

# Polarization Observables in Kaon Photoproduction

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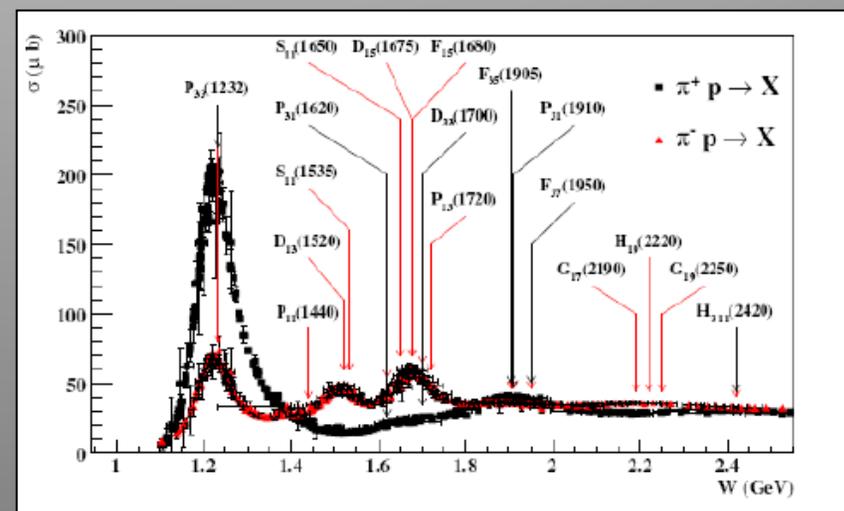
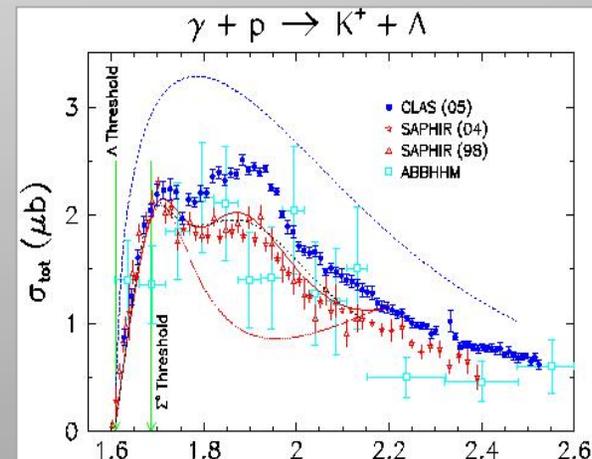
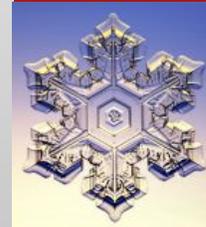
# Outline

- Introduction
- Experimental Setup
- Event Selection
- Preliminary Results
- Conclusion

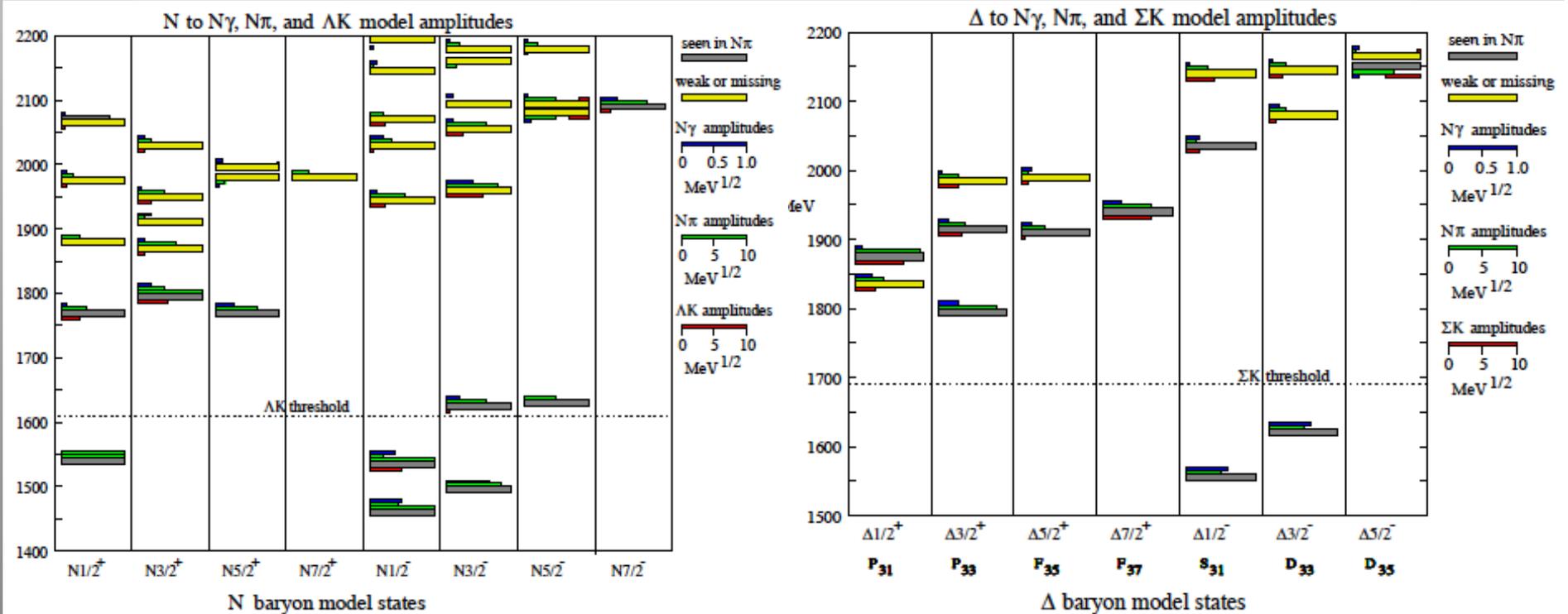


# Baryon Resonances

- Approximate models are used to describe the nucleon spectrum
- Most resonances found in  $\pi N$  PWA
- Other channels may provide info on resonances that do NOT couple to  $\pi N$
- $K^+ \Lambda$  is an isospin filter....no coupling to  $\Delta^*$  ( $I=3/2$ )
- $K^+ \Lambda$  cross section easier disentangled since it only couples to a few  $N^*$  resonances (and those might couple weakly to  $\pi N$ !)

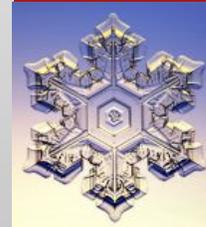


# Constituent Quark Model

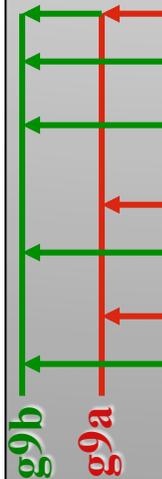


- Above 1850 MeV ( $N^*$ ) and 1950 MeV ( $\Delta^*$ ) most have predicted states that have not been seen experimentally
- More model states predicted than observed so far

# Polarization Observables



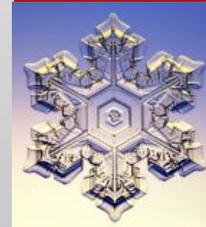
Spin observable	Helicity representation
$\check{\Omega}^1 \equiv \mathcal{I}(\theta)$	$\frac{1}{2}( H_1 ^2 +  H_2 ^2 +  H_3 ^2 +  H_4 ^2)$
$\check{\Omega}^4 \equiv \check{\Sigma}$	$\text{Re}(-H_1H_4^* + H_2H_3^*)$
$\check{\Omega}^{10} \equiv -\check{T}$	$\text{Im}(H_1H_2^* + H_3H_4^*)$
$\check{\Omega}^{12} \equiv \check{P}$	$\text{Im}(-H_1H_3^* - H_2H_4^*)$
$\check{\Omega}^3 \equiv \check{G}$	$\text{Im}(H_1H_4^* - H_3H_2^*)$
$\check{\Omega}^5 \equiv \check{H}$	$\text{Im}(-H_2H_4^* + H_1H_3^*)$
$\check{\Omega}^9 \equiv \check{E}$	$\frac{1}{2}( H_1 ^2 -  H_2 ^2 +  H_3 ^2 -  H_4 ^2)$
$\check{\Omega}^{11} \equiv \check{F}$	$\text{Re}(-H_2H_1^* - H_4H_3^*)$
$\check{\Omega}^{14} \equiv \check{O}_x$	$\text{Im}(-H_2H_1^* + H_4H_3^*)$
$\check{\Omega}^7 \equiv -\check{O}_z$	$\text{Im}(H_1H_4^* - H_2H_3^*)$
$\check{\Omega}^{16} \equiv -\check{C}_x$	$\text{Re}(H_2H_4^* + H_1H_3^*)$
$\check{\Omega}^2 \equiv -\check{C}_z$	$\frac{1}{2}( H_1 ^2 +  H_2 ^2 -  H_3 ^2 -  H_4 ^2)$
$\check{\Omega}^6 \equiv -\check{T}_x$	$\text{Re}(-H_1H_4^* - H_2H_3^*)$
$\check{\Omega}^{13} \equiv -\check{T}_z$	$\text{Re}(-H_1H_2^* + H_4H_3^*)$
$\check{\Omega}^8 \equiv \check{L}_x$	$\text{Re}(H_2H_4^* - H_1H_3^*)$
$\check{\Omega}^{15} \equiv \check{L}_z$	$\frac{1}{2}(- H_1 ^2 +  H_2 ^2 +  H_3 ^2 -  H_4 ^2)$



- Photoproduction of single pseudoscalar mesons is described by four complex helicity amplitudes, which describe all spin combinations of incoming and outgoing particles, leading to 16 bilinear products
- Polarization observables are combinations of the 16 bilinear products and can be extracted based on target, beam, and recoil polarization
- Not all observables are independent from each other

	Photon			Target			Recoil			Target + Recoil		
	$x$	$y$	$z$	$x'$	$y'$	$z'$	$x''$	$y''$	$z''$	$x'''$	$y'''$	$z'''$
unpolarized	$\sigma_0$	0	$T$	0	0	$P$	0	$T_{x'}$	$-L_{x'}$	$T_{z'}$	$L_{z'}$	
linear pol.	$-\Sigma$	$H$	$(-P)$	$-G$	$O_{x'}$	$(-T)$	$O_{z'}$	$(-L_{z'})$	$(T_{z'})$	$(-L_{x'})$	$(-T_{x'})$	
circular pol.	0	$F$	0	$-E$	$-C_{x'}$	0	$-C_{z'}$	0	0	0	0	

# Available World Data



$\gamma p \rightarrow K^+ \Lambda$	Observ.	$N_{\text{data}}$	$\chi^2_1/N_{\text{data}}$
[43] CLAS	$d\sigma/d\Omega$	1320	0.69
[51] LEPS	$\Sigma$	45	2.11
[50] GRAAL	$\Sigma$	66	2.95
[43] CLAS	$P$	1270	1.82
[50] GRAAL	$P$	66	0.59
[52] GRAAL	$T$	66	1.62
[40] CLAS	$C_x$	160	1.52
[40] CLAS	$C_z$	160	1.58
[52] GRAAL	$O_{x'}$	66	1.95
[52] GRAAL	$O_{z'}$	66	1.66

Available data used by Bonn-Gatchina solution (BG2011-12)

Clear lack in data for kaon photoproduction!!

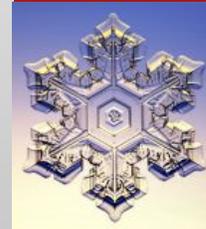
$\gamma p \rightarrow K^+ \Sigma^0$	Observ.	$N_{\text{data}}$	$\chi^2_1/N_{\text{data}}$
[62] CLAS	$d\sigma/d\Omega$	1590	1.44
[51] LEPS	$\Sigma$	45	1.23
[52] GRAAL	$\Sigma$	42	1.99
[62] CLAS	$P$	344	2.69
[40] CLAS	$C_x$	94	1.95
[40] CLAS	$C_z$	94	1.66

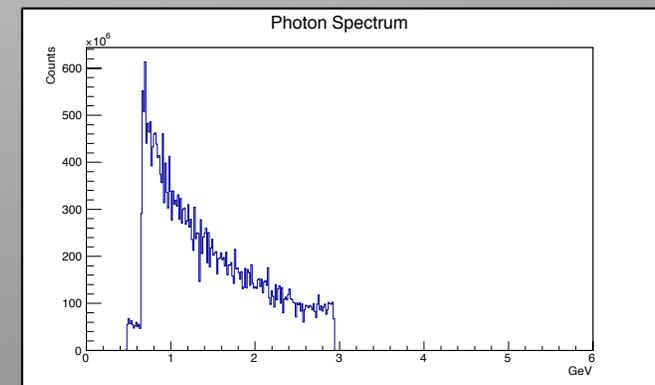
$\gamma p \rightarrow K^0 \Sigma^+$	Obsv.	$N_{\text{data}}$	$\chi^2_1/N_{\text{data}}$
[63] CLAS	$d\sigma/d\Omega$	48	3.84
[64] SAPHIR	$d\sigma/d\Omega$	160	1.91
[65] CBT	$d\sigma/d\Omega$	72	0.76
[66] CBT	$d\sigma/d\Omega$	72	0.62
[65] CBT	$P$	72	0.90
[66] CBT	$P$	24	0.94
[66] CBT	$\Sigma$	15	1.73

# Experimental Setup

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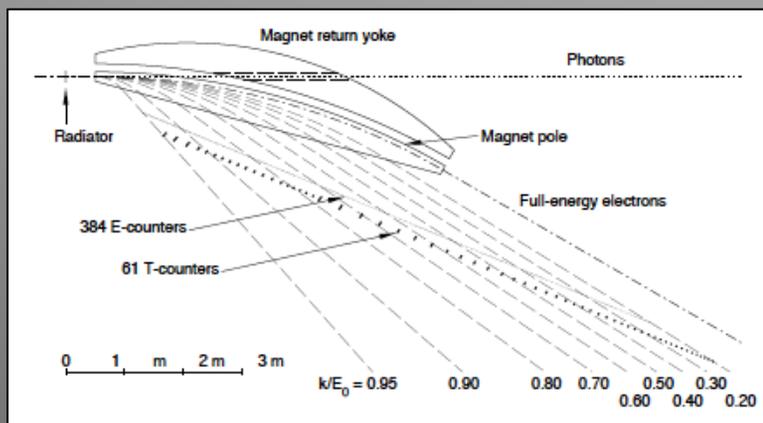
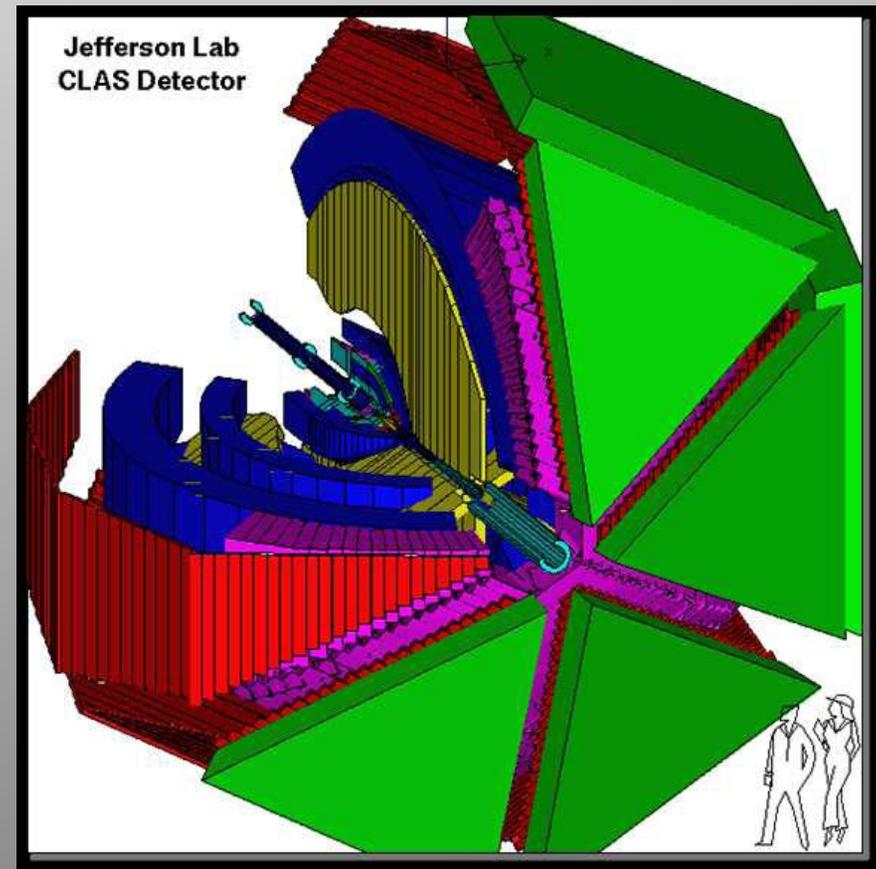
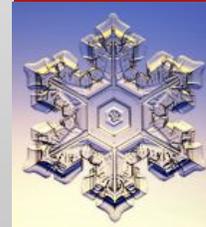


- The **FROST** experiment was first approved in 2002 with CLAS, ran in two parts in 2007-2008 (g9a-longitudinally polarized target) and 2010 (g9b-transversely polarized target)
- Butanol **FRO**zen **S**pin **T**arget with free protons polarized
- Polarized photon beam
  - Circularly (Au radiator)
  - Linearly (Diamond radiator)
- Photon beam energies from 0.5 to 3.0 GeV  
1.1 to 2.1 GeV (linear)
- 10 billion events collected (g9a)  
14 billion events collected (g9b)
- 'Complete measurement': all beam-target and target-recoil observables from  $K^+ \Lambda$  and  $K^+ \Sigma^0$  final states



# JLab, CLAS, and the Tagger

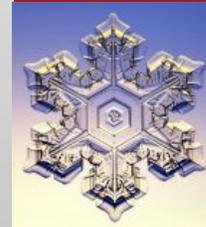
- Up to 5 passes for a max of ~ 6 GeV (upgrade allows ~12 GeV)
- After bremsstrahlung, recoil electrons are bent towards the electron dump via a dipole magnetic field created by the tagger magnet
- Tagger had ability to measure electron energies that are then used to calculate the energy associated with the photons and timing of accelerator
- CLAS had almost full acceptance, 80% of  $4\pi$  coverage



$$E_{\gamma} = E_{\text{beam}} - E_{\text{e scattered}}$$

# FROST Target

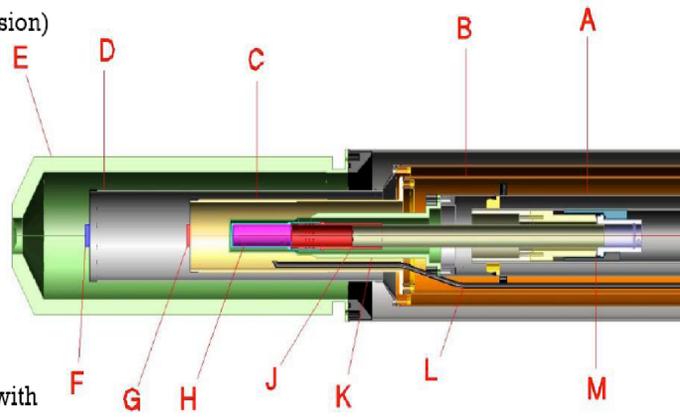
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## The FroST target and its components:

- A: Primary heat exchanger
- B: 1 K heat shield
- C: Holding coil
- D: 20 K heat shield
- E: Outer vacuum can (Rohacell extension)
- F: CH<sub>2</sub> target
- G: Carbon target
- H: Butanol target
- J: Target insert
- K: Mixing chamber
- L: Microwave waveguide
- M: Kapton coldseal

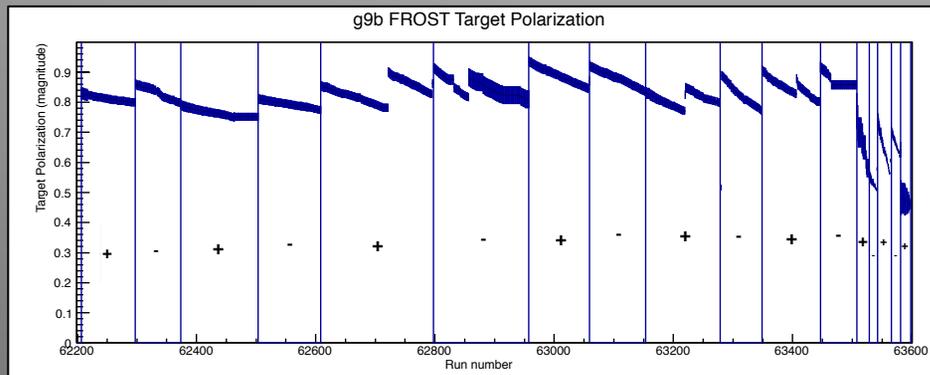
Butanol Composition:  
C<sub>4</sub>H<sub>9</sub>OH + liquid He



## Performance Specs:

- Base Temp: 28 mK w/o beam, 30 mK with
- Cooling Power: 800  $\mu$ W @ 50 mK, 10 mW @ 100 mK, and 60 mW @ 300 mK
- Polarization: +82%, -90%
- 1/e Relaxation Time: 2800 hours (+Pol), 1600 hours (-Pol)

- Butanol in LHe bath
- Polarizing 5 Tesla magnet aligns free proton spins
- Holding coil keeps proton polarized



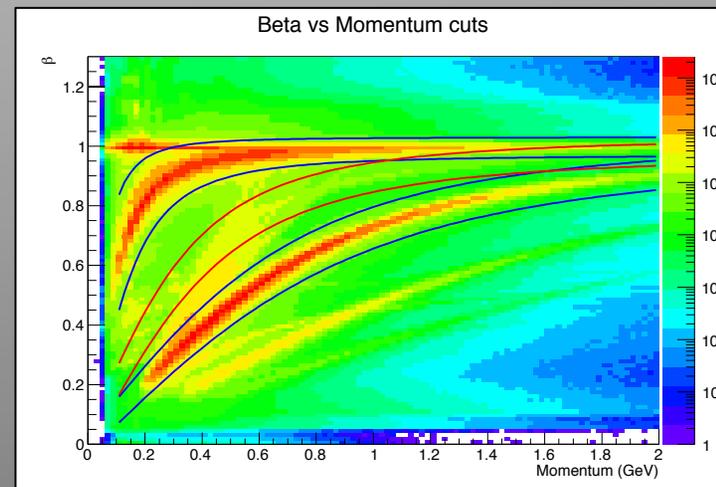
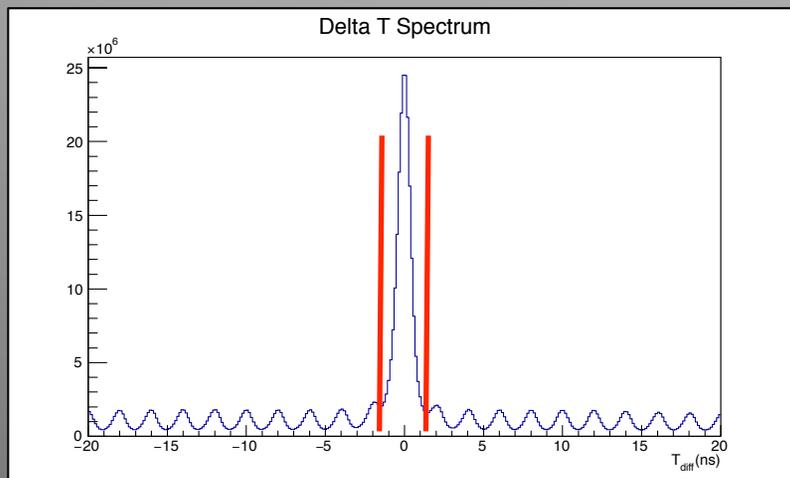
Target re-polarized  
~once per week!!

# Event Selection

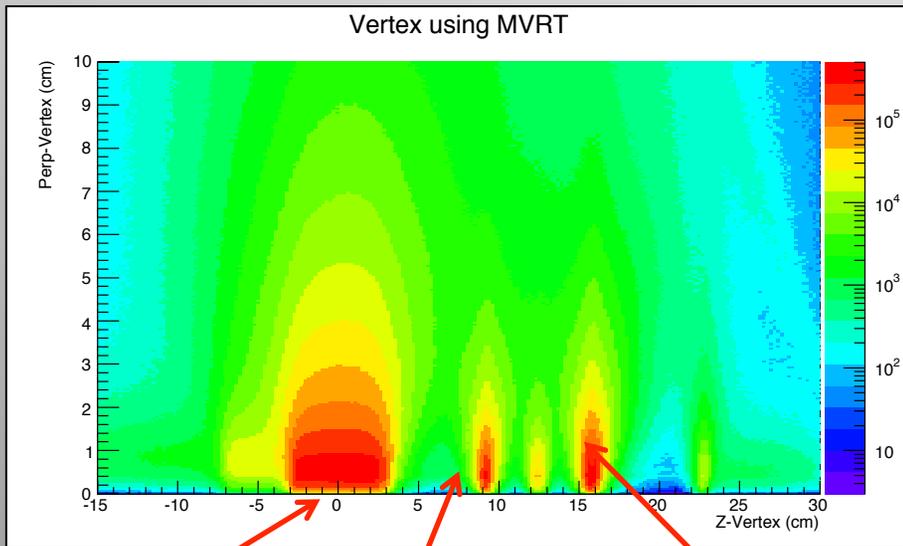
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- Skimmed data for events
  - $\gamma p \rightarrow K^+ \Lambda \rightarrow K^+ p(\pi^-)$  AND  $\gamma p \rightarrow K^+ \Sigma^0 \rightarrow K^+ \Lambda \gamma \rightarrow K^+ p(\gamma \pi^-)$
- One proton, one kaon identified
- One photon identified with cut on coincidence of  $\pm 1$  ns
- Only two positively charged particles



# Vertices

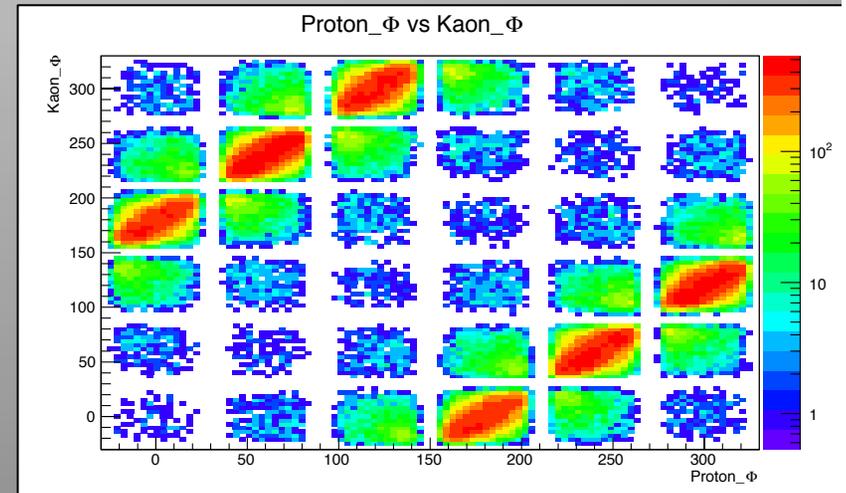
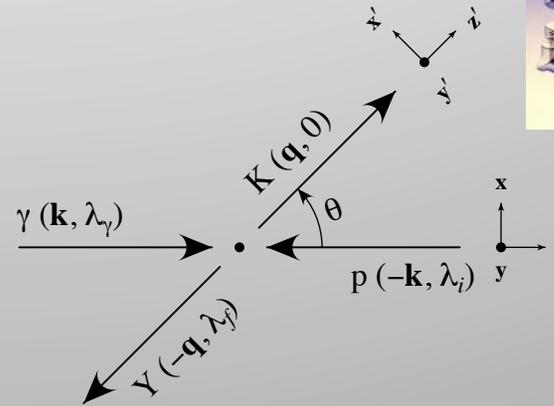


Butanol

Carbon

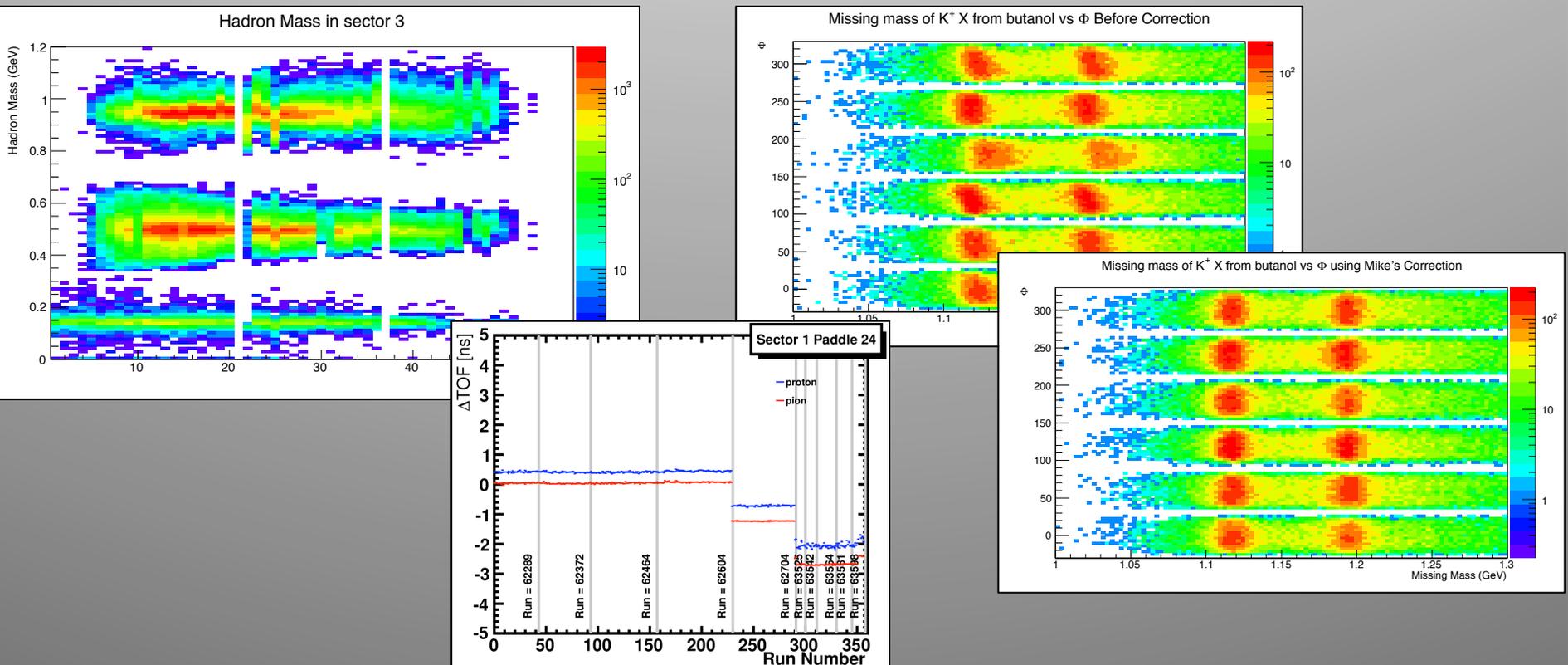
CH<sub>2</sub>

- Cut on kaon event vertex
- Check whether p from  $\Lambda$  decay vertex by comparing azimuthal angles of p and  $K^+$  (p almost in same direction as  $\Lambda$ , which is opposite of  $K^+$  in CM frame)



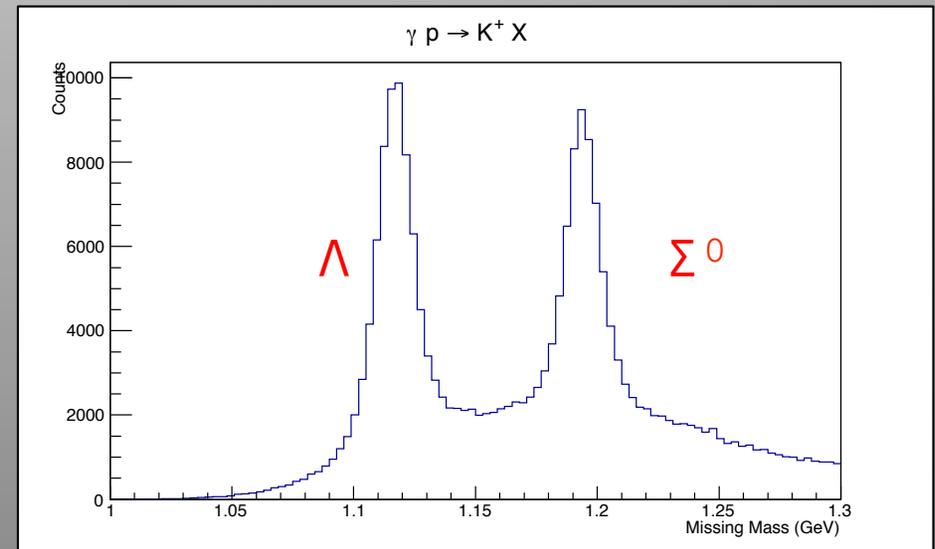
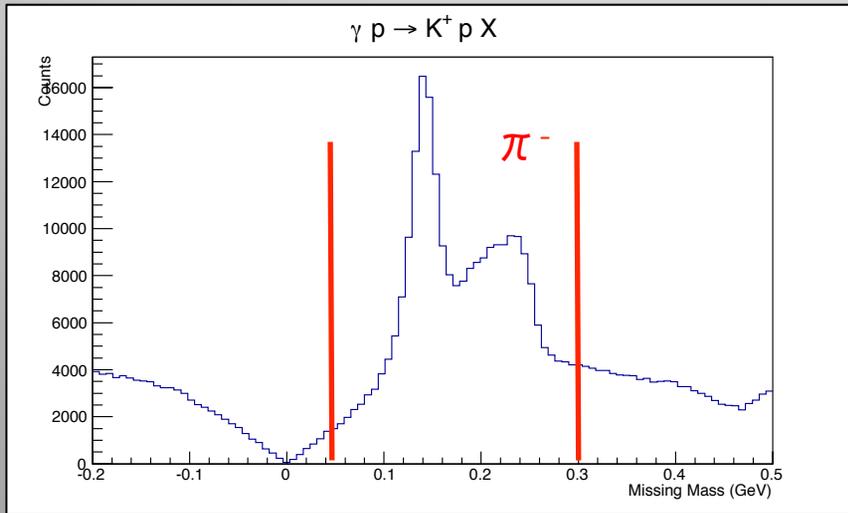
# Corrections to Data

- Bad TOF paddles cut
- Sector dependent momentum correction applied
- Timing offset between protons and pions in TOF corrected



# Missing Mass Cuts

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# Extracting $\varphi$ -dependent Observables: Moment Method

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$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} \left( 1 + P_{XY}^{lab} P_c F \cos\phi - P_{XY}^{lab} T \sin\phi \right)$$

Define phi dependent density function within each W and cosine bin

$$f^{i,j}(\varphi) \equiv \rho L \int_{E_{i-1}}^{E_i} \int_{\cos\theta_{j-1}}^{\cos\theta_j} \varepsilon(E, \theta, \varphi) \frac{d^3\sigma}{d(\cos\theta)dEd\varphi} d(\cos\theta)dE$$

Expand density function  $f(\phi)$  in Fourier series...

$$f_a^{i,j}(\varphi) = a_0 + \sum_{m=1}^{\infty} [a_m \cos(m\varphi) + b_m \sin(m\varphi)]$$

$$Y_{l,n} = \int_0^{2\pi} f_i^{i,j}(\phi) \cos(n\phi) d\phi$$

$$Z_{l,n} = \int_0^{2\pi} f_i^{i,j}(\phi) \sin(n\phi) d\phi$$

Separate cosine/sin terms

# Moment Method Continued



$$Y_{l,n} = \int_0^{2\pi} f_l^{i,j}(\phi) \cos(n\phi) d\phi \quad Z_{l,n} = \int_0^{2\pi} f_l^{i,j}(\phi) \sin(n\phi) d\phi$$

$$T = 2 \frac{\bar{Z}_{A,1} + \bar{Z}_{B,1} - \bar{Z}_{C,1} - \bar{Z}_{D,1}}{P_C(\bar{Y}_{A,0} + \bar{Y}_{B,0} - \bar{Y}_{A,2} - \bar{Y}_{B,2}) + P_A(\bar{Y}_{C,0} + \bar{Y}_{D,0} - \bar{Y}_{C,2} - \bar{Y}_{D,2})}$$

$$F = \frac{2(P_A + P_C)}{P_A P_C (\lambda_A + \lambda_C)} \frac{P_C(\bar{Y}_{A,1} - \bar{Y}_{B,1}) + P_A(\bar{Y}_{D,1} - \bar{Y}_{C,1})}{P_C(\bar{Y}_{A,0} + \bar{Y}_{B,0} + \bar{Y}_{A,2} + \bar{Y}_{B,2}) + P_A(\bar{Y}_{C,0} + \bar{Y}_{D,0} + \bar{Y}_{C,2} + \bar{Y}_{D,2})}$$

$\lambda_A$  – positive helicity  
 $\lambda_C$  – negative helicity

$P_A$  – positive target polarization  
 $P_C$  – negative target polarization

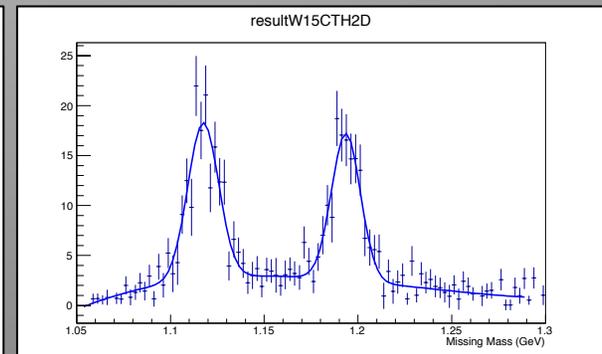
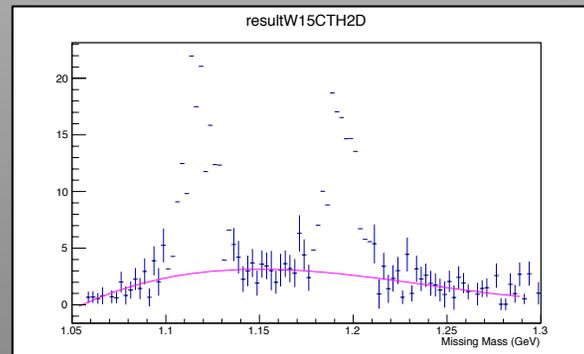
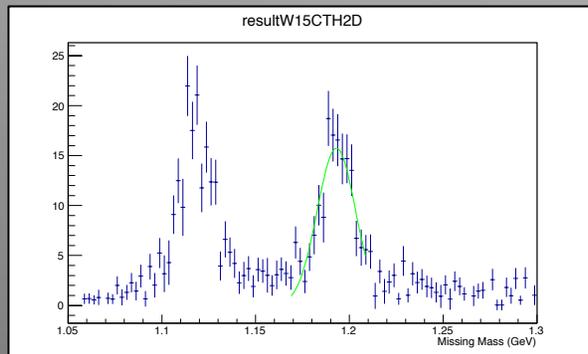
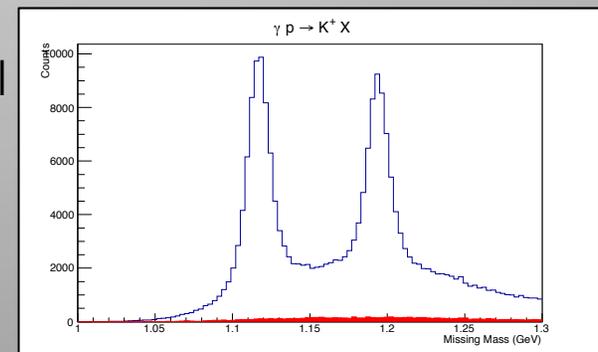
$T_x$  and  $T_z$  are double polarization observables with a transverse target polarization and recoil polarization in the  $\Lambda$  decay plane and calculated in similar way with moments!!

# Background Subtraction

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- Quasi-free kaon production is suppressed on **carbon** – so need to subtract free protons from bound protons
  - Fit  $\Lambda$  and  $\Sigma^0$  signals with Gaussian
  - Fit remaining background with cubic polynomial
  - Then make a combined fit
  - Do for every  $\cos \theta$  bin in every W bin!



Butanol –  $C_4H_9OH$  – only **10** free protons, 64 bound protons!!

# Background Subtraction

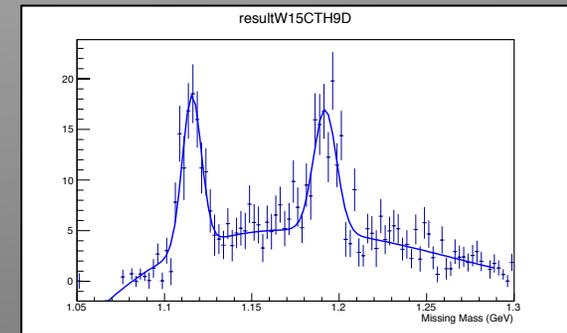
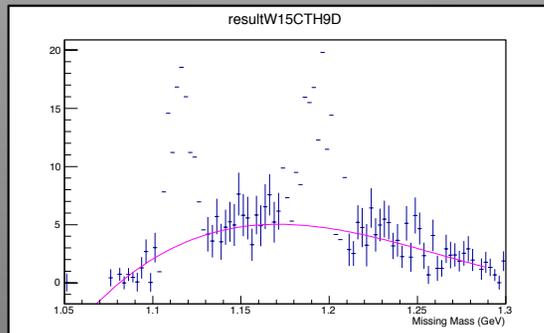
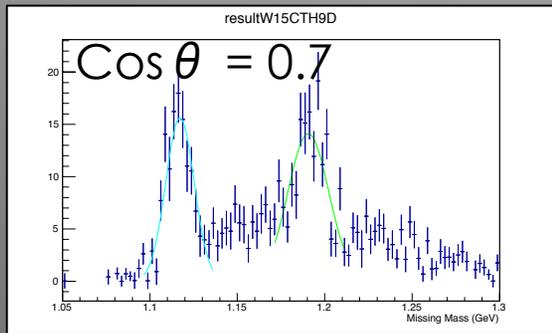
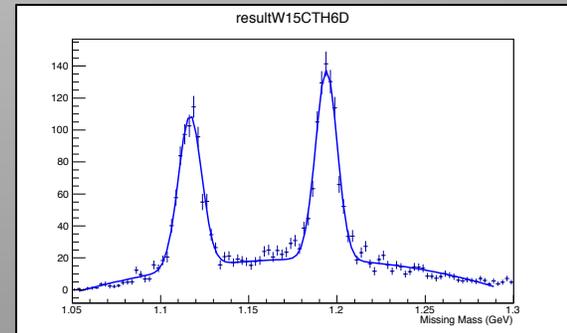
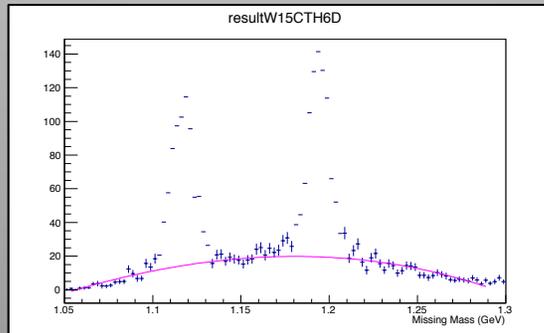
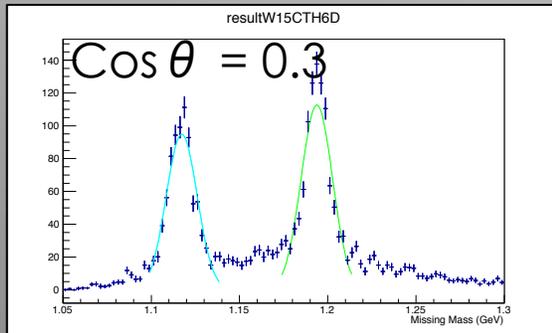
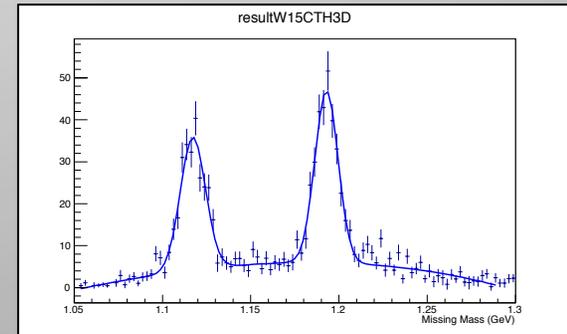
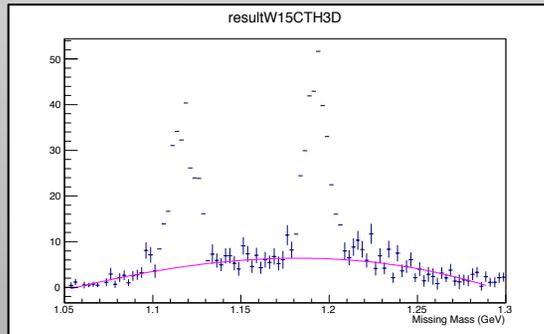
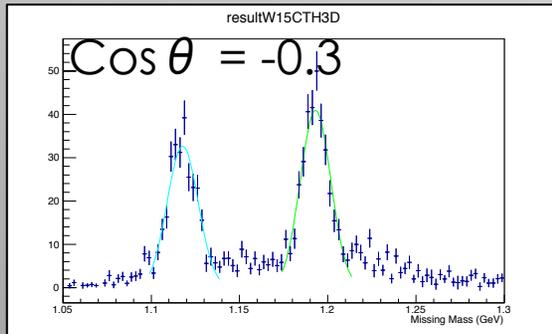
Example of Background Subtraction for  $W = 1875$  MeV



Gaussian

3<sup>rd</sup> Order Polynomial

Global

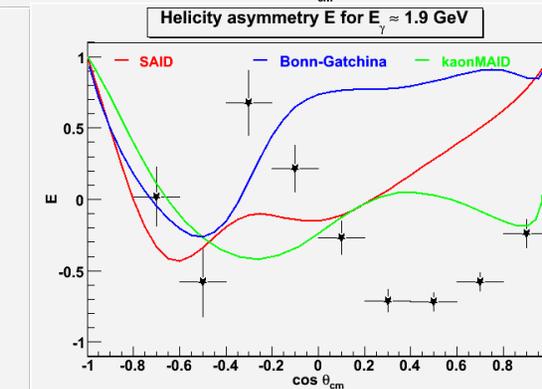
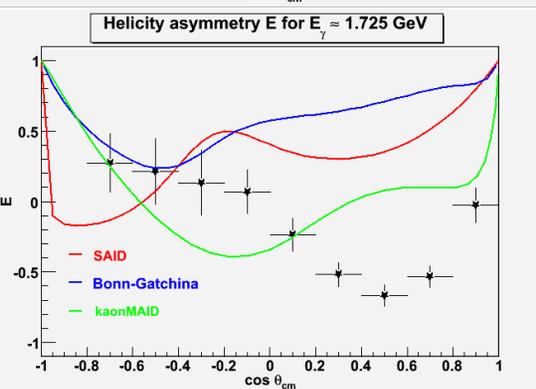
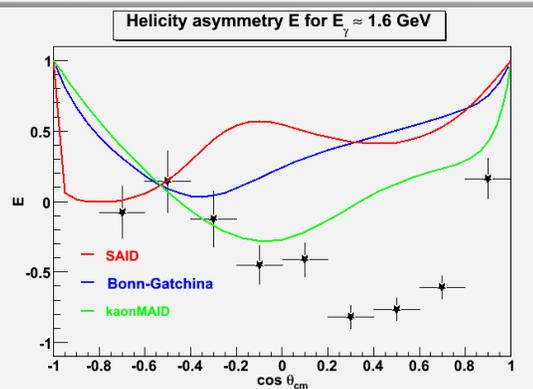
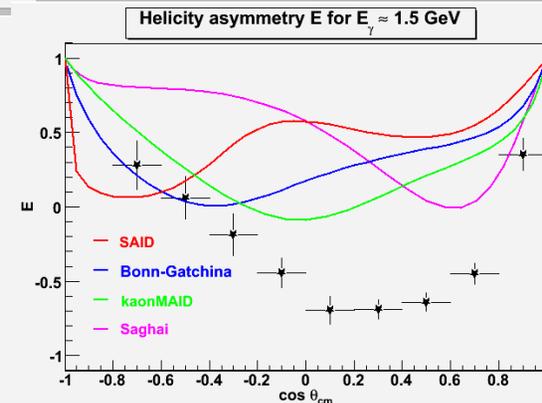
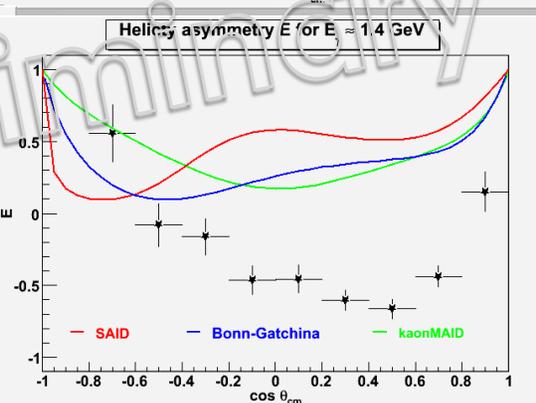
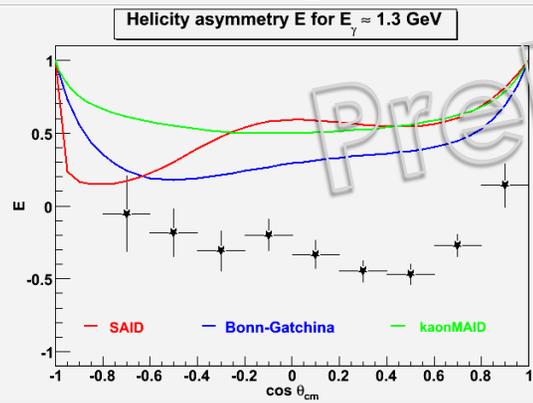
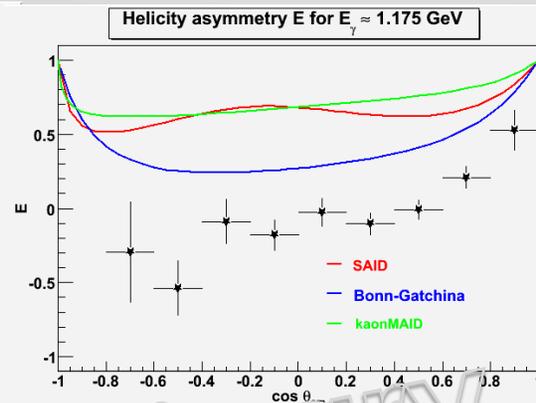
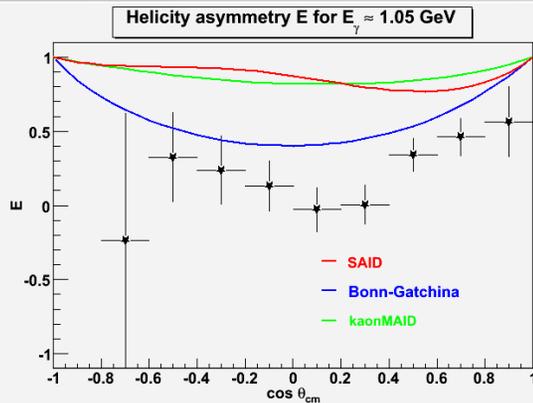


# Results

- Results for  $E$ ,  $L_x$ ,  $L_z$ ,  $T$ ,  $F$ ,  $T_x$ , and  $T_z$
- Compared to theoretical models
  - KAON-MAID...isobar model
  - Bonn-Gatchina (BOGA)...coupled channel PWA
  - RPR-Ghent...isobar model

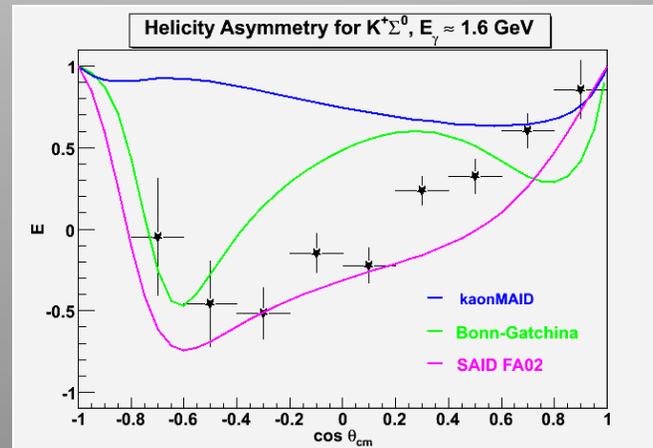
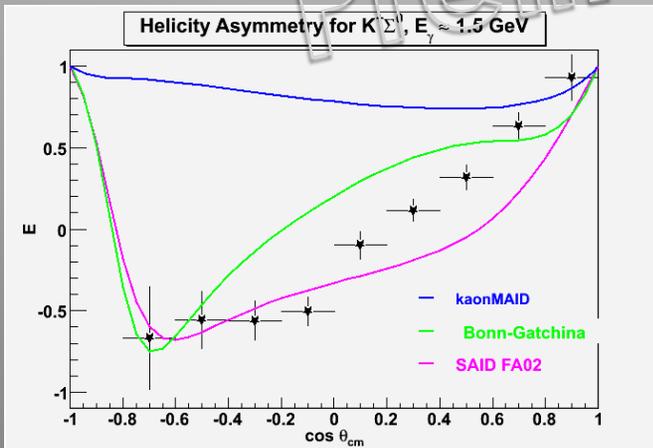
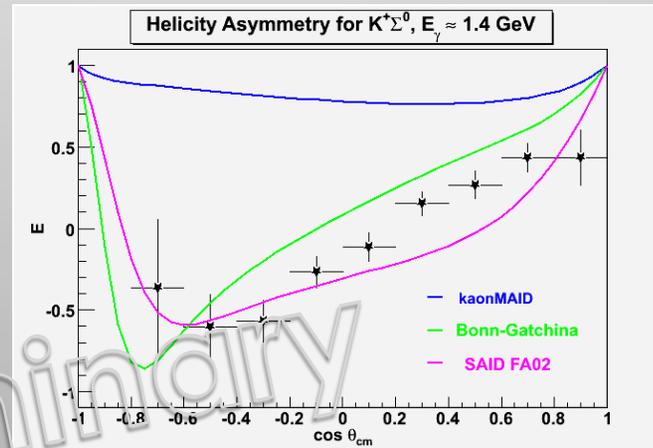
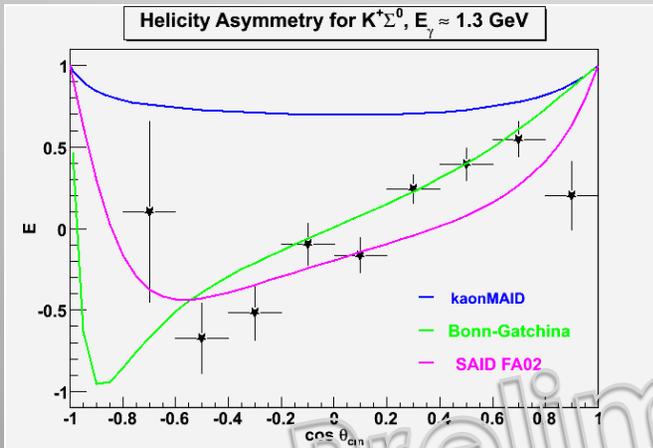


# $E$ for $K^+ \Lambda$



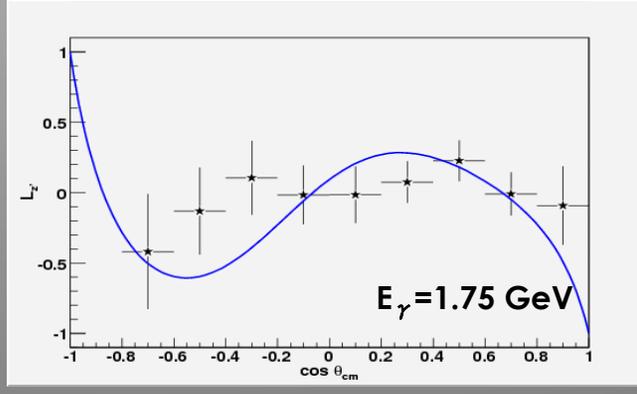
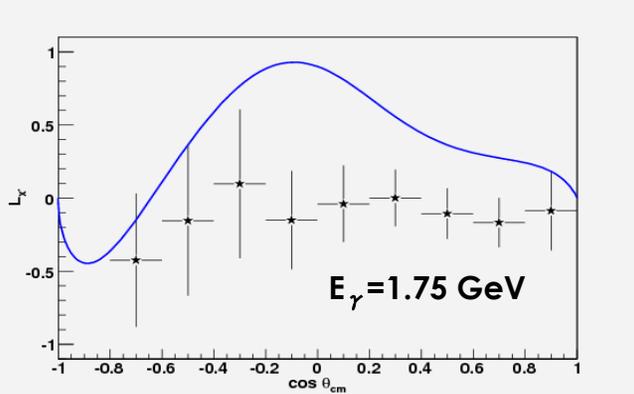
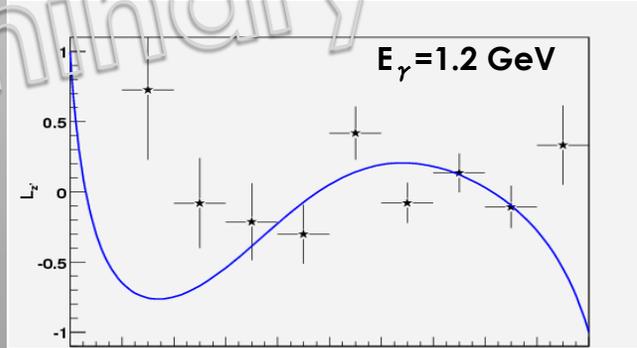
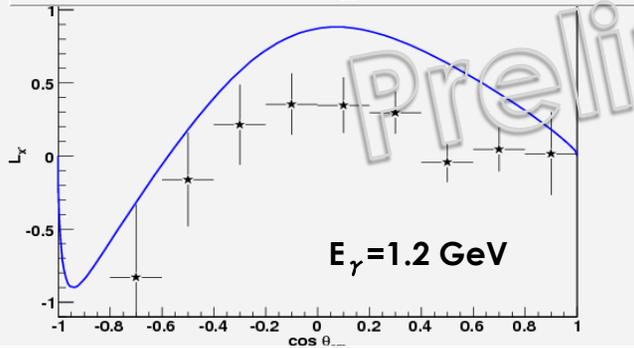
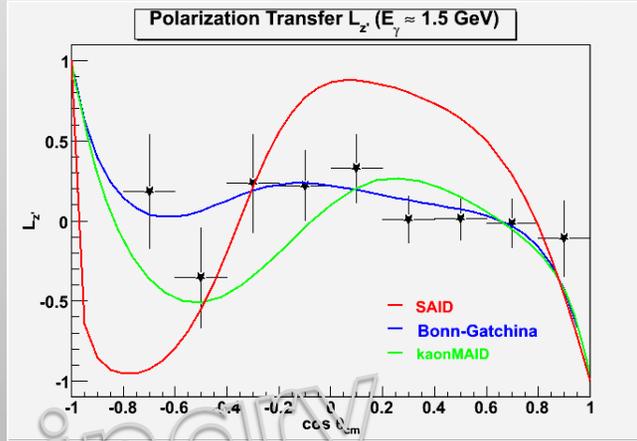
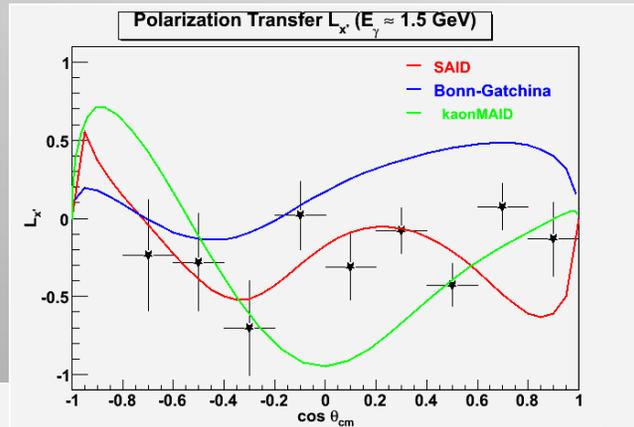
$$E = \frac{D_{\text{eff}}}{P_T P_Y} \frac{N_{1/2} - N_{3/2}}{N_{1/2} + N_{3/2}}$$

# $E$ for $K^+ \Sigma^0$



$$E = \frac{D_{eff}}{P_T P_y} \frac{N_{1/2} - N_{3/2}}{N_{1/2} + N_{3/2}}$$

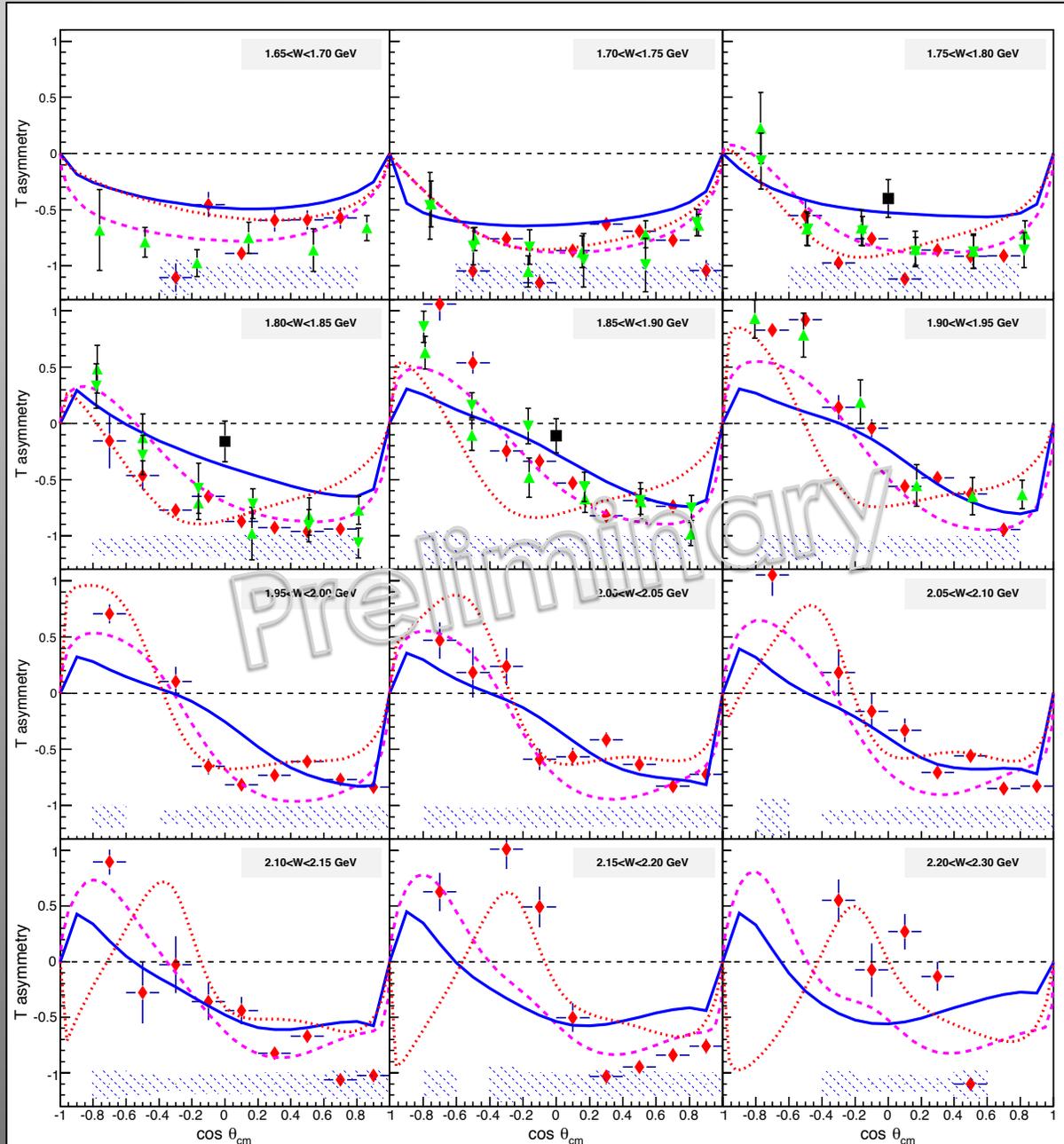
# $L_x$ and $L_z$ for $K^+ \Lambda$



Preliminary

# T for $K^+ \Lambda$

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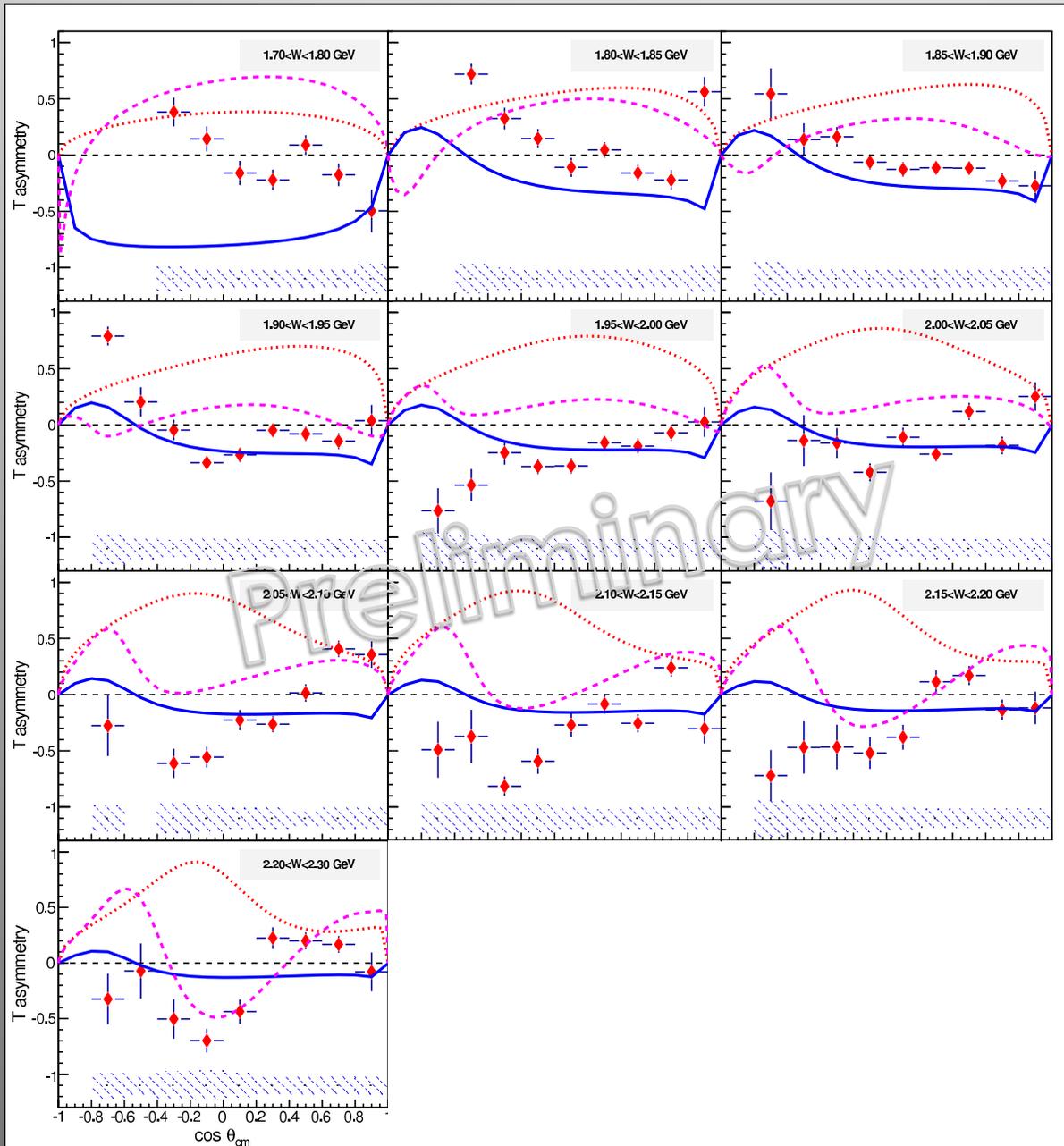
Data:  
CLAS g9b  
Bonn78  
GRAAL09

Models:  
RPR-Ghent  
Kaon-MAID  
BOGA

Not yet compared to  
Paterson *et al.*,  
PRC **93** 065201 (2016)

# T for $K^+ \Sigma^0$

23

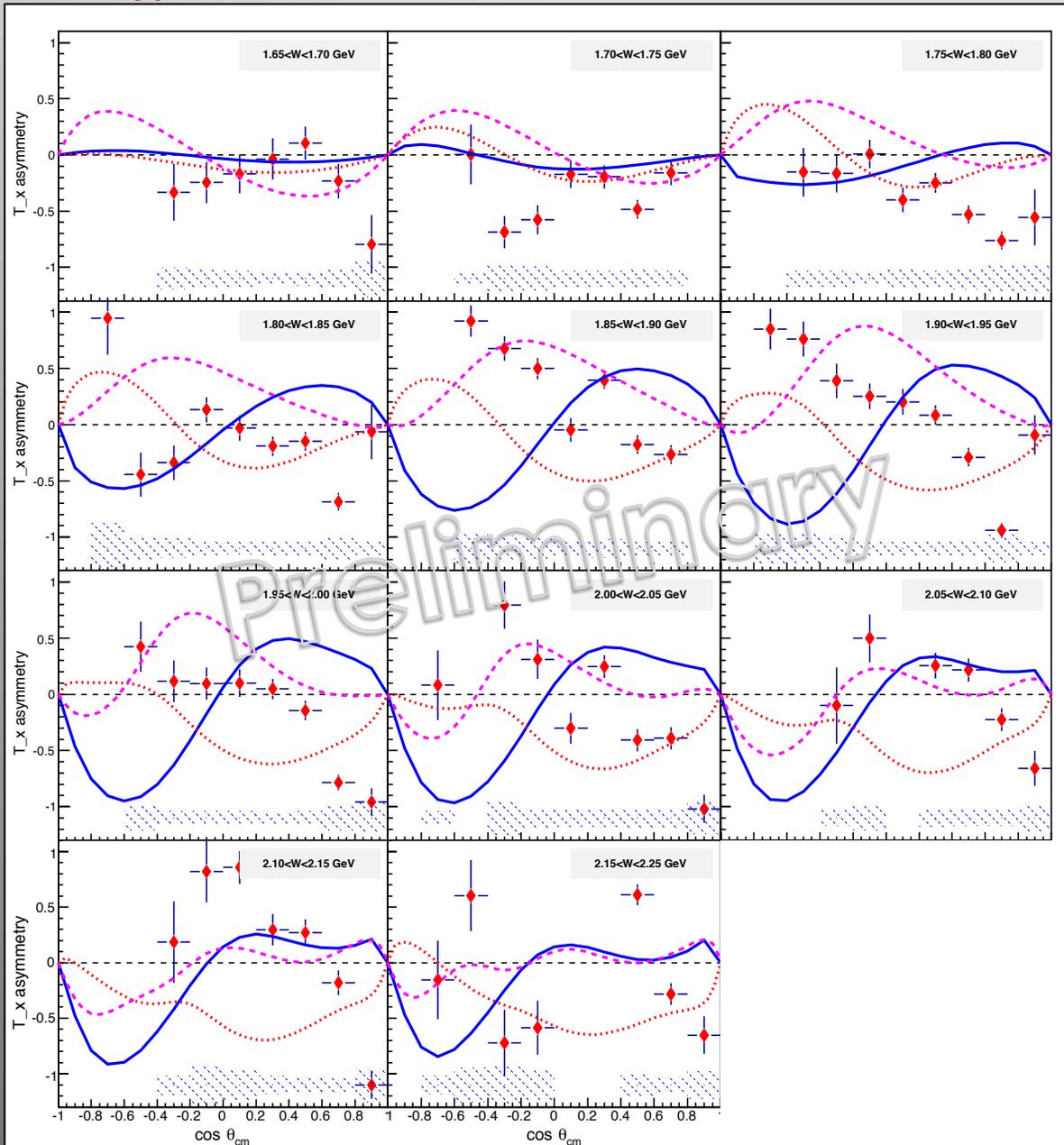


Data:  
CLAS g9b

Models:  
RPR-Ghent  
Kaon-MAID  
BOGA

Not yet compared to  
Paterson *et al.*,  
PRC **93** 065201 (2016)

# $T_x$ for $K^+ \Lambda$



24

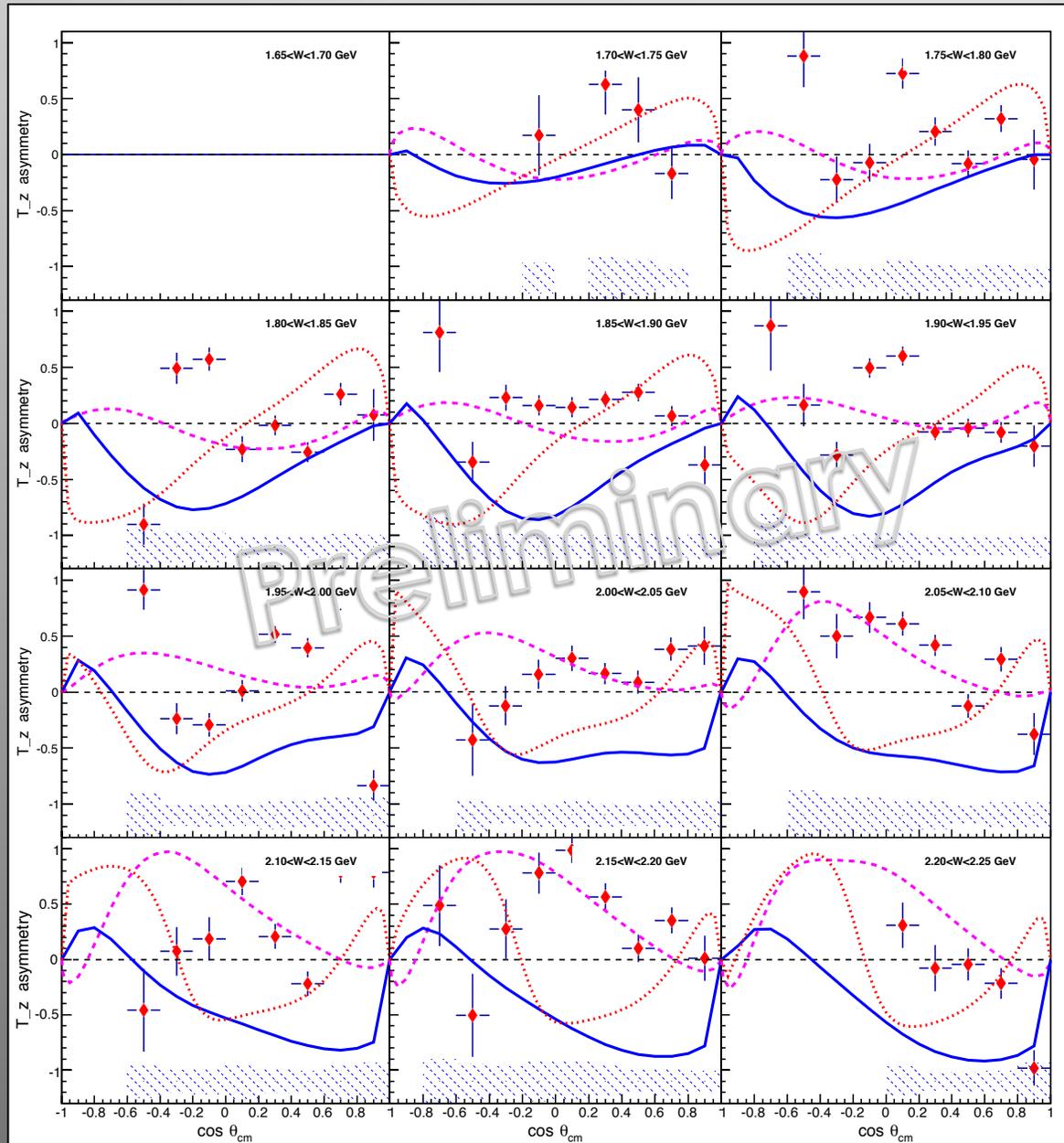


Data:  
CLAS g9b

Models:  
RPR-Ghent  
Kaon-MAID  
BOGA

# $T_z$ for $K^+ \Lambda$

25

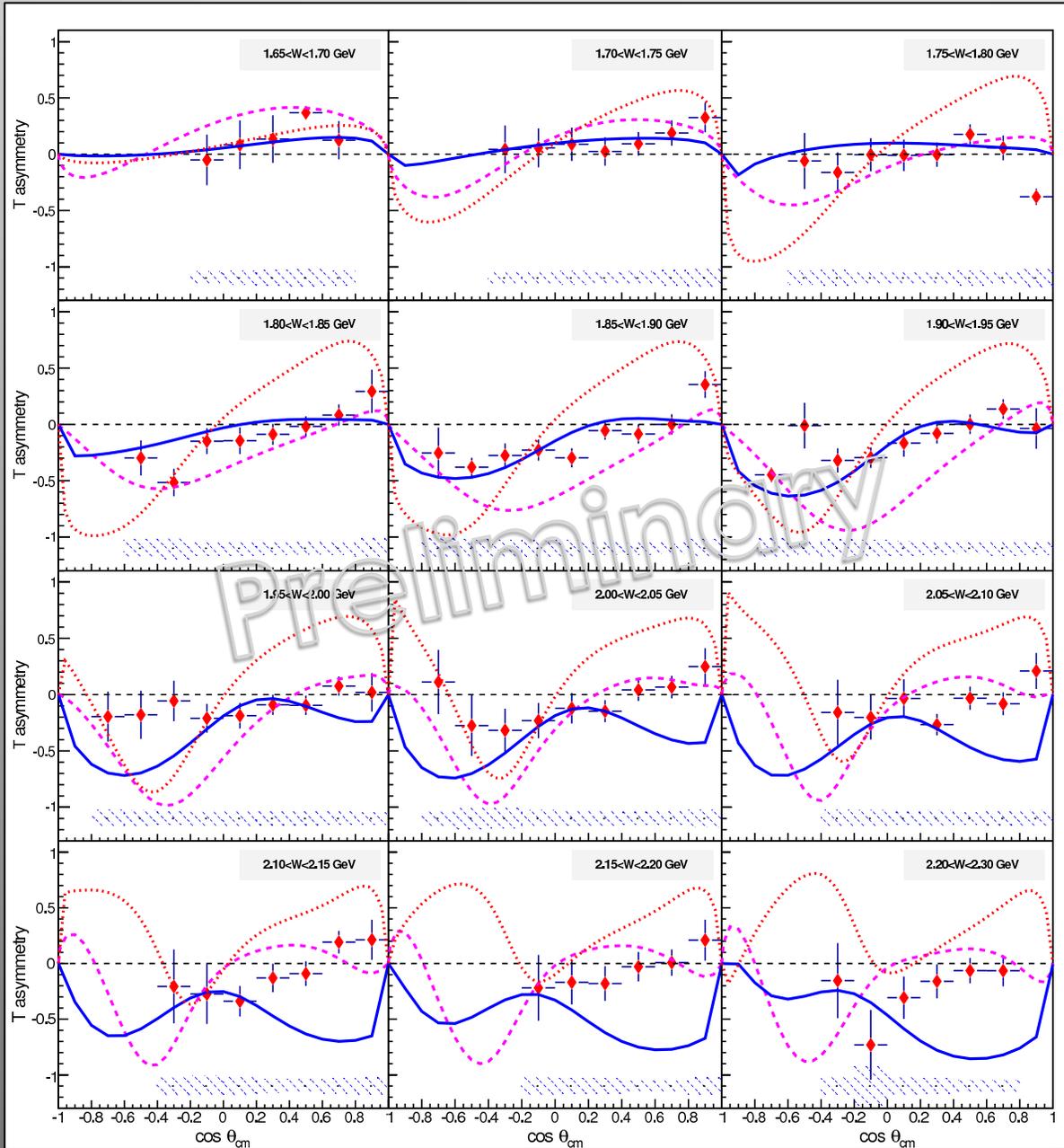


Data:  
CLAS g9b

Models:  
RPR-Ghent  
Kaon-MAID  
BOGA

# F for $K^+ \Lambda$

26

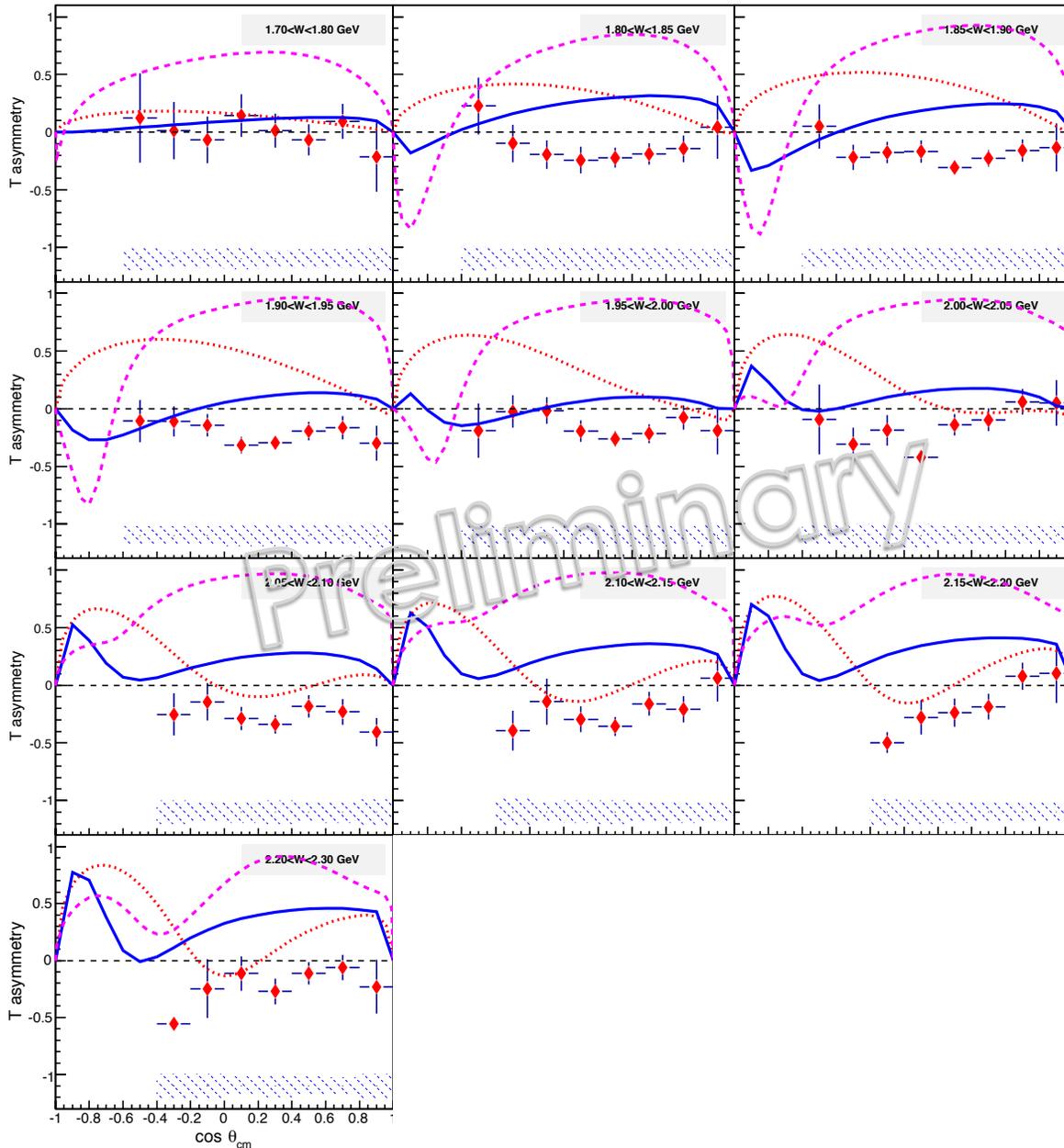


Data:  
CLAS g9b

Models:  
RPR-Ghent  
Kaon-MAID  
BOGA

# F for $K^+ \Sigma^0$

27



Data:  
CLAS g9b

Models:  
RPR-Ghent  
Kaon-MAID  
BOGA

# Conclusion

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- More kaon photoproduction data necessary to help solve missing resonance problem
- First results for many of the observables for kaon photoproduction
- Working on publishing results...slowly...
- Models and PWA results only partially consistent with data: can expect that resonance parameters will greatly improve with this data