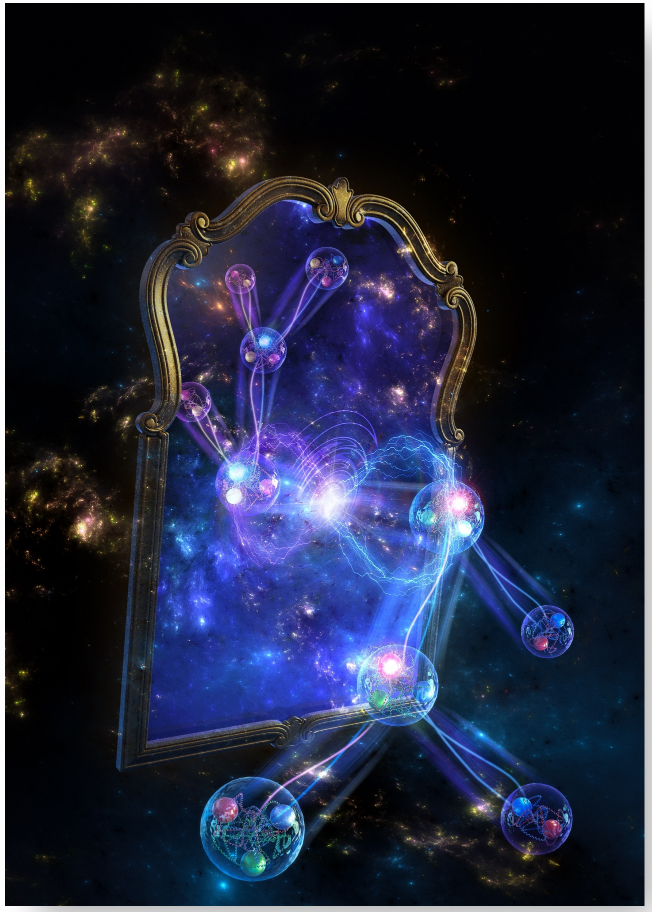
BESIII



CP-symmetry studies of baryon-antibaryon pairs with the BESIII experiment

Patrik Adlarson

EDP Seminar, June 9, 2022

with Karin Schönning and Andrzej Kupsc

Knut and Alice Wallenberg Foundation
OLLE ENGKVISTS STIFTELSE
Swedish Research Council
Lundström-Åmans Foundation

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Outline

Introduction

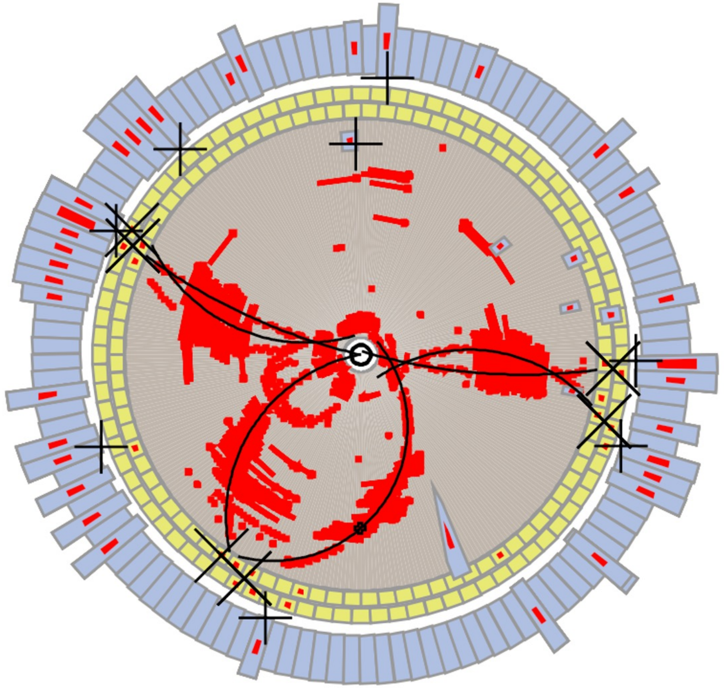
BESIII Experiment

Results Single Weak Decays

New Result: *First Weak Phase Measurement in Baryon Decays*

Future prospects

Summary and Outlook



Display of simulated
$\Xi^-\bar{\Xi}^+ \to \Lambda\pi^-\bar{\Lambda}\pi^+ \to p\pi^-\pi^-\bar{p}\pi^+\pi^+$

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Matter Antimatter asymmetry

Universe likely began with equal abundance of matter and antimatter

Matter and antimatter are created and annihilate pair wise

Yet almost no existing antimatter in Universe

Strong observational evidence against symmetric Universe

Initial condition? Not likely. Standard Model washes out asymmetry

Local fraction of anti-stars over normal stars in galactic disk to be < 2.5 × 10−6 at 95% CL

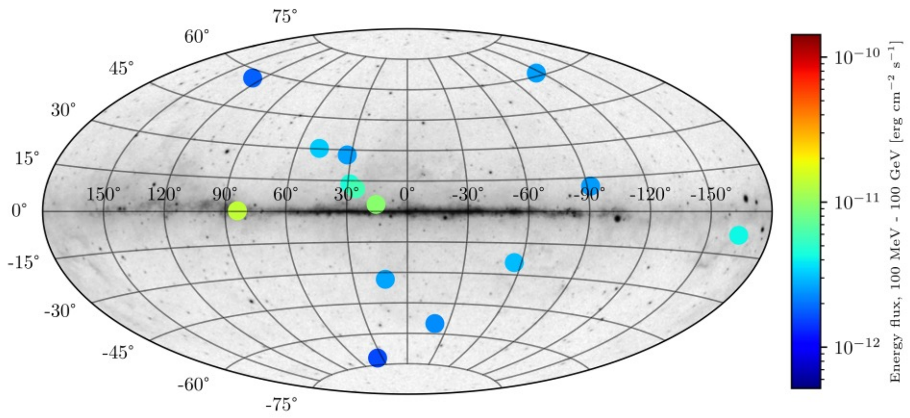

FIG. 1. Positions and energy flux in the 100 MeV–100 GeV range of antistar candidates selected in 4FGL-DR2. Galactic coordinates. The background image shows the *Fermi* 5-year all-sky photon counts above 1 GeV (image credit: NASA/DOE/Fermi LAT Collaboration).

Fourteen anti-star candidates in Fermi 10 year data
PRD 103, 083016(2021)

*A. D. Sakharov, J. Exp. Theor. Phys. Lett. 5, 24

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Baryogenesis

The dynamical mechanism, *baryogenesis,* not understood

Sakharov's three criteria *

1) Baryon number violation

2) Charge, *C,* and Charge conjugation Parity, *P,* violating processes

3) Departure from thermal equilibrium

CP violation is subtle effect requiring precision studies of many particle physics processes using complementary methods

**A. D. Sakharov, J. Exp. Theor. Phys. Lett. 5, 24*

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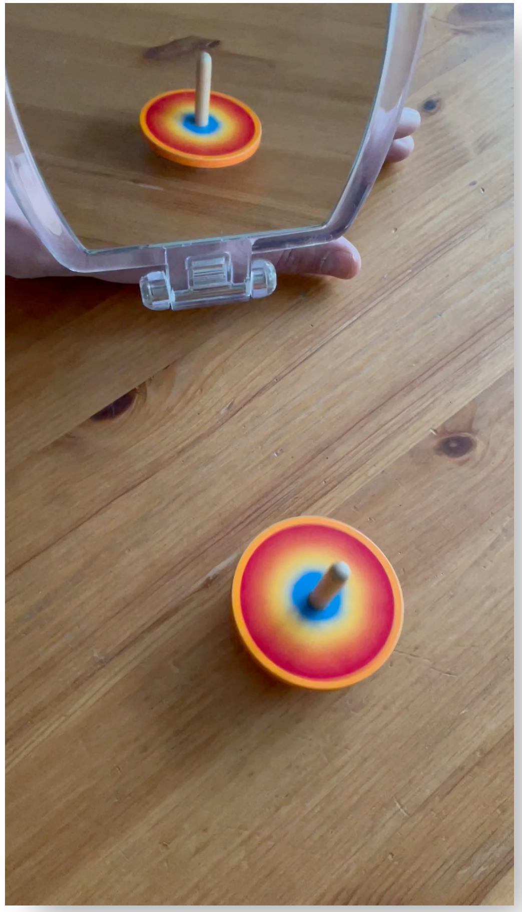
Spinning baryons



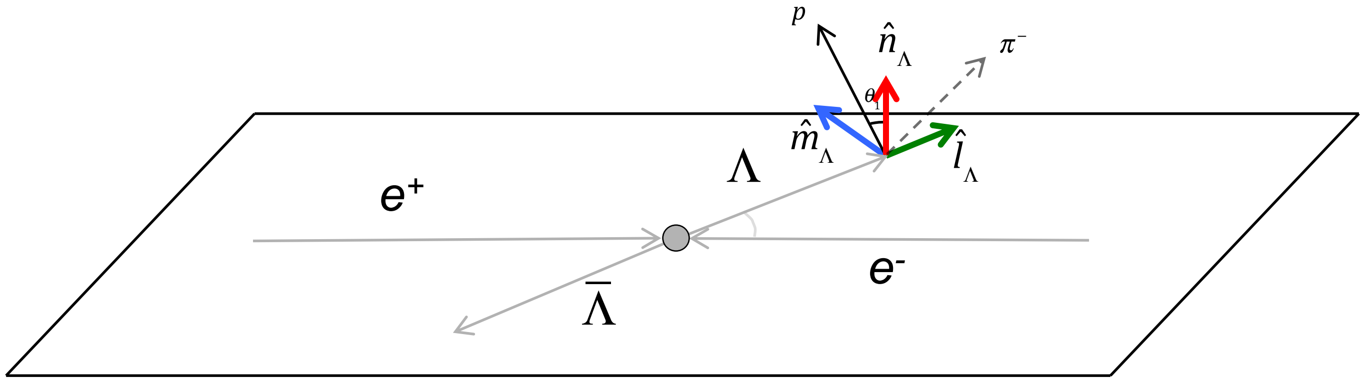
No CP violation detected for *baryons*

Additional degree of freedom for baryons compared to mesons : spin

Spin behaves differently compared to momentum when inverting spatial coordinates

Studying baryons provides complementary path in understanding CP symmetry

Focus on *hyperons*, strange quark systems and heavier cousins of proton and neutron



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Strangeness $\Delta S = 1$ mesons

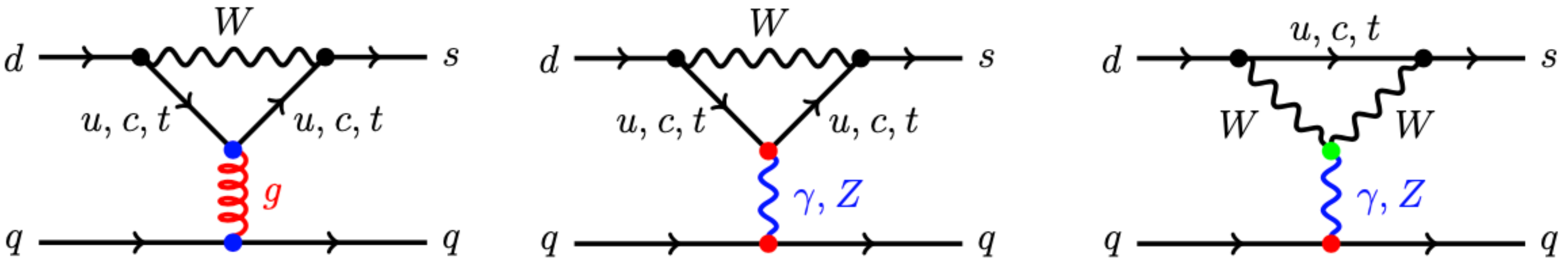
In strange sector most precise probe is $\mathbf{\Delta S = 1}$ direct CPV (ε') relative to indirect CPV (ε) in $K_{S,L} \to \pi\pi$ decays

CPV mechanism in SM requires penguin diagrams involving all three quark families

$$(\varepsilon'/\varepsilon)_{EXP} = (16.6 \pm 2.3)\times 10^{-4} \ *$$

$$(\varepsilon'/\varepsilon)_{SM} = (17.4 \pm 6.1)\times 10^{-4} \ + (\varepsilon'/\varepsilon)_{BSM} = (-4 \ - \ +10)\times 10^{-4} \ **$$

SM calculation involves partial cancellation of QCD and EW penguins which posed challenge until recently



QCD (left) and EW penguin diagrams (middle, right)***

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* Phys. Lett. B544 (2002) 97–112; 0909.2555 [hep-ex]
** *Eur. Phys. J. C* 80 (2020) 8, 705
*** arXiv: 2203.03035

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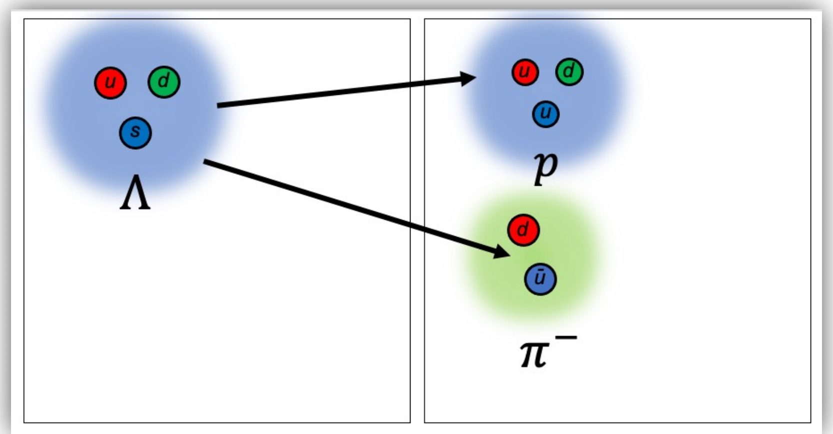
Strangeness $\Delta S = 1$ baryons

For $K_{S,L} \to \pi\pi$ the direct CPV ε' comes from | ΔI | = 1/2 and | ΔI | = 3/2

Hyperon non-leptonic two-body weak decays tests $\Delta S = 1$ CP

Hyperon weak decays offer complementary approach to meson decays as mainly | ΔI | = 1/2 transition occur



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Recent methodological breakthrough to be able to perform these CPV tests more precisely than before

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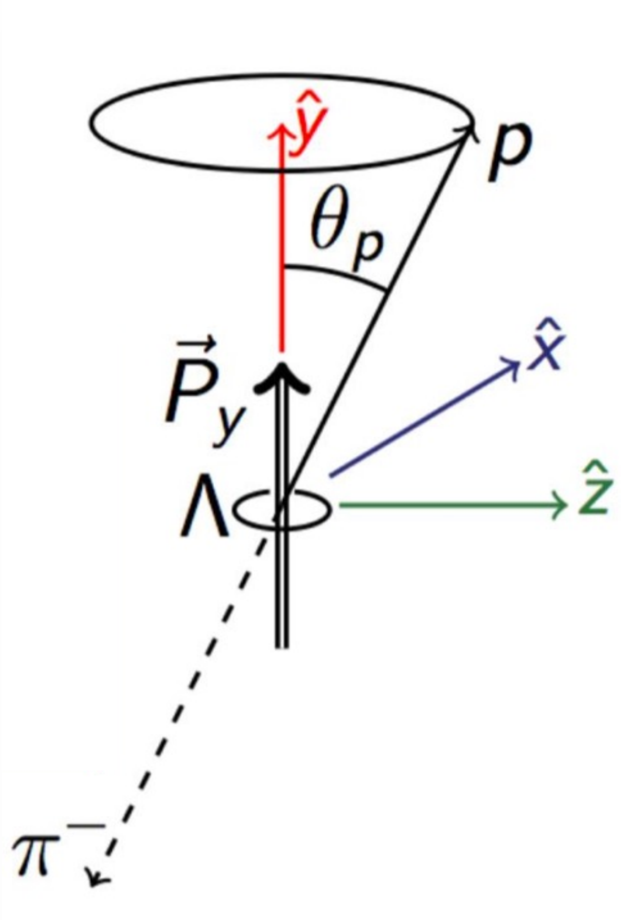
Asymmetry parameters and Polarization



Polarization of hyperons experimentally accessible in weak parity violating decays

They are *self analysing*: daughter particles are emitted according to polarization of mother hyperon

Example: Angular distribution of $\Lambda \to p\pi^-$

$$I(\cos\theta_p) \propto 1 + \alpha\, P_\Lambda \cos\theta_p$$

Asymmetry parameter
CP-observable

Polarization

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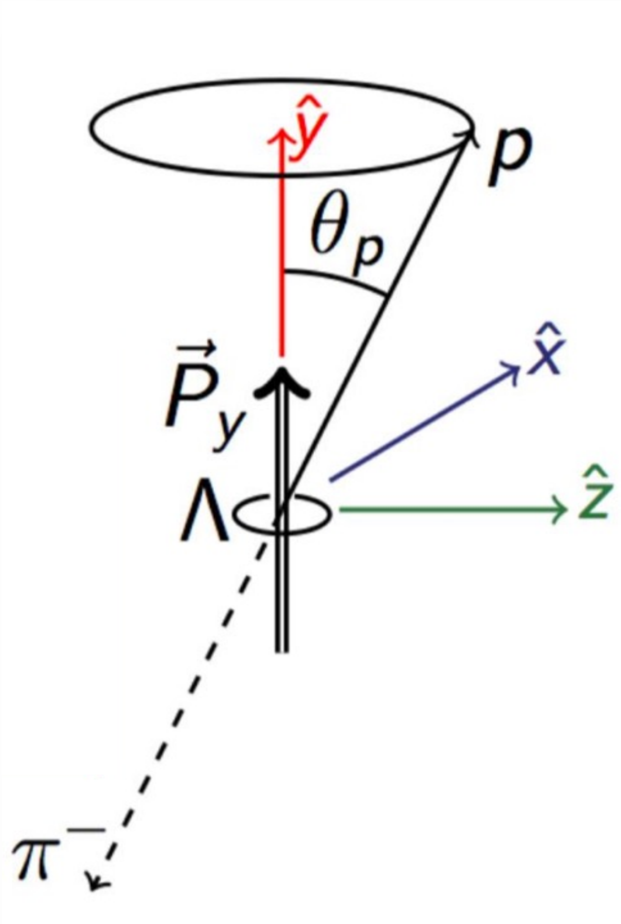
Asymmetry parameters and Polarization



Asymmetry parameters describe relationship between the amplitudes *S* (parity violating) and *P* (parity conserving)

$$\alpha = 2Re(A_{s^*} \cdot A_p), \quad \beta = 2Im(A_{s^*} \cdot A_p) \quad \gamma = |A_s|^2 - |A_p|^2$$

$$\beta = \sqrt{(1-\alpha^2)}\sin(\phi_Y), \; \gamma = \sqrt{(1-\alpha^2)}\cos(\phi_Y)$$

α and ϕ_Y are determined experimentally

ϕ_Y more challenging: polarimeter or via sequential weak decays, e.g. Ξ

α and ϕ_Y are CP-odd observables

$-1 \leq \alpha \leq 1$ $\quad\quad -\pi \leq \phi \leq \pi$

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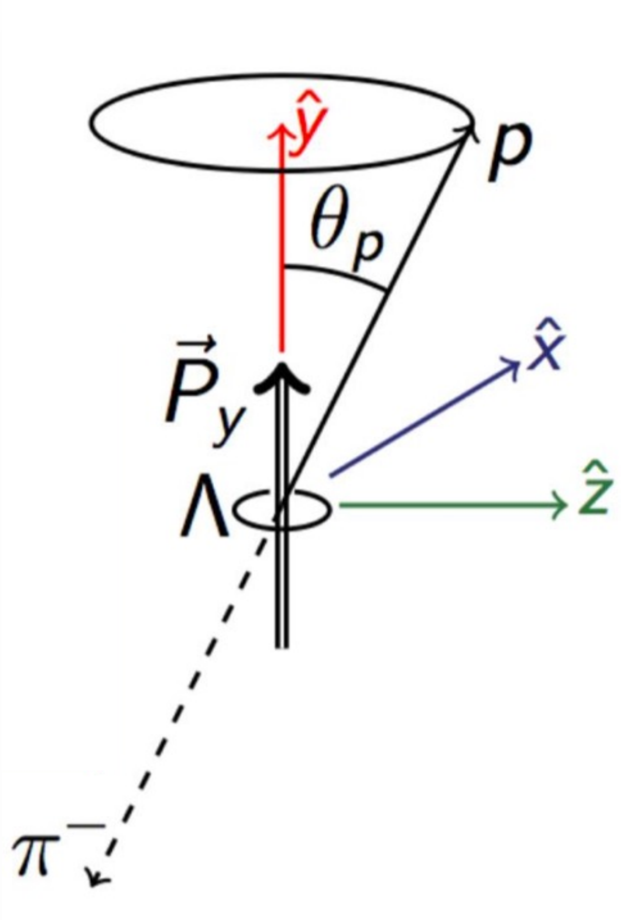
Testing CP via A_{CP}



We determine α from $\Lambda \to p\pi^-$ and $\bar{\alpha}$ from $\bar{\Lambda} \to \bar{p}\pi^+$

If CP symmetry holds then $\alpha = -\bar{\alpha}$

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

This test not limited only to $\Lambda \to p\pi^-$ but all non-leptonic two-body weak decays

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CP tests and phases

$$S = |S|e^{i\delta_S}e^{i\xi_S} \qquad P = |P|e^{i\delta_P}e^{i\xi_P}$$
$$\bar{S} = -|\bar{S}|e^{i\delta_S}e^{-i\xi_S} \qquad P = |P|e^{i\delta_P}e^{-i\xi_P}$$

δ strong baryon pion phase shift at cm energy of hyperon mass

ξ weak CP-odd phase for ΔI = 1/2

Under assumption that isospin ½ transitions dominate

$$A_{CP} = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} \approx -\tan(\delta_P - \delta_S)\tan(\xi_P - \xi_S)\ ^*$$

strong phase diff
non-zero iff FSI

weak phase diff

Corrections from isospin 3/2 are only a few percent, hence sufficiently good approximation

* Phys. Rev Lett 55 162 (1985)

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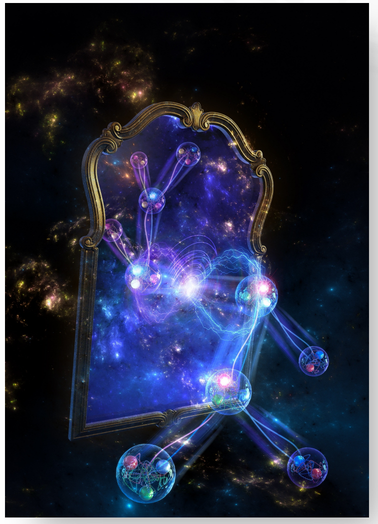
CP and weak phase difference

$$\Xi^- \to \Lambda\pi^-, \Lambda \to p\pi^-$$

$$A_{CP}^{\Xi} = \frac{\alpha_\Xi + \bar{\alpha}_\Xi}{\alpha_\Xi - \bar{\alpha}_\Xi} \approx -\sin\langle\phi_\Xi\rangle \frac{\sqrt{1-\alpha_\Xi^2}}{\alpha_\Xi} \tan(\xi_P - \xi_S)_\Xi \;*$$

$$\Delta\phi_{CP} = \frac{\phi_\Xi + \bar{\phi}_\Xi}{2} \approx \cos\langle\phi_\Xi\rangle \frac{\alpha_\Xi}{\sqrt{1-\alpha_\Xi^2}} \tan(\xi_P - \xi_S)_\Xi \;*$$



strong contribution $\phi_\Xi \approx 0$ weak phase diff - potentially CPV

$\Delta\phi_{CP}$ more sensitive to CP-violating effects cf A_{CP}^{Ξ}*

* Phys. Rev Lett 55 162 (1985)

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Strangeness $\Delta S = 1$ BSM

$K_{S,L} \to \pi\pi$

$$(\varepsilon'/\varepsilon)_{EXP} = (16.6 \pm 2.3)\times 10^{-4} \; *$$

$$(\varepsilon'/\varepsilon)_{SM} = (17.4 \pm 6.1)\times 10^{-4} \; + (\varepsilon'/\varepsilon)_{BSM} = (-4 \; - \; +10)\times 10^{-4} \; **$$

$Y \to B\pi$

$$(\xi_P - \xi_S)_{\text{BSM}} = \frac{C'_B}{B_G}\left(\frac{\epsilon'}{\epsilon}\right)_{\text{BSM}} + \frac{C_B}{\kappa}\epsilon_{\text{BSM}}$$

***

	$\xi_P - \xi_S$ $(\eta\lambda^5 A^2)$ SM	$\xi_P - \xi_S$ $[10^{-4}$ rad] SM	C_B BSM	C'_B BSM
$\Lambda \to p\pi^-$	-0.1 ± 1.5	-0.2 ± 2.2	0.9 ± 1.8	0.4 ± 0.9
$\Xi^- \to \Lambda\pi^-$	-1.5 ± 1.2	-2.1 ± 1.7	-0.5 ± 1.0	0.4 ± 0.7

Wolfenstein parameters $\eta\ \lambda^5 A^2$

$1.36(7)\text{x}10^{-4}$

Chromomagnetic BSM penguin operators

Phys. Rev. D 67, 056001 (2003)
Phys. Rev. D 69, 076008 (2004)

* Phys. Lett. B544 (2002) 97–112; 0909.2555 [hep-ex]
** *Eur. Phys. J. C* 80 (2020) 8, 705
*** arXiv: 2203.03035

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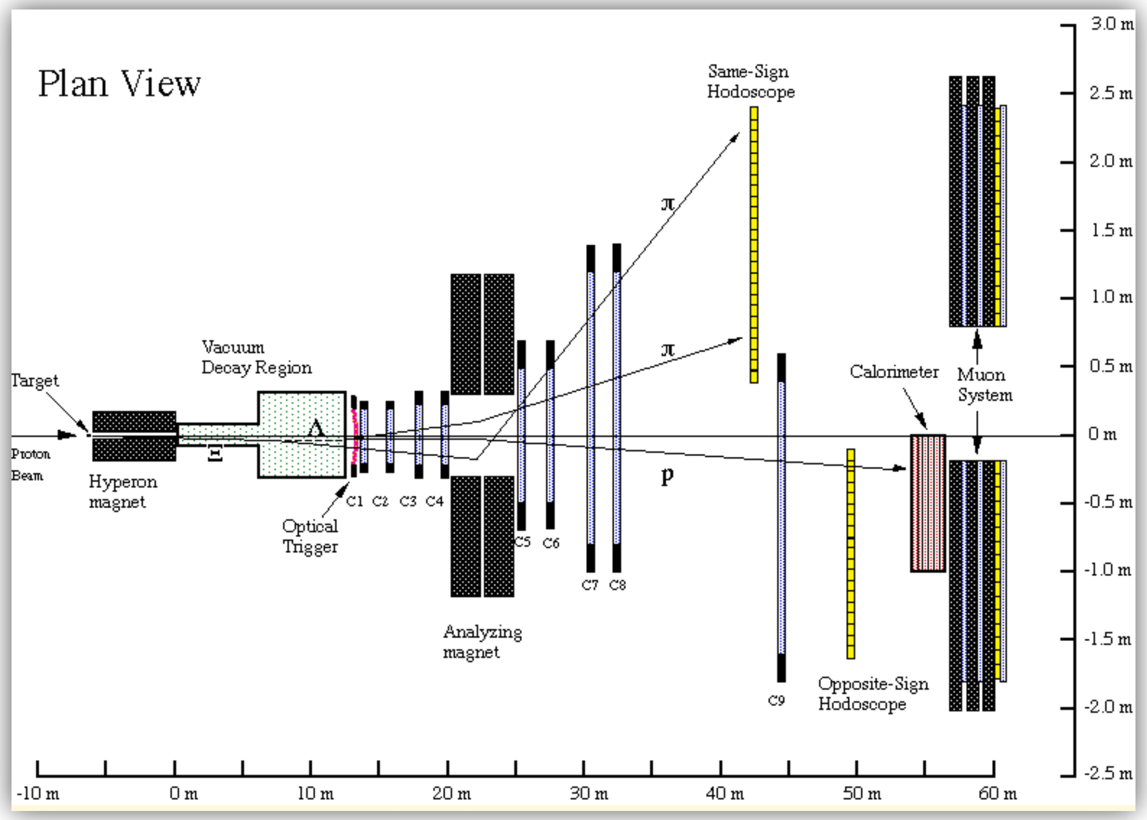
HyperCP



HyperCP (E871) Fermilab

800 Gev/c proton on fixed target Cu

Best A_{CP} limits obtained so far 117M Ξ and 41M $\bar{\Xi}$

$$A_{CP\ \Xi\Lambda} = \frac{\alpha_\Xi\alpha_\Lambda + \bar{\alpha}_\Xi\bar{\alpha}_\Lambda}{\alpha_\Xi\alpha_\Lambda - \bar{\alpha}_\Xi\bar{\alpha}_\Lambda} = (0.0 \pm 5.1 \pm 4.7)\times10^{-4} \ *$$

$$|A_{SM\ \Xi\Lambda}| \leq 5\times10^{-5} \ **$$

144M polarized Ξ (~5%) $\phi_{\Xi,\mathrm{HyperCP}} = -0.042 \pm 0.011 \pm 0.011$

862M Ξ & 230M $\bar{\Xi}$ $A_{CP\ \Xi\Lambda} = \frac{\alpha_\Xi\alpha_\Lambda+\bar{\alpha}_\Xi\bar{\alpha}_\Lambda}{\alpha_\Xi\alpha_\Lambda-\bar{\alpha}_\Xi\bar{\alpha}_\Lambda} = (-6.0 \pm 2.1 \pm 2.0)\times10^{-4}$ ***

*PRL 93, 262001 (2004)
** PRD 67, 056001 (2003)
*** NPB, Proc Suppl 187, 208 (2009)

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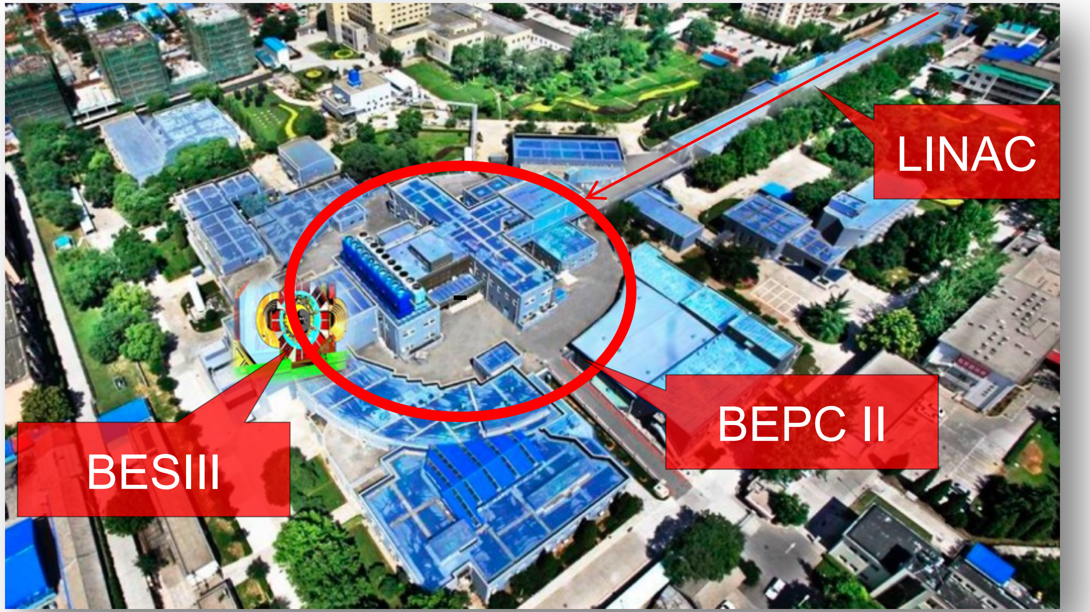
Beijing Electron Positron Collider BEPC II



Aerial view of BEPC II and BESIII

e^+e^- collider in CMS range 2.0 – 4.95 GeV
Optimized in τ - charm region
Data taking since 2009, peak luminosity 10^{33} cm^{-2}s^{-1}

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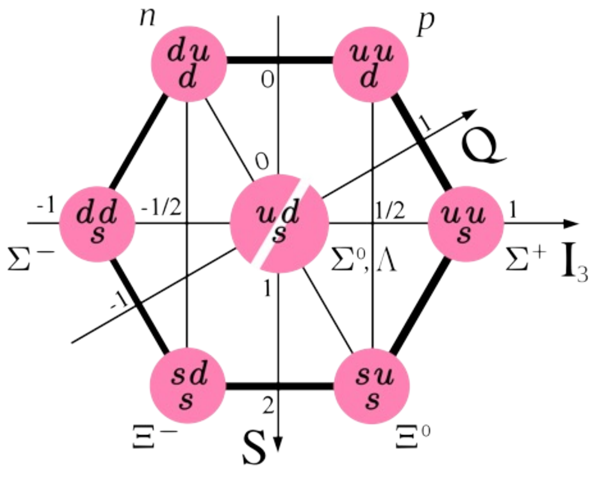
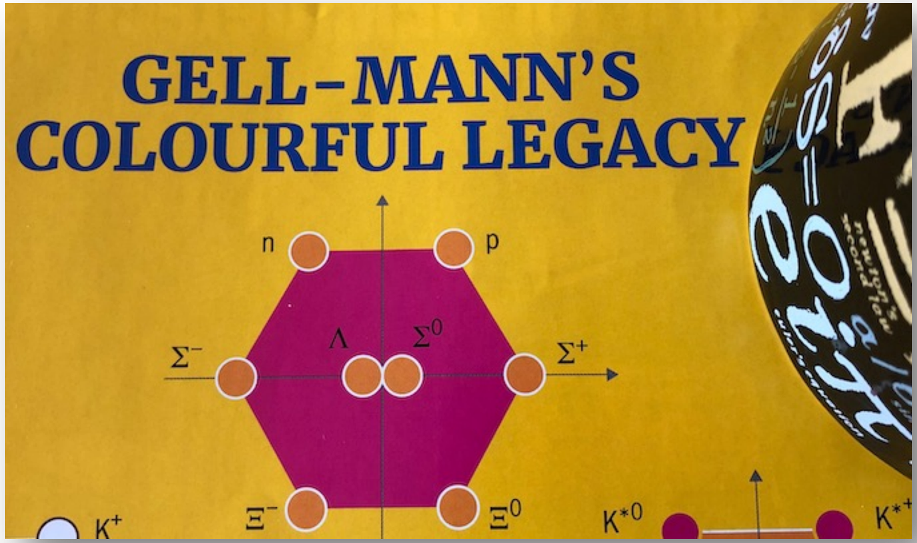
Baryon Octet at BESIII



hyperon	Mass [GeV/c²]	$c\tau$ [cm]	decay (BF)
$\Lambda(uds)$	1.116	7.9	$p\pi^-$ (63.9%)
			$n\pi^0$ (35.8%)
$\Sigma^-(dds)$	1.197	4.4	$n\pi^-$ (99.8%)
$\Sigma^+(uus)$	1.189	2.4	$p\pi^0$ (51.6%)
			$n\pi^+$ (48.3%)
$\Xi^0(uss)$	1.315	8.7	$\Lambda\pi^0$ (99.5%)
$\Xi^-(dss)$	1.321	5.1	$\Lambda\pi^-$ (99.8%)

From CERN Courier cover July-August 2019



Thresholds:

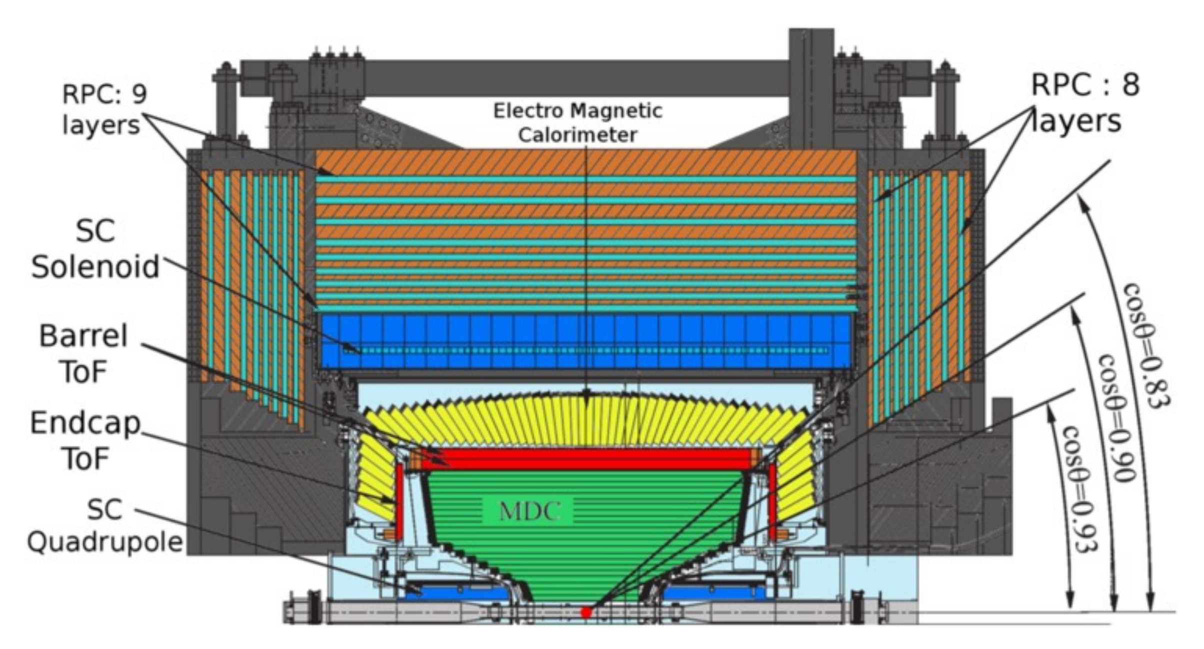
$\Lambda\bar{\Lambda}$ 2.231 GeV

$\Sigma^+\bar{\Sigma}^-$ 2.379 GeV $\Sigma^0\bar{\Sigma}^0$ 2.385 GeV $\Sigma^-\bar{\Sigma}^+$ 2.395 GeV

$\Xi^0\bar{\Xi}^0$ 2.630 GeV $\Xi^-\bar{\Xi}^+$ 2.643 GeV

Full baryon octet kinematically accessible at J/ψ resonance

BESIII ❤ Hyperons



- Multipurpose detector with very good resolution, near 4π angular coverage
- Symmetric particle – anti-particle conditions and produced in a quantum entangled state
- e^+e^- experiment low hadronic background and controlled systematic uncertainties
- World's largest charmonia data sample collected $N_{J/\psi} = (1.0087 \pm 0.0044) \times 10^{10}$

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BESIII ❤ Hyperons

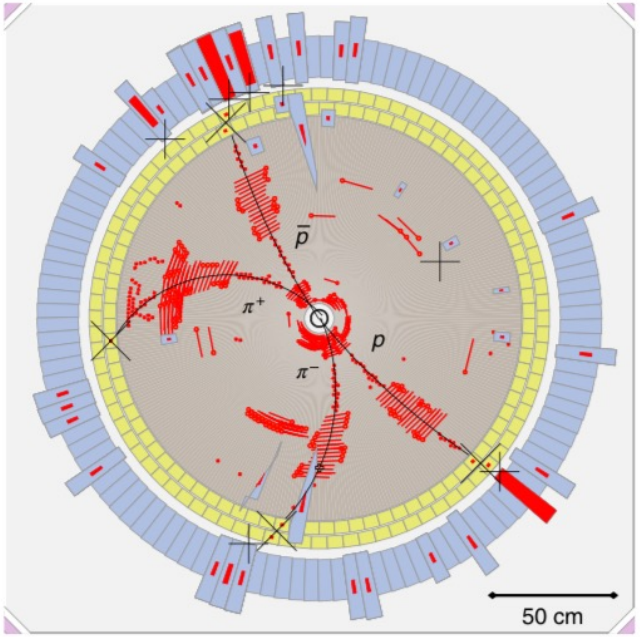

Fig. 2 | An example $J/\psi \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$ event in the BESIII detector. Cross-section of the detector in the plane perpendicular to the colliding electron–positron beams and a schematic representation of the information collected for the event. The mean decay length of the neutral $\Lambda(\bar{\Lambda})$ is 5 cm. The curved tracks of the charged particles from the subsequent $\Lambda(\bar{\Lambda})$ decays are registered in the drift chamber, indicated by the brown region of the display. The momenta of (anti-)baryons are greater than 750 MeV c^{-1} and pions are less than 300 MeV c^{-1}.

BESIII, Nature Physics 15 (2019) 631

Charged track coverage $|\cos\theta| < 0.93$

Mom. res of charged tracks 0.5% at 1 GeV/c

Neutrals $|\cos\theta| < 0.8$ and $0.86 < |\cos\theta| < 0.92$

Energy resolution 2.5% (5%) at 1 GeV for barrell (end cap)

ToF can be used together with *dE/dx* MDC for PID

But for fully charged modes e.g. Λ and Ξ momentum requirements enough to separate protons from pions

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BESIII

Formalism $e^+e^- \to \bar{Y}Y$

Production parameters of spin ½ baryons at ccbar : angular distribution parameter α_ψ and relative phase $\Delta\Phi$
Decay parameters for 2-body decays: α and $\bar{\alpha}$

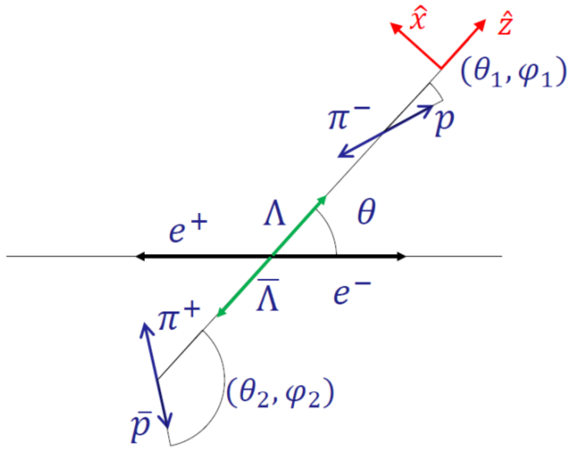
$\mathcal{T}_0 - \mathcal{T}_6$ are functions with experimentally measured observables

Unpolarised part — Polarised part — Spin correlated part

$$W(\xi) = \mathcal{T}_0(\xi) + \alpha_\psi \mathcal{T}_5(\xi) - \alpha\bar{\alpha}\left[\mathcal{T}_1(\xi) + \sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)\,\mathcal{T}_2(\xi) + \alpha_\psi \mathcal{T}_6(\xi)\right] + \sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)\left[\alpha\mathcal{T}_3(\xi) - \bar{\alpha}\mathcal{T}_4(\xi)\right]$$

Polarization necessary to "disentangle" α from $\bar{\alpha}$

$$\begin{aligned}
\mathcal{T}_0(\xi) &= 1\\
\mathcal{T}_1(\xi) &= \sin^2\theta\sin\theta_1\sin\theta_2\cos\phi_1\cos\phi_2 + \cos^2\theta\cos\theta_1\cos\theta_2\\
\mathcal{T}_2(\xi) &= \sin\theta\cos\theta(\sin\theta_1\cos\theta_2\cos\phi_1 + \cos\theta_1\sin\theta_2\cos\phi_2)\\
\mathcal{T}_3(\xi) &= \sin\theta\cos\theta\sin\theta_1\sin\phi_1\\
\mathcal{T}_4(\xi) &= \sin\theta\cos\theta\sin\theta_2\sin\phi_2\\
\mathcal{T}_5(\xi) &= \cos^2\theta\\
\mathcal{T}_6(\xi) &= \cos\theta_1\cos\theta_2 - \sin^2\theta\sin\theta_1\sin\theta_2\sin\phi_1\sin\phi_2
\end{aligned}$$



PLB 772 (2017) 16.

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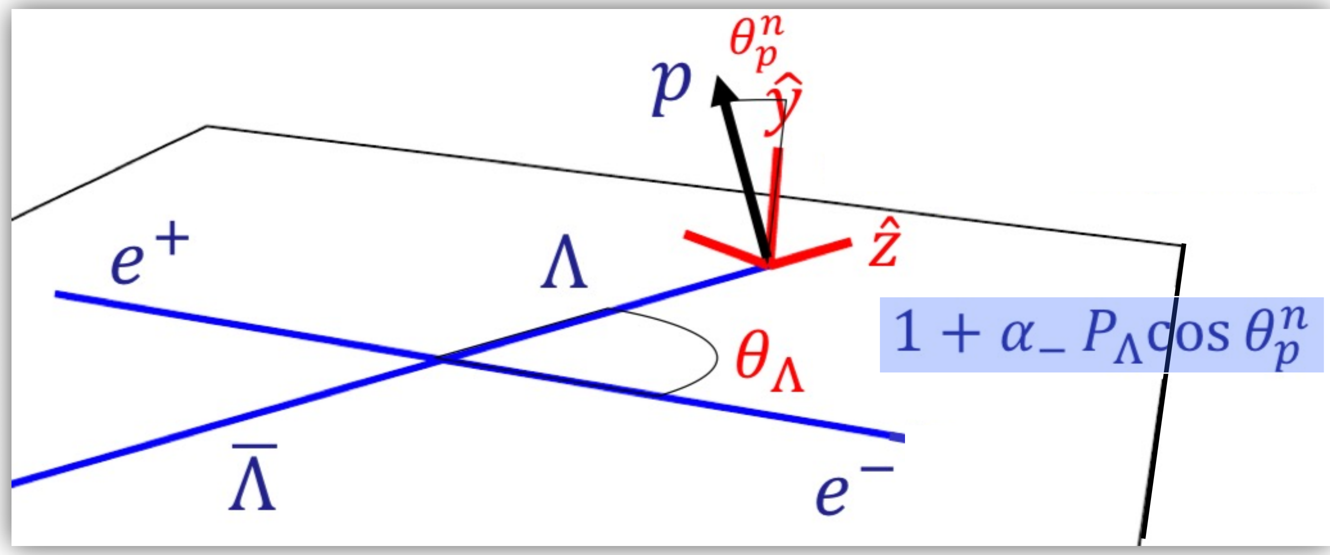
Polarization

When initial state is unpolarized and process is parity conserving, hyperons polarized perpendicular to production plane

Phase is production related, depending on CMS energy and scattering angle $\Delta\Phi \neq 0$ from interfering amplitudes (e.g. s- and d- waves) $\Delta\Phi = 0$ threshold

Analyticity requires that SL FF ~ TL FF as $|q^2|$ approaches ∞ $\Delta\Phi = 0$



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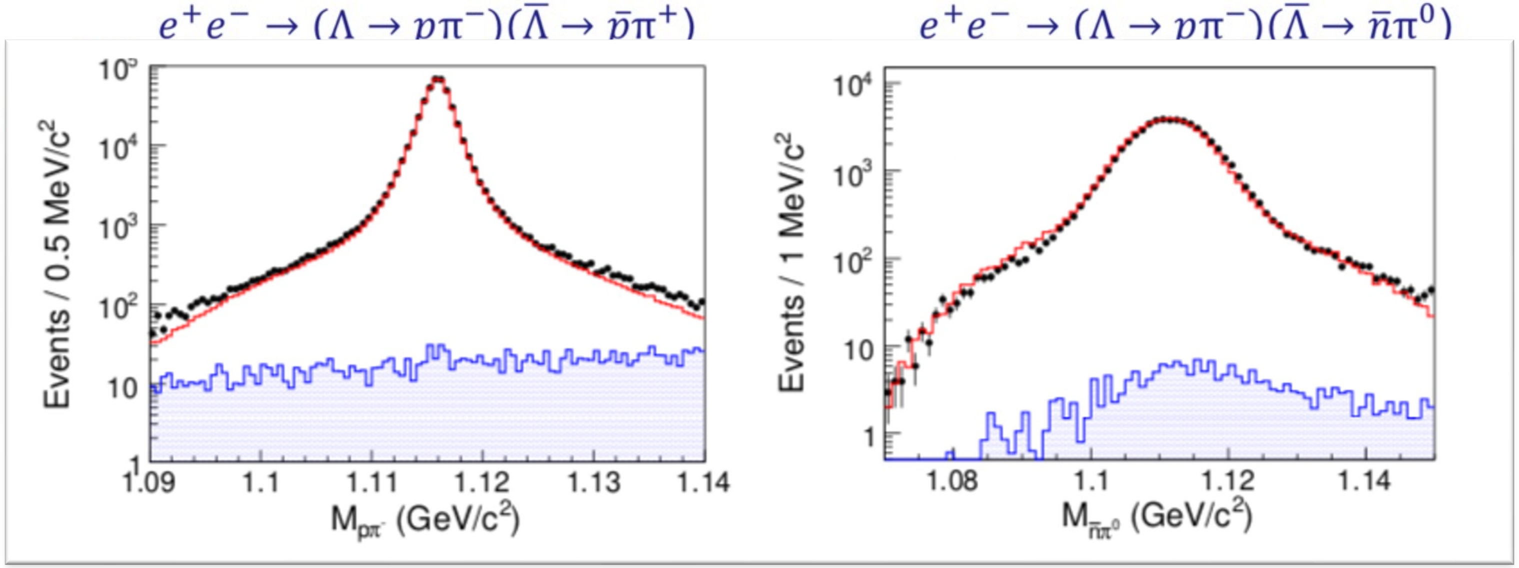
$$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda} \to p\pi^-\bar{p}\pi^+(n\pi^0)$$

BESIII, Nature Physics 15 (2019) 631



420 593 events
399 background

47 009 events
66 background

Results based on 1.3×10^9 J/ψ events

Excellent agreement between data and simulation

Background levels at fraction of percent

Unbinned maximum log-likelihood approach used for estimation of parameters

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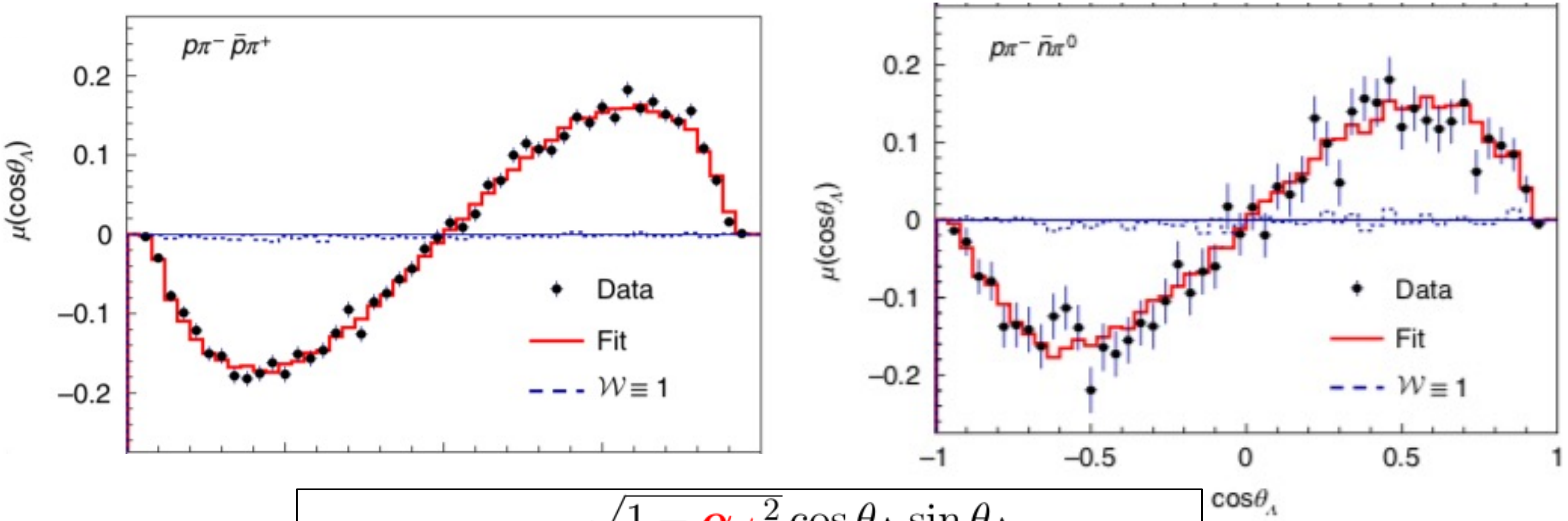
$$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda} \to p\pi^-\bar{p}\pi^+(n\pi^0)$$

BESIII, Nature Physics 15 (2019) 631



$$\bar{P}_Y(\cos\theta_\Lambda) = \frac{\sqrt{1-\alpha_\psi{}^2}\cos\theta_\Lambda\sin\theta_\Lambda}{1+\alpha_\psi\cos^2\theta_\Lambda}\sin(\Delta\Phi)$$

First measurement of hyperon polarization at J/ψ resonance

Non-zero ΔΦ allows for direct and precise measurements of asymmetry parameters

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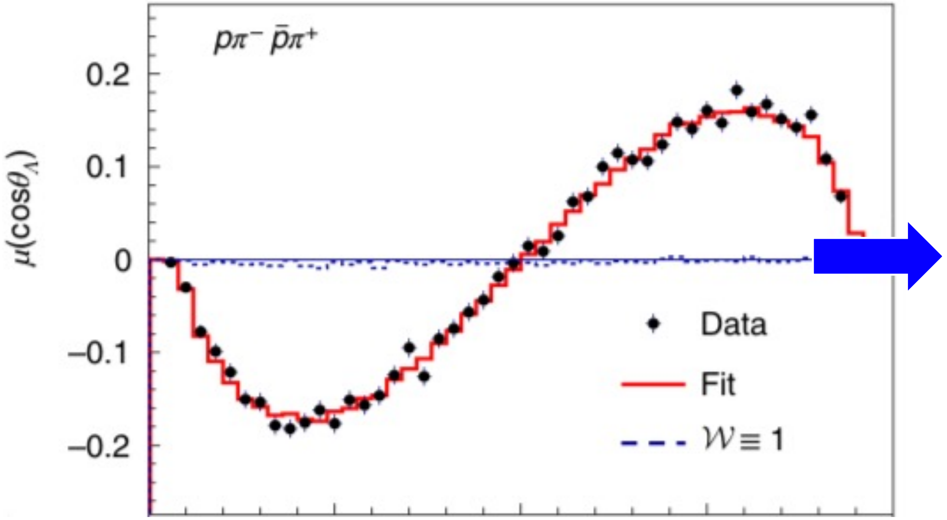
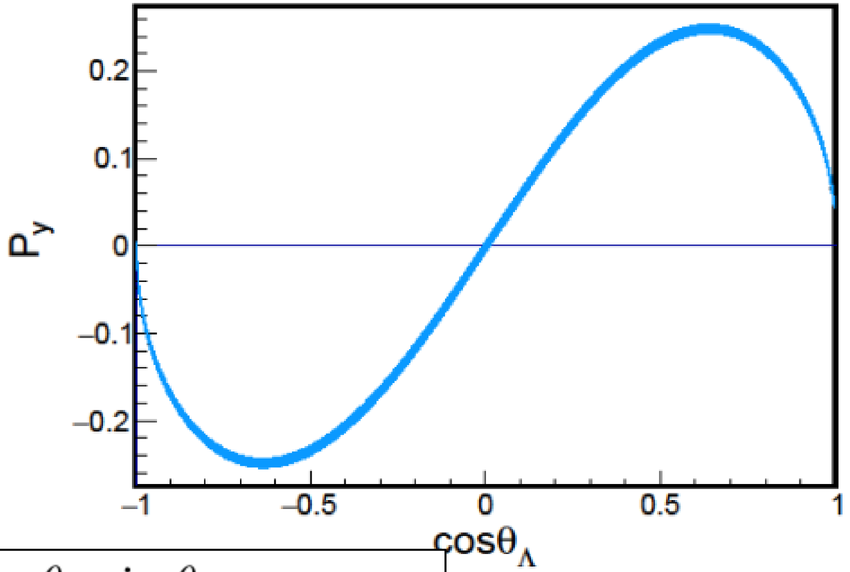
$$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda} \to p\pi^-\bar{p}\pi^+(n\pi^0)$$

BESIII, Nature Physics 15 (2019) 631



For $\Delta\Phi = 42.3°$, max polarization 25%



$$\bar{P}_Y(\cos\theta_\Lambda) = \frac{\sqrt{1-\alpha_\psi{}^2}\cos\theta_\Lambda \sin\theta_\Lambda}{1+\alpha_\psi\cos^2\theta_\Lambda}\sin(\Delta\Phi)$$

First measurement of hyperon polarization at J/ψ resonance

Non-zero ΔΦ allows for direct and precise measurements of asymmetry parameters

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$\alpha(\Lambda \to p\pi^-)$

BESIII, Nature Physics 15 (2019) 631

2019 Review of Particle Physics.
M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 update.

Λ DECAY PARAMETERS

See the ``Note on Baryon Decay Parameters" in the neutron Listings. Some early results have been omitted.

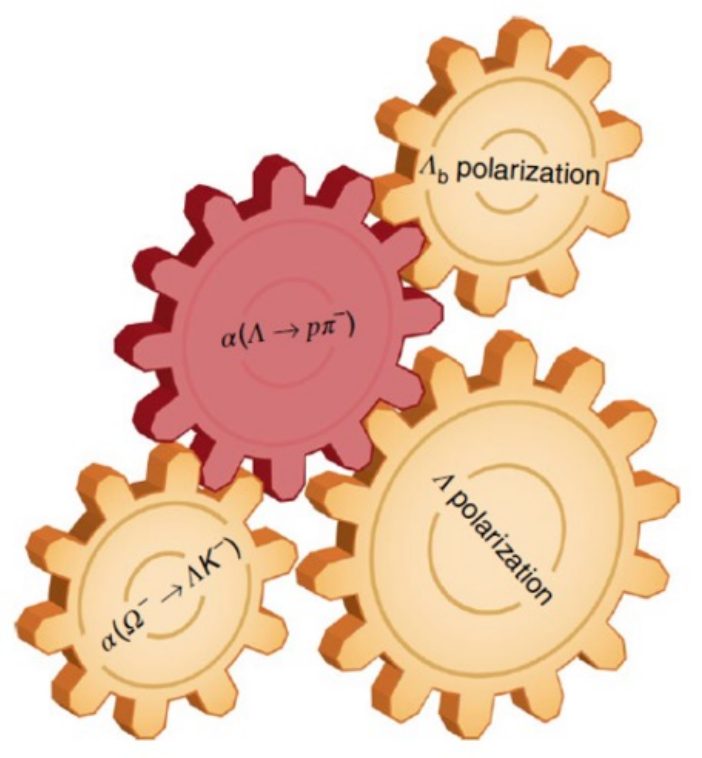
α_- FOR $\Lambda \to p\pi^-$

INSPIRE search

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.750 ±0.009 ±0.004	420k	ABLIKIM	2018AG	BES3	J/ψ to $\Lambda\bar{\Lambda}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.584 ±0.046	8500	ASTBURY	1975	SPEC	
0.649 ±0.023	10325	CLELAND	1972	OSPK	
0.67 ±0.06	3520	DAUBER	1969	HBC	From Ξ decay
0.645 ±0.017	10130	OVERSETH	1967	OSPK	Λ from $\pi^- p$
0.62 ±0.07	1156	CRONIN	1963	CNTR	Λ from $\pi^- p$

References:

ABLIKIM	2018AG	arXiv:1808.08917	
ASTBURY	1975	NP B99 30	Measurement of the Differential Cross Section and the Spin Correlation Parameters P, A, and R in the Backward Peak of $\pi^- p \to K^0\Lambda$ at 5 GeV/c
CLELAND	1972	NP B40 221	A Measurement of the β-Parameter in the Charged Nonleptonic Decay of the Λ^0 Hyperon
DAUBER	1969	PR 179 1262	Production and Decay of Cascade Hyperons
OVERSETH	1967	PRL 19 391	Time Reversal Invariance in Λ Decay
CRONIN	1963	PR 129 1795	Measurement of the Decay Parameters of the Λ Particle



news & views

PARTICLE PHYSICS

Anomalous asymmetry

A measurement based on quantum entanglement of the parameter describing the asymmetry of the Λ hyperon decay is inconsistent with the current world average. This shows that relying on previous measurements can be hazardous.

Ulrik Egede

"Relying on previous measurements can be hazardous"

$\alpha(\Lambda \to p\pi^-) = 0.750(9)_{stat}(4)_{syst}$

17±3 % off from old $\alpha_{PDG}(\Lambda \to p\pi^-) = 0.642(13)$ established in 1978. Sets the new PDG standard

Consequences for all results relying on 2018 PDG α_{PDG} . Measurements re-scaled or re-measured

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$\alpha(\Lambda \rightarrow p\pi^-)$

2019 Review of Particle Physics.
M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 update.

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α_- FOR $\Lambda \rightarrow p\pi^-$

INSPIRE search

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.750 ±0.009 ±0.004	420k	ABLIKIM	2018AG	BES3	J/ψ to $\Lambda\bar{\Lambda}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.584 ±0.046	8500	ASTBURY	1975	SPEC	
0.649 ±0.023	10325	CLELAND	1972	OSPK	
0.67 ±0.06	3520	DAUBER	1969	HBC	From Ξ decay
0.645 ±0.017	10130	OVERSETH	1967	OSPK	Λ from $\pi^- p$
0.62 ±0.07	1156	CRONIN	1963	CNTR	Λ from $\pi^- p$

References:

ABLIKIM 2018AG arXiv:1808.08917
ASTBURY 1975 NP B99 30 Measurement of the Differential Cross Section and the Spin Correlation Parameters P, A, and R in the Backward Peak of $\pi^- p \rightarrow K^0\Lambda$ at 5 GeV/c
CLELAND 1972 NP B40 221 A Measurement of the β-Parameter in the Charged Nonleptonic Decay of the Λ^0 Hyperon
DAUBER 1969 PR 179 1262 Production and Decay of Cascade Hyperons
OVERSETH 1967 PRL 19 391 Time Reversal Invariance in Λ Decay
CRONIN 1963 PR 129 1795 Measurement of the Decay Parameters of the Λ Particle

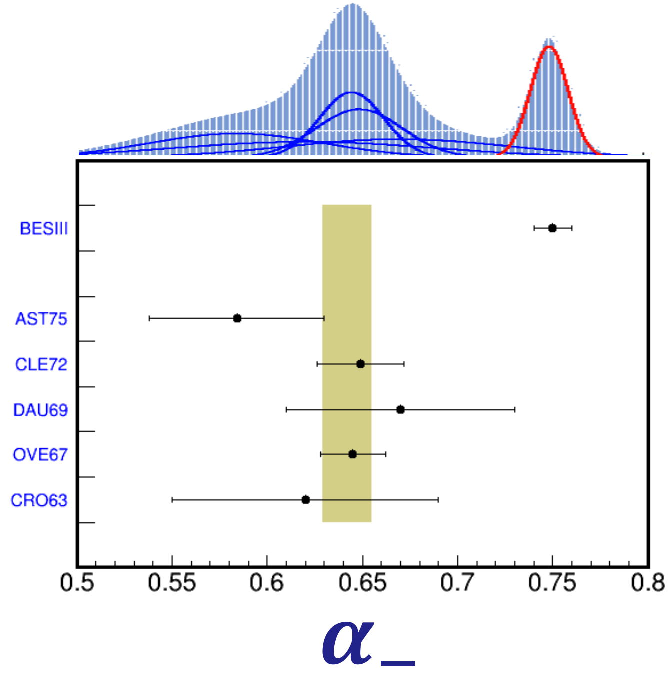

Fig. A. Kupsc

Re-measurement $\alpha(\Lambda \rightarrow p\pi^-)$ = 0.721(6)$_{stat}$(5)$_{syst}$ **

Even this result not compatible; $\langle\alpha(\Lambda \rightarrow p\pi^-)\rangle_{\mathrm{BESIII}} = \mathbf{0.754(3)(2)}$, assuming α_- = -α_+, ρ = 0.82

$\alpha_{\Lambda,\mathrm{PDG}} = \mathbf{0.732 \pm 0.014}_{tot}$ based on the two mutually incompatible values

More input was needed!

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* *BESIII, Nature Physics 15 (2019) 631*
** *Phys. Rev. Lett. 123 (2019) 18, 182301*

BESIII

$A_{CP\,\Lambda}$

BESIII, Nature Physics 15 (2019) 631

$$A_{CP,\Lambda} = \frac{\alpha_\Lambda + \bar{\alpha}_\Lambda}{\alpha_\Lambda - \bar{\alpha}_\Lambda} = -0.006 \pm 0.012_{stat} \pm 0.007_{syst}$$

$-3 \times 10^{-5} \leq A_{\Lambda\,SM} \leq 4 \times 10^{-5}$ *

$A_{CP,\Lambda\,prev} = 0.013 \pm 0.021_{tot}$ **

Most precise test of CP for Λ and compatible with SM expectations

Table 1 | Summary of the results

Parameters	This work	Previous results
α_ψ	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027 (ref. [14])
$\Delta\Phi$	$42.4 \pm 0.6 \pm 0.5°$	-
α_-	$0.750 \pm 0.009 \pm 0.004$	0.642 ± 0.013 (ref. [6])
α_+	$-0.758 \pm 0.010 \pm 0.007$	-0.71 ± 0.08 (ref. [6])
$\bar{\alpha}_0$	$-0.692 \pm 0.016 \pm 0.006$	-
A_{CP}	$-0.006 \pm 0.012 \pm 0.007$	0.006 ± 0.021 (ref. [6])
$\bar{\alpha}_0/\alpha_+$	$0.913 \pm 0.028 \pm 0.012$	-

Parameters: $J/\psi \to \Lambda\bar{\Lambda}$ angular distribution parameter α_ψ, helicity phase $\Delta\Phi$, asymmetry parameters for the $\Lambda \to p\pi^-$ (α_-), $\bar{\Lambda} \to \bar{p}\pi^+$ (α_+) and $\bar{\Lambda} \to \bar{n}\pi^0$ ($\bar{\alpha}_0$) decays, CP asymmetry A_{CP} and ratio $\bar{\alpha}_0/\alpha_+$. The first uncertainty is 1 s.d. statistical, and the second is systematic, calculated as described in the Methods.

*. Phys. Rev. D67, 056001 (2003)
** Phys Rev C54, 1877 (1996)

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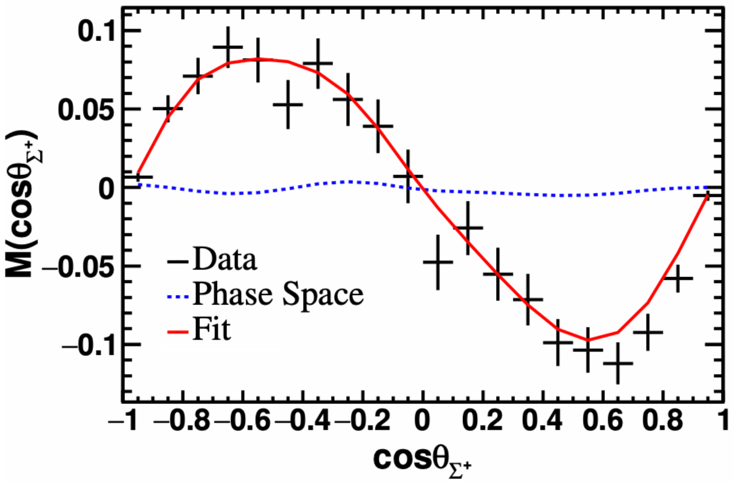
$J/\psi \to \Sigma^{+}\bar{\Sigma}^{-} \to p\pi^{0}\bar{p}\pi^{0}$

Results based on 83k events

Parameter	Measured value
$\alpha_{J/\psi}$	$-0.508 \pm 0.006 \pm 0.004$
$\Delta\Phi_{J/\psi}$	$-0.270 \pm 0.012 \pm 0.009$
$\alpha_{\psi'}$	$0.682 \pm 0.03 \pm 0.011$
$\Delta\Phi_{\psi'}$	$0.379 \pm 0.07 \pm 0.014$
α_0	$-0.998 \pm 0.037 \pm 0.009$
$\bar{\alpha}_0$	$0.990 \pm 0.037 \pm 0.011$



$\langle\alpha_{\Sigma}\rangle = -0.994 \pm 0.004 \pm 0.002$

First CP measurement for *any* Σ decay

$$A_{CP\,\Sigma} = \frac{\alpha_{\Sigma} + \alpha_{\bar{\Sigma}}}{\alpha_{\Sigma} - \alpha_{\bar{\Sigma}}} = -0.004 \pm 0.037_{stat} \pm 0.010_{syst} \ ^{*}$$

$A_{CP\,\Sigma\,SM}\ 3.6\times10^{-6}$ **

* *Phys.Rev.Lett.* 125 (2020) 5, 052004
** *Phys. Rev. D67, 056001 (2003)*

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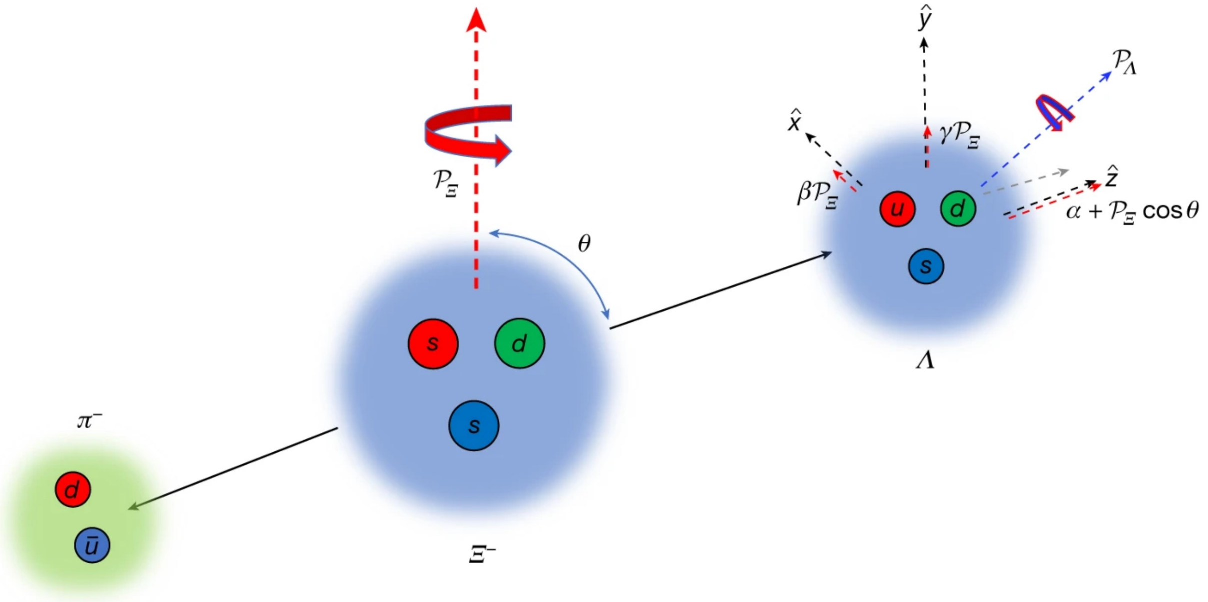
$J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda\pi^-\bar{\Lambda}\pi^+$

Nature 606 64-69 (2022)



Longitudinal polarization α and P ; transversal polarization ϕ

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

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CP and weak phase difference

$$A_{CP}^{\Xi} = \frac{\alpha_{\Xi}+\bar{\alpha}_{\Xi}}{\alpha_{\Xi}-\bar{\alpha}_{\Xi}} \approx -\sin\langle\phi_{\Xi}\rangle \frac{\sqrt{1-\alpha_{\Xi}^2}}{\alpha_{\Xi}} \tan(\xi_P-\xi_S)_{\Xi} \;*$$

$$\Delta\phi_{CP} = \frac{\phi_{\Xi}+\bar{\phi}_{\Xi}}{2} \approx \cos\langle\phi_{\Xi}\rangle \frac{\alpha_{\Xi}}{\sqrt{1-\alpha_{\Xi}^2}} \tan(\xi_P-\xi_S)_{\Xi} \;*$$

strong contribution $\phi_{\Xi} \approx 0$ weak phase diff - potentially CPV

$\Delta\phi_{CP}$ more sensitive to CP-violating effects cf A_{CP}^{Ξ}.
Proposed more 35 years ago but not measured until now!

* Phys. Rev Lett 55 162 (1985)

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BESIII

Formalism sequential weak decays

- The formalism exploits polarisation, entanglement and sequential decays * **

$$\mathcal{W}(\boldsymbol{\xi};\boldsymbol{\omega}) = \sum_{\mu,\nu=0}^{3} C_{\mu\nu} \sum_{\mu'\nu'=0}^{3} a^{\Xi}_{\mu\mu'} a^{\overline{\Xi}}_{\nu\nu'} a^{\Lambda}_{\mu'0} a^{\overline{\Lambda}}_{\nu'0}$$

- Nine-dimensional phase space given by nine helicity angles

- Eight free parameters determined by maximum log likelihood method:

α_{ψ}, $\boldsymbol{\Delta\Phi}$, $\boldsymbol{\alpha_{\Xi}}$, $\boldsymbol{\overline{\alpha}_{\Xi}}$, ϕ_{Ξ}, $\boldsymbol{\overline{\phi}_{\Xi}}$, α_{Λ}, $\overline{\alpha}_{\Lambda}$

not measured before

Formalism developed in Uppsala

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

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$C_{\mu\nu}$ 4x4 real matrix representing polarizations and spin correlations

Spin density matrices $a_{\mu\nu}$

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

$$\begin{pmatrix} 1 & 0 & 0 & \alpha_D \\ \alpha_D \sin\theta\cos\varphi & \gamma_D\cos\theta\cos\varphi - \beta_D\sin\varphi & -\beta_D\cos\theta\cos\varphi - \gamma_D\sin\varphi & \sin\theta\cos\varphi \\ \alpha_D\sin\theta\sin\varphi & \beta_D\cos\varphi + \gamma_D\cos\theta\sin\varphi & \gamma_D\cos\varphi - \beta_D\cos\theta\sin\varphi & \sin\theta\sin\varphi \\ \alpha_D\cos\theta & -\gamma_D\sin\theta & \beta_D\sin\theta & \cos\theta \end{pmatrix}$$

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

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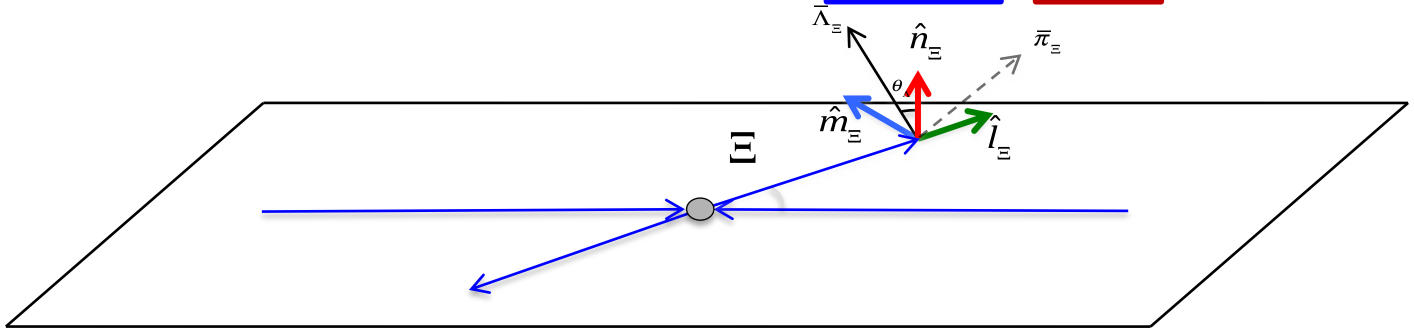
Formalism $J/\psi \to \Xi\bar{\Xi} \to \Lambda(\to p\pi)\bar{\Lambda}\pi(\to \bar{p}\pi^+)$

Here $\Delta\Phi \neq 0$ is not needed to measure decay parameters! *, **

		$\Xi^-\bar{\Xi}^+$	$\Lambda\bar{\Lambda}$
$\Delta\Phi \neq 0$:	$M =$	72	(7)
$\Delta\Phi = 0$:	$M =$	56	(5)



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

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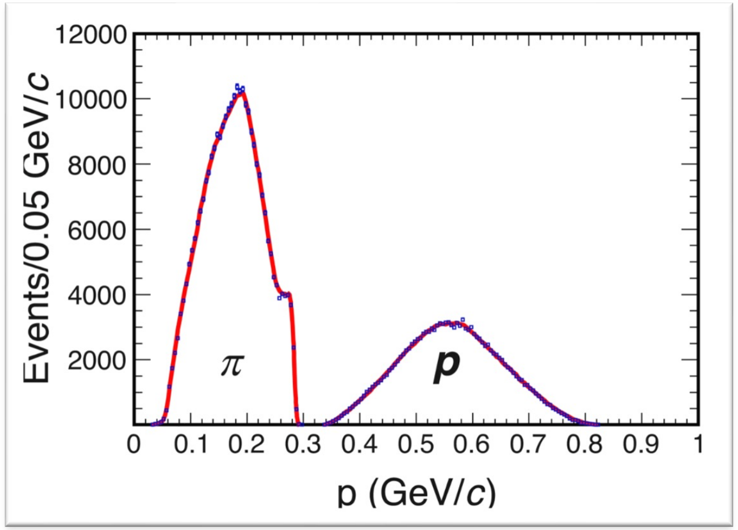
Analysis steps

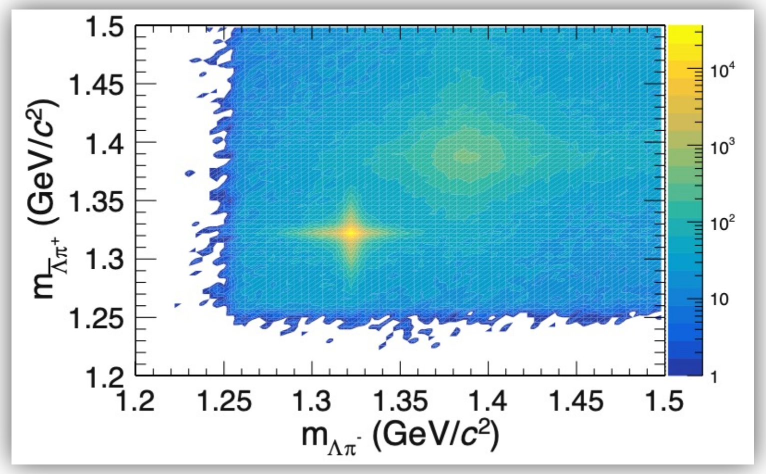
Nature 606 64-69 (2022)



at least one proton, one anti-proton, two positively and two negatively charged pion candidates

momentum criteria used to select proton ($p > 0.32$ GeV/c) and pion ($p < 0.30$ GeV/c) candidates

Λ and Ξ candidates formed with succesful vertex fits



Mass windows $|m(p\pi) - m_\Lambda| < 11.5$ MeV/c^2) and $|m(\Lambda\pi) - m_\Xi| < 12.0$ MeV/c^2

4C-kinematic fit on the hypothesis $e^+e^- \to J/\Xi \to \Xi^-\bar{\Xi}^+$ is used as veto

The decay lengths of Λ and Ξ candidates greater than 0.

For improved data-MC consistency only events with $|\cos\theta| < 0.84$

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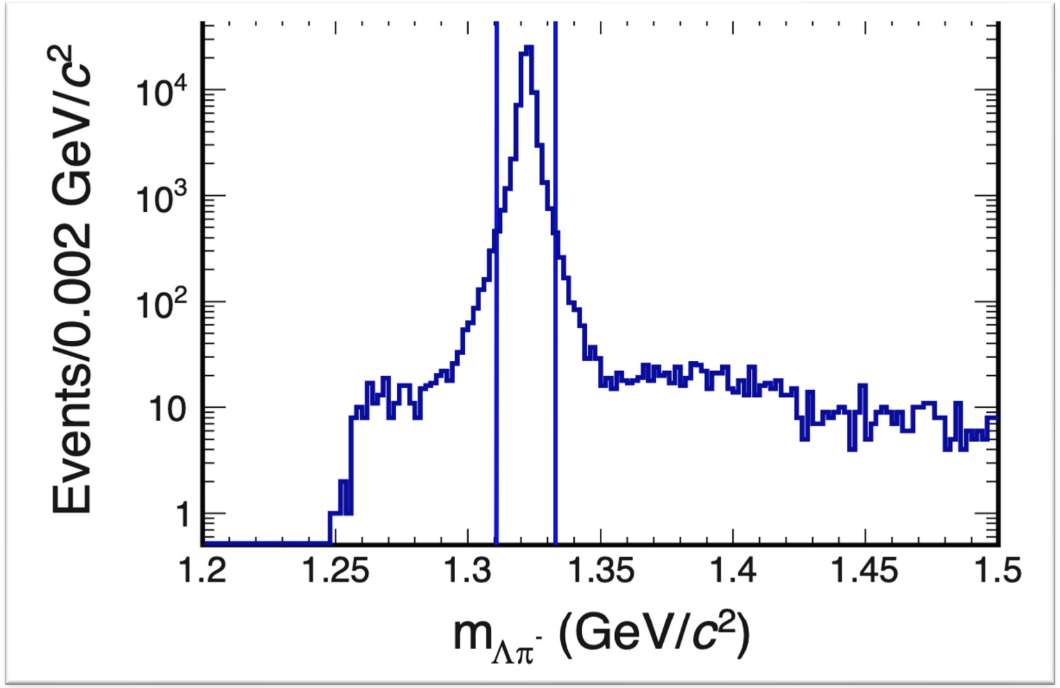
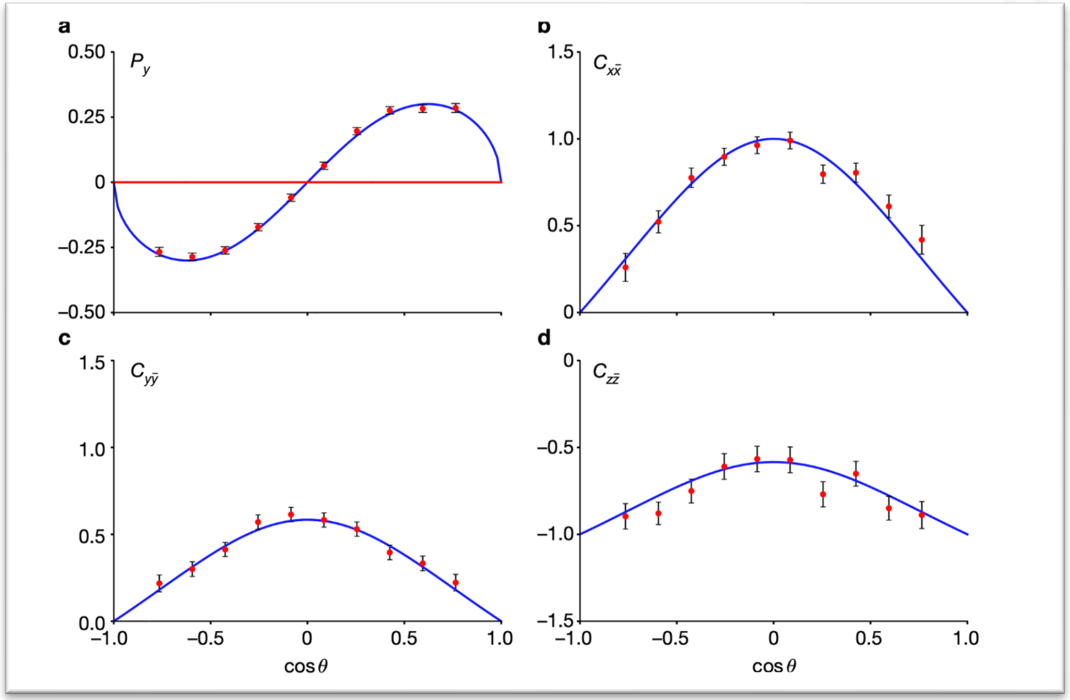
Analysis summary

Nature 606 64-69 (2022)





73 200 exclusively measured $\Xi^-\bar{\Xi}^+ \to \Lambda\pi^-\bar{\Lambda}\pi^+$ events

Very low level of background, 199±17 events

Here *entanglement* from spin correlations allows us to *"disentangle"* the weak and strong contributions

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Results highlights

Table 1 | Summary of results

Parameter	This work	Previous result	Reference	
α_ψ	0.586±0.012±0.010	0.58±0.04±0.08	Ref. [49]	*
$\Delta\Phi$	1.213±0.046±0.016 rad	–		
α_Ξ	−0.376±0.007±0.003	−0.401±0.010	Ref. [26]	**
ϕ_Ξ	0.011±0.019±0.009 rad	−0.037±0.014 rad	Ref. [26]	**
$\bar{\alpha}_\Xi$	0.371±0.007±0.002	–		
$\bar{\phi}_\Xi$	−0.021±0.019±0.007 rad	–		
α_Λ	0.757±0.011±0.008	0.750±0.009±0.004	Ref. [4]	***
$\bar{\alpha}_\Lambda$	−0.763±0.011±0.007	−0.758±0.010±0.007	Ref. [4]	***
$\xi_P-\xi_S$	$(1.2\pm3.4\pm0.8)\times10^{-2}$ rad	–		
$\delta_P-\delta_S$	$(-4.0\pm3.3\pm1.7)\times10^{-2}$ rad	$(10.2\pm3.9)\times10^{-2}$ rad	Ref. [3]	****
A^Ξ_{CP}	$(6\pm13\pm6)\times10^{-3}$	–		
$\Delta\phi^\Xi_{CP}$	$(-5\pm14\pm3)\times10^{-3}$ rad	–		
A^Λ_{CP}	$(-4\pm12\pm9)\times10^{-3}$	$(-6\pm12\pm7)\times10^{-3}$	Ref. [4]	***
$\langle\phi_\Xi\rangle$	0.016±0.014±0.007 rad			

The $J/\psi\to\Xi^-\bar{\Xi}^+$ angular distribution parameter α_ψ, the hadronic form factor phase $\Delta\Phi$, the decay parameters for $\Xi^-\to\Lambda\pi^-$ (α_Ξ, ϕ_Ξ), $\bar{\Xi}^+\to\bar{\Lambda}\pi^+$ $(\bar{\alpha}_\Xi, \bar{\phi}_\Xi)$ $\Lambda\to p\pi^-$ (α_Λ) and $\bar{\Lambda}\to\bar{p}\pi^+$ $(\bar{\alpha}_\Lambda)$; the CP asymmetries A^Ξ_{CP}, $\Delta\phi^\Xi_{CP}$ and A^Λ_{CP}, and the average $\langle\phi_\Xi\rangle$. The first and second uncertainties are statistical and systematic, respectively.

First measurement of polarisation

First direct determination of all $\Xi^-\bar{\Xi}^+$ decay parameters

Previous experiments determined product $\alpha_\Xi\ \alpha_\Lambda$

Independent measurement of Λ decay parameters. Excellent agreement with previous BESIII results. Similar precision despite 6x smaller data sample

* PRD 93, 072003 (2018)
** PDG 2020
*** Nat. Ph. 15, 631 (2019)
**** PRL 93, 011802 (2004)

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Nature 606 64-69 (2022)

First extraction of weak phase diff for *any* weakly decaying baryon

$$(\xi_p-\xi_s) = (1.2\ \pm 3.4 \pm 0.8)\times10^{-2}\ \text{rad}$$

Consistent with SM expectation

$$(\xi_p-\xi_s)_{SM} = (1.8\ \pm 1.5)\times10^{-4}\ \text{rad}$$

New method for direct weak phase extraction!

Three CP-tests, (two independent) in *single* measurement

* PRD 93, 072003 (2018)
** PDG 2020
*** Nat. Ph. 15, 631 (2019)
**** PRL 93, 011802 (2004)

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Nature 606 64-69 (2022)

We obtain the same precision for ϕ as HyperCP with ***three orders of magnitude*** smaller data sample!

$$\phi_{\Xi,\mathrm{HyperCP}} = -0.042 \pm 0.011 \pm 0.011$$
$$\langle\phi_\Xi\rangle = 0.016 \pm 0.014 \pm 0.007$$

Strong phase measurement compatible with SM $(1.9\pm4.9)\times10^{-2}$ but in tension with HyperCP 2.6σ

PRD 67 056001 (2004)

* PRD 93, 072003 (2018)
** PDG 2020
*** Nat. Ph. 15, 631 (2019)
**** PRL 93, 011802 (2004)

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Results highlights

Article

Extended Data Table 1 | Correlation coefficients for the production and asymmetry decay parameters

	α_ψ	$\Delta\Phi$	α_Ξ	ϕ	α_Λ	$\bar{\alpha}_\Xi$	$\bar{\alpha}_\Lambda$	$\bar{\phi}_\Xi$
α_ψ	1.0	0.414	-0.008	-0.006	0.107	0.014	0.120	0.003
$\Delta\Phi$		1.0	-0.016	0.016	0.133	0.008	0.138	-0.029
α_Ξ			1.0	-0.000	0.280	0.024	0.071	0.010
ϕ_Ξ				1.0	-0.002	-0.010	-0.010	0.013
α_Λ					1.0	0.070	0.401	0.014
$\bar{\alpha}_\Xi$						1.0	0.269	0.001
$\bar{\alpha}_\Lambda$							1.0	0.006
$\bar{\phi}_\Xi$								1.0

Correlation between α_Λ and $\bar{\alpha}_\Lambda$ lower compared to $\Lambda\bar{\Lambda}$

Low correlation between ϕ_Ξ and all other parameters

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Nature 606 64-69 (2022)

BESIII

Wait, was this it?

We have presented a novel *model-independent method that uses spin entanglement in sequential weak decay chain* $\Xi^- \rightarrow \Lambda\pi^-, \Lambda \rightarrow p\pi^-$

First measurement of weak phase difference for any baryon decay published yesterday. First Nature publication of BESIII, but why does it matter?

"…the most striking finding in the current paper is the demonstrated improvement that the use of entanglement , the imprimatur of quantum mechanics, gives in leveraging the sensitivity of tests of CP violation" - Anonymous Nature referee 1

"In reality, a theory in natural science cannot be without experimental foundations; physics, in particular, comes from experimental work." -丁肇中

Consider how far we have come from the original discovery of J/ψ!

Samuel Chao Chung Ting 丁肇中
Discovered J/ψ Nobel prize 1976

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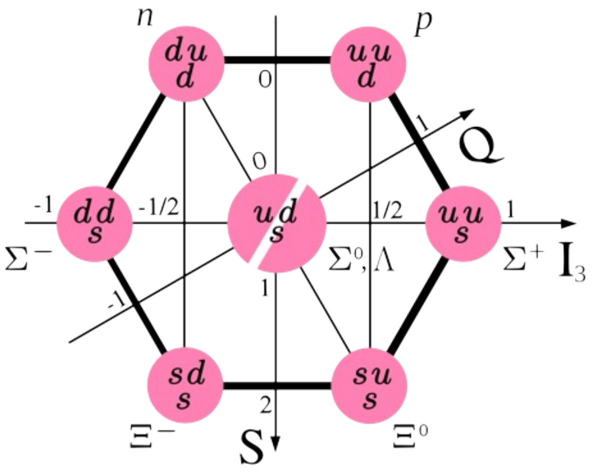
The BESIII future

Based on these discoveries and 10^{10} J/ψ data set there are many more modes which can be analyzed by BESIII

In particular reactions with neutral final state particles n, γ



	D	$\mathcal{B}$	$\langle\alpha_D\rangle$	$\langle\phi_D\rangle$ [rad]	A_{CP}	Comment
$\Lambda \to p\pi^-$	[Λp]	64%	**0.755(03)**[a]	**−0.113(61)**[b]	**−0.005(10)**[a]	
			0.754(3)(2)	–	−0.006(12)(7)	BESIII [31]
			0.721(6)(5)*	–	–	CLAS [47]
			0.760(6)(3)	–	−0.004(12)(9)	BESIII [32]
$\Lambda \to n\pi^0$	[Λn]	36%	**0.692(17)**[c]	–	–	BESIII [31]
$\Sigma^+ \to p\pi^0$	[Σp]	52%	**−0.994(04)**[d]	**0.63(59)**[g]	**−0.004(37)**[d]	
$\Sigma^+ \to n\pi^+$	[Σn]	48%	**0.068(13)***	**2.91(35)***	–	PDG [28]
$\Sigma^- \to n\pi^-$	[Σ−]	100%	**−0.068(08)***	**0.17(26)***	–	PDG [28]
$\Xi^0 \to \Lambda\pi^0$	[Ξ0]	100%	**−0.345(08)**[e]	**0.36(21)***	–	AVG [48, 49]
$\Xi^- \to \Lambda\pi^-$	[Ξ−]	100%	**−0.379(04)**[f]	−0.042(16)*	–	AVG [28, 50]
			−0.373(5)(2)	0.016(14)(7)	**0.006(13)(6)**	BESIII [32]

$\Xi^0 \to \Lambda\pi^0, \Lambda \to p\pi^-$ only few hundred events required to match the current PDG precision of ϕ_{Ξ^0}

Only indirect determination of α_{Ξ} exists

$$\phi_{\Xi^0 \to \Lambda\pi^0} = 21(12)_{tot}^{\circ}$$

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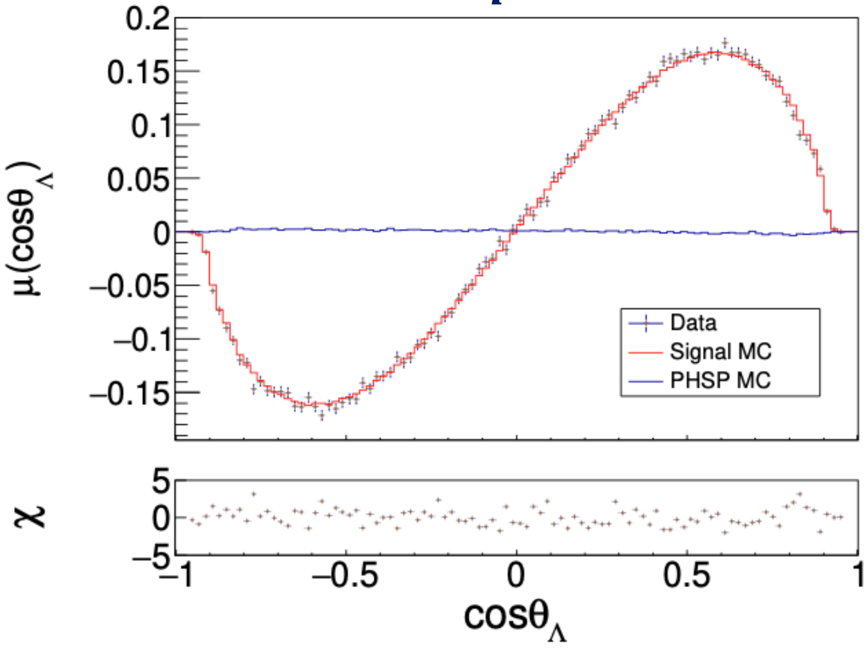
The BESIII future is already here

$\Lambda \to p\pi^-$



Based on 3.23M $\bar{\Lambda}\Lambda$

Par.	This work	Previous results [8]
$\alpha_{J/\psi}$	$0.4748 \pm 0.0022 \pm 0.0024$	$0.461 \pm 0.006 \pm 0.007$
$\Delta\Phi$	$0.7521 \pm 0.0042 \pm 0.0080$	$0.740 \pm 0.010 \pm 0.009$
α_-	$0.7519 \pm 0.0036 \pm 0.0019$	$0.750 \pm 0.009 \pm 0.004$
α_+	$-0.7559 \pm 0.0036 \pm 0.0029$	$-0.758 \pm 0.010 \pm 0.007$
A_{CP}	$-0.0025 \pm 0.0046 \pm 0.0011$	$0.006 \pm 0.012 \pm 0.007$
α_{avg}	$0.7542 \pm 0.0010 \pm 0.0020$	-

arXiv: 2204.11058

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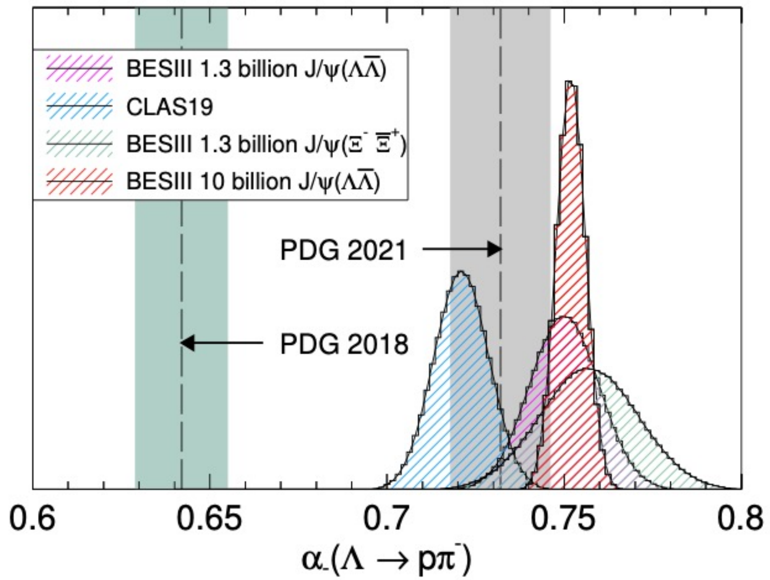

$$\langle\alpha(\Lambda \to p\pi^-)\rangle_\Lambda = 0.754(1)(2)$$
$$\langle\alpha(\Lambda \to p\pi^-)\rangle_\Xi = 0.760(6)(3)$$

Precision determined by this new result
Most precise $A_{CP,\Lambda}$!

Indication of what precision to expect

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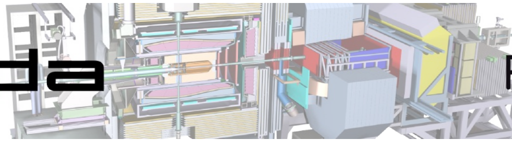
Other experimental facilities

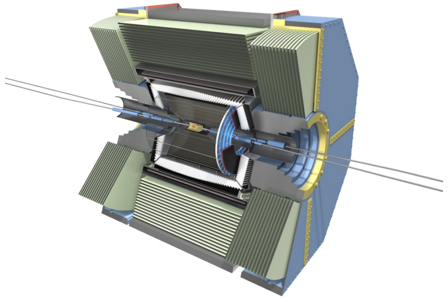
PANDA@FAIR



The potential of ΛΛ and Ξ−Ξ− studies with PANDA at FAIR

Eur. Phys. J. A 57 No. 154 (2021), arXiv: 2009.11582,

BELLE-II



Super τ charm factories

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Case study Super τ charm factories

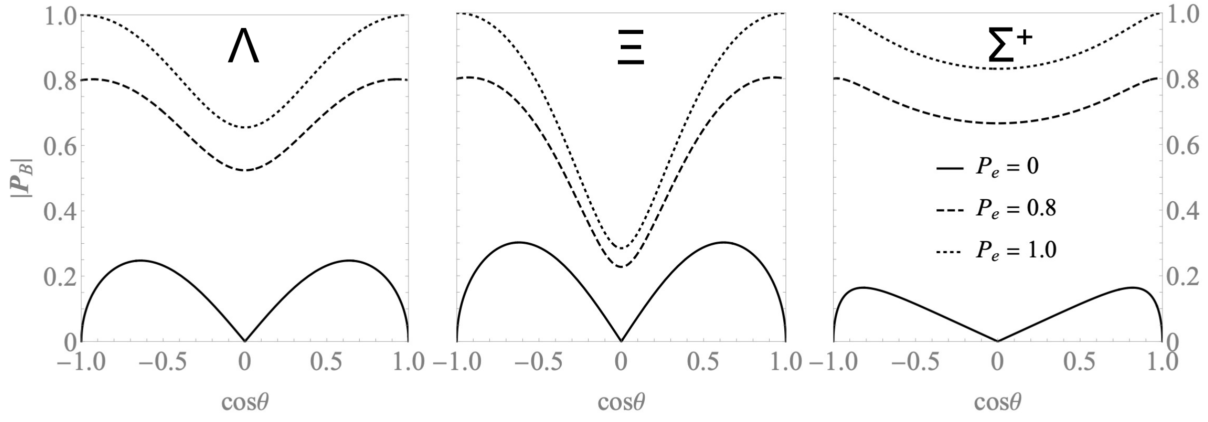
Using polarized electron beam can greatly enhance sensitivity!

Non-polarized beam

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

polarized beam

$$\frac{3}{3+\alpha_\psi}\cdot\begin{pmatrix} 1+\alpha_\psi\cos^2\theta & \gamma_\psi P_e \sin\theta & \beta_\psi \sin\theta\cos\theta & (1+\alpha_\psi)P_e\cos\theta \\ \gamma_\psi P_e\sin\theta & \sin^2\theta & 0 & \gamma_\psi \sin\theta\cos\theta \\ -\beta_\psi \sin\theta\cos\theta & 0 & \alpha_\psi\sin^2\theta & -\beta_\psi P_e\sin\theta \\ -(1+\alpha_\psi)P_e\cos\theta & -\gamma_\psi \sin\theta\cos\theta & -\beta_\psi P_e \sin\theta & -\alpha_\psi - \cos^2\theta \end{pmatrix}$$



arXiv 2203:03035

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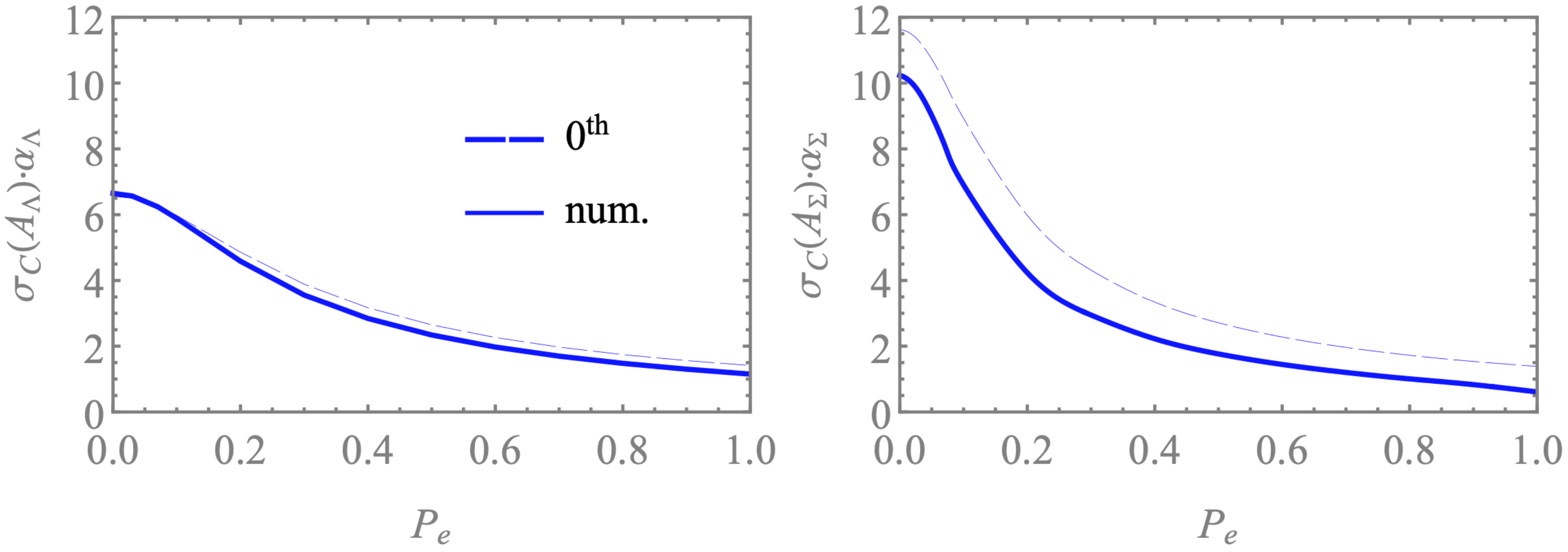
SτCF: single weak decay

$$\sigma_C(\omega_k) := \sigma(\omega_k) \times \sqrt{N}$$



Double tag

0^{th} order approximation $$\sigma(A_{CP})\sqrt{N} = \sigma_C(A_{CP}) \approx \sqrt{\frac{3}{2}} \frac{1}{\alpha_D \sqrt{\langle \mathbf{P}_B^2 \rangle}}$$

arXiv 2203:03035

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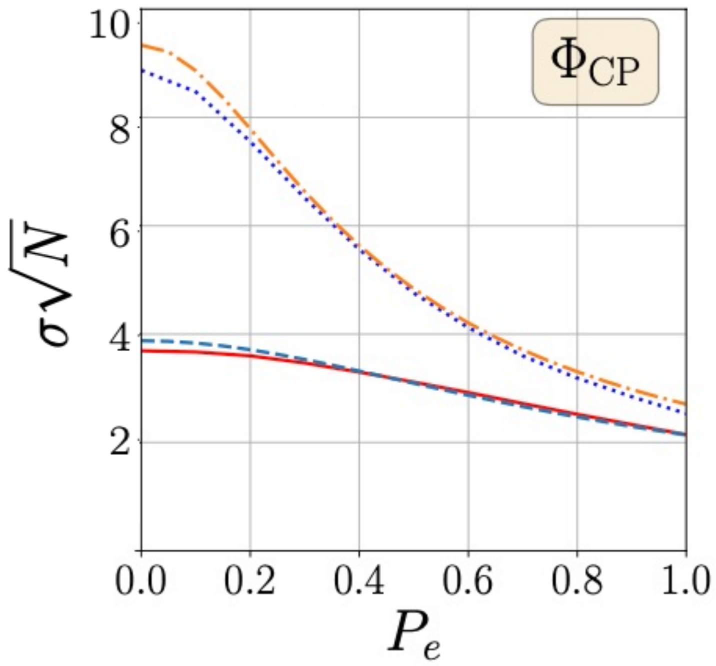
SτCF: sequential weak decay

Using polarized electron beam can greatly enhance sensitivity!

$$\mathcal{I}_0(\Phi_{\rm CP}) = \frac{2N}{27}\left(1-\alpha_\Xi^2\right)\alpha_\Lambda^2\left[\left(3+\alpha_\Xi^2\alpha_\Lambda^2\right)\langle\mathbb{P}_\Xi^2\rangle + \frac{2}{3}\left(\alpha_\Xi^2\left(3-2\alpha_\Lambda^2\right)+3\alpha_\Lambda^2\right)\langle\mathbb{S}_{\Xi\bar{\Xi}}^2\rangle\right]$$

Spin correlation contributions

$$\sigma(\Phi_{\rm CP}) = 1/\sqrt{\mathcal{I}(\Phi_{\rm CP})}$$



Dotted: ST
Solid: DT

Analytic approximation: dashed dotted dashed

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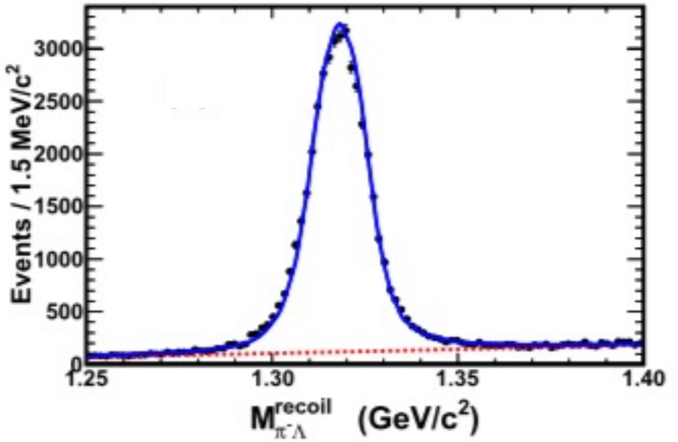
Super τ charm factories

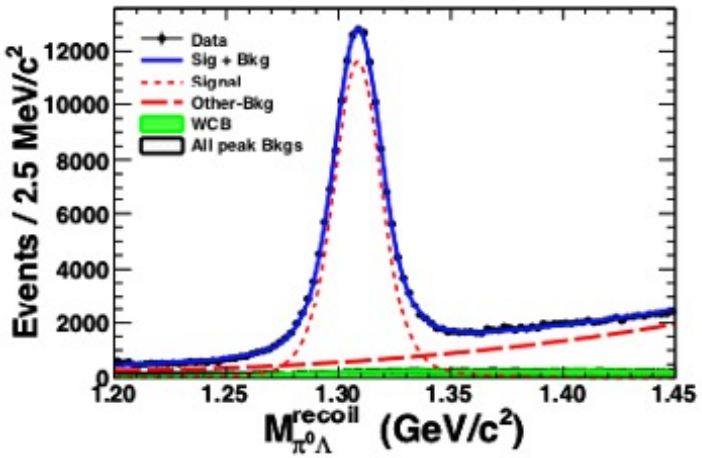
It becomes beneficial to also include single-tag events

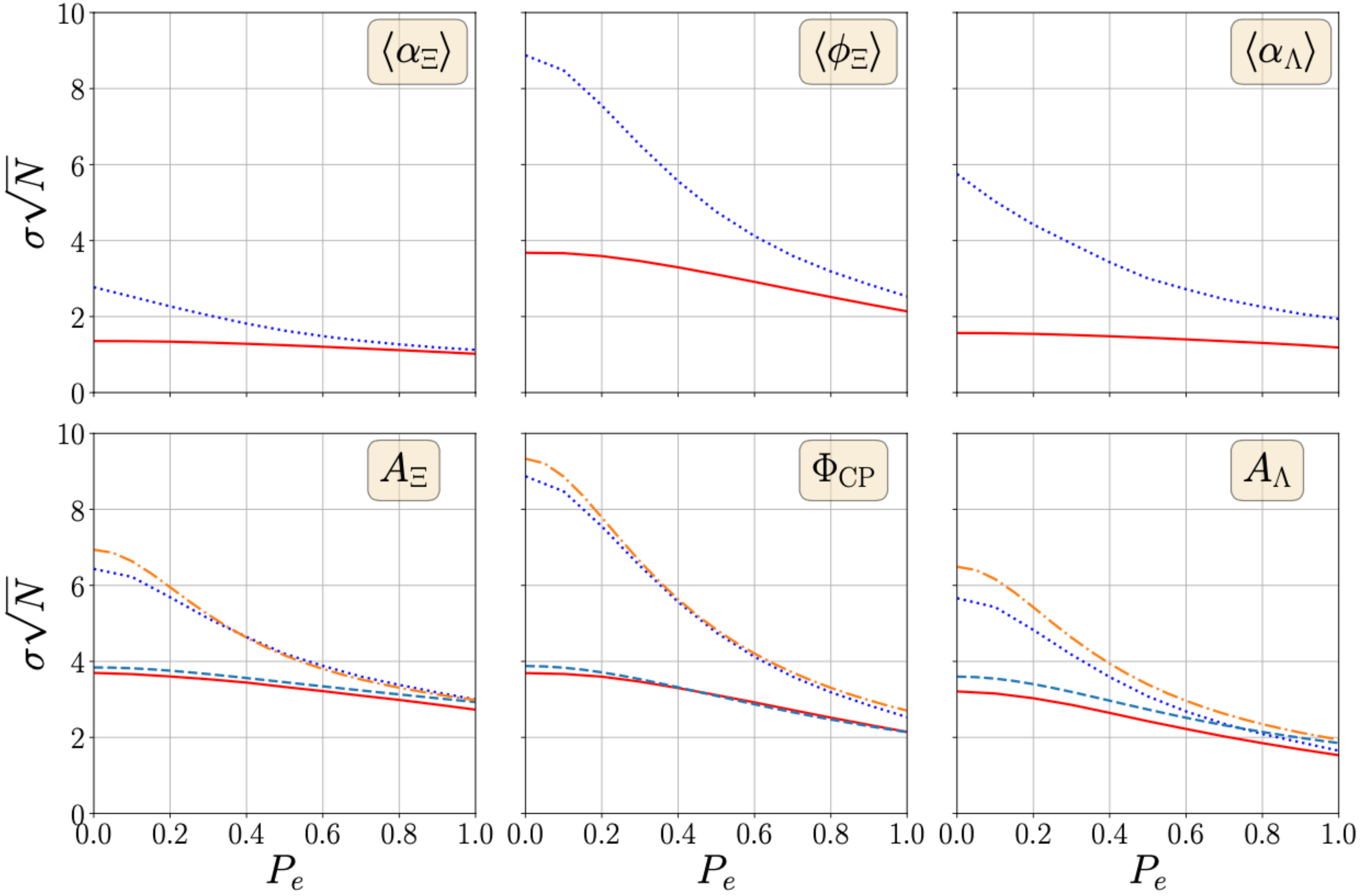
(BESIII) PHYSICAL REVIEW D 93, 072003 (2016)

Bkg % level



(BESIII) Phys Lett B 770, 217 (2017)





arXiv 2203:03035

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Summary & Outlook

We have presented a novel *model-independent method that uses spin entanglement in sequential weak decay chain* $\Xi^- \to \Lambda\pi^-, \Lambda \to p\pi^-$

First measurement of weak phase difference for any baryon decay published yesterday. First Nature publication of BESIII

The benefits of using entangled pairs can be adopted by other experiments e.g. PANDA, BELLE-II and Super-tau Charm factories. Polarization of 0.8 possible?

BESIII recently collected 1.0 x 10^{10} J/ψ events. More results to be expected in future!

Thank you for your attention!

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Spare

Extended Data Table 2 | Contributing systematic uncertainties, and the sum in quadrature

$\times 10^2$	α_ψ	$\Delta\Phi$	α_Ξ	$\bar{\alpha}_\Xi$	α_Λ	$\bar{\alpha}_\Lambda$	ϕ_Ξ	$\bar{\phi}_\Xi$
Statistical	1.2	4.6	0.70	0.70	1.05	1.06	1.91	1.93
Kin. fit	0.36	1.5	0.18	0.17	0.21	0.43	0.77	0.44
mass win Λ	0.44	0.44	0.07	0.02	0.56	0.33	0.17	0.46
mass win Ξ	0.25	-	-	-	0.36	-	0.46	-
dec. length Λ	-	-	-	-	0.30	0.40	-	-
Track. eff.	0.80	0.41	0.27	0.05	0.21	0.14	0.16	0.16
Sum syst.	1.0	1.6	0.33	0.18	0.79	0.69	0.93	0.66

First row: statistical uncertainty as reference. The uncertainties of $\Delta\Phi$ and ϕ are given in radians. All values multiplied by a factor 10^2, as indicated at top left.

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$\times 10^2$	$A_{\Lambda,CP}$	$A_{\Xi,CP}$	$\Delta\phi_{CP}$ (rad)	$\delta_P - \delta_S$ (rad)	$\zeta_P - \zeta_S$ (rad)
Statistical	1.17	1.34	1.37	3.3	3.4
Kin. fit	0.32	0.47	0.16	1.3	0.4
mass win. Λ	0.59	0.07	0.14	0.8	0.4
mass win. Ξ	0.38	-	0.20	0.7	0.5
dec. length Λ	0.46	-	-	-	-
Track. eff.	0.05	0.29	0.003	0.4	$2 \cdot 10^{-3}$
Sum syst.	0.90	0.56	0.29	1.7	0.75

First row: statistical uncertainty as reference. All values multiplied by a factor 10^2, as indicated at top left.

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