The potential of multi-strange physics with PANDA at FAIR

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On behalf of the PANDA collaboration

Fysikdagarna, Lund
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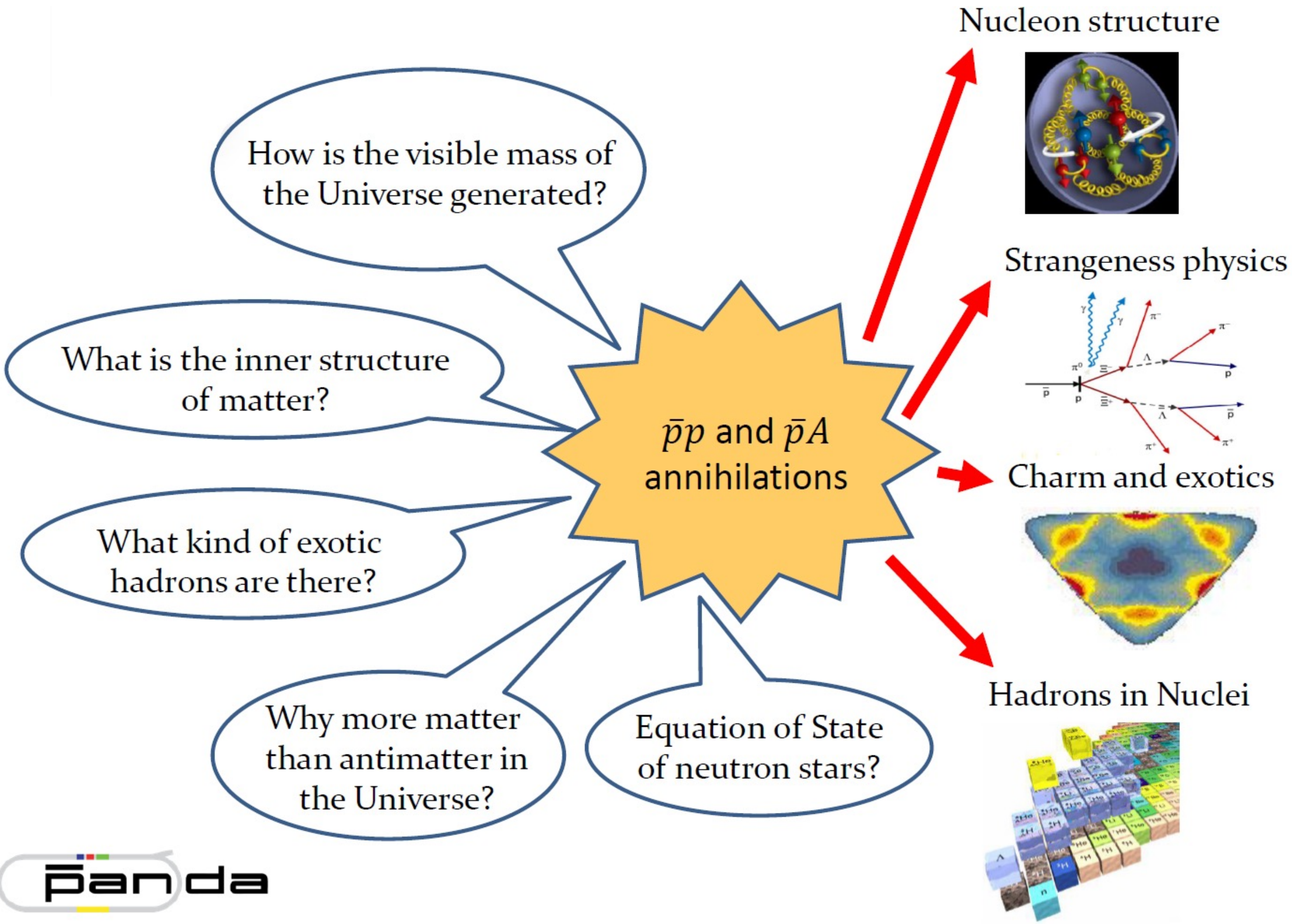
Outline

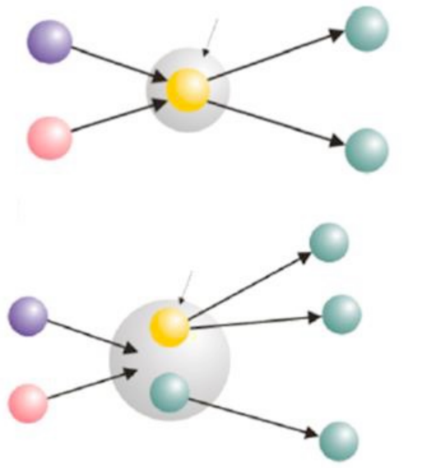
- Physics Objectives
- PANDA at FAIR
- Strangeness physics at PANDA
  - Hyperon spectroscopy
  - Hyperon spin observables
  - Hypernuclei
- Summary

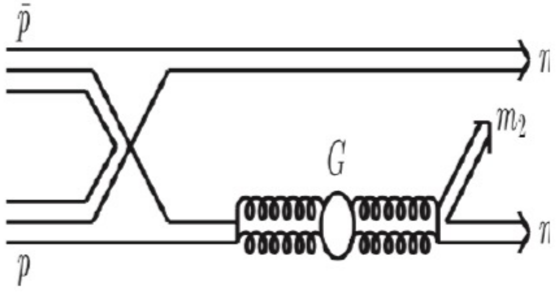
Physics with PANDA

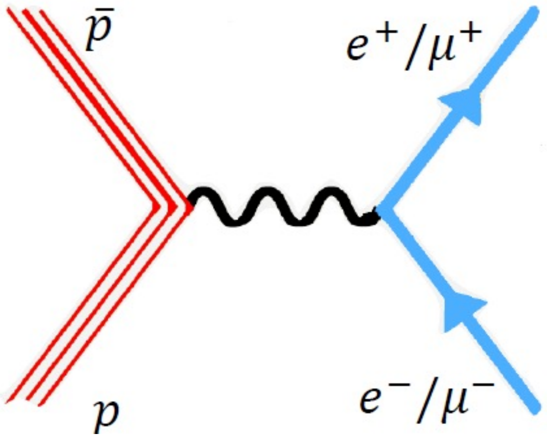


Virtues of low-energy antiprotons

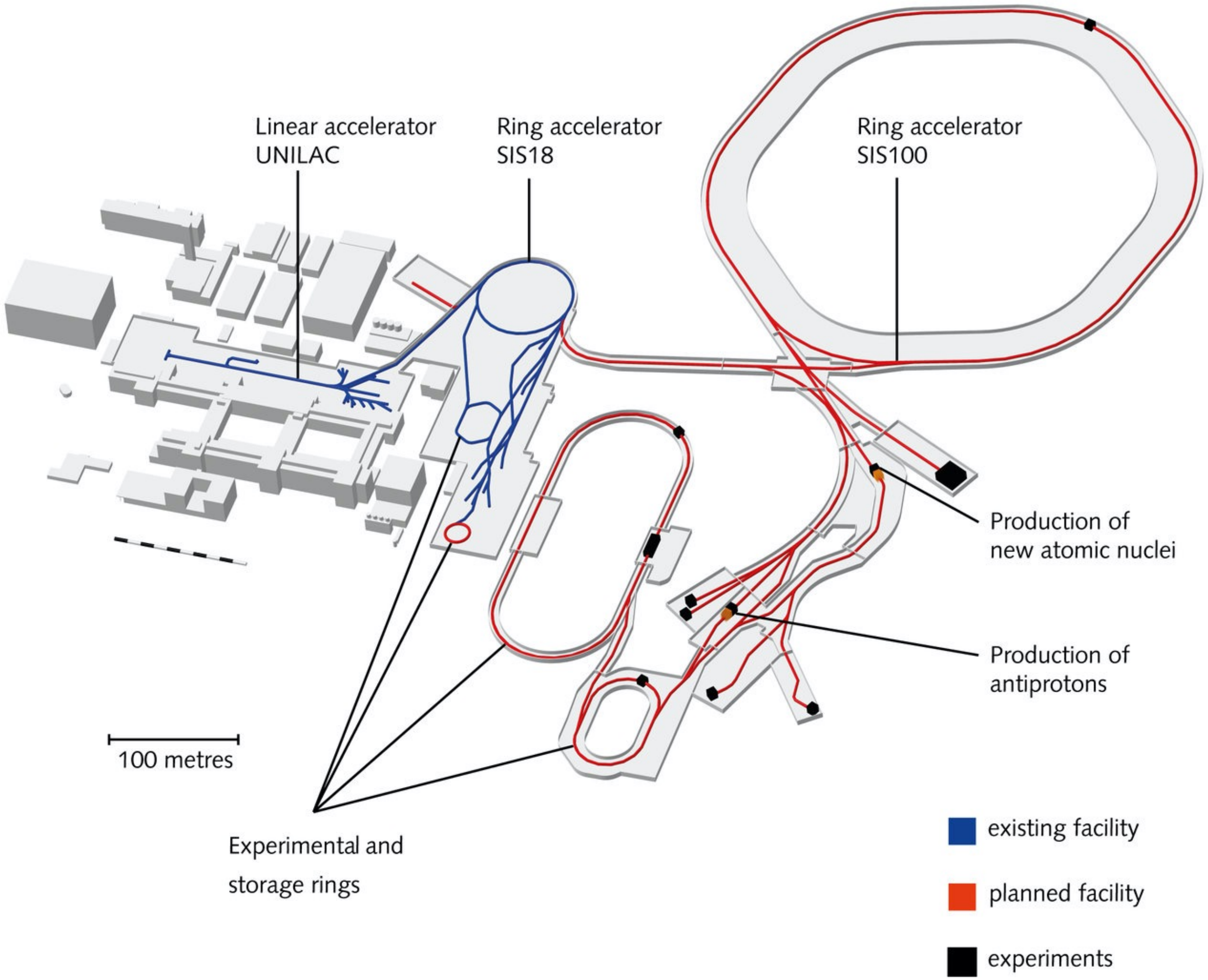
- Annihilations provide a gluon-rich environment
- All neutral, hidden-flavour, meson-like states accessible in formation
- Multi-strange and charmed $\bar{Y}Y$ final states in 2-body production
- Time-like structure observables with electron and muon "probes"
- Provide secondary hyperons that can form hypernuclei







Facility for Antiproton and Ion Research (FAIR)



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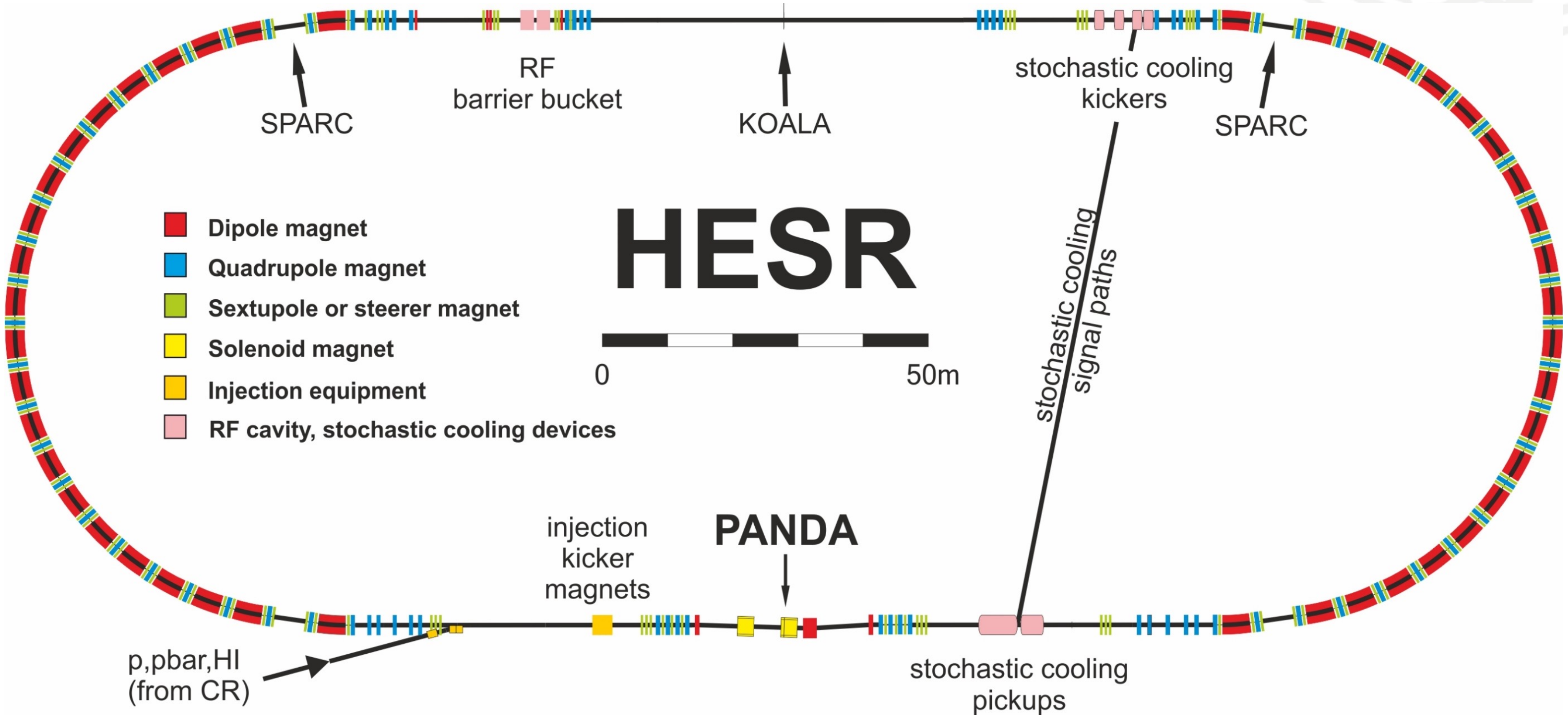
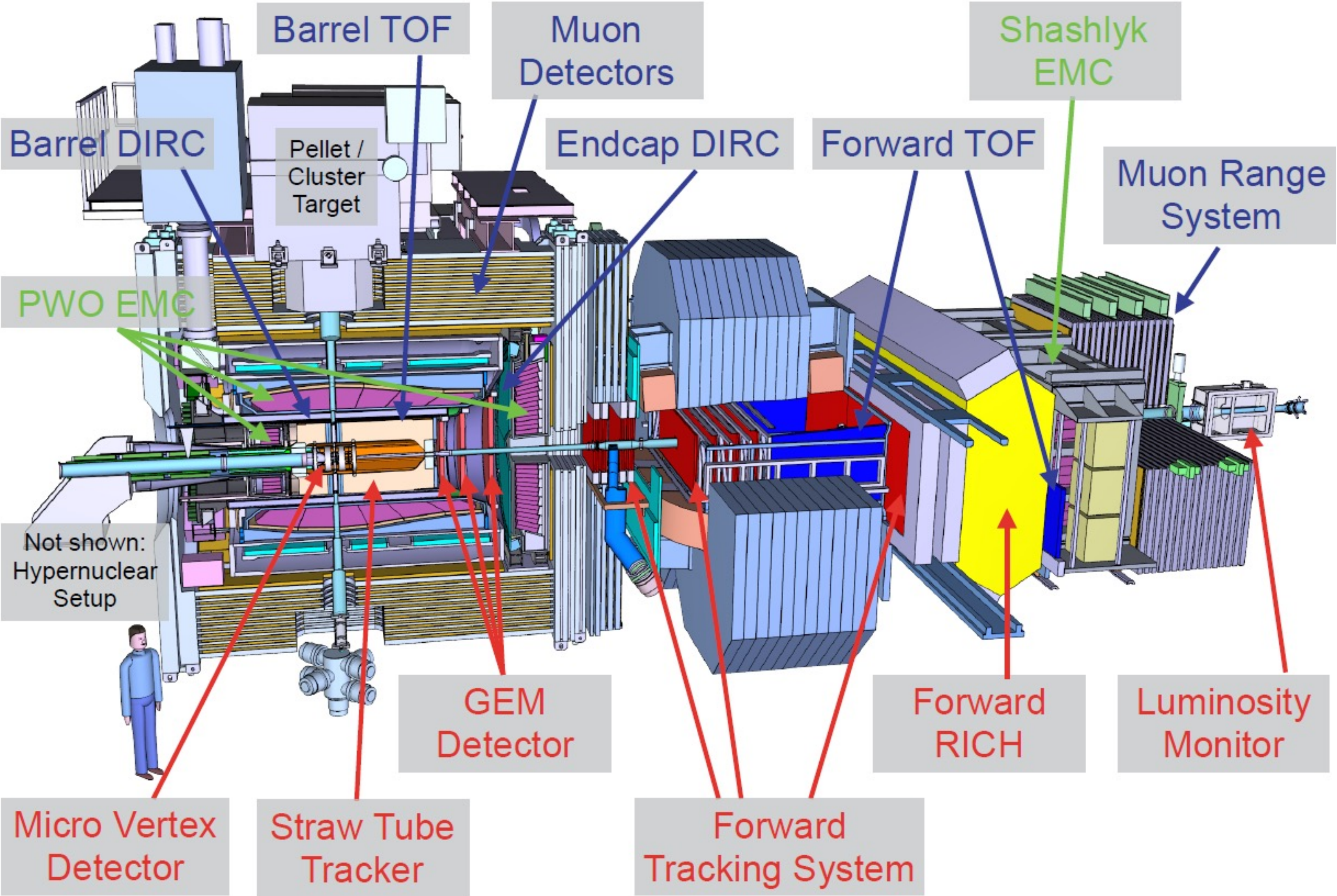
Construction of FAIR

High Energy Storage Ring (HESR)

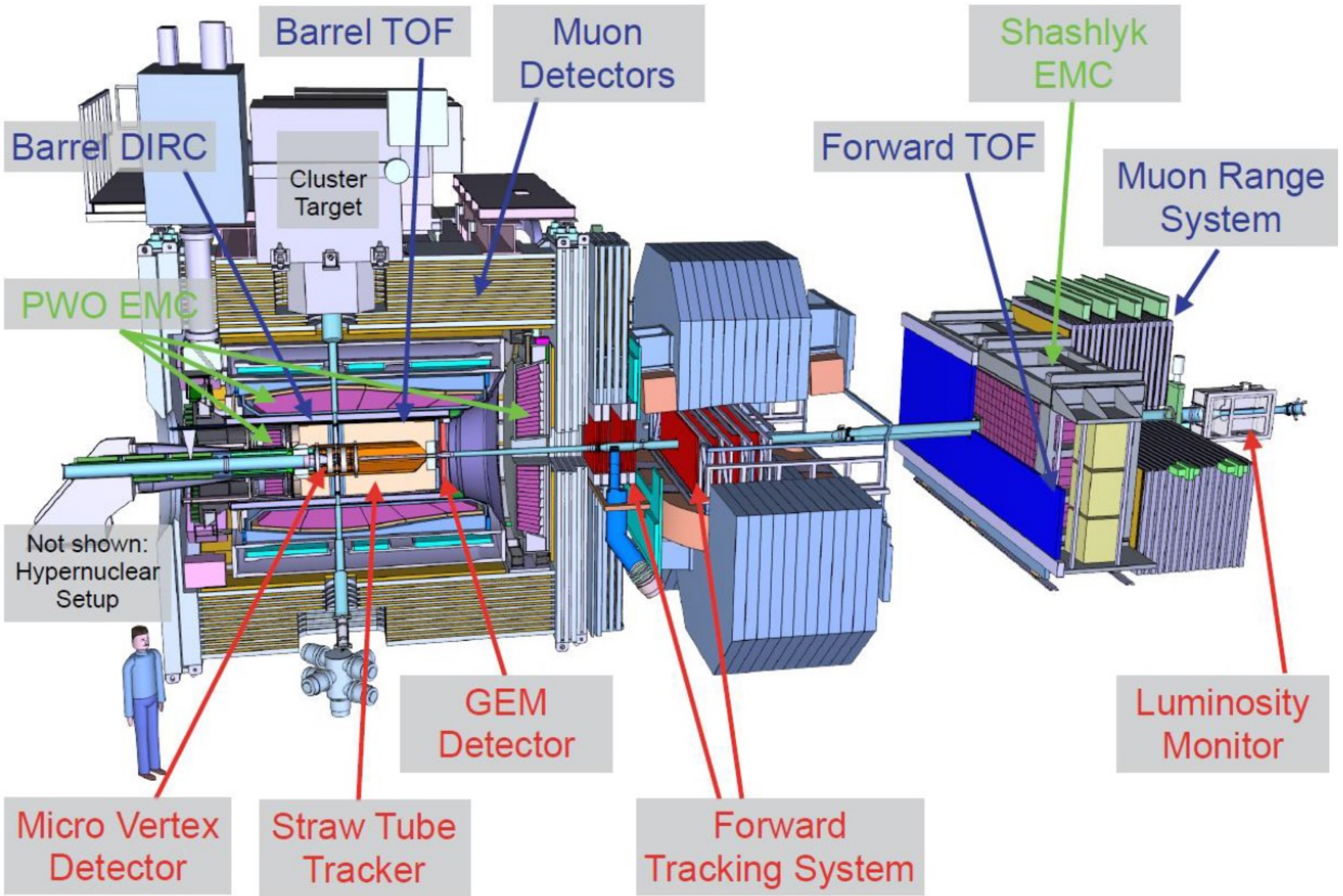
- Anti-protons with $1.5 < p_{beam} < 15\ \text{GeV}/c$
- Internal targets
  - Cluster-jet and pellet ($\bar{p}p$)
  - Foils ($\bar{p}A$)
- Luminosity
  - Design $\sim 2 \cdot 10^{32} \text{cm}^{-2}\text{s}^{-1}$
  - Phase One $\sim 10^{31} \text{cm}^{-2}\text{s}^{-1}$
- Quasi-continuous beam



PANDA – full setup



PANDA – Phase One setup



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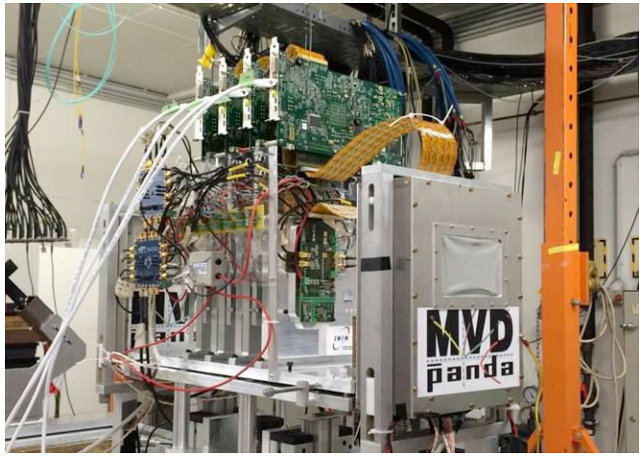
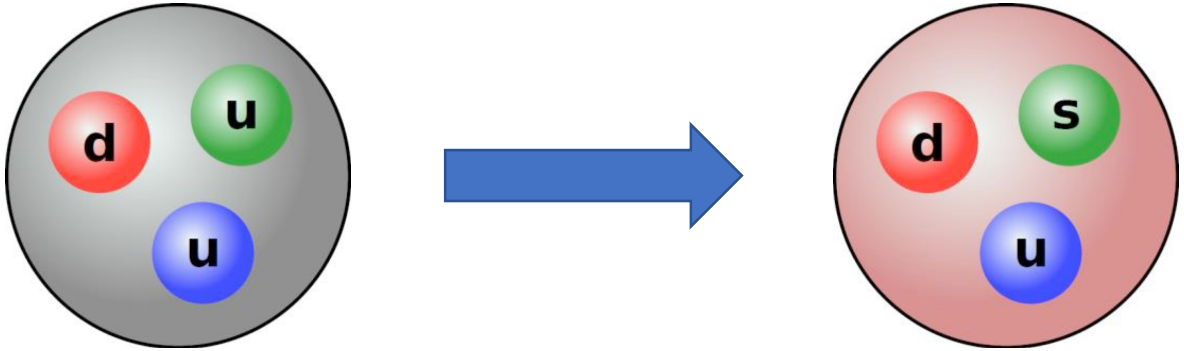
Construction of PANDA



And many more!

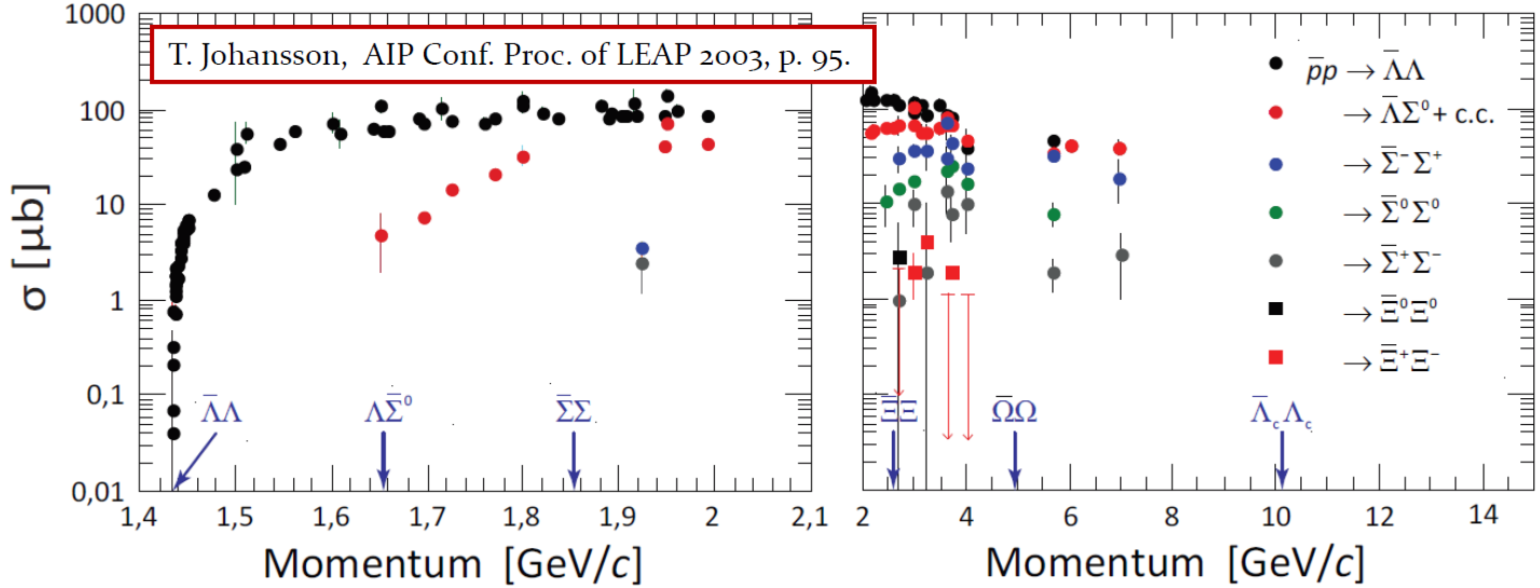
Strangeness Physics with PANDA



What happens if we replace one of the light quarks in the nucleon with a heavier one?

- Main objectives
  - Structure and production dynamics of established states
  - Search for hitherto unknown states
  - Search for CP violation in hyperon decays

Advantages of PANDA



- Measured cross sections of ground state hyperons $\bar{p}p \to \bar{Y}Y$ 1-100 μb*
- Excited hyperon cross sections should 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

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PANDA is a strangeness factory

- 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

p_{beam} (GeV/c)	Reaction	$\sigma(\mu b)$	$\varepsilon(\%)$	Rate (s^{-1}) @ $10^{31}\ cm^{-2}s^{-1}$	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**	207000
6.0	$\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda$	20	6.1	5.0	21	432000
4.6	$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	~ 1	8.2	0.3	274	26000
7.0	$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	~ 0.3	7.9	0.1	65	86000

** 90% C.L.

*By W. Ikegami Andersson (PhD thesis, Uppsala 2020) and G. Perez Andrade (Master thesis, Uppsala 2019)

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    - Exclusive measurements of
        - $\bar{p}p \to \bar{\Lambda}\Lambda, \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$
        - $\bar{p}p \to \bar{\Sigma}^0\Lambda, \Lambda \to p\pi^-, \bar{\Sigma}^0 \to \bar{\Lambda}\gamma, \bar{\Lambda} \to \bar{p}\pi^+$
        - $\bar{p}p \to \bar{\Xi}^+\Xi^-, \Xi^- \to \Lambda\pi^-, \Lambda \to p\pi^-, \bar{\Xi}^+ \to \bar{\Lambda}\pi^+, \bar{\Lambda} \to \bar{p}\pi^+$
    - Id
    - B

PANDA will be a hyperon factory already during Phase One!

Approx 20 times larger rates with full luminosity!

1.64	$\bar{p}p \to \bar{\Lambda}\Lambda$	64.0	16.0	44	114	$3.8 \cdot 10^6$
1.77	$\bar{p}p \to \bar{\Sigma}^0\Lambda$	10.9	5.3	2.4	>11**	207000
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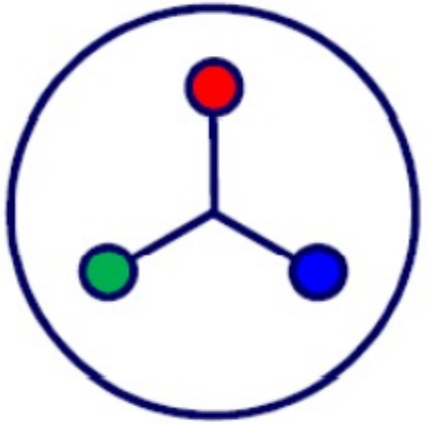
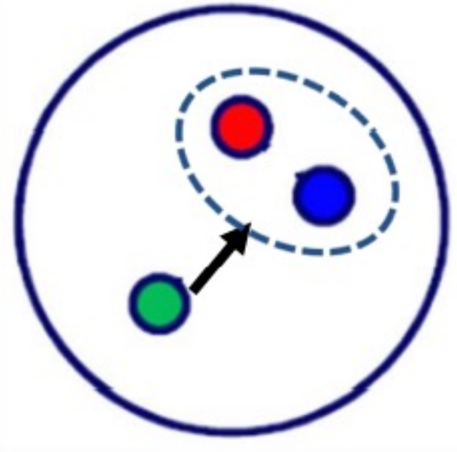
Hyperon spectroscopy

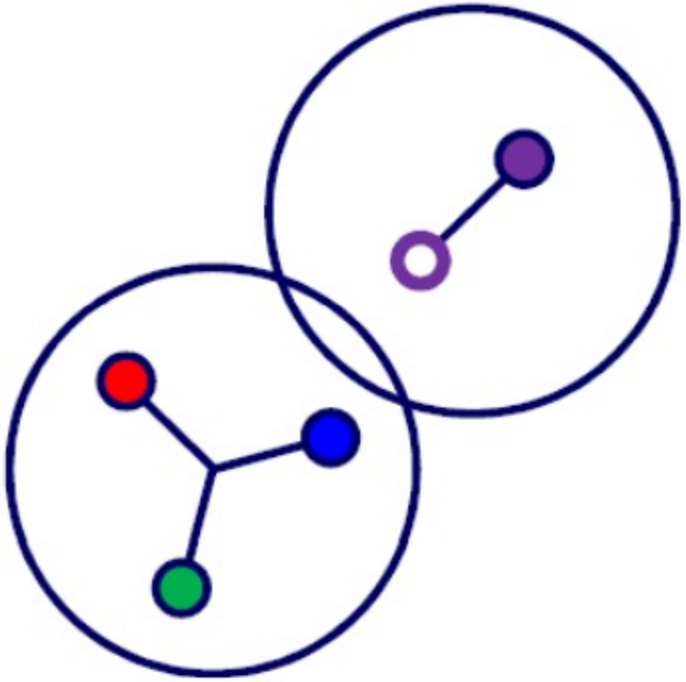
- How do quarks form baryons?
  - Which forces are involved?
  - What are the degrees of freedom?



Symmetric quark model



Quark - diquark

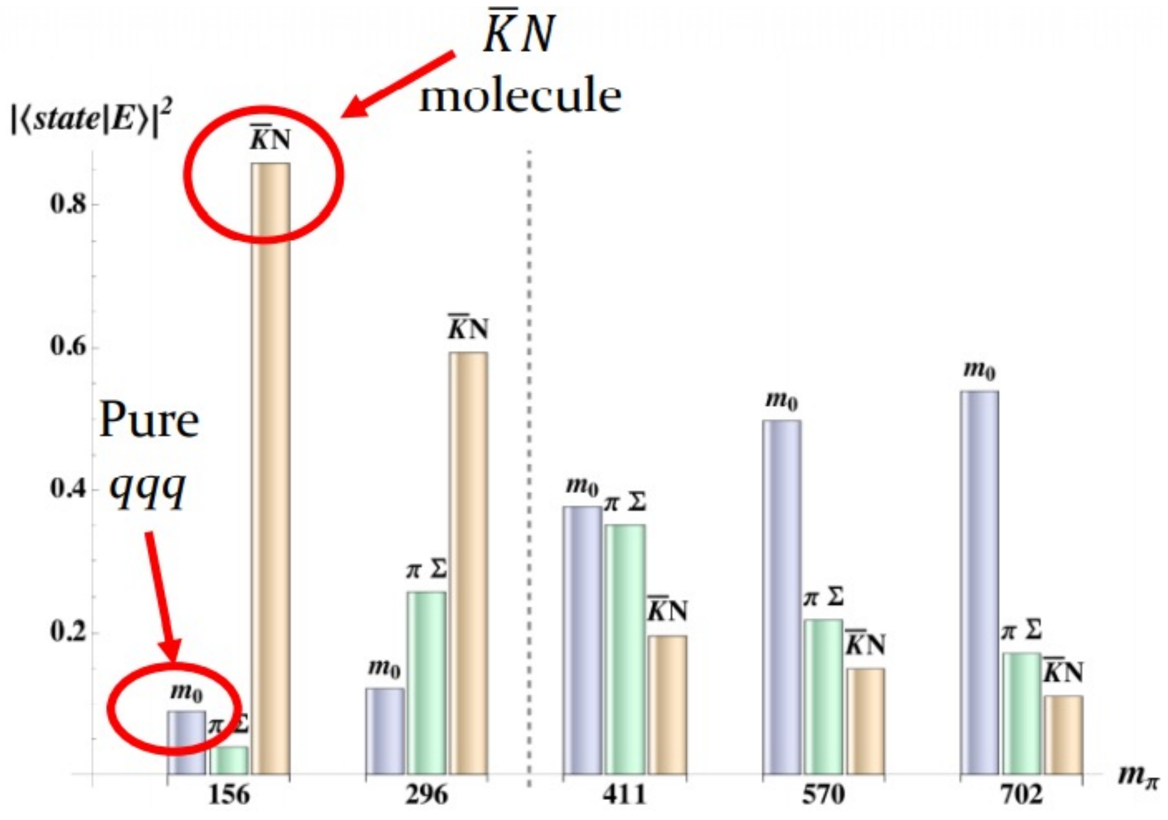


Molecule / hadronic d.o.f.

Hyperon spectroscopy

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

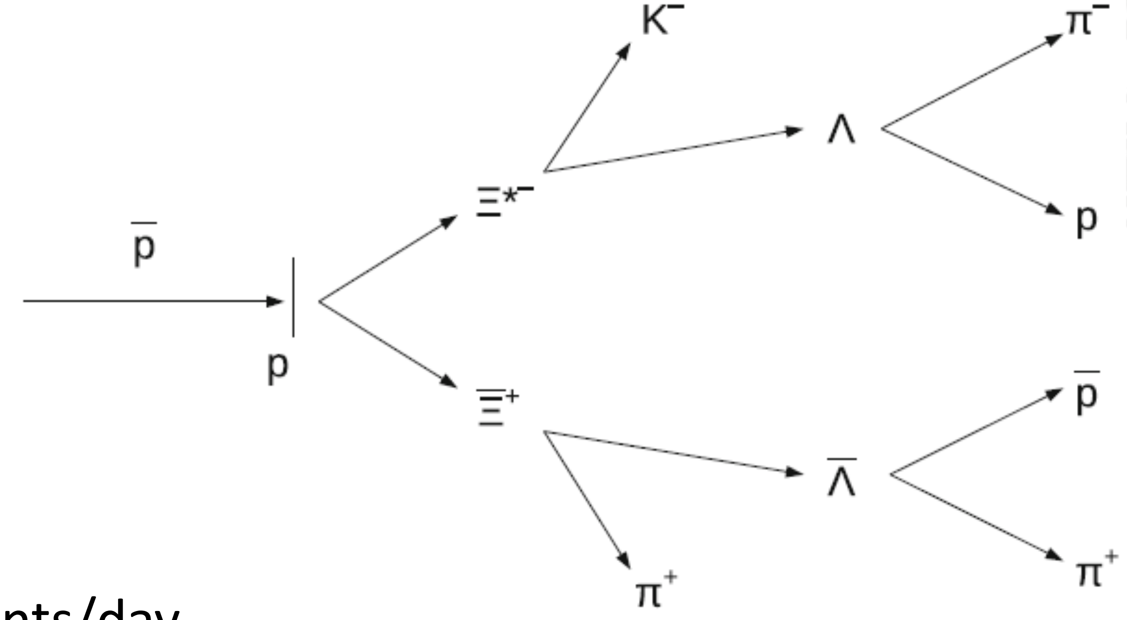
- Light baryon spectrum*
  - “Missing” states
  - Parity pattern
- Single strange spectrum
  - “Missing” states
  - Non-*qqq* features e.g. of $\Lambda(1405)$**
- Multi-strange spectrum
  - Data scarce

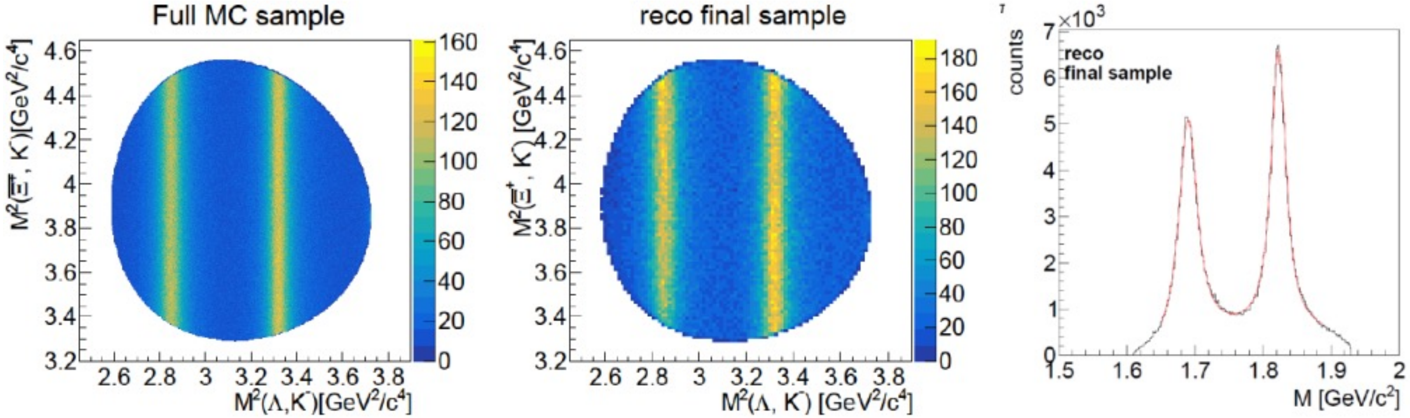


*EPJA 48 (2012) 127, EPJA 10 (2001) 395
**PRL 114 (2015) 132002

Feasibility study of $\bar{p}p \rightarrow \bar{\Xi}^{+}\Lambda K^{-} + c.c.$

- Simplified simulation framework
- $p_{beam} = 4.6\ \mathrm{GeV}/c$
- $\sigma = 1\mu\mathrm{b}$ and $L = 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Results*
  - Efficiency $\sim 5\%$, $\frac{S}{B} \sim 20$
  - ~ 37000 exclusive $\bar{\Xi}^{+}\Lambda K^{-} + c.c.$ events/day





Simulations by J. Puetz and A. Gillitzer

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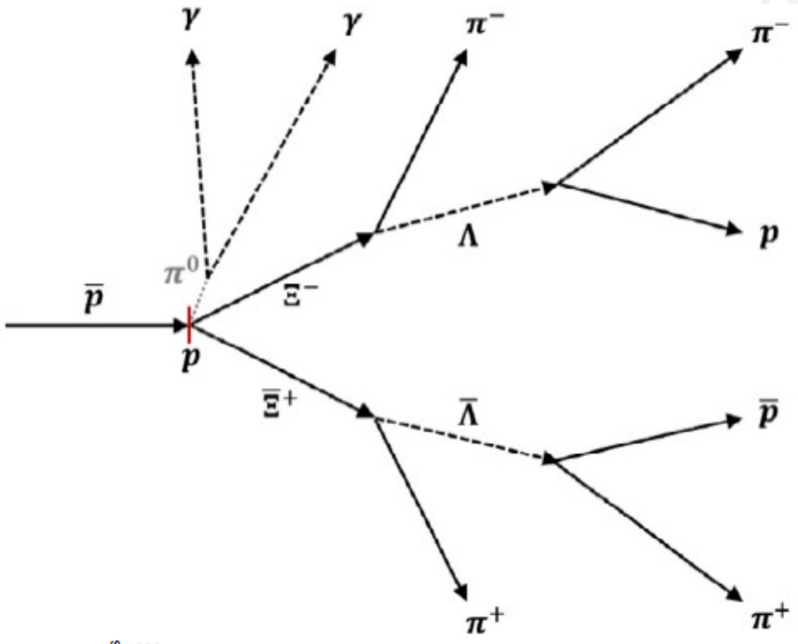
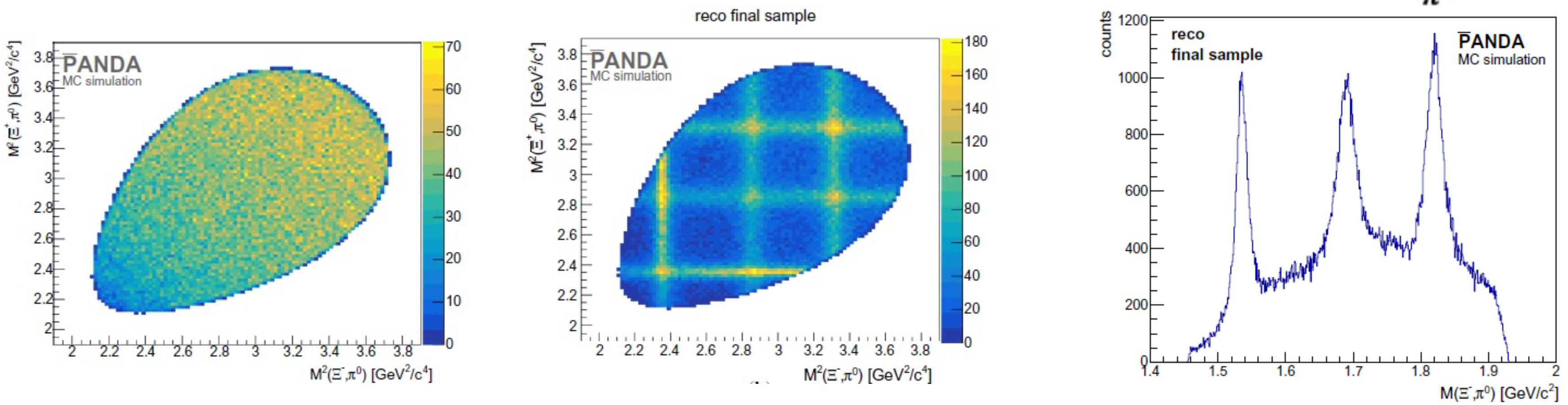
*J. Puetz, PhD Thesis, Bonn University (2020), EPJA (2021) 57:149

Feasibility study of $\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-\pi^0$



- Simplified simulation framework
- $p_{beam} = 4.6 \text{ GeV}/c$
- $\sigma = 1\mu\text{b}$ and $L = 10^{31}\text{cm}^{-2}\text{s}^{-1}$
- Continuum and resonant states $\Xi(1530)^-, \Xi(1690)^-, \Xi(1820)^-$
- Results*
  - Efficiency $\sim 3.6\%$, $\frac{S}{B} \sim 22$



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EPJA (2021) 57:149

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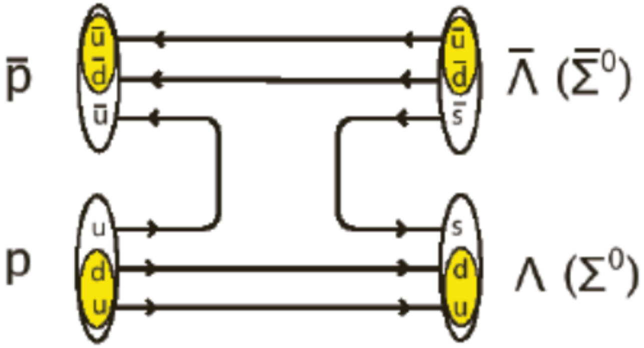
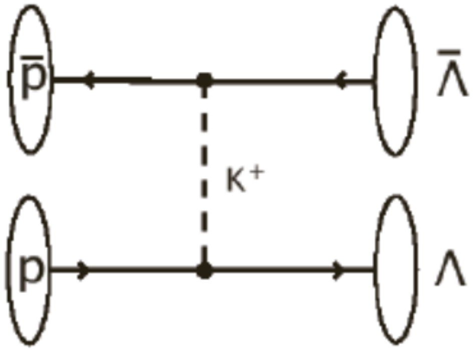
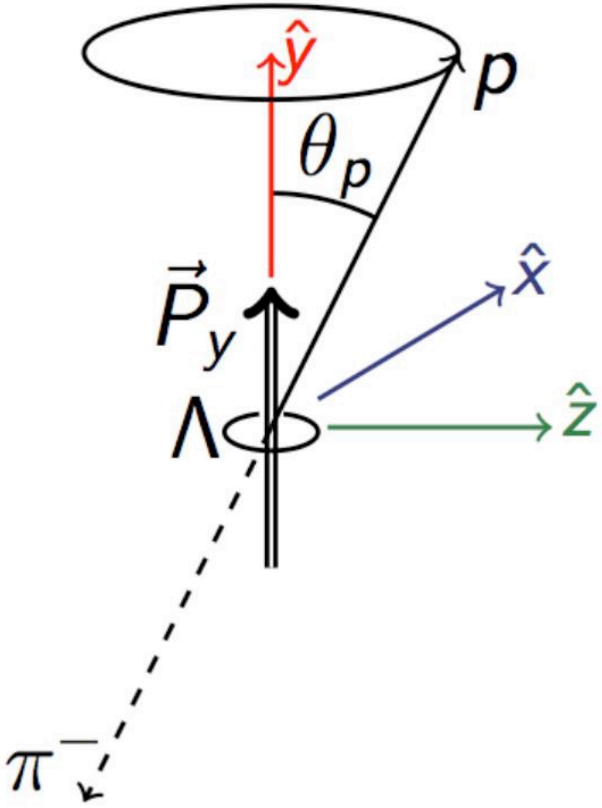
Hyperon spin properties

- Accessible, e.g., through $I(\cos\theta_p) = N(1 + \alpha P_\Lambda \cos\theta_p)$
  - α decay asymmetry, sensitive to CP violation
  - CP symmetry: $\alpha = -\bar{\alpha}$
  - P_Λ production related



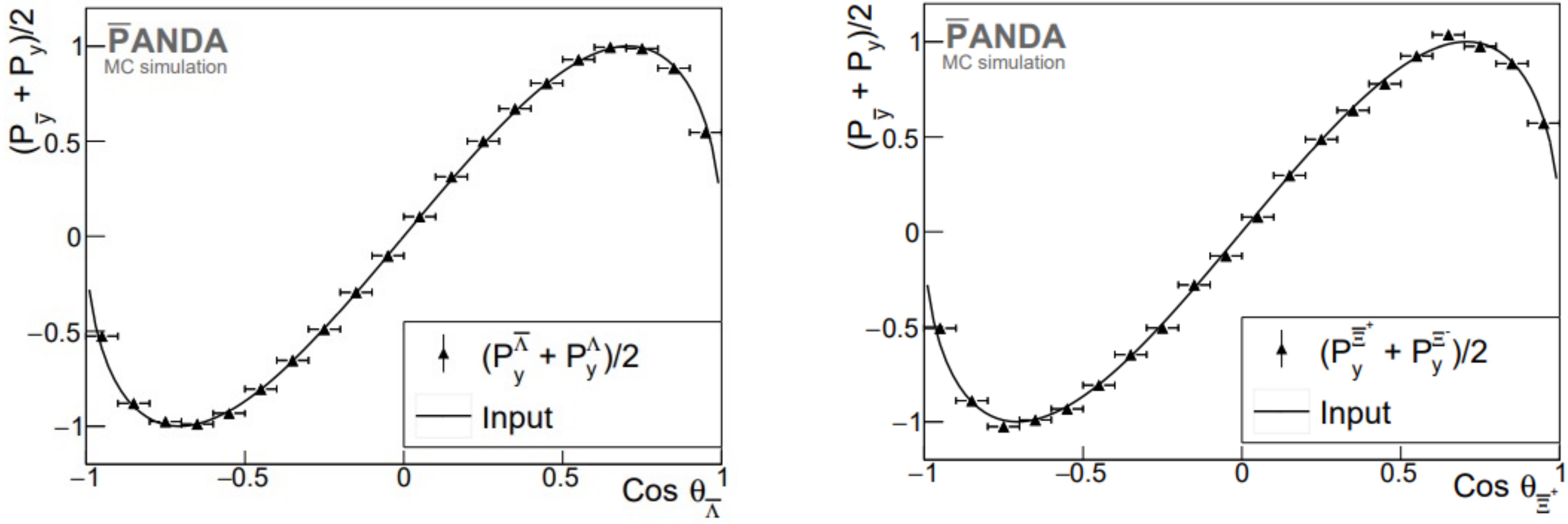




Hyperon prospects with PANDA

$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ at $p_{beam} = 1.64$ GeV/c

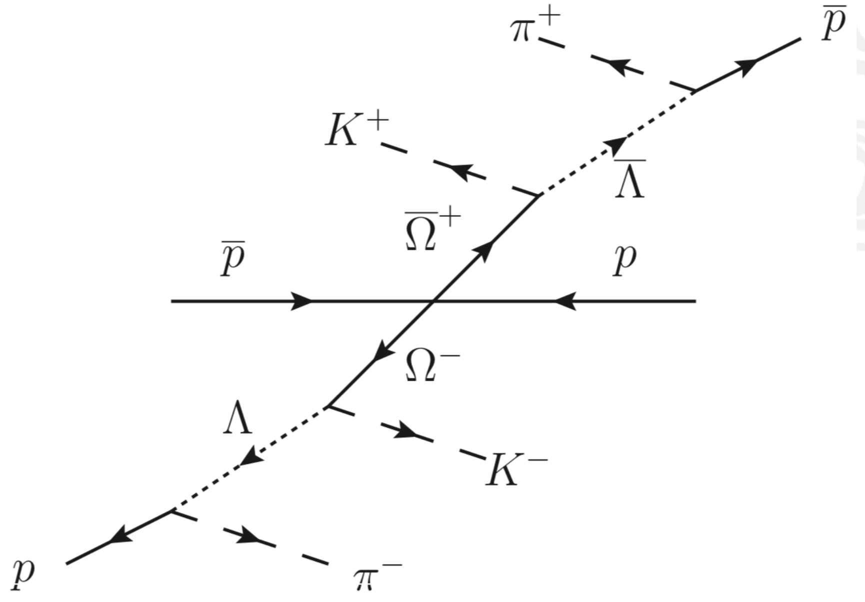
$\bar{p}p \rightarrow \bar{\Xi}\Xi$ at $p_{beam} = 4.6$ GeV/c



Spin observables in production of single- and multistrange hyperons*

*EPJA (2021) 57:154

$\bar{Y}Y$ spin observables in $\bar{p}p$ collisions

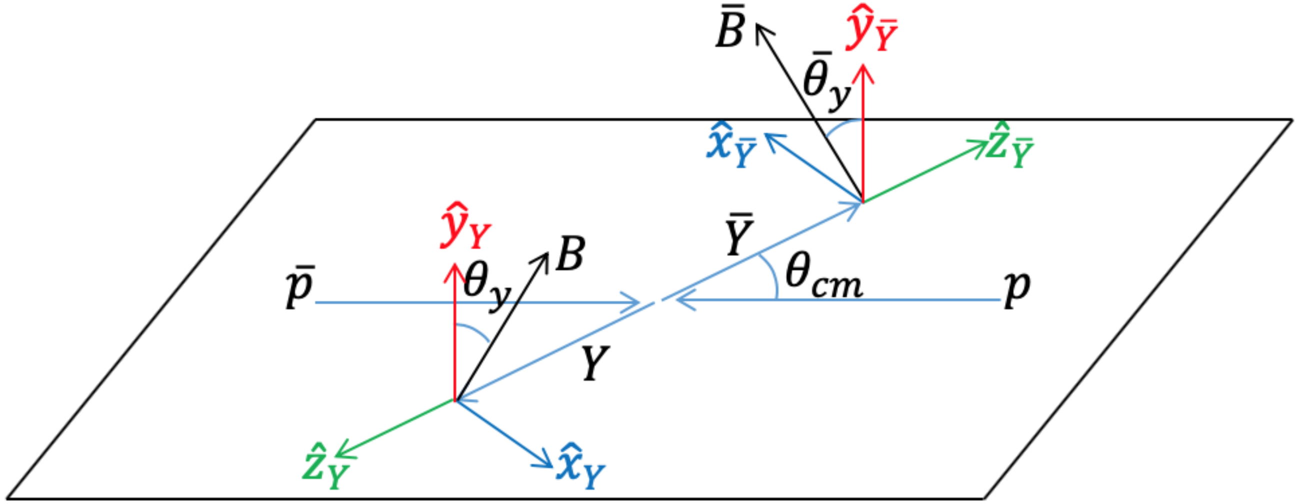


- Density matrix of a hyperon given by

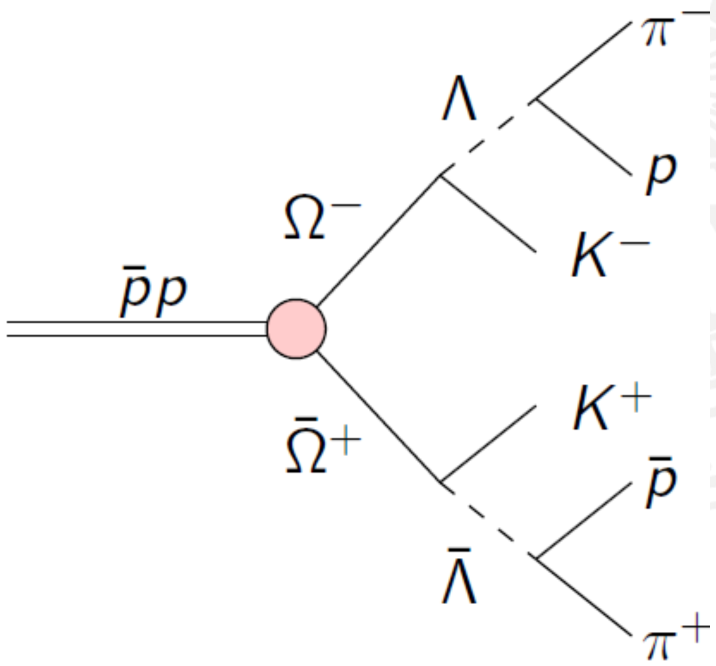
$$\rho = \frac{1}{2j+1}\mathcal{I} + \sum_{L=1}^{2j} \frac{2j}{2j+1} \sum_{M=-L}^{L} Q_M^L r_M^L$$

- Angular distributions of daughters given by operating T and taking trace

$$I = Tr\left(T\rho T^\dagger\right), \qquad T|\psi_i\rangle = |\psi_f\rangle$$



Polarisation in $\bar{\Omega}^+\Omega^-$



- Fifteen polarisation parameters: $r^L_M, L = 1,2,3, M = -L, \dots, L$
- Eight are zero due to symmetry
- Determine r^1_{-1}, r^3_{-1} from Λ decay

$$I(\theta_p, \phi_p) = \frac{1}{4\pi}\left(1 + \alpha_\Omega \alpha_\Lambda \cos\theta_p + \alpha_\Lambda \left(\sqrt{\frac{3}{5}} r^1_{-1} + \frac{1}{2\sqrt{10}} r^3_{-1}\right)(\beta_\Omega \cos\phi_p + \gamma_\Omega \sin\phi_p) \sin\theta_p\right)$$

- This also means

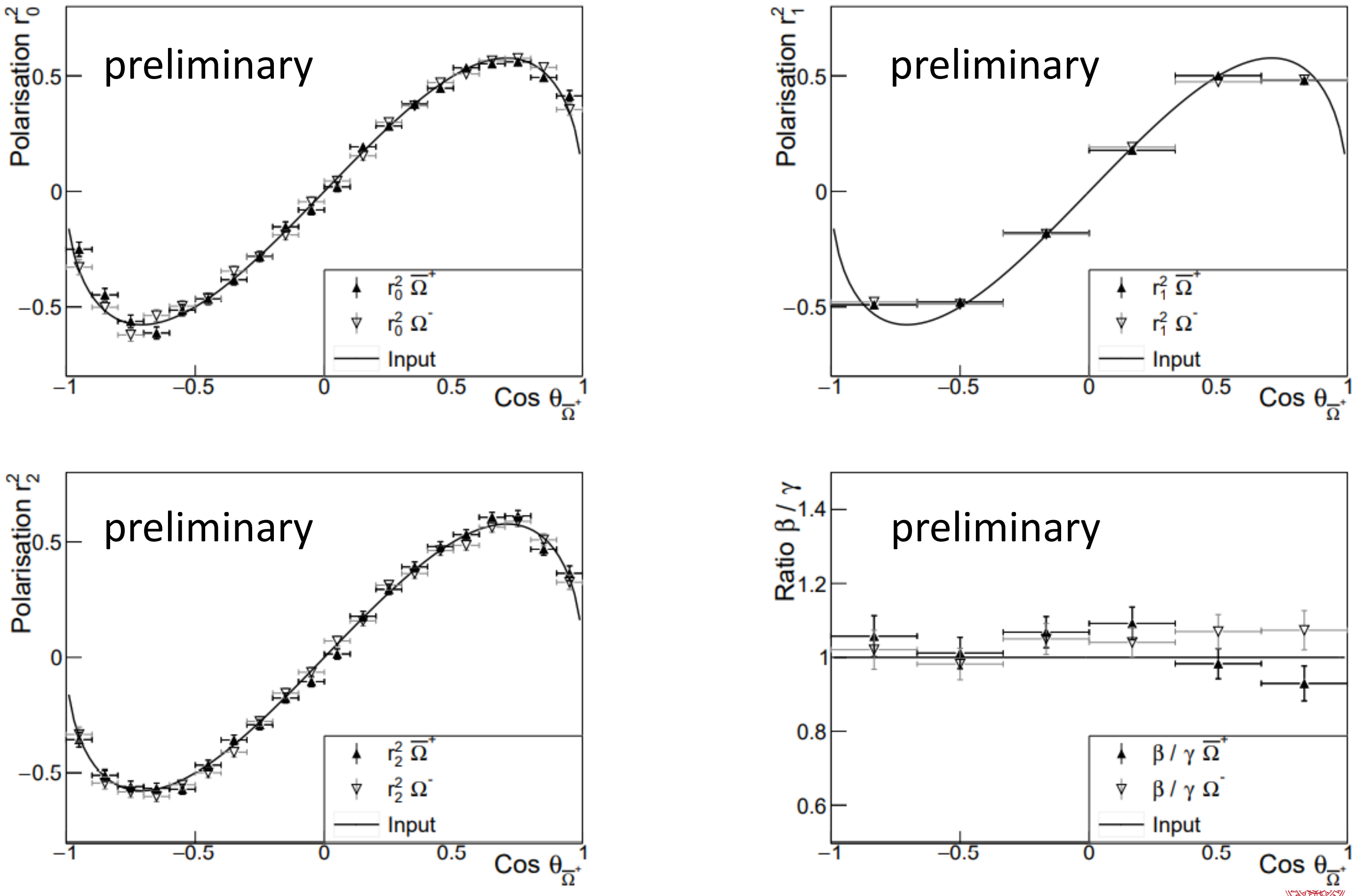
$$\frac{\beta_\Omega}{\gamma_\Omega} = \frac{\langle \cos\phi_p \rangle}{\langle \sin\phi_p \rangle}$$

- CP violation parameters $\beta_\Omega, \gamma_\Omega$ can be determined to a sign for the first time $(\alpha^2 + \beta^2 + \gamma^2 = 1)$
- See also E. Perotti, J. Phys.: Conf. Ser. **1024** 012019

$\bar{\Omega}^{+}\Omega^{-}$ Polarisation at 7 GeV/c

- High luminosity
- Low cross section
- Idealised reconstruction and particle identification
- 80 days of data taking under ideal conditions

Simulations by W. Ikegami Andersson



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$\bar{\Omega}^+\Omega^-$ Polarisation at 7 GeV/*c*

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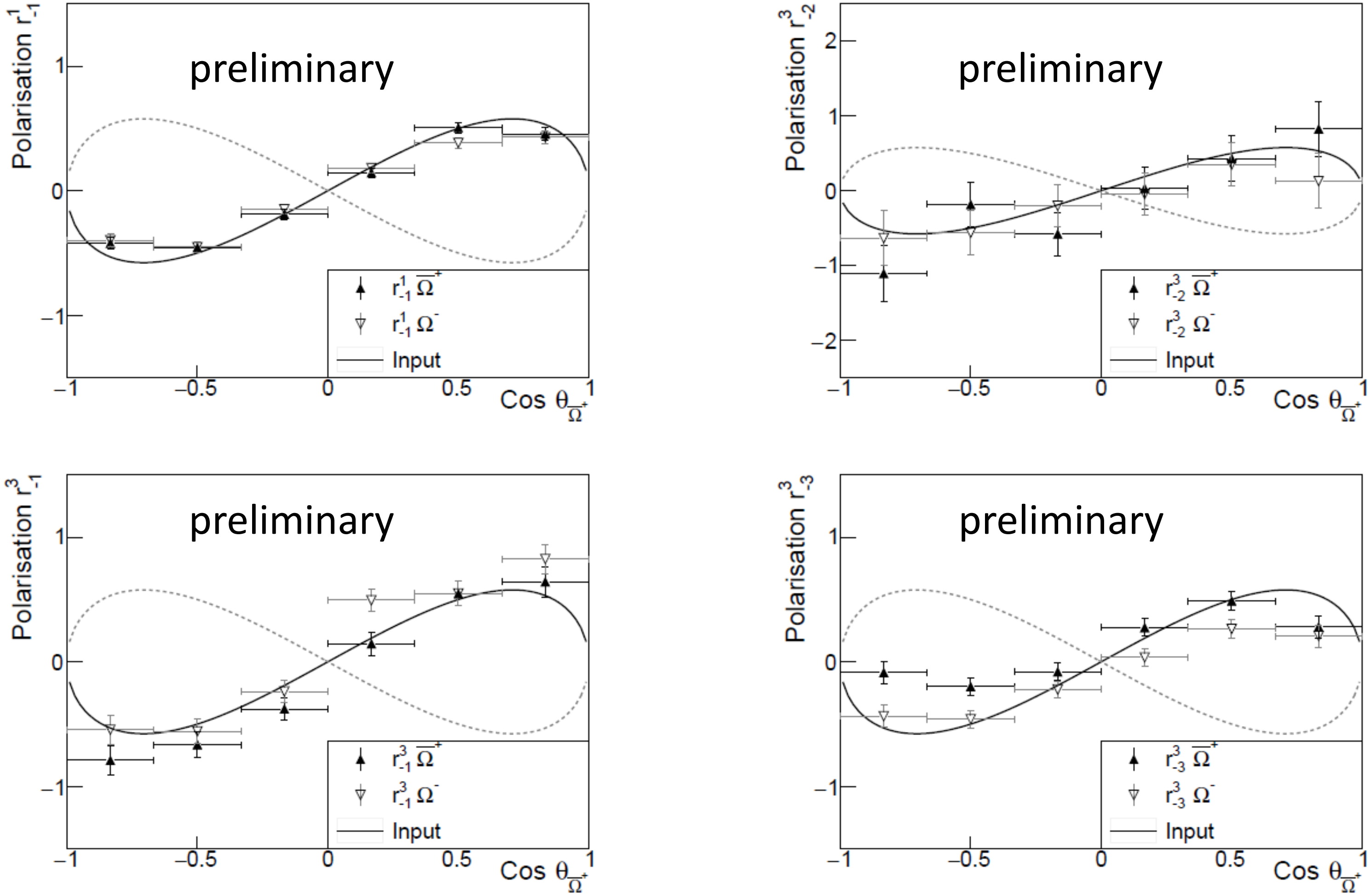

Simulations by W. Ikegami Andersson

Precision CP tests at BESIII

Table 1 | Summary of results

Param		
α_ψ		
$\Delta\Phi$		
α_Ξ		
ϕ_Ξ		
$\bar{\alpha}_\Xi$		
$\bar{\phi}_\Xi$		
α_Λ		
$\bar{\alpha}_\Lambda$		
$\xi_P-\xi_S$		
$\delta_P-\delta_S$		
A_{CP}^{Ξ}	$(6\pm13\pm6)\times10^{-3}$	–
$\Delta\phi_{CP}^{\Xi}$	$(-5\pm14\pm3)\times10^{-3}$ rad	–
A_{CP}^{Λ}	$(-4\pm12\pm9)\times10^{-3}$	$(-6\pm12\pm7)\times10^{-3}$
$\langle\phi_\Xi\rangle$	$0.016\pm0.014\pm0.007$ rad	

- Formalism by Perotti *et al.** and Adlarson & Kupsc**

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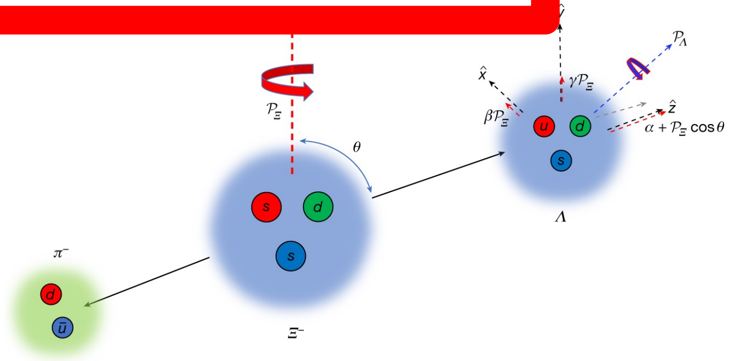
Article | Open Access | Published: 01 June 2022

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

The BESIII Collaboration

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

- What can PANDA do?
  - Binary production, high rates
  - Exclusive measurements
  - ➢ Exploit entanglement



* Phys. Rev. D 99, 056008 (2019)

** Phys. Rev. D 100, 114005 (2019)

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

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

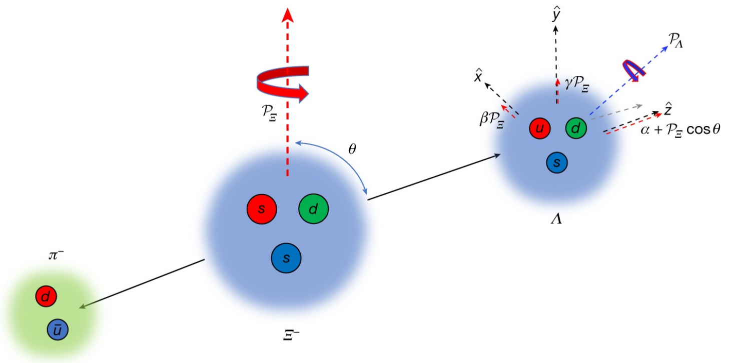
Precision CP tests at BESIII

Table 1 | Summary of results

Parameter	This work	Previous result
α_ψ	$0.586\pm0.012\pm0.010$	$0.58\pm0.04\pm0.08$
$\Delta\Phi$	$1.213\pm0.046\pm0.016$ rad	–
α_Ξ	$-0.376\pm0.007\pm0.003$	-0.401 ± 0.010
ϕ_Ξ	$0.011\pm0.019\pm0.009$ rad	-0.037 ± 0.014 rad
$\bar{\alpha}_\Xi$	$0.371\pm0.007\pm0.002$	–
$\bar{\phi}_\Xi$	$-0.021\pm0.019\pm0.007$ rad	–
α_Λ	$0.757\pm0.011\pm0.008$	$0.750\pm0.009\pm0.004$
$\bar{\alpha}_\Lambda$	$-0.763\pm0.011\pm0.007$	$-0.758\pm0.010\pm0.007$
$\xi_P-\xi_S$	$(1.2\pm3.4\pm0.8)\times10^{-2}$ rad	–
$\delta_P-\delta_S$	$(-4.0\pm3.3\pm1.7)\times10^{-2}$ rad	$(10.2\pm3.9)\times10^{-2}$ rad
A_{CP}^{Ξ}	$(6\pm13\pm6)\times10^{-3}$	–
$\Delta\phi_{CP}^{\Xi}$	$(-5\pm14\pm3)\times10^{-3}$ rad	–
A_{CP}^{Λ}	$(-4\pm12\pm9)\times10^{-3}$	$(-6\pm12\pm7)\times10^{-3}$
$\langle\phi_\Xi\rangle$	$0.016\pm0.014\pm0.007$ rad	

- Formalism by Perotti *et al.** and Adlarson & Kupsc**
- Exploits polarisation, entanglement, and sequential decays
- First measurement of weak phase difference
- First direct measurement of $\bar{\Xi}$ decay parameters
- Independent measurement of decay parameter α_Λ
- Strong phase difference consistent with zero

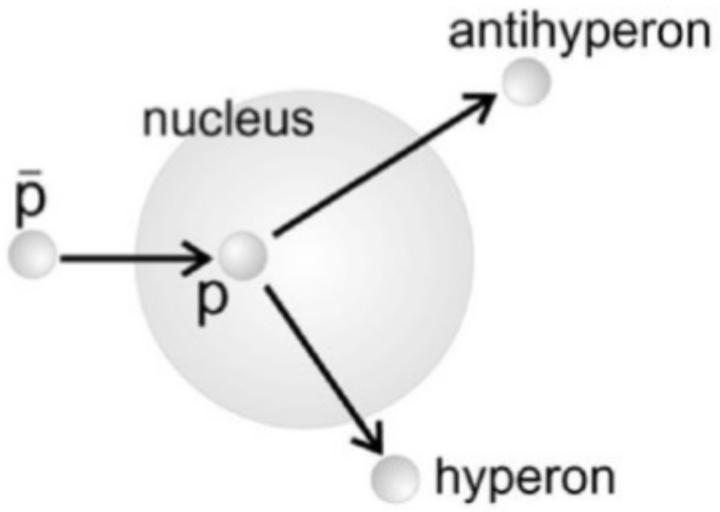
- What can PANDA do?
  - Binary production, high rates
  - Exclusive measurements
  - ➢ Exploit entanglement



* Phys. Rev. D 99, 056008 (2019)
** Phys. Rev. D 100, 114005 (2019)

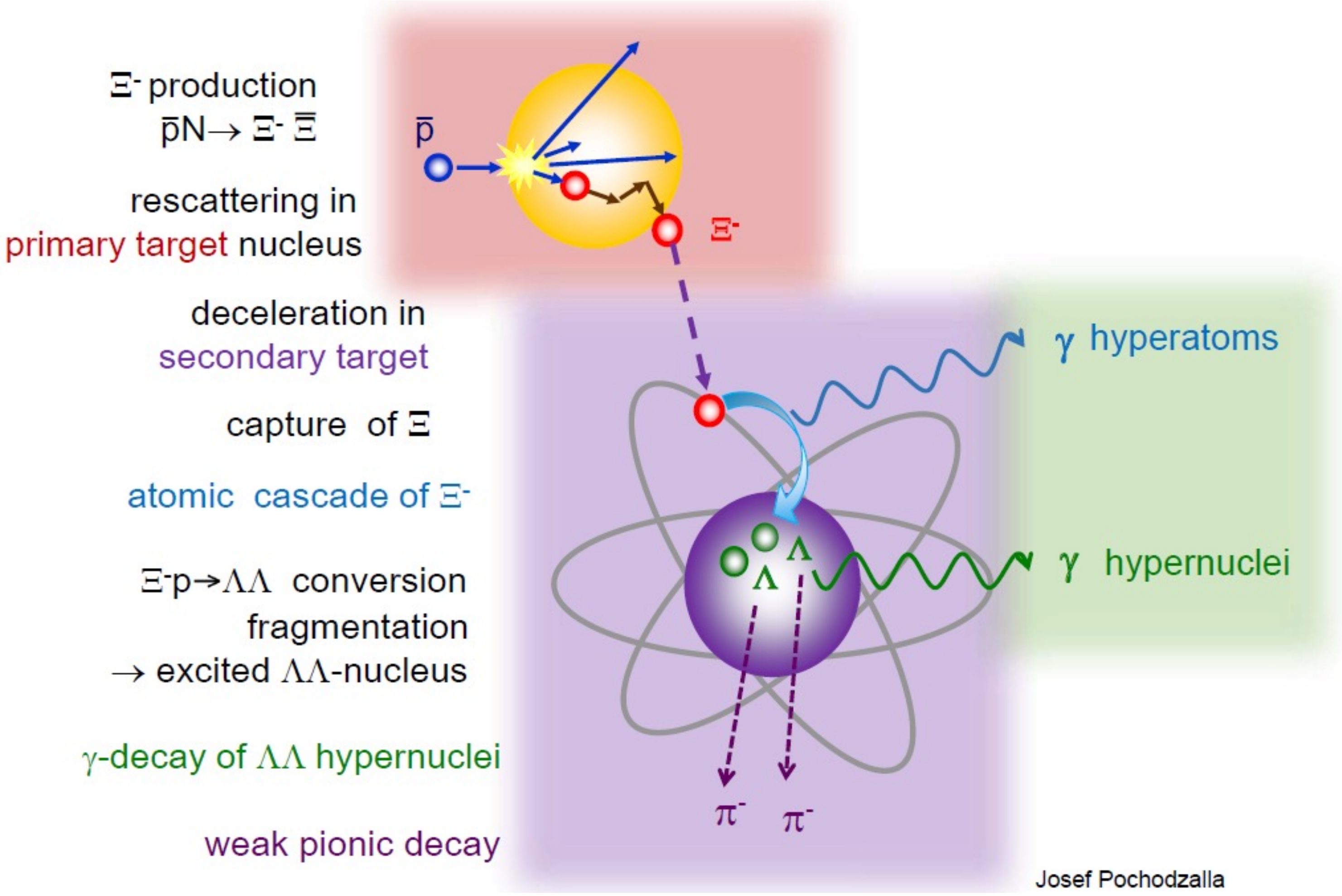
Hadrons in Nuclei

- Multi-baryon interactions crucial to understand macroscopic systems such as neutron stars
- In PANDA, these interactions can be studies in*
  - Antihyperons in nuclei
  - Hyperatom spectroscopy
  - Hypernuclear spectroscopy

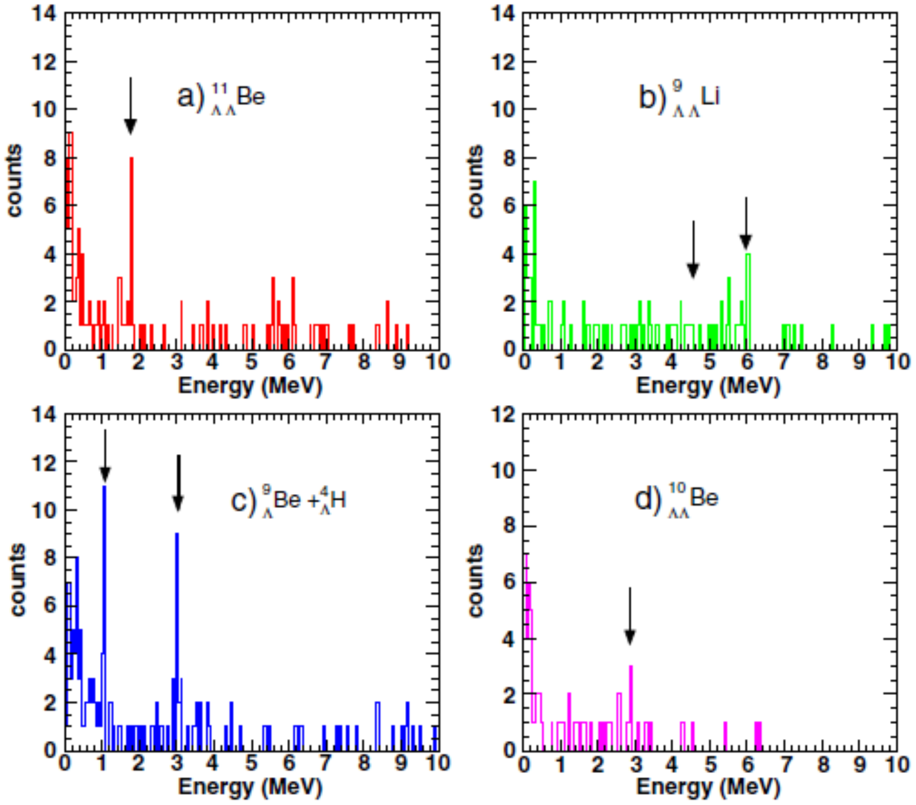


*Nucl. Phys. A 954, 323 (2016)

Hyperatoms and hypernuclei



Alicia Sanchez Lorente, Hyperfine Interact 213, 41 (2012)



~ 33000 stopped Ξ per day!

Summary

- PANDA is a next-generation antiproton facility for hadron and nuclear physics
- The physics programme consists of four pillars:
  - Nucleon structure
  - Strangeness physics
  - Charm and exotics
  - Hadrons in nuclei
- PANDA has great prospects in strangeness physics
  - Hyperon spectroscopy
  - Hyperon spin observables
  - Hypernuclei

Thank you for your attention!

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Backup

Polarisation in $\bar{\Xi}^+\Xi^-$

- Decays: $\Xi^- \rightarrow \Lambda\pi^-,\ \Lambda \rightarrow \pi^- p$
- Three polarisation parameters:

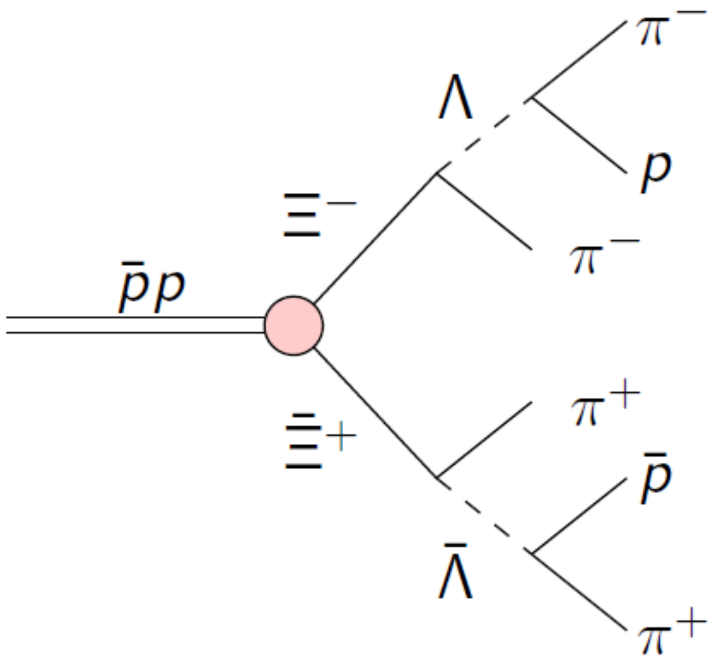
$$r^1_1, r^1_0, r^1_{-1}$$

- Directly related to P_x, P_y, P_z
  Symmetry $\Rightarrow P_x = P_z = 0$
- First decay $\Xi^- \rightarrow \Lambda\pi^-$ $\Rightarrow$ polarisation P_y

$$I(\cos\theta_y) = \frac{1}{4\pi}(1 + \alpha P_y \cos\theta_y)$$

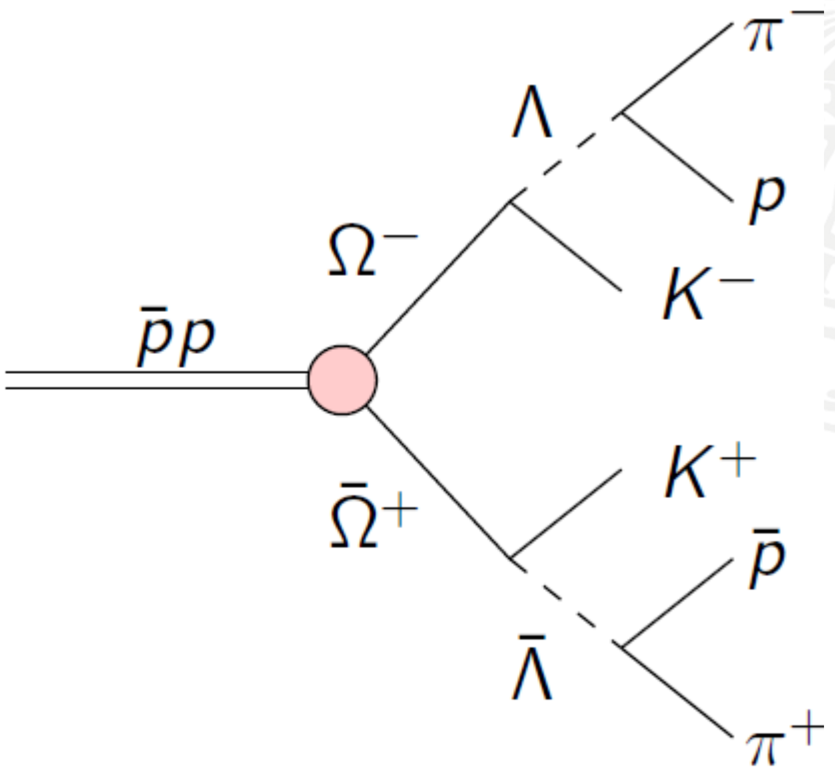
- Polarisation can be extracted using moments

$$\langle\cos\theta_y\rangle = \int_{-1}^{1} I(\cos\theta_y) \times \cos\theta_y \, d\cos\theta_y = \frac{3}{\alpha} P_y$$



Polarisation in $\bar{\Omega}^+\Omega^-$

- Decays: $\Omega^- \to \Lambda K,\ \Lambda \to \pi^- p$
- Fifteen polarisation parameters:
  $r_M^L, L = 1,2,3, M = -L$
- Eight are zero due to symmetry
- Angular distribution of first decay $\Omega^- \to \Lambda K$:



$$I(\theta_\Lambda, \phi_\Lambda) = \frac{1}{4\pi}[1 + \frac{\sqrt{3}}{2}(1 - 3\cos^2\theta_\Lambda)r_0^2 - \frac{3}{2}\sin^2\theta_\Lambda \cos 2\phi\, r_2^2 + \frac{3}{2}\sin 2\theta_\Lambda \cos\phi\, r_1^2$$

$$- \frac{1}{40}\alpha \sin\theta_\Lambda\,(8\sqrt{15}r_{-1}^1 \sin\theta_\Lambda + 9\sqrt{10}r_{-1}^3(3 + 5\cos 2\theta_\Lambda \sin\phi_\Lambda)$$

$$+30(3r_2^3 \sin 2\phi_\Lambda \sin 2\theta_\Lambda + \sqrt{6}r_3^3 \sin 3\phi \sin^2\theta_\Lambda))]$$

Polarisation in $\bar{\Omega}^+\Omega^-$

- Determine r_0^2, r_1^2, r_2^2 from Ω decay

- $\langle \sin\theta_\Lambda \rangle = \int_0^\pi \int_0^{2\pi} I(\theta_\Lambda, \phi_\Lambda) \times \sin\theta_\Lambda \sin\theta_\Lambda \, d\theta_\Lambda d\phi_\Lambda = \frac{\pi}{32}(8 + \sqrt{3} r_0^2)$
- $\langle \cos\theta_\Lambda \cos\phi_\Lambda \rangle = \int_0^\pi \int_0^{2\pi} I(\theta_\Lambda, \phi_\Lambda) \times \cos\theta_\Lambda \cos\phi_\Lambda \sin\theta_\Lambda \, d\theta_\Lambda d\phi_\Lambda = -\frac{\pi}{32} r_1^2$
- $\langle \sin^2\phi_\Lambda \rangle = \int_0^\pi \int_0^{2\pi} I(\theta_\Lambda, \phi_\Lambda) \times \sin^2\phi_\Lambda \sin\theta_\Lambda \, d\theta_\Lambda d\phi_\Lambda = \frac{1}{4}(2 + r_2^2)$

Polarisation in $\bar{\Omega}^+\Omega^-$

- Determine r^1_{-1}, r^3_{-1} from Λ decay

$$I(\theta_p, \phi_p) = \frac{1}{4\pi}\left(1 + \alpha_\Omega \alpha_\Lambda \cos\theta_p + \alpha_\Lambda \left(\sqrt{\frac{3}{5}} r^1_{-1} + \frac{1}{2\sqrt{10}} r^3_{-1}\right)(\beta_\Omega \cos\phi_p + \gamma_\Omega \sin\phi_p)\sin\theta_p\right)$$

- This also means

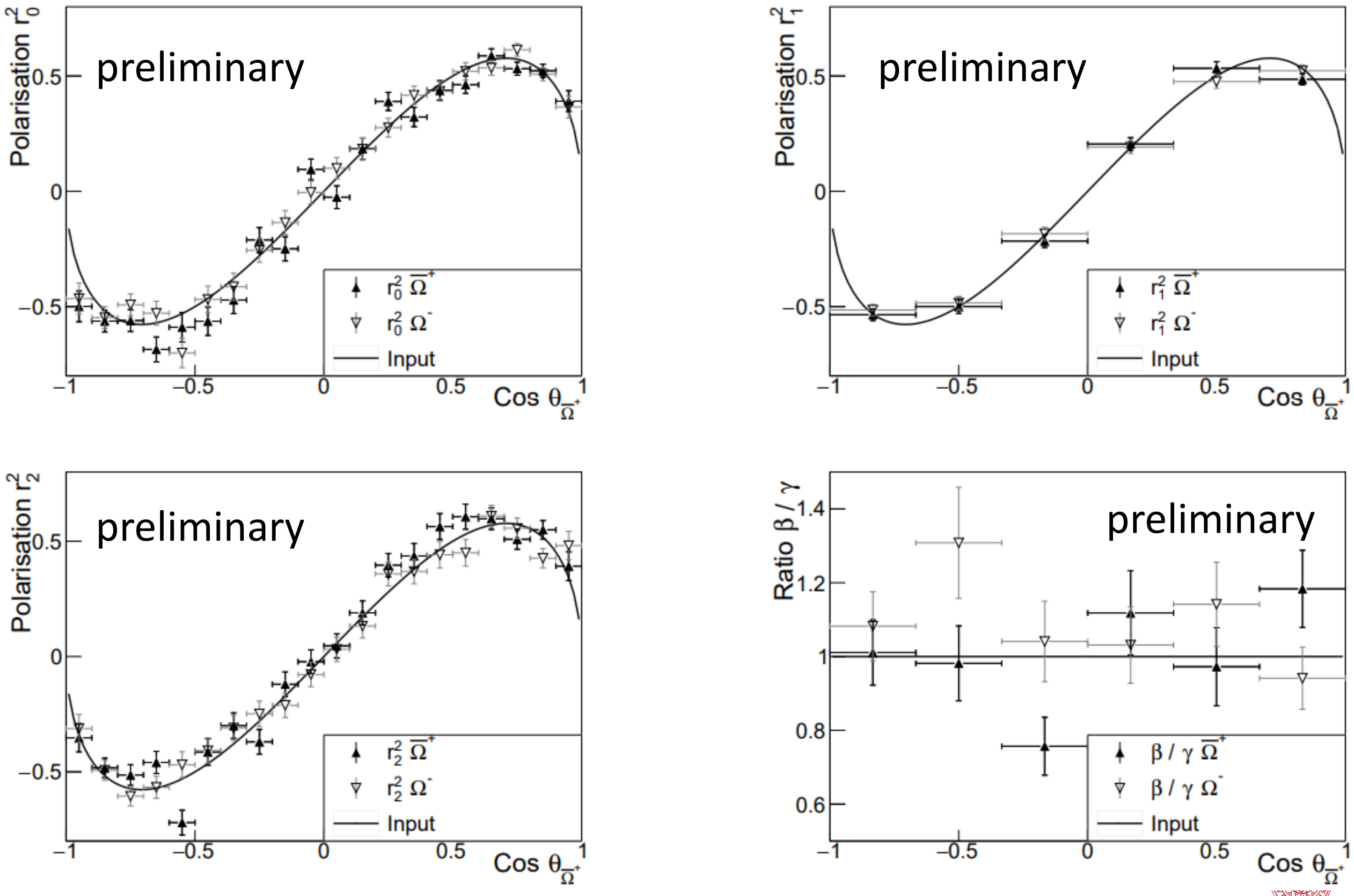
$$\frac{\beta_\Omega}{\gamma_\Omega} = \frac{\langle \cos\phi_p \rangle}{\langle \sin\phi_p \rangle}$$

- Four more polarisation parameters accessible similarly
- CP violation parameters $\beta_\Omega, \gamma_\Omega$ can be determined to a sign for the first time ($\alpha^2 + \beta^2 + \gamma^2 = 1$)
- See also E. Perotti, J. Phys.: Conf. Ser. **1024** 012019

$\bar{\Omega}^{+}\Omega^{-}$ Polarisation at 15 GeV/c

- High luminosity
- Low cross section
- Idealised reconstruction and particle identification
- 80 days of data taking under ideal conditions

Simulations by W. Ikegami Andersson



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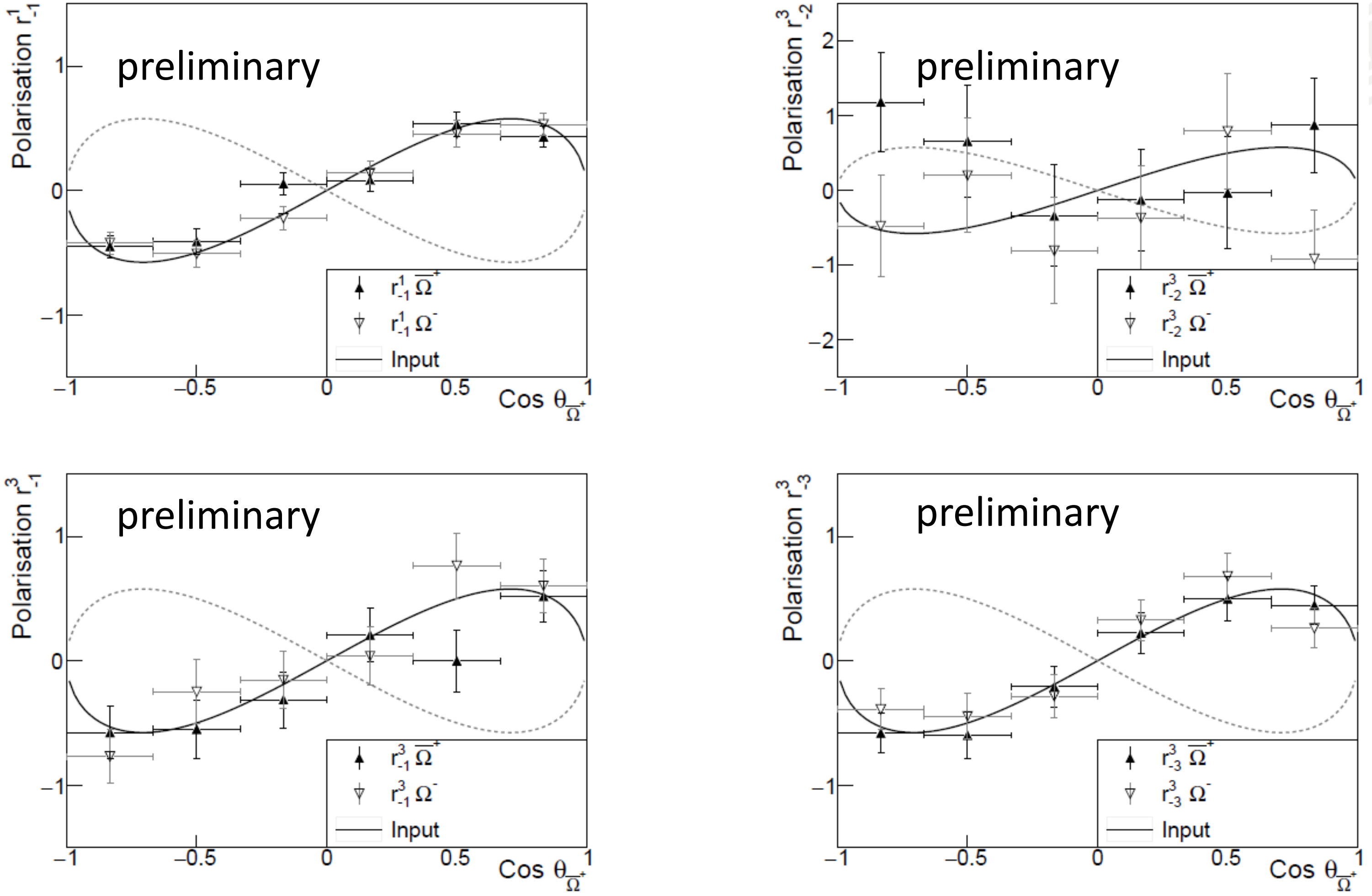
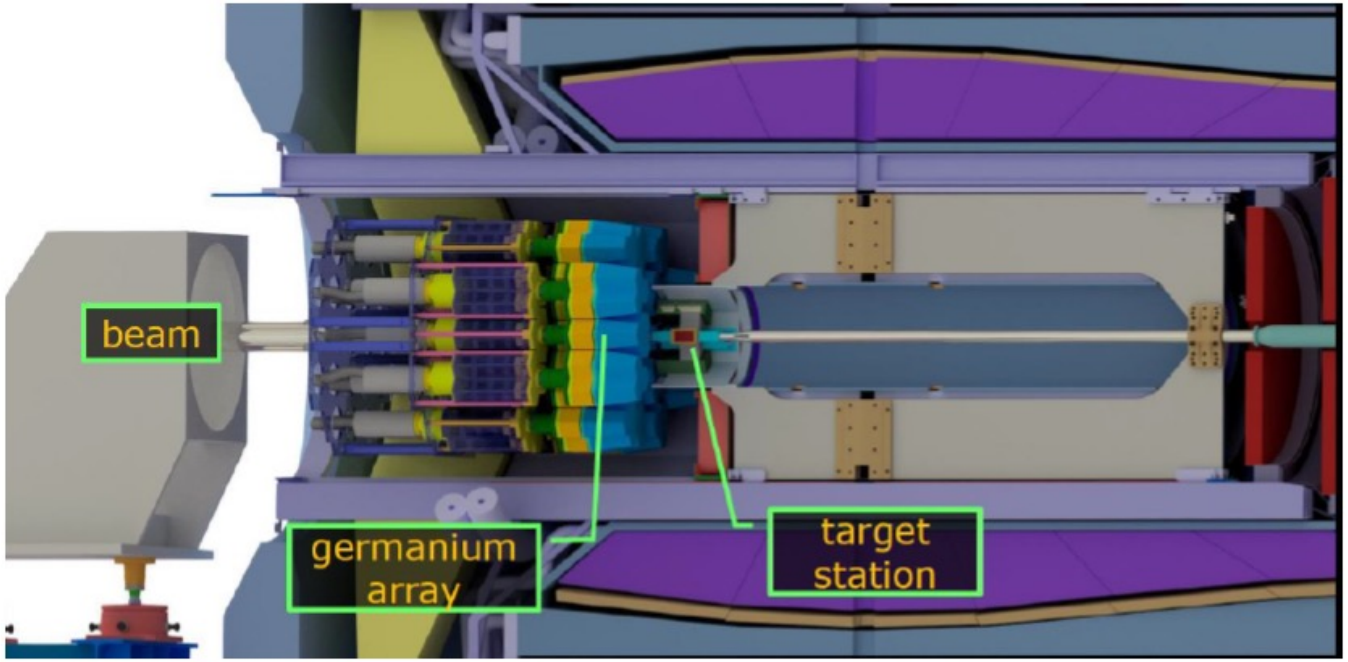
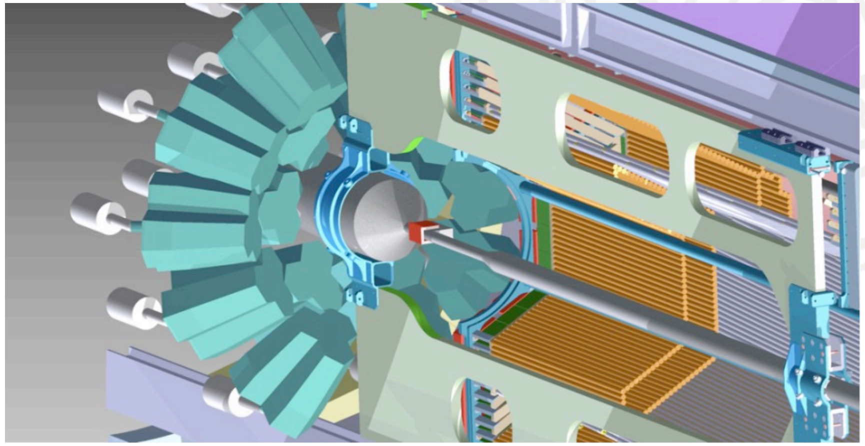
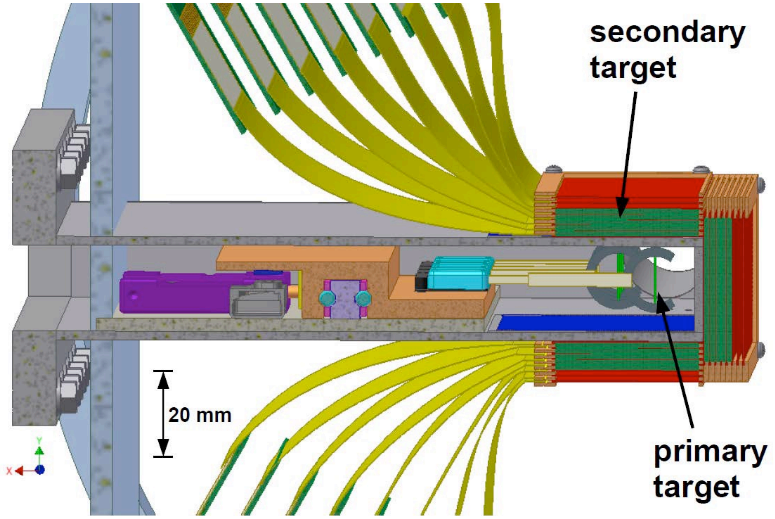


Hyperatoms and hypernuclei







- Large $\bar{Y}Y$ production rates
  - Opportunity for multi-strange physics
- Secondary target
- Germanium detector array for γ-spectroscopy

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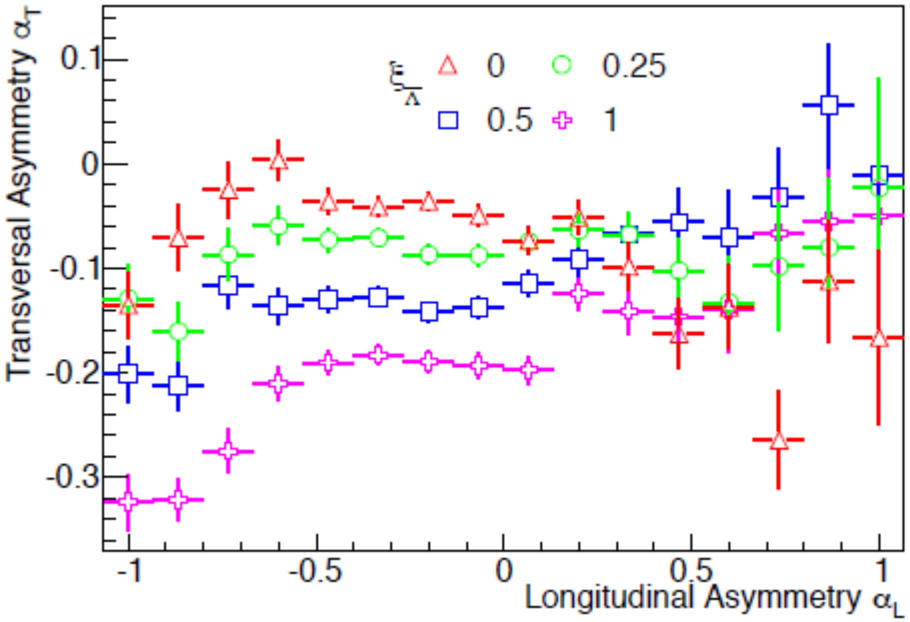
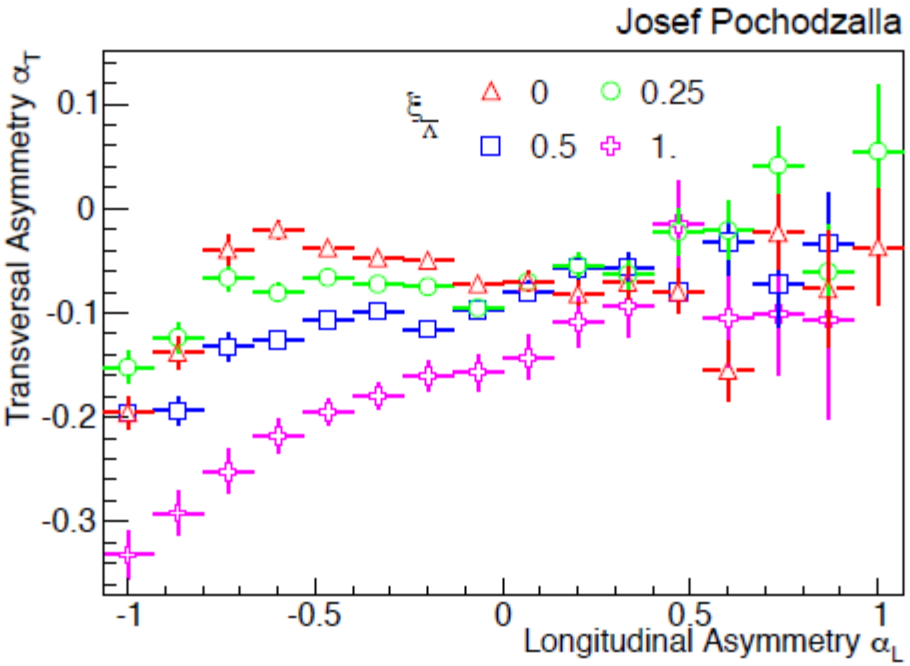
Antihyperons in nuclei

- Study antihyperon potential in nuclei
- Exploit plentiful production of $\bar{Y}Y$ pairs near threshold
- Benchmark for describing hyperon dynamics in heavy-ion collisions





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