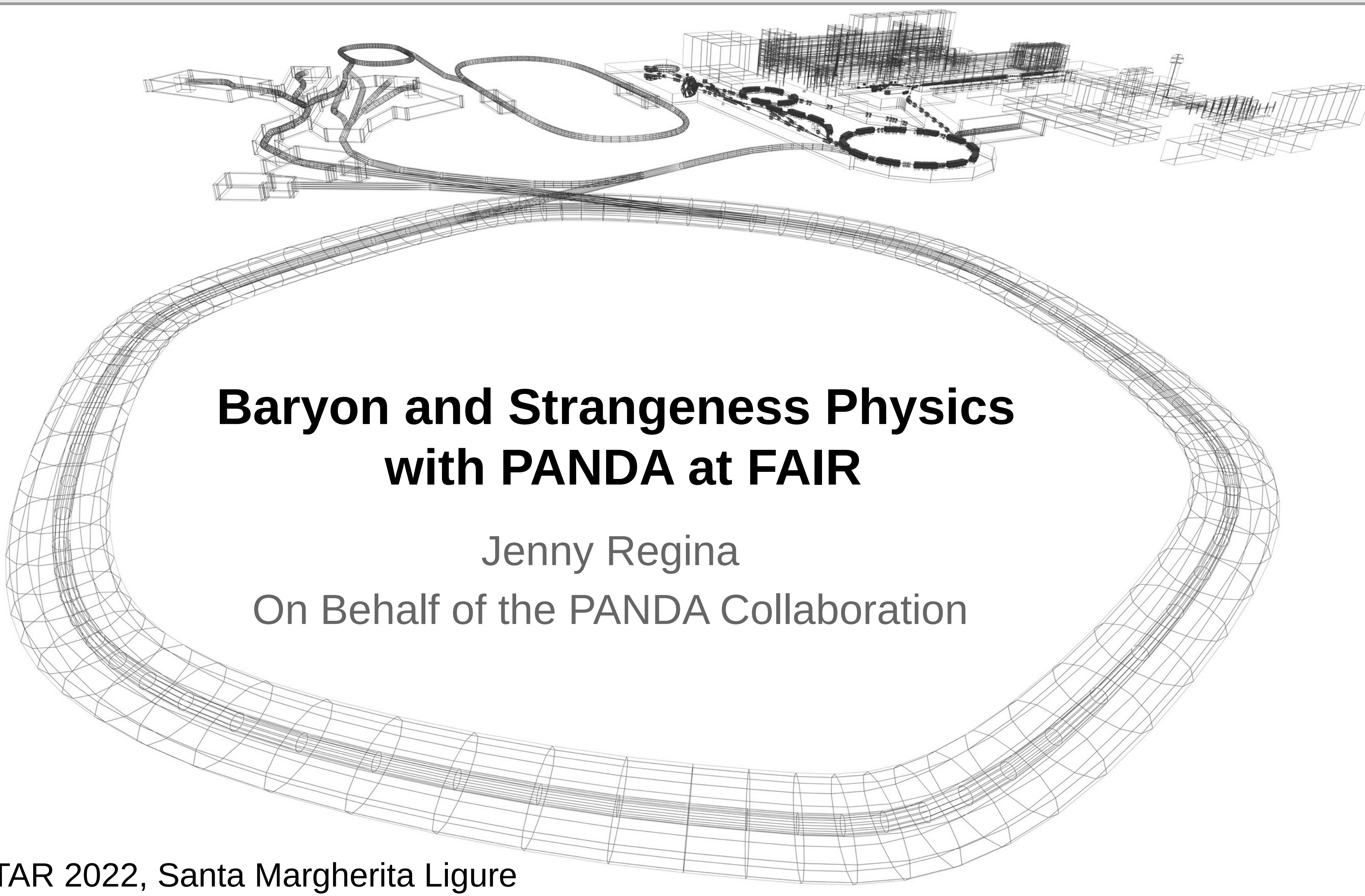


Baryon and Strangeness Physics with PANDA at FAIR

Jenny Regina

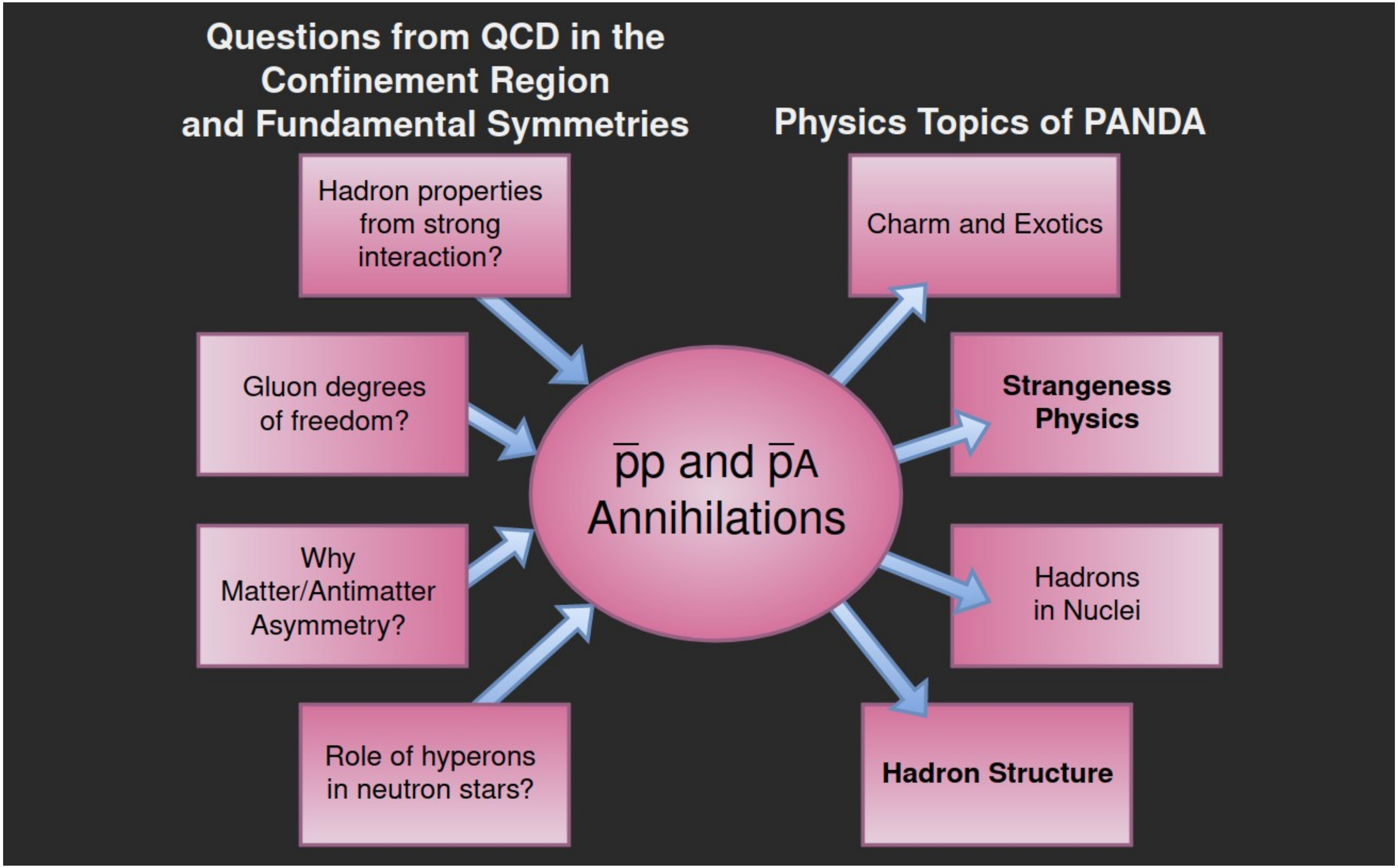
On Behalf of the PANDA Collaboration

NSTAR 2022, Santa Margherita Ligure

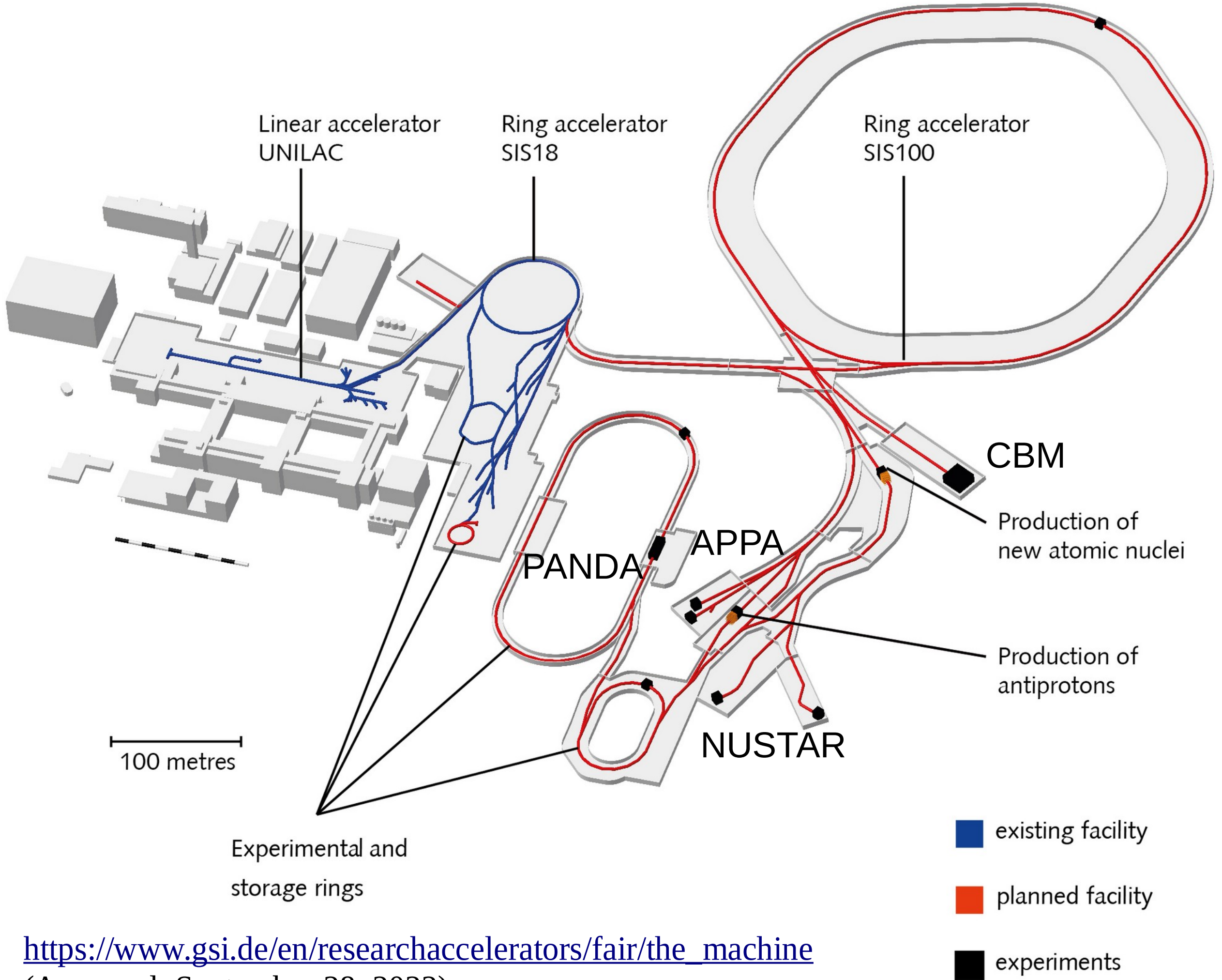
Outline

- Physics Motivation of PANDA
- PANDA at FAIR
- Baryon Structure
- Baryon Spectroscopy
- Strangeness Physics
- Summary

Physics Pillars of PANDA



Facility for Antiproton and Ion Research (FAIR)

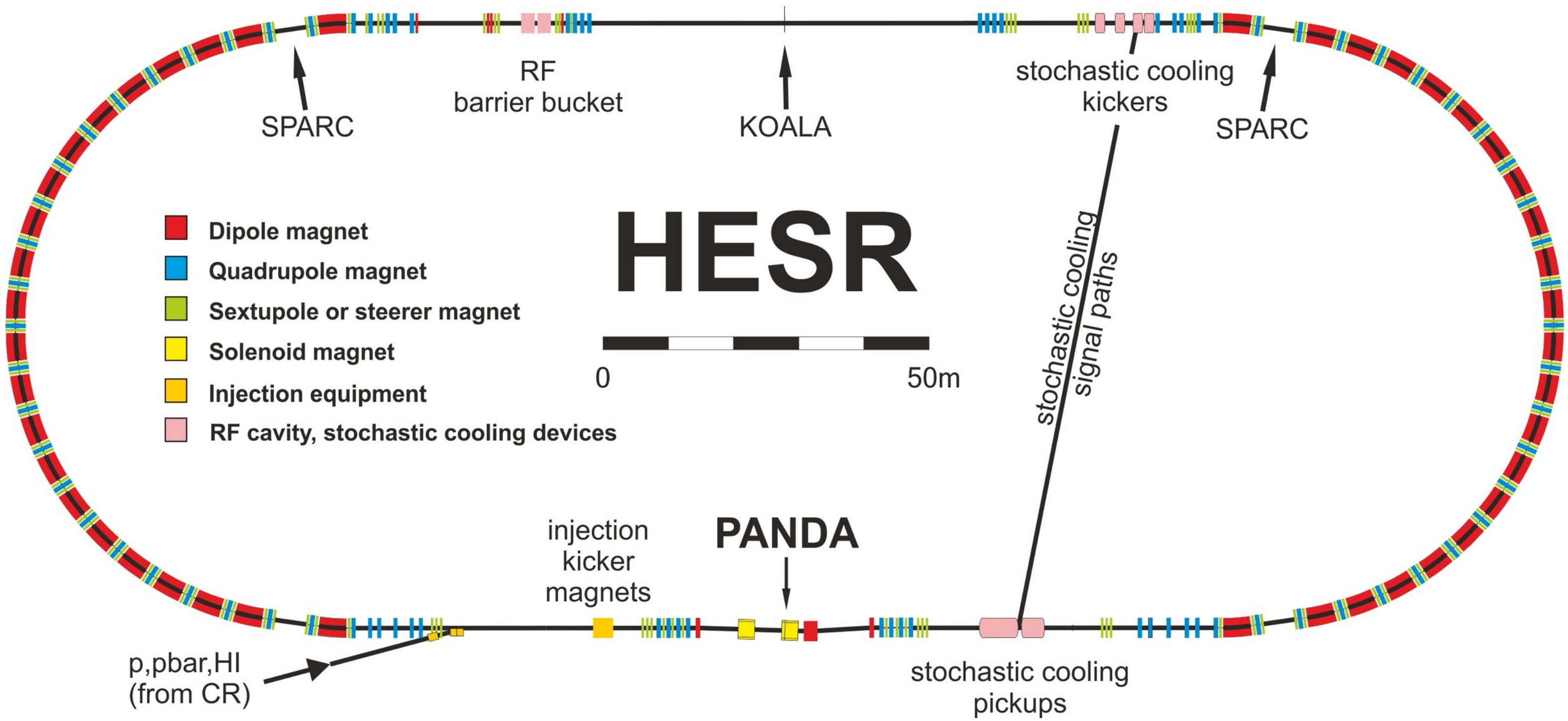


https://www.gsi.de/en/researchaccelerators/fair/the_machine
(Accessed: September 28, 2022)

Facility for Antiproton and Ion Research (FAIR)

FAIR Construction site in May 2022

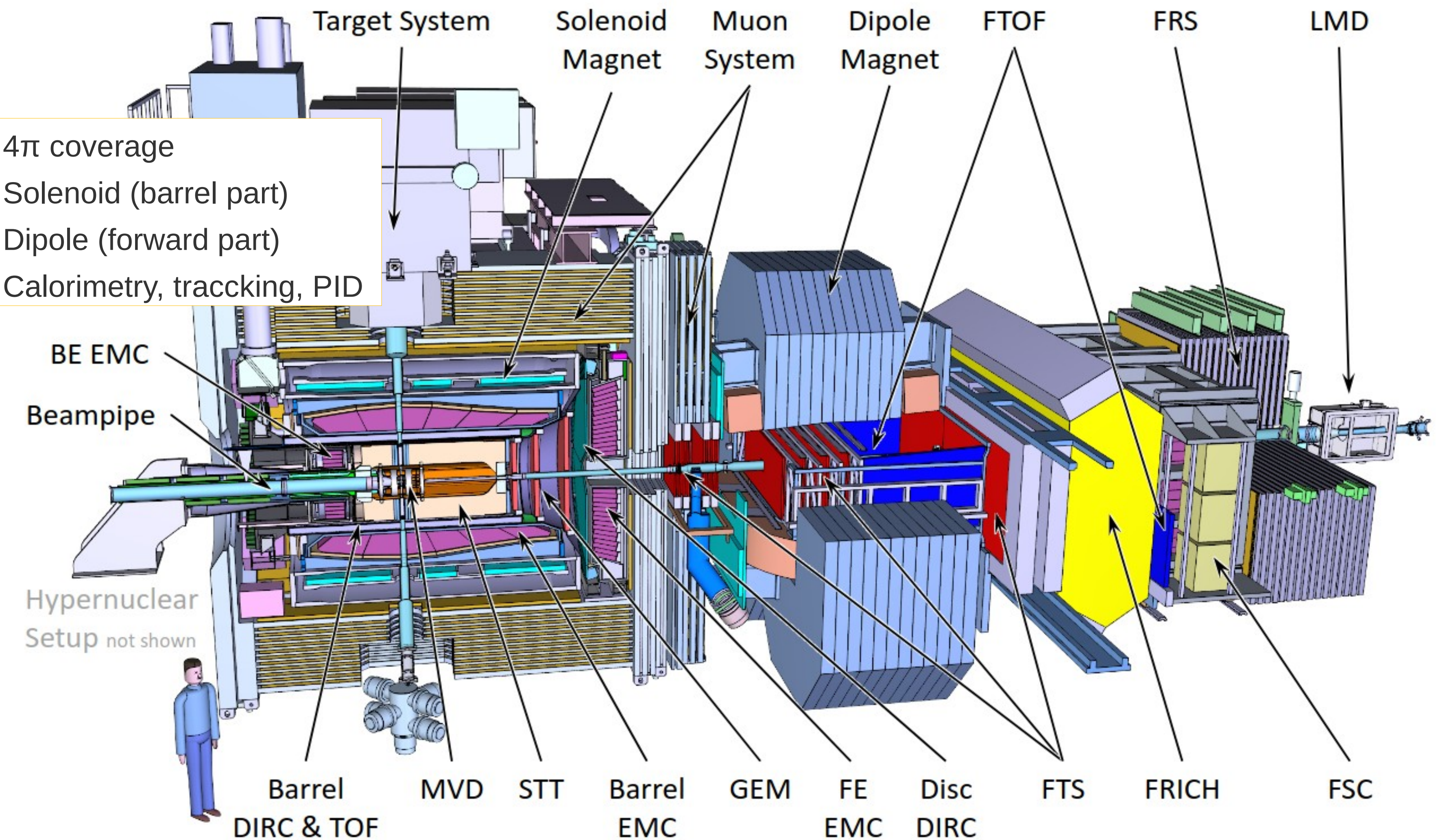
High Energy Storage Ring (HESR)



- Circumference: 574 m
- 10^{11} stored antiprotons
- $p_{beam} = 1.5$ GeV/c - 15.0 GeV/c
- $L = 1{\cdot}10^{31}$ cm^{-2}s^{-1} - $2{\cdot}10^{32}$ cm^{-2}s^{-1}
- $dp/p = 2{\cdot}10^{-4}$ (stochastic cooling) - $4{\cdot}10^{-5}$ (electron cooling)

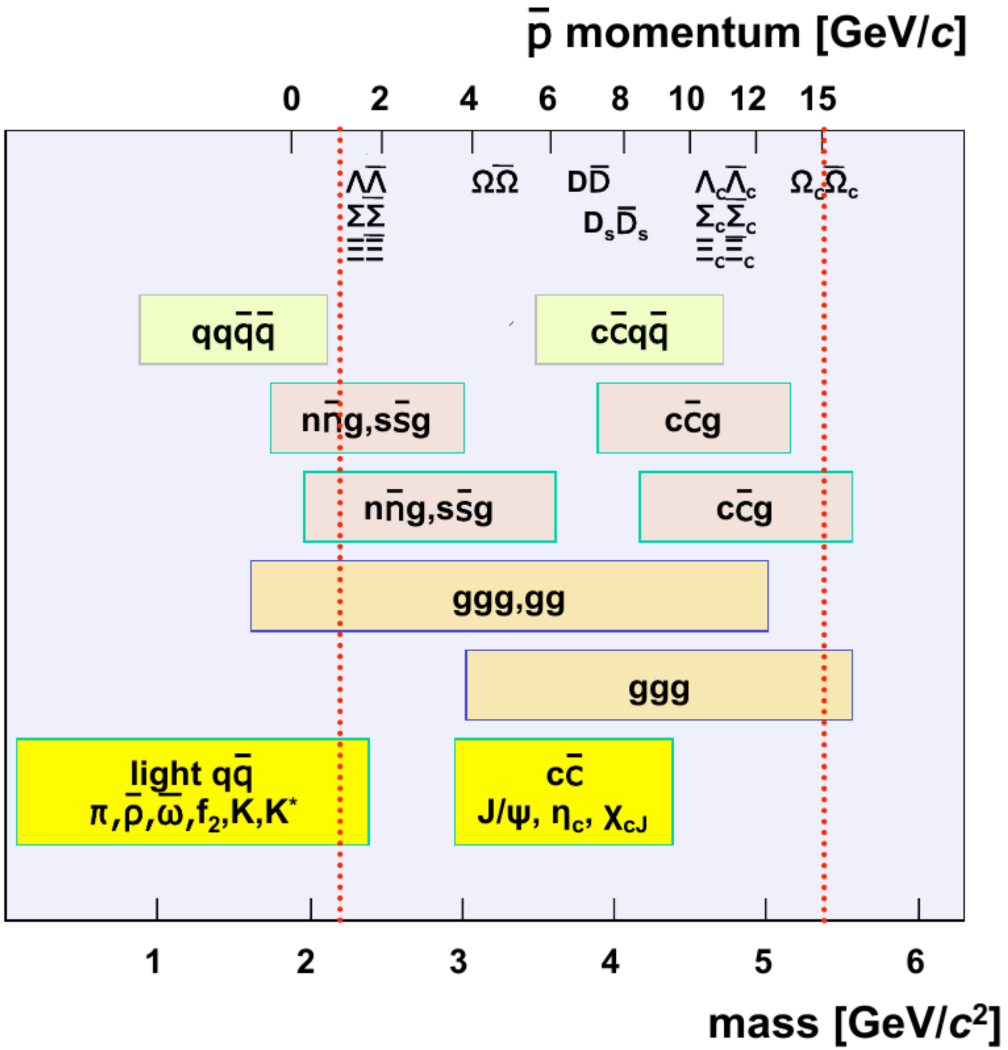
AntiProton ANnihilations at DArmstadt (PANDA)

- 4π coverage
- Solenoid (barrel part)
- Dipole (forward part)
- Calorimetry, traccking, PID



Physics with antiprotons

- **Large mass-scale coverage**
- Can produce matter/antimatter close to threshold
- Direct formation of all conventional J^{PC} states
- Hadron spectroscopy
  - Abundant strangeness production
  - Exotic matter (large production rates, discovery potential)
  - Charmonium states
- Nucleon structure
  - Time-like form factors
- Hypernuclei



Electromagnetic Form Factors

- Fourier transform of G_E and G_M correspond to charge and magnetization densities
  - Quantifies deviation from point like particle
- Time-Like and Space-Like region can be connected via dispersion relations
- Hyperon EMFFs accessible in Time-Like region

$$G_E(q^2) = |G_E(q^2)|e^{i\Phi_E}$$
$$G_M(q^2) = |G_M(q^2)|e^{i\Phi_M}$$

Attains complex values in time-like region -> quantify with magnitude + phase

$$R = \frac{G_E(q^2)}{G_M(q^2)}$$

- Obtain from angular distribution

$$\Delta\Phi(q^2) = \Phi_E\,(q^2) - \Phi_M\,(q^2)$$

- Obtain from polarization measurements

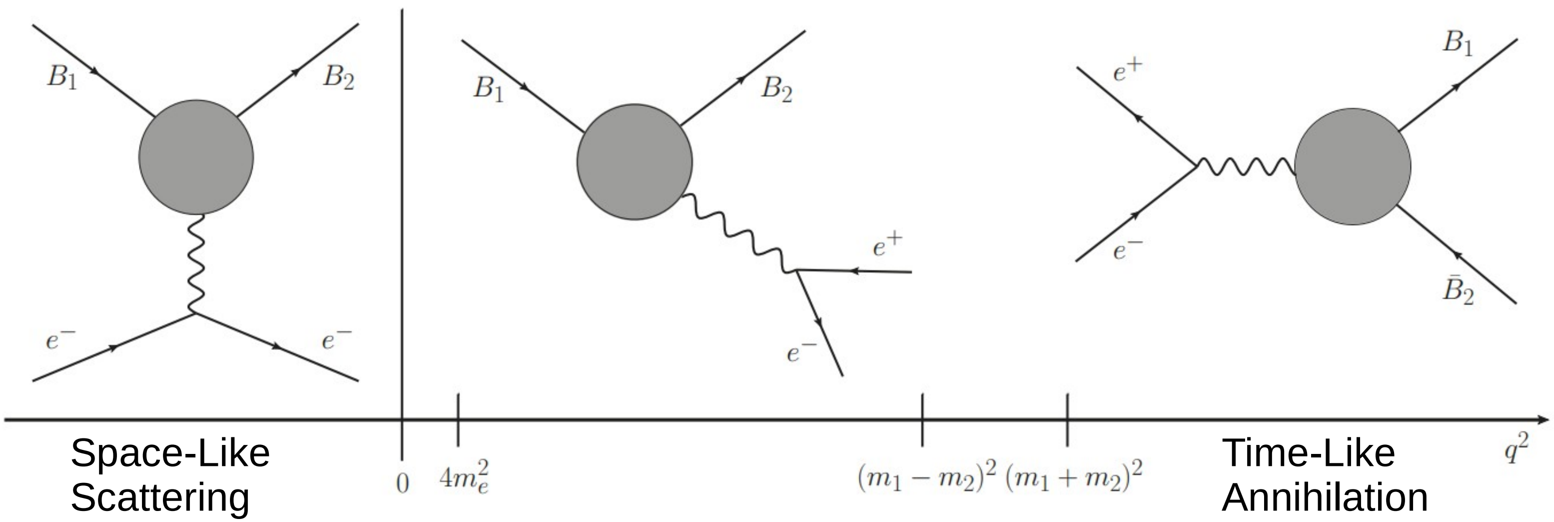
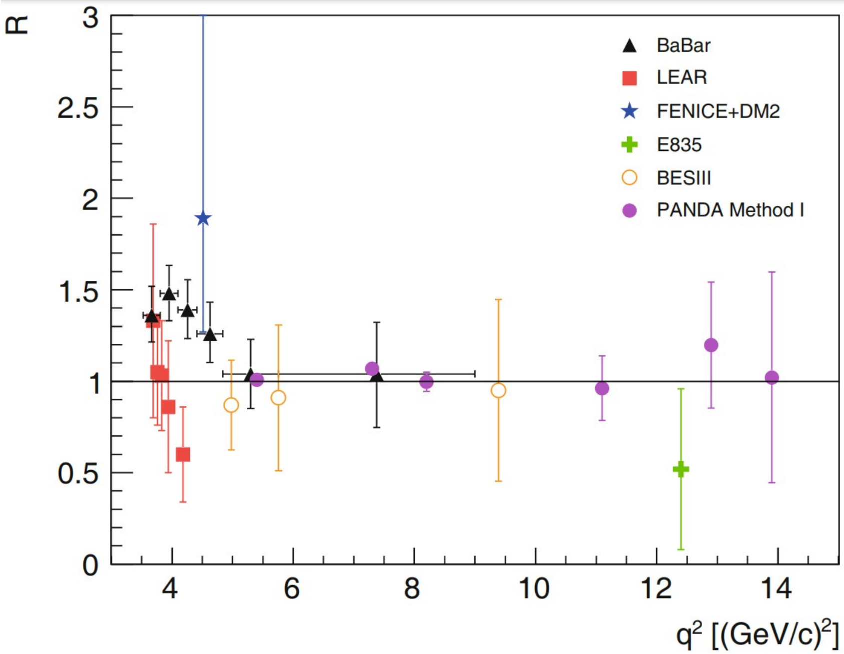


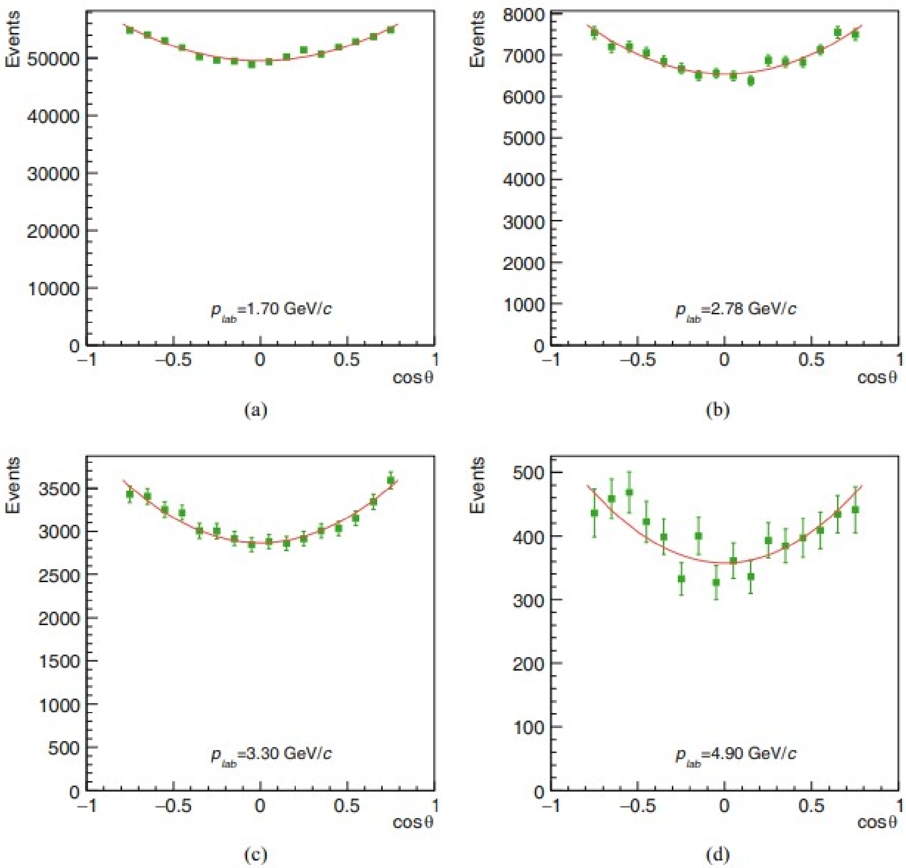
Figure from E. Perotti, PhD thesis, UU (2020)

Electromagnetic Form Factors in $\bar{p}p \rightarrow e^+e^-$

- PANDA will be able to contribute with measurements at many different beam momenta
  - EMC and 4π coverage
- PANDA reaches high q^2



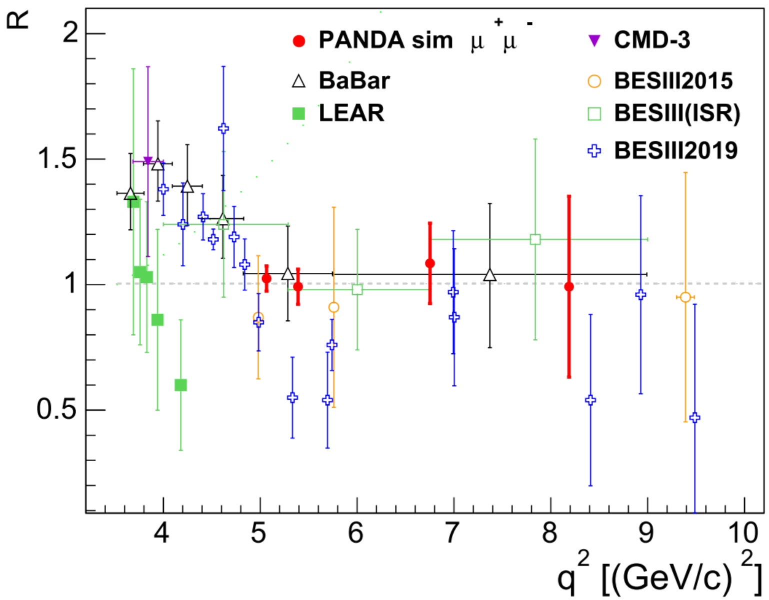
Eur. Phys. J. A (2016) 52: 325

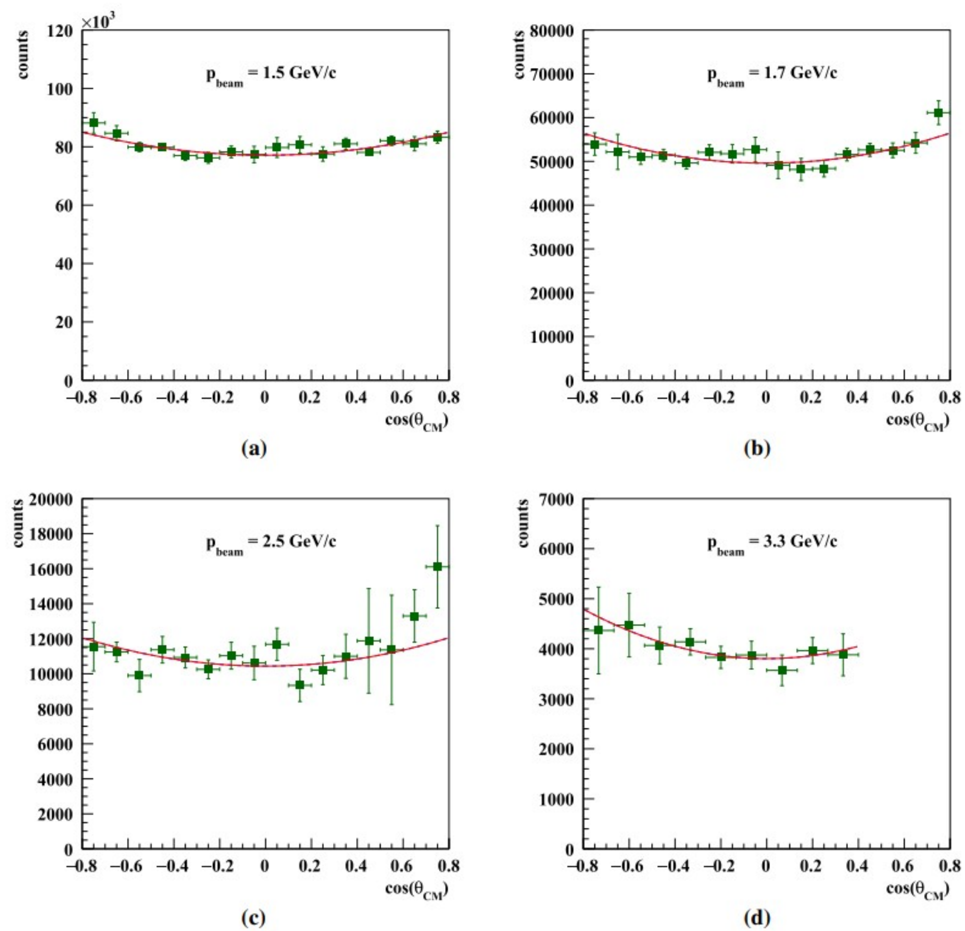


Electromagnetic Form Factors in $\bar{p}p \to \mu^+\mu^-$

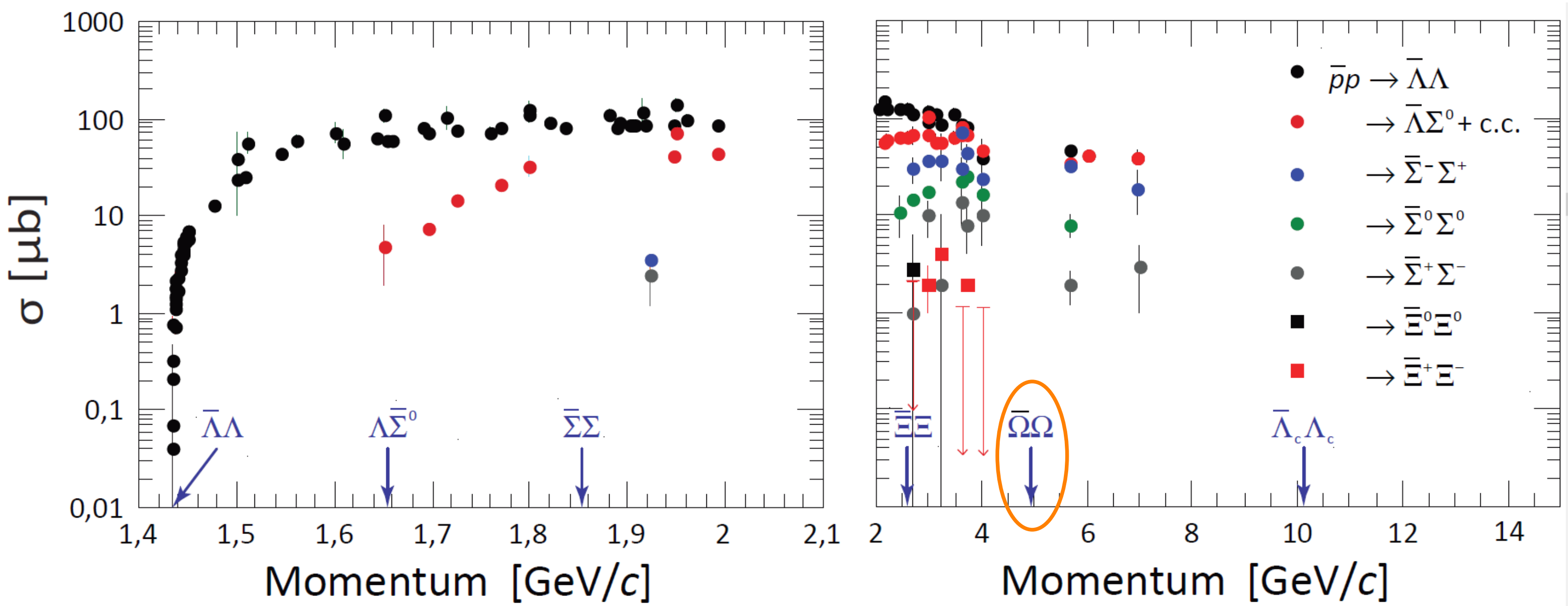
Eur. Phys. J. A (2021) 57 :30

- PANDA will be able to measure di-muons
- Not possible final state in e^+e^- collisions
- Unique for PANDA





Hyperon Data Base



- Much data for hyperons from PS185 at LEAR
- Sparse data bank for multi-strange hyperons
- Cross section $\bar{p}p \rightarrow \bar{\Omega}\Omega$ has never been measured
- Potential for PANDA to contribute

T. Johansson, Proceedings of 8th Int. Conf. on Low Energy Antiproton Physics 95 (2003)

Hyperon Production at PANDA

Eur. Phys. J. A (2021) 57:184

P_{beam} (GeV/c)	Reaction	σ (μb)	ε (%)	Rate @ 10^{31} $cm^{-2}s^{-1}$ [s^{-1}]	S/B	Events/Day
1.64	$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$	64.0	16.0	44	114	$3.8 \cdot 10^6$
1.77	$\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda$	10.9	5.3	2.4	> 11 **	207 000
6.0	$\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda$	20	6.1	5.0	21	432 000
4.6	$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	~ 1	8.2	0.3	274	26 000
7.0	$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	~ 0.3	7.9	0.1	65	8 600

**90% C.L.

- Start setup and luminosity assumed
- Large production rates already at early phases of PANDA
- Antiproton-proton collisions allow antihyperon-hyperon pairs to be created without additional particles
- Can also be done at BESIII, JLAB, JPARC, HADES, MAMI, ELSA …
  - PANDA has advantage in cross section compared to *e.g.* e^+e^- collisons

Excited Baryon Spectrum

- Need more multi-strange excited baryon data for spin and parity assignments
- Focus on excited Ξ states
- Ω also needs investigations

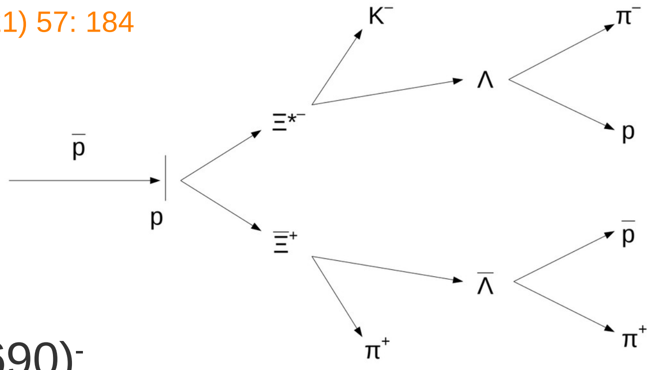
J^P	(D, L^P_N)	S	Octet members				Singlets
$1/2^+$	$(56,0^+_0)$	1/2	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	
$1/2^+$	$(56,0^+_2)$	1/2	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$	$\Xi(1690)^\dagger$	
$1/2^-$	$(70,1^-_1)$	1/2	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(?)$	$\Lambda(1405)$
					$\Sigma(1560)^\dagger$		
$3/2^-$	$(70,1^-_1)$	1/2	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
$1/2^-$	$(70,1^-_1)$	3/2	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(?)$	
					$\Sigma(1620)^\dagger$		
$3/2^-$	$(70,1^-_1)$	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	$\Delta(1700)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
$5/2^+$	$(56,2^+_2)$	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	$\Delta(2420)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	

Prog. Theor. Exp. Phys.2020, 083C01 (2020) and 2021 update

PWA of Excited Cascades

- PWA with **PA**rtial **W**ave **I**nteractive **AN**alysis: PAWIAN [*]
- $\Xi(1690)^-$ and $\Xi(1820)^-$
- p_{beam} = 4.6 GeV/c
- 600 000 events generated
- Full simulation and reconstruction chain applied
- 30 000 events in fit
- Maximum likelihood fit (MINUIT2) applied event-by-event
- Measure of significance : ΔAIC and ΔBIC
  - Should be minimized
- Fit identifies generated spin-parity
  - Well suited to use at PANDA!

Eur. Phys. J. A (2021) 57: 184



ΔAIC $\Xi(1690)^-$

Gen. ↓ / Fit →	$1/2^+$	$1/2^-$	$3/2^+$	$3/2^-$
$1/2^+$	0.0	2,550.6	2,310.6	2,706.8
$1/2^-$	316.7	0.0	328.2	2,332.2
$3/2^+$	4,973.9	5,228.0	0.0	584.6
$3/2^-$	5,345.6	3,118.6	833.1	0.0

Δ(AIC+BIC) $\Xi(1820)^-$

Gen. ↓ / Fit →	$1/2^+$	$1/2^-$	$3/2^+$	$3/2^-$
$1/2^+$	0.0	139.9	158.7	208.1
$1/2^-$	96.8	0.0	211.1	887.4
$3/2^+$	7473.3	7604.5	0.0	198.4
$3/2^-$	7617.6	6900.8	490.2	0.0

[*] https://www.ep1.ruhr-uni-bochum.de/forschung/partialwellenanalyse/

Strangeness Creation

- What is the role of spin in strangeness creation?
- Quark-gluon or meson degrees of freedom can be used to describe strangeness creation
- Relevant degrees of freedom in intermediate energy range?

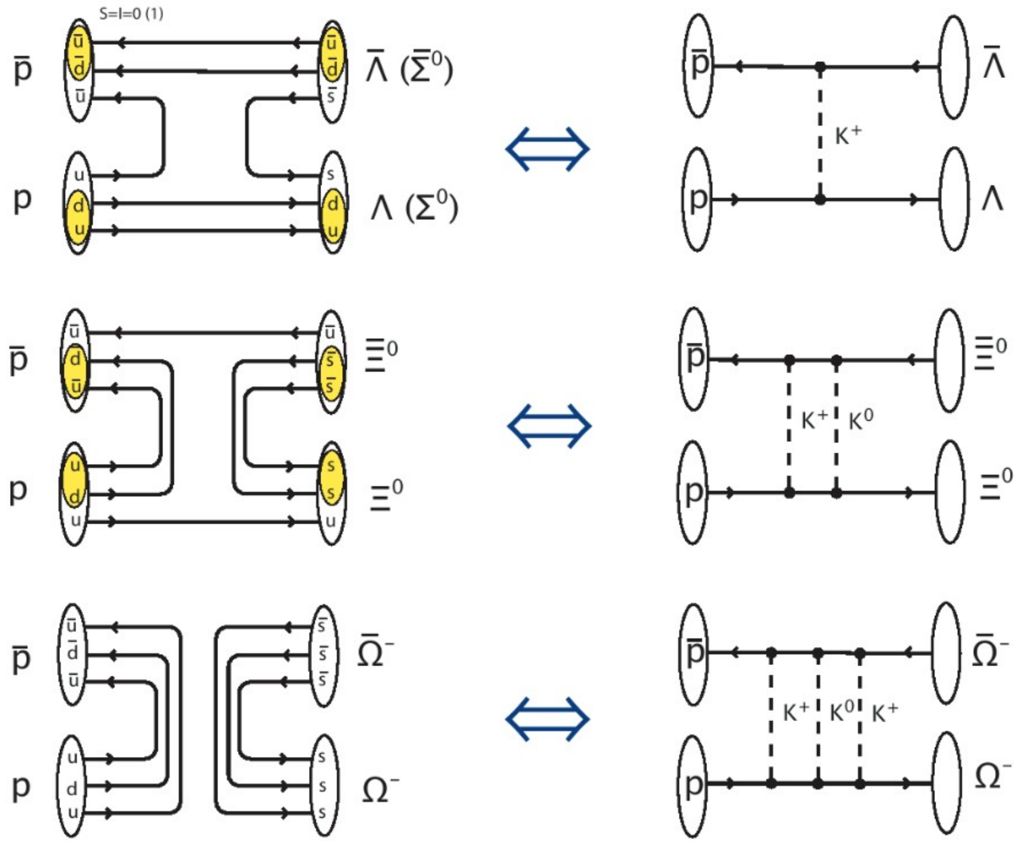


Figure from T. Johansson, Proceedings of 8th Int. Conf. on Low Energy Antiproton Physics 95 (2003)

Spin Observables

- Rich set of spin observables obtainable for hyperon decays
- Theoretical predictions [*] relate sign and value of some observables to the production model
- Hyperon spin observables can shed light on relevant degrees of freedom!
- Polarization accessible via weak, parity-violating decay of hyperons

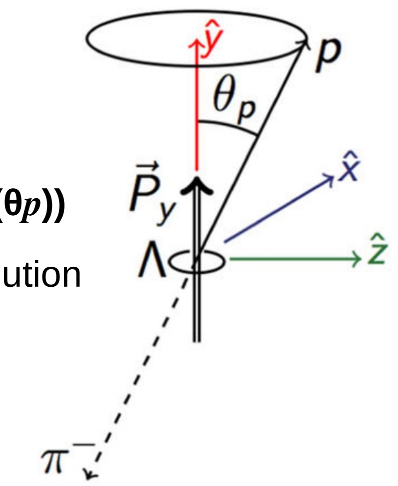
$\Lambda \rightarrow p\pi^-$

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

$I(\cos(\theta_p))$: angular distribution

P_Λ : polarization

α: asymmetry parameter



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

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

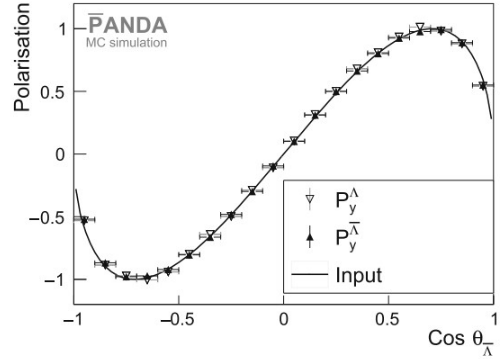
Measure of CP violation in decay

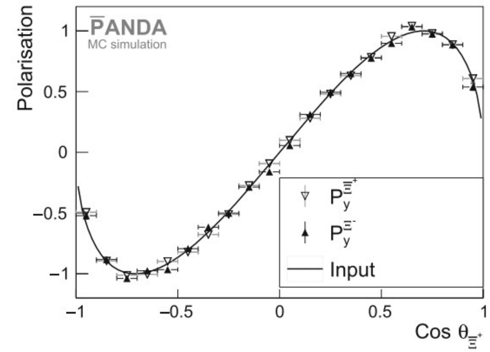
[*] Nucl. Phys. A 655 (1999) 1.

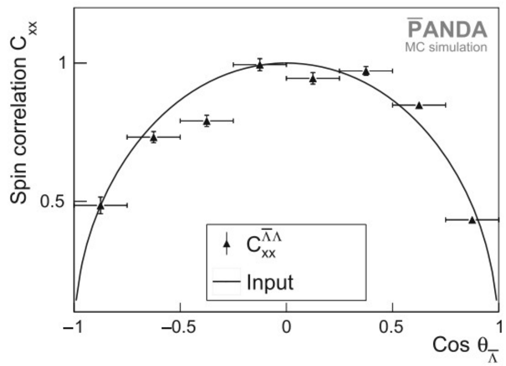
Polarization and Spin Correlations of Λ and Ξ

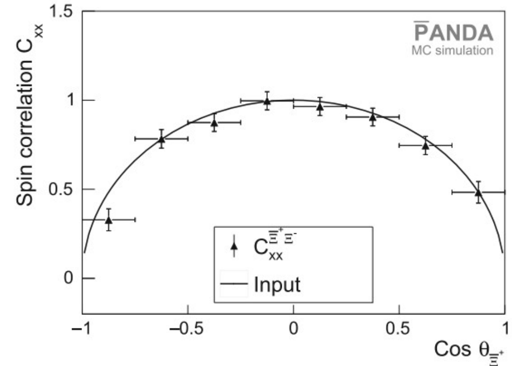
- Polarization, spin correlations were reconstructed
- Spin correlations, C_{xx}, C_{yy} and C_{zz} used for calculating the singlet fraction, F_s
- 10^6 Λ and Ξ events generated
- Results obtained after a full event selection
- Events after selection:
  - $1.572 \cdot 10^5$ Λ
  - $7.23 \cdot 10^4$ Ξ (4.6 GeV/c)
  - $6.76 \cdot 10^4$ Ξ (7 GeV/c)
- **Polarization, spin correlation and singlet fraction can be reconstructed at PANDA**

Eur. Phys. J. A (2021) 57:154





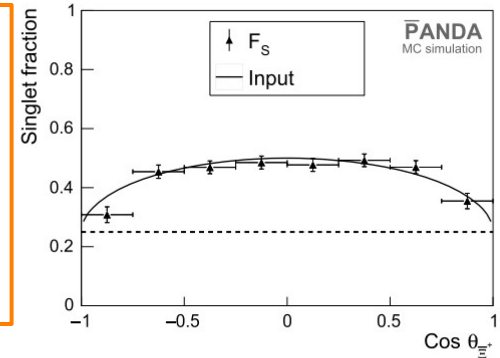




$$F_S = \frac{1}{4}\left(1 + C_{xx}^{\bar{Y}Y} - C_{yy}^{\bar{Y}Y} + C_{zz}^{\bar{Y}Y}\right)$$

F_S = 1: singlet state (anti-parallel spin)

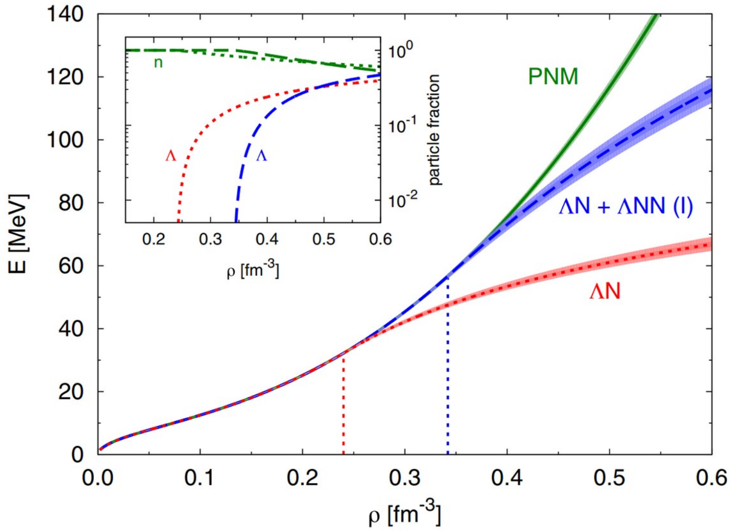
F_S = 0: triplet state (parallel spin)

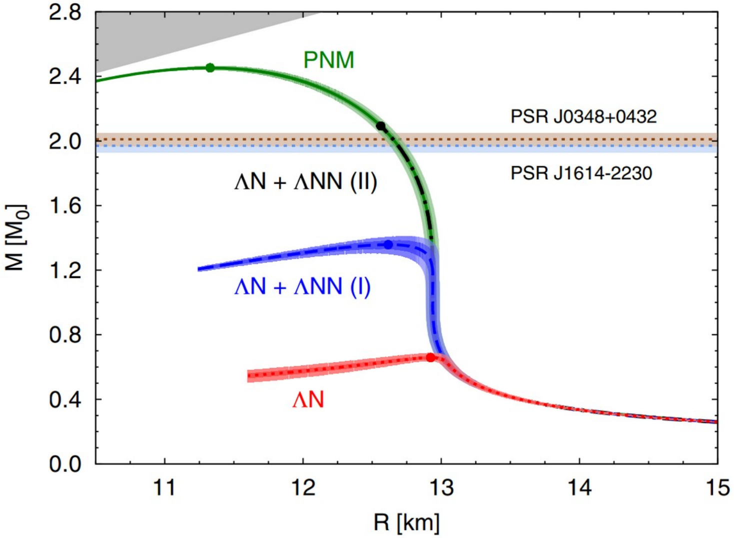


Hyperon Puzzle in Neutron Stars

- Hyperons energetically favorable to be created in neutron star cores
  - Reduction of Fermi pressure
  - Softer EOS
    - Allowed masses lower than those observed!
- Could solve the puzzle:
  - Three-body hyperon interactions
  - Strong repulsion in YN and YNN forces
- Stronger constraints on the hyperon-neutron force are necessary
- **PANDA is well suited to perform interaction studies**

D. Lonardoni et al., PRL114, 092301 (2015)





CP Violation in Double Strange Systems

- Recent measurement at BESIII
- $e^+e^- \rightarrow J/\psi \rightarrow \bar{\Xi}^+\Xi^-$ reaction
- Spin-entangeled CP eigenstates instead of polarized Ξ^-
- 73 244 events after event selection
- $\xi_P - \xi_S = (1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$
- **PANDA could reach same sensitivity in 3 days**

$$A_{CP}^{\Xi} \approx -\tan(\delta_P - \delta_S)\tan(\xi_P - \xi_S)$$

$$(\xi_P - \xi_S)_{LO} = \frac{\beta + \bar{\beta}}{\alpha - \bar{\alpha}} \approx \frac{\sqrt{1 - \langle\alpha\rangle^2}}{\langle\alpha\rangle} \Delta\phi_{CP}$$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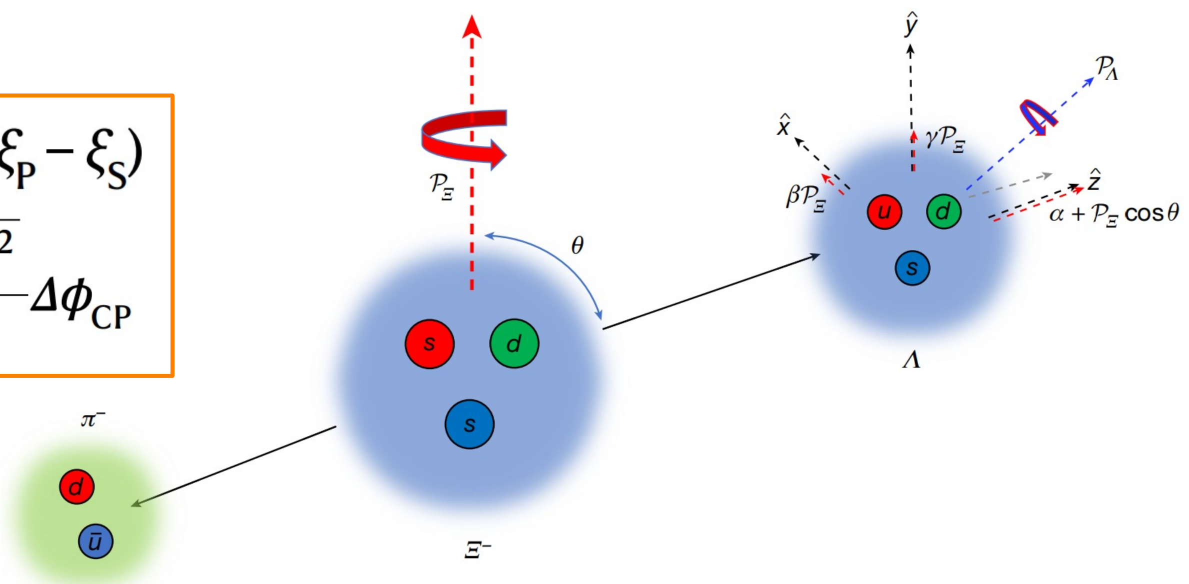
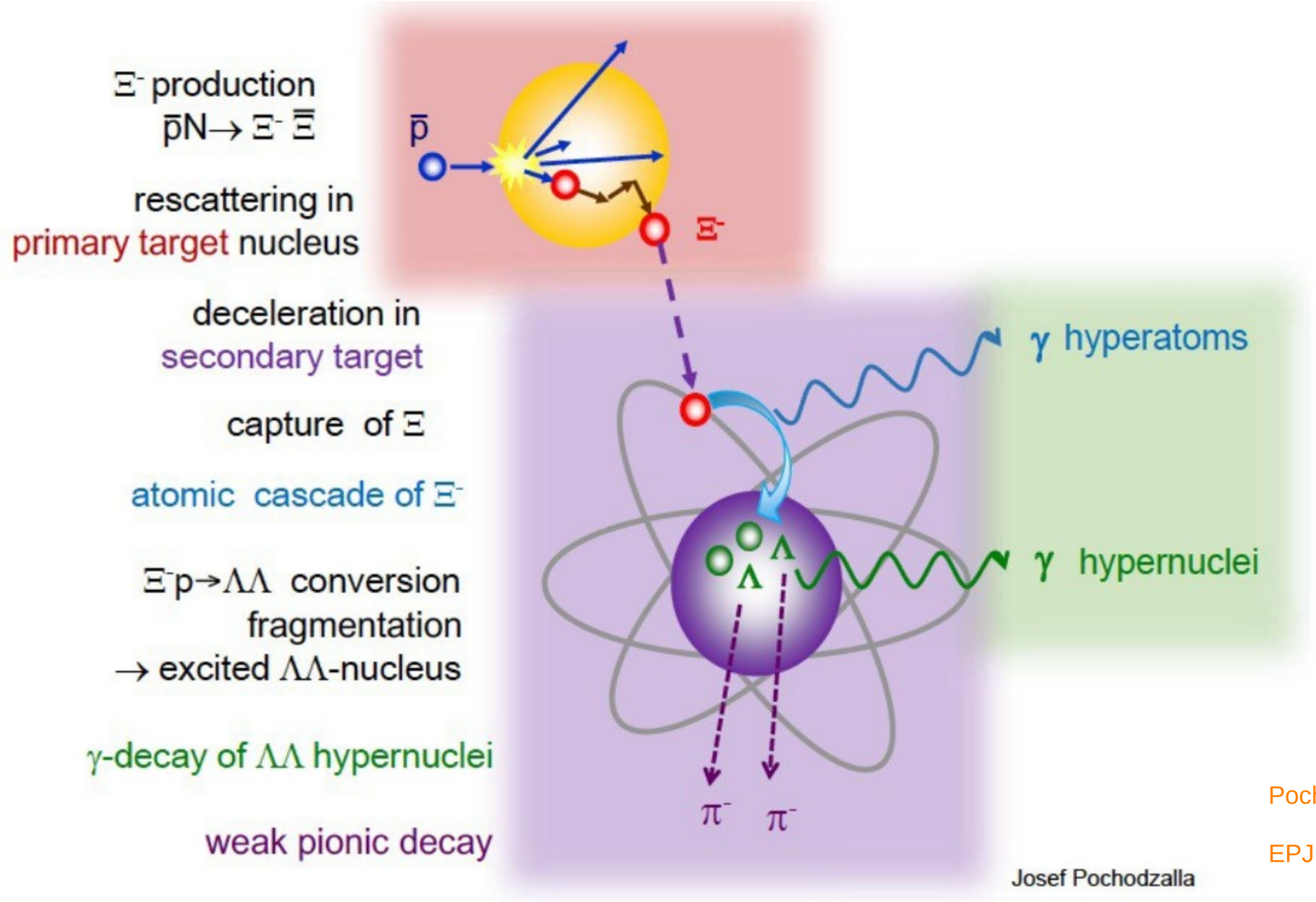
Probing CP symmetry and weak phases with entangled double-strange baryons

The BESIII Collaboration

Nature **606**, 64–69 (2022) | Cite this article



Hypernuclear Physics and Hyperon Interaction Studies at PANDA



Pochodzalla: PLB 669, 306 (2008)

EPJ A 57, 184 (2021)

NP A 954, 323 (2016)

Summary

PANDA

- Broad physics program
- Complementary to experiments at running and future facilities
- Antiproton beam unique
- Physics program covers nuclear, hadron and particle physics
- Precision spectrometry
- Studies show potential of PANDA
- Only part of rich physics program presented

Summary

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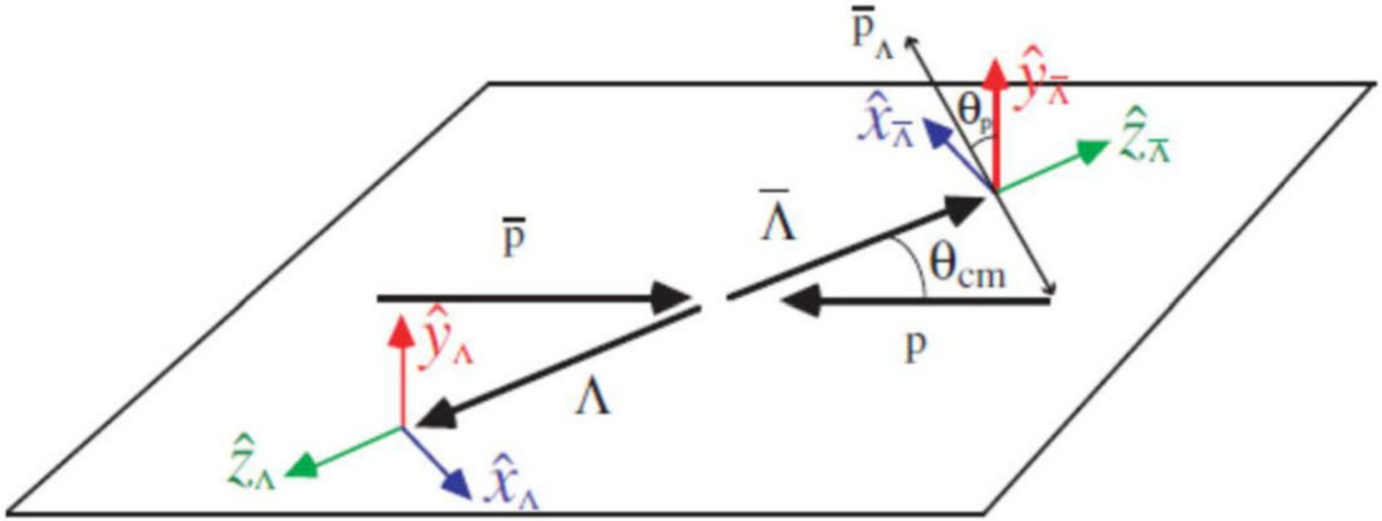
Thank you for your attention!

Questions?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