Polarization Observables *T* and *F* in $K^+\Lambda$ and $K^+\Sigma^0$ from FROST data in CLAS

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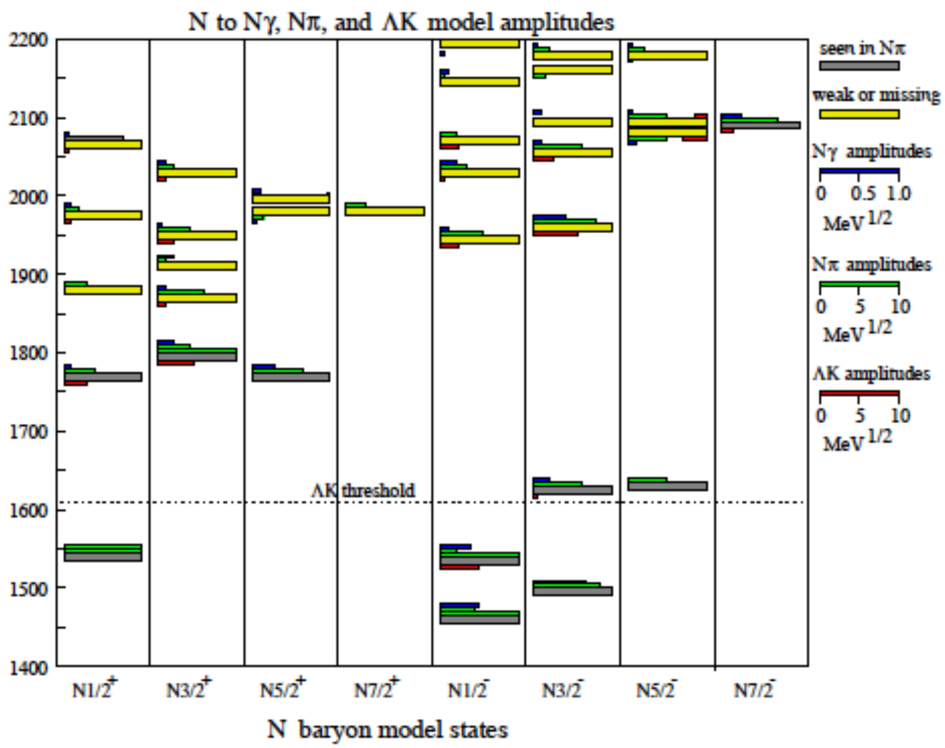
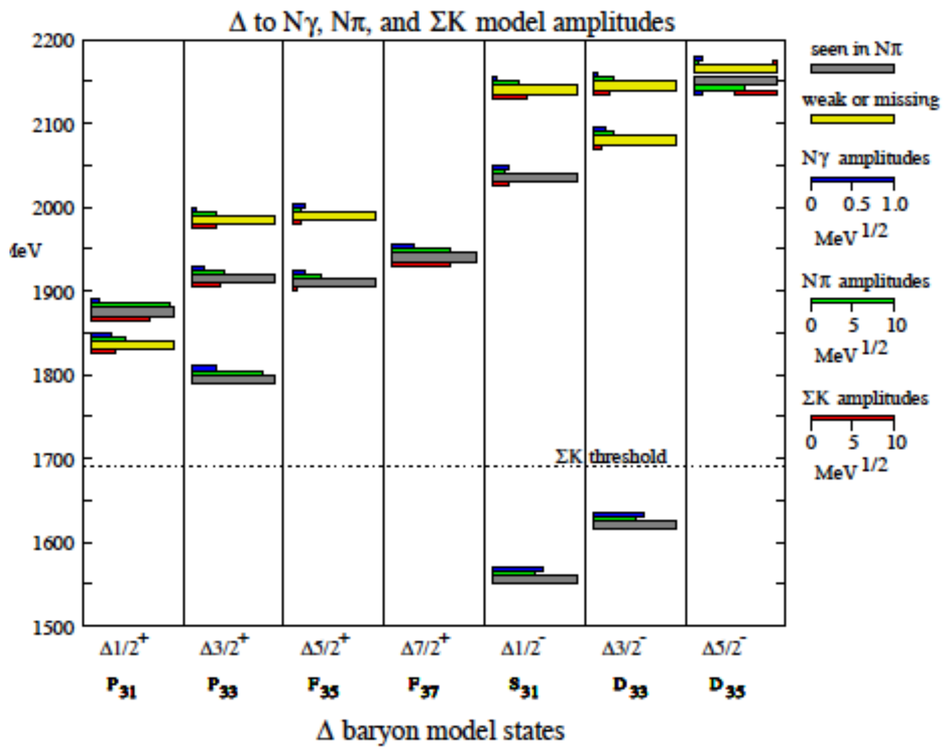
Outline

- Motivation
- Experimental Setup
- Event Selection and Moment Method
- Systematic Studies
- Preliminary Results
- Conclusion

Constituent Quark Model

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





Polarization Observables

Spin Observable	Polarization Beam	Target	Recoil	Transversity Representation	Set
$\left(\frac{d\sigma}{d\Omega}\right)_u$	-	-	-	$\frac{1}{2}(\|b_1\|^2 + \|b_2\|^2 + \|b_3\|^2 + \|b_4\|^2)$	
Σ	l	-	-	$\frac{1}{2}(\|b_1\|^2 + \|b_2\|^2 - \|b_3\|^2 - \|b_4\|^2)$	$\mathcal{S}$
$\boxed{T}$	-	y	-	$\frac{1}{2}(\|b_1\|^2 - \|b_2\|^2 - \|b_3\|^2 + \|b_4\|^2)$	
P	-	-	y'	$\frac{1}{2}(\|b_2\|^2 + \|b_4\|^2 - \|b_1\|^2 - \|b_3\|^2)$	
E	c	z	-	$\mathrm{Re}(b_1 b_3^* + b_2 b_4^*)$	
$\boxed{F}$	c	x	-	$\mathrm{Im}(b_1 b_3^* - b_2 b_4^*)$	$\mathcal{BT}$
G	l	z	-	$\mathrm{Im}(-b_1 b_3^* - b_2 b_4^*)$	
H	l	x	-	$\mathrm{Re}(b_1 b_3^* - b_2 b_4^*)$	
O_x	l	-	x'	$\mathrm{Re}(-b_1 b_4^* + b_2 b_3^*)$	
O_z	l	-	z'	$\mathrm{Im}(b_1 b_4^* + b_2 b_3^*)$	$\mathcal{BR}$
C_x	c	-	x'	$\mathrm{Im}(b_2 b_3^* - b_1 b_4^*)$	
C_z	c	-	z'	$\mathrm{Re}(-b_1 b_4^* - b_2 b_3^*)$	
T_x	-	x	z'	$\mathrm{Re}(b_1 b_2^* - b_3 b_4^*)$	
T_z	-	x	z'	$\mathrm{Im}(b_3 b_4^* - b_1 b_2^*)$	$\mathcal{TR}$
L_x	-	z	x'	$\mathrm{Im}(-b_1 b_2^* - b_3 b_4^*)$	
L_z	-	z	z'	$\mathrm{Re}(-b_1 b_2^* - b_3 b_4^*)$	

Observables help to disentangle partial-waves to identify resonances since spin observables are more sensitive than cross-section

- Photoproduction for K and π production are described by four complex amplitudes
  - Describes spin combinations of incoming and outgoing particles
  - 16 independent measurables calculated
  - Extracted observable based on beam, target, and recoil polarization

Available World Data

$\gamma p \to K^+\Lambda$	Observ.	N_{data}	$\chi_1^2/N_{\mathrm{data}}$
[43] CLAS	$d\sigma/d\Omega$	1320	0.69
[51] LEPS	Σ	45	2.11
[50] GRAAL	Σ	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

$\gamma p \to K^+\Sigma^0$	Observ.	N_{data}	$\chi_1^2/N_{\mathrm{data}}$
[62] CLAS	$d\sigma/d\Omega$	1590	1.44
[51] LEPS	Σ	45	1.23
[52] GRAAL	Σ	42	1.99
[62] CLAS	P	344	2.69
[40] CLAS	C_x	94	1.95
[40] CLAS	C_z	94	1.66

$\gamma p \to K^0\Sigma^+$	Obsv.	N_{data}	$\chi_1^2/N_{\mathrm{data}}$
[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	Σ	15	1.73

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

Clear lack in data for kaon photoproduction!!

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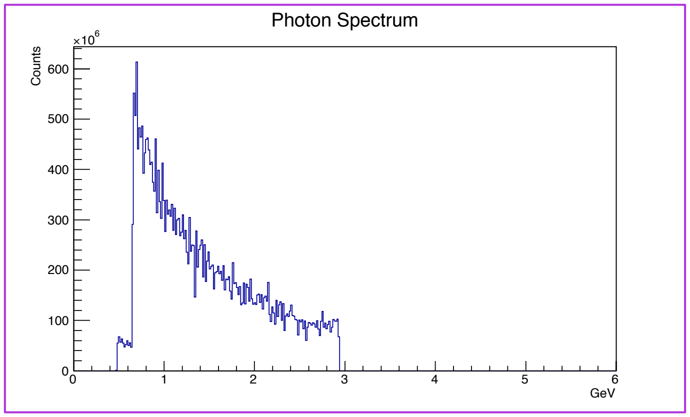
Experimental Setup

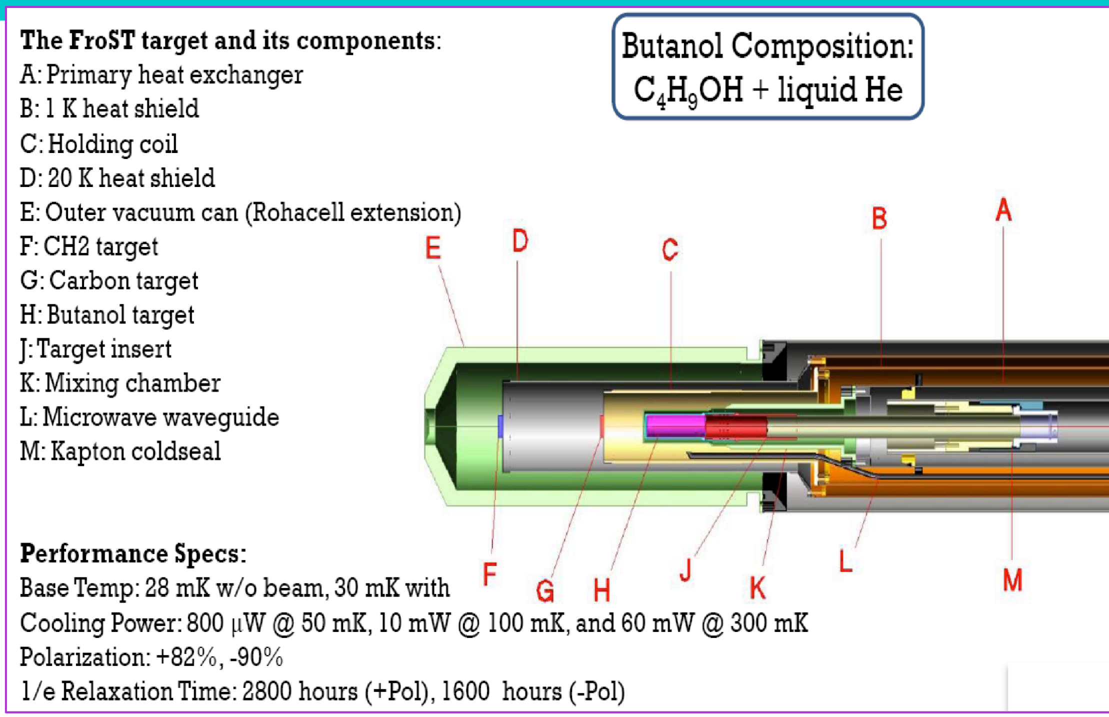
- FROST experiment first approved in 2002 in CLAS, ran in two parts in 2007-2008 (g9a-longitudinally polarized target) and 2010 (g9b-transversely polarized target)
- Butanol FROzen Spin Target with free protons polarized
- Polarized photon beam
  - Circularly (Au radiator)
  - Longitudinally (Diamond radiator)
- Photon beam energies from 0.5 to 3.0 GeV (circular) and 1.1 to 2.1 GeV (linear)



- 14 billion events collected (in g9b)
- Complete measurement: all beam-target and target-recoil observables from $K^+\Lambda$ and $K^+\Sigma^0$ final states

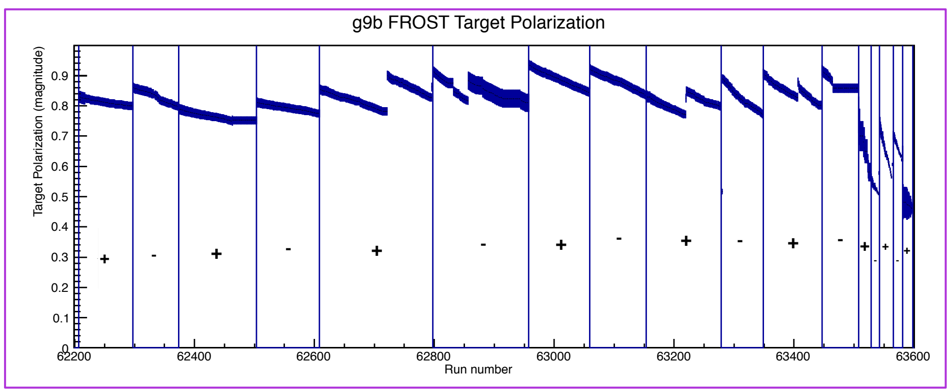
The FROST Target

g9b holding coil



* Butanol dripped into LN_2 bath and then cooled to <1K and then LN_2 is replaced by LHe bath
* Polarizing 5 Tesla magnet aligns free proton spins in the butanol target to about 95% at 1K
* Holding coil keeps protons polarization at 30 mK

Target re-polarized ~once per week!!



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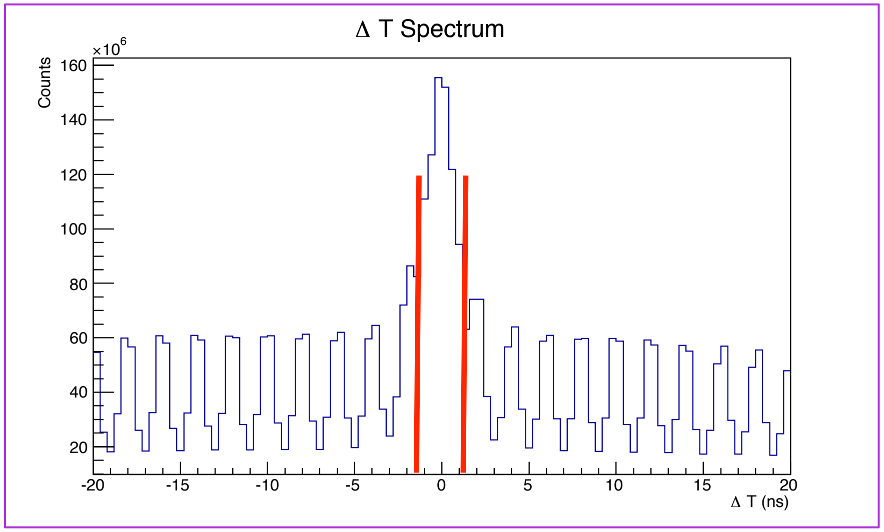
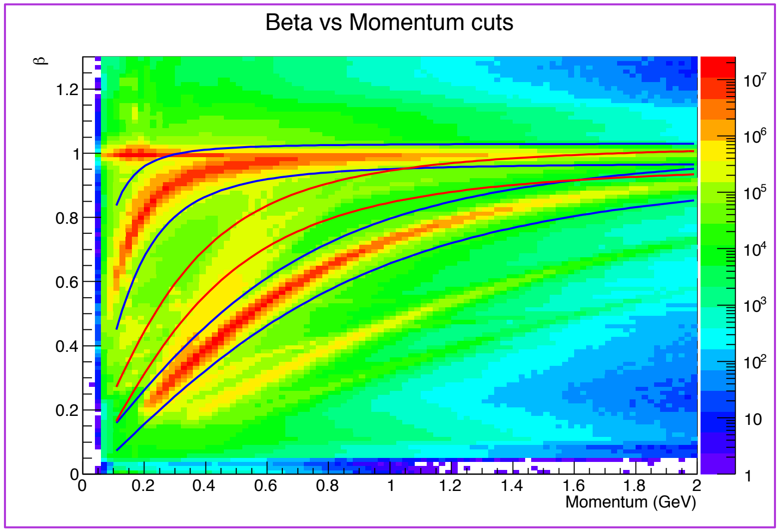
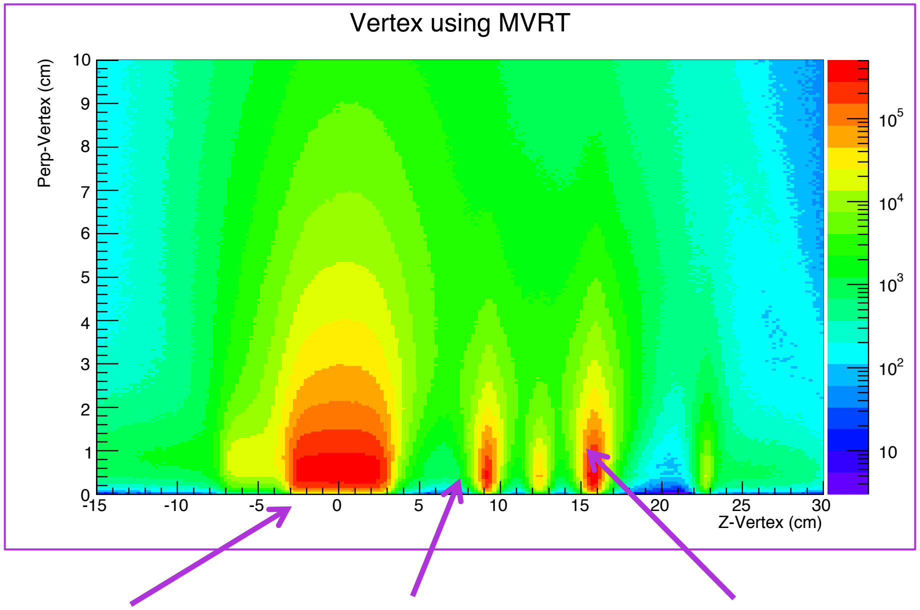
Event Selection

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

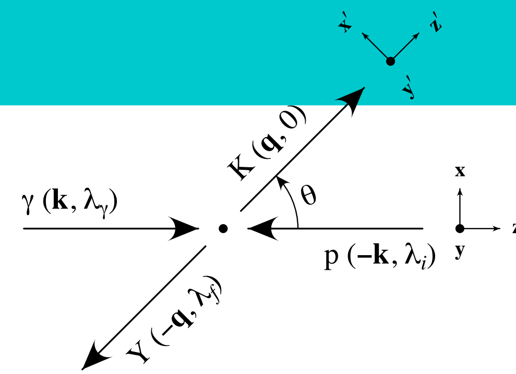


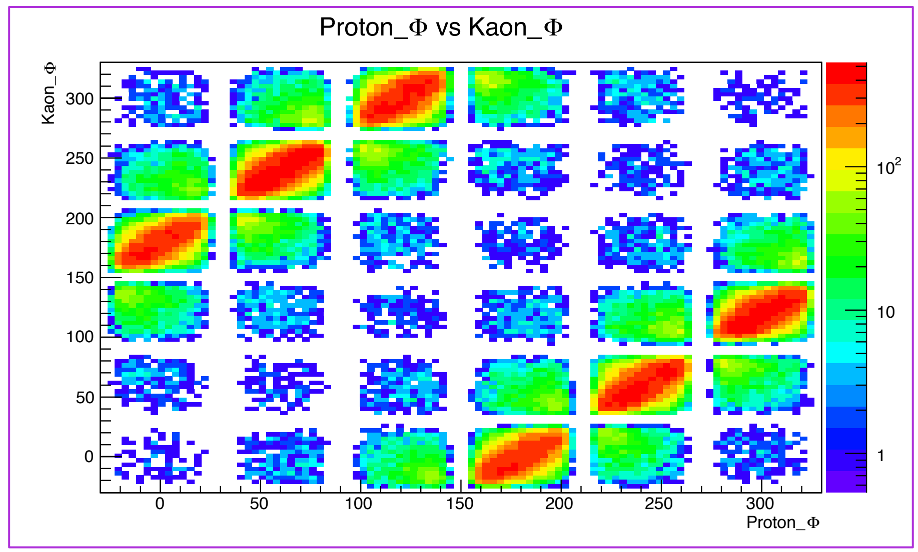


Vertices



Butanol Carbon CH_2

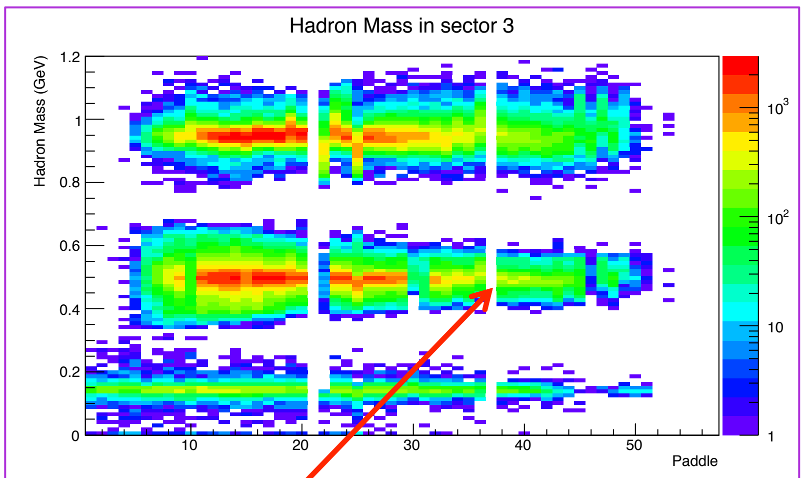


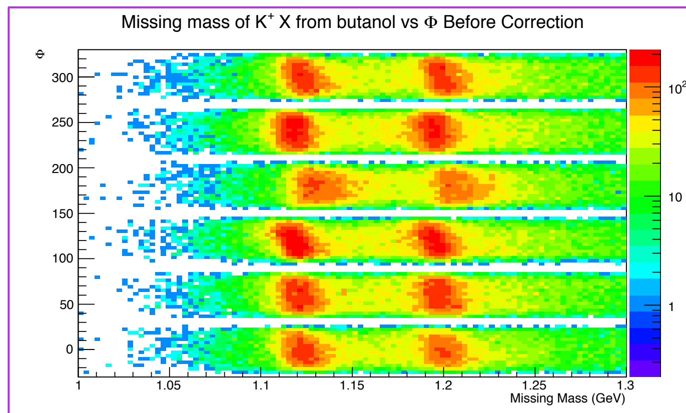


- Cut on kaon event vertex
- Check whether p from Λ decay vertex by comparing azimuthal angles of p and K^+ (p almost in same direction as Λ, which is opposite of K^+ in CM frame)

Corrections

- Bad TOF paddles cut
- Phi-dependence of missing mass found for CLAS sectors, sector dependent momentum correction applied

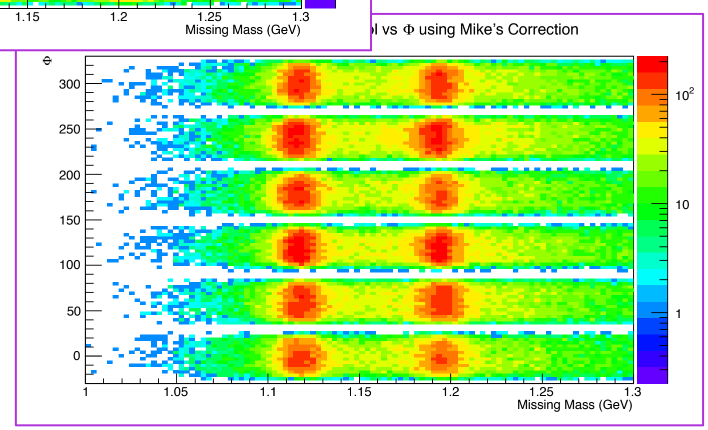




Before

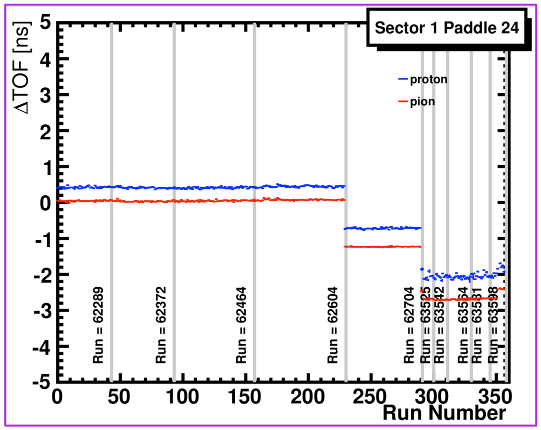
Bad paddle!

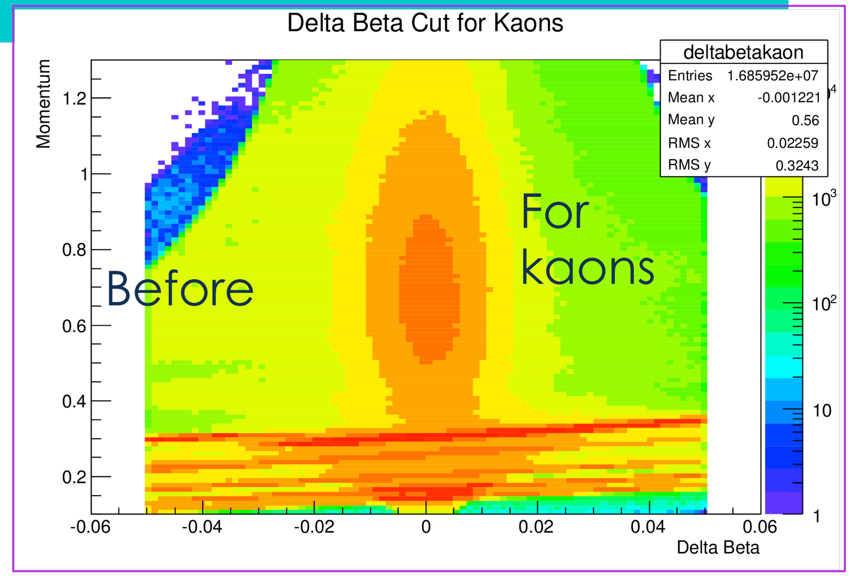
After

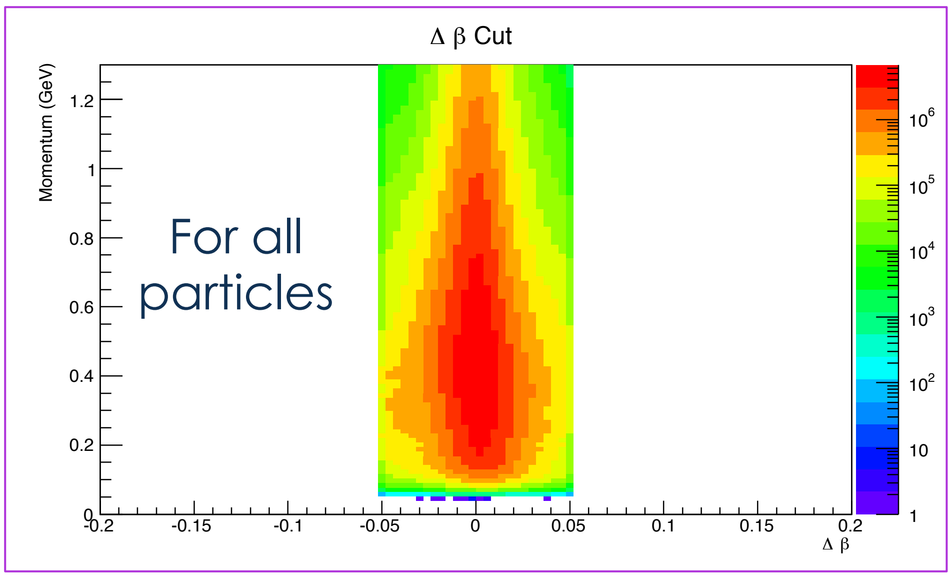


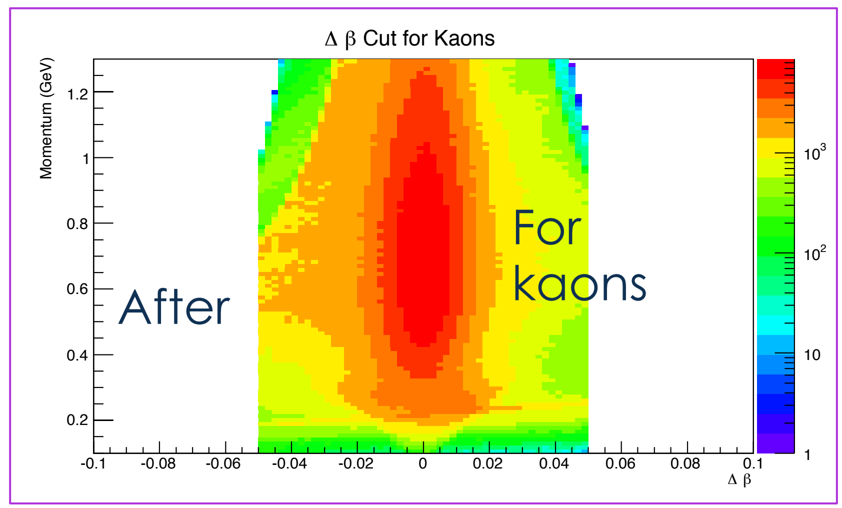
More Corrections

Timing offset between protons and pions in TOF found – correction applied



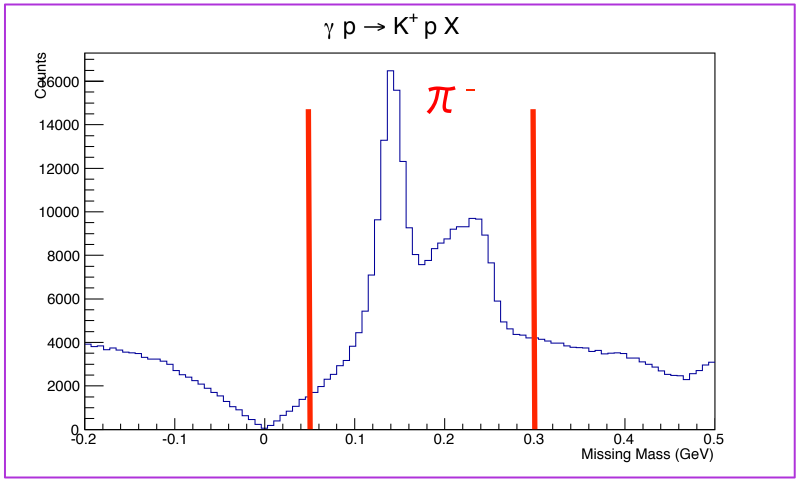


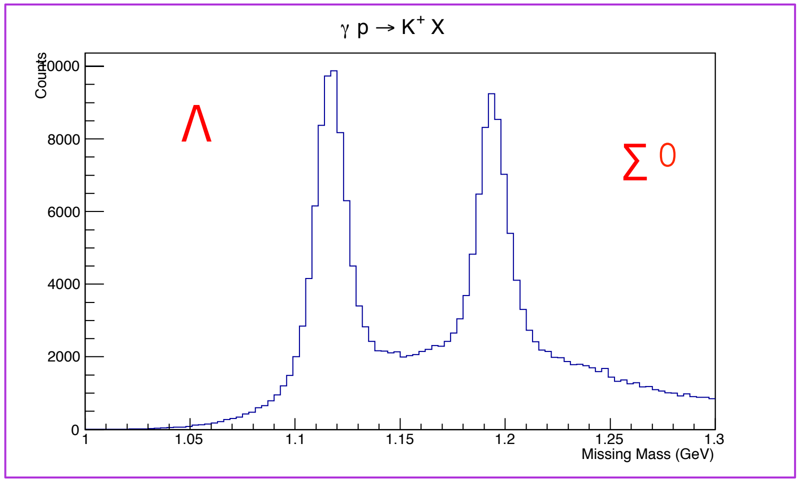


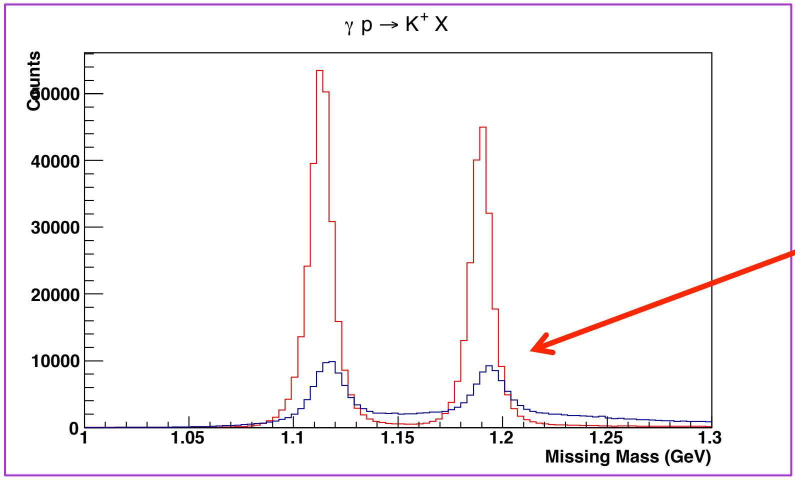


Missing Mass Cuts

With correct beam photon and K and p identified: can construct missing mass





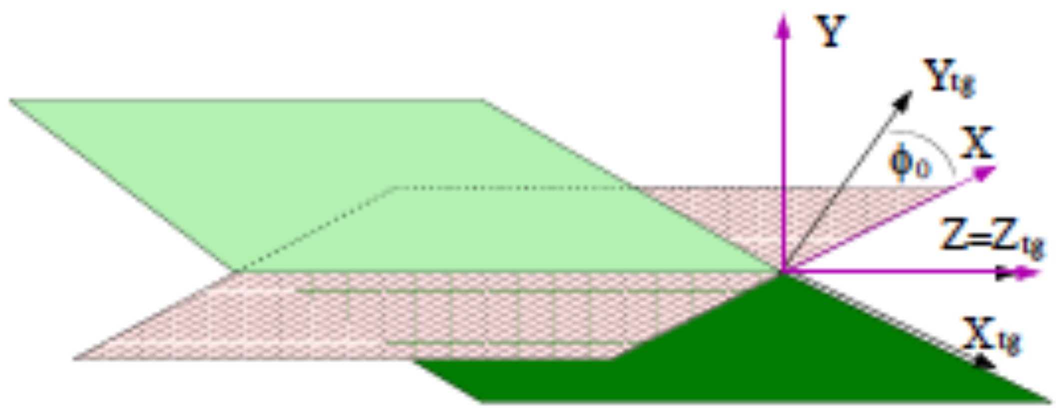


Comparing g9b data to g1c, more background and less events!

Differential Cross-Section

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

- Polarized cross-section depends on:
  - Center-of-mass energy W
  - Polar angle θ_{CM}
  - Azimuthal ϕ ($\phi = \beta_K - \Phi_0$)
  - Direction cosines of proton momentum in Λ rest frame



Extracting ϕ-Dependent Observables: The Moment Method

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega}(1 + P_{XY}^{lab} P_C F cos(\beta_K - \phi_0) - P_{XY}^{lab} T sin(\beta_K - \phi_0))$$

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(ϕ) in Fourier series…

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

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

Separate cosine/sin terms

Moment Method continued…

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

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

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

λ_A – positive helicity
λ_C – negitive helicity

P_A – positive target polarization
P_C – negative target polarization

Comparison of Moment Method using g1c data

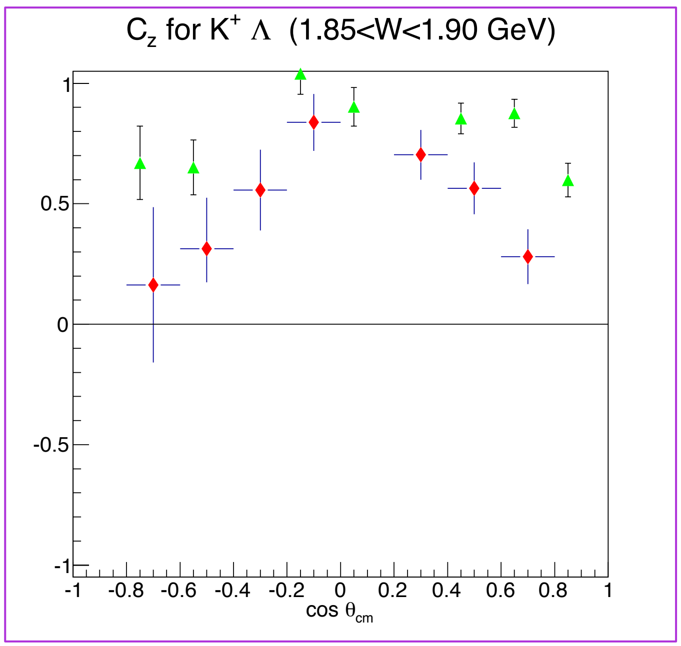
To check the validity of the Moment Method, can compare g9b results to published C_z results (Bradford et al.)

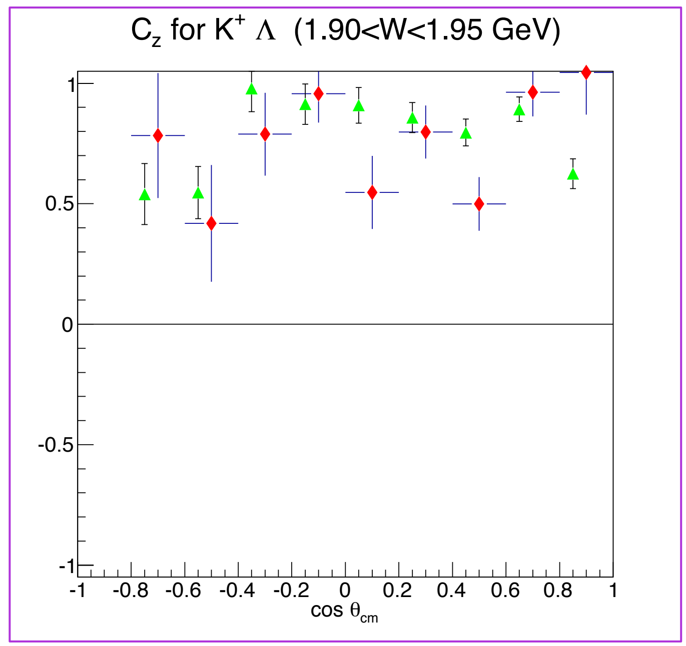
$$C_z = \frac{\bar{Y}_{A,0001} - \bar{Y}_{B,0001}}{\frac{2}{9}\alpha_Y \lambda_A(\bar{Y}_{,0000} + \bar{Y}_{B,0000} + 2\bar{Y}_{A,0002} + 2\bar{Y}_{B,0002})}.$$

<u>Data:</u>

CLAS g9b

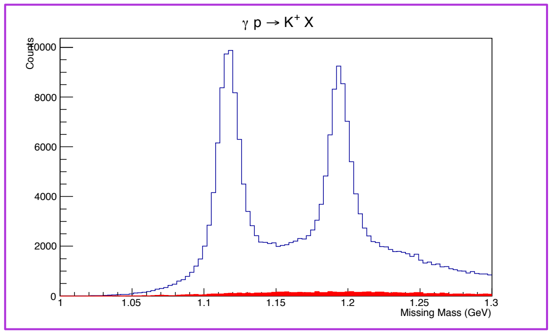
Bradford07

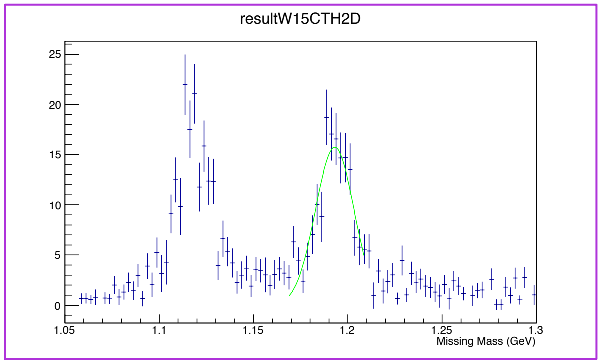


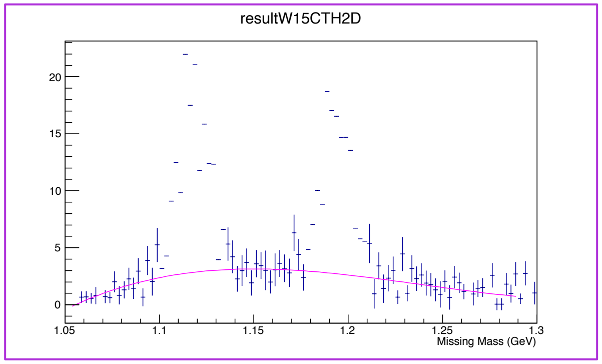


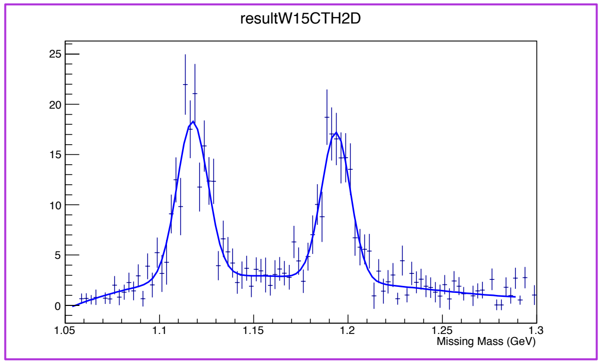
Background Subtraction

- Quasi-free kaon production is suppressed on carbon – so need to subtract free protons from bound protons
  - Fit Λ and Σ^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!!

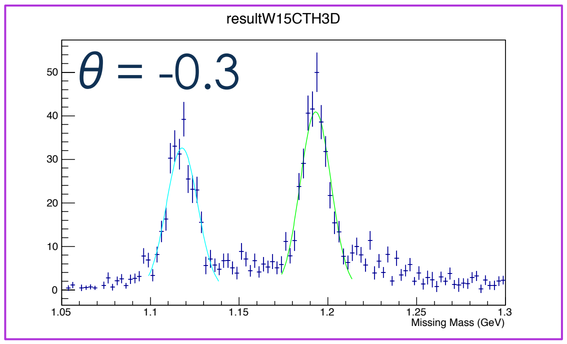
More Background Subtraction

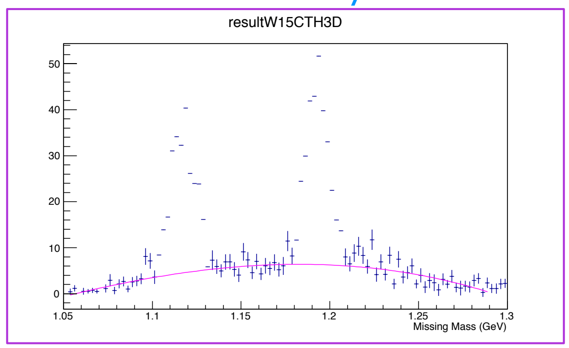
Example of Background Subtraction for W = 1875 MeV

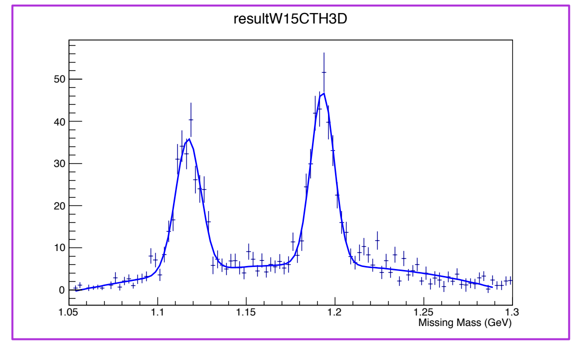
Gaussian

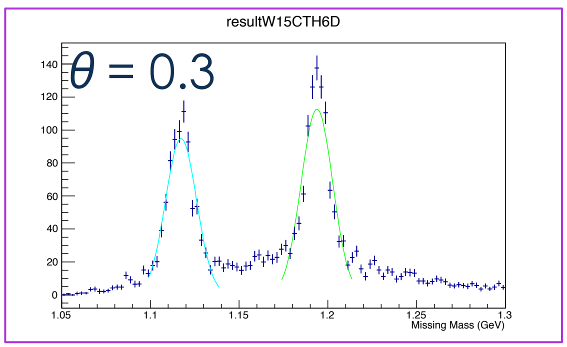
3rd Order Polynomial

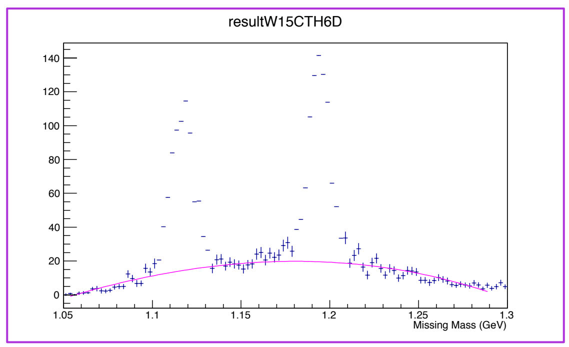
Global

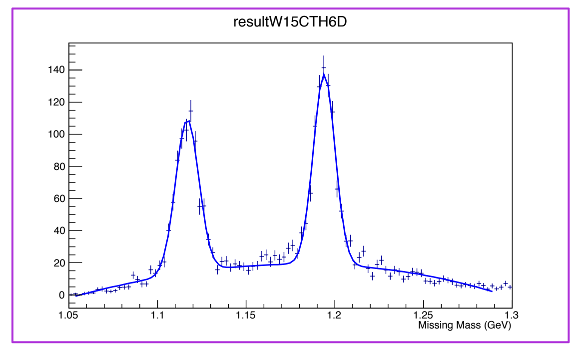


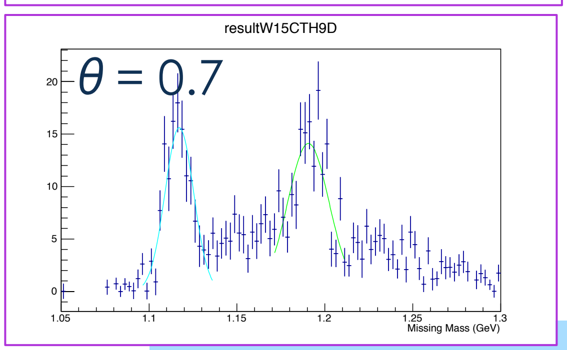


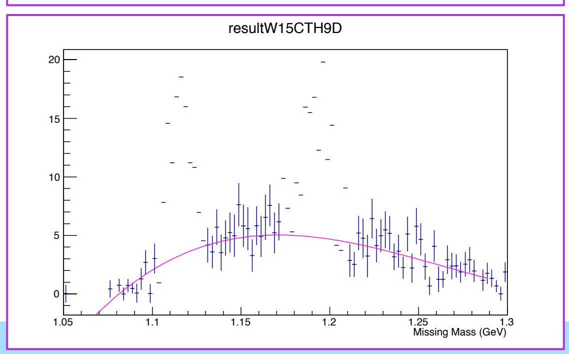


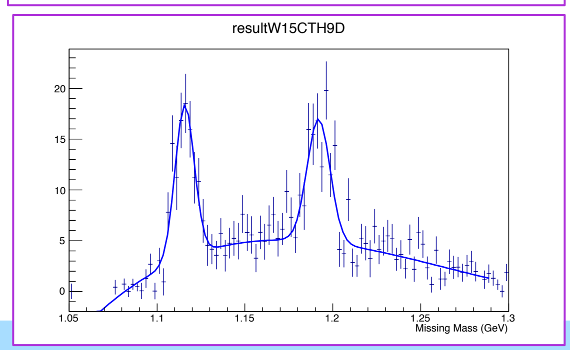












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Total Systematic Uncertainty

* Systematics present in data
* Vary cuts (particle ID, missing mass, order of background polynomial)
* Uncertainties in beam and target polarization
* Relative normalization for data on upwards and downwards target polarization (using all events, all carbon or CH_2 events, etc)

Systematics	Effect
Photon Beam Polarization	3%
Beam Charge Asymmetry	< 0.1%
Target Polarization	~4-5%
Target Quench	<1%
Target Offset	< 0.02 (absolute)
Fiducial Cuts	< 0.04 (absolute)
β Cuts	< 0.04 (absolute)
Missing Mass Cuts	< 0.03 (absolute)
All Cuts Simultaneously	< 0.05 (absolute)
Background Fit	< 0.05 (absolute)
Normalization	< 0.05 (absolute)
Simulation	~5%
Overall Uncertainty	± 0.09 (absolute) ± 8%

Systematics

Example of varied β cut for W = 2075 MeV

$$\frac{\Delta Y}{Y_0} = \frac{Y_{\rm varied} - Y_{\rm normal}}{Y_{\rm normal}} \quad \text{(in \%)}$$

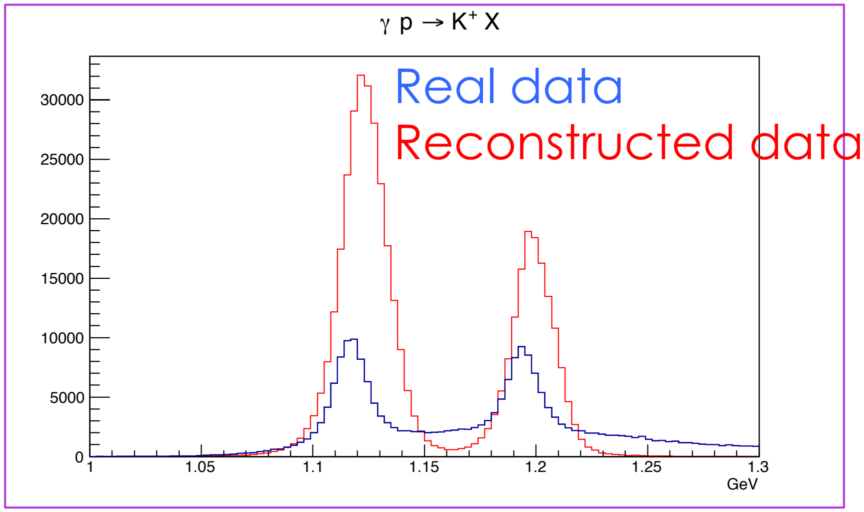
$$\mathrm{DSR} = \frac{T_{\rm varied} - T_{\rm normal}}{\sqrt{\sigma^2_{T_{\rm varied}} + \sigma^2_{T_{\rm normal}}}}$$

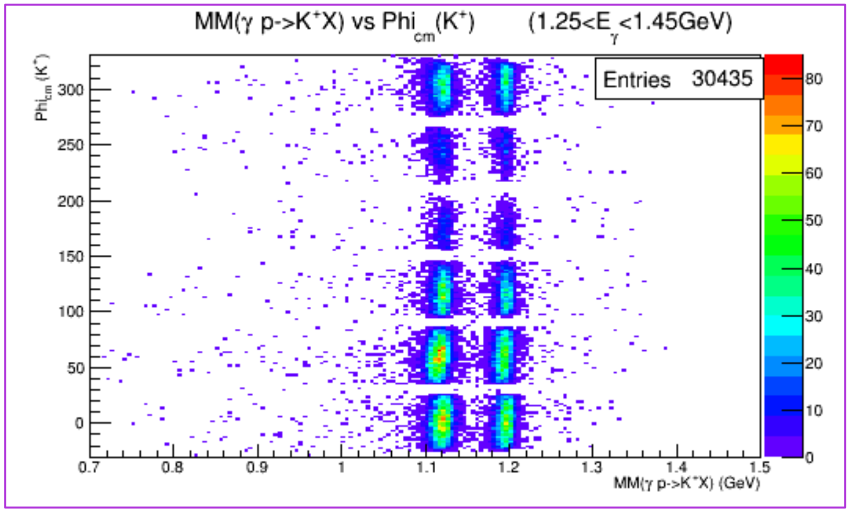
$$\sigma_T = \sqrt{\left(\sum_{i=1}^{10} \frac{1}{(\delta T^{(i)}_{\rm normal})^2}\right)^{-1} \sum_{i=1}^{10} \frac{(T^{(i)}_{\rm varied} - T^{(i)}_{\rm normal})^2}{(\delta T^{(i)}_{\rm normal})^2}} \;.$$

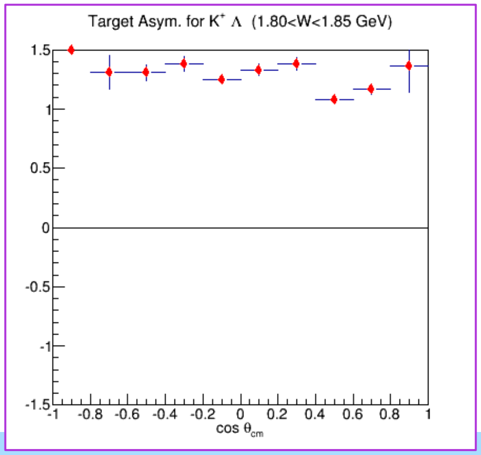
	Normal Cuts:	Loose Cuts:	Tight Cuts:
π range	0.11-0.2	0.06-0.25	0.11-0.17
K range	0.44-0.55	0.39-0.60	0.46-0.54
p range	0.85-1.05	0.80-1.10	0.9-1.0
$W = 2075$ MeV, $\cos\theta_{K^+} = -0.5$			
Λ yield (background):	55 (27)	55 (27)	55 (27)
Λ gain/loss %:			
Σ^0 yield (background):	69 (41)	70 (41)	66 (41)
Σ^0 gain/loss %:		1.45 (0)	-4.35 (0)
χ^2/NDF:	0.95	0.96	0.92
T Λ asymmetry:	n/a	n/a	n/a
T Λ change (DSR):			
T Σ^0 asymmetry:	-0.087±0.273	-0.022±0.267	-0.094±0.273
T Σ^0 change (DSR):	0	0.17	-0.0181
$W = 2075$ MeV, $\cos\theta_{K^+} = 0.1$			
Λ yield (background):	405 (118)	411 (118)	374 (110)
Λ gain/loss %:		1.48 (0)	- 7.65 (-6.78)
Σ^0 yield (background):	618 (241)	628 (242)	613 (225)
Σ^0 gain/loss %:		1.62 (0.41)	-0.81 (-6.64)
χ^2/NDF:	0.98	0.98	1.08
T Λ asymmetry:	-0.66±0.074	-0.63±0.075	-0.834±0.027
T Λ change (DSR):		0.285	-2.21
T Σ^0 asymmetry:	-0.21±0.084	-0.203±0.082	-0.189±0.084
T Σ^0 change (DSR):		0.0596	0.177
$W = 2075$ MeV, $\cos\theta_{K^+} = 0.9$			
Λ yield (background):	308 (97)	313 (28)	307 (95)
Λ gain/loss %:		1.62 (-71.13)	-0.32 (-2.06)
Σ^0 yield (background):	221 (191)	226 (194)	218 (186)
Σ^0 gain/loss %:		2.26 (1.57)	-1.36 (-2.62)
χ^2/NDF:	1.22	1.24	1.13
T Λ asymmetry:	-0.597±0.09	-0.567±0.091	-0.542±0.094
T Λ change (DSR):		0.234	0.423
T Σ^0 asymmetry:	-0.211±0.142	-0.16±0.14	-0.202±0.141
T Σ^0 change (DSR):		0.256	0.045
σ_T (Λ):		0.030	0.070
σ_T (Σ^0):		0.016	0.036

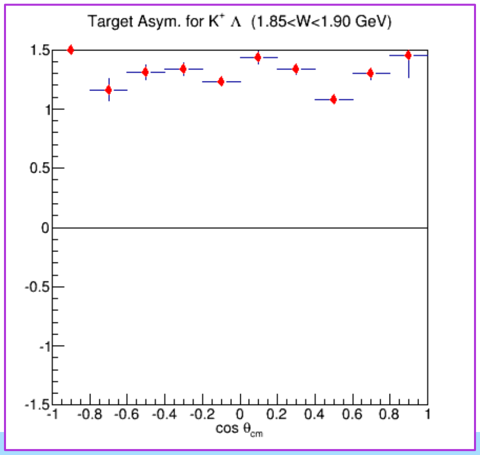
Simulations

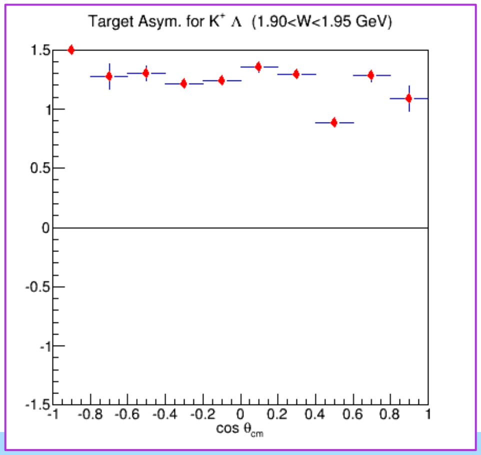
Check whether simulated T asymmetry (T=1.0) is correctly reconstructed











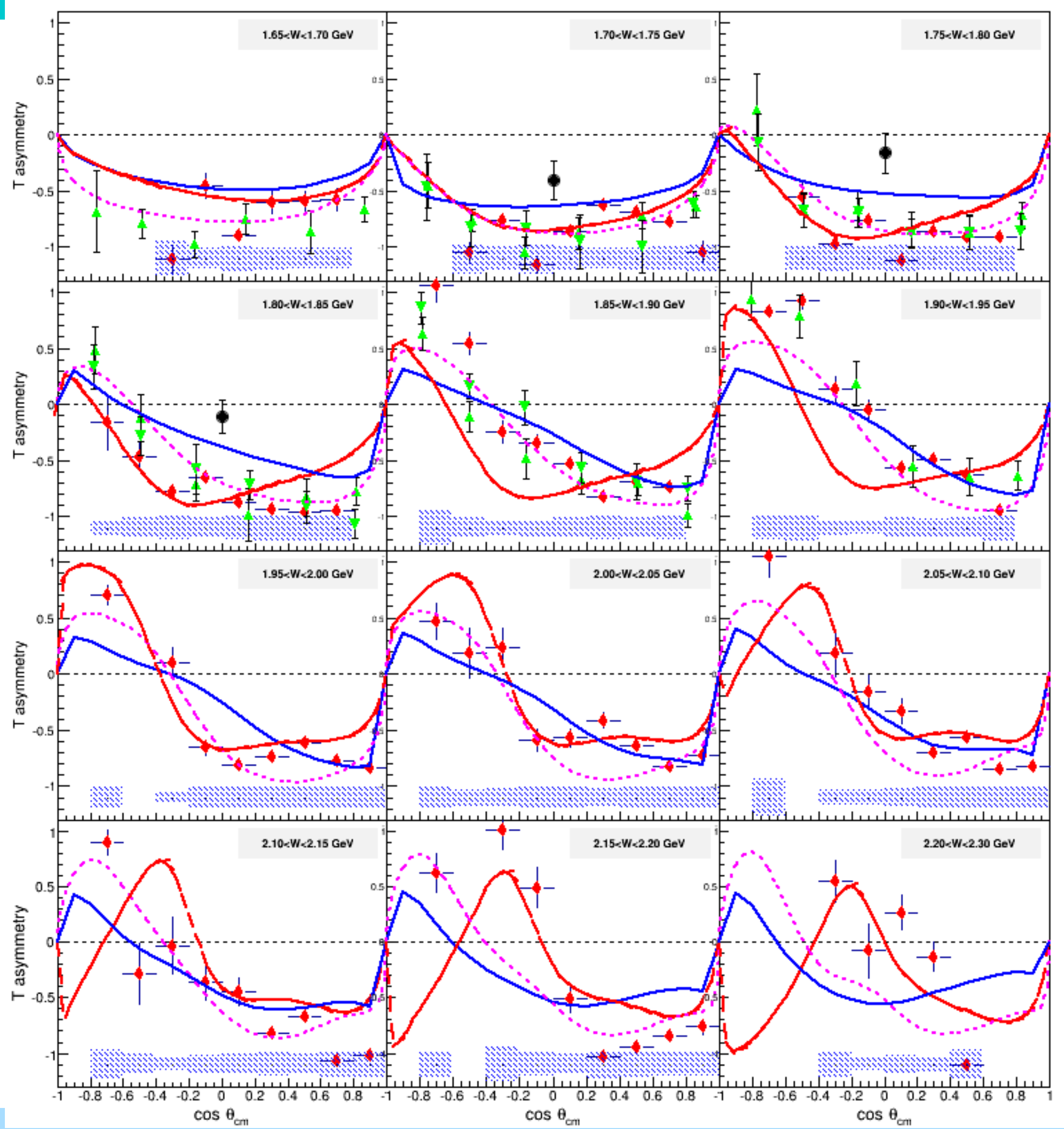
Outline

- Motivation
- Experimental Setup
- Event Selection and Moment Method
- Systematic Studies
- Preliminary Results
- Conclusion

Results

- All results are preliminary
- T observable has previously published results for $K^+\Lambda$ (GRAAL in green triangles and Bonn in black circles)
- T observable measurements for $K^+\Sigma^0$ is the first of its kind
- F observable measurements is the first of its kind for both $K^+\Lambda$ and $K^+\Sigma^0$
- Compared to three theoretical models
  - KAON-MAID
  - Bonn-Gatchina (BOGA)
  - RPR-Ghent

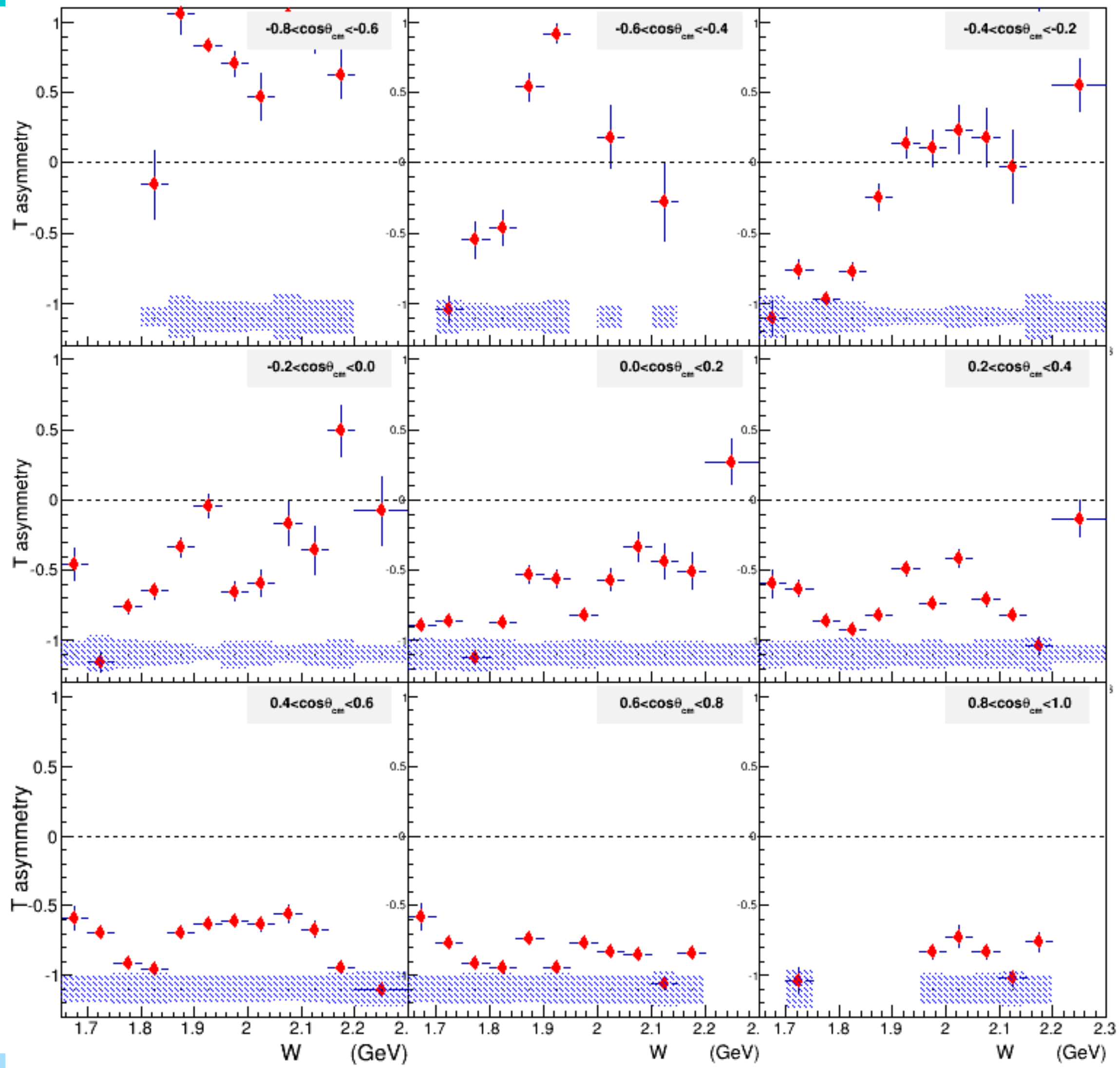
T for K⁺ Λ



Data:
CLAS g9b
Bonn78
GRAAL09

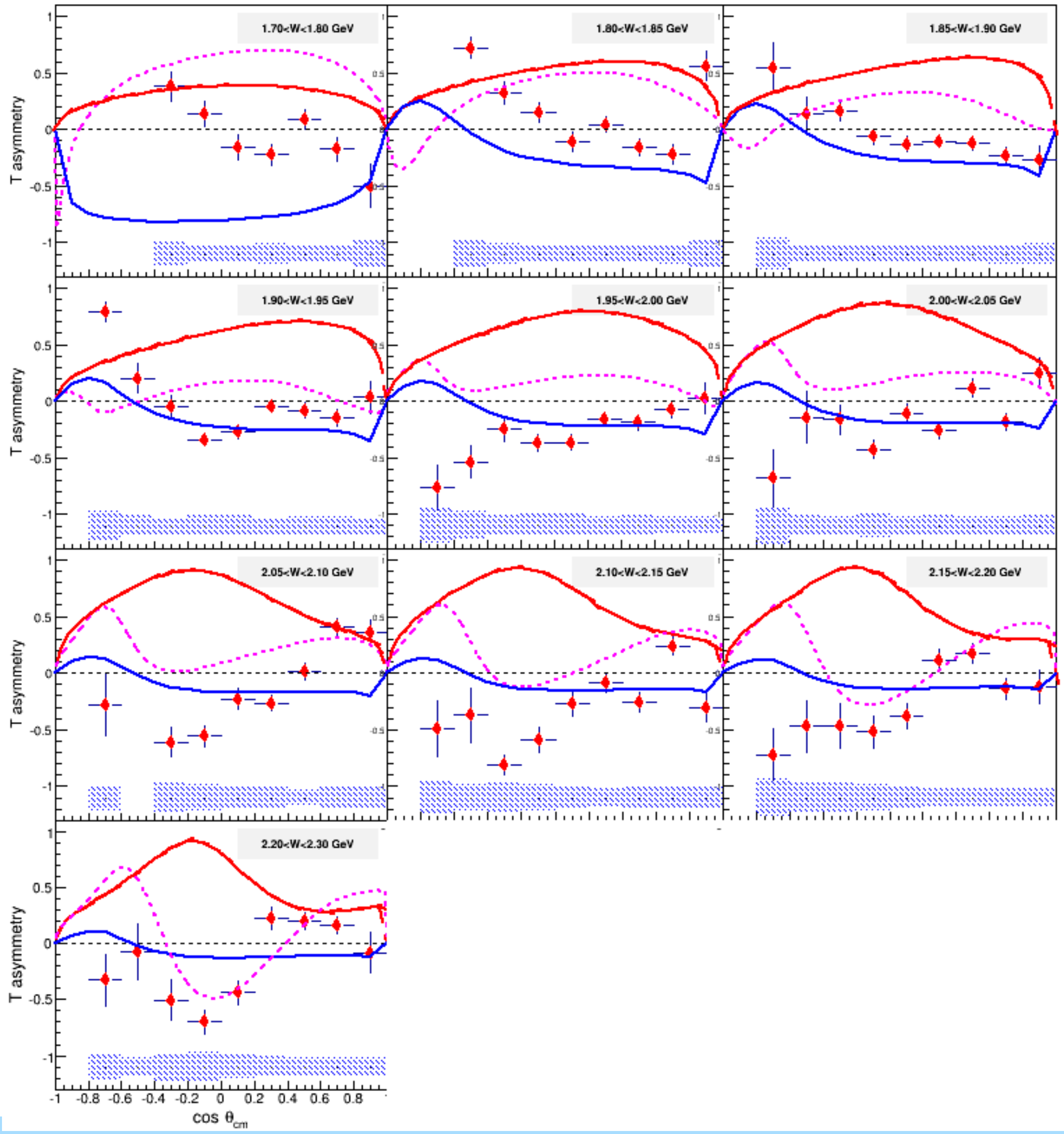
Models:
RPR-Ghent
Kaon-MAID
BOGA

T for K⁺ Λ



Data:
CLAS g9b

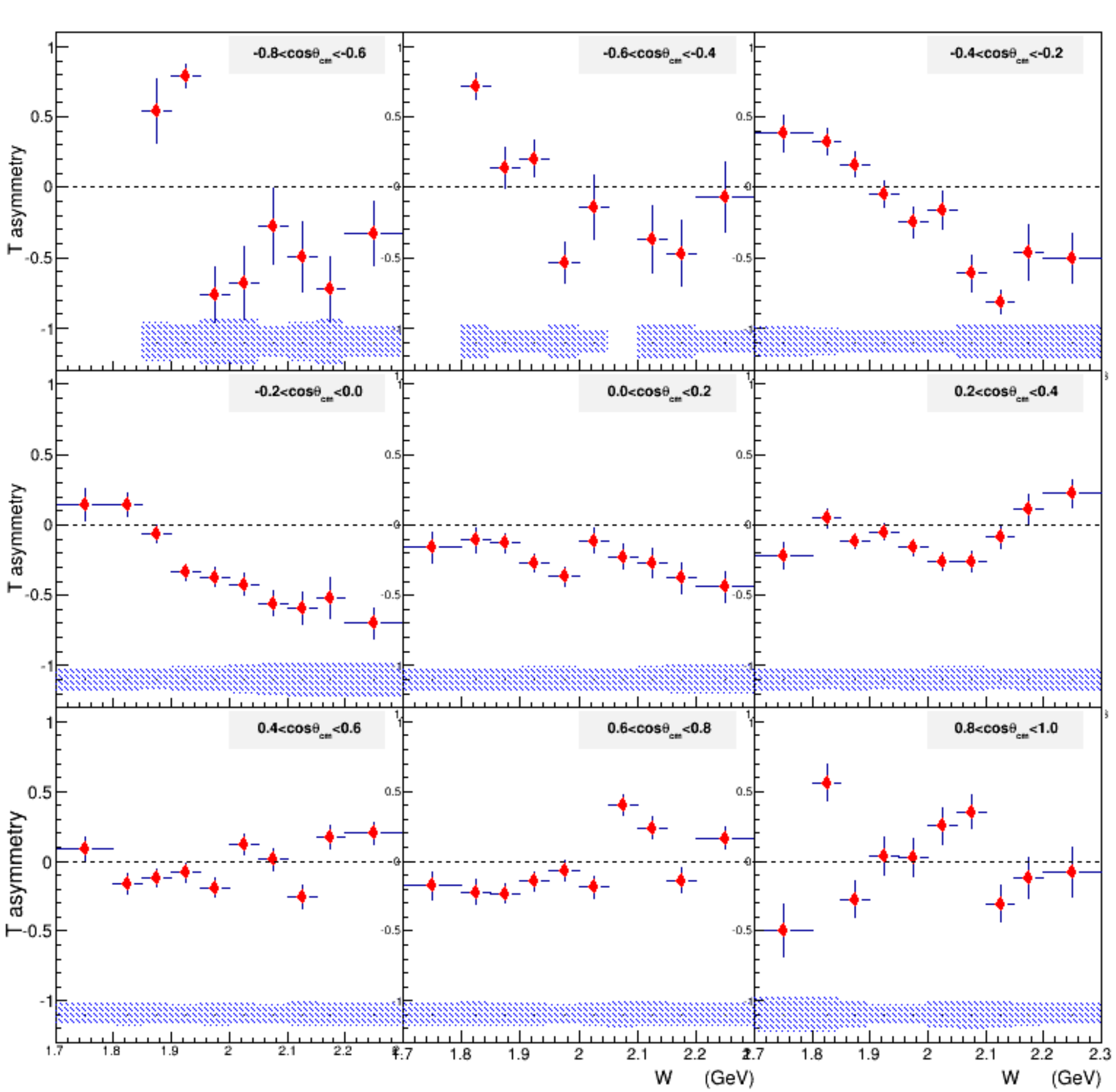
T for $K^+ \Sigma^0$



Data:
CLAS g9b

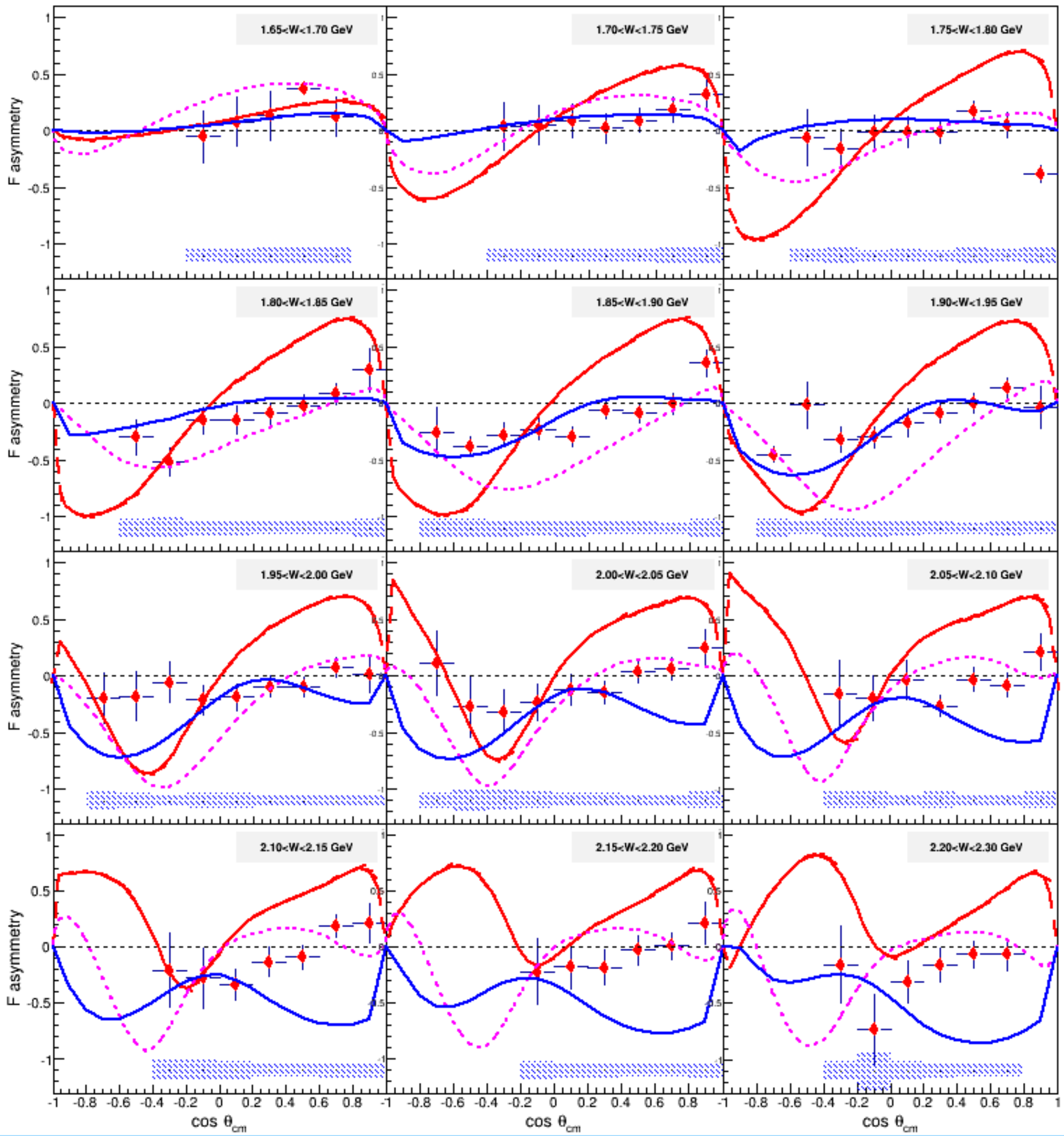
Models:
RPR-Ghent
Kaon-MAID
BOGA

T for $K^+ \Sigma^0$



Data:
CLAS g9b

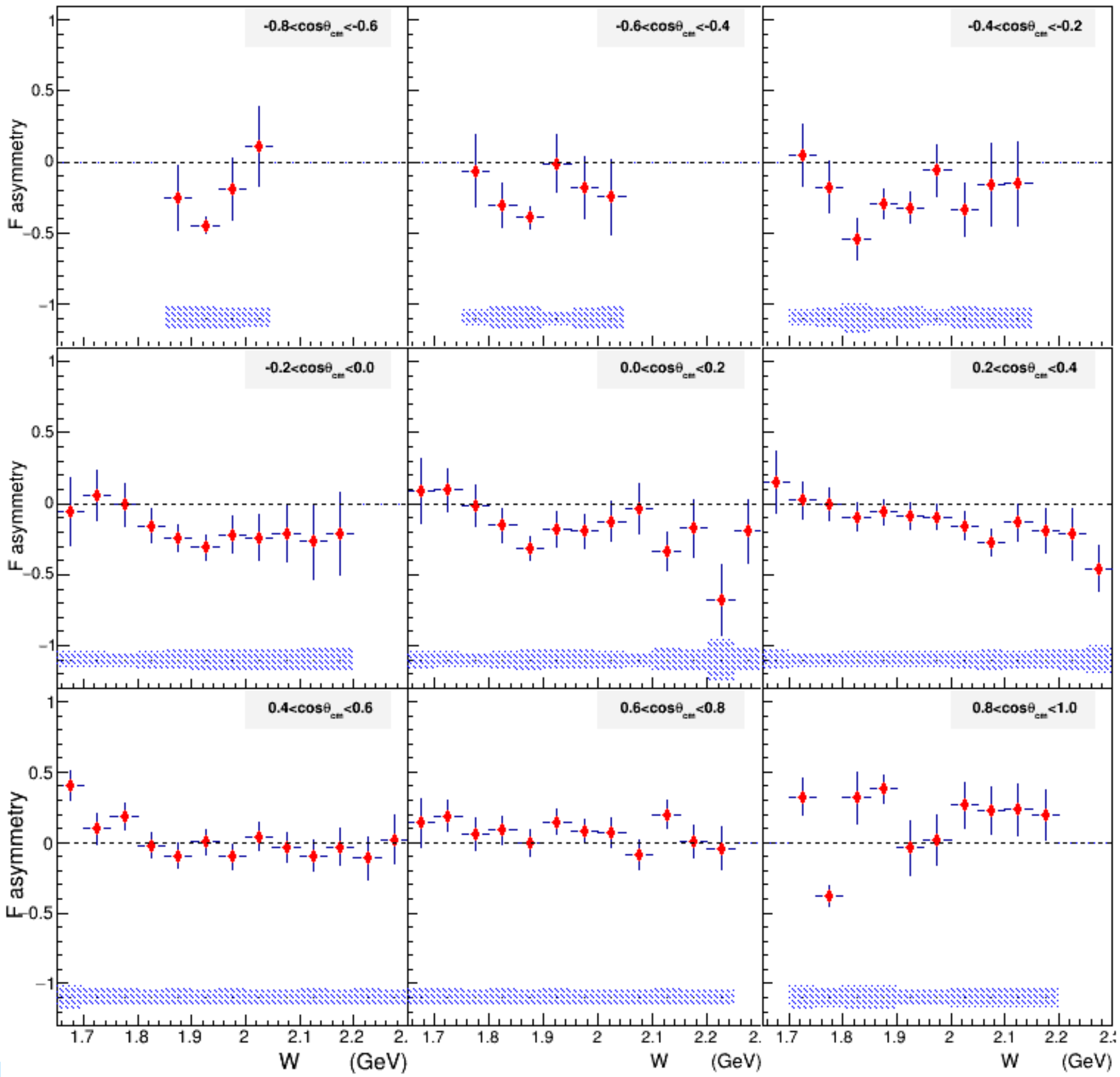
F for $K^+ \Lambda$



Data:
CLAS g9b

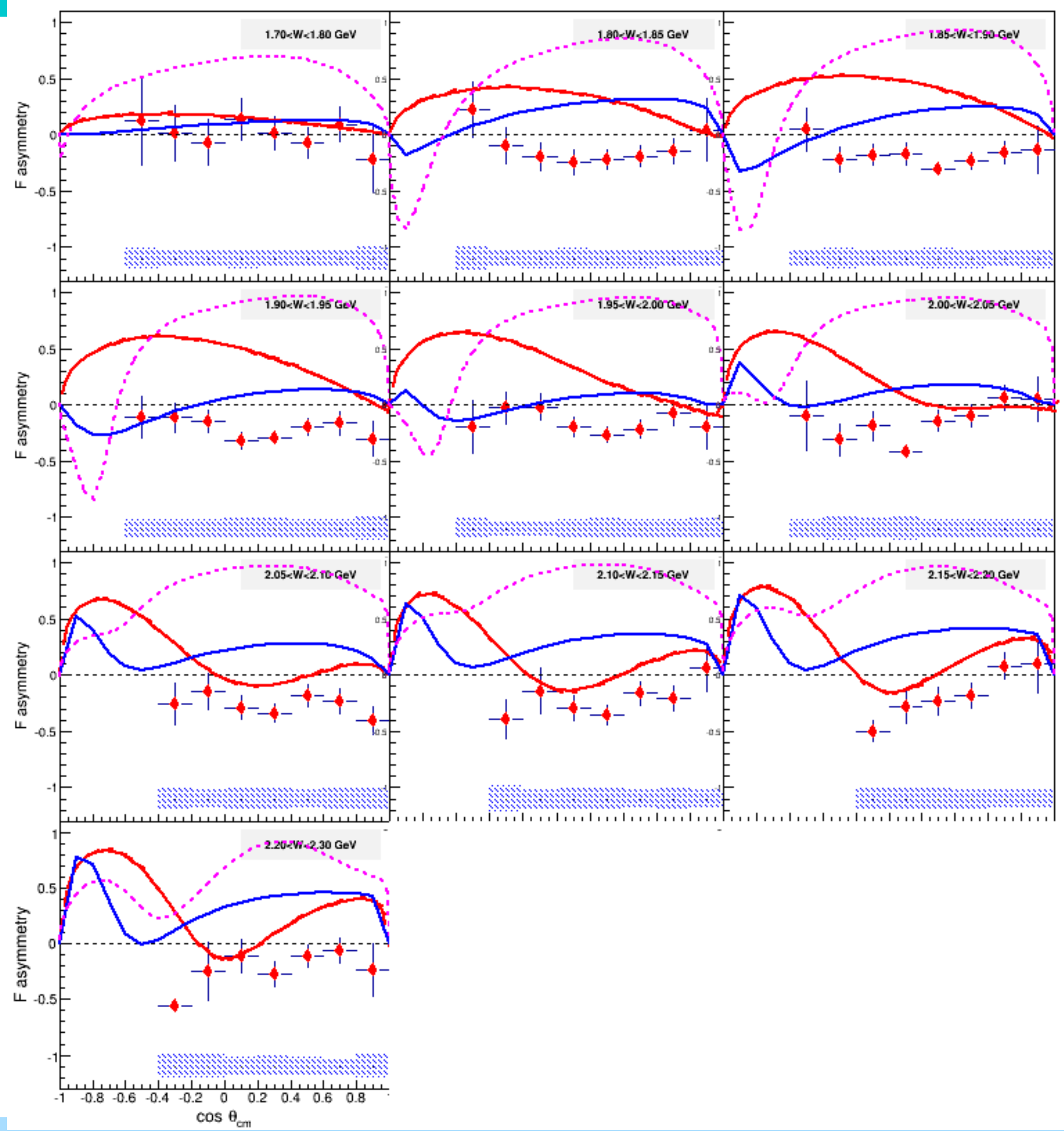
Models:
RPR-Ghent
Kaon-MAID
BOGA

F for K⁺ Λ



Data:
CLAS g9b

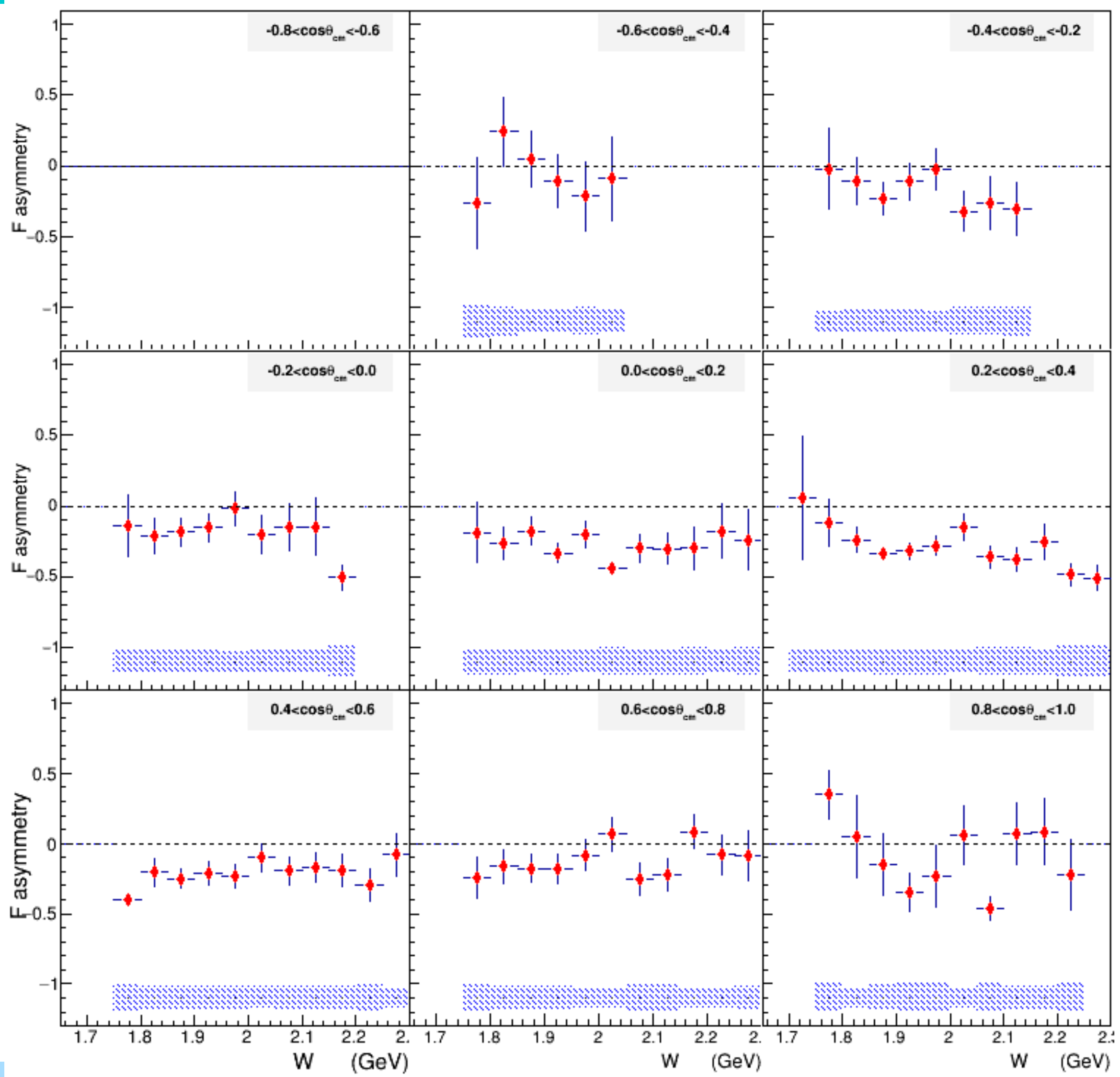
F for $K^+ \Sigma^0$



Data:
CLAS g9b

Models:
RPR-Ghent
Kaon-MAID
BOGA

F for $K^+ \Sigma^0$



Data:
CLAS g9b

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Conclusion

- These new FROST results will add greatly to the world database which needs more kaon photoproduction
- First results of its kind for *F* for both $K^+\Lambda$ and $K^+\Sigma^0$
- First results of its kind for *T* for $K^+\Sigma^0$
- Comparisons to GRAAL and Bonn for *T* for $K^+\Lambda$ show good consistency with GRAAL (GRAAL did NOT have a polarized target, used double polarization data O_x and O_z to extract *T*)
- Analysis note ready to be submitted
- Can then move on to finish up T_x *and* T_z from thesis for $K^+\Lambda$ and $K^+\Sigma^0$ and also E, L_x and L_z $K^+\Lambda$ and $K^+\Sigma^0$ from g9a