Study of the Hyperon-Nucleon (*YN*) Interaction in Exclusive Λ Photoproduction off the Deuteron

Nicholas Zachariou

Systematic Studies on method for extracting observables

UNIVERSITY OF SOUTH CAROLINA

Why study the *YN* interaction?

The understanding of both *nucleon-nucleon (NN)* and *hyperon-nucleon (YN)* potentials is necessary in order to have a comprehensive picture of the strong interaction

- Understand the composition of neutron stars
- Understand hyper-nuclear structure and hyperon matter
- Extend *NN* to a more unified picture of the baryon-baryon interaction

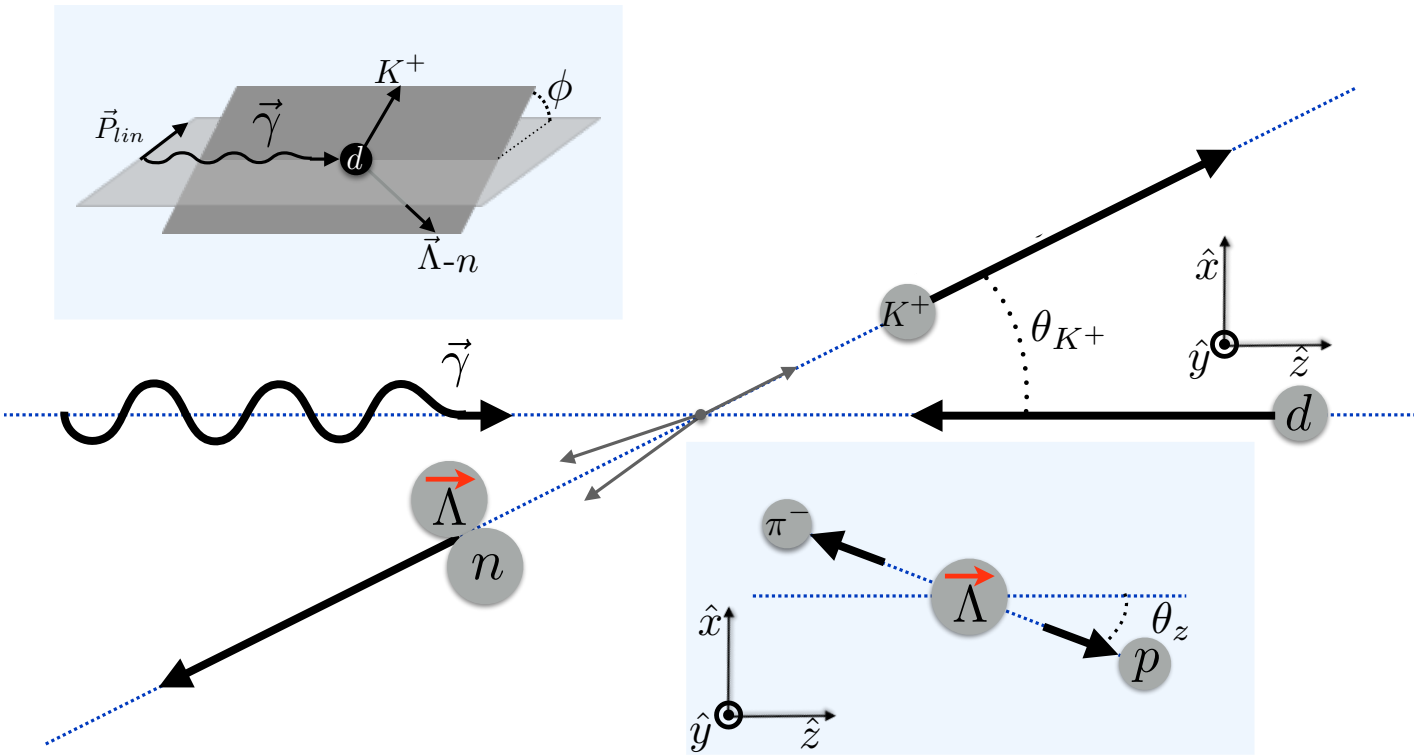
How can we study the *YN* interaction?

- Extending *NN* to *YN* potentials using SU(3) symmetry
  free parameters remain
- Elastic *YN* Scattering
  poor database
- Study of Hypernuclei
  no direct access on bare *YN* interaction
- **Final State Interactions (FSI) in Hyperon Production**
  simple target
  sufficient counting rates in modern accelerators
  model-dependent data interpretation

$$\vec{\gamma}d \rightarrow K^{+}\vec{\Lambda}(n)$$

Experimentally Accessible Observables

$$\frac{d\sigma}{d\Omega} = \sigma_0\{1 - P_{lin}\Sigma\cos 2\phi + \alpha\cos\theta_x(-P_{lin}O_x\sin 2\phi - P_{circ}C_x)$$
$$- \alpha\cos\theta_y(-P_y + P_{lin}T\cos 2\phi) - \alpha\cos\theta_z(P_{lin}O_z\sin 2\phi + P_{circ}C_z)\}$$



Beam Polarization

linearly polarized γ beam

circularly polarized γ beam

Λ Recoil Polarization

self-analyzing power

α=0.642

E06-103 Experiment

- Liquid Deuterium Target (40 cm long)
- Tagged photon beam (linearly and circularly polarized)

g13b

- Current 10 nA
- Eight e-beam energies between 3.30 and 5.16 GeV
- ~2 mm collimator
- Two orientations of linear polarization (*Para* & *Perp*)
- Data obtained at photon energies between 1.1 and 2.3 GeV
- ~30 billion events collected

$\overline{P}_\gamma = 75\%$

g13a

- Current 40 nA
- Two e-beam energies (1.99 and 2.66 GeV)
- Two orientation of circular polarization (+/- *helicities*)
- Data obtained at photon energies between 0.4 and 2.6 GeV
- ~20 billion events collected

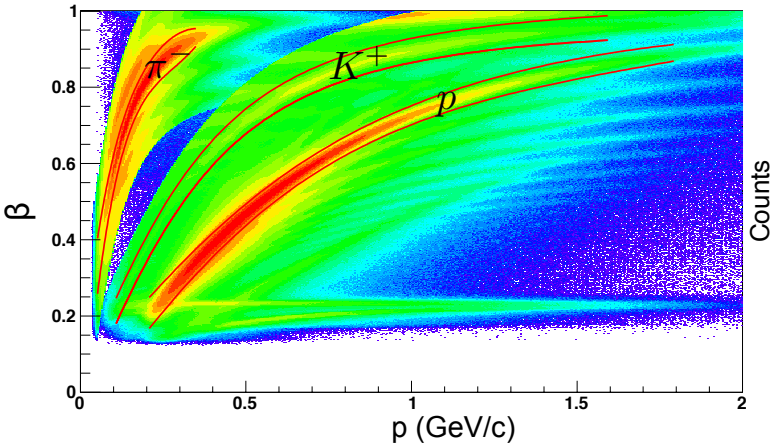
$\overline{P}_e = 80\% \rightarrow \overline{P}_{circ} = 32\% - 80\%$

Analysis of $\gamma d \to K^+\Lambda(n)$

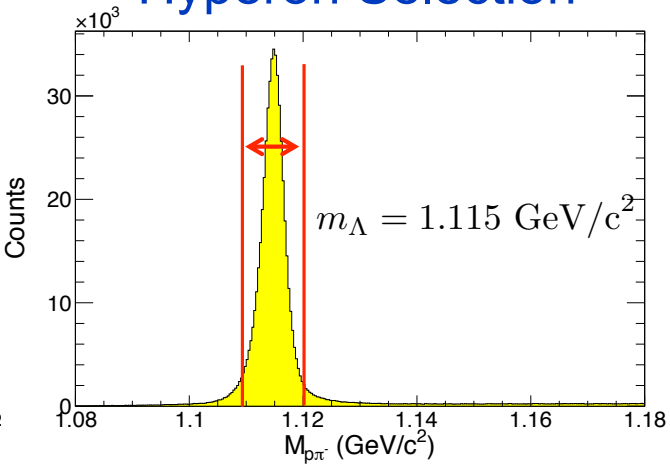
$\hookrightarrow p\pi^-$ (Branching ratio 63.9%)

- Selection of 3-charged track events
- Identification of Λ
- Eliminate contributions from the QF mechanism and enhance rescattering contributions
- Reconstruct reaction

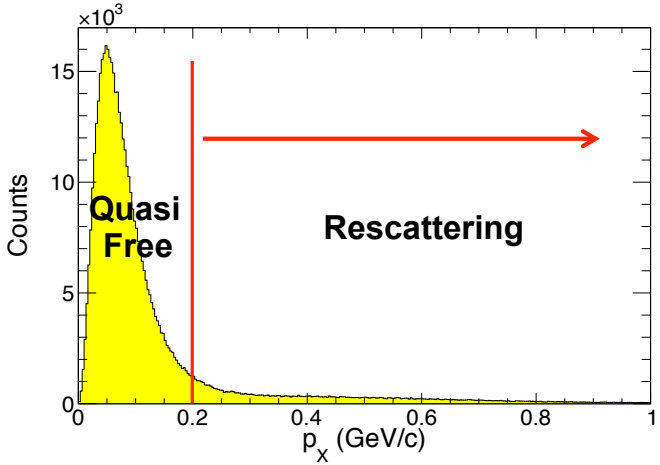
Particle Identification



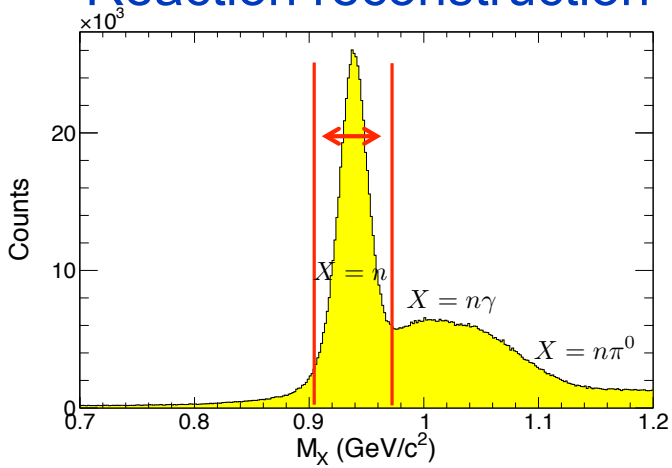
Hyperon Selection



Mechanism Selection



Reaction reconstruction

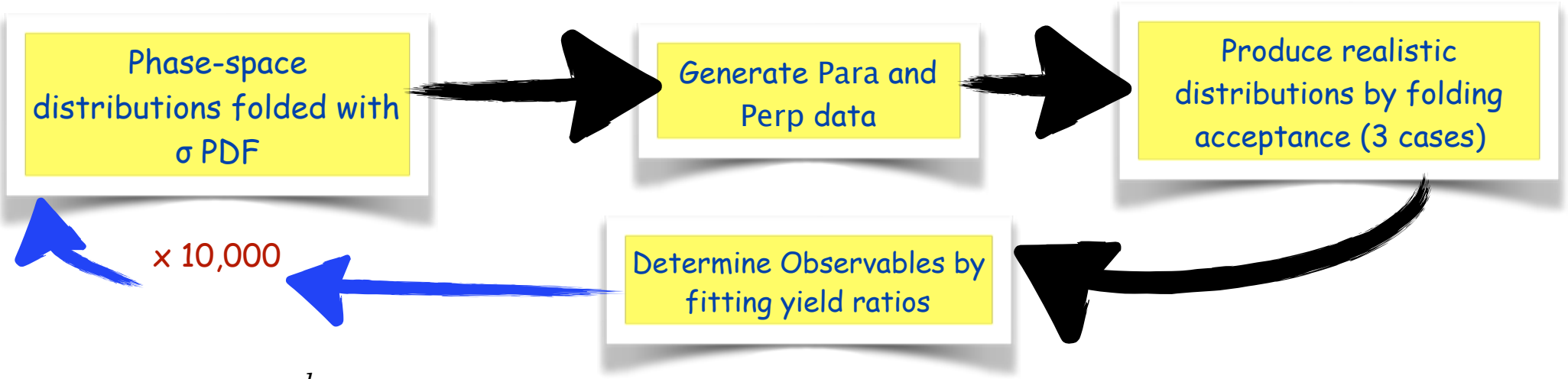


$$\gamma d \to K^+ p\pi^- X$$

Extracting Polarization Observables

Binned Technique

$$A(\phi) = \frac{N(\phi)^{||} - N(\phi)^{\perp}}{N(\phi)^{||} + N(\phi)^{\perp}} = \frac{F_R - 1 - \frac{F_R P_R + 1}{P_R + 1} 2\bar{P}\Sigma \cos[2(\phi - \phi_0)]}{F_R + 1 - \frac{F_R P_R - 1}{P_R + 1} 2\bar{P}\Sigma \cos[2(\phi - \phi_0)]}$$



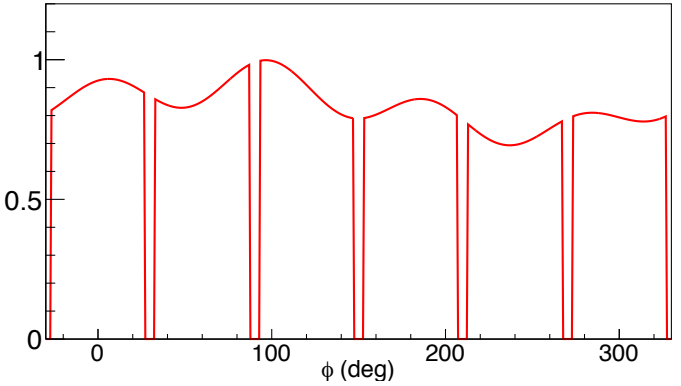
$$\frac{d\sigma}{d\Omega} = \sigma_0\{1 - P_{lin}\Sigma\cos 2\phi + \alpha\cos\theta_x(-P_{lin}O_x\sin 2\phi - P_{circ}C_x) - \alpha\cos\theta_y(-P_y + P_{lin}T\cos 2\phi) - \alpha\cos\theta_z(P_{lin}O_z\sin 2\phi + P_{circ}C_z)\}$$

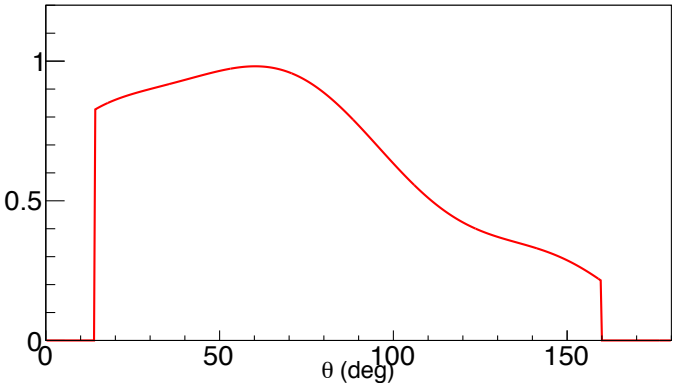
$$\frac{N(\phi,\cos\theta_{x,z})^{||} - N(\phi,\cos\theta_{x,z})^{\perp}}{N(\phi,\cos\theta_{x,z})^{||} + N(\phi,\cos\theta_{x,z})^{\perp}} = \frac{F_R - 1 - \frac{F_R P_R + 1}{P_R + 1} 2\bar{P}\left(\Sigma\cos[2(\phi)] + O_{x,z}\alpha\sin[2(\phi)]\cos\theta_{x,z}\right)}{F_R + 1 - \frac{F_R P_R - 1}{P_R + 1} 2\bar{P}\left(\Sigma\cos[2(\phi)] + O_{x,z}\alpha\sin[2(\phi)]\cos\theta_{x,z}\right)}$$

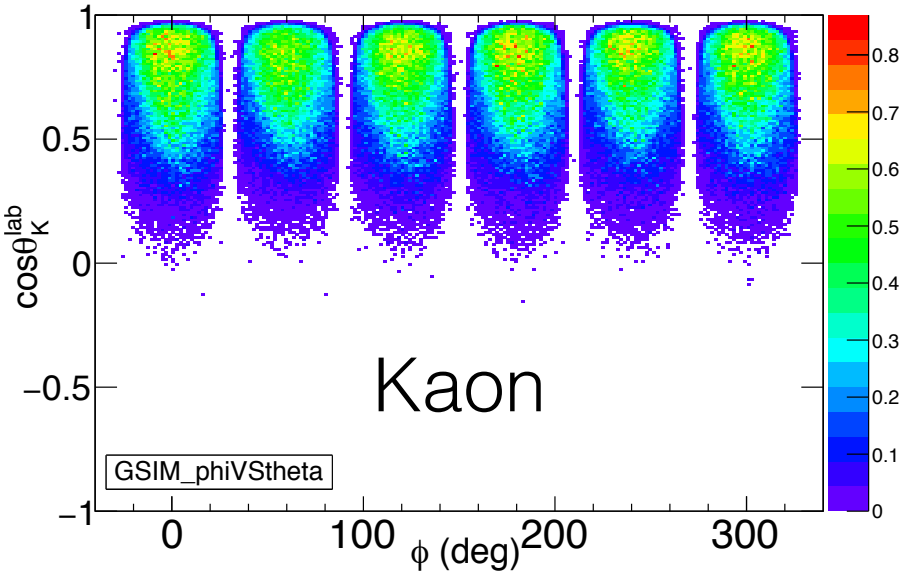
Extracting Polarization Observables

Acceptance Cases

- Case 1: Acceptance =1
- Case 2: Geometric acceptance
  - removed coil regions and detector holes
- Case 3: GSIM acceptance
  - determined from ratios of gsim-processed and generated events (protons, kaons, pios)



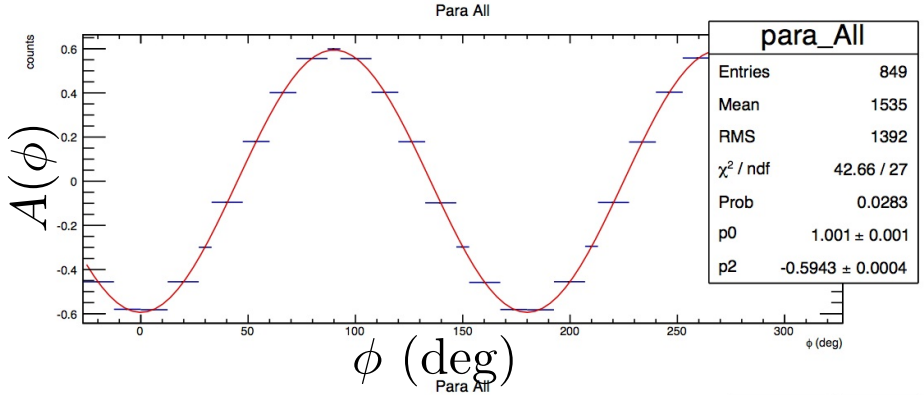


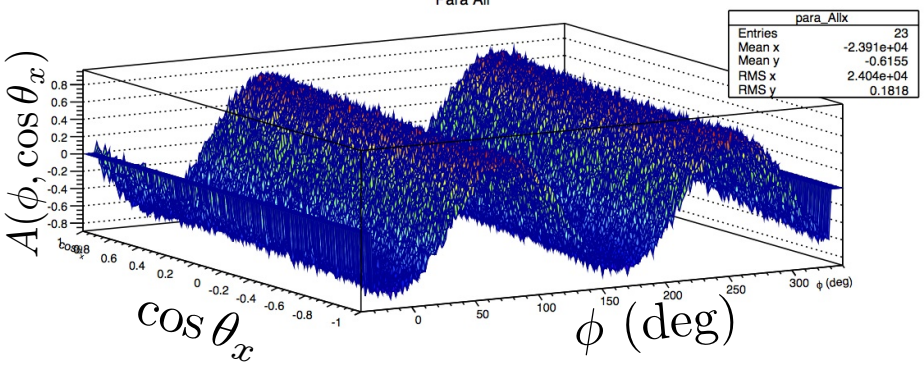


Extracting Polarization Observables

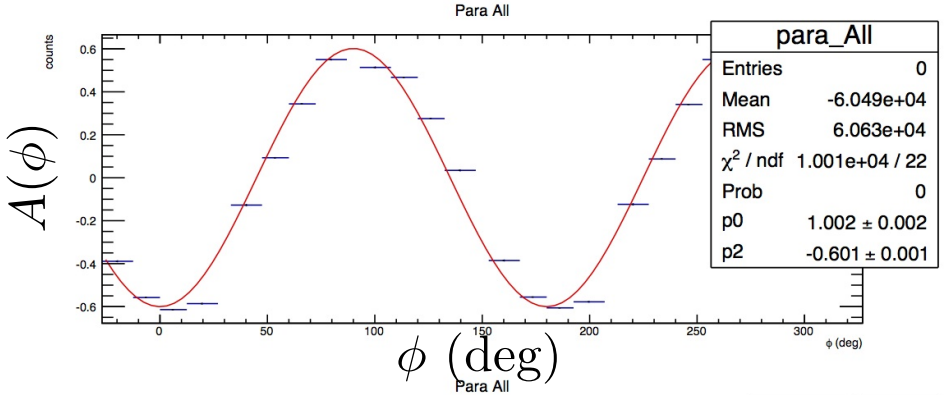
Binned Technique

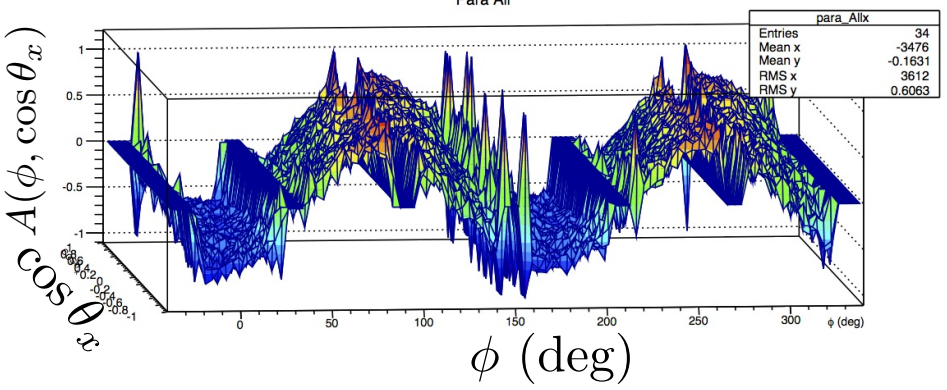
Acceptance 1





Acceptance 3

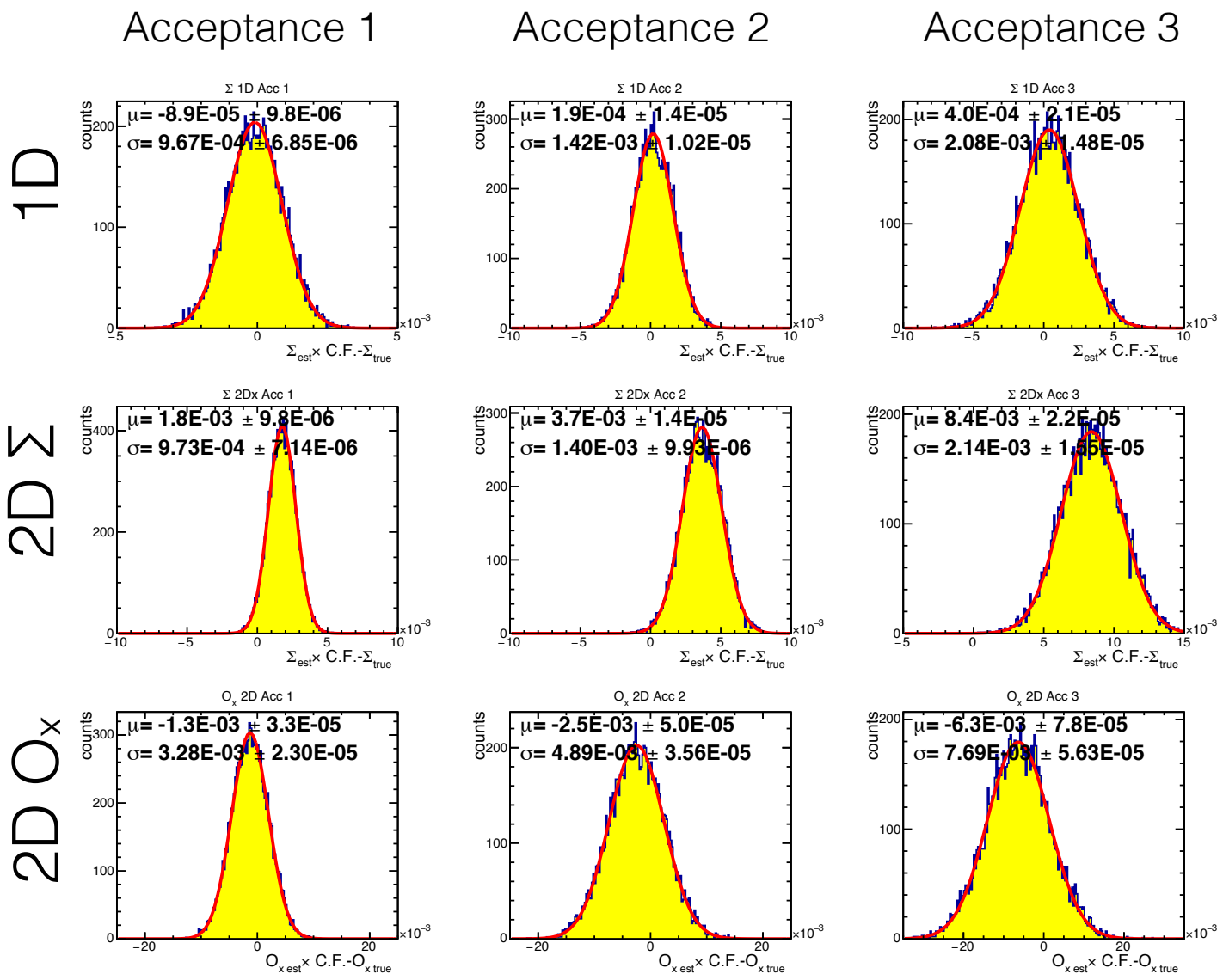




Extracting Polarization Observables

Binned Technique

- 1D fits biased when acceptance is folded
- Bias varies based on true value of observables
- 2D fits biased



Extracting Polarization Observables

Likelihood Technique

$$
\begin{aligned}
L_i &= c^{||,\perp}(1 \pm P_i^{||,\perp} A_i + \alpha \cos\theta_{yi} P_y), \text{ where} \\
A_i &= \Sigma \cos 2\phi_i + \alpha \cos\theta_{xi} O_x \sin 2\phi_i + \alpha \cos\theta_{zi} O_z \sin 2\phi_i \\
&\quad + \alpha \cos\theta_{yi} T \cos 2\phi.
\end{aligned}
$$

$$
\begin{aligned}
\log L &= b + \sum_{i=1}^{N^{||}} \log(1 + P_i^{||} A_i + \alpha \cos\theta_{yi} P_y) \\
&\quad + \sum_{i=1}^{N^{\perp}} \log(1 - P_i^{\perp} A_i + \alpha \cos\theta_{yi} P_y).
\end{aligned}
$$

Extracting Polarization Observables

Studies

- 1D binned technique
- Approximate Log Likelihood techniques
  - Σ contributions only

$$\log L = b + \sum_{i=1}^{N^{||}} \log(1 + P_i^{||} \Sigma \cos 2\phi_i) + \sum_{i=1}^{N^{\perp}} \log(1 - P_i^{\perp} \Sigma \cos 2\phi_i)$$

  - Analytic solution

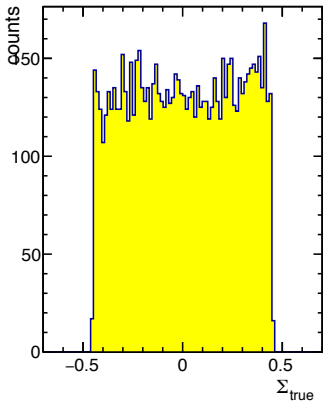
$$\hat{\Sigma} = \frac{\sum_{i=0}^{N^{||}} P_i^{||} \cos 2\phi_i - \sum_{i=0}^{N^{\perp}} P_i^{\perp} \cos 2\phi_i}{\sum_{i=0}^{N^{||}} (P_i^{||} \cos 2\phi_i)^2 + \sum_{i=0}^{N^{\perp}} (P_i^{\perp} \cos 2\phi_i)^2}$$

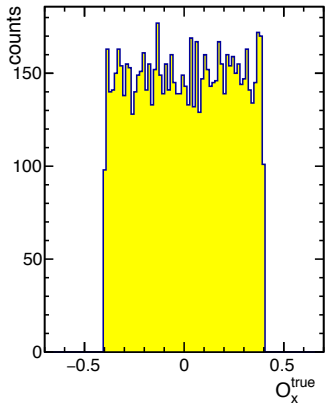
  - Minuit minimization
- Full Log Likelihood
  - unstable (5 f.p. $\Sigma,\ O_x,\ O_z,\ T,\ P_y$)
  - extended (3 f.p. $\Sigma,\ O_x,\ O_z$)

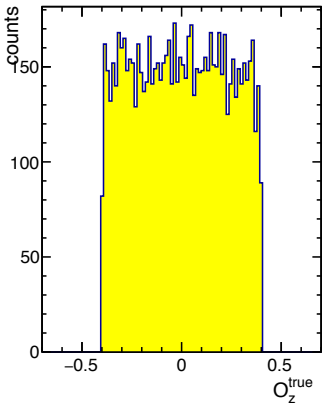
Extracting Polarization Observables

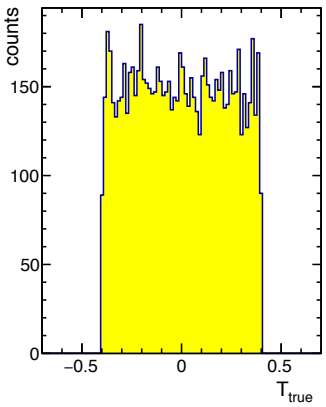
Systematic studies

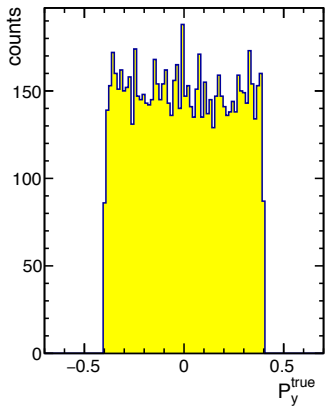
Σ	O_x	O_z	T	P_y
-0.75 — 0.75	+/- 1.0	0	0	0
-0.75 — 0.75	0	+/- 1.0	0	0
-0.45 — 0.45	0	0	+/- 1.0	0
-0.45 — 0.45	0	0	0	+/- 1.0
-0.35 — 0.35	+/- 0.5	+/- 0.5	+/- 0.5	+/- 0.5
-0.45 — 0.45	-0.4 — 0.4	-0.4 — 0.4	-0.4 — 0.4	-0.4 — 0.4





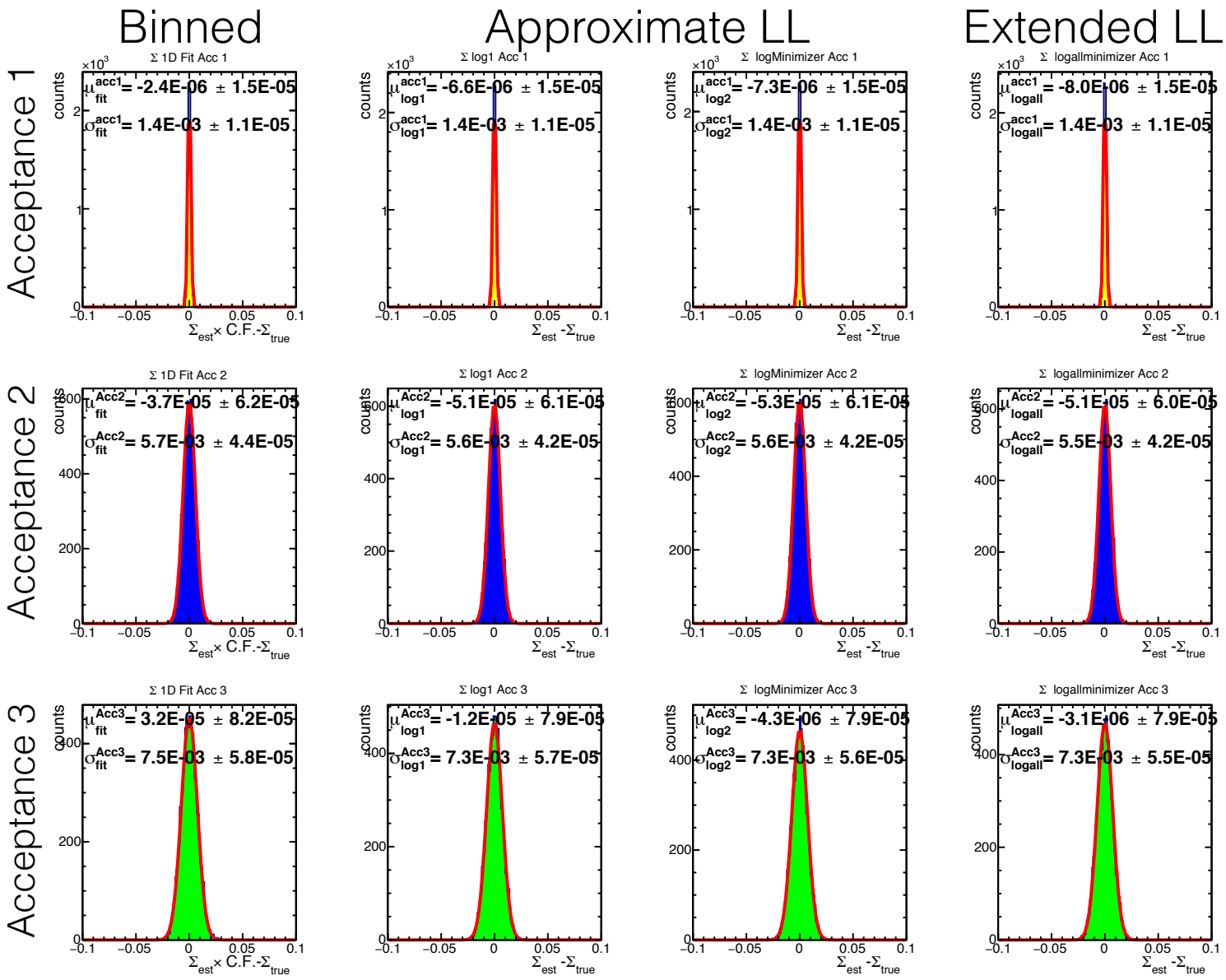






Extracting Polarization Observables

Studies of estimating Σ

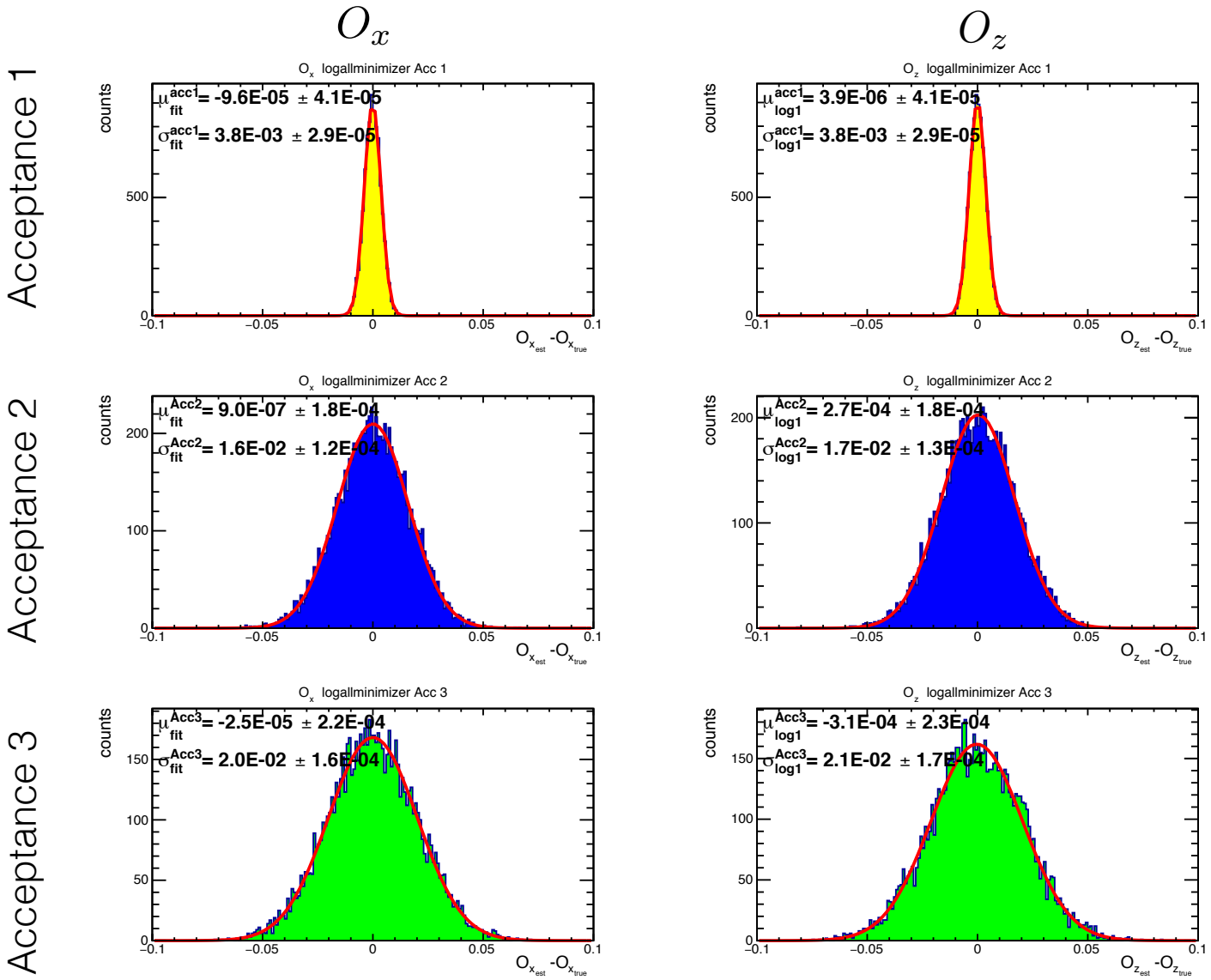


Extracting Polarization Observables

Studies of estimating $O_{x/z}$

Extended LL

$$\Sigma\ bias < 0.003$$
$$O_x\ bias < 0.004$$
$$O_z\ bias < 0.002$$



Extracting Polarization Observables

Studies

- Studies on F_R and P_R were also performed
  - conditions and true parameters from table

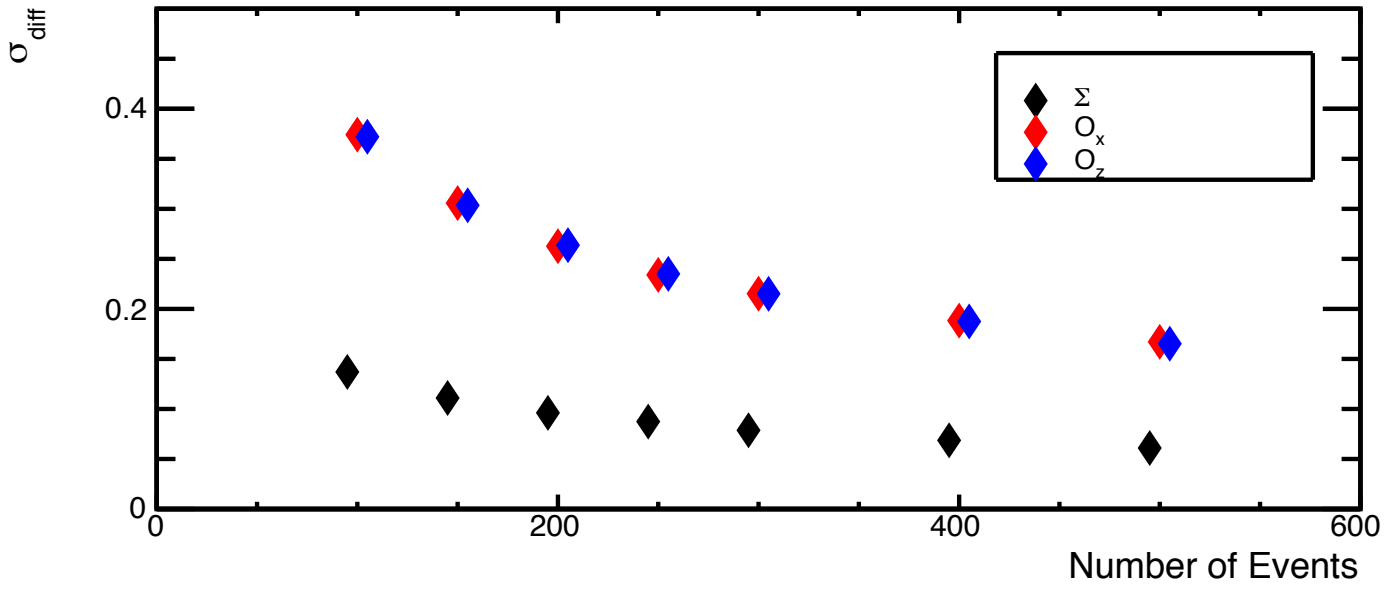
$F^{\|\|}$	$F^{\perp}$	$P_\gamma^{\|\|}$	$P_\gamma^{\perp}$	$\|\Sigma\|$	$\|O_x\|$	$\|O_z\|$	$\|T\|$	$\|P_y\|$
60%	40%	1.0	1.0	<0.45	<0.4	<0.4	<0.4	<0.4
40%	60%	1.0	1.0	<0.45	<0.4	<0.4	<0.4	<0.4
60%	40%	1.0	1.0	<0.45	<0.4	<0.4	0	0
50%	50%	0.75	0.75	<0.45	<0.4	<0.4	<0.4	<0.4
50%	50%	0.70	0.75	<0.45	<0.4	<0.4	<0.4	<0.4
50%	50%	0.75	0.70	<0.45	<0.4	<0.4	<0.4	<0.4
50%	50%	0.70	0.75	<0.45	<0.4	<0.4	<0.4	<0.4
60%	40%	0.70	0.75	<0.45	<0.4	<0.4	<0.4	<0.4
60%	40%	0.75	0.70	<0.45	<0.4	<0.4	<0.4	<0.4

- Log-likelihood biased when $F_R \neq 1$ and acceptance $\neq 1$
  - bias $\mathcal{O}(10^{-3})$
- Bias can be corrected using F_R estimate from binned technique

Extracting Polarization Observables

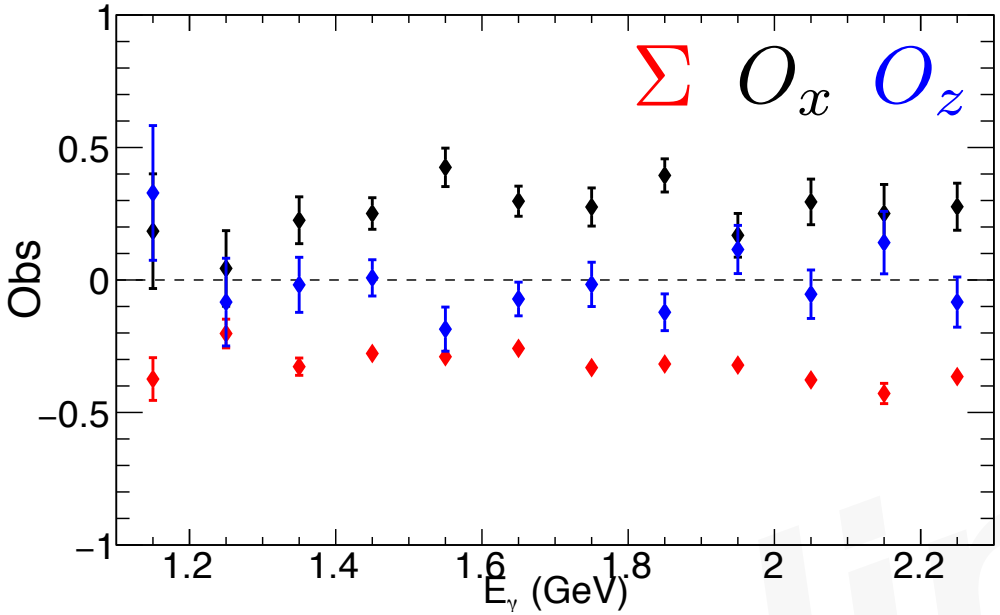
Summary

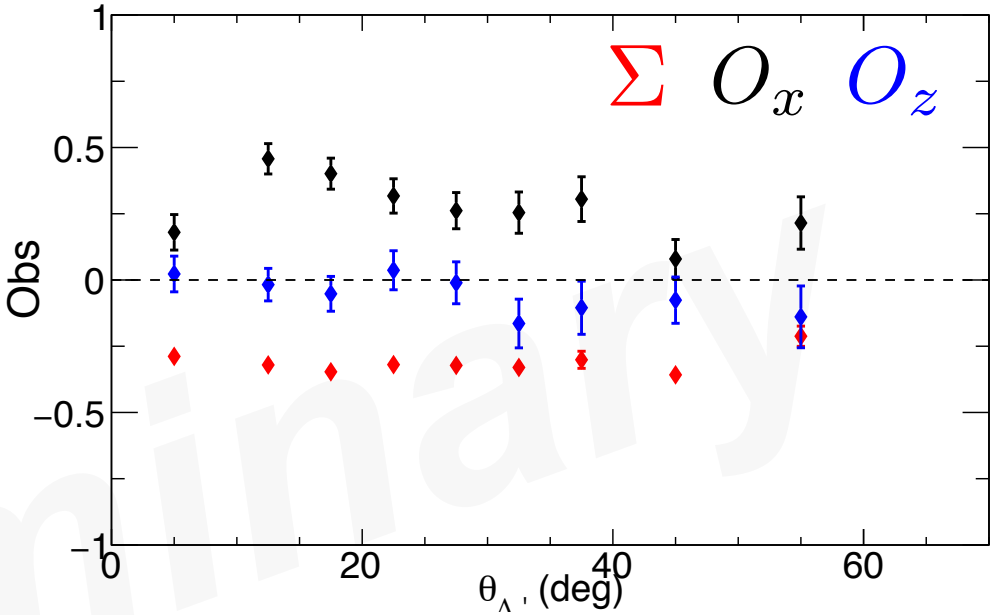
- Maximum log-likelihood technique is robust
- Allows the simultaneous extraction of 3 polarisation observables $\Sigma,\ O_x,\ O_z$
  - Can be extended to get first estimates of P_y and T
- Produces reliable results in low statistics
  - Statistical Uncertainties of log-likelihood

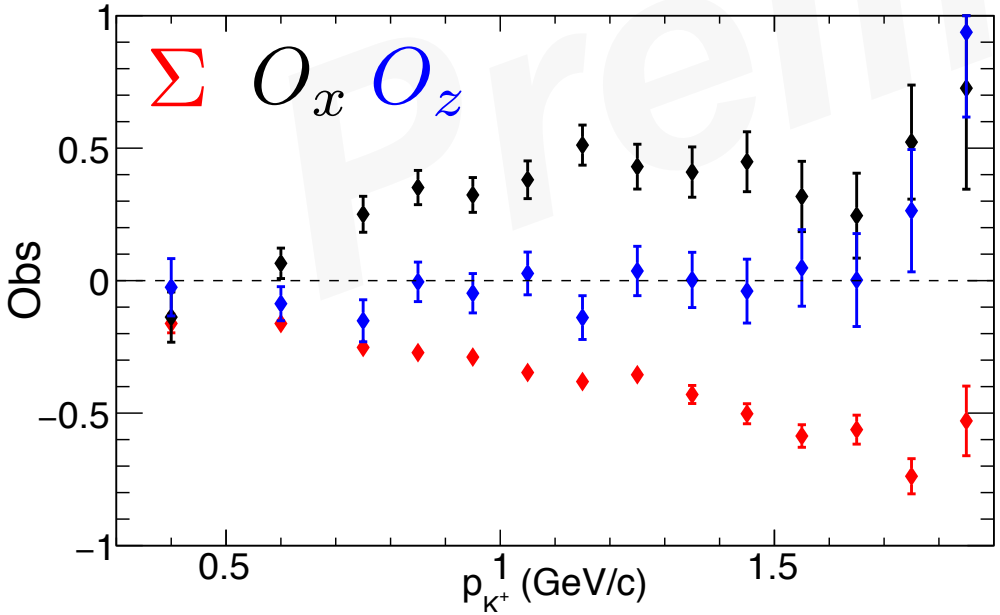


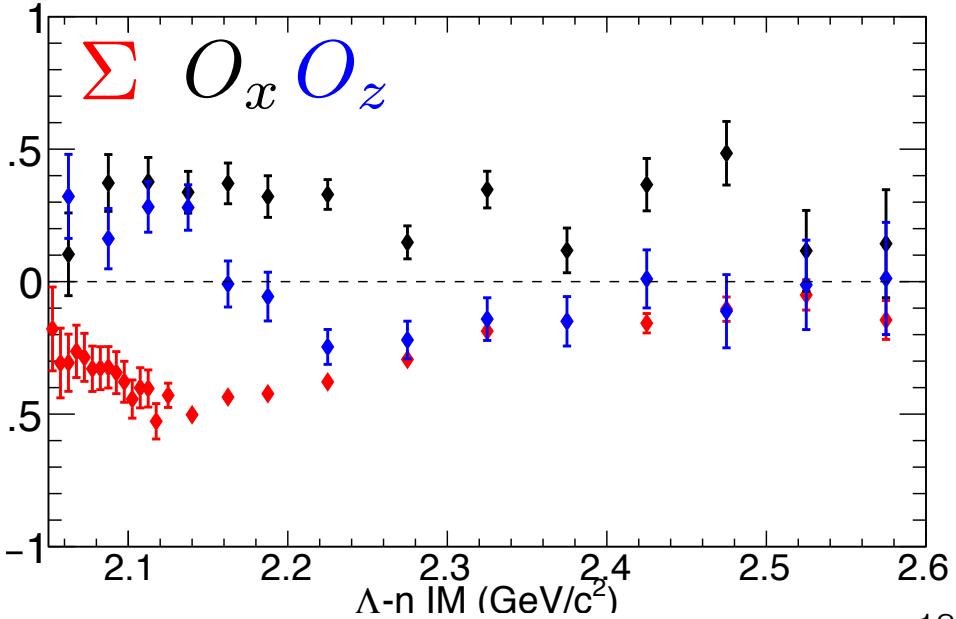
$\vec{\gamma}d \to K^+\vec{\Lambda}(n)$

FSI Results



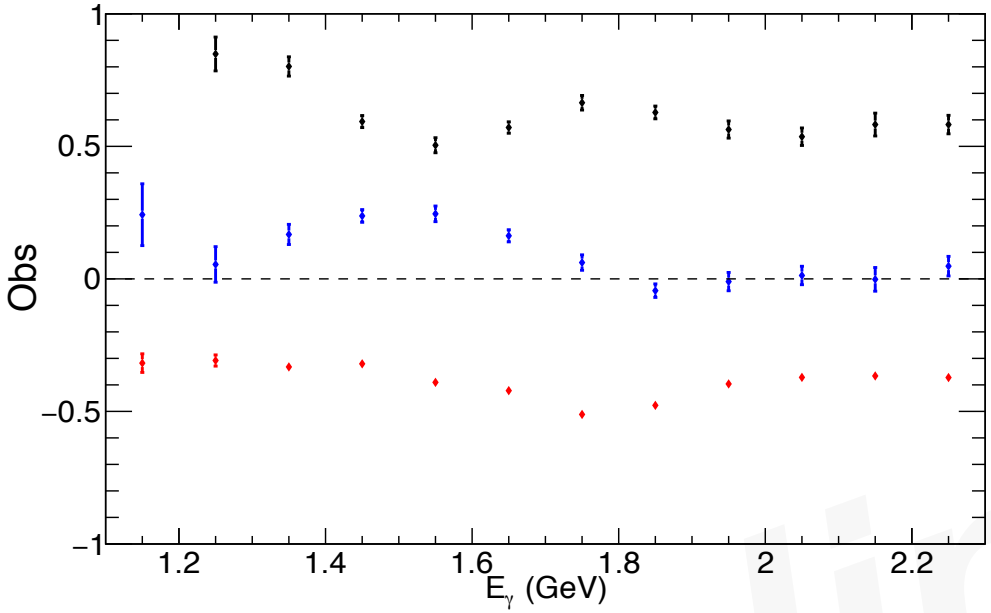


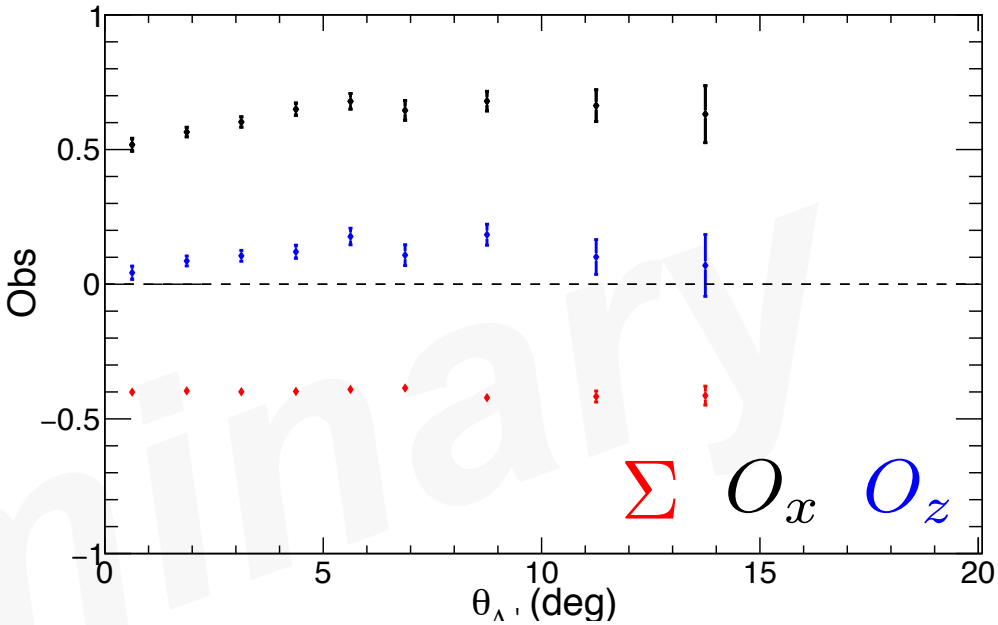


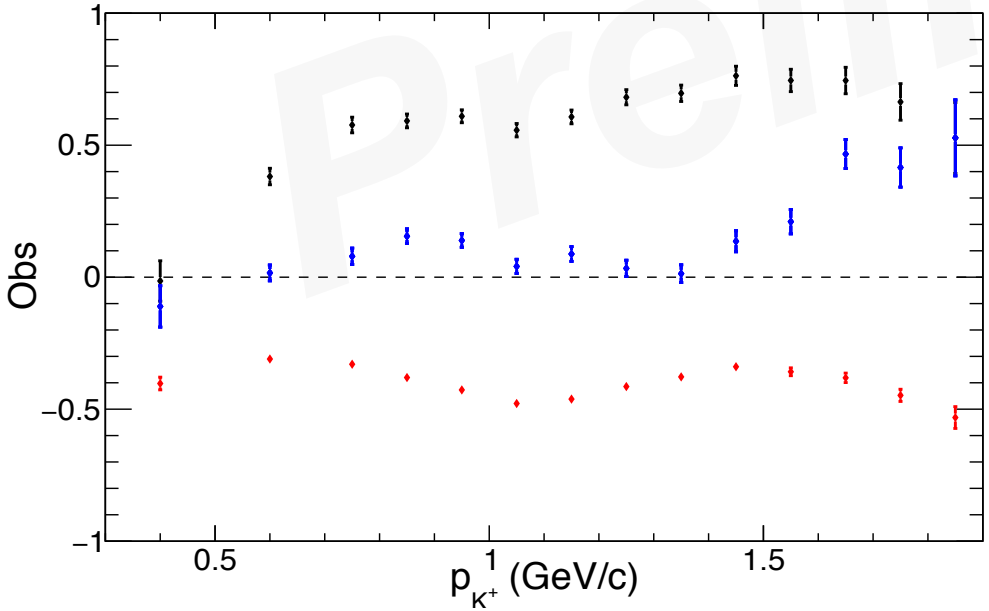


$\vec{\gamma}d \to K^+\vec{\Lambda}(n)$

QF Results







- Sizable effects from FSI in observables
- Use QF results to study method/ systematics
- QF consistent with results from $\gamma p \to K^+\Lambda$

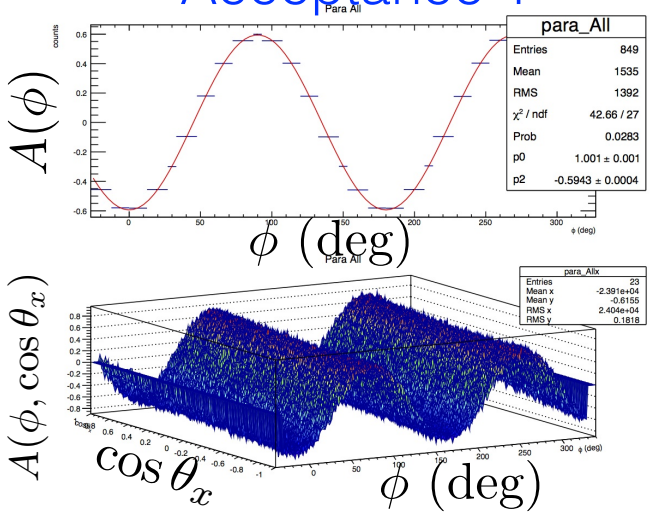
Extra

Study of the Hyperon-Nucleon (*YN*) Interaction in Exclusive Λ Photoproduction off the Deuteron

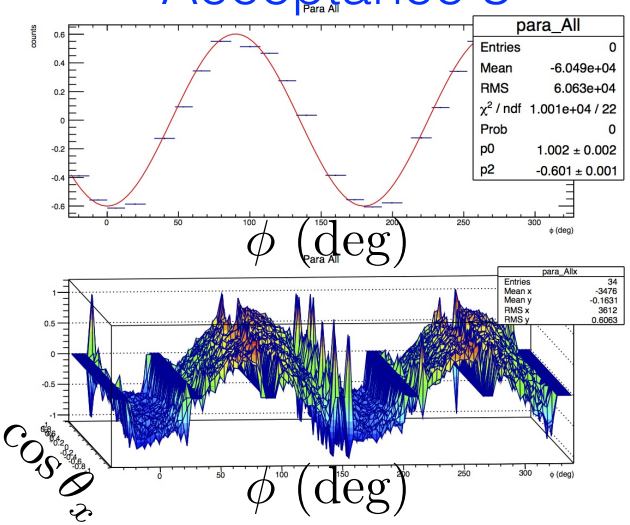
Systematic Studies of method for extracting observables

- Goal: Extract single and double polarisation observables for FSI in $\gamma d \to K^+ \Lambda n$
- Systematic studies of binned technique (fitting asymmetries)

Acceptance 1



Acceptance 3



Generated 10^4 samples each with 10^6 events

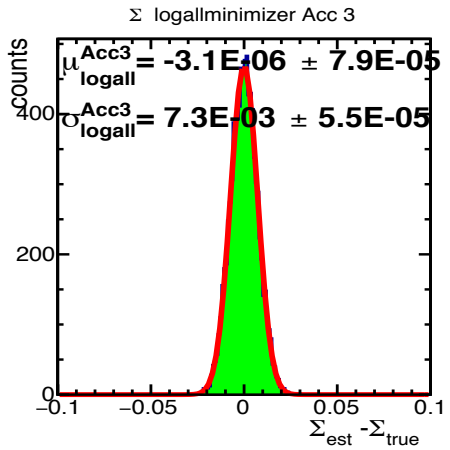
- 1D binned technique produces reliable results
- 2D binned techniques produces strongly biased results

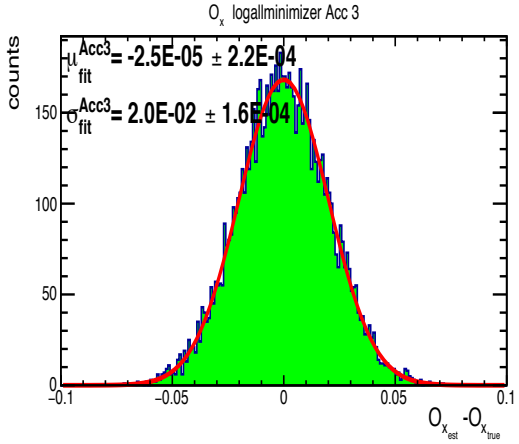
Nicholas Zachariou

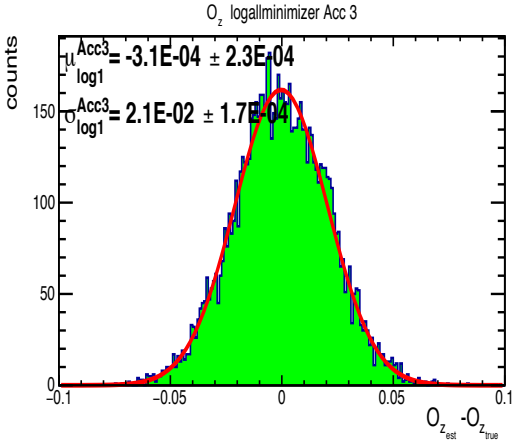
Study of the Hyperon-Nucleon (*YN*) Interaction in Exclusive Λ Photoproduction off the Deuteron

Systematic Studies of method for extracting observables

- Different log likelihood (LL) techniques ware developed based on various assumptions
  - Allows the simultaneous determination of single and double polarisation observables
  - LL technique has been extensively studied using generated data
  - Systematic bias due to acceptance assumptions is $\mathcal{O}(10^{-3})$ (order of magnitude smaller than stat. uncertainty)







- LL method is more robust for low statistic bins compared to the binned techniques

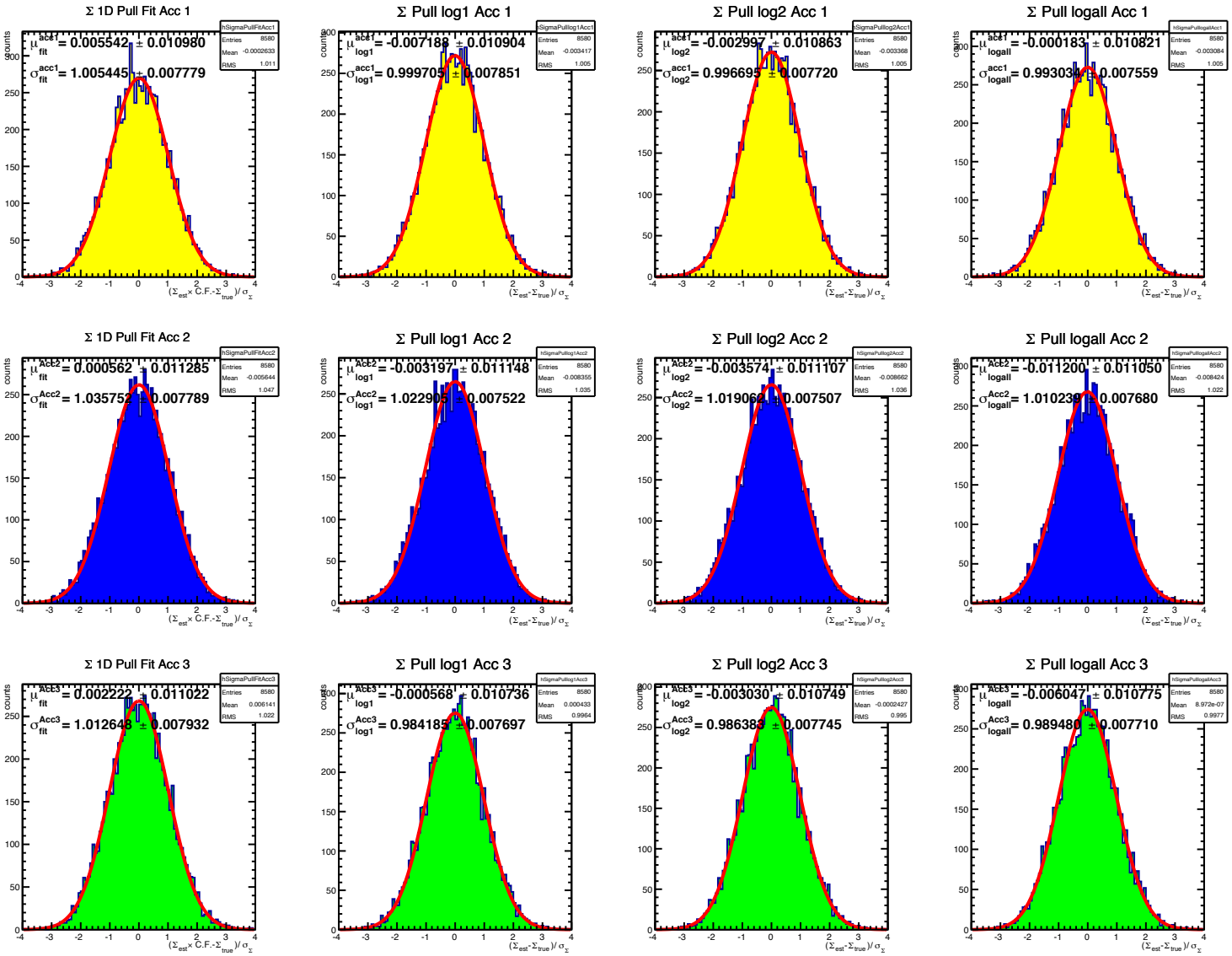
Nicholas Zachariou

Extracting Polarization Observables

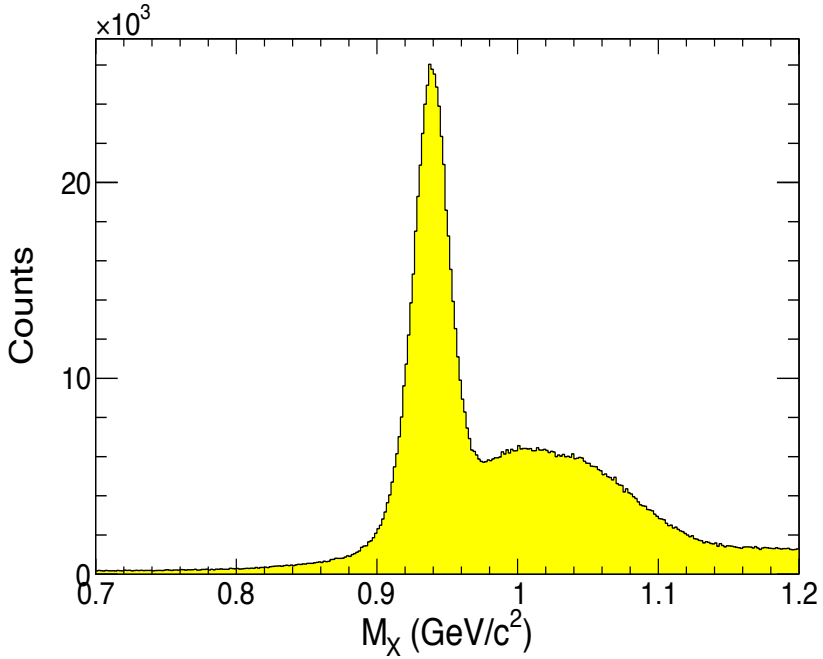
Studies of estimating Σ

Pull Distributions

$$\frac{(Obs_{det} - Obs_{true})}{\sigma_{Obs_{det}}}$$



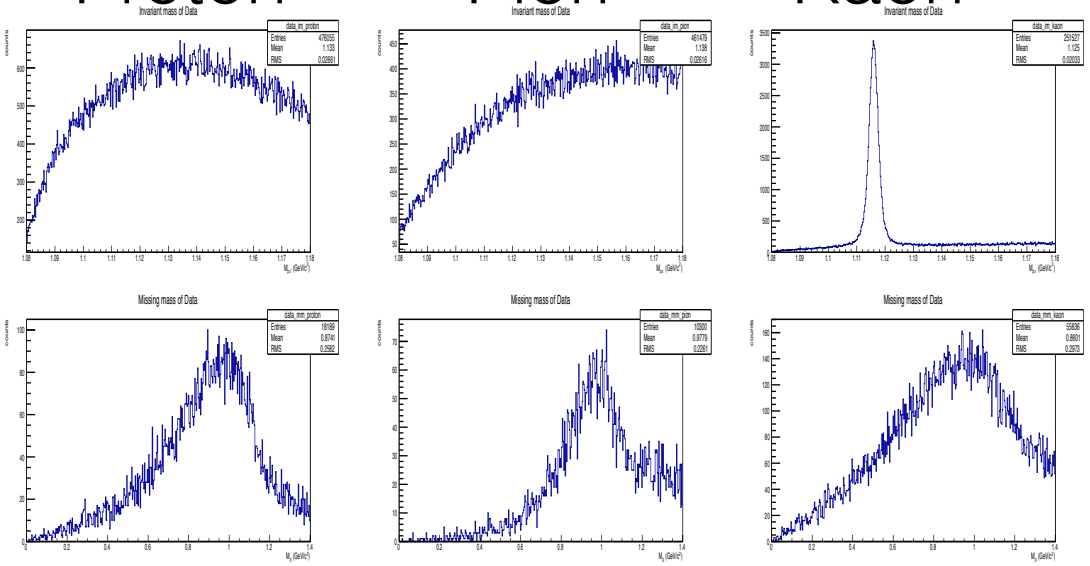
Background Contributions



accidental background

event mixing

Proton Pion Kaon



$$MM_{\gamma d \to K^+ p \pi^- X}$$

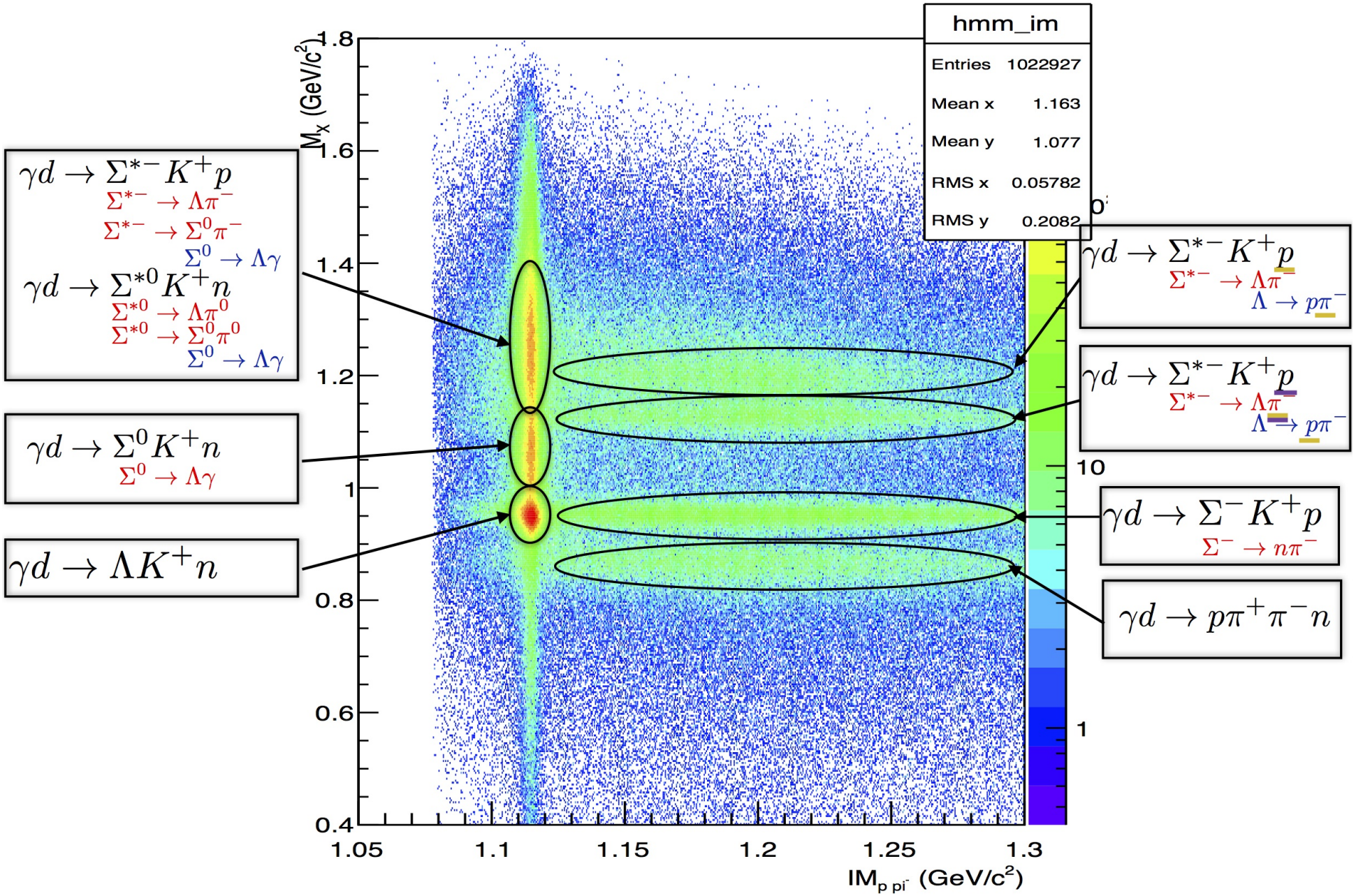
Reactions

$\gamma n \to \pi^0 n$	$\pi^0 p \to \Lambda K^+$
$\gamma p \to \Lambda K^+$	$K^+ n \to K^+ n$
$\gamma p \to \Lambda K^+$	$\Lambda n \to \Lambda n$
$\gamma p \to \Sigma K^+$	$\Sigma n \to \Sigma n$
$\gamma p \to \pi^+ n$	$\pi^+ n \to \Lambda K^+$
$\gamma p \to K^+ \Sigma^{*0}$	$\Sigma^{*0} \to \Lambda \pi^0$
$\gamma n \to K^+ \Sigma^{*-}$	$\Sigma^{*-} \to \Lambda \pi^-$

$\gamma p \to \Lambda K^+$

$\gamma p \to \Sigma K^+$

Background Contributions



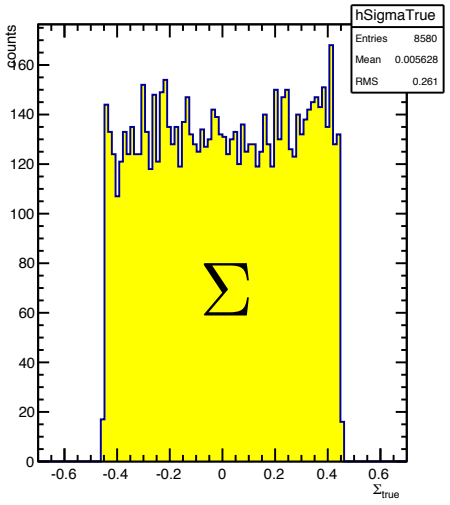
Extracting Polarization Observables

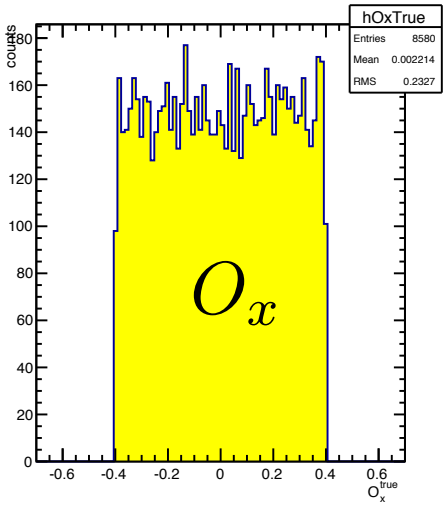
Systematic studies

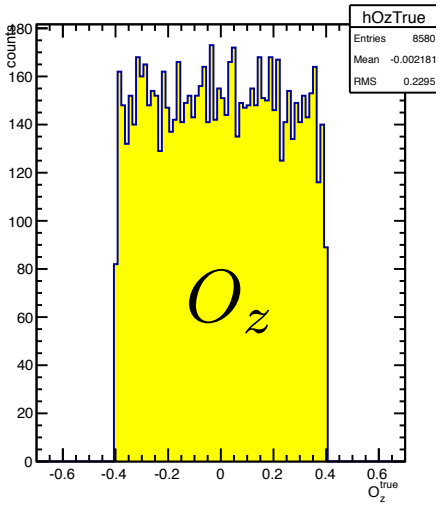
True Values

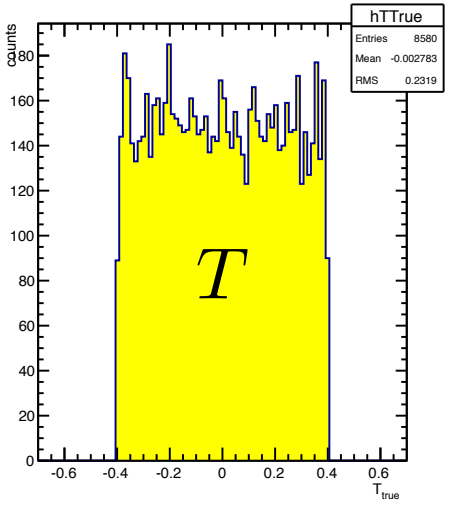
Per estimate

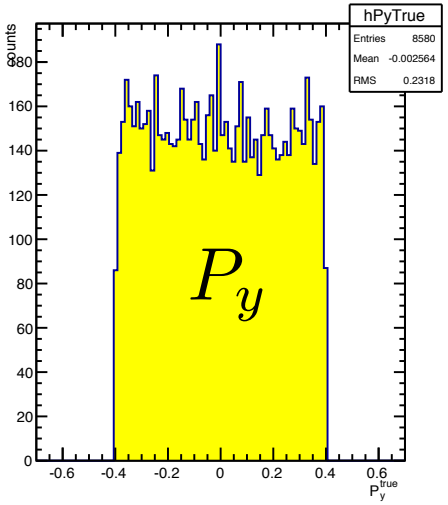
- Randomly choose observable
- Calculate polarized cross section and generated events
- Obtain estimates







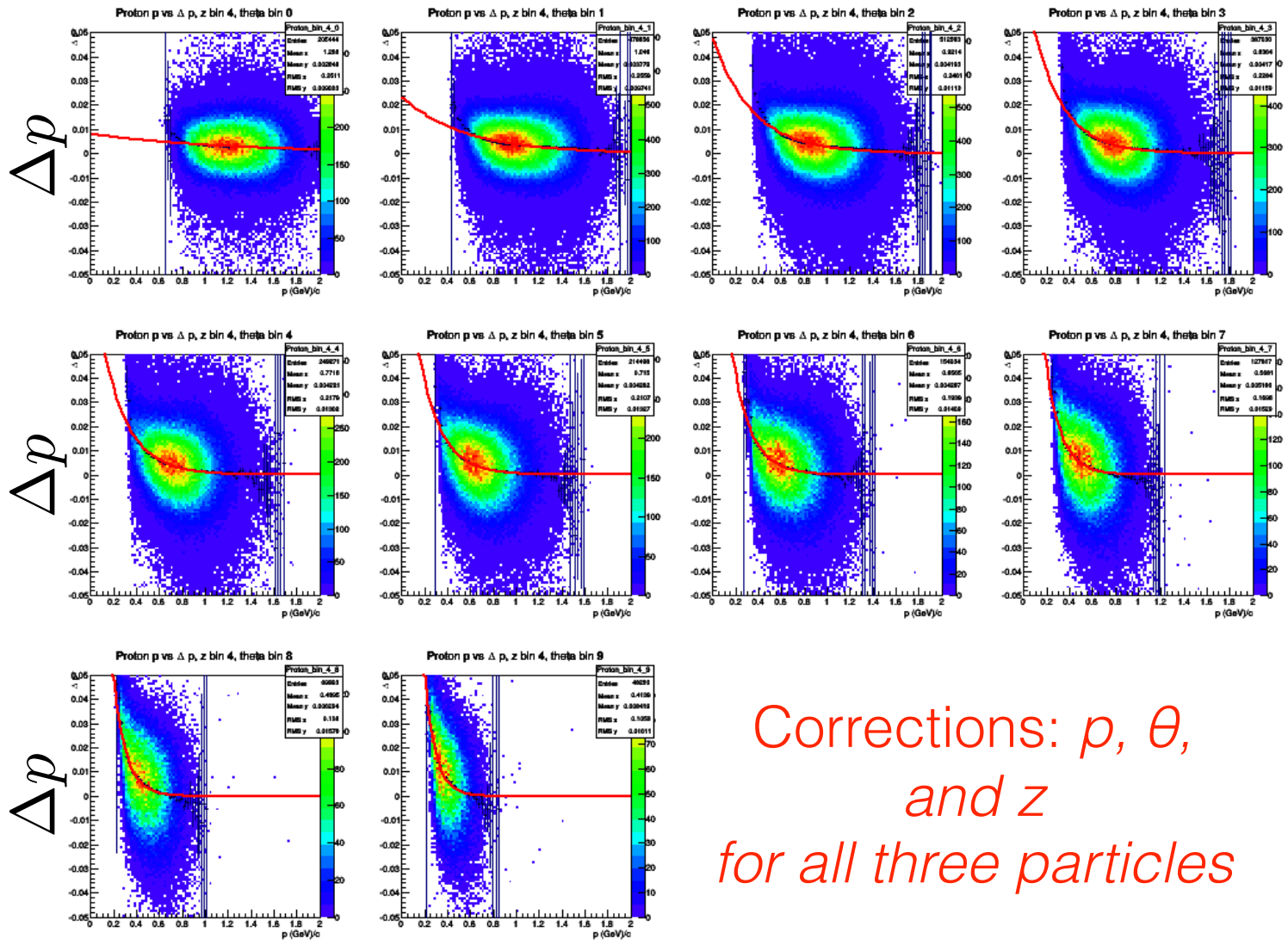




Background Contributions

GSIM Momentum Corrections $\gamma p \to K^+ \Lambda$

Robust comparison between data and simulation



Data *p*-corrections established via kinematic fitting of $\gamma d \to pp\pi^-$

Corrections: *p, θ, and z for all three particles*

Background Contributions

ALL

Signal

Σ^0 (FSI and QF)

Σ^{*-} and Σ^{*0}

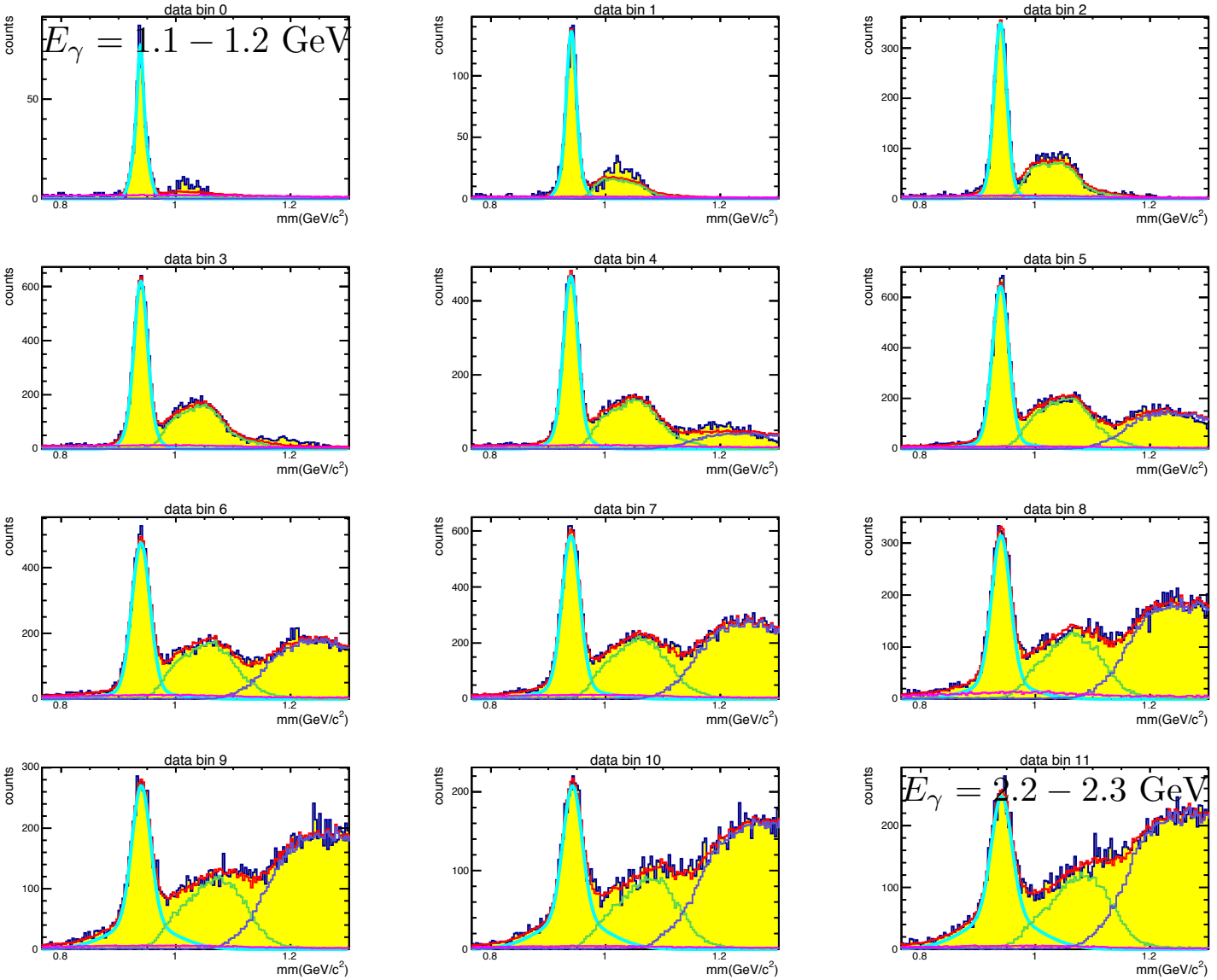
Accidentals

Background can be polarized

Fit MM

$\phi, \cos\theta_x, \cos\theta_z, \ldots$

establish weight for each event



Background Contributions

Another Approach

$$\frac{d\sigma^T}{d\Omega} = \sigma^T[1 \mp \Sigma^T \cos 2\phi \mp \alpha \cos\theta_x O_x^T \sin 2\phi \mp \alpha \cos\theta_z O_z^T \sin 2\phi + \cdots],$$

$$\frac{d\sigma^S}{d\Omega} = \sigma^S[1 \mp \Sigma^S \cos 2\phi \mp \alpha \cos\theta_x O_x^S \sin 2\phi \mp \alpha \cos\theta_z O_z^S \sin 2\phi + \cdots],$$

$$\frac{d\sigma^B}{d\Omega} = \sigma^B[1 \mp \Sigma^B \cos 2\phi \mp \alpha \cos\theta_x O_x^B \sin 2\phi \mp \alpha \cos\theta_z O_z^B \sin 2\phi + \cdots], \text{ and}$$

$$\frac{d\sigma^A}{d\Omega} = \sigma^A[1 \mp \Sigma^A \cos 2\phi \mp \alpha \cos\theta_x O_x^A \sin 2\phi \mp \alpha \cos\theta_z O_z^A \sin 2\phi + \cdots],$$

$$\begin{aligned}
\sigma^T &= \sigma^S + \sigma^B + \sigma^A \\
\sigma^T\Sigma^T &= \sigma^S\Sigma^S + \sigma^B\Sigma^B \\
\sigma^T O_x^T &= \sigma^S O_x^S + \sigma^B O_x^B \\
\sigma^T O_z^T &= \sigma^S O_z^S + \sigma^B O_z^B
\end{aligned}$$

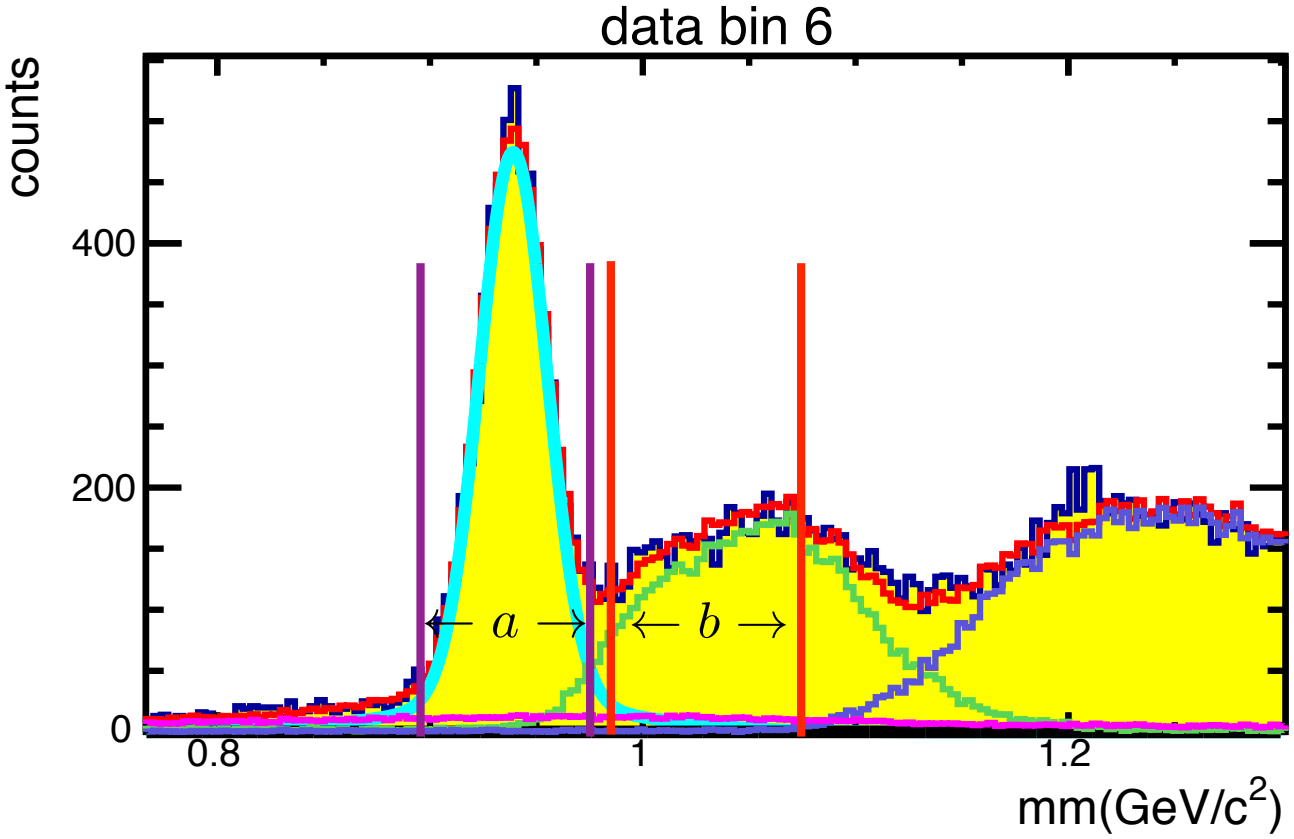
Background Contributions

Another Approach

$$\Sigma^S = \frac{r_a^B \Sigma_b^T - r_b^B \Sigma_a^T}{r_a^B - r_a^B r_b^A - r_b^B + r_a^A r_b^B}$$

$$O_x^S = \frac{r_a^B O_{xb}^T - r_b^B O_{xa}^T}{r_a^B - r_a^B r_b^A - r_b^B + r_a^A r_b^B}$$

$$O_z^S = \frac{r_a^B O_{zb}^T - r_b^B O_{za}^T}{r_a^B - r_a^B r_b^A - r_b^B + r_a^A r_b^B}$$



Systematic Studies underway

Extracting Polarization Observables

Binned Technique

$$\gamma p \to K^+ \Lambda \hookrightarrow p\pi^-$$

$\Sigma = 0.6$

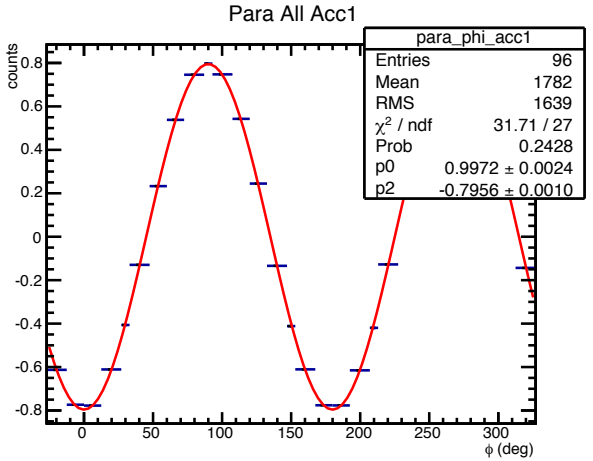
$O_x = 0.5$

$O_z = -0.5$

$T = 0.5$

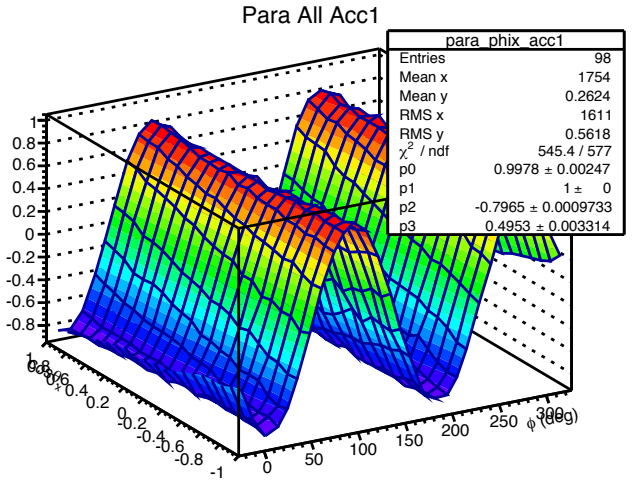
$P_y = 0.5$

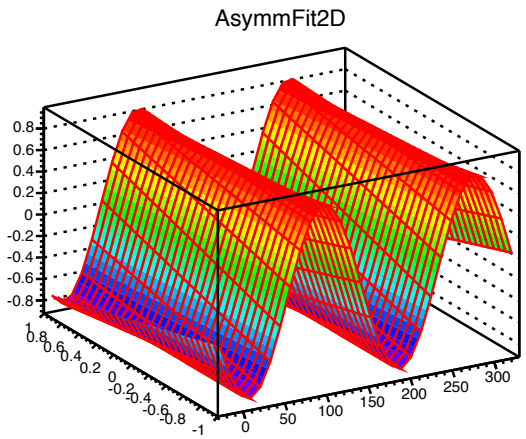
$P_{lin} = 1.0$



ϕ_{K^+}

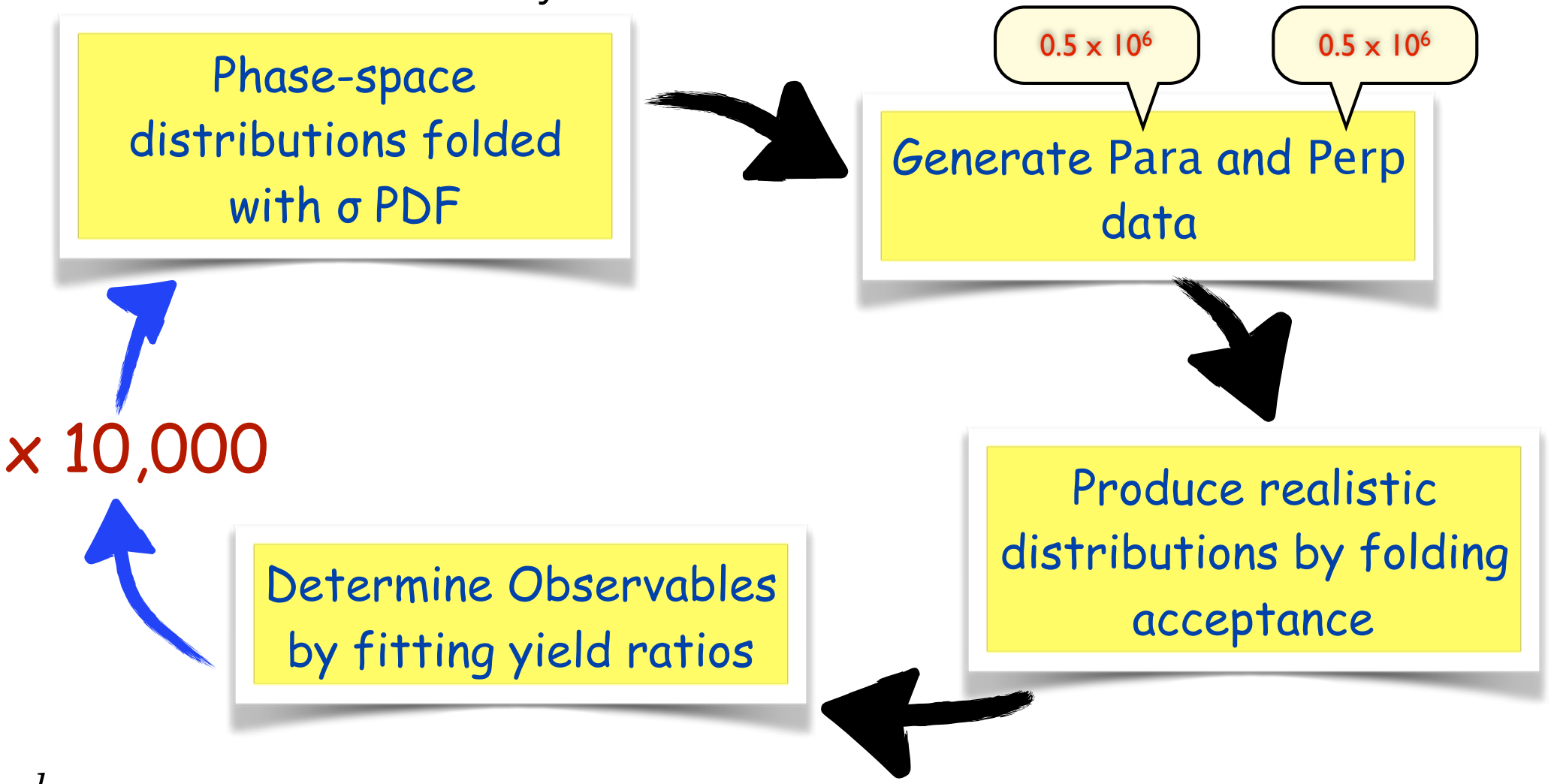
$\phi_{K^+}, \cos\theta_x^p$





Extracting Polarization Observables

Systematic Studies



$$\frac{d\sigma}{d\Omega} = \sigma_0\{1 - P_{lin}\Sigma\cos 2\phi + \alpha\cos\theta_x(-P_{lin}O_x\sin 2\phi - P_{circ}C_x)$$

$$- \alpha\cos\theta_y(-P_y + P_{lin}T\cos 2\phi) - \alpha\cos\theta_z(P_{lin}O_z\sin 2\phi + P_{circ}C_z)\}$$