Hyperon Spectroscopy and Dynamics with PANDA at FAIR

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for the PANDA collaboration

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Outline

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

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Introduction

Key questions

How is the visible mass of the universe generated?

What is the structure of matter?

Why and how are quarks confined into hadrons?

Matter-antimatter asymmetry of the universe?

Hypothesis

Hyperons as diagnostic tool

Topic

Hyperon spectroscopy

Hyperon production and spin dynamics

CP violation in hyperon decays

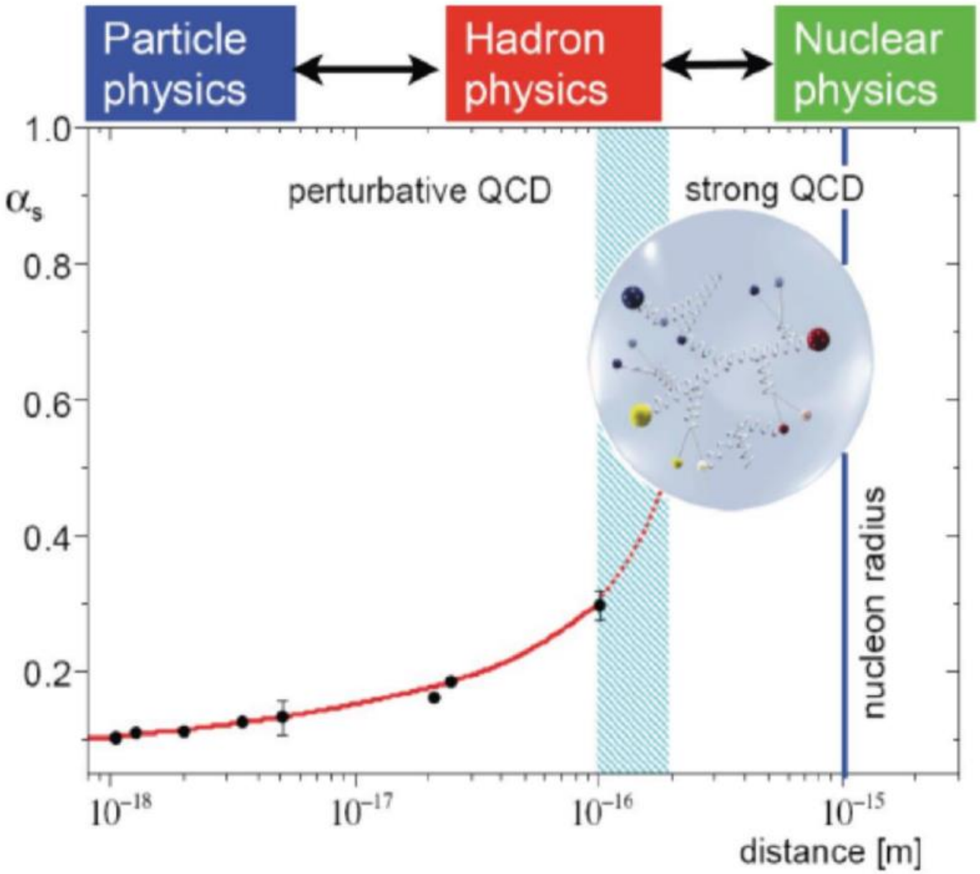
Introduction

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?

Why hyperons?

Hyperon Spectroscopy

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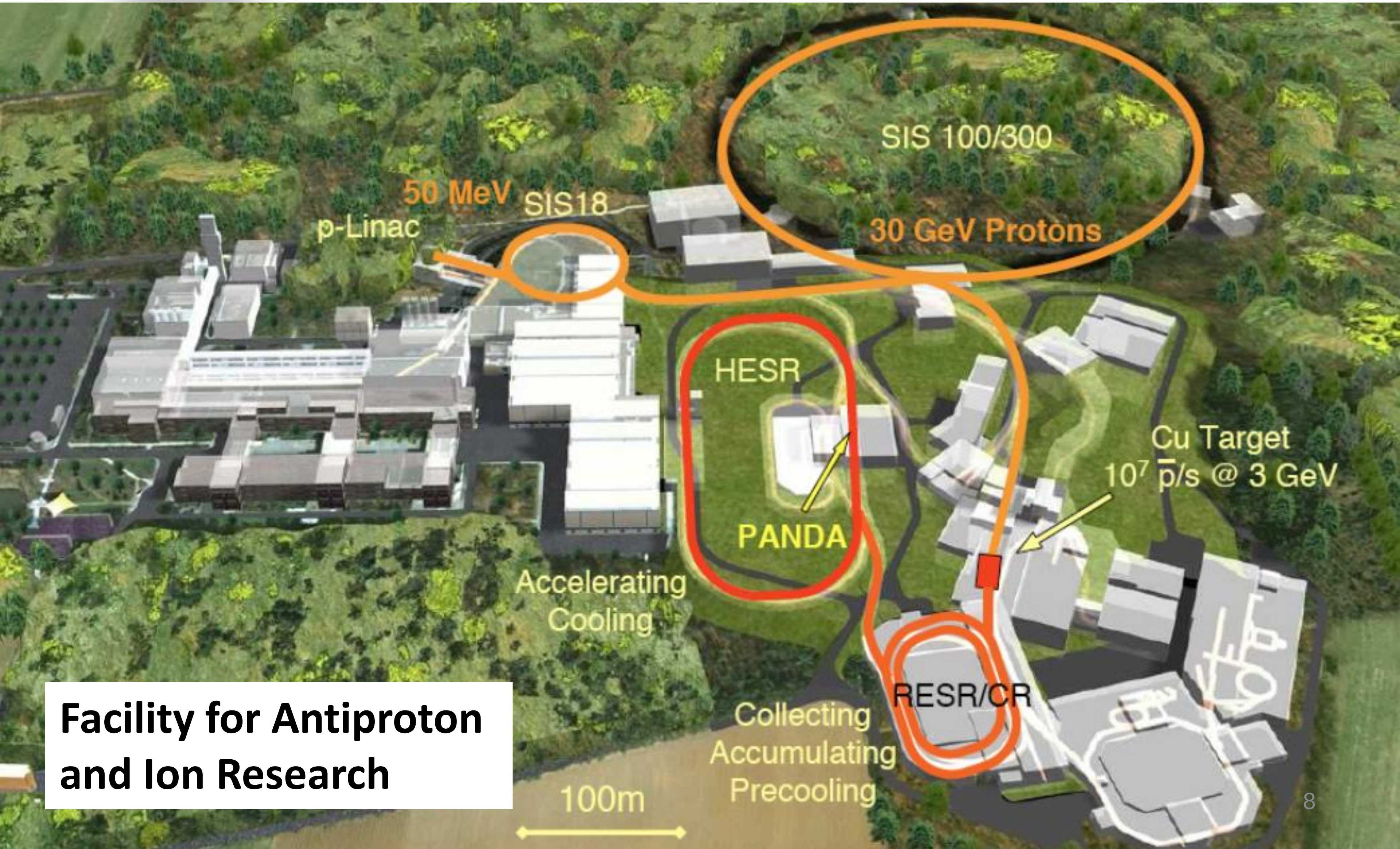
Hyperon Spin Dynamics

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

The PANDA experiment at FAIR

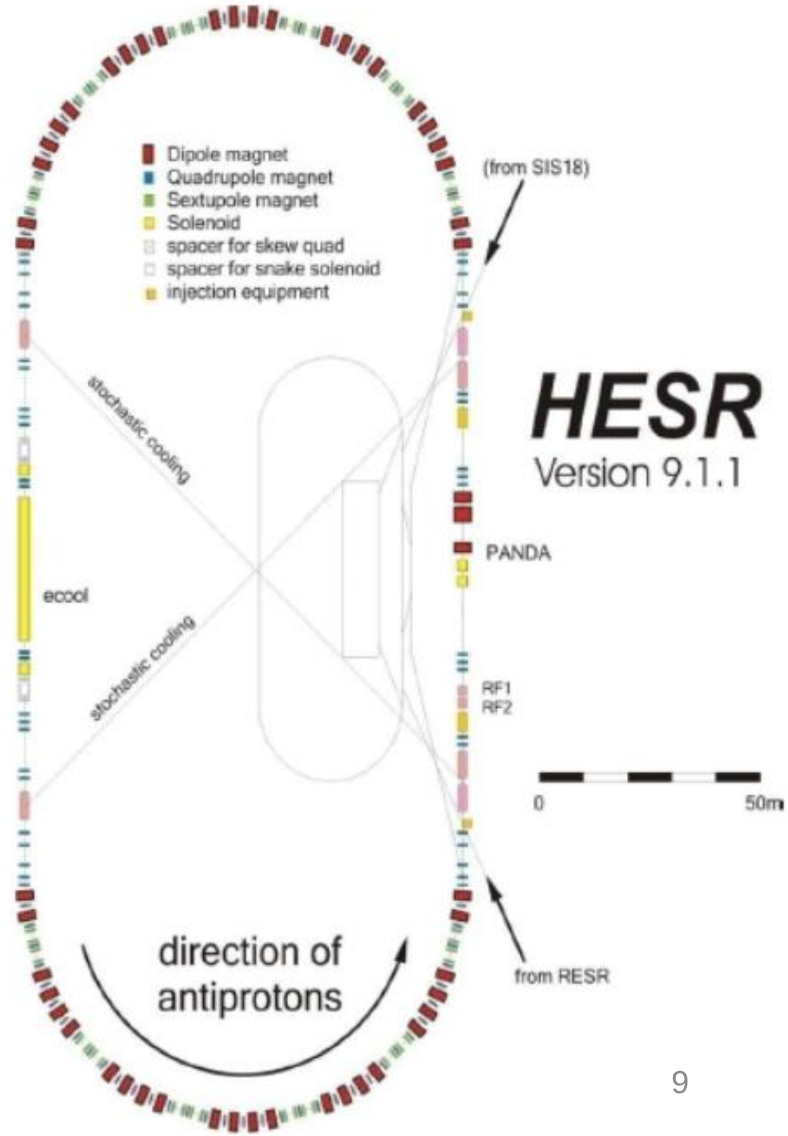


Facility for Antiproton and Ion Research

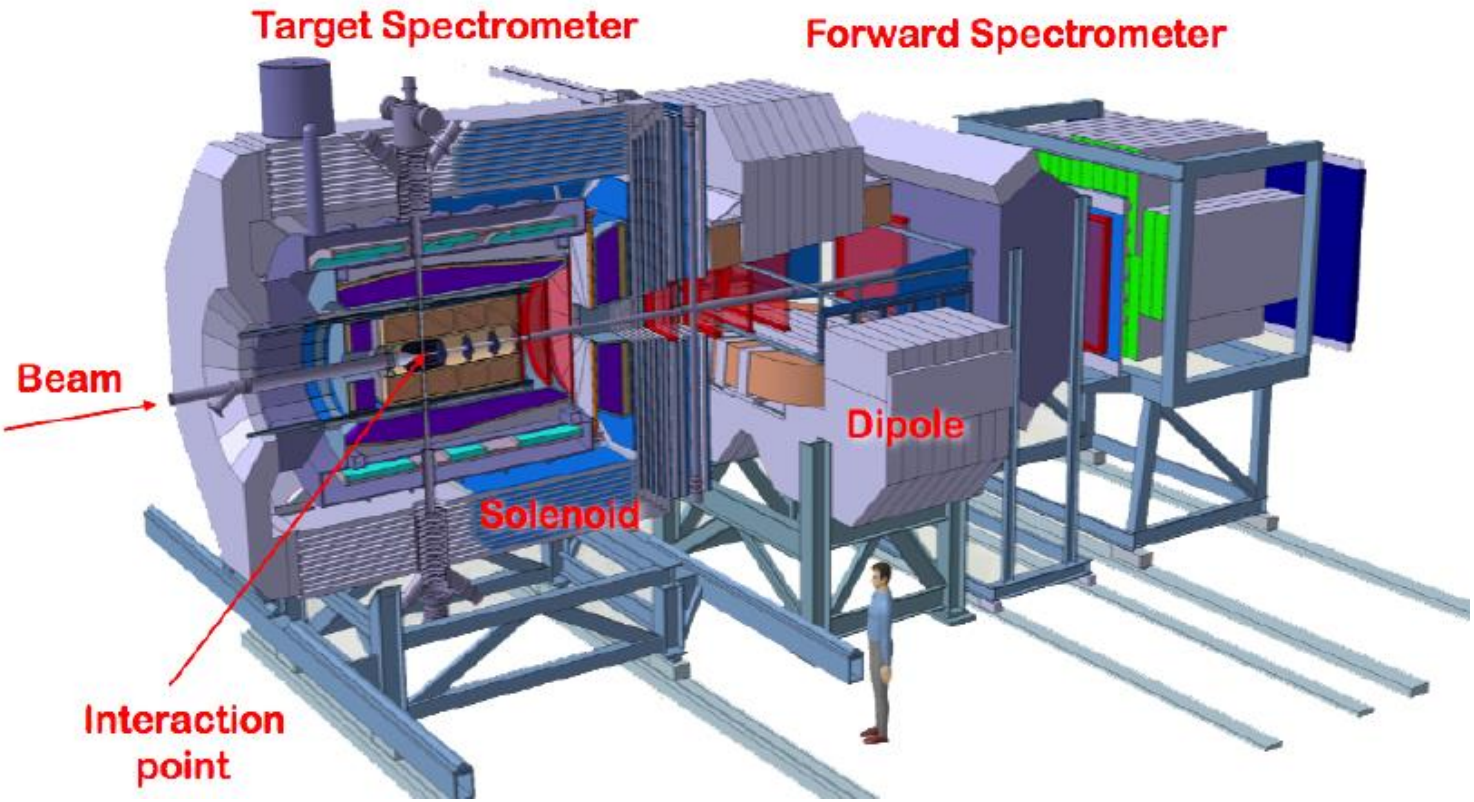
The PANDA experiment at FAIR

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}
  – $\Delta p/p < 5\cdot10^{-5}$
  – stochastic + electric cooling < 9 GeV/c
- High Luminosity Mode
  – $L = 2\cdot10^{32}$ 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

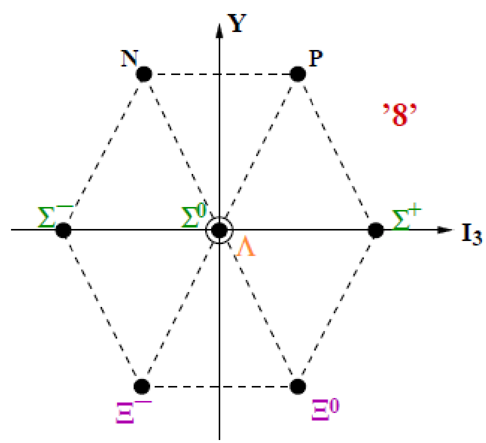


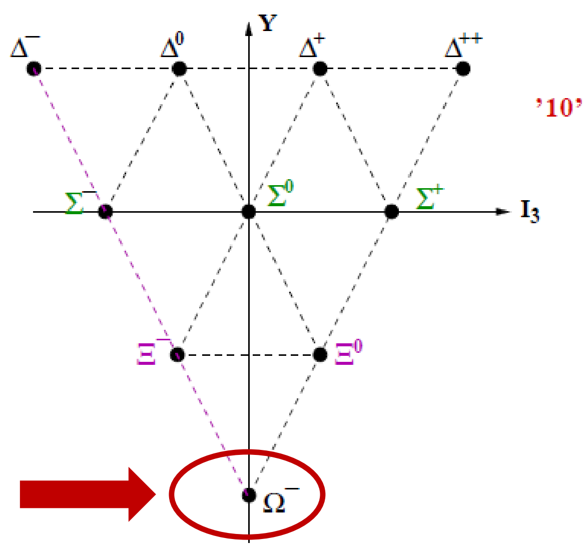
- 4π coverage
- Precise tracking
- PID
- Calorimetry
- Vertex detector
- Modular design
- Time-based data acquisition with software trigger

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

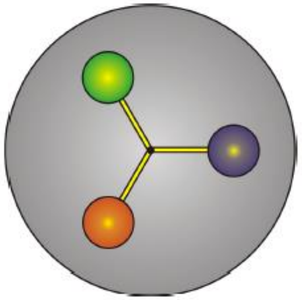
*PR 125 (1962) 1067
**PRD 58 (1998) 094030

Light baryon spectroscopy

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

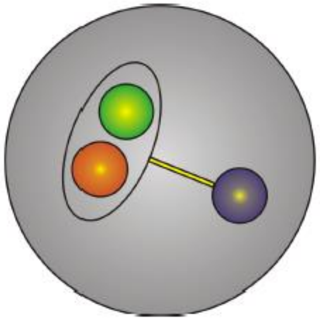
Open questions regarding the excited light baryon spectrum:*

- Missing states?
- Order of states?
- Parity doublets?



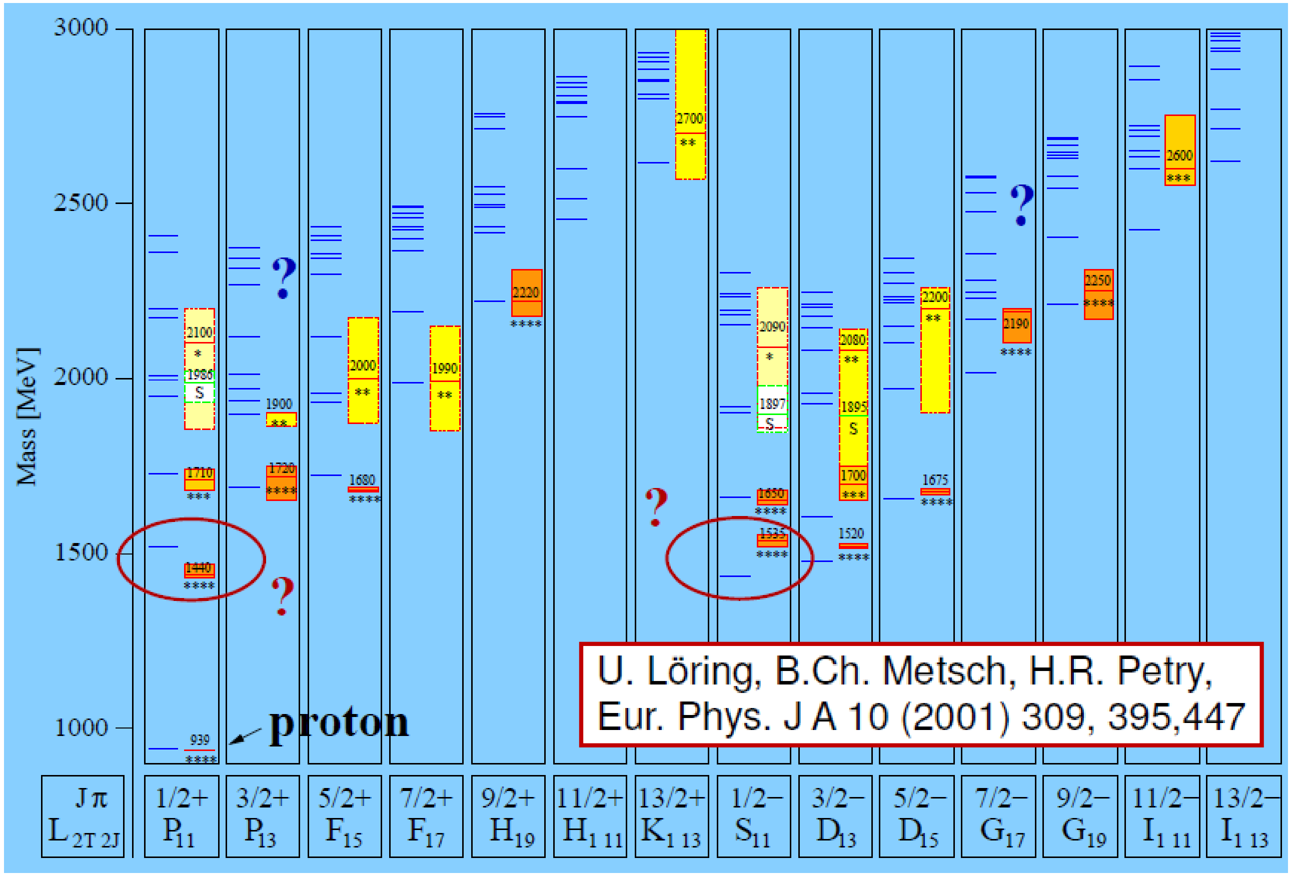
Degrees of freedom and effective forces?

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



*EPJA 48 (2012) 127

Light baryon spectroscopy

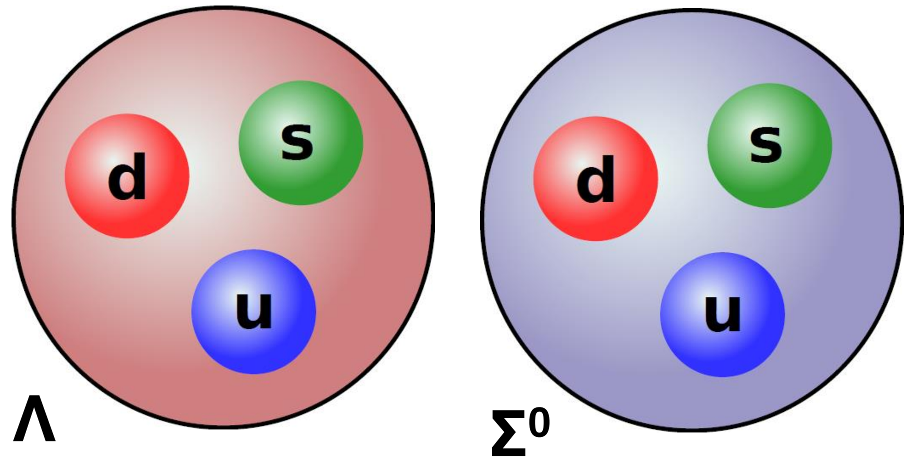


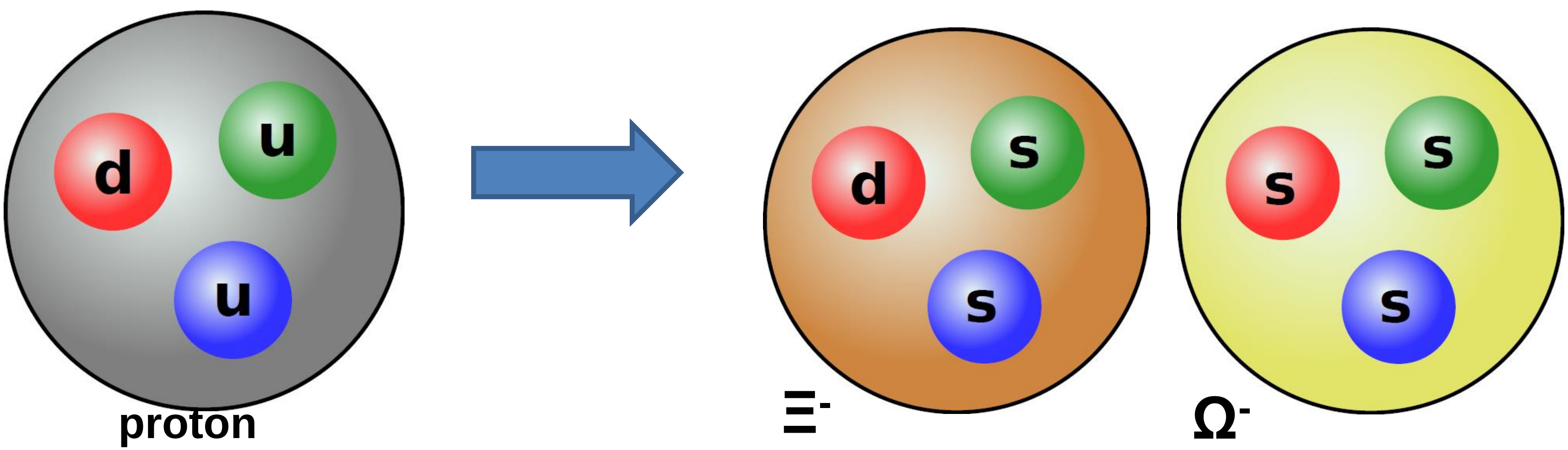
Missing states: # of observed states < # of predicted states

- Because there are no such states
- or because they do not couple to $N\pi$ final states?

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

- 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_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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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

- PANDA @ FAIR:
  - Hyperons from $\bar{p}p \to \bar{Y}^{*}Y, \to \bar{Y}Y^{*}$.
  - Large expected cross sections for multi-strange baryons.
  - Clean, well defined final state.
  - Symmetry in hyperon and antihyperon observables.
  - Exclusive measurements → low background.
  - All decay modes - charged and neutral – accessible.

Facilities for strange hyperon spectroscopy

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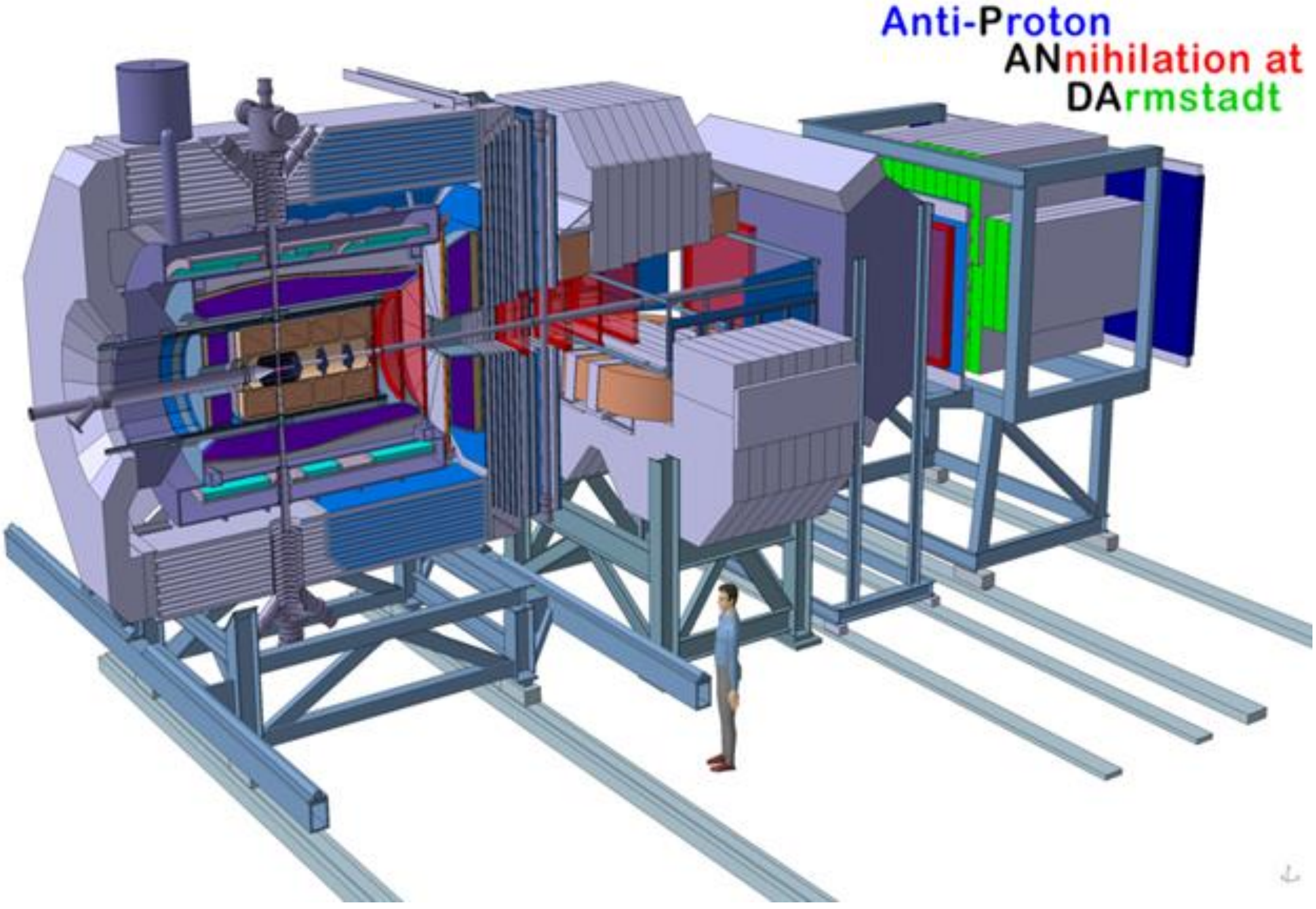
PANDA is a strangeness factory:
Can fill the gap in the strange sector!

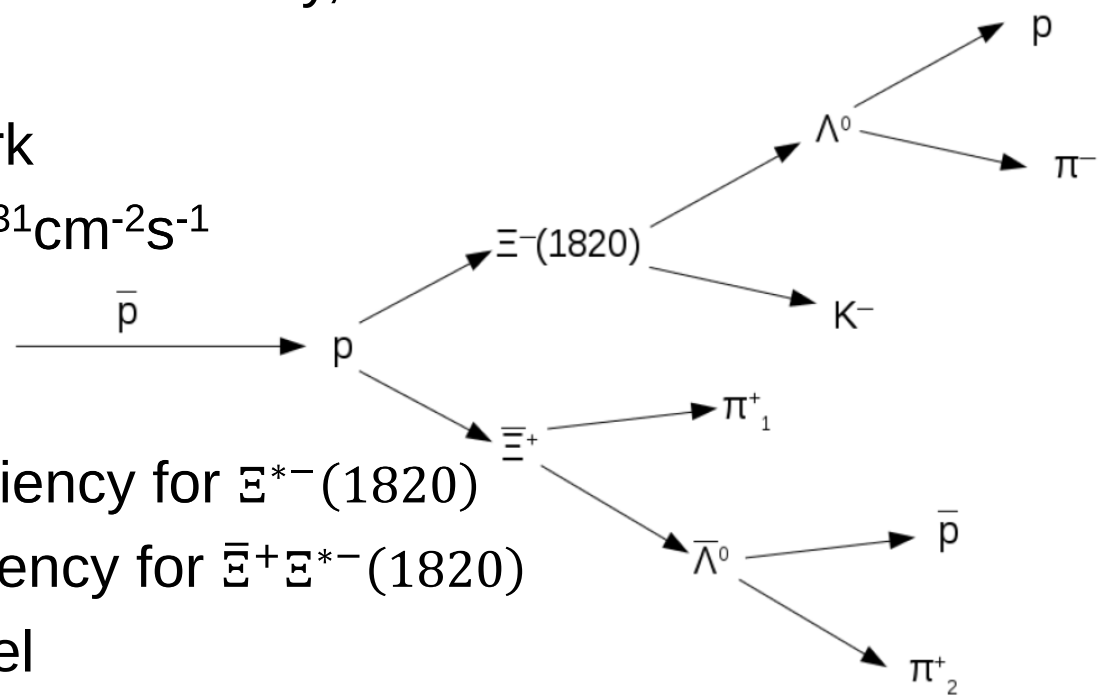
Prospects for PANDA



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: $10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

- Results:
  - ~30 % inclusive efficiency for $\Xi^{*-}(1820)$
  - ~5 % exclusive efficiency for $\bar{\Xi}^{+}\Xi^{*-}(1820)$
  - Low background level
  - ~15000 exclusive events / day



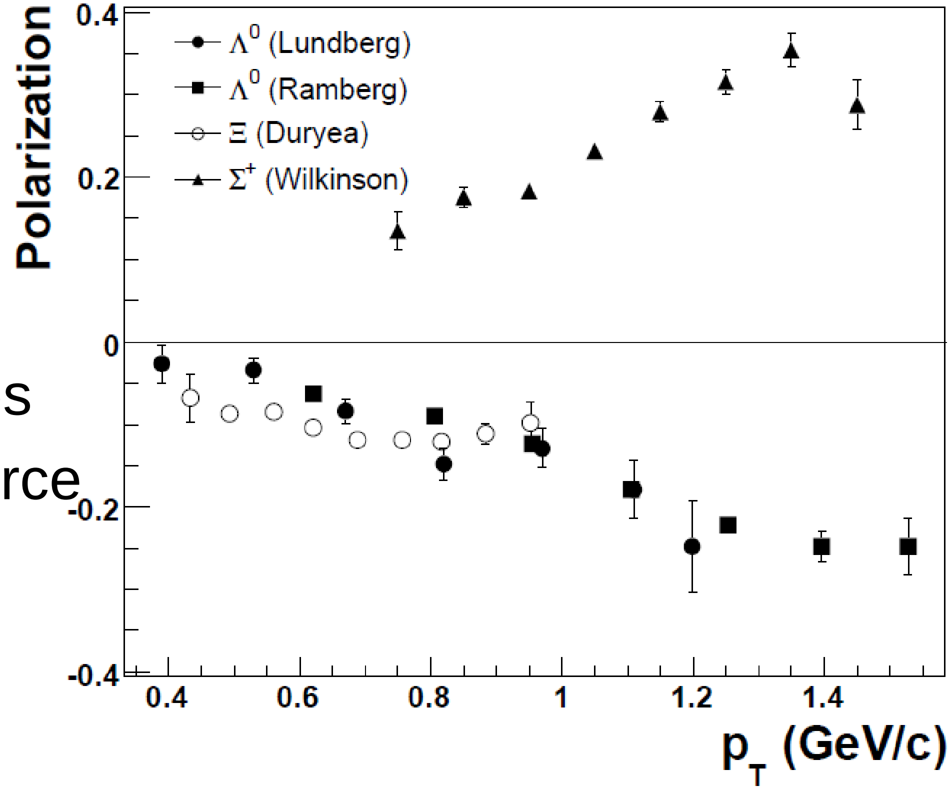
J. Pütz, talk at FAIRNESS 2016

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.

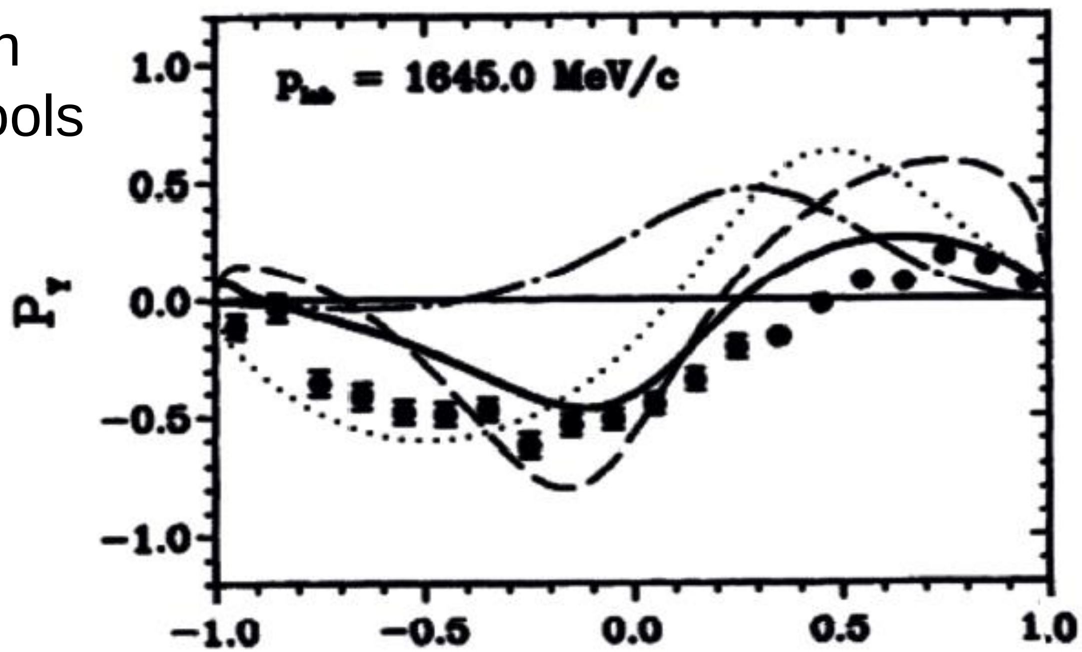


Figure from Phys. Rep. 368 (2002) 119.

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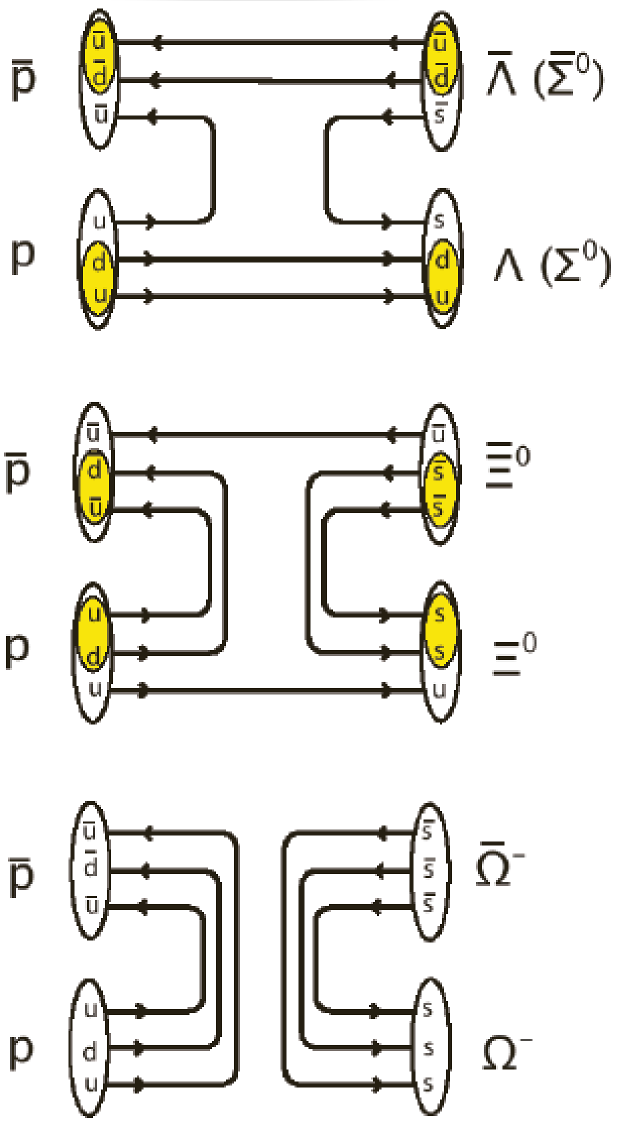
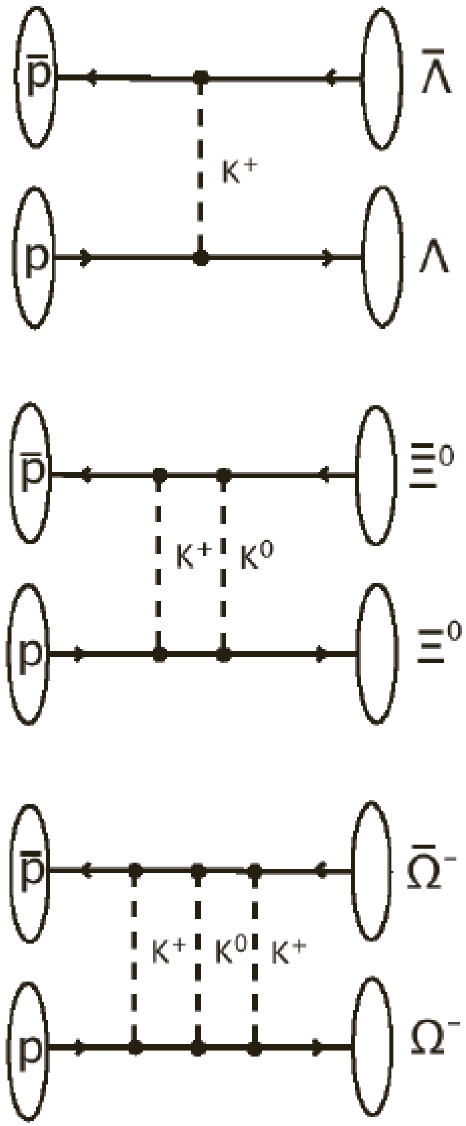
Hyperons from $\bar{p}p$ reactions





Available models based on

i) constituent quark-gluons*

ii) hadrons**

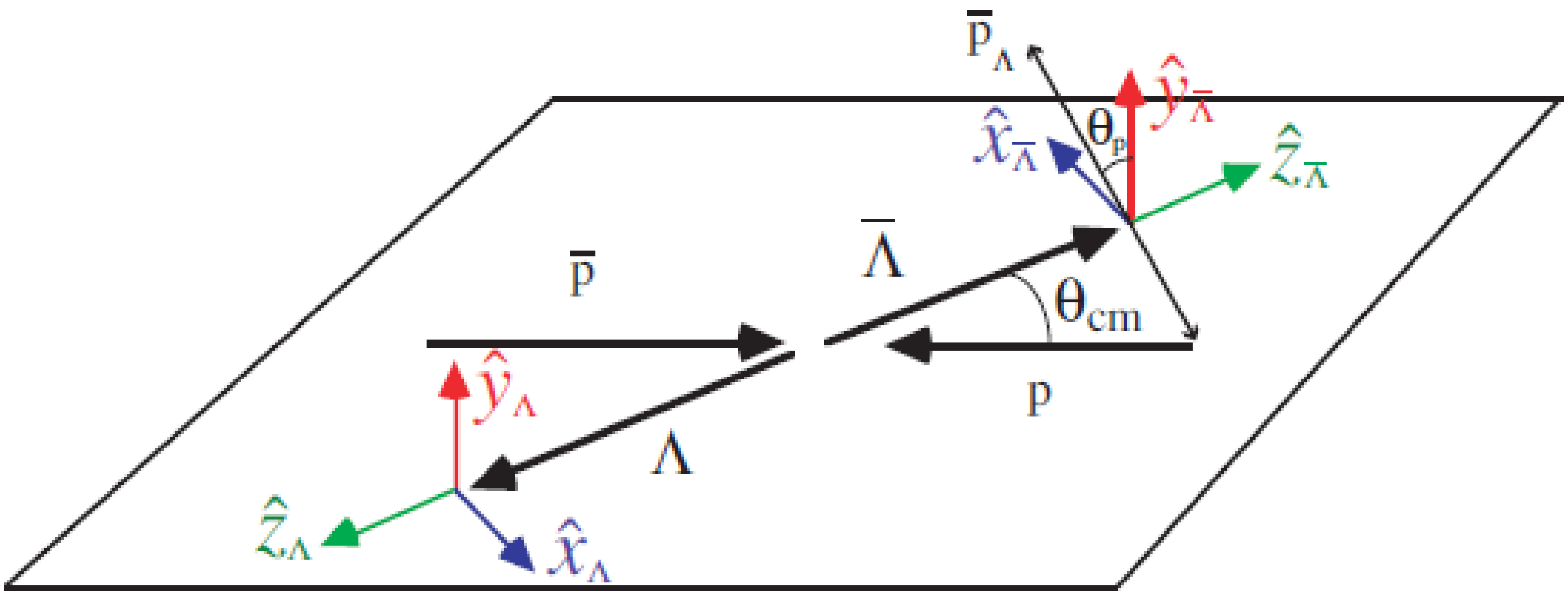
ii) a combination ***

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

Polarisation

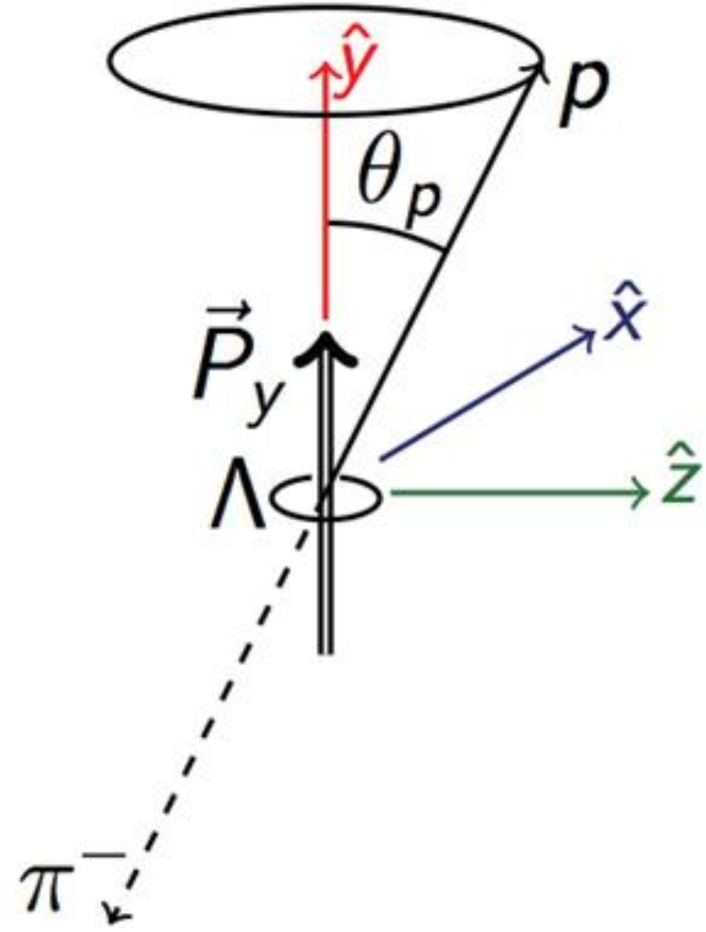
Accessible by the parity violating decay:
Decay products preferentially emitted along the spin of the hyperon.

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

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

P_Λ : polarisation

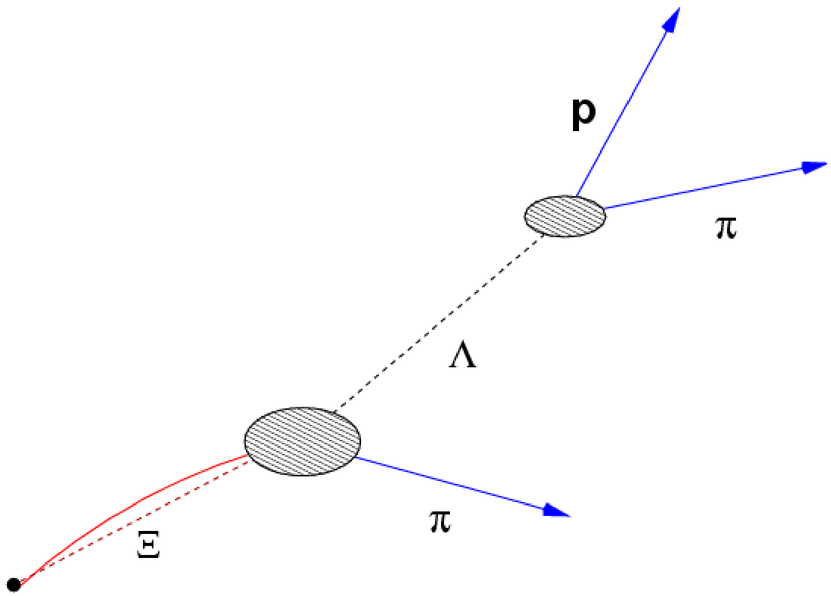
α = 0.64 asymmetry parameter



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

If the decay product of the hyperon is a hyperon, *e.g.* $\Xi \rightarrow \Lambda\pi$, 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 in $\bar{p}p \to \bar{Y}Y$

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

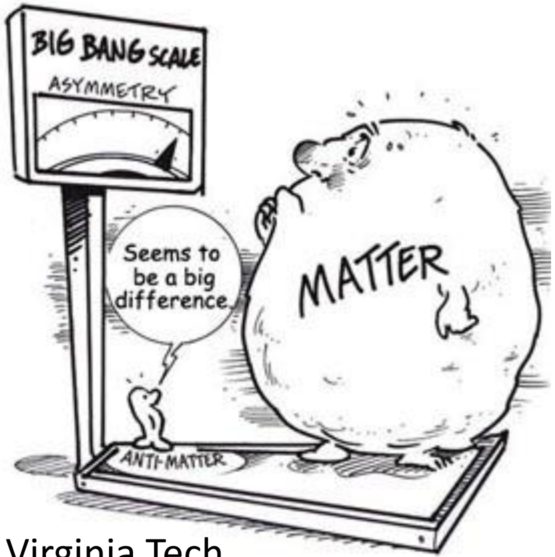
$$d(\rho) = \sqrt{\sum_{L=1}^{2j} \sum_{M=-L}^{L} (r_M^L)^2}$$

More details in talk by W. Ikegami Andersson (SFS-KF)

CP violation in hyperon decays

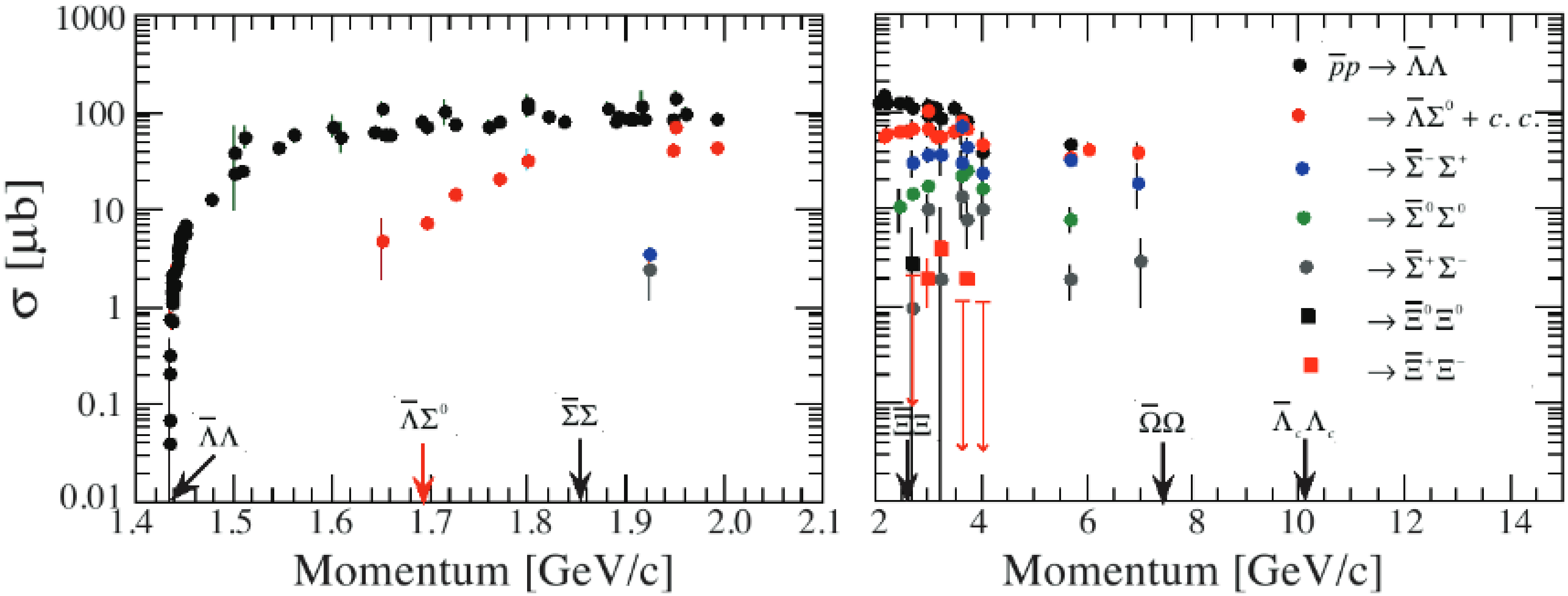
- CP violation in baryon decays necessary condition for matter-antimatter asymmetry (Sakharov).
- Standard Model CP violation too small to explain asymmetry
- CP violation never observed for baryons.
- The $\bar{p}p \rightarrow \bar{Y}Y$ process suitable for CP measurements (clean, no mixing)
- If CP valid, $\alpha = -\bar{\alpha}$.
- CP violation quantified by *e.g.*:

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



Picture from Virginia Tech

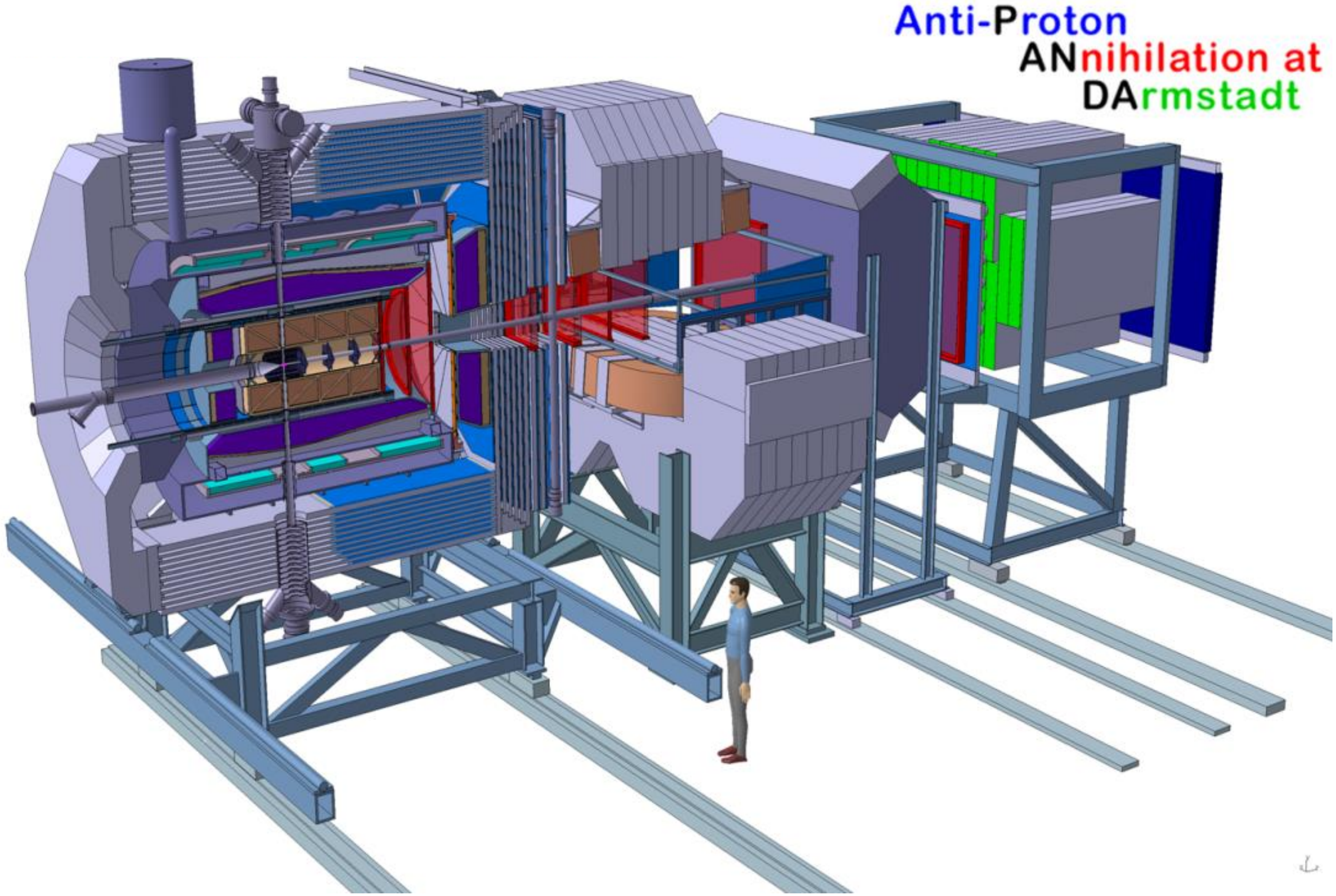
Previous measurements of $\bar{p}p \to \bar{Y}Y$



- 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.

Prospects for PANDA



Prospects for PANDA

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

	$\bar{\Lambda}\Lambda$	$\bar{\Sigma}^-\Sigma^+$	$\bar{\Sigma}^0\Sigma^0$	$\bar{\Sigma}^-\Sigma^+$	$\bar{\Xi}^0\Xi^0$	$\bar{\Xi}^+\Xi^-$	$\bar{\Omega}^+\Omega^-$	$\bar{\Lambda}_c^-\Lambda_c^+$
$\downarrow$	$p\pi^-$	$p\pi^0$	$\Lambda\gamma$	$n\pi$	$\Lambda\pi^0$	$\Lambda\pi$	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 $\bar{p}p \to \bar{\Lambda}\Lambda$ and $\bar{p}p \to \bar{\Lambda}\Sigma^o$ known near threshold.
- $\bar{p}p \to \bar{\Xi}^+\Xi^-$ measured with large uncertainty.
- Conservative theoretical predictions of $\bar{p}p \to \bar{\Omega}^+\Omega^-$ and $\bar{p}p \to \bar{\Lambda}_c^-\Lambda_c^+$

Prospects for PANDA

Momentum (GeV/c)	Reaction	σ (μb)	Efficiency (%)	Rate (with 10^{31} $cm^{-1}s^{-1}$)
1.64	$\bar{p}p \to \bar{\Lambda}\Lambda$	64	10	30 s^{-1}
4	$\bar{p}p \to \bar{\Lambda}\Sigma^o$	~40	30	30 s^{-1}
4	$\bar{p}p \to \bar{\Xi}^+\Xi^-$	~2	20	2 s^{-1}
12	$\bar{p}p \to \bar{\Omega}^+\Omega^-$	~0.002	30	~4 h^{-1}
12	$\bar{p}p \to \bar{\Lambda}_c^-\Lambda_c^+$	~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

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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 $p\bar{p} \rightarrow \Omega\bar{\Omega}$ derived (talk by WIA)
- 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.

Thanks to:

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

Backup

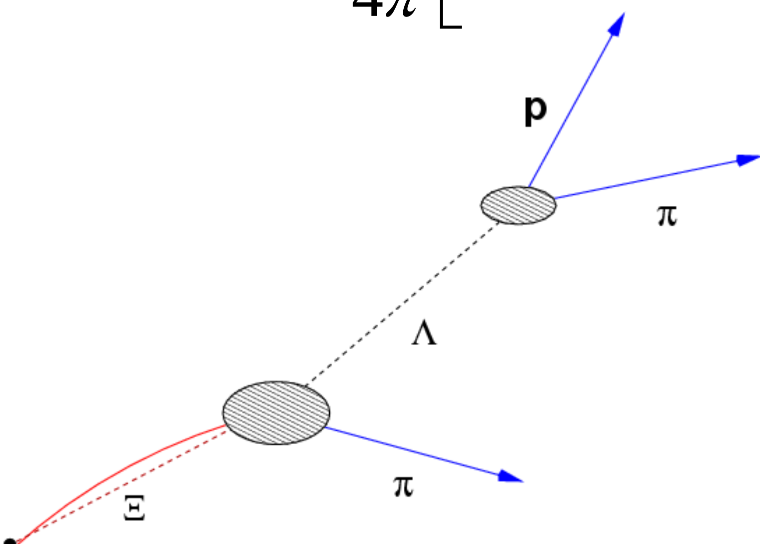
Spin observables for spin $\frac{1}{2}$ hyperons

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:

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

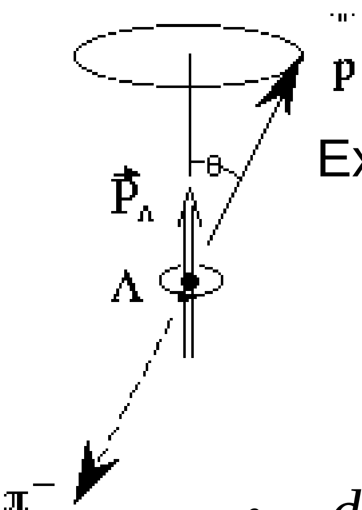


Spin observables for spin $\frac{1}{2}$ hyperons

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