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Probing CP symmetry with polarised and entangled hyperons

2022 International Conference on the Structure of Baryons

Prof. Dr. Karin Schönning, Uppsala University
for the BESIII and PANDA collaborations

BESIII

The logo for the PANDA experiment, featuring the word 'panda' in a stylized font inside an oval with colored horizontal bars (blue, red, green, yellow) at the top and bottom.

Outline

- Introduction
- The present: BESIII
- The future: PANDA
- Summary



Matter-antimatter asymmetry

More matter than anti-matter in the Universe –why?

- As much baryons as anti-baryons, should have been created in the Big Bang.
- Dynamically generated abundance: *Baryogenesis?*
 - Requires existence of processes that violate charge conjugation and parity
 - established for K -, D - and B -mesons
 - No evidence in the baryon sector



Picture from Virginia Tech

CP violation in hadron decays

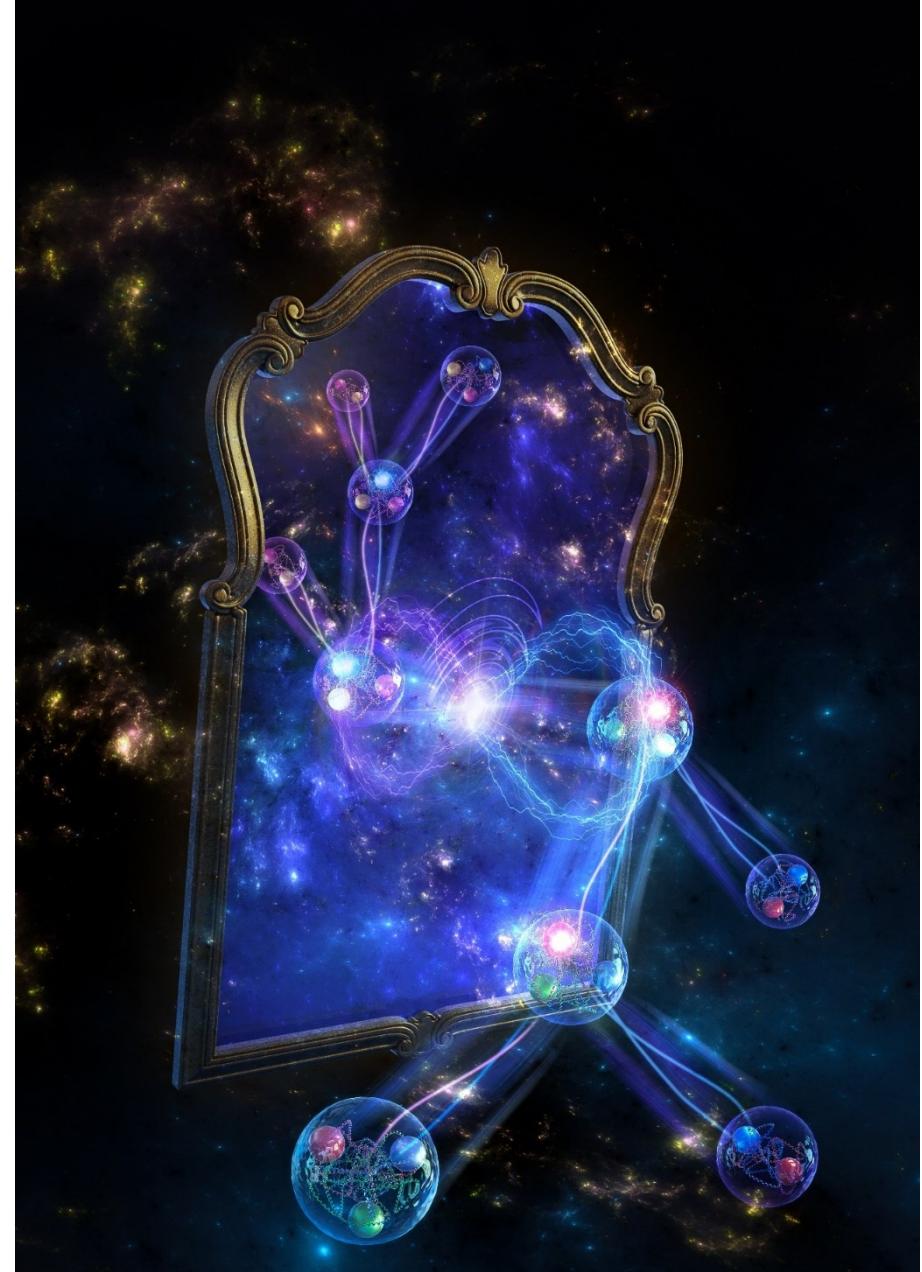
- Hadrons decay through a complex interplay between
 - Strong
 - EM
 - Weak/BSM?
 - ...interactions
- Possible that strong interactions dilute or hide CP violating weak or BSM signals?
- Two-body decays of spin 0 mesons: $\frac{\varepsilon}{\varepsilon'}$ needs non-zero strong contribution to reveal CP violation



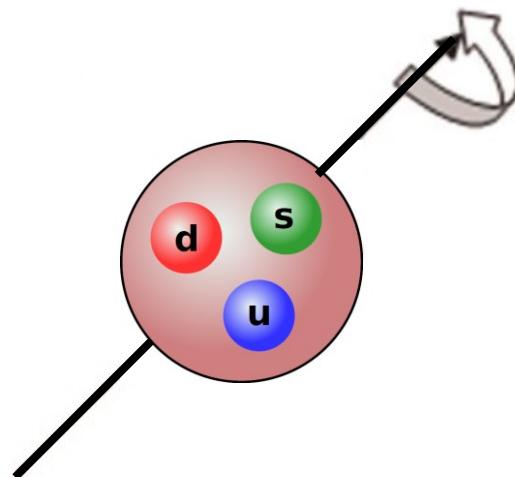


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What can we learn from spin-carrying hyperons?

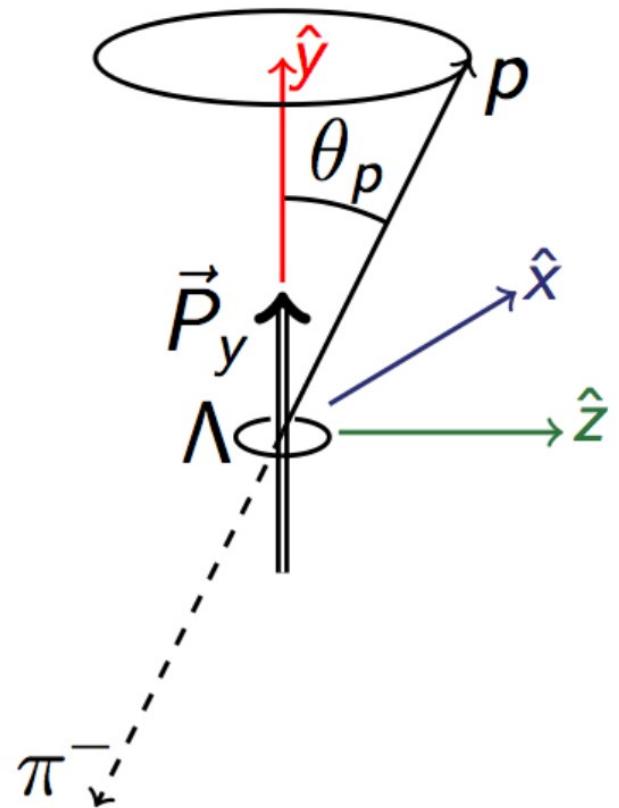


Advantage of hyperons



Spin accessible in decay, e.g.

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



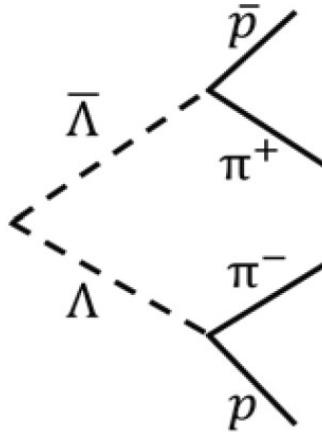
Precision CP tests

CP symmetry means...

Qualitatively: Hyperons and antihyperons have the same decay patterns with inverted spatial coordinates.

Accessible in direct decays

$$\text{e.g. } \Lambda \rightarrow p\pi^-$$



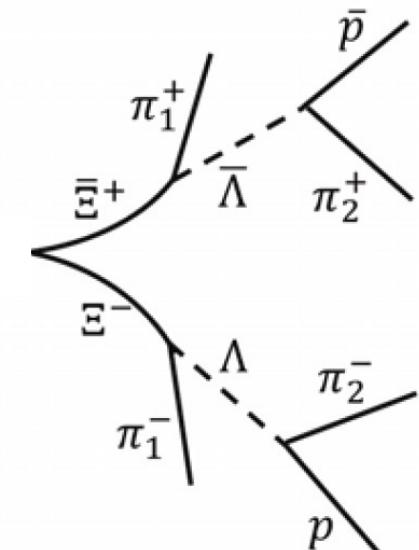
Quantitatively:

$$\alpha, \beta, \gamma, \phi = -\bar{\alpha}, -\bar{\beta}, -\bar{\gamma}, -\bar{\phi}$$

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

$$\Delta\phi_{CP} = \frac{\phi + \bar{\phi}}{2}$$

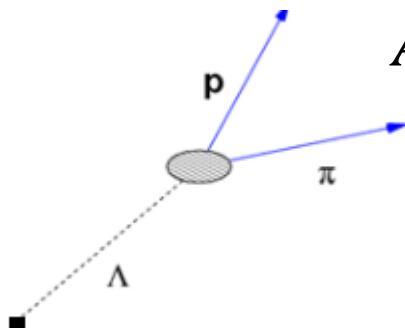
Accessible in sequential decays
e.g. $\Xi^- \rightarrow \Lambda\pi^-, \Lambda \rightarrow p\pi^-$



Precision CP tests

Challenge: Hyperon decays interplay of **strong** and **weak** processes!

→ CP observable from direct decay
= function of **strong** and **weak** phases.



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

Strong phase diff.
CP conserving

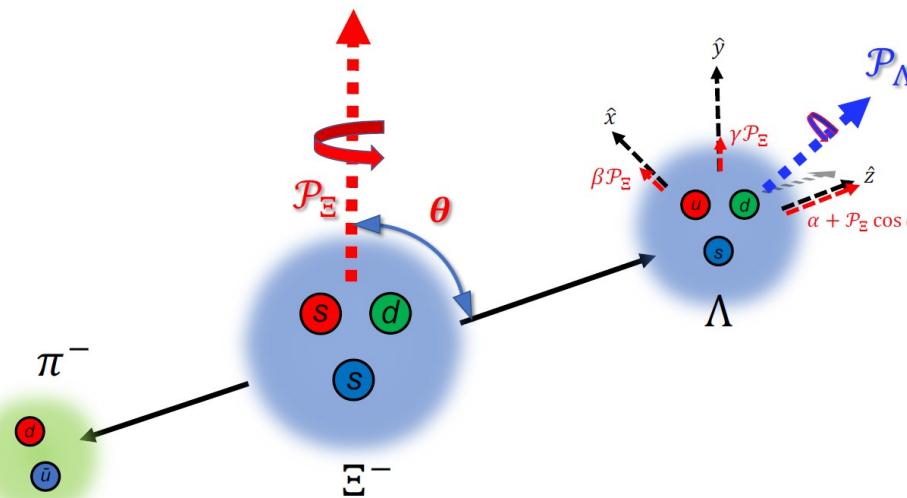
Weak phase diff.
Possibly
CP violating

Precision CP tests

CP observable from sequential decay function of
weak phase difference only!

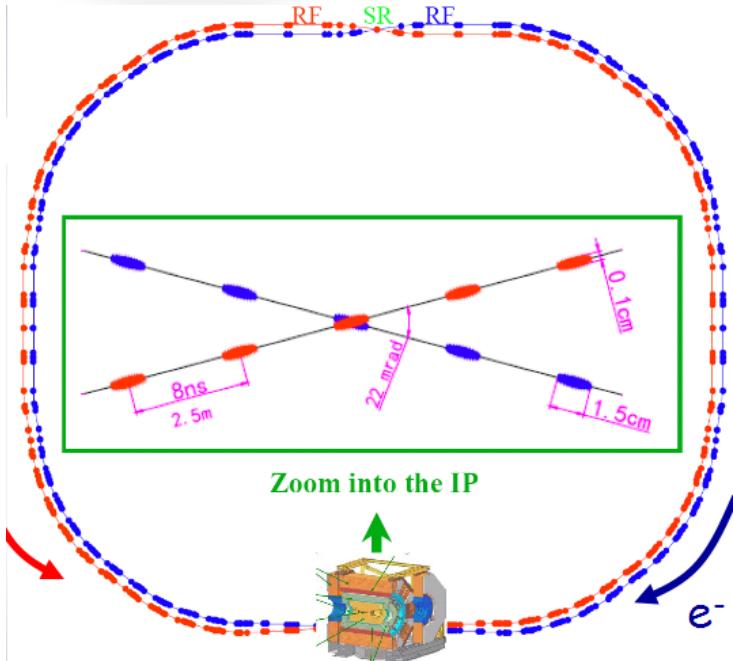
$$\Delta\phi_{CP} = \frac{\phi + \bar{\phi}}{2} \approx \frac{\alpha}{\sqrt{1-\alpha^2}} (\xi_p - \xi_s)_{LO}$$

→ More sensitive to CP violating effects*!



*Donogue, He and Pakvasa, PRD 34, 833 (1986)
 Picture from BESIII: Nature 606, p. 64–69 (2022)

The present: BESIII @ BEPC II

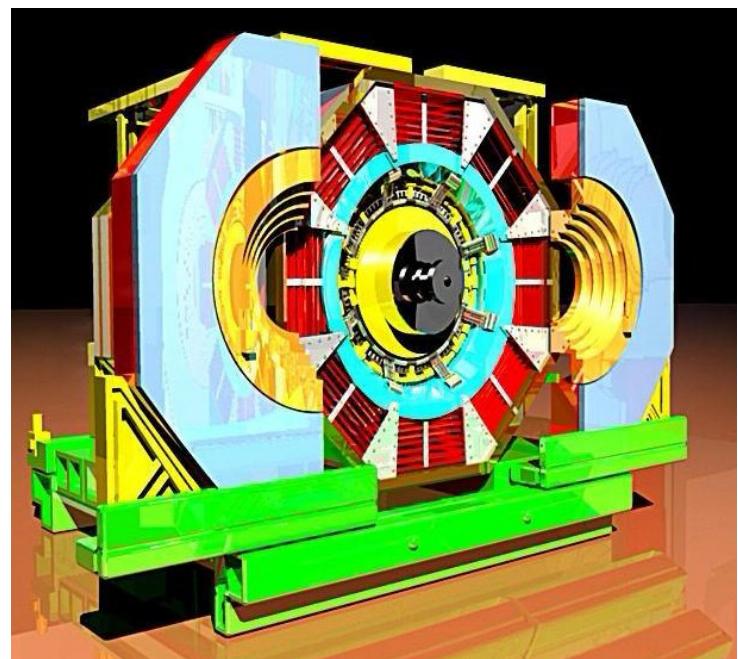


Beijing Electron Positron Collider
(BEPC II):

- CMS range 2.0 – 4.95 GeV.
- Optimised in the τ -charm region.
- Hyperons from $e^+ e^- \rightarrow J/\Psi \rightarrow Y\bar{Y}$

Beijing Spectrometer (BES III):

- Near 4π coverage
 - Tracking
 - PID
- Calorimetry



Sequential hyperon decays

- Formalism by Perotti *et al.**
- Exploits **polarisation**, **entanglement** and **sequential decays**

$$\mathcal{W}(\xi; \omega) = \sum_{\mu, v=0}^3 C_{\mu v} \sum_{\mu' v'=0}^3 a_{\mu \mu'}^{\Xi} a_{v v'}^{\Xi} a_{\mu' 0}^{\Lambda} a_{v' 0}^{\Lambda}$$

$$C_{\mu v} = (1 + \alpha_\psi \cos^2 \theta) \begin{pmatrix} 1 & 0 & P_y & 0 \\ 0 & C_{xx} & 0 & C_{xz} \\ -P_y & 0 & C_{yy} & 0 \\ 0 & -C_{xz} & 0 & C_{zz} \end{pmatrix}$$

New results from BESIII

- Nature **606**, p. 64–69 (2022): ~70 000 $\Xi^-\bar{\Xi}^+$ events

$$\rightarrow A_{\Lambda CP} = -0.0037 \pm 0.0117 \pm 0.0090$$

$$\rightarrow A_{\Xi CP} = -0.0060 \pm 0.0134 \pm 0.0056$$

$$\rightarrow \Delta\phi_{CP} = -0.0048 \pm 0.0137 \pm 0.0029 \text{ radians}$$

First measurement!

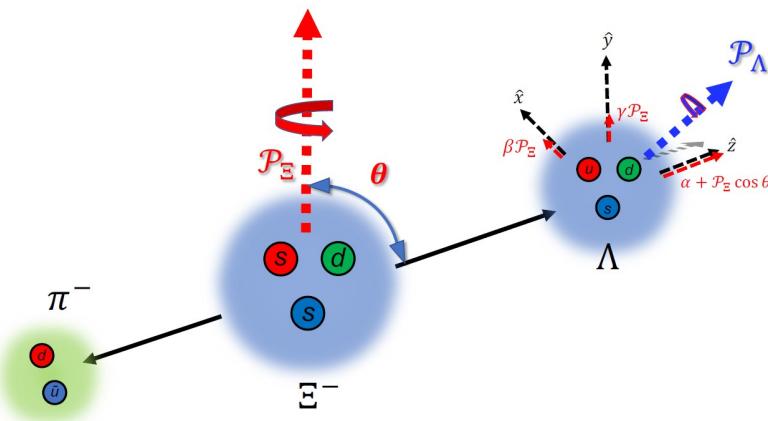
First measurement!

$$\text{Weak phase } (\xi_p - \xi_s) = 0.012 \pm 0.034 \pm 0.008 \text{ radians} \quad \text{First measurement!}$$

$$\text{Strong phase } (\delta_p - \delta_s) = -0.04 \pm 0.033 \pm 0.017 \text{ radians}$$

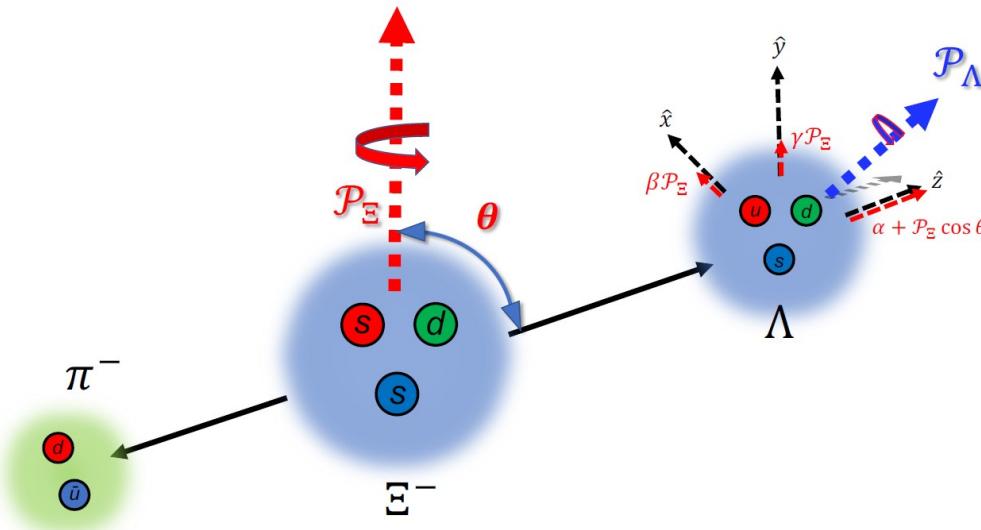


More details in talk by Jianyu Zhang



Sequential *versus* direct decays

- $400\,000 e^+e^- \rightarrow J/\Psi \rightarrow \Lambda\bar{\Lambda}$ events*
 - $\sigma(\alpha_{\Lambda \rightarrow p\pi}) = 0.009$
- $70\,000 e^+e^- \rightarrow J/\Psi \rightarrow \Xi^-\bar{\Xi}^+, \Xi^- \rightarrow \Lambda\pi^-, \bar{\Xi}^+ \rightarrow \bar{\Lambda}\pi^+$ events**
 - $\sigma(\alpha_{\Lambda \rightarrow p\pi}) = 0.011$



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

BESIII, Nature, **606, p. 64-69 (2022)

Proton probe *versus* e^+e^-

- HyperCP
 - $144 \cdot 10^6 pCu \rightarrow \Xi^- X, \Xi^- \rightarrow \Lambda \pi^-$ events*
 - $\sigma(\phi) \sim 0.01$ radians
 - $117 \cdot 10^6 pCu \rightarrow \Xi^- X$ & $41 \cdot 10^6 pCu \rightarrow \bar{\Xi}^+ X$ events **
 - $\sigma(A_{\Xi\Lambda}) \sim 10^{-4}$
- BESIII***
 - $70\,000 e^+e^- \rightarrow J/\Psi \rightarrow \Xi^-\bar{\Xi}^+, \Xi^- \rightarrow \Lambda\pi^-, \bar{\Xi}^+ \rightarrow \bar{\Lambda}\pi^+$ events
 - $\sigma(\phi) \sim 0.01$ radians
 - $\sigma(A_{\Xi}) \sim 10^{-2}$

Sensitive measurements thanks to

- well-known production process
- spin correlations in $Y\bar{Y}$ final state

*HyperCP, Phys. Rev. Lett. 93, 011802 (2004)

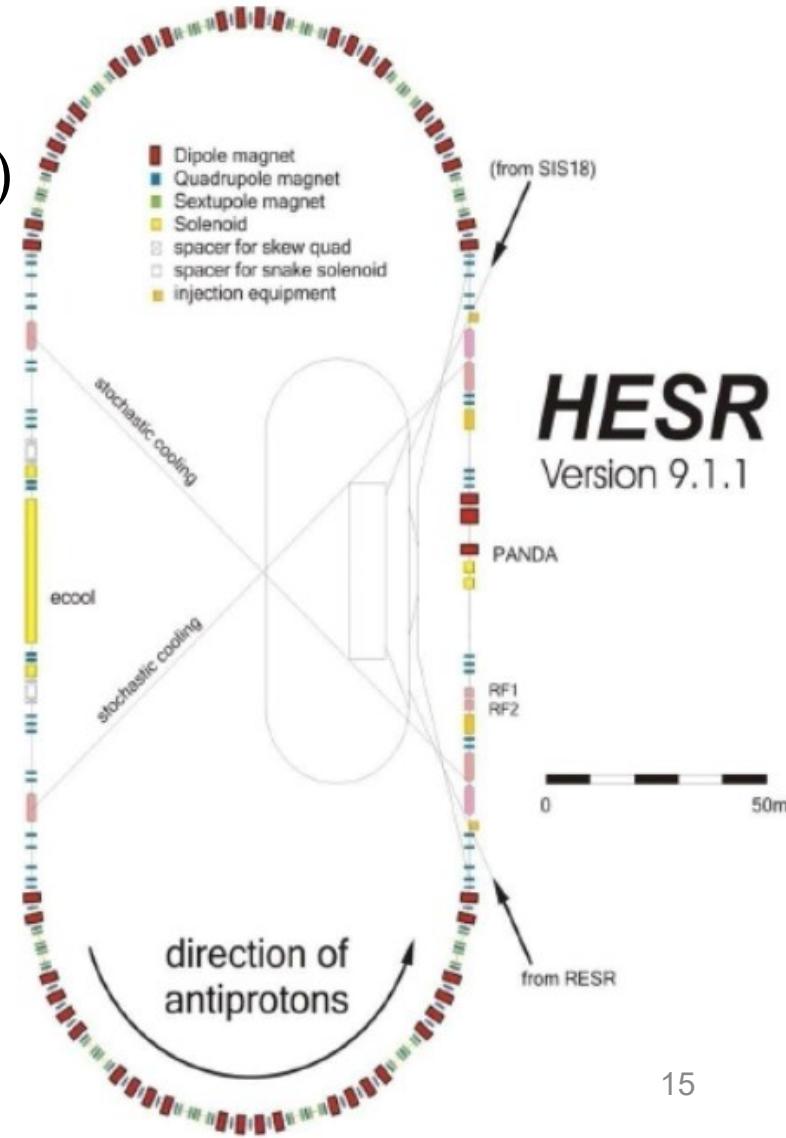
**HyperCP, Phys. Rev. Lett. 93, 262001 (2004)

***BESIII, Nature, 606, p. 64–69 (2022)

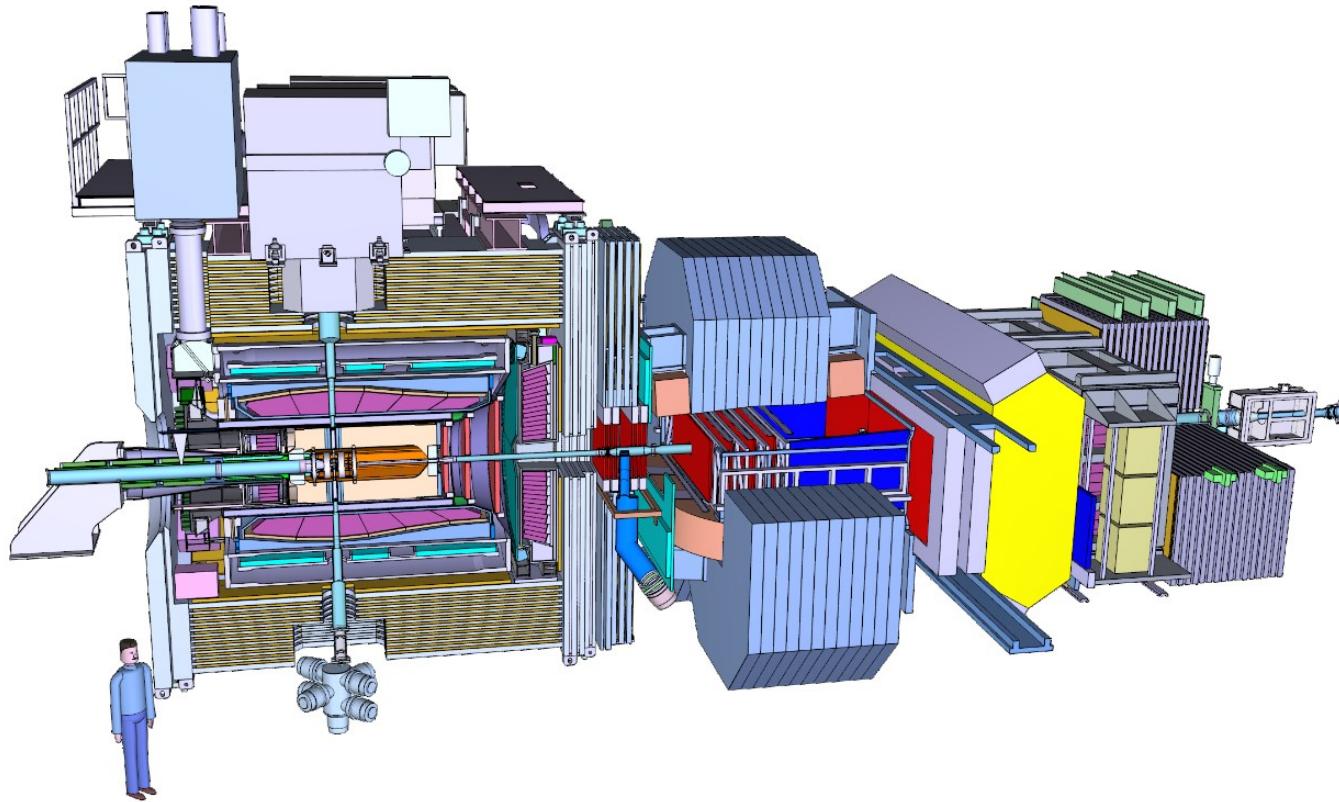
The future: PANDA at FAIR

The High Energy Storage Ring (HESR)

- Hyperons from $\bar{p}p \rightarrow Y\bar{Y}$
- Anti-protons within $1.5 < p_{beam} < 15 \text{ GeV}/c$
- Luminosity:
 - Design $\sim 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
 - Phase One $\sim 10^{31} \text{ cm}^{-2}\text{s}^{-1}$

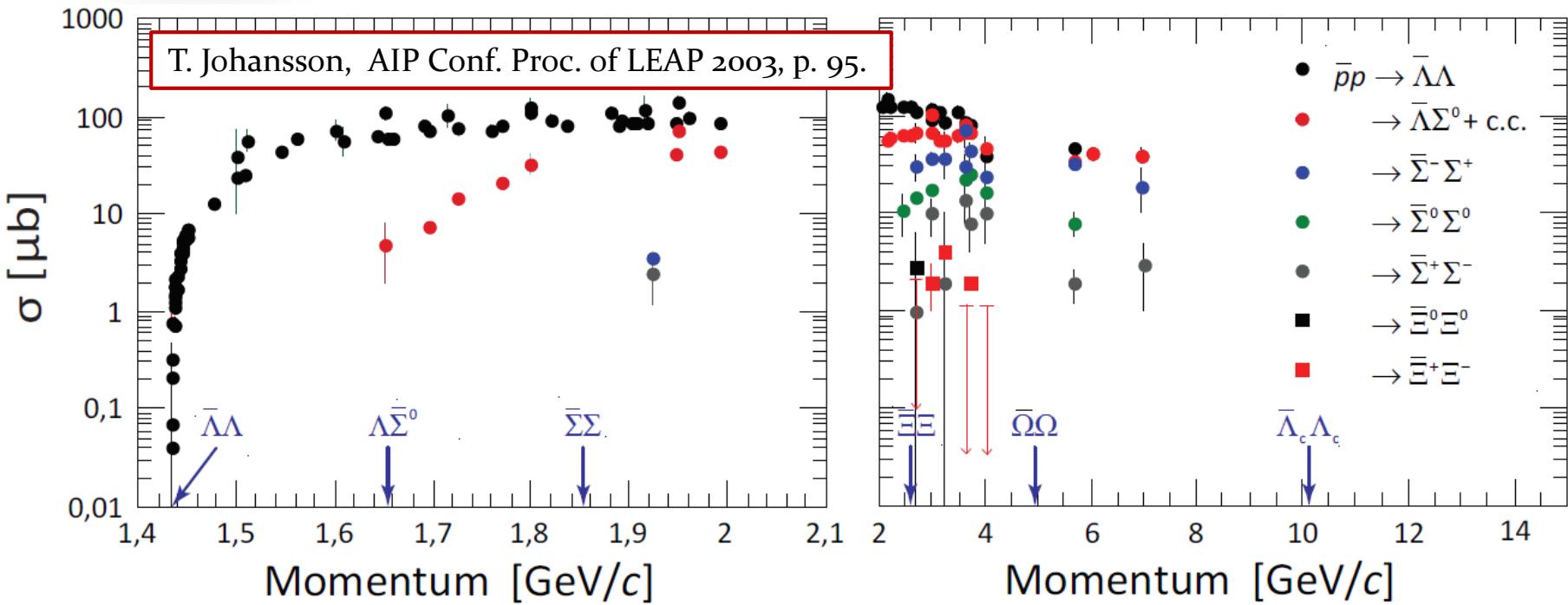


The future: PANDA at FAIR



- Precise tracking
- Modular design
- PID
- Software trigger
- Calorimetry

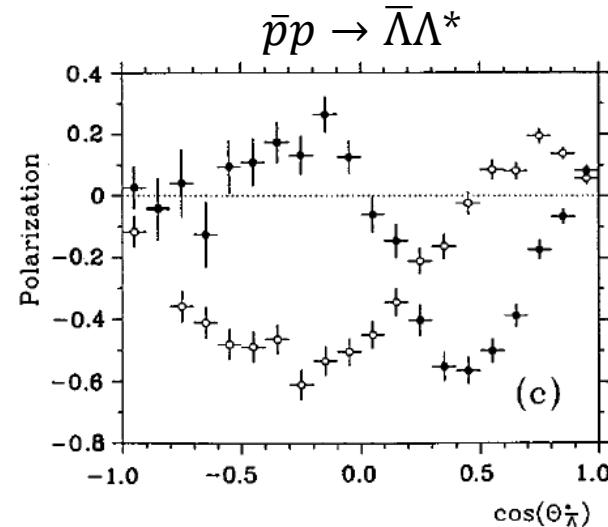
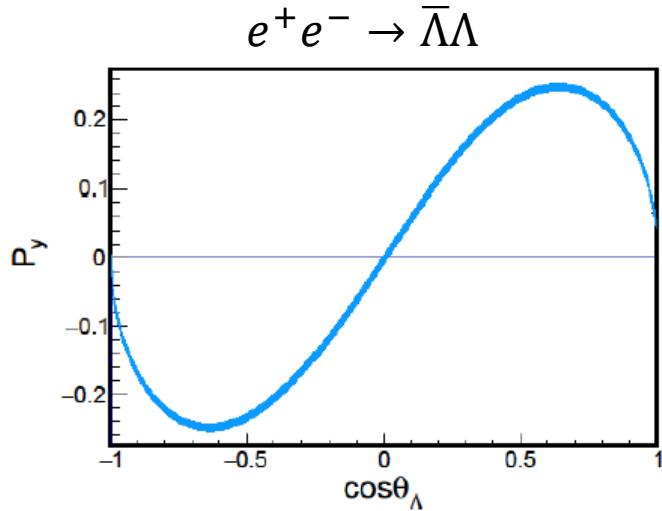
Hyperons from $\bar{p}p \rightarrow \bar{Y}Y$



Measured cross sections of ground-state hyperons in $\bar{p}p \rightarrow \bar{Y}Y$ 1-100 μb .

→ Large expected production rates!

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



$J^P = 1^-$ dominates \rightarrow 2 amplitudes
 \rightarrow 2 **global** observables η and $\Delta\Phi$.

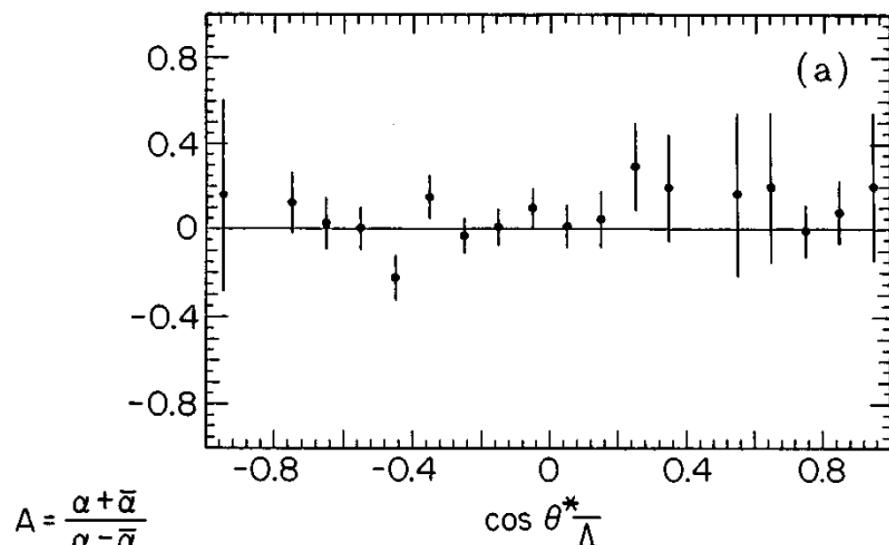
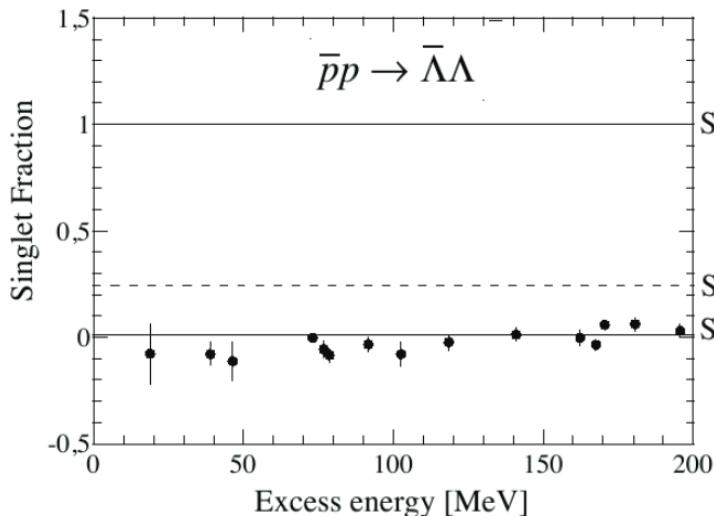
Cross section, polarization and spin correlations **well-defined** functions of scattering angle.

Several initial J^P contribute \rightarrow complicated final state.

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

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

- PS185 @LEAR: $\bar{\Lambda}\Lambda$ produced in a triplet state*
 - Spin correlations prerequisite for precise CP tests!
 - CP test with $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$: $\sigma(A_\Lambda) \sim 0.02$ for 96000 $\bar{\Lambda}\Lambda$ events**
 - CP test with $e^+e^- \rightarrow \bar{\Lambda}\Lambda$: $\sigma(A_\Lambda) \sim 0.01$ for 400000 $\bar{\Lambda}\Lambda$ events***



*T. Johansson, LEAP 2003

**PS185, Phys. Rev. C 54, 1877 (1996)

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

Future: CP tests with PANDA

Hyperons @PANDA:

- Two-body production of spin correlated $Y\bar{Y}$ pairs
- High production rate
- High efficiency
- Low background



*PANDA: Eur. Phys. J A57, 4, 154 (2021)

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

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

p_{beam} (GeV/c)	Reaction	σ (μb)	ϵ (%)	Rate @ $10^{31} \text{ cm}^{-2}\text{s}^{-1}$	S/B	Events /day
1.64	$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$	64.0	16.0*	44 s^{-1}	114	$3.8 \cdot 10^6$
1.77	$\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda$	10.9	5.3**	2.4 s^{-1}	>11*	207 000
6.0	$\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda$	20	6.1**	5.0 s^{-1}	21	432 000
4.6	$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	~ 1	8.2*	0.3 s^{-1}	274	26000
7.0	$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	~ 0.3	7.9*	0.1 s^{-1}	65	8600
4.6	$\bar{p}p \rightarrow \bar{\Lambda}K^+\Xi^- + \text{c.c.}$	~ 1	5.4***	0.2 s^{-1}	>19*	17000
7.0	$\bar{p}p \rightarrow \bar{\Omega}^+\Omega^-$	0.002-0.06	14			50 -1300

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1.64	$\bar{p}p \rightarrow \bar{\Lambda}^0$	6.0	60 *	~1000	~100	$3.8 \cdot 10^6$
1.77						207 000
6.0						432 000
4.6						26000
7.0						8600
4.6	$\bar{p}p$			• $\bar{\Lambda}\Lambda$: World record in < 1 day		
				• $\Xi^+\Xi^-$: $\sigma(\xi_p - \xi_s) \sim 0.01$ in < 3 days		
7.0	$\bar{p}p \rightarrow \bar{\Omega}^+ \Omega^-$	0.002-0.06	14			50 -1300

PANDA - a strangeness factory!

Phase 1:

- $\bar{\Lambda}\Lambda$: World record in < 1 day
- $\Xi^+\Xi^-$: $\sigma(\xi_p - \xi_s) \sim 0.01$ in < 3 days

Summary

- **Polarised and entangled $Y\bar{Y}$ pairs enable**
 - Complete determination of hyperon time-like structure
 - CP tests in hyperon decays
- **Sequentially decaying hyperons enable**
 - Separation of strong and weak decay phases
 - More sensitive CP tests!
- New results from **BESIII** very precise even with modest sample sizes
- The antiproton beam at **PANDA** will yield unprecedented samples of $Y\bar{Y}$ pairs → New level of precision possible!



Thanks for your attention!

Special thanks to Göran Fäldt

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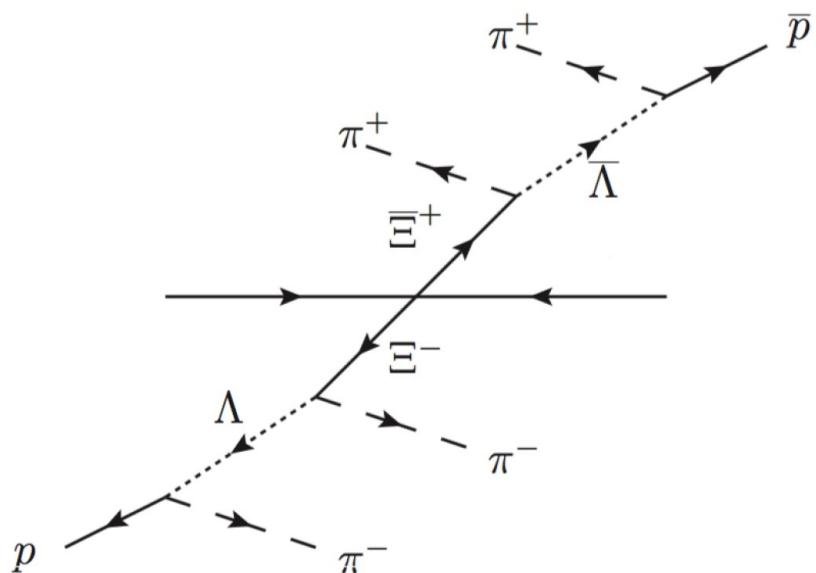
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Backup

New results from BESIII

Event selection

- 3 negative and 3 positive tracks in the MDC, i.e. $\cos\theta_{lab} < 0.93$
- Protons fulfill $p_p > 0.32 \text{ GeV}/c$, pions $p_\pi < 0.30 \text{ GeV}/c$
- Successful vertex fits for Ξ and Λ decay vertices
- Combination must minimise $(m_{p\pi\pi} - m_\Xi)^2 + (m_{p\pi} + m_\Lambda)^2$
- $|m_{p\pi} - m_\Lambda| < 11.5 \text{ MeV}/c^2$
- $|m_{\Lambda\pi} - m_\Xi| < 11.0 \text{ MeV}/c^2$
- Positive decay length $\frac{\Delta L}{L} > 0$
- 4C fit of $e^+e^- \rightarrow J/\Psi \rightarrow \Xi^-\bar{\Xi}^+$
- $|\cos\theta_\Xi| < 0.84$

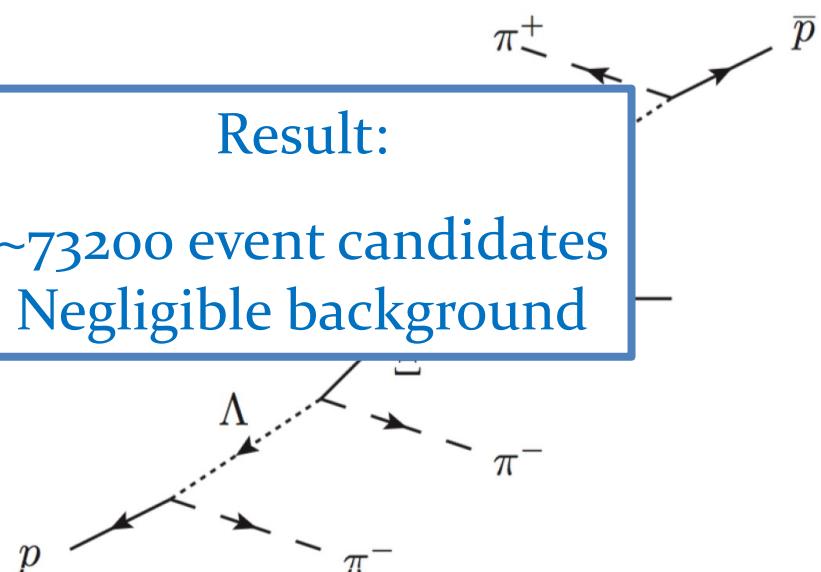


New results from BESIII

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- Positive decay length $\frac{\Delta L}{L} > 0$
- 4C fit of $e^+e^- \rightarrow J/\Psi \rightarrow \Xi^-\bar{\Xi}^+$
- $|\cos\theta_\Xi| < 0.84$

Result:
~73200 event candidates
Negligible background



Hyperon pairs in $e^+e^- \rightarrow Y\bar{Y}$

Initial state has $J^{PC} = 1^{--}$

→ spin of hyperon and antihyperon entangled

Decay parameters for 2-body decays: α and $\bar{\alpha}$ extracted from the joint angular distribution*

Unpolarized part	Polarised part	Correlated part
$W(\xi) = F_0(\xi) + \eta F_5(\xi)$	$- \alpha \bar{\alpha} (F_1(\xi) + \sqrt{1 - \eta^2} \cos(\Delta\Phi) F_2(\xi) + \eta F_6(\xi))$	$+ \sqrt{1 - \eta^2} \sin(\Delta\Phi) (\alpha F_3(\xi) - \bar{\alpha} F_4(\xi))$

This formalism

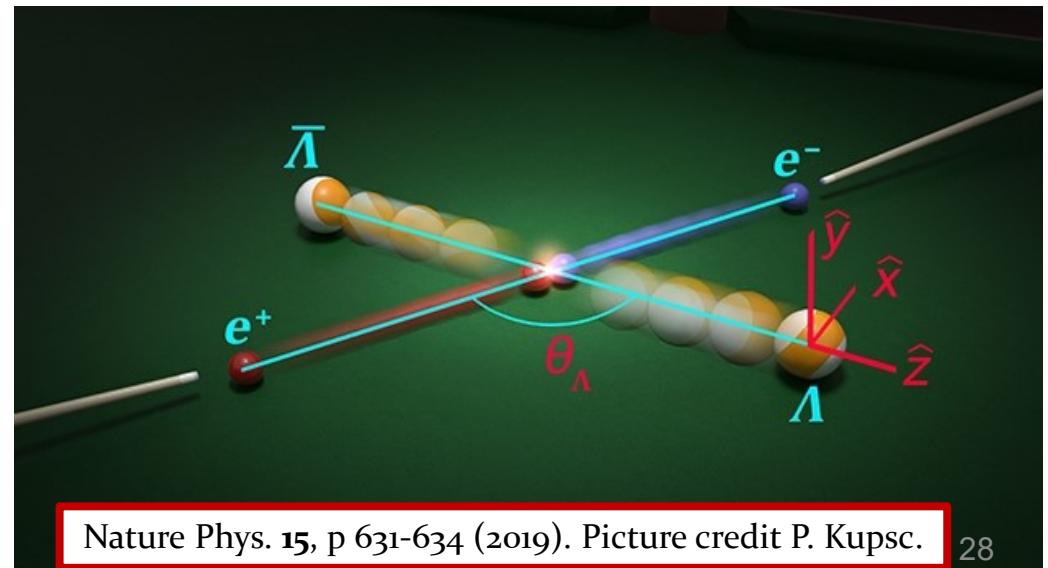
- Is model independent
- Takes full process (production and decay) into account.
- Maximizes information → larger precision for a given sample size

Recent progress by BESIII

- Nature Phys. 15, p. 631-634 (2019): ~400 000 $\Lambda\bar{\Lambda}$ events
 $\rightarrow A_{CP} = -0.006 \pm 0.012 \pm 0.007$
- Phys. Rev. Lett. 125, 052004 (2020): ~90 000 $\Sigma^+\bar{\Sigma}^-$ events
 $\rightarrow A_{CP} = -0.004 \pm 0.0037 \pm 0.0010$
- Phys. Rev. Lett. 129, 131801 (2022): ~3000 000 $\Lambda\bar{\Lambda}$ events
 $\rightarrow A_{CP} = -0.0025 \pm 0.0046 \pm 0.0012$

BESIII

More details in talk by Jianyu Zhang



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