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Antihyperon Hyperon Physics for the PANDA Experiment

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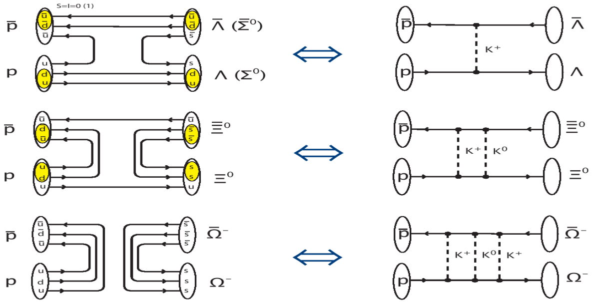
Outline

$\bar{p}p \to \bar{Y}Y$

What are the relevant degrees of freedom to describe a process?
Quarks and gluons or hadronic degrees of freedom?



PANDA (1.5-15 GeV) is in the transition regime between the two descriptions.

Hyperon Spin Variables

Hyperons decay with a parity violating weak decay to a spin 1/2 baryon and aspin 0 meson $\Rightarrow L = 0, 1$ ($L = 1, 2$ for Ω). Decay asymmetry parameters

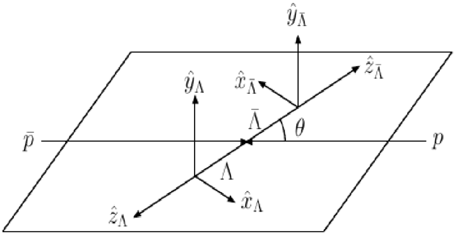
$$\alpha = \frac{2\mathrm{Re}(A_S^* A_P)}{|A_S|^2 + |A_P|^2}, \quad \beta = \frac{2\mathrm{Im}(A_S^* A_P)}{|A_S|^2 + |A_P|^2}, \quad \gamma = \frac{|A_S|^2 - |A_P|^2}{|A_S|^2 + |A_P|^2} \tag{1}$$

Polarisation P is given from angular distribution

$$I(\cos\Theta) = \frac{1}{2}(1 + \alpha P \cos\Theta) \tag{2}$$

In $\bar{\mathrm{p}}\mathrm{p} \rightarrow \bar{\mathrm{Y}}\mathrm{Y}$ spin correlations are also be measured. For $\bar{\Lambda}\Lambda$ this relates to how the spins of the $\bar{\mathrm{s}}\mathrm{s}$ pair are correlated.
(β and γ appears in the angular distribution of the decay of the daughter particle)

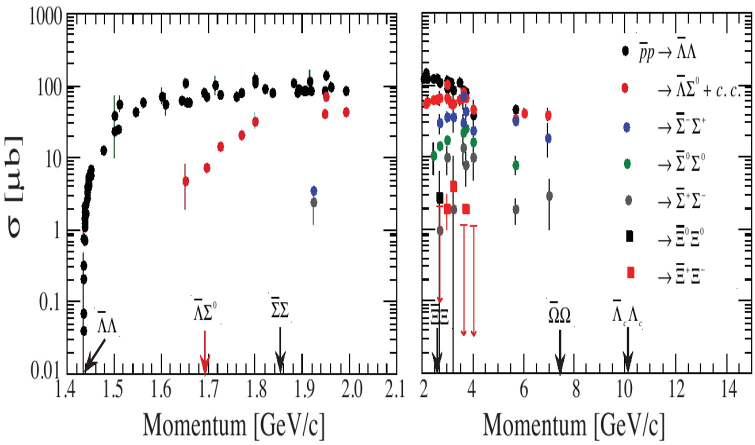
Definition of the Hyperon Rest System



The hyperon rest systems are defined to make maximum use of C and P invariance

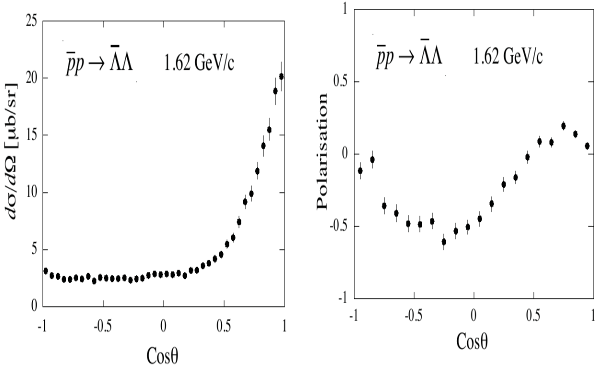
$$I_{\bar{p}p}(\Theta_{\bar{\Lambda}}, \hat{k}_{\bar{p}}, \hat{k}_{p}) = \frac{I_0}{64\pi^3} \begin{pmatrix} 1 \\ +P_y(\bar{\alpha}\hat{k}_{\bar{p}y} + \alpha\hat{k}_{py}) \\ +C_{xx}\bar{\alpha}\alpha\hat{k}_{\bar{p}x}\hat{k}_{px} \\ +C_{yy}\bar{\alpha}\alpha\hat{k}_{\bar{p}y}\hat{k}_{py} \\ +C_{zz}\bar{\alpha}\alpha\hat{k}_{\bar{p}z}\hat{k}_{pz} \\ +C_{xz}\bar{\alpha}\alpha\hat{k}_{\bar{p}x}\hat{k}_{pz} \\ +C_{zx}\bar{\alpha}\alpha\hat{k}_{\bar{p}z}\hat{k}_{px} \end{pmatrix} \quad (3)$$

Existing Experimental Data

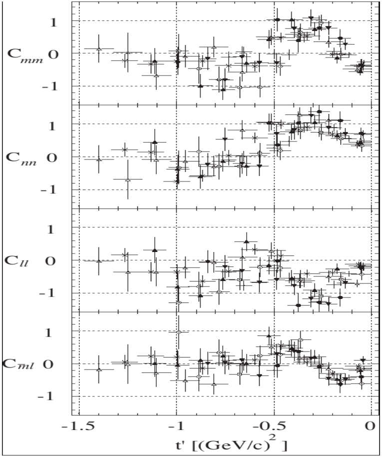


Data from PS185 at LEAR

Largest amount of data, $\sim$ 40k events,from PS185 experiment at LEAR.

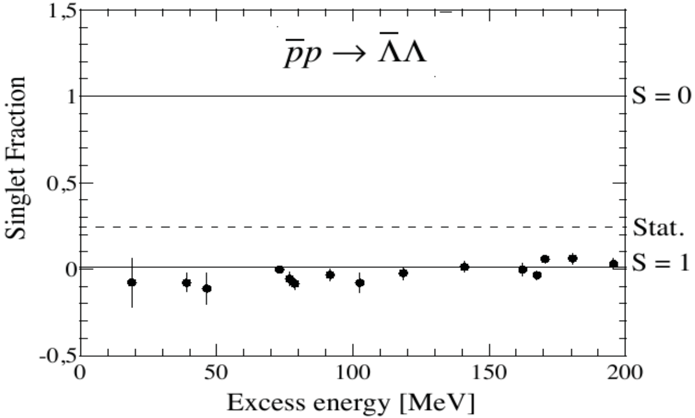


Spin Correlations



Singlet Fraction

$$SF = \frac{1}{4}(1 + Cxx - Cyy + Czz) \tag{4}$$



$\bar{\Lambda}\Lambda$ (and consequently the $\bar{s}s$) are always produced with parallel spins.

CP Violation Parameters

$$
\begin{aligned}
D &= \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} \\
A &= \frac{\Gamma\alpha + \bar{\Gamma}\bar{\alpha}}{\Gamma\alpha - \bar{\Gamma}\bar{\alpha}} \approx \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} \\
B &= \frac{\Gamma\beta + \bar{\Gamma}\bar{\beta}}{\Gamma\beta - \bar{\Gamma}\bar{\beta}} \approx \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}} \\
B' &= \frac{\Gamma\beta + \bar{\Gamma}\bar{\beta}}{\Gamma\alpha - \bar{\Gamma}\bar{\alpha}} \approx \frac{\beta + \bar{\beta}}{\alpha - \bar{\alpha}}
\end{aligned}
\tag{5}
$$

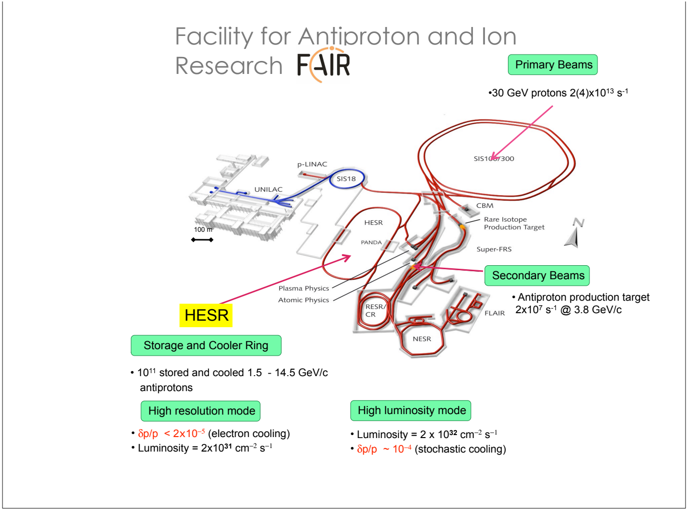
Theoretical estimate $A \approx 5 \cdot 10^{-4}$ and

$$0.1O(B) \approx O(B') \approx 10O(A) \approx 100O(D) \tag{6}$$

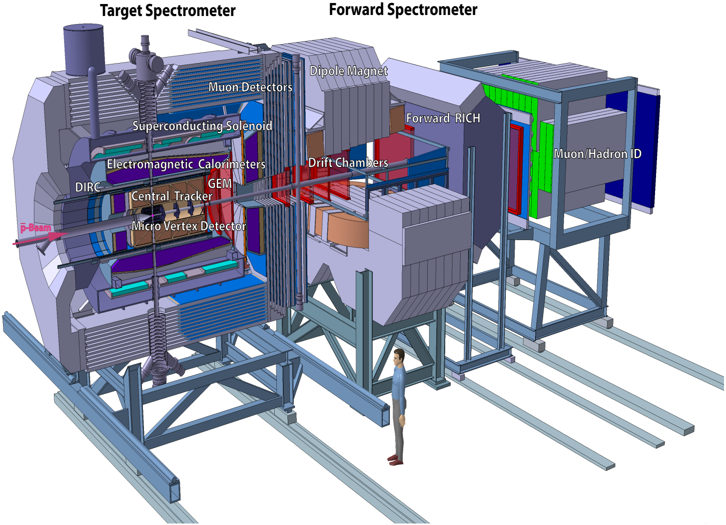
Experimental limits: $A_\Lambda = 0.013 \pm 0.021$ (PDG average), $A_\Xi = (0.0 \pm 5.1 \pm 4.4) \cdot 10^{-4}$ (HYCP, 158M events, p Cu, 800 GeV).

No experimental limits on B_Ξ and B'_Ξ

FAIR


Facility for Antiproton and Ion Research FAIR
Primary Beams
•30 GeV protons 2(4)x10^13 s^-1
SIS100/300
p-LINAC
SIS18
UNILAC
100 m
CBM
Rare Isotope Production Target
HESR
PANDA
Super-FRS
Secondary Beams
Plasma Physics
Atomic Physics
• Antiproton production target 2x10^7 s^-1 @ 3.8 GeV/c
RESR/CR
FLAIR
NESR
HESR
Storage and Cooler Ring
• 10^11 stored and cooled 1.5 - 14.5 GeV/c antiprotons
High resolution mode
• δp/p < 2x10^-5 (electron cooling)
• Luminosity = 2x10^31 cm^-2 s^-1
High luminosity mode
• Luminosity = 2 x 10^32 cm^-2 s^-1
• δp/p ~ 10^-4 (stochastic cooling)

PANDA Detector



New for PANDA

- Very large increase in statistics for Λ and Σ hyperons and possibility to measure at higher beam momenta
- Opens up new channels: Ξ, Ω, Λ_c, ...
- Increase in statistics for CP violation measurements and access to the unmeasured (more sensitive parameters) B_Ξ and B'_Ξ

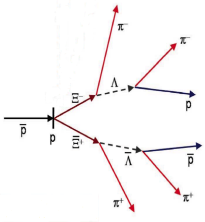
Hyperon Properties

Hyperon	Quarks	Mass [MeV/ c^2]	$c\tau$ [cm]	Main decay	B [%]	α_Y
Λ	uds	1116	8.0	$p\pi^-$	64	+0.64
Σ^+	uus	1189	2.4	$p\pi^0$	52	-0.98
Σ^0	uds	1193	$2.2 \cdot 10^{-9}$	$\Lambda\gamma$	100	-
Σ^-	dds	1197	2.4	$n\pi^-$	100	-0.07
Ξ^0	uss	1315	8.7	$\Lambda\pi^0$	99	-0.41
Ξ^-	dss	1321	4.9	$\Lambda\pi^-$	100	-0.46
Ω^-	sss	1672	2.5	ΛK^-	68	-0.03
Λ_c^+	udc	2286	$6.0 \cdot 10^{-3}$	$\Lambda\pi^+$	1	-0.91(15)
Σ_c^{++}	uuc	2454		$\Lambda_c^+\pi^+$	100	
Σ_c^+	udc	2453		$\Lambda_c^+\pi^0$	100	
Σ_c^0	ddc	2454		$\Lambda_c^+\pi^-$	100	
Ξ_c^+	usc	2468	$1.2 \cdot 10^{-2}$	$\Xi^-\pi^+\pi^+$	seen	
Ξ_c^0	dsc	2471	$2.9 \cdot 10^{-3}$	$\Xi^-\pi^+$	seen	-0.6(4)
Ω_c^0	ssc	2697	$1.9 \cdot 10^{-3}$	$\Omega^-\pi^+$	seen	

$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$

- Reconstruction efficiency between 14 and 24%, depending on beam momentum
- Between 100 and 1000 reconstructable events/s
- Polarisation and spin correlations reconstructable
- Most severe background problem is to separate Λ from Σ^0

$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$



- Only existing data from old bubble chamber experiments
- $\Xi^-/\bar{\Xi}^+$ bent by magnetic field, must be corrected for
- Differential cross section not known, isotropic used for simulations
- Four displaced vertices → low background
- Daughter Λ also decays weakly → more parameters reconstructable

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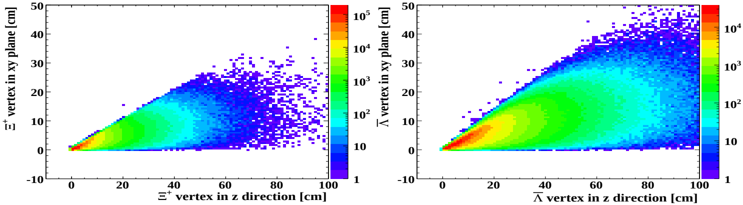
$\bar{p}p \to \bar{\Xi}^+\Xi^-$

- Simulations at 4 GeV/c beam momentum
- Reconstruction efficiency $\sim 17\% \to\sim 30$ reconstructable events/s
- Background from $\bar{p}p \to \bar{\Sigma}^-(1385)\Sigma^+(1385)$ investigated. Background/Signal smaller than $2 \cdot 10^{-4}$



Decay vertices of $\bar{\Xi}^+$ and $\bar{\Lambda}$.

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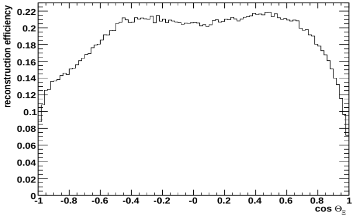
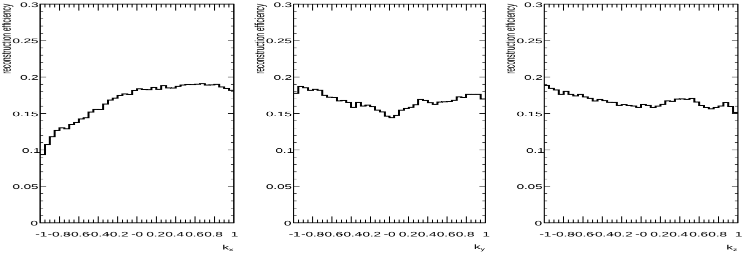
Reconstruction Efficiency Depending on Production and Decay Angles



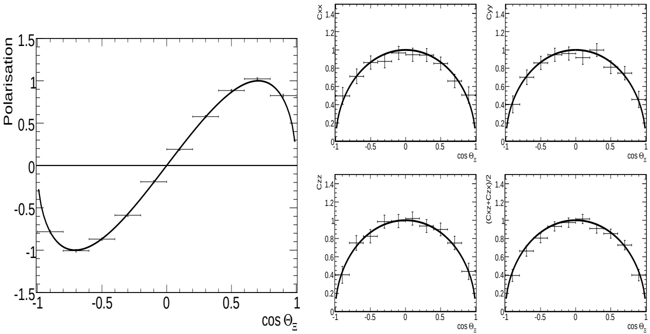


$\Xi^-/\bar{\Xi}^+$ Spin Variables

Spin variables can be calculated from averages of the reconstructed decay angles ($\hat{k}$). The acceptance depends on the angle in the hyperon decay $\Rightarrow$ need to use MC based acceptance functions

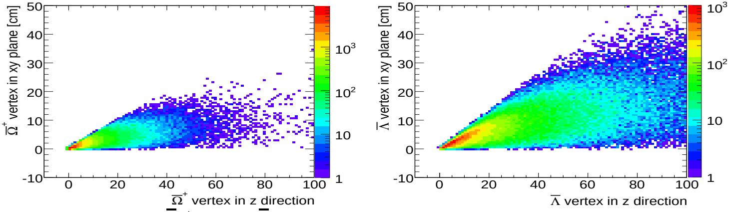
$$P_y = \frac{3}{\alpha}\sum_{n=1}^{N}\frac{k_{y,n}}{A(k_{y,n})}, \qquad C_{ij} = \frac{9}{\alpha\bar{\alpha}}\sum_{n=1}^{N}\frac{\bar{k}_{i,n}k_{j,n}}{A(\bar{k}_{i,n}, k_{j,n})} \qquad (7)$$

Reconstructed spin variables from 350000 reconstructed events. ($P = \sin 2\Theta$, $C_{ij} = \sin\Theta$ as input)



$\bar{p}p \rightarrow \bar{\Omega}^{+}\Omega^{-}$

- Differential cross section not known, isotropic used for simulations
- Cross section estimate $\sim$ 2 nb, branching ratio for $\Omega \rightarrow \Lambda K$ $\sim$ 68%
- Simulations at 12 GeV/c beam momentum
- Reconstruction efficiency $\sim$ 30% $\rightarrow \sim$ 80 reconstructable events/hour
- Acceptance for all production angles of $\bar{\Omega}^{+}$



Decay vertices of $\bar{\Omega}^{+}$ and $\bar{\Lambda}$.

Density Matrix of Ω

spin 3/2 particle $\rightarrow$ 15 polarisation parameters r instead of only the vector polarisation as for spin 1/2

Parity invariance $\rightarrow$ 8 are equal to zero

$$\rho = \frac{1}{4}\begin{bmatrix} 1+\sqrt{3}r_0^2 & i\frac{3}{\sqrt{5}}r^1_{-1}-\sqrt{3}r_1^2 & \sqrt{3}r_2^2-i\sqrt{3}r^3_{-2} & -i\sqrt{6}r^3_{-3} \\ -i\frac{3}{\sqrt{5}}r^1_{-1}-\sqrt{3}r_1^2 & 1-\sqrt{3}r_0^2 & i2\sqrt{\frac{3}{5}}r^1_{-1}+i3\sqrt{\frac{2}{5}}r^3_{-1} & \sqrt{3}r_2^2+i\sqrt{3}r^3_{-2} \\ \sqrt{3}r_2^2+i\sqrt{3}r^3_{-2} & -i2\sqrt{\frac{3}{5}}r^1_{-1}-i3\sqrt{\frac{2}{5}}r^3_{-1} & 1-\sqrt{3}r_0^2 & i\frac{3}{\sqrt{5}}r^1_{-1}+\sqrt{3}r_1^2 \\ i\sqrt{6}r^3_{-3} & \sqrt{3}r_2^2-i\sqrt{3}r^3_{-2} & -i\frac{3}{\sqrt{5}}r^1_{-1}+\sqrt{3}r_1^2 & 1+\sqrt{3}r_0^2 \end{bmatrix} \quad (8)$$

Degree of polarisation $= \sqrt{\sum r^2}$

Compare spin 1/2

$$\rho = \frac{1}{2}(\mathcal{I} + \bar{P}\cdot\bar{\sigma}) = \frac{1}{2}\begin{bmatrix} 1+P_z & P_x+iP_y \\ P_x-iP_y & 1-P_z \end{bmatrix} \rightarrow \frac{1}{2}\begin{bmatrix} 1 & iP_y \\ -iP_y & 1 \end{bmatrix} \quad (9)$$

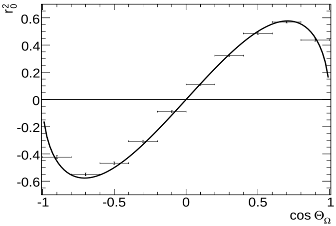
Polarisation of Ω

Angular distribution of $\Omega \to \Lambda \mathrm{K}$ ($\alpha \approx 0$)

$$I(\Theta,\phi) = \frac{1}{4\pi}\left(1 - \frac{\sqrt{3}}{2}(3\cos^2\Theta - 1)r_0^2 - \frac{3}{2}(\sin^2\Theta\cos 2\phi r_1^2 - \sin 2\Theta\cos\phi r_2^2)\right) \quad (10)$$

Angular distribution of $\Lambda \to \mathrm{p}\pi$

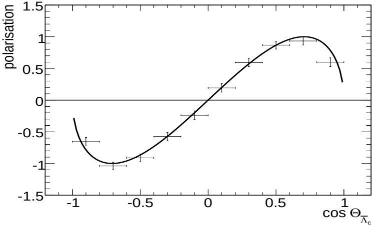
$$I(\Theta,\phi) = \frac{1}{4\pi}\left(1 + \alpha_\Lambda \sin\Theta(16\sqrt{15}r^1_{-1} + 15\sqrt{10}r^3_{-1})(\beta_1\cos\phi + \gamma_1\sin\phi)\right) \quad (11)$$



Reconstructed r_0^2 from 30000 events.
$r_0^2 = \frac{1}{\sqrt{3}}\sin 2\Theta$ as input

$\bar{p}p \rightarrow \bar{\Lambda}_c^{-}\Lambda_c^{+}$

- Treshold momentum 10.2 GeV/c, simulations at 12 GeV/c
- Differential cross section not known, isotropic used for simulations
- Acceptance for all production angles of $\bar{\Lambda}_c^{-}$
- Cross section $\sim 0.1\ \mu$b, branching ratio for $\Lambda_c \rightarrow p\pi \sim 1\%$
- Reconstruction efficiency $\sim 35\% \rightarrow \sim 25$ reconstructable events/day
- Background from Σ resonances, not investigated yet
- Large asymmetry parameter $\alpha = -0.91$, polarisation reasonably well reconstructed from a few thousand events (3500)



Other Charmed Hyperons

- Ξ_c^0 and Ω_c^0 in principle also accessible
- Treshold momentum 12.0 and 14.6 GeV/c
- Assumption: Cross sections reduced by factors $\alpha_s^2 = 1/25$ and $\alpha_s^4 = 1/625$
- Branching ratios not known
- Ξ_c^0 maybe possible, Ω_c^0 probably not

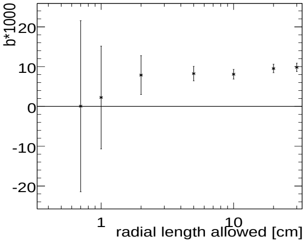
CP Violation

CP violation parmeters can be measured by detecting if the decay particles go up or down with respect to the hyperon production plane

$$b = \frac{N_{+-} - N_{-+}}{N} = \frac{\beta + \bar{\beta}}{4} \quad (12)$$

Experimental considerations:

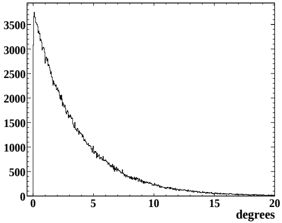
- Uncertainty $\propto P\sqrt{\frac{d\sigma}{d\Omega}}$, choose right angular interval
- Only use events where the hyperons decay in the vacuum of the beam pipe to avoid depolarisation in material
- Use events close to beam axis to make acceptance symmetric



Precession of the Polarisation Vector in the Magnetic Field

$$\frac{\mathrm{d}\bar{\Sigma}}{\mathrm{d}\tau} = -\left[\frac{1}{\gamma+1}\left(\bar{u} \times \frac{\mathrm{d}\bar{u}}{\mathrm{d}\tau}\right) + \frac{ge}{2m}\bar{B}_{(0)}\right] \times \bar{\Sigma} \qquad (13)$$

Uncharged hyperon: construct the coordinate system $\hat{B}_0$, $\hat{B}_0 \times \hat{\Sigma}$, $(\hat{B}_0 \times \hat{\Sigma}) \times \hat{B}_0$.



The precession angle of the Λ polarisation vector at 4 GeV/c.

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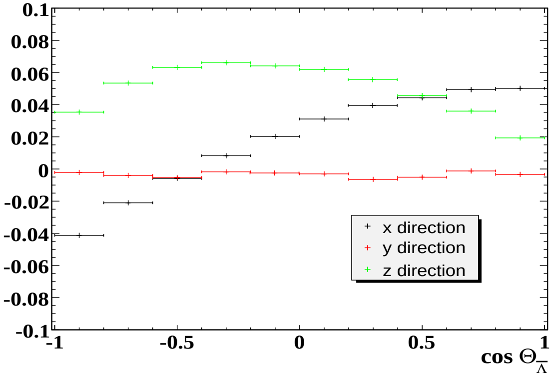
Effect on the Reconstruction of Polarisation



The difference in calculated polarisation using the Λ rest system at production and a rest system which has been rotated in the same way as the polarisation vector.

Spin correlations are not affected.

Conclusions

- High statistics for the lighter hyperons, low background in general
- Many observables for Ξ^- and Ω^- can be measured for the first time: differential cross section, polarisation, spin correlations, CP violation parameters, ...
- Charmed hyperons: Λ_c^+ is possible to study, maybe Ξ_c^0 and probably not Ω_c^0
- A small effect from the strong magnetic field affecting the hyperon spins, for the uncharged hyperons this can be corrected for