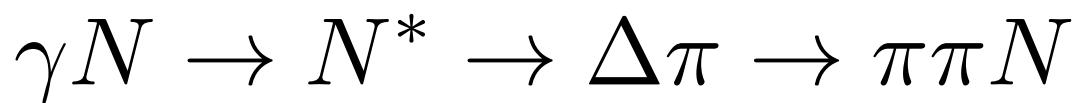
THE THEORY AND THE MODELS

- A QCD solution is not known at low energies (of the order of the nucleon mass and its excited states)
- Different models predict different number of nucleon excited states
- Experimental data will help confirm the existence of these predicted resonances



DOUBLE PION PHOTOPRODUCTION

- Biggest contribution to the photo-production cross section at higher energies
- Branching ratio for N^* decay via double pion channel could be greater than 70% (e.g. $N(1720)$)



Hagiwara et al., 2002

$$\Gamma = 100 - 400 \text{ MeV}$$

POLARIZATION OBSERVABLES

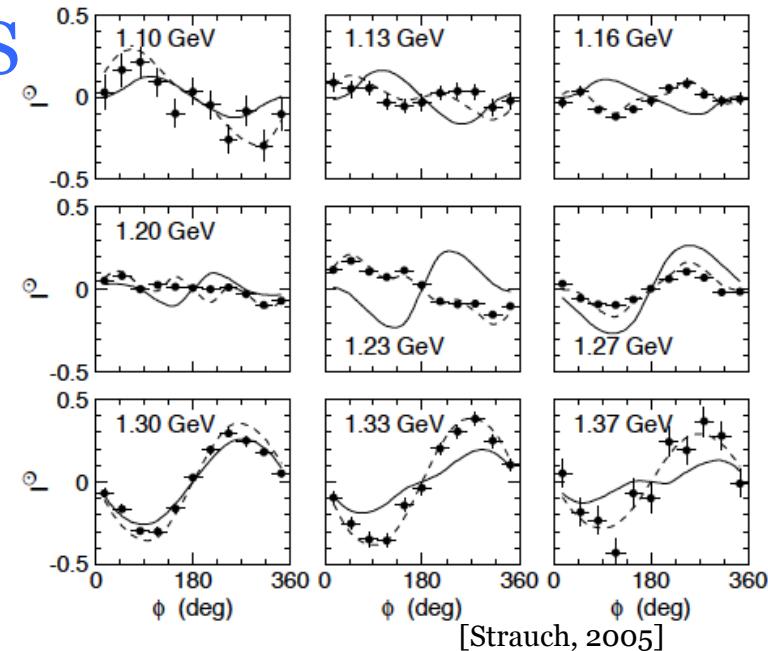
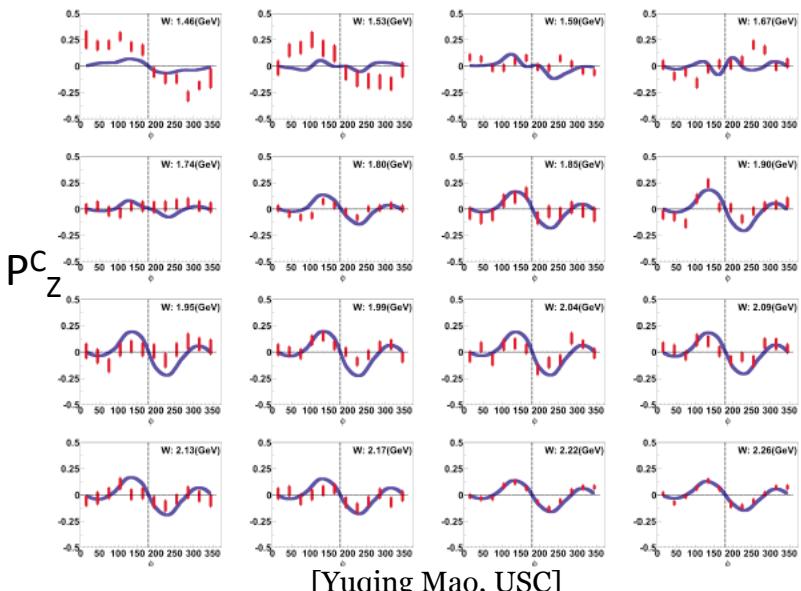
- Different helicity combinations of the initial nucleon, final nucleon and the photon give rise to **8 complex transition amplitudes** describing the reaction:



- The cross section sums up the squares of these transition amplitudes; polarization observables allows access to the amplitude's phase; reveal more information about the reaction dynamics
- This work focused on the extraction of **5 polarization observables**: I^\odot , P_x , P_y , P_x^\odot , P_y^\odot



Previous/Current Studies for Double Pion Photo-production with CLAS



Target

	unpolarized	circular	linear	
unpolarized	I_0	I^\odot	I^s, I^c	g1c
longitudinal	P_z	P_z^\odot	P_z^c, P_z^s	g8
transversal	P_x, P_y	P_x^\odot, P_y^\odot	$P_x^c, P_y^c, P_x^s, P_y^s$	g9



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FROST Experiment (g9 run) at Thomas Jefferson National Accelerator Facility (Newport News, VA)



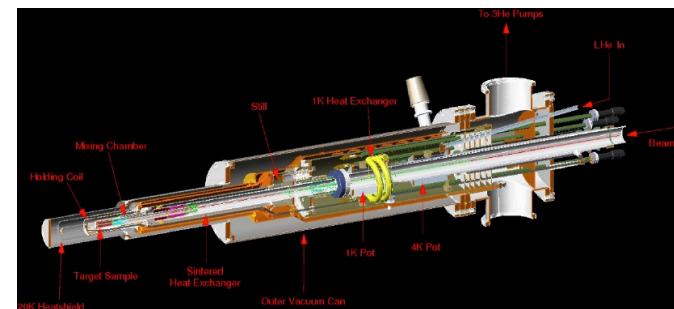
<http://www.phys.vt.edu/research/experiments/JLab-Aerial.jpg>

BEAMS AND TARGETS

- Electron beam: - longitudinally polarized: $\bar{P}_e = 87\%$
- beam energy: 3081.73 MeV
- Photon beam: - circularly polarized

$$\delta_{\odot} = \bar{P}_e \frac{(4E_{\gamma}/E_e) - (E_{\gamma}/E_e)^2}{4 - (4E_{\gamma}/E_e) + (3E_{\gamma}/E_e)^2} \quad E_{\gamma} \approx [0.5 - 3.0 \text{ GeV}]$$

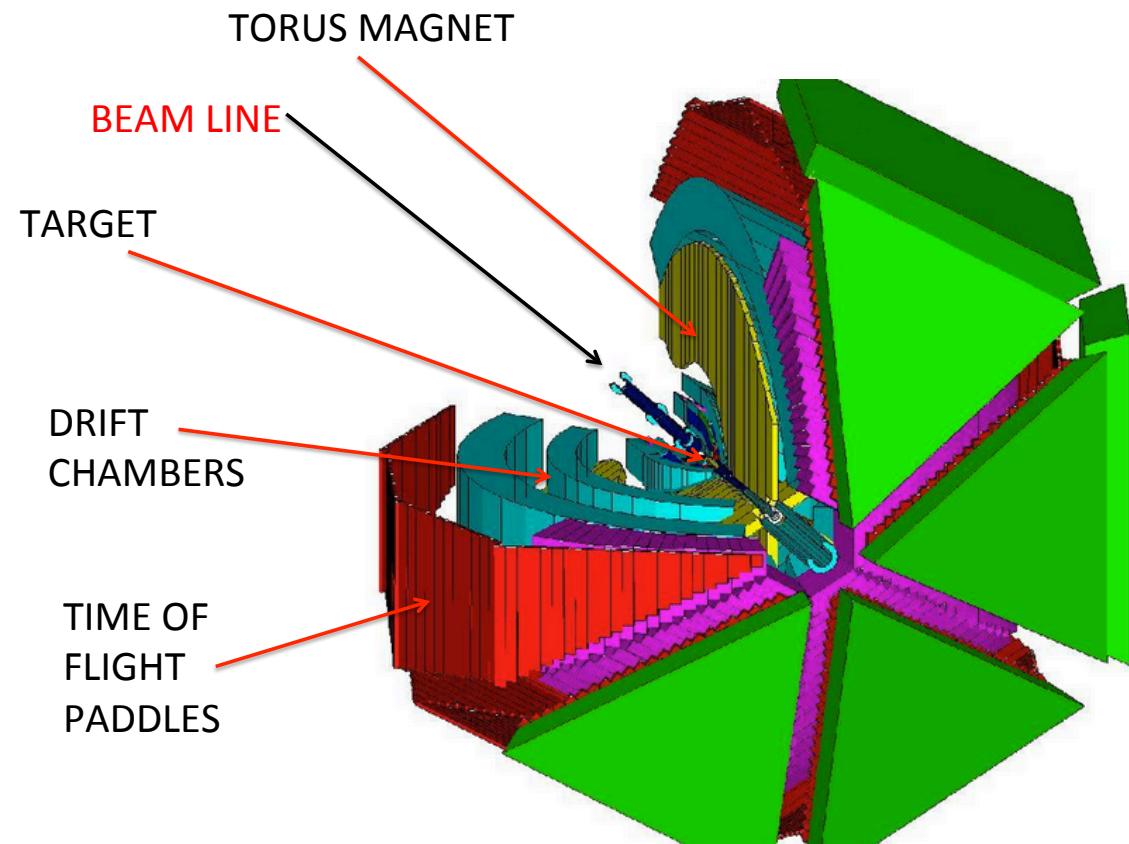
- FROzen Spin Target (FROST) - transversely polarized protons (C_4H_9OH)
- Target polarization: 76% - 86%
- Carbon target: unpolarized
- Polyethylene target: unpolarized





CLAS DETECTOR

- time and momentum measurements



https://www.jlab.org/Hall-B/int-web/clas_large1.jpg

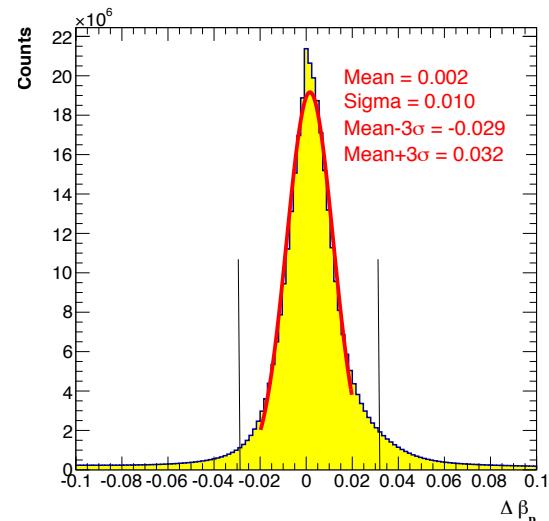
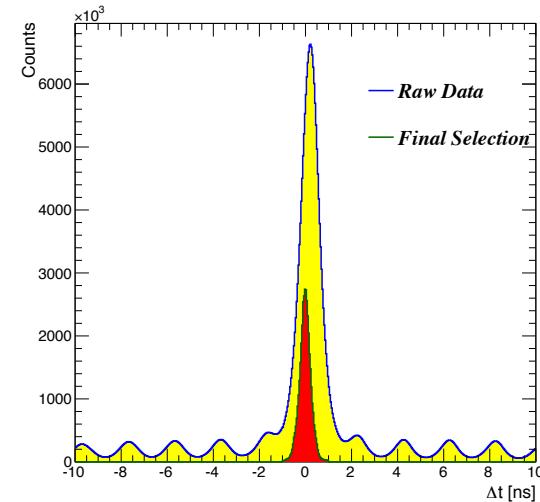
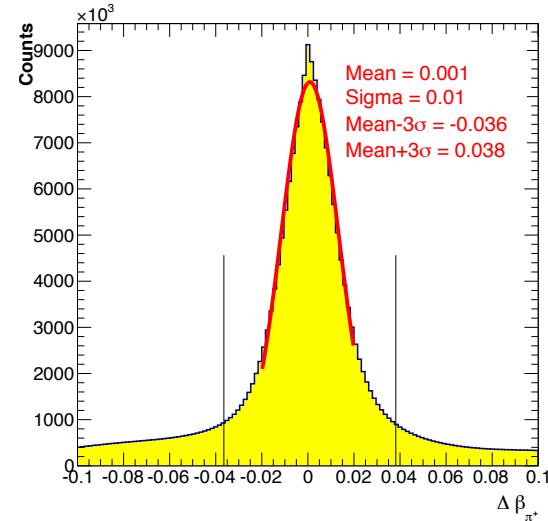
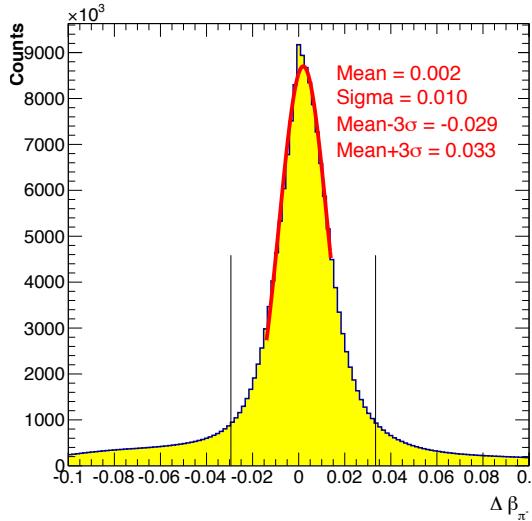


PHOTON SELECTION

$$\begin{aligned}\Delta t &= t_{CLAS,vertex} - t_{\gamma,vertex} = \\ &= t_{ST} - \frac{d_{ST}}{c \cdot \beta_{calc}} - \left[t_{TAGR} + \frac{Z}{c} \right]\end{aligned}$$

PARTICLE ID

$$\Delta \beta = \beta_{meas} - \beta_{calc} = \beta_{meas} - \frac{p}{\sqrt{p^2 + m^2 c^2}}$$



REACTION SELECTION



Final State Composition: 2 positive charges and 1 negative charge

Topology 1: $\vec{\gamma}\vec{p} \rightarrow p\pi^+\pi^-(X)$ nothing missing

Topology 2: $\vec{\gamma}\vec{p} \rightarrow \pi^+\pi^-(X)$ p missing

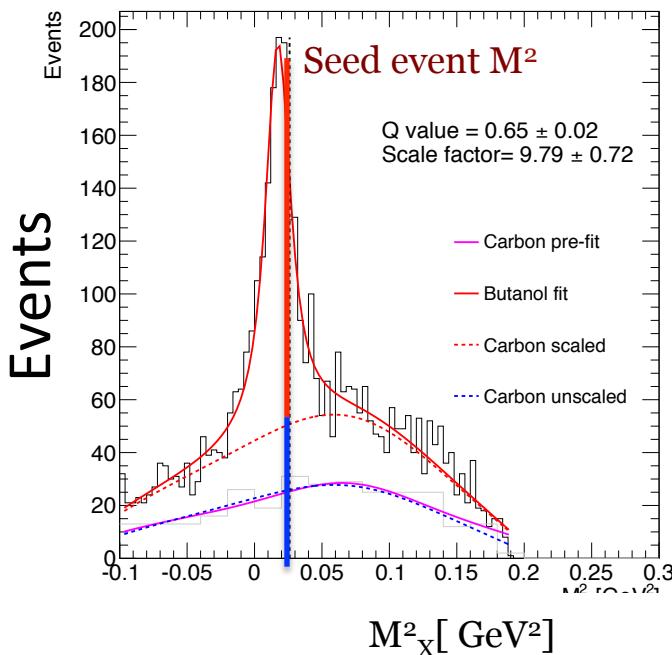
Topology 3: $\vec{\gamma}\vec{p} \rightarrow p\pi^+(X)$ π^- missing

Topology 4: $\vec{\gamma}\vec{p} \rightarrow p\pi^-(X)$ π^+ missing

$$M_X = \sqrt{(\sum E_{in} - \sum E_{out})^2 - \|\sum p_{in} - \sum p_{out}\|^2}$$

SIGNAL BACKGROUND SEPARATION: PROBABILISTIC WEIGHTING METHOD

Q value = the probability for a given event i to be a signal ($Q=1$) or a background event ($Q=0$)



$$Q_i = \frac{\text{Signal}}{\text{Signal} + \text{Background}}$$

Polarization observables for circularly polarized photons off transversely polarized protons

Reaction plane

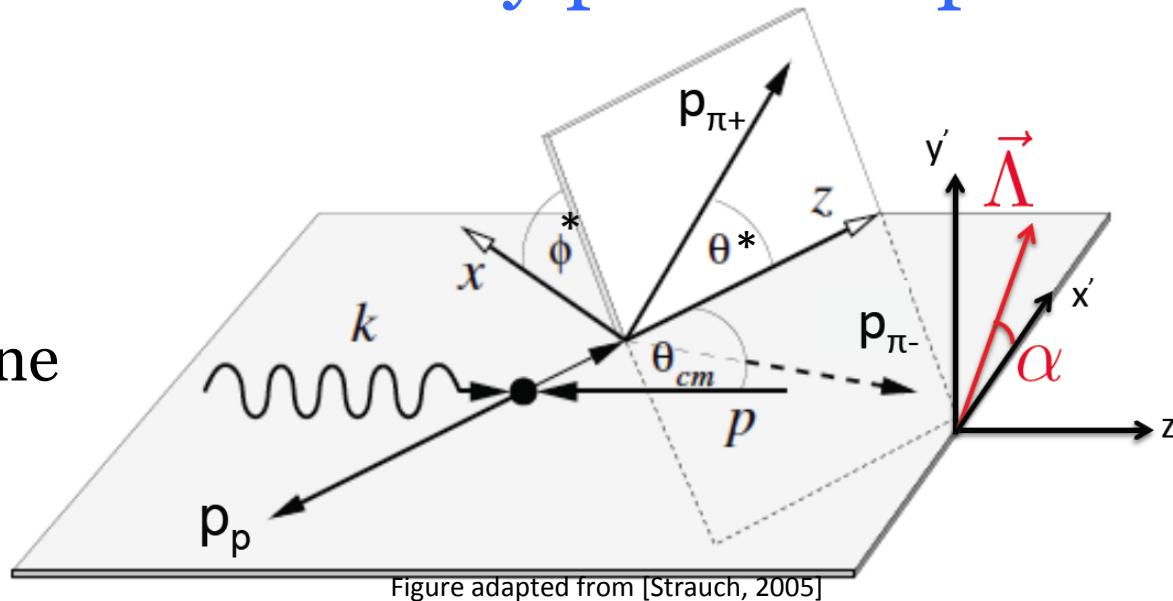


Figure adapted from [Strauch, 2005]

$$Y(\alpha) = Y_0[(1 + \Lambda \cdot \cos \alpha \cdot P_x + \Lambda \cdot \sin \alpha \cdot P_y) \\ + \delta_{\odot}(I^{\odot} + \Lambda \cdot \cos \alpha \cdot P_x^{\odot} + \Lambda \cdot \sin \alpha \cdot P_y^{\odot})]$$

Simplified observable extraction (for illustration)

$$\bar{P}_x = \frac{1}{\bar{\Lambda}} \frac{\sum_i \cos \alpha_i}{\sum_i Q_i \cos^2 \alpha_i}$$

$$\bar{P}_y = \frac{1}{\bar{\Lambda}} \frac{\sum_i \sin \alpha_i}{\sum_i Q_i \sin^2 \alpha_i}$$

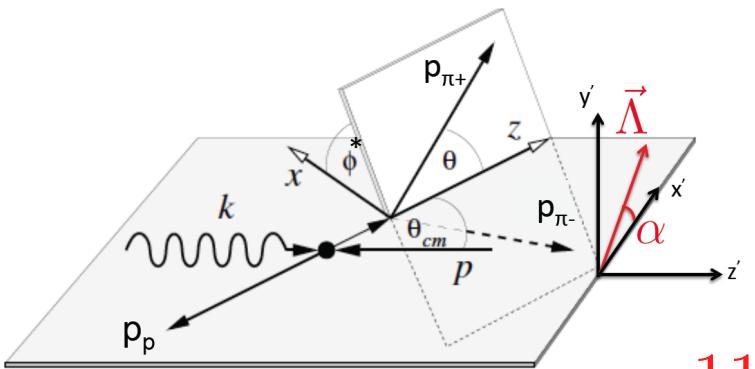
$$\bar{I}^\odot = \frac{\sum_i Q_i H_i}{\bar{\delta}_\odot \sum_i Q_i}$$

$$\bar{P}_x^\odot = \frac{1}{\bar{\Lambda}} \frac{1}{\bar{\delta}_\odot} \frac{\sum_i H_i \cos \alpha_i}{\sum_i Q_i \cos^2 \alpha_i}$$

$$\bar{P}_y^\odot = \frac{1}{\bar{\Lambda}} \frac{1}{\bar{\delta}_\odot} \frac{\sum_i H_i \sin \alpha_i}{\sum_i Q_i \sin^2 \alpha_i}$$

All the final expressions correct for the acceptance effects and for the fact that the target polarization is slightly different for different run groups.

Polarization Observables: Results



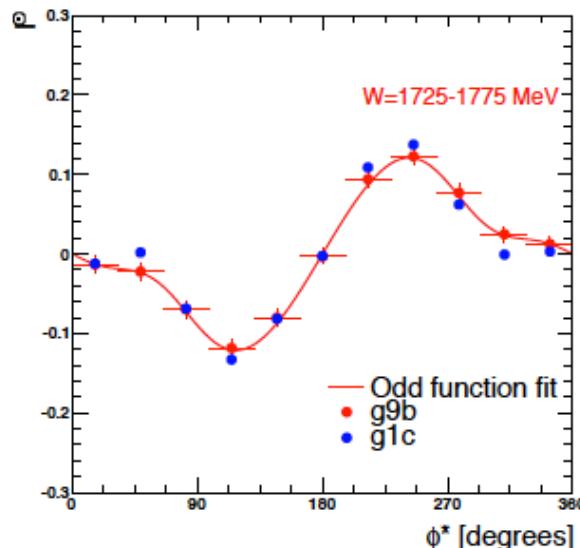
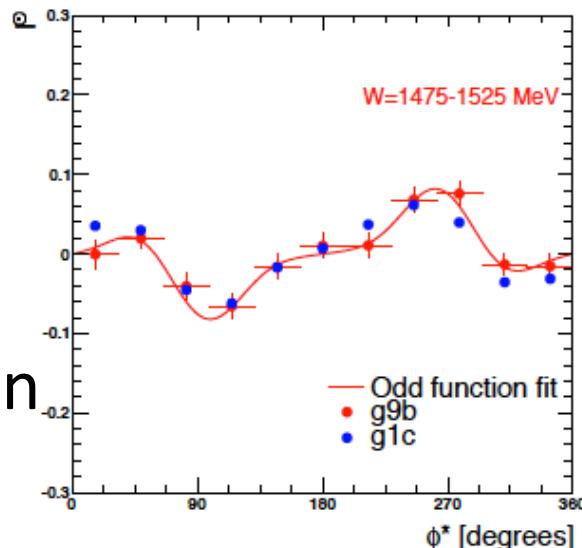
$$\alpha = 116.1^\circ$$

Observables fit functions:

$$F_{odd} = \sum_i^4 b_i \sin(i \cdot x)$$

$$F_{even} = a_0 + \sum_i^4 a_i \cos(i \cdot x)$$

I^{\odot}
g1c, g9b
comparison

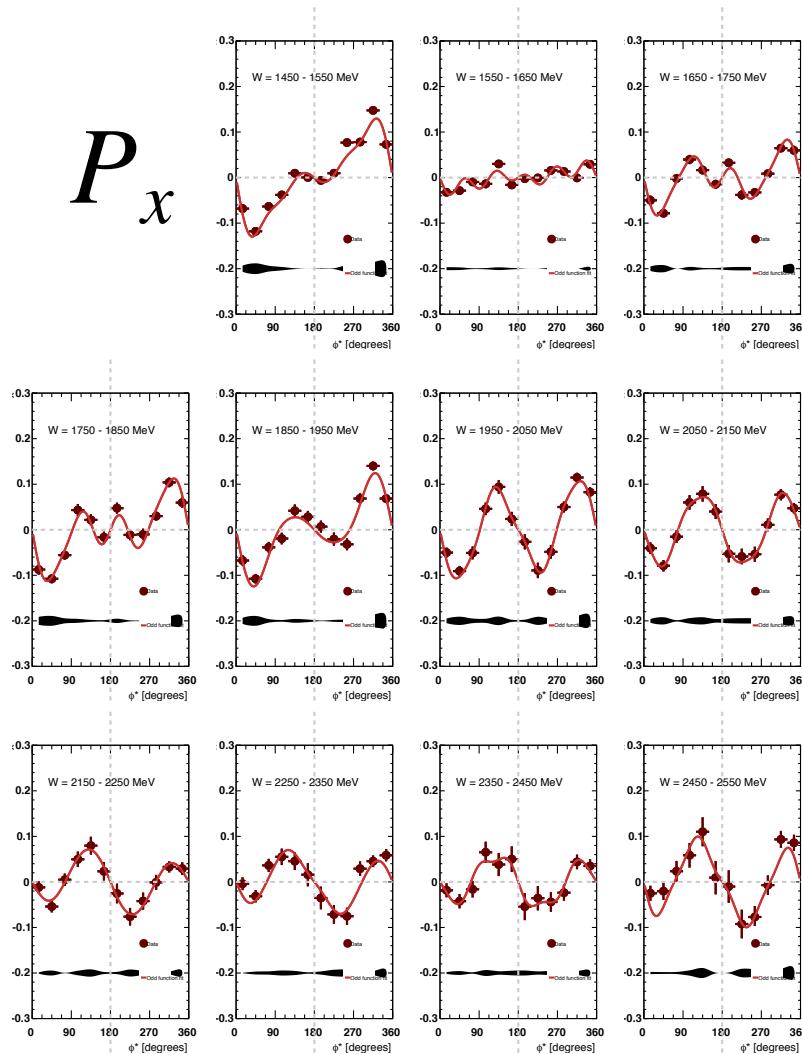


PRELIMINARY

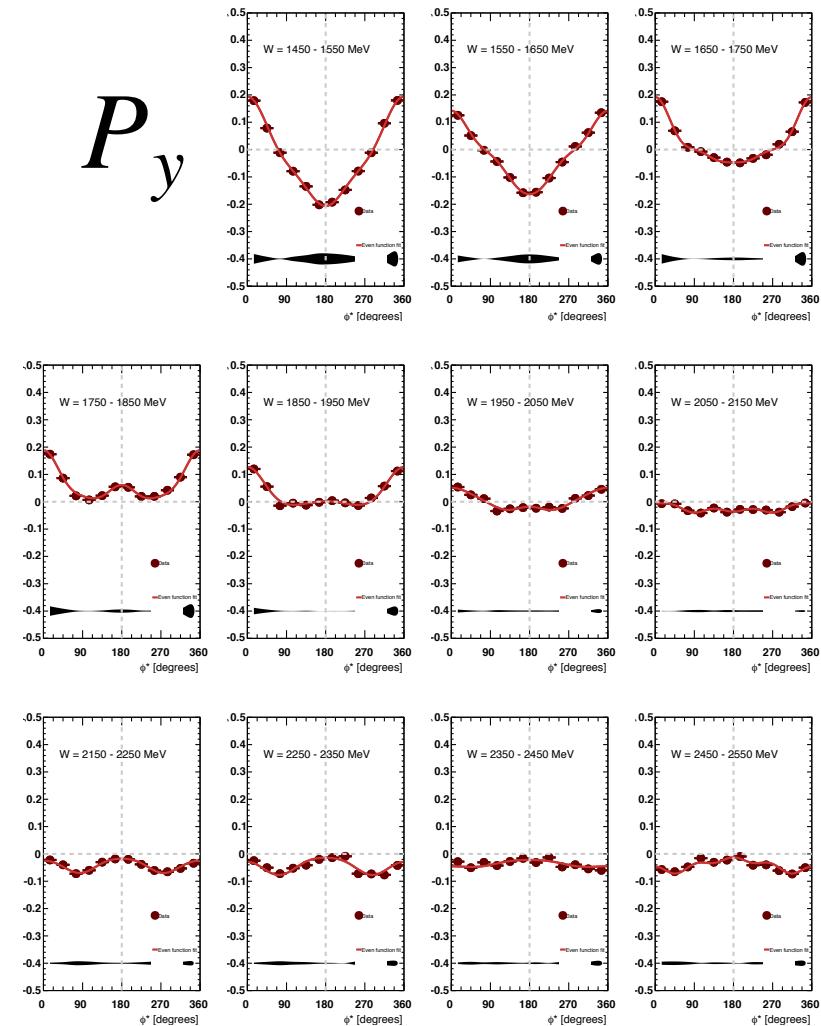


$W=1450\text{--}2550\text{ MeV}$

P_x



P_y

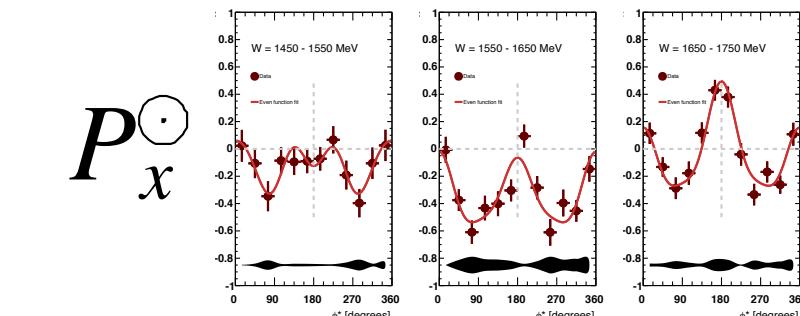


PRELIMINARY

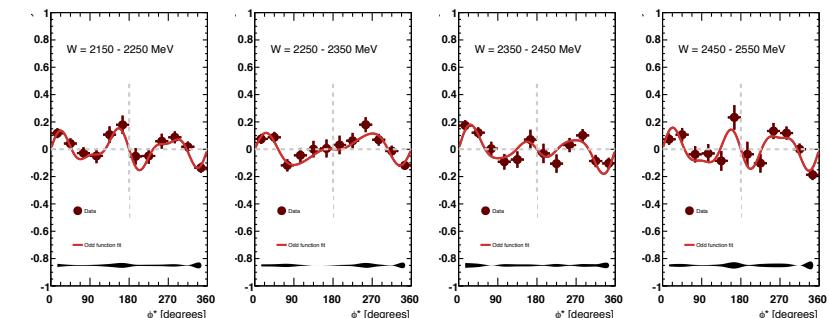
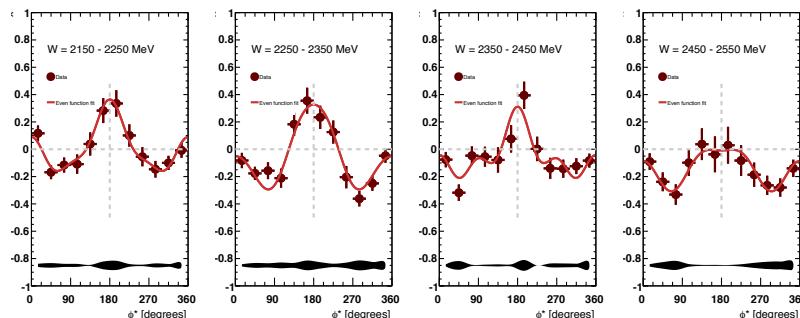
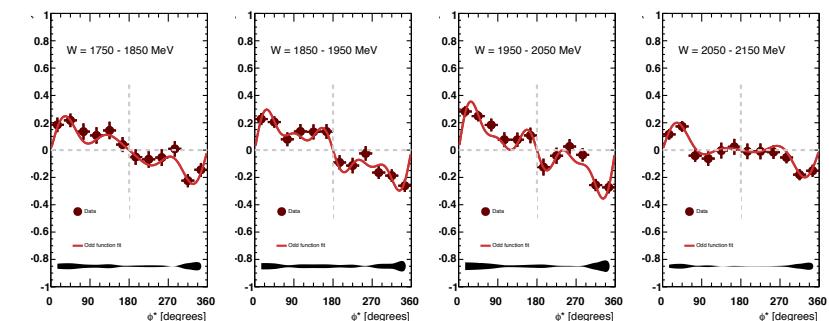
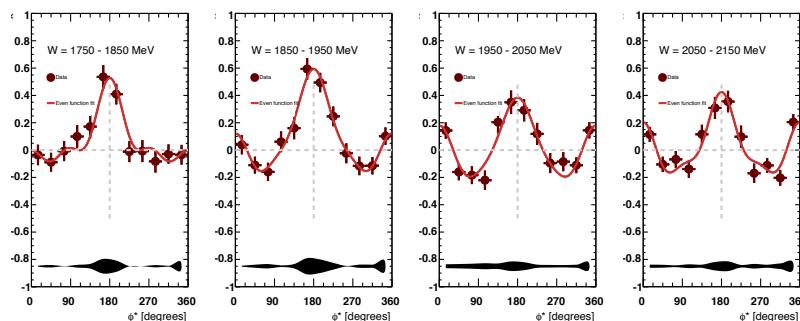
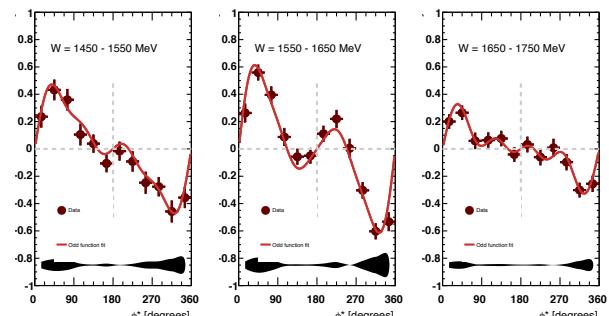


$W=1450\text{--}2550\text{ MeV}$

P_x



P_y

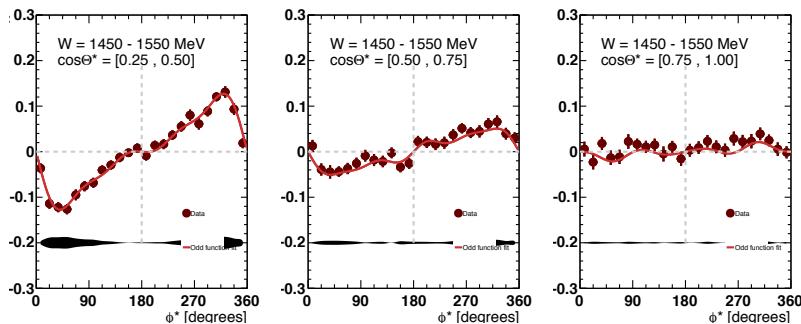
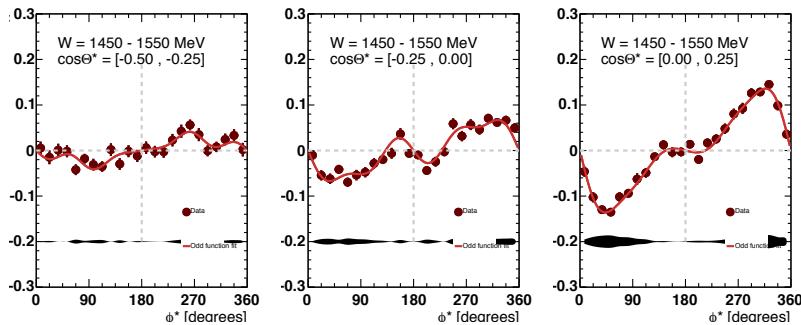
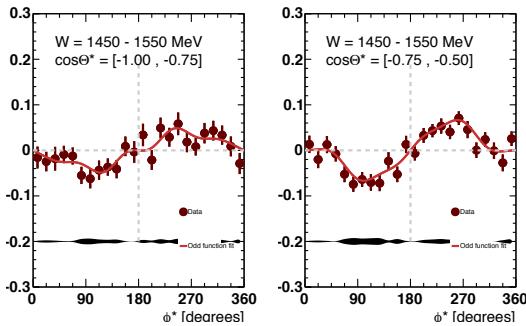


PRELIMINARY



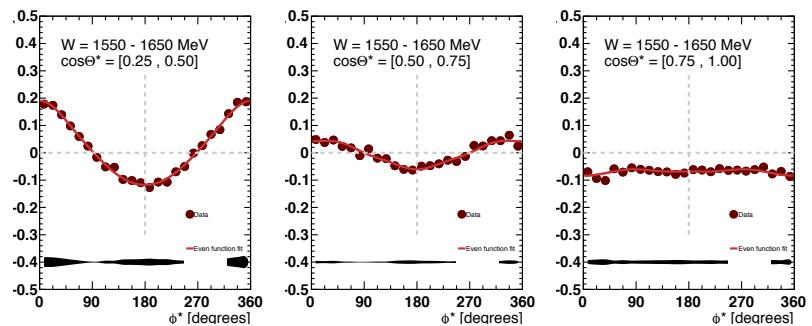
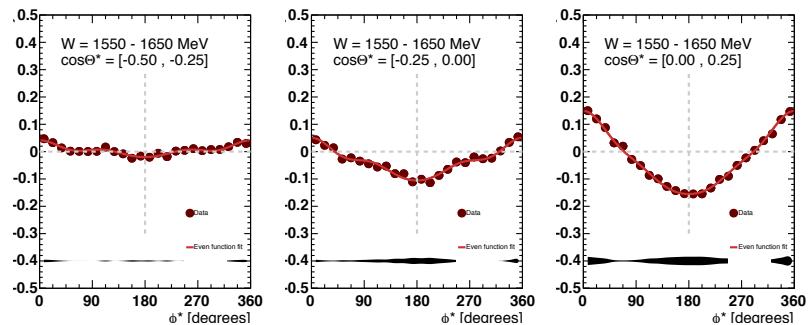
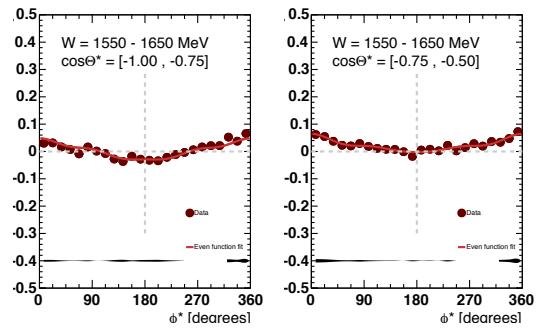
$W = 1450 - 1550 \text{ MeV}, \cos\Theta^* = [-1, 1]$

P_x



$W = 1550 - 1650 \text{ MeV}, \cos\Theta^* = [-1, 1]$

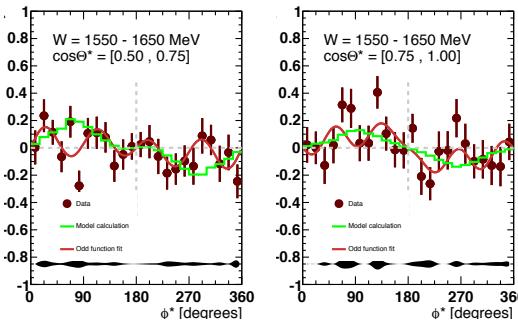
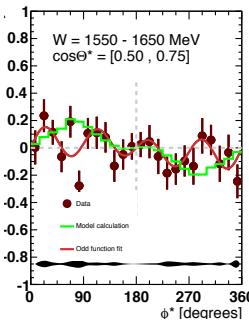
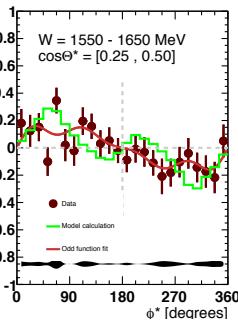
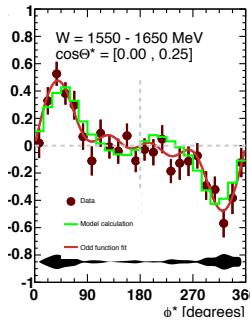
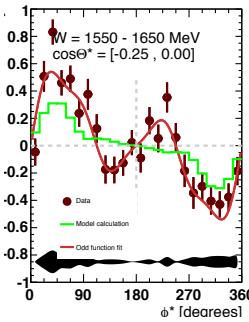
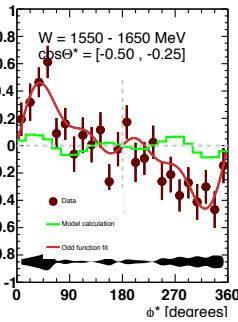
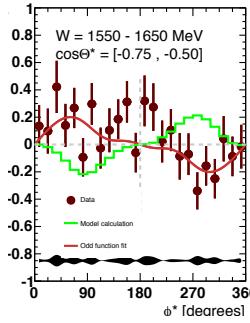
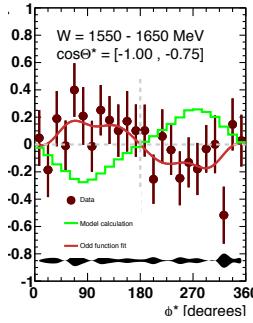
P_y





MODEL CALCULATION - DATA COMPARISON

P_y



Effective Lagrangean Model (A. Fix)

- The comparison between data and the model prediction shows rather a lack of agreement
- The data will help further constrain the model for a better agreement

Summary

- Overview of the methods used to analyze double pion photo-production with circularly polarized photon beam off transversely polarized protons and to extract the polarization observables
- **5 polarization observables** were extracted for $W=1450\text{-}2550 \text{ MeV}$
- Comparison with the model shows some similarities with general features of the data; the data will help constrain the model for a better agreement
- Data will enter PWA study to help identify missing nucleon resonances



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EXTRA SLIDES



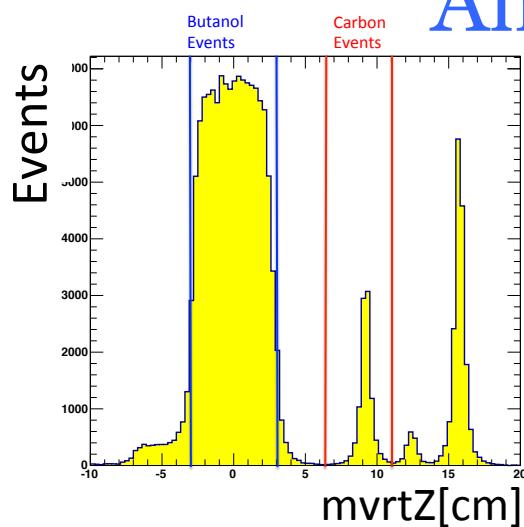
$$\gamma N \rightarrow N^* \rightarrow \Delta\pi \rightarrow \pi\pi N$$

$$\gamma N \rightarrow N^* \rightarrow p\rho \rightarrow \pi\pi N$$

$$\gamma N \rightarrow N^* \rightarrow p\sigma \rightarrow \pi\pi N$$



Analysis: Event Pre-selection



Butanol events: $-3 \text{ cm} < mvrtZ < +3\text{cm}$

Carbon events: $+6\text{cm} < mvrtZ < +11\text{cm}$

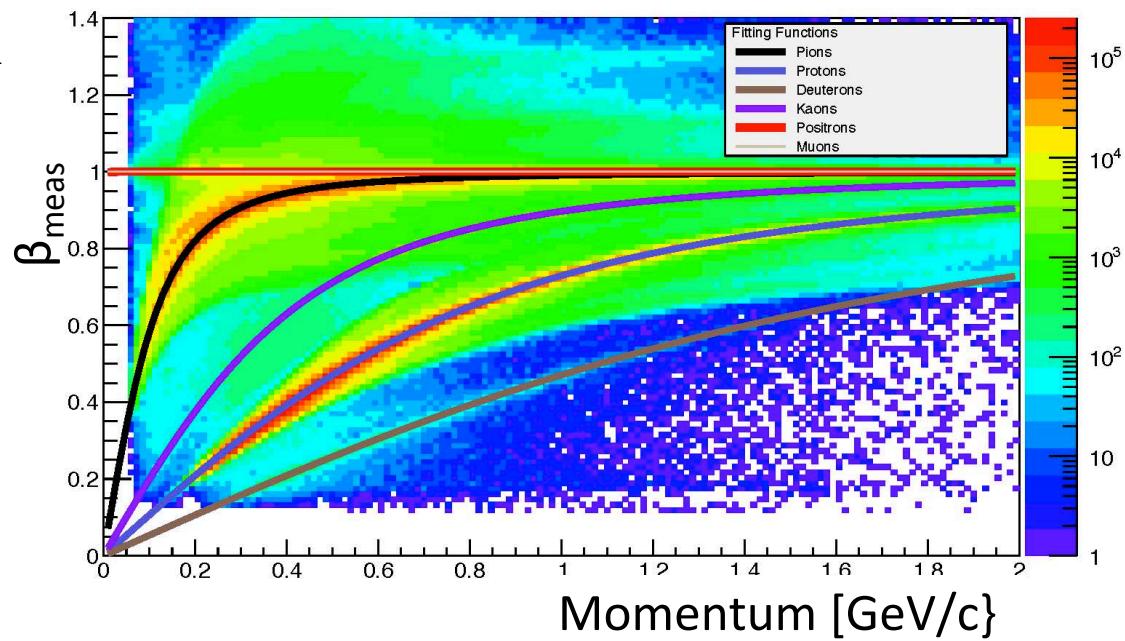
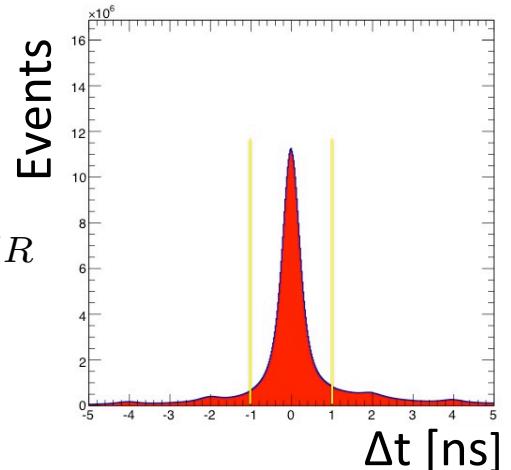
$$\beta_{calc} = \frac{p}{\sqrt{p^2 + m^2}}$$

$$\Delta\beta = \beta_{meas} - \beta_{calc}$$

Photon selection

$$\Delta t = t_{CLAS} - t_{TAGR}$$

$$|\Delta t| < 1 \text{ ns}$$



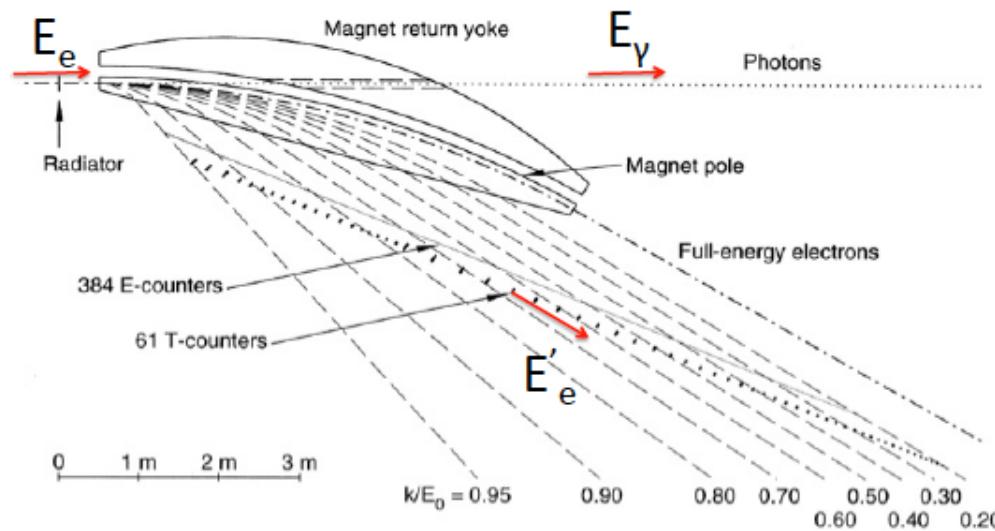


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Electron beam: - longitudinally polarized: $\bar{P}_e = 87\%$
 - beam energy: 3081.73 MeV

Photon beam: - circularly polarized

$$\delta_{\odot} = \bar{P}_e \frac{(4E_{\gamma}/E_e) - (E_{\gamma}/E_e)^2}{4 - (4E_{\gamma}/E_e) + (3E_{\gamma}/E_e)^2} \quad \sigma_{\delta_{\odot}} \approx 3.0\%$$



$$E_{\gamma} = E_e - E'_e$$

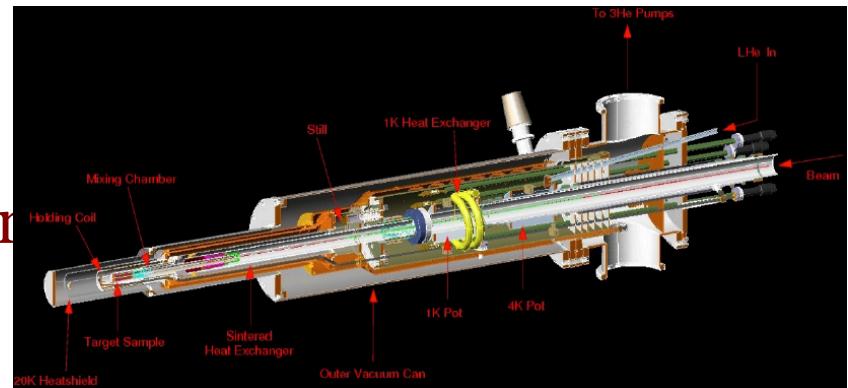
$$E_{\gamma} \approx [20\% - 95\% E_e]$$

$$E_{\gamma} \approx [0.5 - 3.0 \text{ GeV}]$$

E-counter resolution:
 $0.001E_0$

TARGETS

- Repolarized for each run group
- Polarization checked via NMR measurements
- Polarization uncertainty <3.5%
- **FROzen Spin Target (FROST)** - target
 (C_4H_9OH)

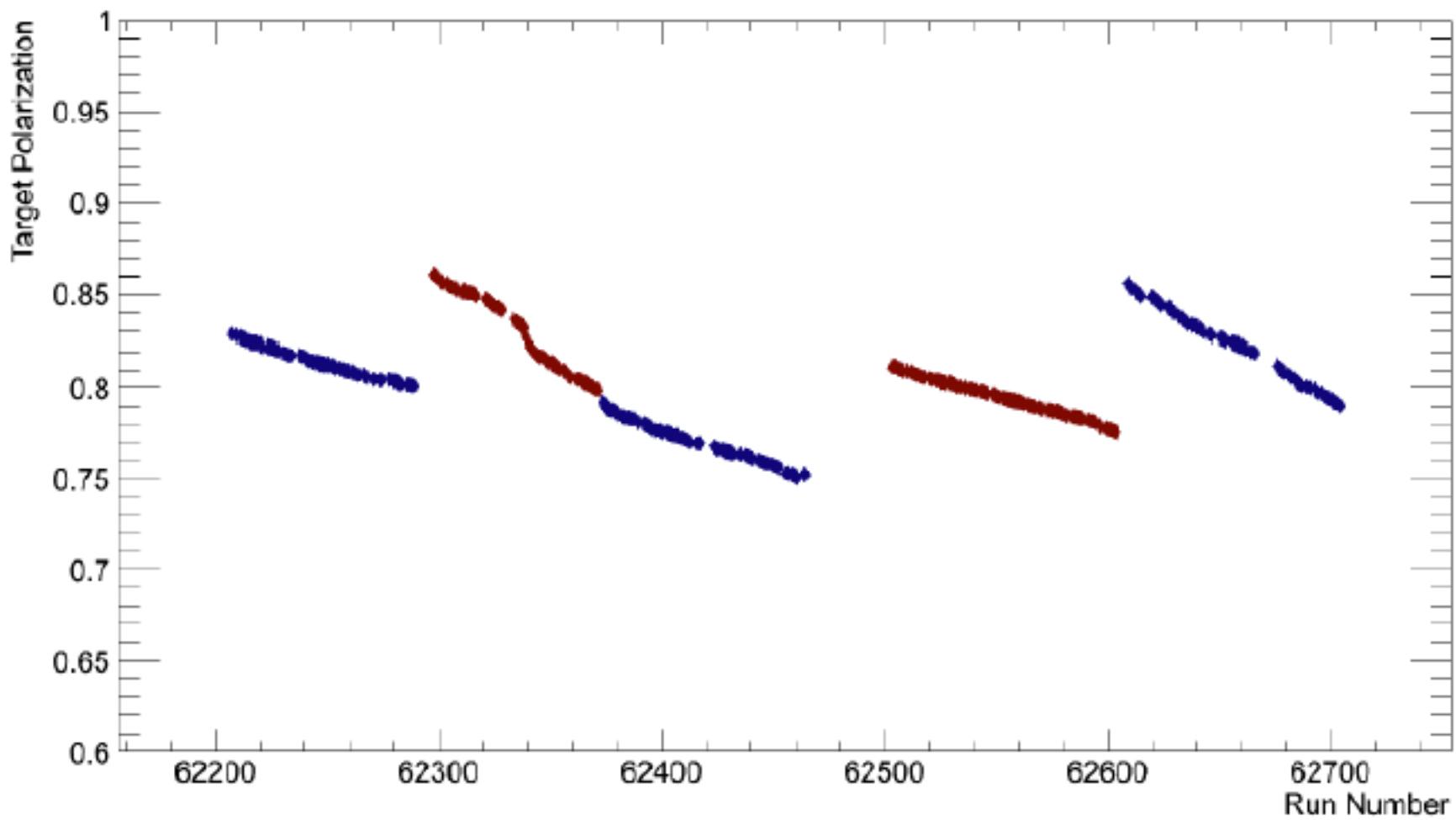


<https://www.jlab.org/highlights/images/physics/CutawayAnnotated-LG.jpg>

- Carbon target: unpolarized, L=0.15 cm, 6 cm downstream
- Polyethylene target: unpolarized, L=0.35 cm, 16 cm downstream



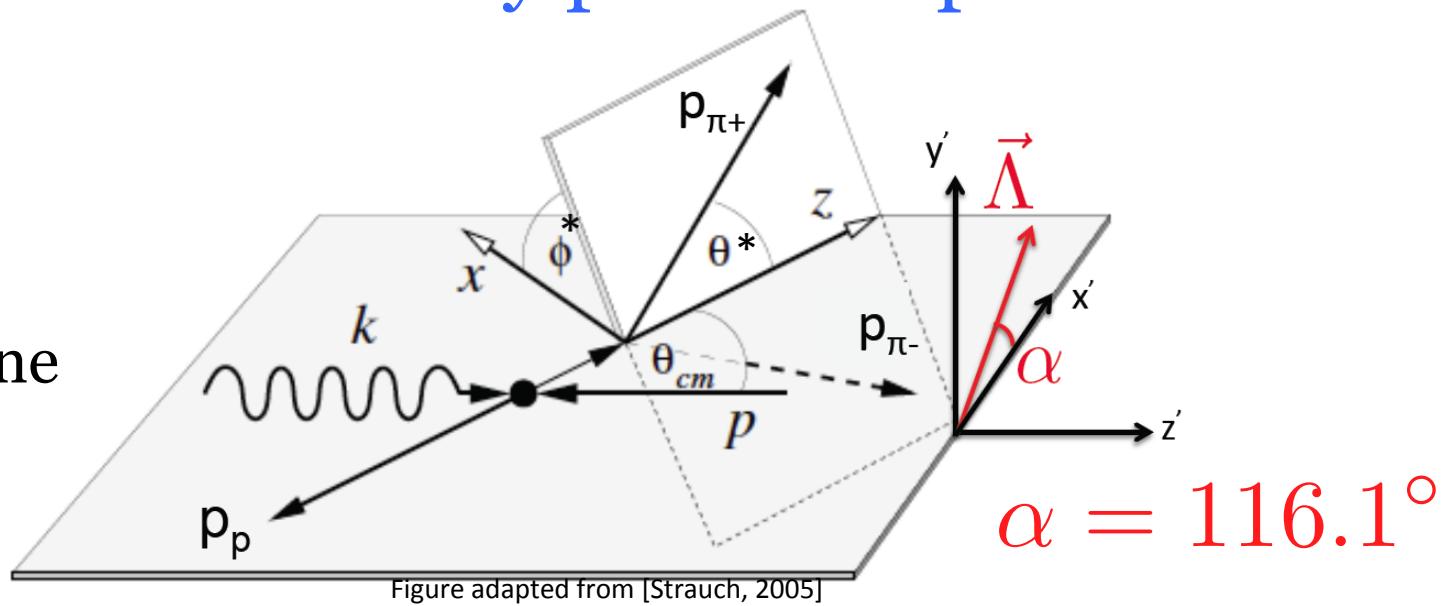
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Hao Jiang

Polarization observables for circularly polarized photons off transversely polarized protons

Reaction plane



$$Y(\alpha) = Y_0[(1 + \Lambda \cdot \cos \alpha \cdot P_x + \Lambda \cdot \sin \alpha \cdot P_y)$$

$$+ \delta_\odot (I^\odot + \Lambda \cdot \cos \alpha \cdot P_x^\odot + \Lambda \cdot \sin \alpha \cdot P_y^\odot)]$$

The moments for the two target polarization directions($0^\circ, 180^\circ$) are:

$$Y^0, Y^{180}, Y_{\sin \alpha}^0, Y_{\sin \alpha}^{180}, Y_{\cos \alpha}^0, Y_{\cos \alpha}^{180}, Y_{\sin 2\alpha}^0, Y_{\sin 2\alpha}^{180}, Y_{\cos 2\alpha}^0, Y_{\cos 2\alpha}^{180}$$

After adding and subtracting different combinations of these yields we get:

$$P_x = 2 \frac{[(Y^0 \bar{\Lambda}^{180} + Y^{180} \bar{\Lambda}^0) - (Y_{\cos 2\alpha}^0 \bar{\Lambda}^{180} + Y_{\cos 2\alpha}^{180} \bar{\Lambda}^0)](Y_{\cos \alpha}^0 + Y_{\cos \alpha}^{180}) - (Y_{\sin 2\alpha}^0 \bar{\Lambda}^{180} + Y_{\sin 2\alpha}^{180} \bar{\Lambda}^0)(Y_{\sin \alpha}^0 + Y_{\sin \alpha}^{180})}{(Y^0 \bar{\Lambda}^{180} + Y^{180} \bar{\Lambda}^0)^2 - (Y_{\cos 2\alpha}^0 \Lambda^{180} + Y_{\cos 2\alpha}^{180} \Lambda^0)^2 - (Y_{\sin 2\alpha}^0 \bar{\Lambda}^{180} + Y_{\sin 2\alpha}^{180} \bar{\Lambda}^0)^2}$$

$$P_y = 2 \frac{[(Y^0 \bar{\Lambda}^{180} + Y^{180} \bar{\Lambda}^0) + (Y_{\cos 2\alpha}^0 \bar{\Lambda}^{180} + Y_{\cos 2\alpha}^{180} \bar{\Lambda}^0)](Y_{\sin \alpha}^0 + Y_{\sin \alpha}^{180}) - (Y_{\sin 2\alpha}^0 \bar{\Lambda}^{180} + Y_{\sin 2\alpha}^{180} \bar{\Lambda}^0)(Y_{\cos \alpha}^0 + Y_{\cos \alpha}^{180})}{(Y^0 \bar{\Lambda}^{180} + Y^{180} \bar{\Lambda}^0)^2 - (Y_{\cos 2\alpha}^0 \Lambda^{180} + Y_{\cos 2\alpha}^{180} \Lambda^0)^2 - (Y_{\sin 2\alpha}^0 \bar{\Lambda}^{180} + Y_{\sin 2\alpha}^{180} \bar{\Lambda}^0)^2}$$

$$P_x^{\odot} = 2 \frac{(\bar{\Lambda}^{180}Y_{\sin 2\alpha}^0 + \bar{\Lambda}^0Y_{\sin 2\alpha}^{180})(Y_{\sin \alpha}^{+0} - Y_{\sin \alpha}^{-0} + Y_{\sin \alpha}^{+180} - Y_{\sin \alpha}^{-180}) - [(Y^0\bar{\Lambda}^{180} + Y^{180}\bar{\Lambda}^0) - (Y_{\cos 2\alpha}^0\bar{\Lambda}^{180} + Y_{\cos 2\alpha}^{180}\bar{\Lambda}^0)](Y_{\cos \alpha}^{+0} - Y_{\cos \alpha}^{-0} + Y_{\cos \alpha}^{+180} - Y_{\cos \alpha}^{-180})}{\delta_{\odot}[(\bar{\Lambda}^{180}Y_{\sin 2\alpha}^0 + \bar{\Lambda}^0Y_{\sin 2\alpha}^{180})^2 - (Y^0\bar{\Lambda}^{180} + Y^{180}\bar{\Lambda}^0)^2 + (Y_{\cos 2\alpha}^0\bar{\Lambda}^{180} + Y_{\cos 2\alpha}^{180}\bar{\Lambda}^0)^2]}$$

$$P_y^{\odot} = 2 \frac{[(Y^0\bar{\Lambda}^{180} + Y^{180}\bar{\Lambda}^0) - (Y_{\cos 2\alpha}^0\bar{\Lambda}^{180} + Y_{\cos 2\alpha}^{180}\bar{\Lambda}^0)](Y_{\sin \alpha}^{+0} - Y_{\sin \alpha}^{-0} + Y_{\sin \alpha}^{+180} - Y_{\sin \alpha}^{-180}) - (\bar{\Lambda}^{180}Y_{\sin 2\alpha}^0 + \bar{\Lambda}^0Y_{\sin 2\alpha}^{180})(Y_{\cos \alpha}^{+0} - Y_{\cos \alpha}^{-0} + Y_{\cos \alpha}^{+180} - Y_{\cos \alpha}^{-180})}{\delta_{\odot}[(Y^0\bar{\Lambda}^{180} + Y^{180}\bar{\Lambda}^0)^2 - (\bar{\Lambda}^{180}Y_{\sin 2\alpha}^0 + \bar{\Lambda}^0Y_{\sin 2\alpha}^{180})^2 - (Y_{\cos 2\alpha}^0\bar{\Lambda}^{180} + Y_{\cos 2\alpha}^{180}\bar{\Lambda}^0)^2]}$$



Run range	Date range	Events	Beam energy	Beam current	Live time	Helicity freq.	H.W.P	Phi_FG	Target pol.
62207 - 62289	3/19 - 3/23	723.1 M	3081.73 MeV	11.9 nA	0.82	240 Hz (octets)	1	90	83% - 80% (+ +)
62298 - 62372	3/24 - 3/30	894.9 M	3081.73 MeV	13.4 nA	0.83	240 Hz (octets)	1	90	86% - 80% (- +)
62374 - 62464	3/30 - 4/05	1129.7 M	3081.73 MeV	13.4 nA	0.78	240 Hz (octets) or 30 Hz (pairs, quartets) ¹	0	90	79% - 75% (+ +)
62504 - 62604	4/07 - 4/13	1307.1 M	3081.73 MeV	13.6 nA	0.83	240 Hz (octets)	0	90	81% - 76% (+ -)
62609 - 62704	4/13 - 4/19	972.6 M	3081.73 MeV	13.5 nA	0.83	240 Hz (octets) or 30 Hz (quartets) ²	0 or 1 ³	90	85% - 79% (- -)

Target polarization: (NMR_sign Holding_magnet_sign) e.g. (+ +) and (- -) means pos.sign; (+ -) and (- +) means neg.sign

POLARIZATION OBSERVABLES

$$I_0 = |M_1^-|^2 + |M_1^+|^2 + |M_2^-|^2 + |M_2^+|^2 + |M_3^-|^2 + |M_3^+|^2 + |M_4^-|^2 + |M_4^+|^2$$

$$I_0 P_x = 2\Re(M_1^- M_3^{-*} + M_1^+ M_3^{+*} + M_2^- M_4^{-*} + M_2^+ M_4^{+*})$$

$$I_0 P_y = -2\Im(M_1^- M_3^{-*} + M_1^+ M_3^{+*} + M_2^- M_4^{-*} + M_2^+ M_4^{+*})$$

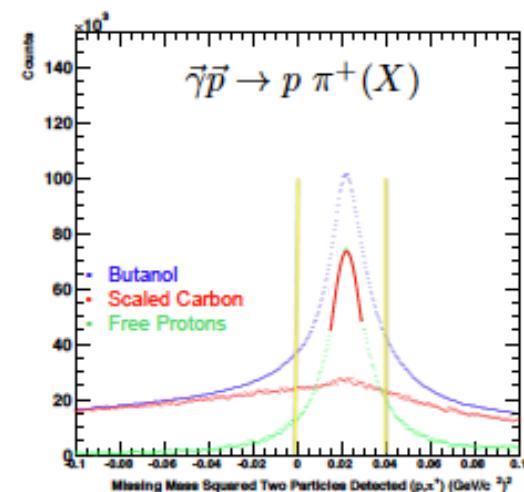
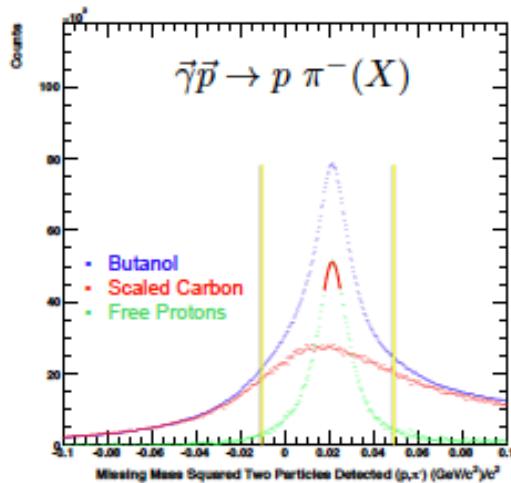
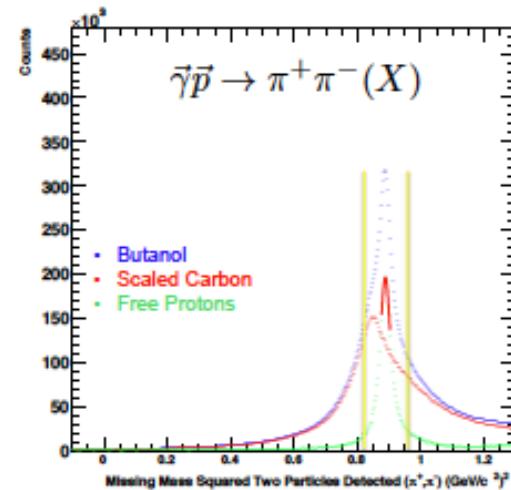
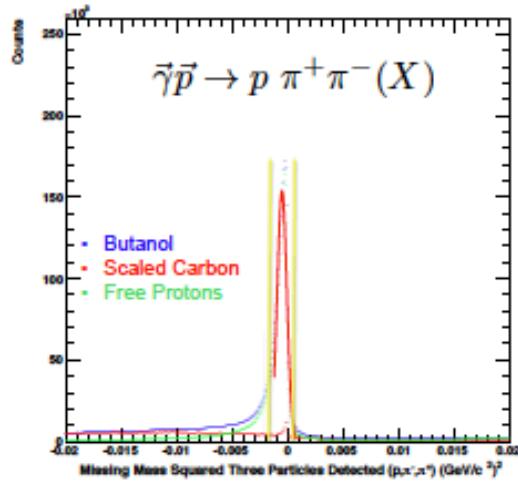
$$I_0 I^\odot = -|M_1^-|^2 + |M_1^+|^2 - |M_2^-|^2 + |M_2^+|^2 - |M_3^-|^2 + |M_3^+|^2 - |M_4^-|^2 + |M_4^+|^2$$

$$I_0 P_x^\odot = 2\Re(-M_1^- M_3^{-*} + M_1^+ M_3^{+*} - M_2^- M_4^{-*} + M_2^+ M_4^{+*})$$

$$I_0 P_y^\odot = 2\Im(M_1^- M_3^{-*} - M_1^+ M_3^{+*} + M_2^- M_4^{-*} - M_2^+ M_4^{+*})$$



Missing Mass Squared Distributions



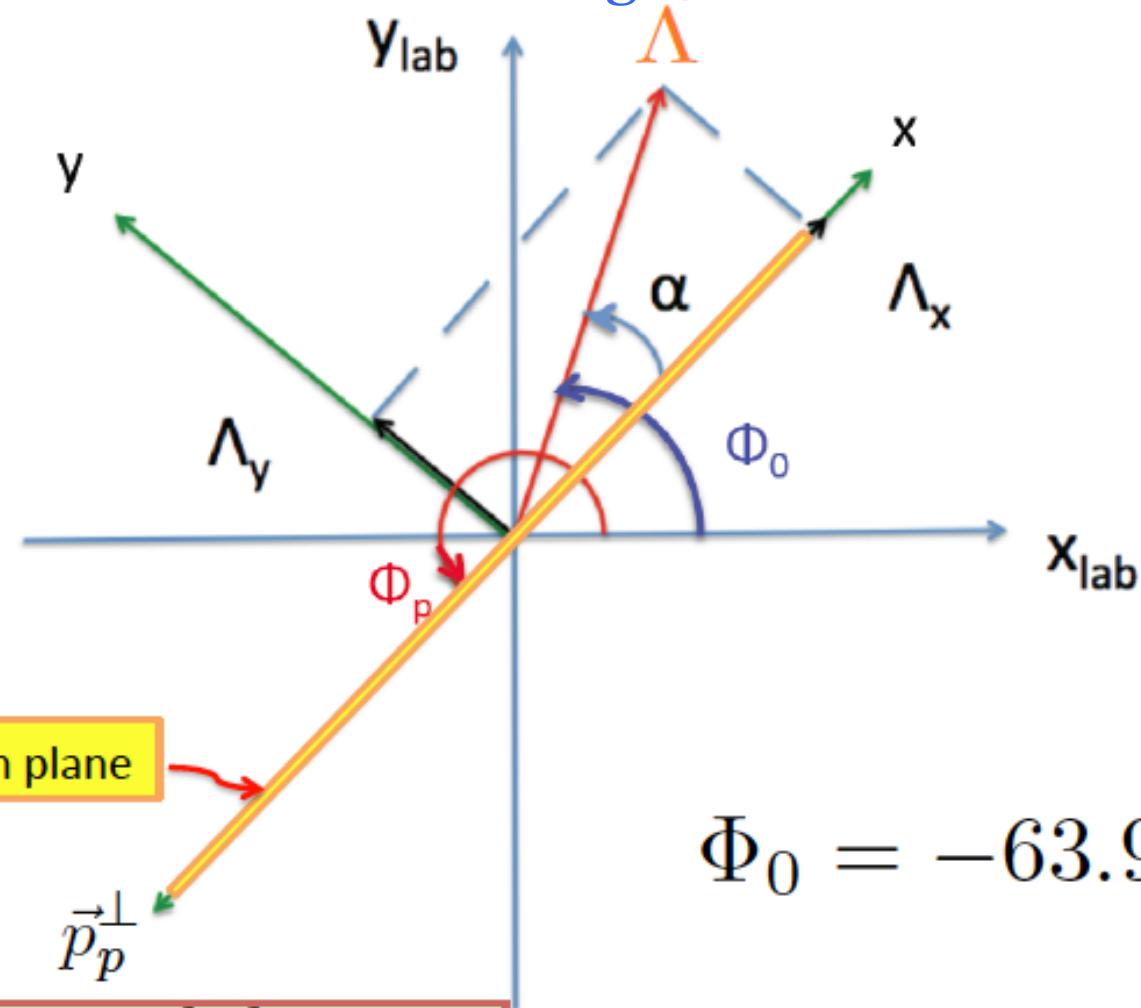
Observables odd/even behavior fit check

$$F_{even} = a_0 + a_1 \cos(\Phi^*) + a_2 \cos(2\Phi^*) + a_3 \cos(3\Phi^*) + a_4 \cos(4\Phi^*)$$

$$F_{odd} = b_1 \sin(\Phi^*) + b_2 \sin(2\Phi^*) + b_3 \sin(3\Phi^*) + b_4 \sin(4\Phi^*)$$

$$\sigma_{Obs} = \sqrt{\frac{\sum_{i=1}^N \frac{[Obs_i^{nom} - Obs_i^{alt}]^2}{(\sigma_i^{nom})^2}}{\sum_{i=1}^N \frac{1}{(\sigma_i^{nom})^2}}}$$

Target polarization orientation angle

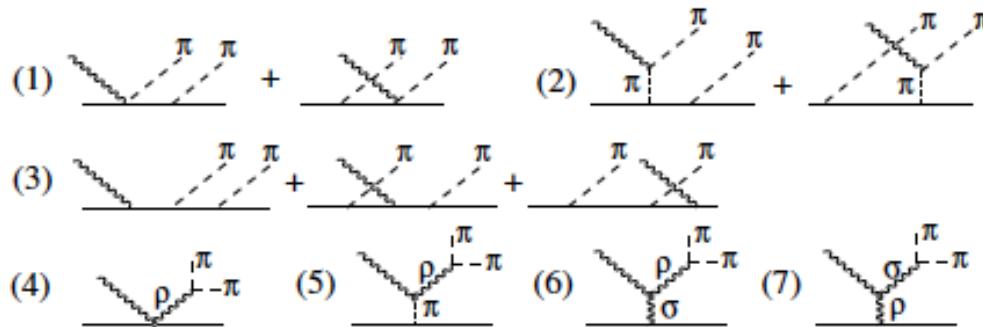


$$\Phi_0 = -63.9^\circ, 116.1^\circ$$

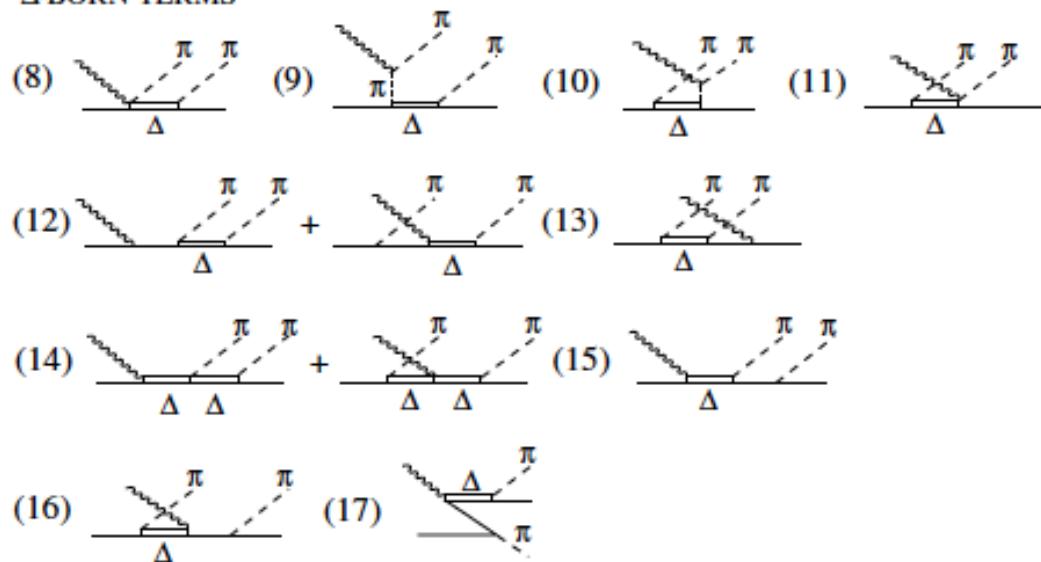
$$\alpha = 180^\circ - \Phi_p^{\text{lab}} + \Phi_0$$



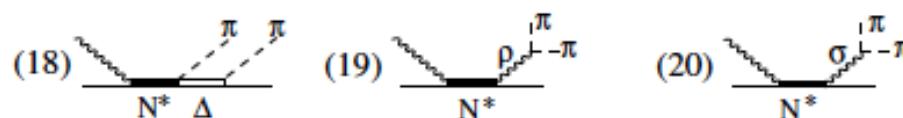
N-BORN TERMS



Δ -BORN TERMS



RESONANCE TERMS





$$|\phi_{sector}| < \begin{cases} 0 & \text{for } \theta < \theta_{min} \\ \phi_{max} \left(\frac{\theta - \theta_{min}}{\theta_{max} - \theta_{min}} \right)^{1/4} & \theta_{min} > \theta > \theta_{max} \\ \phi_{max} & \theta > \theta_{max} \end{cases}$$

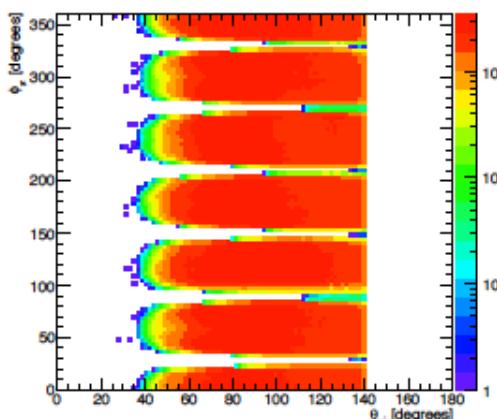
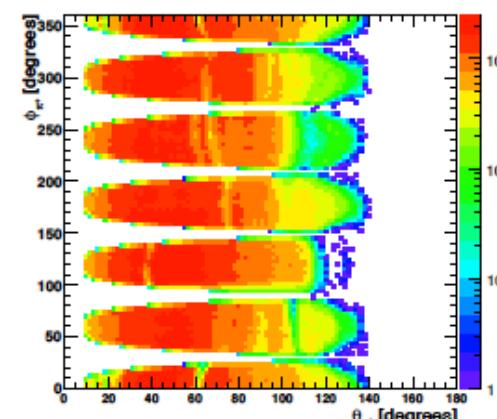
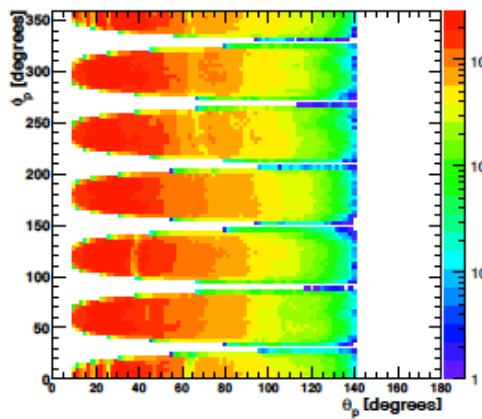
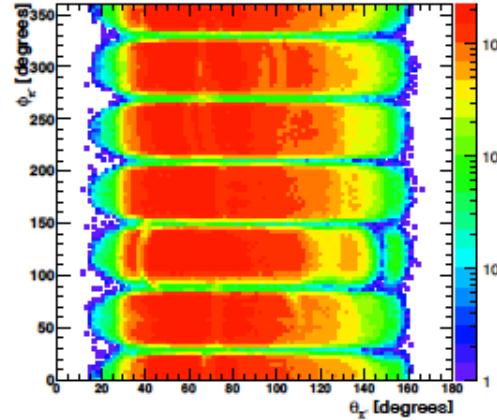
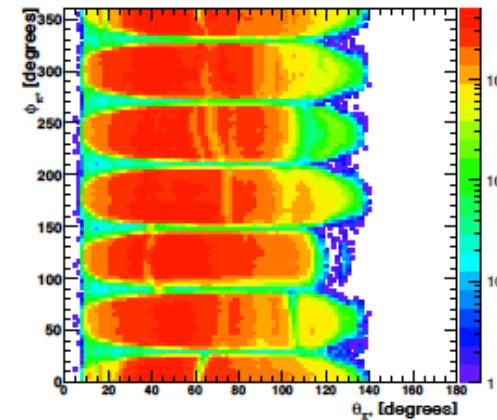
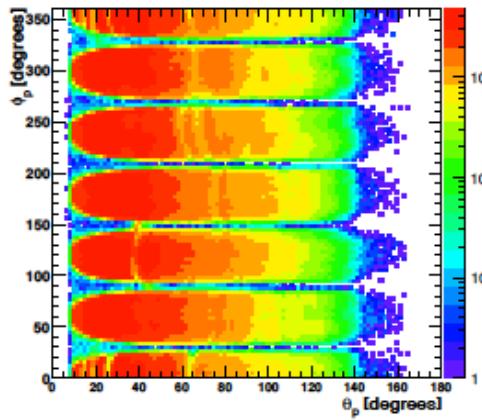
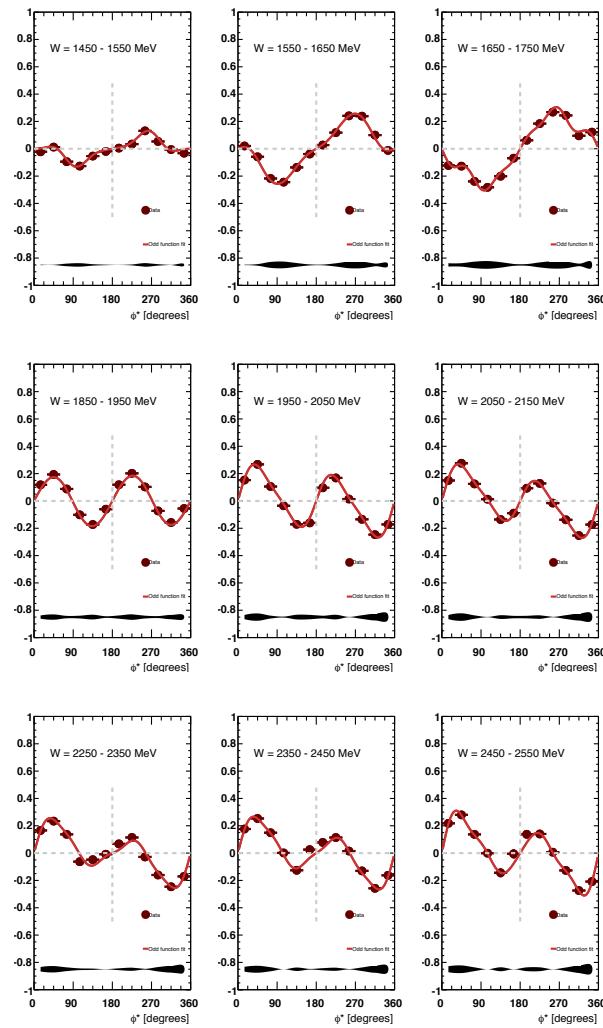


Table 3.1: Bad TOF paddles that were eliminated from this analysis.

Sector	TOF paddle
1	34, 44, 52, 53, 54, 55, 56, 57
2	26, 44, 45, 49, 51, 53, 54, 55, 56, 57
3	23, 26, 50, 51, 52, 53, 54, 55, 56, 57
4	44, 48, 49, 53, 54, 55, 56, 57
5	22, 23, 27, 40, 50, 51, 52, 53, 54, 55, 56, 57
6	14, 33, 49, 52, 53, 54, 55, 56, 57



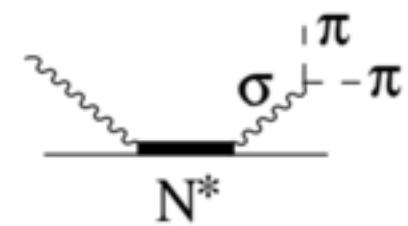
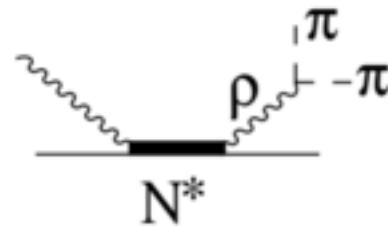
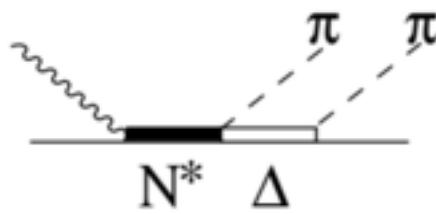
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MODEL CALCULATION AND DATA COMPARISON

Effective Lagrangean Model (A. Fix)

- Nucleon and Delta Born terms, Resonances $\Delta(1232)$, $N^*(1440)$, $N^*(1520)$, $N^*(1535)$, $\Delta(1620)$, $N^*(1675)$, $N^*(1680)$, $N^*(1700)$, $N^*(1720)$



[A.Fix, H. Arenhövel, Eur.Phys.J.A **25**, 115 (2005)]

- The model takes as an input the four momentum vectors of the incident and the final state particles and calculates the differential cross-section in the center of mass frame

SYSTEMATIC UNCERTAINTIES

Source	I^\odot	P_x	P_y	P_x^\odot	P_y^\odot
Beam charge asymmetry	0.01%	0.0%	0.0%	0.01%	0.01%
Photon beam polarization	3.0%	0.0%	0.0%	3.0%	3.0%
Target polarization	0.0%	< 3.5%	< 3.5%	< 3.5%	< 3.5%
Acceptance change	0.0	< 0.01	< 0.01	0.0	0.0
Background subtraction method	0.001	0.001	0.002	0.003	0.002
Target polarization angle offset	0.0	< 0.001	< 0.001	< 0.001	< 0.001
Particle ID	0.01	0.01	0.01	0.02	0.02
TOTAL (absolute)	0.01	0.01	0.01	0.02	0.02
TOTAL (%)	3.0%	3.5%	3.5%	4.6%	4.6%