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Baryon Physics with PANDA

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on behalf of the Hyperon Physics Working Group, PANDA

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Uppsala, Sweden

Outline

- Introduction
- Part I: Baryon Spectroscopy
  - Baryons and the quark model
  - Light baryons
  - Strange hyperons
  - Prospects for PANDA
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  - Spin $\frac{1}{2}$ hyperons
  - Spin $\frac{3}{2}$ hyperons
  - CP violation
  - Previous measurements of $\bar{p}p \to \bar{Y}Y$
  - Prospects for PANDA

Introduction

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

- Systems with strangeness
  - Scale: $m_s \approx 100$ MeV ~ $\Lambda_{QCD} \approx 200$ MeV.
  - Relevant degrees of freedom unclear.
  - **Probes QCD in the intermediate domain.**

- Systems with charm
  - Scale: $m_c \approx 1300$ MeV.
  - Quark and gluon degrees of freedom more relevant.
  - **By comparing strange and charmed hyperons we learn about QCD at two different energy scales.**

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Why baryons?

Baryon Spectroscopy

- New baryon states?
- Properties of already known states.
- Symmetries in the observed spectrum?

Why baryons?

Baryon Spectroscopy

- New baryon states?
- Properties of already known states.
- Symmetries in the observed spectrum?

Spin Observables in baryon production / decay

- Reaction mechanism at different energy scales.
- The role of spin in the production of heavy quarks.
- CP violation

Part I: Baryon Spectroscopy

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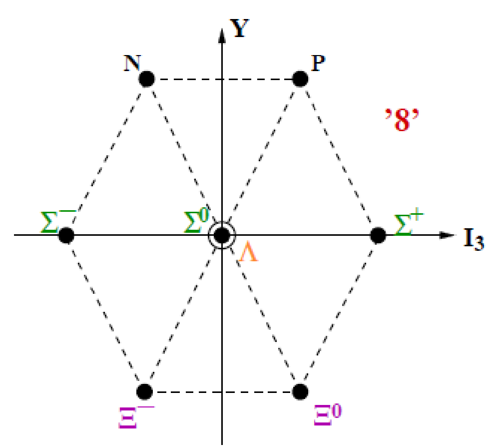
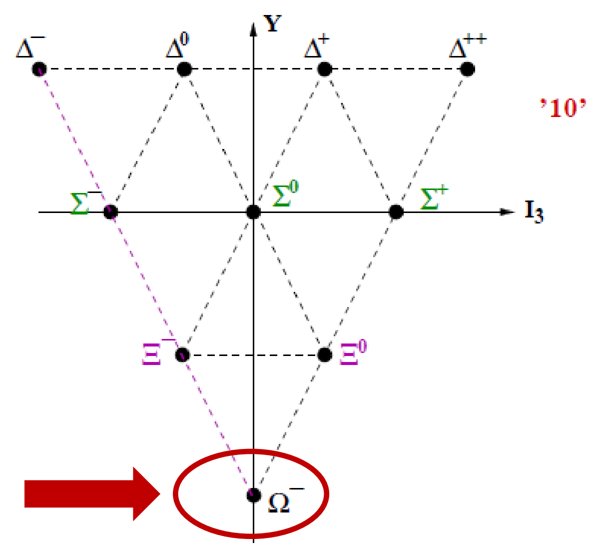
Baryons and the quark model

- 1950’s and 1960’s: a multitude of new particles discovered → obvious they could not all be elementary
- 1961: Eight-fold way, organising mesons and spin $\frac{1}{2}$ baryons into octets and spin $\frac{3}{2}$ into a decuplet as a consequence of SU(3) flavour symmetry
- 1962: Discovery of the predicted Ω^- demonstrates the success of the Eightfold way.
- 1964: Quark model (Gell-Mann and Zweig)





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Baryons and the quark model

- The simple (constituent) quark model* was successful in classifying hadrons and describing some features of the hadron spectra.

- Unable to explain *e.g.*
  - Spin of the nucleon
  - Flavour asymmetry of the nucleon sea
  - Level ordering in light and strange baryon spectra**

*PR 125 (1962) 1067
**PRD 58 (1998) 094030

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The challenging task of baryon spectroscopy

*PR 125 (1962) 1067

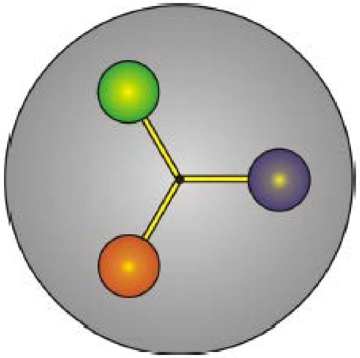
**PRD 58 (1998) 094030

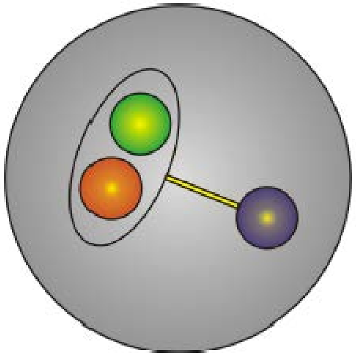
Light baryon spectroscopy

A lot has been lerned from the great progress in light baryon spectroscopy (pion beams, photoproduction).

Open questions regarding the excited light baryon spectrum:*

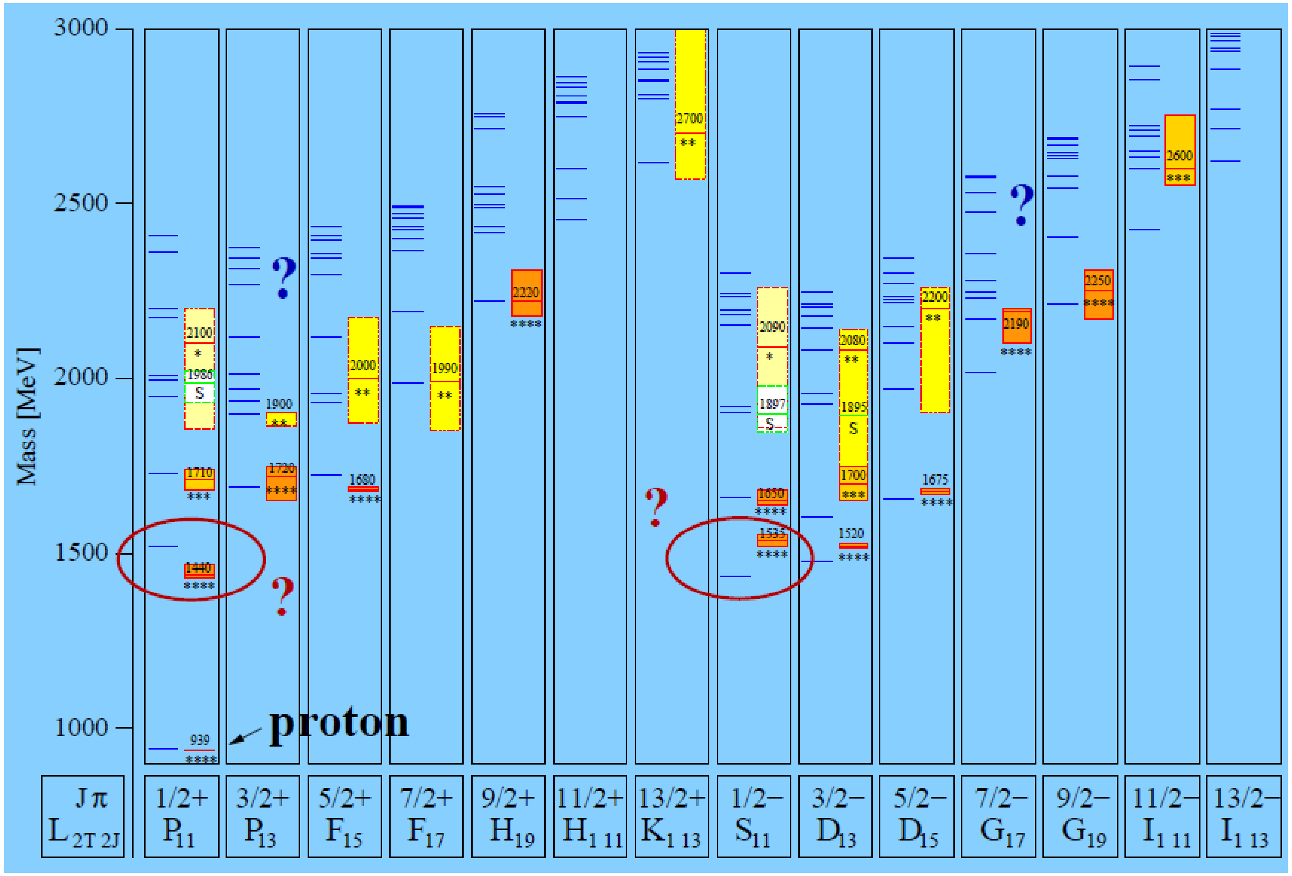
- Relevant degrees of freedom?
- Missing states
- High mass parity doublets
- Order of low mass positive and negative parity states (Roper and $S_{11}(1535)$)





*EPJA 48 (2012) 127

Light baryon spectroscopy

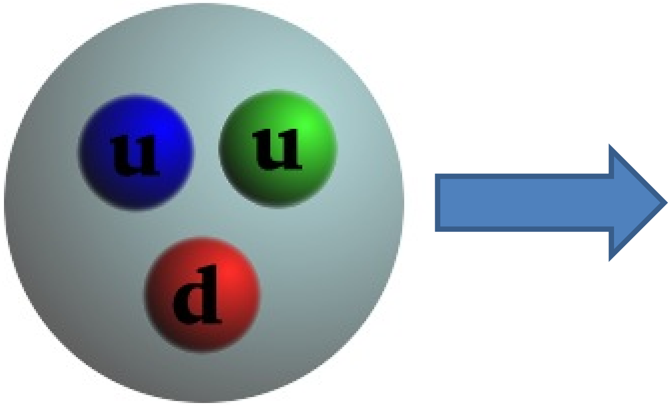


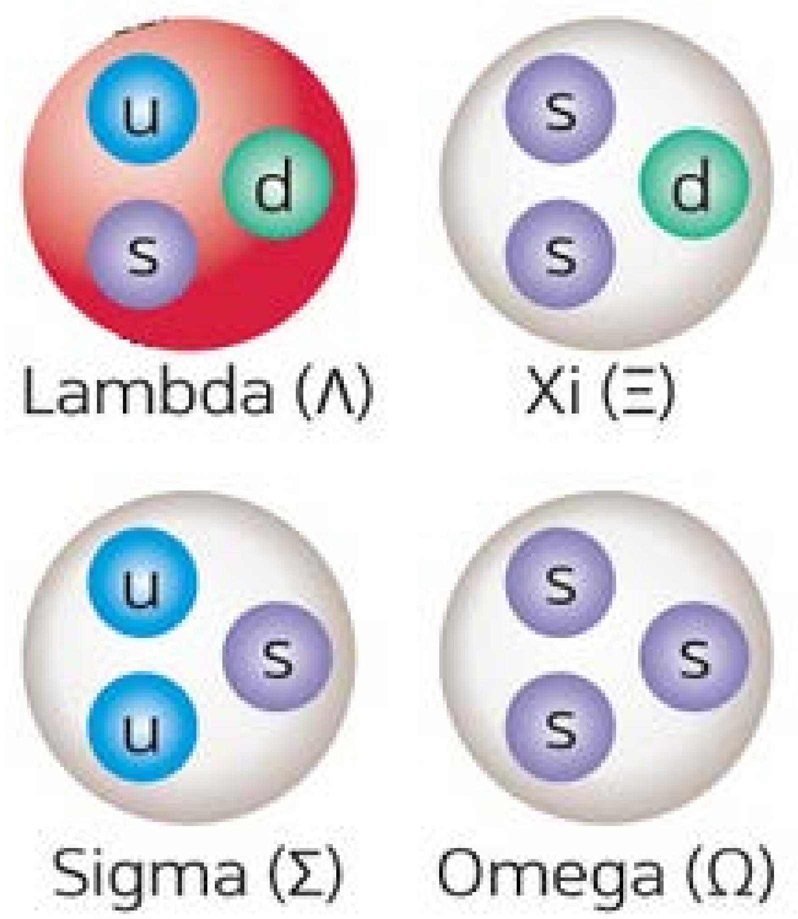
Missing states: # of observed states < # of predicted states

- Because there are no such states
- or because they do not couple to *Nπ* final states?

Strange (and charmed) hyperons

What happens if we replace one of the light quarks in the proton with one - or many - heavier quark(s)?





Strange hyperons

Excited strange hyperon spectrum:

- SU(6) x O(3) classification (spin, flavour and *L*)
- Very scarce data bank on double and triple strangeness
- Octet Ξ partners of *N** ?
  - Only a few found
- Decuplet Ξ and Ω partners of Δ*?
  - Nothing found

J^P	(D, L^P_N)	S	Octet members				Singlets
$1/2^+$	$(56,0_0^+)$	1/2	N(939)	Λ(1116)	Σ(1193)	Ξ(1318)	
$1/2^+$	$(56,0_2^+)$	1/2	N(1440)	Λ(1600)	Σ(1660)	Ξ(?)	
$1/2^-$	$(70,1_1^-)$	1/2	N(1535)	Λ(1670)	Σ(1620)	Ξ(?)	Λ(1405)
$3/2^-$	$(70,1_1^-)$	1/2	N(1520)	Λ(1690)	Σ(1670)	Ξ(1820)	Λ(1520)
$1/2^-$	$(70,1_1^-)$	3/2	N(1650)	Λ(1800)	Σ(1750)	Ξ(?)	
$3/2^-$	$(70,1_1^-)$	3/2	N(1700)	Λ(?)	Σ(?)	Ξ(?)	
$5/2^-$	$(70,1_1^-)$	3/2	N(1675)	Λ(1830)	Σ(1775)	Ξ(?)	
$1/2^+$	$(70,0_2^+)$	1/2	N(1710)	Λ(1810)	Σ(1880)	Ξ(?)	Λ(?)
$3/2^+$	$(56,2_2^+)$	1/2	N(1720)	Λ(1890)	Σ(?)	Ξ(?)	
$5/2^+$	$(56,2_2^+)$	1/2	N(1680)	Λ(1820)	Σ(1915)	Ξ(2030)	
$7/2^-$	$(70,3_3^-)$	1/2	N(2190)	Λ(?)	Σ(?)	Ξ(?)	Λ(2100)
$9/2^-$	$(70,3_3^-)$	3/2	N(2250)	Λ(?)	Σ(?)	Ξ(?)	
$9/2^+$	$(56,4_4^+)$	1/2	N(2220)	Λ(2350)	Σ(?)	Ξ(?)	
			Decuplet members				
$3/2^+$	$(56,0_0^+)$	3/2	Δ(1232)	Σ(1385)	Ξ(1530)	Ω(1672)	
$3/2^+$	$(56,0_2^+)$	3/2	Δ(1600)	Σ(?)	Ξ(?)	Ω(?)	
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$5/2^+$	$(56,2_2^+)$	3/2	Δ(1905)	Σ(?)	Ξ(?)	Ω(?)	
$7/2^+$	$(56,2_2^+)$	3/2	Δ(1950)	Σ(2030)	Ξ(?)	Ω(?)	
$11/2^+$	$(56,4_4^+)$	3/2	Δ(2420)	Σ(?)	Ξ(?)	Ω(?)	

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Strange hyperons

- Are the states missing
  - because they are not there
  - or because previous experiments haven't been optimal for multistrange baryon search?

- PDG note on Ξ hyperons:
  "…nothing of significance on Ξ resonances has been added since our 1988 edition."

- Most previous experiments are performed with kaon beams

  → difficult to measure double and triple strange states

J^P	(D, L_N^P)	S	Octet members				Singlets
$1/2^+$	$(56,0_0^+)$	1/2	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	
$1/2^+$	$(56,0_2^+)$	1/2	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$	$\Xi(?)$	
$1/2^-$	$(70,1_1^-)$	1/2	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(?)$	$\Lambda(1405)$
$3/2^-$	$(70,1_1^-)$	1/2	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
$1/2^-$	$(70,1_1^-)$	3/2	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(?)$	
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$5/2^-$	$(70,1_1^-)$	3/2	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(?)$	
$1/2^+$	$(70,0_2^+)$	1/2	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Xi(?)$	$\Lambda(?)$
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$7/2^-$	$(70,3_3^-)$	1/2	$N(2190)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	$\Lambda(2100)$
$9/2^-$	$(70,3_3^-)$	3/2	$N(2250)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
$9/2^+$	$(56,4_4^+)$	1/2	$N(2220)$	$\Lambda(2350)$	$\Sigma(?)$	$\Xi(?)$	
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$3/2^+$	$(56,0_0^+)$	3/2	$\Delta(1232)$	$\Sigma(1385)$	$\Xi(1530)$	$\Omega(1672)$	
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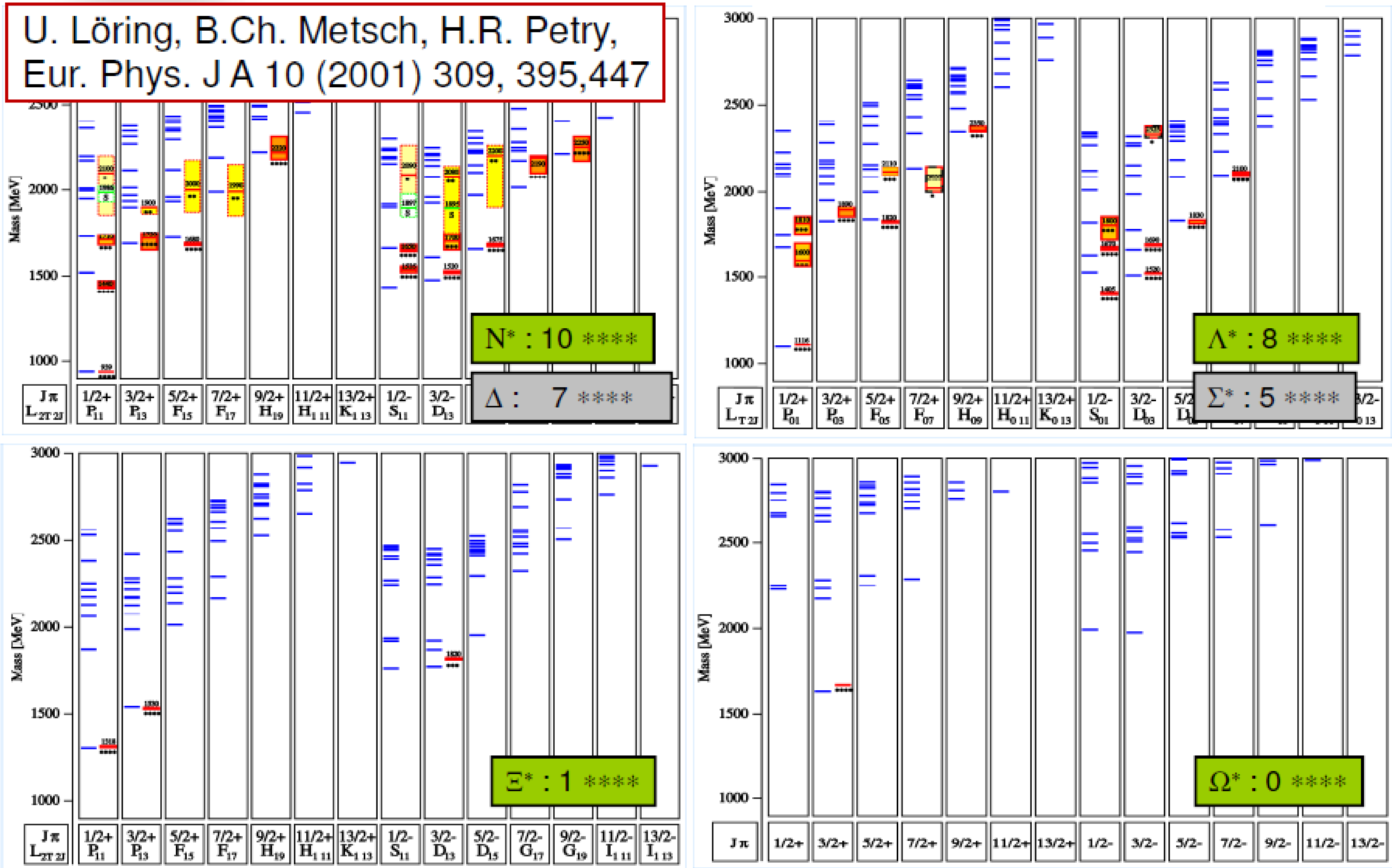
Strange hyperons

U. Löring, B.Ch. Metsch, H.R. Petry,
Eur. Phys. J A 10 (2001) 309, 395,447



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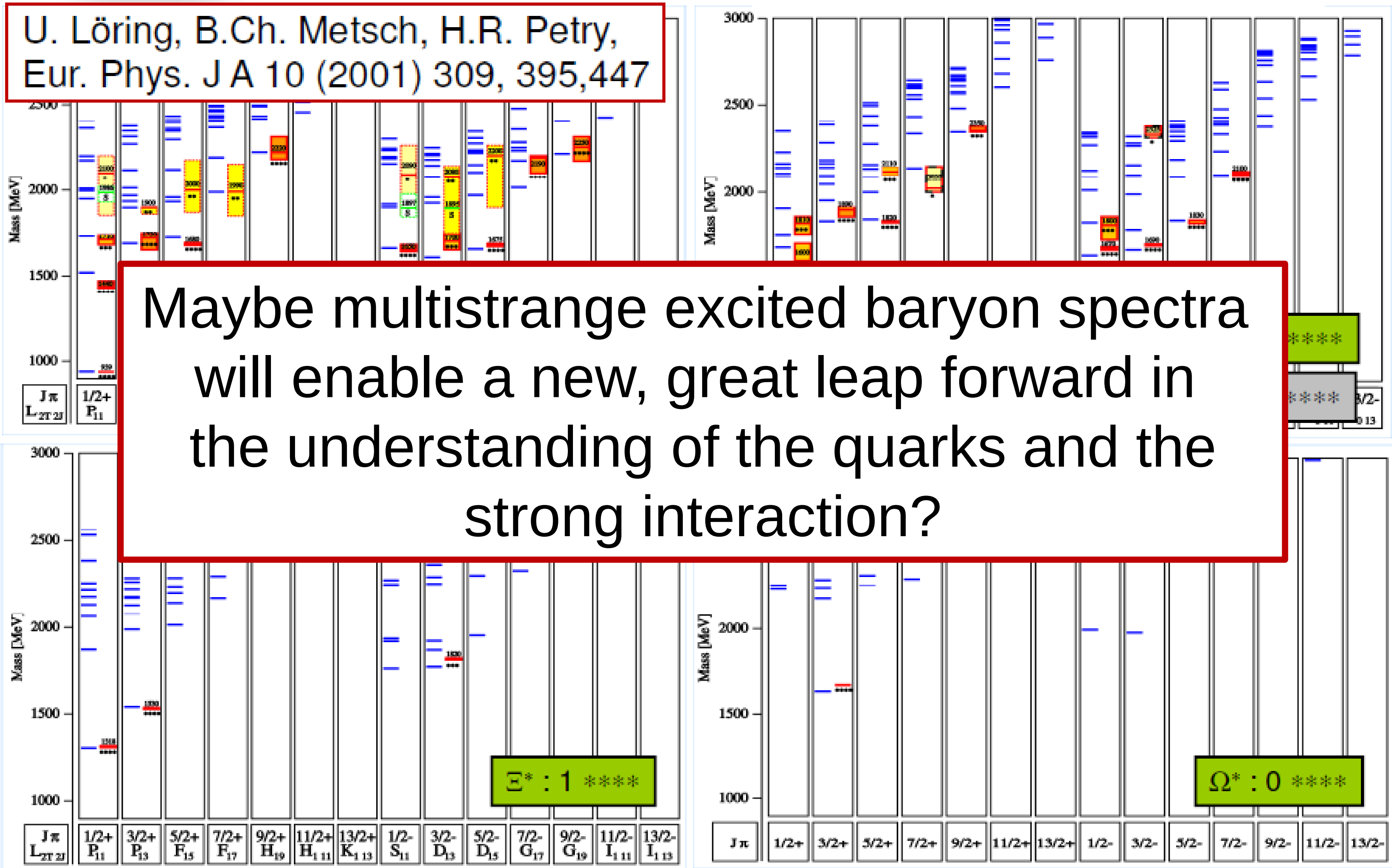

Maybe multistrange excited baryon spectra will enable a new, great leap forward in the understanding of the quarks and the strong interaction?

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Prospects for PANDA

- A lot of previous and ongoing activity in light baryon spectroscopy (CLAS @ JLAB, CBELSA/TAPS)

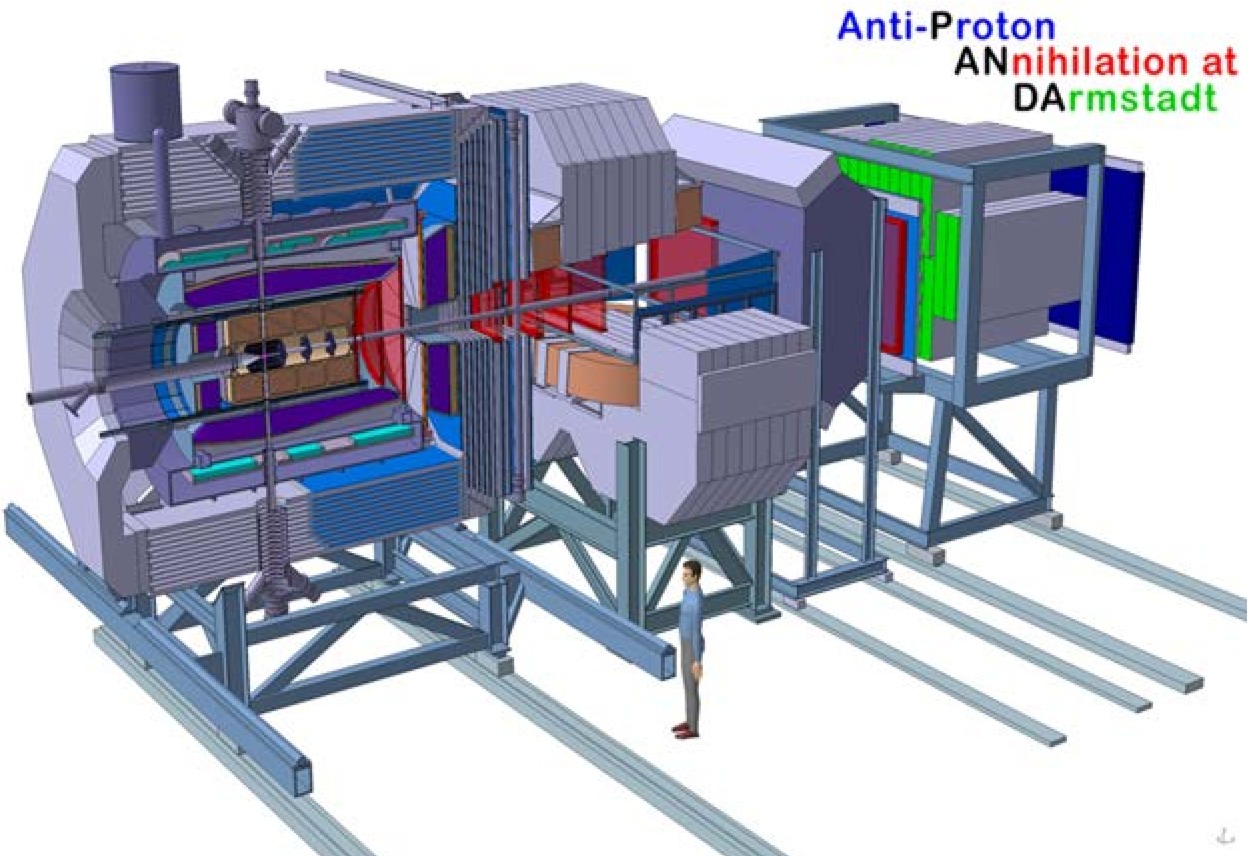
- Charmed baryons often bi-product at b-factories (BaBar, Belle, CLEO, LHCb)

- PANDA can fill the gap in the strange sector

$\rightarrow$ the full Ξ and Ω spectra are accessible with PANDA!

Prospects for PANDA

- 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



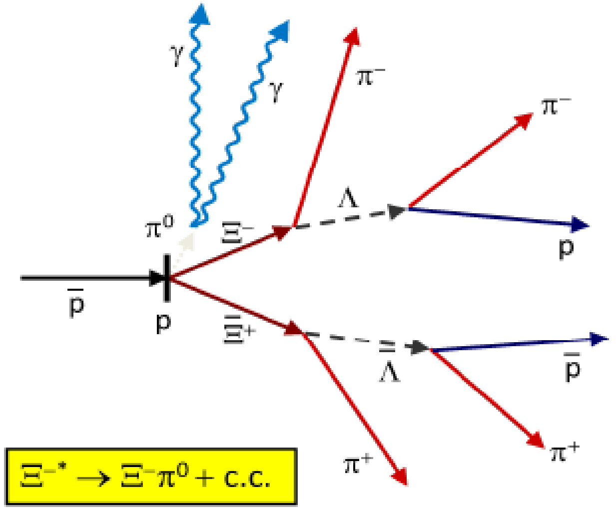
Prospects for PANDA

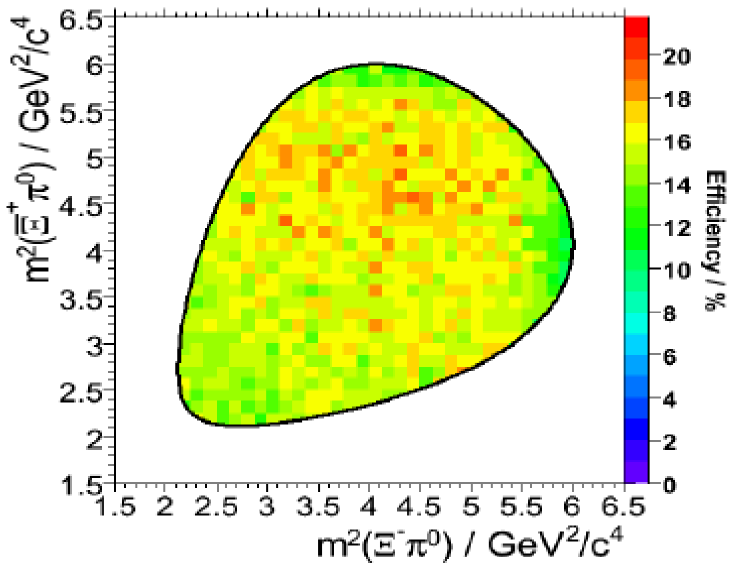
- Large cross sections for $\bar{p}p \rightarrow \bar{Y}Y^{*}$
  - $\bar{p}p \rightarrow \bar{\Xi}\Xi \approx \mu b$
  - $\bar{p}p \rightarrow \bar{\Omega}\Omega \approx 0.03 - 0.1 \mu b$
- No extra mesons in the final state needed for strangeness (or charm) conservation
- Symmetry in hyperon and antihyperon observables
- PANDA detector versatile (coverage, resolution, PID...)

PANDA is a unique experiment in baryon spectroscopy beyond *N and Δ!**

Feasibility study of $\bar{p}p \rightarrow \bar{\Xi}\Xi^*$

- p_{beam} = 6.57 GeV/c
- 10^7 MC events produced
- Consider the $\Xi^{-*} \rightarrow \Xi^- \pi^0$ decay
- Background generated with DPM
- Simple MC framework taking efficiencies and detector resolution into account
- Results*:
  - 10-20% efficiency
  - Smooth efficiency
  - S/B > 19





* PANDA Physics Book (2009)

Baryon spectroscopy subtopics with PANDA

Study excited states of

- double-strange hyperons (Ξ^*)
- triple-strange hyperons (Ω^*)
- charmed hyperons (Λ_c^*, Σ_c^*)
- hidden-charm nucleons ($N_{c\bar{c}}$)

- non-strange baryons (N^*)
- single-strange hyperons (Λ^*, Σ^*)

Part II: Spin Observables in Hyperon production

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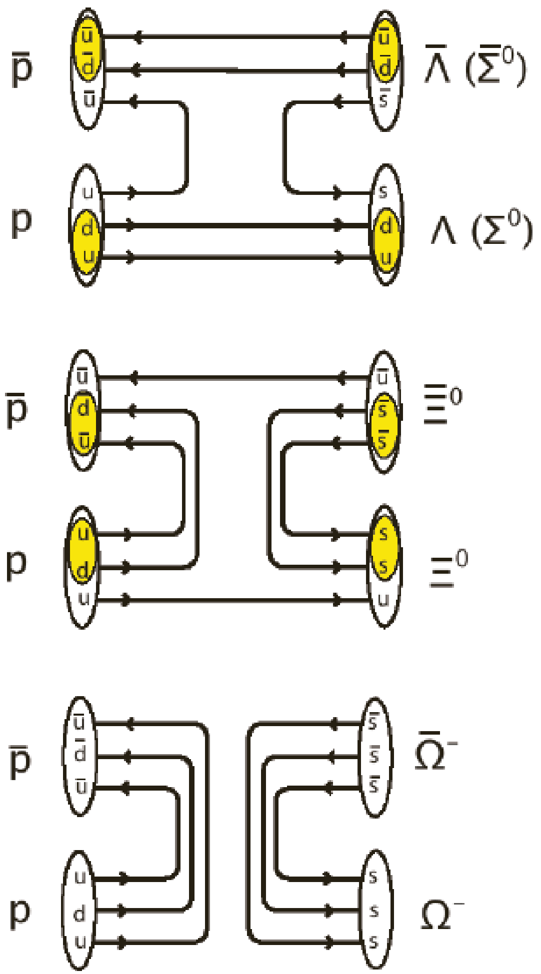
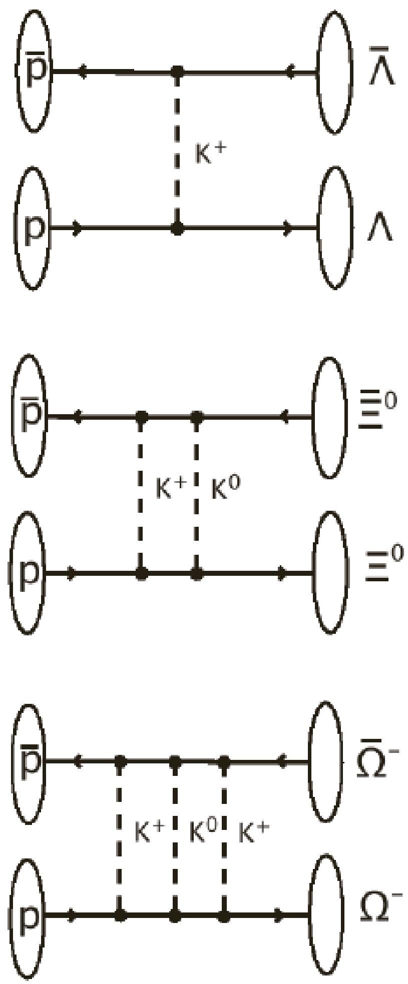
Or: what can we learn from looking into detail how known hyperons are produced?

Strange and charm production

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 $\bar{p}p \rightarrow \bar{Y}Y$

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

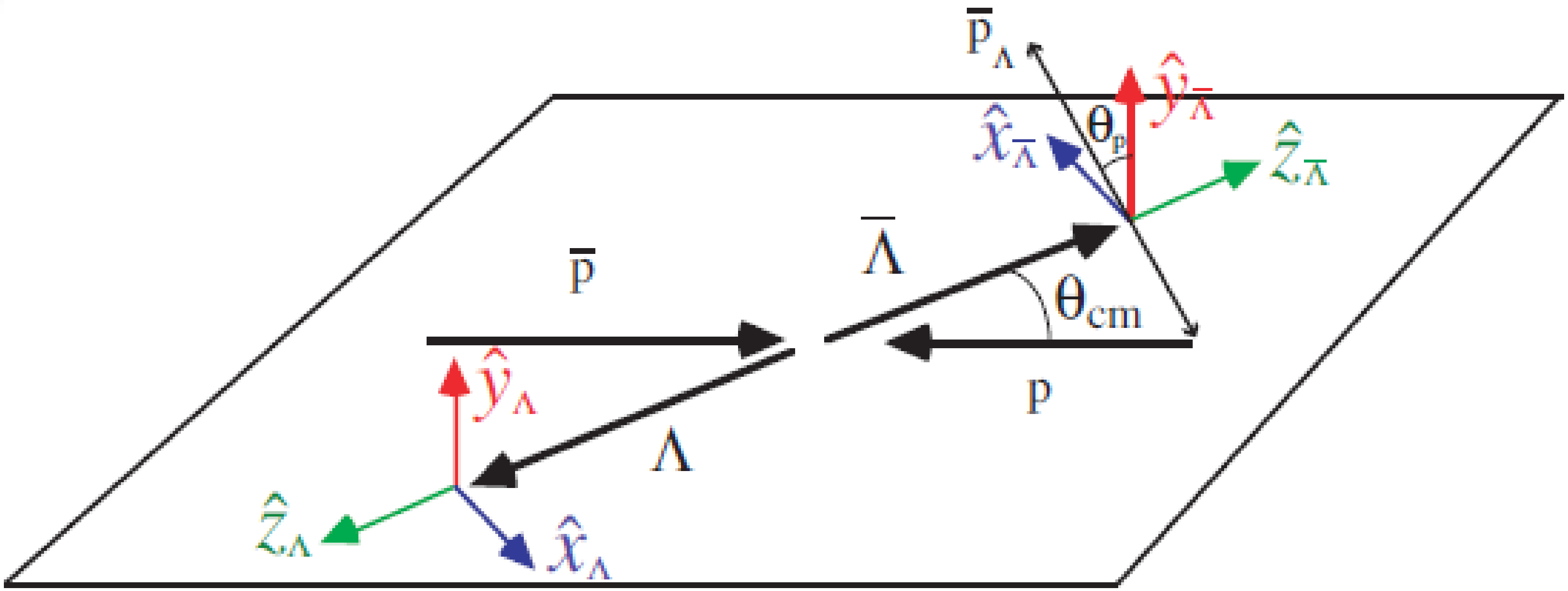
$$\rho = \frac{1}{2j+1}\mathscr{I} + \sum_{L=1}^{2j} \rho^L \quad \text{with} \quad \rho^L = \frac{2j}{2j+1}\sum_{M=-L}^{L} Q_M^L r_M^L$$

Unpolarised (first term); Polarised (second term)

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

- Spin $\frac{1}{2}$: **3** polarisation parameters: r_{-1}^1, r_0^1 and r_1^1.
- Spin $\frac{3}{2}$: **15** polarisation parameters: 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 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

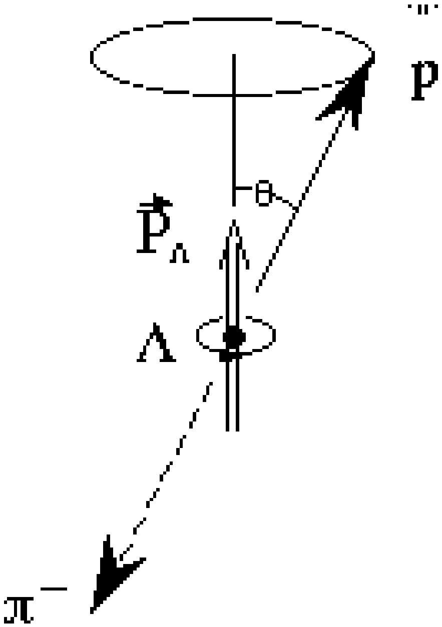
Hyperons decay weakly:
→ decay matrix has one **parity conserving** part and one **parity violating** part.

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.



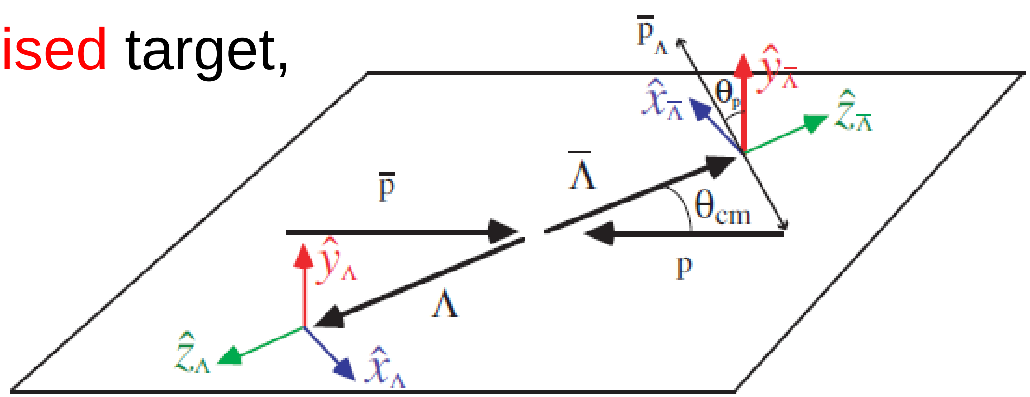
→ The polarisation is accessible by the angular distribution of the decay products!

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

Polarised Particle	None	Beam	Target	Both
None	I_{0000}	A_{i000}	A_{0j00}	A_{ij00}
Scattered	$P_{00\mu 0}$	$D_{i0\mu 0}$	$K_{0j\mu 0}$	$M_{ij\mu 0}$
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 $C_{00\nu\mu}$ (v,μ = x,y,z) are accessible.



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

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

15 polarisation parameters, **7** are accessible in $\Omega \rightarrow \Lambda K$ 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 $\alpha_\Omega = 0$ consistent with experiment.**

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

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

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

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

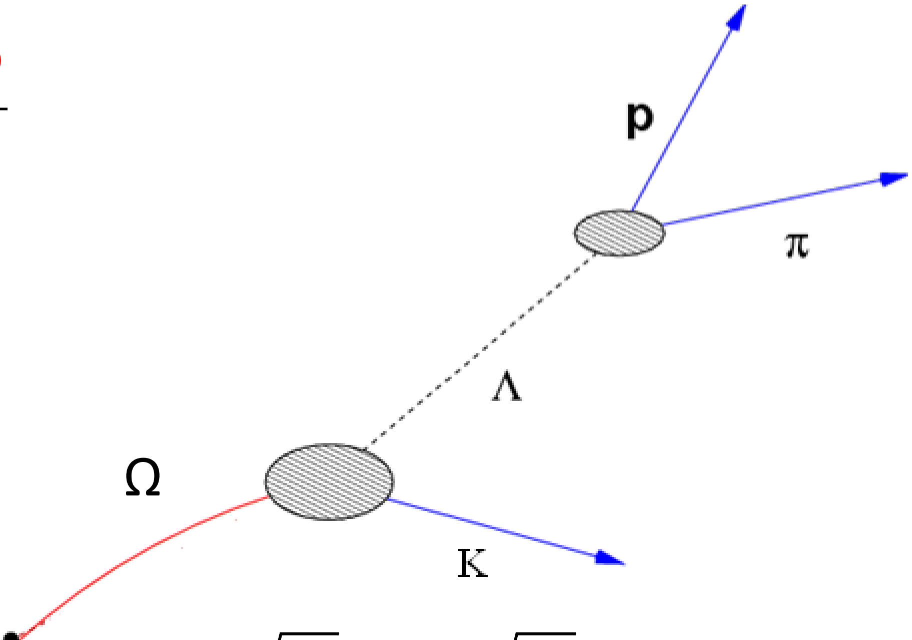
Spin observables for spin $\frac{3}{2}$ hyperons

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 ($\Omega \rightarrow \Lambda K$):
  - 7 polarisation parameters + degree of polarisation.

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

CP violation in hyperon systems

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

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

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

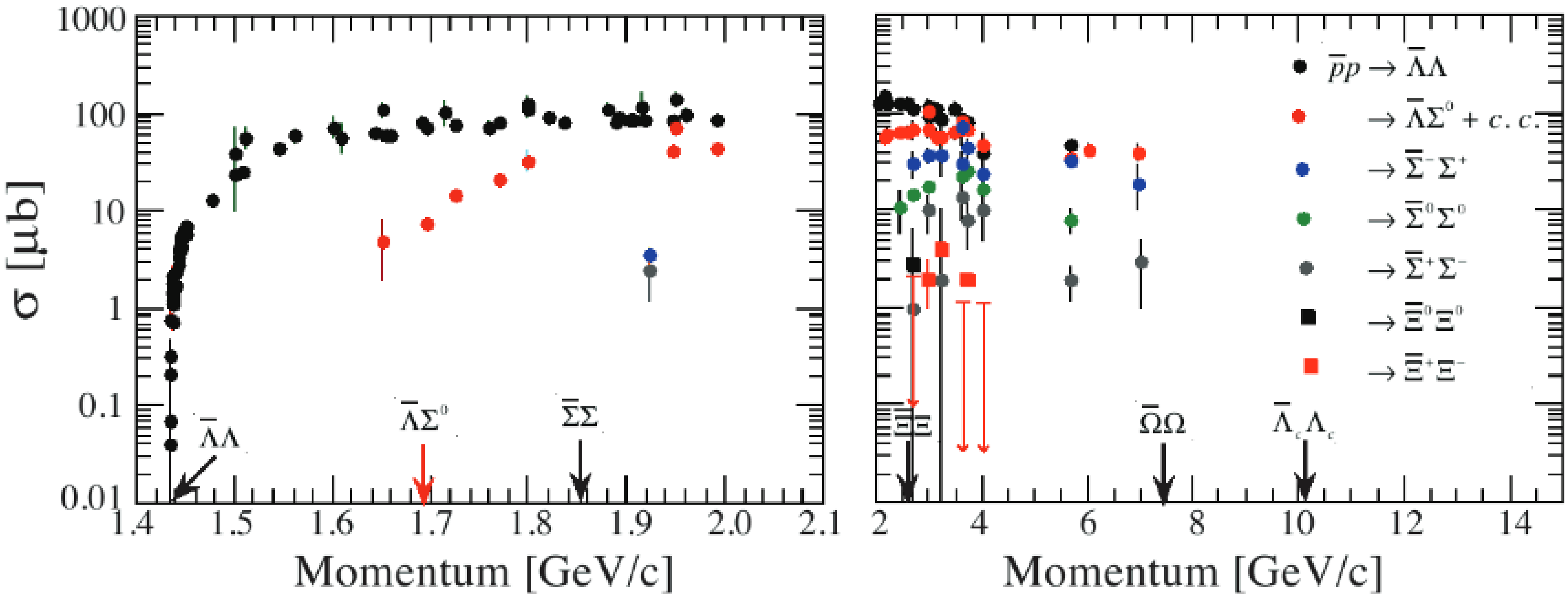
$$B = \frac{\Gamma\beta + \bar{\Gamma}\bar{\beta}}{\Gamma\beta - \bar{\Gamma}\bar{\beta}} \approx \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}}$$

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

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

No previous measurement.

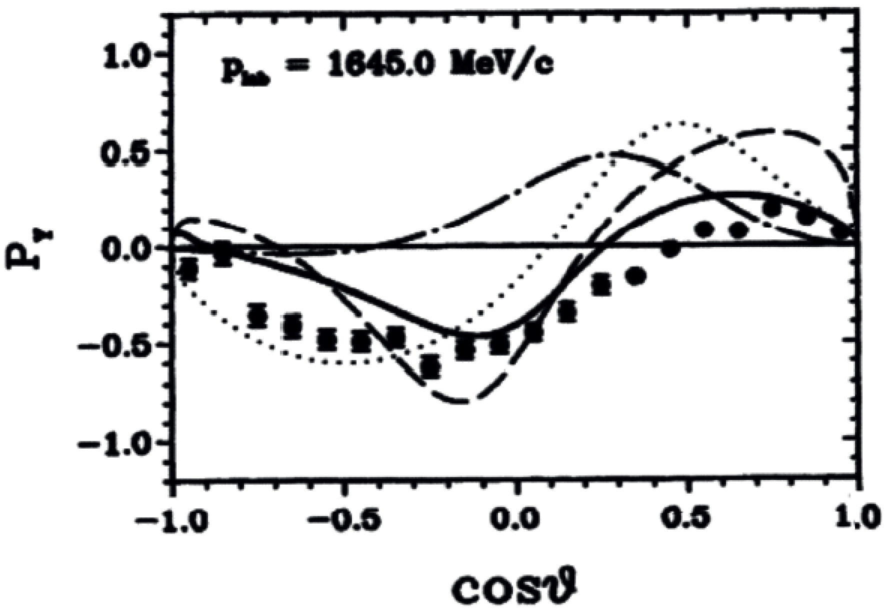
Previous measurements of $\bar{p}p \to \bar{Y}Y$

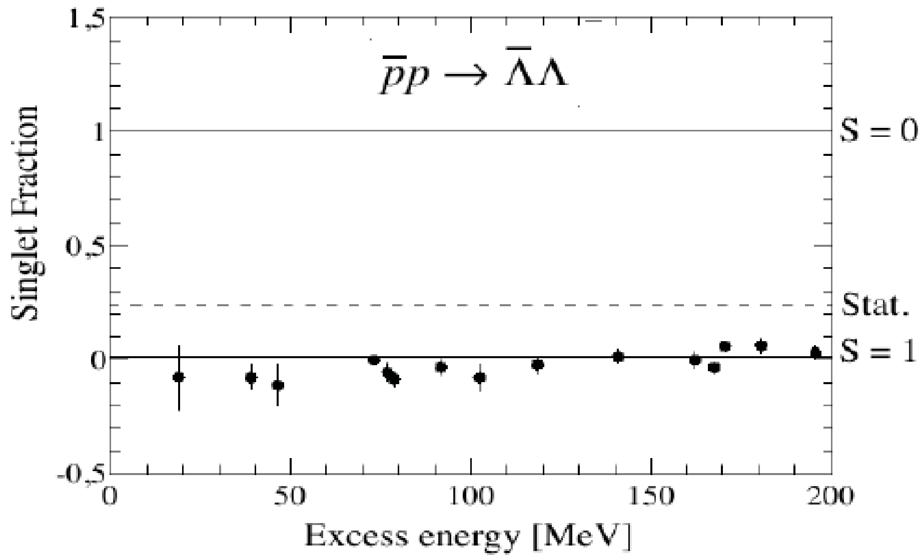


- A lot of data on $\bar{p}p \to \bar{\Lambda}\Lambda$ near threshold, mainly from PS185 at LEAR*.
- Very scarce data bank above 4 GeV.
- Only a few bubble chamber events on $\bar{p}p \to \bar{\Xi}\Xi$
- No data on $\bar{p}p \to \bar{\Omega}\Omega$ nor $\bar{p}p \to \bar{\Lambda}_c\Lambda_c$

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

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





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

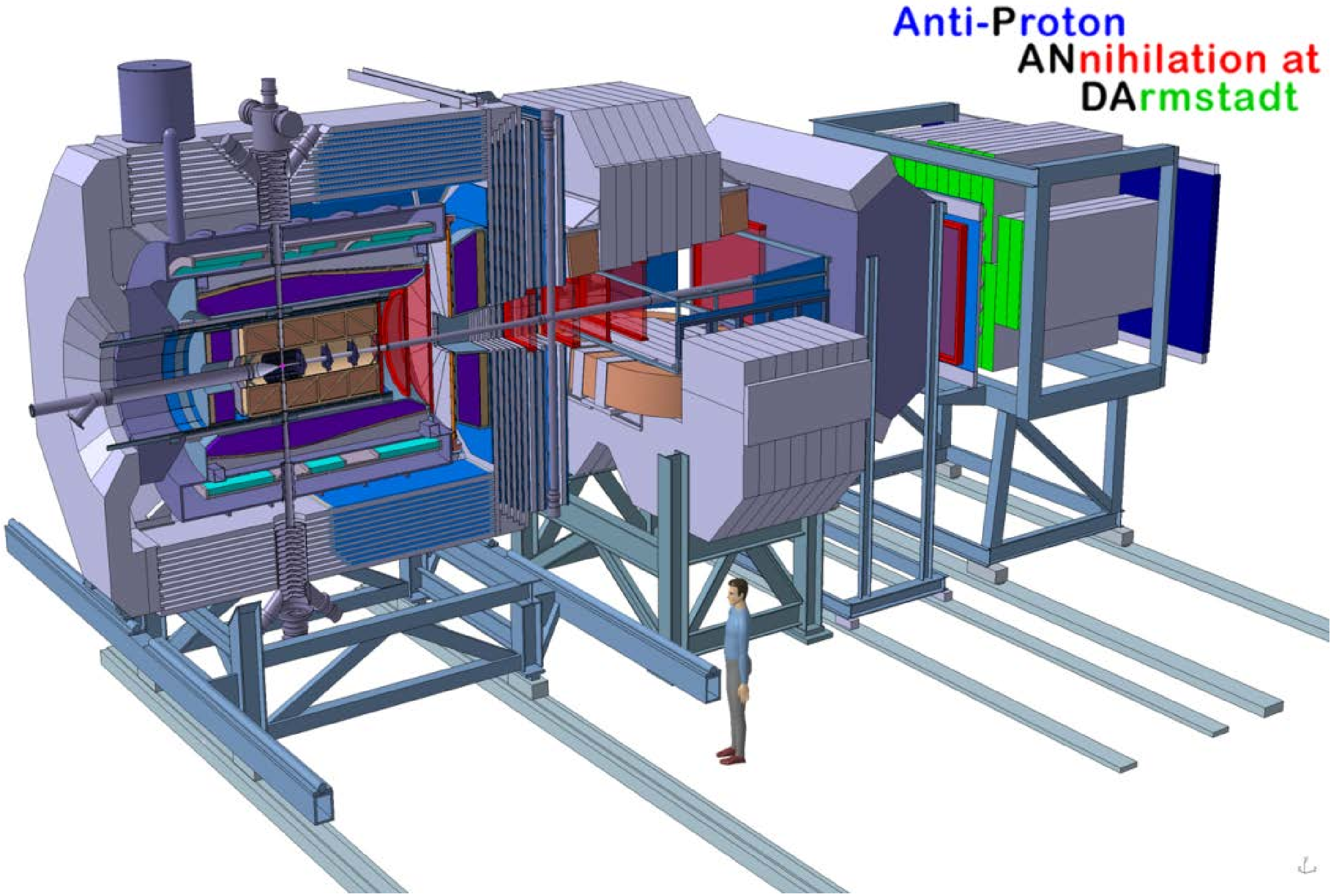
$$SF = \frac{1}{4}(1 + C_{xx} - C_{yy} + C_{zz})$$

- 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



Prospects for PANDA

$$\bar{p}p \rightarrow \bar{\Lambda}\Lambda,\ \bar{\Sigma}^-\Sigma^+,\ \bar{\Sigma}^0\Sigma^0,\ \bar{\Sigma}^-\Sigma^+,\ \bar{\Xi}^0\Xi^0,\ \bar{\Xi}^+\Xi^-,\ \bar{\Omega}^+\Omega^-,\ \bar{\Lambda}_c^-\Lambda_c^+$$

	$\bar{\Lambda}\Lambda$	$\bar{\Sigma}^-\Sigma^+$	$\bar{\Sigma}^0\Sigma^0$	$\bar{\Sigma}^-\Sigma^+$	$\bar{\Xi}^0\Xi^0$	$\bar{\Xi}^+\Xi^-$	$\bar{\Omega}^+\Omega^-$	$\bar{\Lambda}_c^-\Lambda_c^+$
$\downarrow$	$p\pi^-$	$p\pi^0$	$\Lambda\gamma$	$n\pi$	$\Lambda\pi^0$	$\Lambda\pi$	ΛK	$\Lambda\pi$
BR:	64%	52%	$\approx 100\%$	$\approx 100\%$	$\approx 100\%$	$\approx 100\%$	68%	$\approx 1\%$

- 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 $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ and $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^o$ known near threshold, the $\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$ measured with large uncertainty.
- Only theoretical predictions of $\bar{p}p \rightarrow \bar{\Omega}^+\Omega^-$ and $\bar{p}p \rightarrow \bar{\Lambda}_c^-\Lambda_c^+$

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Prospects for PANDA

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}

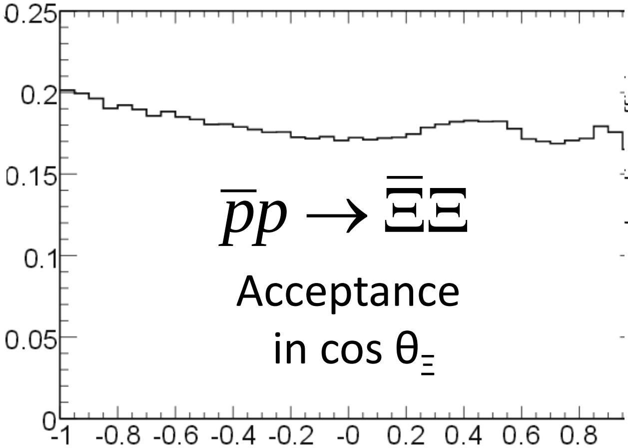
- High event rates for Λ and Σ *.
- Low background for Λ and Σ *.
- Even with conservative cross section estimates, Ω and Λ_c channels are feasible. **
- New efficiencies obtained with a more sophisticated MC framework are underway.

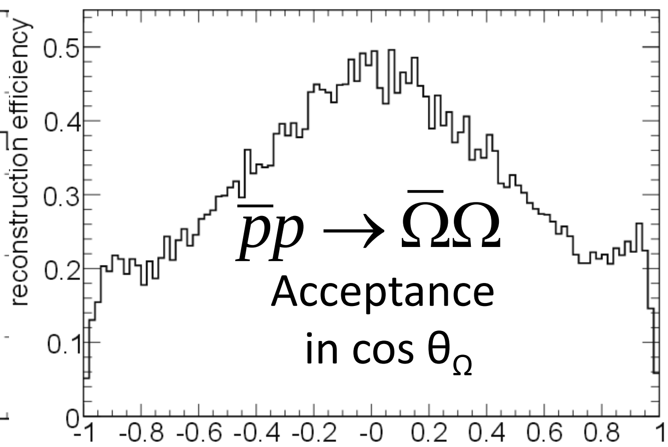
*Sophie Grape, Ph. D. Thesis, Uppsala University 2009

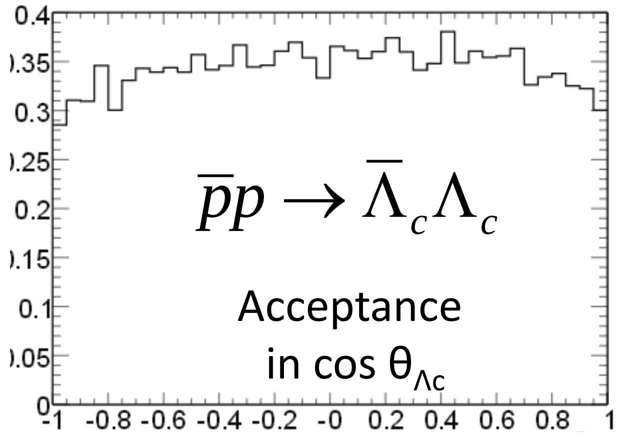
** Erik Thomé, Ph. D. Thesis, Uppsala University 2012

Prospects for PANDA

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







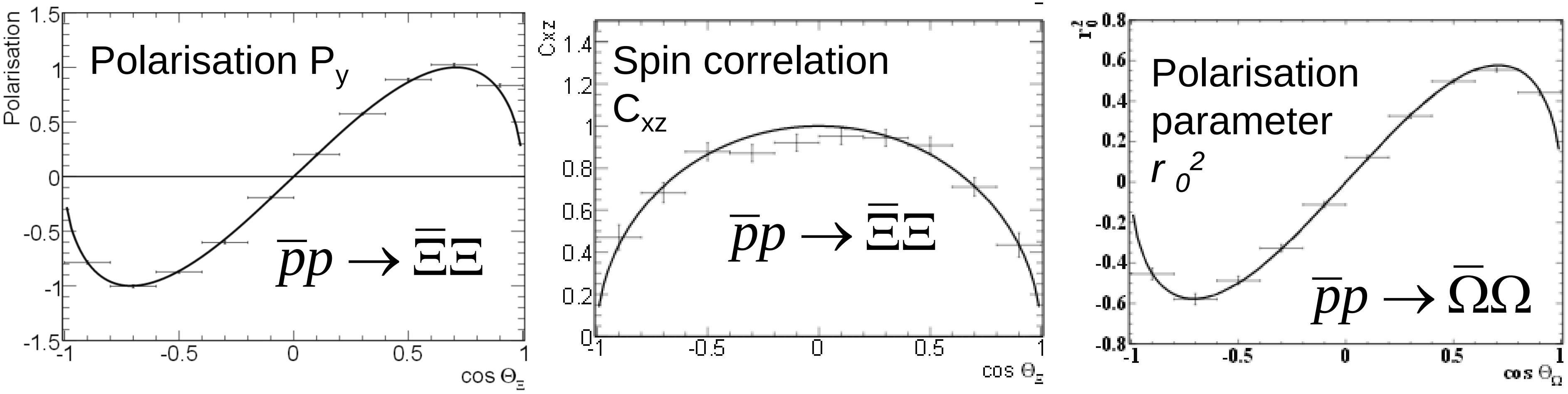
Results by Erik Thomé, Ph. D. Thesis, Uppsala University (2012).

Prospects for PANDA at FAIR

- Parametrisation of spin variables using weights:

$$P_{\Xi,y} = sin2\theta_{\Xi} \qquad C_{\Xi,xz} = sin\theta_{\Xi} \qquad r_0^2 = sin2\theta_{\Omega}/\sqrt{3}$$

- 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).

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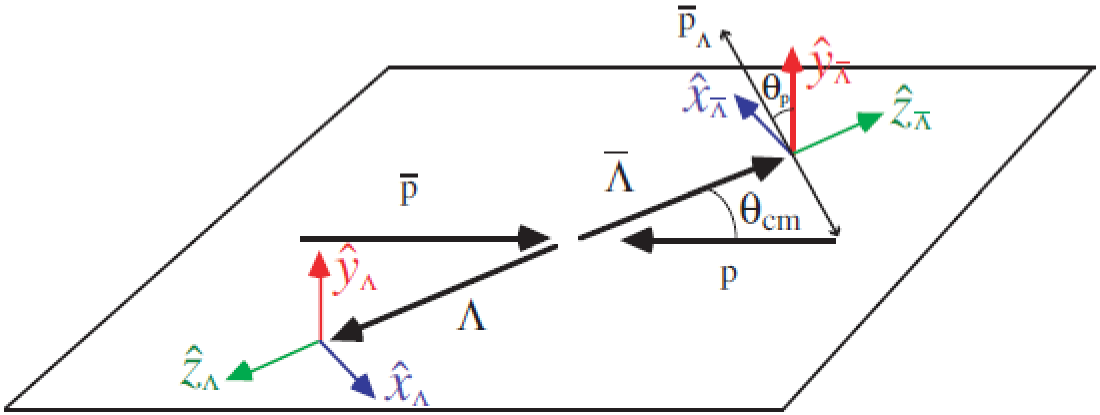
Summary and Outlook

- Strange hyperons probe the Strong Interaction in the confinement domain.
- Several open questions in baryon spectroscopy show that there is much more to learn on how quarks interact inside baryons.
- What happens if light quarks are replaced with heavier? Very little is known about the excited strange hyperon spectra.
- PANDA can fill a gap in the strange sector
- Production of strange and charmed hyperons probe QCD at two different energy scales.
- Polarisation parameters of $p\bar{p} \to \Omega\bar{\Omega}$ have been derived.
- Simulation studies show excellent prospects for antihyperon-hyperon channels with PANDA.

Thanks to: Albrecht Gillitzer,
Stefan Leupold, 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

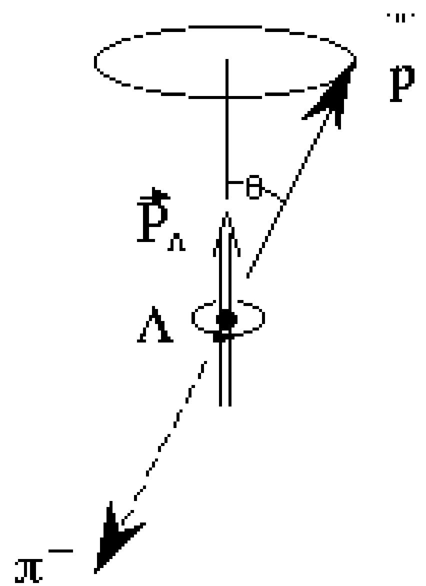
Parity violating decay → direction of the decay products depends on the polarisation of the mother hyperon.

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

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

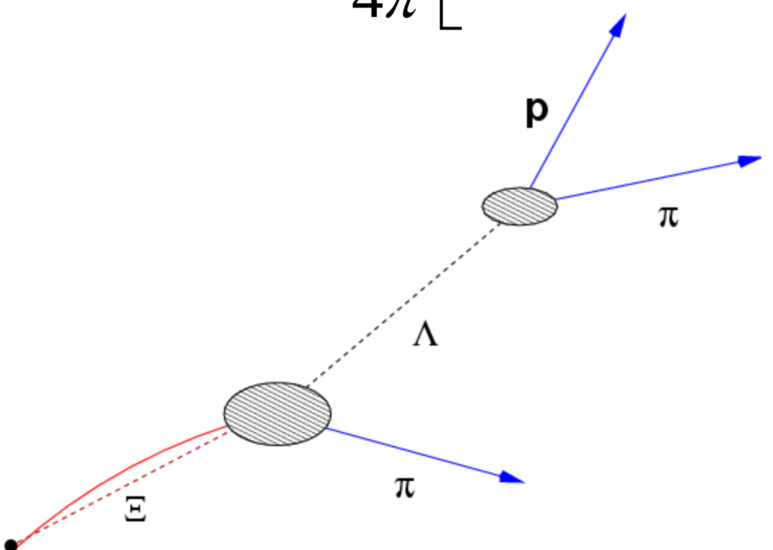
Spin observables for spin $\frac{1}{2}$ hyperons

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

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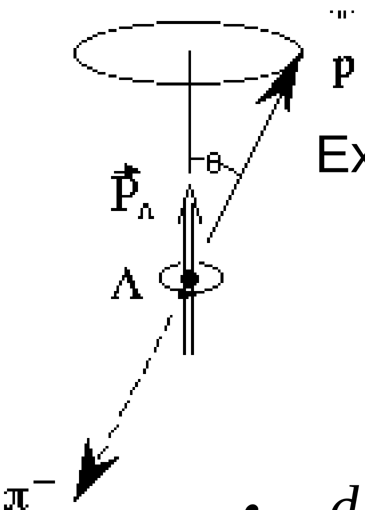
Method of Moments

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 π*. 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:

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

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

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

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

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

No previous measurement.

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

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

$$= \frac{1}{4}\begin{bmatrix} 1+\sqrt{3}r_0^2 & i\frac{3}{\sqrt{5}}r_{-1}^1 - \sqrt{3}r_1^2 & \sqrt{3}r_2^2 - i\sqrt{3}r_{-2}^3 & -i\sqrt{6}r_{-3}^3 \\ -i\frac{3}{\sqrt{5}}r_{-1}^1 - \sqrt{3}r_1^2 & 1-\sqrt{3}r_0^2 & i2\sqrt{\frac{3}{5}}r_{-1}^1 + i3\sqrt{\frac{2}{5}}r_{-1}^3 & \sqrt{3}r_2^2 + i\sqrt{3}r_{-2}^3 \\ \sqrt{3}r_2^2 + i\sqrt{3}r_{-2}^3 & -i2\sqrt{\frac{3}{5}}r_{-1}^1 - i3\sqrt{\frac{2}{5}}r_{-1}^3 & 1-\sqrt{3}r_0^2 & i\frac{3}{\sqrt{5}}r_{-1}^1 + \sqrt{3}r_1^2 \\ i\sqrt{6}r_{-3}^3 & \sqrt{3}r_2^2 - i\sqrt{3}r_{-2}^3 & -i\frac{3}{\sqrt{5}}r_{-1}^1 + \sqrt{3}r_1^2 & 1+\sqrt{3}r_0^2 \end{bmatrix}$$

*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

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

$$\langle (3\cos\Theta_\Lambda - 1)\sin\phi_p \rangle =$$
$$= \int_0^\pi \int_0^{2\pi} \int_0^\pi \int_0^{2\pi} I(\Theta_\Lambda, \phi_\Lambda, \Theta_p, \phi_p) \times$$
$$\sin\Theta_\Lambda (3\cos\Theta_\Lambda - 1)\sin\Theta_p \sin\phi_p d\Theta_\Lambda d\phi_\Lambda d\Theta_p d\phi_p =$$
$$= -\frac{3\pi\alpha_\Lambda\gamma_\Omega r^1_{-1}}{20\sqrt{10}}$$

$$\langle (15\cos\Theta_\Lambda - 1)\sin\phi_p \rangle =$$
$$= \int_0^\pi \int_0^{2\pi} \int_0^\pi \int_0^{2\pi} I(\Theta_\Lambda, \phi_\Lambda, \Theta_p, \phi_p) \times$$
$$\sin\Theta_\Lambda (15\cos\Theta_\Lambda - 1)\sin\Theta_p \sin\phi_p d\Theta_\Lambda d\phi_\Lambda d\Theta_p d\phi_p =$$
$$= \frac{\sqrt{3}\pi\alpha_\Lambda\gamma_\Omega r^3_{-1}}{2\sqrt{5}}$$

$$\langle \sin\phi_\Lambda \cos\phi_p \rangle =$$
$$= \int_0^\pi \int_0^{2\pi} \int_0^\pi \int_0^{2\pi} I(\Theta_\Lambda, \phi_\Lambda, \Theta_p, \phi_p) \times$$
$$\sin\Theta_\Lambda \sin\Theta_p \sin\phi_\Lambda \cos\phi_p d\Theta_\Lambda d\phi_\Lambda d\Theta_p d\phi_p =$$
$$= -\frac{3\pi^2\alpha_\Lambda\gamma_\Omega r^3_{-2}}{1024}$$

$$\langle \sin\phi_\Lambda \cos\phi_\Lambda \sin\phi_p \rangle =$$
$$= \int_0^\pi \int_0^{2\pi} \int_0^\pi \int_0^{2\pi} I(\Theta_\Lambda, \phi_\Lambda, \Theta_p, \phi_p) \times$$
$$\sin\Theta_\Lambda \sin\Theta_p \sin\phi_\Lambda \cos\phi_\Lambda \sin\phi_p d\Theta_\Lambda d\phi_\Lambda d\Theta_p d\phi_p =$$
$$= -\frac{\pi\alpha_\Lambda\gamma_\Omega}{640}\left(5\sqrt{6}r^3_{-3} - 4\sqrt{15}r^3_{-1} - 3\sqrt{10}r^1_{-1}\right)$$