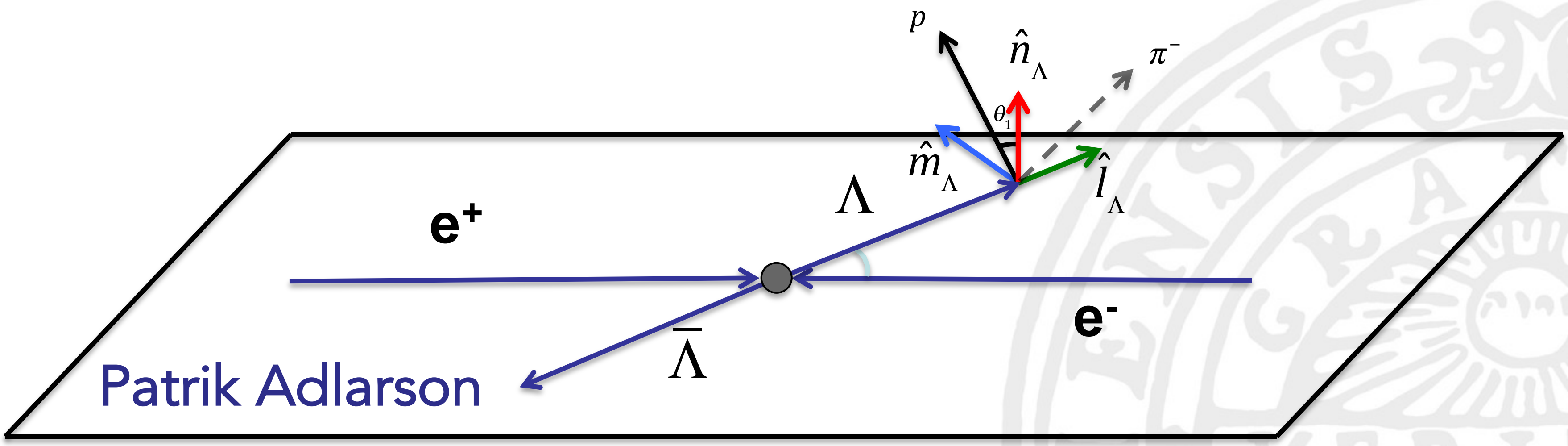
CP-violation studies of hyperon-antihyperon pairs with BESIII



Patrik Adlarson

on behalf of the BESIII collaboration

OLLE ENGKVISTS STIFTELSE

Knut and Alice Wallenberg Foundation

28th Intl. WIN Workshop

Outline

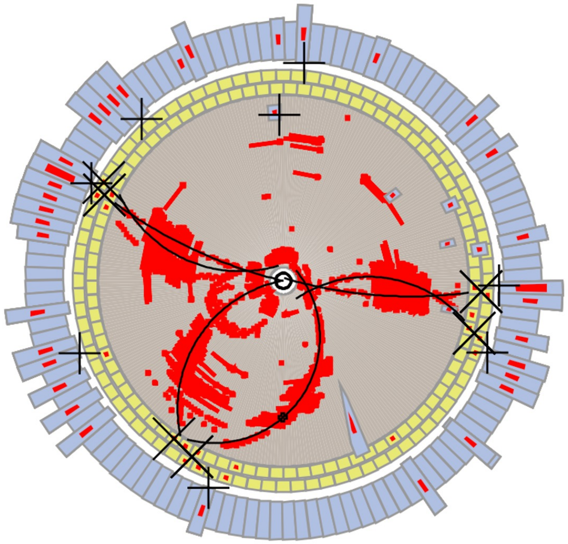
Motivation

BESIII Experiment

Results Single Weak Decays

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

Summary and Outlook



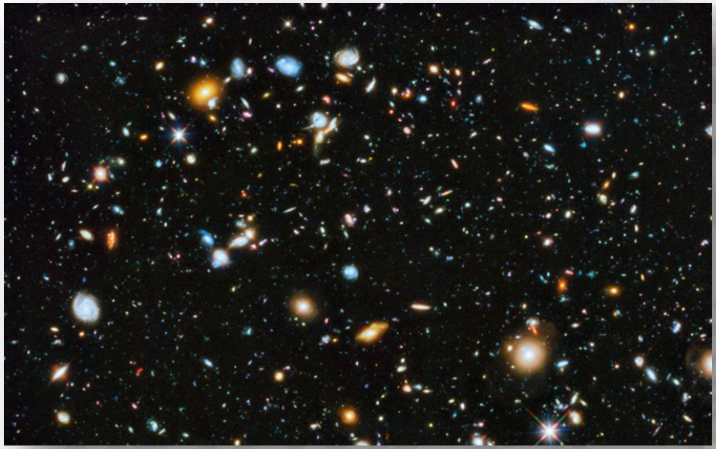
Display of simulated
$\Xi^-\overline{\Xi}^+ \to \Lambda\pi^-\overline{\Lambda}\pi^+ \to p\pi^-\pi^-\overline{p}\pi^+\pi^+$

Motivation

We have known about CP violation (CPV) more than 50 years. Only confirmed in meson decays

SM CPV not sufficient to explain observed matter-antimatter asymmetry

Baryogenesis requires C and CP violating processes*



Understanding CPV in flavour sector requires systematical mapping with different hadronic systems and complementary methods

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

Strangeness $\Delta S = 1$

MESONS:

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

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

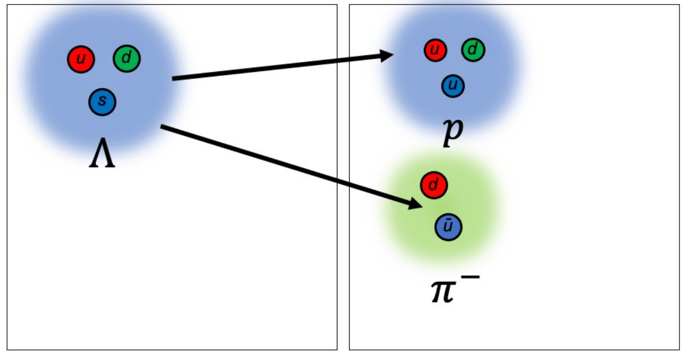
$$(\varepsilon'/\varepsilon)_{SM} = (17.4 \pm 6.1)\times 10^{-4} \; + (\varepsilon'/\varepsilon)_{BSM} = (-4 \; - \; +10)\times 10^{-4} \; **$$

SM calculation partial cancellation of QCD and EW penguins

BARYONS:

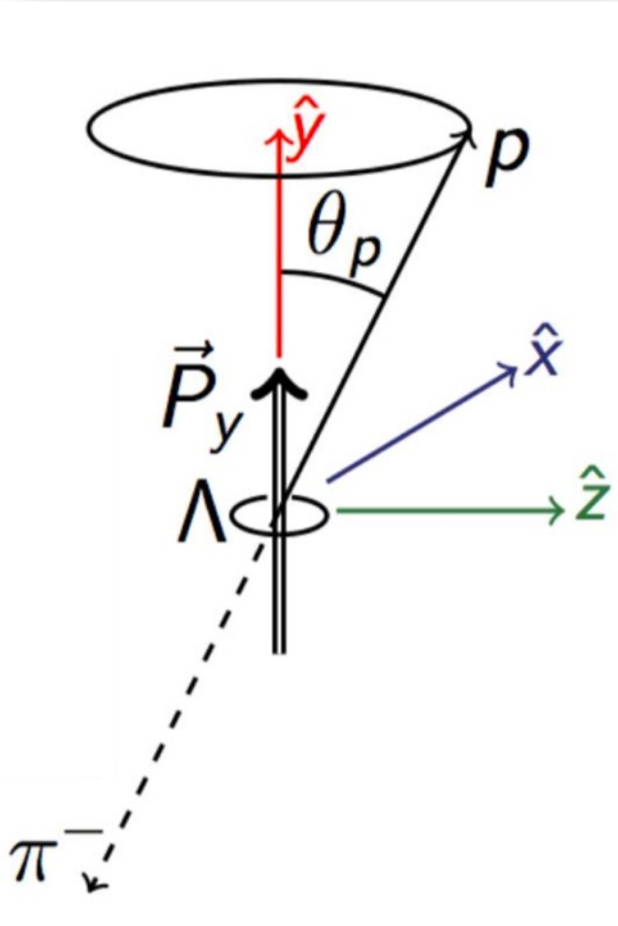
Hyperon non-leptonic two-body weak decays tests $\Delta S = 1$ CP

Recent methodological breakthrough



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

Asymmetry parameters and Polarisation



Polarisation of hyperons experimentally accessible in weak parity violating decays.

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

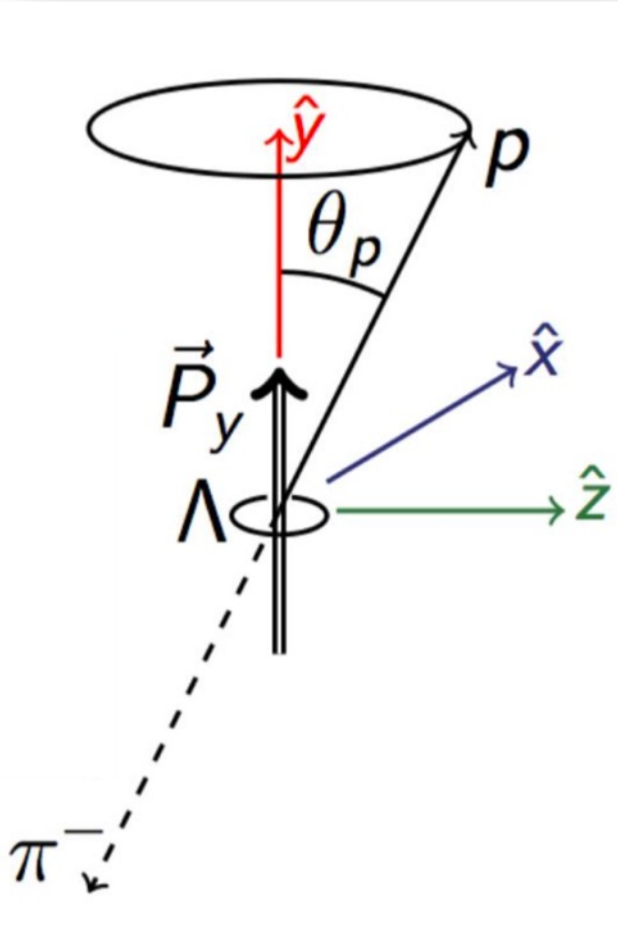
Example: Angular distribution of $\Lambda \to p\pi^-$

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

Asymmetry parameter CP-odd

Polarisation

Test of CP via A_{CP}

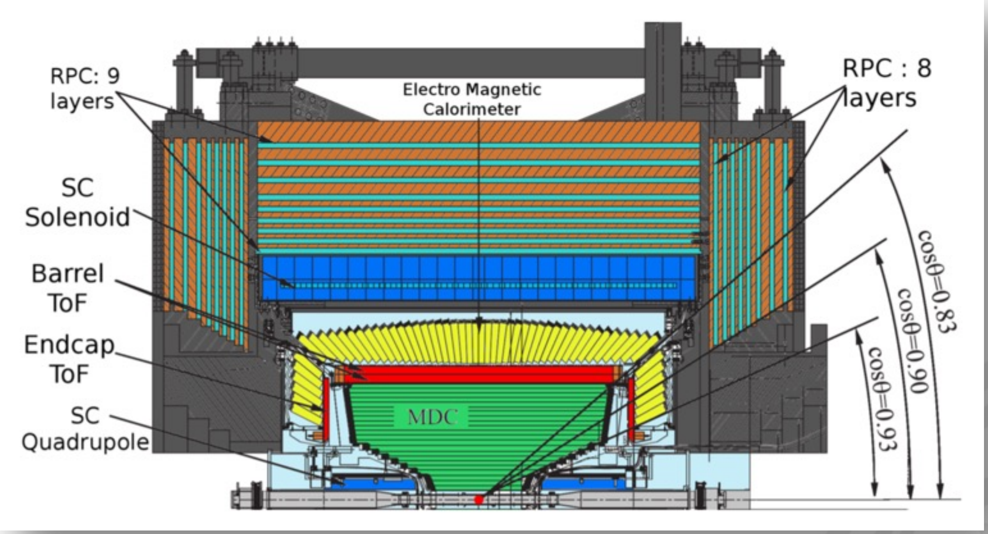


If CP conservation holds then $\alpha = -\bar{\alpha}$

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

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

BESIII ❤ Hyperons



- Multipurpose detector with very good resolution, near 4π angular coverage
- Symmetric particle – anti-particle conditions
- e^+e^- experiment low hadronic background
- Controlled systematic uncertainties
- World's largest charmonia data sample and full baryon-antibaryon octet kin. accessible

Formalism $e^+e^- \to \bar{Y}Y, Y \to BM + c.c.$

Production parameters of spin ½ baryons:

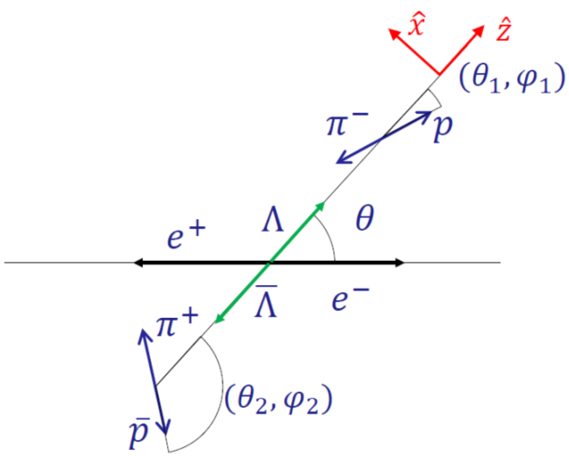
- Angular distribution parameter α_ψ
- Phase $\Delta\Phi$

Decay parameters for 2-body decays: α and $\bar{\alpha}$

Unpolarised part | Polarised part | Spin correlated part

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

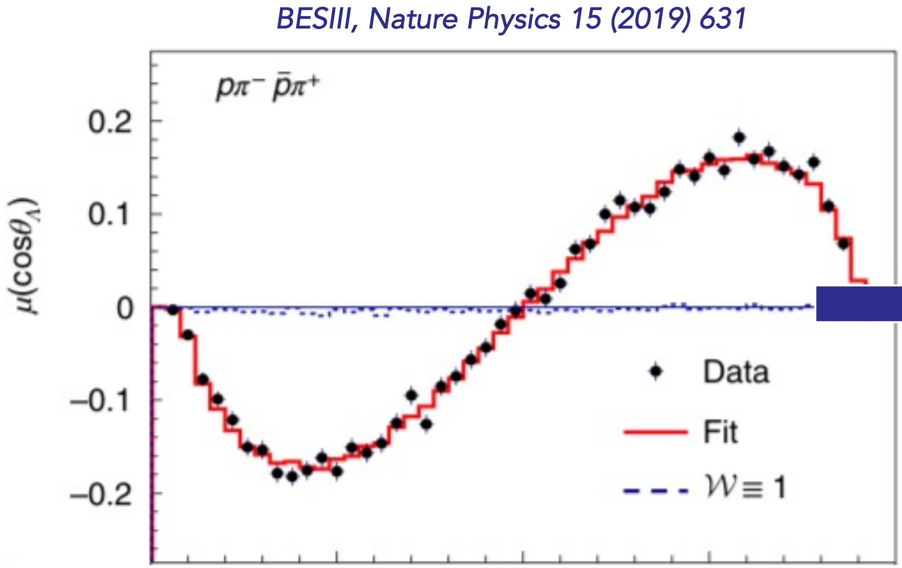
$$\mathcal{T}_0(\xi) = 1$$
$$\mathcal{T}_1(\xi) = \sin^2\theta \sin\theta_1 \sin\theta_2 \cos\phi_1 \cos\phi_2 + \cos^2\theta \cos\theta_1 \cos\theta_2$$
$$\mathcal{T}_2(\xi) = \sin\theta\cos\theta\,(\sin\theta_1 \cos\theta_2 \cos\phi_1 + \cos\theta_1 \sin\theta_2 \cos\phi_2)$$
$$\mathcal{T}_3(\xi) =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



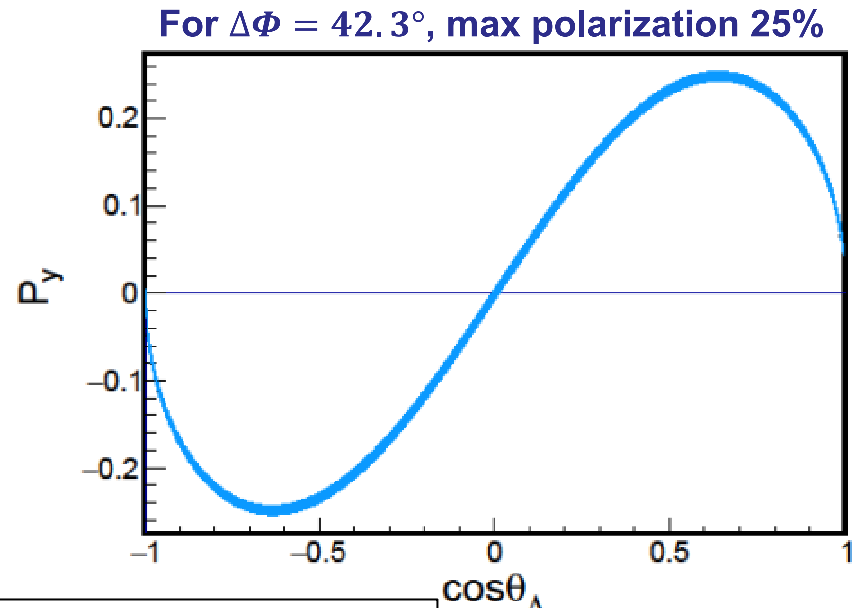
PLB 772 (2017) 16.

$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^- + c.c.$

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 $\Delta\Phi$ allows for direct and precise measurements of asymmetry parameters

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

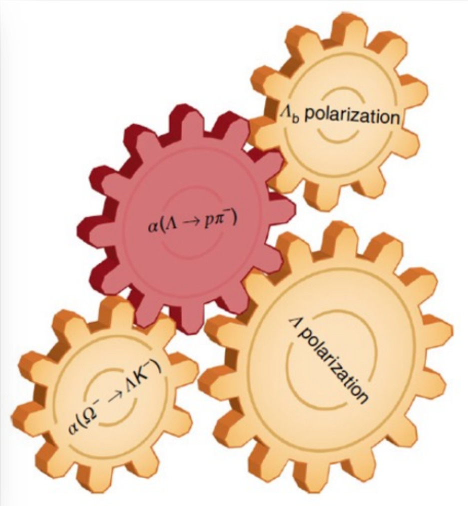
α_- FOR $\Lambda \to p\pi^-$ INSPIRE search

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.732 ± 0.014	**OUR AVERAGE** Error includes scale factor of 2.3.				
0.750 ±0.009 ±0.004	420k	ABLIKIM	2019BJ	BES3	J/ψ to $\Lambda\bar{\Lambda}$
0.721 ±0.006 ±0.005		[1] IRELAND	2019	CLAS	K production
• • • 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 $\pi^- p$

[1] This is a new analysis based on existing kaon photoproduction data of the CLAS collaboration and using spin algebra constraints.

References:

ABLIKIM	2019BJ	NATP 15 631	
IRELAND	2019	PRL 123 182301	Kaon Photoproduction and the Λ Decay Parameter α_-
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



BESIII $\alpha_\Lambda = 0.750 \pm 0.009_{stat} \pm 0.004_{syst}$*

Re-measurement using CLAS data, $\alpha_\Lambda = 0.721 \pm 0.006_{stat} \pm 0.005_{syst}$**

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

More input needed!

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

$A_{CP\,\Lambda}$

BESIII, Nature Physics 15 (2019) 631

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

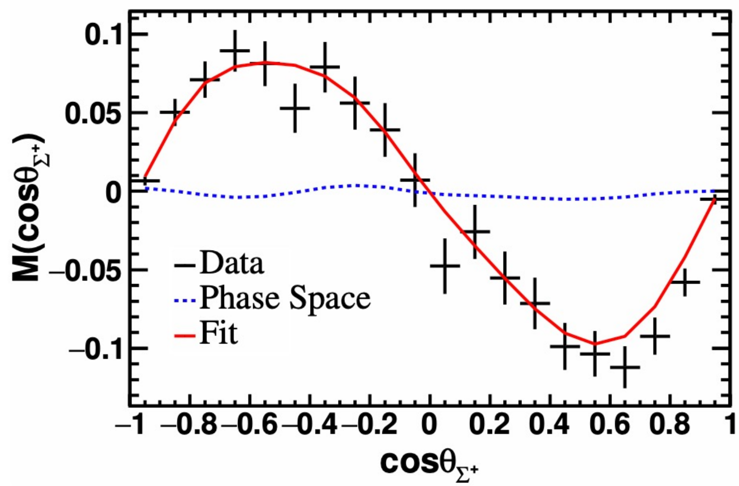
$$-3 \times 10^{-5} \leq A_{\Lambda\,SM} \leq 4 \times 10^{-5}\,{}^{*}$$

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

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

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

$J/\psi \rightarrow \Sigma^+\overline{\Sigma}^- \rightarrow p\pi^0\overline{p}\pi^0$



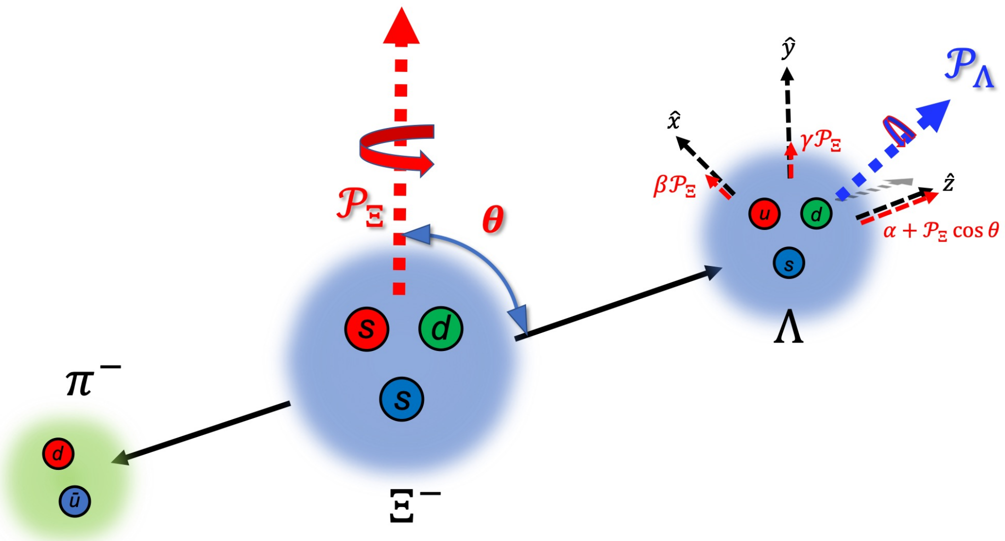
First CP measurement for *any* Σ decay

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

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

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

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

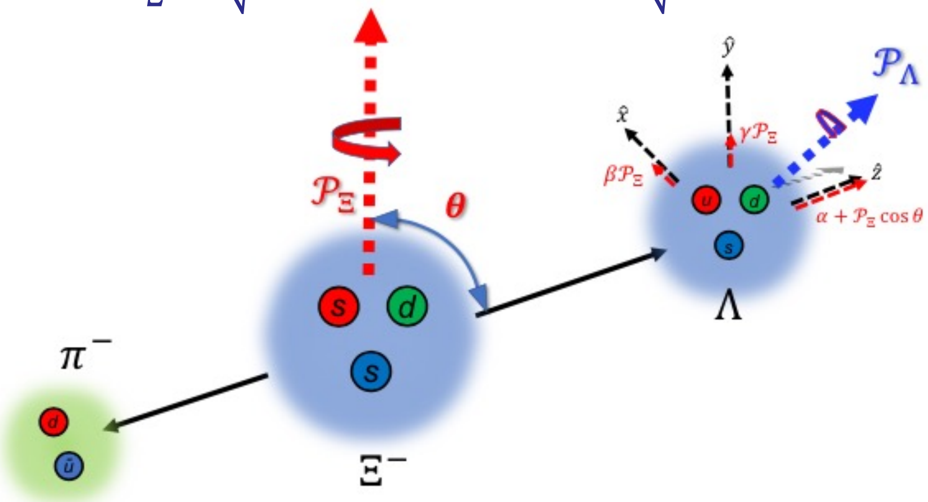


Weak phases and CP-symmetry tests in sequential decays of entangled double-strange baryons
arXiv:2105.11155

Asymmetry parameters, continued

From decay amplitudes one can construct CP-odd decay parameters $\alpha_\Xi, \beta_\Xi, \gamma_\Xi$

$$\beta_\Xi = \sqrt{1-\alpha_\Xi^2}\, sin\, \phi_\Xi;\ \gamma_\Xi = \sqrt{1-\alpha_\Xi^2}\, cos\, \phi_\Xi$$



Longitudinal polarization of Λ governed by α_Ξ
ϕ_Ξ gives rotation of P_Λ with respect to P_Ξ

ϕ_Ξ allows for new CP test: $\Delta\phi_{CP} = (\phi_\Xi + \bar{\phi}_\Xi)/2$

CP tests and phases

$$S = |S| e^{i\delta_S} e^{i\xi_S} \quad P = |P| e^{i\delta_P} e^{i\xi_P}$$

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

Under assumption that isospin ½ transitions dominate

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

strong phase diff weak phase diff

* Phys. Rev Lett 55 162 (1985)

CP and weak phase difference

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

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

weak phase diff

$\Delta\phi_{CP}$ 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)

Formalism sequential weak decays

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

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

- Nine-dimensional phase space given by nine helicity angles

- Eight free parameters determined by maximum log likelihood method:

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

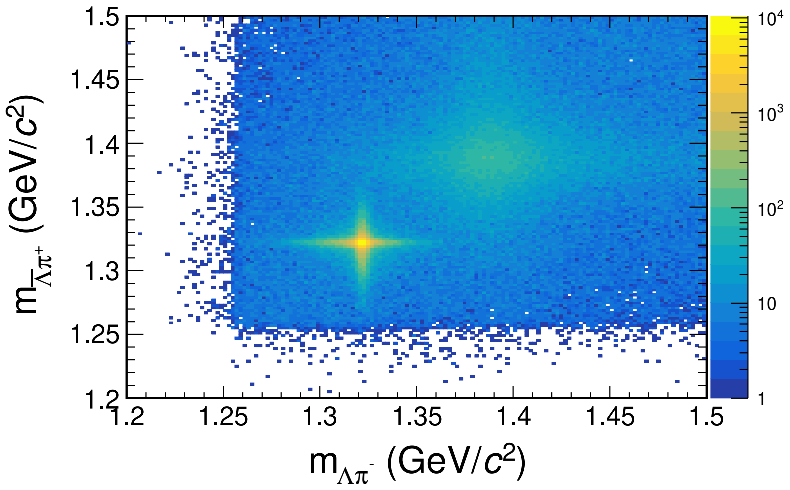
↑ ↑ ↑ ↑

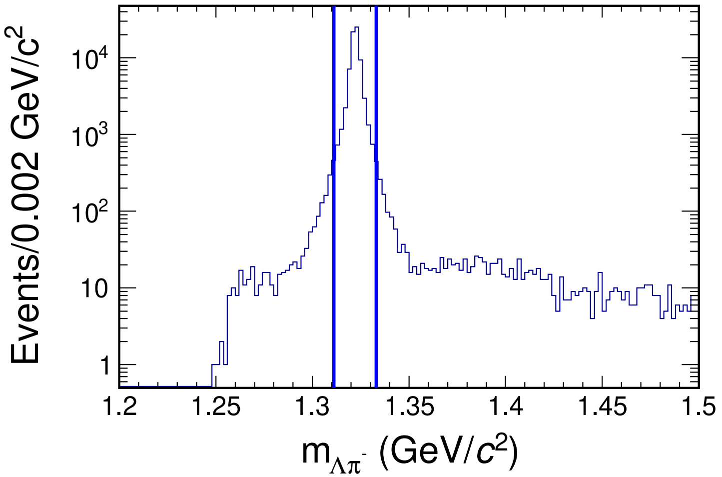
not measured before

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

Analysis summary

arXiv:2105.11155





Results based on 1.3 x 10^9 J/ψ events

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

Very low level of background

Systematic uncertainties are small, mainly from selection criteria

Results

Parameter	This work	Previous result	
α_ψ	$0.586 \pm 0.012 \pm 0.010$	$0.58 \pm 0.04 \pm 0.08$	*
$\Delta\Phi$	$1.213 \pm 0.046 \pm 0.016$ rad	–	
α_Ξ	$-0.376 \pm 0.007 \pm 0.003$	-0.401 ± 0.010	**
ϕ_Ξ	$0.011 \pm 0.019 \pm 0.009$ rad	-0.037 ± 0.014 rad	**
$\overline{\alpha}_\Xi$	$0.371 \pm 0.007 \pm 0.002$	–	
$\overline{\phi}_\Xi$	$-0.021 \pm 0.019 \pm 0.007$ rad	–	
α_Λ	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$	***
$\overline{\alpha}_\Lambda$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$	***
$\xi_P - \xi_S$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad	–	
$\delta_P - \delta_S$	$(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2}$ rad	$(10.2 \pm 3.9) \times 10^{-2}$ rad	****
A_{CP}^{Ξ}	$(6.0 \pm 13.4 \pm 5.6) \times 10^{-3}$	–	
$\Delta\phi_{CP}^{\Xi}$	$(-4.8 \pm 13.7 \pm 2.9) \times 10^{-3}$ rad	–	
A_{CP}^{Λ}	$(-3.7 \pm 11.7 \pm 9.0) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$	***
$\langle\phi_\Xi\rangle$	$0.016 \pm 0.014 \pm 0.007$ rad		

First measurement of polarisation

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

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

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

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

$$(\xi_p - \xi_s) = (1.2 \ \pm 3.4 \pm 0.8)\times 10^{-2} \text{ rad}$$

Consistent with SM expectation

$$(\xi_p - \xi_s)_{SM} = (1.8 \ \pm 1.5)\times 10^{-4} \text{ rad}$$

New method for direct weak phase extraction!

* PRD 93, 072003 (2018)
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New method for direct weak phase extraction!

Three independent CP-tests in *single* measurement

* PRD 93, 072003 (2018)
** PDG 2020
*** Nat. Ph. 15, 631 (2019)
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A_{CP}^{Λ}	$(-3.7 \pm 11.7 \pm 9.0) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$	***
$\langle\phi_\Xi\rangle$	$0.016 \pm 0.014 \pm 0.007$ rad		

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

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

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

Results

Parameter	This work	Previous result	
α_ψ	$0.586 \pm 0.012 \pm 0.010$	$0.58 \pm 0.04 \pm 0.08$	*
$\Delta\Phi$	$1.213 \pm 0.046 \pm 0.016$ rad	–	
α_Ξ	$-0.376 \pm 0.007 \pm 0.003$	-0.401 ± 0.010	**
ϕ_Ξ	$0.011 \pm 0.019 \pm 0.009$ rad	-0.037 ± 0.014 rad	**
$\overline{\alpha}_\Xi$	$0.371 \pm 0.007 \pm 0.002$	–	
$\overline{\phi}_\Xi$	$-0.021 \pm 0.019 \pm 0.007$ rad	–	
α_Λ	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$	***
$\overline{\alpha}_\Lambda$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$	***
$\xi_P - \xi_S$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad	–	
$\delta_P - \delta_S$	$(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2}$ rad	$(10.2 \pm 3.9) \times 10^{-2}$ rad	****
A_{CP}^{Ξ}	$(6.0 \pm 13.4 \pm 5.6) \times 10^{-3}$	–	
$\Delta\phi_{CP}^{\Xi}$	$(-4.8 \pm 13.7 \pm 2.9) \times 10^{-3}$ rad	–	
A_{CP}^{Λ}	$(-3.7 \pm 11.7 \pm 9.0) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$	***
$\langle\phi_\Xi\rangle$	$0.016 \pm 0.014 \pm 0.007$ rad		

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

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

Our strong phase measurement compatible with SM. In tension with HyperCP

* PRD 93, 072003 (2018)
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Summary & Outlook

BESIII has rich program of testing CP from comparing hyperon and anti-hyperon decays

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

First measurement of weak phase difference for any baryon decay

$\Delta\phi_{CP}$ tests CP without (the strong phase) suppression factor present in A_{CP} tests.

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

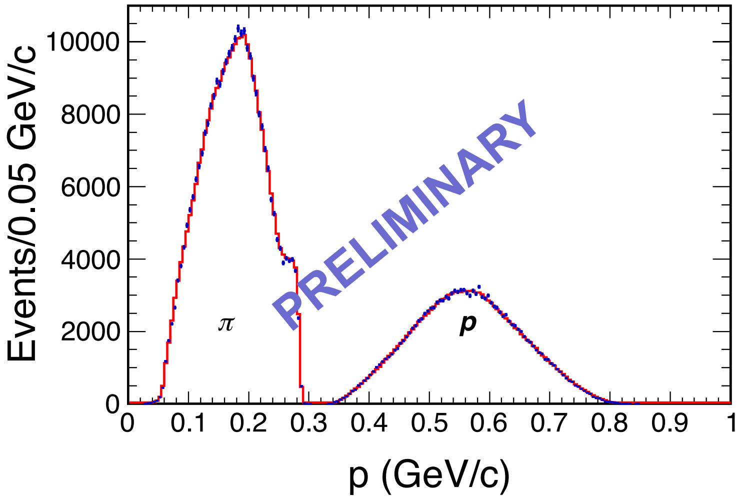
BESIII recently collected 1.0 x 10^{10} J/ψ events. More results to be expected in future!

Thank you for your attention!

Spare slides

Analysis steps

arXiv:2105.11155



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 |cosθ|< 0.84