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Hyperon Physics with PANDA at FAIR

Prof. Karin Schönning for the PANDA Collaboration

Open Symposium on Hyperons @ FAIR

October 25th, 2021

Outline

- Introduction
- Hyperons
- PANDA at FAIR
- Hyperon topics in PANDA
- Summary

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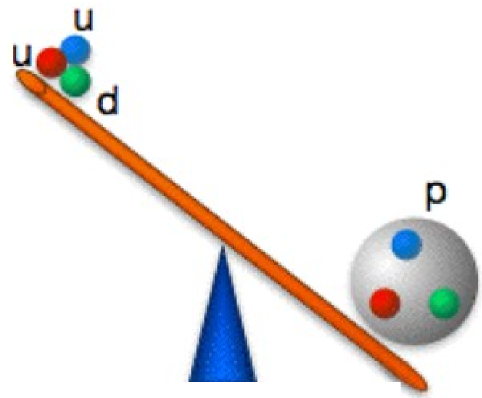
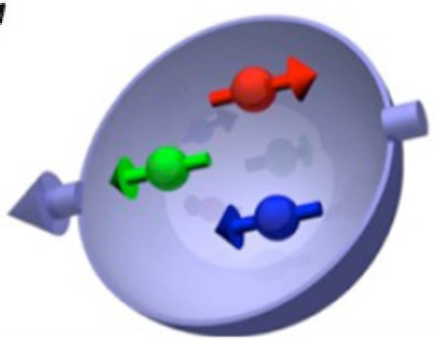
Introduction

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

- Abundance*
- Spin**
- Inner structure***





*L. Canetti et al., NJP 14 (2012) 095012
**C. A. Aidala *et al.,* RMP 85 (2013) 655-691.
*** G. A. Miller, PRL 99 (2007) 112001.

Introduction

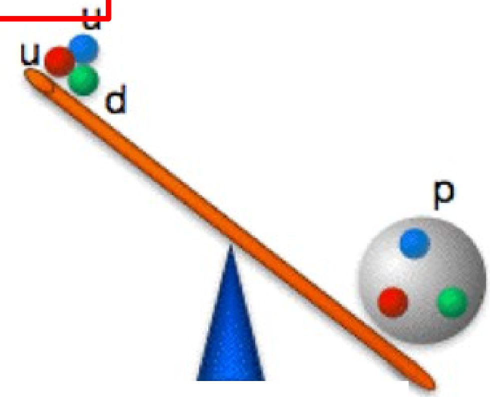
Many challenges in modern physics concern the **nucleon:**

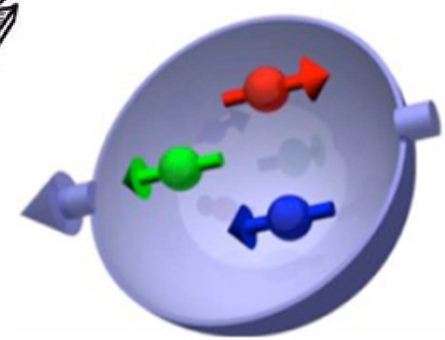
– Abundance* Standard Model and beyond

– Spin**

– Inner structure***

Non-pQCD





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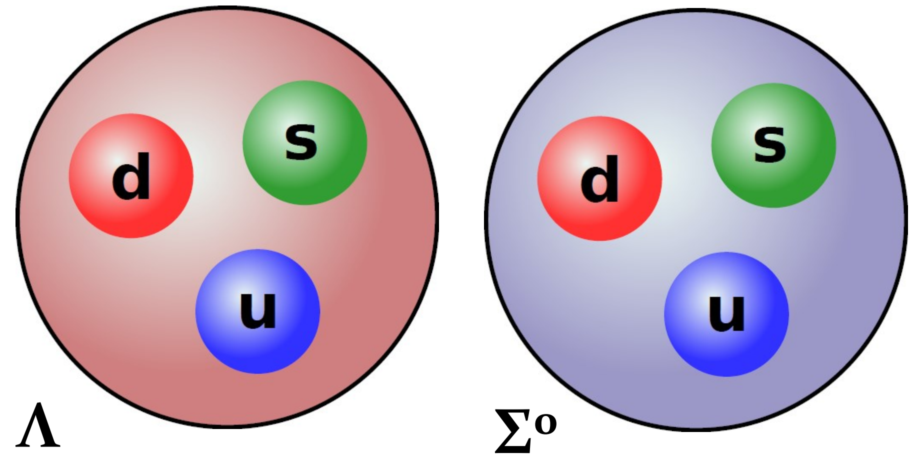
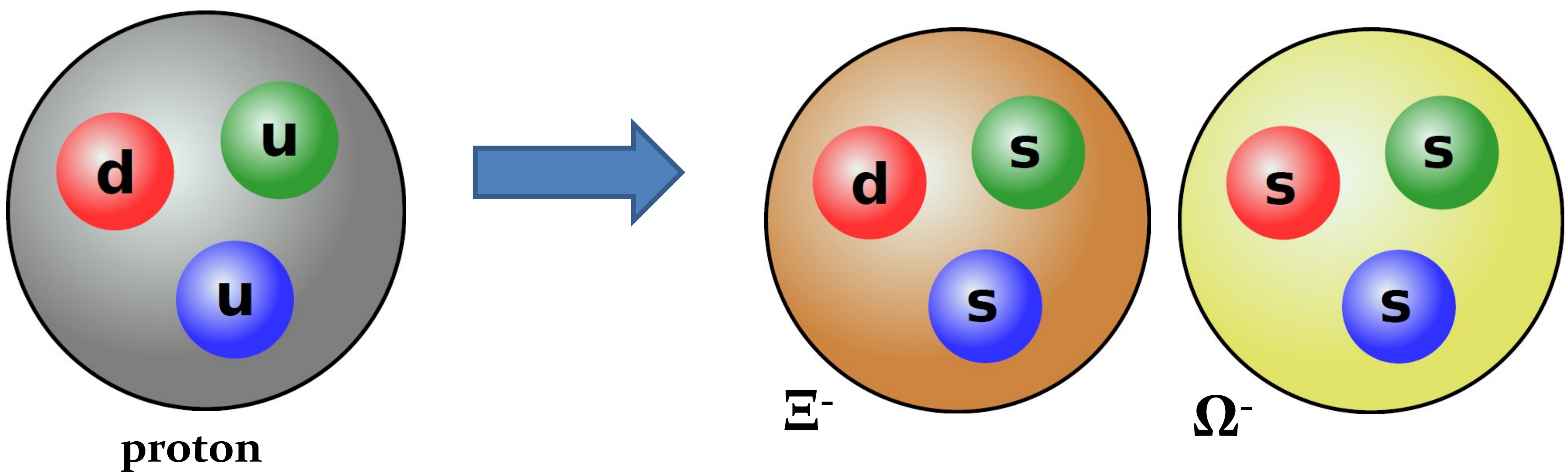
Hyperons

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





Why hyperons?

Traceable spin:

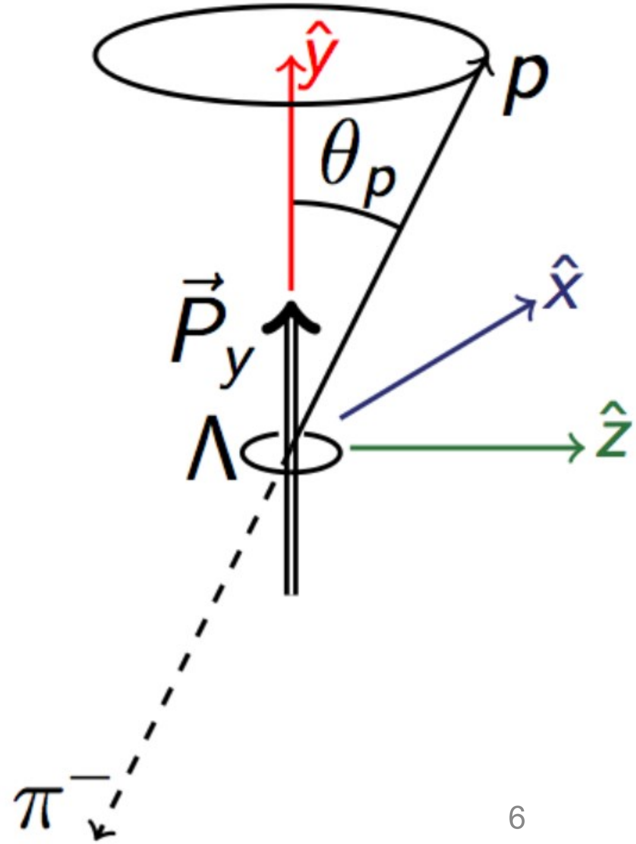
Polarization experimentally accessible by the weak, parity violating decay:

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

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

P_Λ : polarisation

α = asymmetry parameter



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Why hyperons?

Neutron stars:

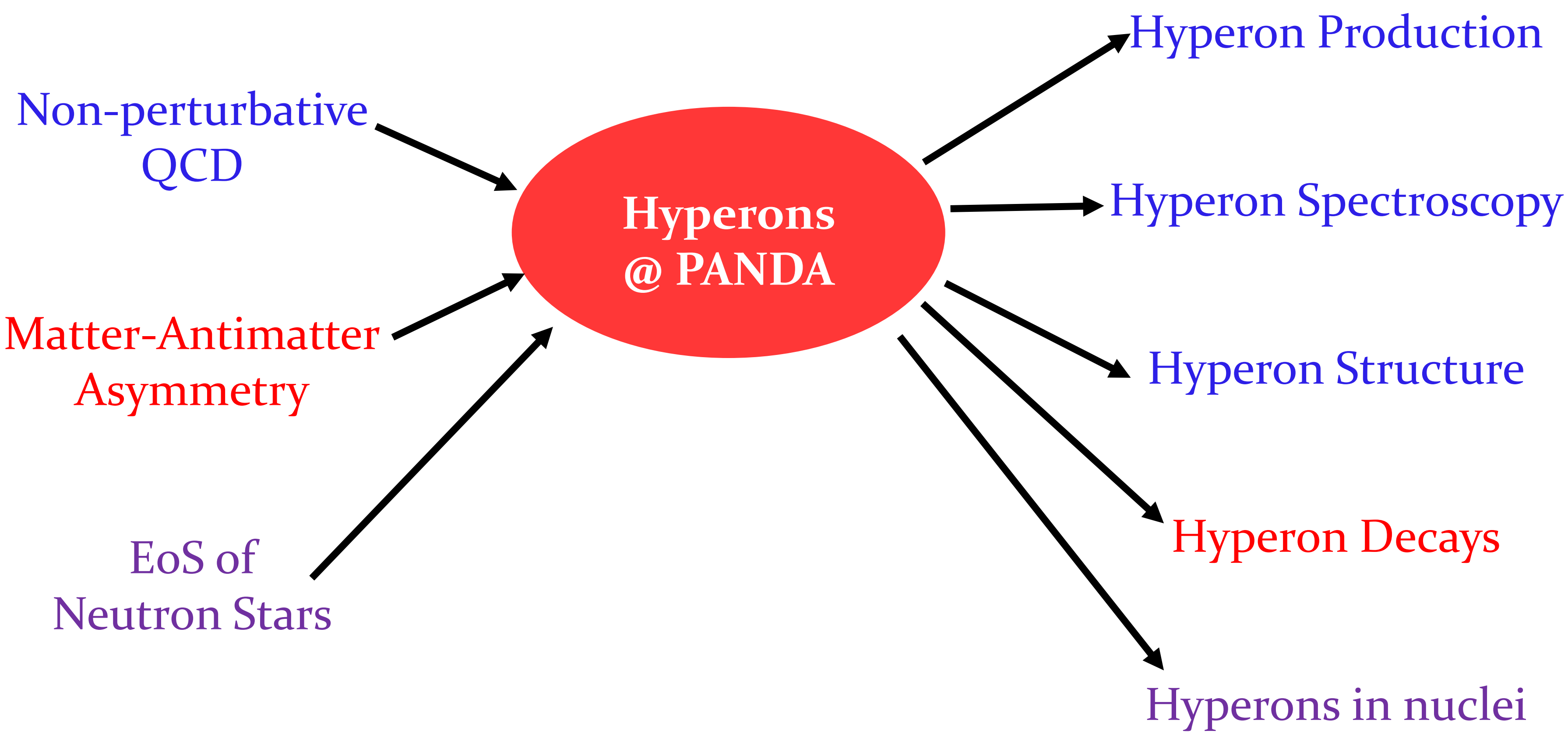
- Described by the Equation of State (EoS)
- Large masses (~2 M_{sol}) and small radii (~10 km) observed.
- Extreme conditions near centre implies presence of hyperons*
  - should soften EoS and result in smaller masses

  → **Hyperon puzzle**

Need to understand hyperon-hyperon and hyperon-nucleon interactions!

*Chatterjee & Vindana, EPJA 52, 29 (2016)

Fundamental Question | **Topic**



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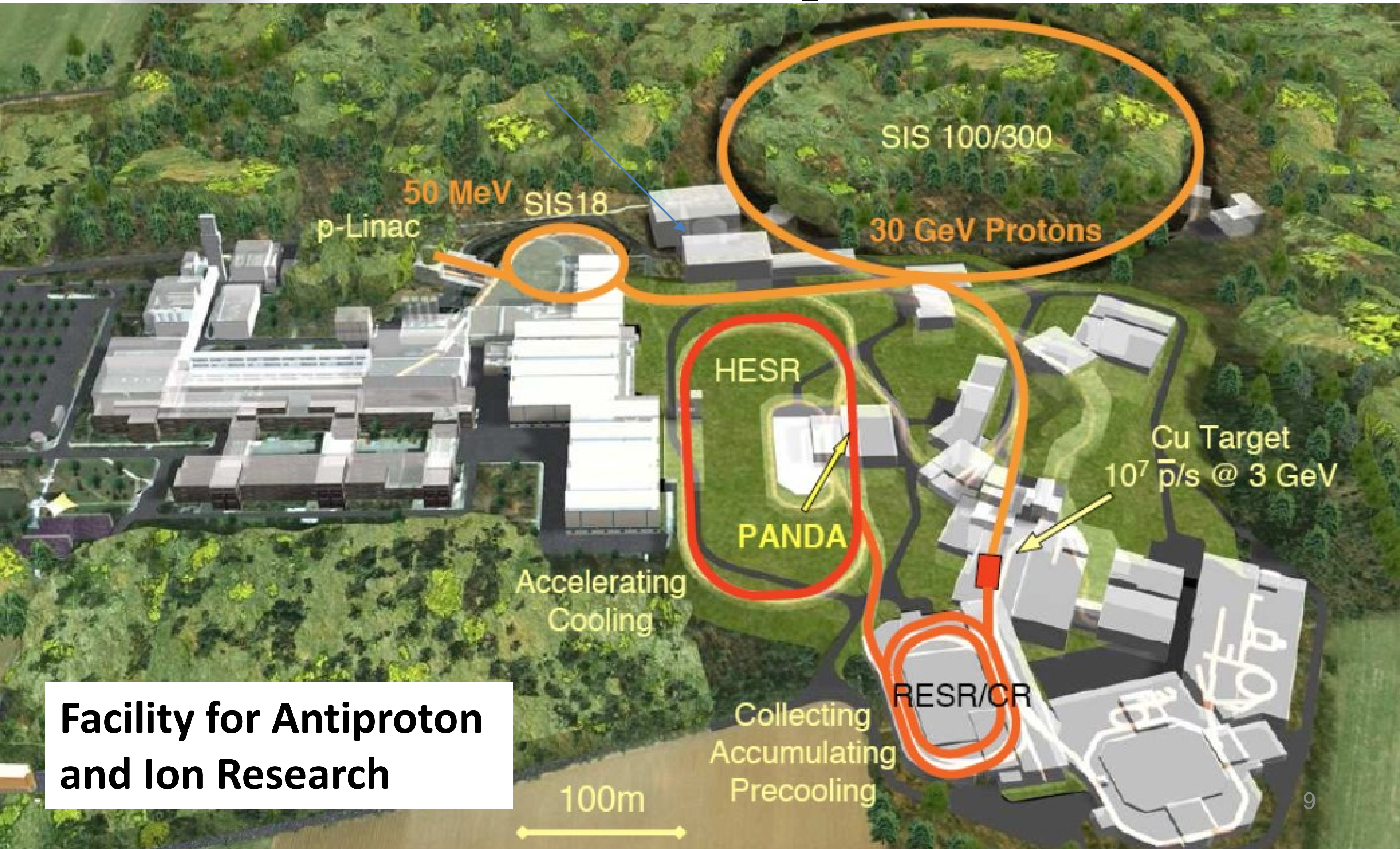
The PANDA experiment at FAIR

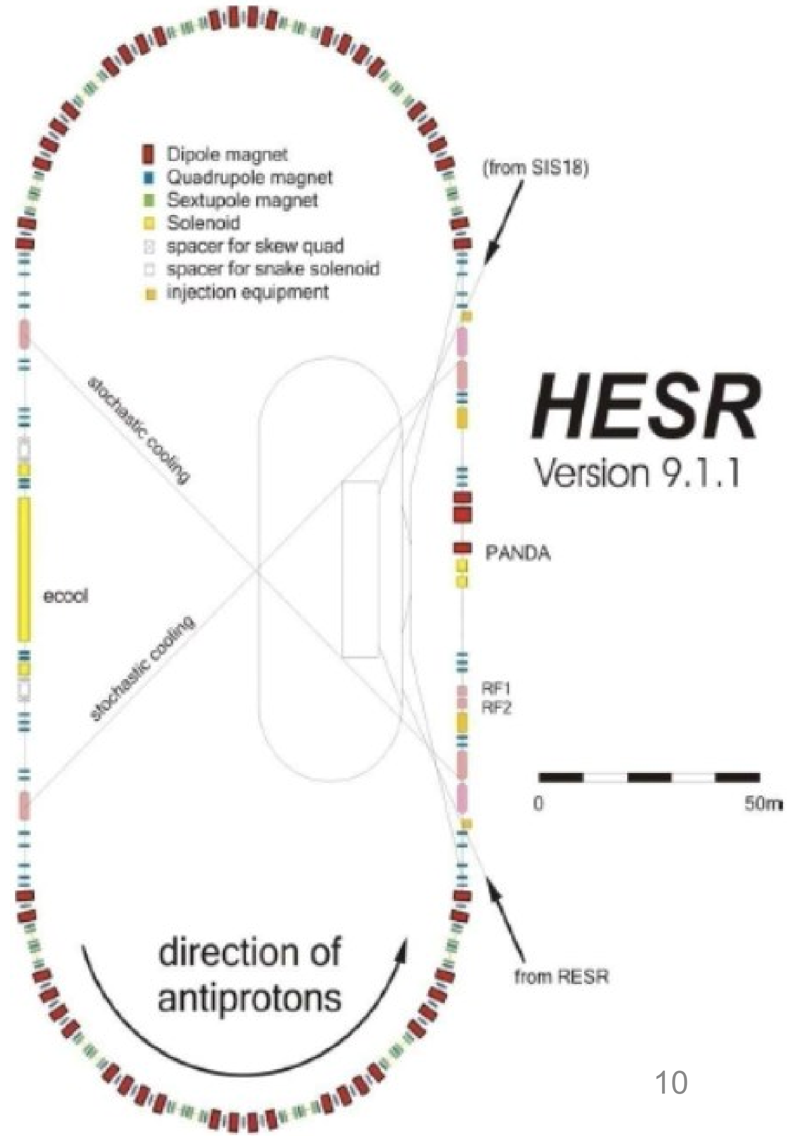


Facility for Antiproton and Ion Research

The PANDA experiment at FAIR

The High Energy Storage Ring (HESR)

- Anti-protons within
  $1.5 < p_{beam} < 15$ GeV/c
- Internal targets
  - Cluster jet and pellet ($\bar{p}p$)
  - Foils ($\bar{p}A$)
- Luminosity:
  - Design ~2×10^{32} cm^{-2}s^{-1}
  - Phase One ~10^{31} cm^{-2}s^{-1}



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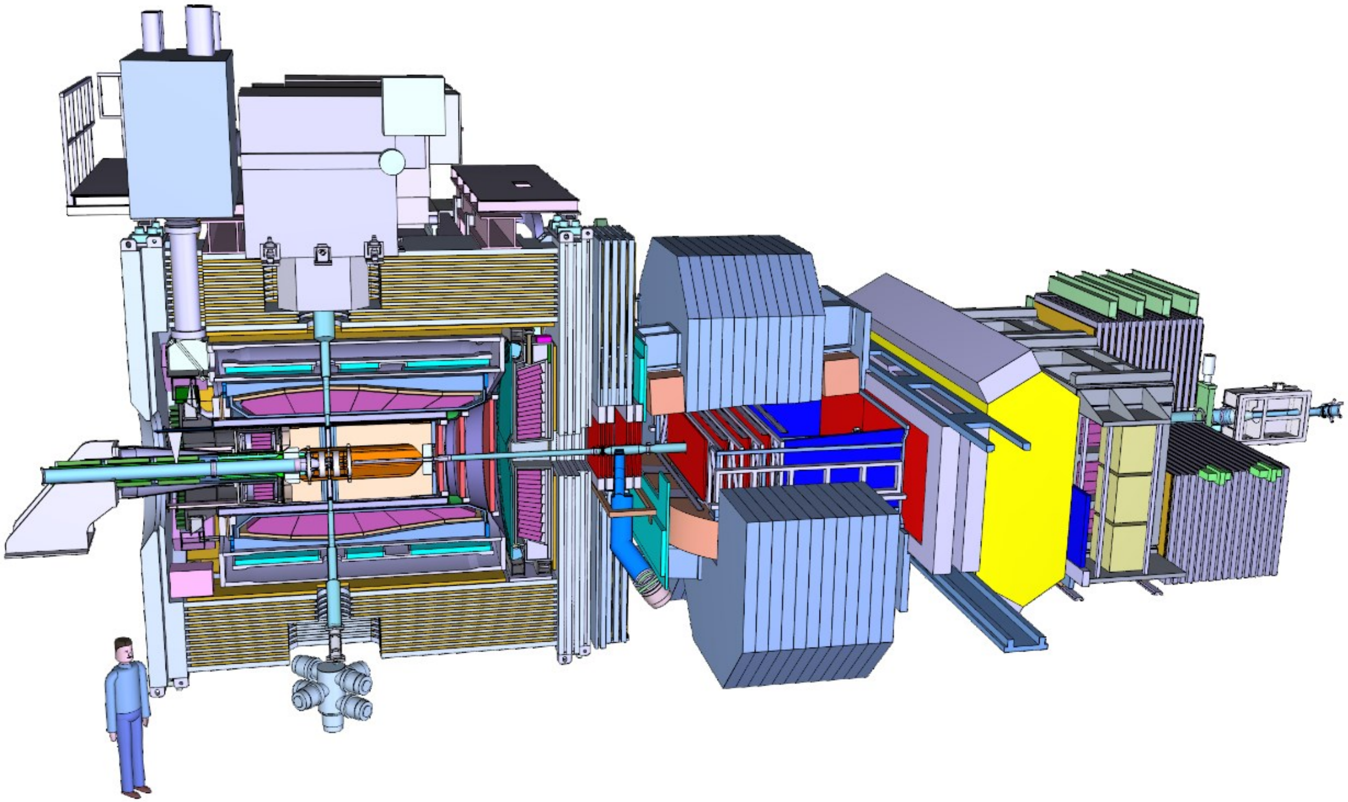
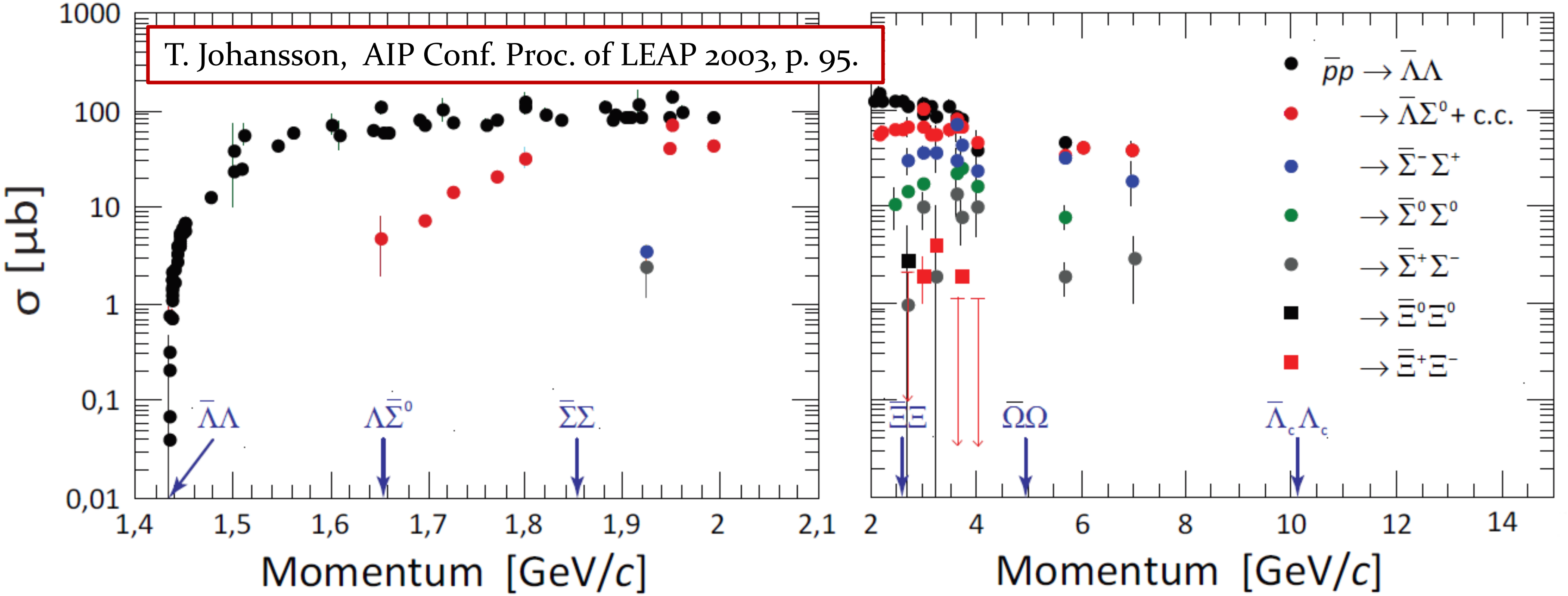


- Precise tracking
- PID
- Calorimetry

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

Advantages of PANDA



T. Johansson, AIP Conf. Proc. of LEAP 2003, p. 95.

- 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**.

→ Large expected production rates!

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

Advantages of PANDA

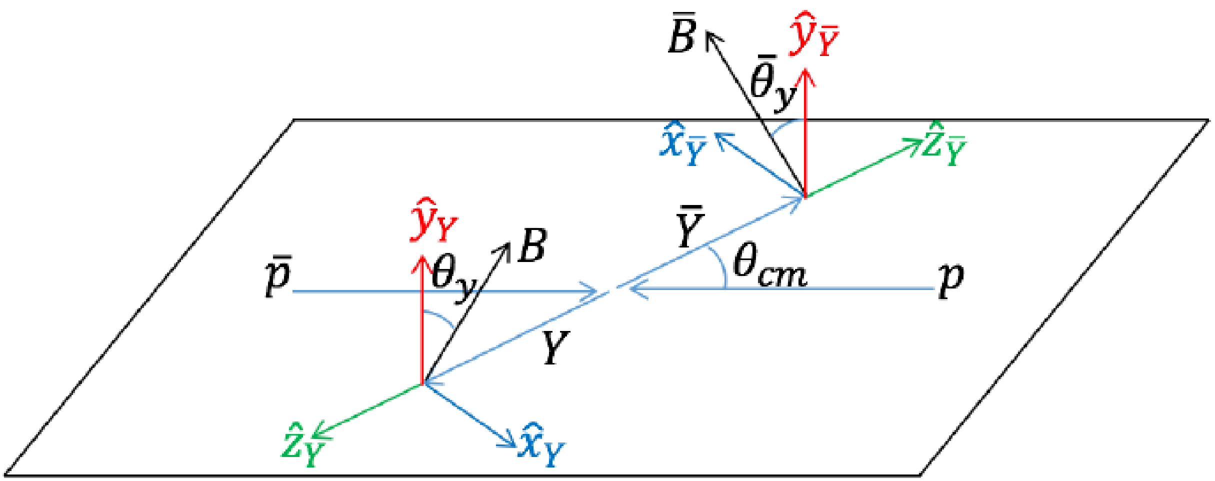
Antihyperon – hyperon pair production:

- Two-body processes

  → well-defined kinematics

- Symmetric particle-antiparticle final state

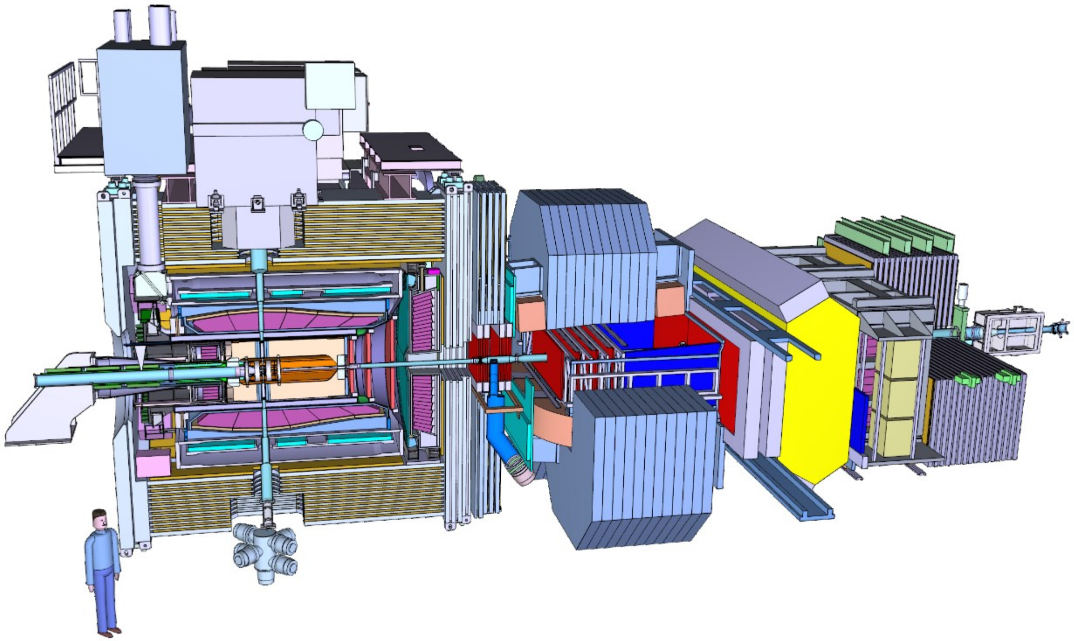
  → entangled system → correlated decays



Advantages of PANDA

Near 4π detectors → exclusive measurements:

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



Hyperon Topics in PANDA

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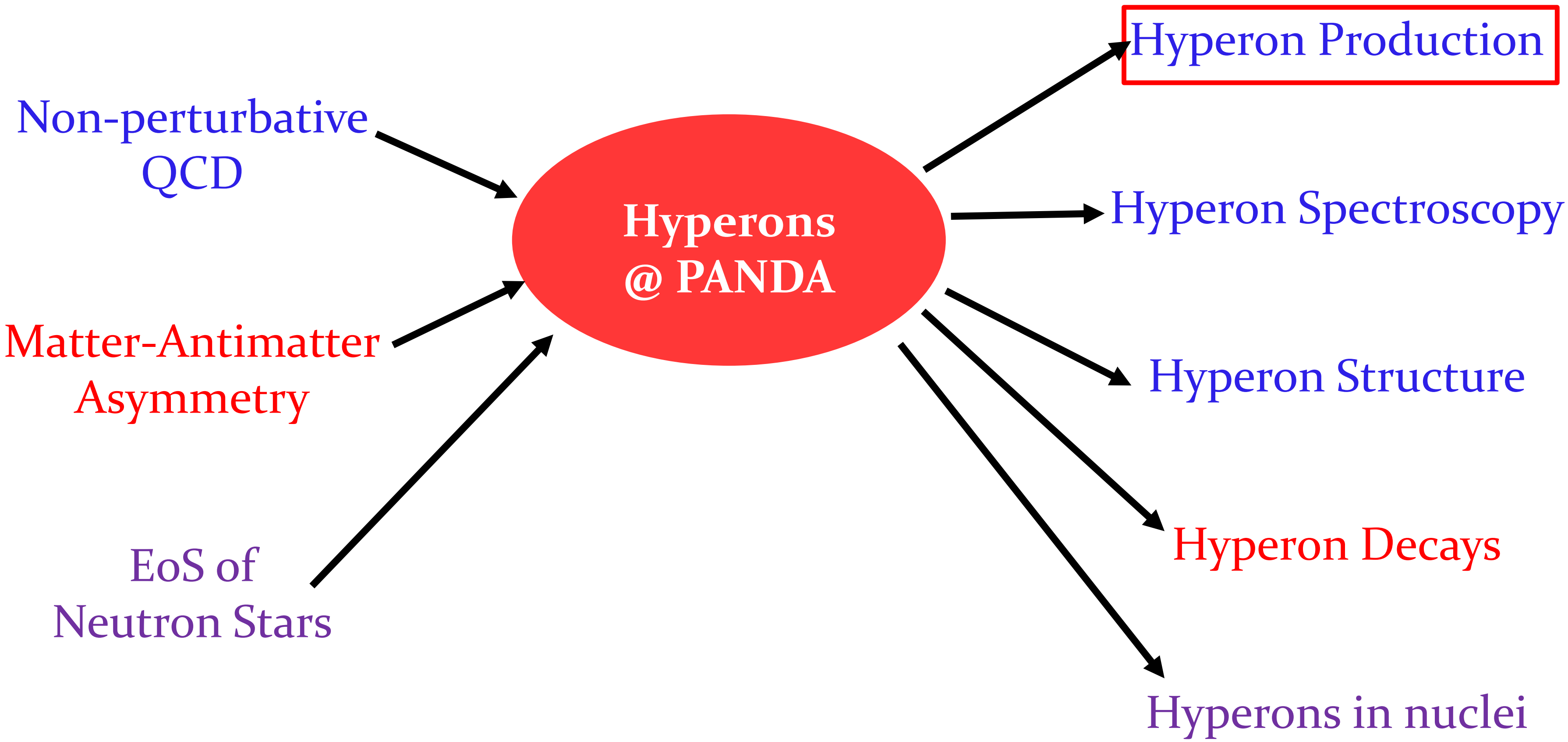
Fundamental Question **Topic**



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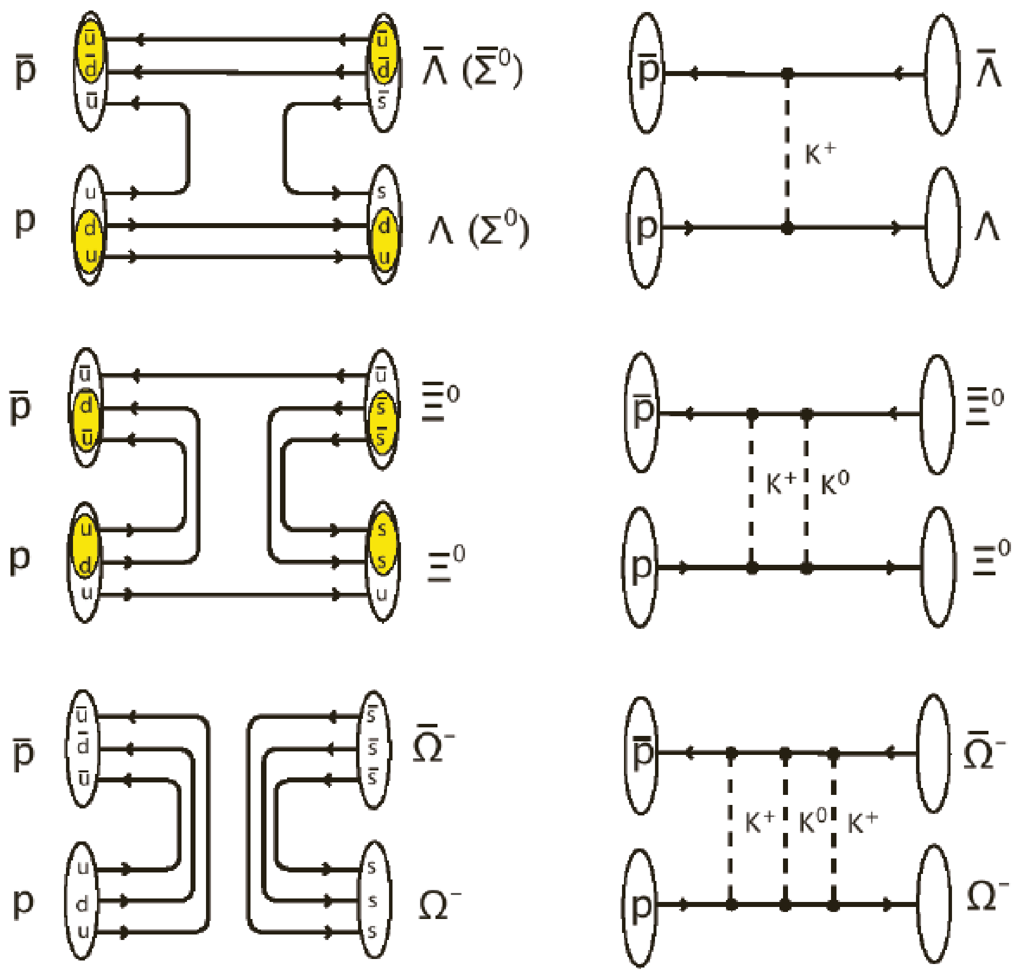
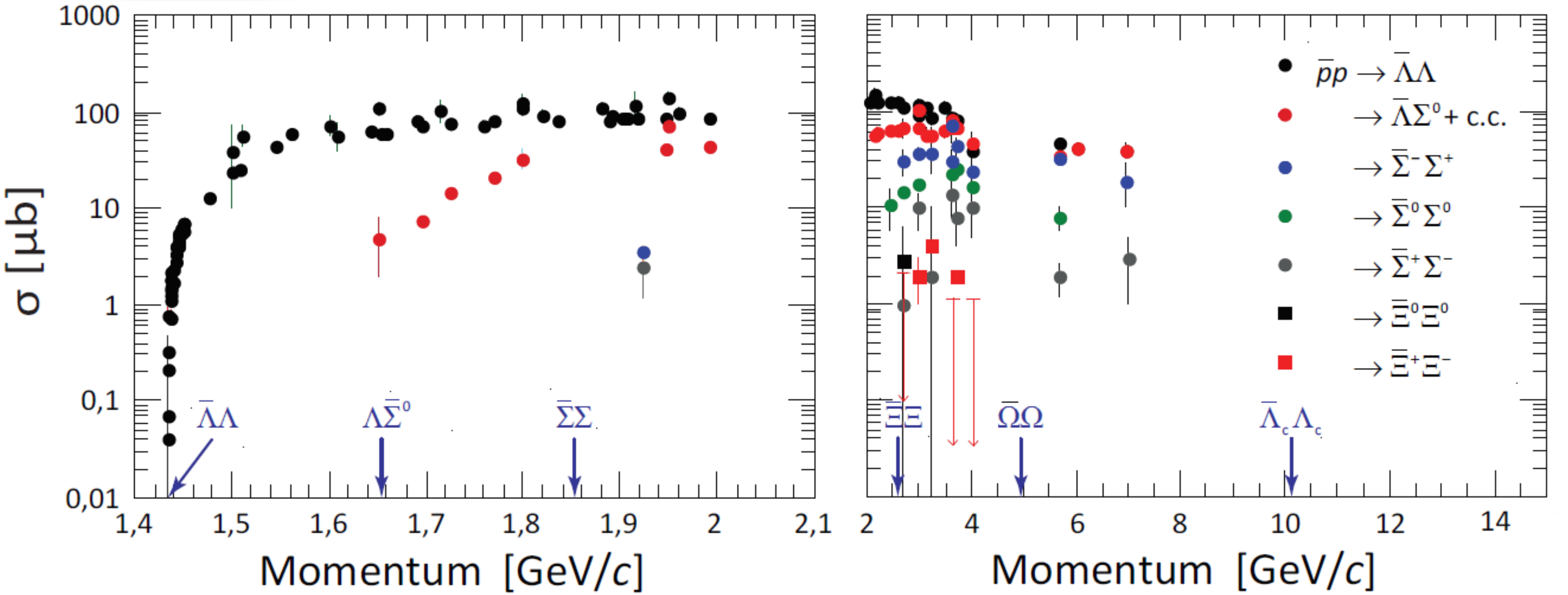
Hyperon production

Strong production dynamics

- Relevant degrees of freedom?
- Strange *versus* charm sector?
- Role of spin?



Hyperon production



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

T. Johansson, AIP Conf. Proc. of LEAP 2003, p. 95.

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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

PANDA, EPJA 57, 184 (2021)
PANDA, EPJA 57, 154 (2021)

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^{-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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  - $\bar{p}p \to \bar{\Sigma}^0\Lambda, \Lambda \to p\pi^-, \bar{\Sigma}^0 \to \bar{\Lambda}\gamma, \bar{\Lambda} \to \bar{p}\pi^+$.
  - $\bar{p}p \to \bar{\Xi}^+\Xi^-, \Xi^- \to \Lambda\pi^-, \Lambda \to p\pi^-, \bar{\Xi}^+ \to \bar{\Lambda}\pi^+, \bar{\Lambda} \to \bar{p}\pi^+$.
- Ideal pattern recognition and PID
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PANDA, EPJA 57, 184 (2021)
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p_{beam} (GeV/c)	Reaction	σ (μb)	ε (%)	Rate @ 10^{31} $cm^{-2}s^{-1}$	S/B	Events /day
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7.0	$\bar{p}p \to \bar{\Xi}^+\Xi^-$	~0.3	7.9	0.1^{-1}	65	8600

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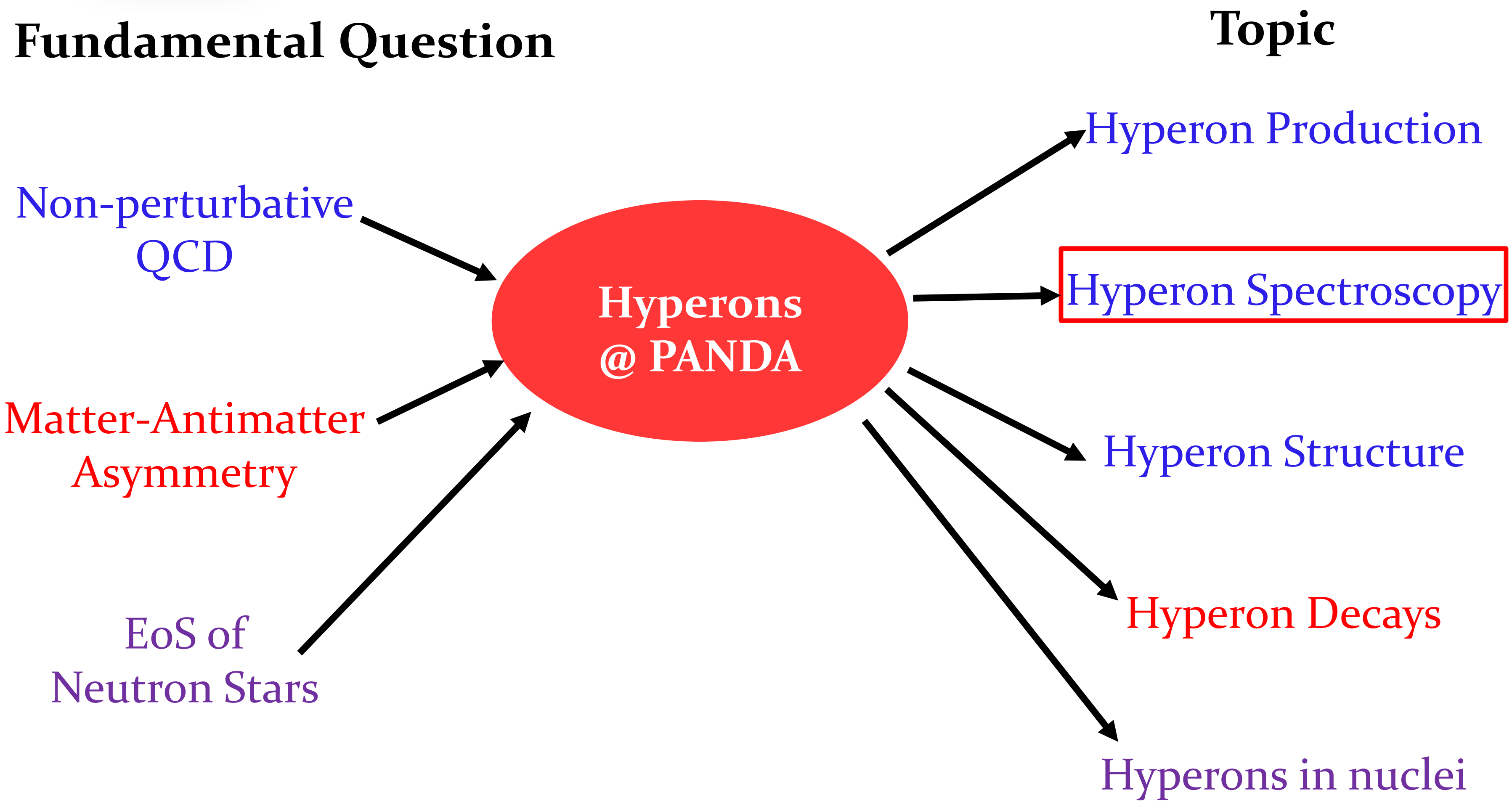
PANDA will be a strangeness factory!

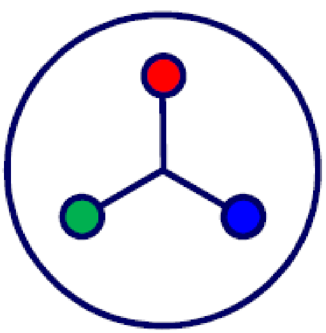
Hyperon Topics in PANDA



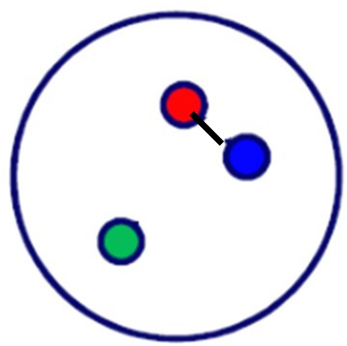
Hyperon Spectroscopy

How do quarks form baryons?

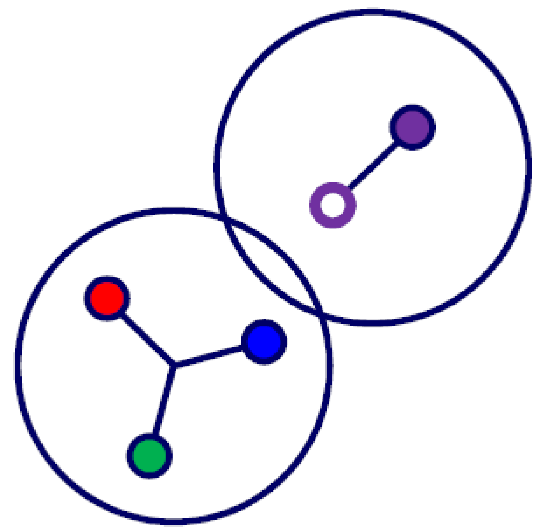
- Forces?
- Degrees of freedom?



Symmetric quark model



Quark - diquark



Molecule / hadronic d.o.f.

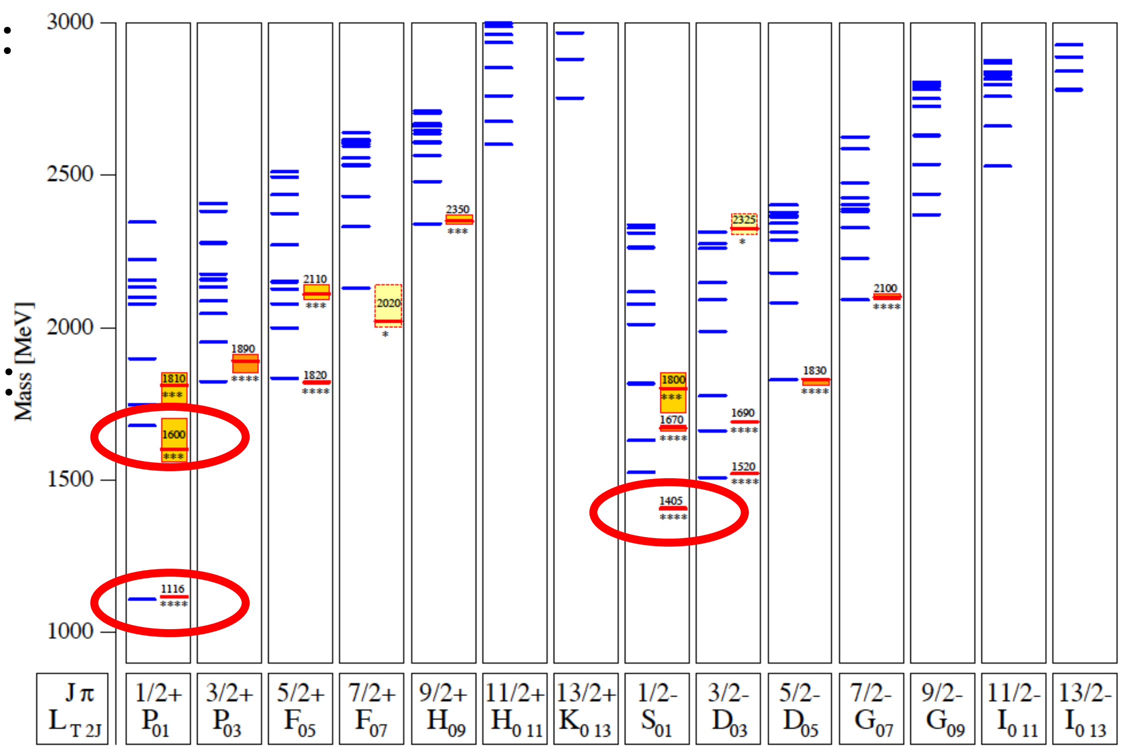
Hyperon spectroscopy

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

- Light baryon spectrum*:
  - ”Missing” states
  - Parity pattern:

    ++- (exp.) +-+ (QM)

- Single strange spectrum:
  - ”Missing” states
  - The unbearable lightness of Λ(1405)



*EPJA 48 (2012) 127, EPJA 10 (2001) 395

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Hyperon spectroscopy

- Impressive progress world-wide in
  - Single-strange spectroscopy (JLAB, CBELSA/TAPS, BGO-OD)
  - Charm and bottom baryons (Belle/Belle-II, LHCb)

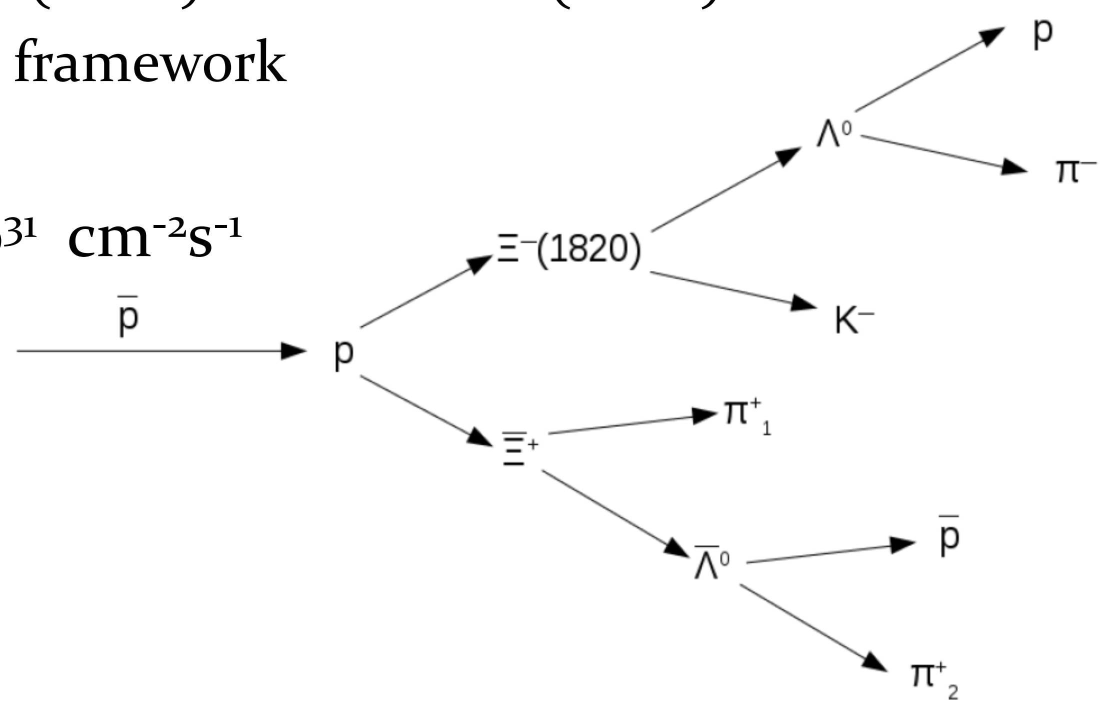
- Very scarce data bank on multi-strange hyperons:

Gap to be filled by PANDA?

*PDG

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} $cm^{-2}s^{-1}$ luminosity

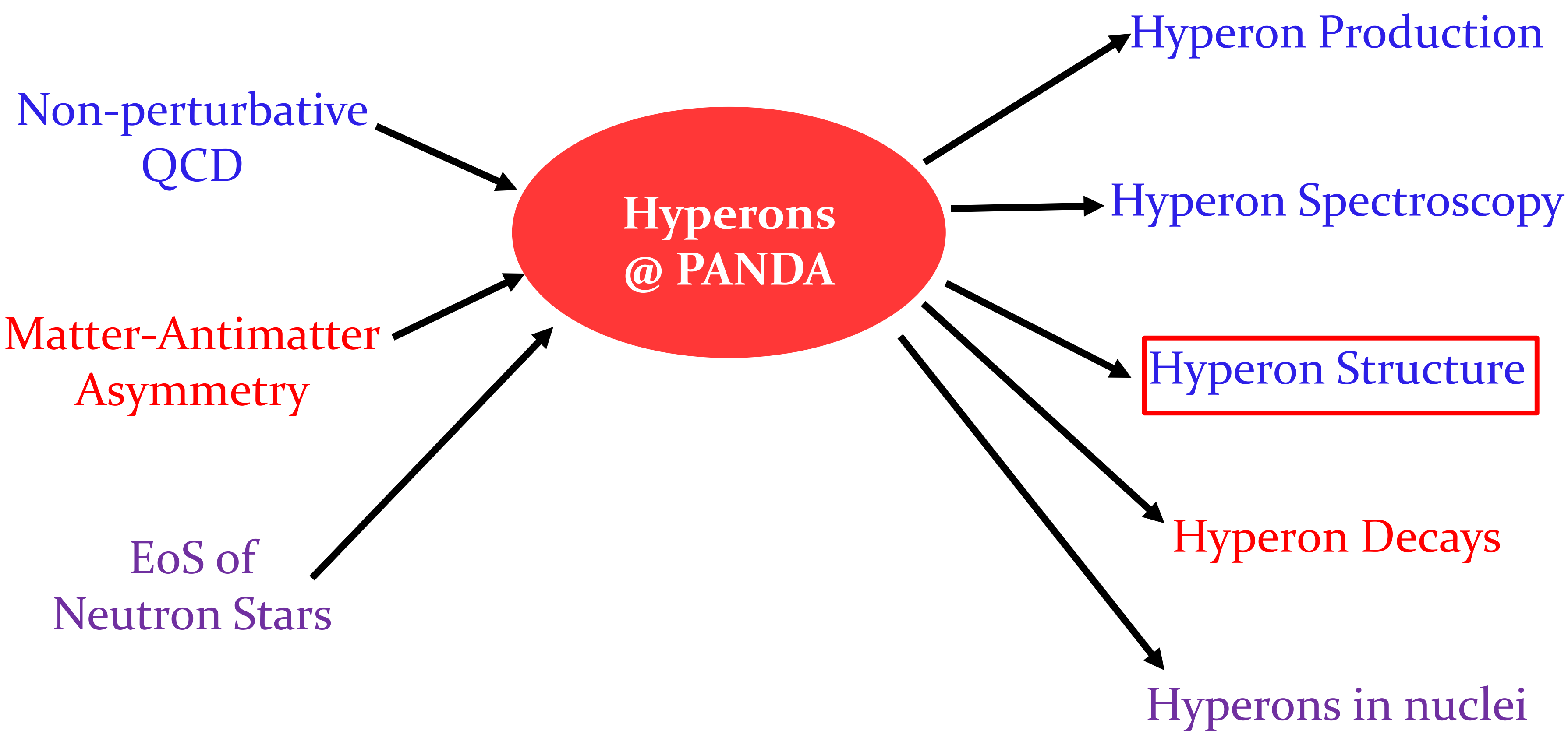


PANDA, EPJA 57, 184 (2021)
PANDA, EPJA 57, 149 (2021)

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

Hyperon Topics in PANDA

Fundamental Question | **Topic**



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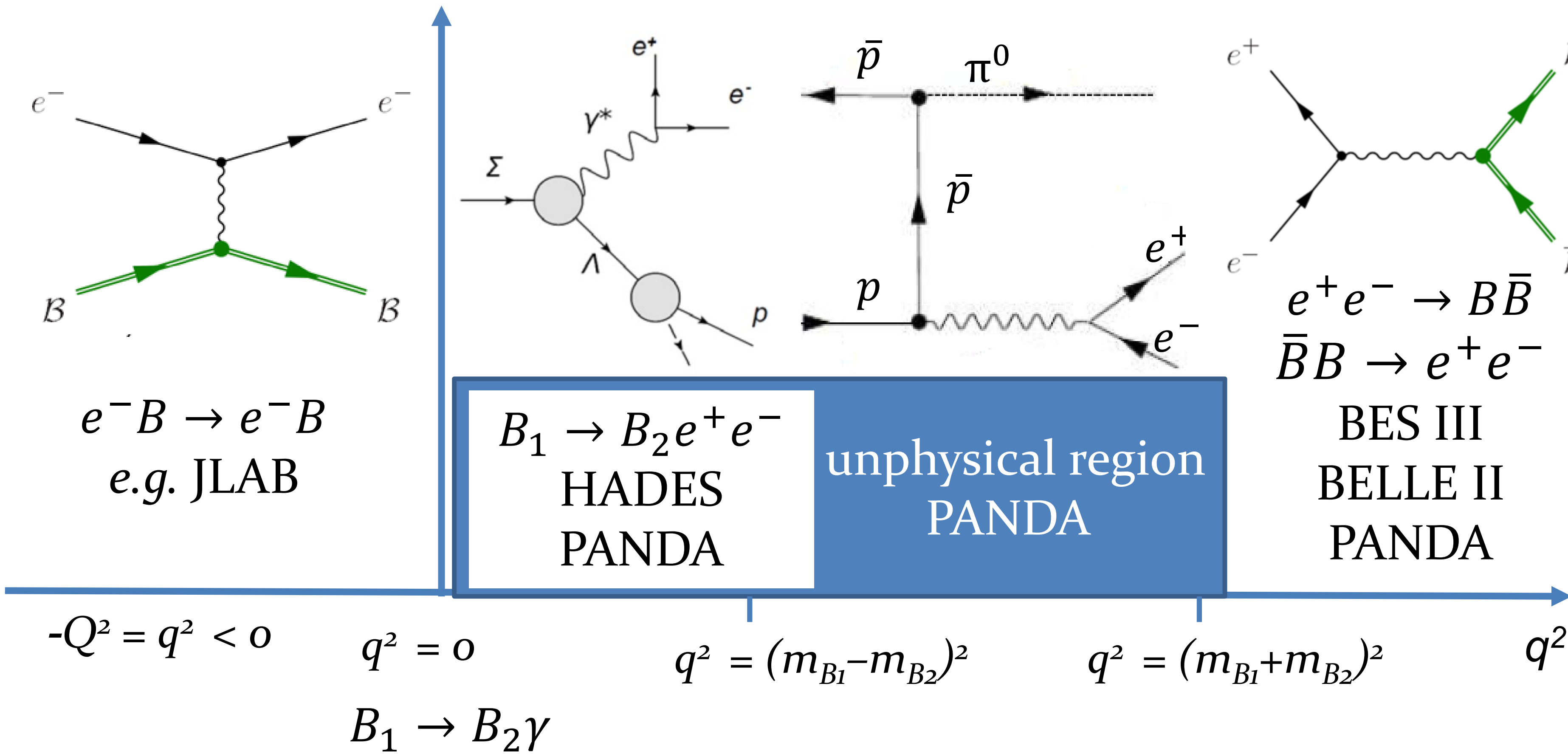
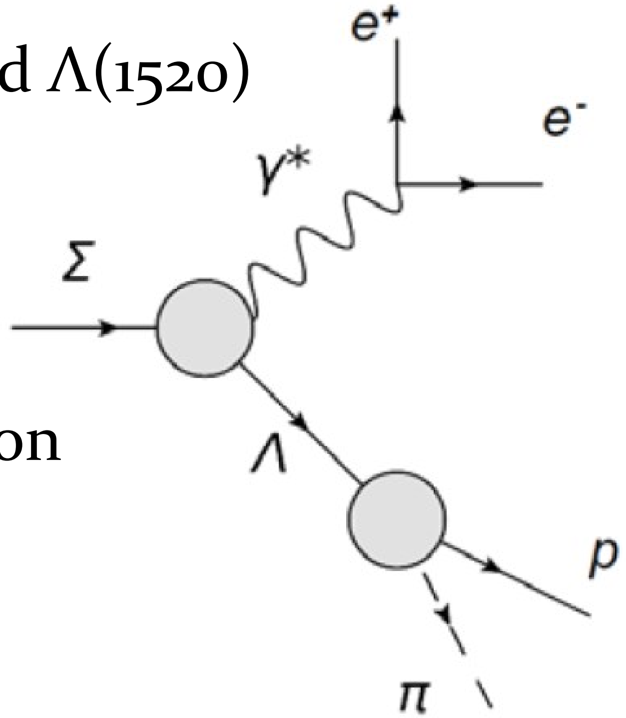
Hyperon structure



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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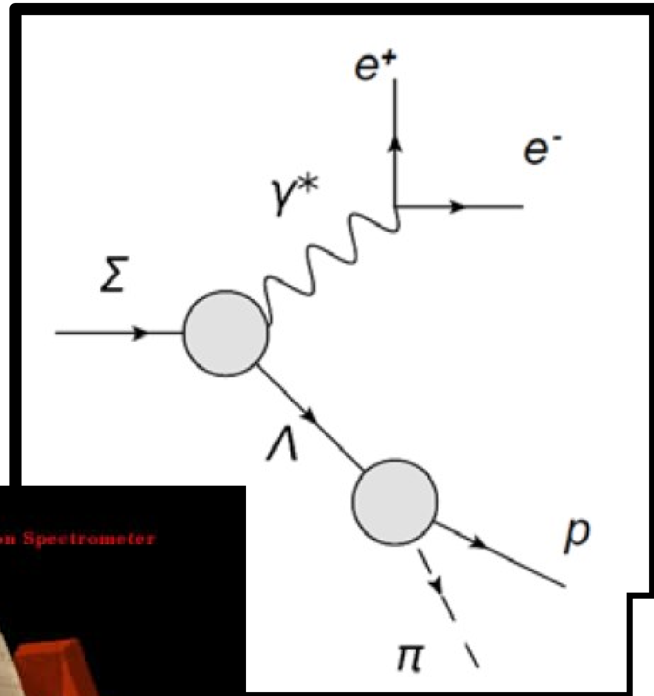
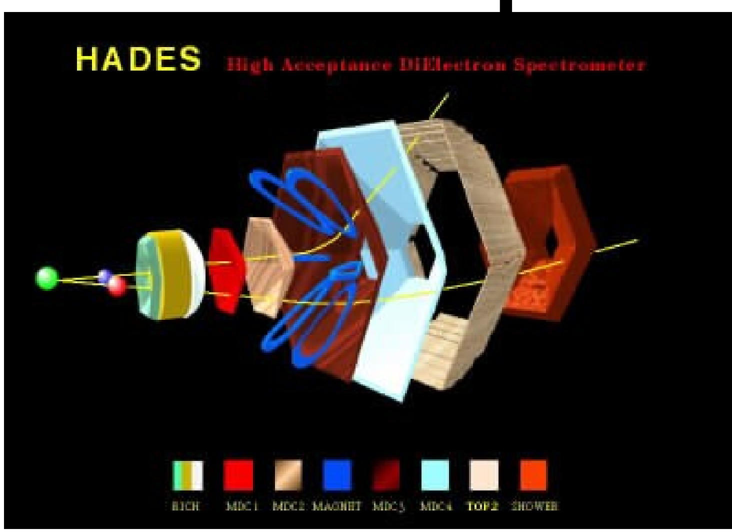
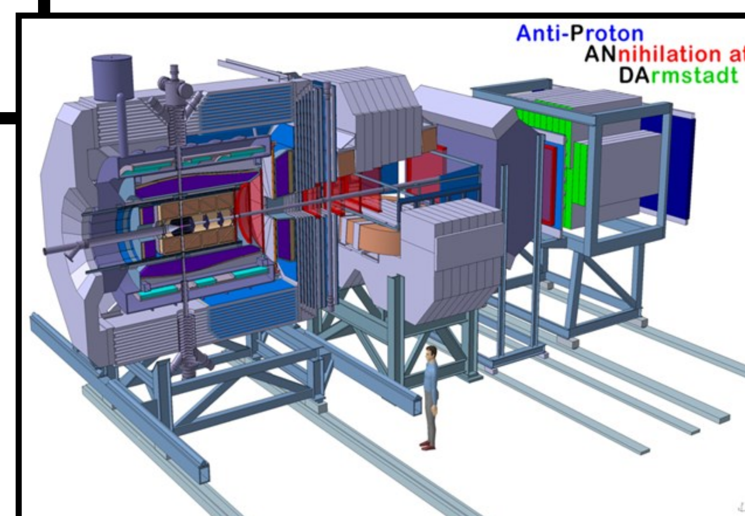
Hyperon Structure



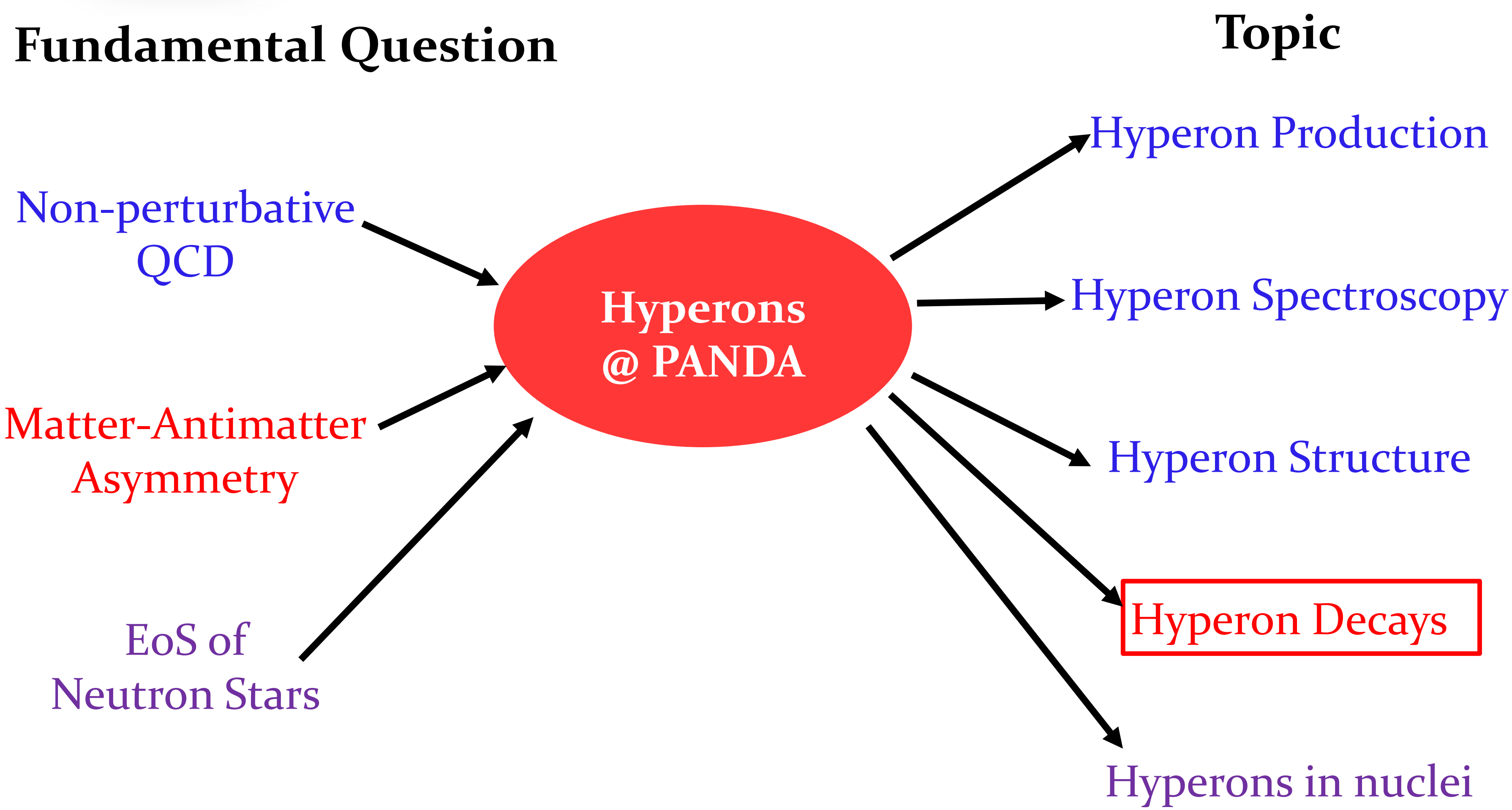
Possible already during Phase 0 with HADES +PANDA FTS!





HADES + PANDA@HADES, EPJA 57, 138 (2021)

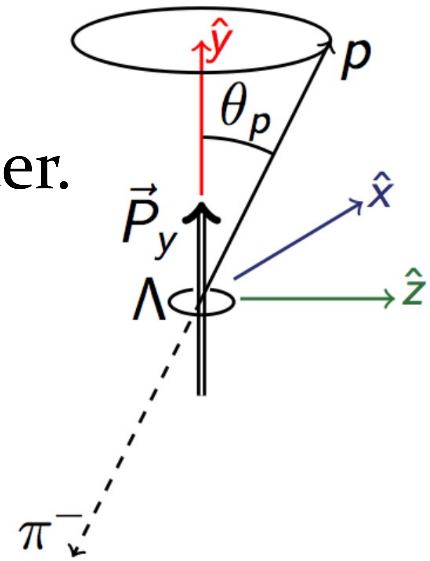
Hyperon Topics in PANDA



Hyperon decays

Promising hunting ground for CP violation

- necessary for dynamic enrichment of matter.

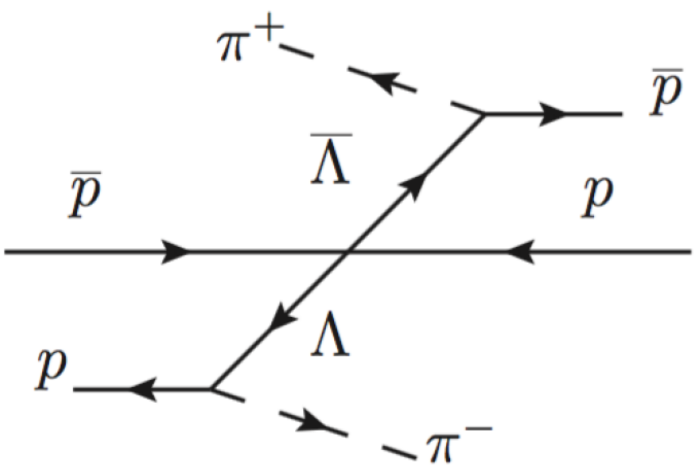


- Recall: $I(\cos\theta_p) = N(1+\alpha P_\Lambda \cos\theta_p)$

- CP symmetry if:

$$\alpha = -\bar{\alpha},$$

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



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Hyperon decays

Recent progress by BESIII:

- Nature Phys. 15, p. 631-634 (2019): ~400 000 $\Lambda\bar{\Lambda}$ events
- Phys. Rev. Lett. 125, 052004 (2020): ~90 000 $\Sigma^{+}\bar{\Sigma}^{-}$ events
- arXiv[hep-ex]:2105.11155: ~ 70 000 $\Xi^{-}\bar{\Xi}^{+}$ events

All consistent with CP symmetry,

but testing SM and BSM predictions requires 10-100 times better precision!

PANDA, EPJA 57, 184 (2021)
PANDA, EPJA 57, 154 (2021)

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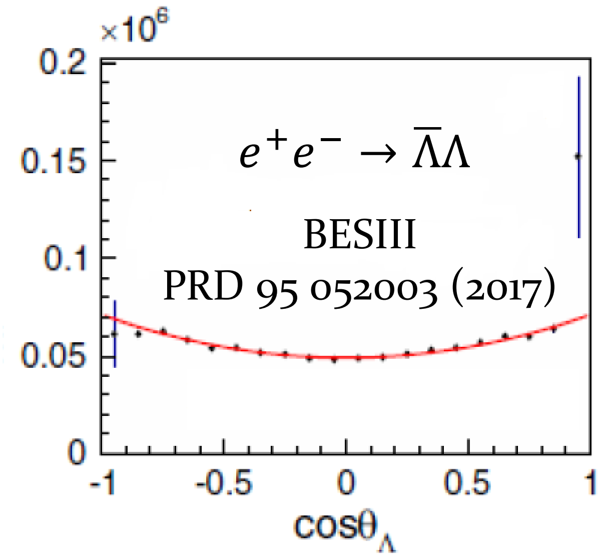

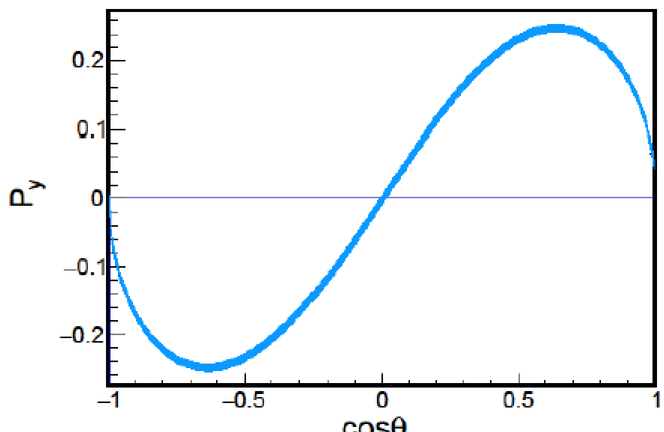

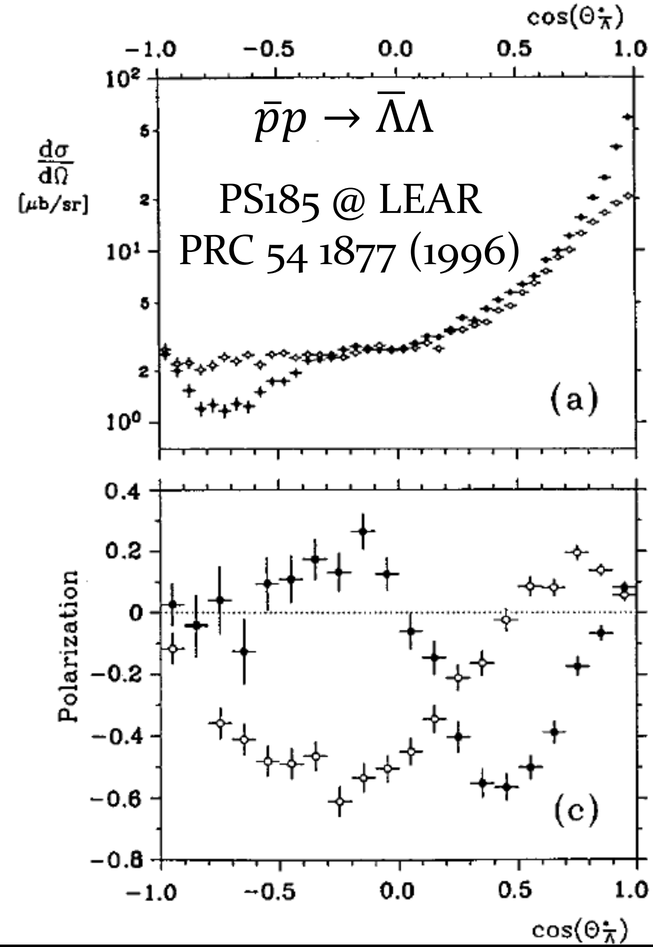

$J^P = 1^-$ dominates → 2 amplitudes → 2 **global** observables η and ΔΦ.

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

Several initial J^P contribute → complicated final state.

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

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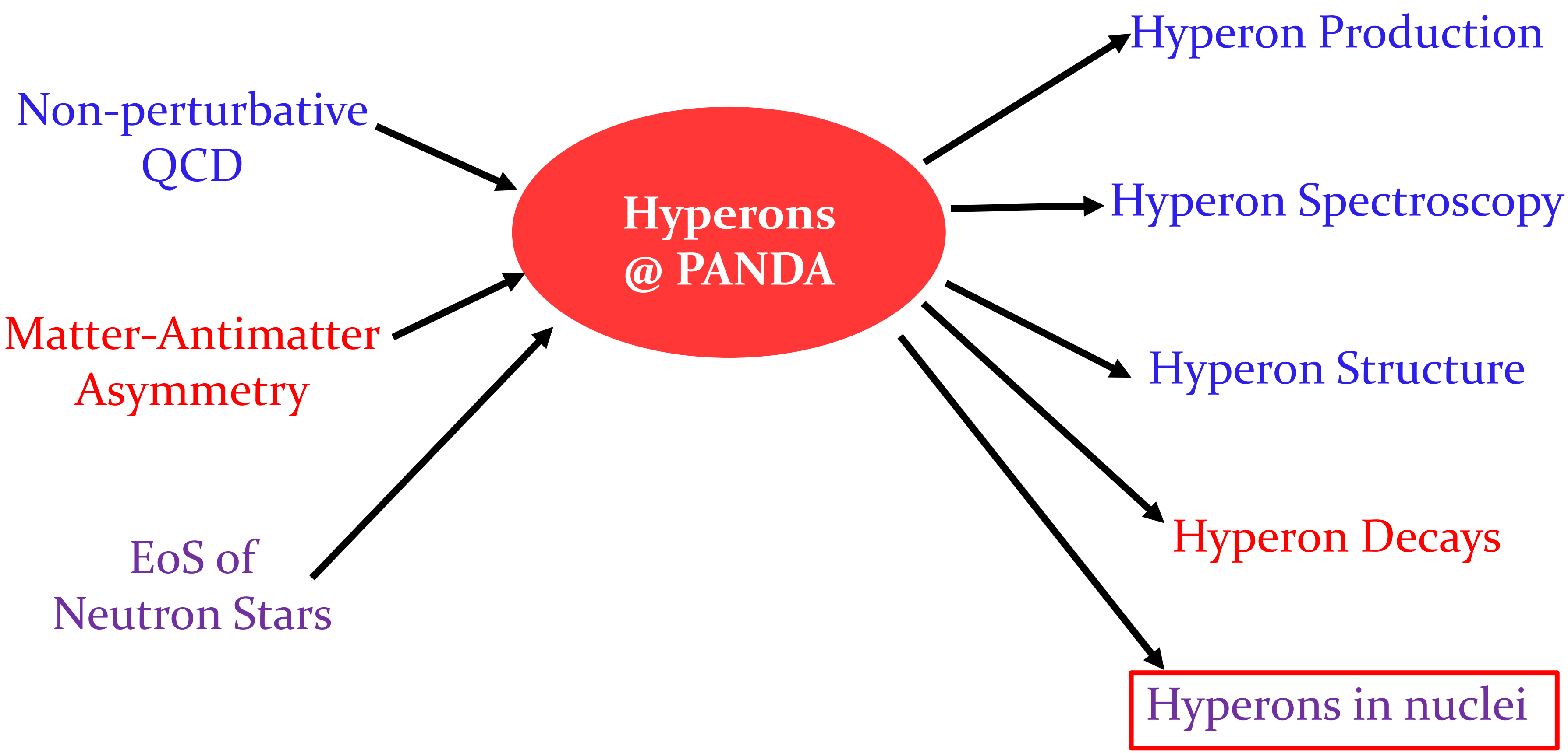
Hyperon Topics in PANDA

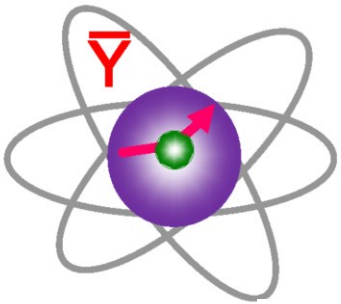
Fundamental Question **Topic**



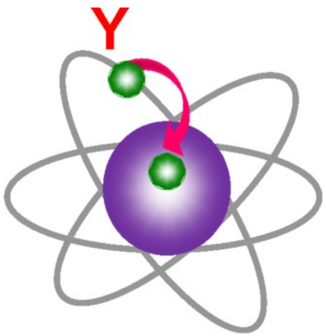
Hyperons in Nuclei

Hyperon-nucleus potential: Component of EoS of neutron stars.

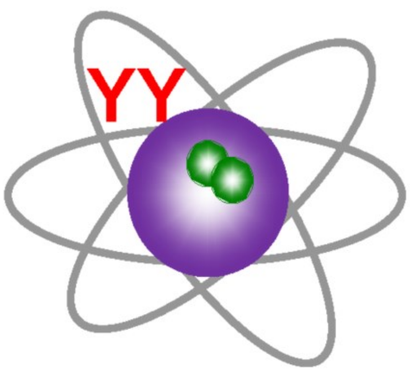
- **Antihyperons in nuclei:**
  - $\bar{p}A \rightarrow \bar{\Xi}X$ possible during Phase One with regular setup.



- **Hyperatoms:**
  - Atomic cascade of the Ξ: ΞN-interactions at lower nuclear densities
  - Dedicated hyperatom/hypernuclear setup with HPGe-detector array.



- **Hypernuclei:**
  - PANDA unique for heavy multistrange hypernuclei.



PANDA, EPJA 57, 184 (2021)
PANDA, NPA 954, p. 323-340 (2016)

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Hyperon physics with PANDA

- **Phase 1**:
  - Hyperon production and spin observables
  - Single- and double strange hyperon spectroscopy
  - Antihyperons in nuclei
- **Phase 2**:
  - Triple-strange hyperon spectroscopy
  - Hyperon structure
  - CP tests in hyperon decays
  - Hyperatom physics
- **Phase 3**:
  - High-precision CP violation tests
  - Hypernuclear physics

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Summary

- Hyperons constitute a probe for
  - The strong interaction
  - Matter-antimatter asymmetry
  - Neutron stars

- PANDA will be a strangeness factory already during Phase One

  → Rich hyperon physics programme!

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Thank you for listening!