Hyperon Recoil Polarization from Analysis of RG-K Data

Infinite Strangeness

Outline:

- KY Electroproduction Formalism
- Existing CLAS Recoil Polarization Data
- Analysis Details, Issues, Next Steps
- Summary/Conclusions

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CLAS Collaboration Meeting, March 12-15, 2024

Pseudoscalar Meson Production Formalism

$$
\frac{d\sigma_v}{d\Omega_K^{c.m.}} = \mathcal{K}\sum_{\alpha,\beta} S_\alpha S_\beta \Big[R_T^{\beta\alpha} + \epsilon R_L^{\beta\alpha} + c_+ ({}^cR_{LT}^{\beta\alpha}\cos\Phi + {}^sR_{LT}^{\beta\alpha}\sin\Phi)
$$

$$
+ \quad \epsilon({}^cR_{TT}^{\beta\alpha}\cos 2\Phi + {}^sR_{TT}^{\beta\alpha}\sin 2\Phi) + hc_-({}^cR_{LT'}^{\beta\alpha}\cos\Phi + {}^sR_{LT'}^{\beta\alpha}\sin\Phi) + hc_0 R_{TT'}^{\beta\alpha}\Big]
$$

Photoproduction and electroproduction of eta mesons

G. Knochlein (Mainz U., Inst. Kernphys.), D. Drechsel (Mainz U., Inst. Kernphys.), L. Tiator (Mainz U., Inst. Kernphys.) (Jun, 1995)

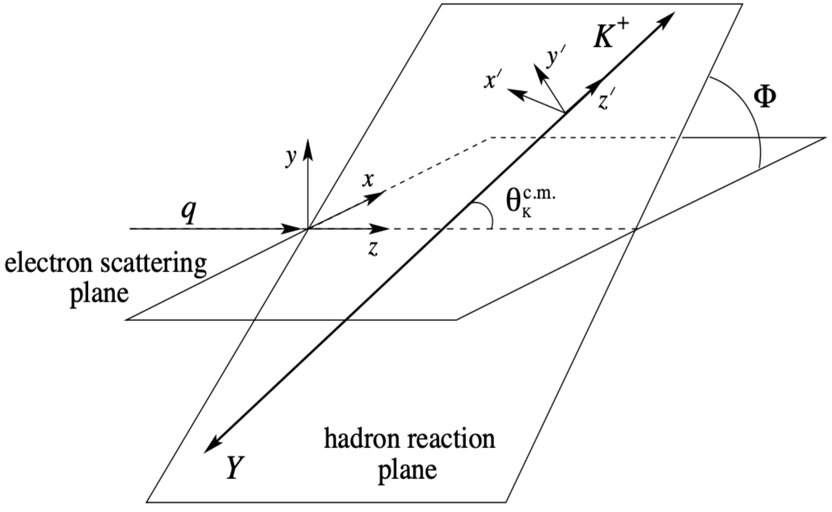
Published in: Z.Phys.A 352 (1995) 327-343 • e-Print: nucl-th/9506029 [nucl-th]

<u>Response functions</u>

$R(Q^2, W, \cos\theta_K^{c.m.})$

TABLE I. Polarization observables in pseudoscalar meson electroproduction. A star denotes a response function which does not vanish but is identical to another response function via a relation in App. A.

	Target				Recoil			Target + Recoil								
β	–	–	–	–	x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
α	–	x	y	z	–	–	–	x	y	z	x	y	z	x	y	z
T	R_T^{00}	0	R_T^{0y}	0	0	$R_T^{y'0}$	0	$R_T^{x'x}$	0	$R_T^{x'z}$	0	$*$	0	$R_T^{z'x}$	0	$R_T^{z'z}$
L	R_L	0	R_L^{0y}	0	0	$*$	0	$R_L^{x'x}$	0	$R_L^{x'z}$	0	$*$	0	$*$	0	$*$
${}^cTL$	${}^cR_{TL}^{00}$	0	${}^cR_{TL}^{0y}$	0	0	$*$	0	${}^cR_{TL}^{x'x}$	0	$*$	0	$*$	0	${}^cR_{TL}^{z'x}$	0	$*$
${}^sTL$	0	${}^sR_{TL}^{0x}$	0	${}^sR_{TL}^{0z}$	${}^sR_{TL}^{x'0}$	0	${}^sR_{TL}^{z'0}$	0	$*$	0	$*$	0	$*$	0	$*$	0
${}^cTT$	${}^cR_{TT}^{00}$	0	$*$	0	0	$*$	0	$*$	0	$*$	0	$*$	0	$*$	0	$*$
${}^sTT$	0	${}^sR_{TT}^{0x}$	0	${}^sR_{TT}^{0z}$	${}^sR_{TT}^{x'0}$	0	${}^sR_{TT}^{z'0}$	0	$*$	0	$*$	0	$*$	0	$*$	0
${}^cTL'$	0	${}^cR_{TL'}^{0x}$	0	${}^cR_{TL'}^{0z}$	${}^cR_{TL'}^{x'0}$	0	${}^cR_{TL'}^{z'0}$	0	$*$	0	$*$	0	$*$	0	$*$	0
${}^sTL'$	${}^sR_{TL'}^{00}$	0	${}^sR_{TL'}^{0y}$	0	0	$*$	0	${}^sR_{TL'}^{x'x}$	0	$*$	0	$*$	0	${}^sR_{TL'}^{z'x}$	0	$*$
TT'	0	$R_{TT'}^{0x}$	0	$R_{TT'}^{0z}$	$R_{TT'}^{x'0}$	0	$R_{TT'}^{z'0}$	0	$*$	0	$*$	0	$*$	0	$*$	0



KY Polarization Formalism

$\mathcal{P}^0$ = recoil polarization

$\mathcal{P}'$ = transferred polarization

Φ-integrated

(x′,y′,z′)		(x,y,z)	
$\mathcal{P}^0_{x'}$	0	$\mathcal{P}^0_{x}$	0
$\mathcal{P}^0_{y'}$	$K_I(R_T^{y'0} + \epsilon R_L^{y'0})$	$\mathcal{P}^0_{y}$	$\frac{1}{2}\sqrt{\epsilon(1+\epsilon)}K_I(R_{LT}^{x'0}\cos\theta_K^{c.m.} + R_{LT}^{y'0} + R_{LT}^{z'0}\sin\theta_K^{c.m.})$
$\mathcal{P}^0_{z'}$	0	$\mathcal{P}^0_{z}$	0
$\mathcal{P}'_{x'}$	$K_I\sqrt{1-\epsilon^2}R_{TT'}^{x'0}$	$\mathcal{P}'_{x}$	$\frac{1}{2}\sqrt{\epsilon(1-\epsilon)}K_I(R_{LT'}^{x'0}\cos\theta_K^{c.m.} - R_{LT'}^{y'0} + R_{LT'}^{z'0}\sin\theta_K^{c.m.})$
$\mathcal{P}'_{y'}$	0	$\mathcal{P}'_{y}$	0
$\mathcal{P}'_{z'}$	$K_I\sqrt{1-\epsilon^2}R_{TT'}^{z'0}$	$\mathcal{P}'_{z}$	$\sqrt{1-\epsilon^2}K_I(-R_{TT'}^{x'0}\sin\theta_K^{c.m.} + R_{TT'}^{z'0}\cos\theta_K^{c.m.})$

D.S. Carman et al., PRC 79, 065205 (2009)

- Polarization is a 3-vector whose components are defined in terms of response functions
- Polarization components extracted selecting hyperons from MM(e′K⁺) and measuring hyperon decay proton angular distribution
- Transferred polarization extracted from beam helicity asymmetry
- Recoil polarization extracted from forward-backward asymmetry in hyperon decay frame

PHYSICAL REVIEW C **105**, 065201 (2022)

Beam-recoil transferred polarization in K^+Y electroproduction in the nucleon resonance region with CLAS12

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D.S. Carman et al. (CLAS), PRC 79, 065205 (2022)

KY Recoil Polarization Formalism

Λ Production

$$\frac{dN}{d\cos\theta_p^{\Lambda RF}} = N_0\left(1 + \alpha P_\Lambda^0 \cos\theta_p^{\Lambda RF}\right)$$

Weak decay parameter
α = 0.732

Self-analyzing weak decay

"forward"

$$N_F = \int_0^1 \frac{dN}{d\cos\theta_p^{\Lambda RF}} d\cos\theta_p^{\Lambda RF} = \int_0^1 N_0\left(1 + \alpha P_\Lambda^0 \cos\theta_p^{\Lambda RF}\right) d\cos\theta_p^{\Lambda RF}$$

$$= N_0 + N_0 \frac{\alpha P_\Lambda^0}{2}$$

"backward"

$$N_B = \int_{-1}^0 \frac{dN}{d\cos\theta_p^{\Lambda RF}} d\cos\theta_p^{\Lambda RF} = \int_{-1}^0 N_0\left(1 + \alpha P_\Lambda^0 \cos\theta_p^{\Lambda RF}\right) d\cos\theta_p^{\Lambda RF}$$

$$= N_0 - N_0 \frac{\alpha P_\Lambda^0}{2}$$

$$A = \frac{N_F - N_B}{N_F + N_B} = \frac{\alpha P_\Lambda^0}{2}$$

$$P_\Lambda^0 = \frac{2A}{\alpha} = 2.732 \cdot A$$

KY Recoil Polarization Formalism

Σ^0 Production

$$\frac{dN}{d\cos\theta_p^{\Sigma RF}} = N_0\left(1 + \nu_\Sigma \alpha P_\Sigma^0 \cos\theta_p^{\Sigma RF}\right)$$

"forward"

$$N_F = \int_0^1 \frac{dN}{d\cos\theta_p^{\Sigma RF}} d\cos\theta_p^{\Sigma RF} = \int_0^1 N_0\left(1 + \nu_\Sigma \alpha P_\Sigma^0 \cos\theta_p^{\Sigma RF}\right) d\cos\theta_p^{\Sigma RF}$$

$$= N_0 + N_0 \frac{\nu_\Sigma \alpha P_\Sigma^0}{2}$$

"backward"

$$N_B = \int_{-1}^0 \frac{dN}{d\cos\theta_p^{\Sigma RF}} d\cos\theta_p^{\Sigma RF} = \int_{-1}^0 N_0\left(1 + \nu_\Sigma \alpha P_\Sigma^0 \cos\theta_p^{\Sigma RF}\right) d\cos\theta_p^{\Sigma RF}$$

$$= N_0 - N_0 \frac{\nu_\Sigma \alpha P_\Sigma^0}{2}$$

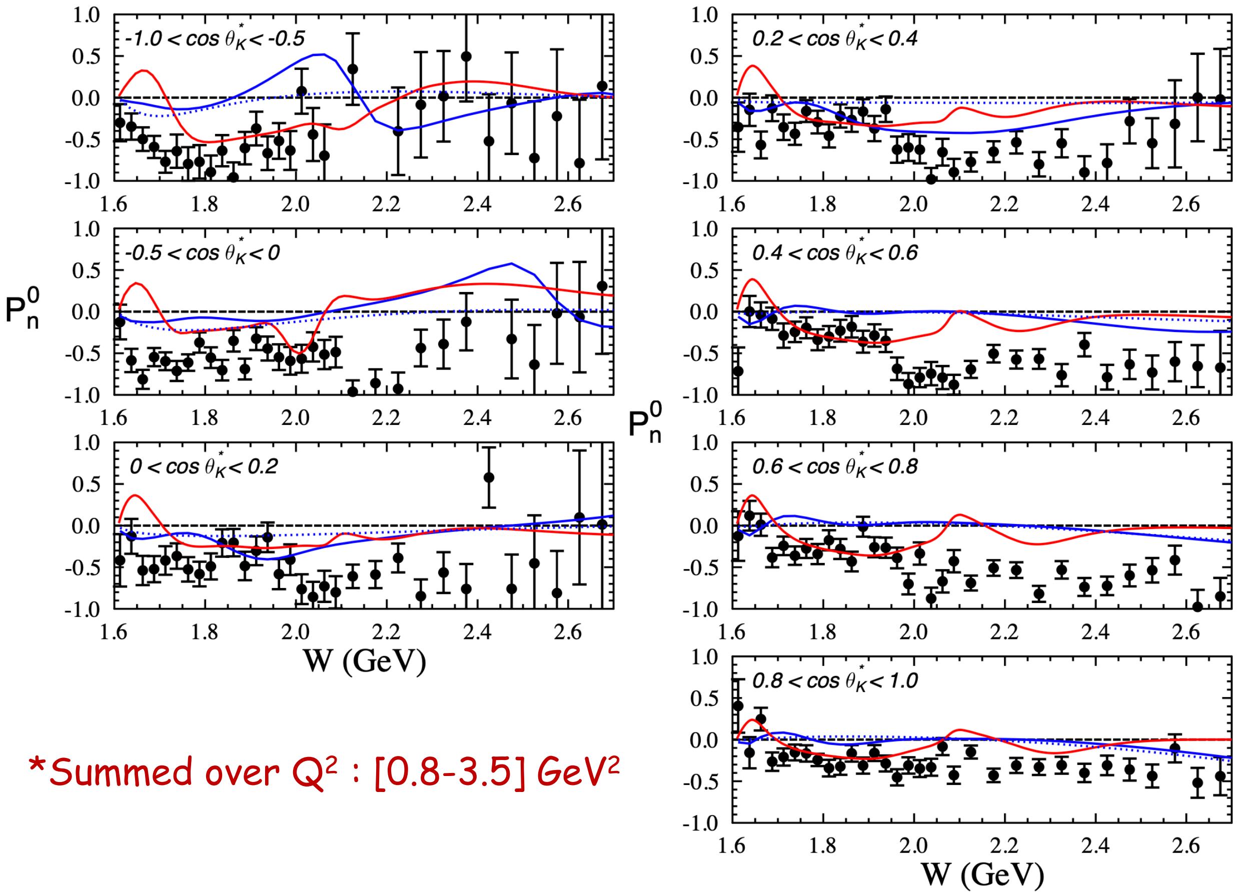
$$A = \frac{N_F - N_B}{N_F + N_B} = \frac{\nu_\Sigma \alpha P_\Sigma^0}{2}$$

$$P_\Sigma^0 = \frac{2A}{\nu_\Sigma \alpha} = -10.655 \cdot A$$

ν_Σ = -0.265 includes depolarization for $\Sigma^0 \rightarrow \Lambda\gamma$ (-⅓) AND use of $\theta_p^{\Sigma RF}$ instead of $\theta_p^{\Lambda RF}$

KY Recoil Polarization

CLAS Data – Λ Polarization



*Summed over Q^2 : [0.8-3.5] GeV^2

M. Gabrielyan et al, PRC 90, 035202 (2014)

CLAS e1f

CLAS/CLAS12 Data – Λ and Σ^0 Polarization

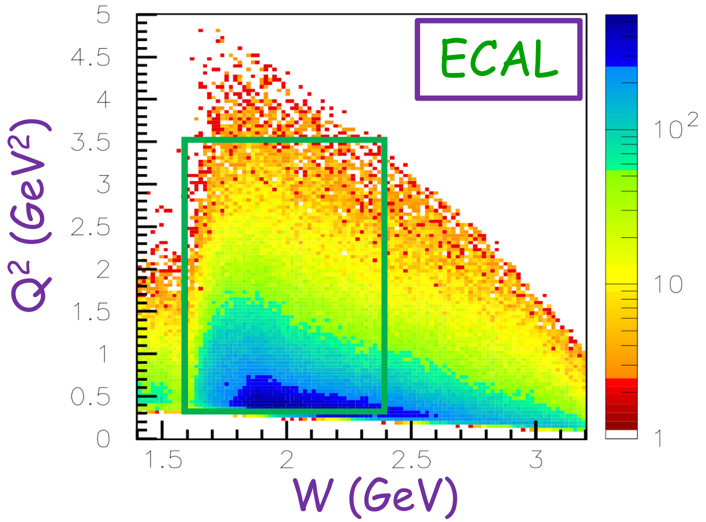
	E_b (GeV)	W (GeV)	Q^2 (GeV^2)	Charge (mC)
Published	CLAS e1f run: Apr. – Jun. 2003			
	5.479 GeV	1.6-3.0	0.8-3.5	15.7
Analysis in progress	CLAS12 RG-K run #1: Dec. 2018			
	6.535 GeV	1.6-2.4	0.3-3.5	18.2
	7.546 GeV	1.6-2.4	0.4-4.5	10.8
Spr24	CLAS12 RG-K run #2: Jan. – Mar. 2024			
	6.4 GeV	1.6-2.4	0.3-3.5	91.4
	8.4 GeV	1.6-2.4	0.4-4.5	81.8
Upcoming	CLAS12 RG-K run #3: Planned fall 2025			
	6.6 GeV	1.6-2.4	0.3-3.5	200
	8.8 GeV	1.6-2.4	0.4-4.5	200

Data Analysis

$e + p \rightarrow e' + K^+ + \Lambda, \quad \Lambda \rightarrow p\pi^-$ $\qquad$ $e + p \rightarrow e' + K^+ + \Sigma^0, \quad \Sigma^0 \rightarrow \Lambda\gamma, \quad \Lambda \rightarrow p\pi^-$

electrons

Cut	Value
Track Status	$2000 \leq$ abs(STATUS) < 4000
Event Builder PID	11
p_e	$[1.0{:}p_{beam}]$ GeV
TOF_e	[21:26] ns
v_z	[-10:2] cm
ECAL Sampling Fraction	$\pm 3.5\sigma$
ECAL Fiducial Cut	7 cm edge cut on U, V, W
π^- contamination	$E_{ECin}/p_e < -0.84 * E_{PCAL}/p_e + 0.17$
DC Fiducial Cuts	on



6.535 GeV

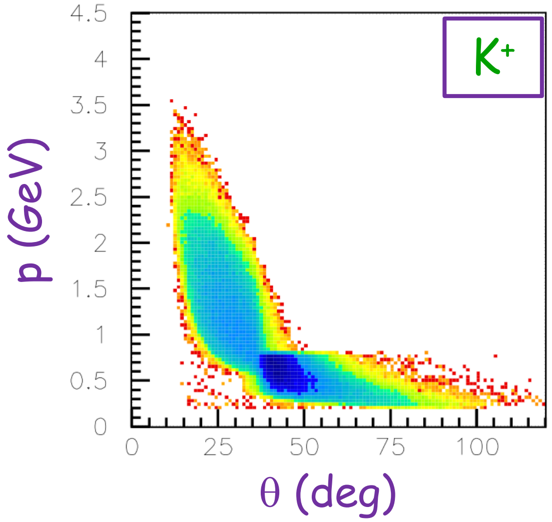
hadrons

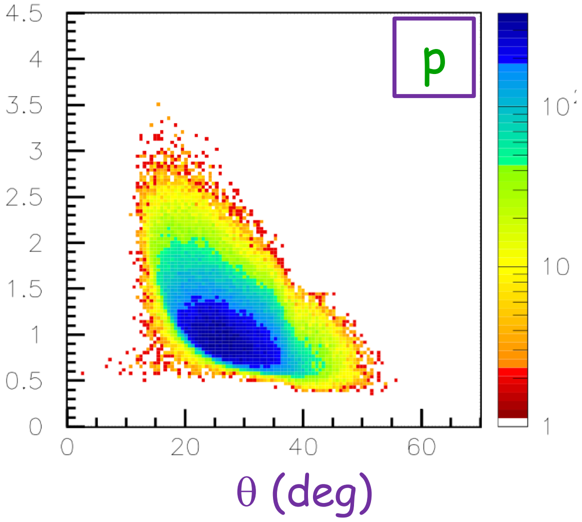
Forward Detector

Cut	Value
Track status	$2000 \leq \|STATUS\| < 4000$
q	$\neq 0$
p_h	$[0.4{:}p_{beam}]$ GeV
β_h	[0.4:1.1]
Event Builder PID	± 211, ± 321, or ± 2212
TOF_h	[20:55] ns ($q > 0$), [20:35] ns ($q < 0$)
v_z	[-10:2] cm (K^+ candidates)
DC Fiducial Cuts	on

Central Detector

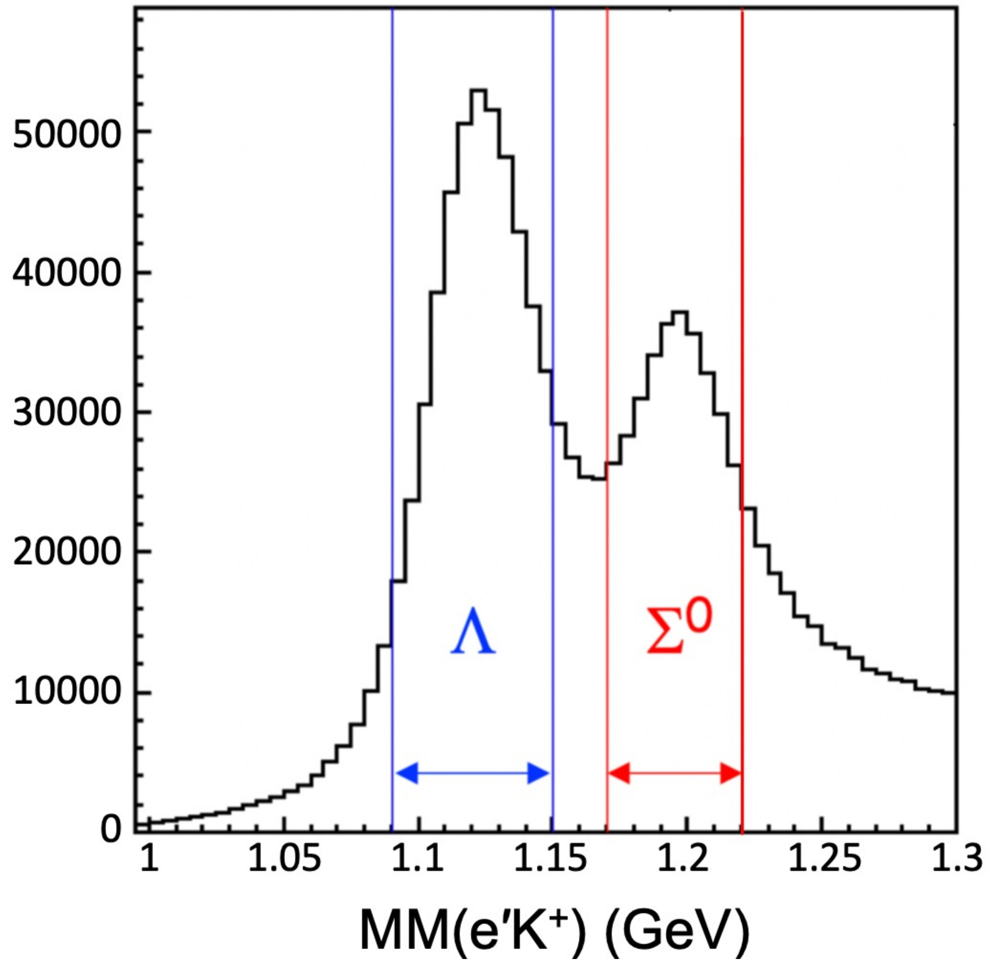
Cut	Value
Track status	$\|STATUS\| \geq 4000$
q	$\neq 0$
p_h	[0.2:1.5] GeV
β_h	[0.2:1.1]
Event Builder PID	± 211, ± 321, or ± 2212
TOF_h	[0.5:4.0] ns
v_z	[-10:2] cm (K^+ candidates)
Duplicate FD/CD hadron	on





Data Binning

Hyperon Analysis Regions



1D Binning Sort

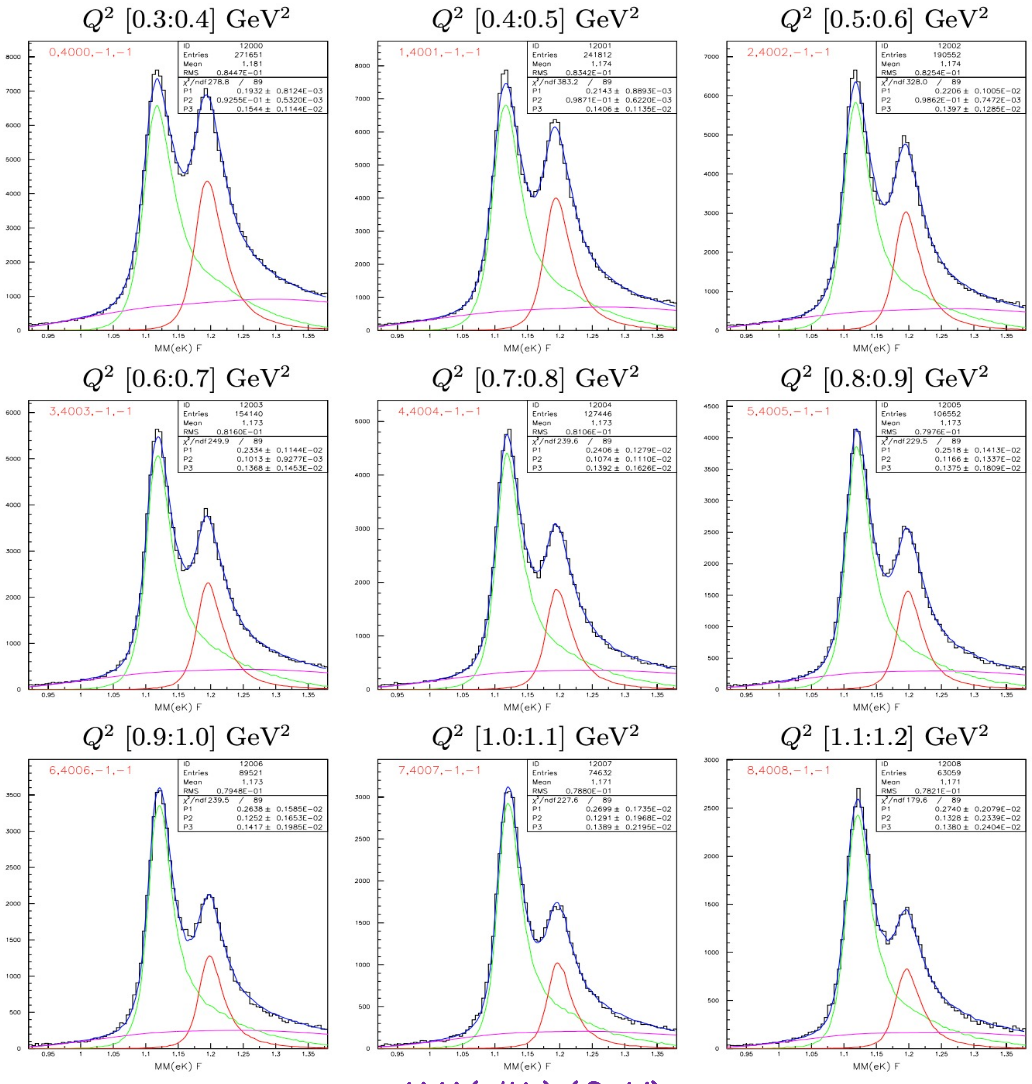
Dependence	Range	Bin Size	
Q^2	$[Q^2_{min}$:1.5] GeV^2	0.1 GeV^2	20 bins
	[1.5:2.5] GeV^2	0.2 GeV^2	
	[2.5:3.1] GeV^2	0.3 GeV^2	
	[3.1:3.5] GeV^2	0.4 GeV^2	
W	$[W_{min}$:2.4] GeV	25 MeV	31 bins
$\cos\theta_K^{c.m.}$	[−1:1]	0.08	25 bins

- Sort vs. Q^2 – sum over W, cos $\theta_K^{c.m.}$, Φ
- Sort vs. W – sum over Q^2, cos $\theta_K^{c.m.}$, Φ
- Sort vs. cos $\theta_K^{c.m.}$ – sum over Q^2, W, Φ

Analysis bounds: Q^2 [0.3:3.5] GeV^2, W [thr:2.4] GeV

MM Spectrum Fits

6.535 GeV



Sum all FD/CD topologies together

<u>Yield fitting approach:</u>

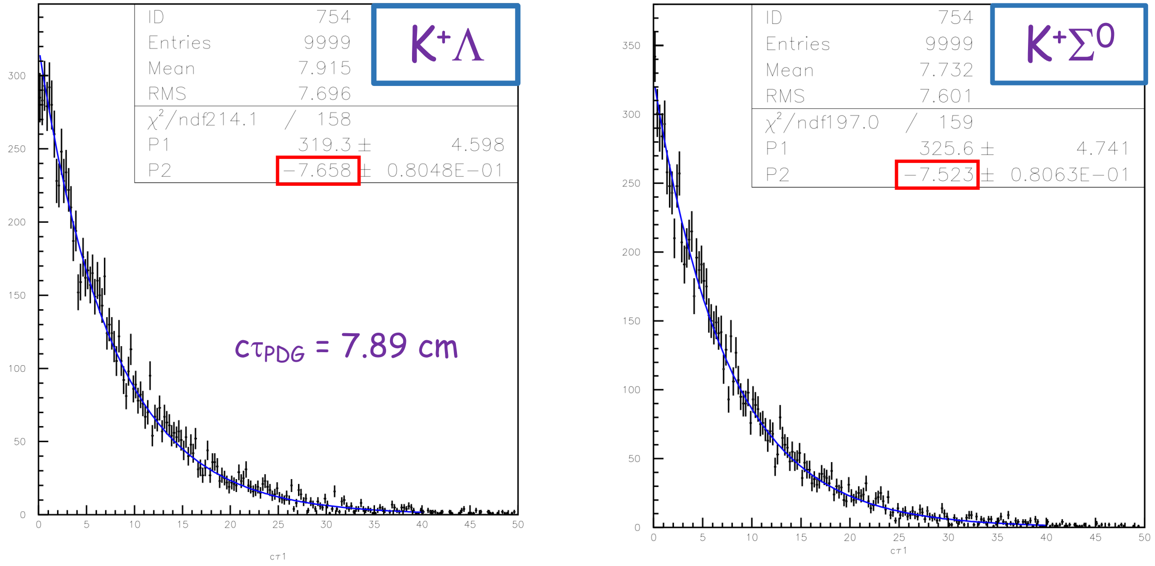
- Generate Monte Carlo $K^+\Lambda$ and $K^+\Sigma^0$ samples to use as fitting templates in bins matched to the data
- The background can be modeled with a polynomial or with the background channel
  - $e'\pi^+\pi^- p$ - with π^+ misidentified as a K^+
- Fit function:
  - Include resolution smearing on reconstructed electron and hadrons
  - Include simple-minded $1/E_\gamma$ model for internal electron radiation

$$MM = A*[TEMPLATE_\Lambda] + B*[TEMPLATE_\Sigma] + C*[bck]$$

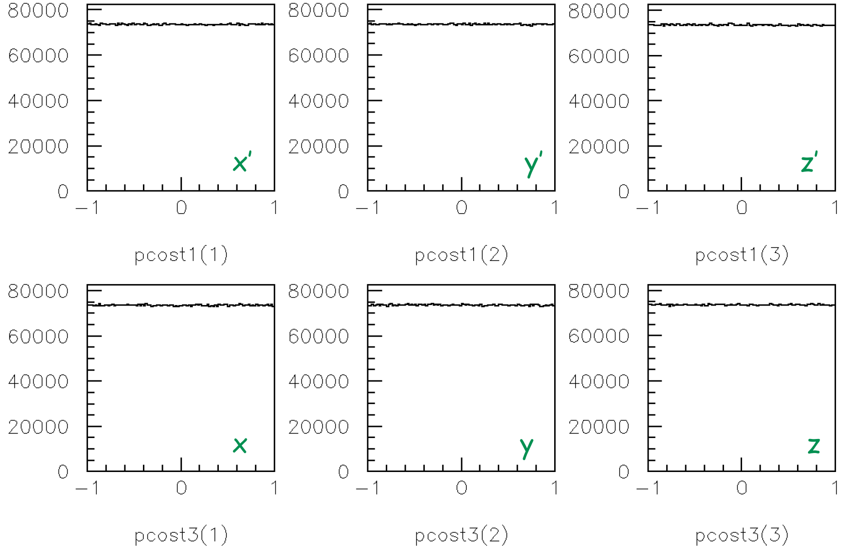
Final MM($e'K^+$) spectra fit only after $e'/K^+/p$ momentum and hadron energy loss corrections

Event Generator

cτ check

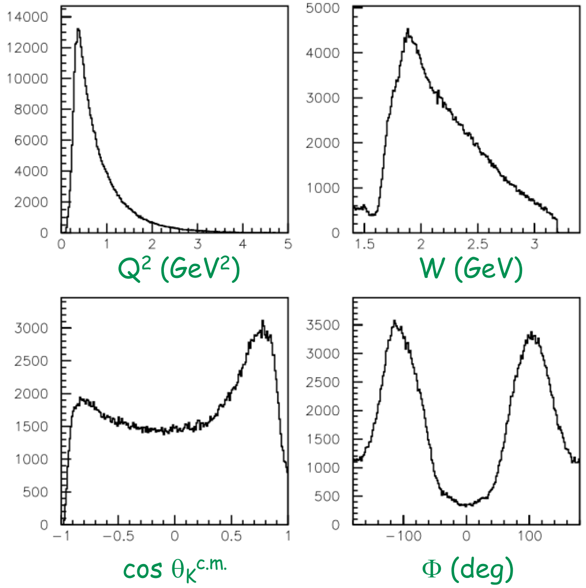


Generated Distributions

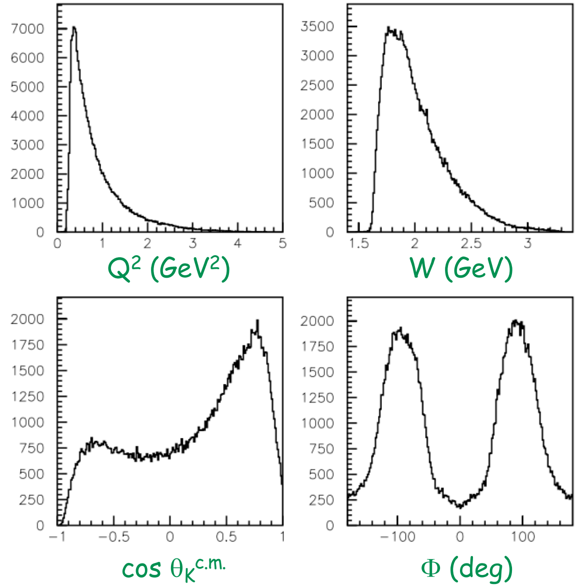


EG based on fit to CLAS KY ep data
CLAS12-Note 2021-003
V. Klimenko, D.S. Carman, V.I. Mokeev
genKYandOnePion

Data Plots



MC Plots



EG decays Λ and Σ^0 hyperons isotropically in their rest frames

MC Acceptance

$$ACC = \frac{N_{rec}(Q^2, W, \cos\theta_K{}^{c.m.}, \Phi, \cos\theta_p^{RF})}{N_{gen}(Q^2, W, \cos\theta_K{}^{c.m.}, \Phi, \cos\theta_p^{RF})}$$

N_{rec} and N_{gen} from MC sample

ACC2D:

1) Q^2 : 20 Q^2 bins, 2 $\cos\theta_p{}^{RF}$ bins
2) W : 31 W bins, 2 $\cos\theta_p{}^{RF}$ bins
3) $\cos\theta_K{}^{c.m.}$: 25 $\cos\theta_K{}^{c.m.}$ bins, 2 $\cos\theta_p{}^{RF}$ bins

$$ASM_{2D} = \frac{\frac{\sum_i N_{rec}^F}{ACC_{2D}} - \frac{\sum_i N_{rec}^B}{ACC_{2D}}}{\frac{\sum_i N_{rec}^F}{ACC_{2D}} + \frac{\sum_i N_{rec}^B}{ACC_{2D}}}$$

Apply ACC after sorting binned yields

ACC4D:

Q^2 : 20 Q^2 bins, 8 W bins, 8 $\cos\theta_K{}^{c.m.}$ bins, 2 $\cos\theta_p{}^{RF}$ bins
W : 31 W bins, 8 Q^2 bins, 8 $\cos\theta_K{}^{c.m.}$ bins, 2 $\cos\theta_p{}^{RF}$ bins
$\cos\theta_K{}^{c.m.}$: 25 $\cos\theta_K{}^{c.m.}$ bins, 8 Q^2 bins, 8 W bins, 2 $\cos\theta_p{}^{RF}$ bins

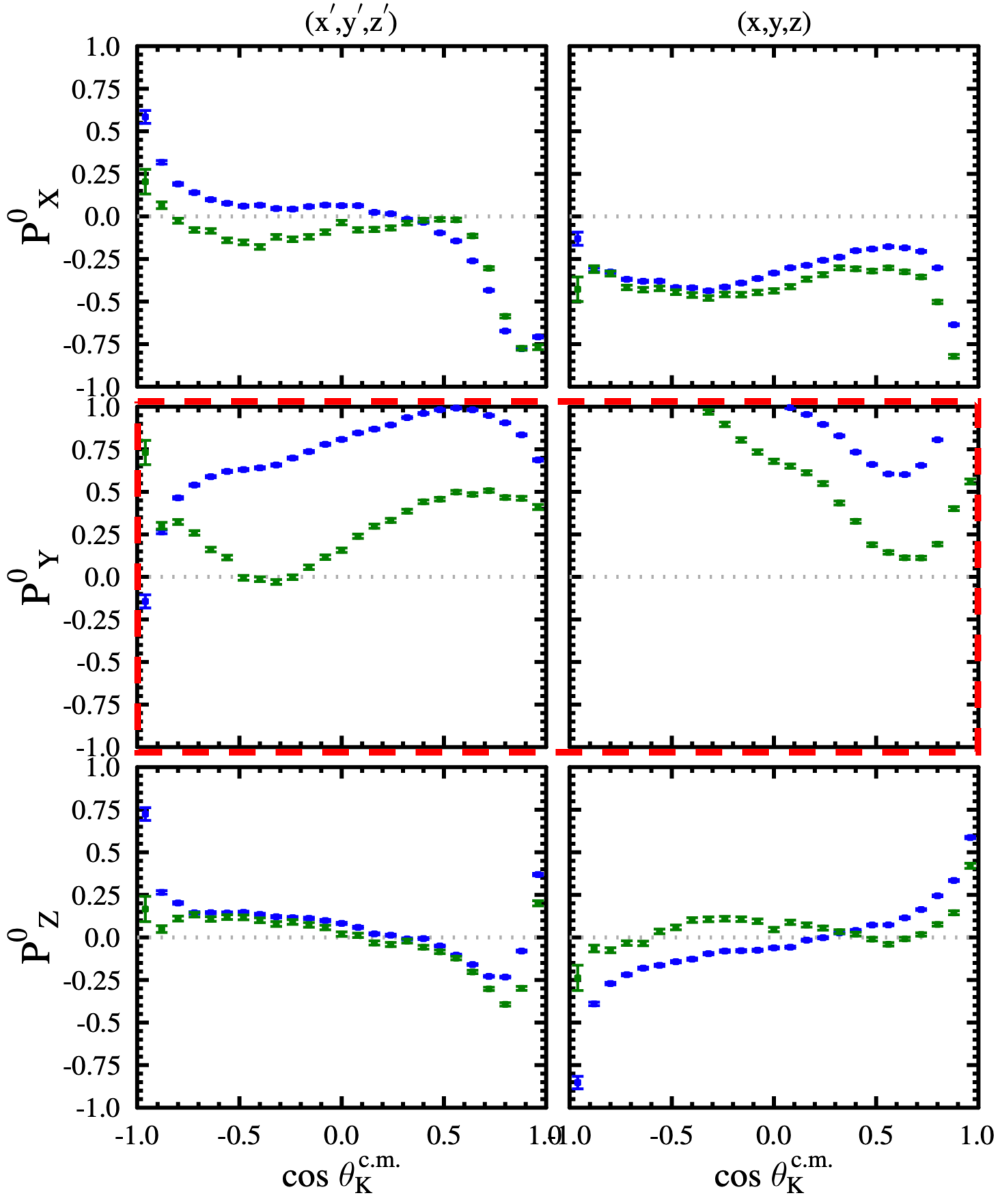
$$ASM_{4D} = \frac{\sum_i \left(\frac{N_{rec}^F}{ACC_{4D}}\right)_i - \sum_i \left(\frac{N_{rec}^B}{ACC_{4D}}\right)_i}{\sum_i \left(\frac{N_{rec}^F}{ACC_{4D}}\right)_i + \sum_i \left(\frac{N_{rec}^B}{ACC_{4D}}\right)_i}$$

Apply ACC event-by-event as event weight with WGT = 1/ACC

"Raw" Polarization Results – Data vs. MC

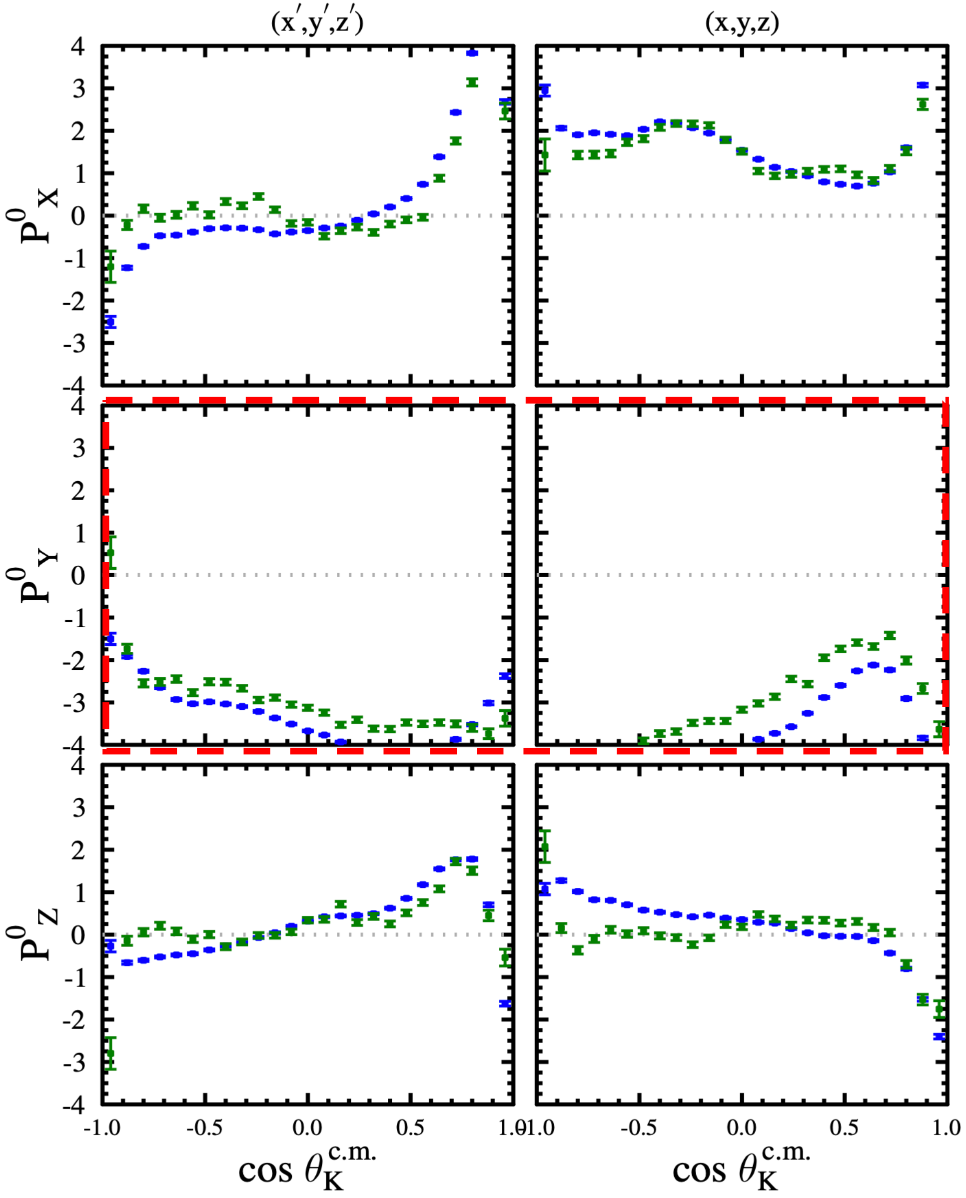
No ACC

$K^+\Lambda$



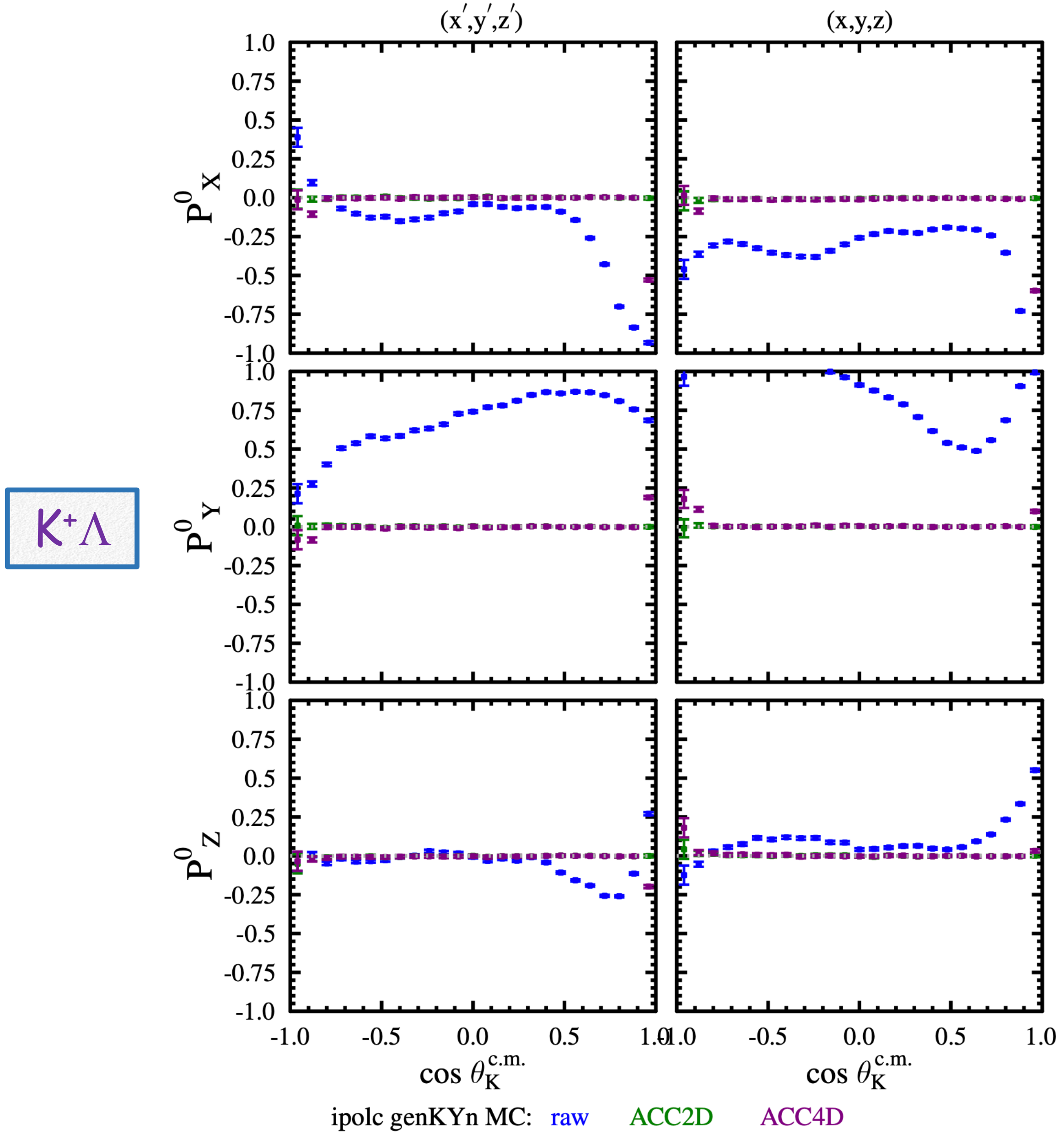
ipolc genKYn MC: raw MC raw data

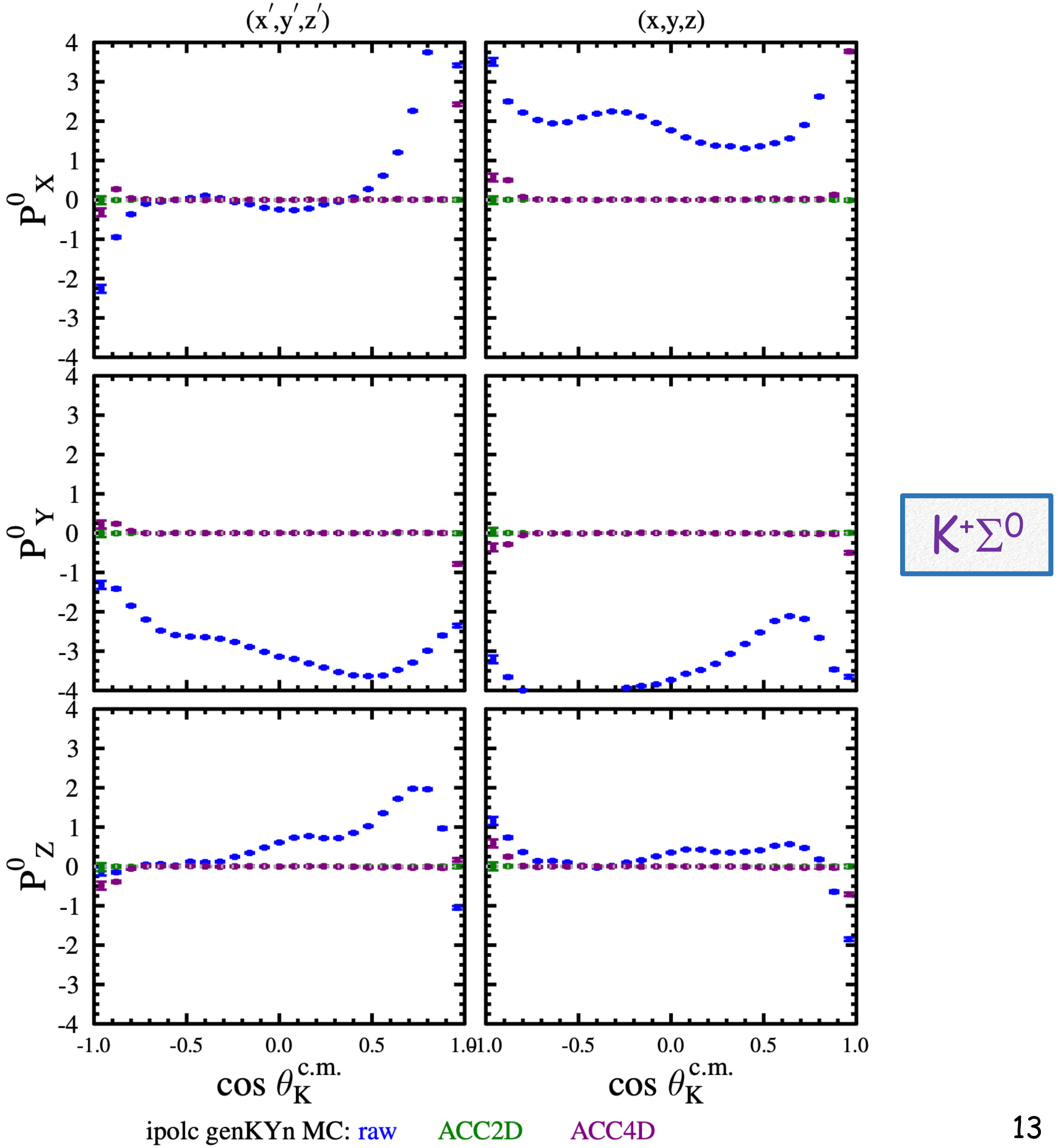
$K^+\Sigma^0$



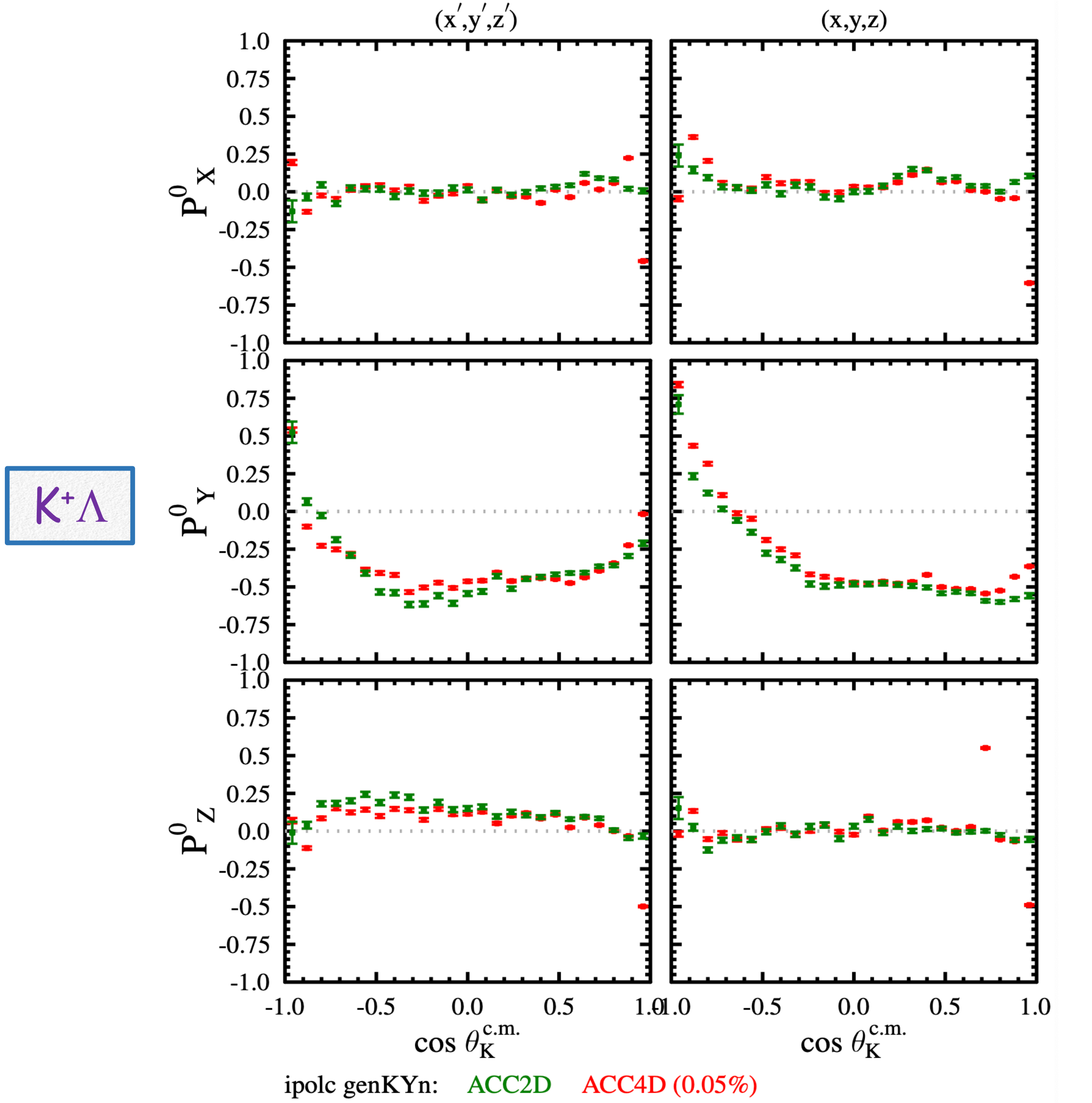
ipolc genKYn MC: raw MC raw data

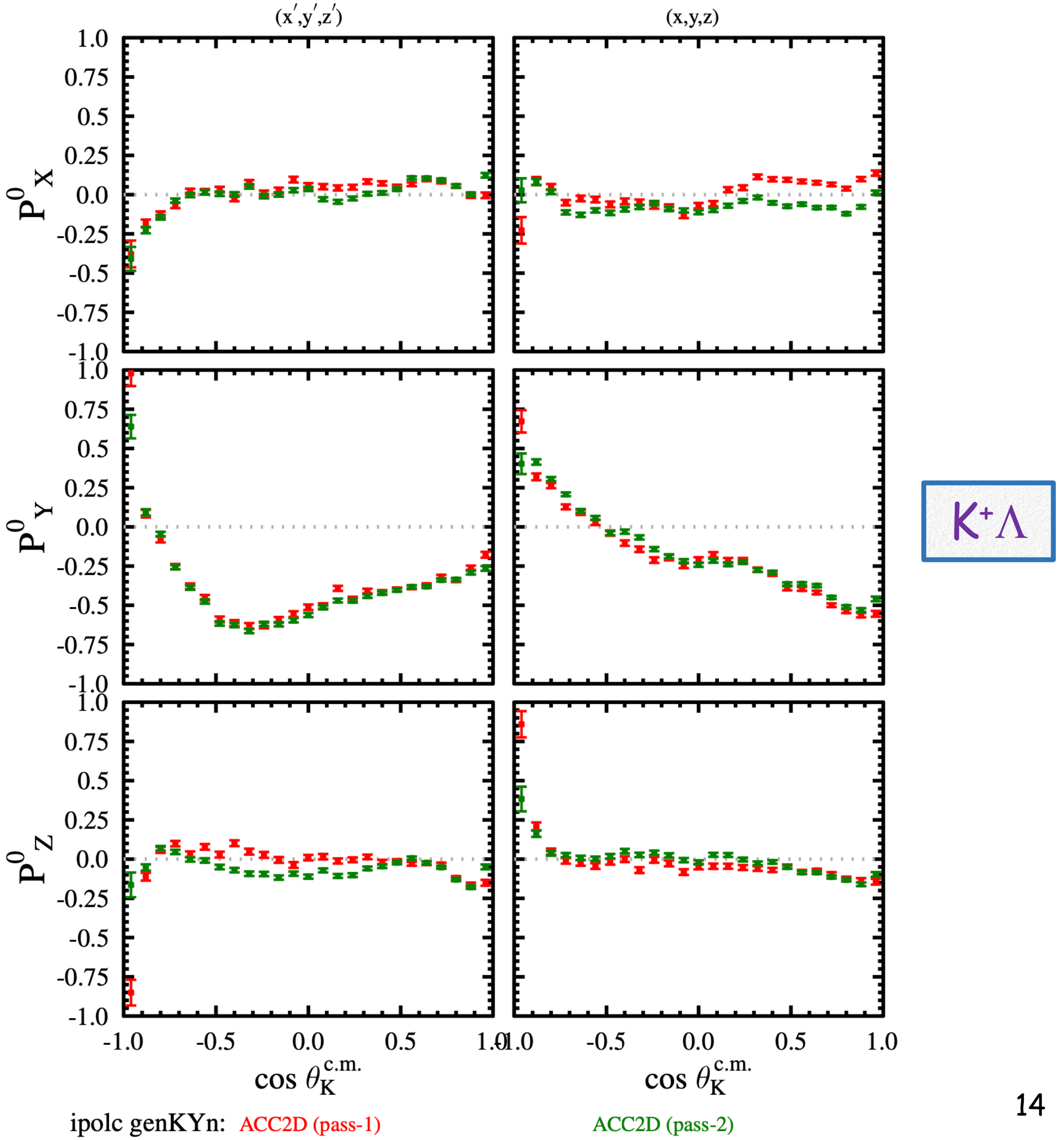
MC Polarization Results





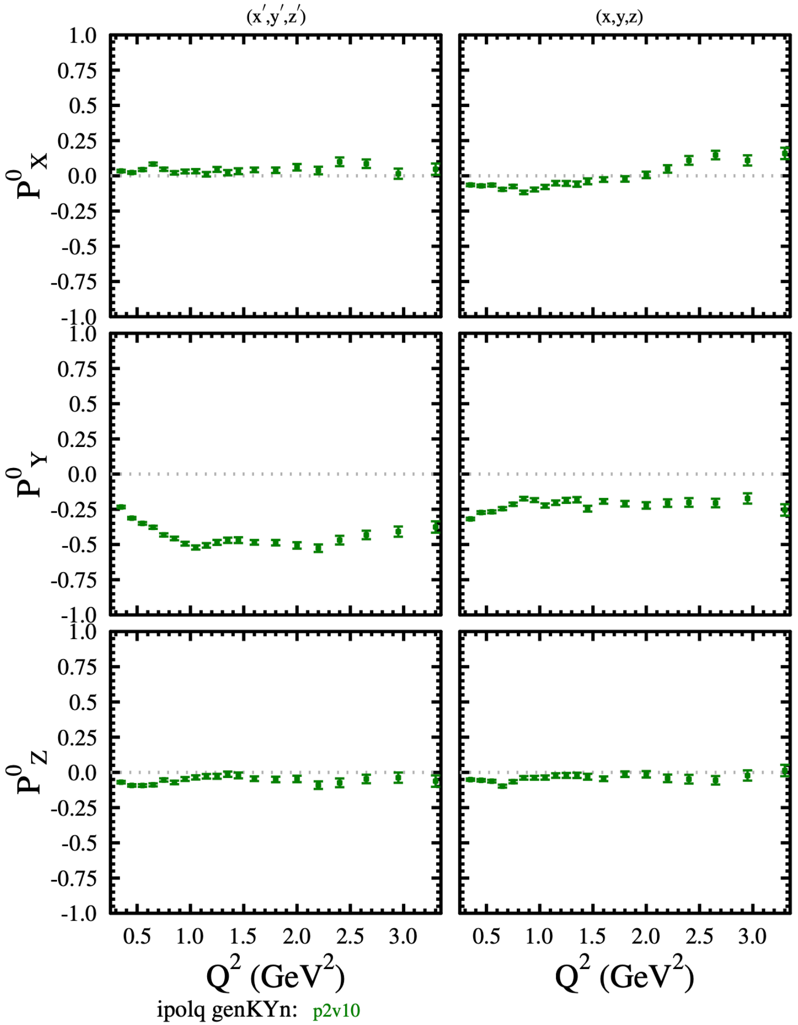
Data Polarization Results



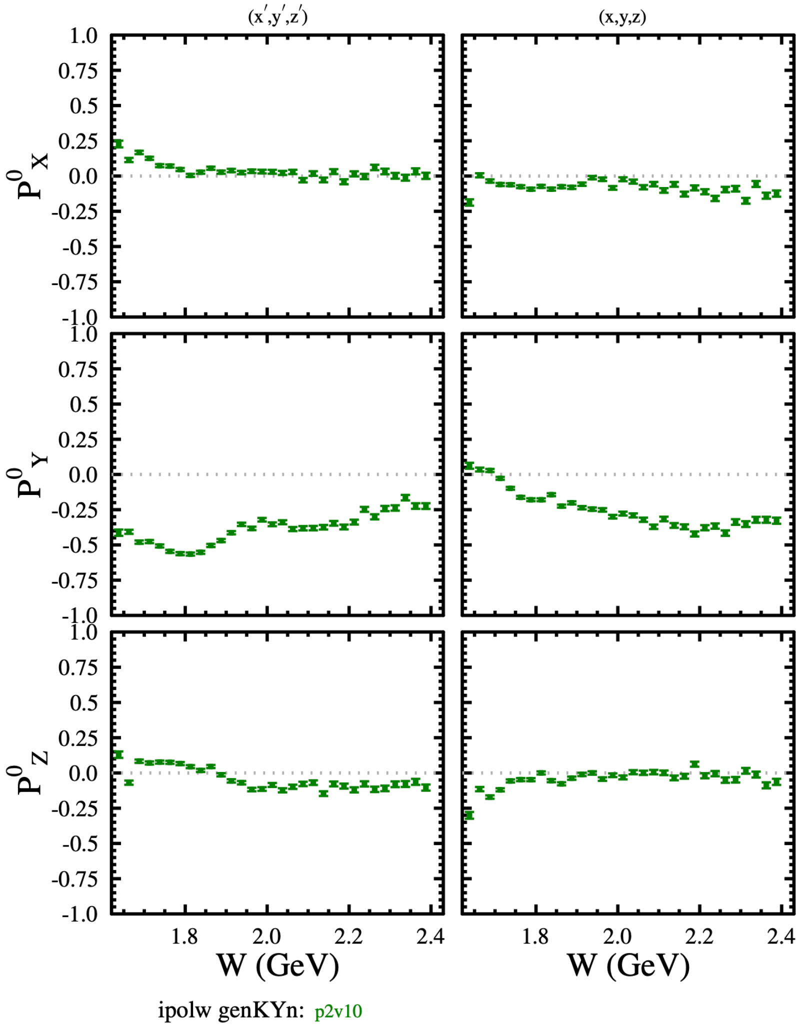


Data Polarization Results

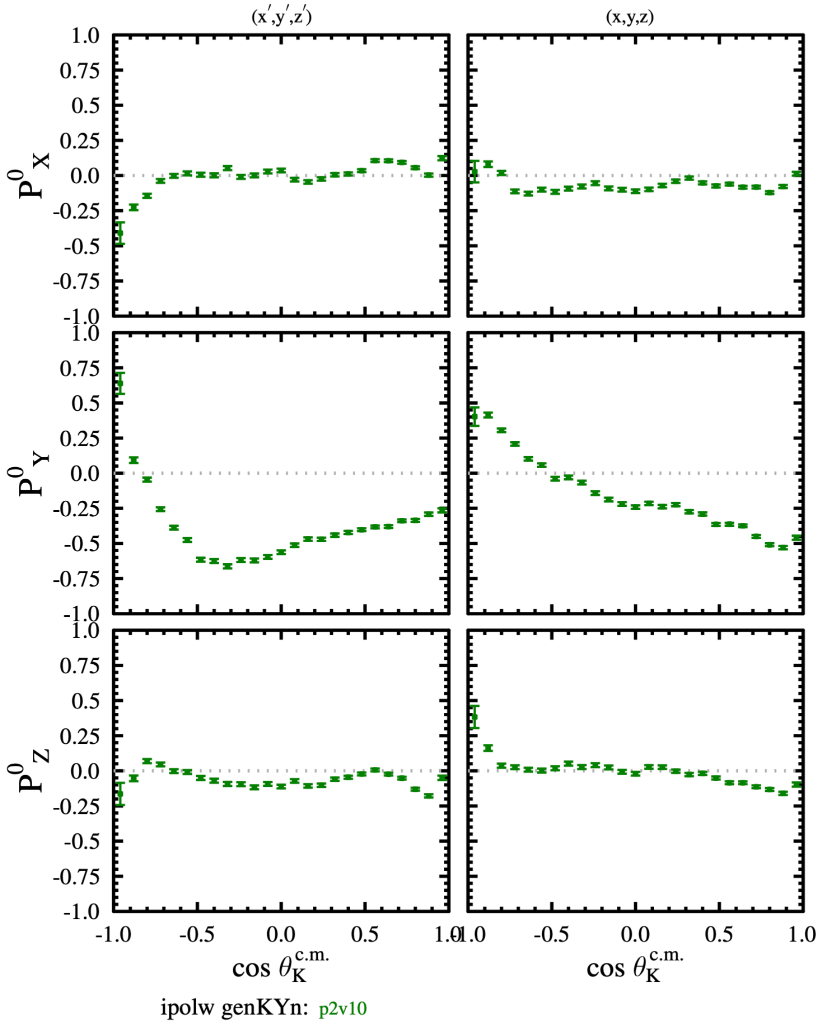
$K^+\Lambda$



$K^+\Lambda$

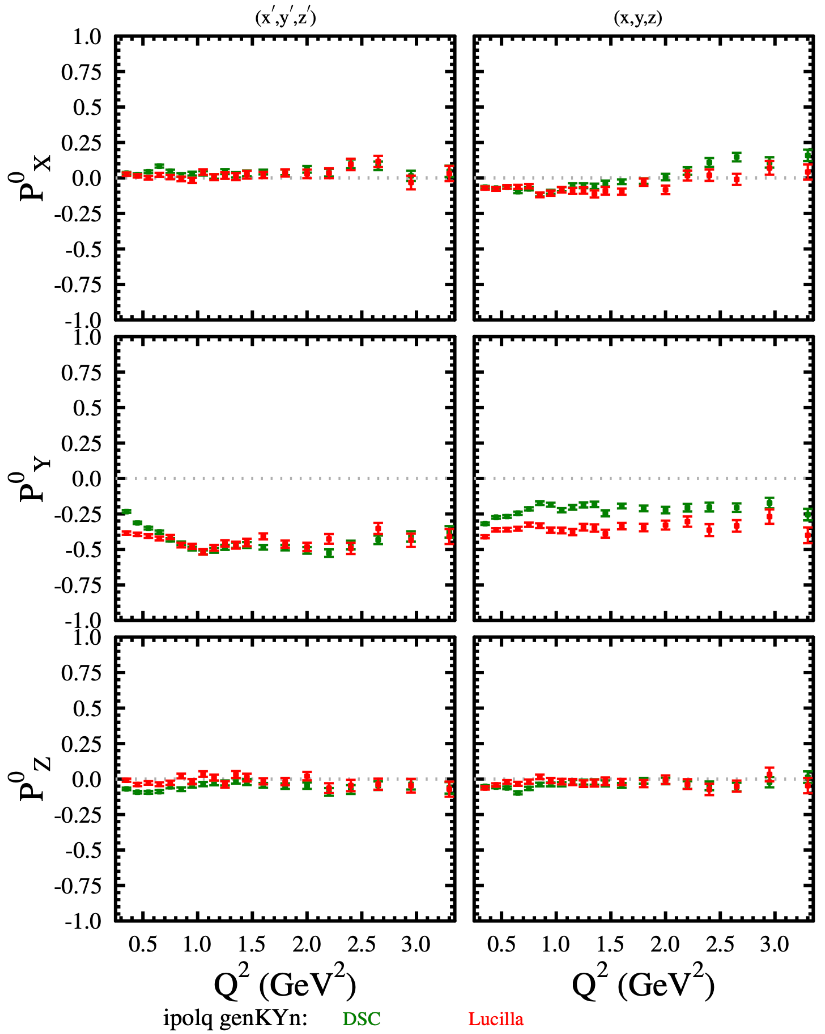


$K^+\Lambda$

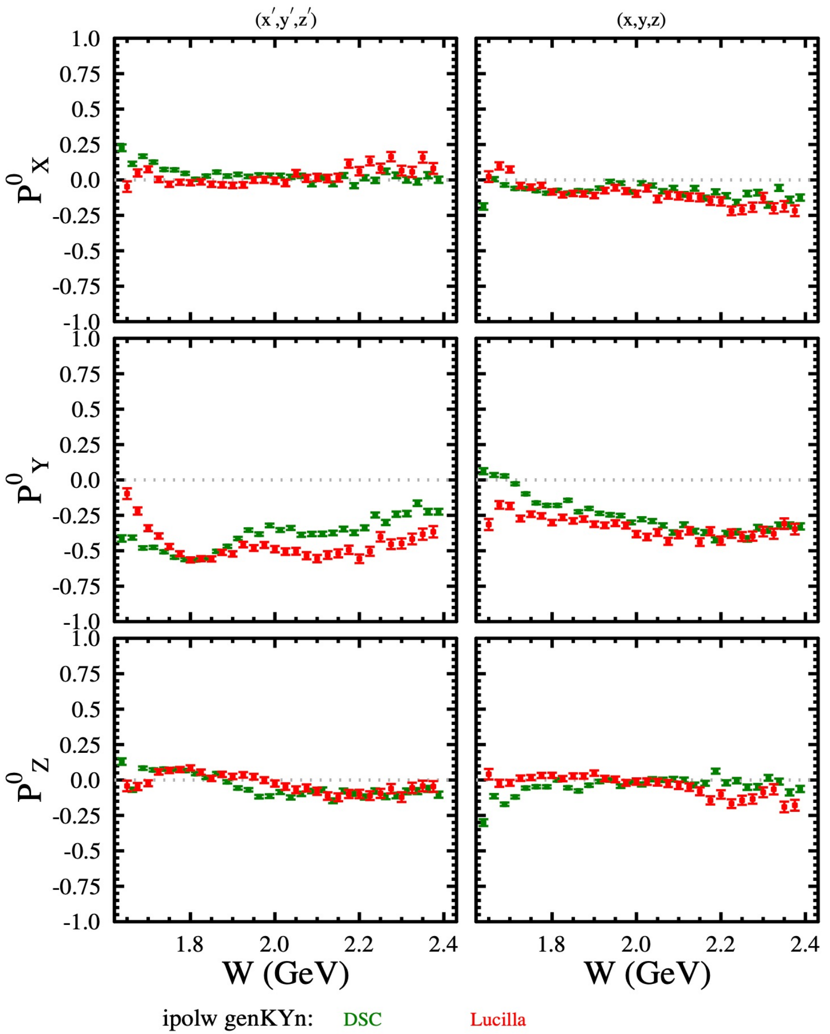


Data Polarization Results

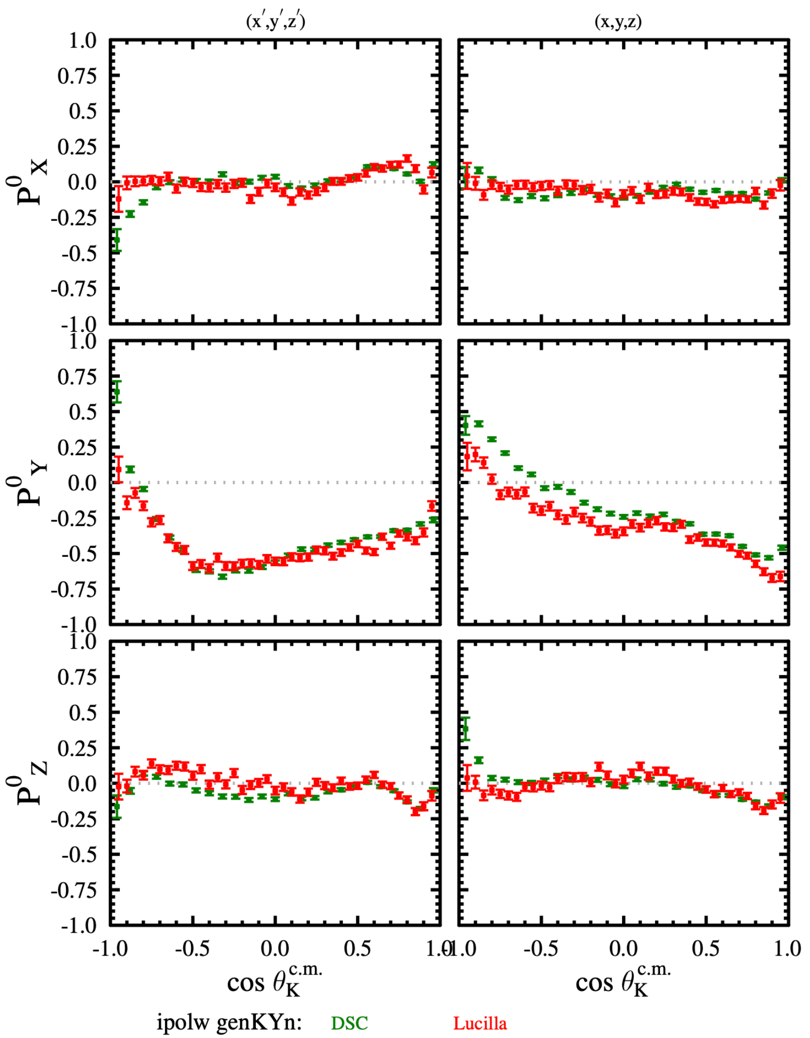
$K^+\Lambda$



$K^+\Lambda$



$K^+\Lambda$

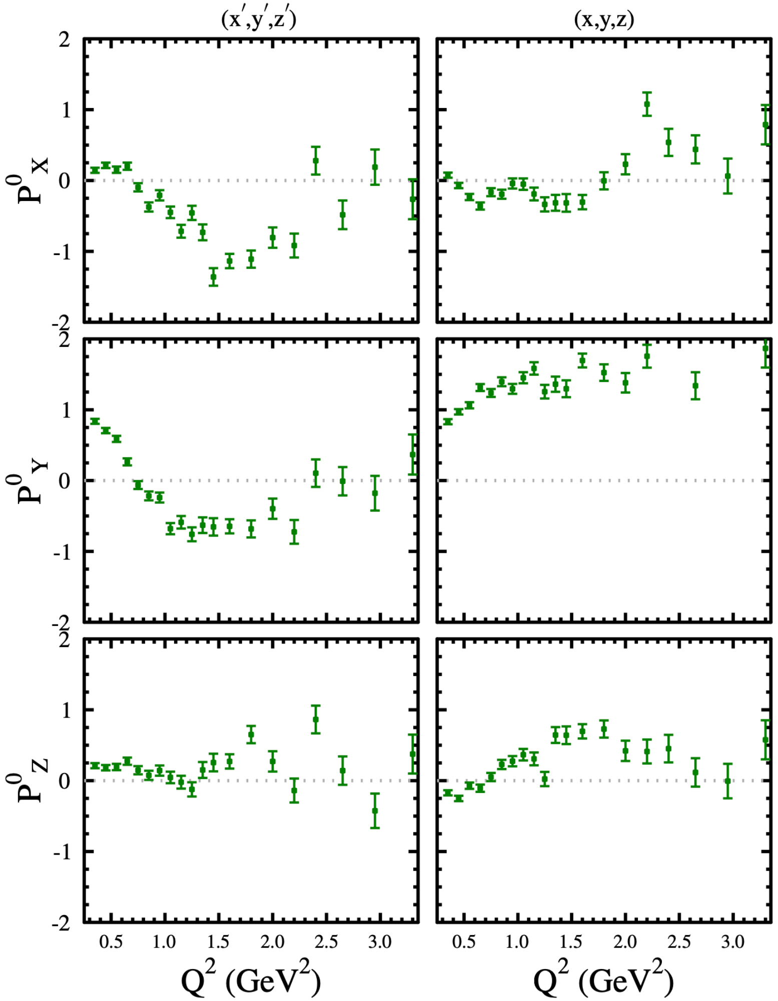


Comparison with parallel analysis by Lucilla Lanza

Data Polarization Results

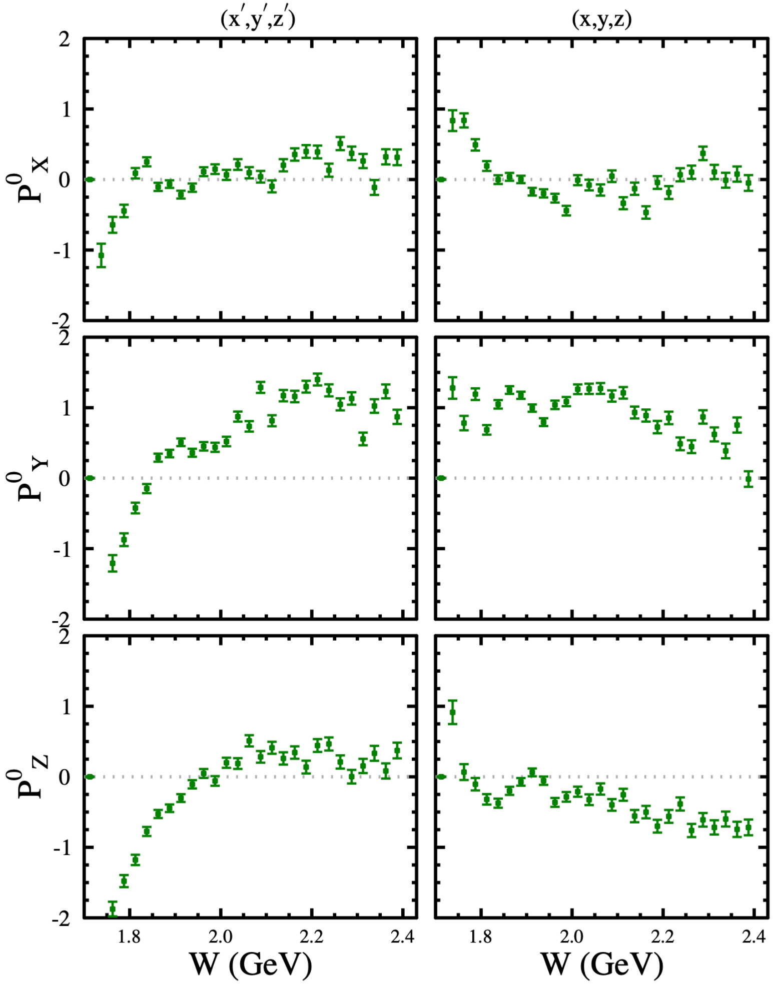
Issues are exposed here ...

$K^+\Sigma^0$



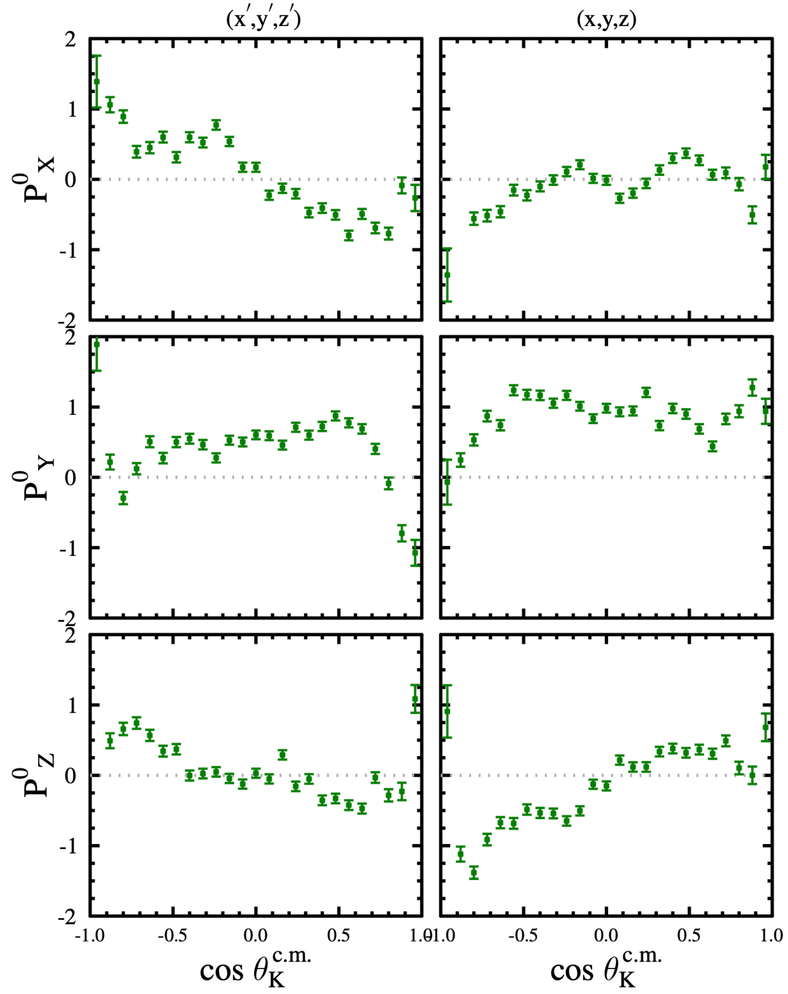
ipolc genKYn: ACC2D (p2v13g)

$K^+\Sigma^0$



ipolc genKYn: ACC2D (p2v13g)

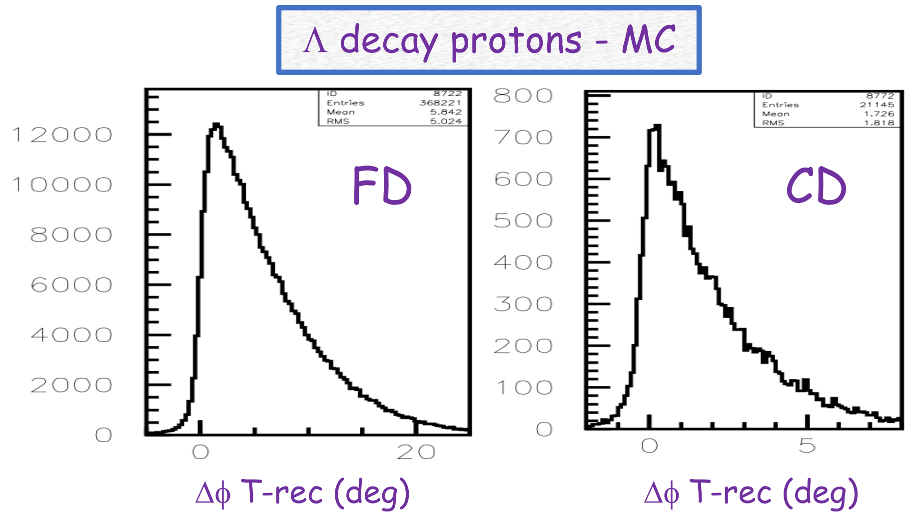
$K^+\Sigma^0$



ipolc genKYn: ACC2D (p2v13g)

Current Status of Analysis

- Significant advancement of the analysis has been made over the past year:
  - Updated event generator to include hyperon decays
  - Included resolution smearing of reconstructed Monte Carlo (significant time savings over old Gaussian convolution smearing)
  - Included model for electron radiation (necessary to account for full Λ radiative tail beneath Σ^0)
  - Developed improved momentum corrections for e′, K^+, and p
  - *A long list of systematic studies have been completed to understand effects on polarization components*
- Still a number of hurdles to cross:
  - Model of radiation too crude; need proper theoretical approach
  - Model of resolution smearing too ad hoc and needs improvement
  - **Need to properly separate resolution smearing from radiative tail as polarization components are sensitive to these details**
  - Must account of reconstruction biases of detached vertex decays
    - U-Track bank removes bias of vertex constraint in CD



- I had hoped to bring the RG-K Win18 data to publication but understanding and reducing the systematics is taking time
  - Σ^0 results still non-physical (but have gotten much better with the recent work)
  - It likely makes sense to use Win18 to understand the issues and complete analysis on the Spr24 data with its much improved momentum resolution

Summary

- As a companion analysis to the recent KY transferred polarization measurement, analysis of the KY recoil polarization is in progress.
  - Λ results are not so bad, but systematic uncertainties of ±0.1 in P^0 are apparent, depending on Q^2, W, cos $\theta_K^{c.m.}$ and axis choice.
  - Σ^0 results have larger systematics – The scaling factor ($\nu_\Sigma = 1/0.256$) exposes the problems.
- The biggest remaining issue is the lack of proper radiative effects in the EG:
  - Need to properly separate radiative effects from resolution effects due to the sizable radiative tail from the Λ beneath the Σ^0.
  - The improved resolution (expected) from the Spr24 data will be most welcome.
- The analysis of P^0 (and P') in a full multi-dimensional binning is important for the development of an accurate reaction model.
  - Extend the existing CLAS P^0 measurements for $K^+\Lambda$.
  - The measurements of P^0 for $K^+\Sigma^0$ are the new observable.

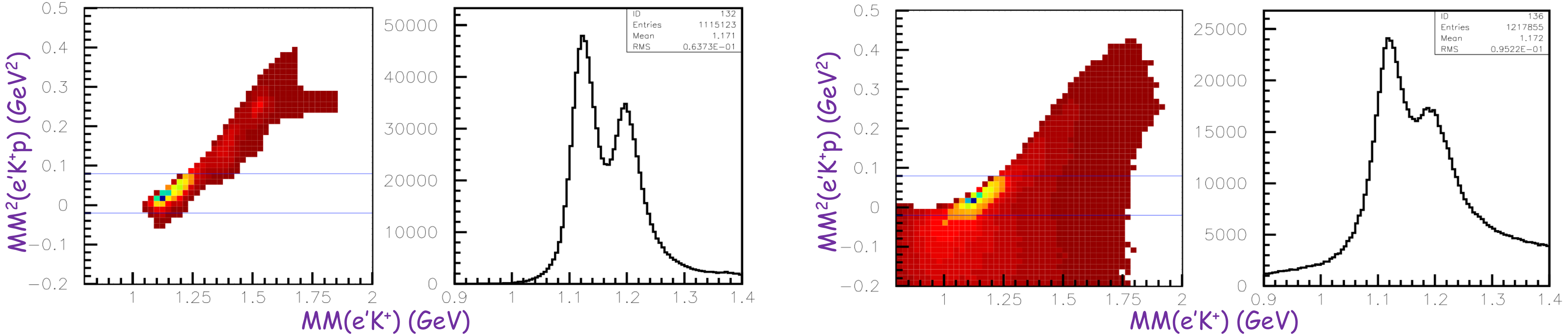
Backup

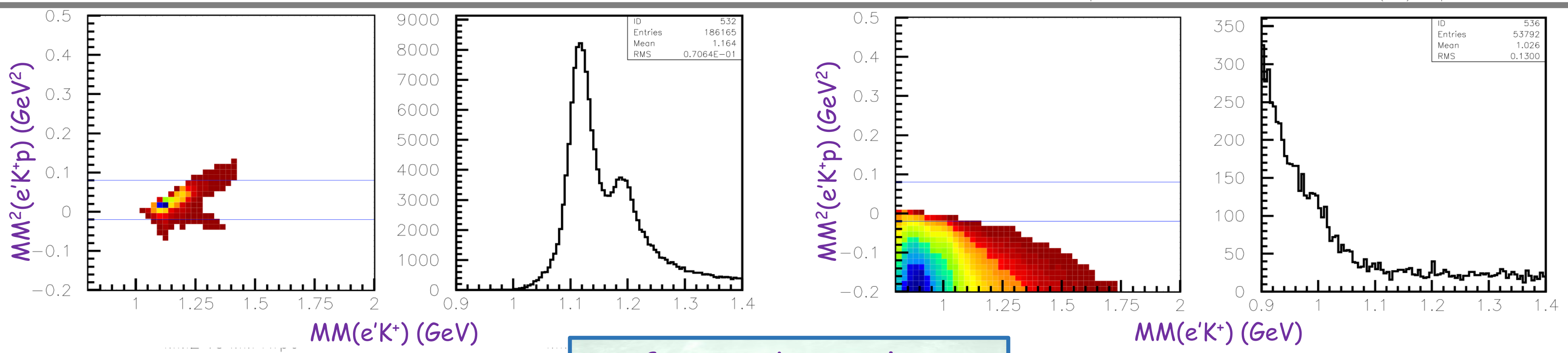
e′K⁺p Topologies

Favored Topologies

K⁺ forward, p forward

K⁺ central, p forward





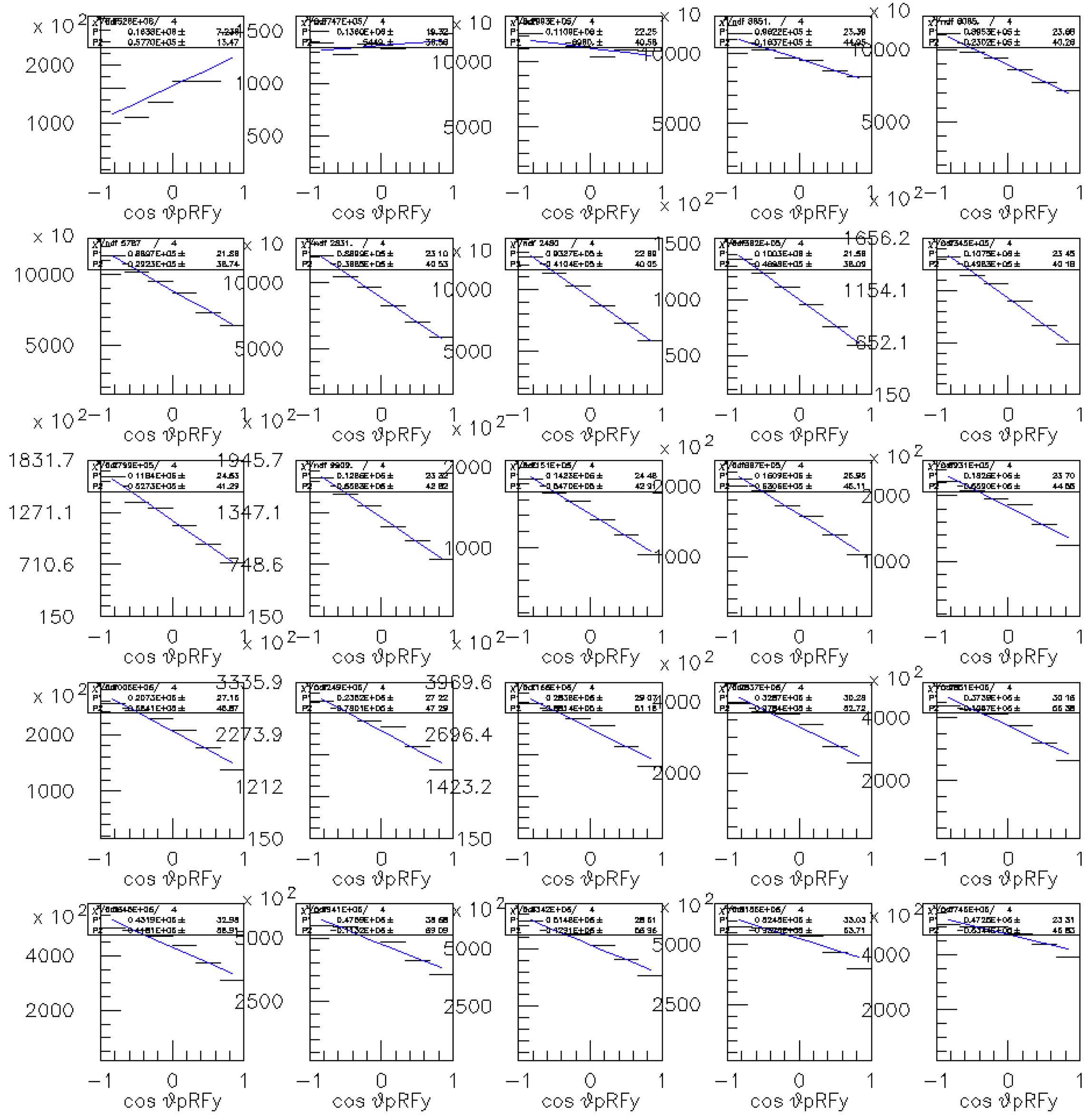
Unfavored Topologies

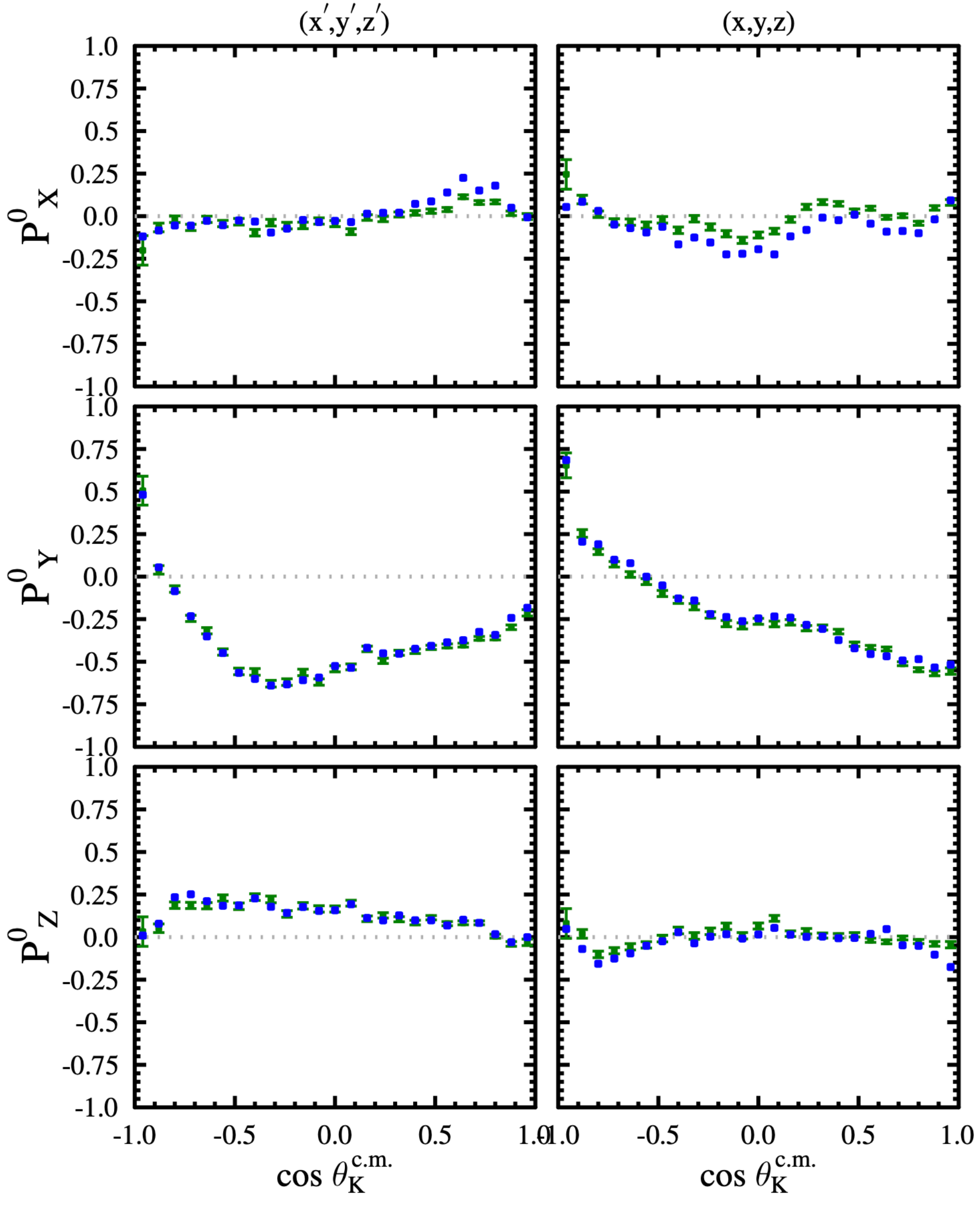
K⁺ forward, p central

K⁺ central, p central

Data Polarization Results

Increasing N_{bins}



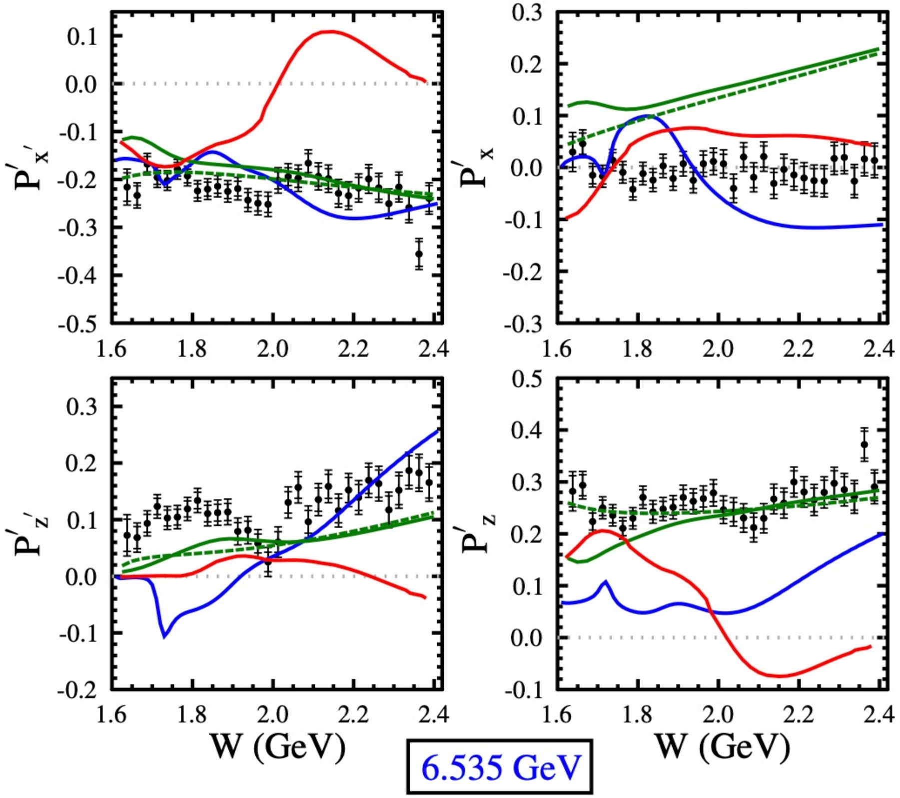


$K^+\Lambda$

CLAS12 KY Beam-Recoil Transferred Polarization

RG-K
Win18

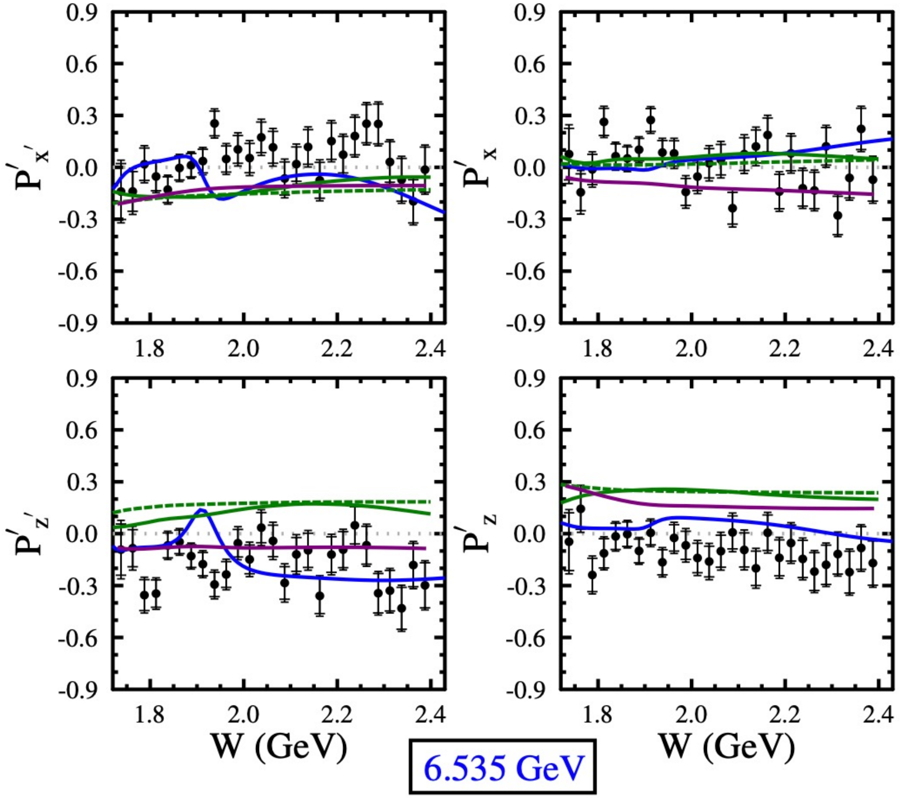
K+Λ



Model	Year	Type	Fit Data	N* States
Kaon-MAID	2000	Isobar	none	1/2, 3/2
RPR	2011	Isobar+Regge	CLAS γp	1/2, 3/2, 5/2
BS3	2018	Isobar	CLAS γp & ep	1/2, 3/2, 5/2

D.S. Carman et al. (CLAS Collaboration), Phys. Rev. C 79, 065205 (2022)

$K^+\Sigma^0$



Model	Year	Type	Fit Data	N* States
SL	1996	Isobar	none	1/2, 3/2
Kaon-MAID	2000	Isobar	none	1/2, 3/2
RPR	2007	Isobar+Regge	CLAS γp	1/2, 3/2, 5/2

Extract KY P' vs. Q^2, W, cos $\theta_K^{c.m.}$

Detached Vertex ϕ Bias

K^+ reconstruction

Monte Carlo

p reconstruction