

Hyperon Physics with PANDA at FAIR

Karin Schönning on behalf of the PANDA collaboration

The 12th International Workshop on Excited Nucleons

Bonn, June 10-14



*Knut och Alice
Wallenbergs
Stiftelse*

Outline

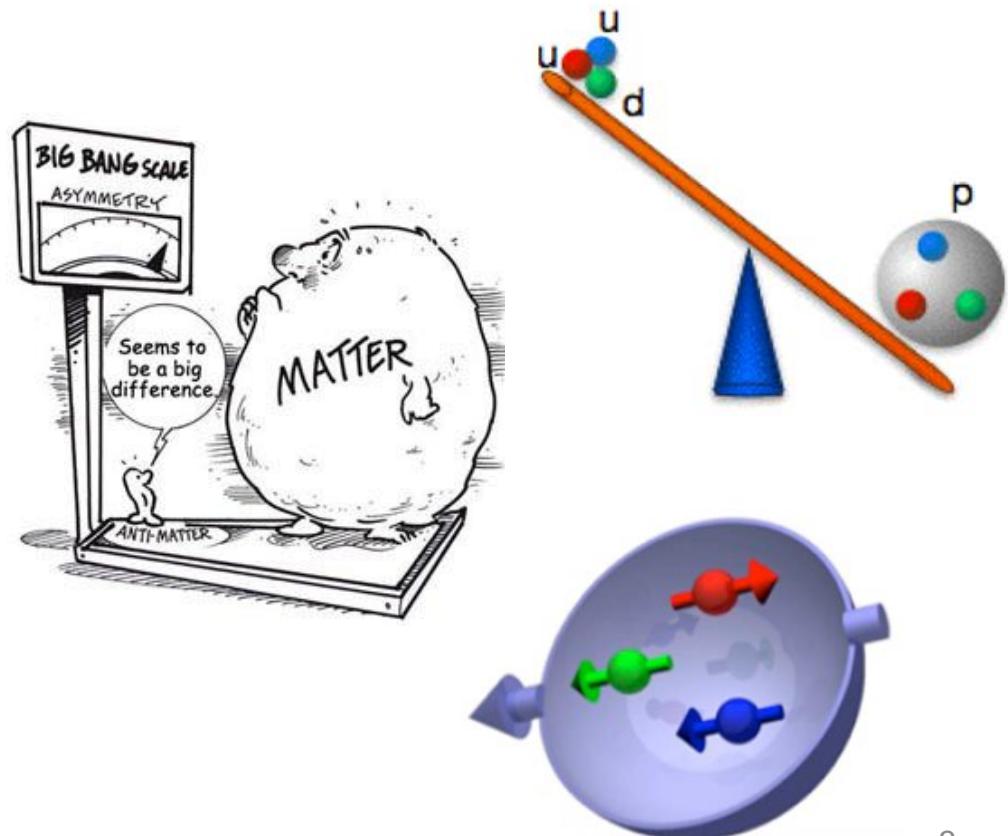
- Introduction
- Hyperons
- PANDA at FAIR
- Hyperon topics in PANDA
- Spin formalism in binary hyperon reactions
- Summary



Introduction

Many challenges in modern physics concern the **nucleon**:

- Abundance
- Mass
- Spin*
- Inner structure**
- Radius***



*C. A. Aidala *et al.*, RMP 85 (2013) 655-691.

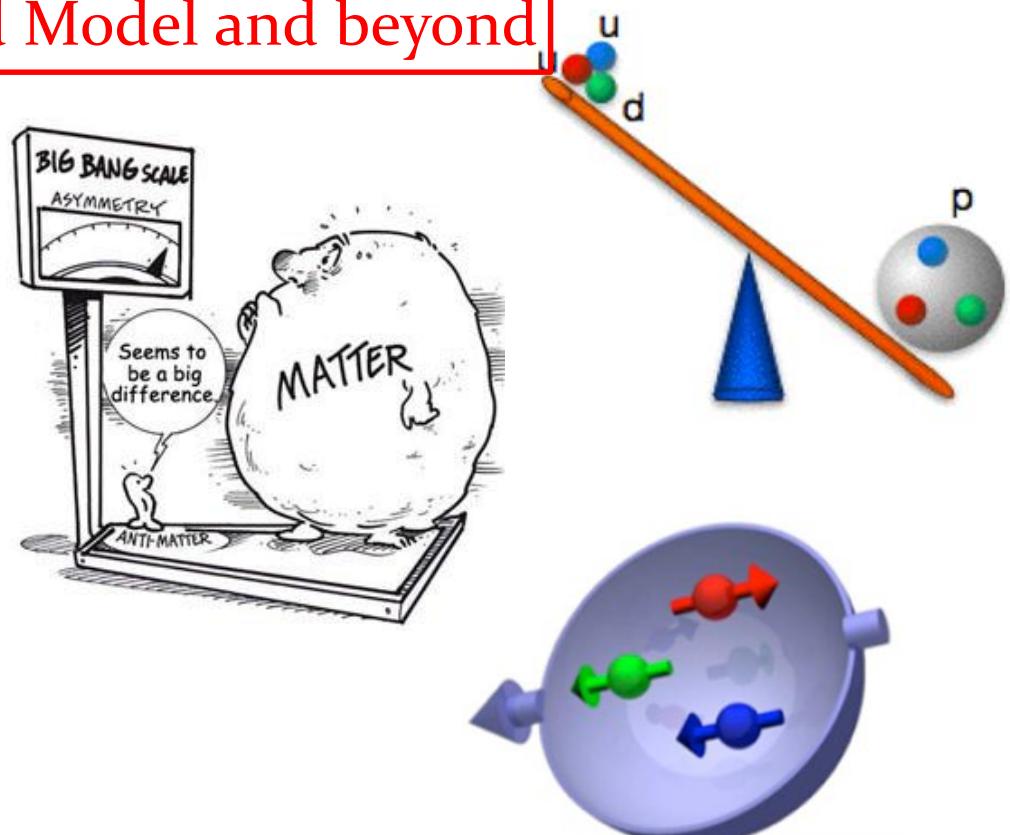
** G. A. Miller, PRL 99 (2007) 112001.

***R. Pohl, Nature 466 (2010) 7303, 213-216.

Introduction

Many challenges in modern physics concern the **nucleon**:

- Abundance **Standard Model and beyond**
- Mass
- Spin*
- Inner structure**
- Radius***



*C. A. Aidala *et al.*, RMP 85 (2013) 655-691.

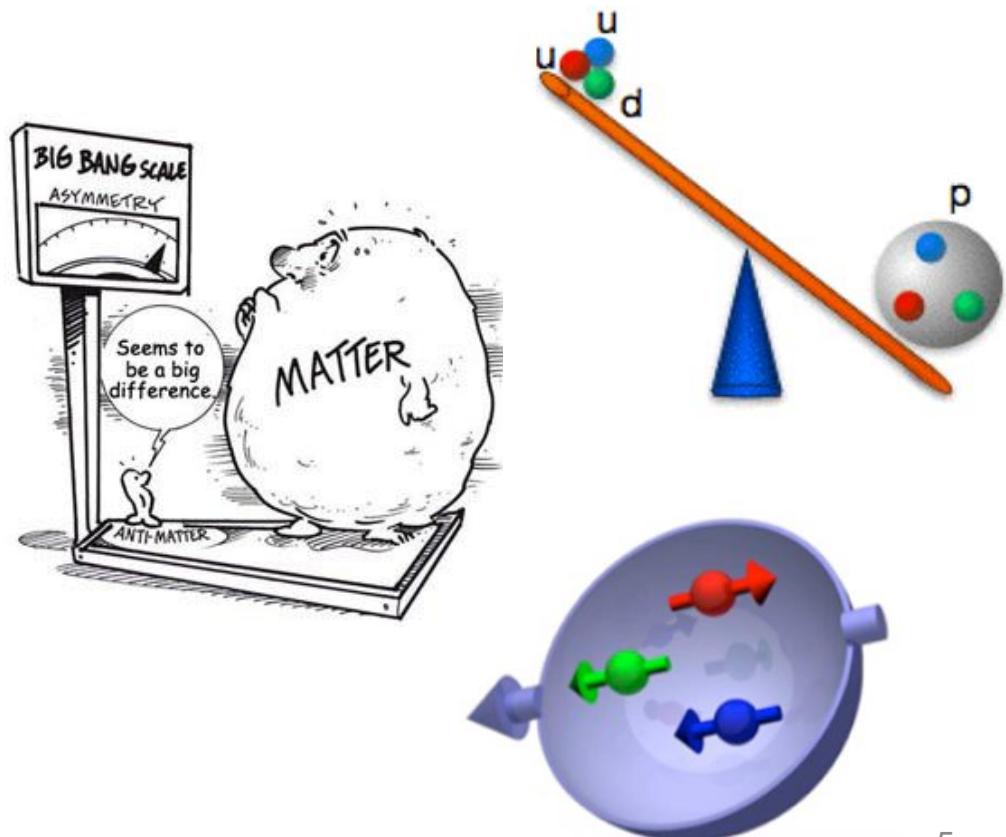
** G. A. Miller, PRL 99 (2007) 112001.

***R. Pohl, Nature 466 (2010) 7303, 213-216.

Introduction

Many challenges in modern physics concern the **nucleon**:

- Abundance
- Mass
- Spin* Non-perturbative QCD
- Inner structure**
- Radius*** ?



*C. A. Aidala *et al.*, RMP 85 (2013) 655-691.

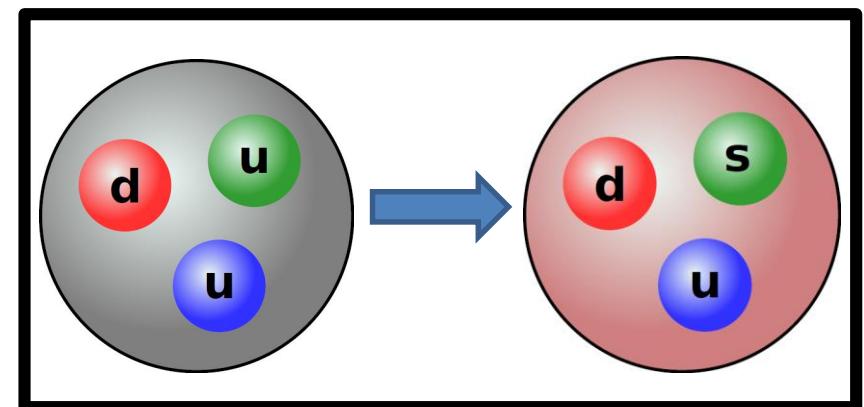
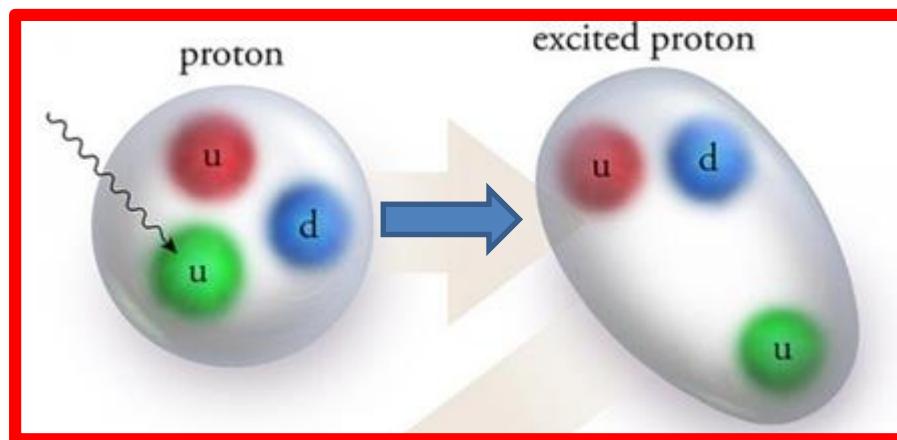
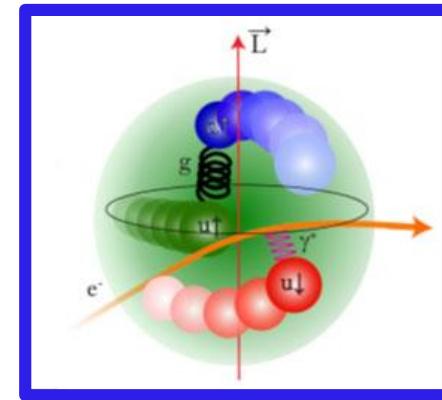
** G. A. Miller, PRL 99 (2007) 112001.

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Approaches

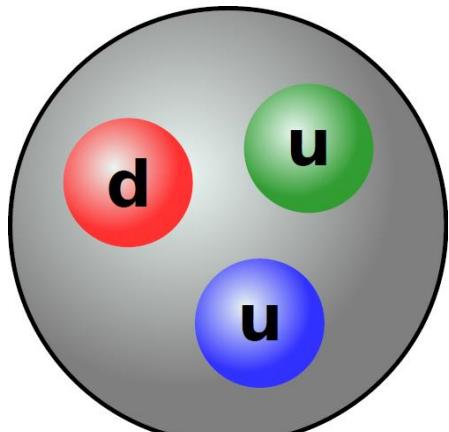
When you don't understand a system, you can*

- Scatter on it
- Excite it
- Replace one of the building blocks

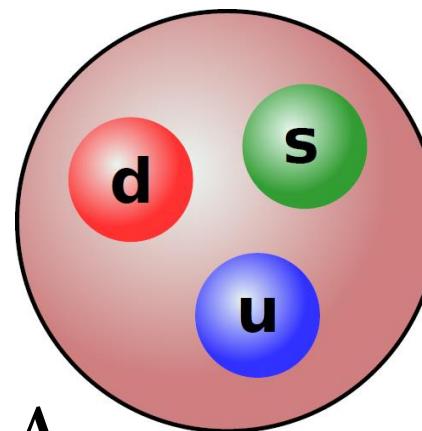


Hyperons

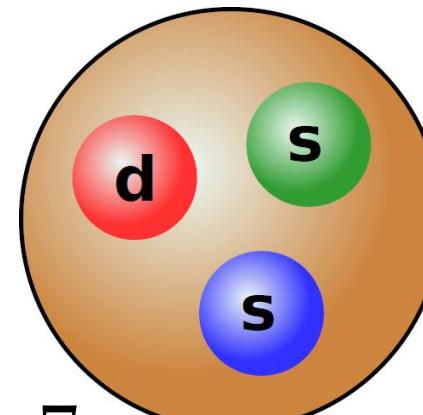
What happens if we replace one of the light quarks in the proton with one - or many - heavier quark(s)?



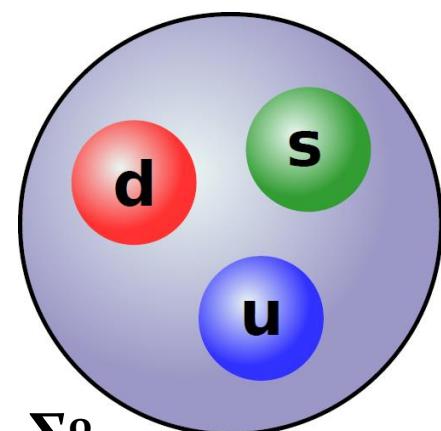
proton



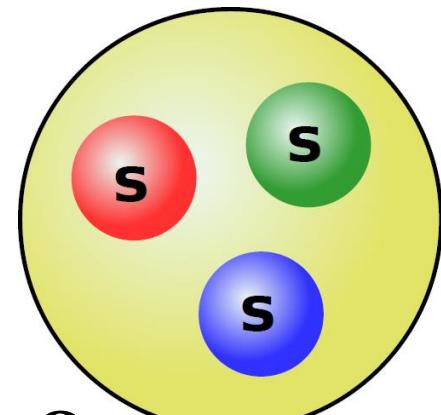
Λ



Ξ⁻



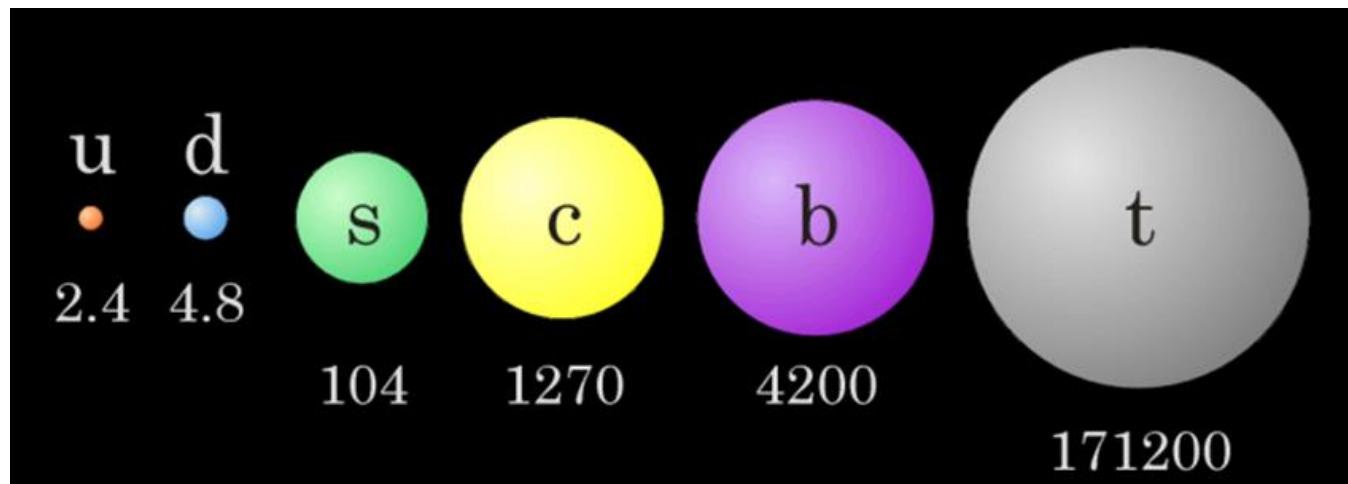
Σ⁰



Ω⁻

Hyperons

- Systems with strangeness
 - Scale: $m_s \approx 100$ MeV $\sim \Lambda_{\text{QCD}} \approx 200$ MeV: Relevant degrees of freedom?
 - **Probes QCD in the confinement domain.**
- Systems with charm
 - Scale: $m_c \approx 1300$ MeV: Quarks and gluons more relevant.
 - **Probes QCD just below pQCD.**



Hyperons

Traceable spin:

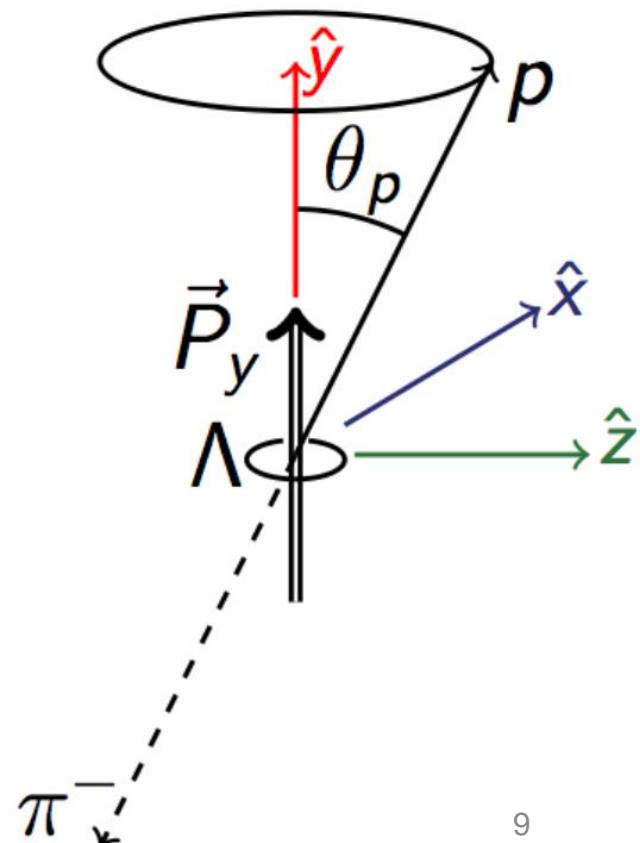
Polarization experimentally accessible
by the weak, parity violating decay:

Example: $\Lambda \rightarrow p\pi^-$ decay

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

P_Λ : polarisation

α = asymmetry parameter



Fundamental Question

Topic

Non-perturbative
QCD

Matter-Antimatter
Asymmetry

Hyperons
@ PANDA

Hyperon Production

Hyperon Spectroscopy

Hyperon Structure

Hyperon Decays



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Fundamental Question

Non-perturbative
QCD

Matter-Antimatter
Asymmetry



Topic

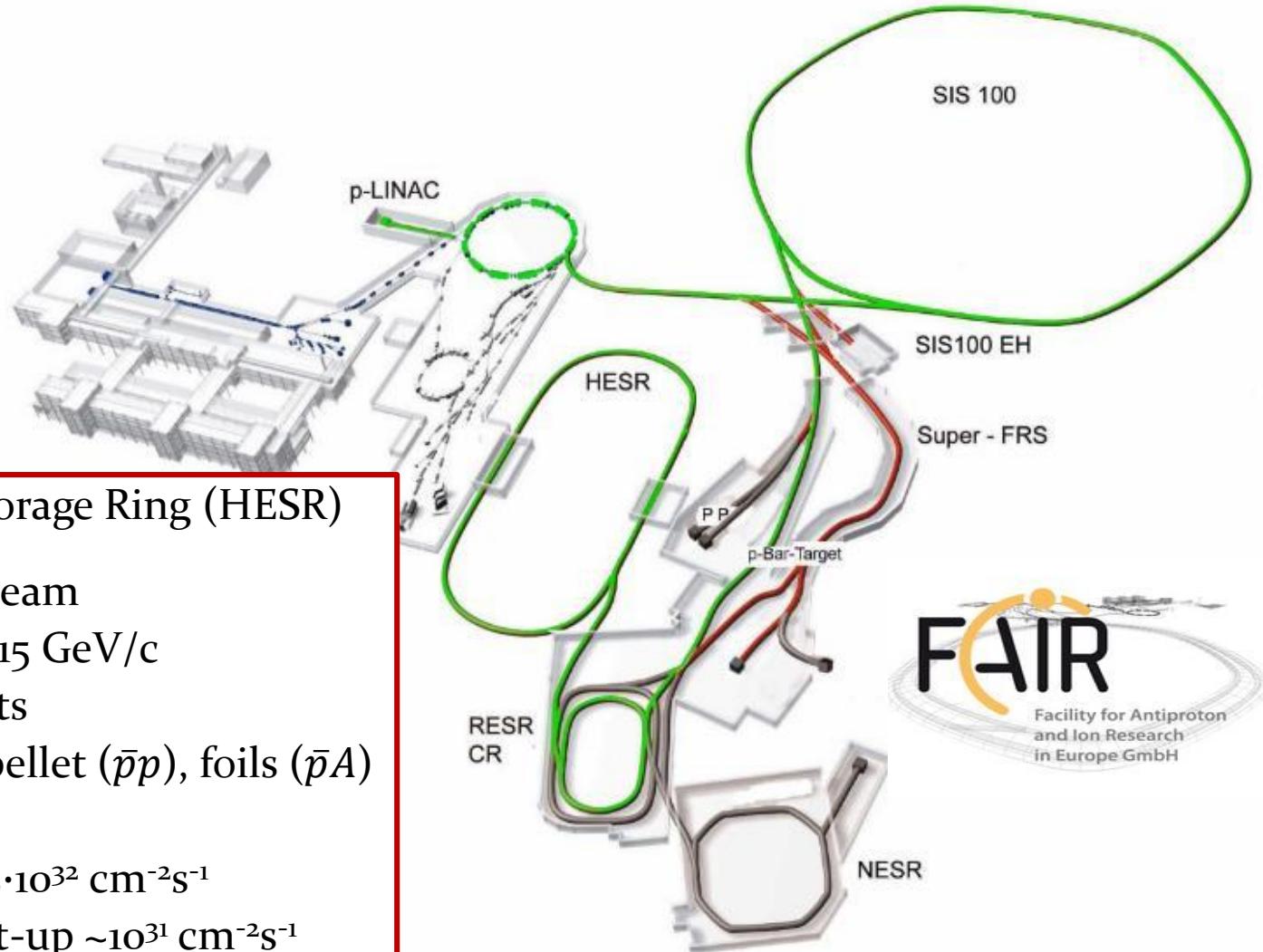
Hyperon Production

Hyperon Spectroscopy

Hyperon Structure

Hyperon Decays

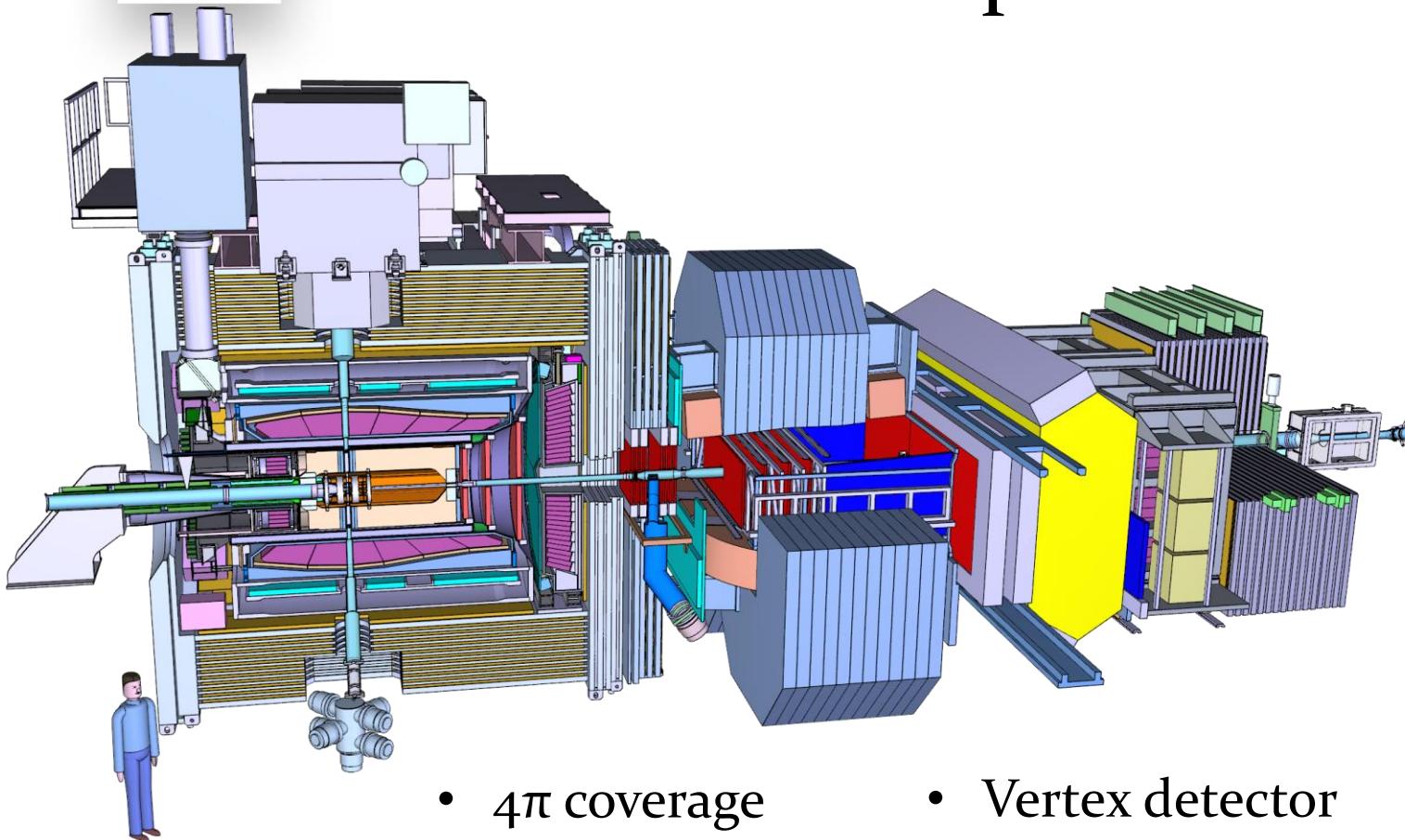
The PANDA experiment at FAIR



High Energy Storage Ring (HESR)

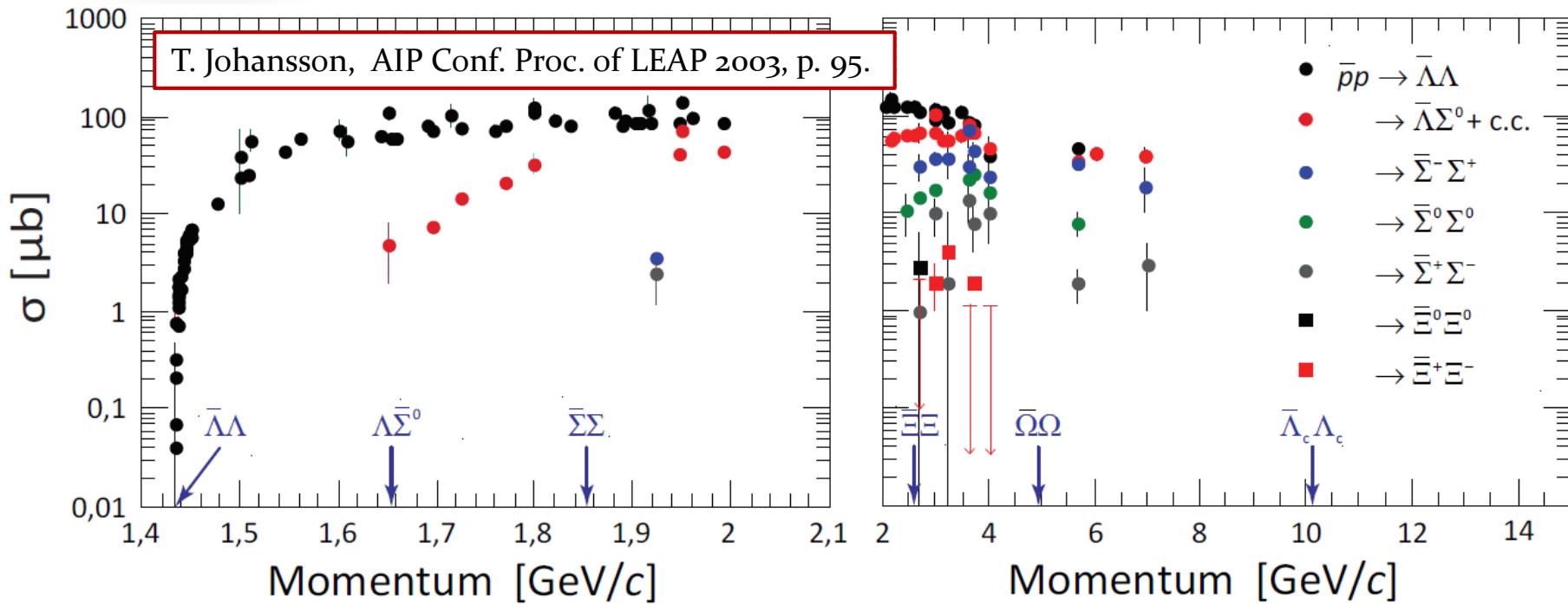
- Anti-proton beam
 $1.5 < p_{beam} < 15 \text{ GeV}/c$
- Internal targets
Cluster jet & pellet ($\bar{p}p$), foils ($\bar{p}A$)
- Luminosity:
 - Design $\sim 2 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
 - FAIR Start-up $\sim 10^{31} \text{ cm}^{-2}\text{s}^{-1}$

The PANDA experiment at FAIR



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

Advantages of PANDA



- Measured cross sections of ground-state hyperons in $\bar{p}p \rightarrow \bar{Y}Y$ 1-100 μb^* .
- Excited hyperon cross sections should be similar to those of ground-states**.

→ Large expected production rates!

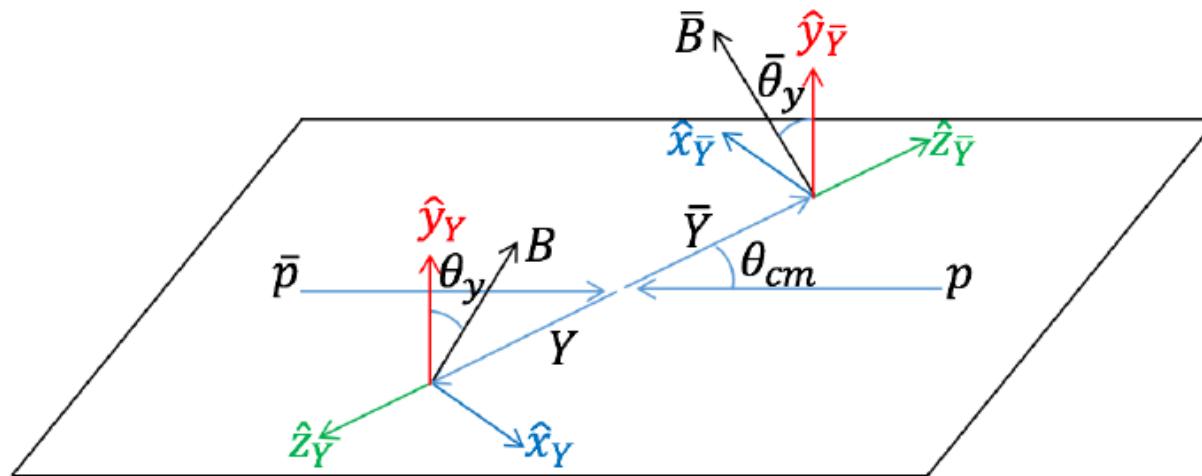
* Mainly PS185 @ LEAR. Review by E. Klemp et al., Phys. Rept. 368 (2002) 119-316

** V. Flaminio et al., CERN-HERA 84-01

Advantages of PANDA

Antihyperon – hyperon pair production:

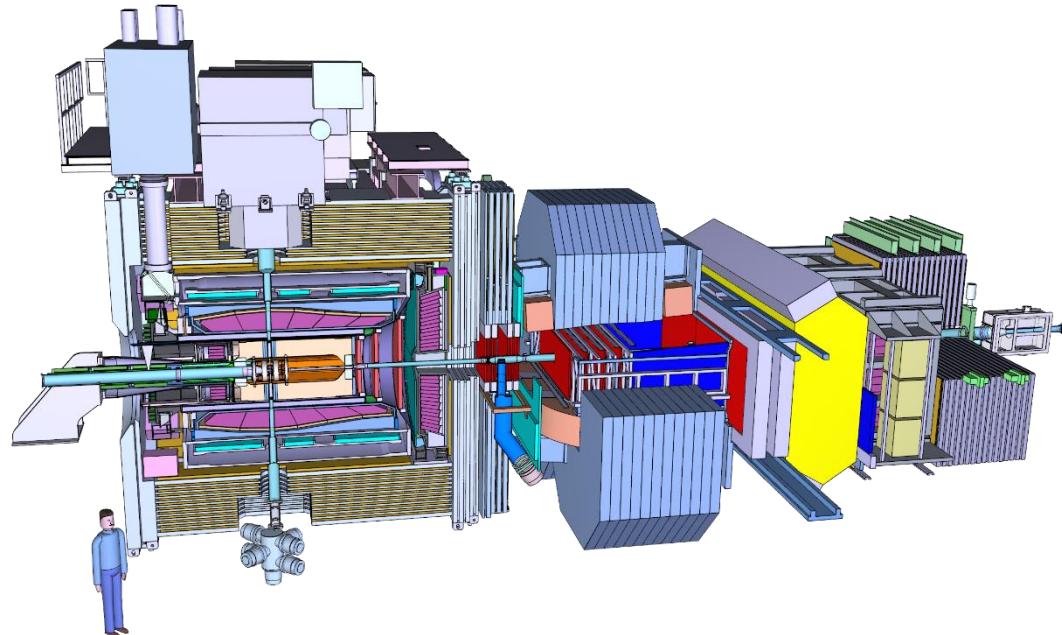
- Two-body processes
 - well-defined kinematics
 - possible to parameterize in terms of scattering angle.
- Symmetric particle-antiparticle final state
 - controllable systematics.



Advantages of PANDA

Near 4π detectors → exclusive measurements:

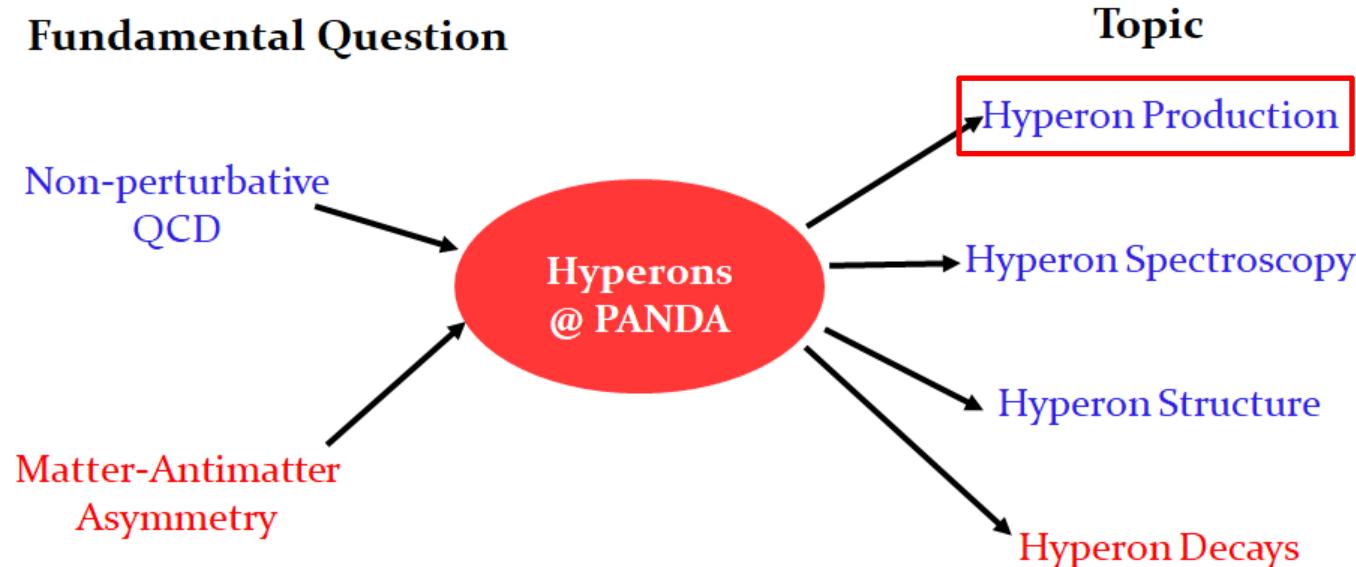
- Larger reconstruction efficiency
- Smaller reconstruction bias
- Prerequisite for model-independent partial wave analysis.



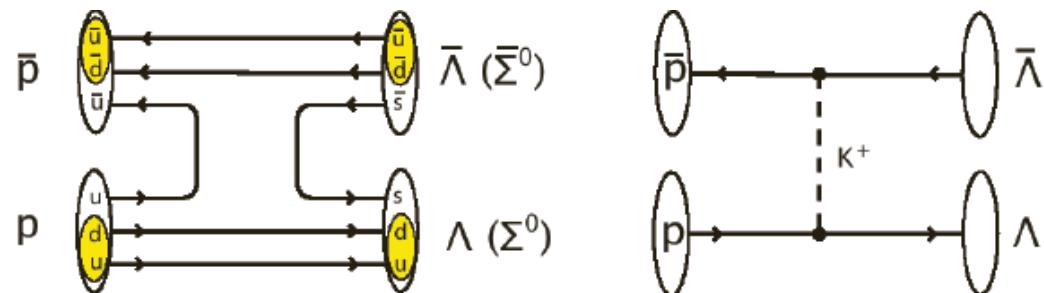


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HYPERON TOPICS IN PANDA

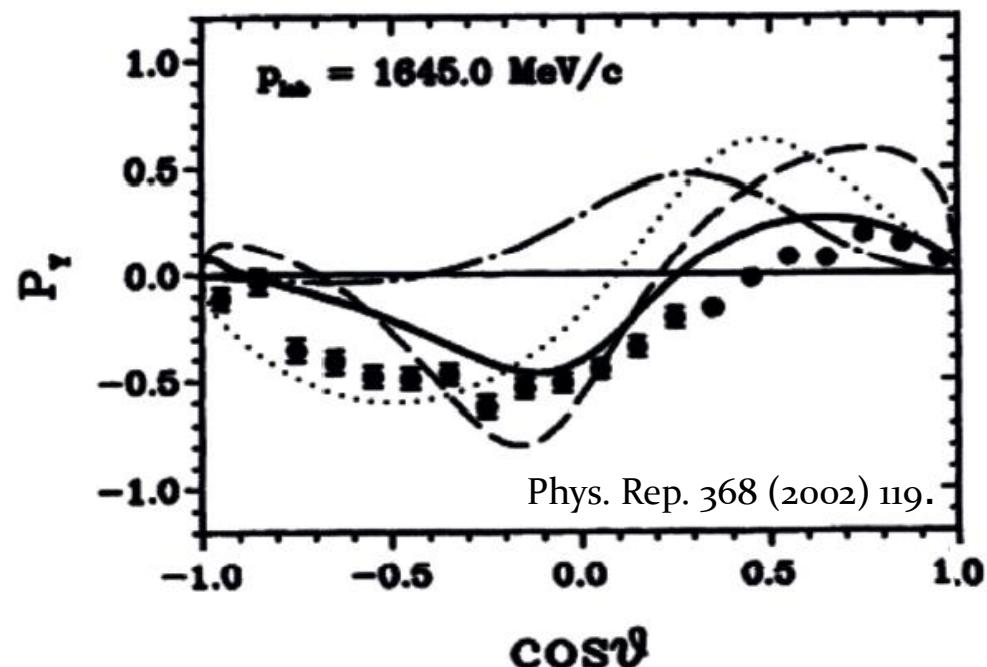


Hyperon production

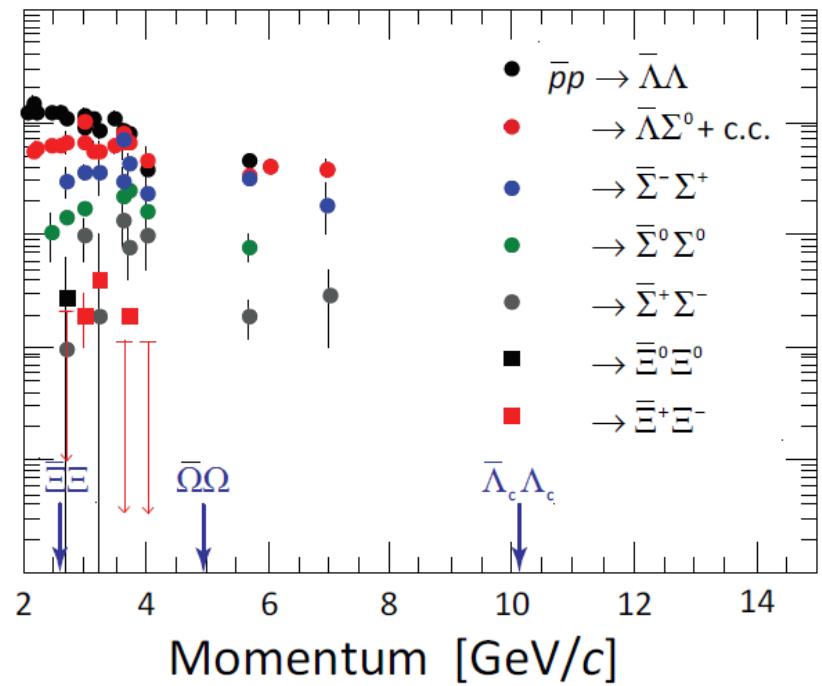
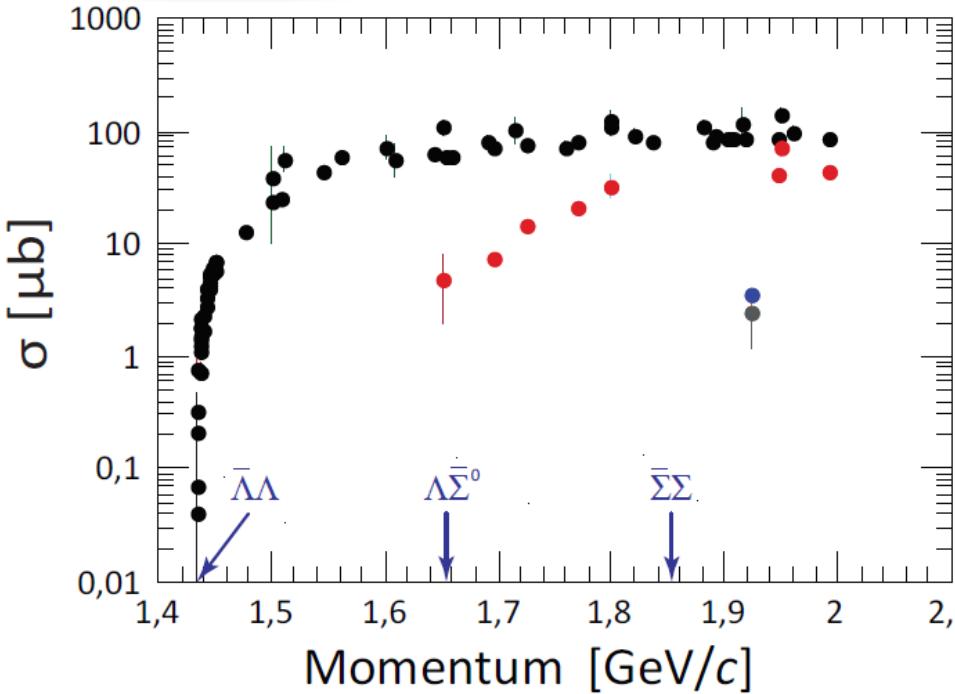


Strong production dynamics

- Relevant degrees of freedom?
 - Spin observables.
- Strange *versus* charm sector?



Hyperon production



- Mainly single-strange data.
- Scarce data bank above 4 GeV.
- No data on Ω nor Λ_c .

Hyperon production prospects with PANDA

New simulation studies of single- and double-strange hyperons*:

- Exclusive measurements of
 - $\bar{p}p \rightarrow \bar{\Lambda}\Lambda, \Lambda \rightarrow p\pi^-, \bar{\Lambda} \rightarrow \bar{p}\pi^+$.
 - $\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda, \Lambda \rightarrow p\pi^-, \bar{\Sigma}^0 \rightarrow \bar{\Lambda}\gamma, \bar{\Lambda} \rightarrow \bar{p}\pi^+$.
 - $\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-, \Xi^- \rightarrow \Lambda\pi^-, \Lambda \rightarrow p\pi^-, \bar{\Xi}^+ \rightarrow \bar{\Lambda}\pi^+, \bar{\Lambda} \rightarrow \bar{p}\pi^+$.
- Ideal pattern recognition and PID
- Background using Dual Parton Model

* By W. Ikegami-Andersson (talk at FAIRNESS 2019)
and G. Perez Andrade (master thesis, Uppsala 2019)

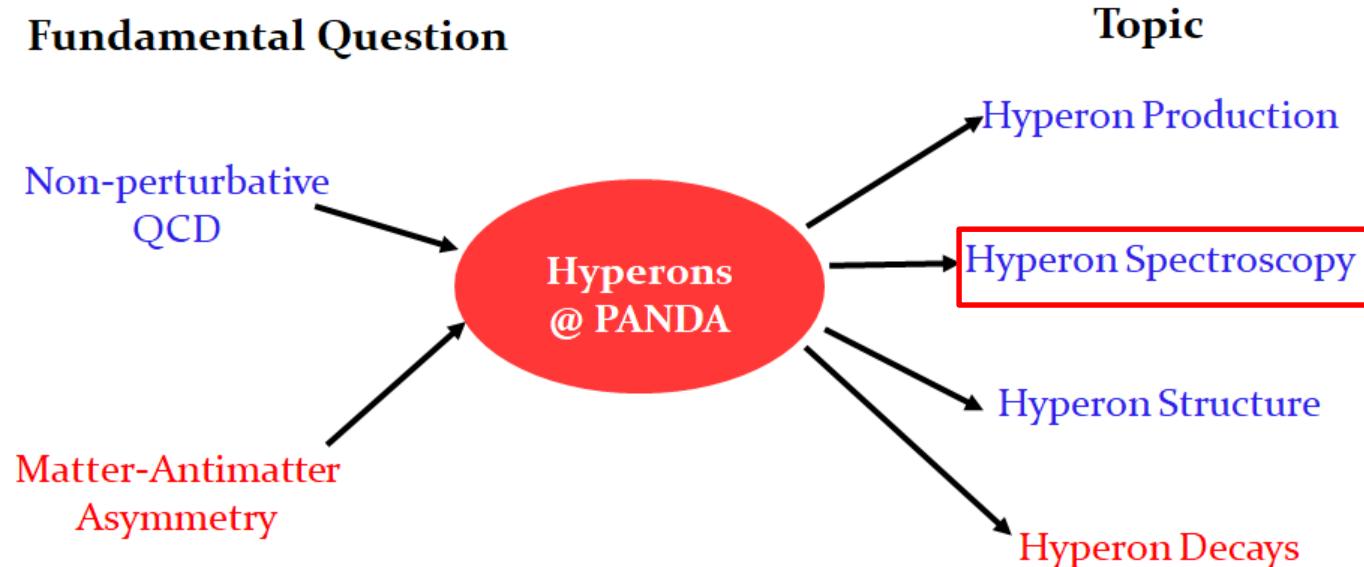
p_{beam} (GeV/c)	Reaction	σ (μ b)	ϵ (%)	Rate @ 10^{31} cm $^{-2}$ s $^{-1}$	S/B	Events /day
1.64	$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$	64.0	16.0	44 s $^{-1}$	114	$3.8 \cdot 10^6$
1.77	$\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda$	10.9	5.3	2.4 s $^{-1}$	>11**	207 000
6.0	$\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda$	20	6.1	5.0 s $^{-1}$	21	432 000
4.6	$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	~1	8.2	0.3 $^{-1}$	274	26000
7.0	$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	~0.3	7.9	0.1 $^{-1}$	65	8600

** 90% C.L.



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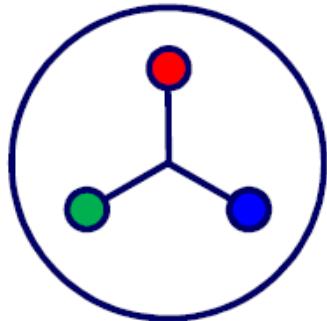
HYPERON TOPICS IN PANDA



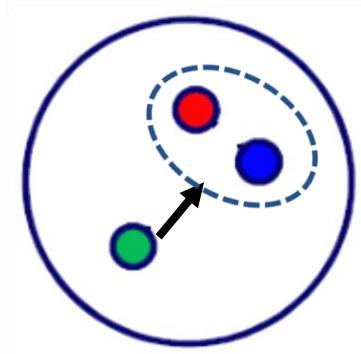
Hyperon Spectroscopy

How do quarks form baryons?

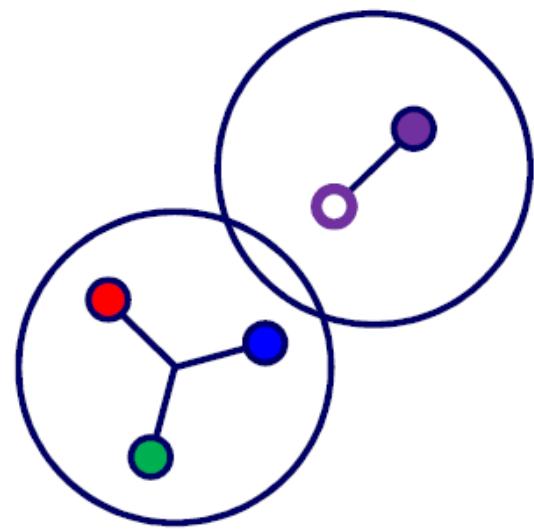
- Forces?
- Degrees of freedom?



Symmetric quark model



Quark - diquark

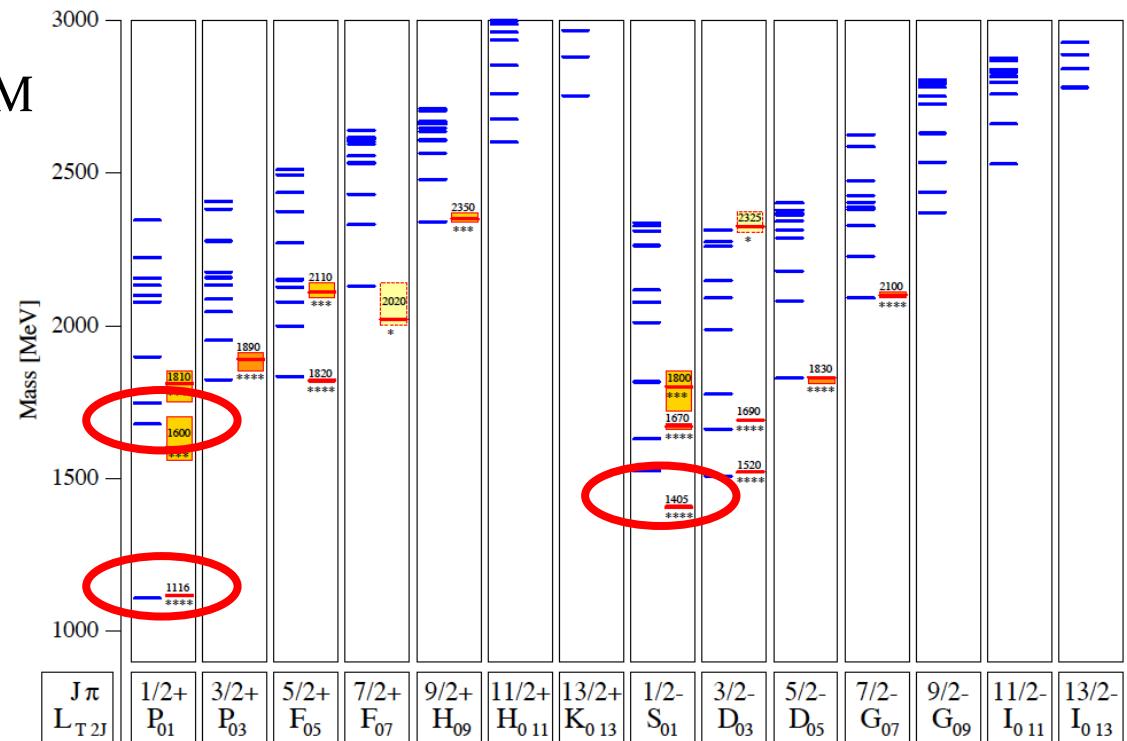


Molecule / hadronic d.o.f.

Hyperon spectroscopy

How do the puzzles of the light- and single strange baryon spectrum carry over to the multi-strange sector?

- Light baryon spectrum*:
 - "Missing" states w.r.t. CQM
 - Parity pattern:
++- (exp.) +-+ (QM)
- Single strange spectrum:
 - "Missing" states
 - "The unbearable lightness of $\Lambda(1405)$ "



Multi-strange hyperon spectrum

- Ξ^* : Few excited states found, only one with ****
 - Spin and parity only determined for two excited states.
- Ω^* : Two excited states listed, none with ****
 - No spin or parity measurement
- Ground-state Ξ and Ω : Parity not measured.
- Ground-state Ω :

No model-independent spin measurement.

PDG 2018

Particle	J^P	Overall status	Status as seen in —					Decays weakly
			$\Xi\pi$	ΛK	ΣK	$\Xi(1530)\pi$	Other channels	
$\Xi(1318)$	$1/2+$	****						
$\Xi(1530)$	$3/2+$	****	****					
$\Xi(1620)$		*	*					
$\Xi(1690)$		***		***		**		
$\Xi(1820)$	$3/2-$	***	**	***	**		**	
$\Xi(1950)$		***	**	**			*	
$\Xi(2030)$		***		**	***			
$\Xi(2120)$		*		*				
$\Xi(2250)$		**						3-body decays
$\Xi(2370)$		**						3-body decays
$\Xi(2500)$		*		*		*		3-body decays

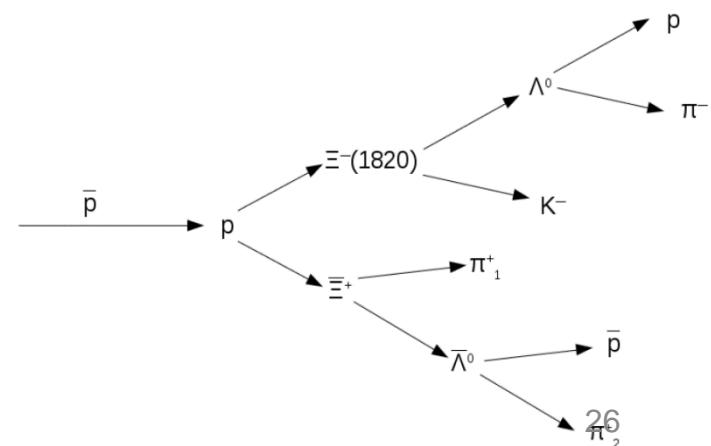
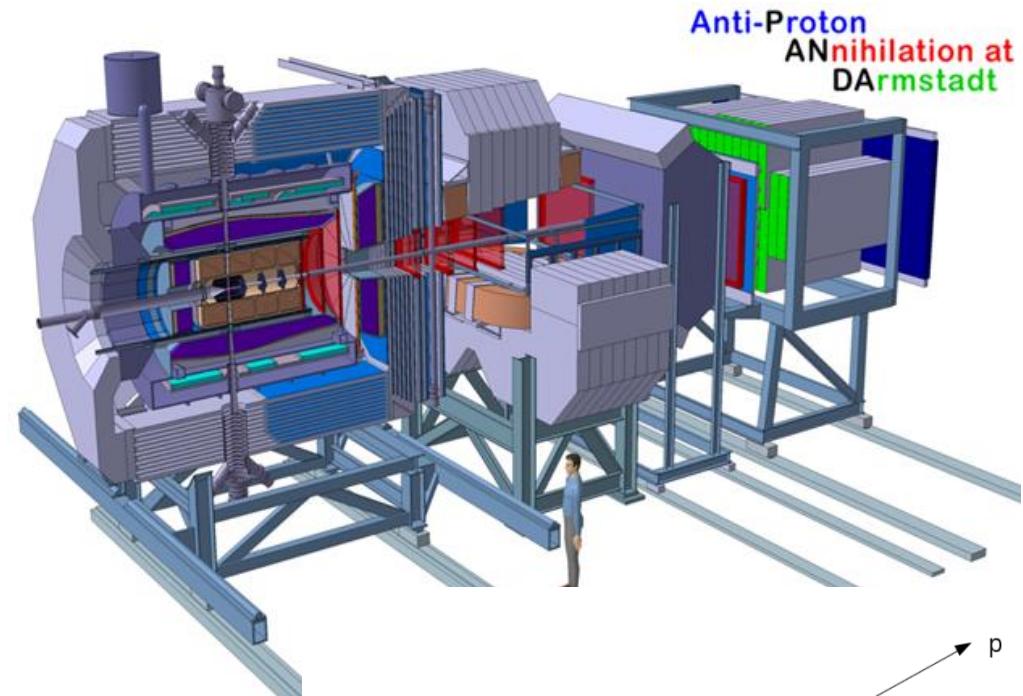
Facilities world-wide

Impressive progress

- in N^* , Δ and single-strange spectroscopy
(*e.g.* JLAB, ELSA, MAMI..)
 - in charm- and beauty spectroscopy
(BaBar, Belle/Belle-II, CLEO, LHCb)
- Gap to fill in the multi-strange sector!

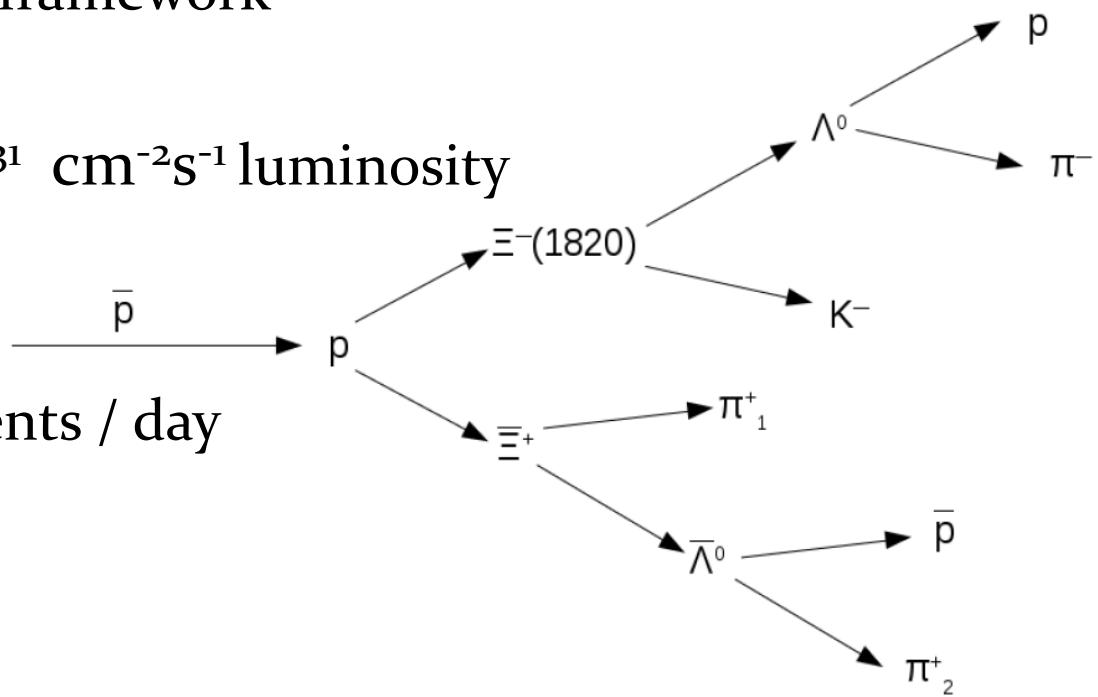
Hyperon Spectroscopy @ PANDA

- Multi-strange hyperons from $\bar{p}p \rightarrow \bar{Y}^*Y, \rightarrow \bar{Y}Y^*$.
- Cross sections $nb - \mu b$.
- Two-body production.
- Symmetry in antihyperon-hyperon observables.
- Exclusive measurements.
- Charged and neutral modes accessible.



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

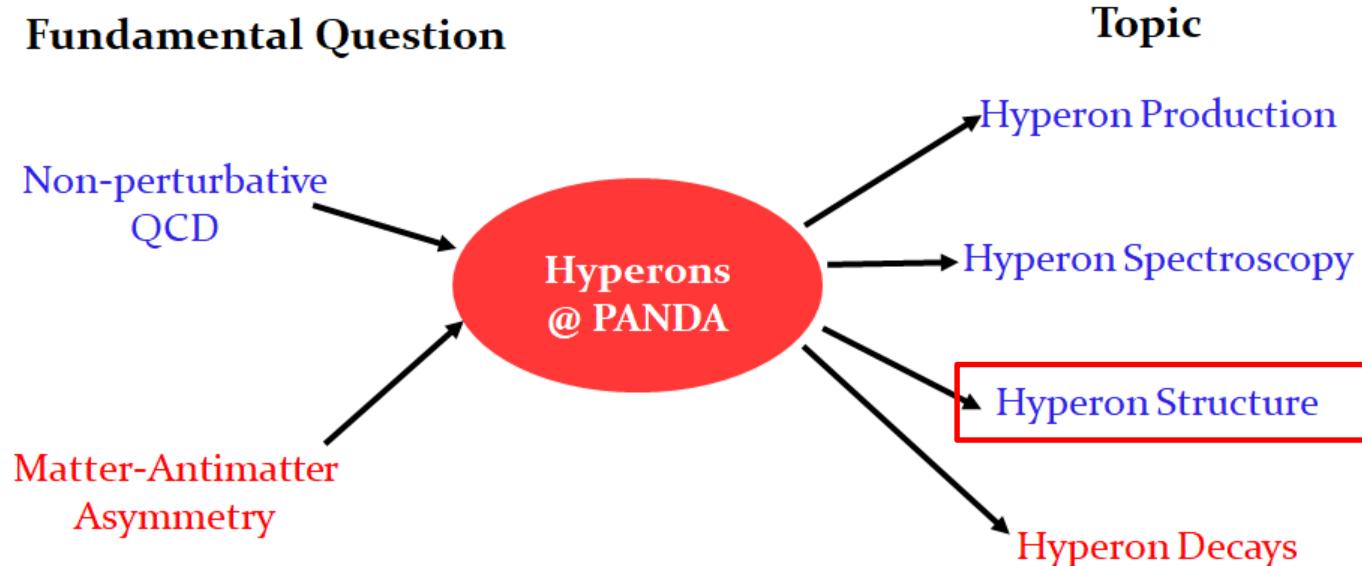
- $\bar{p}p \rightarrow \bar{\Xi}^+ \Lambda K^- + c.c.$
 - ΛK^- from $\Xi^{*-}(1690)$, $\Xi^{*-}(1820)$ or continuum
- Simplified PANDA MC framework
- $p_{beam} = 4.6 \text{ GeV}/c$
- Assume $\sigma = 1 \mu\text{b}$ and $10^{31} \text{ cm}^{-2}\text{s}^{-1}$ luminosity
- Results:
 - S/B ~ 30
 - ~ 18000 exclusive events / day



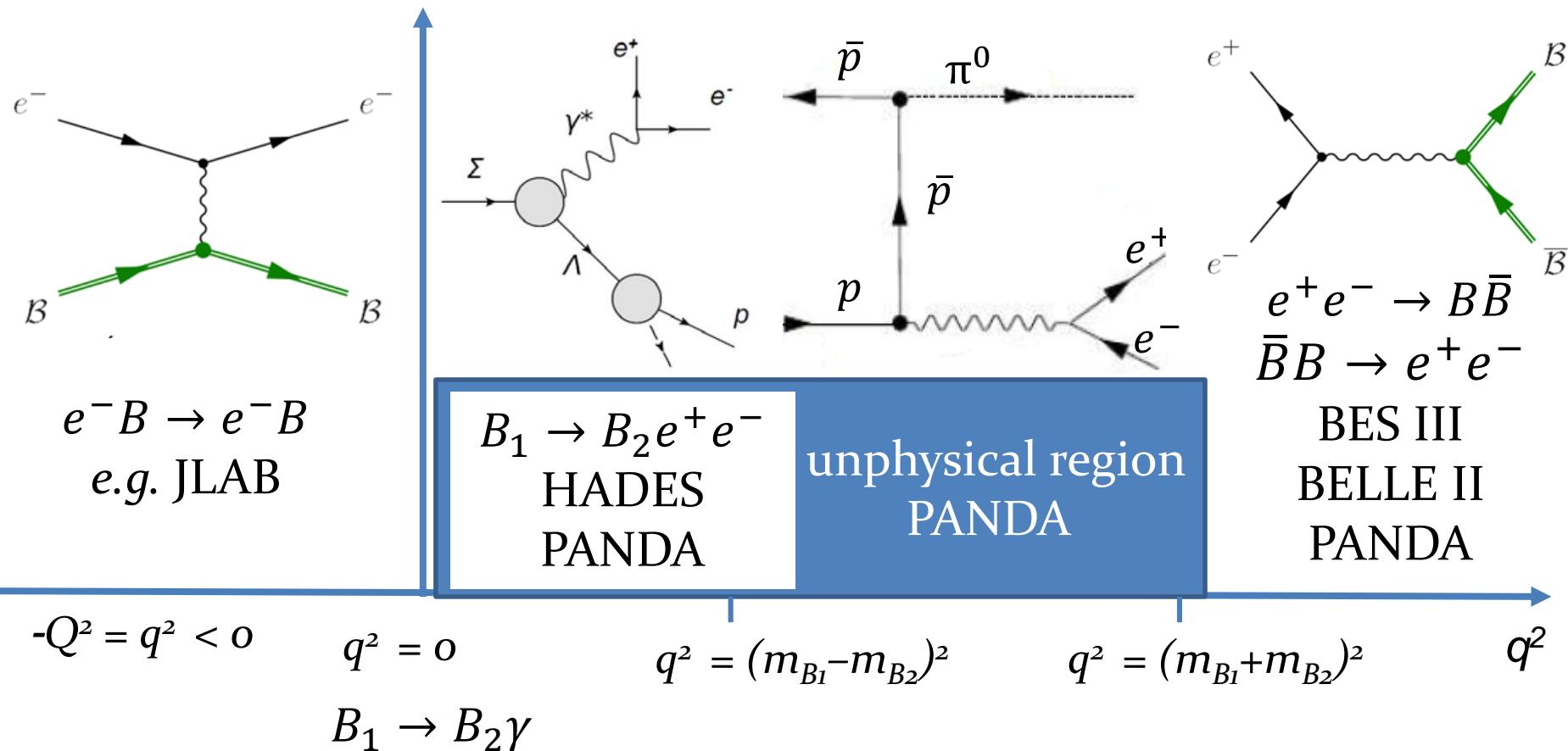


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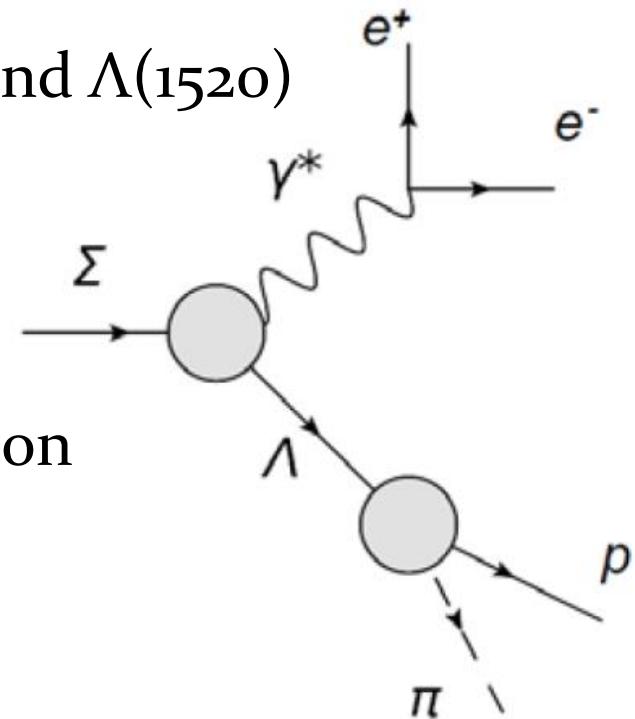


Hyperon Structure



Hyperon structure

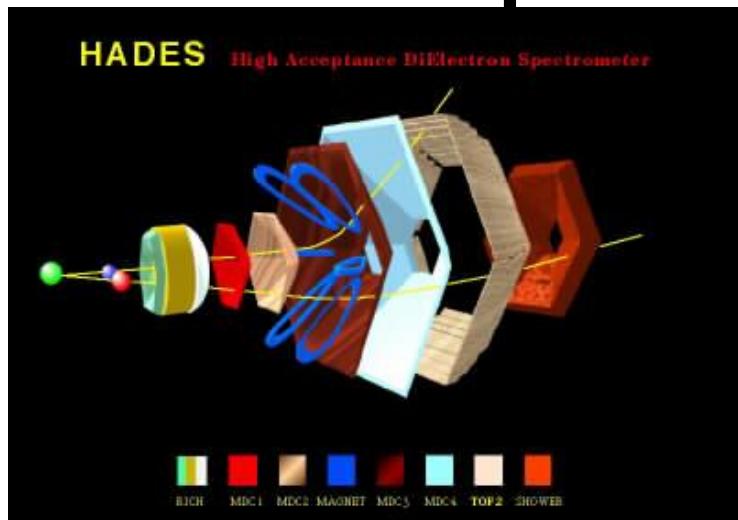
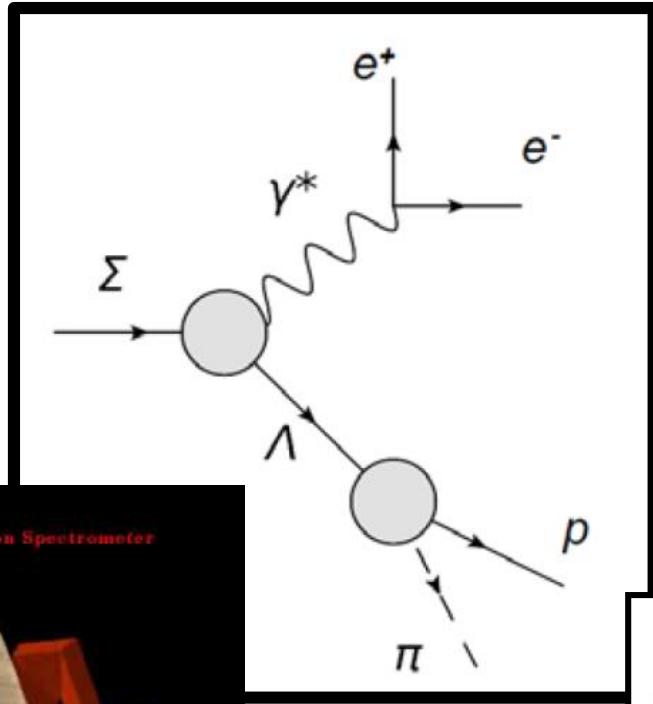
- Transition form factors accessible from Dalitz decays
- Possible in case of *e.g.* Σ^0 , $\Sigma^*(1385)$ and $\Lambda(1520)$
- **Challenge:** Small predicted BR's ($10^{-3} - 10^{-6}$)
- **Good news:** Large hyperon production cross sections.



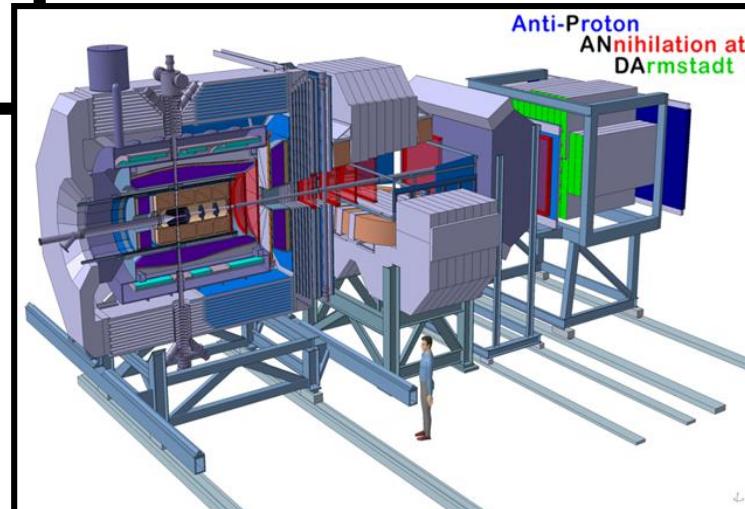


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Hyperon Structure



Possible already during
Phase 0 with
HADES +PANDA FTS!



More details in talks by e.g.
P. Salabura and B. Rammstein



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SPIN FORMALISM IN BINARY HYPERON REACTIONS

Spin formalism in hyperon reactions

In PANDA we expect

- Very large hyperon samples
- Exclusive measurements

Benefits of hyperons

- Self-analyzing decays

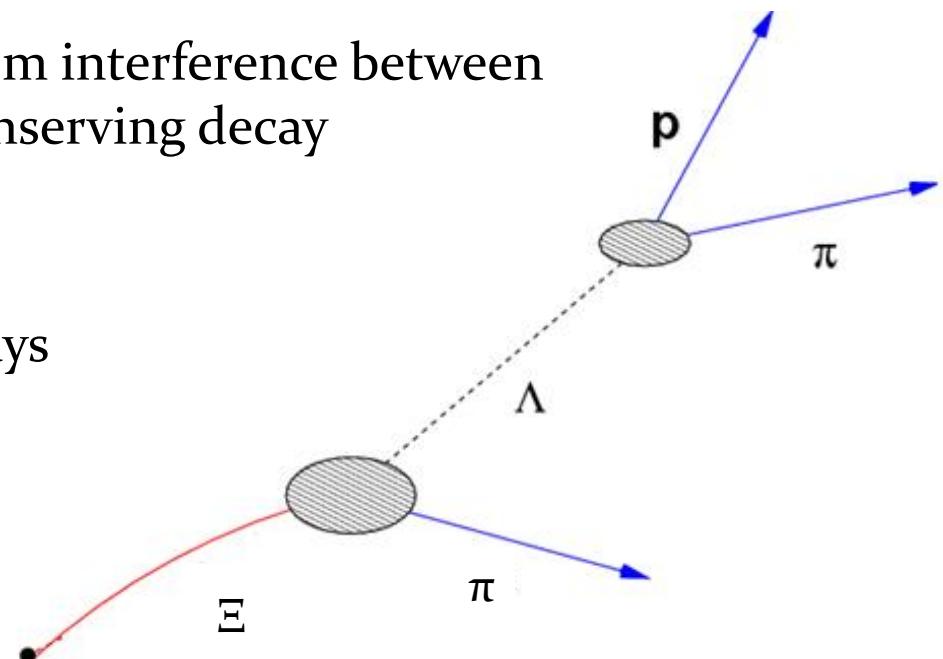
This open up new possibilities to make multi-dimensional,
model-independent spin decomposition of hyperon
reactions!

Hyperon spin observables

Weak hyperon decay gives access to full spin density matrix

- Decay parameters α, β, γ from interference between parity violating and parity conserving decay amplitudes.

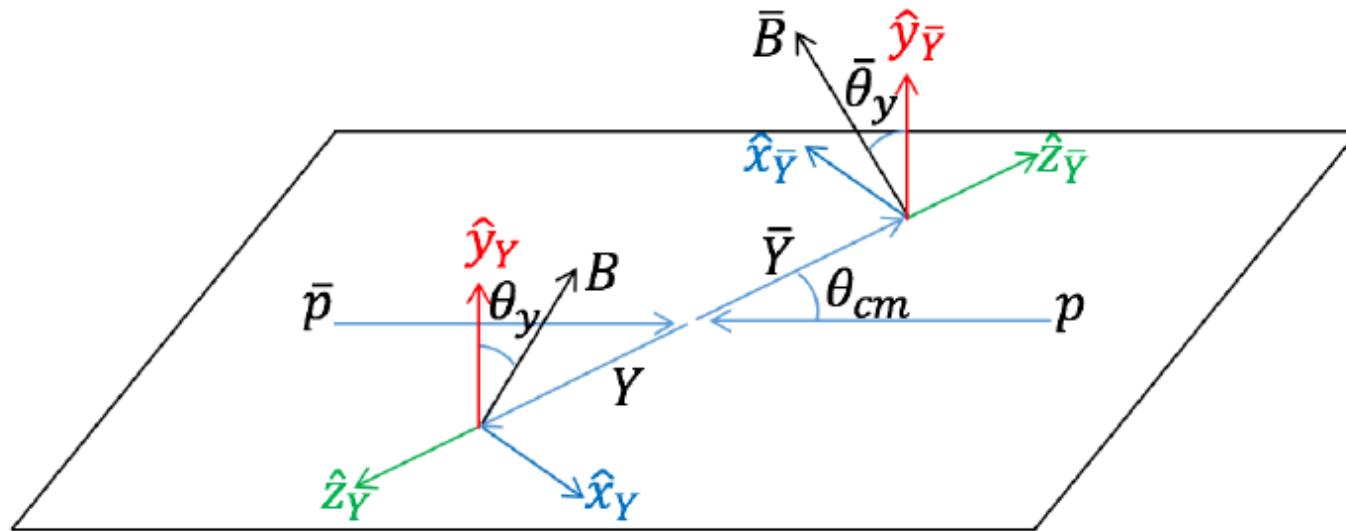
- α in primary decay
 - β and γ in sequential decays



- Production dependent spin observables from interference between production amplitudes.

Hyperon spin observables

- EM and strong interactions with unpolarized beam and target: non-zero **polarization** normal to the production plane.
- The produced $\bar{Y}Y$ pair is entangled *i.e.* their spins are **correlated**.



Hyperon joint angular distribution

Simple example: $e^+e^- \rightarrow J/\Psi \rightarrow \Lambda\bar{\Lambda}, \Lambda \rightarrow p\pi^-, \bar{\Lambda} \rightarrow \bar{p}\pi^+ *$

- $\Lambda\bar{\Lambda}$ pair in $J^P = 1^-$ state \rightarrow Two complex amplitudes dominate
 \rightarrow can parameterise in terms of production related parameters e.g.
- Angular distribution parameter η
 - Phase $\Delta\Phi$

and decay parameters α_1 and α_2

$$W(\xi) = F_0(\xi) + \boxed{\eta} F_5(\xi) + \boxed{\alpha_1 \alpha_2} (F_1(\xi) + \boxed{\sqrt{1 - \eta^2} \cos(\Delta\Phi)} F_2(\xi) + \boxed{\eta} F_6(\xi)) \\ + \boxed{\sqrt{1 - \eta^2} \sin(\Delta\Phi)} (\boxed{\alpha_1} F_3(\xi) + \boxed{\alpha_2} F_4(\xi))$$

$$\mathcal{T}_0(\xi) = 1$$

$$\mathcal{T}_1(\xi) = \sin^2 \theta \sin \theta_1 \sin \theta_2 \cos \phi_1 \cos \phi_2 + \cos^2 \theta \cos \theta_1 \cos \theta_2$$

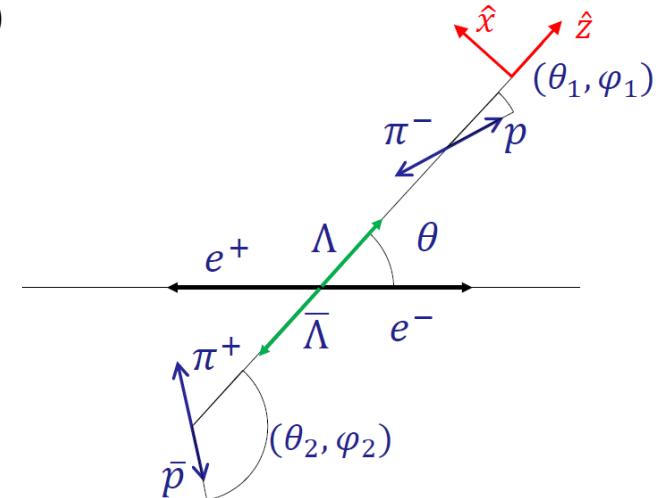
$$\mathcal{T}_2(\xi) = \sin \theta \cos \theta (\sin \theta_1 \cos \theta_2 \cos \phi_1 + \cos \theta_1 \sin \theta_2 \cos \phi_2)$$

$$\mathcal{T}_3(\xi) = \sin \theta \cos \theta \sin \theta_1 \sin \phi_1$$

$$\mathcal{T}_4(\xi) = \sin \theta \cos \theta \sin \theta_2 \sin \phi_2$$

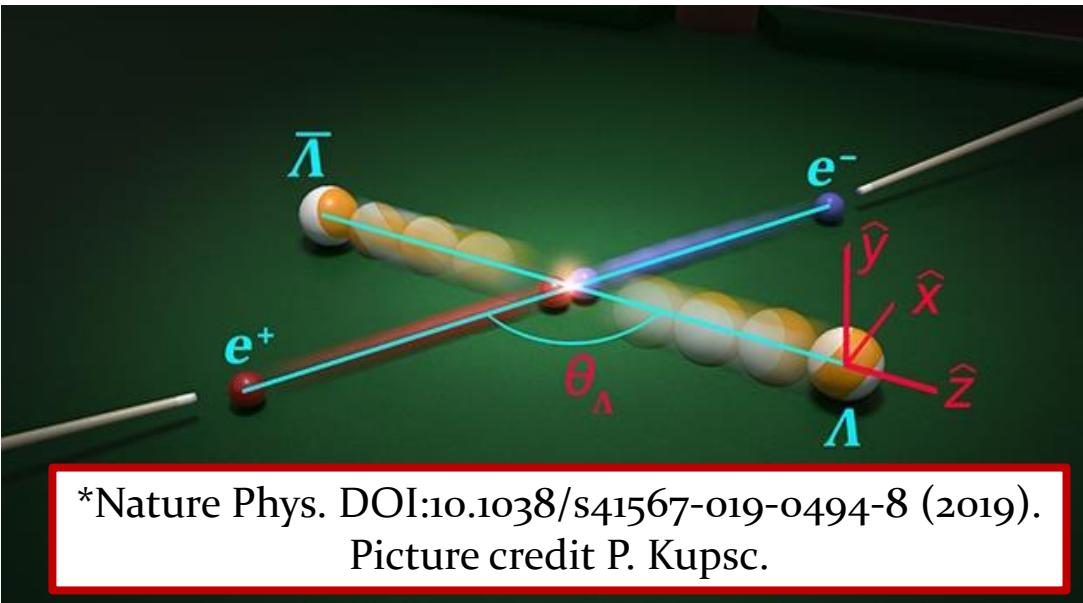
$$\mathcal{T}_5(\xi) = \cos^2 \theta$$

$$\mathcal{T}_6(\xi) = \cos \theta_1 \cos \theta_2 - \sin^2 \theta \sin \theta_1 \sin \theta_2 \sin \phi_1 \sin \phi_2$$



Hyperon joint angular distribution

- Advantages of this approach:
 - Model independent
 - Takes full process (production and decay) into account.
 - Maximizes information → larger precision for a given sample size
- Recently used in BESIII study of $e^+e^- \rightarrow J/\Psi \rightarrow \Lambda\bar{\Lambda}, \Lambda \rightarrow p\pi^-, \bar{\Lambda} \rightarrow \bar{p}\pi^+*$, **



*Nature Phys. DOI:10.1038/s41567-019-0494-8 (2019).
Picture credit P. Kupsc.

- First measurement of phase:
→ evidence for polarization and entanglement
- Most precise measurement of decay parameters α_+ and α_- .
- Significant deviation of α_+ from former PDG → updated.

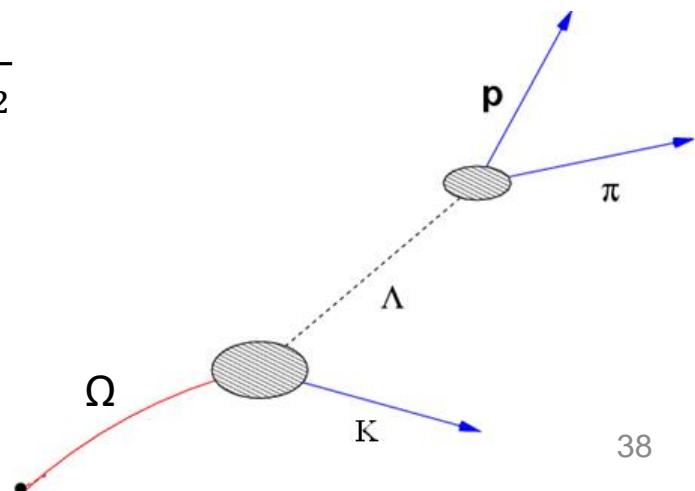
**Details in talk by S. Fang.

Hyperon joint angular distribution

- Extension of formalism to sequential decays of ground-state spin $\frac{1}{2}$ and $\frac{3}{2}$ hyperons:
 - G. Fäldt, PRD **97** 053002 (2018)
 - E. Perotti *et al.*, PRD **99** 056008 (2019)
- Polarization parameters of Ω^- baryons: E. Perotti, JP Conf.1024 012019 (2018)
 - Spin $\frac{1}{2}$: 3 polarisation parameters
 - Spin $\frac{3}{2}$: 15 polarisation parameters

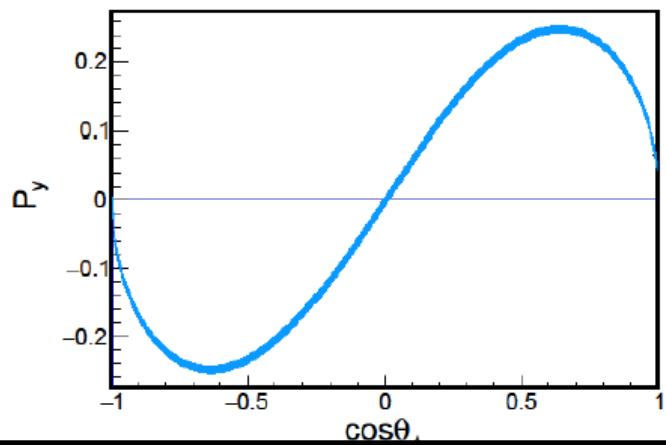
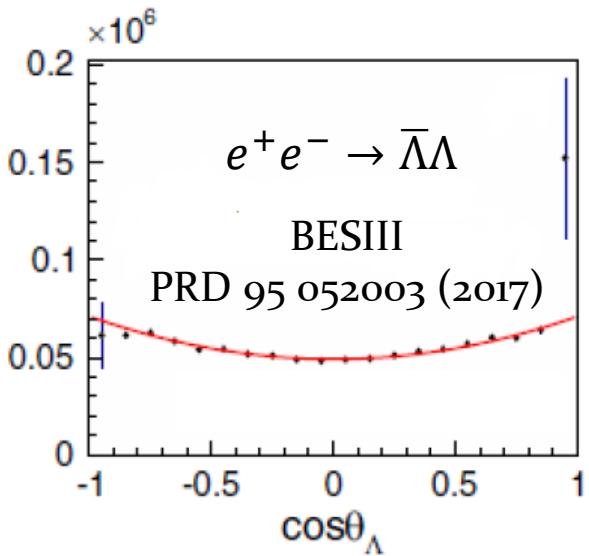
Degree of polarization: $d\left(\frac{3}{2}\right) = \sqrt{\sum_{\mu=1}^{15} \left(\frac{r_\mu}{r_0}\right)^2}$

(M.G. Doncel *et al.*, NPB **38** 477 (1972))



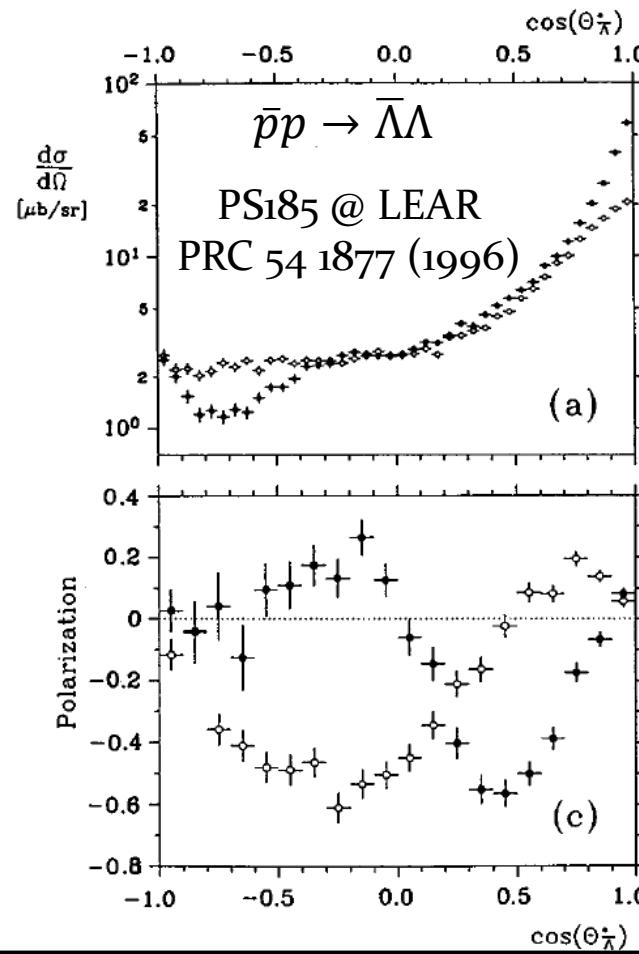
Possible extensions

- $e^+e^- \rightarrow 1^- \rightarrow \bar{Y}Y^* + c.c$
 - Spin determination of excited hyperons in e^+e^- colliders.
- $\bar{p}p \rightarrow \bar{Y}Y$
 - Ground-state hyperon production and decay in PANDA.
- $\bar{p}p \rightarrow \bar{Y}Y^* + c.c.$
 - Spin determination of excited Ξ^* and Ω^* .



$J^P = 1^-$ dominates $\rightarrow 2$ amplitudes
 $\rightarrow 2$ global observables η and $\Delta\Phi$.

Cross section, polarization and spin correlations have well-defined dependence on scattering angle.



Several initial J^P contribute \rightarrow complicated final state.

≥ 5 observables at each θ_Y :
Cross section, polarization and spin correlations with unknown dependence on scattering angle.

e^+e^- versus $\bar{p}p$

Q: Many θ_Y – dependent production parameters in $\bar{p}p$ case.
→ how could that even be feasible?

A: Because the $\bar{Y}Y$ reconstruction rate is **2** orders of magnitude larger at PANDA compared to current e^+e^- experiments
- already during the first phase!

Possible application: Search for CP violating hyperon decays

- CP violation one criterion for Baryogenesis*.
- CP violation beyond SM never observed for baryons.
- The $\bar{p}p \rightarrow \bar{Y}Y$ process suitable for CP measurements:
 - Very large samples expected
 - Symmetric particle – antiparticle conditions.
- If CP valid, $\alpha = -\bar{\alpha}$ i.e. $A_{CP} = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} = 0.0000 \dots$

Hyperon physics with PANDA

- **Phase 1:**
 - Hyperon production and spin observables
 - Single- and double strange hyperon spectroscopy
- **Phase 2:**
 - Triple-strange hyperon spectroscopy
 - Hyperon structure
- **Phase 3:**
 - Search for CP violating hyperon decays

Summary

- Many fundamental questions manifest themselves in the nucleon.
- Strategy: replace one of the building blocks → hyperons!
- Hyperons of different flavour probe different scales of the strong interaction.
- Self-analyzing decay → help pinpointing the role of spin.
- PANDA will be a strangeness factory already in Phase 1
→ Rich hyperon physics programme!

Thanks to:

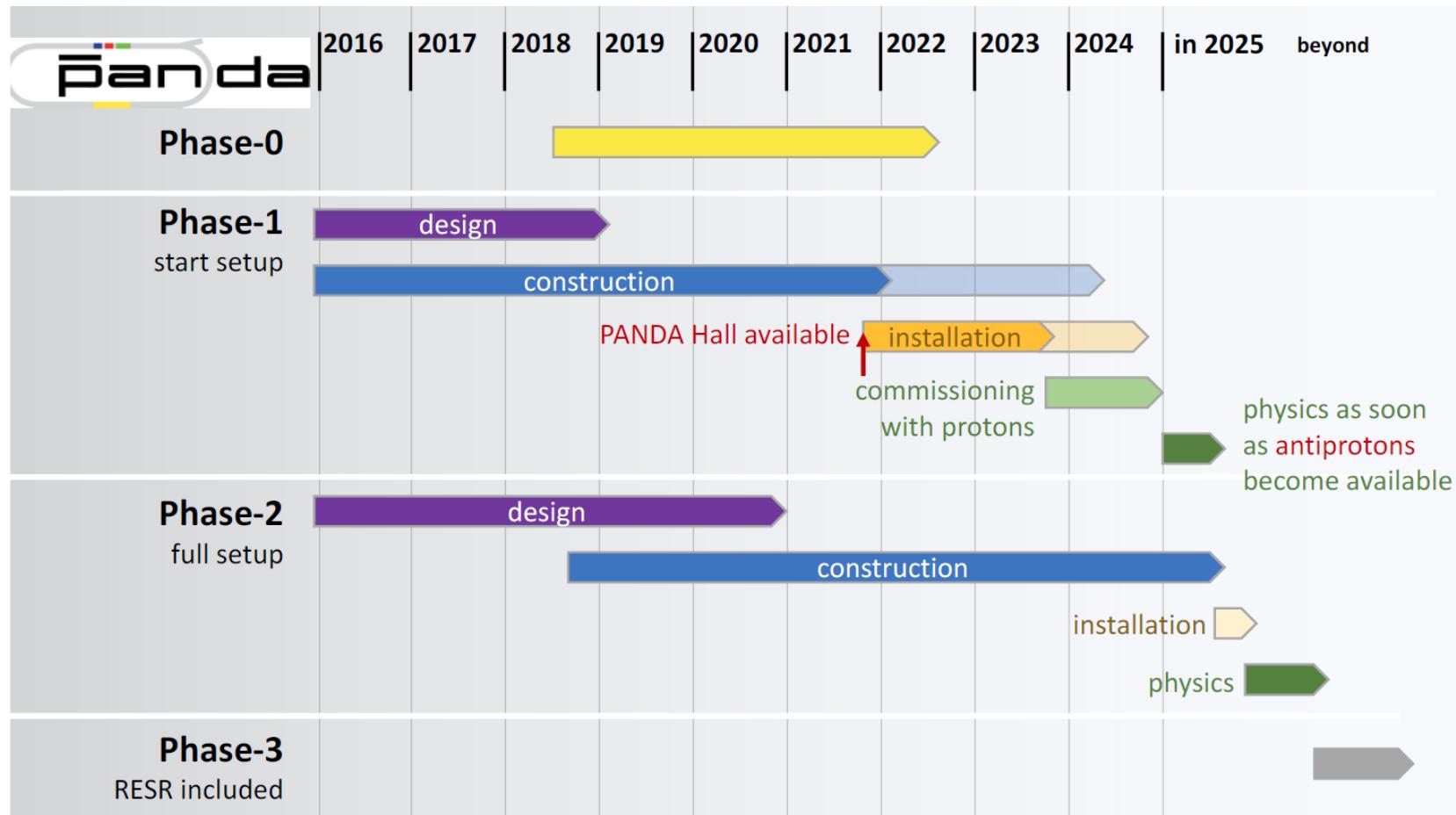
Alaa Dbeysi, Jennifer Pütz, Tord Johansson,
Andrzej Kupsc, Göran Fälldt, Elisabetta Perotti,
Stefan Leupold, Gabriela Perez Andrade
and Walter Ikegami-Andersson





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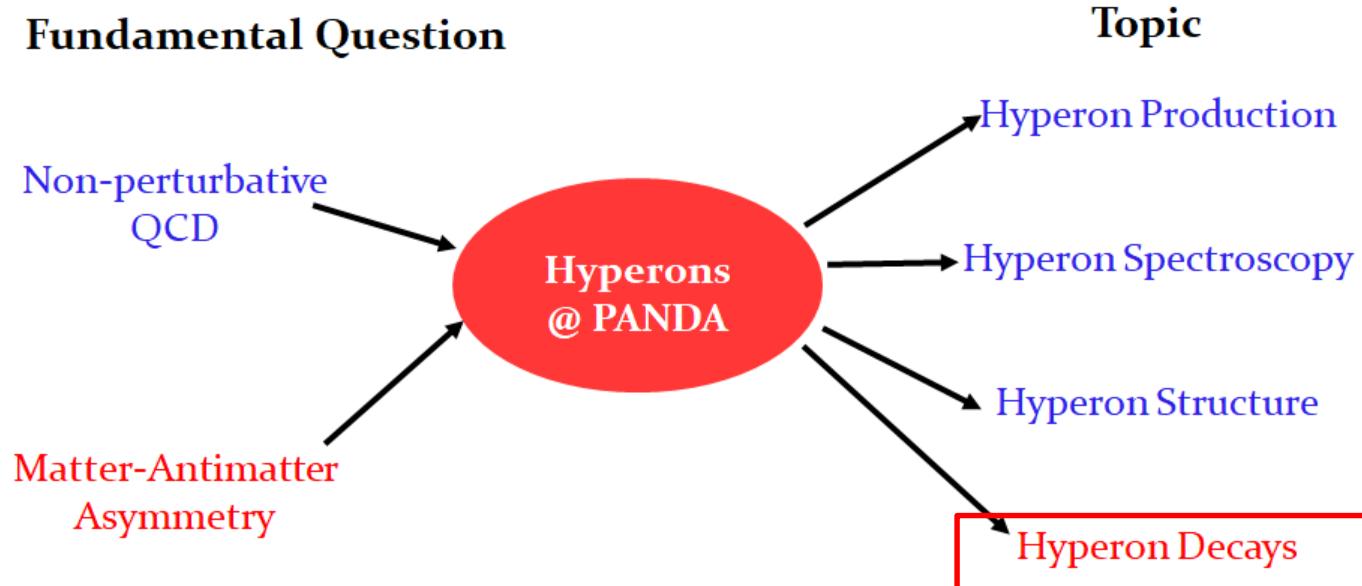
Backup



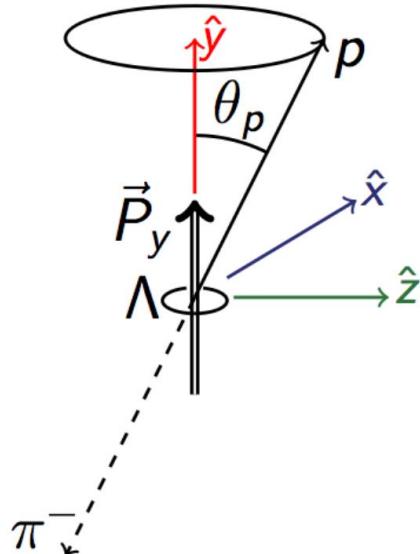


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HYPERON TOPICS IN PANDA



Hyperon decay parameters



Weak hyperon decay $Y \left(\frac{1}{2}\right) \rightarrow B \left(\frac{1}{2}\right) + M(0)$

- has a parity violating amplitude T_s
- has a parity conserving amplitude T_p
- has a decay angular distribution

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

where $\alpha = \frac{2\text{Re}(T_s^* \cdot T_p)}{T_s^2 + T_p^2}$ **Decay asymmetry**

and P_Y = Polarisation **Production dependent**

Hyperon joint angular distribution

Simple example: $e^+e^- \rightarrow \frac{J}{\Psi} \rightarrow \Lambda\bar{\Lambda}, \Lambda \rightarrow p\pi^-, \bar{\Lambda} \rightarrow \bar{p}\pi^+ *$

Unpolarized part **Polarized part** **Spin correlated part**

$$W(\xi) = F_0(\xi) + \eta F_5(\xi) - \alpha_1 \alpha_2 (F_1(\xi) + \sqrt{1-\eta^2} \cos(\Delta\Phi) F_2(\xi) + \eta F_6(\xi)) \\ + \sqrt{1-\eta^2} \sin(\Delta\Phi) (\alpha_1 F_3(\xi) + \alpha_2 F_4(\xi))$$

$$\mathcal{T}_0(\xi) = 1$$

$$\mathcal{T}_1(\xi) = \sin^2 \theta \sin \theta_1 \sin \theta_2 \cos \phi_1 \cos \phi_2 + \cos^2 \theta \cos \theta_1 \cos \theta_2$$

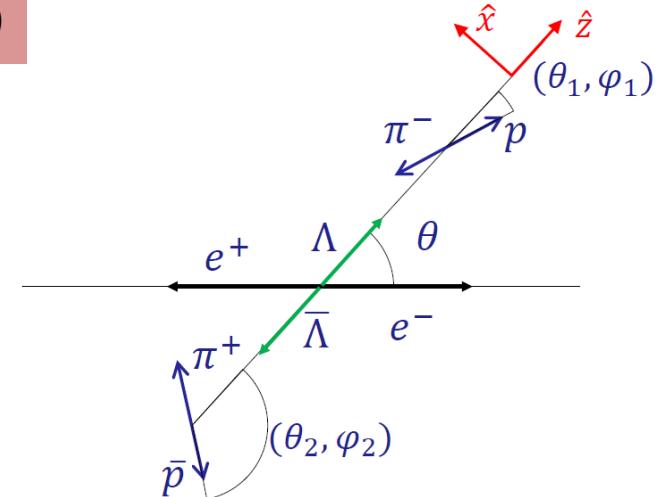
$$\mathcal{T}_2(\xi) = \sin \theta \cos \theta (\sin \theta_1 \cos \theta_2 \cos \phi_1 + \cos \theta_1 \sin \theta_2 \cos \phi_2)$$

$$\mathcal{T}_3(\xi) = \sin \theta \cos \theta \sin \theta_1 \sin \phi_1$$

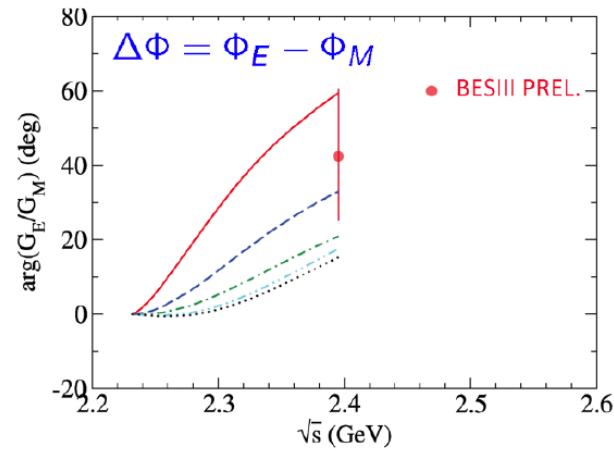
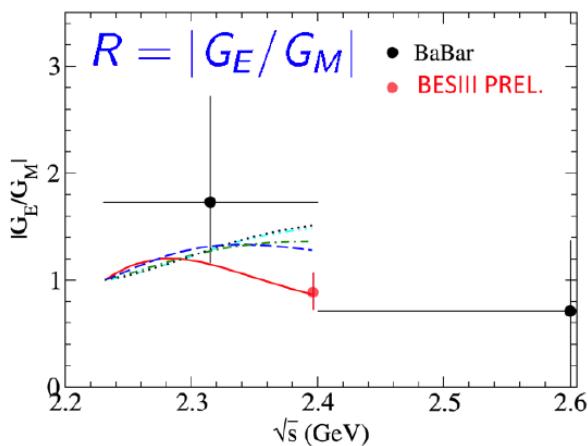
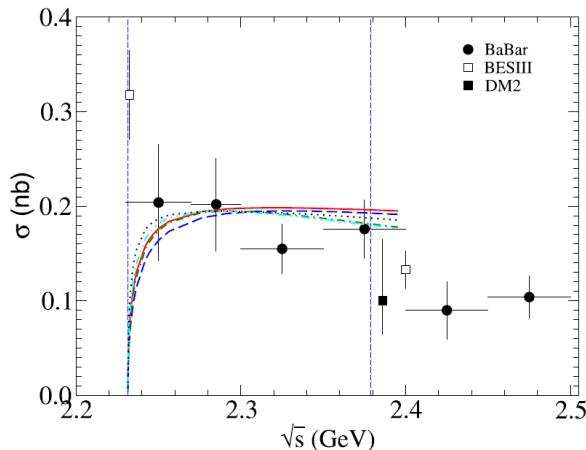
$$\mathcal{T}_4(\xi) = \sin \theta \cos \theta \sin \theta_2 \sin \phi_2$$

$$\mathcal{T}_5(\xi) = \cos^2 \theta$$

$$\mathcal{T}_6(\xi) = \cos \theta_1 \cos \theta_2 - \sin^2 \theta \sin \theta_1 \sin \theta_2 \sin \phi_1 \sin \phi_2$$



Hyperon production



The $\bar{Y}Y$ interaction is important to understand:

- Hyperon structure, studied in $e^+e^- \rightarrow \bar{Y}Y$, predicted using potential models obtained with $\bar{p}p \rightarrow \bar{Y}Y$ data.*
- Spin observables sensitive to $\bar{Y}Y$ potential.
- New data from BaBar** and BESIII***.

*Haidenbauer *et al.*, PLB 761(2016) 456
 **BaBar: PRD 76 (2007) 092006
 ***BES III: Talk by C. Li, BEACH2018

Spin analyses in $\bar{p}p$

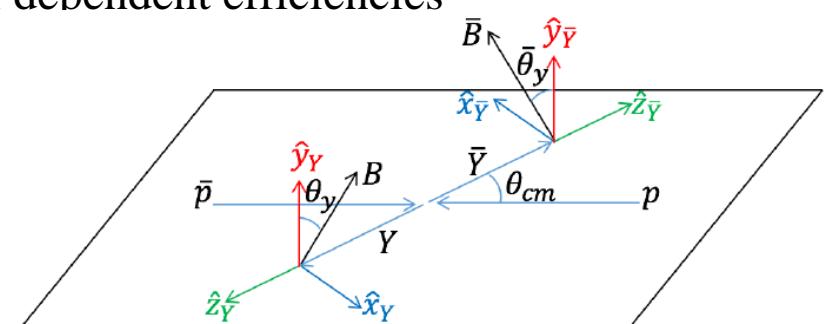
For $\bar{p}p \rightarrow \bar{Y}Y \rightarrow \bar{B}MB\bar{M}$, the angular distribution at each θ_Y is given by

$$I(\theta_i, \theta_j) = N[1 + \bar{\alpha} \sum_i P_i^{\bar{Y}} \cos \theta_i + \alpha \sum_j P_j^Y \cos \theta_i + \alpha \bar{\alpha} \sum_{i,j} C_{ij} \cos \theta_i \cos \theta_j]$$

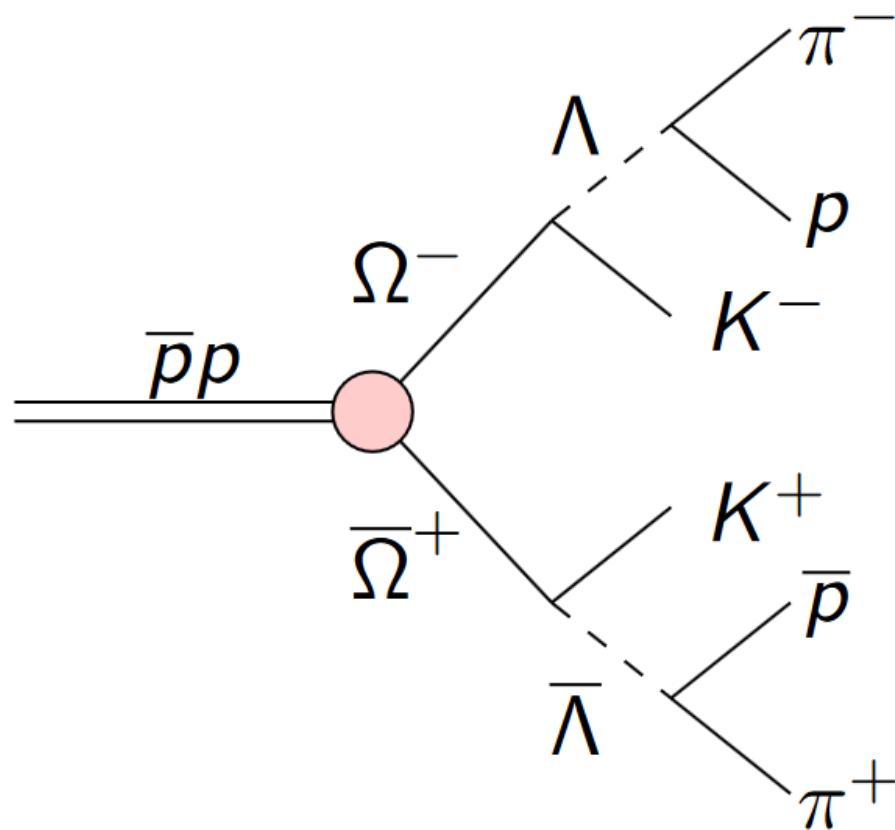
where $P_i^{\bar{Y}} = P_i^{\bar{Y}}(\cos \theta_Y)$, $P_j^Y = P_j^Y(\cos \theta_Y)$, and $C_{ij} = C_{ij}(\cos \theta_Y)$.

In the past, the dependencies on $\cos \theta_Y$ was studied, but only in one variable at a time.

- Gives rise to systematics from model dependent efficiencies
- Loss of information for e.g. PWA.



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



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

Density matrix:

- 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 .
- Strong production process → parity is conserved → **8** polarisation parameters equal 0.
- Resulting density matrix $\rho \left(\frac{3}{2} \right)$:*

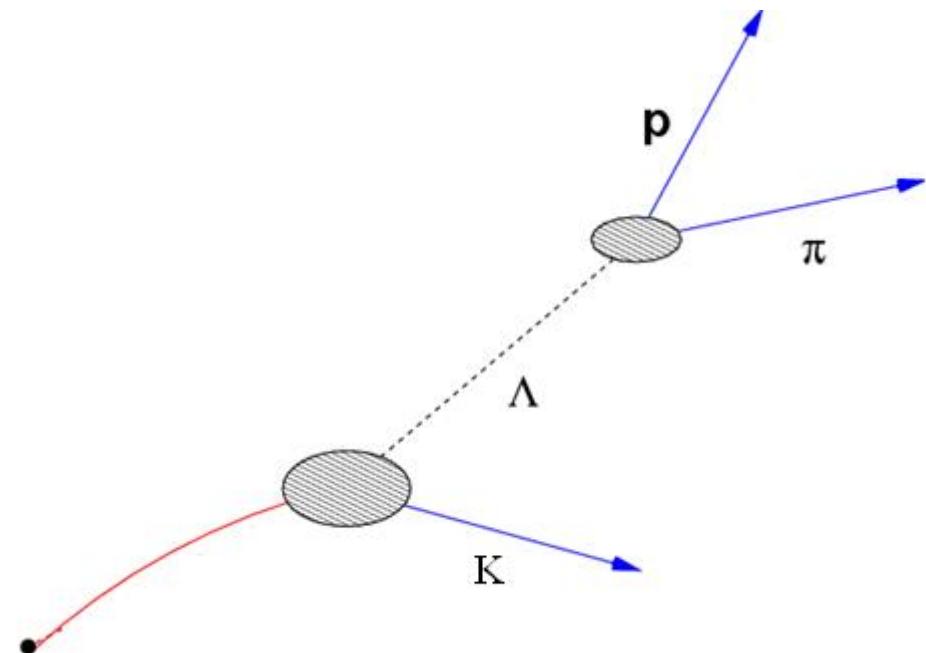
$$\frac{1}{4} \begin{bmatrix} 1 + \sqrt{3}r_0^2 & -i\frac{3}{\sqrt{5}}r_{-1}^1 + \sqrt{3}r_1^2 - i\sqrt{\frac{6}{5}}r_{-1}^3 & \sqrt{3}r_2^2 - i\sqrt{3}r_{-2}^3 & -i\sqrt{6}r_{-3}^3 \\ i\sqrt{\frac{6}{5}}r_{-1}^3 + i\frac{3}{\sqrt{5}}r_{-1}^1 + \sqrt{3}r_1^2 & 1 - \sqrt{3}r_0^2 & -i2\sqrt{\frac{3}{5}}r_{-1}^1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

* Erik Thomé, PhD thesis, Uppsala University (2012)

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

Consider the decay $\Omega^- \rightarrow \Lambda K^- \rightarrow p\pi^- K^-$.

Spinwise this is $\frac{3}{2} \rightarrow \frac{1}{2} 0 \rightarrow \frac{1}{2} 0 0$.

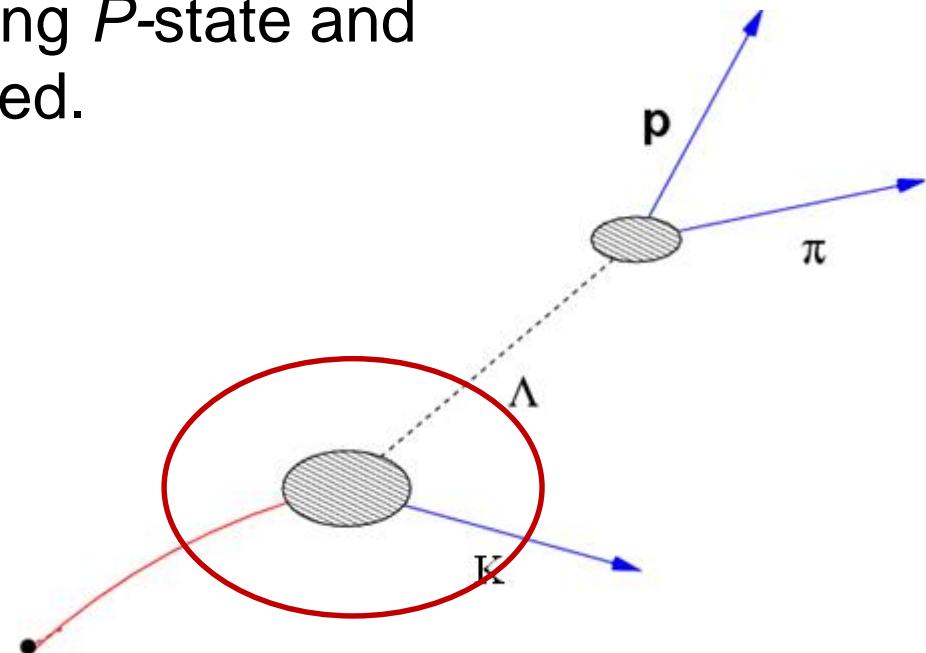


Spin observables for spin $\frac{3}{2}$ hyperons

First, let's focus on $\Omega^- \rightarrow \Lambda K^-$, i.e. $\frac{3}{2} \rightarrow \frac{1}{2} 0$.

Weak decay: parity conserving P -state and parity violating D -state allowed.

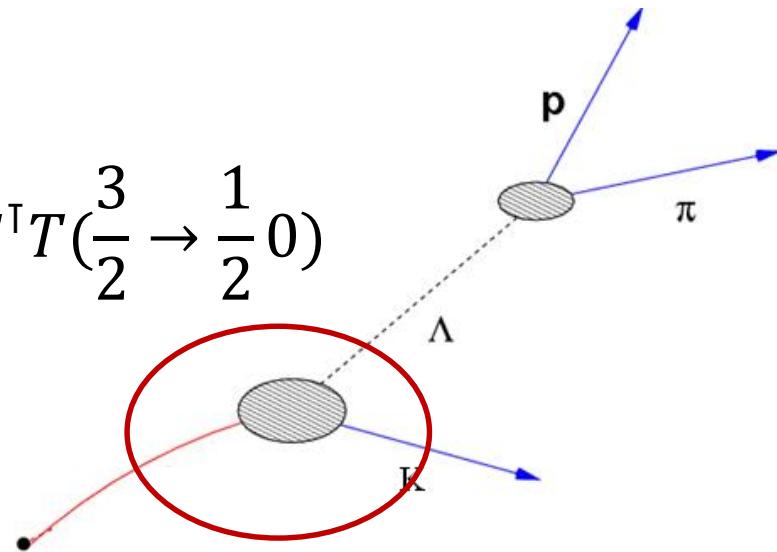
Amplitudes: T_P and T_D .



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

Angular distribution given by

$$I(\theta, \varphi) = \text{Tr}(\rho(\frac{3}{2}) T^\dagger T (\frac{3}{2} \rightarrow \frac{1}{2} 0))$$



$$I(\theta, \phi) = \text{Tr}(\rho(3/2) T^\dagger T (3/2 \rightarrow 1/2 0))$$

$$\begin{aligned}
 &= \frac{1}{4\pi} \left[1 + \frac{\sqrt{3}}{2}(1 - 3\cos^2 \theta)r_0^2 - \frac{3}{2}\sin^2 \theta \cos 2\phi r_2^2 - \frac{3}{2}\sin 2\theta \cos \phi r_1^2 \right. \\
 &+ \frac{1}{40}\alpha \sin \theta \left(8\sqrt{15}r_{-1}^1 \sin \phi - 9\sqrt{10}r_{-1}^3 (3 + 5\cos 2\theta) \sin \phi \right. \\
 &\quad \left. \left. - 30(3r_{-2}^3 \sin 2\phi \sin 2\theta + \sqrt{6}r_{-3}^3 \sin 3\phi \sin^2 \theta) \right) \right]
 \end{aligned}$$

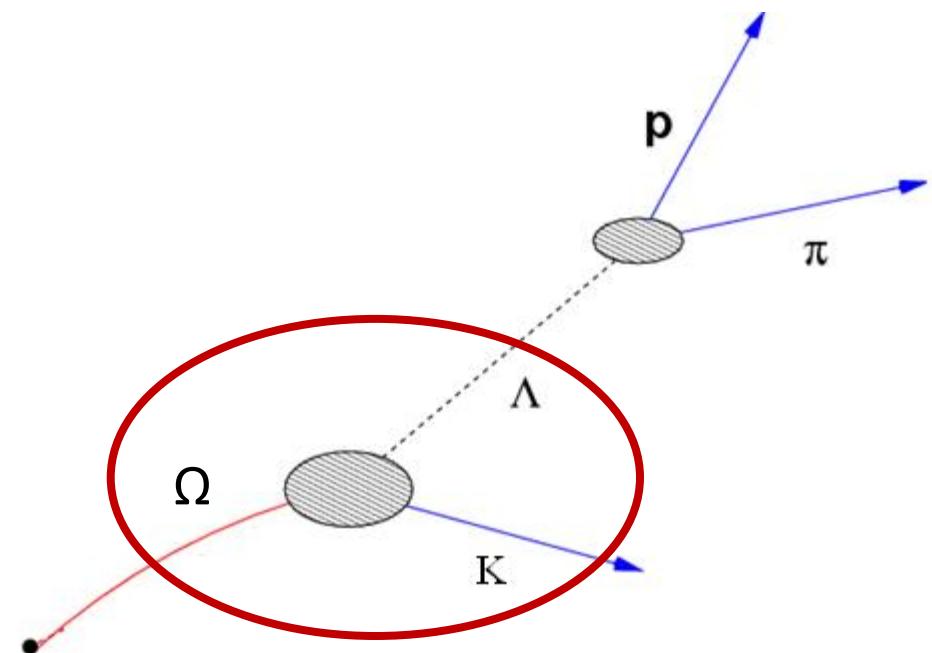
Spin observables for spin $\frac{3}{2}$ hyperons

Using the *method of moments*, the 3 polarisation parameters r_2^2, r_1^2, r_0^2 can be extracted from the angular distribution of the Λ :*

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

$$\langle \cos\varphi_\Lambda \cos\theta_\Lambda \rangle = -\frac{3\pi}{32} r_1^2$$

$$\langle \sin^2\varphi_\Lambda \rangle = \frac{1}{4} (2 + r_2^2)$$



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

$$\langle \sin \phi_\Lambda \cos \phi_p \rangle$$

$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_p, \phi_p) \times \sin \phi_\Lambda \cos \phi_p d\Omega_\Lambda d\Omega_p =$$

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

$$\langle (3 \cos \theta_\Lambda - 1) \sin \phi_p \rangle$$

$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_p, \phi_p) \times (3 \cos \theta_\Lambda - 1) \sin \phi_p d\Omega_\Lambda d\Omega_p =$$

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

$$\langle \sin \phi_p \rangle$$

$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_p, \phi_p) \times \sin \phi_p d\Omega_\Lambda d\Omega_p =$$

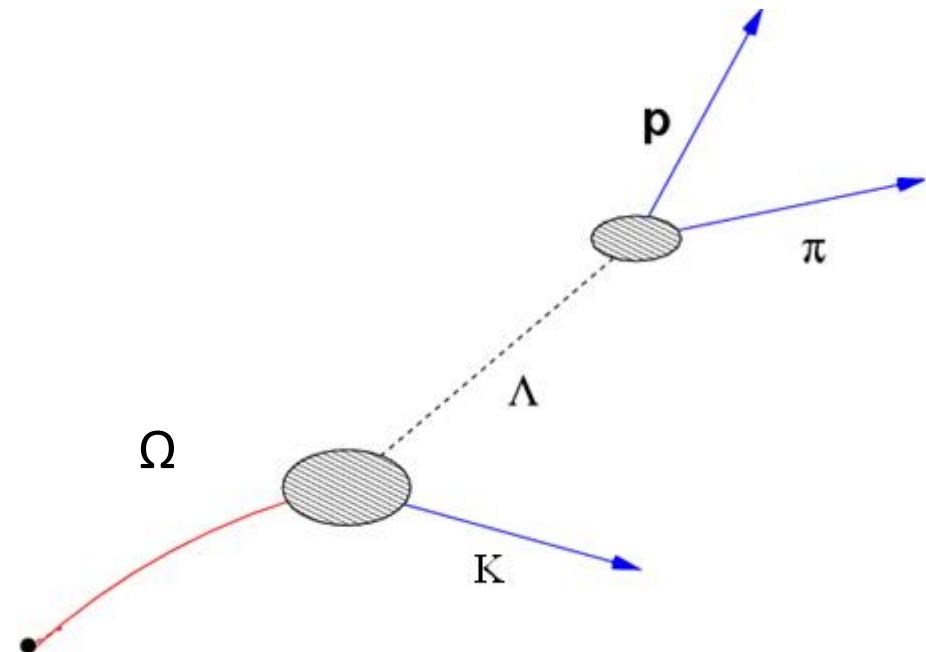
$$= \frac{\pi \alpha_\Lambda \gamma_\Omega}{160} \left(-4\sqrt{15}r_{-1}^1 + \sqrt{10}r_{-1}^3 \right)$$

$$\langle \sin \phi_\Lambda \cos \phi_\Lambda \cos \phi_p \rangle$$

$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_p, \phi_p) \times \sin \phi_\Lambda \cos \phi_\Lambda \cos \phi_p d\Omega_\Lambda d\Omega_p =$$

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

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, FAIRNESS

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

$$\langle \sin \phi_\Lambda \cos \phi_p \rangle$$

$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_p, \phi_p) \times \sin \phi_\Lambda \cos \phi_p d\Omega_\Lambda d\Omega_p =$$

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

$$\langle (3 \cos \theta_\Lambda - 1) \sin \phi_p \rangle$$

$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_p, \phi_p) \times (3 \cos \theta_\Lambda - 1) \sin \phi_p d\Omega_\Lambda$$

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

$$\langle \sin \phi_p \rangle$$

$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_p, \phi_p) \times \sin \phi_p d\Omega_\Lambda d\Omega_p =$$

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

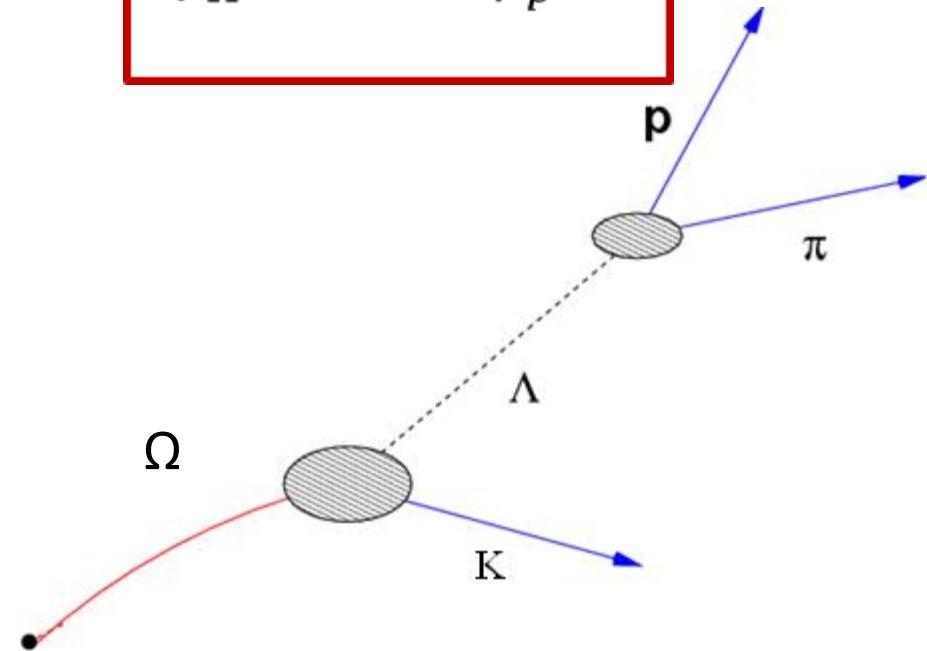
$$\langle \sin \phi_\Lambda \cos \phi_\Lambda \cos \phi_p \rangle$$

$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_p, \phi_p) \times \sin \phi_\Lambda \cos \phi_\Lambda \cos \phi_p d\Omega_\Lambda d\Omega_p =$$

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

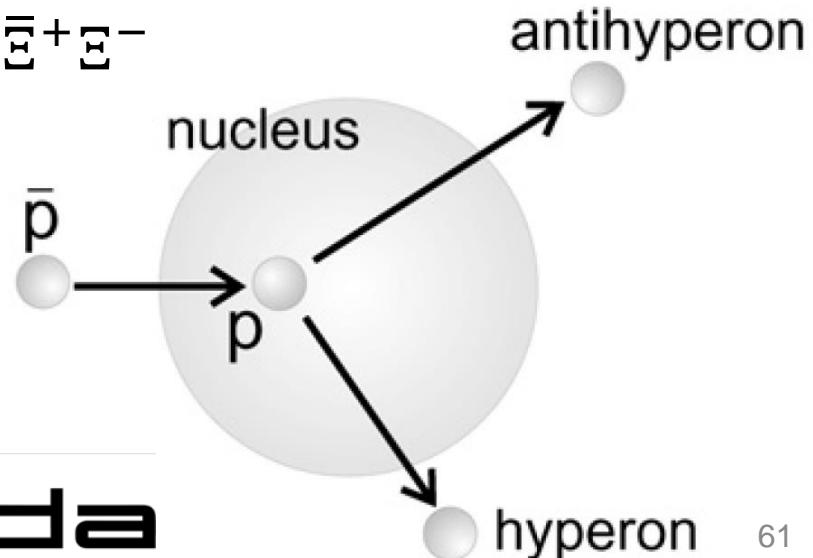
Furthermore:

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



Anti-hyperons in nuclei

- Antibaryon potential in nuclei:
 - Discrepancy theory/data for antiprotons in nuclei.
 - (Anti-) strangeness sector experimentally unknown.*
- Advantage of PANDA:
 - Large production cross sections for $\bar{Y}Y$.
- Simulation studies of $\bar{\Lambda}\Lambda$ and $\bar{\Xi}^+\Xi^-$ show promising results.



*PLB 669 (2008) 306.

** PLB 749 (2015) 421.