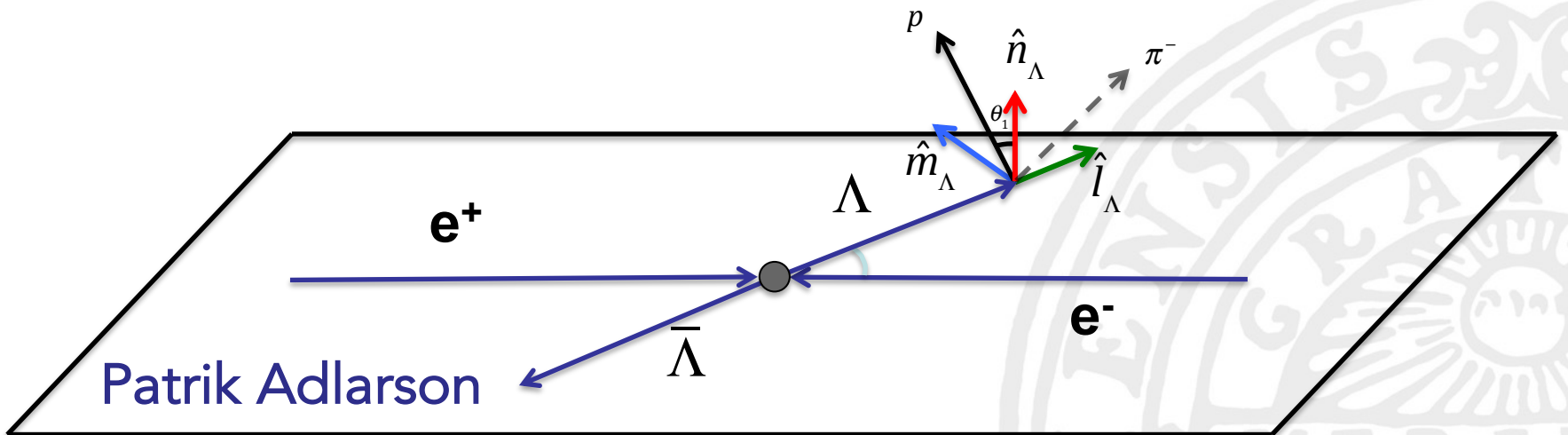




CP-violation studies of hyperon-antihyperon pairs with BESIII



Patrik Adlarson

on behalf of the BESIII collaboration



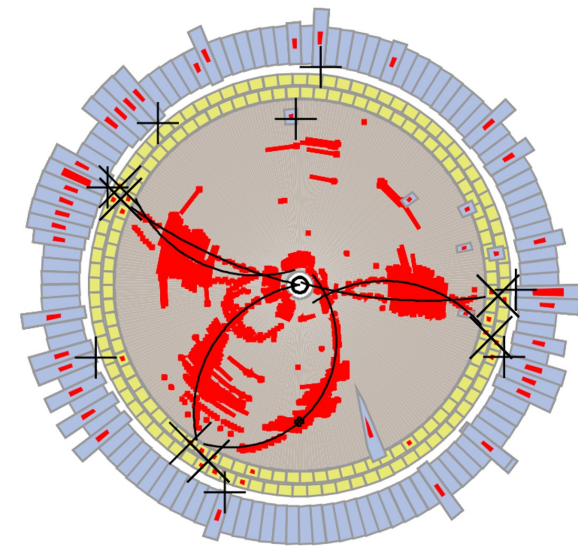
Motivation

BESIII Experiment

Results Single Weak Decays

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

Summary and Outlook



Display of simulated
 $e^-e^+ \rightarrow \Lambda\pi^- \bar{\Lambda}\pi^+ \rightarrow p\pi^- \pi^-\bar{p}\pi^+ \pi^+$

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

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

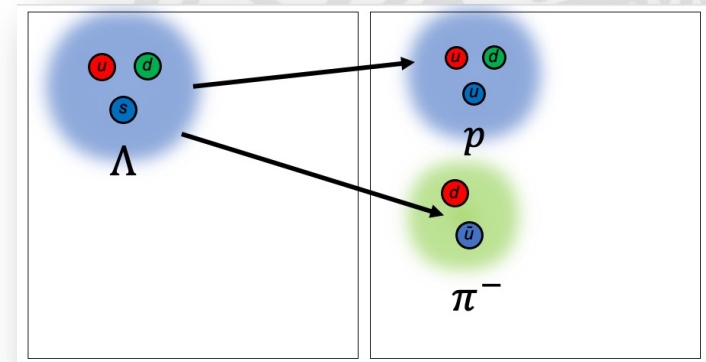
$$(\varepsilon'/\varepsilon)_{SM} = (17.4 \pm 6.1) \times 10^{-4} + (\varepsilon'/\varepsilon)_{BSM} = (-4 - +10) \times 10^{-4} **$$

SM calculation partial cancellation of QCD and EW penguins

BARYONS:

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

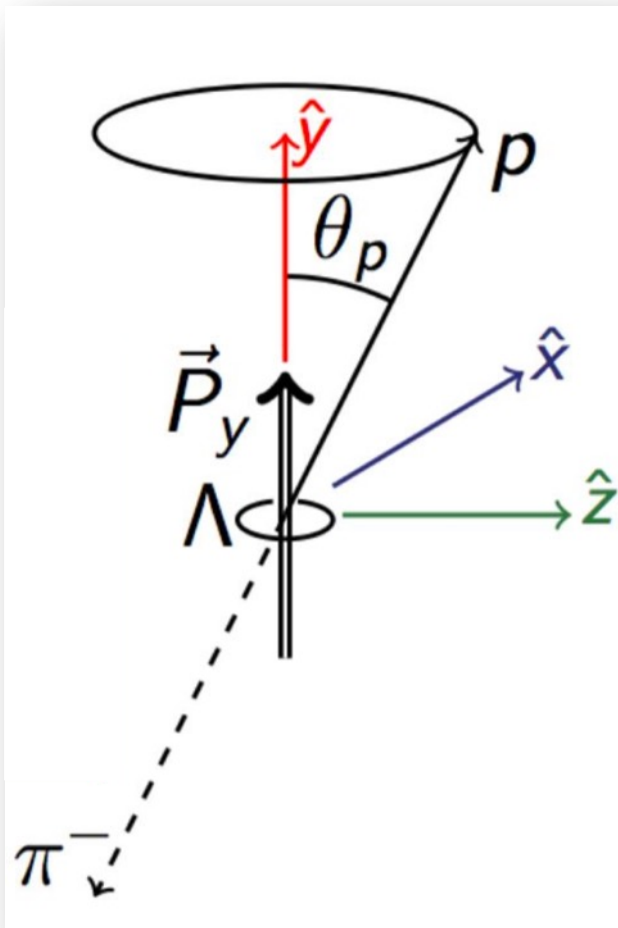
Recent methodological breakthrough



* 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

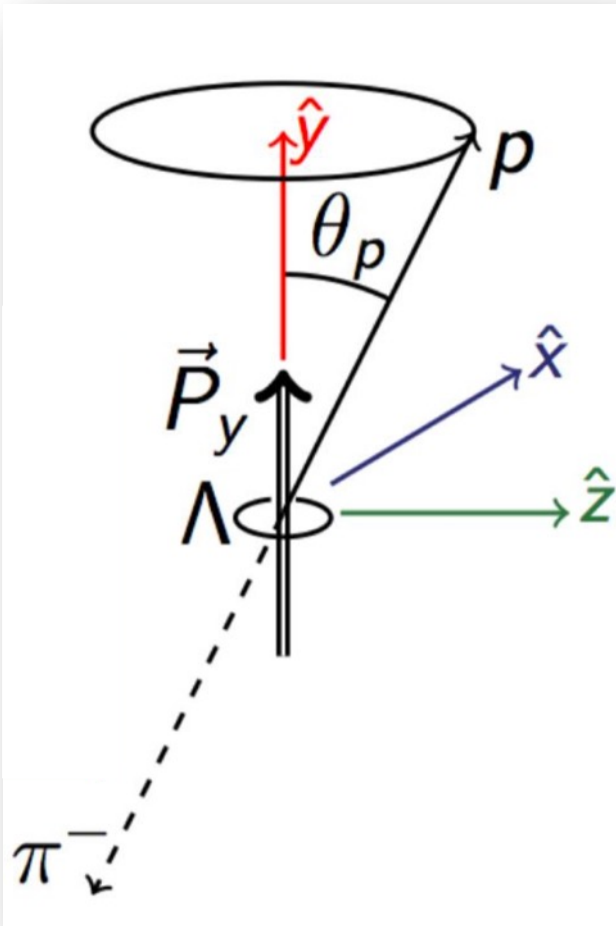
Example: Angular distribution of $\Lambda \rightarrow p\pi^-$

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

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 $\Lambda \rightarrow p\pi^-$ but all non-leptonic two-body weak decays

Beijing Electron Positron Collider BEPC II



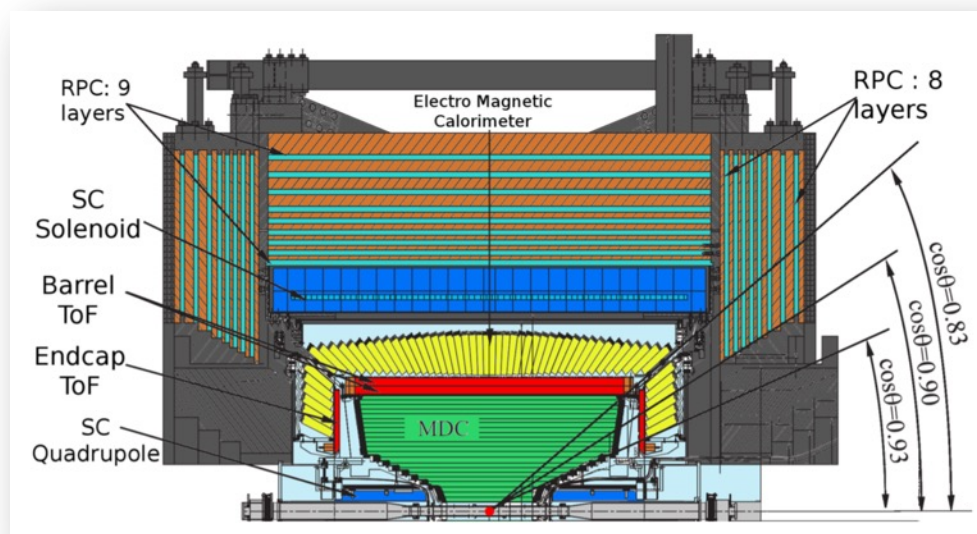
Aerial view of BEPC II and BES III

BES III at BEPC II located in Beijing, China

Data taking since 2009, peak luminosity $10^{33} \text{ cm}^{-2}\text{s}^{-1}$



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

Production parameters of spin 1/2 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

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

$$\mathcal{T}_0(\xi) = 1$$

$$\mathcal{T}_1(\xi) = \sin^2 \theta \sin \theta_1 \sin \theta_2 \cos \phi_1 \cos \phi_2 + \cos^2 \theta \cos \theta_1 \cos \theta_2$$

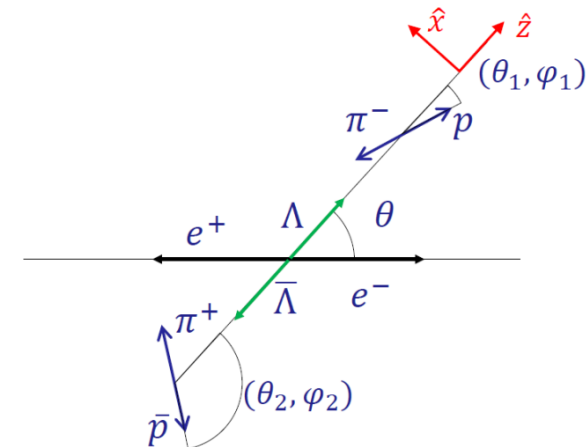
$$\mathcal{T}_2(\xi) = \sin \theta \cos \theta (\sin \theta_1 \cos \theta_2 \cos \phi_1 + \cos \theta_1 \sin \theta_2 \cos \phi_2)$$

$$\mathcal{T}_3(\xi) = \sin \theta \cos \theta \sin \theta_1 \sin \phi_1$$

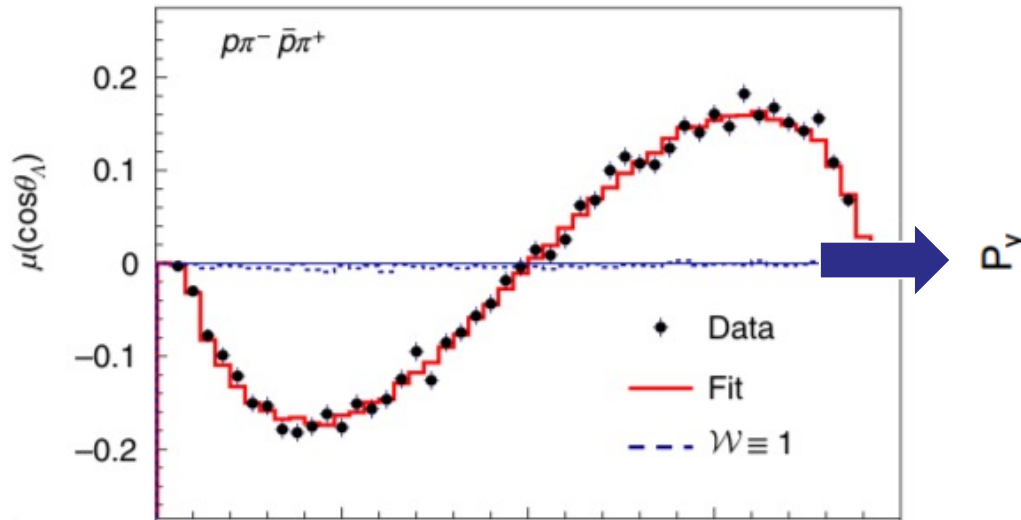
$$\mathcal{T}_4(\xi) = \sin \theta \cos \theta \sin \theta_2 \sin \phi_2$$

$$\mathcal{T}_5(\xi) = \cos^2 \theta$$

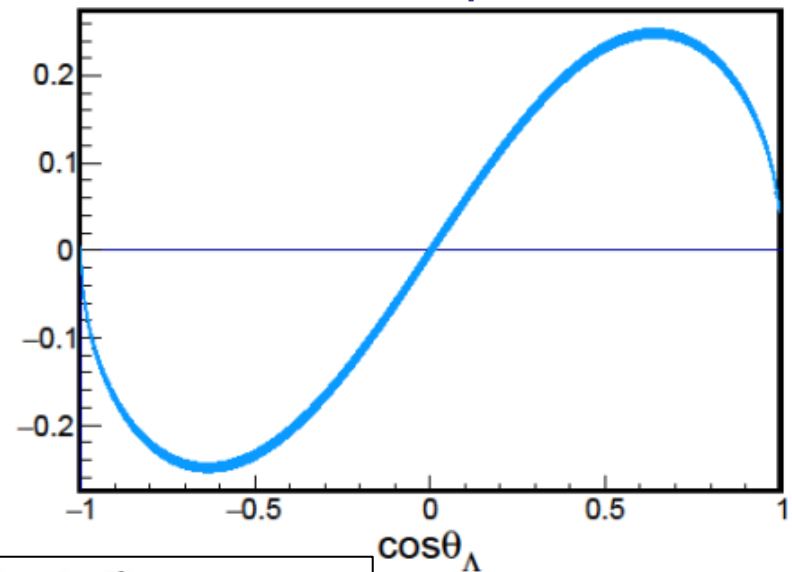
$$\mathcal{T}_6(\xi) = \cos \theta_1 \cos \theta_2 - \sin^2 \theta \sin \theta_1 \sin \theta_2 \sin \phi_1 \sin \phi_2$$



BESIII, Nature Physics 15 (2019) 631



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



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

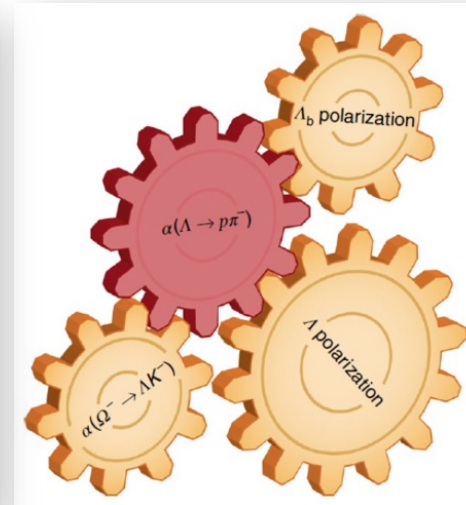
First measurement of hyperon polarization at J/ψ resonance

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

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

α_{Λ} FOR $\Lambda \rightarrow p\pi^-$ 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 π^-p
0.62 ± 0.07	1156	CRONIN 1963	CNTR	Λ from π^-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_{Λ}		
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		



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

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

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

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

More input needed!

DISCRETE Nov. 30, 2021

BESIII, Nature Physics 15 (2019) 631

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

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

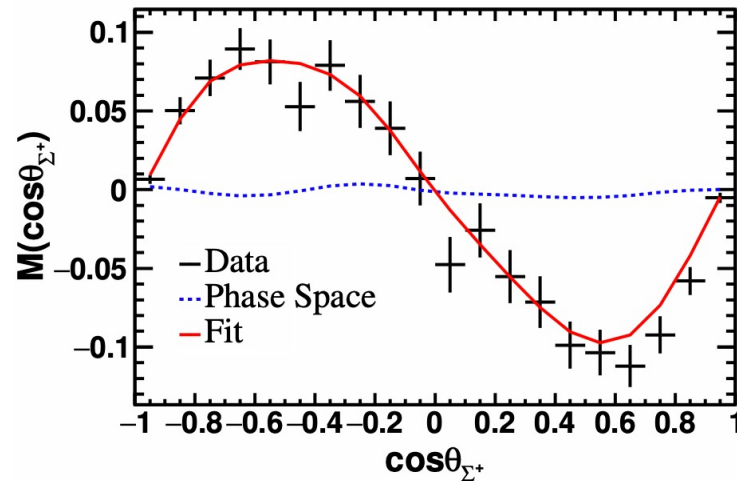
$$A_{CP, \Lambda prev} = 0.013 \pm 0.021_{tot}^{**}$$

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

*. Phys. Rev. D67, 056001 (2003)

** Phys Rev C54, 1877 (1996)

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



First CP measurement for any Σ decay

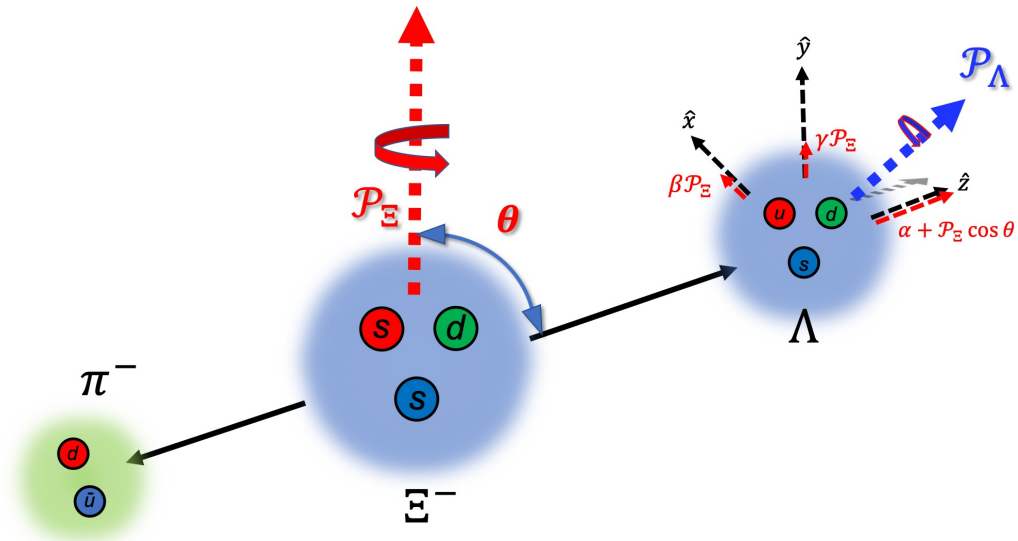
$$A_{CP \Sigma} = \frac{\alpha_{\Sigma} + \alpha_{\bar{\Sigma}}}{\alpha_{\Sigma} - \alpha_{\bar{\Sigma}}} = -0.004 \pm 0.037_{stat} \pm 0.010_{syst} *$$

$$A_{CP \Sigma SM} 3.6 \times 10^{-6} **$$

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

** Phys. Rev. D67, 056001 (2003)

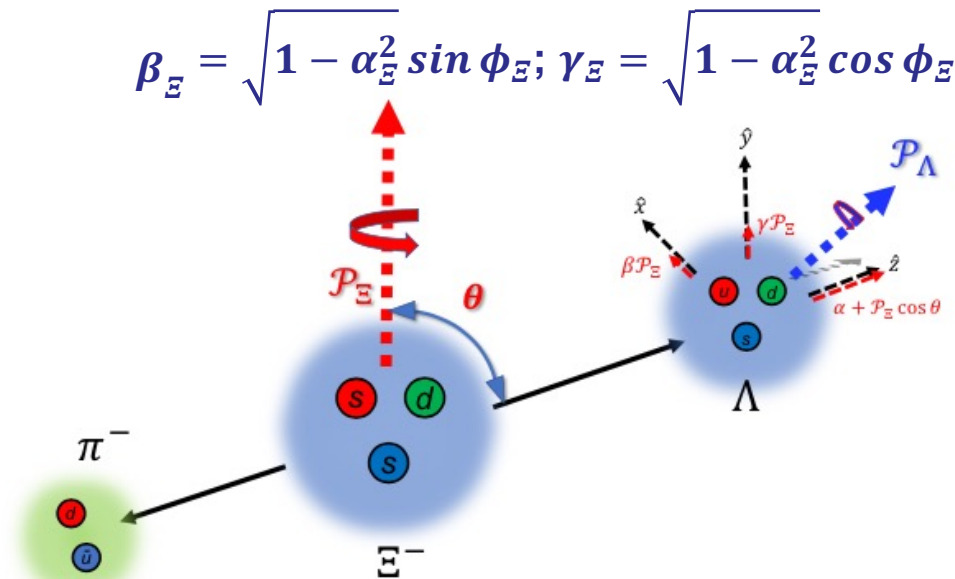
$$J/\psi \rightarrow \Xi^- \bar{\Xi}^+ \rightarrow \Lambda \pi^- \bar{\Lambda} \pi^+$$



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

arXiv:2105.11155

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



Longitudinal polarization of Λ governed by α_{Ξ}
 ϕ_{Ξ} gives rotation of P_{Λ} with respect to P_{Ξ}

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

CP tests and phases

$$\begin{aligned}
 S &= |S| e^{i\delta_S} e^{i\xi_S} & P &= |P| e^{i\delta_P} e^{i\xi_P} \\
 \bar{S} &= -|\bar{S}| e^{i\delta_S} e^{-i\xi_S} & \bar{P} &= |P| e^{i\delta_P} e^{-i\xi_P}
 \end{aligned}$$

Under assumption that isospin $\frac{1}{2}$ 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)

$$A_{CP}^E = \frac{\alpha_E + \bar{\alpha}_E}{\alpha_E - \bar{\alpha}_E} \approx -\sin \phi_E \frac{\sqrt{1 - \alpha_E^2}}{\alpha_E} \tan(\xi_P - \xi_S) *$$

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

weak phase diff

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

* Phys. Rev Lett 55 162 (1985)

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

$$\mathcal{W}(\xi; \omega) = \sum_{\mu, \nu=0}^3 \mathbb{C}_{\mu\nu} \sum_{\mu', \nu'=0}^3 a_{\mu\mu'}^{\bar{E}} a_{\nu\nu'}^{\bar{E}} a_{\mu'0}^{\Lambda} a_{\nu'0}^{\bar{\Lambda}}$$

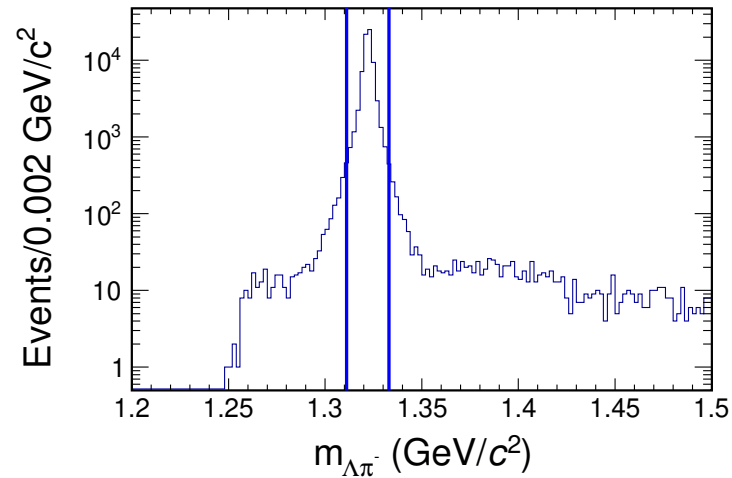
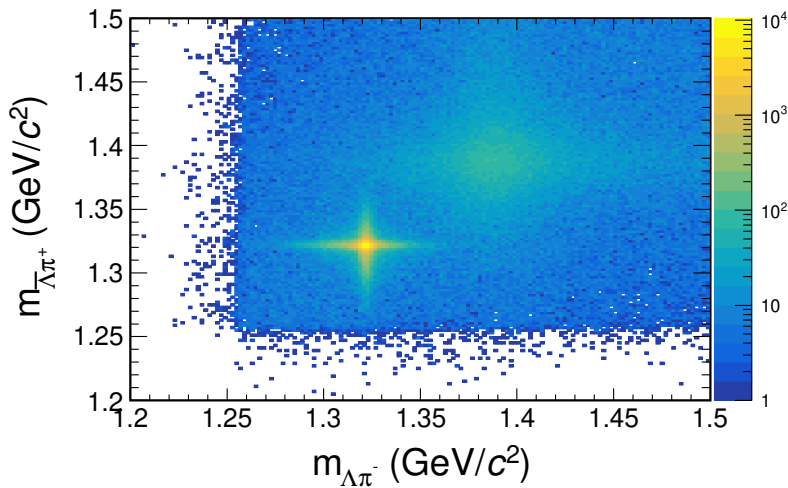
- Nine-dimensional phase space given by nine helicity angles
- Eight free parameters determined by maximum log likelihood method:

$\alpha_{\psi}, \Delta\Phi, \alpha_E, \bar{\alpha}_E, \phi_E, \bar{\phi}_E, \alpha_{\Lambda}, \bar{\alpha}_{\Lambda}$

↑ ↑ ↑ ↑
not measured before

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

arXiv:2105.11155



Results based on 1.3×10^9 J/ψ events

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

Very low level of background

Systematic uncertainties are small, mainly from selection criteria

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	**
$\bar{\alpha}_\Xi$	$0.371 \pm 0.007 \pm 0.002$	–	
$\bar{\phi}_\Xi$	$-0.021 \pm 0.019 \pm 0.007$ rad	–	
α_Λ	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$	***
$\bar{\alpha}_\Lambda$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$	***
$\xi_P - \xi_S$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ 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 $\Xi^- \bar{\Xi}^+$ 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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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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$\langle\phi_\Xi\rangle$	$0.016 \pm 0.014 \pm 0.007$ rad		

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)

** PDG 2020

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for any weakly decaying baryon

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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!

Three independent CP-tests
in *single* measurement

* PRD 93, 072003 (2018)

** PDG 2020

*** Nat. Ph. 15, 631 (2019)

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$\langle\phi_\Xi\rangle$	$0.016 \pm 0.014 \pm 0.007$ rad		

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

$$\phi_{\Xi, \text{HyperCP}} = -0.042 \pm 0.011 \pm 0.011$$

$$\langle\phi_\Xi\rangle = 0.016 \pm 0.014 \pm 0.007$$

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$\bar{\alpha}_\Lambda$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$	***
$\xi_P - \xi_S$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ 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!

$$\phi_{\Xi, \text{HyperCP}} = -0.042 \pm 0.011 \pm 0.011$$

$$\langle\phi_\Xi\rangle = 0.016 \pm 0.014 \pm 0.007$$

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

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

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 $\Xi^- \rightarrow \Lambda\pi^-, \Lambda \rightarrow p\pi^-$*

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-charm τ factories

BESIII recently collected $1.0 \times 10^{10} J/\psi$ events. More results to be expected in future!

Thank you for your attention!

DISCRETE Nov. 30, 2021

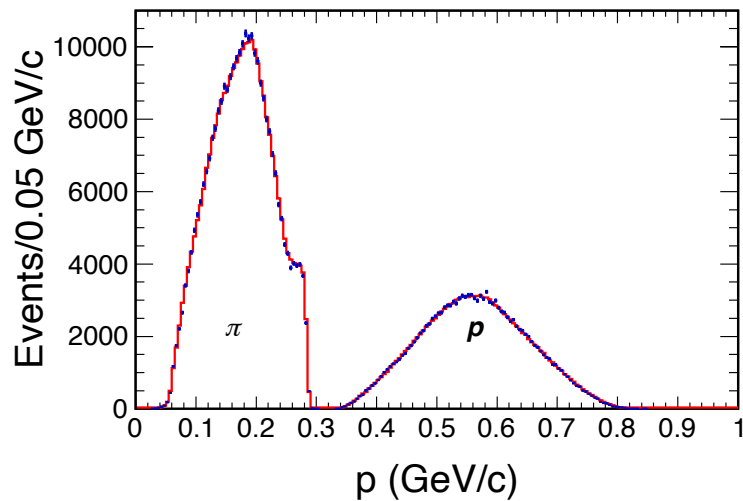


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BES II

Spare slide

arXiv:2105.11155



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

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

Λ and Ξ candidates formed with succesful vertex fits

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

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

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

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