

# Update on Spin Observable Measurements in the $\bar{\Lambda}\Lambda$ Reaction

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on behalf of the  $\bar{\Lambda}$ PANDA collaboration

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GSI



# Motivation

What is special about strangeness production?

- Light quark ( $u, d$ ) production
  - Highly non-perturbative
  - Hadrons as relevant degrees of freedom
- Strangeness production
  - Scale:  $m_s \approx 100\text{MeV} \sim \Lambda_{\text{QCD}} \approx 200\text{MeV}$
  - Relevant degrees of freedom unclear
- Heavier quark ( $c, b$ ) production
  - Quarks and gluons relevant
  - Perturbative QCD applicable

# Hyperon production $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$

Models based on the quark-gluon picture<sup>1</sup> and on the hadron picture<sup>2</sup>.

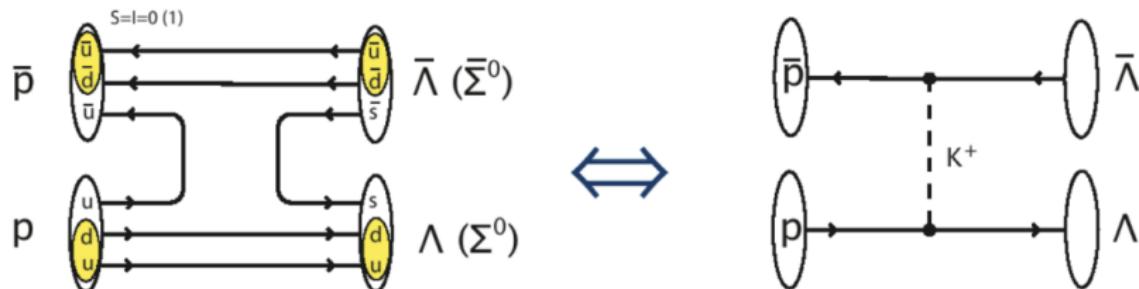


Figure:  $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$  in quark-gluon picture (left) and in Hadron picture (right).

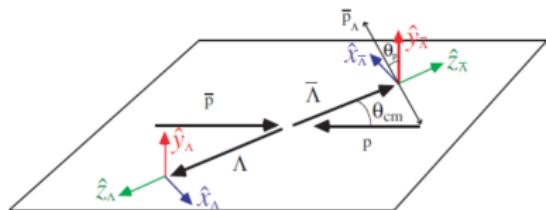
Different models give different predictions of e.g.

- angular distributions
- the correlation of the spin of the antihyperon-hyperon

<sup>1</sup>PLB 179 (1986); PLB 165 (1985) 187; NPA 468 (1985) 669

<sup>2</sup>PRC 31 (1985) 1857; PLB 179 (1986); PLB 214 (1988) 317

# Spin observables in $\bar{p}p \rightarrow \bar{Y}Y$



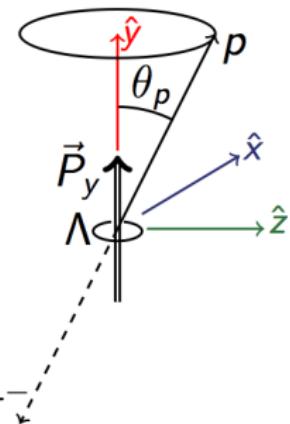
$$\hat{z} = \frac{\vec{p}_\Lambda}{|\vec{p}_\Lambda|}, \hat{y} = \frac{\vec{p}_i \times \vec{p}_f}{|\vec{p}_i \times \vec{p}_f|}, \hat{x} = \hat{y} \times \hat{z}$$

## Polarisation

Proton angular distribution:

$$I(\theta_p) \propto \frac{1}{4\pi} (1 + \alpha P_y(\cos \theta_{\bar{\Lambda}}) \cos \theta_p)$$

$\bar{\alpha}, \alpha$  - decay asymmetry parameter



## Spin correlation

Nucleon angular distribution:

$$I(\theta_i, \theta_j) \propto \frac{1}{16\pi^2} (1 +$$

$$\bar{\alpha}\alpha \sum_{i,j} C_{ij}(\cos \theta_{\bar{\Lambda}}) \cos \theta_i \cos \theta_j)$$

# Reconstructing the Spin Observables

Spin observables can be extracted using Method of Moments:

$$\langle \cos \theta_y \rangle = \langle k_y \rangle = \int_{-1}^1 \int_{-1}^1 I(k_y, k_{\bar{y}}) \times k_y dk_y dk_{\bar{y}}$$

Polarisation and Spin Correlation is given by:

$$P_y = \frac{3}{\alpha} \langle k_y \rangle = \frac{3}{\alpha} \frac{\sum_{m=1}^N k_{y,m}}{N}$$

$$C_{ij} = \frac{9}{\bar{\alpha}\alpha} \langle \bar{k}_i k_j \rangle = \frac{9}{\alpha\bar{\alpha}} \frac{\sum_{m=1}^N \bar{k}_{i,m} k_{j,m}}{N}$$

Erik Thomé, Elisabetta Perotti, Uppsala University

# Reconstructing the Spin Observables

If  $\cos \theta_y$  is symmetric around 0 i.e.

$$A_y(\cos \theta_y) = A_y(-\cos \theta_y)$$

$$A_{\bar{y}}(\cos \theta_{\bar{y}}) = A_{\bar{y}}(-\cos \theta_{\bar{y}}),$$

the spin observables are obtainable without acceptance correction:

$$P = \frac{1}{\alpha} \frac{\langle k_y \rangle}{\langle k_y^2 \rangle}$$

$$C_{yy} = \frac{1}{\alpha \bar{\alpha}} \frac{\langle \bar{k}_y k_y \rangle}{\langle \bar{k}_y^2 \rangle \langle k_y^2 \rangle}$$

$$C_{ij} = \frac{1}{\alpha \bar{\alpha}} \frac{\langle \bar{k}_i k_j \rangle - \langle \bar{k}_i \rangle \langle k_j \rangle}{\langle \bar{k}_i^2 \rangle \langle k_j^2 \rangle}, \quad i, j = x, z$$

# Simulation parameters

Simulations are done with:

- Release feb17p1.
- fairsoft\_may16p1
- Fairroot v16.06b

Parameters:

- Forward-peaking distribution
- Antiproton beam  $p_{\bar{p}} = 1.642$  GeV/c
- Full Detector Setup
- Ideal Mass Hypothesis for Kalman Filter
- Ideal Pattern Recognition
- Ideal Particle Identification

Channel	$\bar{\Lambda}\Lambda$	$\bar{p}p\pi^+\pi^-$	DPM
Sample	1 000 000	1 000 000	10 000 000
Cross section [ $\mu b$ ]	64	10	$63 \times 10^3$
Weight factor	1	0.16	220

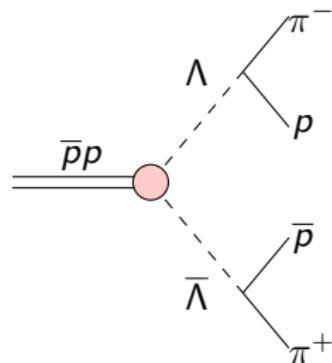
**Table:** Produced channel sample sizes, their respective cross sections and weight factors.

**Note:**  $\bar{\Lambda}\Lambda$  &  $\bar{p}p\pi^+\pi^-$  removed from DPM sample.

# Preselection and event reconstruction

Preselection criteria:

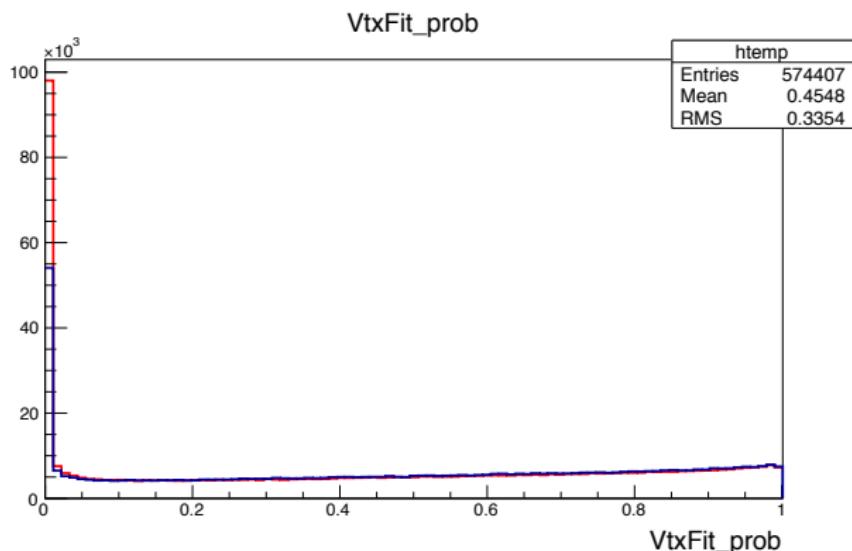
- Combine  $p\pi^-$ ,  $\bar{p}\pi^+$
- Select  $|m_\Lambda - M(p\pi^-)| < 0.3 \text{ GeV}$
- Vertex fit on all combinations of  $p\pi^-$ ,  
 $\bar{p}\pi^+$   
Reject a candidate if  $P(\text{Vtxfit}) < 0.01$   
Select combination with smallest  $\chi^2$   
from the vertex fit
- Use variables from vertex fit in a 4C fit  
over whole decay chain



# Vertex Fit

Red: Lambda

Blue: AntiLambda



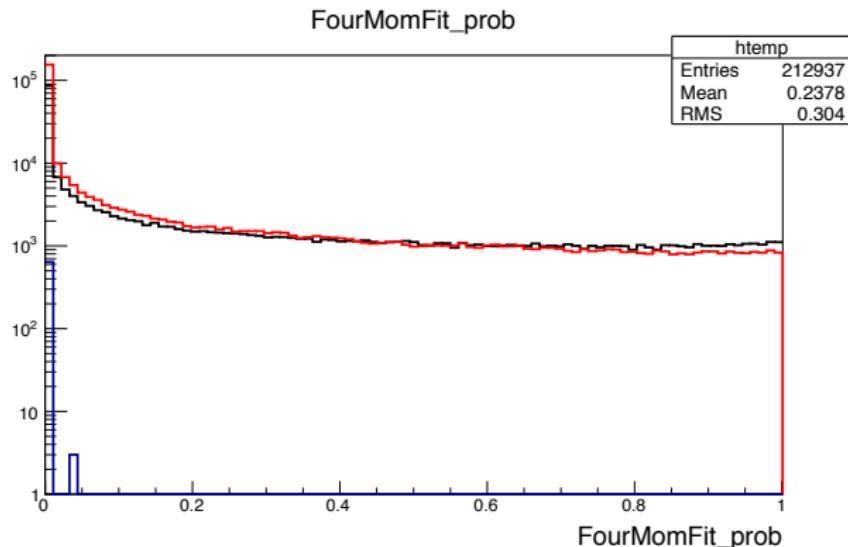
# Four-constraint Fit

Non-scaled samples

Black: Signal

Red: Non resonant

Blue: DPM



# Reconstruction Efficiencies

To get the right ratio of events:

$$\frac{N_{\text{anything}}}{N_{\text{signal}}} = \frac{\sigma(\bar{p}p \rightarrow \text{anything})}{\sigma(\bar{p}p \rightarrow \bar{\Lambda}\Lambda) \text{BR}(\Lambda \rightarrow p\pi)^2}$$

After preselection, the following events survive:

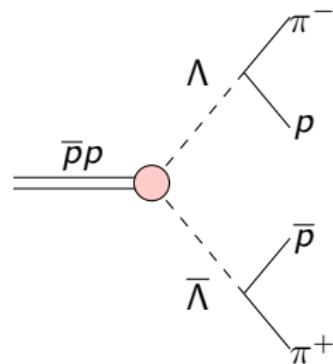
Sample	$\bar{\Lambda}\Lambda$	$\bar{p}p\pi^+\pi^-$	DPM
Efficiency $\bar{p}p$	21.3%	29.7%	0.007%
N scaled $\bar{p}p$	212937	$292700 \times 0.16 = 45734$	$651 \times 220 = 143220$
S/B ratio	1	$\sim 4.7$	$\sim 1.5$

**Table:** Reconstruction efficiency after the preselection for signal events as well as non-resonant and DPM background.

# Final Selection

Final selection criteria:

- Four constraint fit  $\chi^2 < 100$
- Select  $|m_{fit}(\bar{p}\pi^+) - 1115.7| < 5 \cdot 3.0 \text{ MeV}/c^2$
- Select  $|m_{fit}(p\pi^-) - 1115.7| < 5 \cdot 2.9 \text{ MeV}/c^2$
- Select  $z_{\bar{\Lambda}} + z_{\Lambda} > 2 \text{ cm}$



# Four-constraint Quality Cut

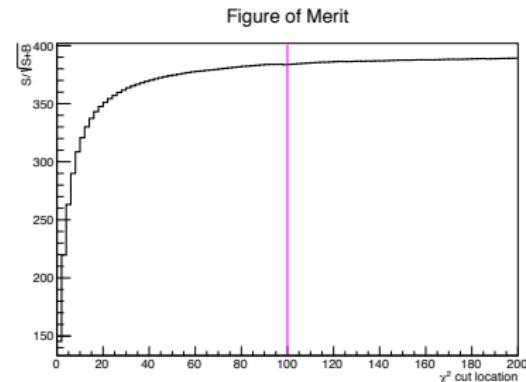
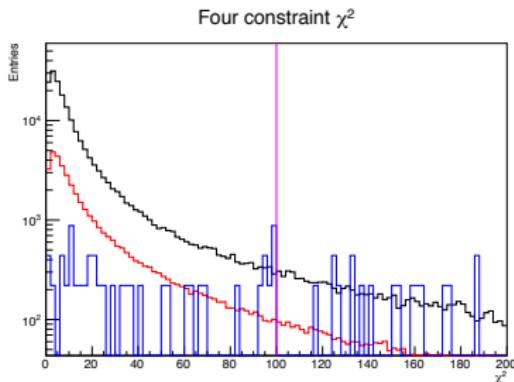
Black: Signal

Red: Non resonant

Blue: DPM

No obvious location to cut. Set to  $\chi^2 < 100$ .

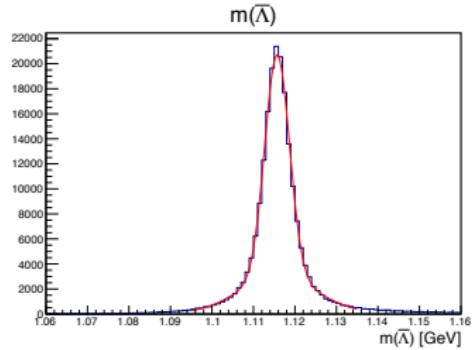
Most DPM events large  $\chi^2$ ,  $> 90\%$  rejected.



# Invariant Mass Cut

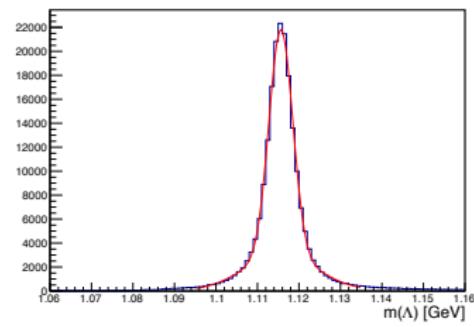
Double Gaussian fit on mass distributions to obtain  $\sigma$  values. Only signal samples considered here. Should do a fit on signal + background.

Anti-Lambda

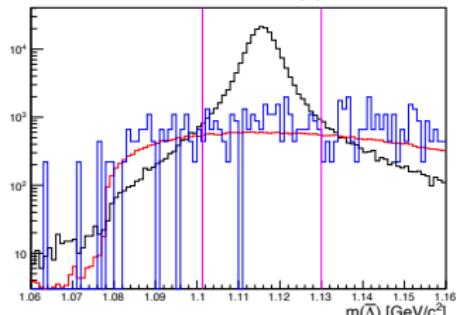


Invariant mass  $m(\bar{\Lambda})$

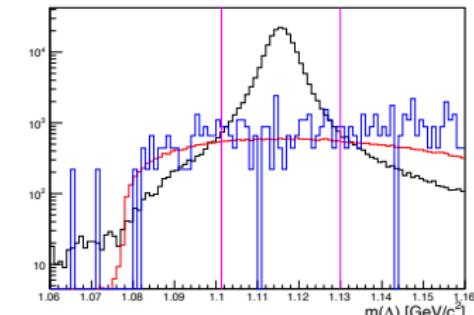
Lambda



Invariant mass  $m(\Lambda)$



Invariant mass  $m(\bar{\Lambda})$



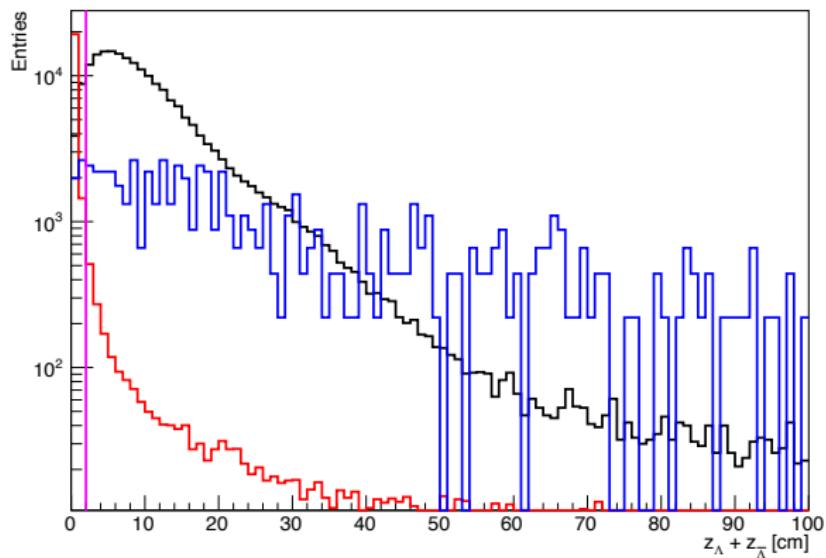
# Displaced Vertex Cut

Black: Signal

Red: Non resonant

Blue: DPM

$$z_{\Lambda} + z_{\bar{\Lambda}}$$



## Final Selection Efficiencies

After the final selection, the following events survive:

Sample	$\bar{\Lambda}\Lambda$	$\bar{p}p\pi^+\pi^-$	DPM
Efficiency $\bar{p}p$	15.7%	0.05%	0.00004%
N scaled $\bar{p}p$	$157184 \pm 397$	$472 \times 0.16 = 76$	$4 \times 220 = 880$
S/B ratio	1	$\sim 2069$	$\sim 179$

**Table:** Reconstruction efficiency after the final selection for signal events as well as non-resonant and generic hadronic background.

- Out of 157184 signal events, 410 are combinatorial background
- Summary:  $S/B = 115$ . Pure sample suitable for spin observable extraction

# Production Rates

Rate [ $10^7 \text{ s}^{-1}$ ]	0.56			1			2		
$n_t [10^{15} / \text{cm}^2]$	1	2	4	1	2	4	1	2	4
HL	-	-	-	34.4	39.0	39.4	36.0	67.1	77.9
HR	-	-	-	3.6	6.8	12.4	3.6	6.8	12.4
HESRr	3.0	4.9	7.6	3.2	5.6	9.1	-	-	-
HESR	2.4	3.8	5.9	2.7	4.5	7.3	-	-	-

**Table:** Average luminosities  $\bar{\mathcal{L}} [10^{30} / (\text{cm}^2 \text{s})] = [\mu b^{-1} \text{s}^{-1}]$  for anti-proton beam momentum  $p_{\bar{p}} = 1.5 \text{ GeV}/c$

Even with lowest average luminosity, PANDA will produce

$$\dot{N}_{rec} = \sigma(\bar{p}p \rightarrow \bar{\Lambda}\Lambda) \times \text{BR}(\Lambda \rightarrow p\pi)^2 \times \mathcal{L} \times \epsilon = 10 \text{ s}^{-1}$$

Which means 1M  $\bar{\Lambda}\Lambda$  events can be reconstructed in  $\sim 27$  hours.

## Polarisation $P_y$ - 1M Events

How to generate  $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$  sample with proper distribution:

- Simulate  $\Lambda \rightarrow p\pi^-$ ,  $\bar{\Lambda} \rightarrow \bar{p}\pi^+$  with flat phase space
- Use input polarisation

$$P_y = P_{\bar{y}} = \sin 2\theta_{\Lambda}$$

- Evaluate

$$w_m = 1 + \alpha P_y k_{y,m},$$

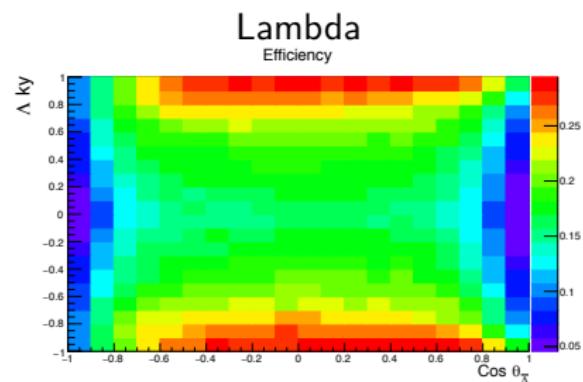
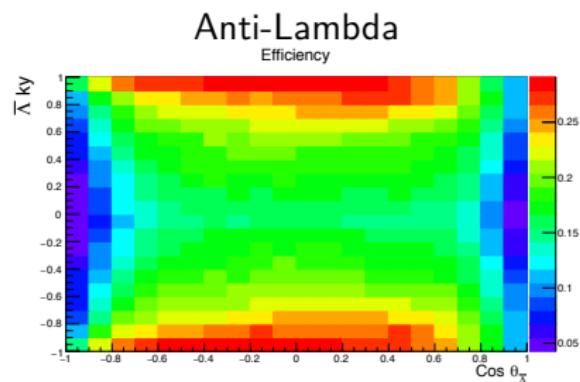
assign as weight to event  $m$

Polarisation reconstructed according to

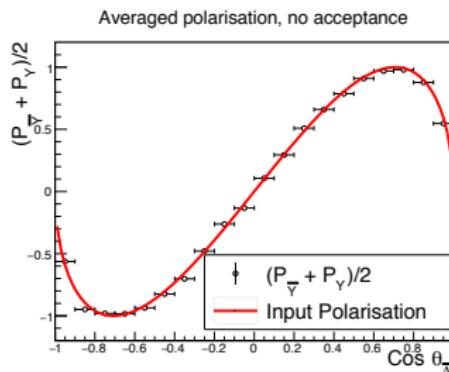
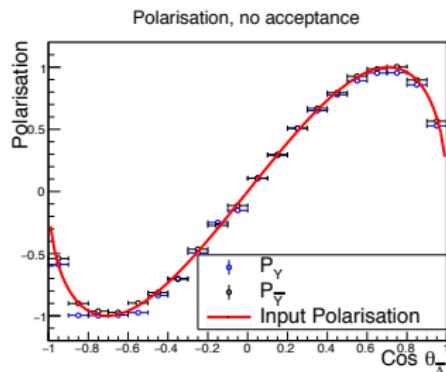
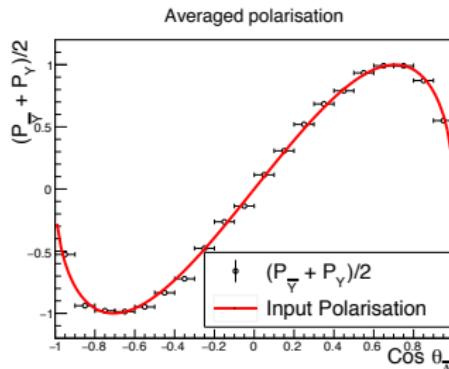
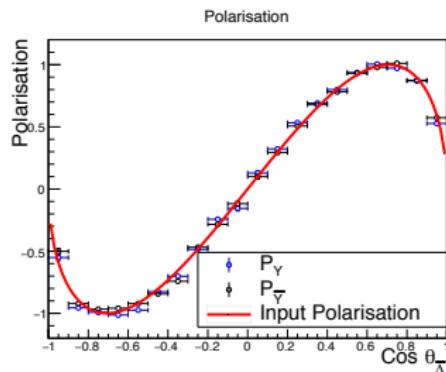
$$P_y = \frac{3}{\alpha} \frac{\sum_{m=1}^N \frac{w_m k_{y,m}}{A(k_{y,m})}}{\sum_{m=1}^N \frac{w_m}{A(k_{y,m})}}$$

# Polarisation $P_y$ - 1M Events

- Simulate  $10^7 \bar{\Lambda}\Lambda$  events with PHSP, no forward peaking.
- Divide into  $20 \times 20$  bins across  $A(\cos \theta_\Lambda, k_y)$



# Polarisation $P_y$ - 1M Events



## Spin Correlation - 2M Events

How to generate  $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$  sample:

- Simulate  $\Lambda \rightarrow p\pi^-$ ,  $\bar{\Lambda} \rightarrow \bar{p}\pi^+$  with flat phase space
- Use input spin correlation

$$C_{ij} = \sin \theta_\Lambda$$

- Evaluate

$$w_m = 1 + \bar{\alpha} \alpha C_{ij} \bar{k}_{i,m} k_{j,m},$$

assign as weight to each event

Spin correlation is reconstructed according to

$$C_{ij} = \frac{9}{\bar{\alpha} \alpha} \frac{\sum_m \frac{w_m}{A(k_{y,m})} \bar{k}_{i,m} k_{j,m}}{\sum_m \frac{w_m}{A(k_{y,m})}}$$

## Spin Correlation - 2M Events

- Three relevant variables when reconstructing  $C_{ij}$
- Consider the case where  $2 \times 10^6 \bar{\Lambda}\Lambda$  events are produced
- Simulate  $10^7$  PHSP events for constructing the efficiency matrix
- Divide into  $8 \times 8 \times 8$  bins across  $A(\cos \theta_\Lambda, k_i, k_j)$

# Spin Correlation - 2M E

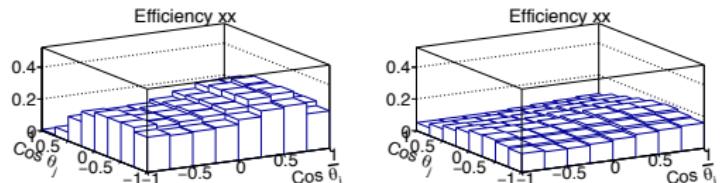
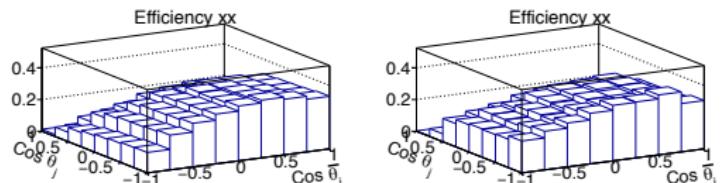
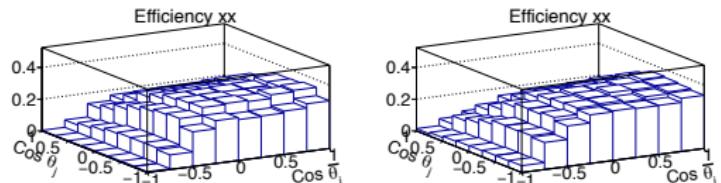
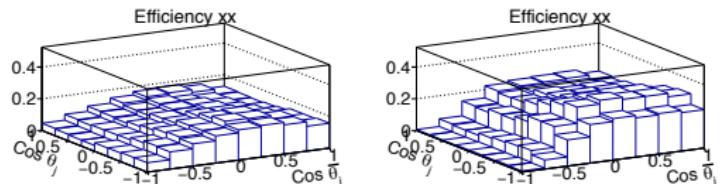
Acceptance used for  $C_{xx}$

Top left:

$$-1 < \cos \theta_{\Lambda} < -0.75$$

Top right:

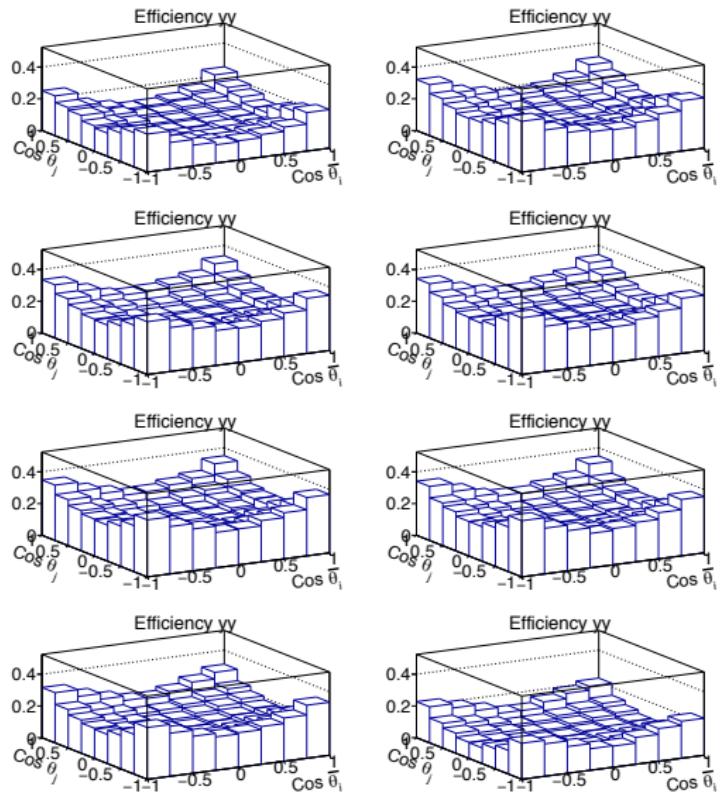
$$-0.75 < \cos \theta_{\Lambda} < -0.5$$



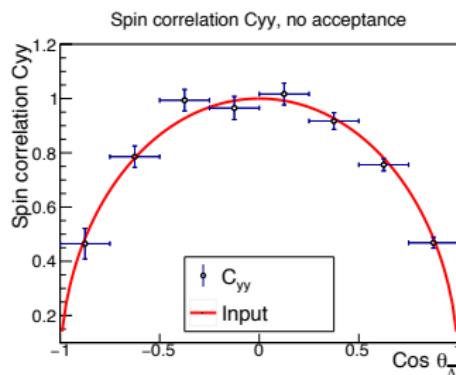
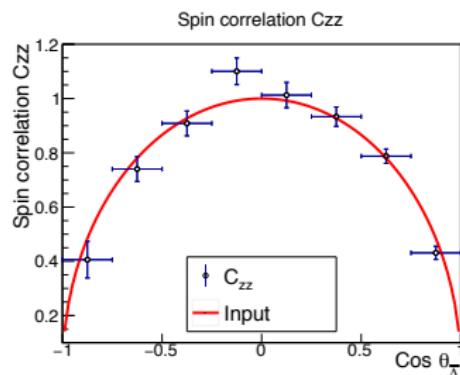
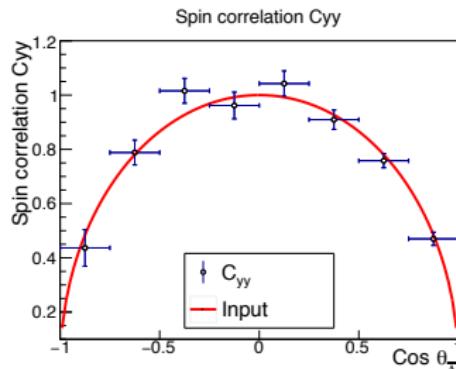
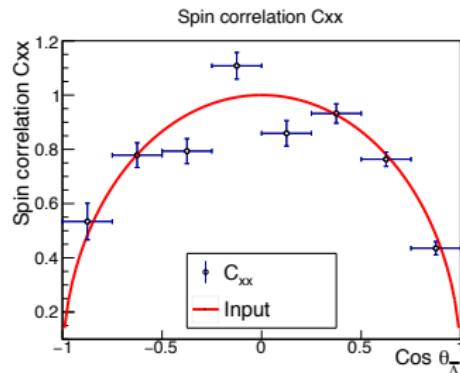
# Spin Correlation - 2M E

Acceptance used for  $C_{yy}$

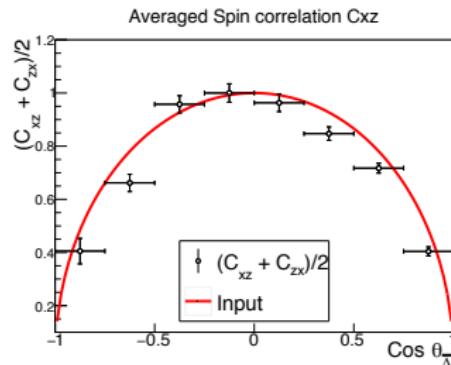
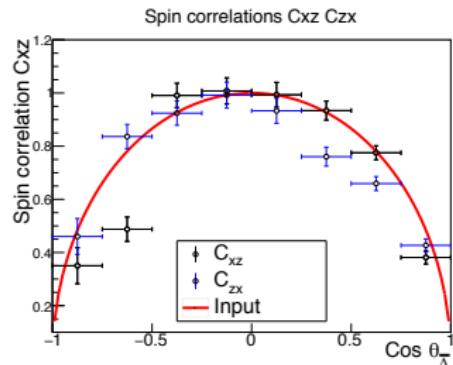
Looks symmetric, can extract  $C_{ij}$  without acceptance function



# Spin Correlation - 2M Events - $C_{ii}$



# Spin Correlation - 2M Events - $C_{ij}$



- Large systematic shift in  $C_{xz}$  second bin and  $C_{zx}$  sixth bin
- Due to low entry regions in efficiency matrix

# Outlook

- Potential improvements
  - Redo invariant mass fit on signal+background spectrum using sidebands
  - Simulate more DPM events
  - Maximum likelihood as alternative parameter estimation method
    - Requires large signal sample
- First draft on memo near completion

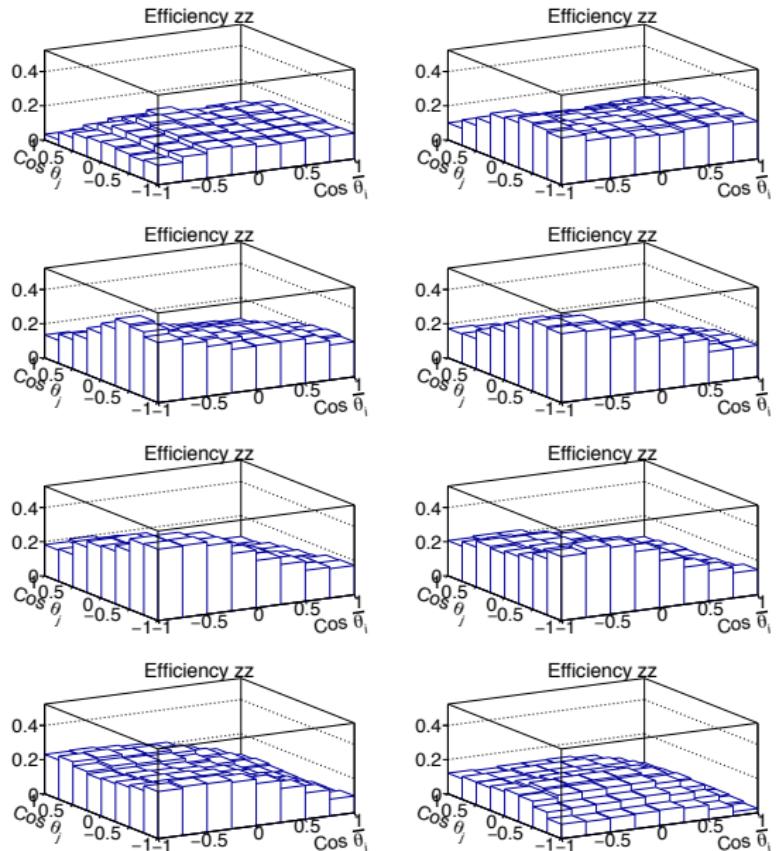
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Thank you for your attention!

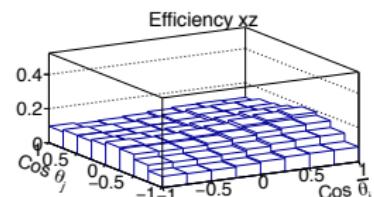
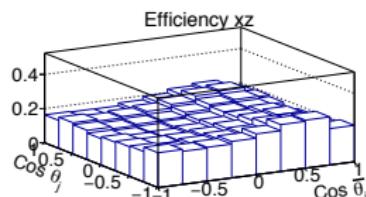
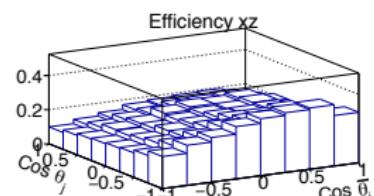
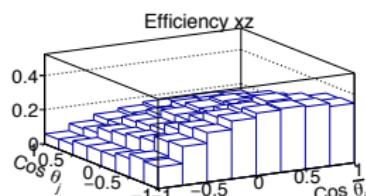
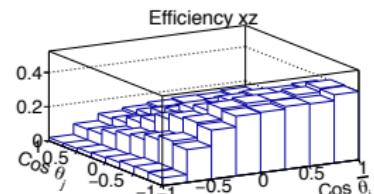
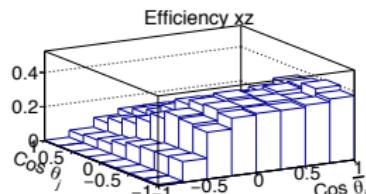
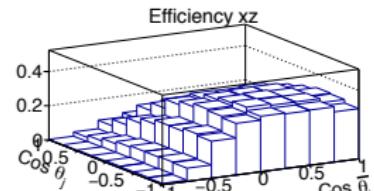
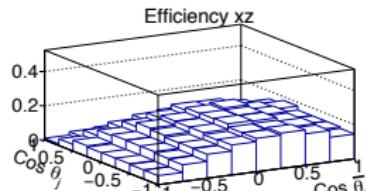
# Acceptance functions

Acceptance used for  
 $C_{zz}$



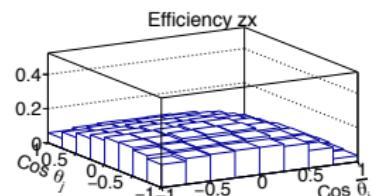
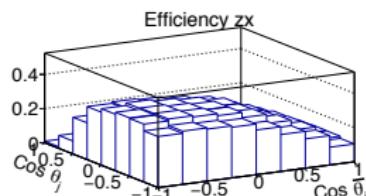
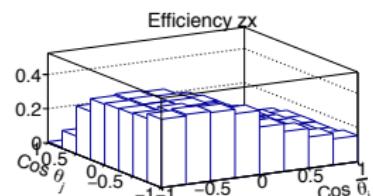
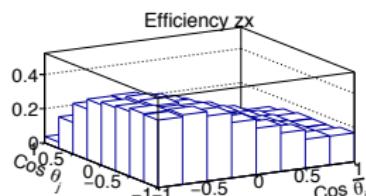
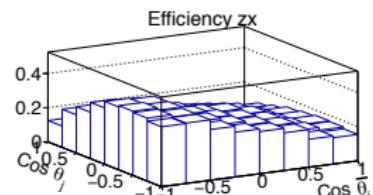
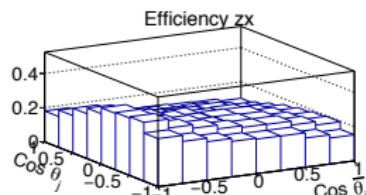
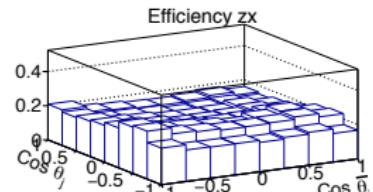
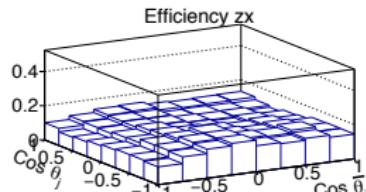
# Acceptance functions

Acceptance used for  
 $C_{xz}$

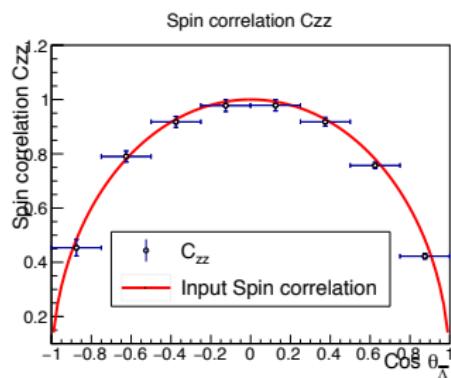
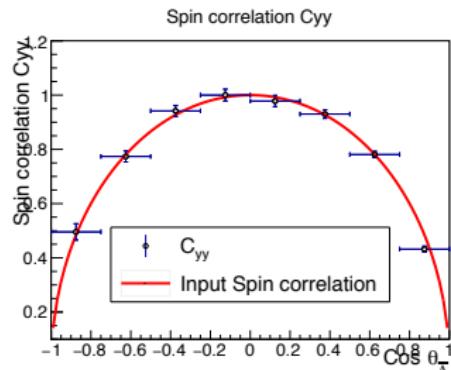
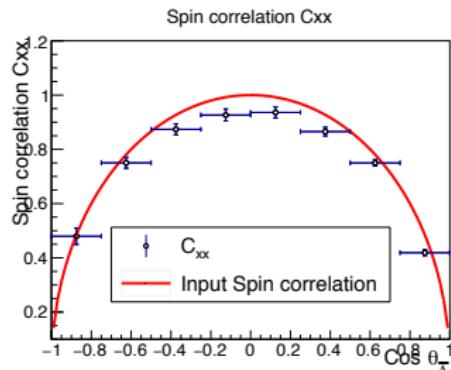


# Acceptance functions

Acceptance used for  
 $C_{zx}$



# Spin Correlation $C_{ij}$ - 10M Events



# Spin Correlation $C_{ij}$ - 10M Events

