UPPSALA UNIVERSITET

STINT
The Swedish Foundation for International Cooperation in Research and Higher Education

Swedish Research Council

Knut and Alice Wallenberg Foundation

Hyperon Physics with Antiproton Beams

Workshop on Future Nuclear and Hadronic Physics at the CERN-AD, Vienna, Austria

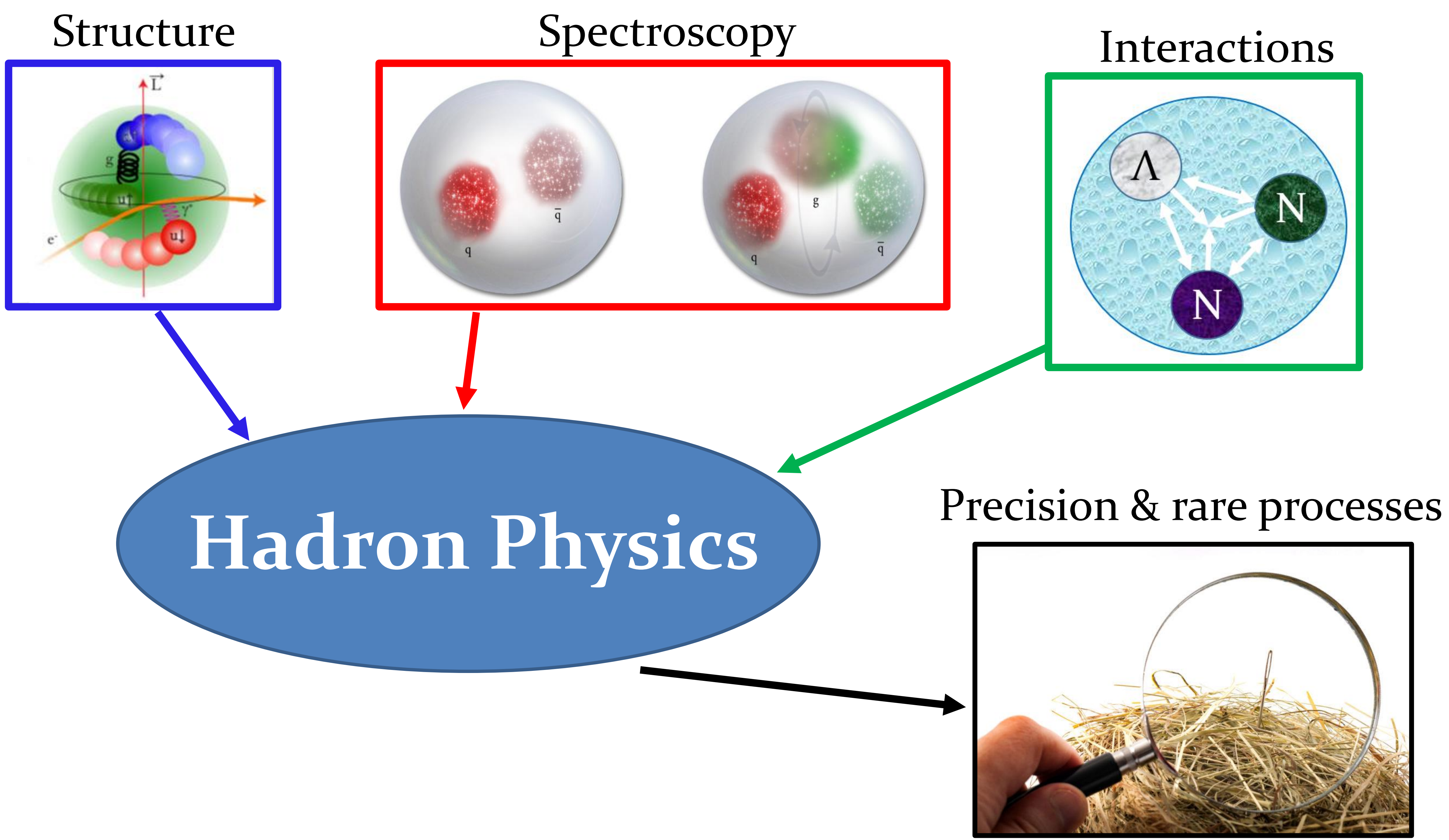
April 8-10 2024

Prof. Dr. Karin Schönning, Uppsala University

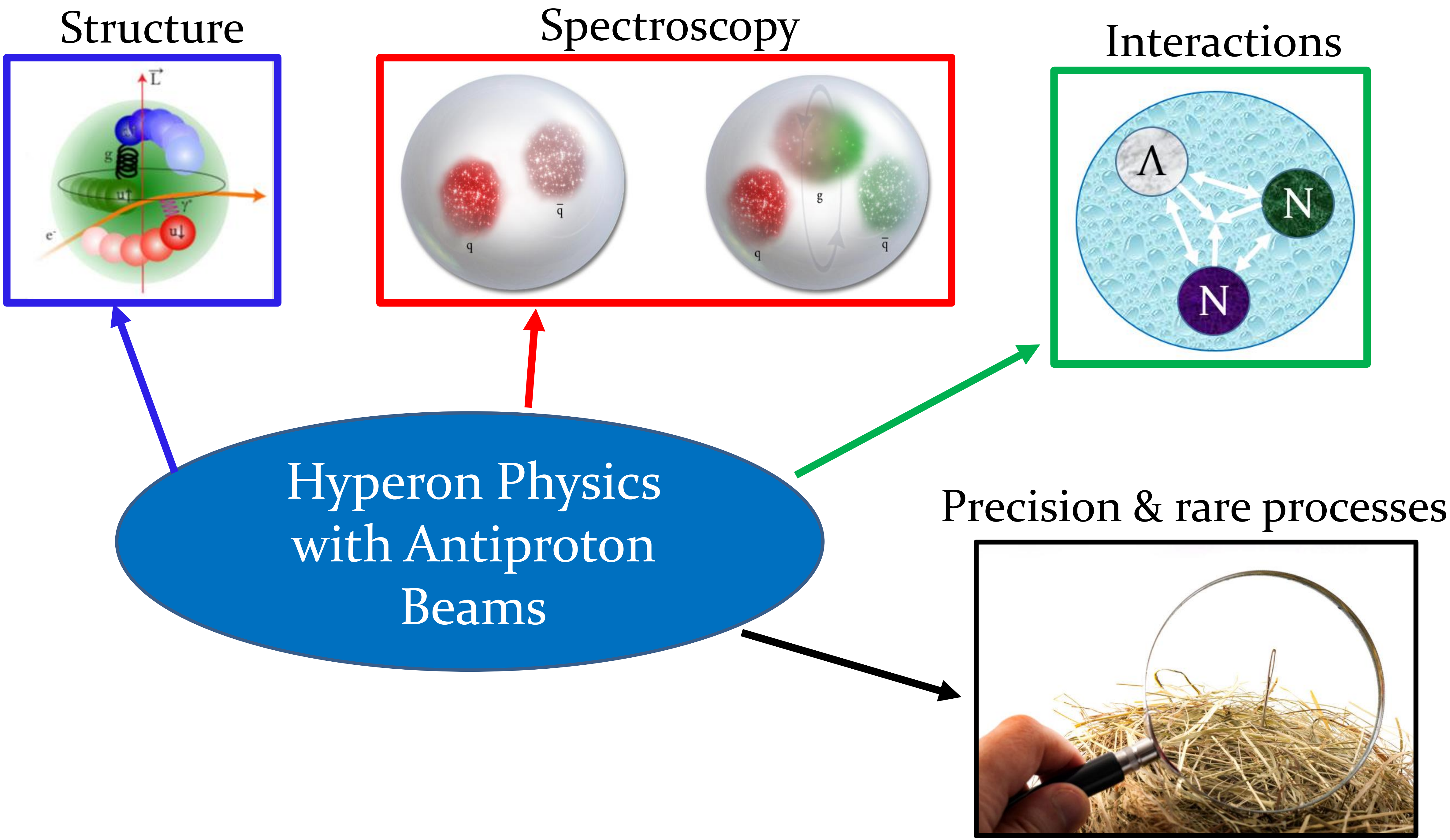
Outline

- Introduction
- Reference: PANDA at FAIR
- Hyperon structure
- Hyperon spectroscopy
- Hyperon interactions
- Precision & rare processes
- Summary

How does the strong interaction form visible matter form the fundamental quarks and gluons?

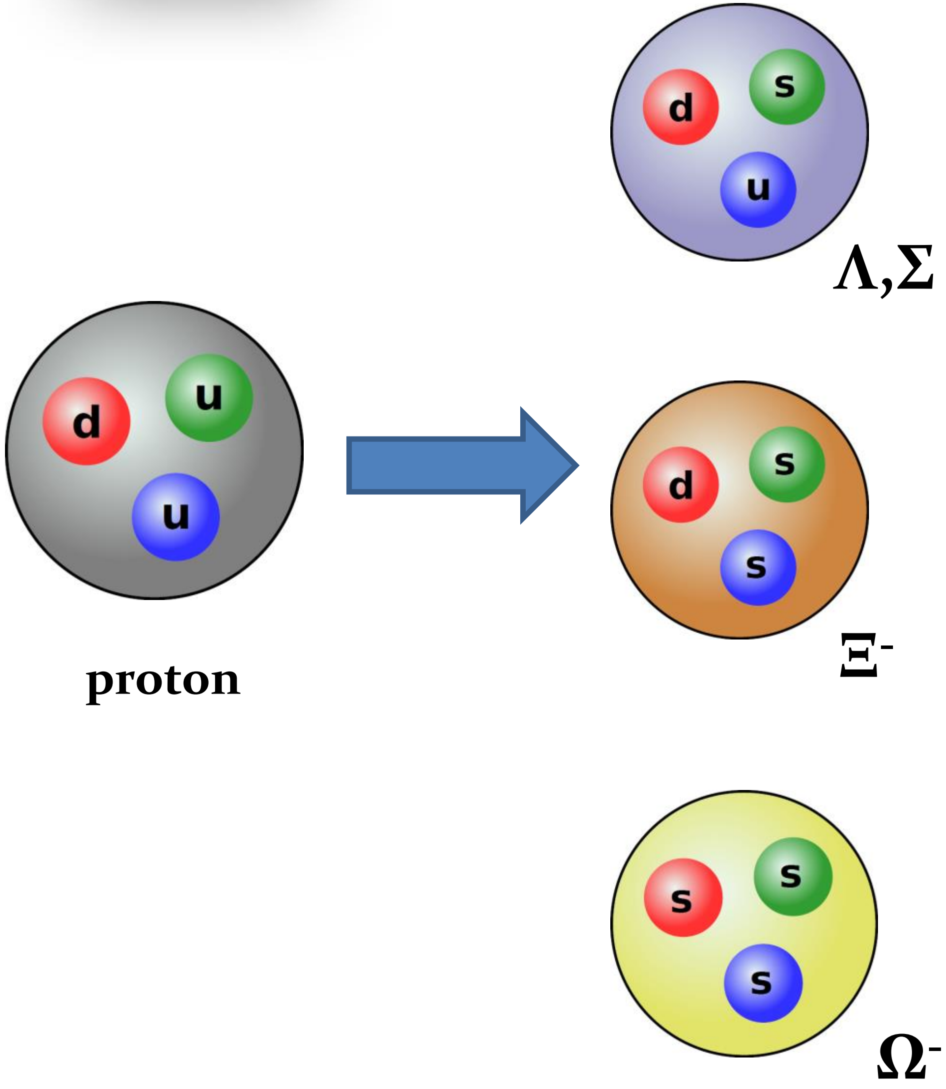


Structure
Spectroscopy
Interactions
Hadron Physics
Precision & rare processes
q
q̄
g
Λ
N
N

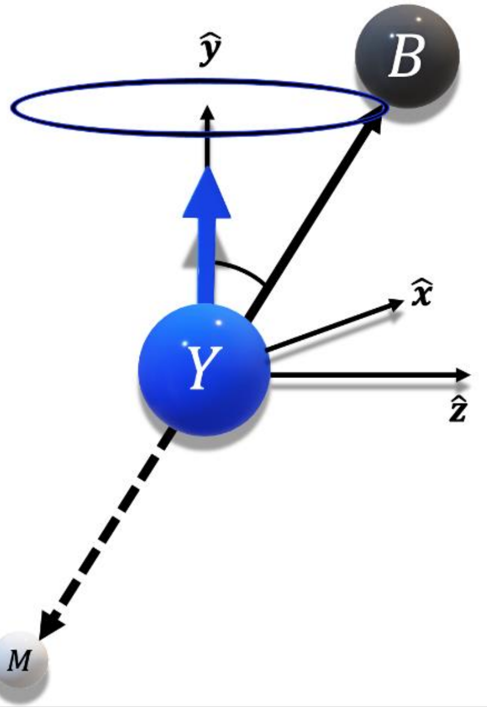

Structure
Spectroscopy
Interactions
Precision & rare processes
Hyperon Physics
with Antiproton
Beams
q
q̄
g
q
q̄
Λ
N
N

UPPSALA UNIVERSITET

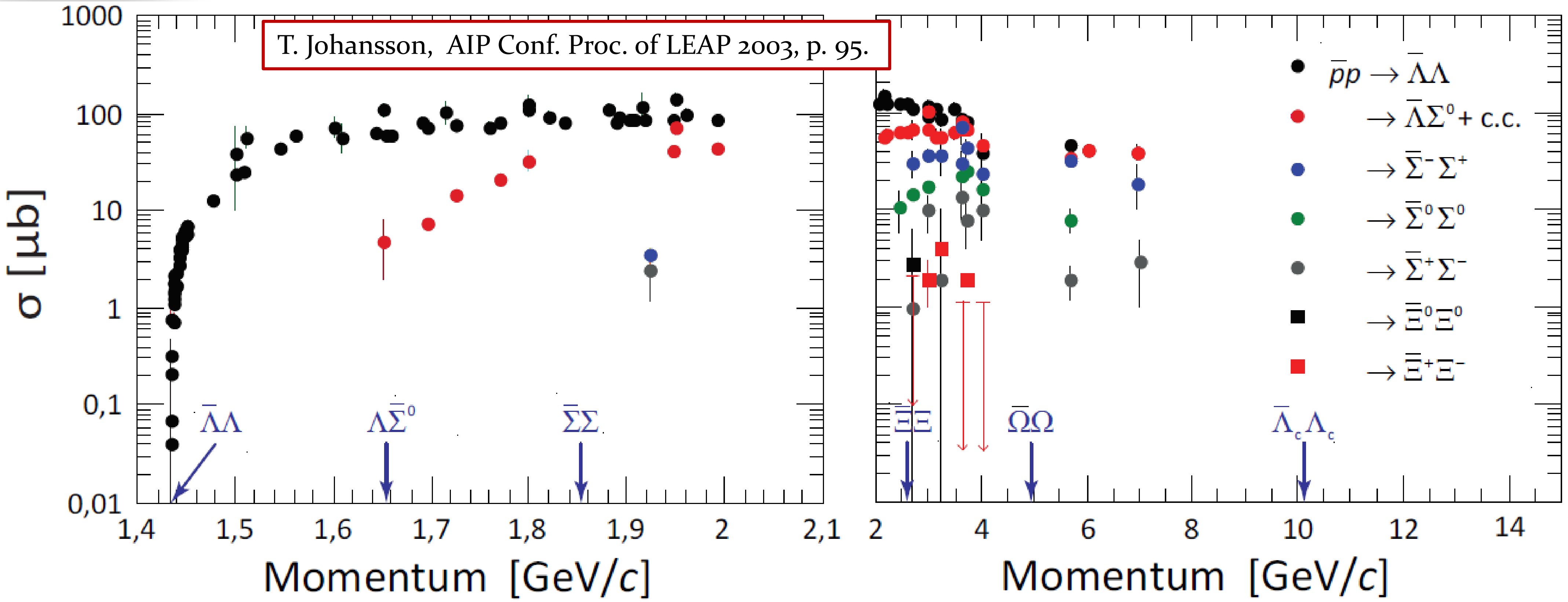
Why hyperons?



- Role of flavour in hadrin properties
- Self-analysing decay → traceable spin
- Strangeness additional degree of freedom in nuclear matter.



Why antiprotons?



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

* E. Klempt *et al.*, Phys. Rept. 368 (2002) 119-316
**V. Flaminio *et al.*, CERN-HERA 84-01

→ Large expected production rates!

Why antiprotons?

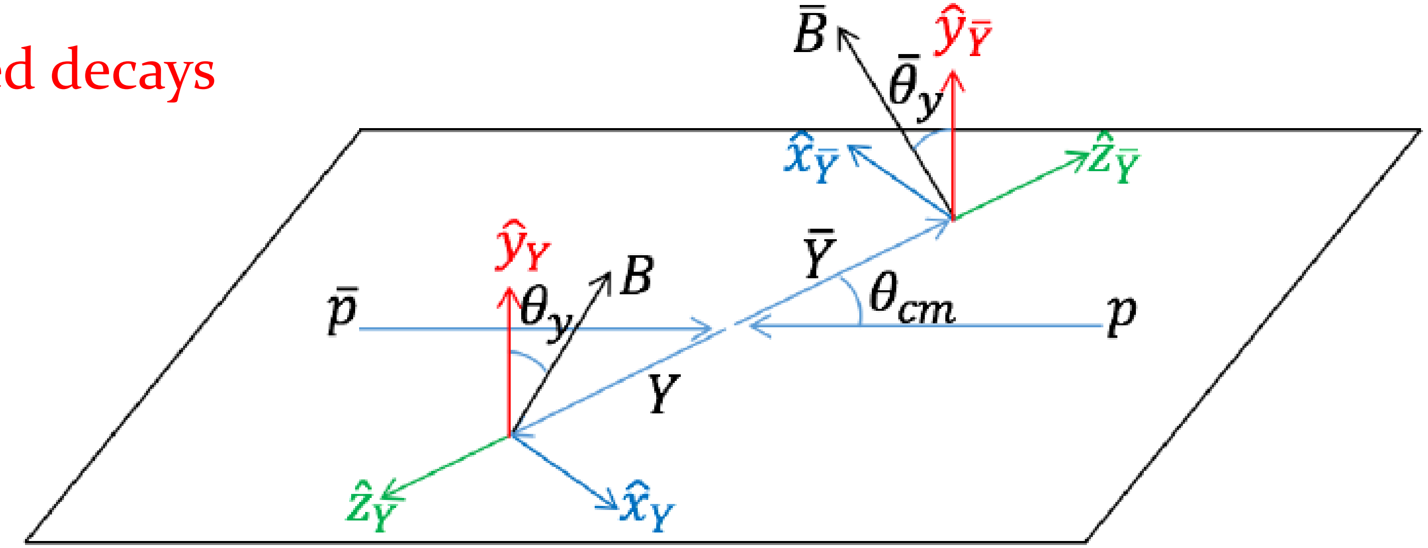
Antihyperon – hyperon pair production in $\bar{p}p \rightarrow \bar{Y}Y$:

- Two-body processes

  → well-defined kinematics

- Symmetric particle-antiparticle final state

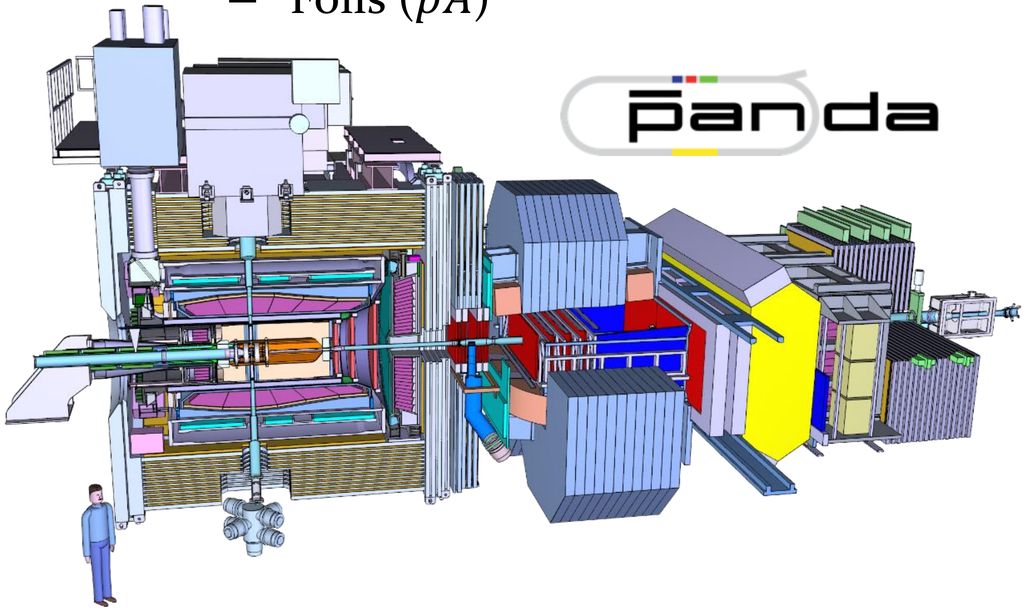
  → entangled system → correlated decays

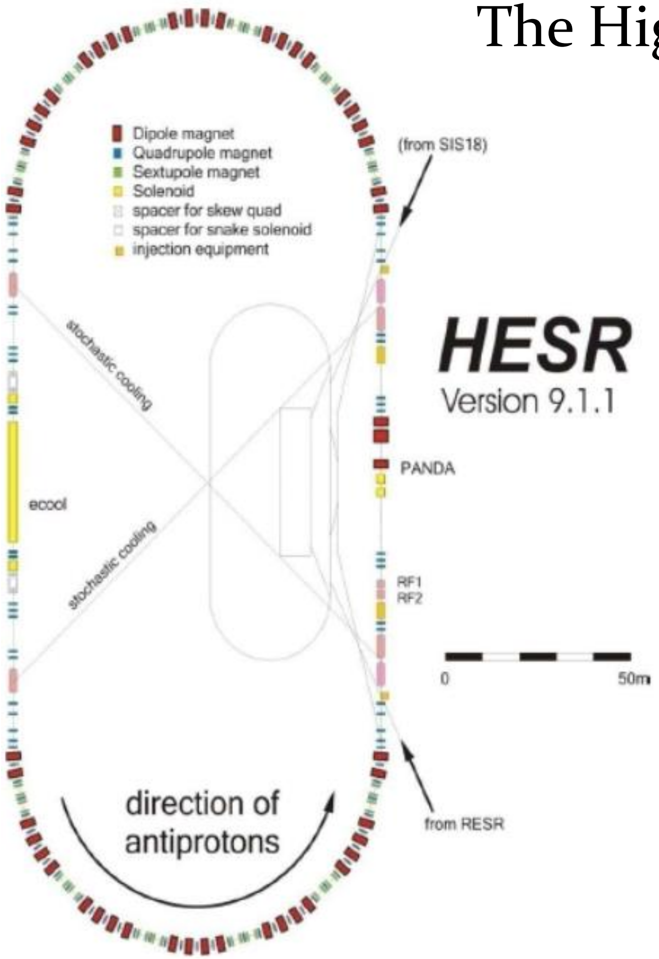


Reference: PANDA at HESR, FAIR

The PANDA detector

- 4π coverage
- Vertexing, Tracking, PID, Calorimetry
- Internal targets:
  - Cluster jet and pellet ($\bar{p}p$)
  - Foils ($\bar{p}A$)





The High Energy Storage Ring

- Anti-protons beam
  - $1.5 < p_{beam} < 15$ GeV/c
- Luminosity:
  - Design ~$2*10^{32}$ $cm^{-2}s^{-1}$
  - Phase One ~10^{31} $cm^{-2}s^{-1}$

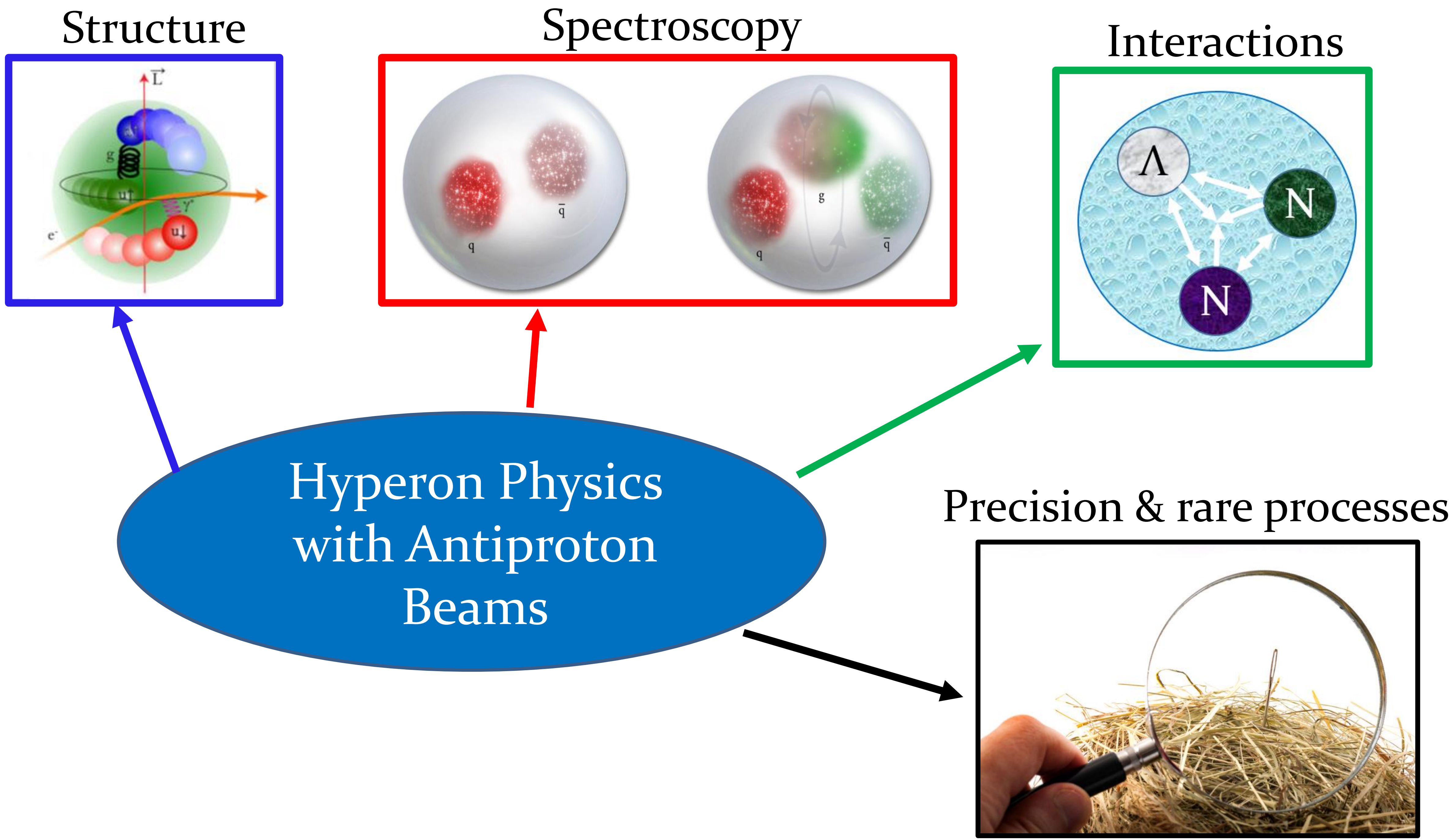
Advantages of PANDA

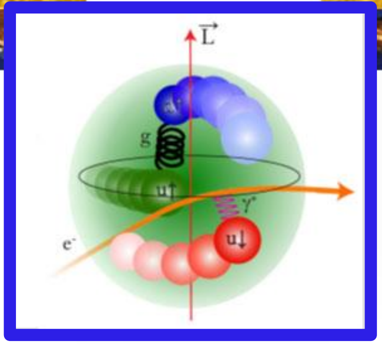
Near 4π detectors → exclusive hyperon-antihyperon measurements:

- Large reconstruction efficiency
- Small reconstruction bias
- Low background

p_{beam} (GeV/c)	Reaction	σ (μb)	ε (%)	Rate @ 10^{31} $cm^{-2}s^{-1}$	S/B	Events /day
1.64	$\bar{p}p \to \bar{\Lambda}\Lambda$	64.0	16.0*	44 s^{-1}	114	$3.8 \cdot 10^6$
1.77	$\bar{p}p \to \bar{\Sigma}^0\Lambda$	10.9	5.3**	2.4 s^{-1}	>11*	207 000
6.0	$\bar{p}p \to \bar{\Sigma}^0\Lambda$	20	6.1**	5.0 s^{-1}	21	432 000
4.6	$\bar{p}p \to \bar{\Xi}^+\Xi^-$	~1	8.2*	0.3 s^{-1}	274	26000
7.0	$\bar{p}p \to \bar{\Xi}^+\Xi^-$	~0.3	7.9*	0.1 s^{-1}	65	8600
4.6	$\bar{p}p \to \bar{\Lambda}K^+\Xi^-$+ c.c.	~1	5.4***	0.2 s^{-1}	>19*	17000
7.0	$\bar{p}p \to \bar{\Omega}^+\Omega^-$	0.002-0.06	14			

*PANDA: Eur. Phys. J A57, 4, 154 (2021)
**PANDA: Eur. Phys. J A 57:184 (2021)
*** PANDA: Eur. Phys. J A57, 4, 149 (2021)

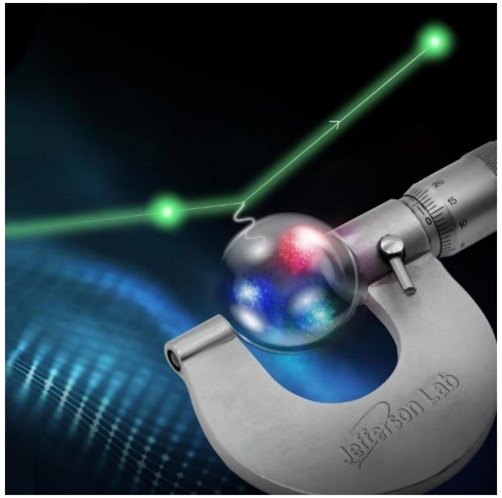

Structure
Spectroscopy
q
$\bar{q}$
q
g
$\bar{q}$
Interactions
Λ
N
N
Hyperon Physics with Antiproton Beams
Precision & rare processes

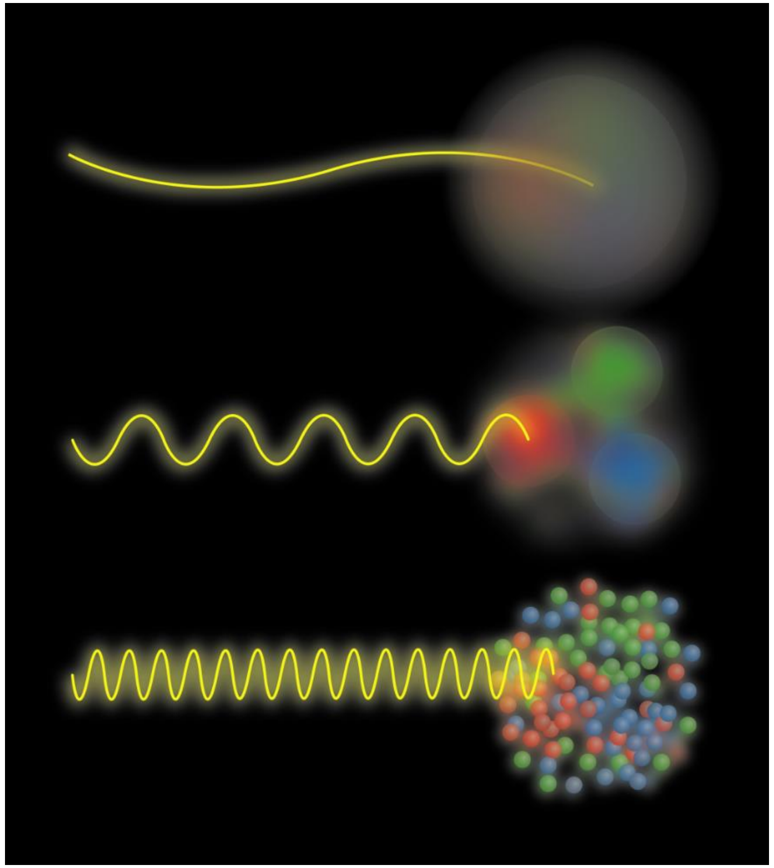


Hyperon structure

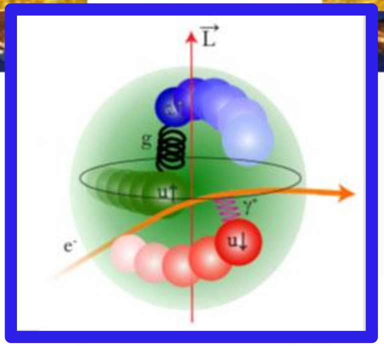
A lot of progress on the proton structure and radius in recent years

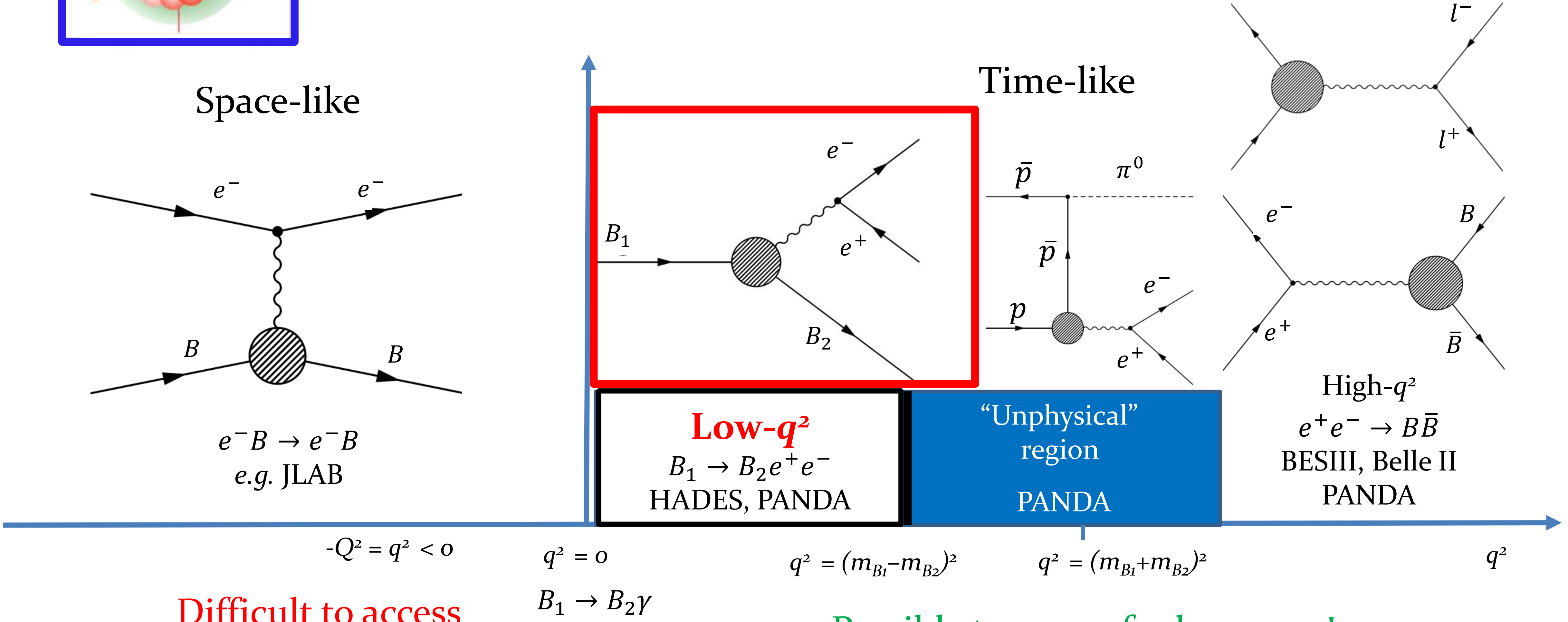
- what about the unstable hyperons?





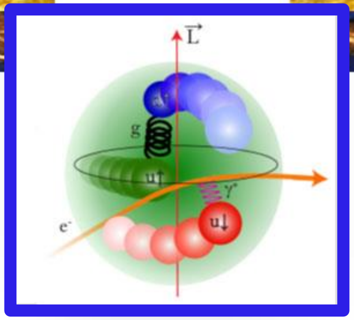
Electromagnetic Form Factors





Difficult to access for hyperons!

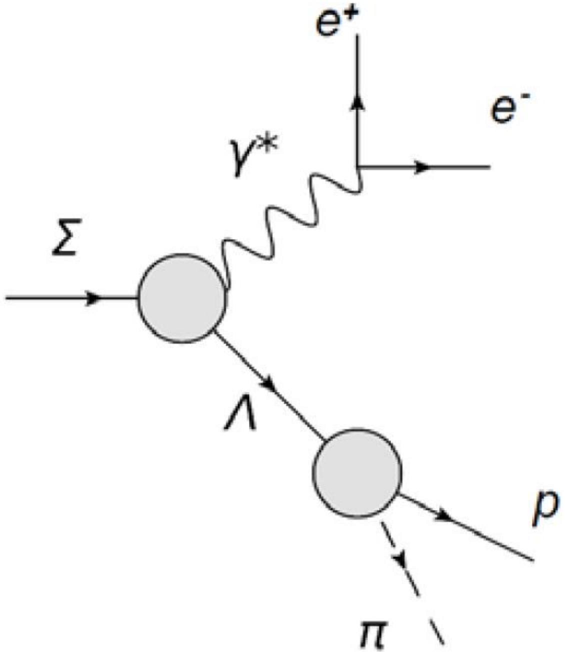
Possible to access for hyperons!



Hyperon transition FF

Transition radii accessible from EMFF behaviour near $q^2 = 0$

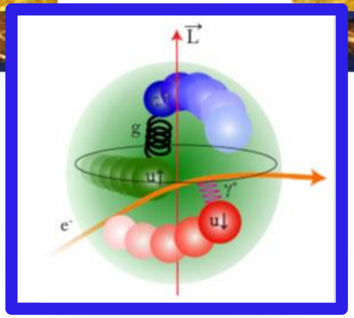
$$< r_E >^2 = 6 \frac{dG_E(q^2)}{dq^2}\Big|_{q^2=0} \quad \text{and} \quad < r_M >^2 = \frac{6}{G_M(0)} \frac{dG_M(q^2)}{dq^2}\Big|_{q^2=0}$$



Ongoing measurements by HADES and PANDA @ HADES:

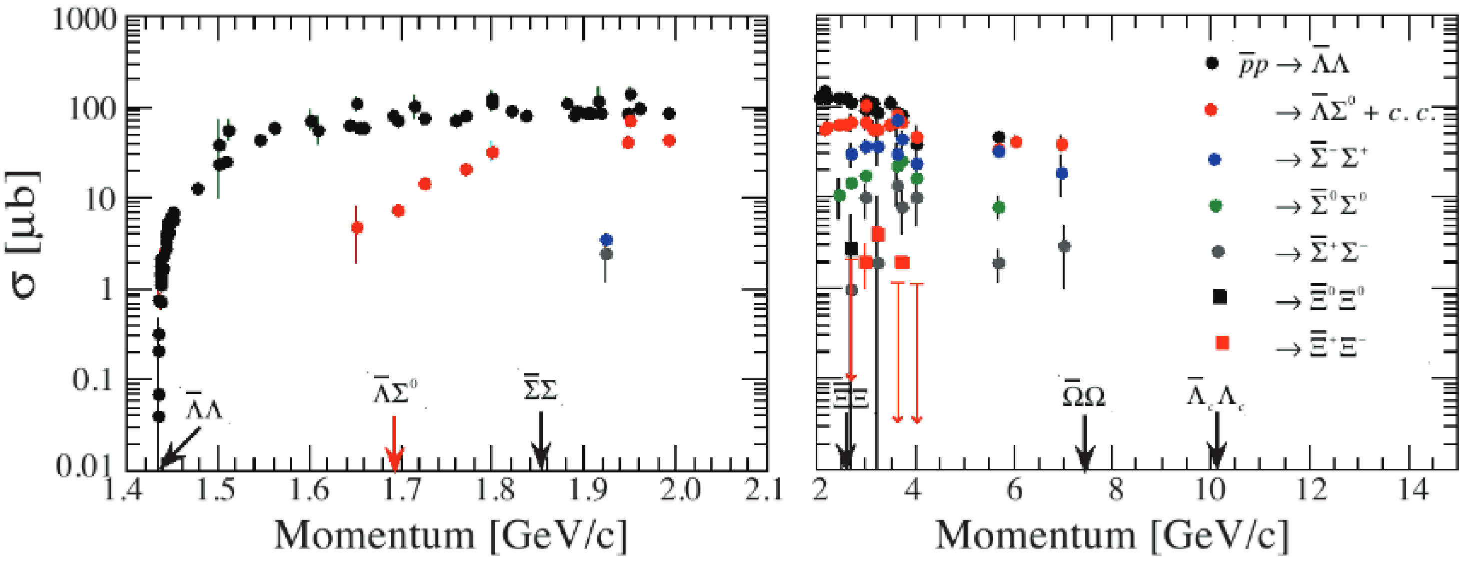
- FAIR Phase 0 initiative
- HADES: Excellent for e^+e^- tagging.
- PANDA: Forward trackers increases hyperon acceptance
- Hyperons from pp collisions*.

* HADES + PANDA@HADES: Eur. Phys. J A **57**, 138 (2021)

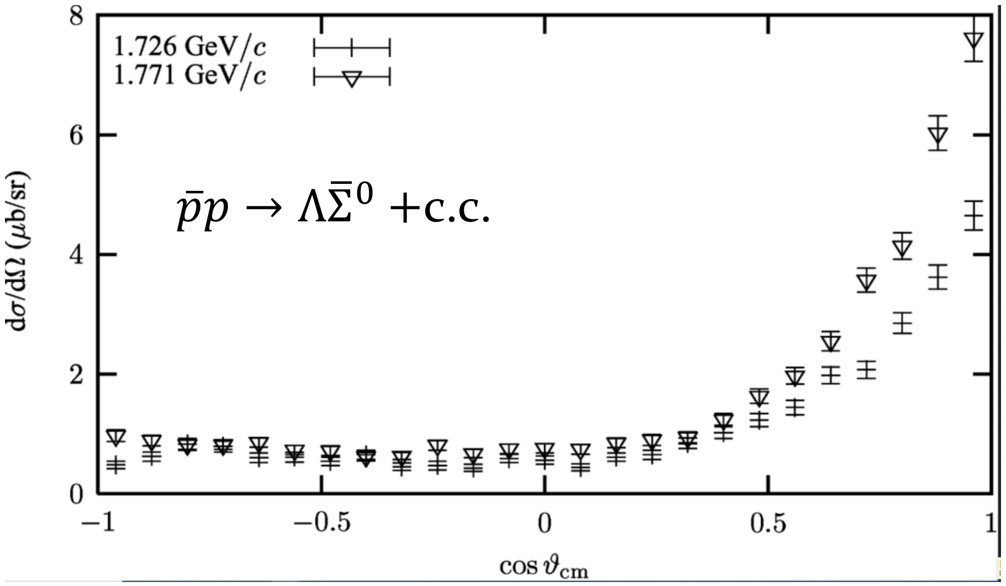


Hyperon transition FFs with antiproton beams

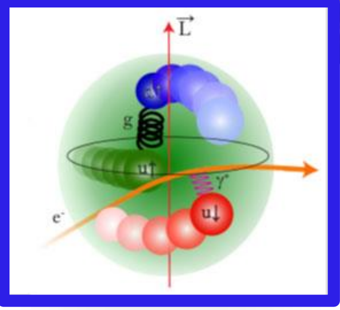
- Large expected Σ^0 and Y* hyperon yields in $\bar{p}p$ annihilations!
- Antihyperons move forward in CMS (and lab) system
  $\rightarrow e^+e^-$ from $\bar{\Sigma}^0$ decay boosted
  $\rightarrow$ better chance to detect e^+e^- ?



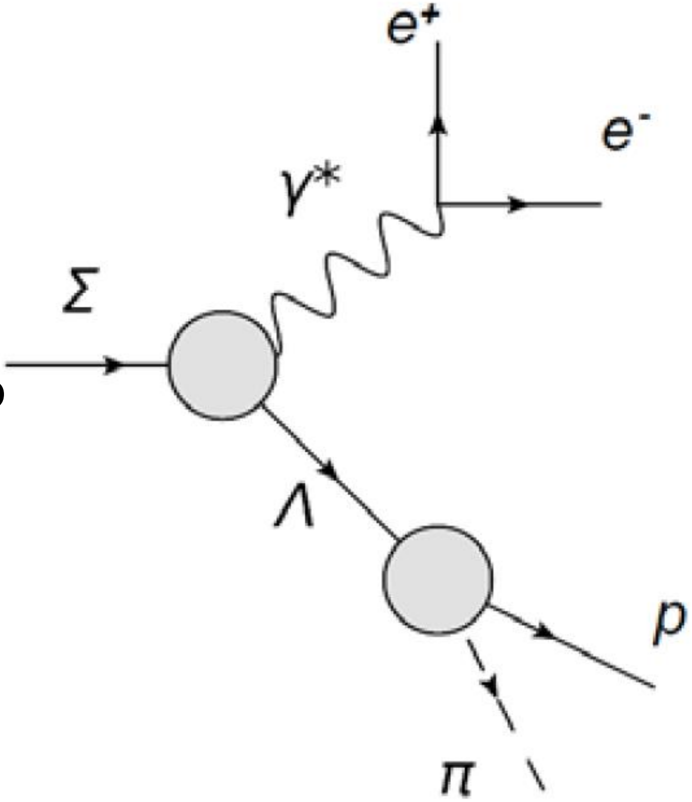
T. Johansson, LEAP Proc. 2003.



Klempt *et al.*, Phys. Rep. 368, p. 119-316 (2002)



Check-list for hyperon structure with antiprotons



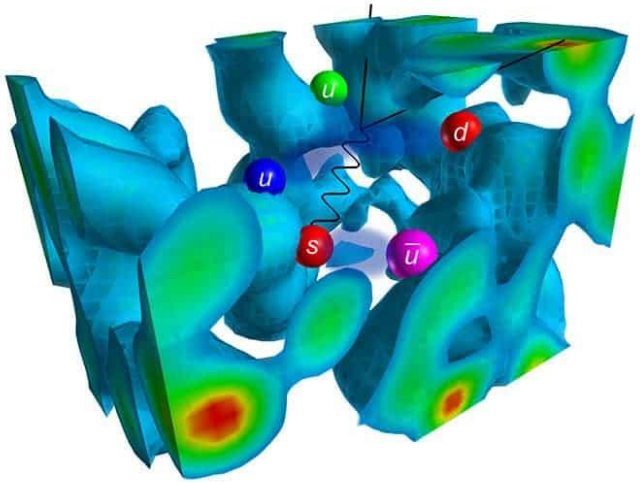
- $p_{beam}^{thr}(\Sigma^0\overline{\Lambda})$ = 1.65 GeV/c
- $p_{beam}^{thr}(\Sigma^*(1385)\overline{\Lambda})$ = 2.20 GeV/c
- $p_{beam}^{thr}(\Lambda(1520)\overline{\Lambda})$ = 2.60 GeV/c
- BR($\Sigma^0 \to \Lambda e^+e^-$) expected to be ~5*$10^{-3}$ & $\sigma(\bar{p}p \to \Sigma^0\overline{\Lambda})$ ~ 10 μb
  - Luminosity of 10^{31} cm^{-2}s^{-1} → ~1000 $\Sigma^0 \to \Lambda e^+e^-$ events takes 1 day
  - Luminosity of 10^{30} cm^{-2}s^{-1} → ~1000 $\Sigma^0 \to \Lambda e^+e^-$ events take 10 days

- Large acceptance tracking

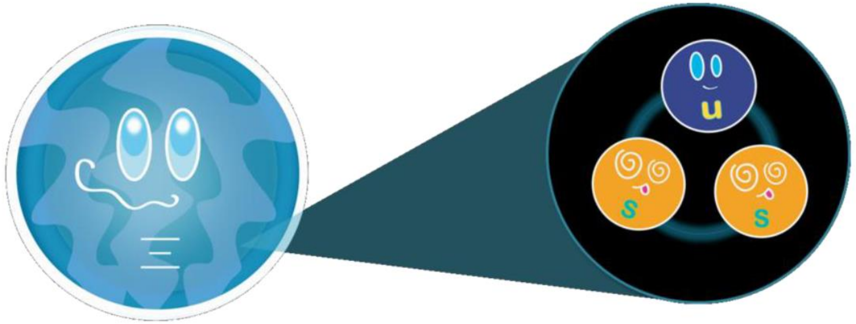
- e^+e^- identification & separation from converted γ

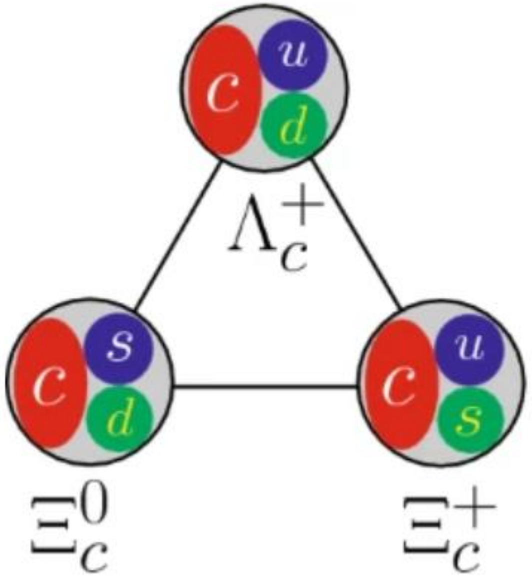
- Not too think target → e^+e^- must not be absorbed!

Hyperon spectroscopy



Derek B. Leinweber
University of Adelaide





Hu *et al.*,
Eur. Phys. J. C **80**, 320 (2020)

Light baryons

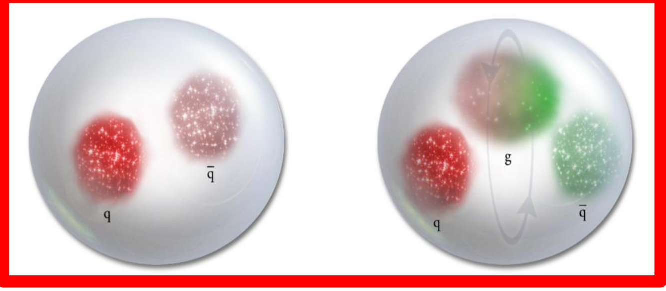
Jlab, ELSA, HADES, J-PARC
A lot of recent progress!

Multi-strange hyperons

Jlab, J-PARC, PANDA

Charm and beauty baryons

Belle II, LHCb
A lot of recent progress!



Multi-strange hyperon spectroscopy

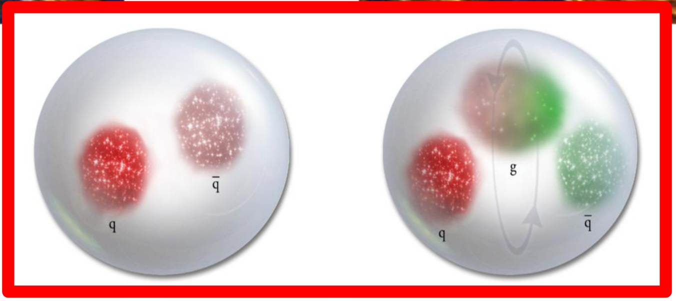
Gap to fill in the multi-strange sector!

- JPARC: $K^-p \to K^+\Xi^*$, $K^-p \to K^+\Omega^*X$
- GluEX @ KLF: $K_Lp \to \Xi^*K$

- PANDA: $\bar{p}p \to Y^*\bar{Y} + c.c.$
  - 2-body process also for Ω^*
  - Exclusive measurements
  - Large rates, low background*,**

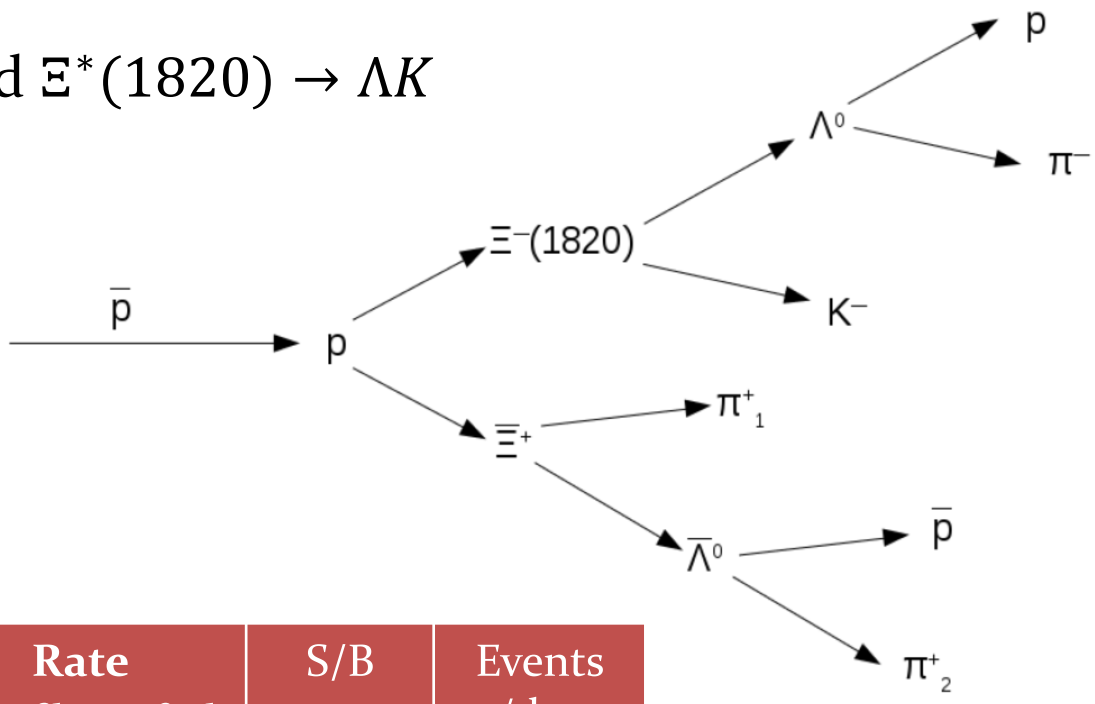
J^P	(D, L^P_N)	S	Octet members				Singlets
$1/2^+$	$(56,0^+_0)$	1/2	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	
$1/2^+$	$(56,0^+_2)$	1/2	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$		
$1/2^-$	$(70,1^-_1)$	1/2	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(1620)$	$\Lambda(1405)$
					$\Sigma(1560)^\dagger$		
$3/2^-$	$(70,1^-_1)$	1/2	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
$1/2^-$	$(70,1^-_1)$	3/2	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(1690)$	
					$\Sigma(1620)^\dagger$		
$3/2^-$	$(70,1^-_1)$	3/2	$N(1700)$	$\Lambda(?)$	$\Sigma(1940)^\dagger$	$\Xi(?)$	
$5/2^-$	$(70,1^-_1)$	3/2	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(1950)^\dagger$	
$1/2^+$	$(70,0^+_2)$	1/2	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Xi(?)$	$\Lambda(1810)^\dagger$
$3/2^+$	$(56,2^+_2)$	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	$N(2220)$	$\Lambda(2350)$	$\Sigma(?)$	$\Xi(?)$	
			Decuplet members				
$3/2^+$	$(56,0^+_0)$	3/2	$\Delta(1232)$	$\Sigma(1385)$	$\Xi(1530)$	$\Omega(1672)$	
$3/2^+$	$(56,0^+_2)$	3/2	$\Delta(1600)$	$\Sigma(1690)^\dagger$	$\Xi(?)$	$\Omega(?)$	
$1/2^-$	$(70,1^-_1)$	1/2	$\Delta(1620)$	$\Sigma(1750)^\dagger$	$\Xi(?)$	$\Omega(?)$	
$3/2^-$	$(70,1^-_1)$	1/2	$\Delta(1700)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(2012)$	
$5/2^+$	$(56,2^+_2)$	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	$\Delta(2420)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	

*PANDA: Eur. Phys. J A57, 4, 149 (2021).
**PANDA: Eur. Phys. J A 57:184 (2021)



PANDA feasibility study of $\bar{p}p \to \bar{\Lambda}K^{+}\Xi^{-} + c.c.$

- Include intermediate $\Xi^{*}(1690) \to \Lambda K$ and $\Xi^{*}(1820) \to \Lambda K$
- Simplified PANDA MC framework
- p_{beam} = 4.6 GeV/c
- Assume σ = 1 μb and 10^{31} $cm^{-2}s^{-1}$
  - $\rightarrow$ 18000 $\bar{\Lambda}K^{+}\Xi^{-}$ events / day



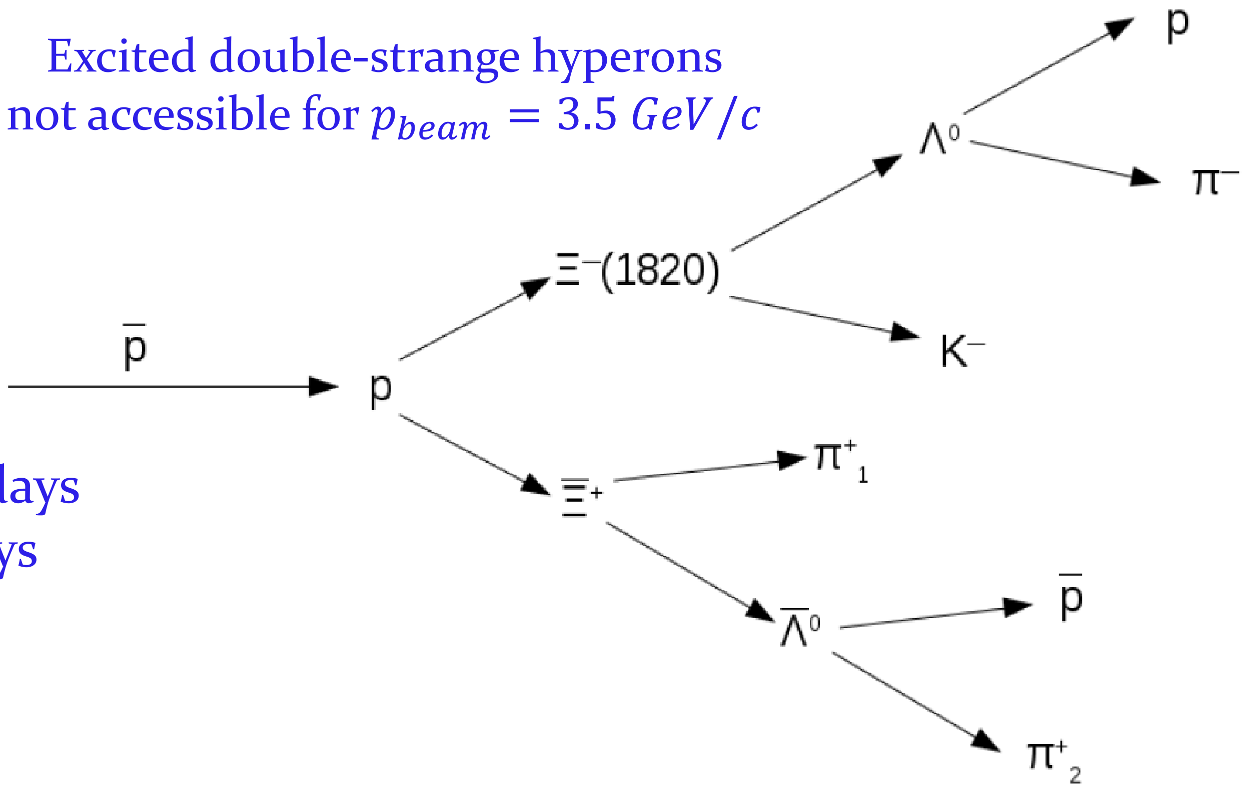
p_{beam} (GeV/c)	Reaction	σ (μb)	ε (%)	Rate @ 10^{31} $cm^{-2}s^{-1}$	S/B	Events /day
4.6	$\bar{p}p \to \bar{\Lambda}K^{+}\Xi^{-} + c.c$	~1	5.4	0.2^{-s}	>19	~18000

PANDA, EPJA 57, 184 (2021)
PANDA, EPJA 57, 149 (2021)

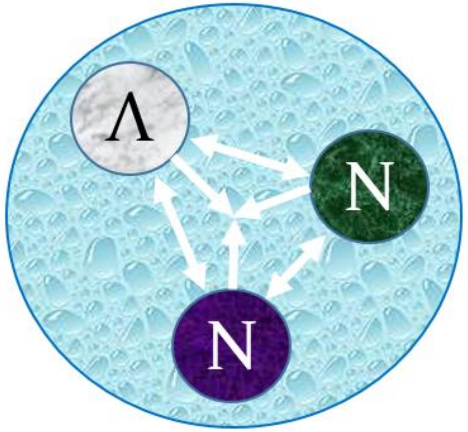
Check-list for hyperon spectroscopy with antiprotons

- Threshold beam momenta for $\bar{p}p \rightarrow Y^{*}\bar{Y} + c.c.$
  - $p_{beam}^{thr}\big(\Lambda^{*}(1405)\big) = 2.26$ GeV/c
  - $p_{beam}^{thr}\big(\Xi^{*}(1620)\big) = 3.55$ GeV/c
  - $p_{beam}^{thr}\big(\Xi^{*}(1690)\big) = 3.78$ GeV/c
  - $p_{beam}^{thr}\big(\Xi^{*}(1820)\big) = 4.22$ GeV/c
  - $p_{beam}^{thr}\big(\Omega^{*}(2100)\big) = 6.58$ GeV/c
- Luminosity:
  - 10^{29} $cm^{-2}s^{-1}$: 18000 events take ~100 days
  - 10^{30} $cm^{-2}s^{-1}$: 18000 events take ~10 days
  - 10^{31} $cm^{-2}s^{-1}$: 18000 events take ~1 day
- Large acceptance tracking
- PID

Excited double-strange hyperons not accessible for $p_{beam} = 3.5\ GeV/c$



Hadron interactions



...or more specifically,

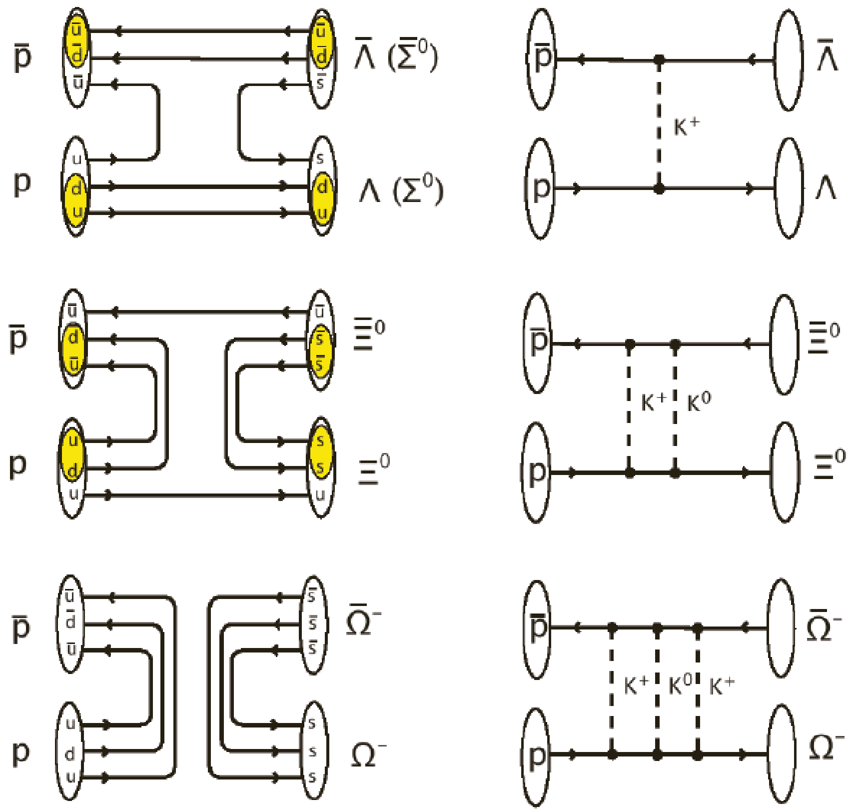
hyperon-antihyperon and

hyperon-nucleon interactions.

Hyperon production

Strong production dynamics

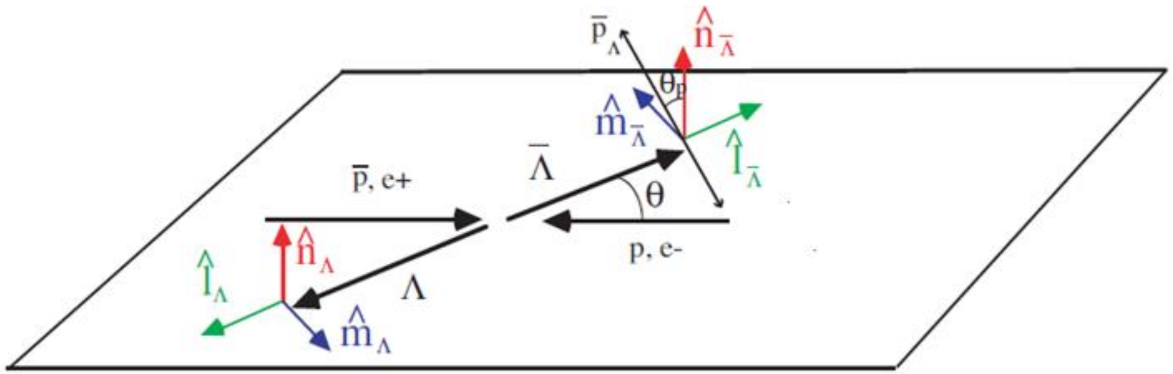
- Relevant degrees of freedom: quark-gluon or mesons?
- Strange *versus* charm sector?
- Role of spin?

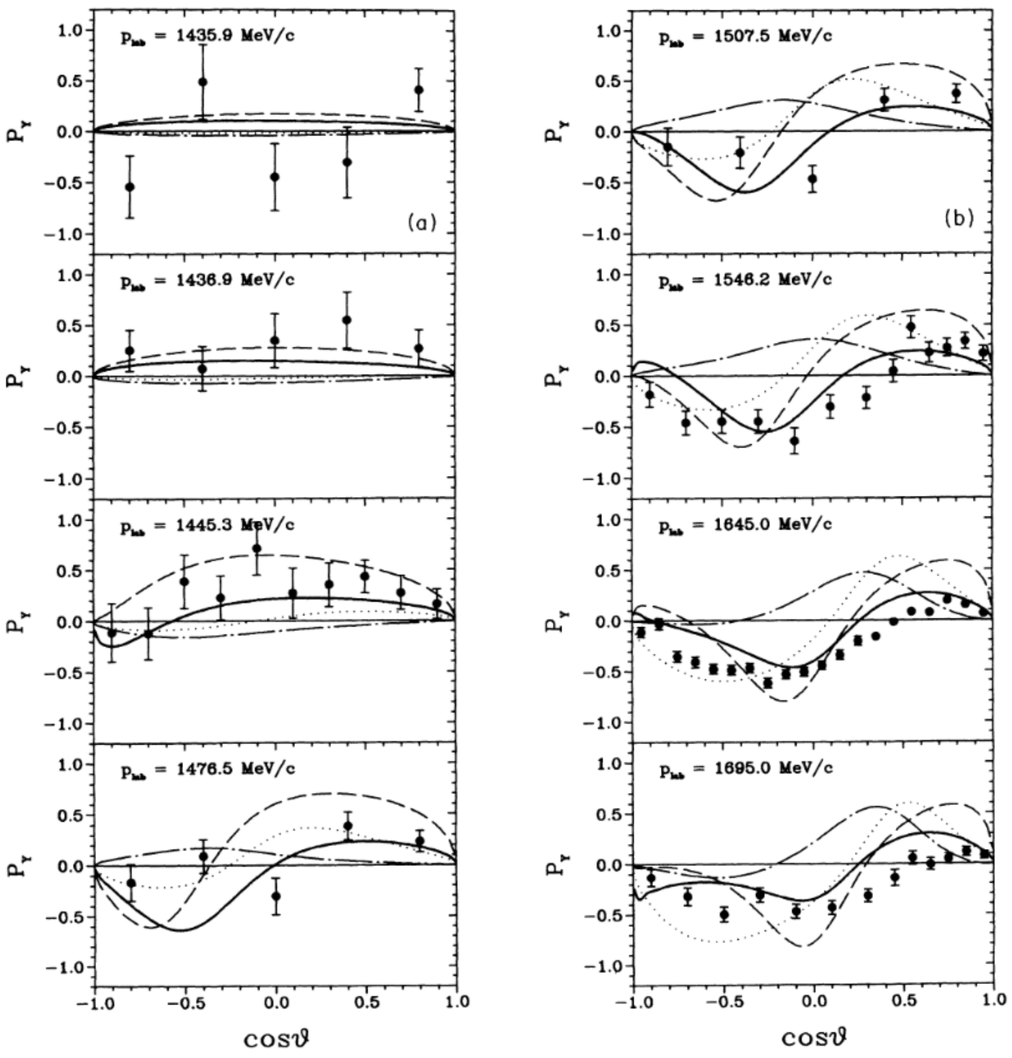


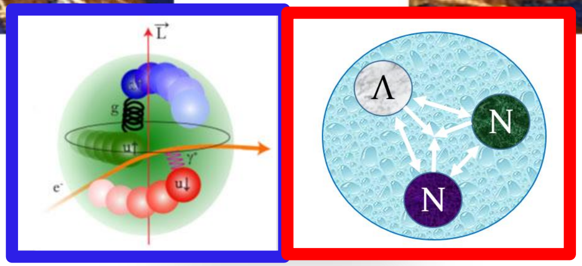
Spin observables in $\bar{p}p \rightarrow \bar{Y}Y$

The differential cross section of a this process can be described in terms of

- Spin observables
- Decay asymmetries
- Angles



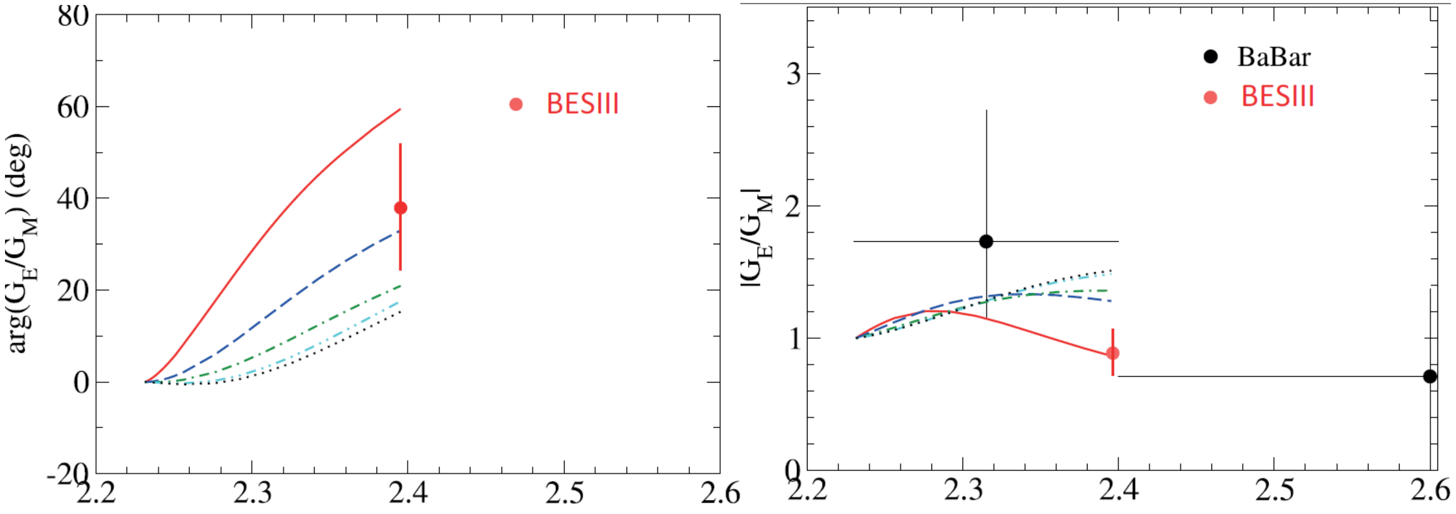




Spin observables in $\bar{p}p \to \bar{Y}Y$

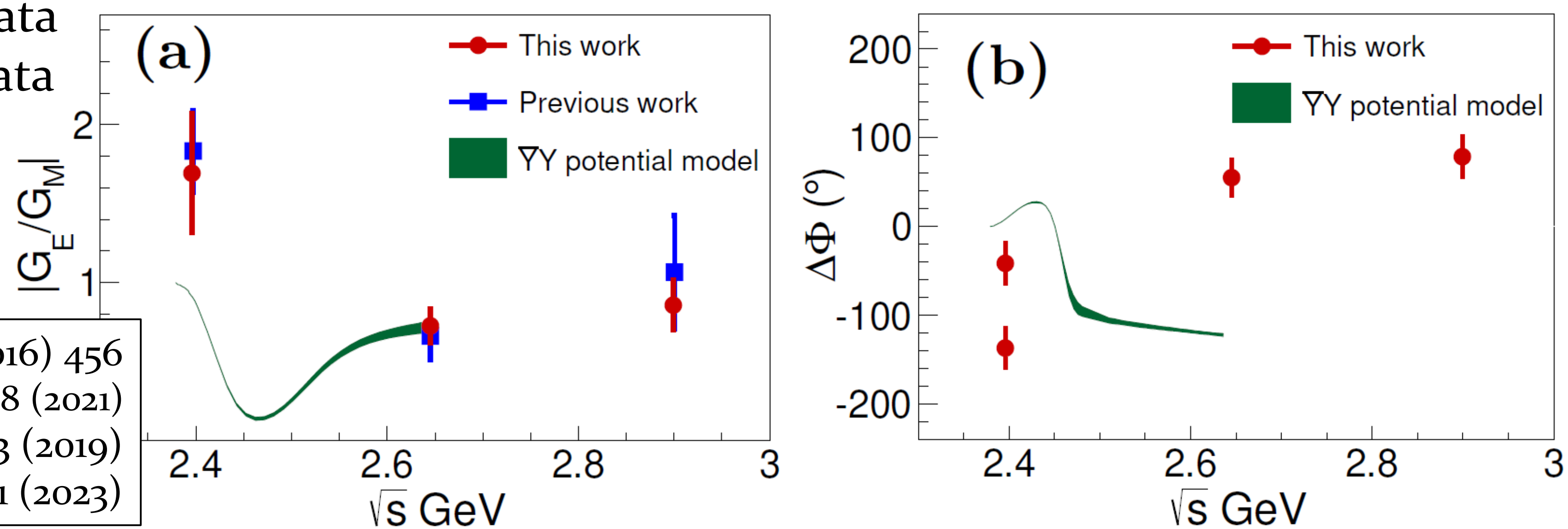
Final state interactions (FSI) of $\bar{Y}Y$ needed for interpretation of hyperon EMFFs from $e^+e^- \to Y\bar{Y}$

- $\bar{Y}Y$ potential models use $\bar{p}p \to \bar{Y}Y$ data as input.

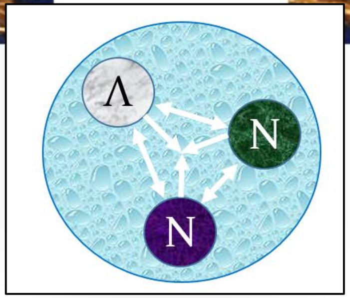


Example:

Calculations*, ** based on PS185 data describe some features of BESIII data from $e^+e^- \to \Lambda\bar{\Lambda}$ ***
and $e^+e^- \to \Sigma^+\bar{\Sigma}^-$ ****



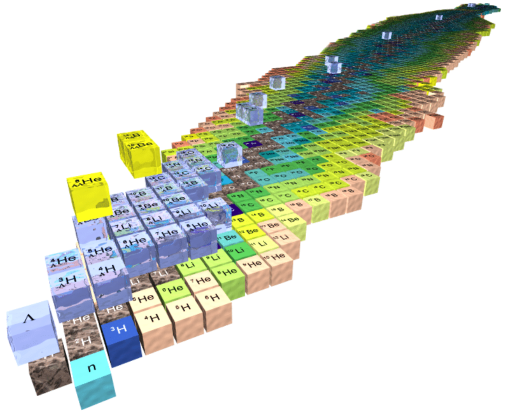
*Haidenbauer et al., Phys. Lett. B 761(2016) 456
** Haidenbauer *et al.*, Phys. Rev. D 103, 014028 (2021)
***BESIII, Phys. Rev. Lett. 123, 122003 (2019)
****BESIII, Phys. Rev. Lett. 131, 191901 (2023)



Hyperon-nucleon (*YN*) interaction

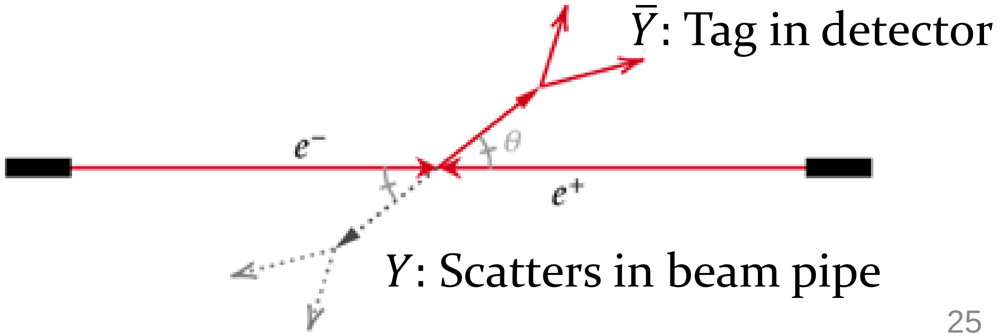
Why?

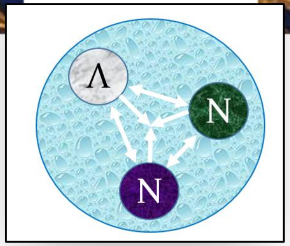
- Crucial component to predict properties of hypernuclei.
- Needed to understand the *hyperon puzzle* of neutron stars.



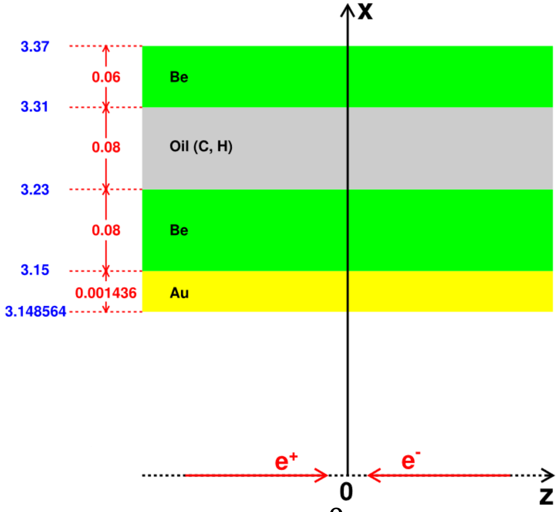
How?

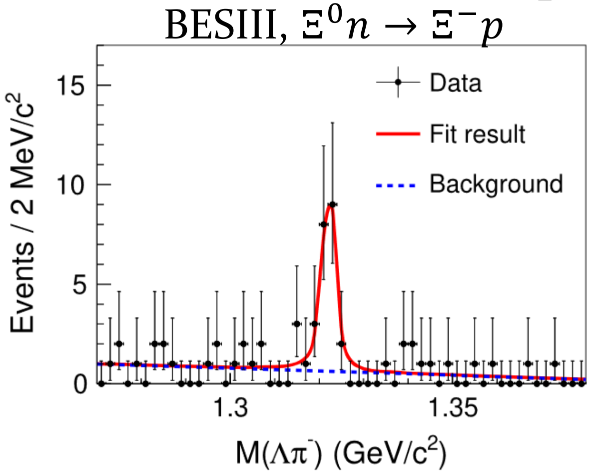
- Hyperon femtoscopy
- Hypernuclear studies
- Secondary *YN* interactions
  - Example: $e^+e^- \to J/\Psi \to Y\bar{Y}$ studied with BESIII





Hyperon interactions with BESIII





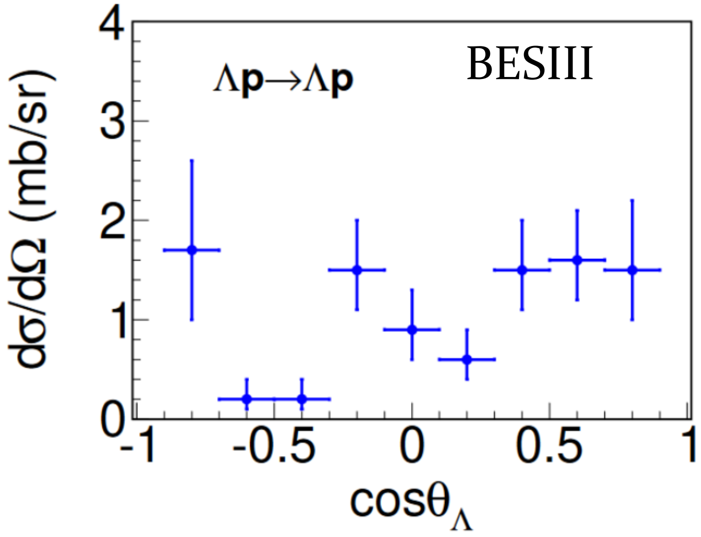
*BESIII, Phys. Rev. Lett. 130, 251902(2023)

**Phys. Lett. B 633, p 214-218 (2006)

***BESIII, arXiv: 2401.09012 (2024)

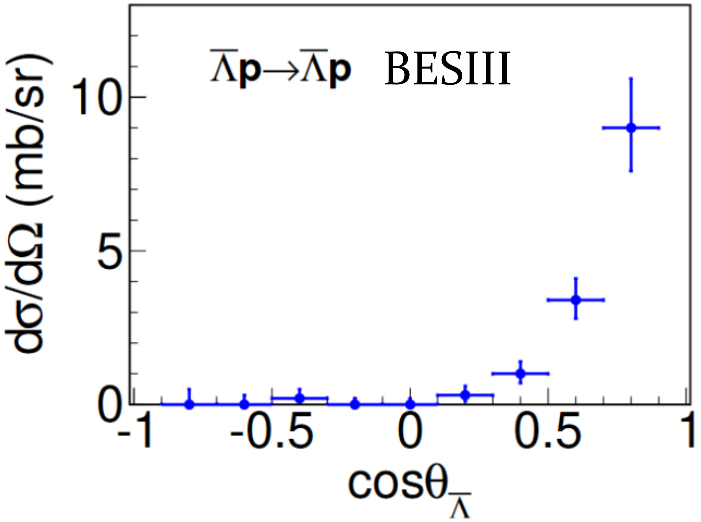
The $\Xi^0 n \rightarrow \Xi^- p$ reaction

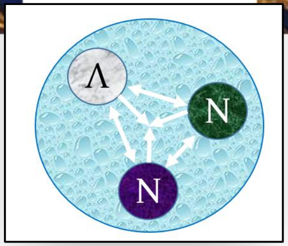
- Primary reaction $e^+e^- \rightarrow J/\Psi \rightarrow \Xi^0\bar{\Xi}^0$.
- Secondary Ξ^0 beam with $p_\Xi = 0.818$ GeV/c.
- Interaction mainly with ^{9}Be in beam pipe.
- Infered cross section from 20 observed events assuming ”effective neutrons” in ^{9}Be **: $\sigma(\Xi^0 n \rightarrow \Xi^- p) = 7.4 \pm 1.8 \pm 1.5$ mb.



The $\Lambda p \rightarrow \Lambda p$ and $\bar{\Lambda} p \rightarrow \bar{\Lambda} p$ reactions

- Primary reaction $e^+e^- \rightarrow J/\Psi \rightarrow \Lambda\bar{\Lambda}$
- Secondary $\Lambda/\bar{\Lambda}$ beam with $p_\Lambda = 1.074$ GeV/c.
- Interaction mainly with protons in the oil between pipes.





Hyperon interactions with an antiproton experiment

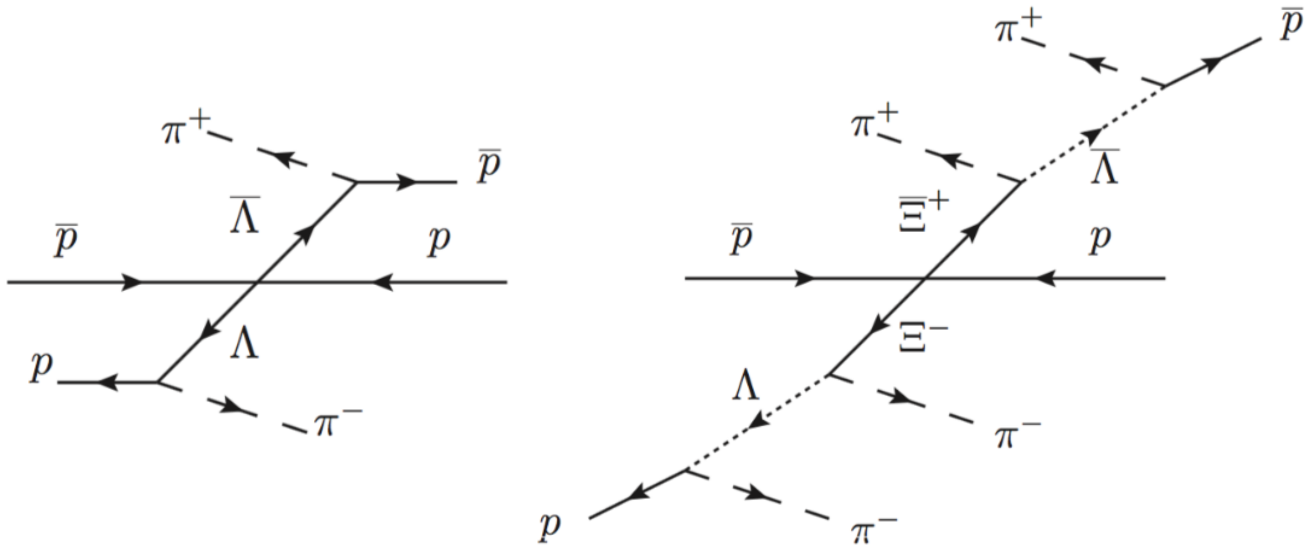
Advantages of using secondary hyperon beams from $\bar{p}p \to \bar{Y}Y$:

- Two-body reaction → hyperon beam properties known (as in $J/\Psi \to \bar{Y}Y$ case)
- Access to a broad hyperon momentum range
  - Advantage compared to $J/\Psi \to \bar{Y}Y$.
- Access to multi-strange hyperons
  - Advantage compared to campaigns planned at Spring-8 and J-PARC.
- Access to antihyperons
  - Advantage compared to primary reactions with photon-, lepton-, and pion beams.
- Large $\bar{p}p \to \bar{Y}Y$ cross sections
  - Advantage compared to primary reactions with photons or leptons.

Check-list for hyperon interaction studies with primary antiproton beams

- Threshold momenta for $\bar{p}p \rightarrow \bar{Y}Y$

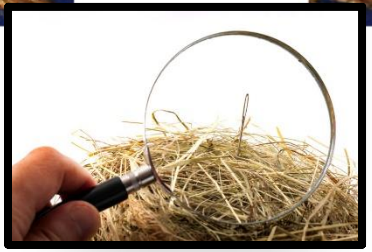
  $p_{beam}^{thr}(\Lambda\bar{\Lambda}) = 1.44$ GeV/c
  $p_{beam}^{thr}(\Sigma^{+}\bar{\Sigma}^{-}) = 1.85$ GeV/c
  $p_{beam}^{thr}(\Xi^{0}\bar{\Xi}^{0}) = 2.58$ GeV/c
  $p_{beam}^{thr}(\Xi^{-}\bar{\Xi}^{+}) = 2.61$ GeV/c
  $p_{beam}^{thr}(\Omega^{-}\bar{\Omega}^{+}) = 4.93$ GeV/c



- Luminosity of 10^{31} cm^{-2}s^{-1}
  - $\Lambda\bar{\Lambda}$ sample of *"BESIII J/Ψ size"* in 1 day
  - $\Xi\bar{\Xi}$ sample of *"BESIII J/Ψ size"* in 20 days

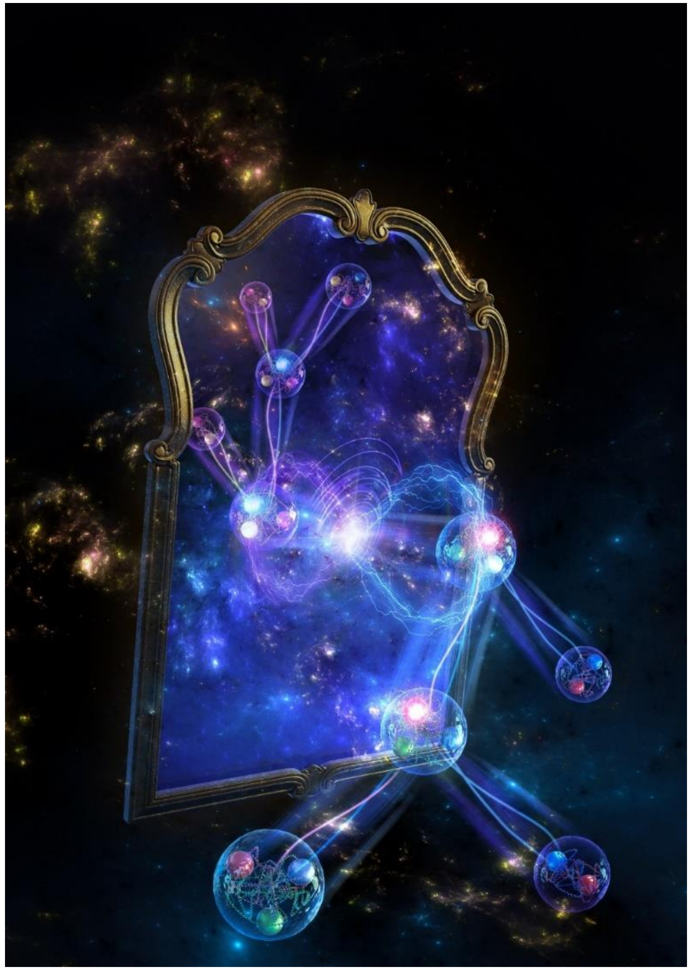
  → For *YN* studies, an extended target may do the job.

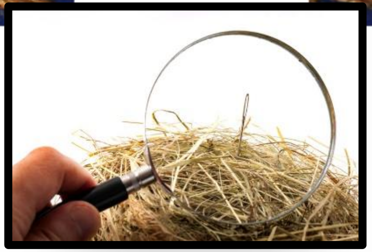
- Large acceptance tracking
- For Σ^{+} and Ξ^{0}: Calorimetry
- For Ω^{-}: PID
- For *YN* interactions: target for secondary interactions



Hadronic effects in precision and rare processes

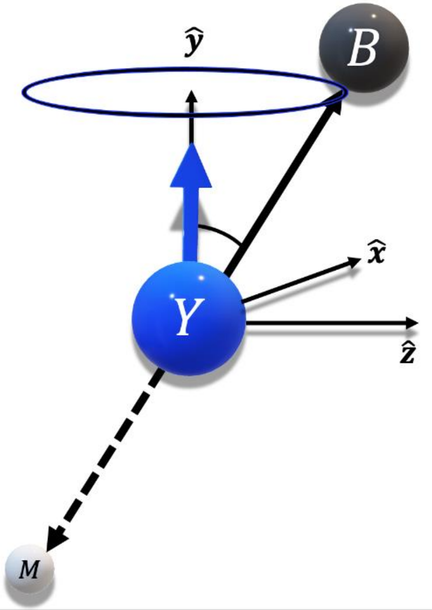
…or more specifically,
CP tests in hyperon decays.





CP violation

- Required for *Baryogenesis**
  = dynamical generation of matter-
  antimatter asymmetry in the universe.
- Common hunting-ground for physics beyond the SM.



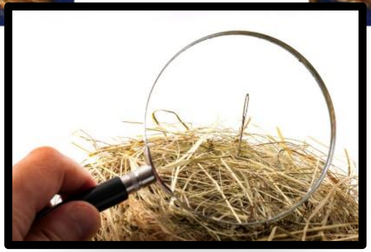
- Quantified by weak phases
- Established in meson sector → consistent with SM
- Hyperons: Simple tests *via* decay asymmetry α :

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

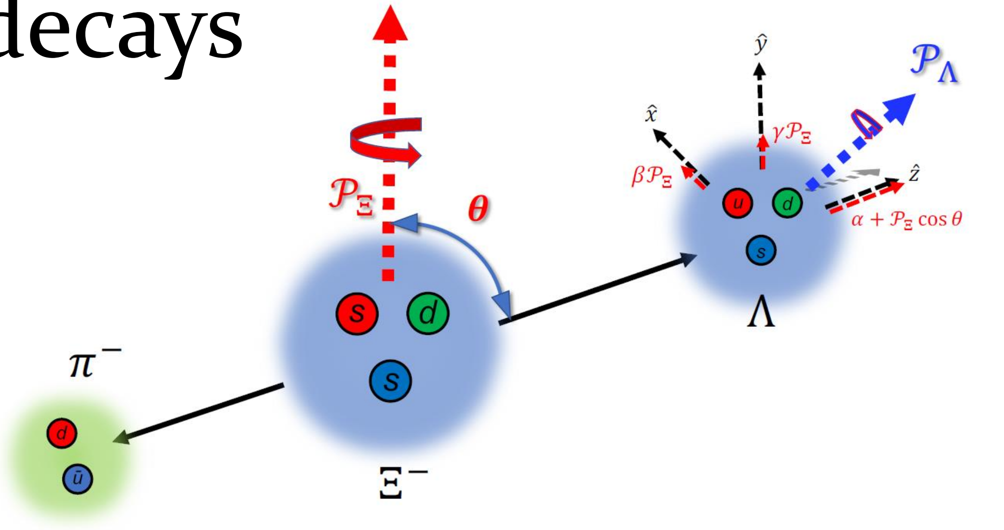
CP symmetry → $\alpha = -\bar{\alpha}$

CP observable $A_{CP} = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}}$

*A. D. Sakharov,. J. Exp. Theor. Phys. Lett. **5**: 24–27.*



CP tests in hyperon decays



Challenge: Hyperon decays interplay of strong and weak processes!

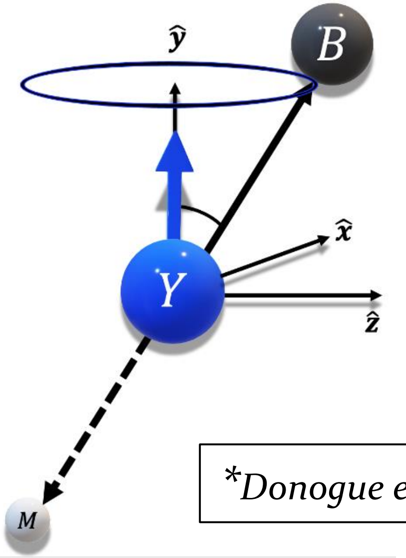
→ CP observable from direct decay

= function of strong and weak phases

Weak phase diff.
Possibly CP violating

$$A_{CP} = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}} \approx -\tan(\delta_p - \delta_s)\tan(\xi_p - \xi_s)\ ^*$$

Strong phase diff.
CP conserving

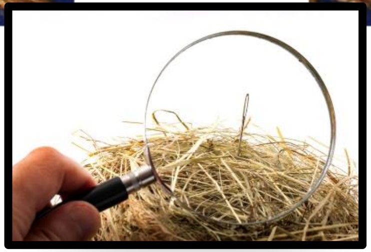


*Donogue et al., PRD 34, 833 (1986)

Sequential decays

- Decay parameters α, β, γ, ϕ accessible:
  - $\alpha^2 + \beta^2 + \gamma^2 = 1\ , \quad \tan\phi = \frac{\beta}{\gamma}$
- CP symmetry:
  $$\alpha, \beta, \gamma, \phi = -\bar{\alpha}, -\bar{\beta}, -\bar{\gamma}, -\bar{\phi}$$
- Additional CP observable:
  - $\Delta\phi_{CP} = \frac{\phi+\bar{\phi}}{2} = \frac{\alpha}{\sqrt{1-\alpha^2}}(\xi_p - \xi_s)_{LO}$

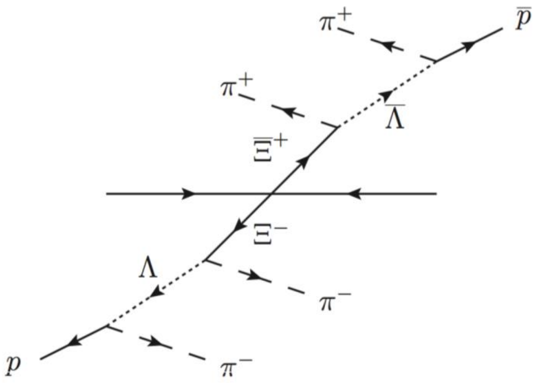
  → More sensitive to CP violating effects!

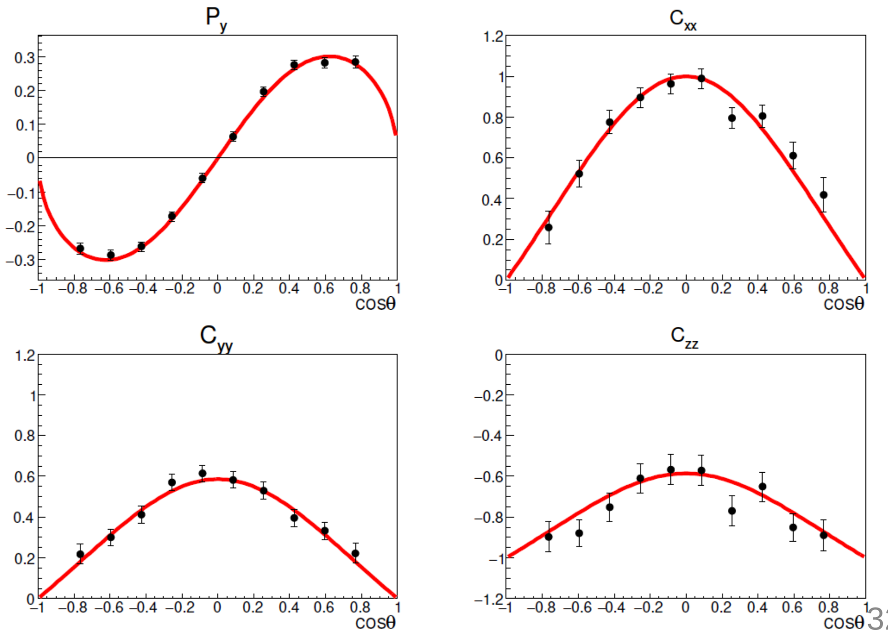


CP tests in $e^+e^- \to J/\Psi \to \Xi^-\bar{\Xi}^+$

- Analysis of $e^+e^- \to J/\Psi \to \Xi^-\bar{\Xi}^+$, $\Xi^- \to \Lambda\pi^- \to p p\pi^-$ + c.c.
- 73000 $J/\Psi \to \Xi^-\bar{\Xi}^+$ events from 2009 and 2012
- First measurement of weak phase difference:

$$(\xi_p - \xi_s) = (1.2 \pm 3.4 \pm 0.8) \times 10^{-2}\ \text{rad}$$





nature

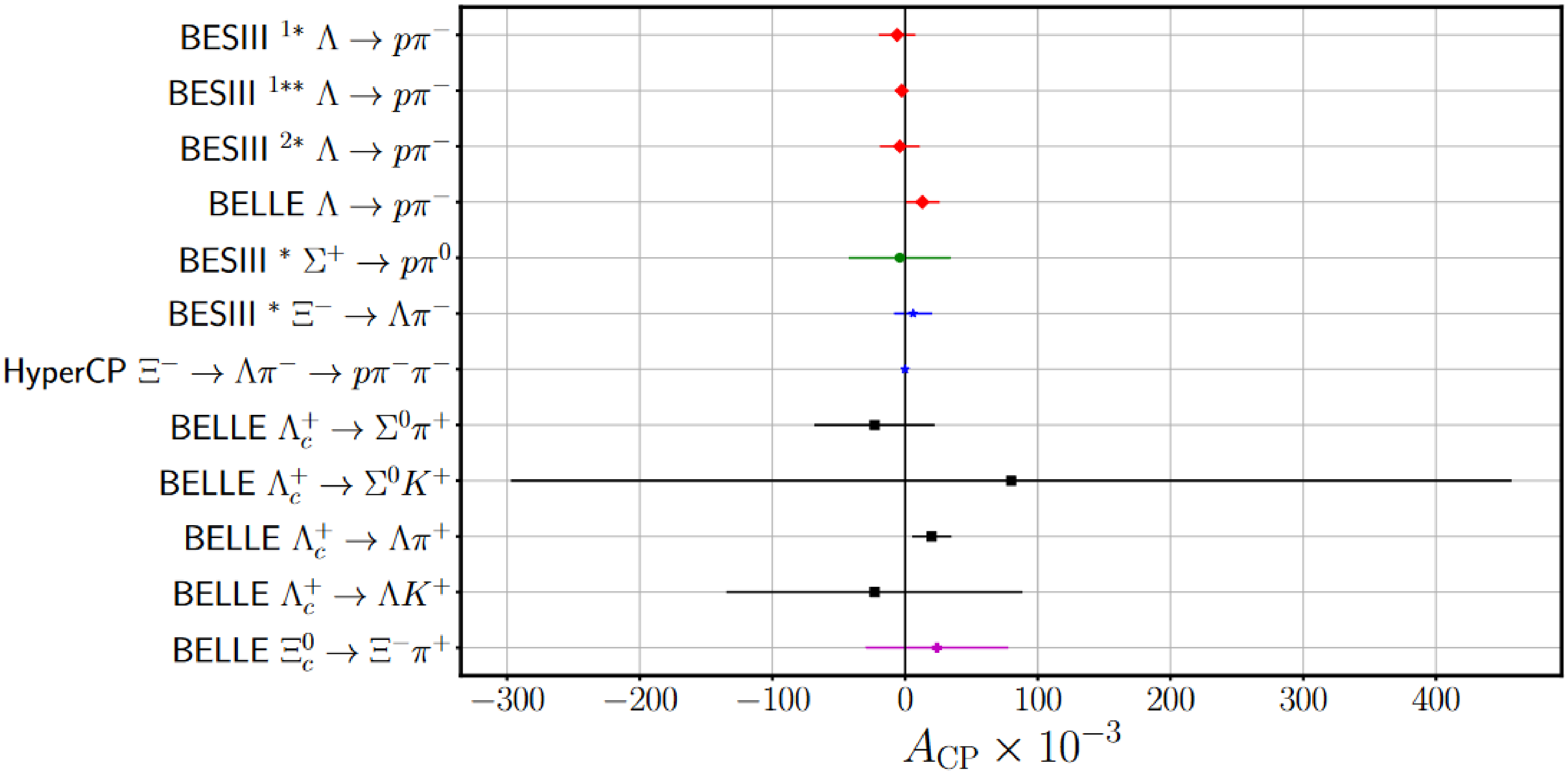
Article | Open Access | Published: 01 June 2022

Probing CP symmetry and weak phases with entangled double-strange baryons

The BESIII Collaboration

606, 64–69 (2022) | Cite this article

CP tests, world data



BESIII:

Nature Phys. **15**, p 631-634 (2019)

Phys. Rev. Lett. 125, 052004 (2020)

Nature 606, 64-69 (2022)

Phys. Rev. Lett. 129, 131801 (2022)

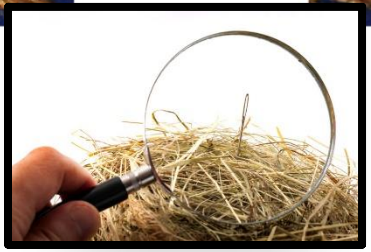
Phys. Rev. D 108, L031106 (2023)

Belle:

Sci. Bull. 68, 583-592 (2023)

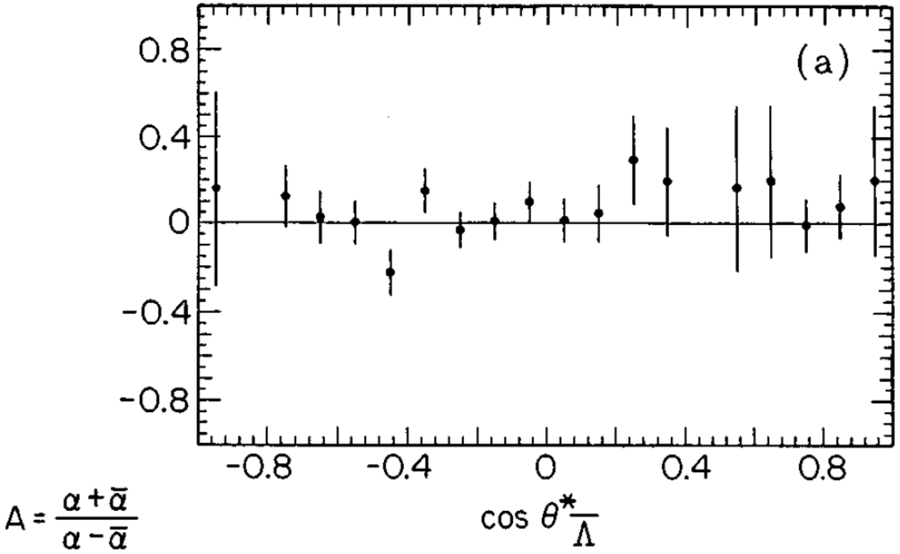
HyperCP:

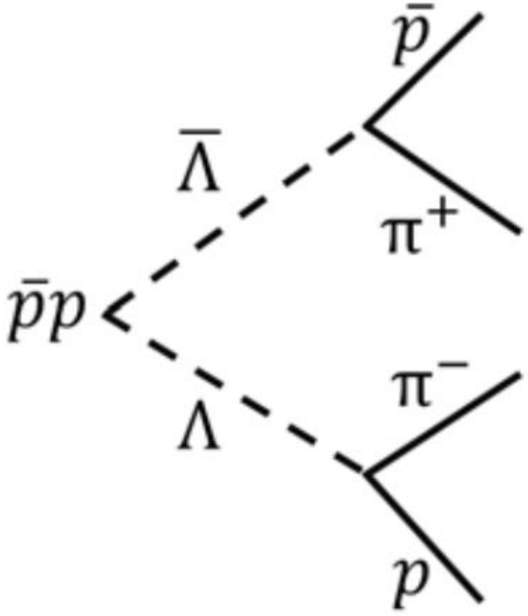
Phys. Rev. Lett. 93, 262001, 2004.



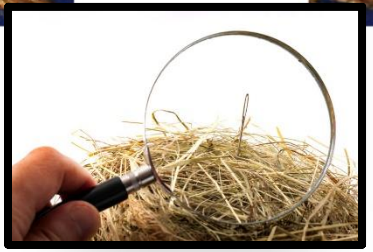
CP tests in $\bar{p}p \rightarrow Y\bar{Y}$

- $\bar{Y}Y$ pair produced spin polarised and correlated
  $\rightarrow$ possible to extract CP observables*
- More complicated production dynamics than in e^+e^-
  - polaristion + spin correlations depend on θ_Y
- CP test with PS185: $\mathcal{O}(\mathrm{A})\sim 0.02$ for 96000 $\bar{\Lambda}\Lambda$ events**
  - PDG world average $\mathcal{O}(\mathrm{A})\sim 0.01$





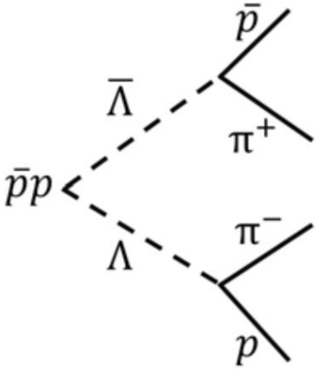
*Durand & Sandweiss, Phys. Rev. 135, 2b (1964)
**PS185, Phys. Rev. C 54, 1877 (1996)



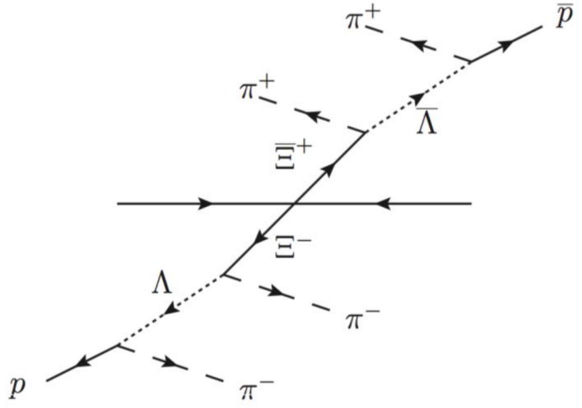
CP tests in $\bar{p}p \rightarrow Y\bar{Y}$

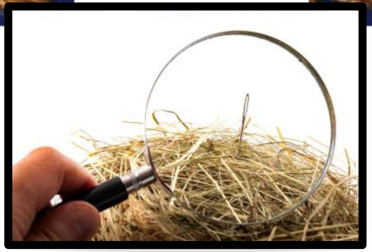
Hyperons @PANDA:

- Two-body production of spin correlated hyperon-antihyperon pairs
- Large cross sections = high production rate
- Exclusive reconstruction = high efficiency, low background



p_{beam} (GeV/c)	Reaction	σ (μb)	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 s^{-1}	274	26000
7.0	$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	~0.3	7.9*	0.1 s^{-1}	65	8600
4.6	$\bar{p}p \rightarrow \bar{\Lambda}K^+\Xi^-$+ c.c.	~1	5.4***	0.2 s^{-1}	>19*	17000
7.0	$\bar{p}p \rightarrow \bar{\Omega}^+\Omega^-$	0.002-0.06	14			50 -1300

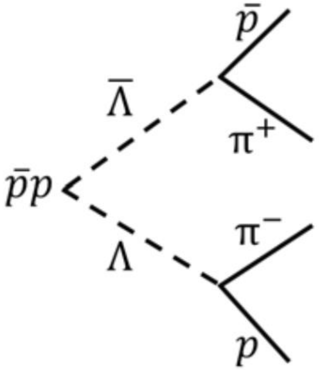




Check-list for CP tests in $\bar{p}p \rightarrow Y\bar{Y}$

- Threshold momenta for $\bar{p}p \rightarrow \bar{Y}Y$

  $p^{thr}_{beam}(\Lambda\bar{\Lambda}) = 1.44$ GeV/c
  $p^{thr}_{beam}(\Sigma^+\bar{\Sigma}^-) = 1.85$ GeV/c
  $p^{thr}_{beam}(\Xi^0\bar{\Xi}^0) = 2.58$ GeV/c
  $p^{thr}_{beam}(\Xi^-\bar{\Xi}^+) = 2.61$ GeV/c
  $p^{thr}_{beam}(\Omega^-\bar{\Omega}^+) = 4.93$ GeV/c

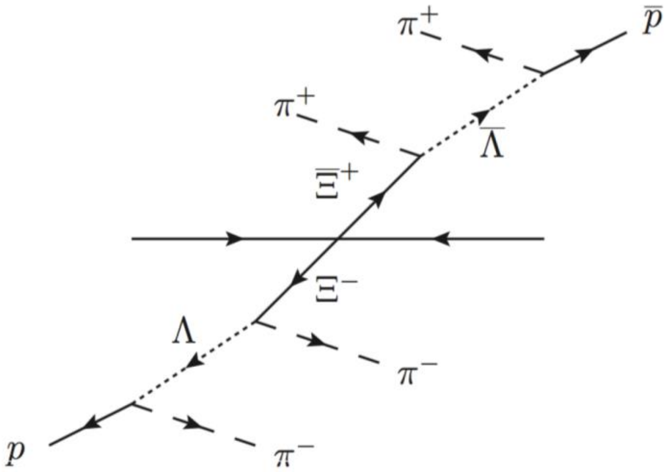


- Luminosity of 10^{31} cm^{-2}s^{-1}
  - $\Lambda\bar{\Lambda}$ sample of *"BESIII J/Ψ size"* in 1 day
  - $\Xi\bar{\Xi}$ sample of *"BESIII J/Ψ size"* in 20 days

  → An extended target may yield high luminosity but affect precision.

- Large acceptance tracking

- For Σ^+ and Ξ^0: Calorimetry



Summary

- Hyperons provide insights to hadron structure, spectroscopy, interactions and fundamental symmetries.

- Several advantages of studying hyperons with antiproton beams.

- Single-strange and ground-state double-strange hyperons can be studied with a 3.5 GeV/c antiproton beam.

- The feasibility of future hyperon endeavors at the CERN-AD depends crucially on
  - Luminosity
  - Target
  - Available beam-time
  - Detector setup

UPPSALA UNIVERSITET

Thanks for your attention!

Knut and Alice Wallenberg Foundation

Swedish Research Council

STINT
The Swedish Foundation for International Cooperation in Research and Higher Education