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Hyperon Spectroscopy and Dynamics with PANDA at FAIR

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for the PANDA collaboration

Hadron Physics Seminar, GSI, Germany,
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Outline

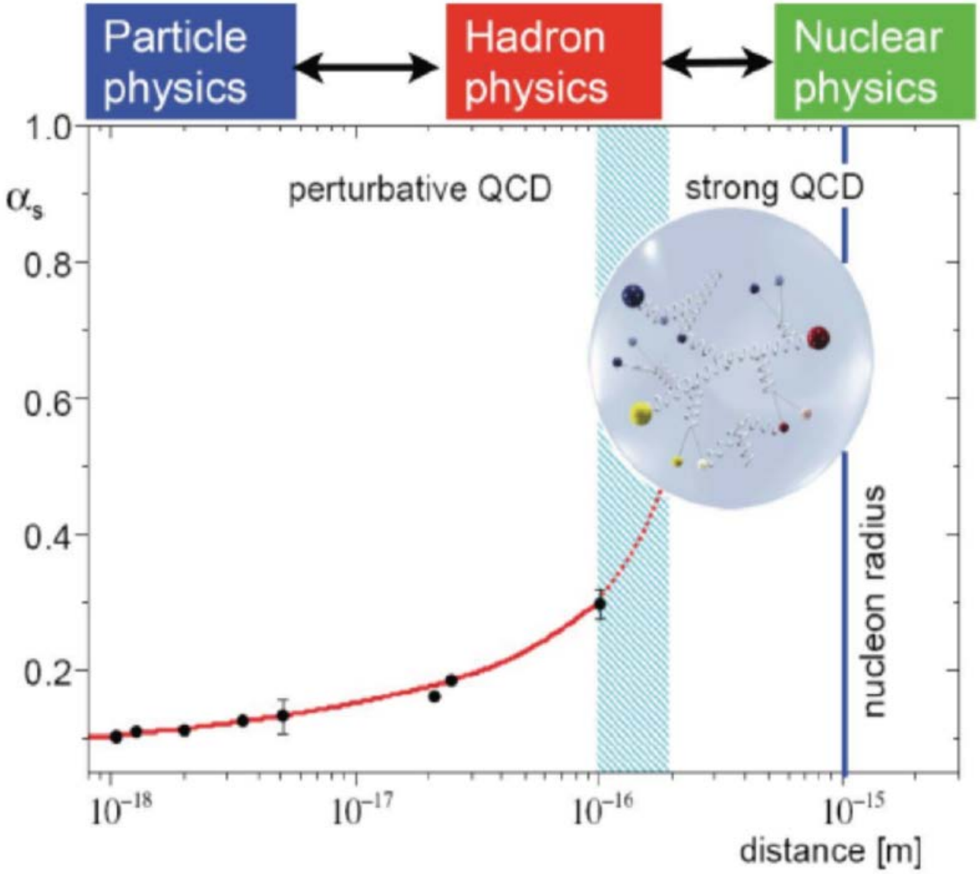
- Introduction
- The PANDA experiment @ FAIR
- Part I: Hyperon Spectroscopy
- Part II: Hyperon spin dynamics
- Summary
- Time-line

Introduction

Missing in the Standard Model of particle physics:

A complete understanding of the strong interaction.

- Short distances pQCD rigorously and successfully tested.
- Charm scale and above: pQCD fails, no analytical solution possible.



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?
  - **Probes QCD in the confinement 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 hyperons?

Hyperon Spectroscopy

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

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Why hyperons?

Hyperon Spectroscopy

- New baryon states?
- Properties of already known states.
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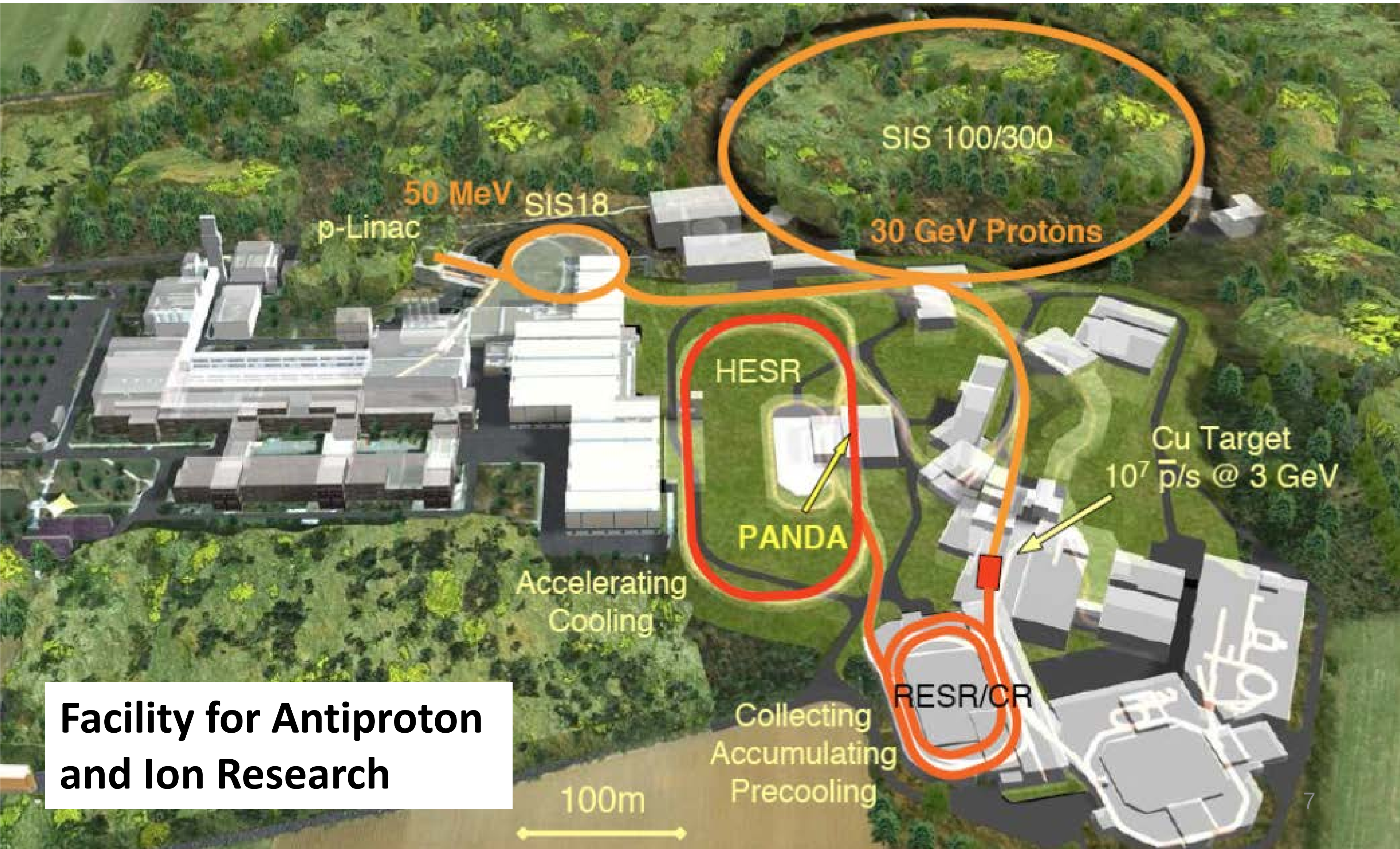
Hyperon Spin Dynamics

- Reaction mechanism at different energy scales.
- The role of spin in the strong interaction.
- CP violation

The PANDA experiment at FAIR

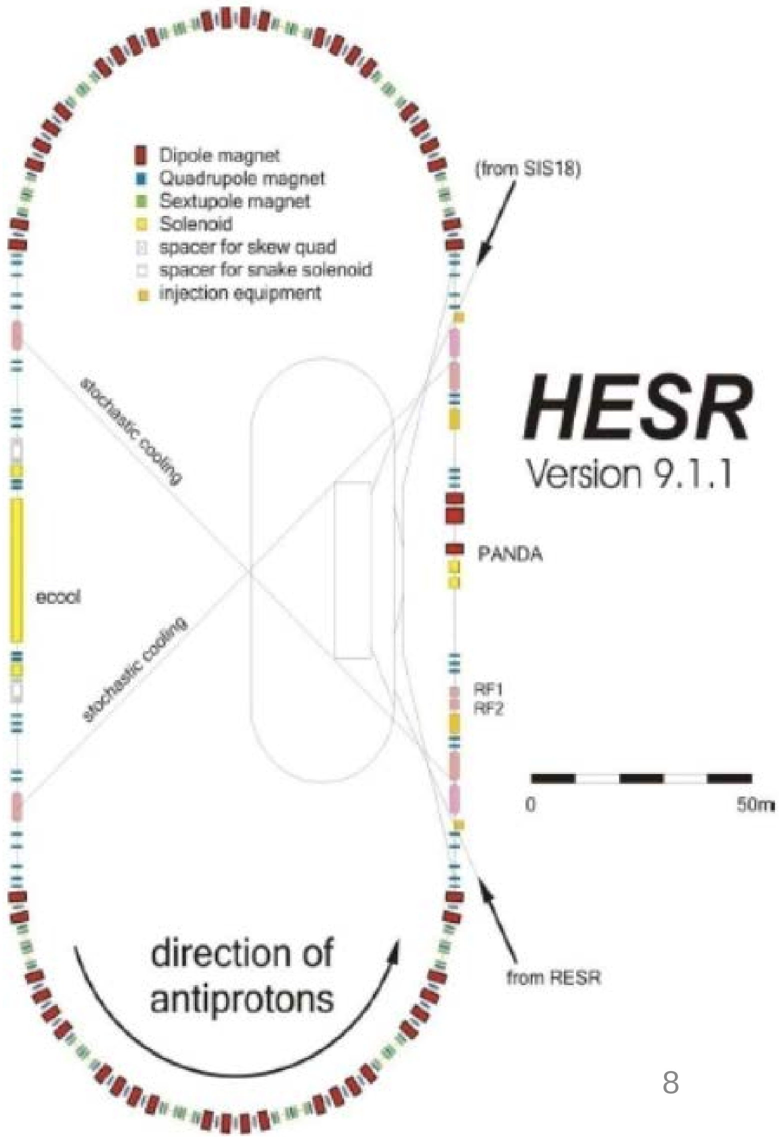


Facility for Antiproton and Ion Research

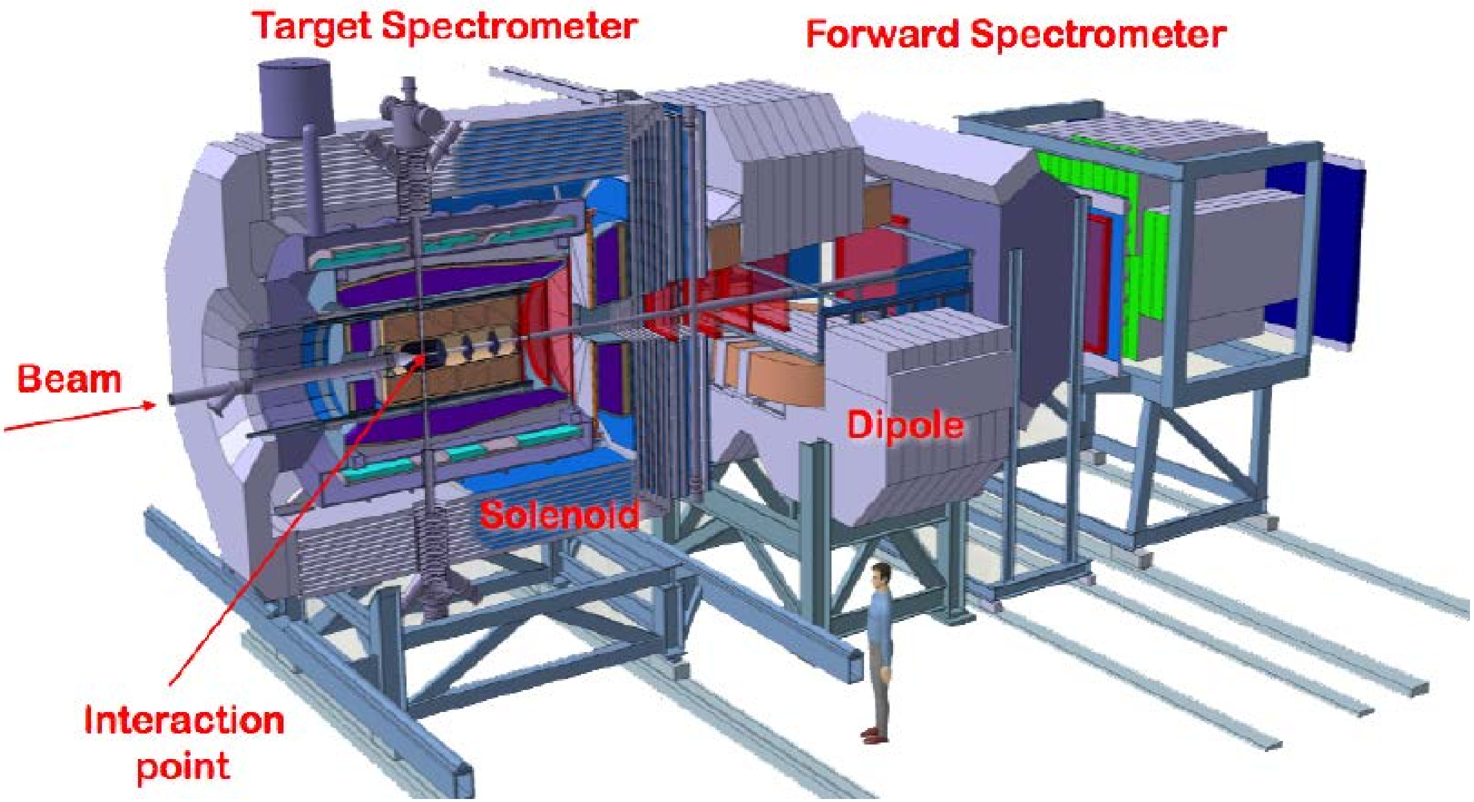
The PANDA experiment at FAIR

The High Energy Storage Ring (HESR)

- Anti-protons within
  1.5 GeV/c < p_{pbar} < 15 GeV/c
  (2.0 < $\sqrt{s}$ < 5.5 GeV)
- Internal targets
  - Cluster jet and pellet ($\bar{p}p$)
  - Foils ($\bar{p}A$)
- High Resolution Mode (HESRr)
  - $L = 10^{31}$ cm^{-2} s^{-1}
  - $\Delta p/p < 5 \cdot 10^{-5}$
  - stochastic + electric cooling < 9 GeV/c
- High Luminosity Mode
  - $L = 2 \cdot 10^{32}$ cm^{-2} s^{-1}
  - $\Delta p/p \sim 10^{-4}$
  - Stochastic cooling
- Modularized Start Version
  - $L = 10^{31}$ cm^{-2} s^{-1}



The PANDA experiment at FAIR



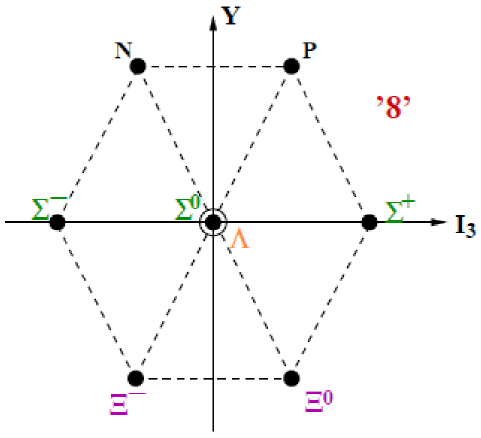
- 4π coverage
- Precise tracking
- PID
- Calorimetry

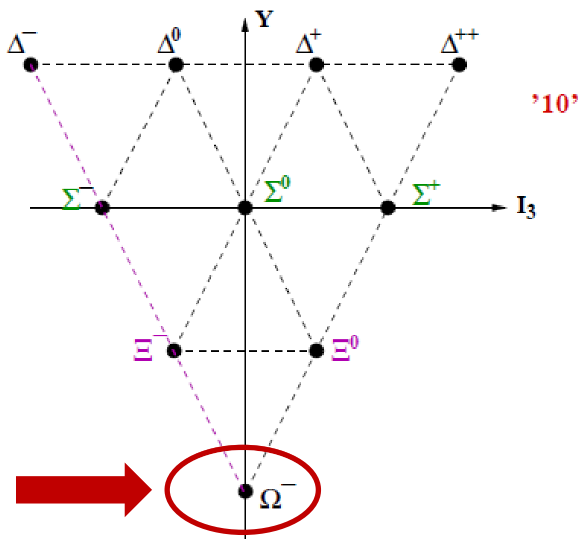
- Vertex detector
- Modular design
- Time-based data acquisition with software trigger

Part I: Hyperon Spectroscopy

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 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 Eight-fold way.
- 1964: Quark model (Gell-Mann and Zweig)





Baryons and the quark model

- The simple (constituent) quark model* was successful in classifying hadrons and describing static properties of hadrons.

- Unable to explain *e.g.*
  - Spin structure of the nucleon.
  - Flavour asymmetry of the nucleon sea.
  - Certain features of the light baryon spectrum**.

*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

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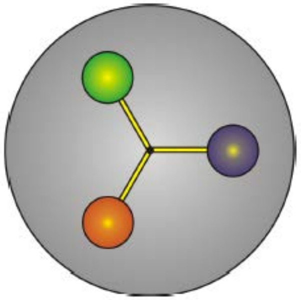
Light baryon spectroscopy

A lot was learned from the great progress in light baryon spectroscopy (pion beams, photoproduction).

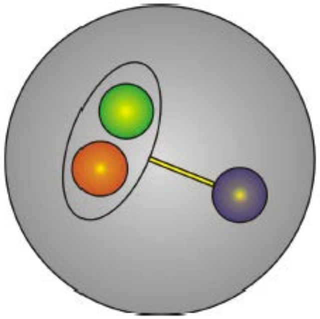
Open questions regarding the excited light baryon spectrum:*

- Missing states?
- Level ordering?
- Parity doublets?



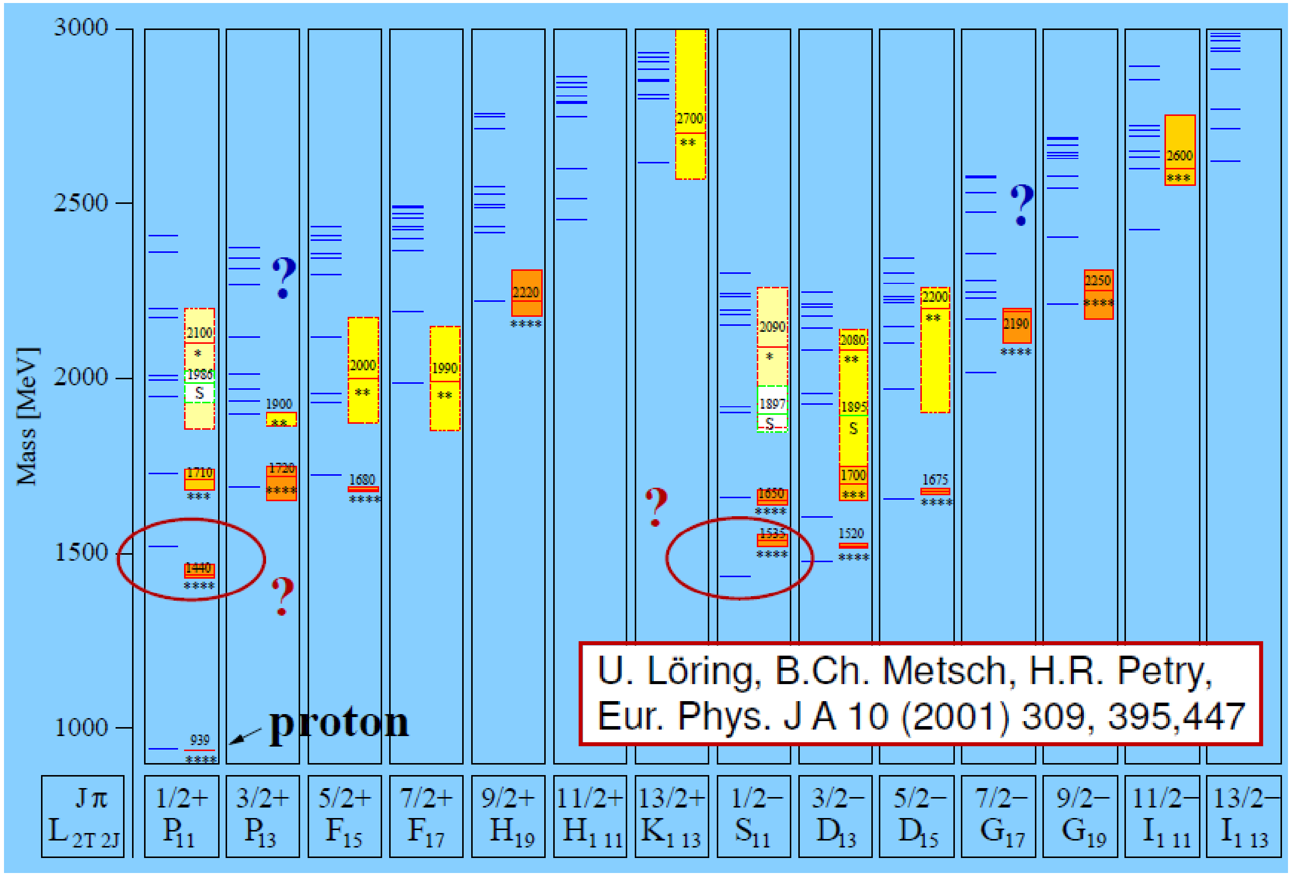
Degrees of freedom and effective forces?

- 3-quark?
- Quark-diquark?
- Meson-baryon?



*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 $N\pi$ final states?

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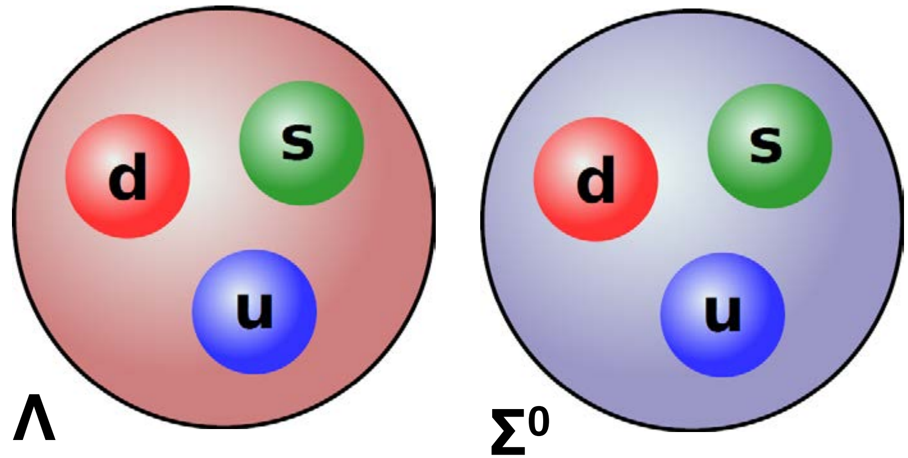
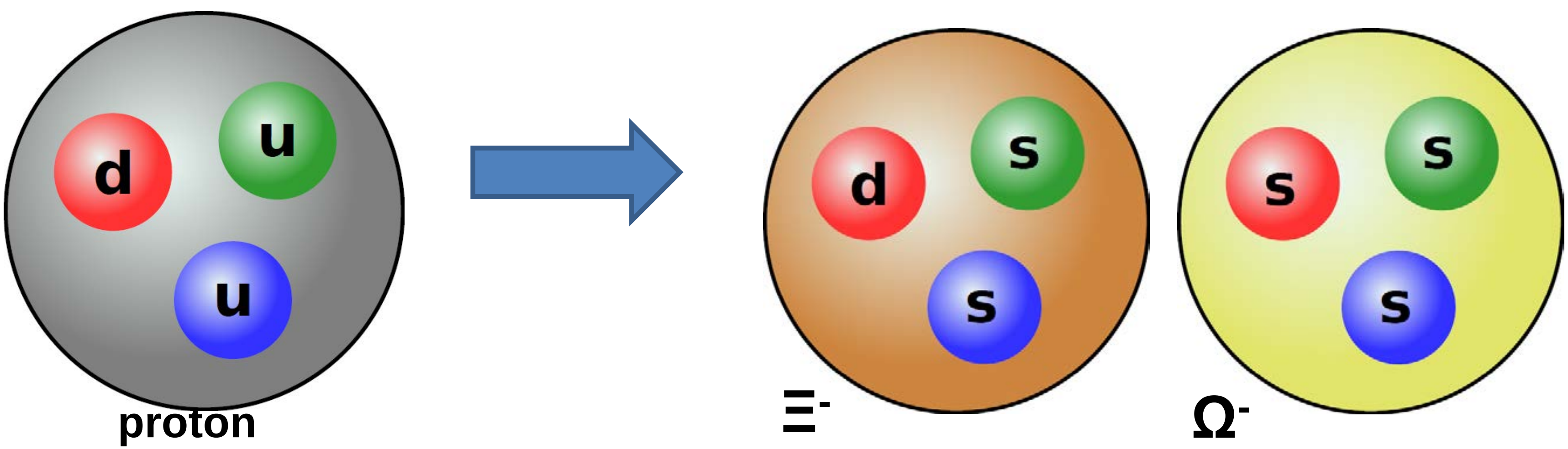
Strange and charmed hyperons

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





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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_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	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(?)$	
$3/2^-$	$(70,1_1^-)$	3/2	$N(1700)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
$5/2^-$	$(70,1_1^-)$	3/2	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(?)$	
$1/2^+$	$(70,0_2^+)$	1/2	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Xi(?)$	$\Lambda(?)$
$3/2^+$	$(56,2_2^+)$	1/2	$N(1720)$	$\Lambda(1890)$	$\Sigma(?)$	$\Xi(?)$	
$5/2^+$	$(56,2_2^+)$	1/2	$N(1680)$	$\Lambda(1820)$	$\Sigma(1915)$	$\Xi(2030)$	
$7/2^-$	$(70,3_3^-)$	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	$N(2220)$	$\Lambda(2350)$	$\Sigma(?)$	$\Xi(?)$	

J^P	(D, L_N^P)	S	Decuplet members			
$3/2^+$	$(56,0_0^+)$	3/2	$\Delta(1232)$	$\Sigma(1385)$	$\Xi(1530)$	$\Omega(1672)$
$3/2^+$	$(56,0_2^+)$	3/2	$\Delta(1600)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
$1/2^-$	$(70,1_1^-)$	1/2	$\Delta(1620)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
$3/2^-$	$(70,1_1^-)$	1/2	$\Delta(1700)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
$5/2^+$	$(56,2_2^+)$	3/2	$\Delta(1905)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
$7/2^+$	$(56,2_2^+)$	3/2	$\Delta(1950)$	$\Sigma(2030)$	$\Xi(?)$	$\Omega(?)$
$11/2^+$	$(56,4_4^+)$	3/2	$\Delta(2420)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$

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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."

J^P	(D, L^P_N)	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	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$	$\Xi(?)$	
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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	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Xi(?)$	$\Lambda(?)$
3/2+	$(56,2_2^+)$	1/2	$N(1720)$	$\Lambda(1890)$	$\Sigma(?)$	$\Xi(?)$	
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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	$N(2250)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
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			Decuplet members				
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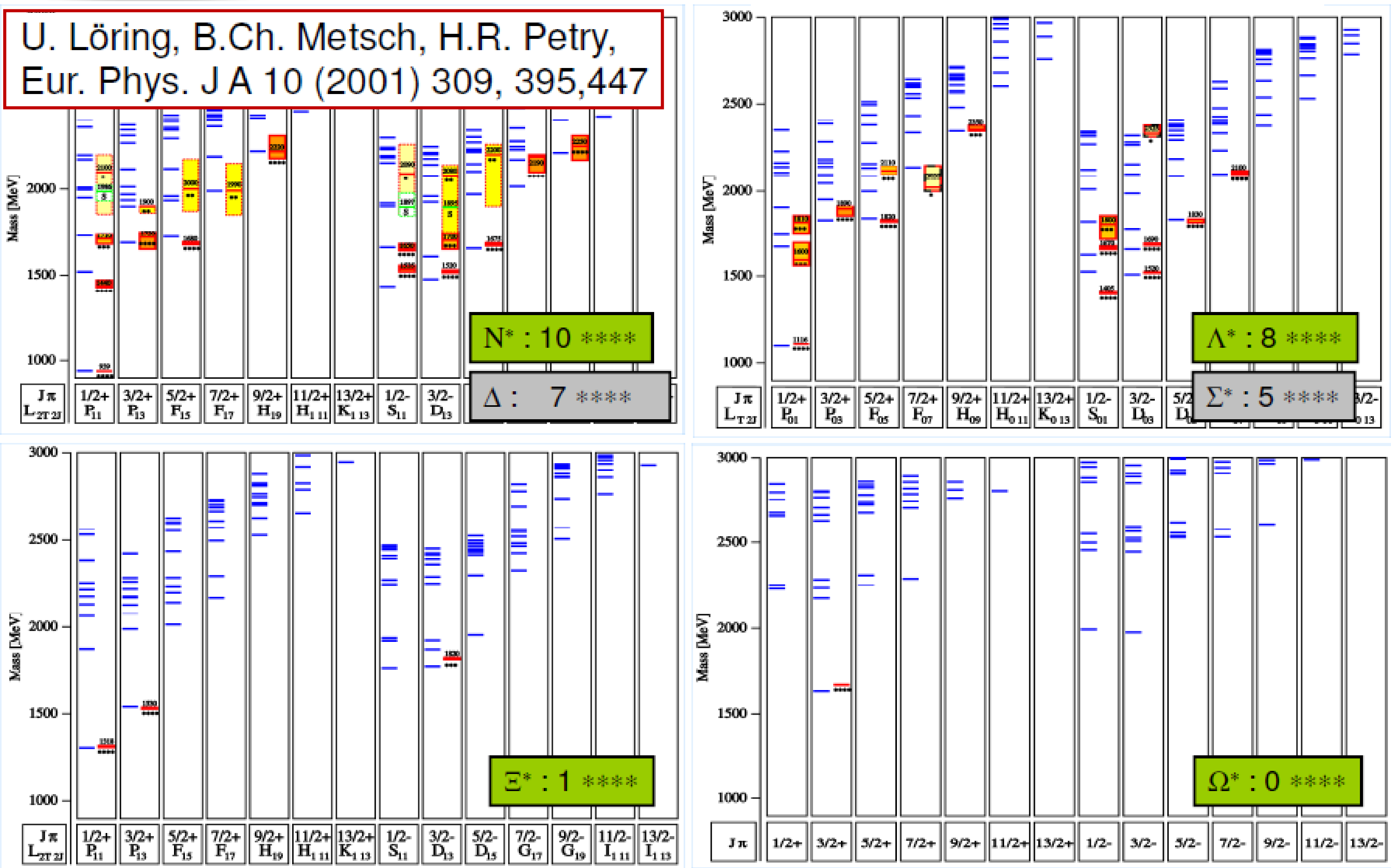
Strange hyperons

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



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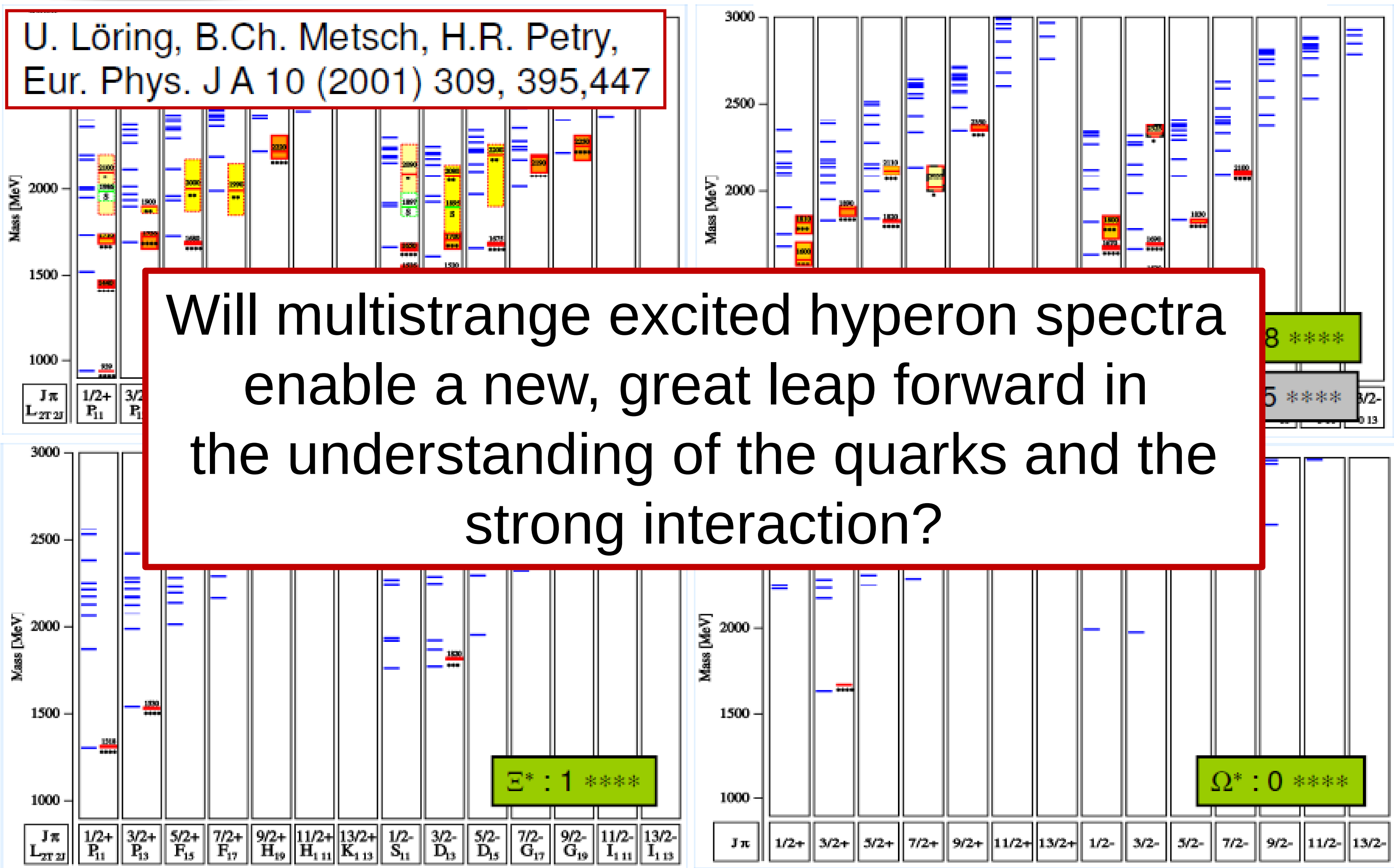

Will multistrange excited hyperon spectra enable a new, great leap forward in the understanding of the quarks and the strong interaction?

Baryon spectroscopy world-wide

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

- Charmed hyperons often by-product at b-factories (BaBar, Belle, CLEO, LHCb)

- Gap to fill in the strange sector!

Facilities for strange hyperon spectroscopy

- LHCb
  - Inclusive production in *pp* $\rightarrow Y^{*} X$
  - Spin & parity determination require known initial state
    $\rightarrow$ use Λ_{b} decays $\rightarrow$ lower rates.
- BES III
  - Hyperons from *e.g.* $J/\psi \rightarrow Y^{*}\bar{Y}^{*}$ and $\psi' \rightarrow Y^{*}\bar{Y}^{*}$
    $\rightarrow$ small BR $\rightarrow$ low event rates.
- Belle II
  - Hyperons from $\Upsilon(nS)$ decays
    $\rightarrow$ small BR $\rightarrow$ low event rates.
  - Belle: only small Ξ*(1820) peak on top of large ΛK background.

Facilities for strange hyperon spectroscopy

- CLAS12 and GlueX @ JLAB:
  - Hyperons from $\gamma p \rightarrow \Xi^* + 2K^+$, $\gamma p \rightarrow \Omega^* + 3K^+$.
  - Probably low cross section → low rates.
- Hall D K_L @ JLAB
  - Hyperons from $K_L\, p \rightarrow K^+ \Xi^{*-}$.
  - Large background from $K_L\, p \rightarrow K^+ X$.
- JPARC
  - Hyperons from $K^-\, p \rightarrow K^+ \Xi^{*-}$, $K^-\, p \rightarrow 2K^+ \Omega^{*-}$
  - Identification by missing mass technique → no spin-parity determination of Y^{*-}.
  - Large acceptance detector planned, design and financing not clear.

Facilities for strange hyperon spectroscopy

- PANDA @ FAIR:
  - Hyperons from $\bar{p}p \rightarrow \bar{Y}^{*}Y$, $\rightarrow \bar{Y}Y^{*}$.
  - Large σ: ~ 1*μb* for Ξ^*, 0.01-0.1 *μb* for Ω^*.
  - No extra mesons in the final state needed for strangeness conservation.
  - Symmetry in hyperon and antihyperon observables.
  - Large acceptance detector for exclusive measurements → low background.
  - All decay modes - charged and neutral – accessible.

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Facilities for strange hyperon spectroscopy

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  - Large σ: ~ 1μb for Ξ^{*}, 0.01-0.1 μb for Ω^{*} (?)
  - No extra mesons in the final state needed for strangeness conservation.
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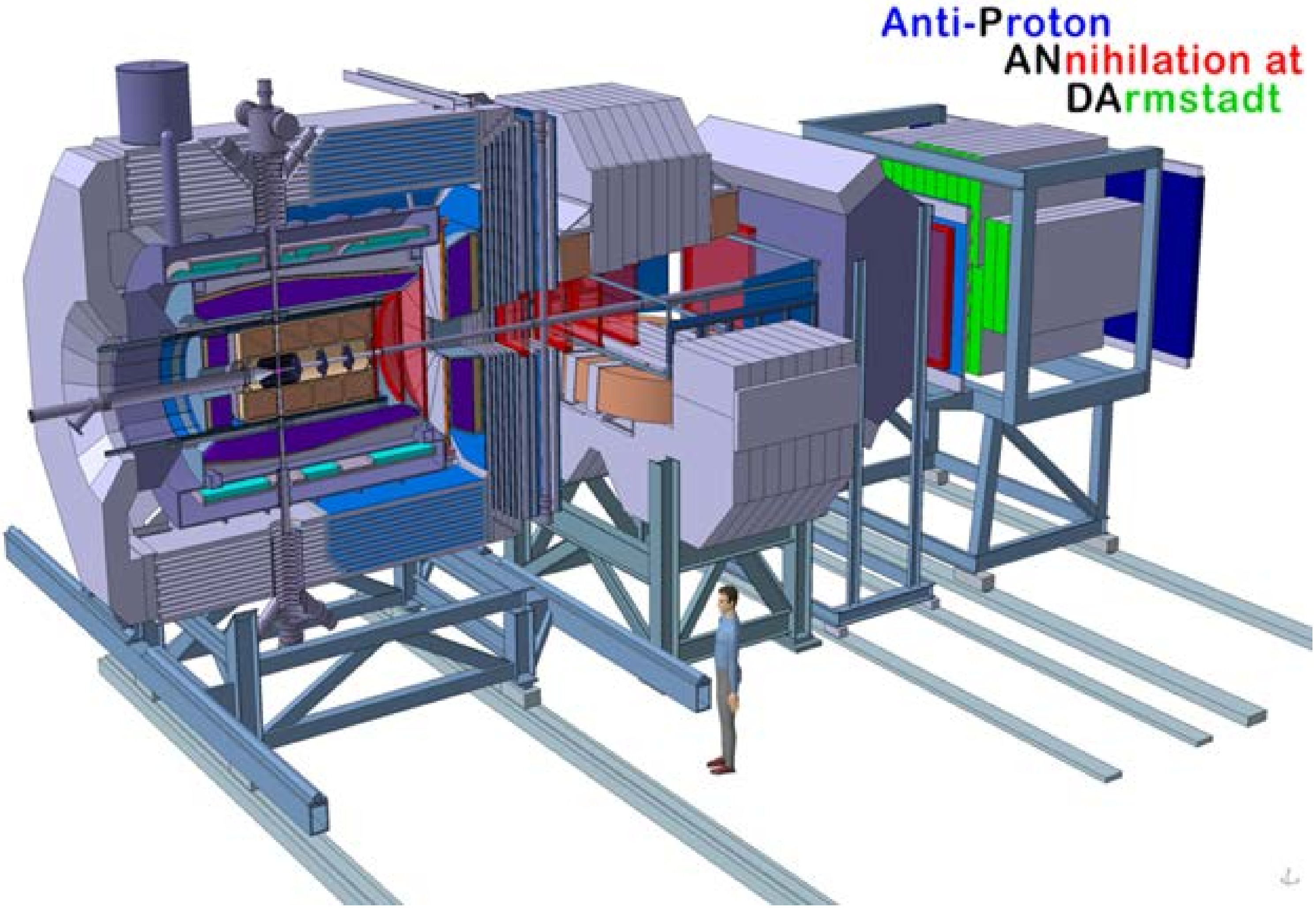
  - All decay modes - charged and neutral – accessible.

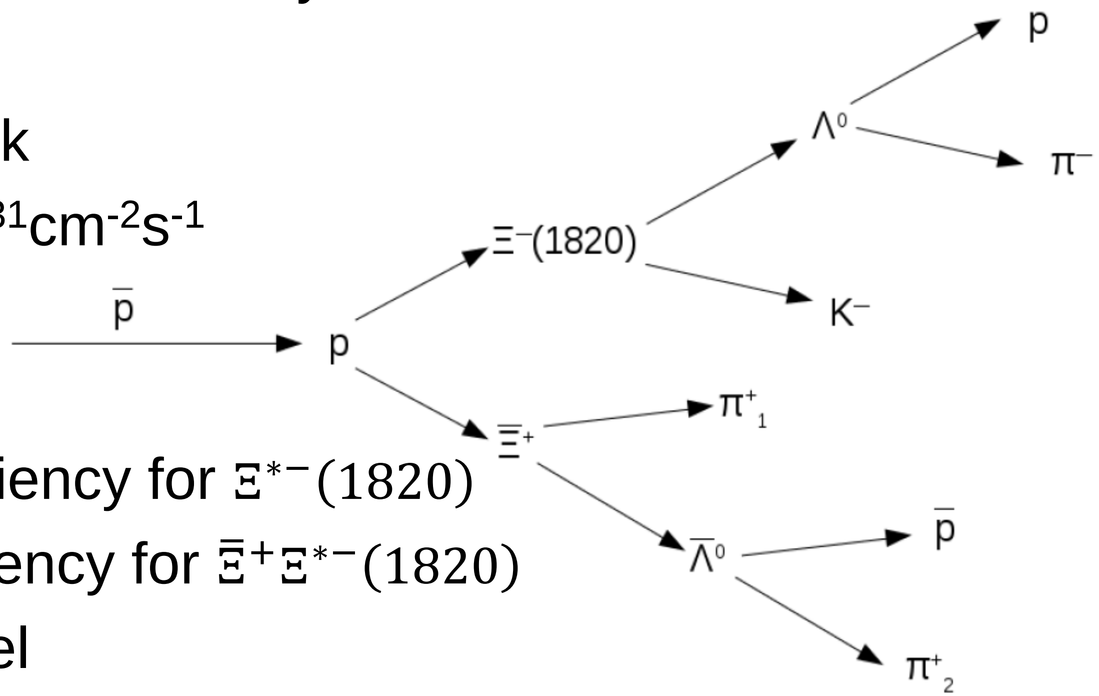
PANDA is a strangeness factory:
Can fill the gap in the strange sector!

Prospects for PANDA



Feasibility study of $\bar{p}p \rightarrow \bar{\Xi}^{+}\Xi^{*-}(1820)$

- p_{beam} = 4.6 GeV/c
- Consider the $\Xi^{*-}(1820) \rightarrow \Lambda$ K decay, assume BR = 100%
- Assume σ = 1 μb
- Simplified MC framework
- *Day One* luminosity: $10^{31}cm^{-2}s^{-1}$
- Results:
  - ~30 % inclusive efficiency for $\Xi^{*-}(1820)$
  - ~5 % exclusive efficiency for $\bar{\Xi}^{+}\Xi^{*-}(1820)$
  - Low background level
  - ~15000 exclusive events / day



J. Pütz, talk at FAIRNESS 2016

Time-line, baryon spectroscopy with PANDA

- PANDA physics from **Day One**:
  - Single- and double strange hyperons (Λ^*, Σ^* and Ξ^*)
  - Light baryons (N^*, Δ^*)
- **First years** of PANDA:
  - Triple strange hyperons (Ω^*)
- **Long-term** projects with high luminosity:
  - Single charm baryons (Λ_c^*, Σ_c^*)
  - Hidden charm baryons ($N_{c\bar{c}}$)

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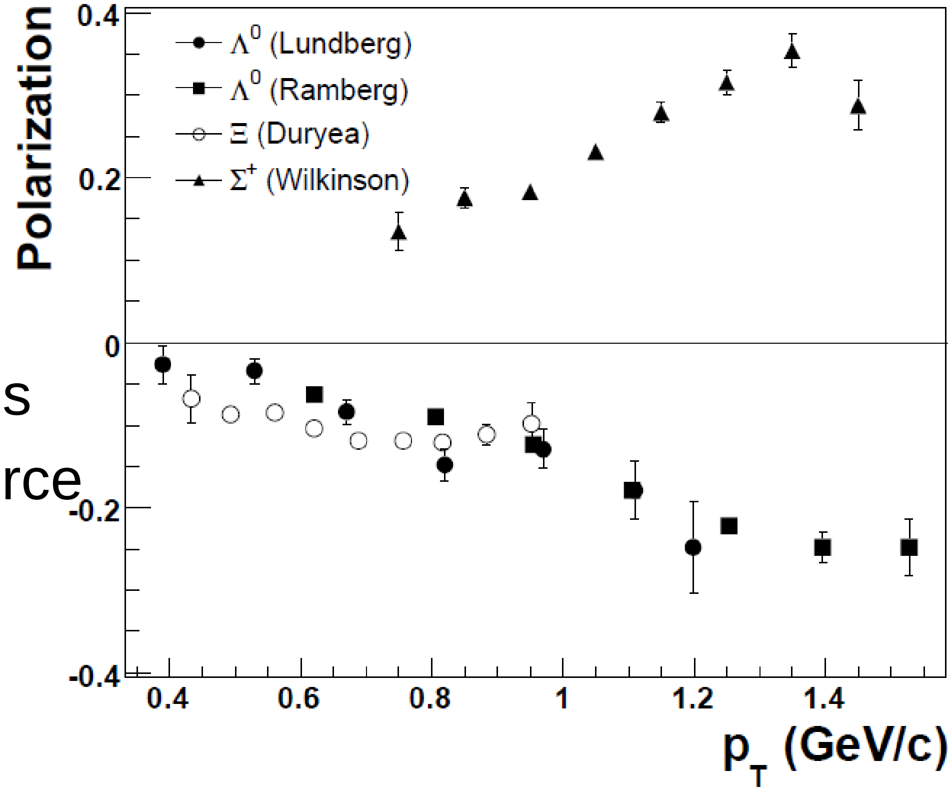
Clarify the pentaquark situation?

Part II: Hyperon spin dynamics

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

Hyperons from *pp* and *pA* reactions

- Polarization a result of interfering amplitudes.
- In hadronic reactions, many contributing sub-processes.
- High energies: total polarization should be 0.
- Data: hyperons produced polarized at high energies → contrast to naïve expectations.
- Many contributing amplitudes → difficult to pinpoint the source of polarization.



K. Heller, Colloque de Physique C6 (1990) 163

Hyperons from $\bar{p}p$ reactions

- Hyperons and anti-hyperons can be produced at low energies → fewer amplitudes contributing.

- Symmetry in hyperon and anti-hyperon observables.

- Polarization + other spin observables powerful tools for testing models of production dynamics and structure.

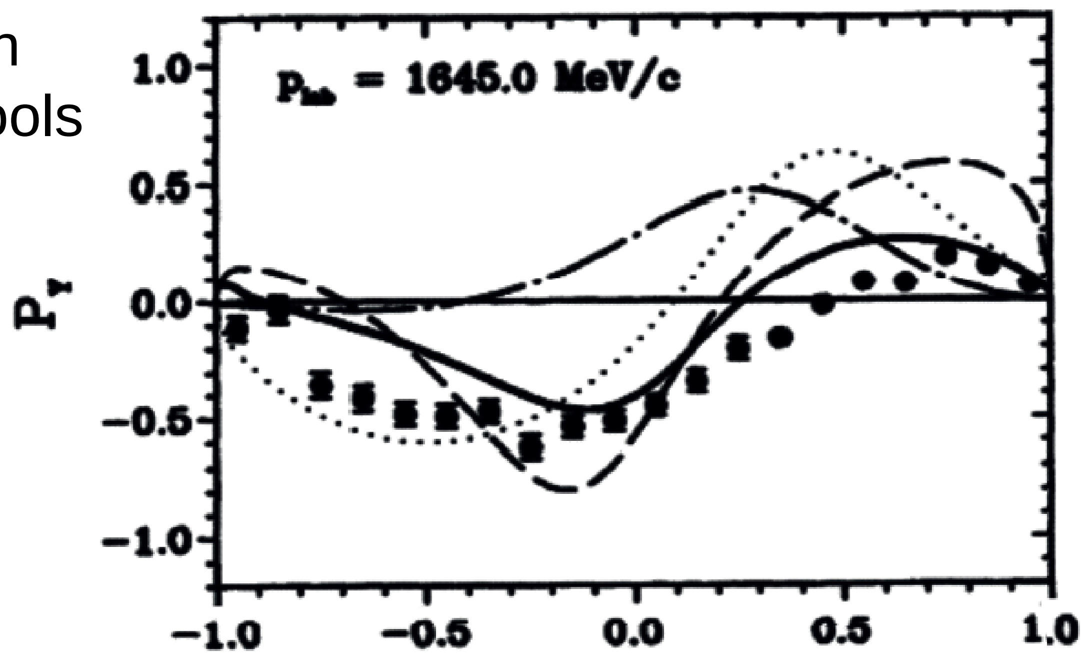
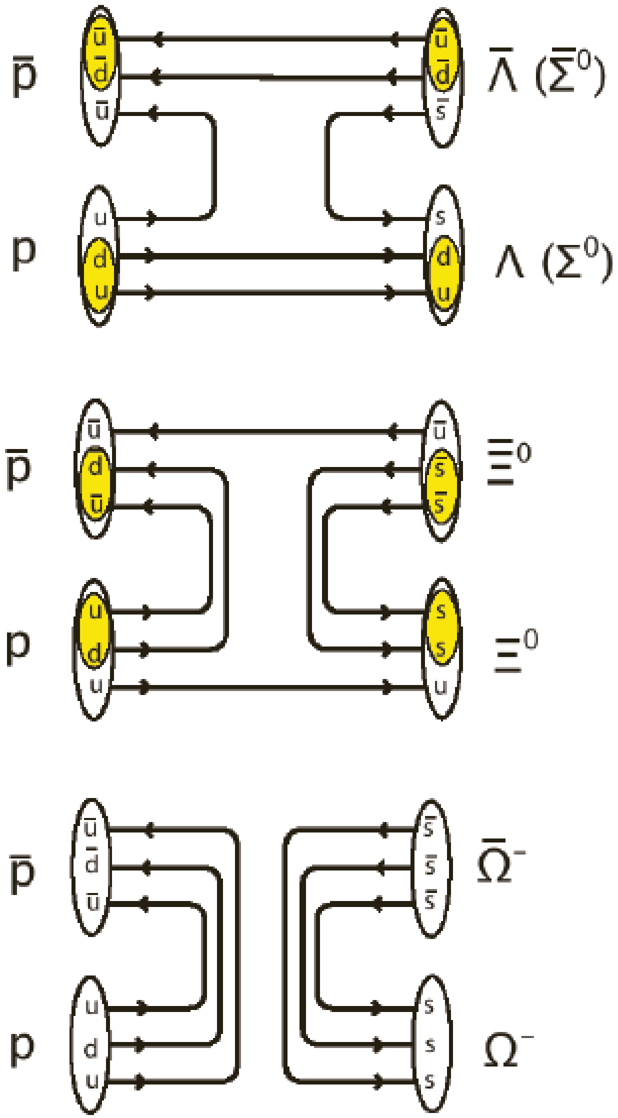
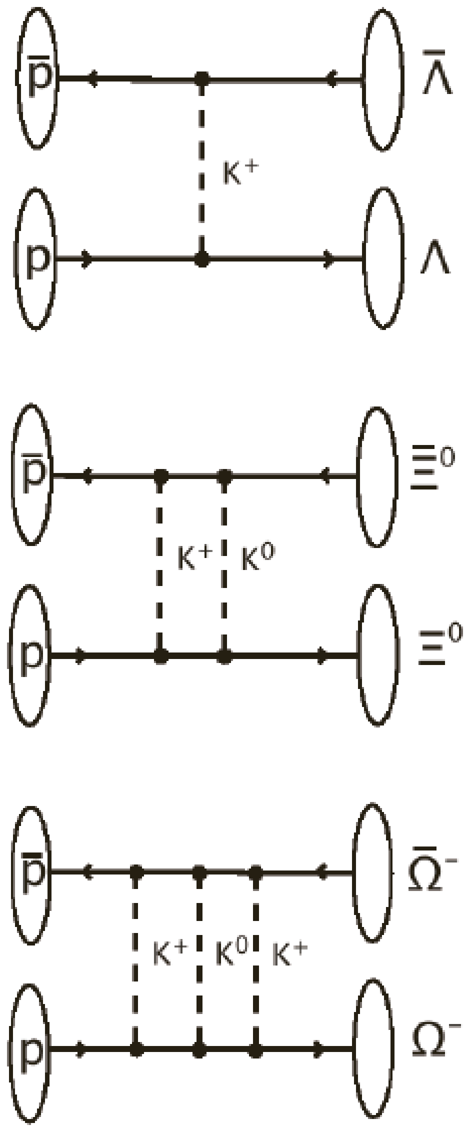


Figure from Phys. Rep. 368 (2002) 119.

Hyperons from $\bar{p}p$ reactions





Available models based on

i) constituent quark-gluons*

ii) hadrons**

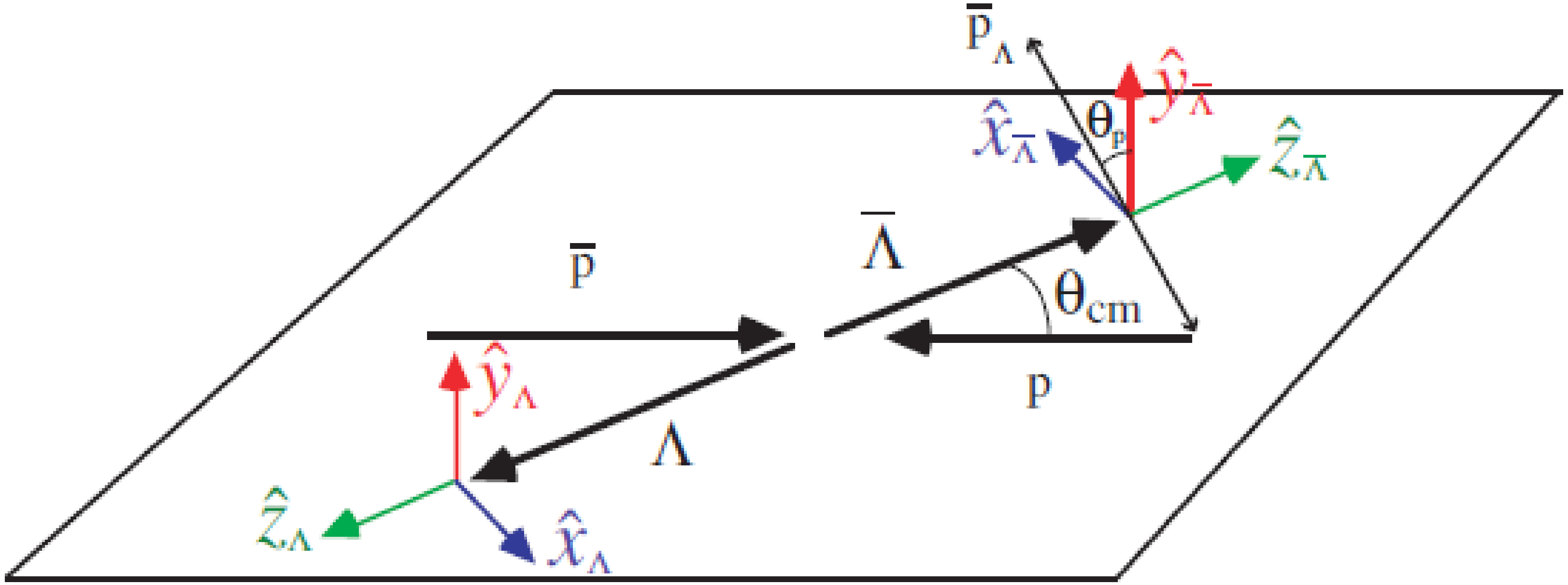
ii) a combination ***

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

- *Vector polarisation* P the most straight-forward observable for spin $\frac{1}{2}$ hyperons.

- Strong interactions: normal to the production plane (y-direction)



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

Polarisation

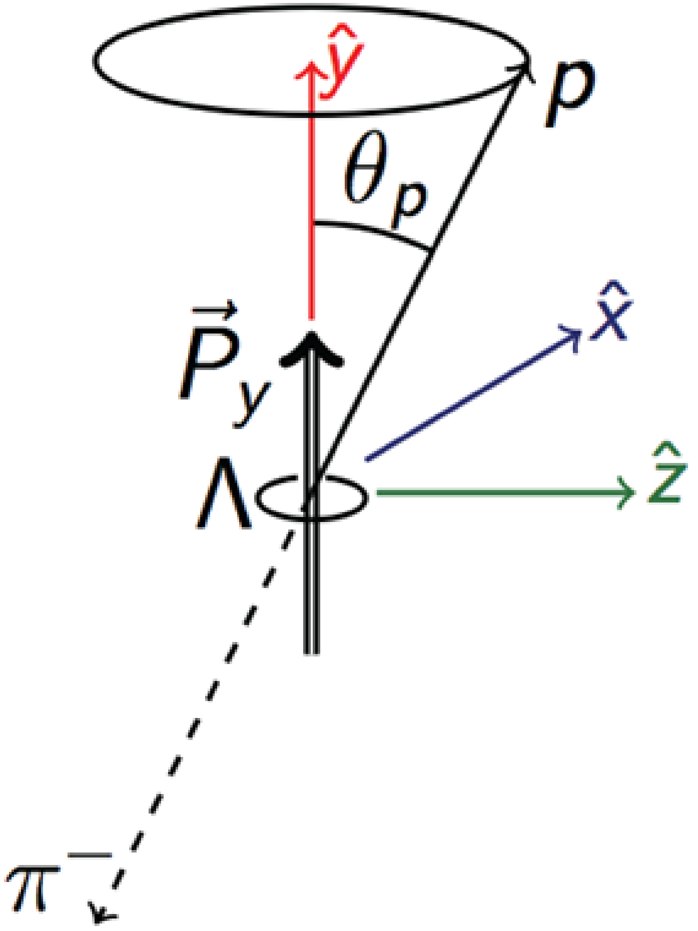
Accessible by the parity violating decay:
Decay products preferentially emitted along the spin of the hyperon.

$\Lambda \to p\pi^-$:
Proton angular distribution

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

P_Λ : polarisation

α = 0.64 asymmetry parameter

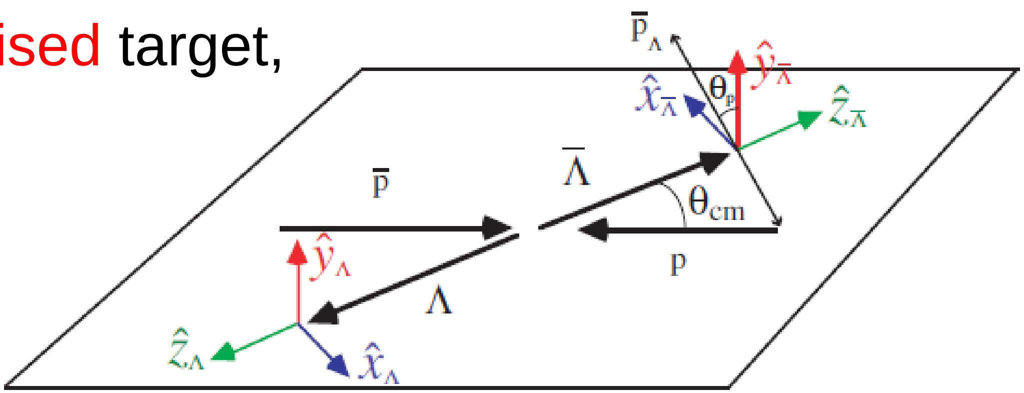


Spin observables for spin $\frac{1}{2}$ hyperons

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 $\bar{p}p \rightarrow \bar{Y}Y$ reaction there are 256 spin variables.

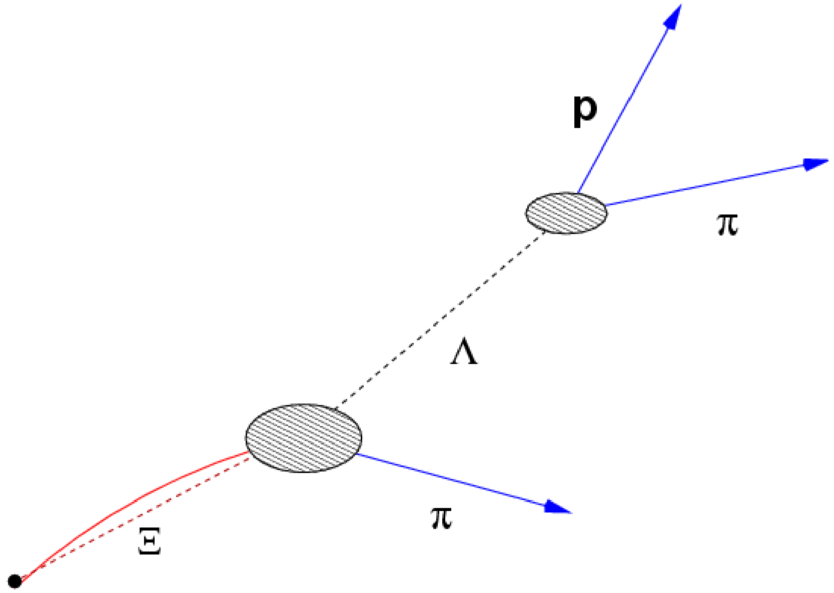
Unpolarised beam and unpolarised target, the polarisation P_{00y0} and P_{000y} and the spin correlations $C_{00\nu\mu}$ (ν,μ = x,y,z) are accessible.



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

If the decay product of the hyperon is a hyperon, *e.g.* $\Xi \to \Lambda\pi$, more information can be obtained from the decay protons of the Λ.

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



α, β, γ decay parameters.
related to the decay amplitudes T_s and T_p

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

The Ω hyperon is more complicated.

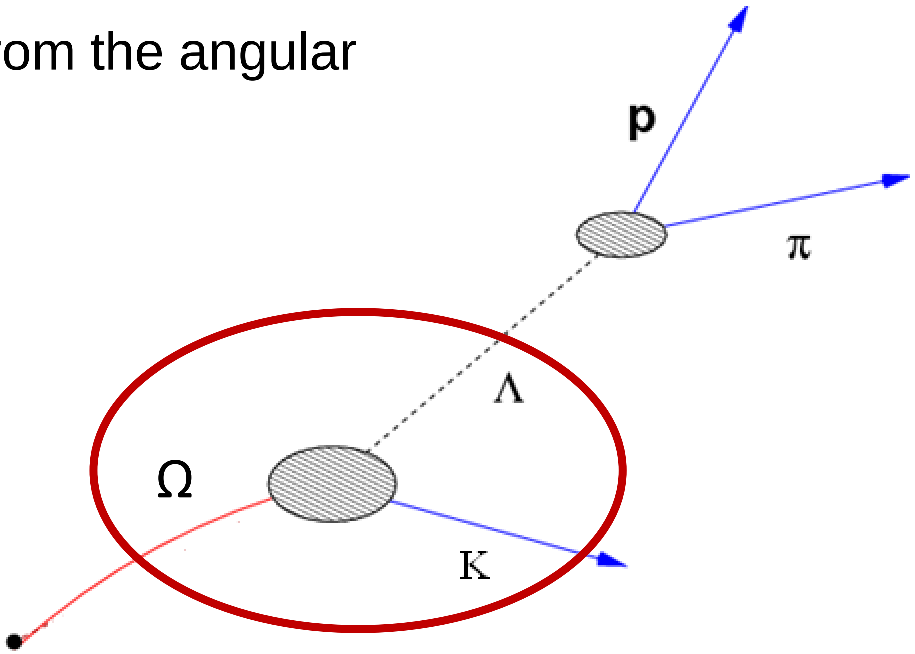
- Spin $\frac{1}{2}$: **3** polarisation parameters: r_{-1}^{1}, r_{0}^{1} and r_{1}^{1} (P_x, P_Y and P_z)
- Spin $\frac{3}{2}$: **15** polarisation parameters: r_{-1}^{1}, r_{0}^{1} , r_{1}^{1}, r_{-2}^{2}, r_{-1}^{2} ,r_{0}^{2}, r_{1}^{2}, r_{2}^{2}, r_{-3}^{3}, r_{-2}^{3}, r_{-1}^{3} , r_{0}^{3}, r_{1}^{3}, r_{2}^{3} and r_{3}^{3}.

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 $\boldsymbol{r_2^2, r_1^2, r_0^2}$ from the angular distribution of the Λ:*



$$< sin\theta_\Lambda > = \frac{\pi}{32}(8 + \boldsymbol{r_0^2}\sqrt{3})$$

$$< cos\varphi_\Lambda cos\theta_\Lambda > = -\frac{3\pi}{32}\boldsymbol{r_1^2}$$

$$< sin^2\varphi_\Lambda > = \frac{1}{4}(2 + \boldsymbol{r_2^2})$$

*calculated by Elisabetta Perotti, Uppsala U (2016)

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

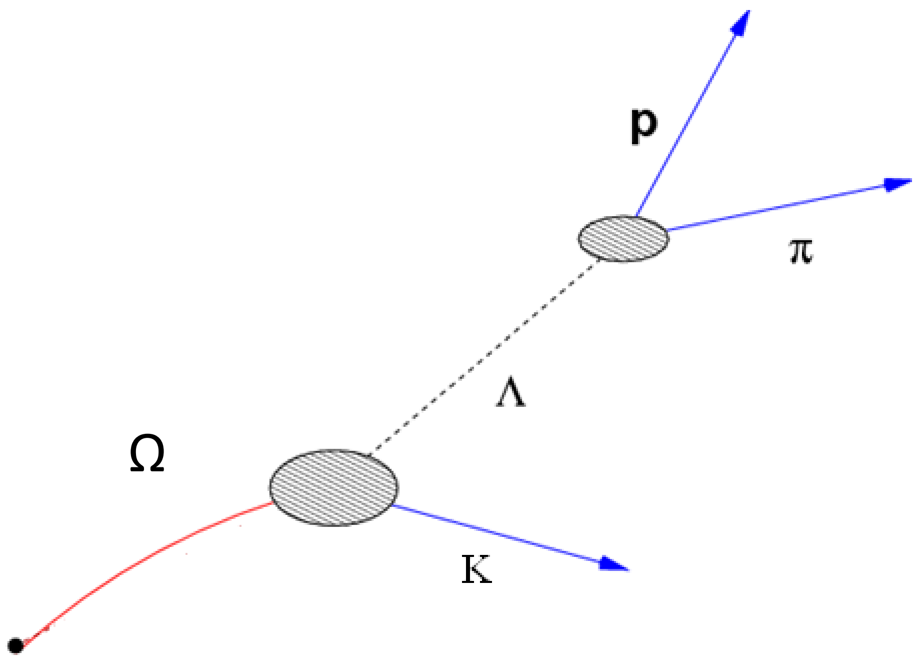
$$\langle \sin\phi_\Lambda \cos\phi_\mathrm{p} \rangle$$
$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_\mathrm{p}, \phi_\mathrm{p}) \times \sin\phi_\Lambda \cos\phi_\mathrm{p} d\Omega_\Lambda d\Omega_\mathrm{p} =$$
$$= -\frac{3\pi^2 \alpha_\Lambda \gamma_\Omega r^3_{-2}}{1024}$$

$$\langle (3\cos\theta_\Lambda - 1)\sin\phi_\mathrm{p} \rangle$$
$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_\mathrm{p}, \phi_\mathrm{p}) \times (3\cos\theta_\Lambda - 1)\sin\phi_\mathrm{p} d\Omega_\Lambda$$
$$= -\frac{\pi \alpha_\Lambda \gamma_\Omega r^3_{-1}}{4\sqrt{10}}$$

$$\langle \sin\phi_\mathrm{p} \rangle$$
$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_\mathrm{p}, \phi_\mathrm{p}) \times \sin\phi_\mathrm{p} d\Omega_\Lambda d\Omega_\mathrm{p} =$$
$$= \frac{\pi \alpha_\Lambda \gamma_\Omega}{160}\left(-4\sqrt{15} r^1_{-1} + \sqrt{10} r^3_{-1}\right)$$

$$\langle \sin\phi_\Lambda \cos\phi_\Lambda \cos\phi_\mathrm{p} \rangle$$
$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_\mathrm{p}, \phi_\mathrm{p}) \times \sin\phi_\Lambda \cos\phi_\Lambda \cos\phi_\mathrm{p} d\Omega_\Lambda d\Omega_\mathrm{p} =$$
$$= \frac{\pi \alpha_\Lambda \gamma_\Omega}{640}\left(5\sqrt{6} r^3_{-3} + 4\sqrt{15} r^1_{-1} - \sqrt{10} r^3_{-1}\right)$$

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



*Erik Thomé, Ph. D. Thesis and Elisabetta Perotti, private communication

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

$$\langle \sin\phi_\Lambda \cos\phi_{\rm p}\rangle$$

$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_{\rm p}, \phi_{\rm p}) \times \sin\phi_\Lambda \cos\phi_{\rm p} d\Omega_\Lambda d\Omega_{\rm p} =$$

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

$$\langle (3\cos\theta_\Lambda - 1)\sin\phi_{\rm p}\rangle$$

$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_{\rm p}, \phi_{\rm p}) \times (3\cos\theta_\Lambda - 1)\sin\phi_{\rm p} d\Omega_\Lambda$$

$$= -\frac{\pi \alpha_\Lambda \gamma_\Omega r^3_{-1}}{4\sqrt{10}}$$

$$\langle \sin\phi_{\rm p}\rangle$$

$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_{\rm p}, \phi_{\rm p}) \times \sin\phi_{\rm p} d\Omega_\Lambda d\Omega_{\rm p} =$$

$$= \frac{\pi \alpha_\Lambda \gamma_\Omega}{160}\left(-4\sqrt{15} r^1_{-1} + \sqrt{10} r^3_{-1}\right)$$

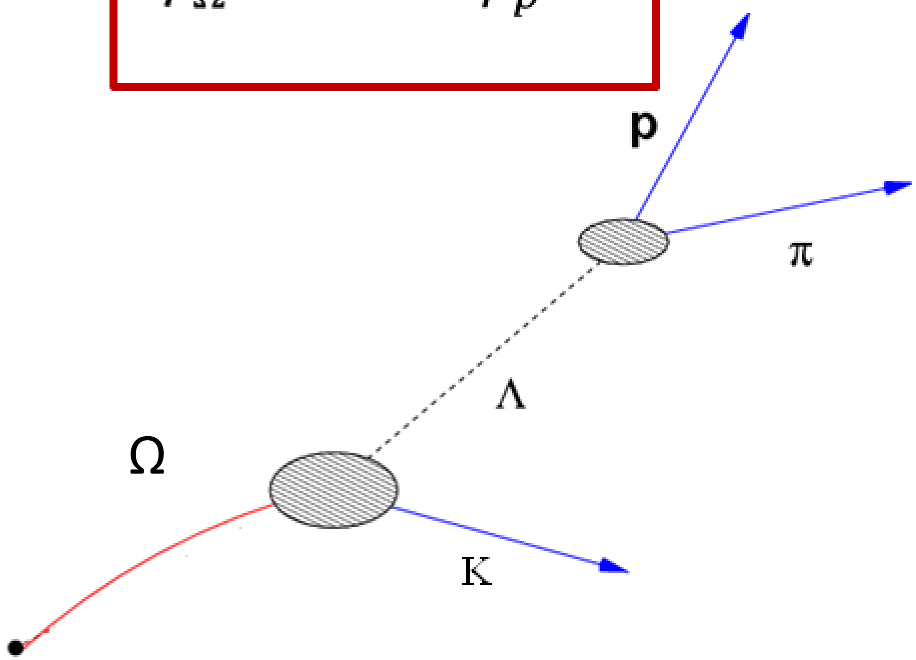
$$\langle \sin\phi_\Lambda \cos\phi_\Lambda \cos\phi_{\rm p}\rangle$$

$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_{\rm p}, \phi_{\rm p}) \times \sin\phi_\Lambda \cos\phi_\Lambda \cos\phi_{\rm p} d\Omega_\Lambda d\Omega_{\rm p} =$$

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

Furthermore:

$$\frac{\beta_\Omega}{\gamma_\Omega} = \frac{< cos\varphi_p >}{< sin\varphi_p >}$$



*Erik Thomé, Ph. D. Thesis and Elisabetta Perotti, private communication

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 decays

- CP violation of baryon decays has never been observed.
- The $\bar{p}p \to \bar{Y}Y$ process suitable for CP measurements (clean, no mixing)
- If CP valid, $\alpha = -\bar{\alpha}$ and $\beta = -\bar{\beta}$.
- CP violation parameters:

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

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

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

- More precise measurements needed.
- A accessible for Λ, Ξ and Λ_c .
- B, B' accessible for Ξ and Λ_c .
- Controlling systematics the main challenge.

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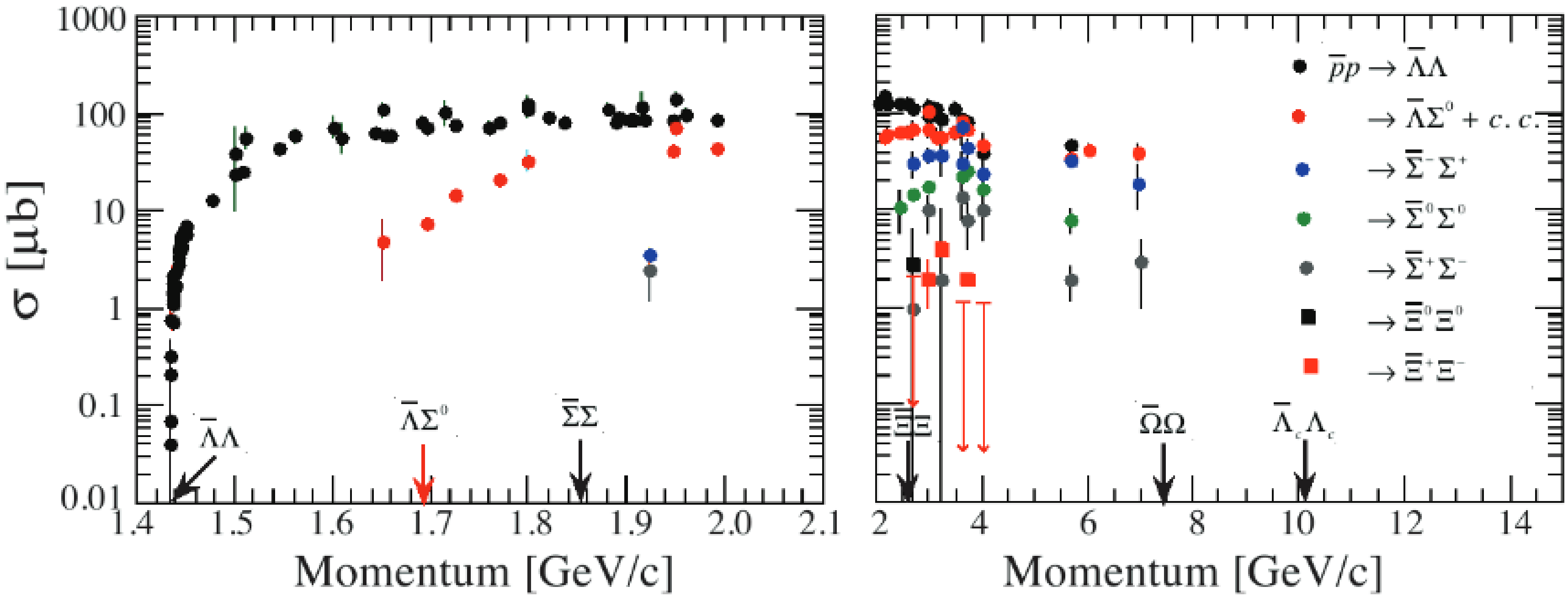
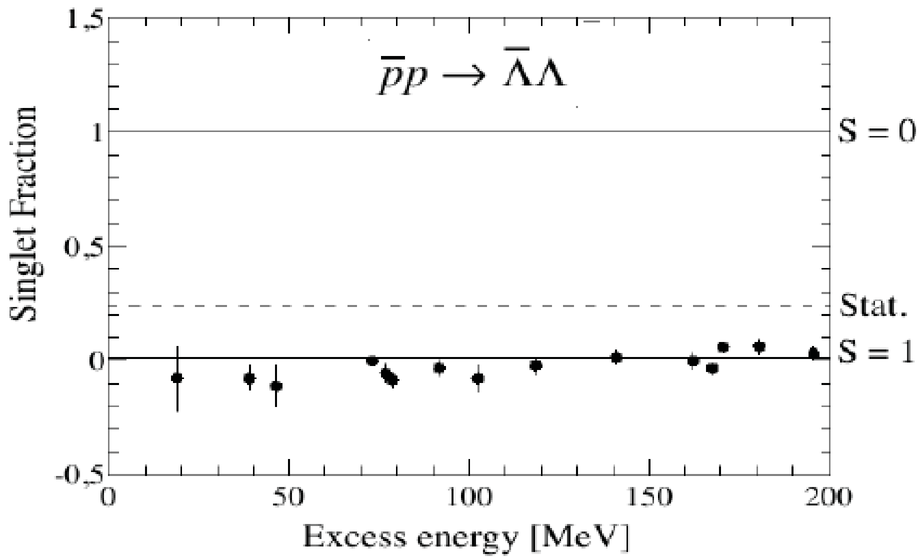
Previous measurements of $\bar{p}p \to \bar{Y}Y$

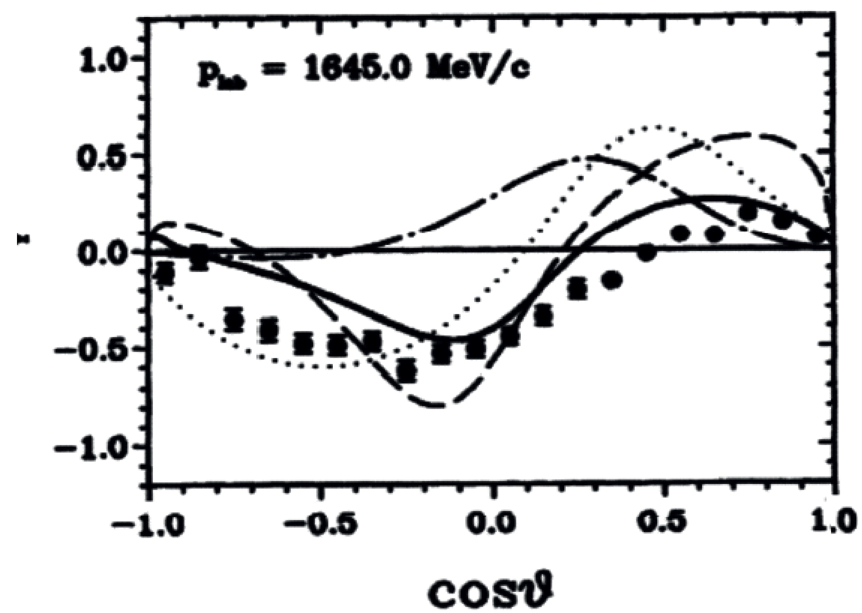


- A lot of data on $\bar{p}p \to \bar{\Lambda}\Lambda$ near threshold, mainly from PS185 at LEAR*.
- Very scarce data bank above 4 GeV.
- Only a few bubble chamber events on $\bar{p}p \to \bar{\Xi}\Xi$
- No data on $\bar{p}p \to \bar{\Omega}\Omega$ nor $\bar{p}p \to \bar{\Lambda}_c\Lambda_c$

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

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





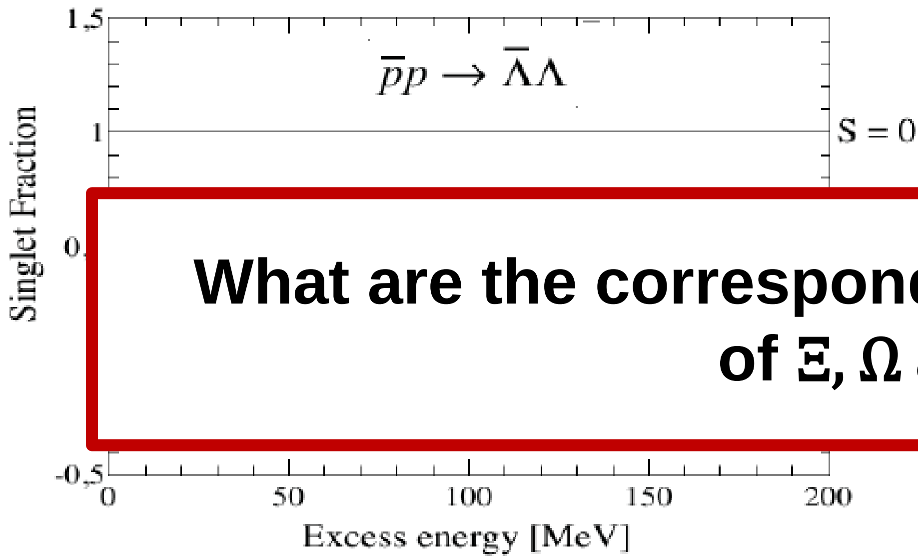
- $\bar{\Lambda}\Lambda$ almost always produced in a spin triplet state*:

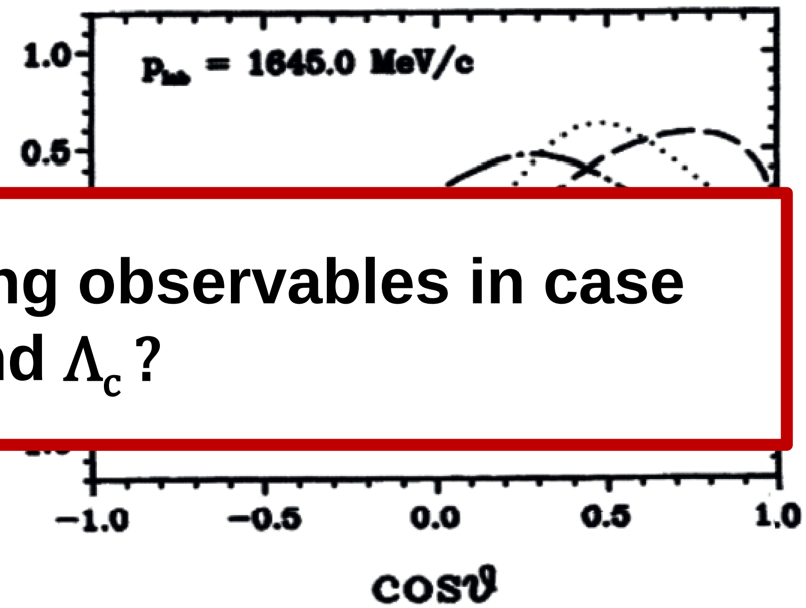
$$SF = \frac{1}{4}(1 + C_{xx} - C_{yy} + C_{zz})$$

- 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.

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





What are the corresponding observables in case of Ξ, Ω and Λ_c?

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

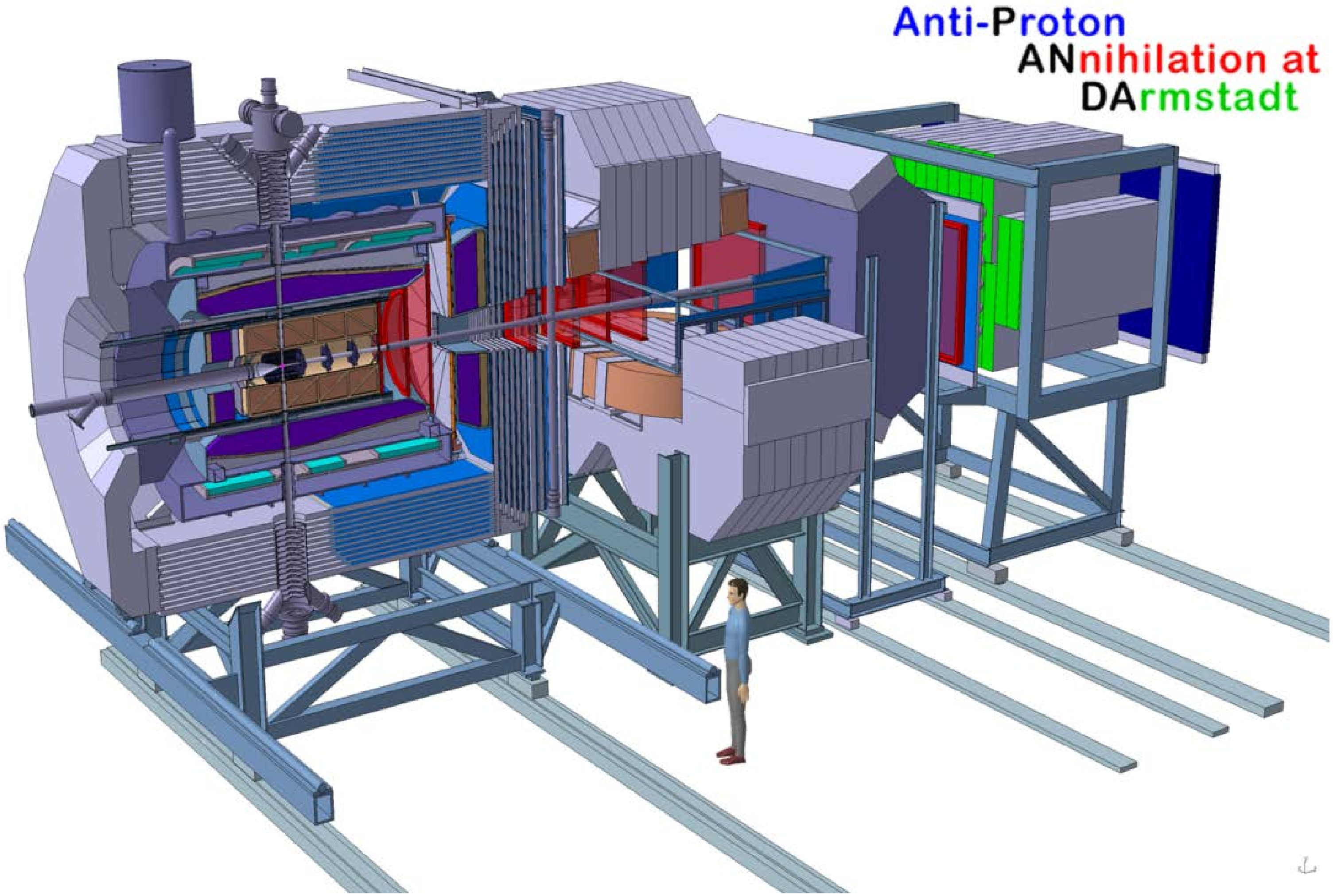
$$SF = \frac{1}{4}(1 + C_{xx} - C_{yy} + C_{zz})$$

- 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



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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.
- Assume Day One luminosity of the HESR.
- Cross sections of $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ and $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^o$ known near threshold.
- $\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$ measured with large uncertainty.
- Conservative 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 (with 10^{31} $cm^{-1}s^{-1}$)
1.64	$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$	64	10	30 s^{-1}
4	$\bar{p}p \rightarrow \bar{\Lambda}\Sigma^o$	~40	30	30 s^{-1}
4	$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	~2	20	2 s^{-1}
12	$\bar{p}p \rightarrow \bar{\Omega}^+\Omega^-$	~0.002	30	~4 h^{-1}
12	$\bar{p}p \rightarrow \bar{\Lambda}_c^-\Lambda_c^+$	~0.1	35	~2 day^{-1}

Gain a factor of 100 with inclusive measurement

*Sophie Grape, Ph. D. Thesis, Uppsala University 2009, ** Erik Thomé, Ph. D. Thesis, UU 2012

Prospects for PANDA

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12	$\bar{p}p \rightarrow \bar{\Lambda}_{c}^{-}\Lambda_{c}^{+}$	~0.1	35	~2 day^{-1}

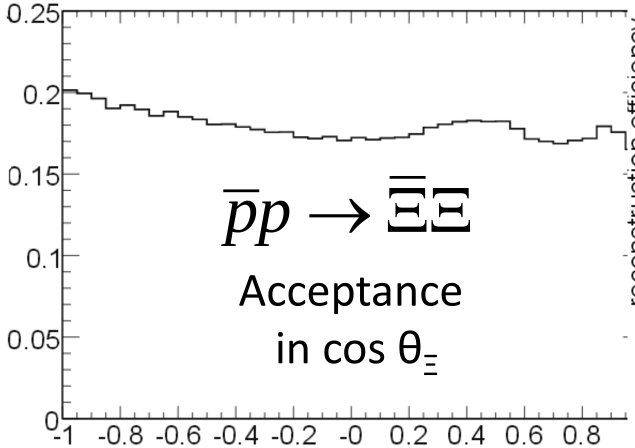
Gain a factor of 100 with inclusive measurement

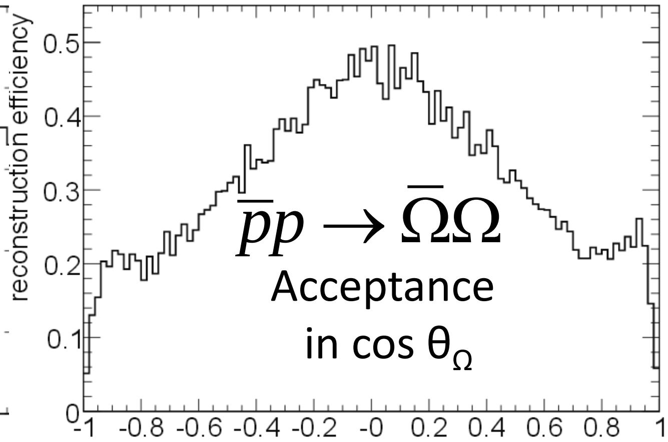
- High event rates for Λ and Σ *.
- Low background for Λ and Σ *.
- Even with conservative cross section estimates, Ω and Λ_c channels are feasible. **
- New efficiency studies using sophisticated MC framework underway.

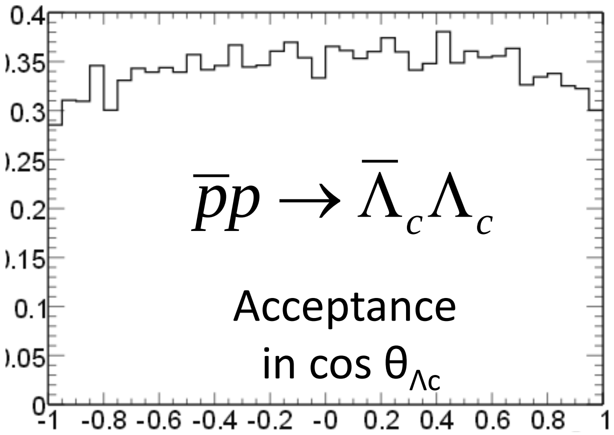
*Sophie Grape, Ph. D. Thesis, Uppsala University 2009, ** Erik Thomé, Ph. D. Thesis, UU 2012

Prospects for PANDA

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







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

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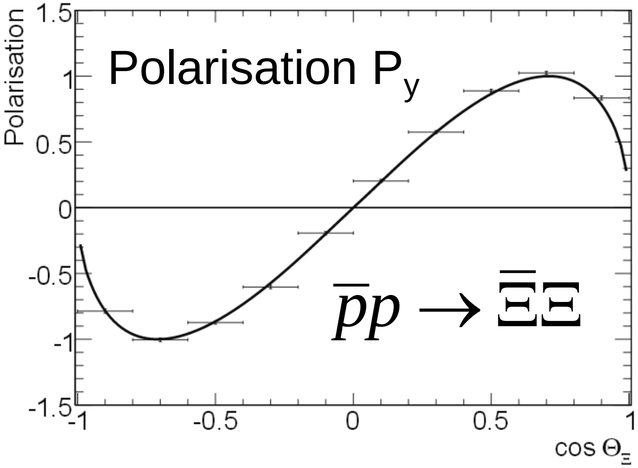
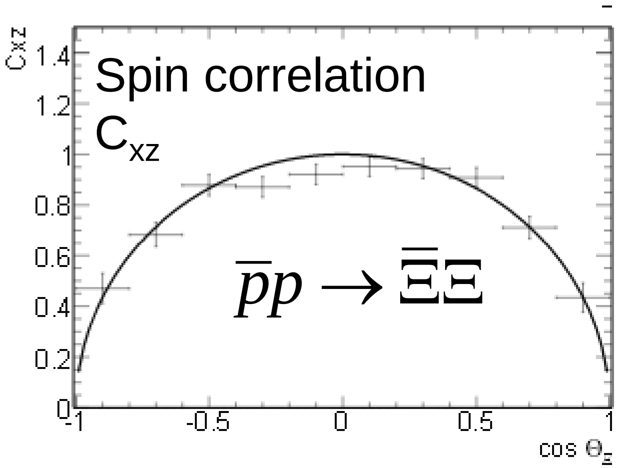
Prospects for PANDA at FAIR

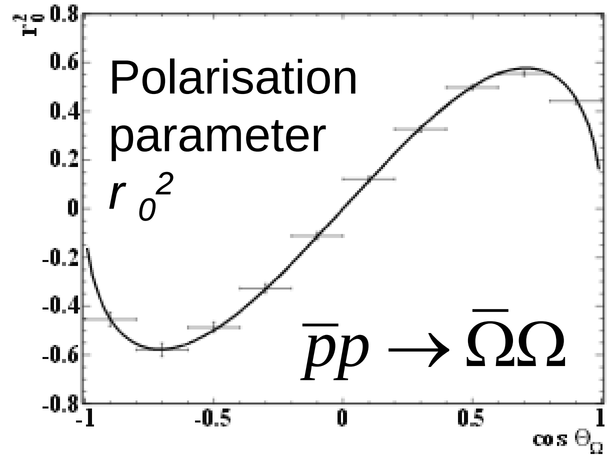
- Parametrisation of spin variables using weights:

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

- 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).

Time-line, hyperon spin dynamics with PANDA

- PANDA physics from **Day One**:
  - Spin observables of single- and double strange hyperons.
- **First years** of PANDA:
  - Polarisation parameters of Ω^-.
- **Long-term** projects with high luminosity:
  - Spin observables of Λ^+_c .
  - CP violation in Λ and Ξ decays.

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Summary

- 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:
  - **Best** prospects for double- and triple strange hyperon spectroscopy.
  - **Only** possible experiment for spin observables in $\bar{p}p \to \bar{Y}Y$.

Summary and Outlook

- Production of strange and charmed hyperons probe QCD at two different energy scales.
- The role of spin in the strong interaction can be explored with hyperon spin observables.
- Polarisation parameters of $p\overline{p} \to \Omega\overline{\Omega}$ have been derived.
- Simulation studies show excellent prospects for antihyperon-hyperon channels with PANDA.

Time-line, hyperon physics with PANDA

- PANDA physics from **Day One**:
  - Single- and double strange hyperon spectroscopy.
  - Spin observables of single- and double strange hyperons.
- **First years** of PANDA:
  - Triple strange hyperon spectroscopy.
  - Polarisation parameters of Ω^-.
- **Long-term** projects with high luminosity:
  - Single charm baryon spectroscopy.
  - Spin observables of Λ^+_c .
  - CP violation in Λ and Ξ decays.

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Thanks to:

Albrecht Gillitzer, Stefan Leupold, Vasiliy Mocharov, Elisabetta Perotti, Sophie Grape, Tord Johansson and Erik Thomé.

Backup

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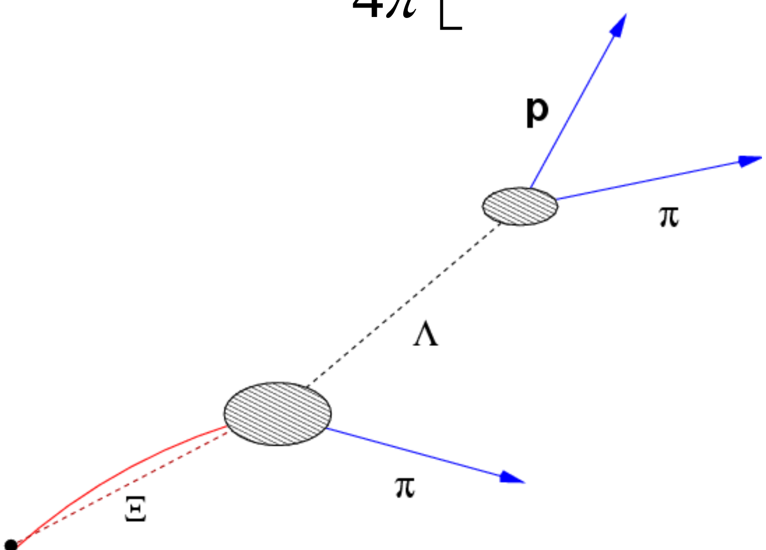
Spin observables for spin $\frac{1}{2}$ hyperons

If the decay product of the hyperon is a hyperon, *e.g.* $\Xi \rightarrow \Lambda K$, 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:

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

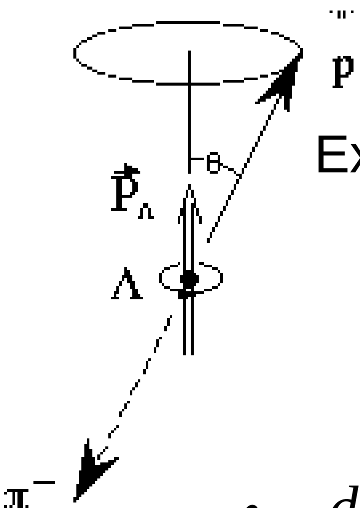


Spin observables for spin $\frac{1}{2}$ hyperons

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 $P_n = \frac{3}{\alpha_\Lambda}\langle\cos\theta_p\rangle$