Spin observables in antihyperon-hyperon production with PANDA

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Outline

- Introduction
- Spin observables in $\bar{p}p \rightarrow \bar{Y}Y$
  - Spin $\frac{1}{2}$ hyperons
  - Spin $\frac{3}{2}$ hyperons
- Previous measurements of $\bar{p}p \rightarrow \bar{Y}Y$
- Prospects for PANDA

Introduction: Strangeness production

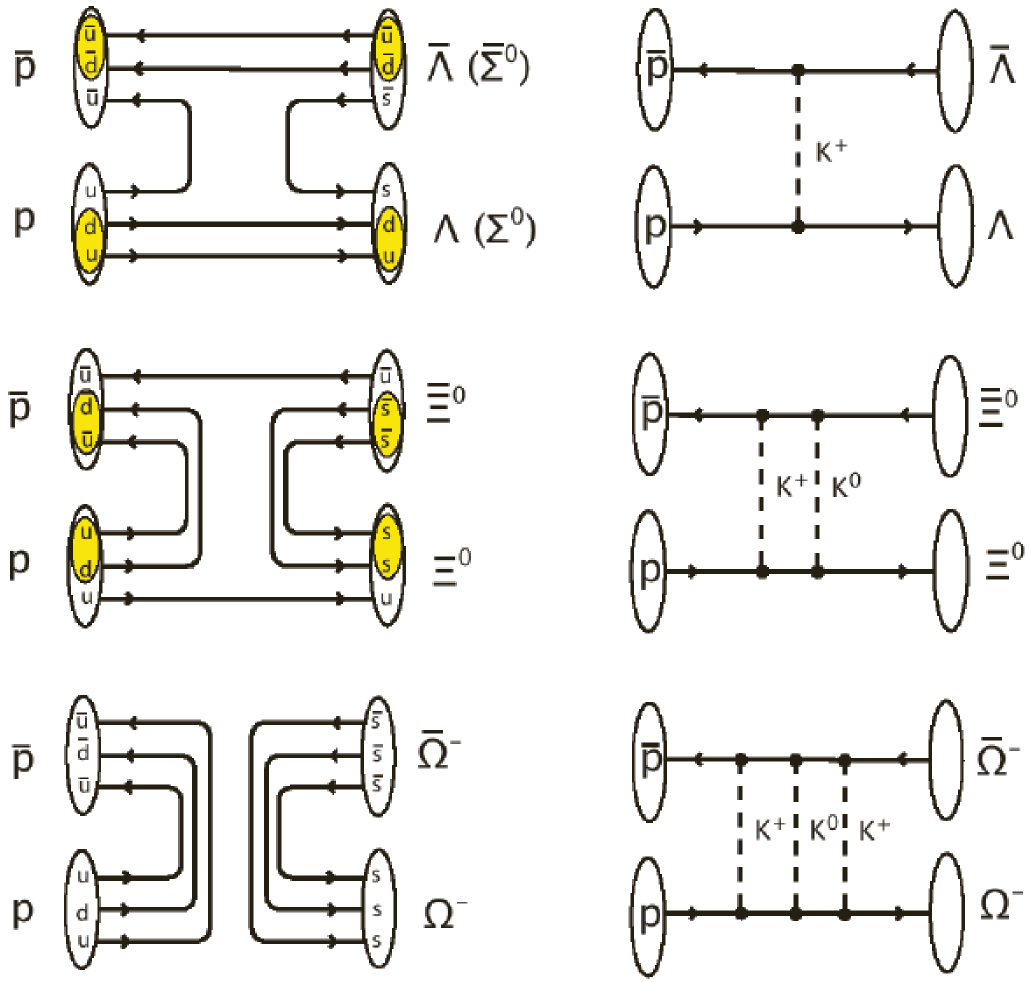
- Light quark (*u, d*) production:
  - Highly non-perturbative.
  - Relevant degrees of freedom are hadrons.

- Strangeness production
  - Scale: $m_s \approx 100$ MeV ~ $\Lambda_{\text{QCD}} \approx 200$ MeV.
  - Relevant degrees of freedom unclear.
  - **Strangeness production is a probe of QCD in the intermediate domain.**

- Charm production
  - $m_c \approx 1300$ MeV
  - Quark and gluon degrees of freedom more relevant.
  - **Comparing strange and charmed hyperon production probes QCD at two different energy scales.**

Introduction: Strange and charmed hyperons

Models based on the constituent quark-gluon picture* and on the hadron picture** or a combination of the two ***



Different models give different predictions of *e.g.*

- the polarisation of the outgoing hyperon
- the correlation of the spin of the hyperon-antihyperon

*PLB 179 (1986) 15; PLB 165 (1985) 187; NPA 468 (1985) 669;
** PR**C** 31(1985) 1857; PLB179 (1986) 15; PLB 214 (1988) 317;
*** PLB 696 (2011) 352.

Spin observables in $\bar{p}p \to \bar{Y}Y$

Spin observables are powerful tools in testing models.
The spin density matrix ρ of a particle with arbitrary spin *j* is given by

$$\rho = \frac{1}{2j+1}\mathscr{I} + \sum_{L=1}^{2j} \rho^L \qquad \text{with} \qquad \rho^L = \frac{2j}{2j+1}\sum_{M=-L}^{L} Q_M^L r_M^L$$

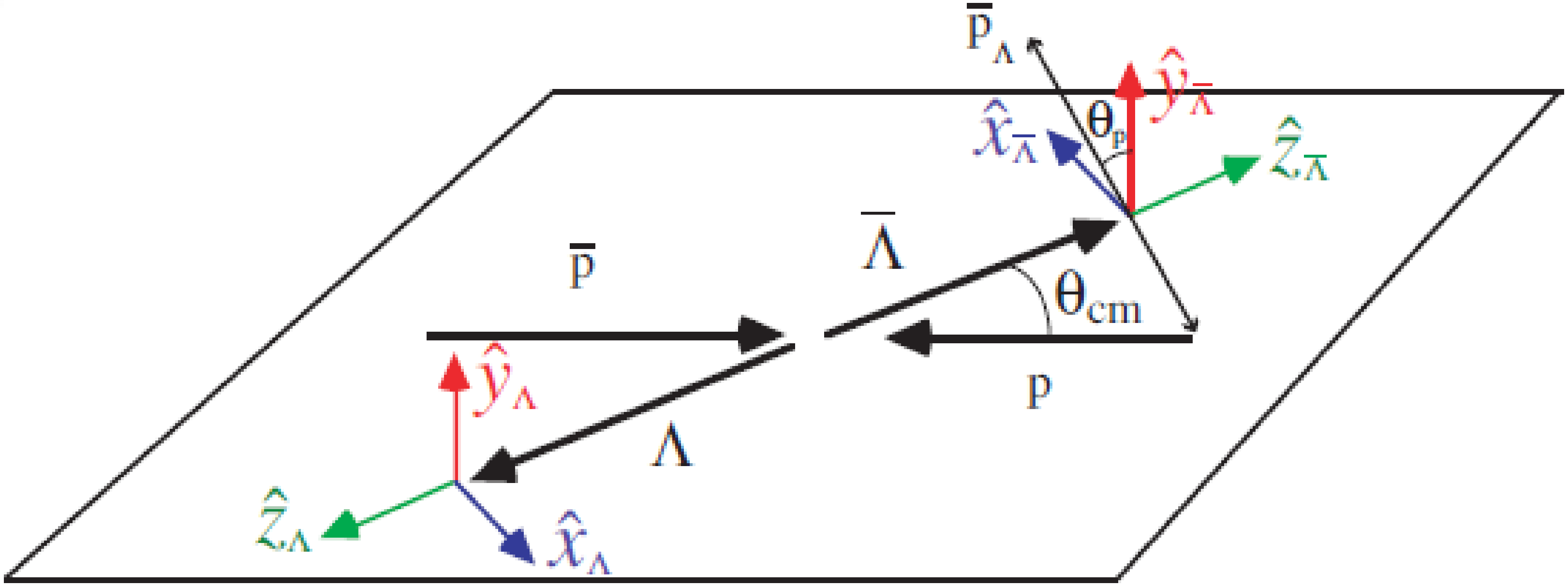
Unpolarised

Polarised

where Q_M^L are hermitian matrices and r_M^L polarisation parameters.

- Spin $\frac{1}{2}$: **3** polarisation parameters: $\boldsymbol{r_{-1}^{1}, r_{0}^{1}}$ and $\boldsymbol{r_{1}^{1}}$.
- Spin $\frac{3}{2}$: **15** polarisation parameters: $\boldsymbol{r_{-1}^{1}, r_{0}^{1}, r_{1}^{1}, r_{-2}^{2}, r_{-1}^{2}, r_{0}^{2}, r_{1}^{2}, r_{2}^{2}, r_{-3}^{3}, r_{-2}^{3}, r_{-1}^{3}, r_{0}^{3}, r_{1}^{3}, r_{2}^{3}}$ and $\boldsymbol{r_{3}^{3}}$.
- Degree of polarisation given by: $d(\rho) = \sqrt{\sum_{L=1}^{2j}\sum_{M=-L}^{L}(r_M^L)^2}$

Spin observables for spin $\frac{1}{2}$ hyperons



- The Q_M^L from $\rho^L = \frac{2j}{2j+1} \sum_{M=-L}^{L} Q_M^L r_M^L$ are the Pauli matrices.
- Polarisation parameters r_0^1, r_{-1}^1 and r_1^1 denoted P_x, P_y and P_z.
- Symmetry from parity conservation (strong production) requires $P_x = P_z = 0$

→ **polarisation normal of the production plane!**

Spin observables for spin $\frac{1}{2}$ hyperons

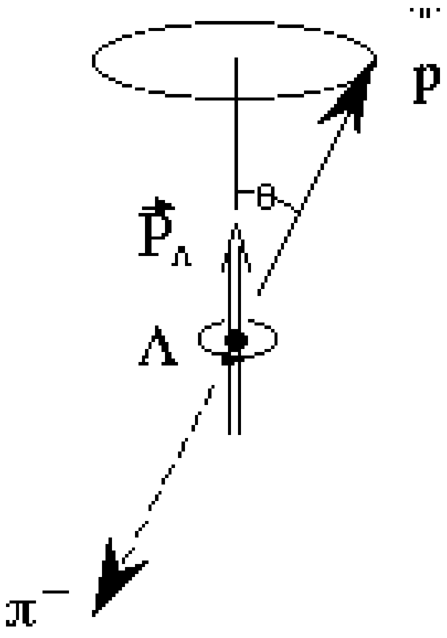
Hyperons decay weakly:
→ decay matrix has one **parity conserving** part and one **parity violating** part.

Parity violating:
→ daughter particles are according to the polarisation of the mother hyperon.

Angular distribution is given by

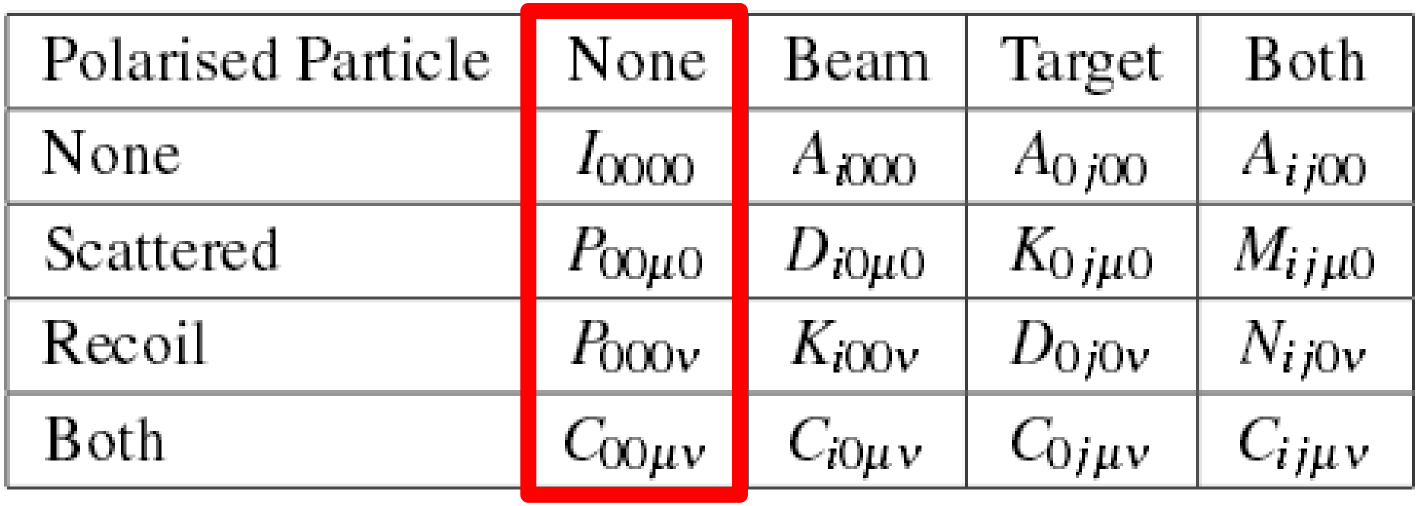
$$I(\cos\theta_p) = N(1+\alpha P_Y \cos\theta_p)$$

α: decay parameter related to the decay matrix.



→ The polarisation is accessible by the angular distribution of the decay products!

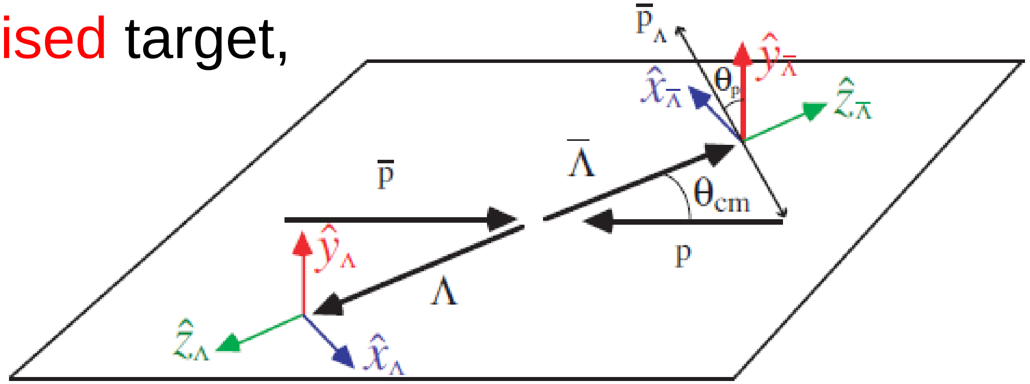
Spin observables for spin $\frac{1}{2}$ hyperons



Polarised Particle	None	Beam	Target	Both
None	I_{0000}	A_{i000}	A_{0j00}	A_{ij00}
Scattered	$P_{00\mu0}$	$D_{i0\mu0}$	$K_{0j\mu0}$	$M_{ij\mu0}$
Recoil	$P_{000\nu}$	$K_{i00\nu}$	$D_{0j0\nu}$	$N_{ij0\nu}$
Both	$C_{00\mu\nu}$	$C_{i0\mu\nu}$	$C_{0j\mu\nu}$	$C_{ij\mu\nu}$

In the $\bar{p}p \to \bar{Y}Y$ reaction there are 256 spin variables.

Unpolarised beam and unpolarised target, the polarisation P_{00y0} and P_{000y} and the spin correlations $C_{00\nu\mu}$ (ν,μ = x,y,z) are accessible.



Spin observables for spin $\frac{3}{2}$ hyperons

The $p\bar{p} \to \Omega\bar{\Omega}$ reaction:

15 polarisation parameters, **7** are accessible in Ω→Λ K with an unpolarised beam and target.

3 polarisation parameters $\boldsymbol{r_2^2, r_1^2, r_0^2}$ can be retrieved from the angular distribution of the Λ*, assuming α_Ω = 0 consistent with experiment.**

$$r_0^2 = \frac{15}{2\sqrt{3}}\left(\frac{1}{3} - \langle \cos^2\theta_\Lambda \rangle\right)$$

$$r_2^2 = \frac{8}{3}\ 1 - \langle \cos^2\theta_\Lambda \rangle - 2\langle \sin^2\theta_\Lambda \sin^2\phi_\Lambda \rangle$$

$$r_1^2 = 5\langle \cos\theta_\Lambda \sin\theta_\Lambda \cos\phi_\Lambda \rangle$$

**Erik Thomé, *Multistrange and Charmed Antihyperon-Hyperon Physics for PANDA Ph. D. Thesis, Uppsala University (2012)*
** PDG, J. Phys. G 33 (2006) 1.

Spin observables for spin $\frac{3}{2}$ hyperons

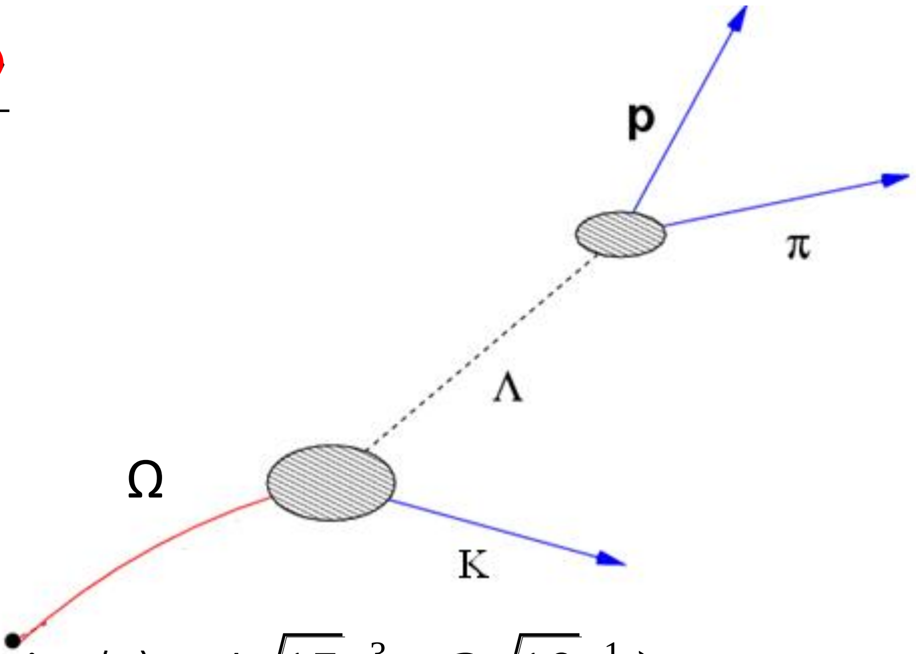
Four polarisation parameters can be determined from the joint angular distributions of the Λ and the proton *:

$$r^{1}_{-1} = -\frac{20\sqrt{10}\langle(3\cos\theta_\Lambda - 1)\sin\phi_p\rangle}{3\pi\alpha_\Lambda\gamma_\Omega}$$

$$r^{3}_{-1} = \frac{2\sqrt{5}\langle(15\cos\theta_\Lambda - 1)\sin\phi_p\rangle}{\sqrt{3}\pi\alpha_\Lambda\gamma_\Omega}$$

$$r^{3}_{-2} = -\frac{1024\langle\sin\phi_\Lambda\cos\phi_p\rangle}{3\pi^2\alpha_\Lambda\gamma_\Omega}$$

$$r^{3}_{-3} = -\frac{1}{5\sqrt{6}}\left(\frac{640}{\pi\alpha_\Lambda\gamma_\Omega}\langle\sin\phi_\Lambda\cos\phi_\Lambda\sin\phi_p\rangle + 4\sqrt{15}r^{3}_{-1} + 3\sqrt{10}r^{1}_{-1}\right)$$



α, β, γ decay parameters.
Assume: $\alpha_\Omega = 0$, $\beta_\Omega \approx 0$

*Erik Thomé, Ph. D. Thesis and later work

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

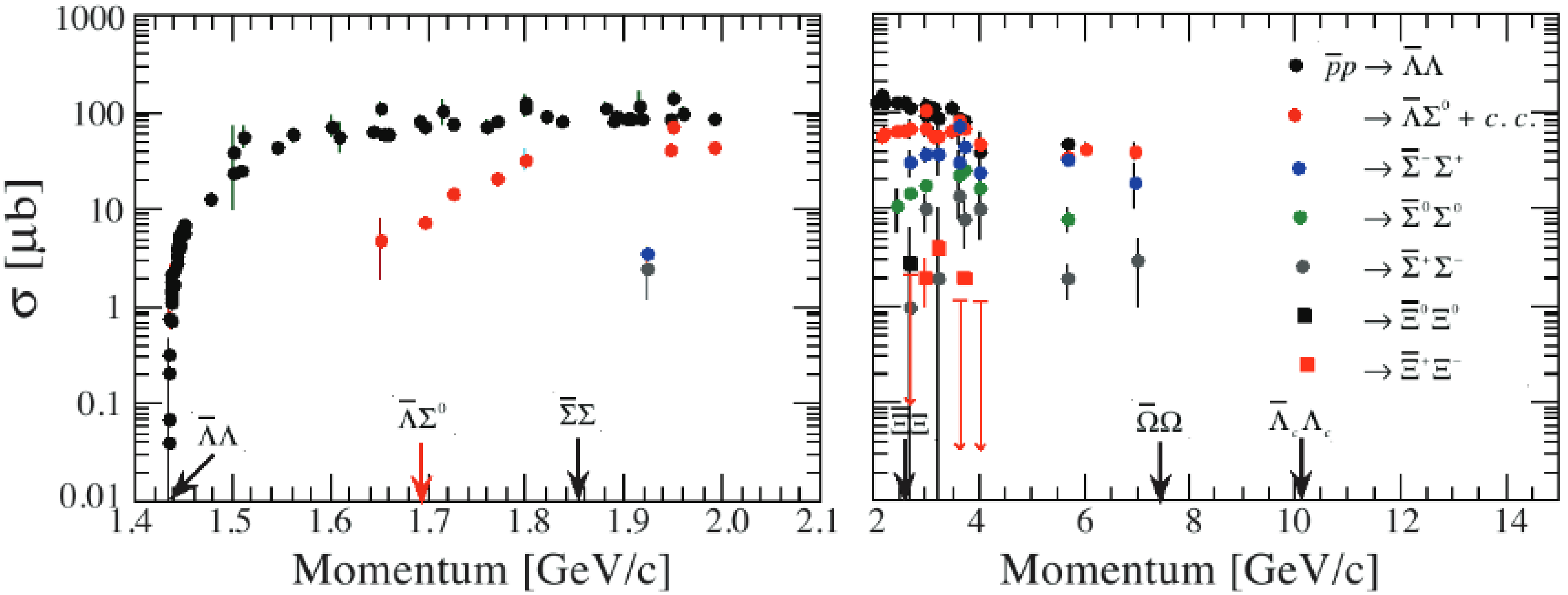
- Spin $\frac{1}{2}$ hyperons (Λ, Ξ, Λ_c) :
  - – Polarisation.
  - – Spin correlations and singlet fraction:

$$SF = \frac{1}{4}(1 + C_{xx} - C_{yy} + C_{zz})$$

- Spin $\frac{3}{2}$ hyperons into spin $\frac{1}{2}$ hyperons (Ω→ΛK):
  - – 7 polarisation parameters + degree of polarisation.

$$d(\rho) = \sqrt{\sum_{L=1}^{2j} \sum_{M=-L}^{L} (r_M^L)^2}$$

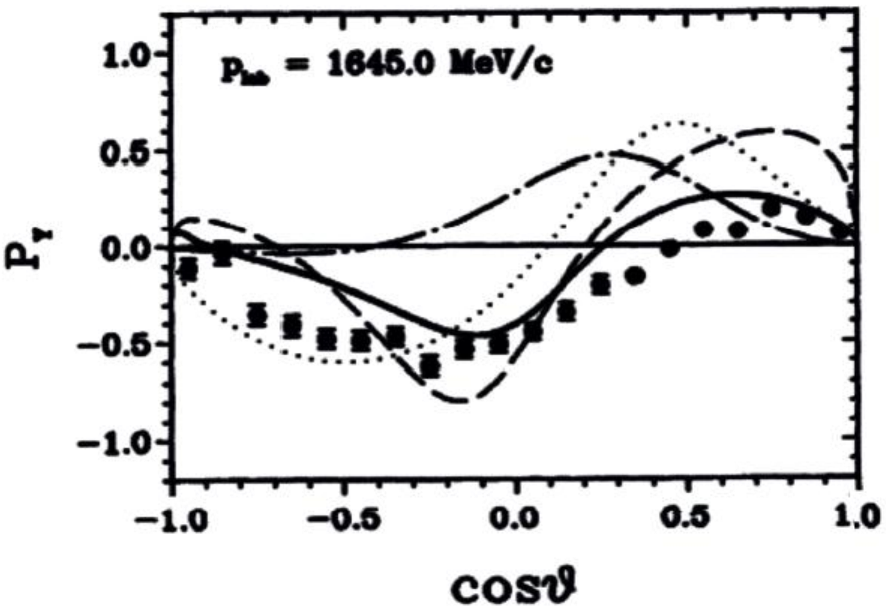
Previous measurements of $\bar{p}p \to \bar{Y}Y$

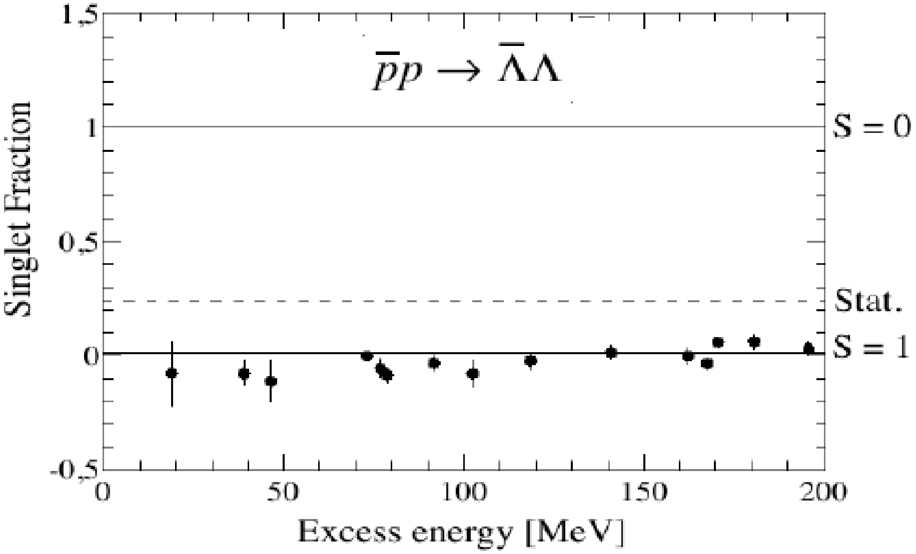


- A lot of data on $\bar{p}p \to \bar\Lambda\Lambda$ near threshold, mainly from PS185 at LEAR*.
- Very scarce data bank above 4 GeV.
- Only a few bubble chamber events on $\bar{p}p \to \bar\Xi\Xi$
- No data on $\bar{p}p \to \bar\Omega\Omega$ nor $\bar{p}p \to \bar\Lambda_c\Lambda_c$

* See *e.g.* T. Johansson, AIP Conf. Proc. Of LEAP 2003, p. 95.

Previous measurements of $\bar{p}p \rightarrow \bar{Y}Y$





- $\bar{\Lambda}\Lambda$ almost always produced in a spin triplet state*:

$$SF = \frac{1}{4}(1 + C_{xx} - C_{yy} + C_{zz})$$

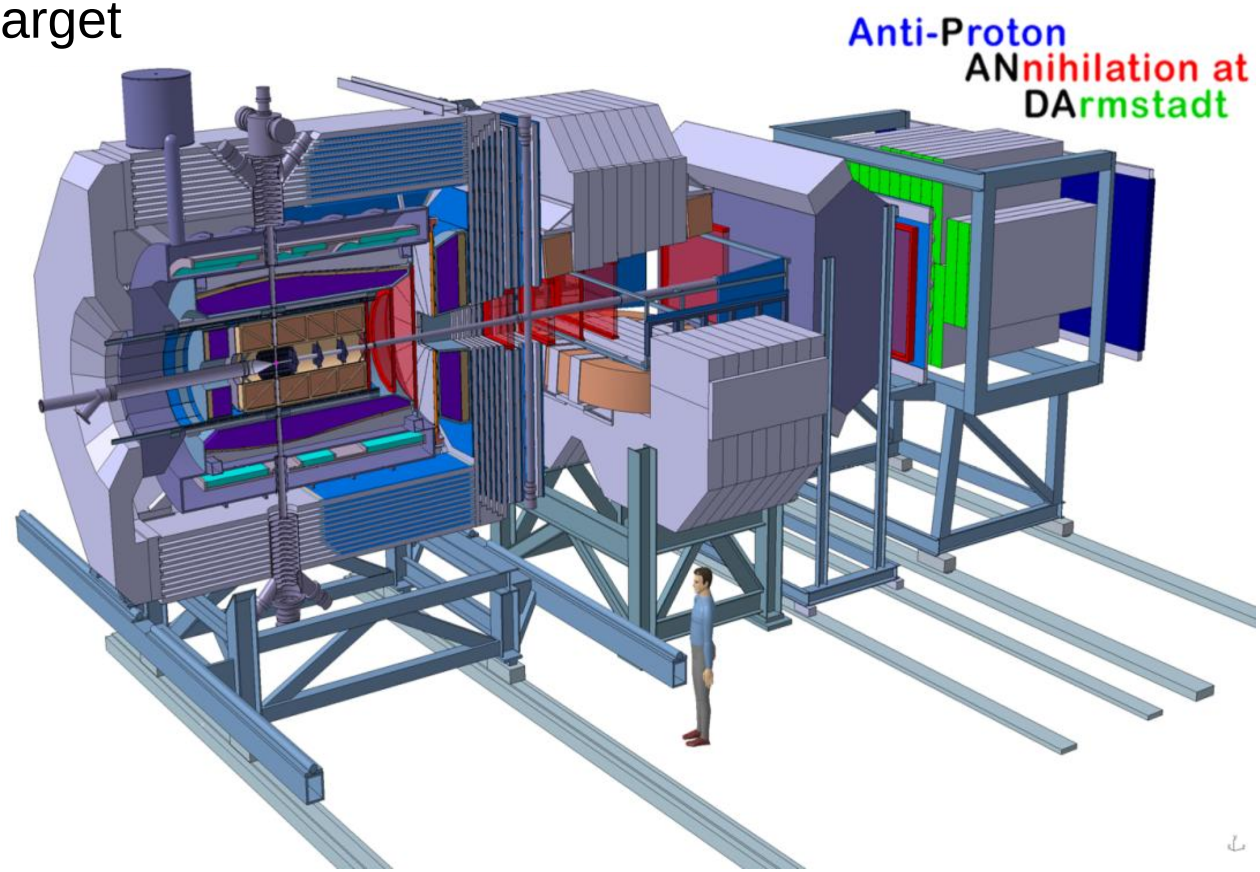
- Neither the quark-gluon picture (dotted) nor hadron exchange (solid and dashed) describe polarisation data perfectly. **

*PRC 54 (1996) 1877

** Phys. Rep. 368 (2002) 119.

Prospects for PANDA at FAIR

- Antiprotons from HESR with momenta 1.5 -15 GeV/c.
- Unpolarised beam and target
- Near 4π coverage
- Good momentum and vertex resolution.
- PID
- EM calorimetry



Prospects for PANDA at FAIR

$$\begin{array}{lcccccccc}
\bar{p}p \to & \bar{\Lambda}\Lambda, & \bar{\Sigma}^-\Sigma^+, & \bar{\Sigma}^0\Sigma^0, & \bar{\Sigma}^-\Sigma^+, & \bar{\Xi}^0\Xi^0, & \bar{\Xi}^+\Xi^-, & \bar{\Omega}^+\Omega^-, & \bar{\Lambda}_c^-\Lambda_c^+ \\
 & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\
 & p\pi^- & p\pi^0 & \Lambda\gamma & n\pi & \Lambda\pi^0 & \Lambda\pi & \Lambda K & \Lambda\pi \\
\textbf{BR:} & 64\% & 52\% & \approx 100\% & \approx 100\% & \approx 100\% & \approx 100\% & 68\% & \approx 1\%
\end{array}$$

- Simulation studies using a simplified MC framework (smearing and acceptance included)
- Quoted rates are valid for high luminosity mode of the HESR ($2*10^{32}$ cm^{-2} s^{-1}).
- Cross sections of $\bar{p}p \to \bar{\Lambda}\Lambda$ and $\bar{p}p \to \bar{\Lambda}\Sigma^o$ known near threshold, the $\bar{p}p \to \bar{\Xi}^+\Xi^-$ measured with large uncertainty.
- Only theoretical predictions of $\bar{p}p \to \bar{\Omega}^+\Omega^-$ and $\bar{p}p \to \bar{\Lambda}_c^-\Lambda_c^+$

Prospects for PANDA at FAIR

Momentum (GeV/c)	**Reaction**	**σ (μb)**	**Efficiency (%)**	**Rate** (high lumi. mode)
1.64	$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$	64	10	580 s^{-1}
4	$\bar{p}p \rightarrow \bar{\Lambda}\Sigma^o$	~40	30	600 s^{-1}
4	$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	~2	20	30 s^{-1}
12	$\bar{p}p \rightarrow \bar{\Omega}^+\Omega^-$	~0.002	30	~80 h^{-1}
12	$\bar{p}p \rightarrow \bar{\Lambda}_c^-\Lambda_c^+$	~0.1	35	~25 day^{-1}

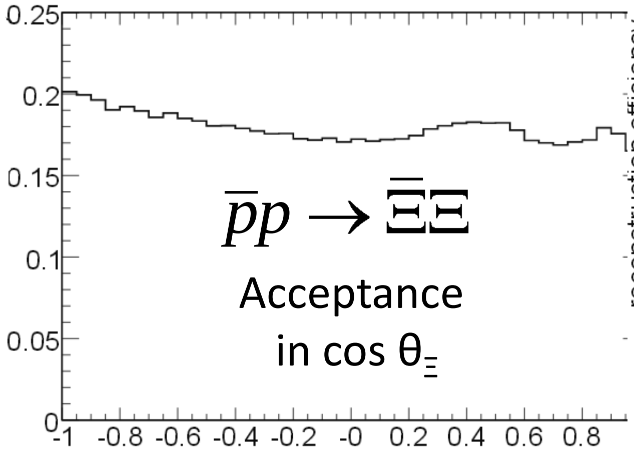
- High event rates for Λ and Σ *.
- Low background for Λ and Σ *.
- Even with conservative cross section estimates, Ω and Λ_c channels are feasible. **
- New efficiencies obtained with a more sophisticated MC framework are underway.

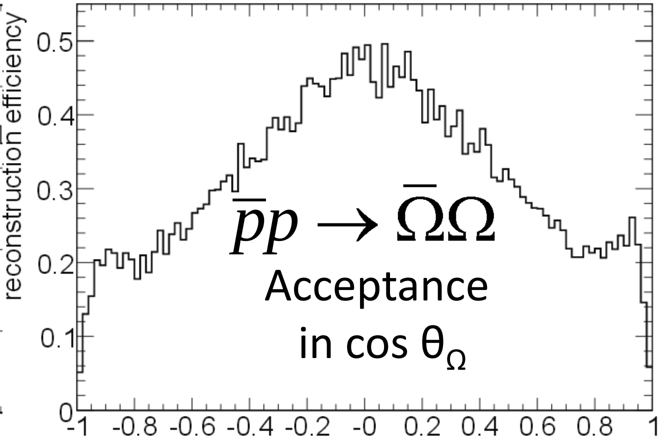
*Sophie Grape, Ph. D. Thesis, Uppsala University 2009

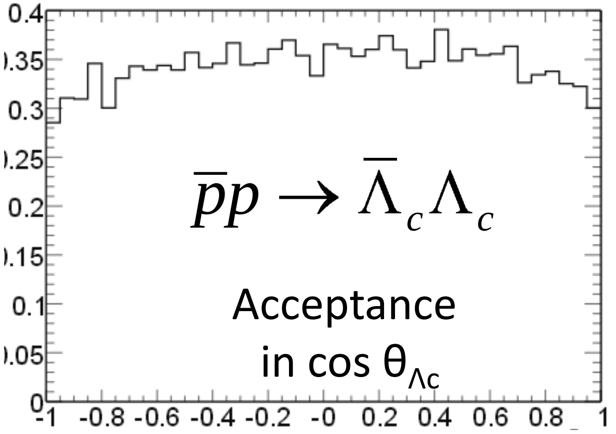
** Erik Thomé, Ph. D. Thesis, Uppsala University 2012

Prospects for PANDA at FAIR

Good angular acceptance also for heavy hyperons → important for polarisarion studies!







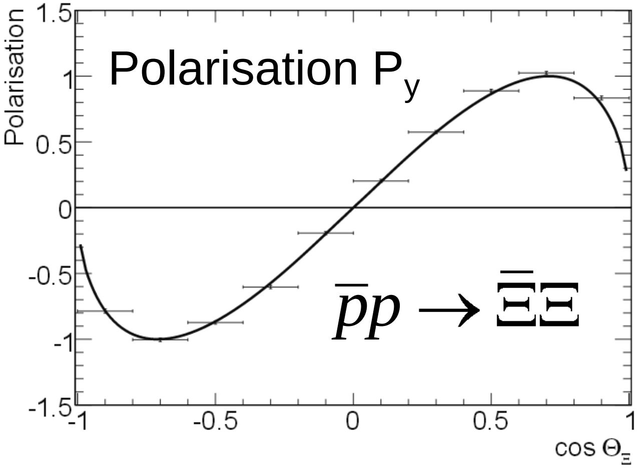
Results by Erik Thomé, Ph. D. Thesis, Uppsala University (2012).

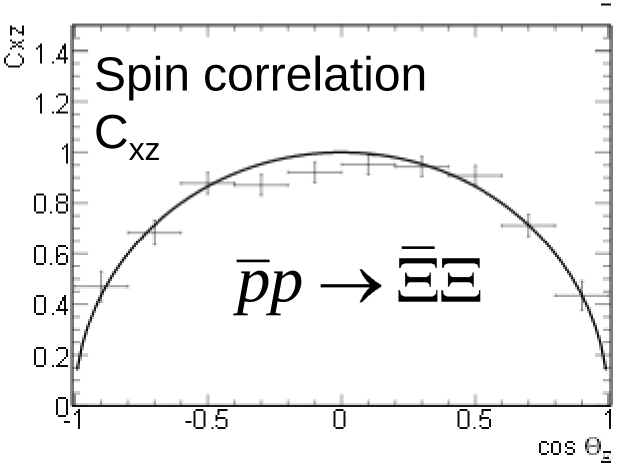
Prospects for PANDA at FAIR

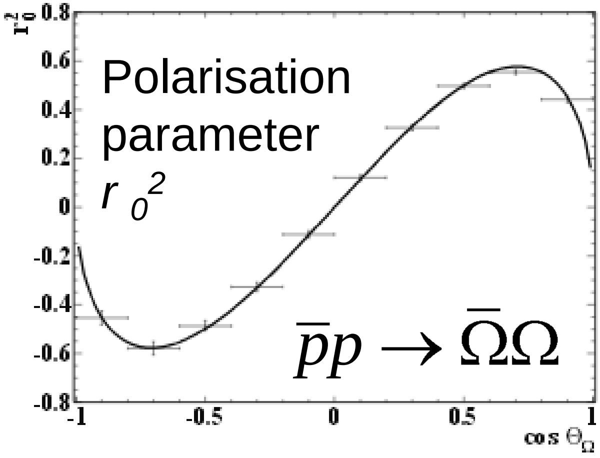
- Parametrisation of spin variables using weights:

$$P_{\Xi,y} = \sin 2\theta_{\Xi} \qquad C_{\Xi,xz} = \sin\theta_{\Xi} \qquad r_0^2 = \sin 2\theta_{\Omega}/\sqrt{3}$$

- Simplifies MC framework including acceptance and detector resolution.







- The polarisation and spin correlations for Ξ and polarisation parameters of the Ω can be well reconstructed with PANDA.

Results by Erik Thomé, Ph. D. Thesis, Uppsala University (2012).

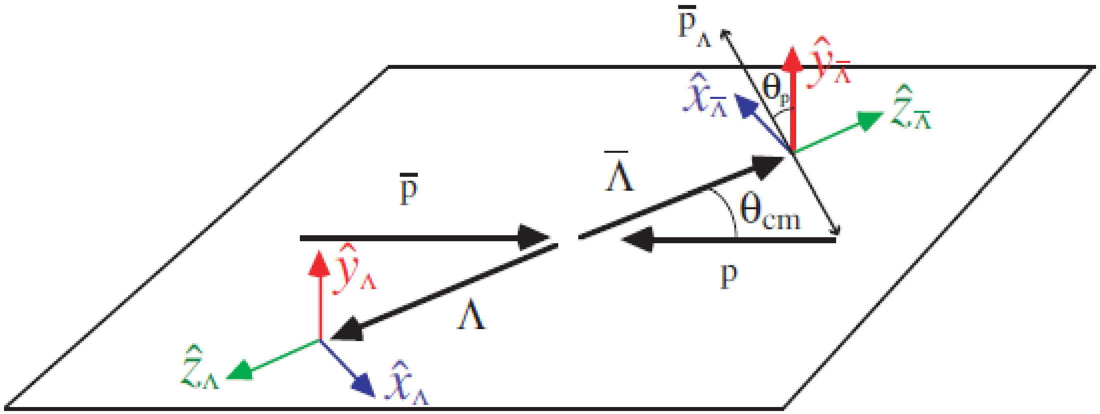
Summary and Outlook

- Hyperon production is an excellent probe of the Strong Interaction in the confinement domain.
- Polarisation parameters of $p\bar{p} \rightarrow \Omega\bar{\Omega}$ have been derived.
- Simulation studies show excellent prospects for antihyperon-hyperon channels with PANDA:
  - High event rate - enables precise CP tests
  - Low background
  - Good detection efficiency over the full phase space
  - Multistrange and charmed hyperons can be studied in $\bar{p}p \rightarrow \bar{Y}Y$ for the first time.

Thanks to: Sophie Grape,
Tord Johansson and Erik Thomé

Backup

Spin observables for spin $\frac{1}{2}$ hyperons



- The Q_M^L are the Pauli matrices.
- Polarisation parameters
  r_0^1, r_{-1}^1 and r_1^1
  are P_x, P_y and P_z.

The spin density matrix of one spin $\frac{1}{2}$ particle is given by:

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

Symmetry from parity conservation (strong production) requires $P_x = P_z = 0$ →

$$\rho(1/2) = \frac{1}{2}\begin{bmatrix} 1 & iP_y \\ -iP_y & 1 \end{bmatrix}$$

Polarisation normal to the production plane!

Spin observables for spin $\frac{1}{2}$ hyperons

Parity violating decay → direction of the decay products depends on the polarisation of the mother hyperon.

Angular distribution of the final state is given by *I(θ,φ) = Tr(TρT*)*

Decay matrix *T* consists of

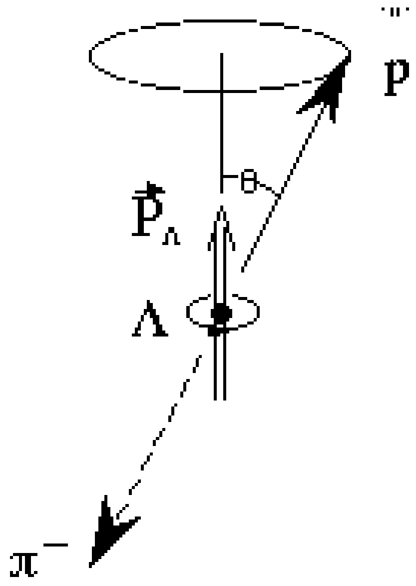
T_s (s-wave, parity conserving) and $T_{p.}$ (p-wave, parity violating)

Define:
$$\alpha = 2\mathrm{Re}(T_s^* T_p)$$
$$\beta = 2\mathrm{Im}(T_s^* T_p)$$
$$\gamma = |T_s|^2 - |T_p|^2$$

Then $\alpha^2 + \beta^2 + \gamma^2 = | T_s |^2 + | T_p |^2 = 1$

and the decay angular distribution becomes

$I(\cos\theta_p) = N(1+\alpha P_Y \cos\theta_p)$



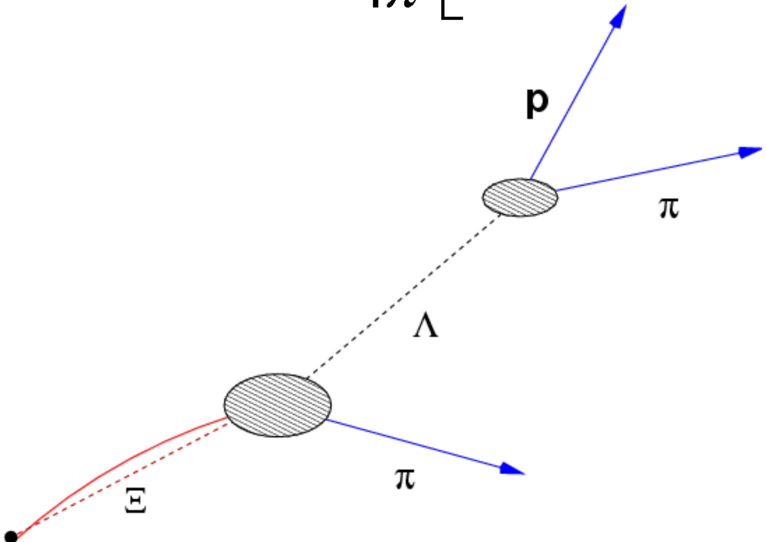
Spin observables for spin $\frac{1}{2}$ hyperons

If the decay product of the hyperon is a hyperon, *e.g.* $\Xi \to \Lambda K$, then also β and γ can be obtained from the decay protons of the Λ.

Redefine reference system such that:
- Spin of Ξ along ž
- p_Λ in xz-plane ($p_y = 0$)

Then the proton angular distribution becomes:

$$I(\theta_p,\phi_p) = \frac{1}{4\pi}\left[1+\alpha_\Xi\alpha_\Lambda\cos\theta_p + \frac{\pi}{4}\alpha_\Lambda P\sin\theta_p(\beta_\Xi\sin\phi_p - \gamma_\Xi\cos\phi_p)\right]$$

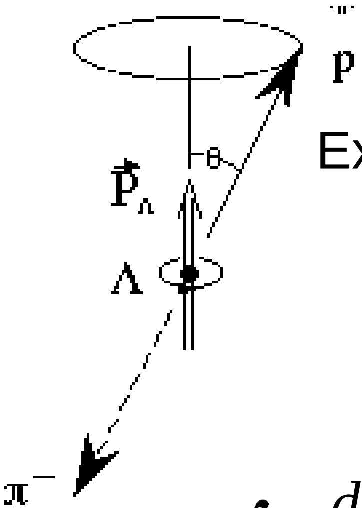


Spin observables for spin $\frac{1}{2}$ hyperons

Method of Moments

The expectation value or the moment of a function *g(x)* can be written

$$\langle g(x)\rangle = \int_{\Omega} g(x)\, f(x\,|\,\theta)\, dx$$



where *f(x|θ)* is a probability density function.

Example: Λ hyperon with polarisation P_n decaying into $p\,\pi^-$. Then

$$f(\theta_p\,|\,P_n) = \frac{dN}{d\cos\theta_p} \propto 1 + \alpha_\Lambda P_n \cos\theta_p$$

and thus

$$\langle\cos\theta_p\rangle = \int \frac{dN}{d\cos\theta_p}\cos\theta_p d\cos\theta_p = \int (1+\alpha_\Lambda P_n\cos\theta_p)\cos\theta_p d\cos\theta_p = \frac{\alpha_\Lambda P_n}{3}$$

which means that the polarisation can be expressed as $P_n = \frac{3}{\alpha_\Lambda}\langle\cos\theta_p\rangle$

CP violation in hyperon systems

- CP violation of baryon system has never been observed.
- The $\bar{p}p \to \bar{Y}Y$ process suitable for CP measurements (clean, no mixing)
- According to experiment, $\alpha = \bar{\alpha}$ for Λ.
- CP violation parameters:

$$A = \frac{\Gamma\alpha + \bar{\Gamma}\bar{\alpha}}{\Gamma\alpha - \bar{\Gamma}\bar{\alpha}} \simeq \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}$$

Consistent with 0 for Λ and Ξ, but to confirm or rule out or confirm χPT, Supersymmetry , more precise measurements are needed.

$$B = \frac{\Gamma\beta + \bar{\Gamma}\bar{\beta}}{\Gamma\beta - \bar{\Gamma}\bar{\beta}} \simeq \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}}$$

Accessible for Ξ since the polarisation of the decay products can be measured.

No previous measurement.

$$B' = \frac{\Gamma\beta + \bar{\Gamma}\bar{\beta}}{\Gamma\alpha - \bar{\Gamma}\bar{\alpha}} \simeq \frac{\beta + \bar{\beta}}{\alpha - \bar{\alpha}}$$

Spin observables for spin $\frac{3}{2}$ hyperons

This case much more complicated.

Erik Thomé has derived the observables in his Ph. D. thesis.*

The spin density matrix is given by

$$\rho(3/2) =$$

$$= \frac{1}{4}\begin{bmatrix} 1+\sqrt{3}r^2_0 & i\frac{3}{\sqrt{5}}r^1_{-1}-\sqrt{3}r^2_1 & \sqrt{3}r^2_2-i\sqrt{3}r^3_{-2} & -i\sqrt{6}r^3_{-3} \\ -i\frac{3}{\sqrt{5}}r^1_{-1}-\sqrt{3}r^2_1 & 1-\sqrt{3}r^2_0 & i2\sqrt{\frac{3}{5}}r^1_{-1}+i3\sqrt{\frac{2}{5}}r^3_{-1} & \sqrt{3}r^2_2+i\sqrt{3}r^3_{-2} \\ \sqrt{3}r^2_2+i\sqrt{3}r^3_{-2} & -i2\sqrt{\frac{3}{5}}r^1_{-1}-i3\sqrt{\frac{2}{5}}r^3_{-1} & 1-\sqrt{3}r^2_0 & i\frac{3}{\sqrt{5}}r^1_{-1}+\sqrt{3}r^2_1 \\ i\sqrt{6}r^3_{-3} & \sqrt{3}r^2_2-i\sqrt{3}r^3_{-2} & -i\frac{3}{\sqrt{5}}r^1_{-1}+\sqrt{3}r^2_1 & 1+\sqrt{3}r^2_0 \end{bmatrix}$$

*Erik Thomé, *Multistrange and Charmed Antihyperon-Hyperon Physics for PANDA*
Ph. D. Thesis, Uppsala University (2012)

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Joint Angular Distribution of the Two Decays

Spin $\frac{3}{2}$ hyperons

Assumptions : $\alpha_\Omega = 0$, $\beta_\Omega \approx 0$

CP-invariance: $\beta_\Omega \approx 0$, $\gamma_\Omega \approx 1$
can be tested by

$$\frac{\beta_\Omega}{\gamma_\Omega} = \frac{\langle \cos\theta_p \sin\phi_p \rangle}{\langle \sin\theta_p \sin\phi_p \rangle}$$

$$\langle (3\cos\Theta_\Lambda - 1)\sin\phi_\mathrm{p} \rangle =$$

$$= \int_0^\pi \int_0^{2\pi} \int_0^\pi \int_0^{2\pi} I(\Theta_\Lambda, \phi_\Lambda, \Theta_\mathrm{p}, \phi_\mathrm{p}) \times$$

$$\sin\Theta_\Lambda (3\cos\Theta_\Lambda - 1)\sin\Theta_\mathrm{p} \sin\phi_\mathrm{p} d\Theta_\Lambda d\phi_\Lambda d\Theta_\mathrm{p} d\phi_\mathrm{p} =$$

$$= -\frac{3\pi\alpha_\Lambda\gamma_\Omega r^1_{-1}}{20\sqrt{10}}$$

$$\langle (15\cos\Theta_\Lambda - 1)\sin\phi_\mathrm{p} \rangle =$$

$$= \int_0^\pi \int_0^{2\pi} \int_0^\pi \int_0^{2\pi} I(\Theta_\Lambda, \phi_\Lambda, \Theta_\mathrm{p}, \phi_\mathrm{p}) \times$$

$$\sin\Theta_\Lambda (15\cos\Theta_\Lambda - 1)\sin\Theta_\mathrm{p} \sin\phi_\mathrm{p} d\Theta_\Lambda d\phi_\Lambda d\Theta_\mathrm{p} d\phi_\mathrm{p} =$$

$$= \frac{\sqrt{3}\pi\alpha_\Lambda\gamma_\Omega r^3_{-1}}{2\sqrt{5}}$$

$$\langle \sin\phi_\Lambda \cos\phi_\mathrm{p} \rangle =$$

$$= \int_0^\pi \int_0^{2\pi} \int_0^\pi \int_0^{2\pi} I(\Theta_\Lambda, \phi_\Lambda, \Theta_\mathrm{p}, \phi_\mathrm{p}) \times$$

$$\sin\Theta_\Lambda \sin\Theta_\mathrm{p} \sin\phi_\Lambda \cos\phi_\mathrm{p} d\Theta_\Lambda d\phi_\Lambda d\Theta_\mathrm{p} d\phi_\mathrm{p} =$$

$$= -\frac{3\pi^2\alpha_\Lambda\gamma_\Omega r^3_{-2}}{1024}$$

$$\langle \sin\phi_\Lambda \cos\phi_\Lambda \sin\phi_\mathrm{p} \rangle =$$

$$= \int_0^\pi \int_0^{2\pi} \int_0^\pi \int_0^{2\pi} I(\Theta_\Lambda, \phi_\Lambda, \Theta_\mathrm{p}, \phi_\mathrm{p}) \times$$

$$\sin\Theta_\Lambda \sin\Theta_\mathrm{p} \sin\phi_\Lambda \cos\phi_\Lambda \sin\phi_\mathrm{p} d\Theta_\Lambda d\phi_\Lambda d\Theta_\mathrm{p} d\phi_\mathrm{p} =$$

$$= -\frac{\pi\alpha_\Lambda\gamma_\Omega}{640}\left(5\sqrt{6}r^3_{-3} - 4\sqrt{15}r^3_{-1} - 3\sqrt{10}r^1_{-1}\right)$$