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Knut and Alice Wallenberg Foundation

Prospects of Baryon Physics with PANDA at FAIR

Karin Schönning

Workshop on Baryon Production at BESIII

Hefei, China, September 14-16 2019

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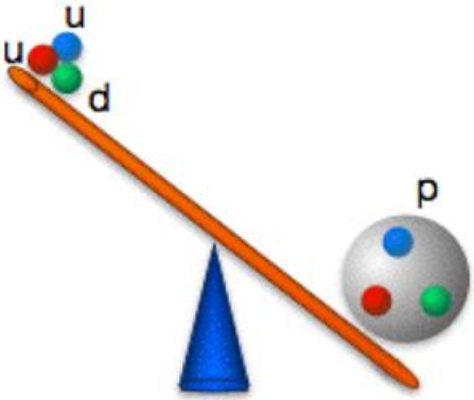
Outline

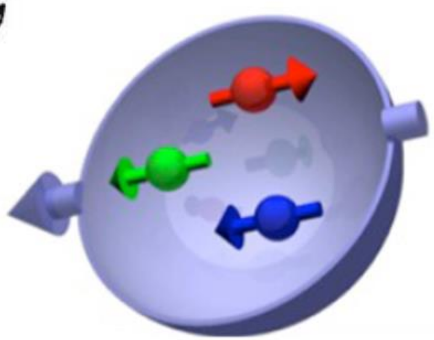
- Introduction
- Nucleon structure
- Hyperons
- PANDA at FAIR
- Nucleon Structure with PANDA
- Hyperon Physics with PANDA
- Summary

Introduction

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

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



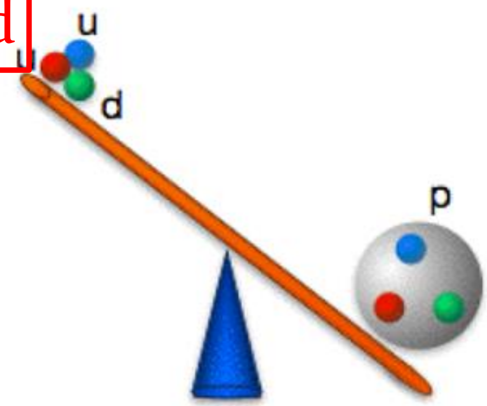


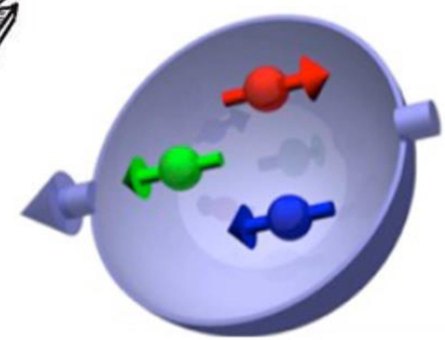
*C. A. Aidala *et al.*, RMP 85 (2013) 655-691.
** G. A. Miller, PRL 99 (2007) 112001.
***R. Pohl, *Nature* 466 (2010)7303, 213-216.

Introduction

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

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





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Introduction

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

- Abundance
- Mass
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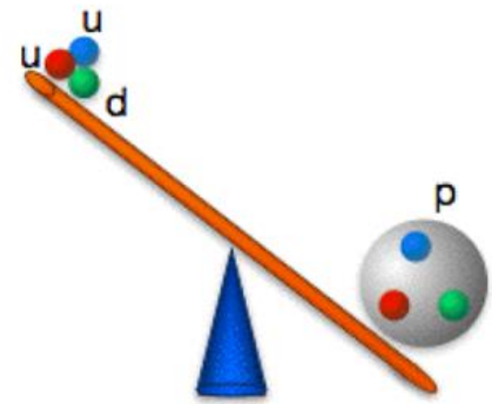
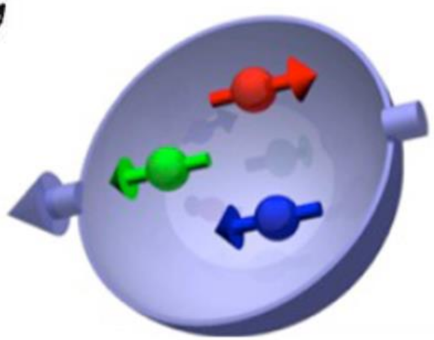
Non-perturbative QCD





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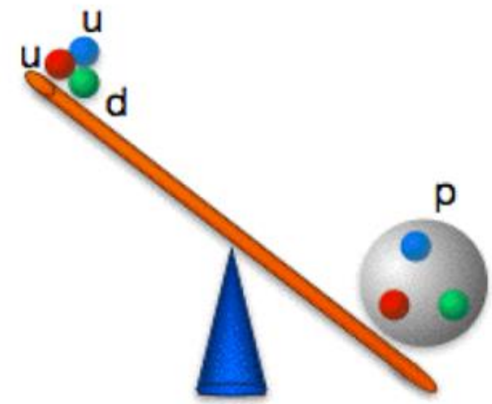
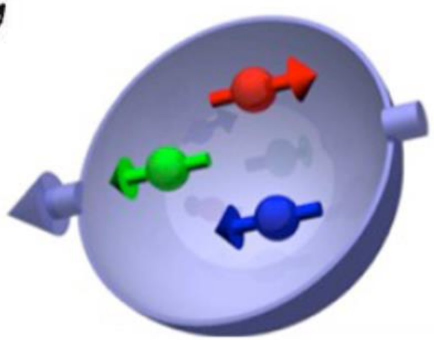
Introduction

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

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





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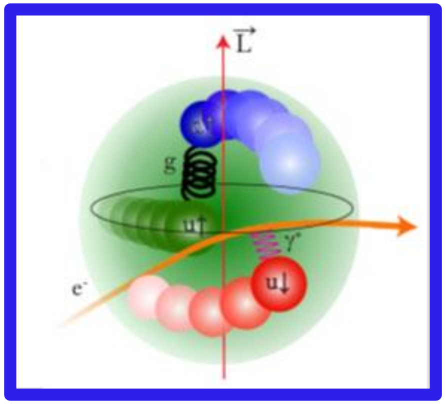
***R. Pohl, *Nature* 466 (2010)7303, 213-216.

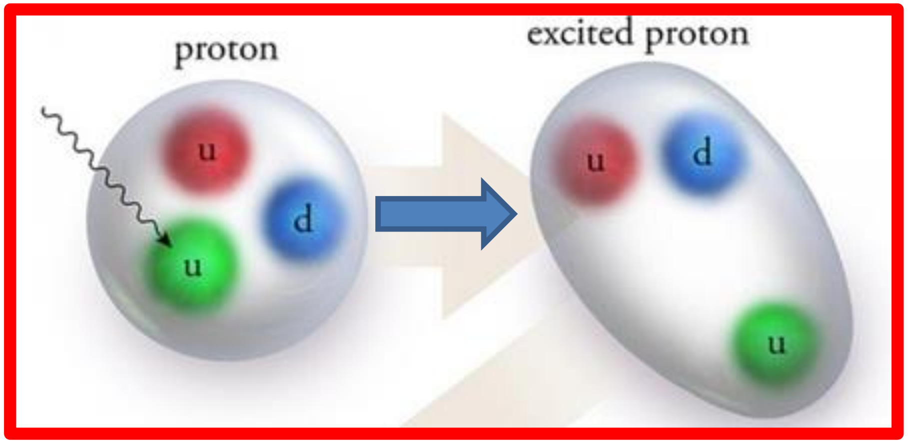
**** N. Bezginov *et al.*, *Science* (2019) 365, 6457, 1007-1012

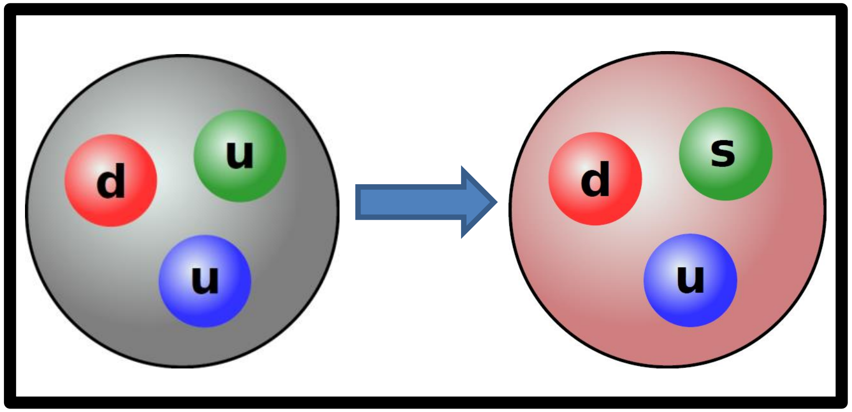
Approaches

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

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







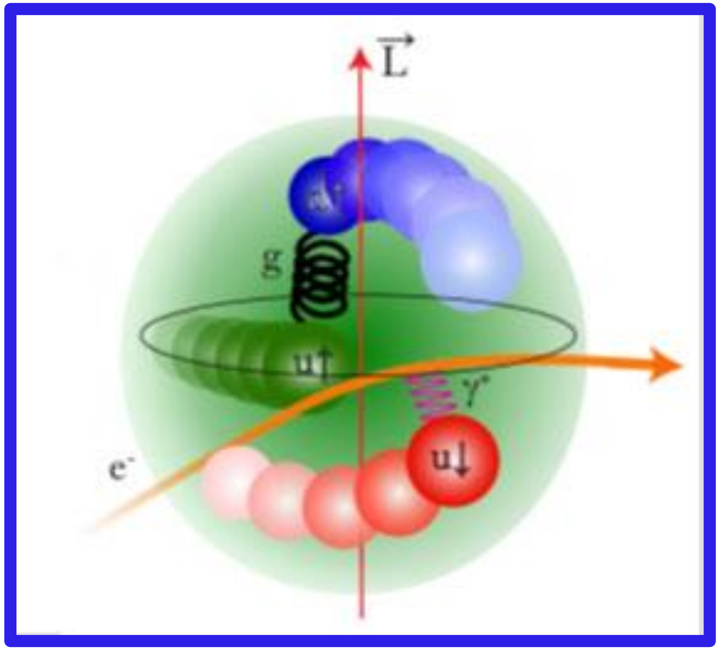
*C. Granados *et al.*, EPJA 53 (2017) 117

Electromagnetic Structure

Let's first scatter!

Can measure *e.g.* EM Form Factors!

- Electromagnetic structure observable:
  - Lattice QCD, ChPT, VDM…
- Measured in interactions
  hadron – virtual photon γ^*.
- Quantify deviation from point-like case
  = depend on q^2 of γ^*.



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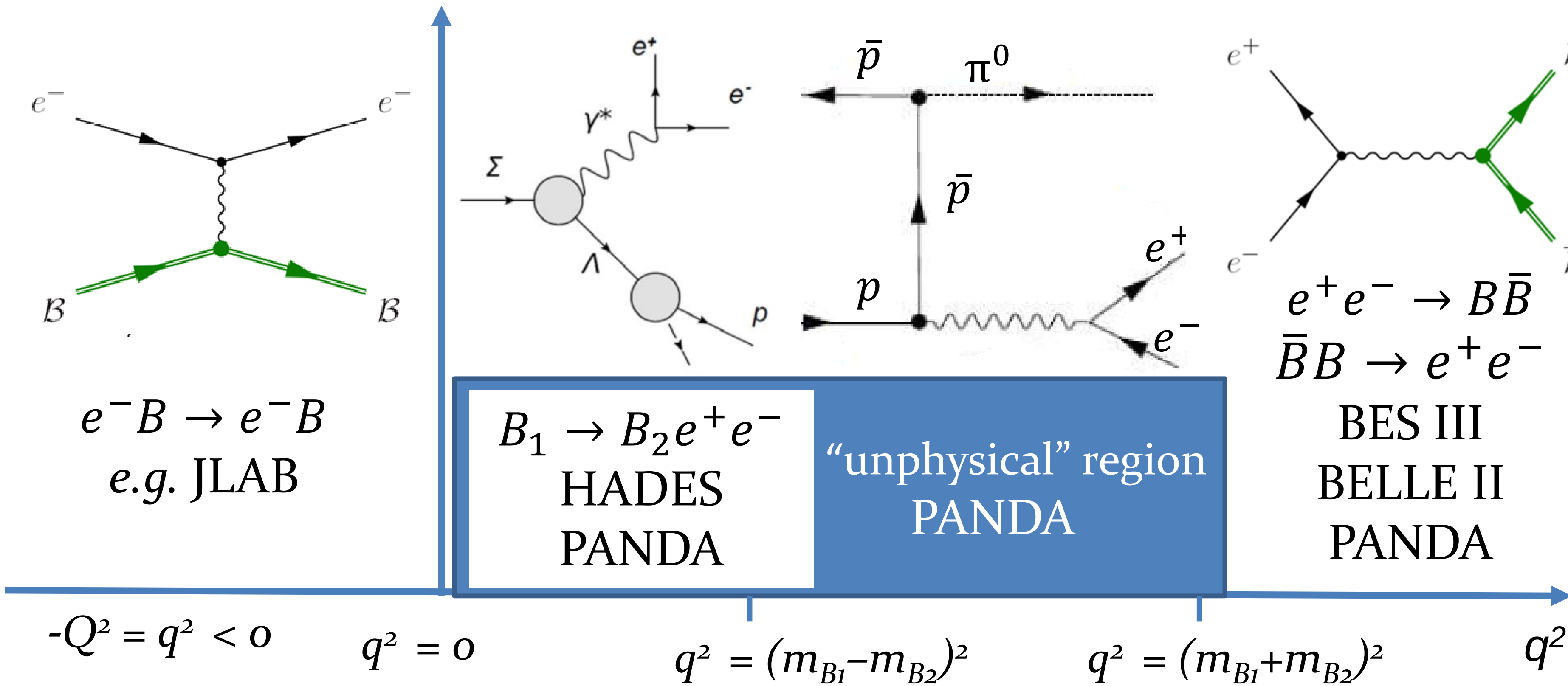
Space-like *vs.* time-like FF's



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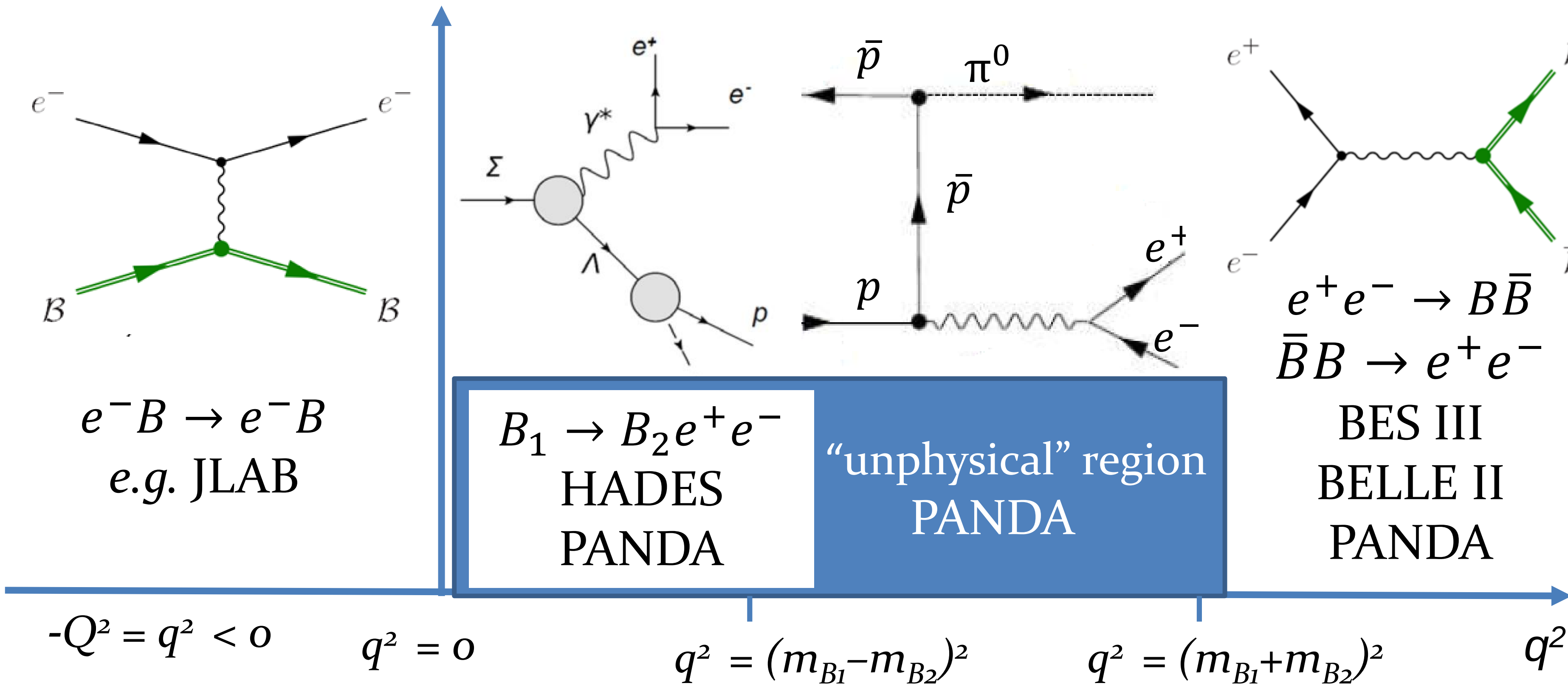
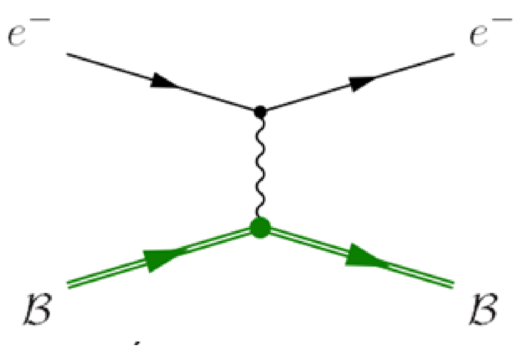
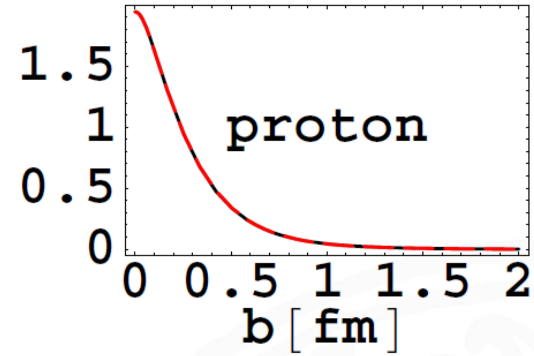


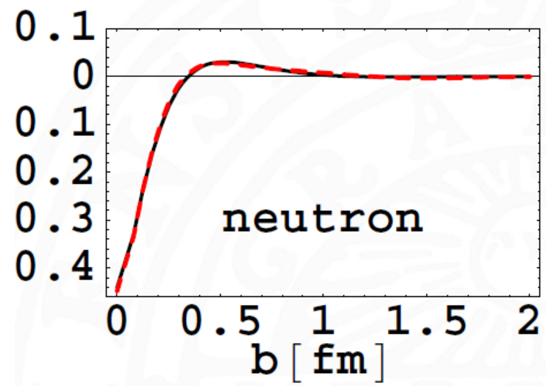
Space-like and time-like are related by dispersion theory!

Electromagnetic Form Factors

- Space-like Sachs FFs G_E and G_M .
  - In Breit frame:
    G_E and G_M
    Fourier transforms of
    charge- and magnetization
    density.







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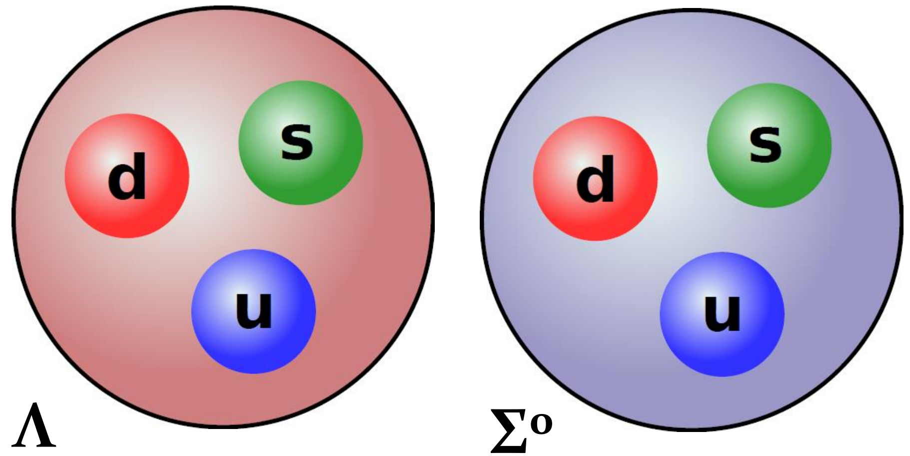
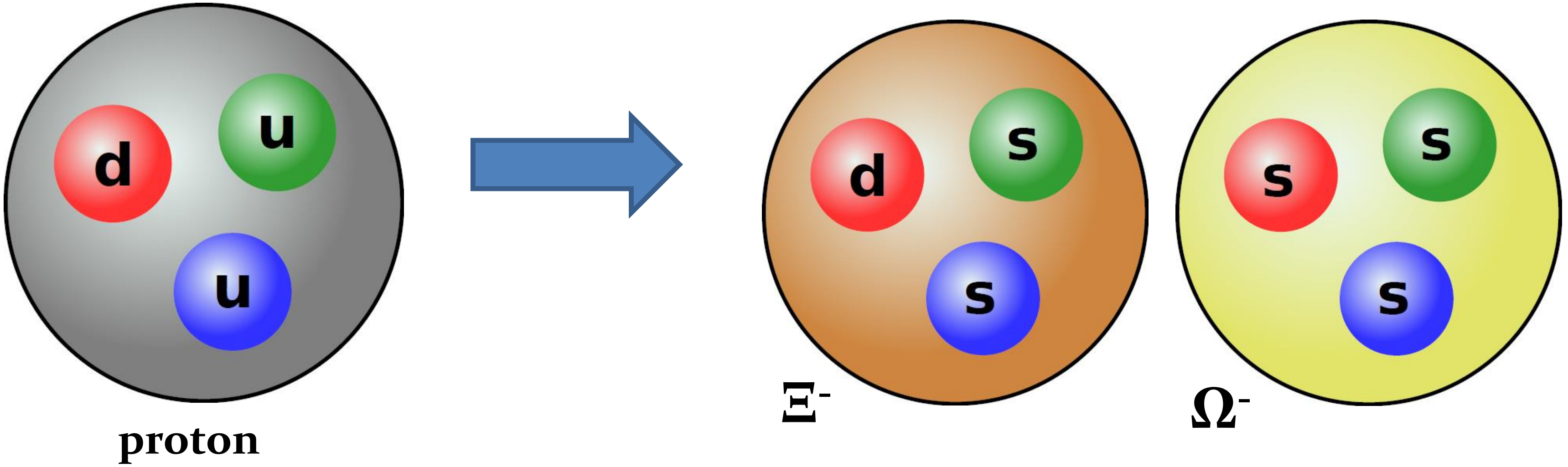
Hyperons

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





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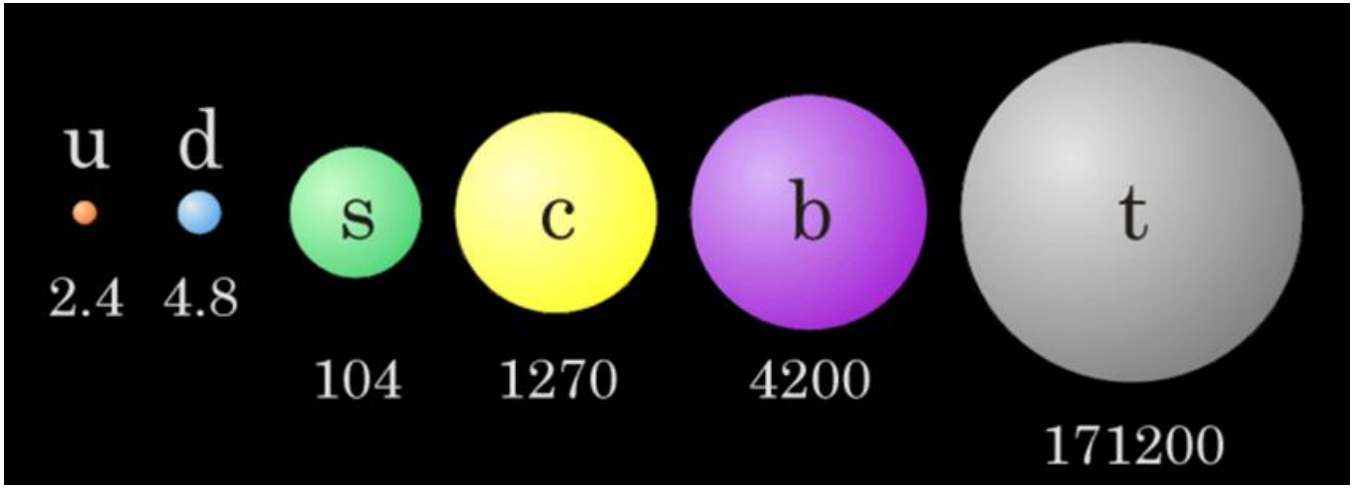
Hyperons

- 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: Quarks and gluons more relevant.
  - **Probes QCD just below pQCD.**



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Hyperons

Traceable spin:

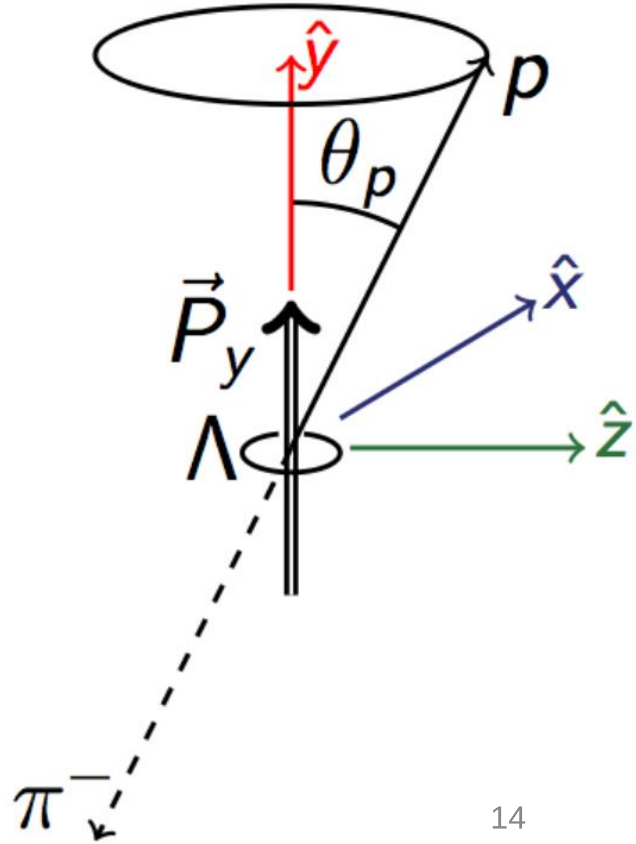
Polarization experimentally accessible by the weak, parity violating decay:

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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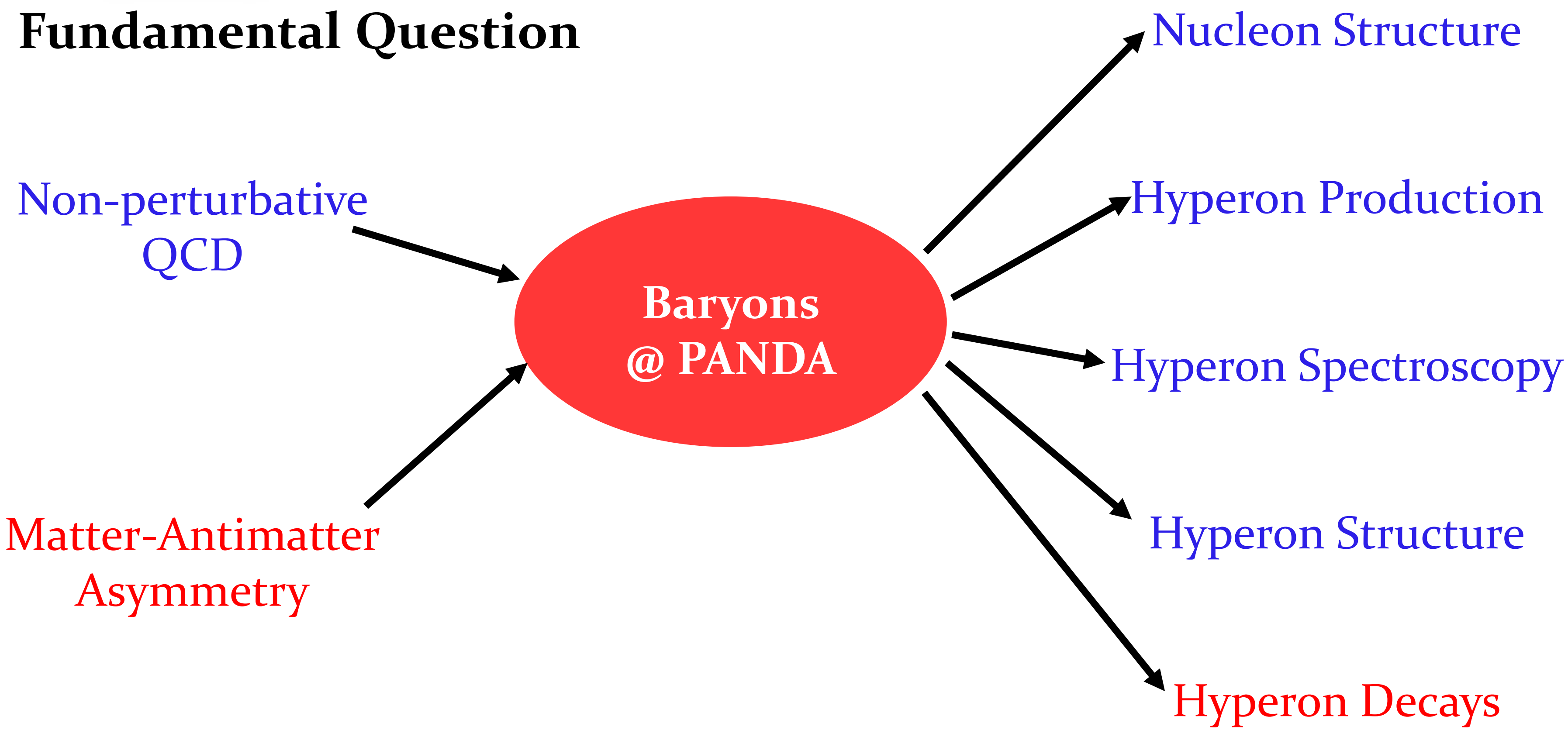
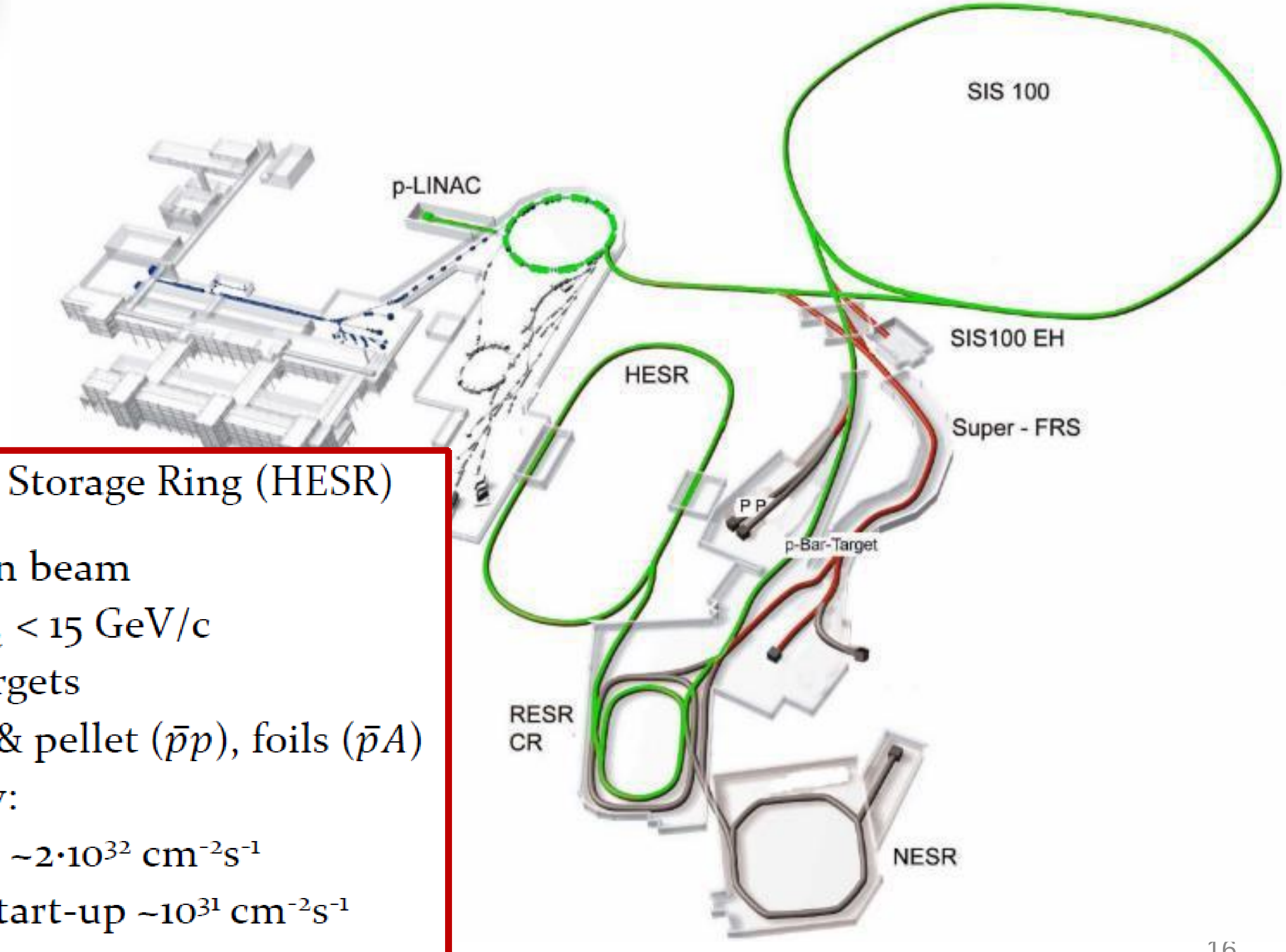
Topic

Fundamental Question



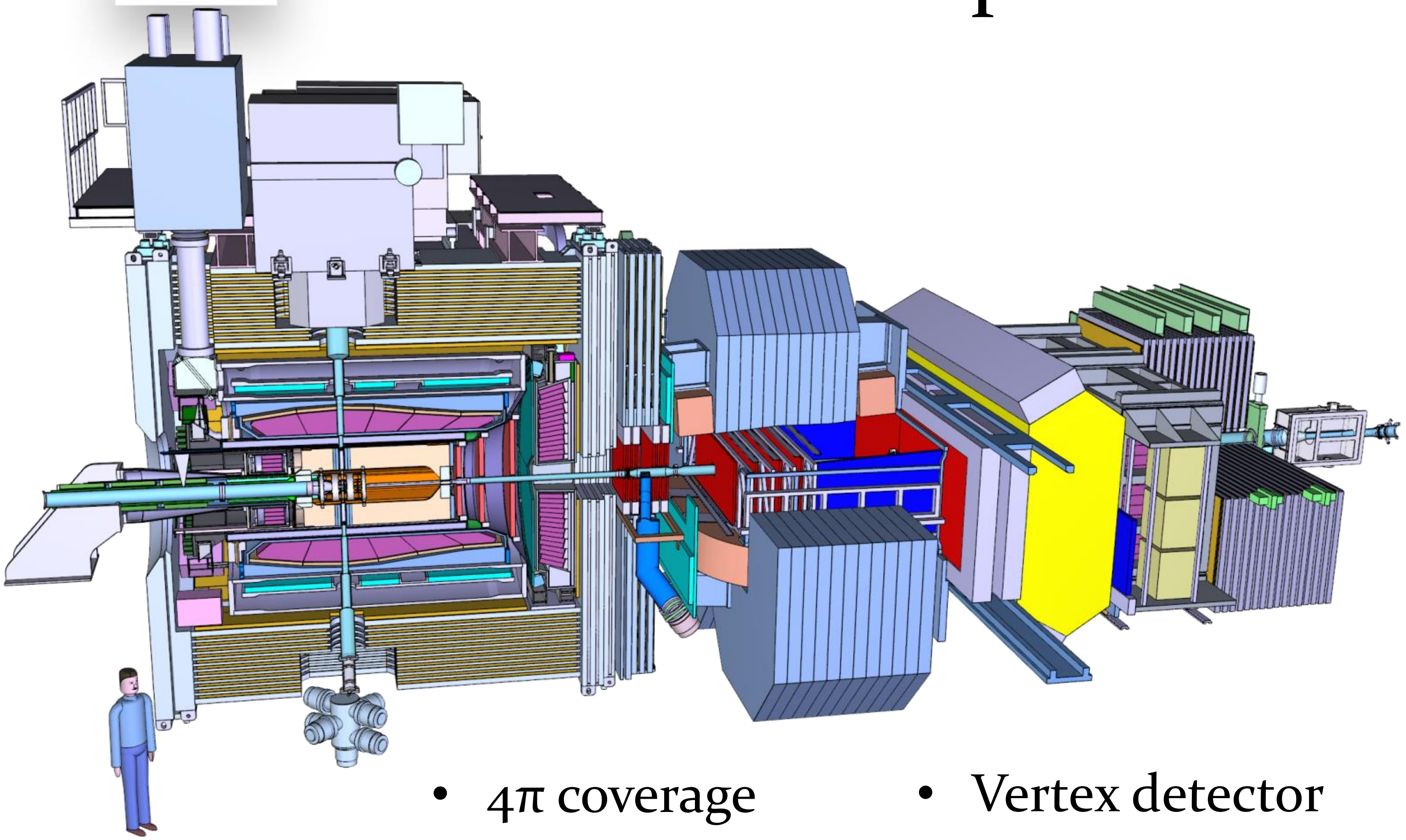
The PANDA experiment at FAIR



High Energy Storage Ring (HESR)

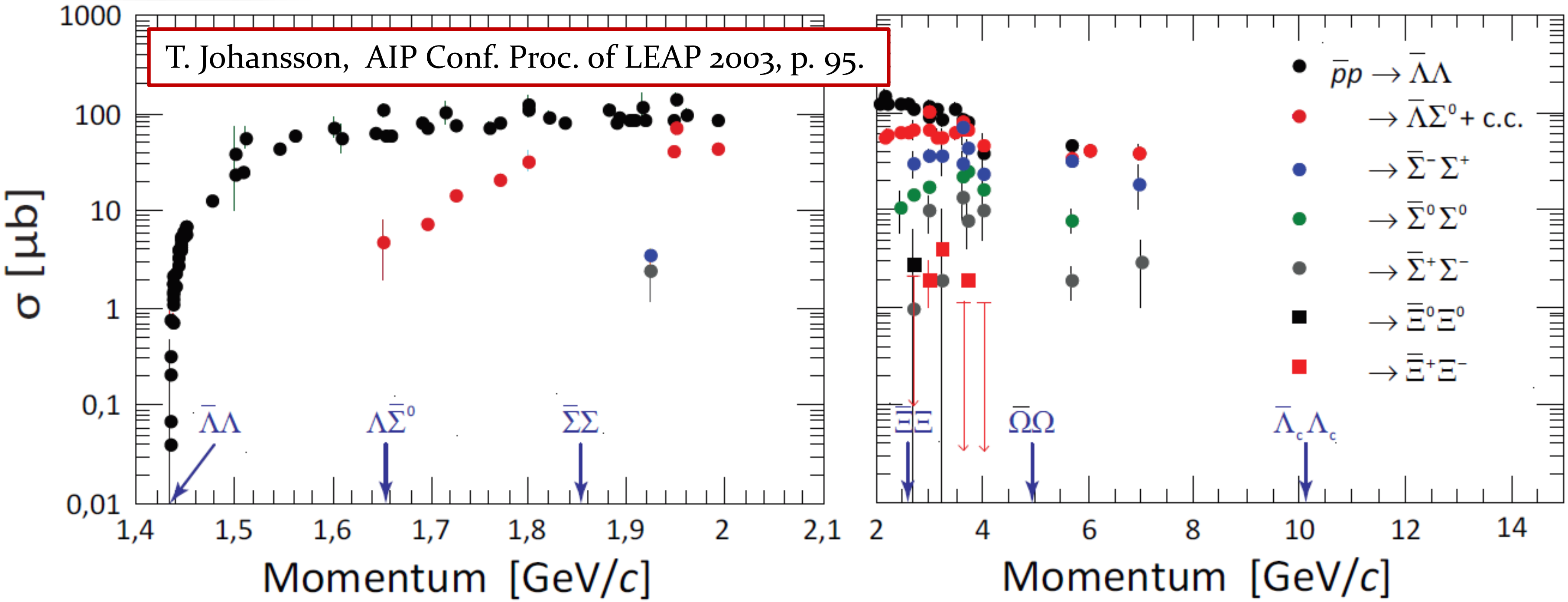
- Anti-proton beam
  $1.5 < p_{beam} < 15$ GeV/c
- Internal targets
  Cluster jet & pellet ($\bar{p}p$), foils ($\bar{p}A$)
- Luminosity:
  - Design ~$2 \cdot 10^{32}$ cm^{-2}s^{-1}
  - FAIR Start-up ~10^{31} cm^{-2}s^{-1}

The PANDA experiment at FAIR



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

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 to be similar to those of ground-states**.

→ Large expected production rates!

* Mainly PS185 @ LEAR. Review by E. Klempt *et al.*, Phys. Rept. 368 (2002) 119-316
**V. Flaminio *et al.*, CERN-HERA 84-01

Advantages of PANDA

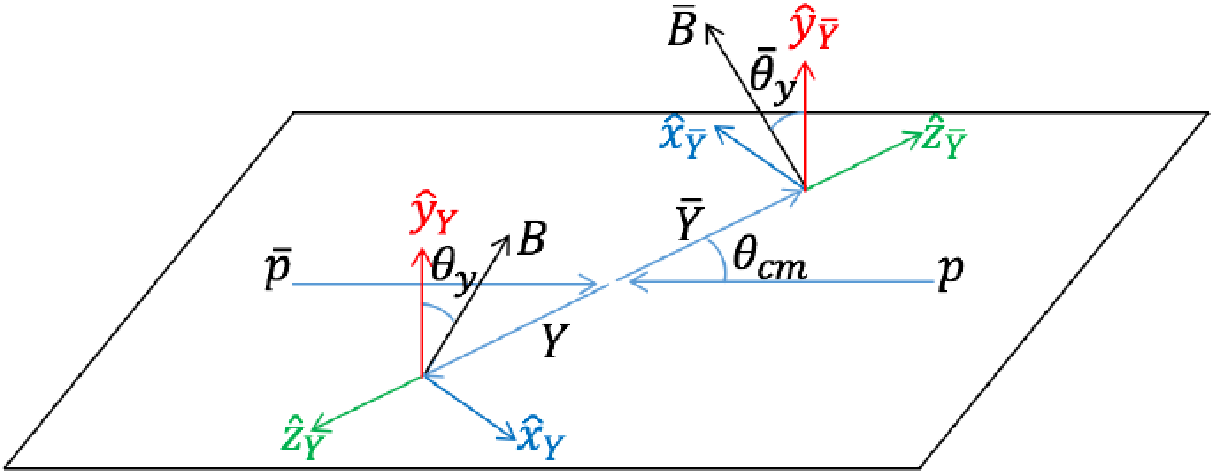
Antipartile – particle pair production:

- Two-body processes

  → well-defined kinematics.

- Symmetric particle-antiparticle final state

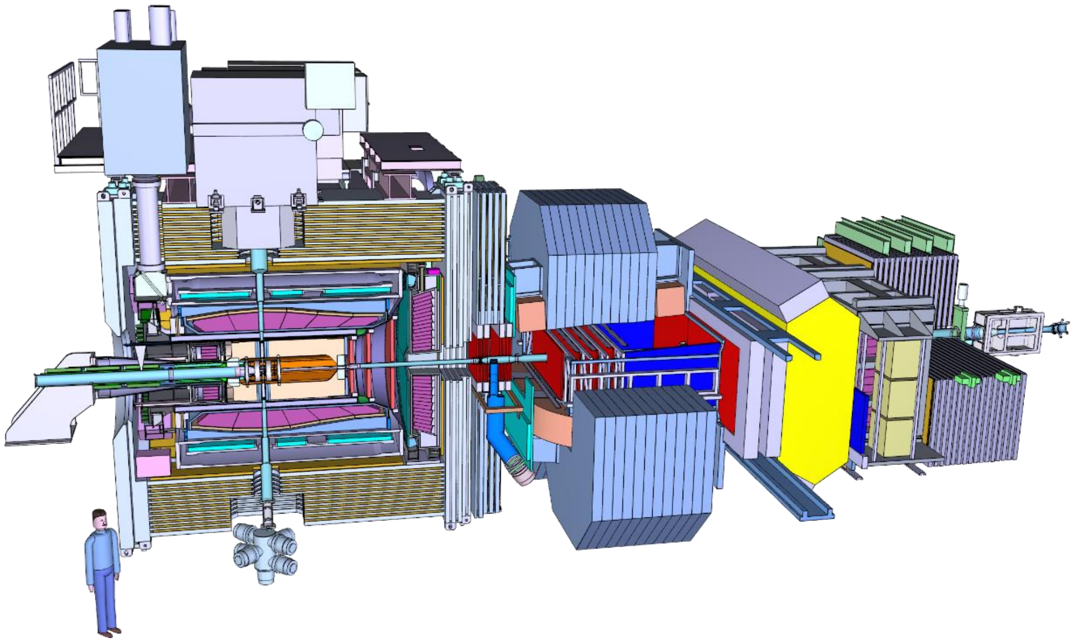
  → controllable systematics.



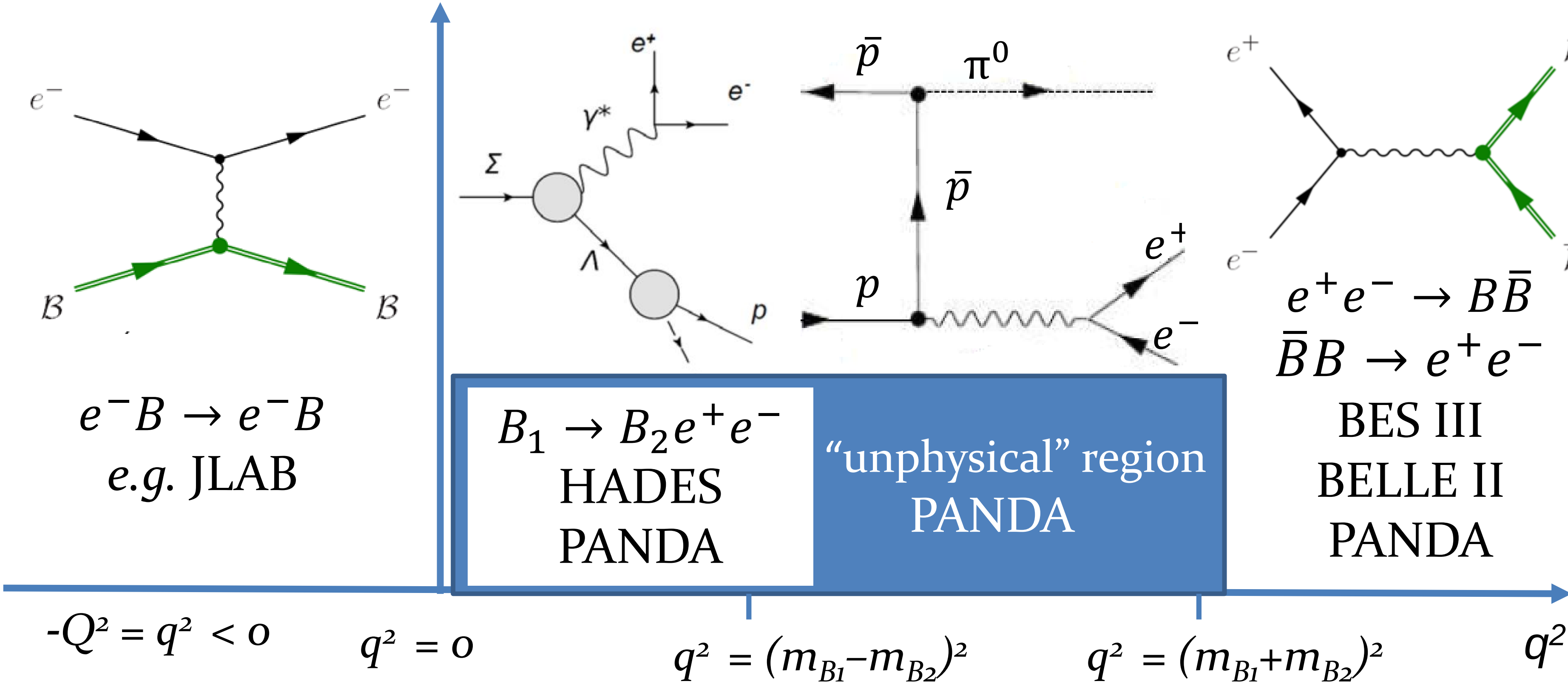
Advantages of PANDA

Near 4π detectors → exclusive measurements:

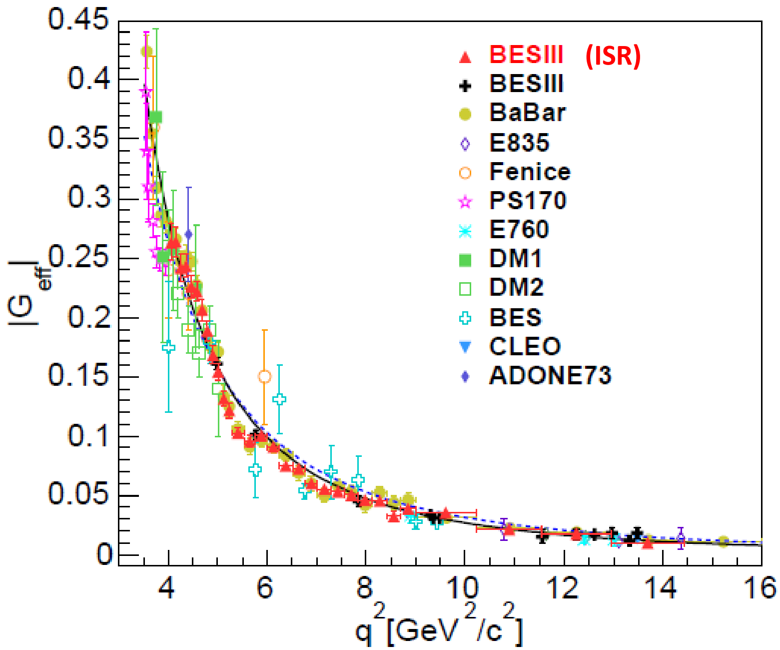
- Larger reconstruction efficiency.
- Smaller reconstruction bias.

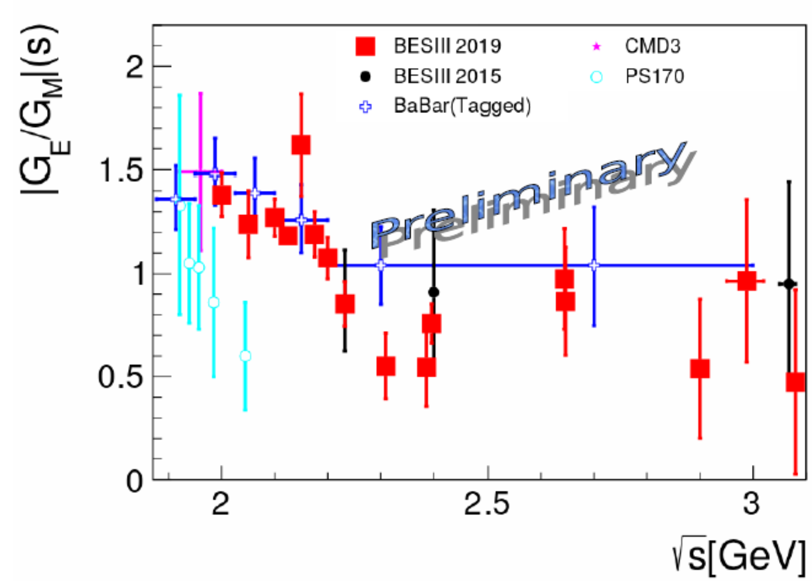


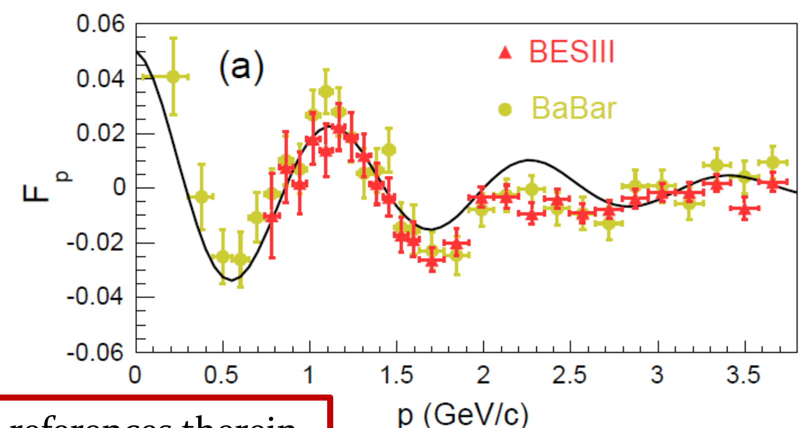
Nucleon Electromagnetic Form Factors



Nucleon Electromagnetic Form Factors





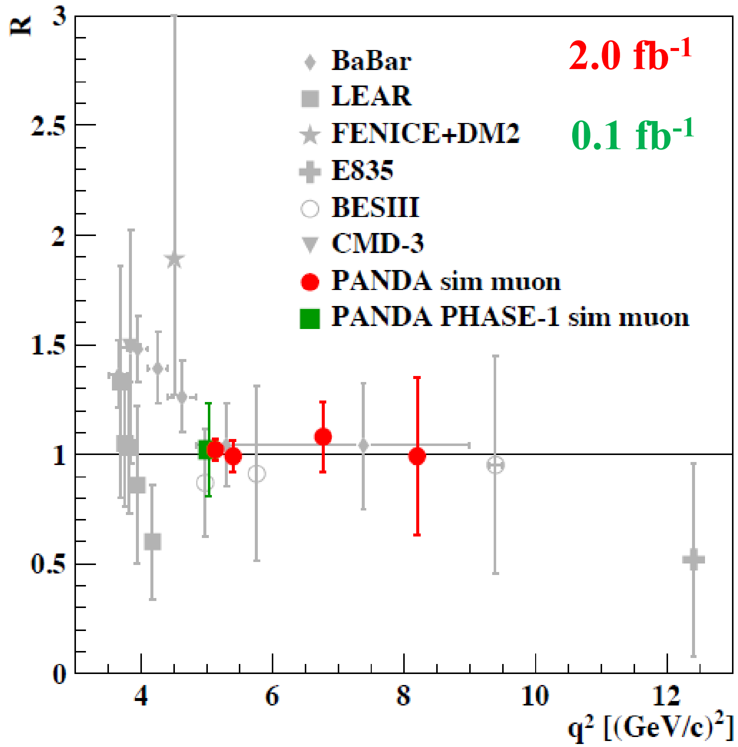


World data in TL region:

- Precision approaching SL region.
- Separation of G_E and G_M at low q^2.
- Oscillating effective form factor.

K. Zhu, Proc. from $\varphi 2\Psi$ 2019, EPJConf. **212**, 07001 (2019) + references therein.

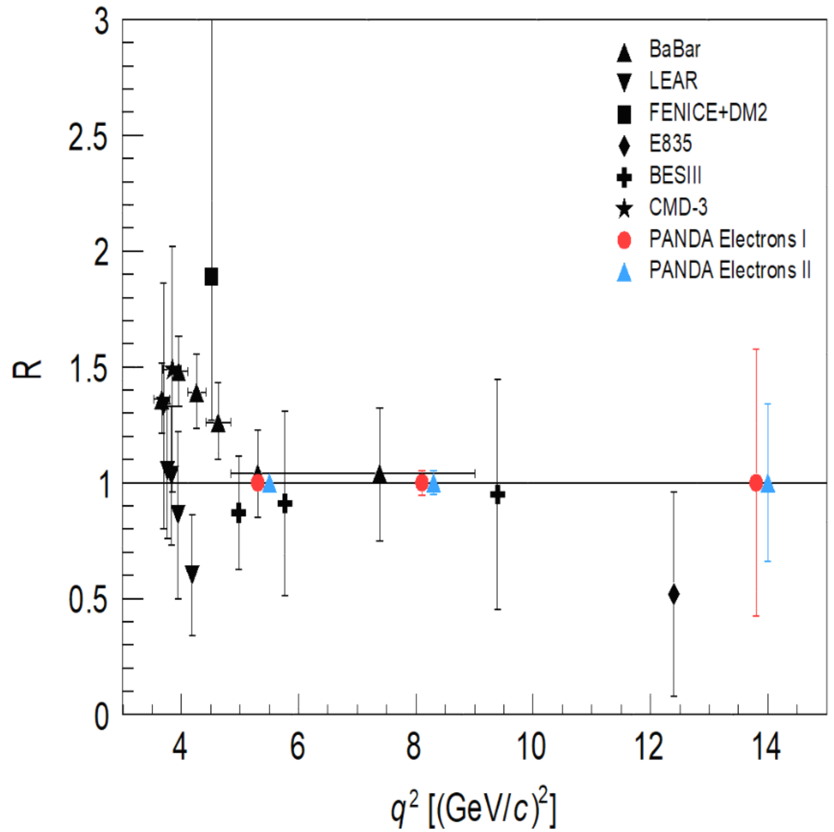
Nucleon EMFFs with PANDA

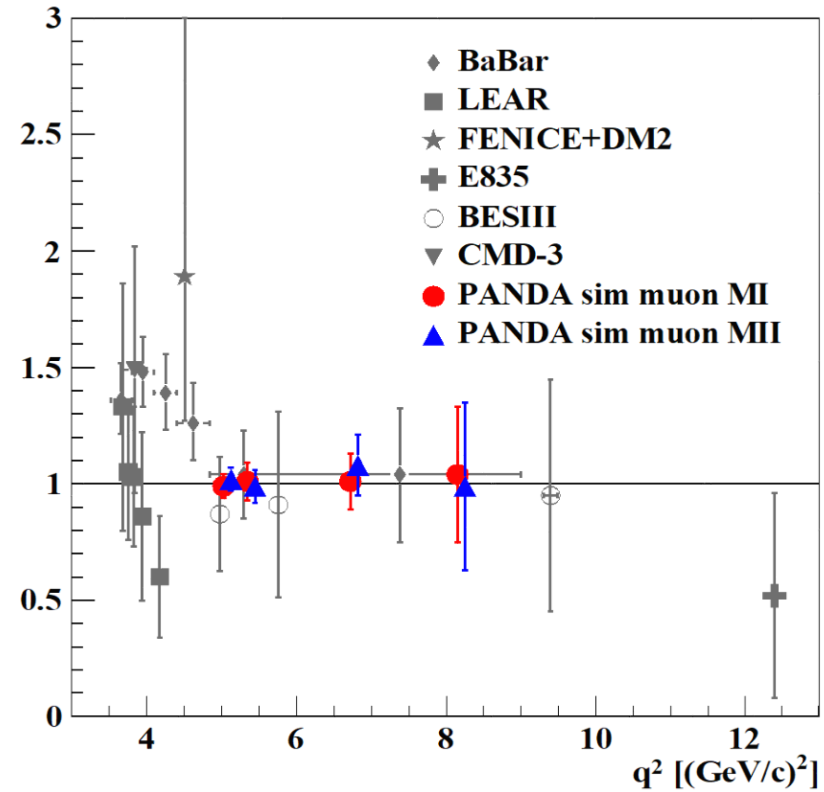


I. Zimmerman *et al.*,, Proc. from
WE-Heraeus Seminar on Baryon Form Factors (2018)

- Possible to study EMFFs in $\bar{p}p \to e^+e^-$ and $\bar{p}p \to \mu^+\mu^-$
  - First measurements of $\bar{p}p \to \mu^+\mu^-$.
  - Enables test of lepton universality.
- Good precision of $R = \ |G_E/G_M|$ already at $L = 0.1\ fb^{-1}$ (Phase 1)

Nucleon EMFFs with PANDA

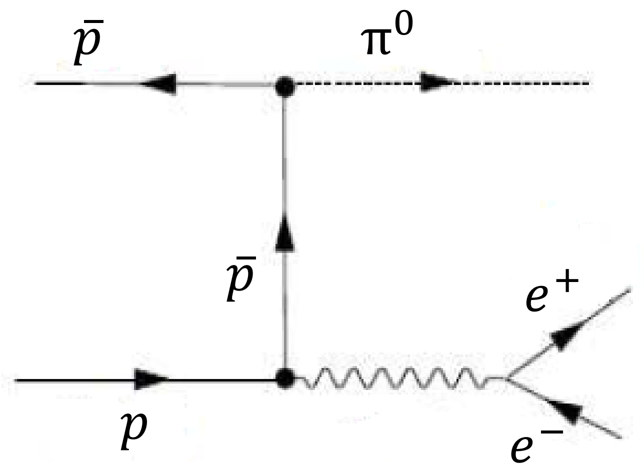




- Unprecedented precision for $L = 2\ fb^{-1}$ of $R = |G_E/G_M|$ at medium q^2.
- Access to high q^2 region.

$\mu^+\mu^-$: I. Zimmerman *et al.*,, Proc. from WE-Heraeus Seminar on Baryon Form Factors (2018)
e^+e^- : EPJA 52 (2016) No. 10, 325.

Nucleon EMFFs with PANDA



"Unphysical" or off-shell region accessible in $\bar{p}p \to \pi^0 e^+ e^-$

- Possible according to preliminary simulation studies*, new underway.
- $\bar{p}p \to \pi^0\gamma$ at q^2, measurable with PANDA, constrain theory models **.
- Further theory development needed.

*J. Boucher, PhD Thesis, U. Paris-Sud XI Orsay and JGU Mainz (2011)
**M.P. Rekalo *et al.*, JNP 1 (1965) 760; A. Z. Dubnickova *et al.*, ZPC 70 (1996) 473-481; C. Adamuscin *et al.*, PRC 75 (2007) 045205.

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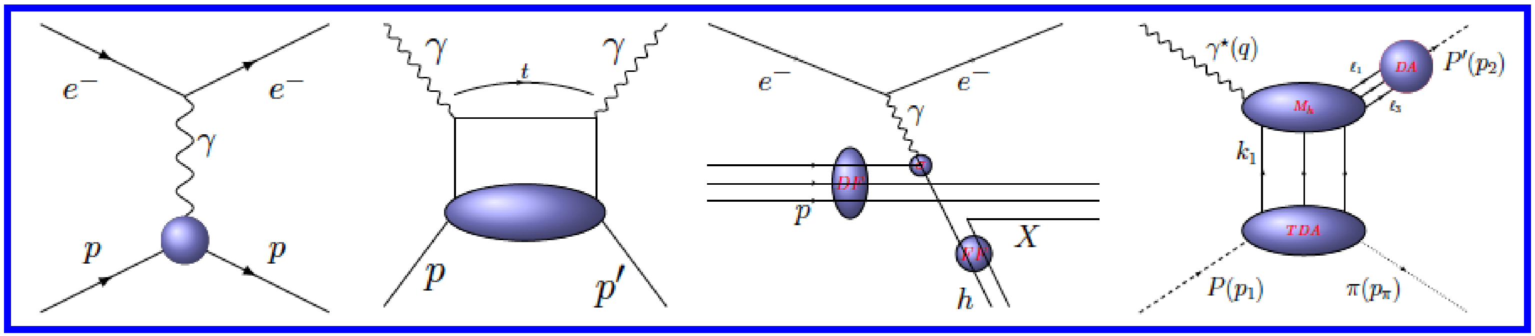
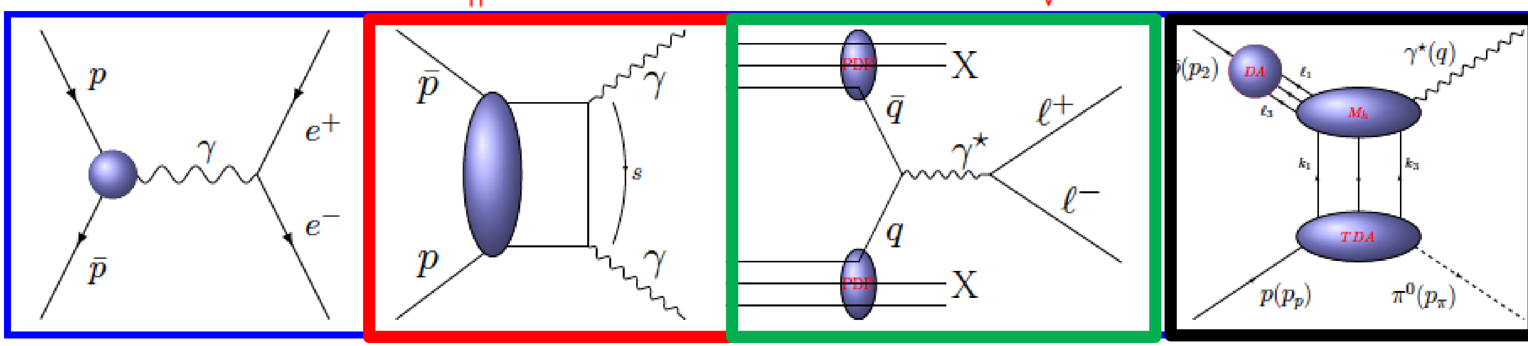
Hard Structure Observables



⇑ CROSSED SYMMETRY ⇓

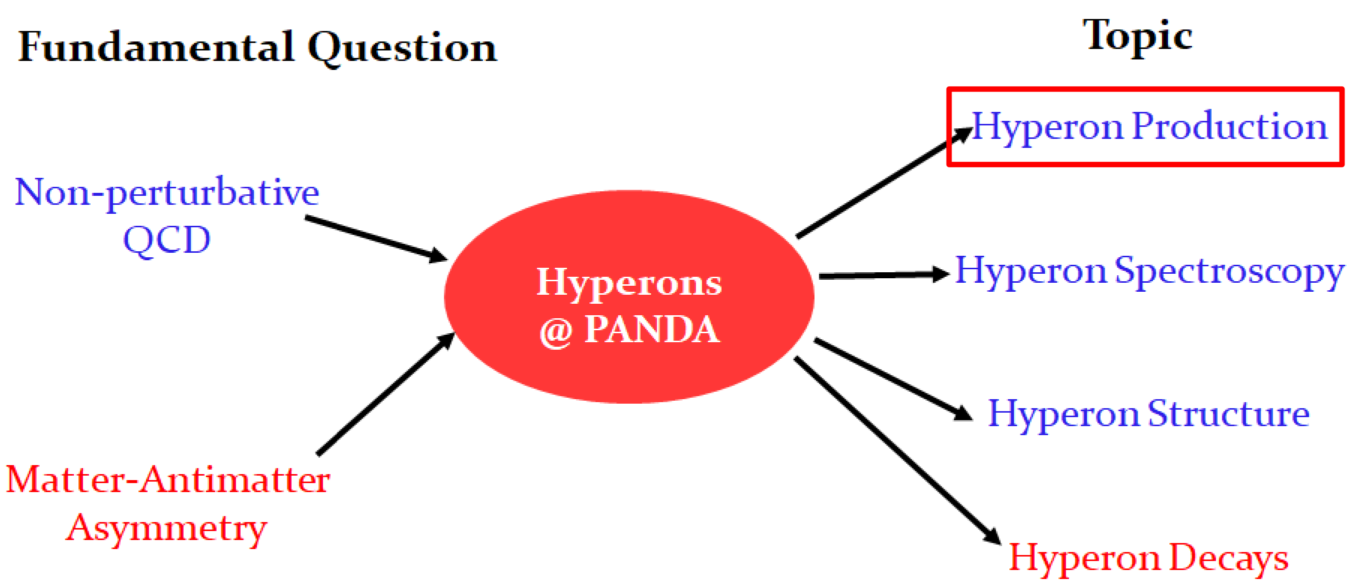


During Phase 3:

- Generalized Distribution Amplitudes **(GDAs)**
- Transverse Momentum Dependent Parton Distributions **(TMD-PDFs)**
- Transition Distribution Amplitudes **(TDAs)***

* EPJA 51 (2015) No. 8, 107.

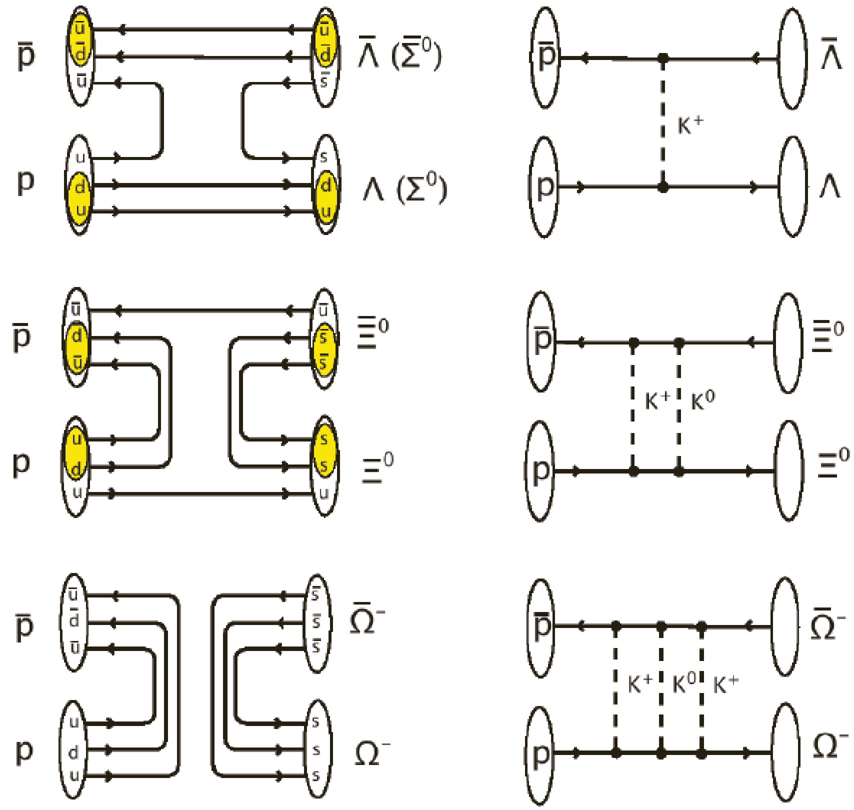
HYPERON PHYSICS IN PANDA



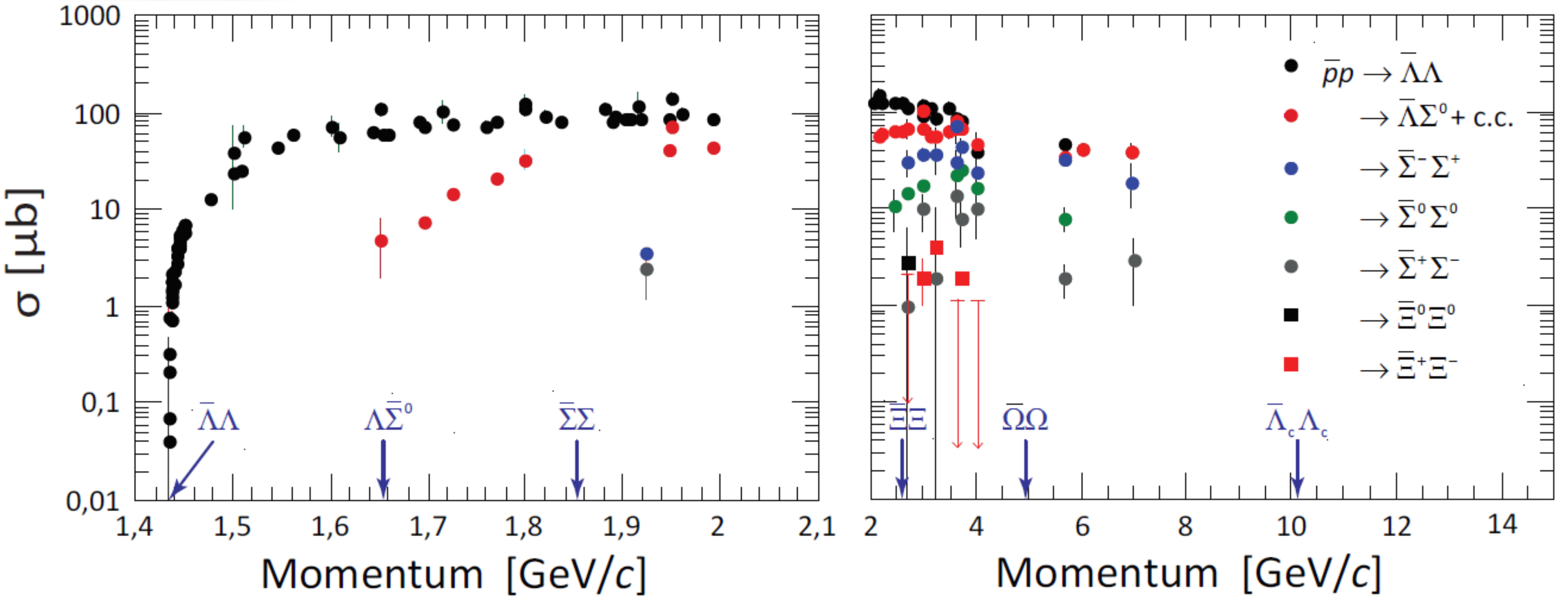
Hyperon production

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.

Hyperon production prospects with PANDA

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

- Exclusive measurements of
  - $\bar{p}p \to \bar{\Lambda}\Lambda, \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$.
  - $\bar{p}p \to \bar{\Sigma}^0\Lambda, \Lambda \to p\pi^-, \bar{\Sigma}^0 \to \bar{\Lambda}\gamma, \bar{\Lambda} \to \bar{p}\pi^+$.
  - $\bar{p}p \to \bar{\Xi}^+\Xi^-, \Xi^- \to \Lambda\pi^-, \Lambda \to p\pi^-, \bar{\Xi}^+ \to \bar{\Lambda}\pi^+, \bar{\Lambda} \to \bar{p}\pi^+$.
- Ideal pattern recognition and PID
- 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 (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^{-1}	274	26000
7.0	$\bar{p}p \to \bar{\Xi}^+\Xi^-$	~0.3	7.9	0.1^{-1}	65	8600

** 90% C.L.

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Hyperon production prospects with PANDA

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  - $\bar{p}p \rightarrow \bar{\Lambda}\Lambda, \Lambda \rightarrow p\pi^-, \bar{\Lambda} \rightarrow \bar{p}\pi^+$.
  - $\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda, \Lambda \rightarrow p\pi^-, \bar{\Sigma}^0 \rightarrow \bar{\Lambda}\gamma, \bar{\Lambda} \rightarrow \bar{p}\pi^+$.
  - $\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-, \Xi^- \rightarrow \Lambda\pi^-, \Lambda \rightarrow p\pi^-, \bar{\Xi}^+ \rightarrow \bar{\Lambda}\pi^+, \bar{\Lambda} \rightarrow \bar{p}\pi^+$.
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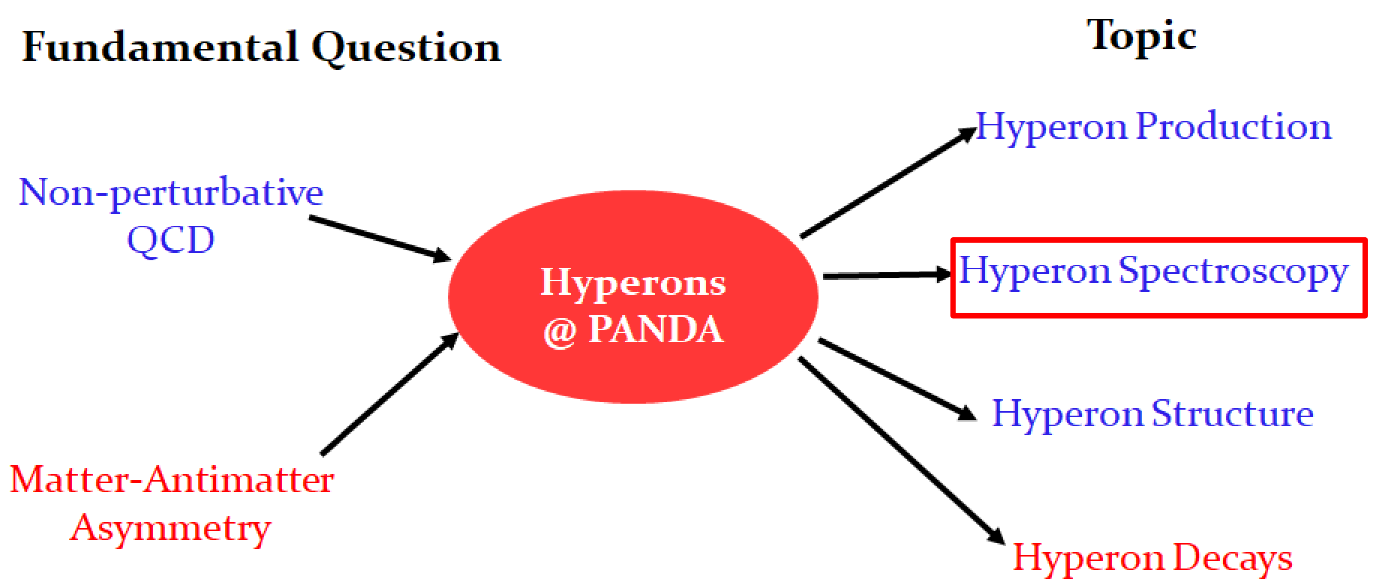
Hyperon factory already during Phase 1!

** 90% C.L.

HYPERON TOPICS IN PANDA



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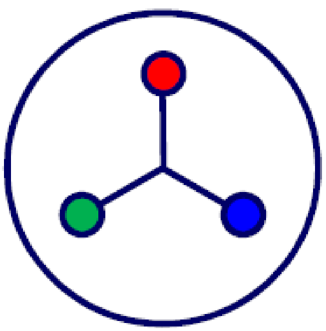
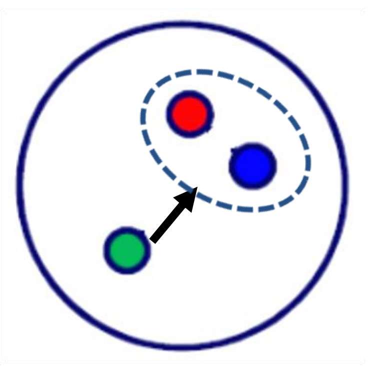
Hyperon Spectroscopy

How do quarks form baryons?

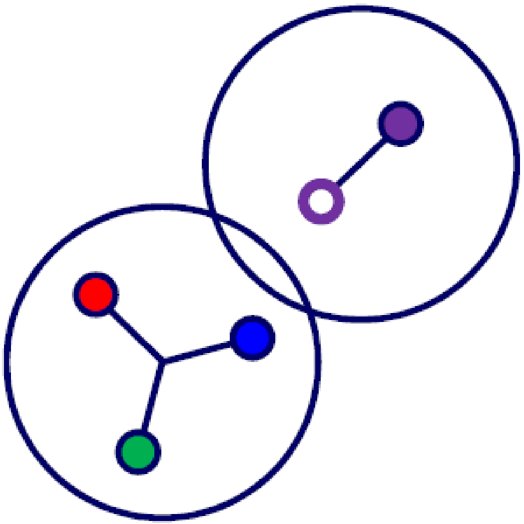
- Forces?
- Degrees of freedom?



Symmetric quark model



Quark - diquark



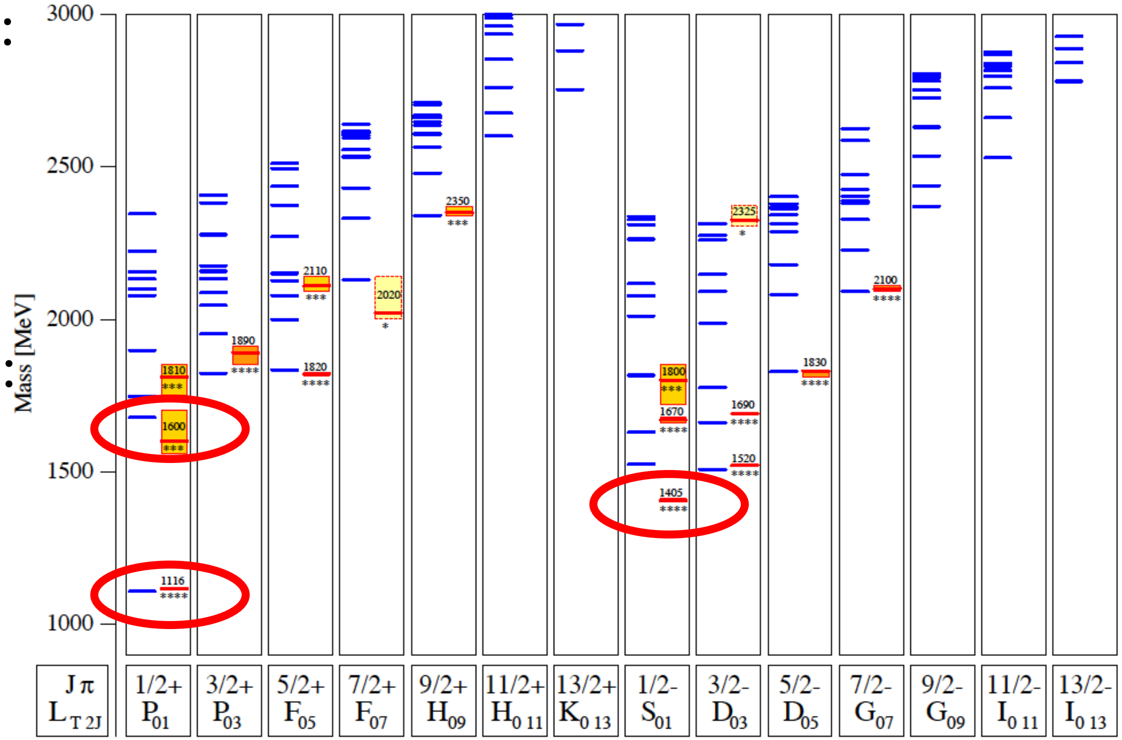
Molecule / hadronic d.o.f.

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

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:

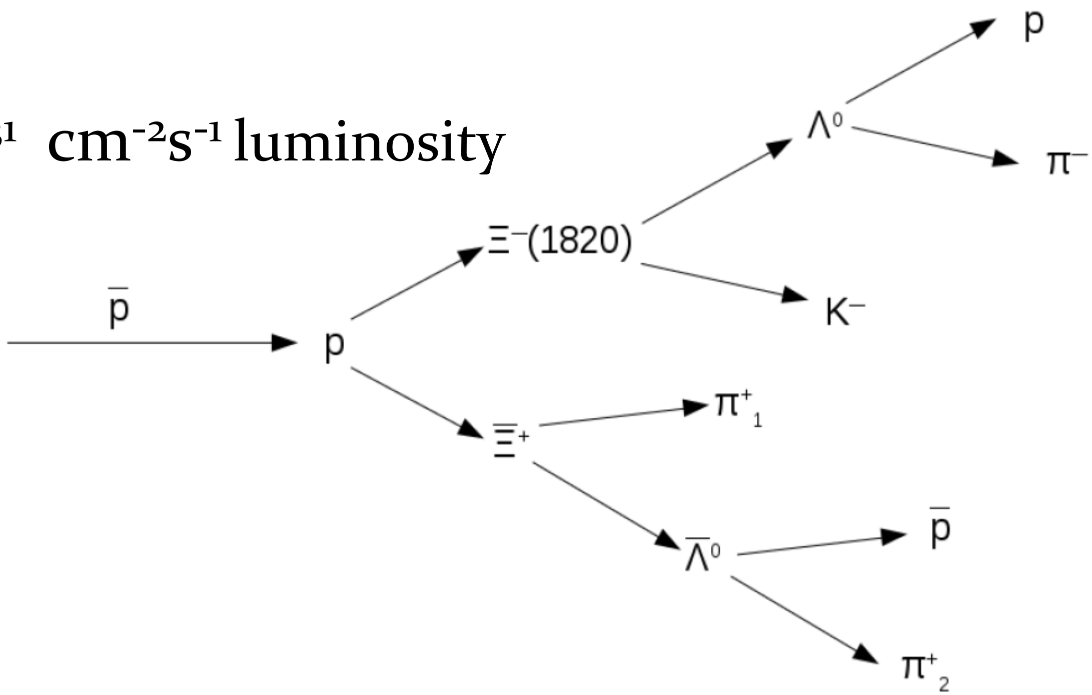
  No model-independent spin measurement.

PDG 2018 →

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

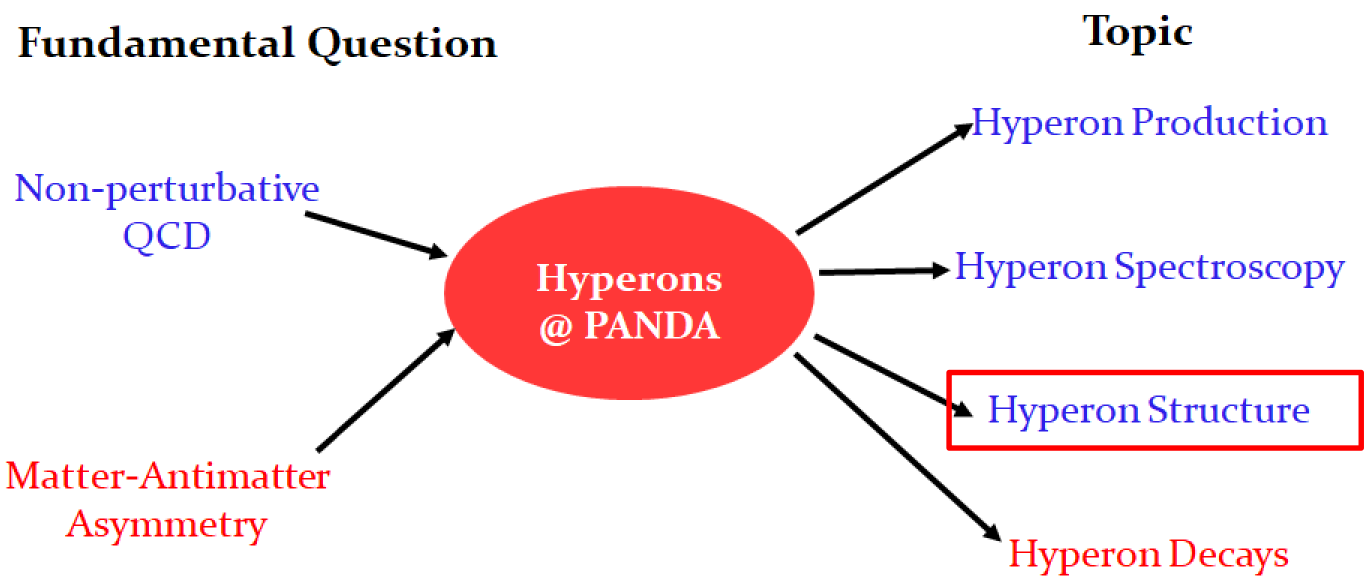
Feasibility study of $\bar{p}p \to \bar{\Xi}^+\Xi^{*-}$

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

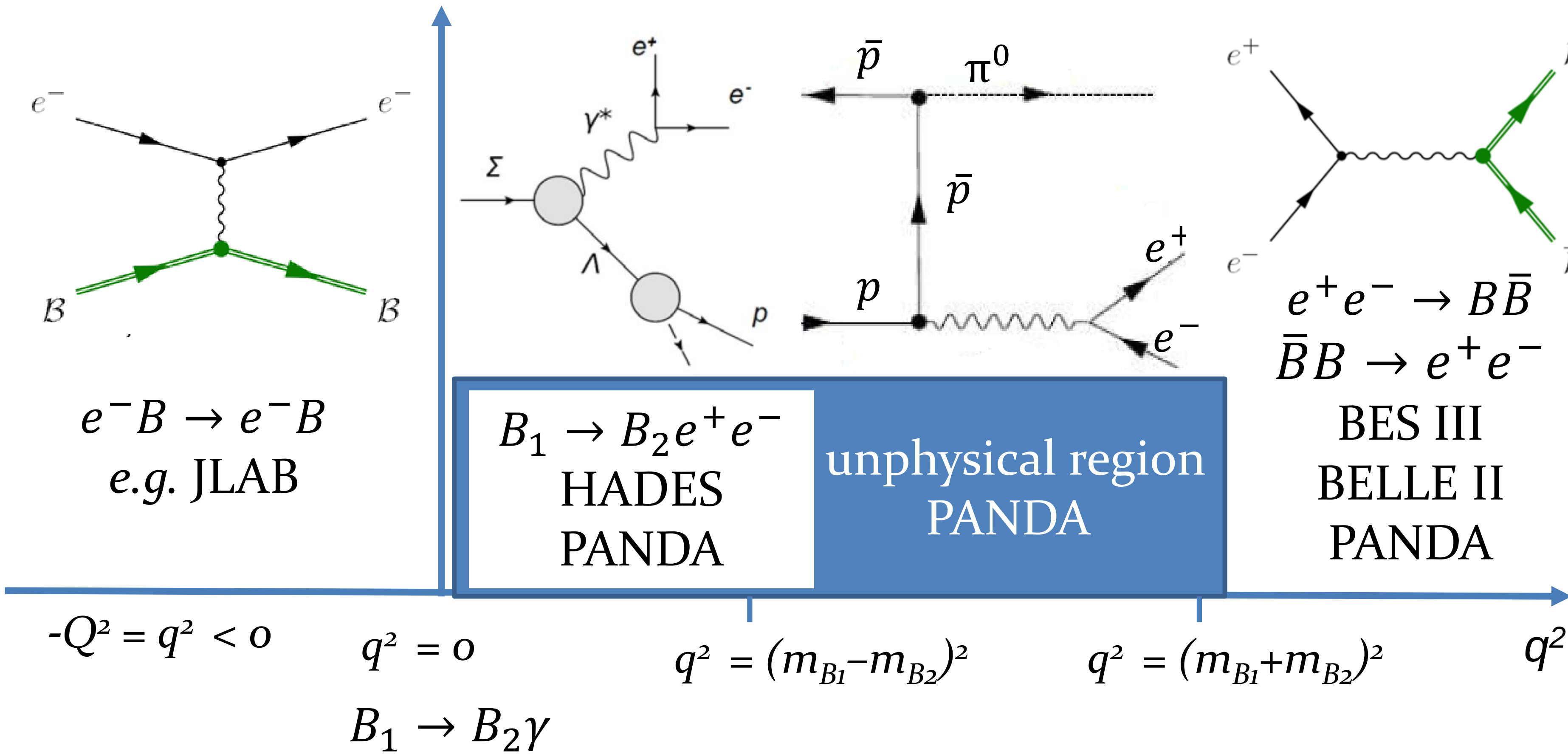


J. Pütz, talk at NSTAR 2019

HYPERON TOPICS IN PANDA

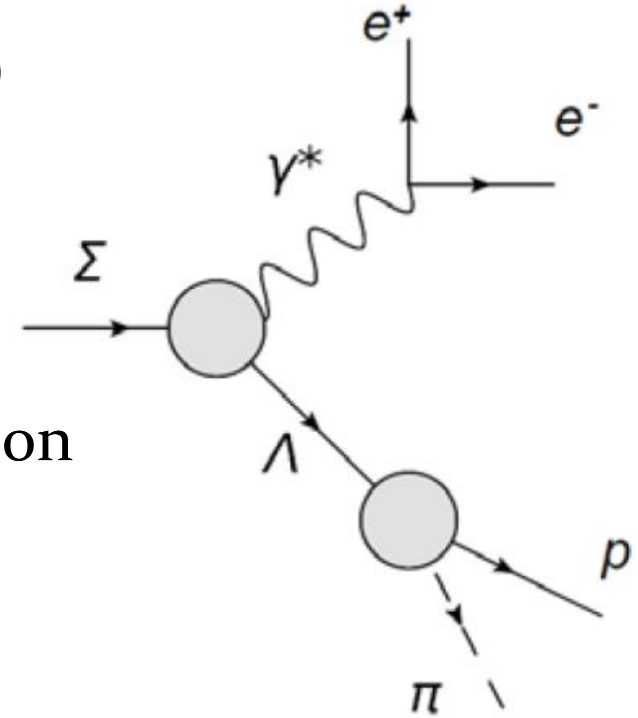


Hyperon Structure

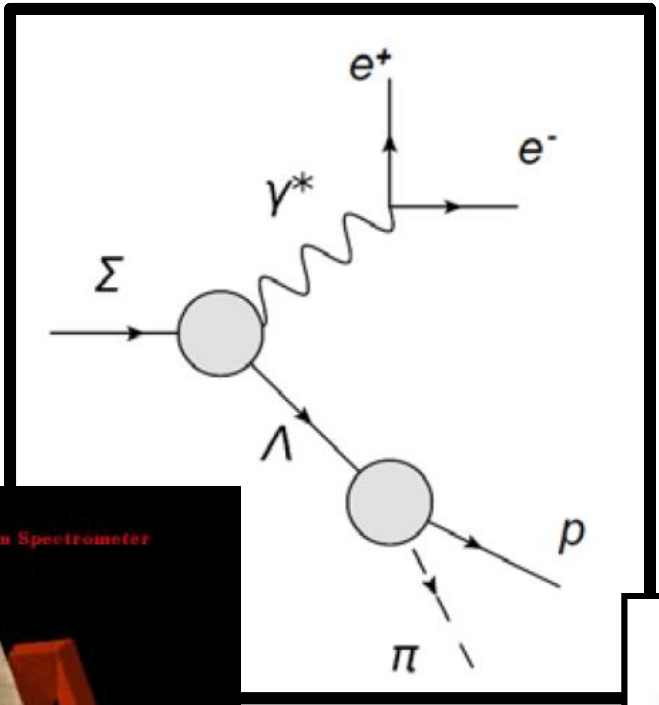


Hyperon structure

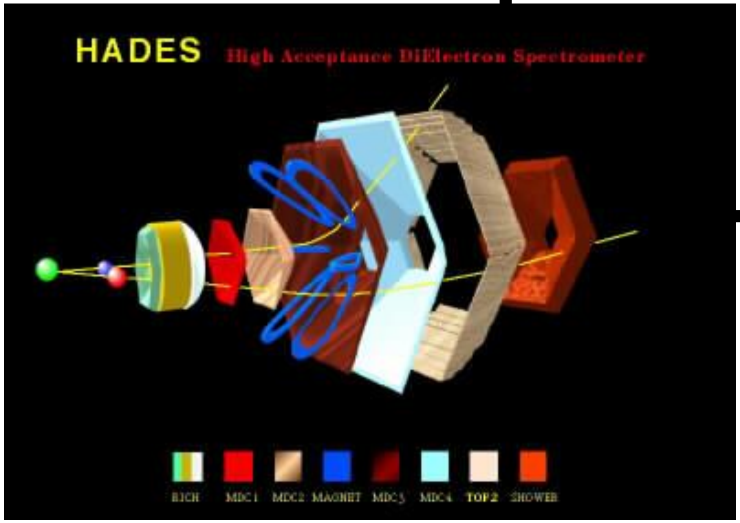
- Transition form factors accessible from Dalitz decays
- Possible in case of *e.g.* Σ^0 and $\Lambda(1520)$
- **Challenge:** Small predicted BR's (10^{-3} - 10^{-6})
- **Good news:** Large hyperon production cross sections.

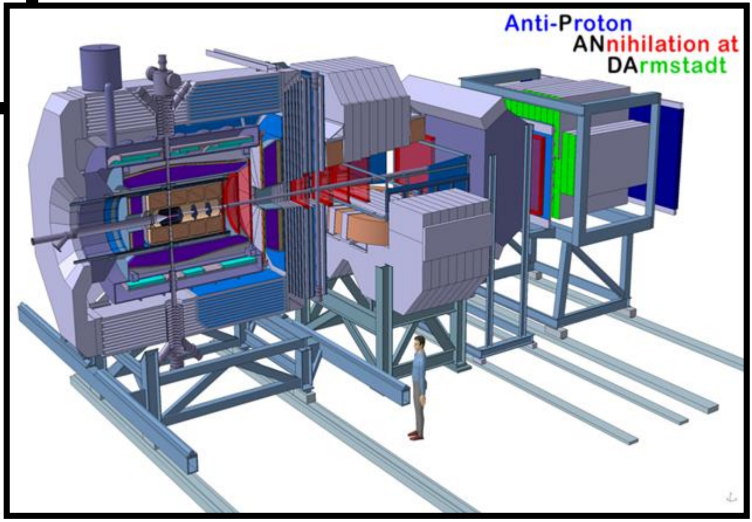


Hyperon Structure

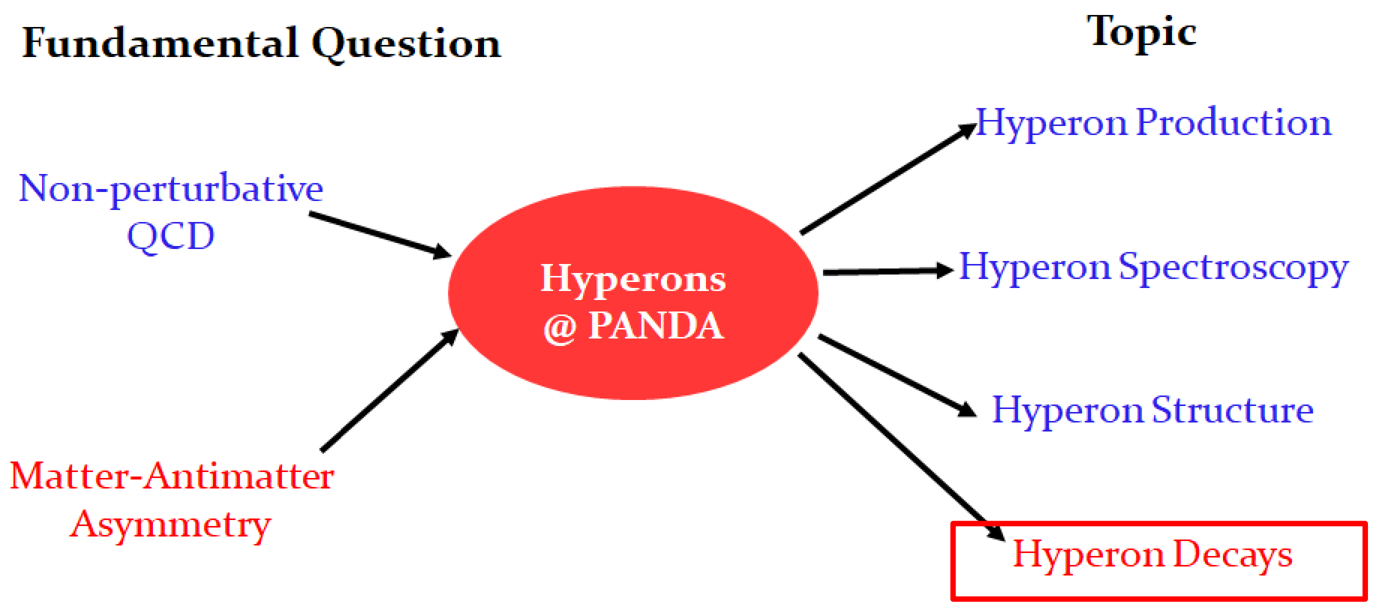


Possible already during Phase 0 with HADES +PANDA FTS!





HYPERON TOPICS IN PANDA



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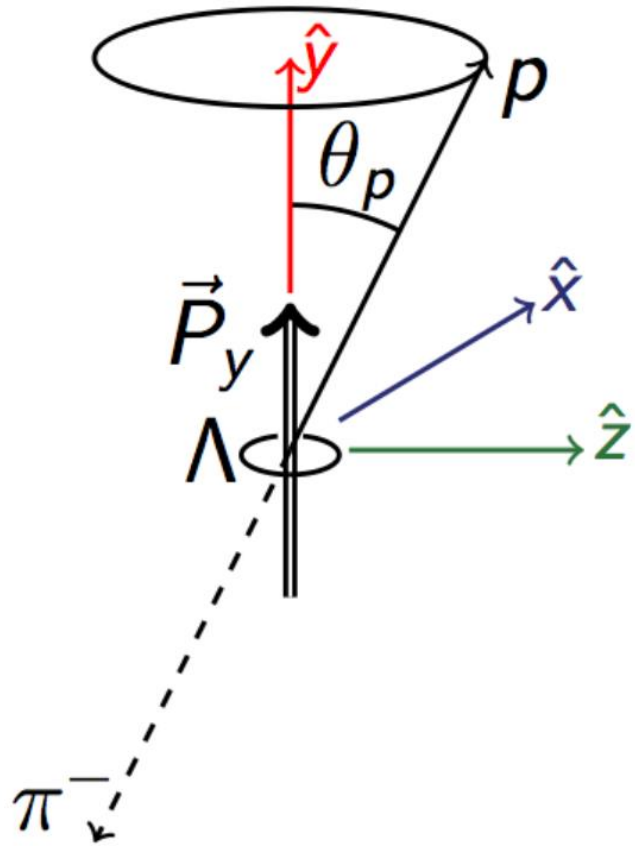
Weak two-body decays

- Parity violating and parity conserving decay amplitudes.
  → interference quantified by decay parameters α, β, γ
  → α accessible in decay
  → β, γ accessible in sequential decays

- CP symmetry:
  $\alpha_-(\Lambda) = -\alpha_+(\bar{\Lambda})$
  $\beta = -\bar{\beta}$ etc.

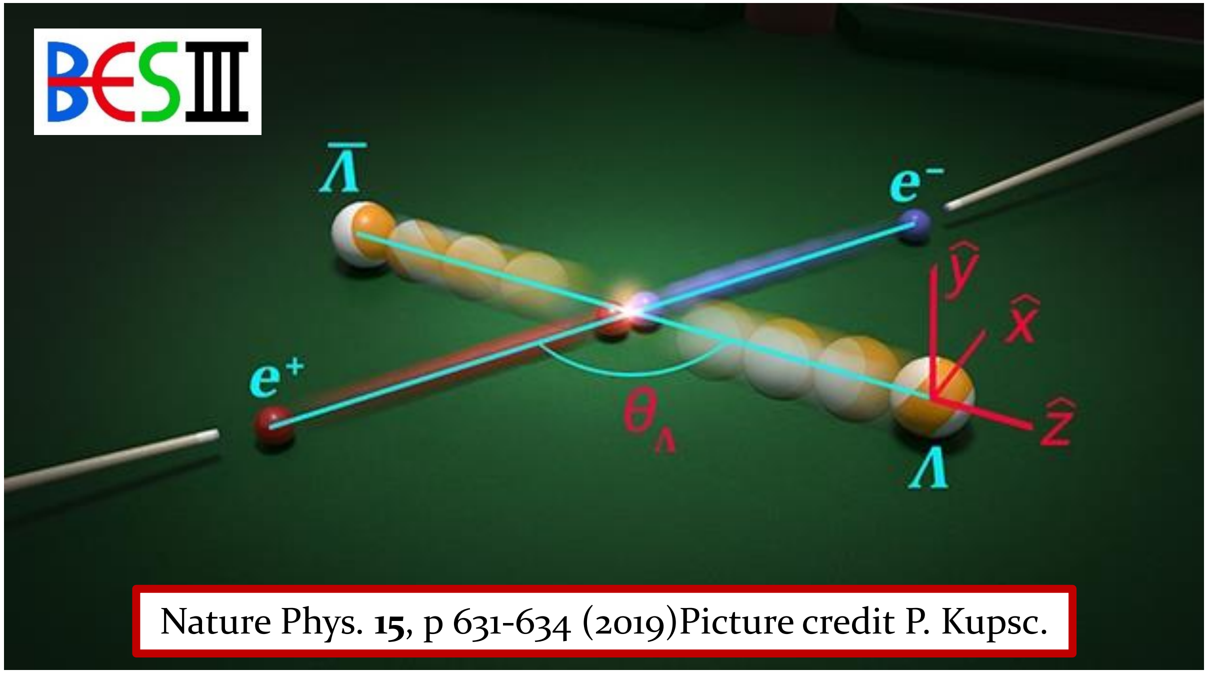
- Clean CP observable defined by *e.g.*:

$$A = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$$



Hyperon Decays

- A_{CP} predictions from SM ~ 10^{-4} - 10^{-5*} ,ChPT 10^{-5**}, SuSy ~10^{-3***}.
- Most precise measurement of $A_{\Xi\Lambda}$ from HyperCP ~10^{-4}.
  - Sample of ~ $4 \cdot 10^7\ \overline{\Xi}^+, 1 \cdot 10^8\ \Xi^-$.
- Most precise measurement of A_Λ from BESIII: A_Λ ~ ~10^{-2}
  - Sample of > $e^+e^- \to J/\Psi \to \Lambda\overline{\Lambda}$ $4 \cdot\ 10^5$ events.



Nature Phys. **15**, p 631-634 (2019)Picture credit P. Kupsc.

* PRD 34 (1986) 833.
** PRD 67 (2003) 056001
*** PRD 61 (2000) 07170
**** PRL 93 (2004) 262001

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Hyperon Decays in PANDA

Phase 3:

HESR design lumiosity = huge $\bar{p}p \rightarrow \bar{Y}Y$ count rates.

p_{beam} (GeV/c)	Reaction	σ (μb)	ε (%)	Rate @ 2·10³² cm⁻²s⁻¹	S/B	Events /day
1.64	$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$	64.0	16.0	880 s^{-1}	114	$7.6 \cdot 10^7$
1.77	$\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda$	10.9	5.3	48 s^{-1}	>11**	$4.1 \cdot 10^6$
6.0	$\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda$	20	6.1	100 s^{-1}	21	$8.6 \cdot 10^6$
4.6	$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	~1	8.2	6 $^{-1}$	274	520 000
7.0	$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	~0.3	7.9	2 $^{-1}$	65	173 000

By W. Ikegami-Andersson (talk at FAIRNESS 2019)
and G. Perez Andrade (Master Thesis, Uppsala 2019)

Baryon physics with PANDA

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

Summary

- Many fundamental questions manifest themselves in the nucleon.
- Strategy 1: Scatter on it!
- Strategy 2: 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 One

  → Rich hyperon physics programme!

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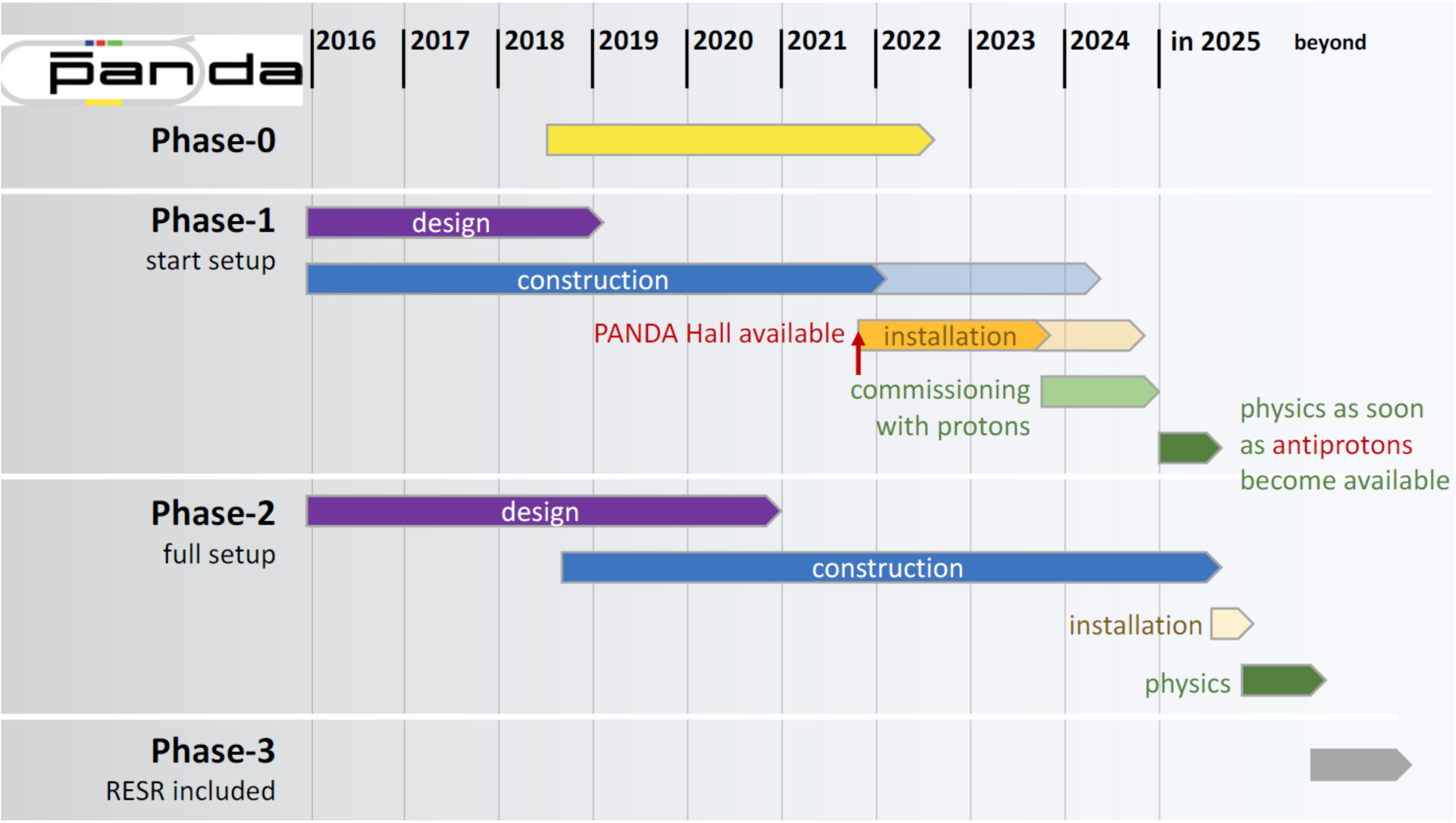
Thanks to:

Jennifer Pütz, Walter Ikegami-Andersson, Gabriela Perez Andrade, Iris Zimmermann, Tord Johansson, Michael Papenbrock,, Alaa Dbeyssi, Jenny Regina and Adeel Akram

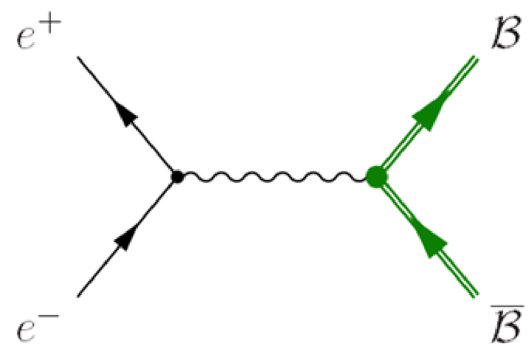
Backup


2016
2017
2018
2019
2020
2021
2022
2023
2024
in 2025
beyond
Phase-0
Phase-1
start setup
design
construction
PANDA Hall available
installation
commissioning
with protons
physics as soon
as antiprotons
become available
Phase-2
full setup
design
construction
installation
physics
Phase-3
RESR included

Time-like form factors

- Time-like FF's are complex →phase $\Delta\Phi(q^2)$ between G_E and G_M .
  - Gives polarized final state*.
  - Straight-forward to access for hyperons, but not nucleons.

- Analyticity requires TL FF ~ SL FF as $|q^2| \rightarrow \infty$ *,***
  - For nucleons, we can measure and compare TL FF and SL FF
  - For hyperons, we can only measure TL FFs, but TL FF = SL FF when $\Delta\Phi(q^2) \rightarrow 0$ for $|q^2| \rightarrow \infty$.



*Nuovo Cim. A **109** (1996) 241.
** Theor. Mat. Fiz. **15** (1973) 332.
*** Phys. Rev. Lett. 31 (1973) 1153.

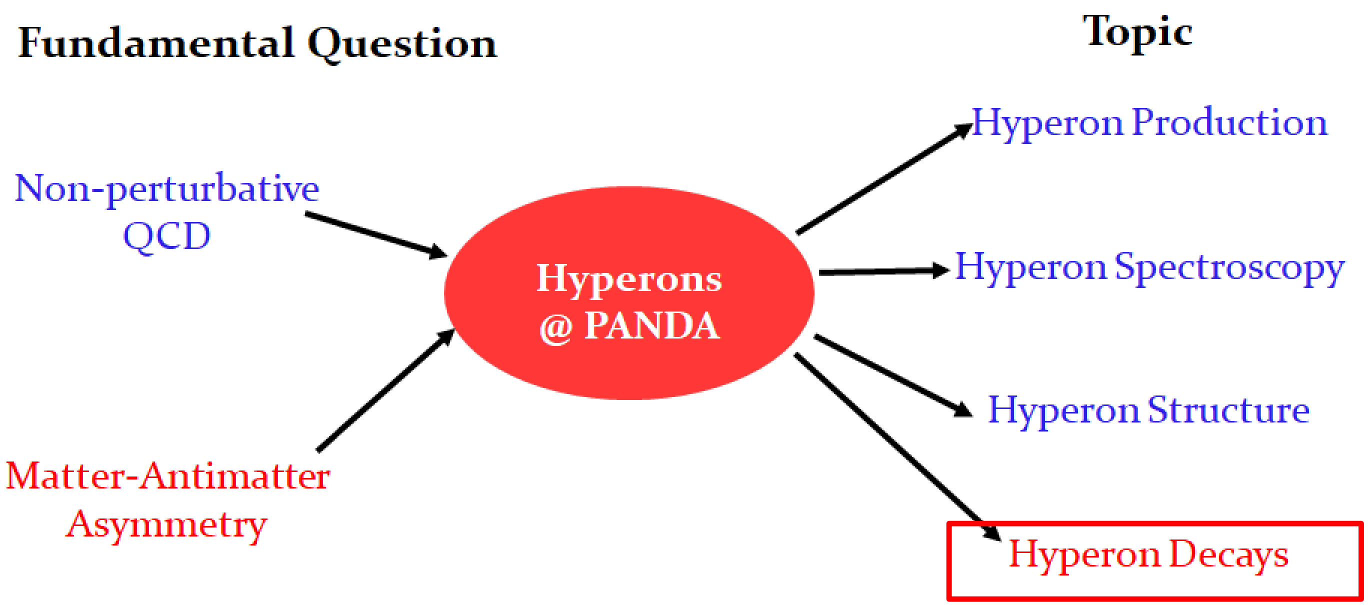
Facilities world-wide

- Previous, ongoing and future activity in N*, Δ and single-strange spectroscopy (*e.g.* CLAS @ JLAB, CBELSA/TAPS, BGO-OD)

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

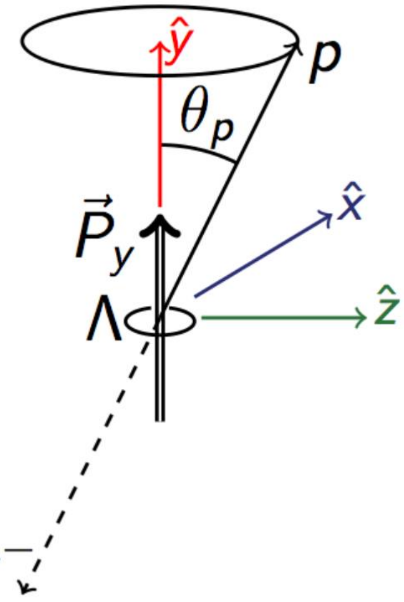
- Gap to fill in the multi-strange sector!

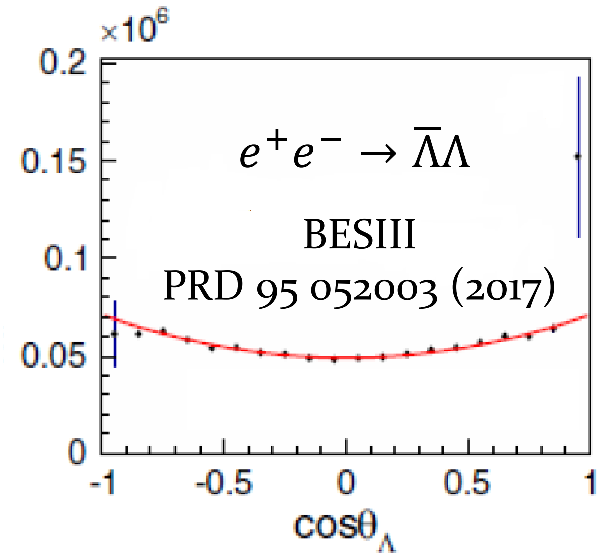
HYPERON TOPICS IN PANDA

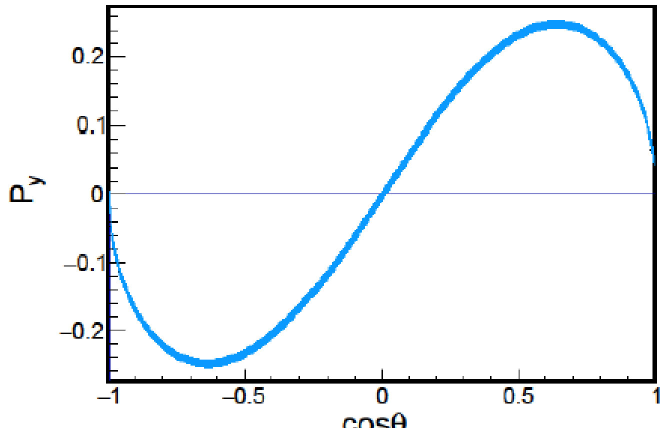


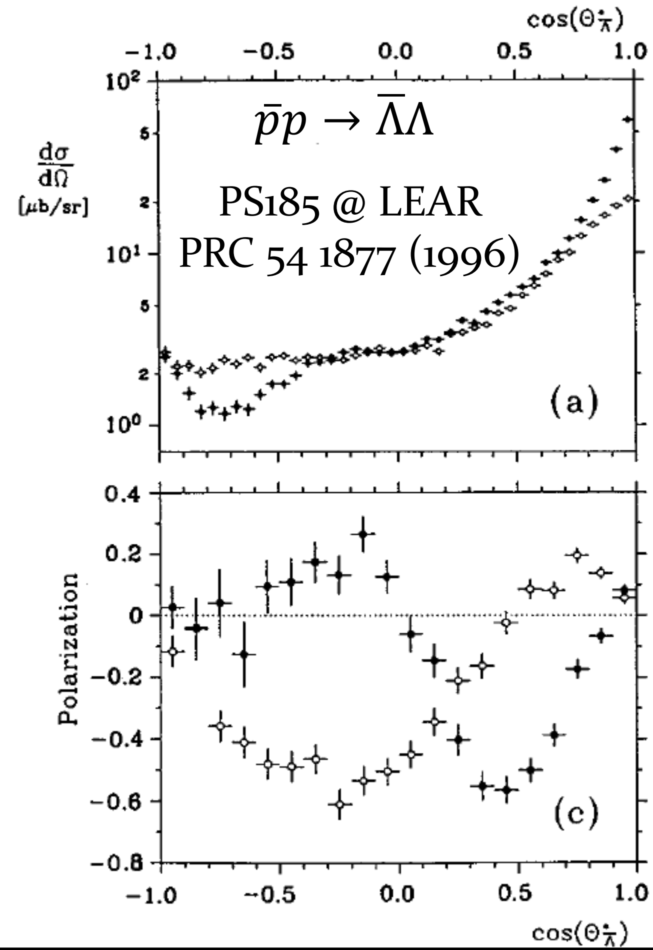
CP violation in hyperon decays

- CP violation in SM insufficient to explain matter-antimatter asymmetry.
- CP violation beyond SM never observed for baryons.
- The $\bar{p}p \rightarrow \bar{Y}Y$ process suitable for CP measurements:
  - Clean, no mixing.
  - Symmetric particle – antiparticle conditions.
- If CP valid, $\alpha = -\bar{\alpha}$ *i.e.* $A_{CP} = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}} = 0.0000 \ldots$









$J^P = 1^-$ 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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Spin analyses in $\bar{p}p$

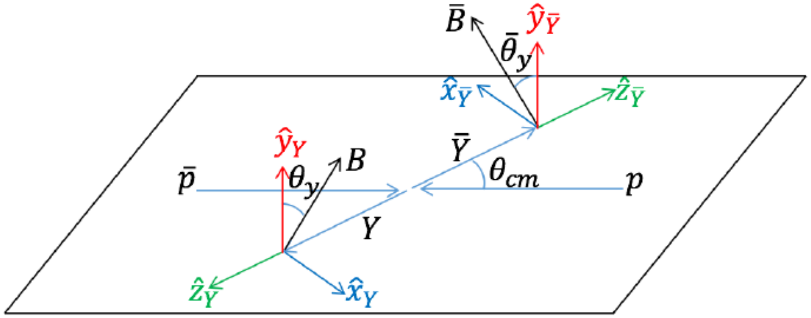
For $\bar{p}p \to \bar{Y}Y \to \bar{B}MB\bar{M}$, the angular distribution at each θ_Y is given by

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

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.



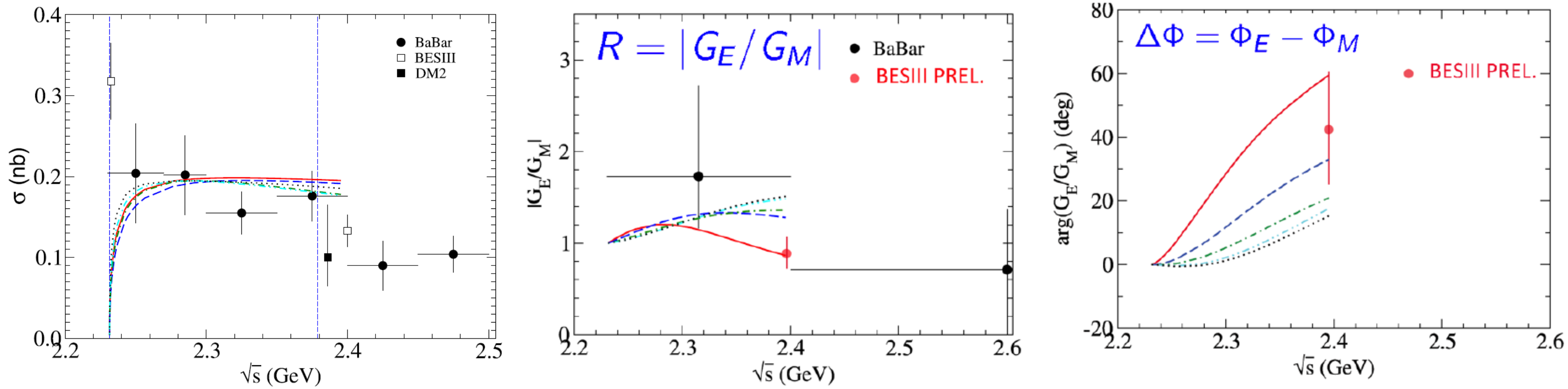
e^+e^- versus $\bar{p}p$

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 magnitide larger at PANDA compared to current e^+e^- experiments

- already during the first phase!

Hyperon production

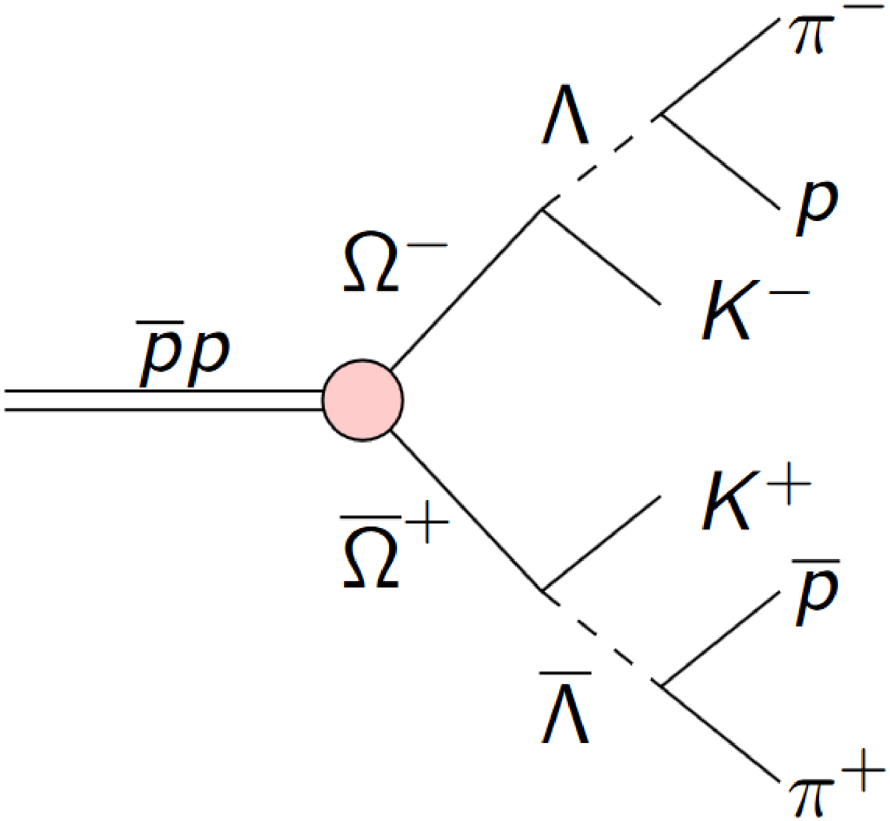


The $\bar{Y}Y$ interaction is important to understand:

- Hyperon structure, studied in $e^+e^- \to \bar{Y}Y$, predicted using potential models obtained with $\bar{p}p \to \bar{Y}Y$ 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 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: $\boldsymbol{r_{-1}^{1}}$, $\boldsymbol{r_{0}^{1}}$ and $\boldsymbol{r_{1}^{1}}$ (P_X, P_Y and P_Z)
- Spin $\frac{3}{2}$: **15** polarisation parameters: $\boldsymbol{r_{-1}^{1}}$, $\boldsymbol{r_{0}^{1}}$, $\boldsymbol{r_{1}^{1}}$, $\boldsymbol{r_{-2}^{2}}$, $\boldsymbol{r_{-1}^{2}}$,$\boldsymbol{r_{0}^{2}}$, $\boldsymbol{r_{1}^{2}}$, $\boldsymbol{r_{2}^{2}}$, $\boldsymbol{r_{-3}^{3}}$, $\boldsymbol{r_{-2}^{3}}$, $\boldsymbol{r_{-1}^{3}}$, $\boldsymbol{r_{0}^{3}}$, $\boldsymbol{r_{1}^{3}}$, $\boldsymbol{r_{2}^{3}}$ and $\boldsymbol{r_{3}^{3}}$.

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 $\rho\left(\frac{3}{2}\right)$:*

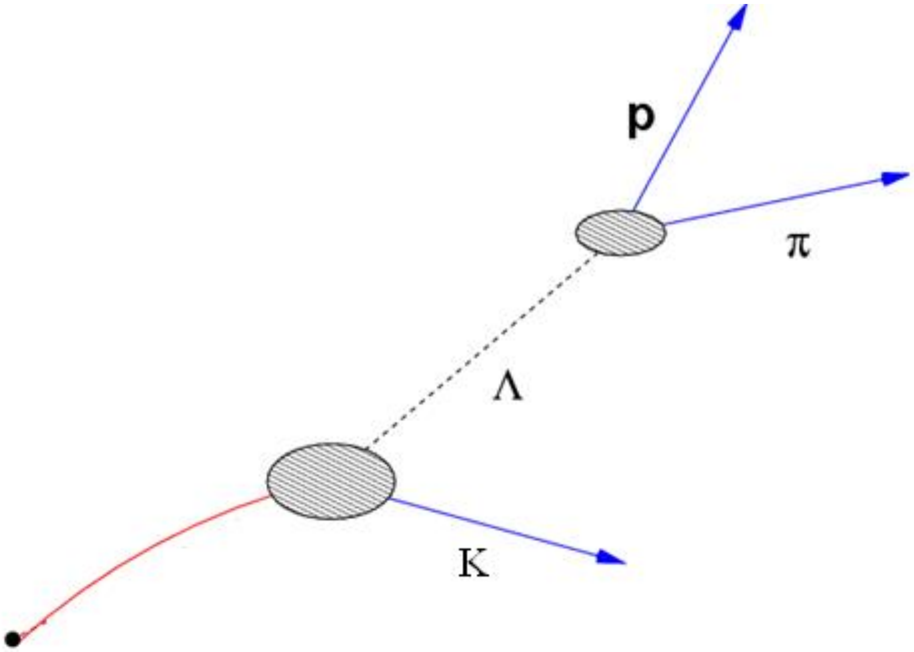
$$\frac{1}{4}\begin{bmatrix} 1+\sqrt{3}r_0^2 & -i\frac{3}{\sqrt{5}}r^1{}_{-1}+\sqrt{3}r_1^2-i\sqrt{\frac{6}{5}}r^3{}_{-1} & \sqrt{3}r_2^2-i\sqrt{3}r^3{}_{-2} & -i\sqrt{6}r^3{}_{-3} \\ i\sqrt{\frac{6}{5}}r^3{}_{-1}+i\frac{3}{\sqrt{5}}r^1{}_{-1}+\sqrt{3}r_1^2 & 1-\sqrt{3}r_0^2 & -i2\sqrt{\frac{3}{5}}r^1{}_{-1}+i3\sqrt{\frac{2}{5}}r^3{}_{-1}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

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

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

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

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

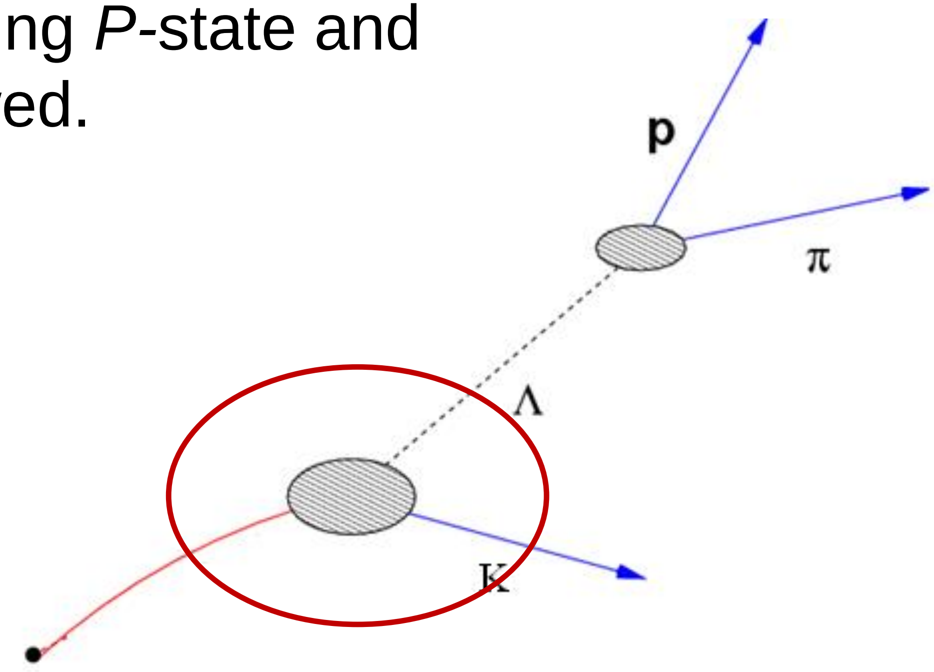


Spin observables for spin $\frac{3}{2}$ hyperons

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

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

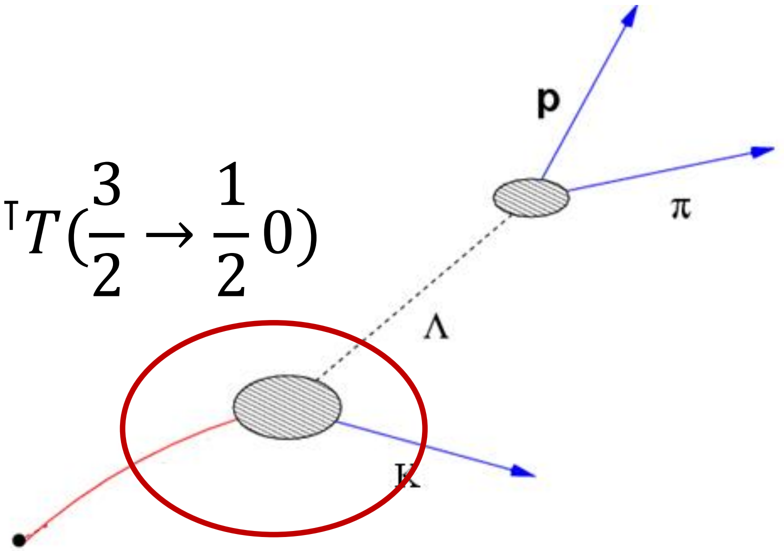
Amplitudes: T_P and T_D.



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

Angular distribution given by

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



$$\begin{aligned} I(\theta,\phi) &= \mathrm{Tr}(\rho(3/2)T^{\dagger}T(3/2 \to 1/2\,0)) \\ &= \frac{1}{4\pi}\Big[1 + \frac{\sqrt{3}}{2}(1-3\cos^2\theta)r_0^2 - \frac{3}{2}\sin^2\theta\cos 2\phi\, r_2^2 - \frac{3}{2}\sin 2\theta\cos\phi\, r_1^2 \\ &+ \frac{1}{40}\alpha\sin\theta\Big(8\sqrt{15}r^1_{-1}\sin\phi - 9\sqrt{10}r^3_{-1}(3+5\cos 2\theta)\sin\phi \\ &- 30(3r^3_{-2}\sin 2\phi\sin 2\theta + \sqrt{6}r^3_{-3}\sin 3\phi\sin^2\theta)\Big)\Big] \end{aligned}$$

*Elisabetta Perotti, FAIRNESS (2017)

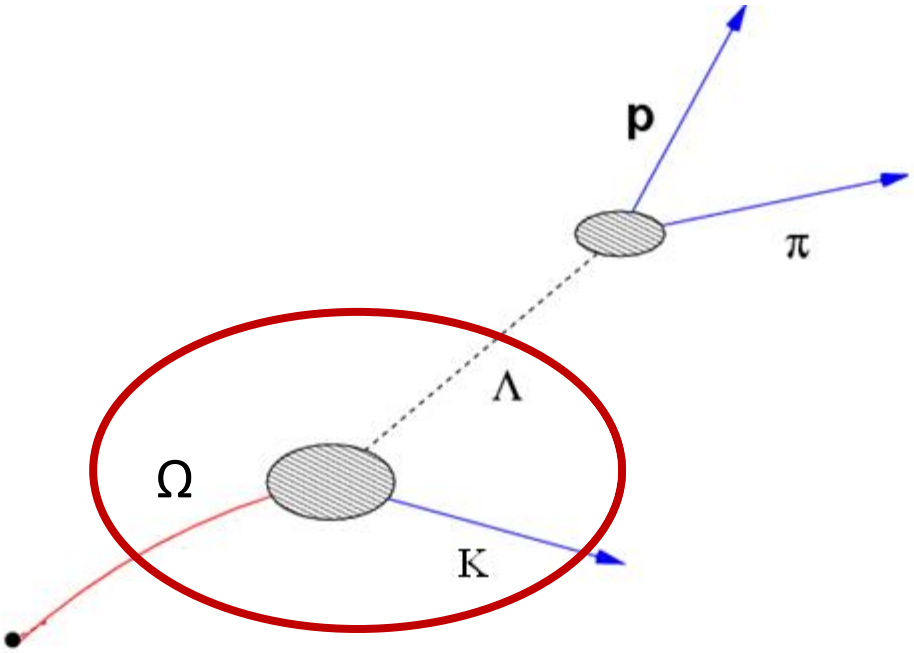
Spin observables for spin $\frac{3}{2}$ hyperons

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

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

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

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



*Elisabetta Perotti, FAIRNESS (2017)

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

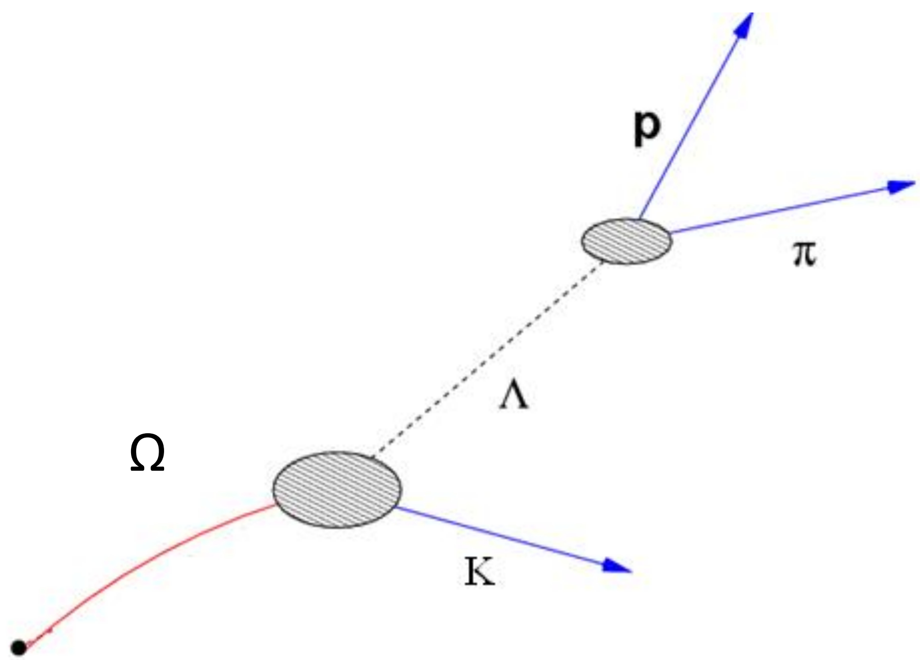
$$\langle \sin\phi_\Lambda \cos\phi_\mathrm{p} \rangle$$
$$= \int I(\theta_\Lambda, \phi_\Lambda, \theta_\mathrm{p}, \phi_\mathrm{p}) \times \sin\phi_\Lambda \cos\phi_\mathrm{p} d\Omega_\Lambda d\Omega_\mathrm{p} =$$
$$= -\frac{3\pi^2 \alpha_\Lambda \gamma_\Omega r^3_{-2}}{1024}$$

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

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

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

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



*Erik Thomé, Ph. D. Thesis and Elisabetta Perotti, FAIRNESS

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

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

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

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

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

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

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

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

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

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

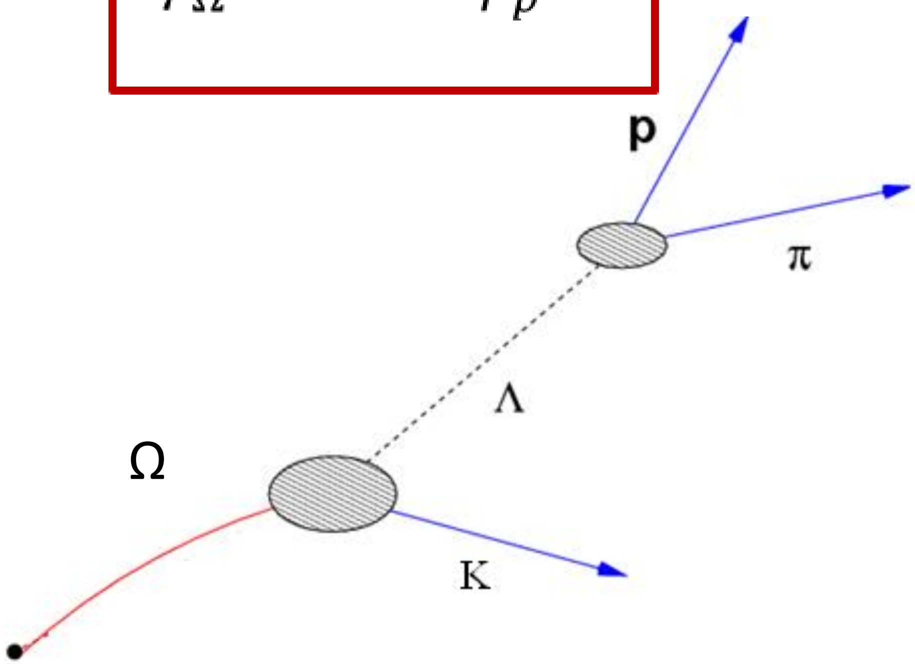
$\langle \sin\phi_\Lambda \cos\phi_\Lambda \cos\phi_\mathrm{p} \rangle$

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

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

Furthermore:

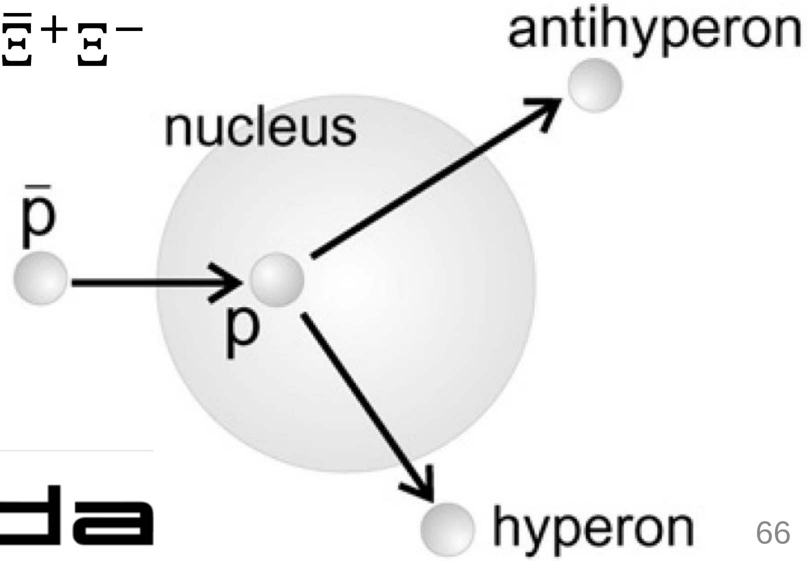
$$\frac{\beta_\Omega}{\gamma_\Omega} = \frac{< cos\varphi_p >}{< sin\varphi_p >}$$



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

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.