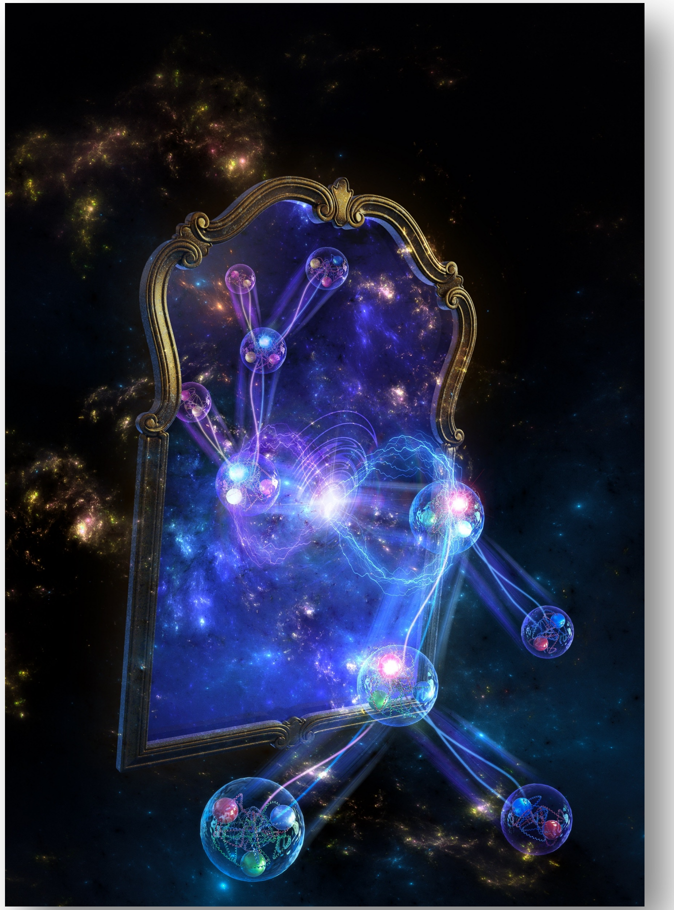

Studies of strange baryon and antibaryon pairs with the BESIII experiment

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Outline

Introduction

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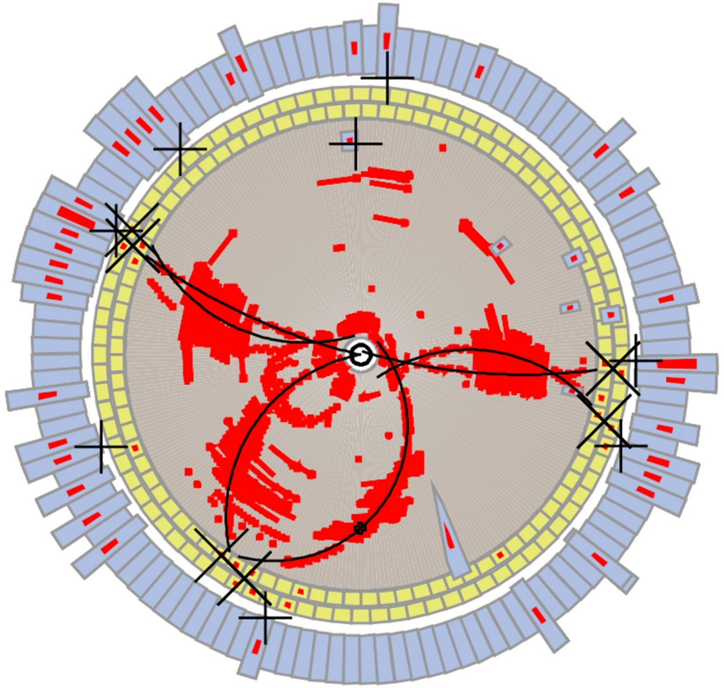
Hadronic Weak Decays

Semi-leptonic weak decays

Radiative 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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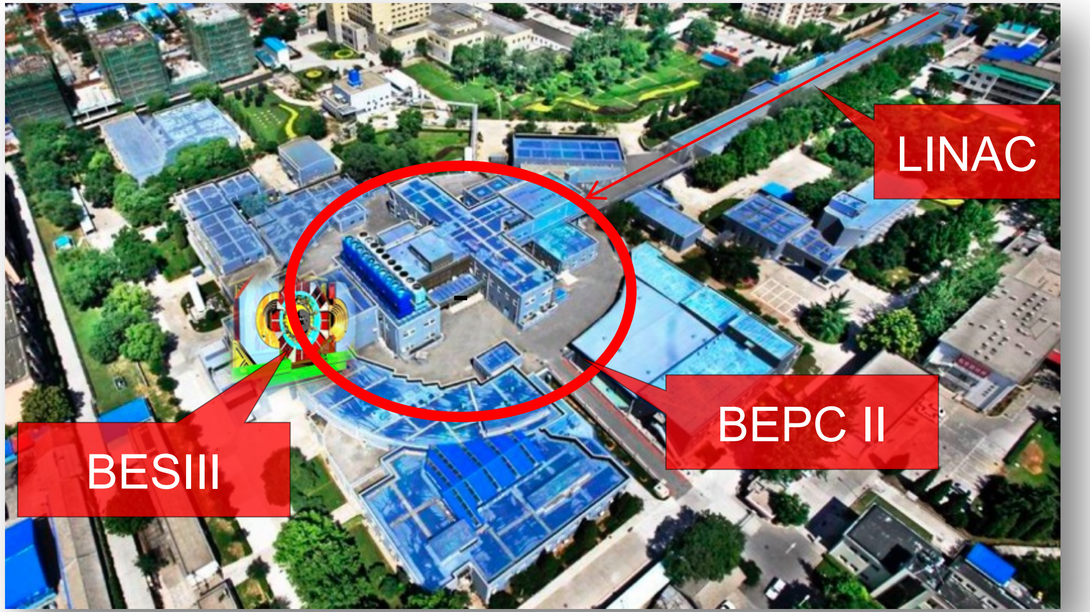
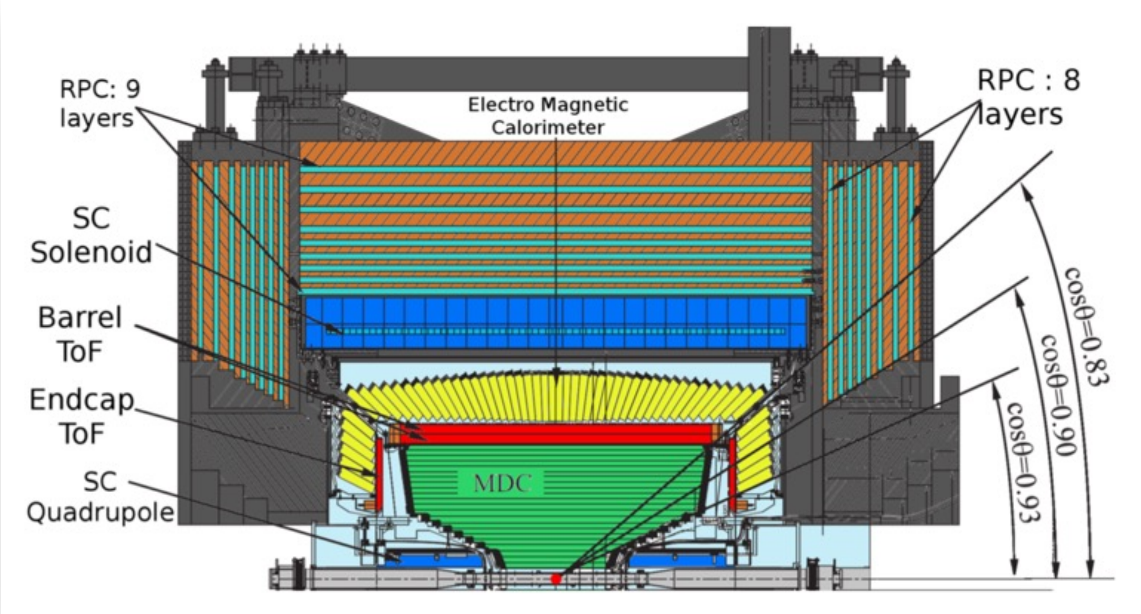
BEPC II and BESIII



Aerial view of BEPC II and BESIII

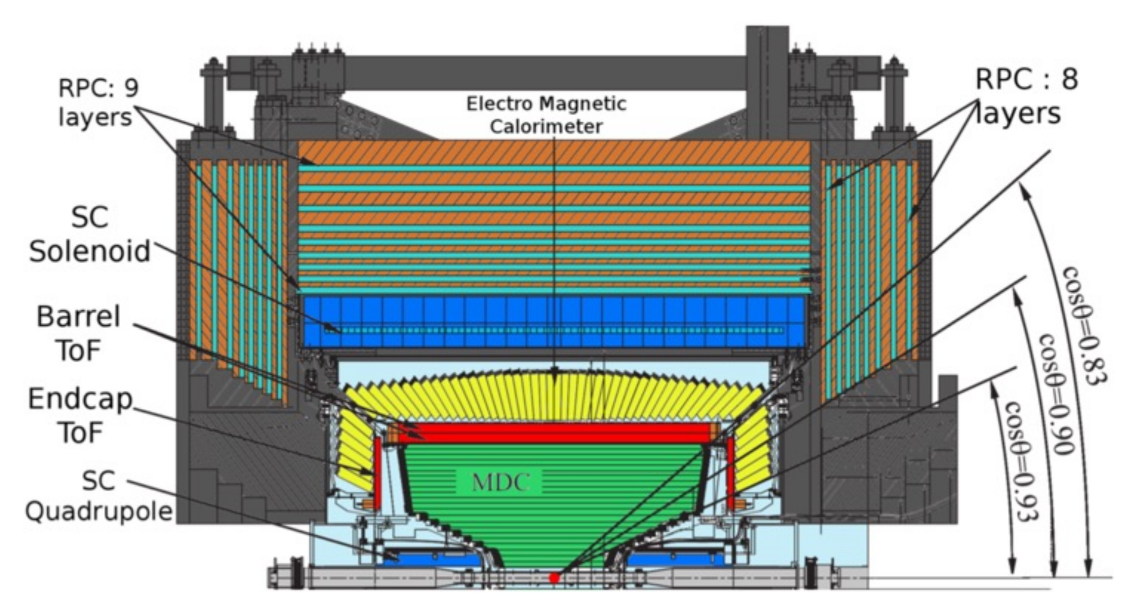


e^+e^- collider in CMS range 2.0 – 4.95 GeV

Optimized in tau - charm region

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

BEPC II and BESIII



- Multipurpose detector, excellent resolution, near 4π coverage
- Symmetric particle – anti-particle conditions, produced in entangled state
- Low hadronic background
- World's largest charmonia data samples

Resonance	Pair	$\mathcal{B}(\cdot 10^{-4})$	$\epsilon(\%)$	$N_{obs}(10^3)$	Reference
J/ψ	$\Lambda\bar{\Lambda}$	$19.43 \pm 0.03 \pm 0.33$	42.37 ± 0.14	441	[PRD95(2017)052003]
	$\Sigma^0\bar{\Sigma}^0$	$11.64 \pm 0.04 \pm 0.23$	17.83 ± 0.06	111	
	$\Xi^-\bar{\Xi}^+$	$10.40 \pm 0.06 \pm 0.74$	18.40 ± 0.04	43	[PRD93(2016)072003]
$\psi(2S)$	$\Lambda\bar{\Lambda}$	$3.97 \pm 0.02 \pm 0.12$	42.83 ± 0.34	31	[PRD95(2017)052003]
	$\Sigma^0\bar{\Sigma}^0$	$2.44 \pm 0.03 \pm 0.11$	14.79 ± 0.12	6.6	
	$\Xi^-\bar{\Xi}^+$	$2.78 \pm 0.05 \pm 0.14$	18.04 ± 0.04	5.3	[PRD93(2016)072003]
	$\Omega^-\bar{\Omega}^+$	$0.59 \pm 0.01 \pm 0.03$	17.1/18.9	4.1	[PRL126(2021)092002]

BESIII ❤ Hyperons

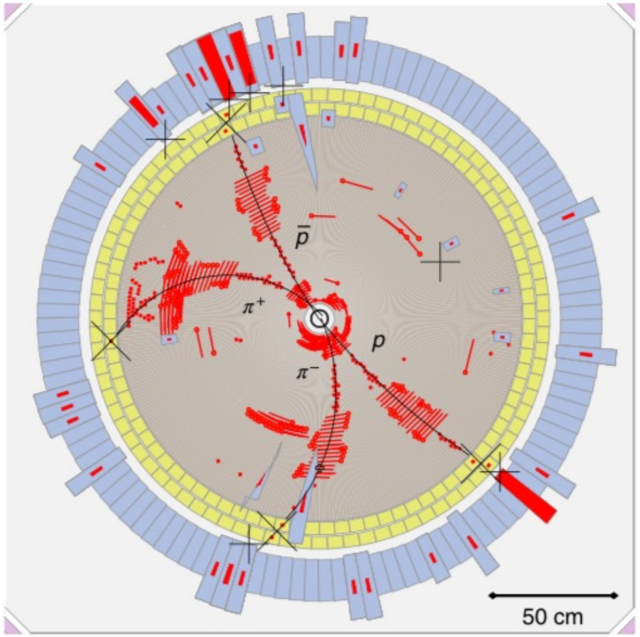


Fig. 2 | An example $J/\psi \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$ event in the BESIII detector. Cross-section of the detector in the plane perpendicular to the colliding electron–positron beams and a schematic representation of the information collected for the event. The mean decay 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 |cosθ| < 0.93

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

Neutrals |cosθ| < 0.8 and 0.86 < |cosθ| < 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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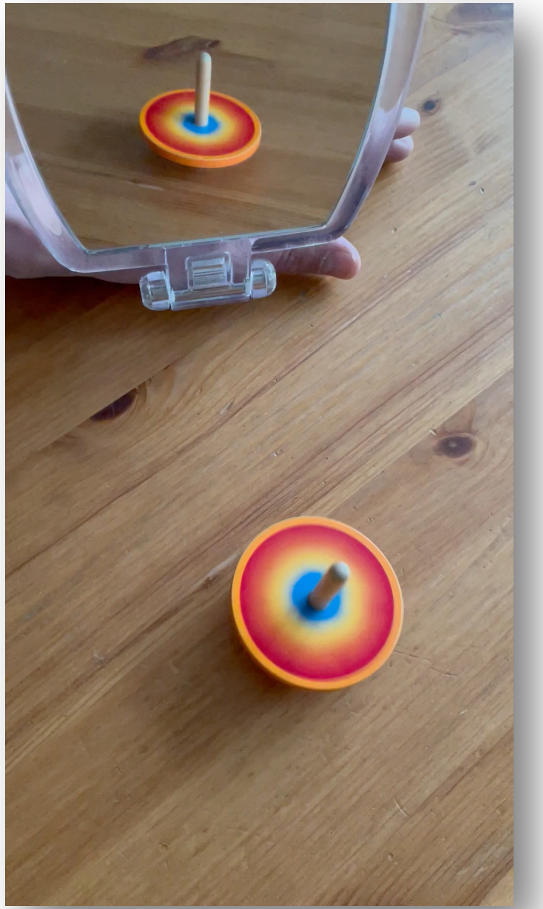
Spinning baryons



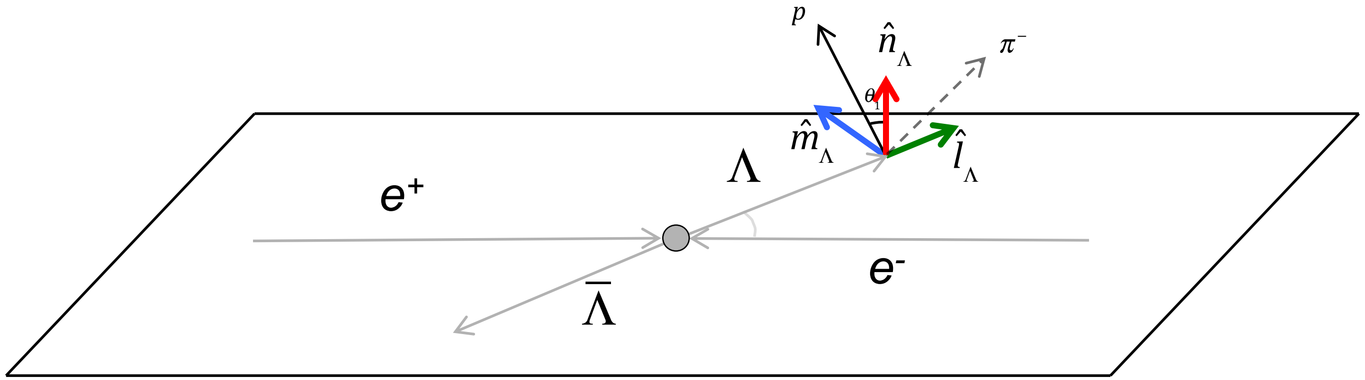
No CP violation detected for *baryons*

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 to understand SM

Focus on *hyperons*, strange quark systems in this talk (see Varvara for other focus)



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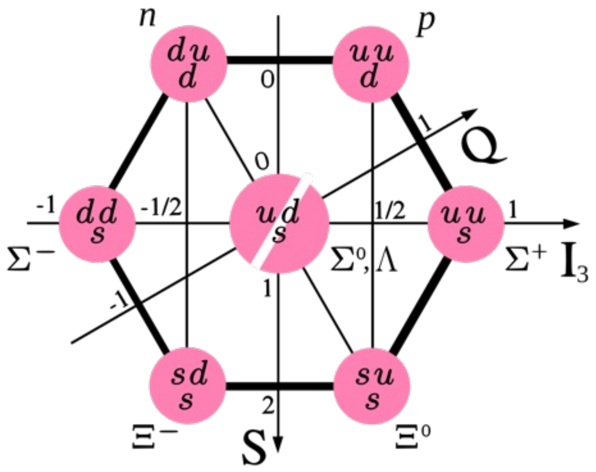
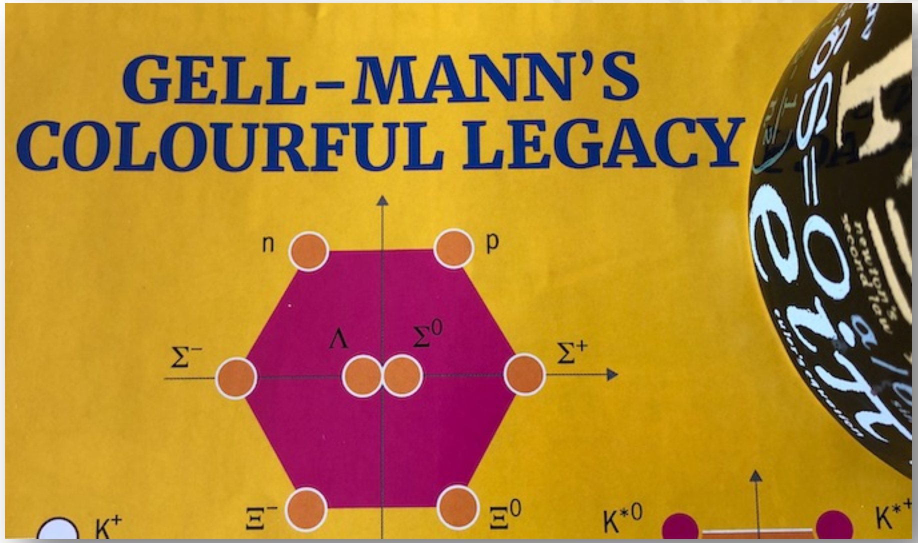
Non-leptonic two body decays



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

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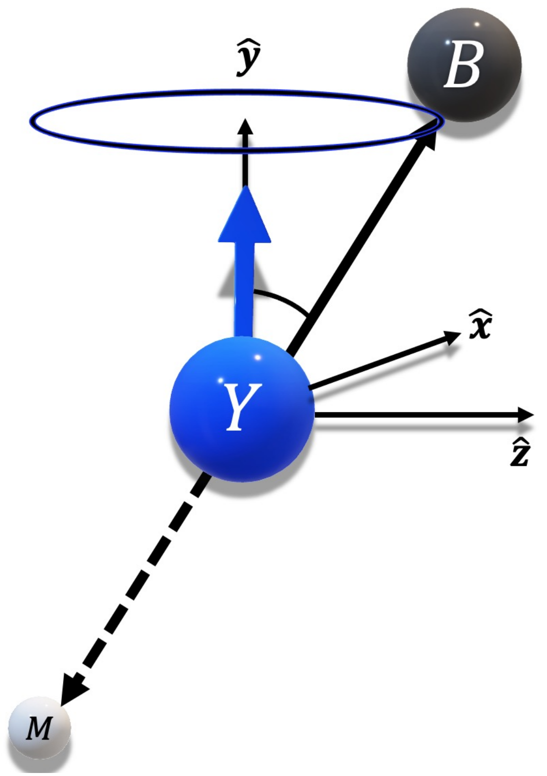
Asymmetry parameters and Polarization



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 $\Lambda \to p\pi^-$

$$I(\cos\theta_B) \propto 1 + \alpha\, P_Y \cos\theta_B$$

Asymmetry parameter
CP-observable

Polarization

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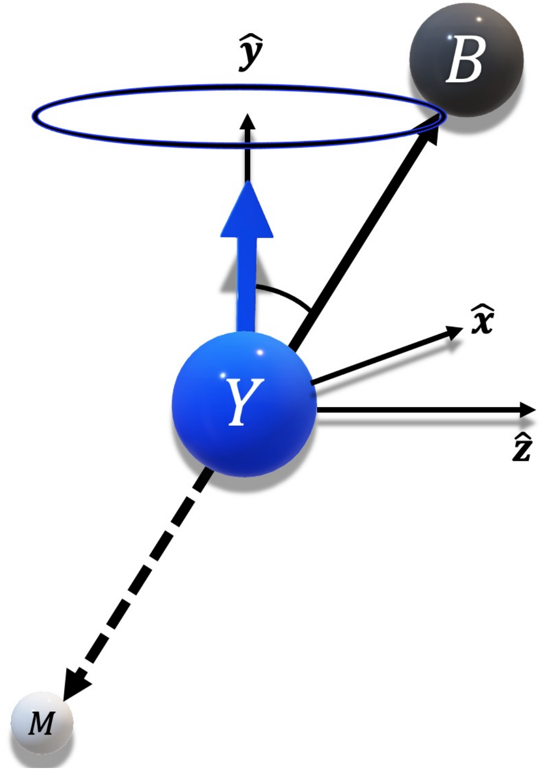
Asymmetry parameters and Polarization



$-1 \leq \alpha \leq 1$

weak CP-odd phases

$$S = |S| exp(\xi_S) exp(i\delta_S)$$
$$P = |P| exp(\xi_P) exp(i\delta_P)$$

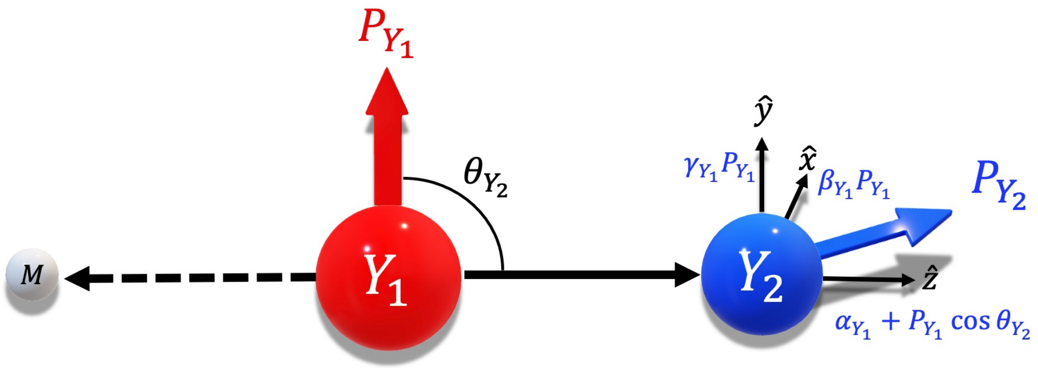
strong phases

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

ξ weak CP-odd phase for ΔI = 1/2

Asymmetry parameters give relationship of
S (parity violating) and *P* (parity conserving) amplitudes

$$\alpha = \frac{2\mathrm{Re}(S*P)}{|S|^2+|P|^2} \qquad \beta = \frac{2\mathrm{Im}(S*P)}{|S|^2+|P|^2} = \sqrt{1-\alpha^2}\sin\phi$$



$-\pi \leq \phi \leq \pi$

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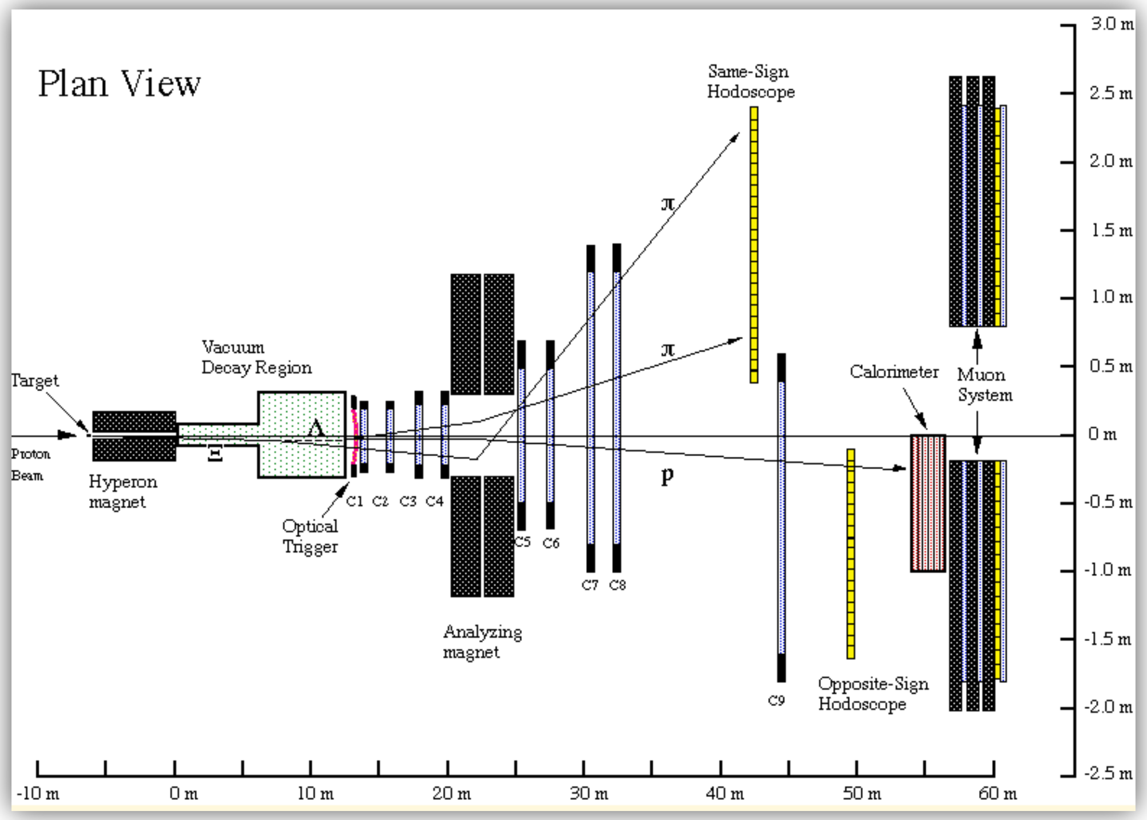
HyperCP



HyperCP (**E871**) Fermilab

800 GeV/c proton on fixed target Cu

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

$$A_{CP\;\Xi\Lambda} = \frac{\alpha_\Xi\alpha_\Lambda + \bar{\alpha}_\Xi\bar{\alpha}_\Lambda}{\alpha_\Xi\alpha_\Lambda - \bar{\alpha}_\Xi\bar{\alpha}_\Lambda} = (0.0 \pm 5.1 \pm 4.7)\times 10^{-4} \; *$$

$$|A_{SM\;\Xi\Lambda}| \leq 5\times 10^{-5} \; **$$

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

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

862M Ξ & 230M $\bar{\Xi}$ $A_{CP\;\Xi\Lambda} = \frac{\alpha_\Xi\alpha_\Lambda + \bar{\alpha}_\Xi\bar{\alpha}_\Lambda}{\alpha_\Xi\alpha_\Lambda - \bar{\alpha}_\Xi\bar{\alpha}_\Lambda} = (-6.0 \pm 2.1 \pm 2.0)\times 10^{-4}$ ***

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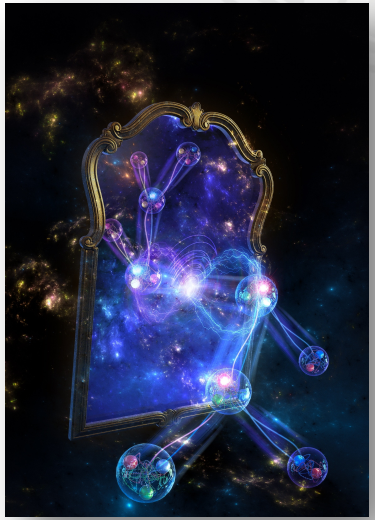
CP and weak phase difference

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

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

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



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 $\Delta S = 1$ mesons

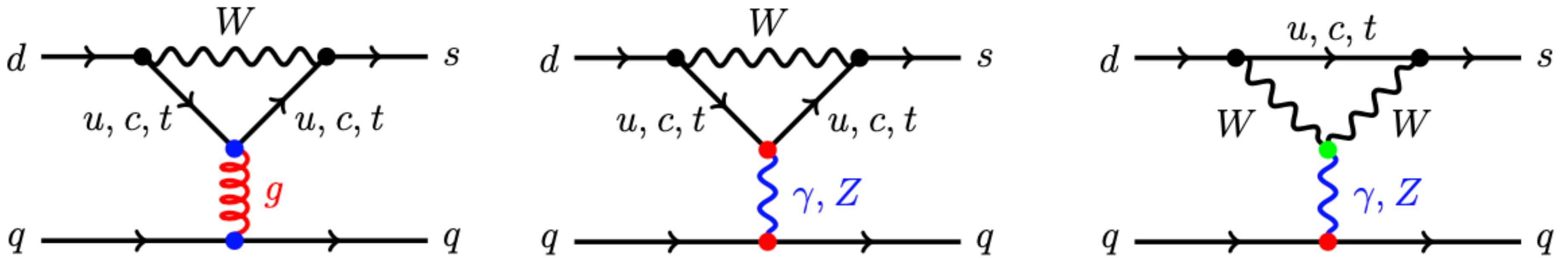
In strange sector most precise probe is $\Delta S = 1$ direct CPV (ε') relative to indirect CPV (ε) in $K_{S,L} \to \pi\pi$ decays

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 $\Delta S = 1$ SM + BSM

$$A_{CP} = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}} = -\sin\phi\tan(\xi_P - \xi_S)\frac{\sqrt{1-\alpha^2}}{\alpha}$$

$$\Phi_{CP} = \frac{\phi+\bar{\phi}}{2} = \cos\phi\tan(\xi_P - \xi_S)\frac{\alpha}{\sqrt{1-\alpha^2}}$$

$$-3\times10^{-5} \leq A_{\Lambda\,\mathrm{SM}} \leq 4\times10^{-5}\,{}^{*}$$
$$0.5\times10^{-5} \leq A_{\Xi\,\mathrm{SM}} \leq 6\times10^{-5}\,{}^{*}$$

SM

Decay mode	$\xi_P - \xi_S$ $[10^{-4}\mathrm{rad}]$ ***
$\Lambda \to p\pi^-$	-0.2 ± 2.2
$\Xi^- \to \Lambda\pi^-$	-2.1 ± 1.7

Chromomagnetic BSM penguin operators

$Y \to B\pi$

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

BSM

$|A_\Lambda + A_\Xi| \leq 11\cdot10^{-4}$

Decay	$\lvert\xi_P - \xi_S\rvert$ ***
$\Lambda \to p\pi^-$	$\lesssim 5.3\cdot10^{-3}$
$\Xi^- \to \Lambda\pi^-$	$\lesssim 3.7\cdot10^{-3}$

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* *Phys. Rev. D 67, 056001 (2003)*

** *Phys. Rev. D 69, 076008 (2004)*

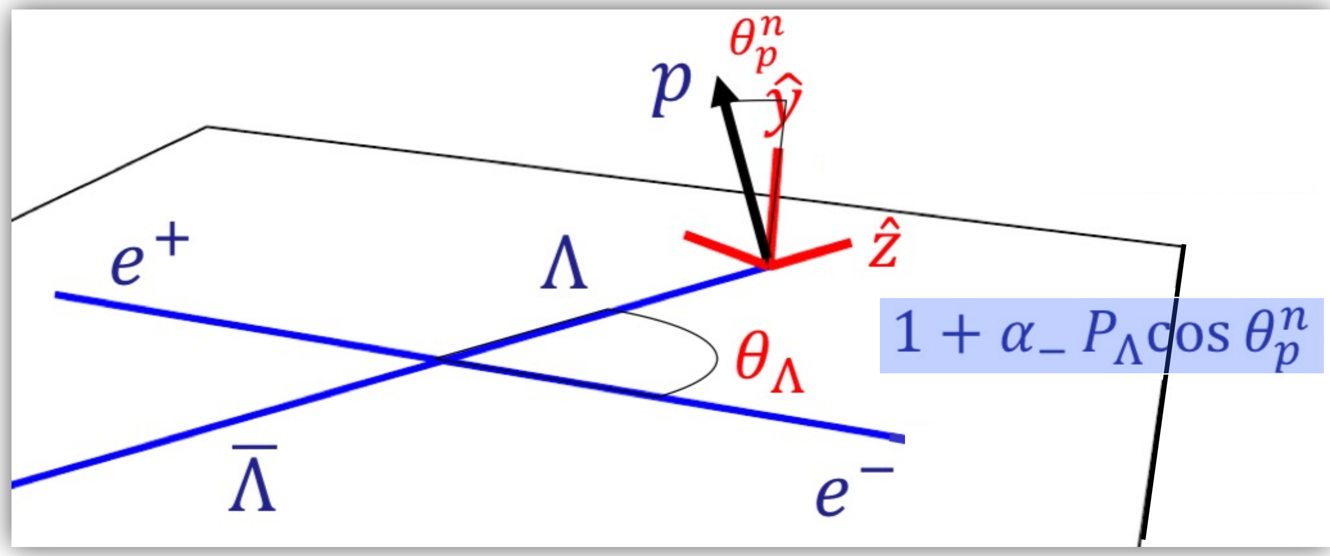
*** PRD105 (2022) 116022

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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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 $\bar{\alpha}$

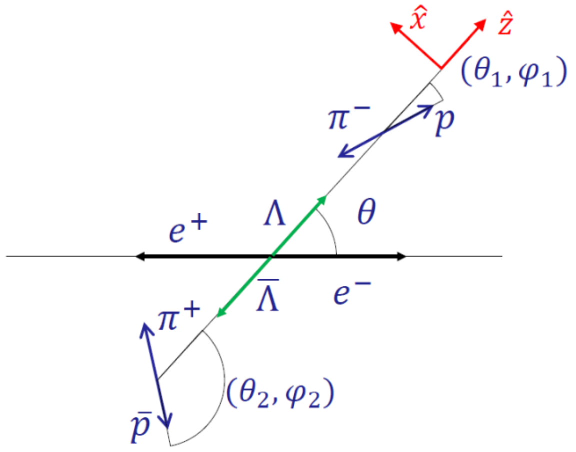
$\mathcal{T}_0 - \mathcal{T}_6$ are functions with experimentally measured observables

Unpolarized part Polarized 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 $\bar{\alpha}$

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



PLB 772 (2017) 16.

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

- Two spin-$\frac{1}{2}$ particle state: $\rho_{1/2,\overline{1/2}} = \frac{1}{4}\sum_{\mu\bar{\nu}} C_{\mu\bar{\nu}}\sigma_{\mu}^{Y_1} \otimes \sigma_{\bar{\nu}}^{\bar{Y}_1}$

Y_1 transverse polarisation

$$C_{\mu\bar{\nu}} = \begin{pmatrix} 1+\alpha_\psi \cos^2\theta & 0 & \beta_\psi \sin\theta\cos\theta & 0 \\ 0 & \sin^2\theta & 0 & \gamma_\psi \sin\theta\cos\theta \\ -\beta_\psi \sin\theta\cos\theta & 0 & \alpha_\psi \sin^2\theta & 0 \\ 0 & -\gamma_\psi \sin\theta\cos\theta & 0 & -\alpha_\psi - \cos^2\theta \end{pmatrix}$$

$\bar{Y}_1$ transverse polarisation

Spin correlations

where $\beta_\psi = \sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)$ and $\gamma_\psi = \sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)$

- Decay can be presented via decay matrices: $\sigma_{\mu}^{Y_1} \to \sum_{\mu'=0}^{3} a_{\mu\mu'}^{Y_1}(\alpha_{Y_1}, \phi_{Y_1}; \theta_{Y_2}, \varphi_{Y_2})\sigma_{\mu'}^{Y_2}$

- Full angular distribution: $\mathcal{W}(\boldsymbol{\xi}, \boldsymbol{\omega}) = \mathrm{Tr}\rho_{Y_2\bar{Y}_2} = \sum_{\mu,\bar{\nu}=0}^{3} C_{\mu\bar{\nu}} a_{\mu 0}^{Y_1} a_{\bar{\nu}0}^{\bar{Y}_1}$

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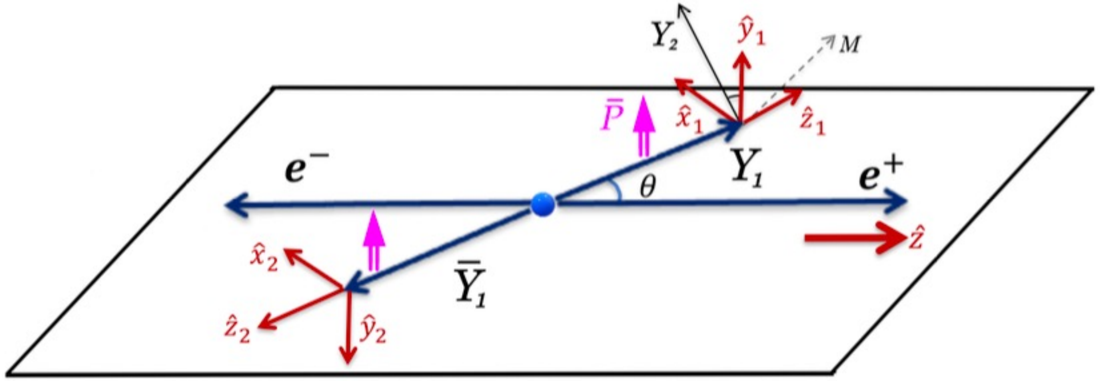
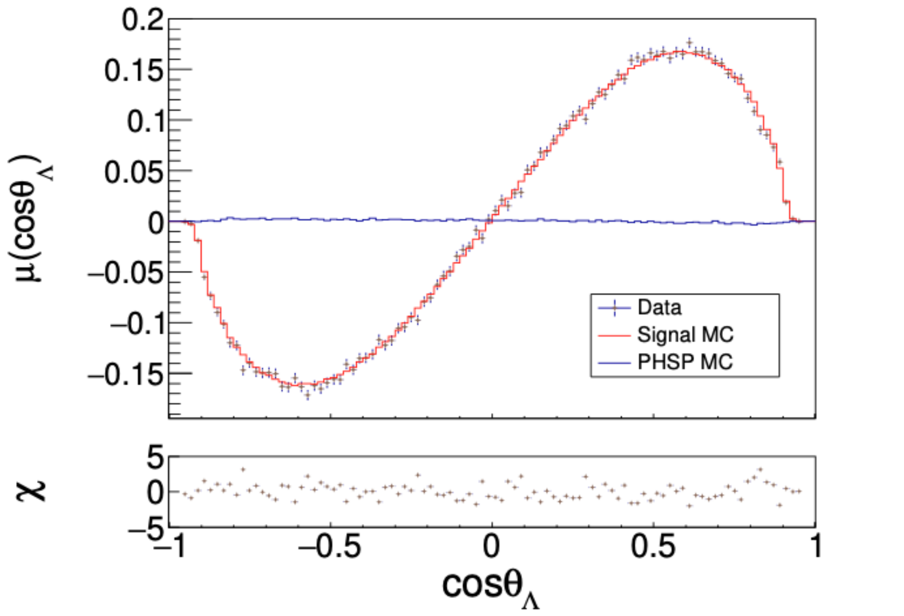
$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda},\ \Lambda \to p\pi^- + \text{c.c.}$

$$\mu(\cos\theta_\Lambda) = \frac{\alpha_\Lambda - \bar{\alpha}_\Lambda}{2}\,\frac{1+\alpha_\psi \cos^2\theta_\Lambda}{3+\alpha_\psi}\,P_y(\cos\theta_\Lambda)$$



[PRL129(2022)131801]

$\Lambda \to p\pi^-$



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}	$0.7542 \pm 0.0010 \pm 0.0020$	-

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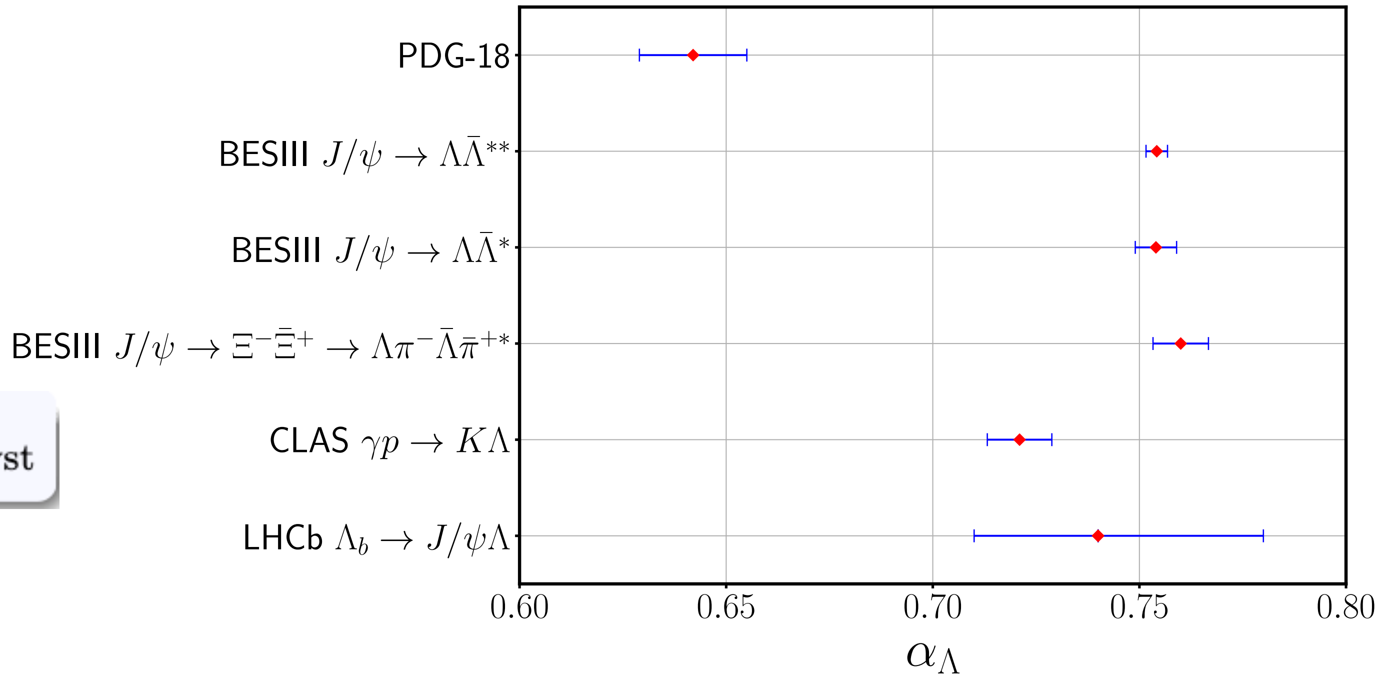
$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda},\ \Lambda \to p\pi^- + \text{c.c.}$

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

$$A_{CP}^{\Lambda} = \frac{\alpha_\Lambda + \bar{\alpha}_\Lambda}{\alpha_\Lambda - \bar{\alpha}_\Lambda} = -0.0025 \pm 0.0046_{\text{stat}} \pm 0.0011_{\text{syst}}$$

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

$\Lambda \to p\pi^-$



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

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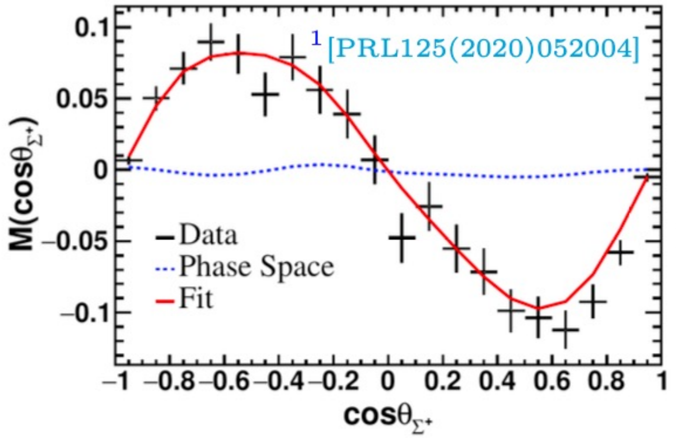
$J/\psi \rightarrow \Sigma^+\bar{\Sigma}^- \rightarrow p\pi^0(n\pi^+)\bar{p}\pi^0(\bar{n}\pi^-)$

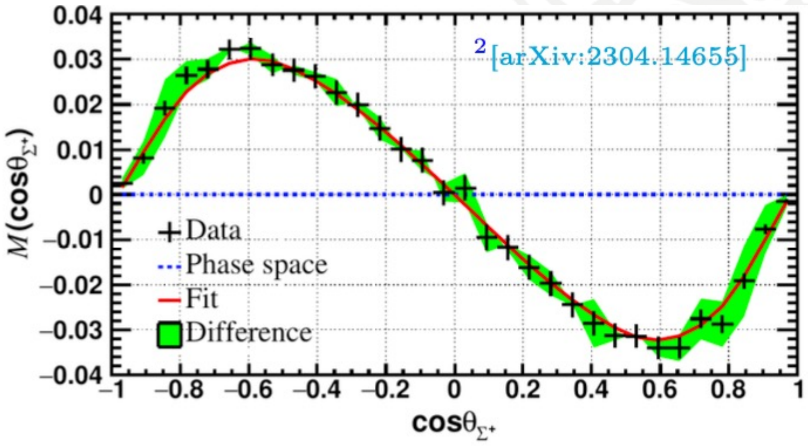
First CP measurements for Σ decay

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

$\Sigma^+ \rightarrow p\pi^0$ based on 83k events

$\Sigma^+ \rightarrow n\pi^+$ based on 310k events





Parameters	$(p\pi^0)(\bar{p}\pi^0)$ [1]	$(p\pi^0)(\bar{n}\pi^-)$ + c.c. [2]
$N_{J/\psi}$	$1.31 \cdot 10^9$	10^{10}
N_{sig}	$87 \cdot 10^3$ with 5% bkg	$(3.1 + 7.5) \cdot 10^5$ with 2% bkg
α_ψ	$-0.508 \pm 0.006 \pm 0.004$	$\mathbf{-0.5156 \pm 0.0030 \pm 0.0061}$
$\Delta\Phi$ [rad]	$-0.270 \pm 0.012 \pm 0.009$	$\mathbf{-0.2772 \pm 0.0044 \pm 0.0041}$
$\langle\alpha_0\rangle$	$-0.994 \pm 0.004 \pm 0.002$	
$\langle\alpha_+\rangle$		$0.0506 \pm 0.0026 \pm 0.0019$
A^0_{CP}	$\mathbf{-0.004 \pm 0.037 \pm 0.010}$	$3.6 \cdot 10^{-6}$ (SM[3])
A^+_{CP}	$3.9 \cdot 10^{-4}$ (SM[3])	$\mathbf{-0.080 \pm 0.052 \pm 0.028}$

BESIII

Formalism sequential weak decays

- The formalism 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, $\Delta\Phi$, α_Ξ, $\overline{\alpha}_\Xi$, ϕ_Ξ, $\overline{\phi}_\Xi$, α_Λ, $\overline{\alpha}_\Lambda$

not measured before

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

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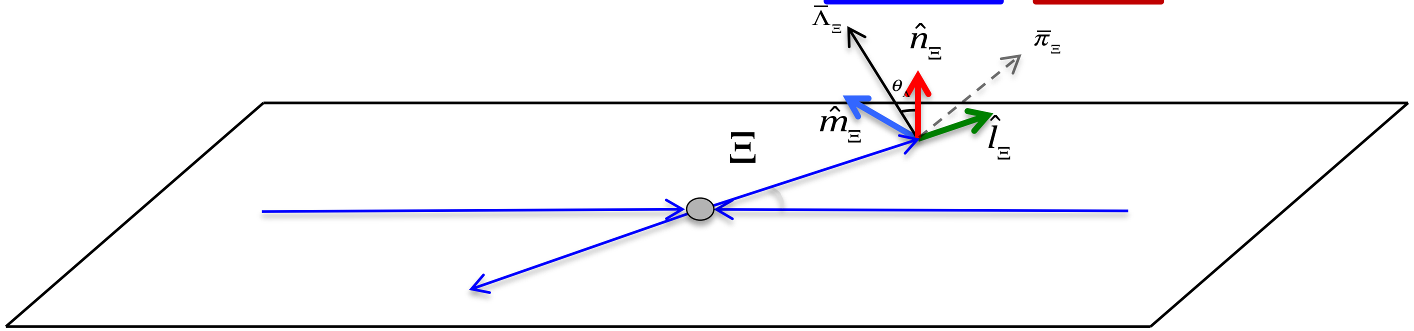
Formalism $J/\psi \to \Xi\bar{\Xi} \to \Lambda(\to p\pi)\bar{\Lambda}\pi(\to \bar{p}\pi^+)$

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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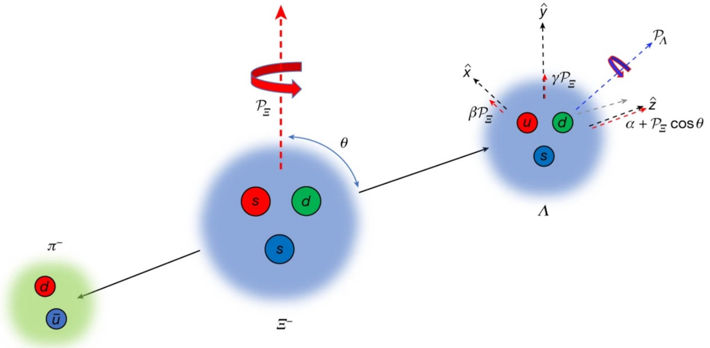
CP and weak phase difference

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

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

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



* Phys. Rev Lett 55 162 (1985)

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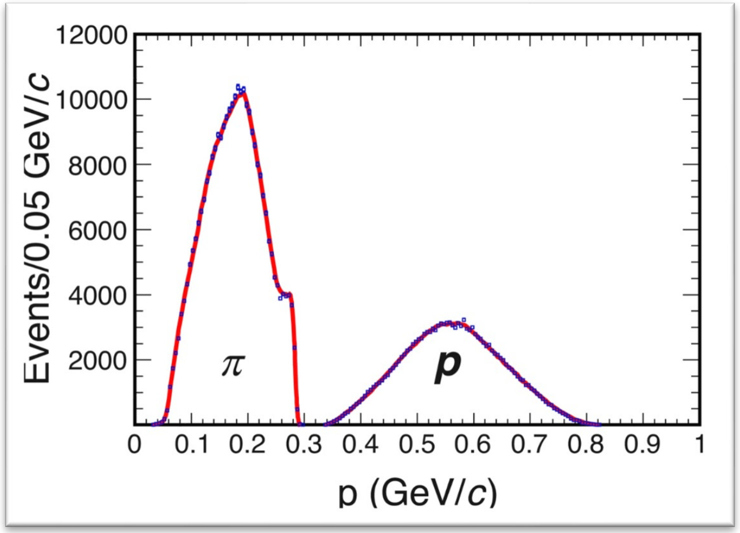
Analysis steps

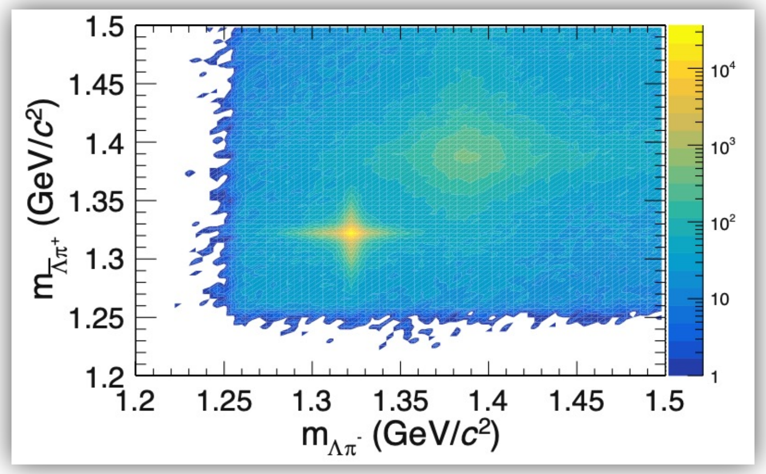
Nature 606 64-69 (2022)



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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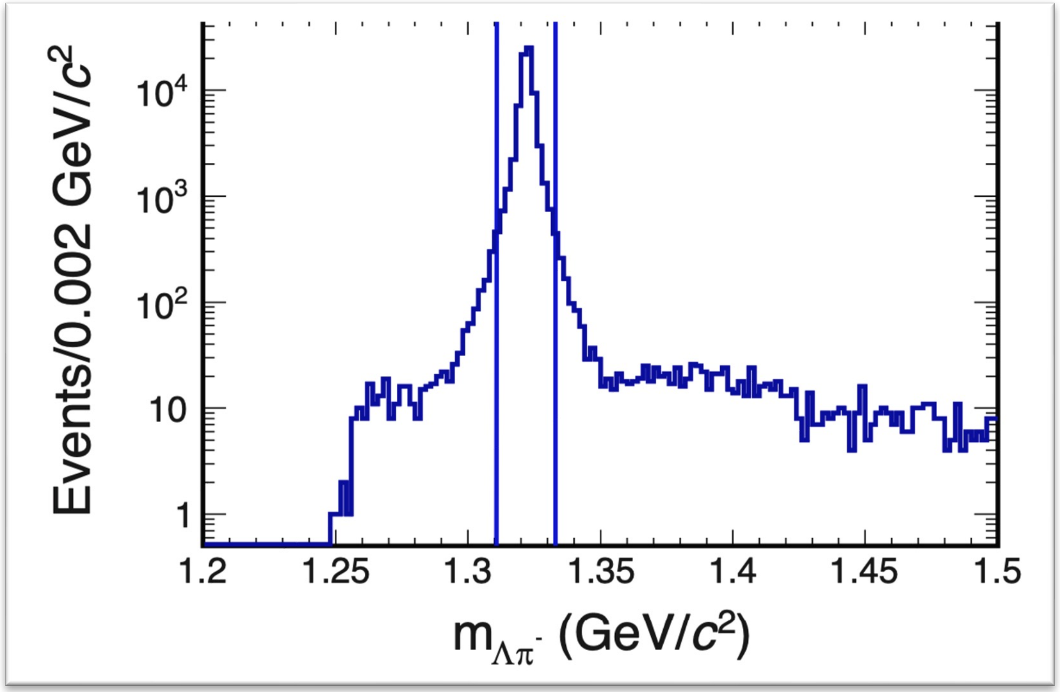
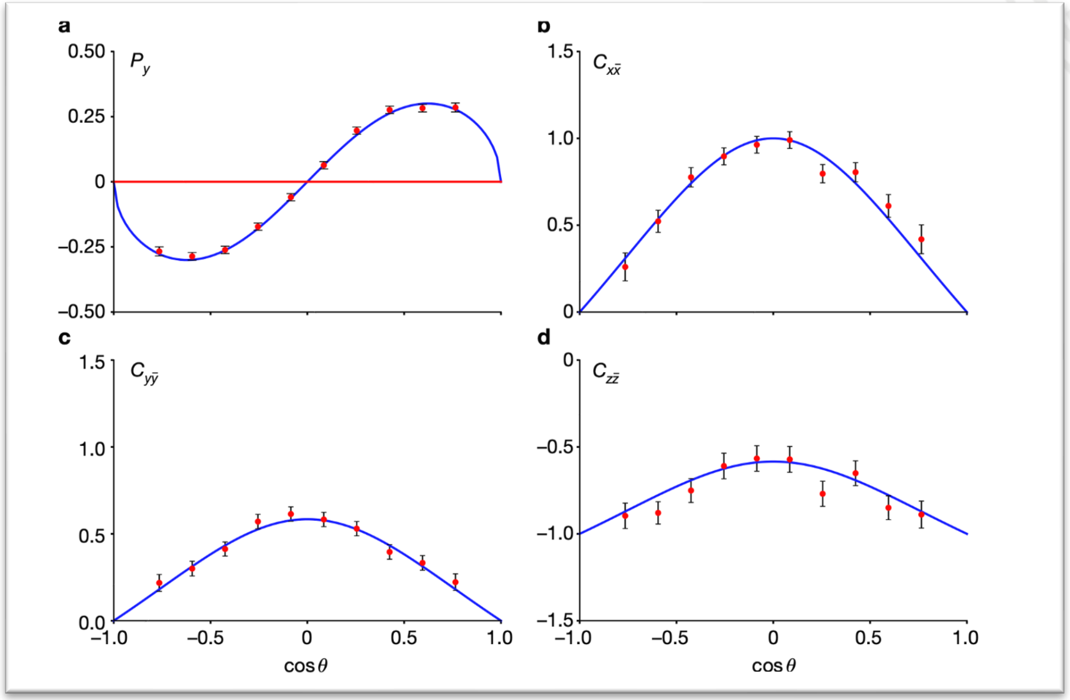
Analysis summary

Nature 606 64-69 (2022)





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

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±3.4±0.8)×10^{-2} rad	–		
$\delta_P-\delta_S$	(−4.0±3.3±1.7)×10^{-2} rad	(10.2±3.9)×10^{-2} rad	Ref. [3]	****
A_{CP}^{Ξ}	(6±13±6)×10^{-3}	–		
$\Delta\phi_{CP}^{\Xi}$	(−5±14±3)×10^{-3} rad	–		
A_{CP}^{Λ}	(−4±12±9)×10^{-3}	(−6±12±7)×10^{-3}	Ref. [4]	***
$\langle\phi_\Xi\rangle$	0.016±0.014±0.007 rad			

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

First measurement of polarization

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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$\Xi^-\bar{\Xi}^+ \to \Lambda(p\pi^-)\pi^-\bar{\Lambda}(\bar{p}\pi^+)\pi^+$

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$\delta_P-\delta_S$	$(-4.0\pm3.3\pm1.7)\times10^{-2}$ 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.

Nature 606 64-69 (2022)

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

$$(\xi_p-\xi_s) = (1.2\ \pm3.4\pm0.8)\times10^{-2}\ \text{rad}$$

Consistent with SM expectation

$$(\xi_p-\xi_s)_{SM} = (1.8\ \pm1.5)\times10^{-4}\ \text{rad}$$

New method for direct weak phase extraction!

Two CP-tests in single measurement

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

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$\Xi^-\bar{\Xi}^+ \rightarrow \Lambda(p\pi^-)\pi^-\bar{\Lambda}(\bar{p}\pi^+)\pi^+$

Table 1 | Summary of results

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$\xi_P-\xi_S$	$(1.2\pm3.4\pm0.8)\times10^{-2}$ 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 $J/\psi\rightarrow\Xi^-\bar{\Xi}^+$ angular distribution parameter α_ψ, the hadronic form factor phase $\Delta\Phi$, the decay parameters for $\Xi^-\rightarrow\Lambda\pi^-$ (α_Ξ,ϕ_Ξ), $\bar{\Xi}^+\rightarrow\bar{\Lambda}\pi^+$ $(\bar{\alpha}_\Xi,\bar{\phi}_\Xi)$ $\Lambda\rightarrow p\pi^-$ (α_Λ) and $\bar{\Lambda}\rightarrow\bar{p}\pi^+$ $(\bar{\alpha}_\Lambda)$; 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.

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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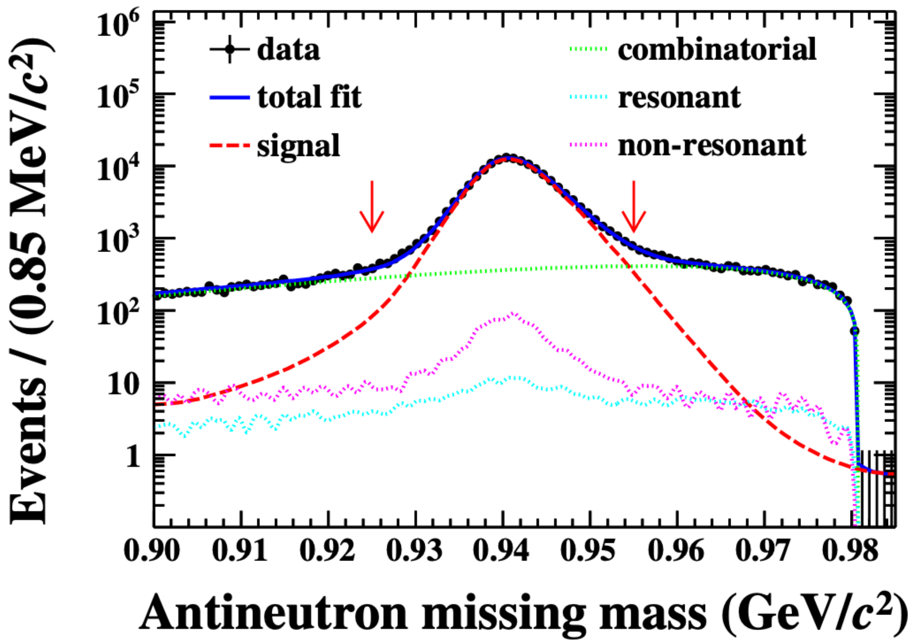
$\Xi^-\bar{\Xi}^+ \rightarrow \Lambda(n\pi^0/p\pi^-)\pi^-\bar{\Lambda}(\bar{p}\pi^+/\bar{n}\pi^0)\pi^+$

Parameters	This work	Previous result
$\alpha_{J/\psi}$	$0.611 \pm 0.007^{+0.013}_{-0.007}$	$0.586 \pm 0.012 \pm 0.010$ [17]
$\Delta\Phi_{J/\psi}$ (rad)	$1.30 \pm 0.03^{+0.02}_{-0.03}$	$1.213 \pm 0.046 \pm 0.016$ [17]
α_Ξ	$-0.367 \pm 0.004^{+0.003}_{-0.004}$	$-0.376 \pm 0.007 \pm 0.003$ [17]
ϕ_Ξ (rad)	$-0.016 \pm 0.012^{+0.004}_{-0.008}$	$0.011 \pm 0.019 \pm 0.009$ [17]
$\bar{\alpha}_\Xi$	$0.374 \pm 0.004^{+0.003}_{-0.004}$	$0.371 \pm 0.007 \pm 0.002$ [17]
$\bar{\phi}_\Xi$ (rad)	$0.010 \pm 0.012^{+0.003}_{-0.013}$	$-0.021 \pm 0.019 \pm 0.007$ [17]
$\alpha_{\Lambda-}$	$0.764 \pm 0.008^{+0.005}_{-0.006}$	$0.7519 \pm 0.0036 \pm 0.0024$ [37]
$\alpha_{\Lambda+}$	$-0.774 \pm 0.009^{+0.005}_{-0.005}$	$-0.7559 \pm 0.0036 \pm 0.0030$ [37]
$\alpha_{\Lambda 0}$	$0.670 \pm 0.009^{+0.009}_{-0.008}$	0.75 ± 0.05 [29]
$\bar{\alpha}_{\Lambda 0}$	$-0.668 \pm 0.008^{+0.006}_{-0.008}$	$-0.692 \pm 0.016 \pm 0.006$ [18]
$\delta_P - \delta_S$ (rad)	$0.033 \pm 0.020^{+0.008}_{-0.012}$	$-0.040 \pm 0.033 \pm 0.017$ [17]
$\xi_P - \xi_S$ (rad)	$0.007 \pm 0.020^{+0.018}_{-0.005}$	$0.012 \pm 0.034 \pm 0.008$ [17]
A^Ξ_{CP}	$-0.009 \pm 0.008^{+0.007}_{-0.002}$	$0.006 \pm 0.013 \pm 0.006$ [17]
$\Delta\phi^\Xi_{CP}$ (rad)	$-0.003 \pm 0.008^{+0.003}_{-0.007}$	$-0.005 \pm 0.014 \pm 0.003$ [17]
A^-_{CP}	$-0.007 \pm 0.008^{+0.002}_{-0.003}$	$-0.0025 \pm 0.0046 \pm 0.0012$ [37]
A^0_{CP}	$0.001 \pm 0.009^{+0.005}_{-0.007}$	-
A^Λ_{CP}	$-0.004 \pm 0.007^{+0.003}_{-0.004}$	-
$\alpha_{\Lambda 0}/\alpha_{\Lambda-}$	$0.877 \pm 0.015^{+0.014}_{-0.010}$	1.01 ± 0.07 [29]
$\bar{\alpha}_{\Lambda 0}/\alpha_{\Lambda+}$	$0.863 \pm 0.014^{+0.012}_{-0.008}$	$0.913 \pm 0.028 \pm 0.012$ [18]

arXiv:2309.14667

New determination based on 144k + 123k events

Strong phase difference sign different (but consistent) from charged mode



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$\Xi^-\bar{\Xi}^+ \to \Lambda(n\pi^0)\pi^-\bar{\Lambda}(\bar{p}\pi^+)\pi^+ + c.c$

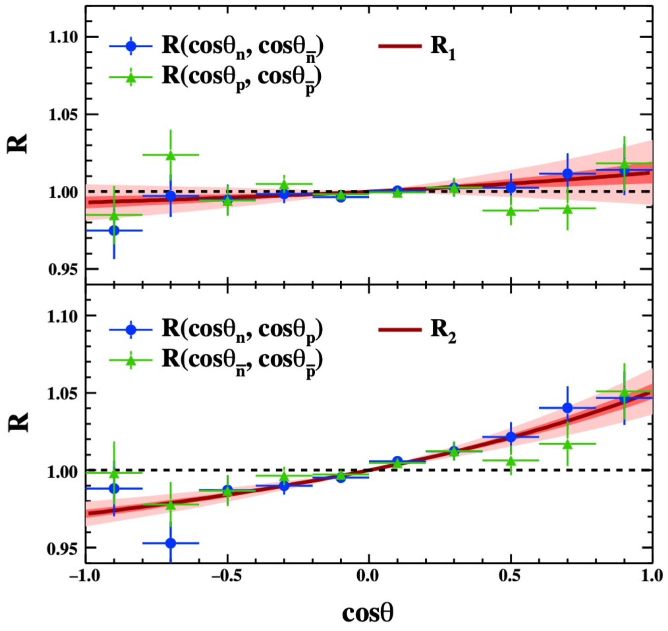

FIG. 2. The ratios of helicity angular distributions for different nucleons in the final states, $R(\cos\theta_p, \cos\theta_{\bar{p}})$ and $R(\cos\theta_n, \cos\theta_{\bar{n}})$ (top) as well as $R(\cos\theta_n, \cos\theta_p)$ and $R(\cos\theta_{\bar{n}}, \cos\theta_{\bar{p}})$ (bottom) versus $\cos\theta$. The dots with errors are determined by independent fits for each $\cos\theta$ bin of the corresponding nucleons. The solid curves in red with 1σ (red) and 3σ (pink) statistical uncertainty bands show the results of the simultaneous fit. The dashed curves in black show the CP-conserving and no $\Delta I = 3/2$ transition expectations.

arXiv:2309.14667

- Test of ΔI = ½ rule. In presence of ΔI = 3/2 transitions
- Ratios $\frac{\alpha 0}{\alpha -}$ and $\frac{\bar{\alpha} 0}{\alpha +}$ consistent with 1 if ΔI = 1/2

$\alpha_{\Lambda 0}/\alpha_{\Lambda -}$	$0.877 \pm 0.015^{+0.014}_{-0.010}$	1.01 ± 0.07 [29]
$\bar{\alpha}_{\Lambda 0}/\alpha_{\Lambda +}$	$0.863 \pm 0.014^{+0.012}_{-0.008}$	$0.913 \pm 0.028 \pm 0.012$ [18]

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$\Xi^0\bar{\Xi}^0 \to \Lambda(p\pi^-)\pi^0\bar{\Lambda}(\bar{p}\pi^+)\pi^0$

$\Xi^0\bar{\Xi}^0$ production and decay parameters with 3.3x10^5 events

Weak phase difference $\Xi^0 \to \Lambda\pi^0$

Previous determination of ϕ based on few hundred events

Consistent $\langle\alpha(\Lambda \to p\pi^-)\rangle_\Lambda$

Parameter	This work	Previous result	
$\alpha_{J/\psi}$	$0.514 \pm 0.006 \pm 0.015$	0.66 ± 0.06	[1]
$\Delta\Phi$(rad)	$1.168 \pm 0.019 \pm 0.018$	-	
α_Ξ	$-0.3750 \pm 0.0034 \pm 0.0016$	-0.358 ± 0.044	[2]
$\bar{\alpha}_\Xi$	$0.3790 \pm 0.0034 \pm 0.0021$	0.363 ± 0.043	[2]
ϕ_Ξ(rad)	$0.0051 \pm 0.0096 \pm 0.0018$	0.03 ± 0.12	[2]
$\bar{\phi}_\Xi$(rad)	$-0.0053 \pm 0.0097 \pm 0.0019$	-0.19 ± 0.13	[2]
α_Λ	$0.7551 \pm 0.0052 \pm 0.0023$	0.7519 ± 0.0043	[3]
$\bar{\alpha}_\Lambda$	$-0.7448 \pm 0.0052 \pm 0.0017$	-0.7559 ± 0.0047	[3]
$\xi_P - \xi_S$(rad)	$(0.0 \pm 1.7 \pm 0.2) \times 10^{-2}$	-	
$\delta_P - \delta_S$(rad)	$(-1.3 \pm 1.7 \pm 0.4) \times 10^{-2}$	-	
A_{CP}^Ξ	$(-5.4 \pm 6.5 \pm 3.1) \times 10^{-3}$	$(-0.7 \pm 8.5) \times 10^{-2}$	[2]
$\Delta\phi_{CP}^\Xi$(rad)	$(-0.1 \pm 6.9 \pm 0.9) \times 10^{-3}$	$(-7.9 \pm 8.3) \times 10^{-2}$	[2]
A_{CP}^Λ	$(6.9 \pm 5.8 \pm 1.8) \times 10^{-3}$	$(-2.5 \pm 4.8) \times 10^{-3}$	[3]
$\langle\alpha_\Xi\rangle$	$-0.3770 \pm 0.0024 \pm 0.0014$	-	
$\langle\phi_\Xi\rangle$(rad)	$0.0052 \pm 0.0069 \pm 0.0016$	-	
$\langle\alpha_\Lambda\rangle$	$0.7499 \pm 0.0029 \pm 0.0013$	0.7542 ± 0.0026	[3]

] [3] [PRL129(2022)131801]

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$\Lambda \rightarrow p\mu^-\bar{\nu}_\mu$

Phys.Rev.Lett. 127 (2021) 12, 121802

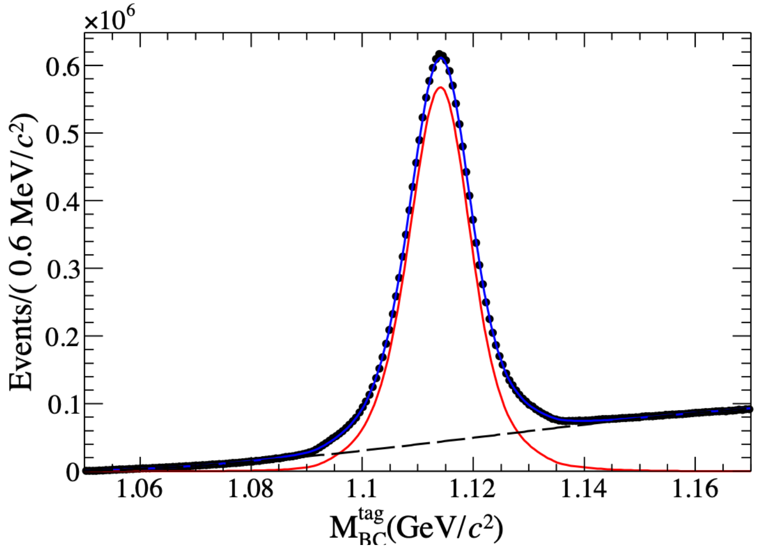
- Possible to determine absolute branching fractions using Double-tag method, pioneered by MARKIII experiment,
- Suitable for rare and/or challenging decay modes

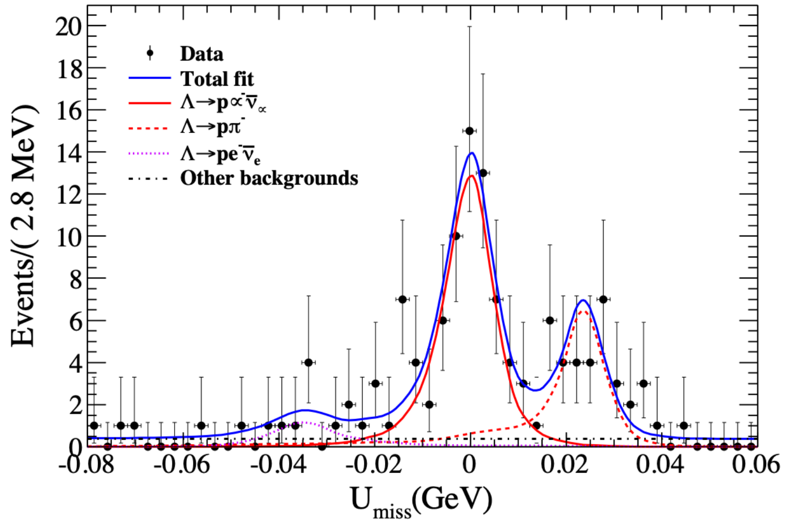
Decay mode	$N_{\rm ST}$ ($\times 10^3$)	$N_{\rm DT}$	$\mathcal{B}_{\rm sig}$ ($\times 10^{-4}$)
$\Lambda \rightarrow p\mu^-\bar{\nu}_\mu + c.c.$	$14,609.8 \pm 7.1$	64 ± 9	1.48 ± 0.21
$\Lambda \rightarrow p\mu^-\bar{\nu}_\mu$	$7,385.9 \pm 5.1$	31 ± 7	1.43 ± 0.30
$\bar{\Lambda} \rightarrow \bar{p}\mu^+\nu_\mu$	$7,391.0 \pm 5.0$	33 ± 6	1.49 ± 0.29

$$\mathcal{B}_{\rm sig} = \frac{N_{\rm DT}/\epsilon_{\rm DT}}{N_{\rm ST}/\epsilon_{\rm ST}}$$

$$\Delta E_{\rm tag} \equiv E_{\bar{\Lambda}} - E_{\rm beam} \qquad M_{\rm BC}^{\rm tag} c^2 \equiv \sqrt{E_{\rm beam}^2 - |\vec{p}_{\bar{\Lambda}} c|^2}$$

$$R^{\mu e} \equiv \frac{\Gamma(\Lambda \rightarrow p\mu^-\bar{\nu}_\mu)}{\Gamma(\Lambda \rightarrow pe^-\bar{\nu}_e)} \qquad R^{\mu e} = 0.178 \pm 0.028 \qquad R_{SM.} = 0.153 \pm 0.008$$





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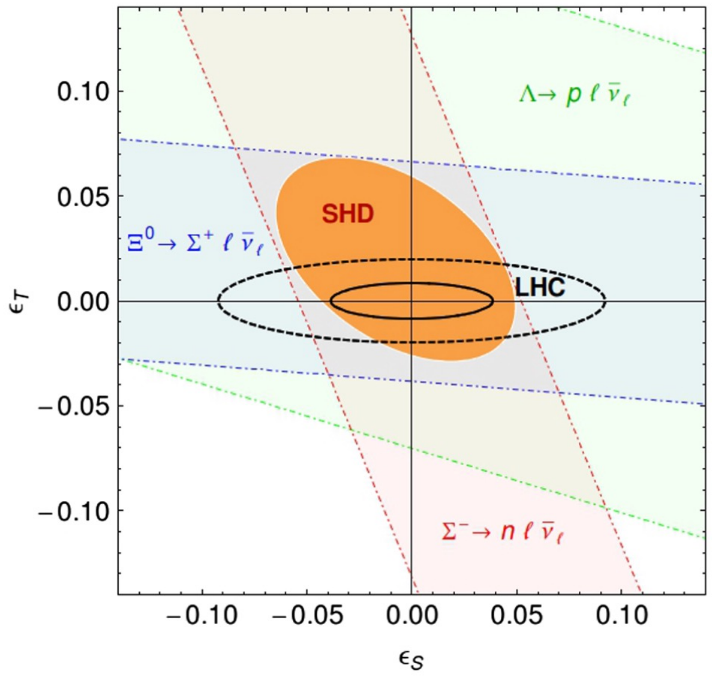
Nonstandard Semileptonic Hyperon Decays

Potential for precise constraint on BSM from Semi-leptonic hyperon decays

PRL 114, 161802 (2015)

$$\mathcal{L}_{\rm eff} = -\frac{G_F V_{us}}{\sqrt{2}}(1+\epsilon_L+\epsilon_R)\sum_{\ell=e,\mu}\{\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell\cdot\bar{u}[\gamma^\mu-(1-2\epsilon_R)\gamma^\mu\gamma_5]s + \bar{\ell}(1-\gamma_5)\nu_\ell\cdot\bar{u}[\epsilon_S-\epsilon_P\gamma_5]s + \epsilon_T\bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell\cdot\bar{u}\sigma^{\mu\nu}(1-\gamma_5)s\} + \text{H.c.}$$

Beyond the SM, the most general effective Lagrangian*



Assuming NP above electroweak symmetry breaking scale 246 GeV one is left with Wilson Coefficients, **ε** assuming real since CP-even

$$\Gamma_{e,\rm SM} \simeq \frac{G_F^2|V_{us}f_1(0)|^2\Delta^5}{60\pi^3}\left[\left(1-\frac{3}{2}\delta\right)+3\left(1-\frac{3}{2}\delta\right)\frac{g_1(0)^2}{f_1(0)^2}-4\delta\frac{g_2(0)}{f_1(0)}\frac{g_1(0)}{f_1(0)}\right]$$

Δ and δ mass dep. terms, vector FF: $f_1(q^2\sim 0)$ - $f_3(0)$ axial vector FF $f_1(0)$ - $g_3(0)$
In electron mode f_3 and g_3 scale with m_e/m_Λ

FIG. 1 (color online). 90% C.L. constraints on $\epsilon_{S,T}$ at $\mu = 2$ GeV from the measurements of $R^{\mu e}$ in different channels (dot-dashed lines) and combined (filled ellipse). LHC bounds obtained from CMS data at $\sqrt{s} = 8$ TeV (7 TeV) are represented by the black solid (dashed) ellipse.

* Neglecting O(**ε**2), only SM field relevant at μ=1 GeV, demanding operators color and EM singlets

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$\Lambda \to p l^- \bar{\nu}_\mu$

TABLE II. SHD data for $g_1(0)/f_1(0)$ and theoretical determinations of $f_{S,T}(0)/f_1(0)$ at $\mu = 2$ GeV used in this work. The corresponding $r_{S,T}$ are shown in the last two lines.

	$\Lambda \to p$	$\Sigma^- \to n$	$\Xi^0 \to \Sigma^+$	$\Xi^- \to \Lambda$
$g_1(0)/f_1(0)$	0.718(15)	−0.340(17)	1.210(50)	0.250(50)
$f_S(0)/f_1(0)$	1.90(10)	2.80(14)	1.36(7)	2.25(11)
$f_T(0)/f_1(0)$	0.72	−0.28	1.22	0.22
r_S	1.60	4.1	0.56	3.7
r_T	5.2	1.7	7.2	1.1

$$R^{\mu e} = \frac{\Gamma(B_1 \to B_2 \mu^- \bar{\nu}_\mu)}{\Gamma(B_1 \to B_2 e^- \bar{\nu}_e)} \qquad \frac{R^{\mu e}}{R^{\mu e}_{SM}} = 1 + r_S \epsilon_S + r_T \epsilon_T$$

$\epsilon_S = 0.003(40), \quad \epsilon_T = 0.017(34)$ at 90% CL from SLWD

Potential for $|V_{us}|$ determimation and test of BSM searches from determination of Wilson coefficients $\boldsymbol{\varepsilon}_S$ and $\boldsymbol{\varepsilon}_T$

Nice example where low-energy precision experiments with direct searches in collider experiments

PRL 114, 161802 (2015)

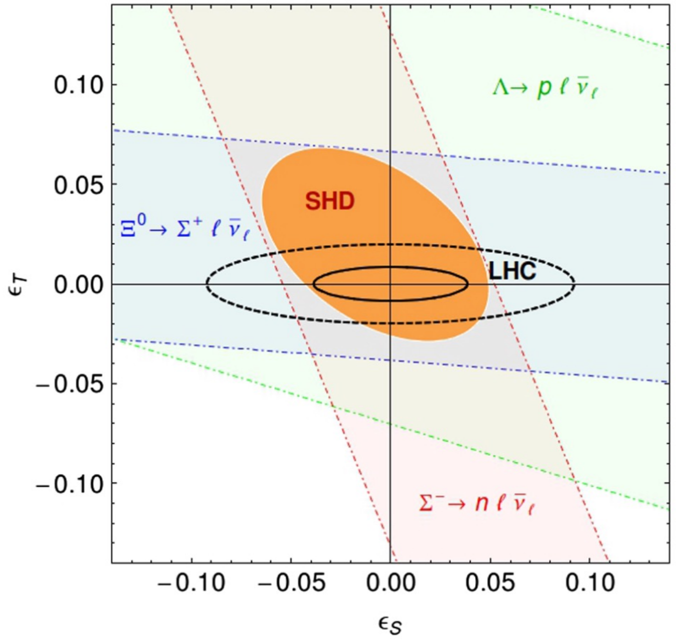


FIG. 1 (color online). 90% C.L. constraints on $\epsilon_{S,T}$ at $\mu = 2$ GeV from the measurements of $R^{\mu e}$ in different channels (dot-dashed lines) and combined (filled ellipse). LHC bounds obtained from CMS data at $\sqrt{s} = 8$ TeV (7 TeV) are represented by the black solid (dashed) ellipse.

$\sigma(pp \to e + \text{MET} + X)$

BESIII

$\Lambda \rightarrow n\gamma$

$\Lambda \rightarrow n\gamma$ decay first observed radiative hyperon decay at BESIII

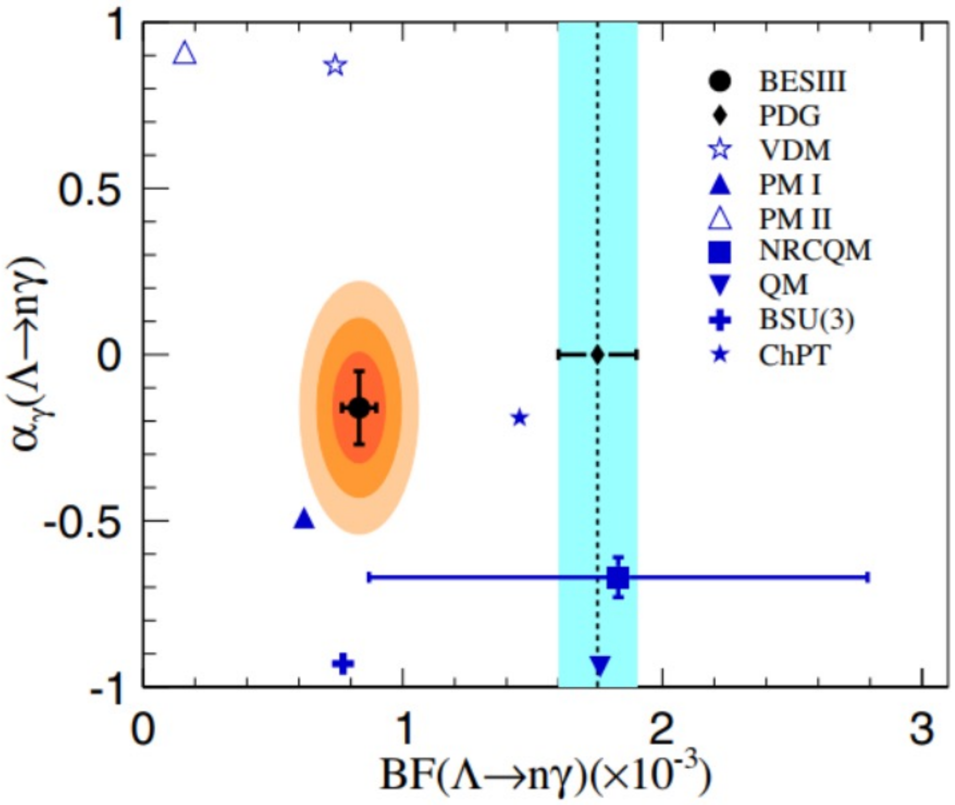
Double tag technique used. BF off by 5.6**σ** from PDG

Nr of events: 723±40 ($\Lambda \rightarrow n\gamma$) + 498±41 ($\bar{\Lambda} \rightarrow \bar{n}\gamma$)

α_γ = -0.16±0.10$_{stat}$±0.05$_{syst}$ agreement with Hara ($\alpha_{\gamma\ \mathrm{Hara}}$= 0)

BF(Λ→nγ) = [0.832 ± 0.038$_{stat}$ ± 0.054$_{syst}$] × 10^{-3}

Phys. Rev. Lett. 129, 212002 (2022)



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$$e^+e^- \to J/\psi \to \Sigma^+\bar{\Sigma}^- \to (p\gamma)(\bar{p}\pi^0) + \text{c.c.}$$

$\Sigma^+ \to p\gamma$ decay first observed radiative hyperon decay

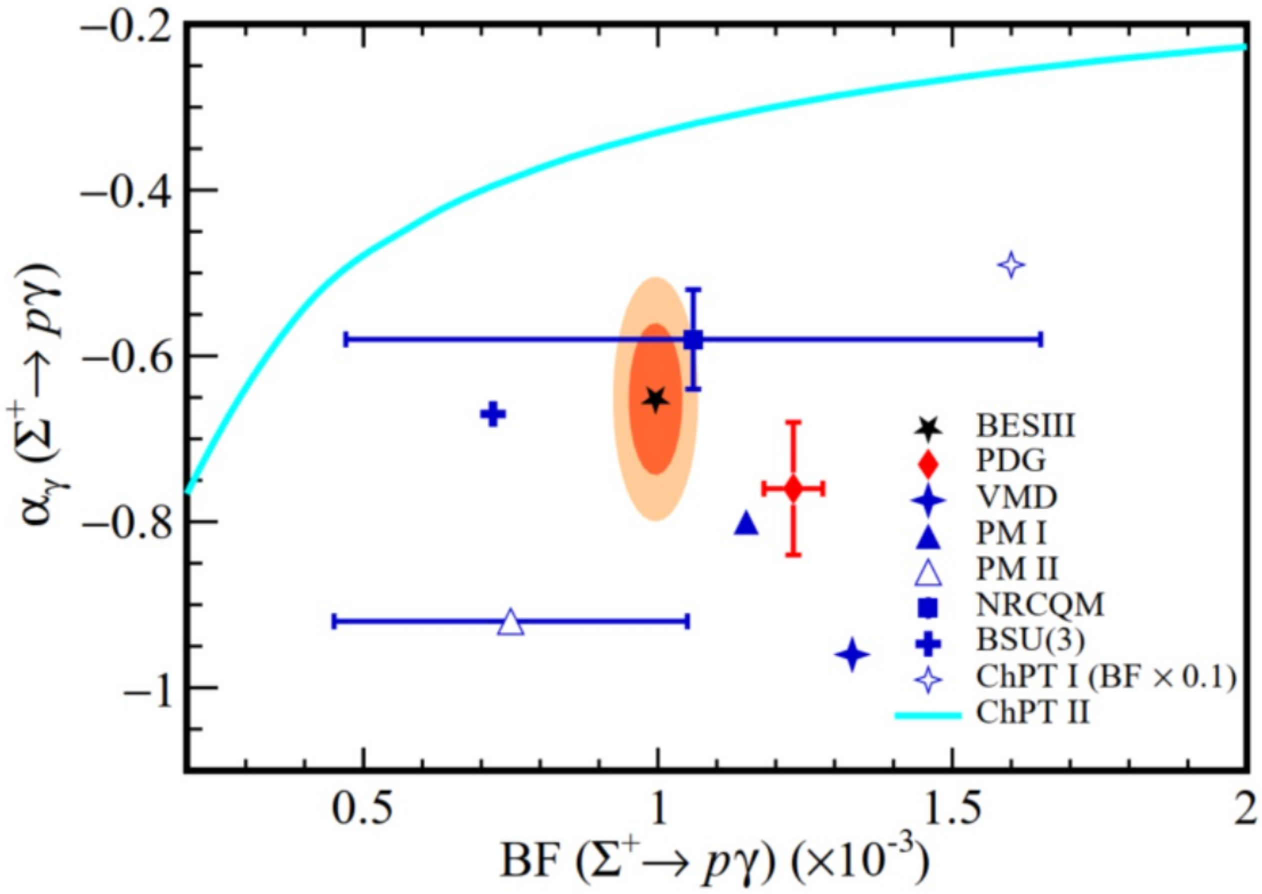
Its large decay asymmetry in violation of Hara's theorem

Double tag technique used

Nr of events: 1189±38 + 1306±39

$$\mathcal{B} = (0.996 \pm 0.021 \pm 0.018) \cdot 10^{-3}$$
$$\langle \alpha_\gamma \rangle = -0.651 \pm 0.056 \pm 0.020$$

$$\Delta_{CP} = \frac{\mathcal{B} - \bar{\mathcal{B}}}{\mathcal{B} + \bar{\mathcal{B}}} = 0.006 \pm 0.011 \pm 0.004$$
$$A_{CP} = \frac{\bar{\alpha}_\gamma + \alpha_\gamma}{\bar{\alpha}_\gamma - \alpha_\gamma} = 0.095 \pm 0.087 \pm 0.018$$

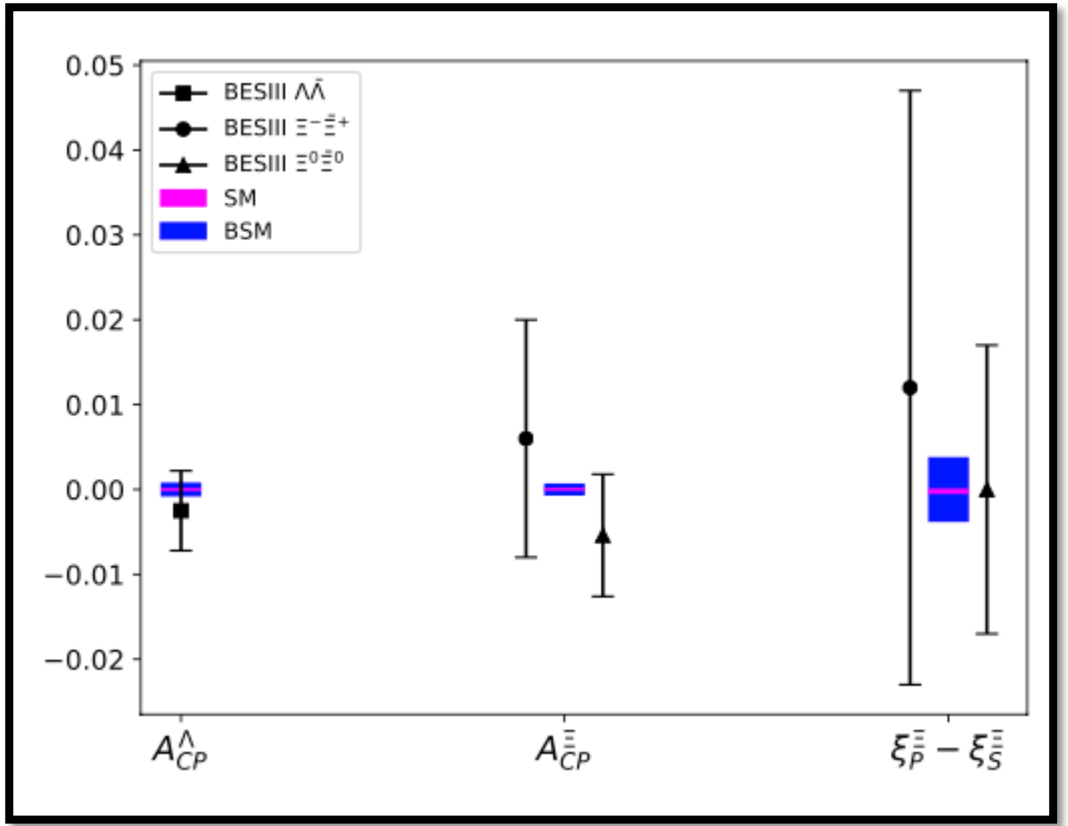


BESIII

The BESIII future

- With 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
- In pipeline: $\Xi^-\bar{\Xi}^+ \rightarrow \boldsymbol{\Lambda(p\pi^-)\pi^-\bar{\Lambda}(\bar{p}\pi^+)\pi^+}$ 10M data set.
- More results from semi-leptonic and radiative hyperon decays in future

SM and BSM sensitivity



Credit: Varvara

Experiment still few orders of magnitude from SM

From BESIII many proof-of-concept determinations

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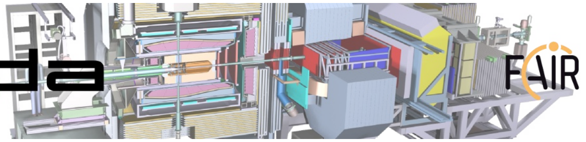
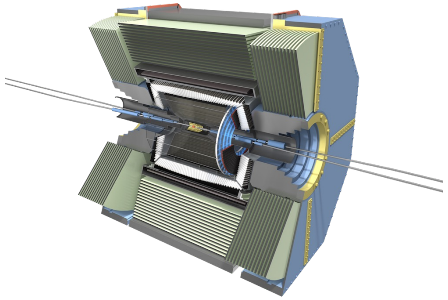
Other experimental facilities

PANDA@FAIR



The potential of $\Lambda\Lambda$ and $\Xi^-\Xi^-$ studies with PANDA at FAIR
Eur. Phys. J. A 57 No. 154 (2021), arXiv: 2009.11582,

BELLE-II



Super τ charm factories

FCC-ee?

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BESIII

Case study Super τ charm factories

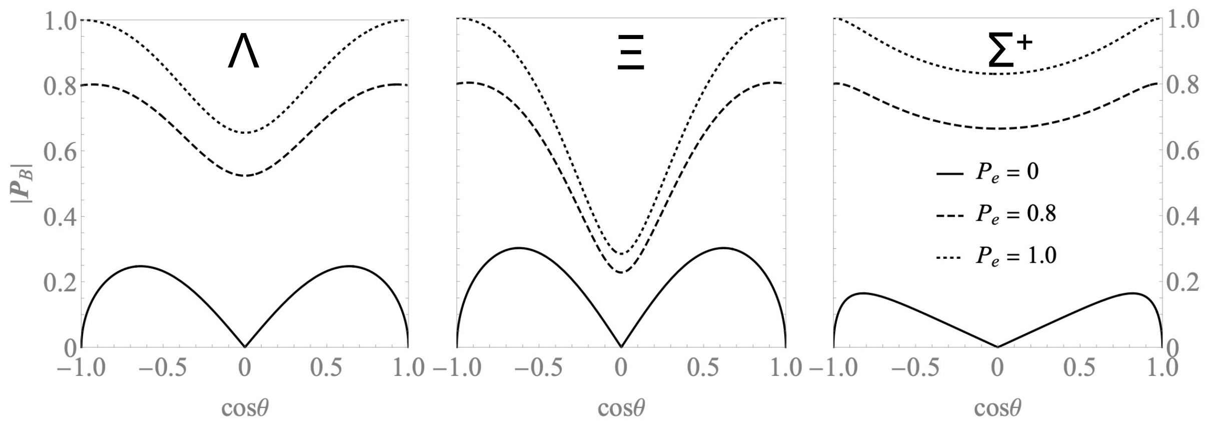
Using polarized electron beam can greatly enhance sensitivity!

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

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



Phys. Rev. D **105**, 116022

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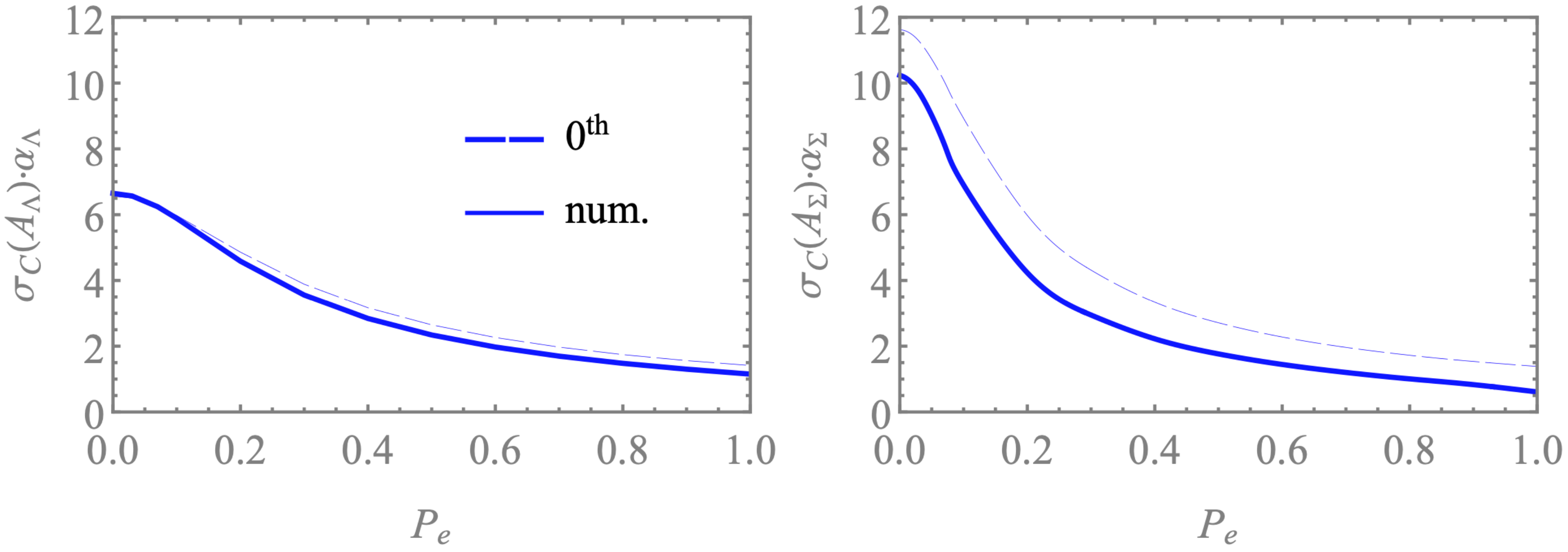
SτCF: single weak decay

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



Double tag

0^{th} order approximation

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

Phys. Rev. D **105**, 116022

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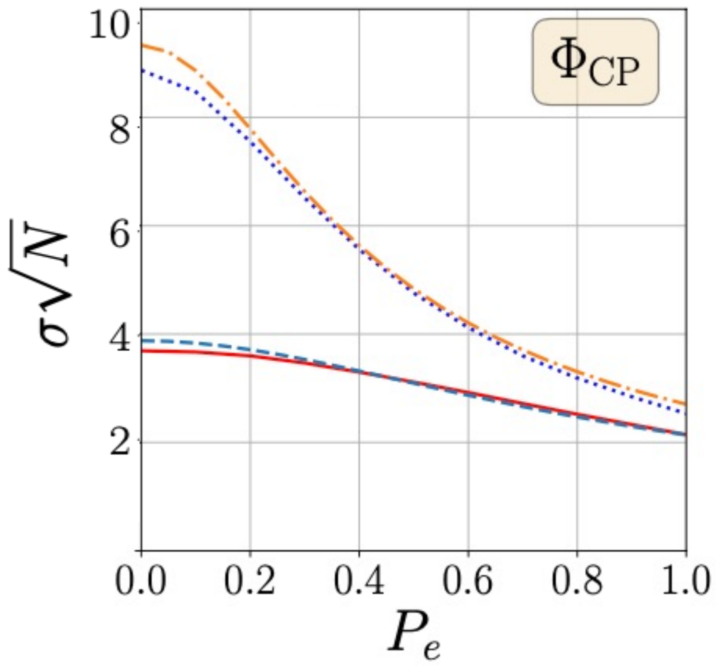
SτCF: sequential weak decay

Using polarized electron beam can greatly enhance sensitivity!

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

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



Spin correlation contributions

Dotted: ST
Solid: DT

Analytic approximation: dashed dotted dashed

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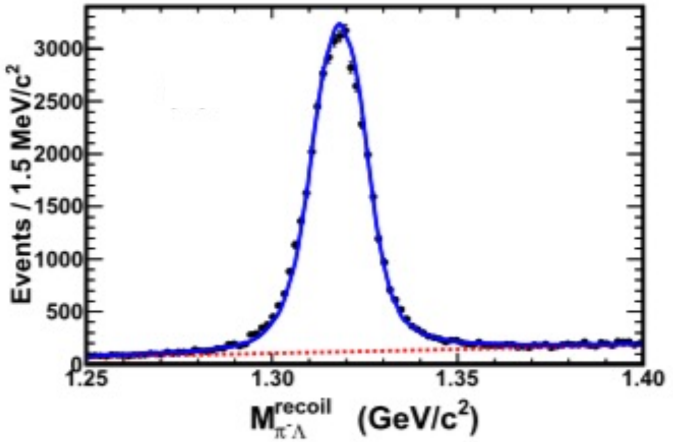
Super τ charm factories

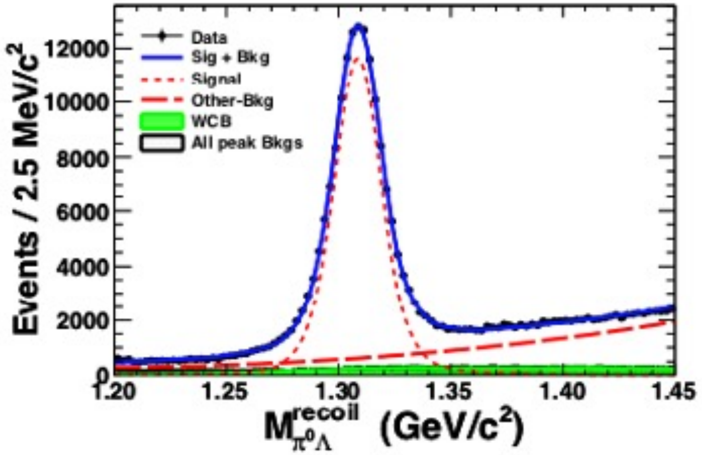
It becomes beneficial to also include single-tag events

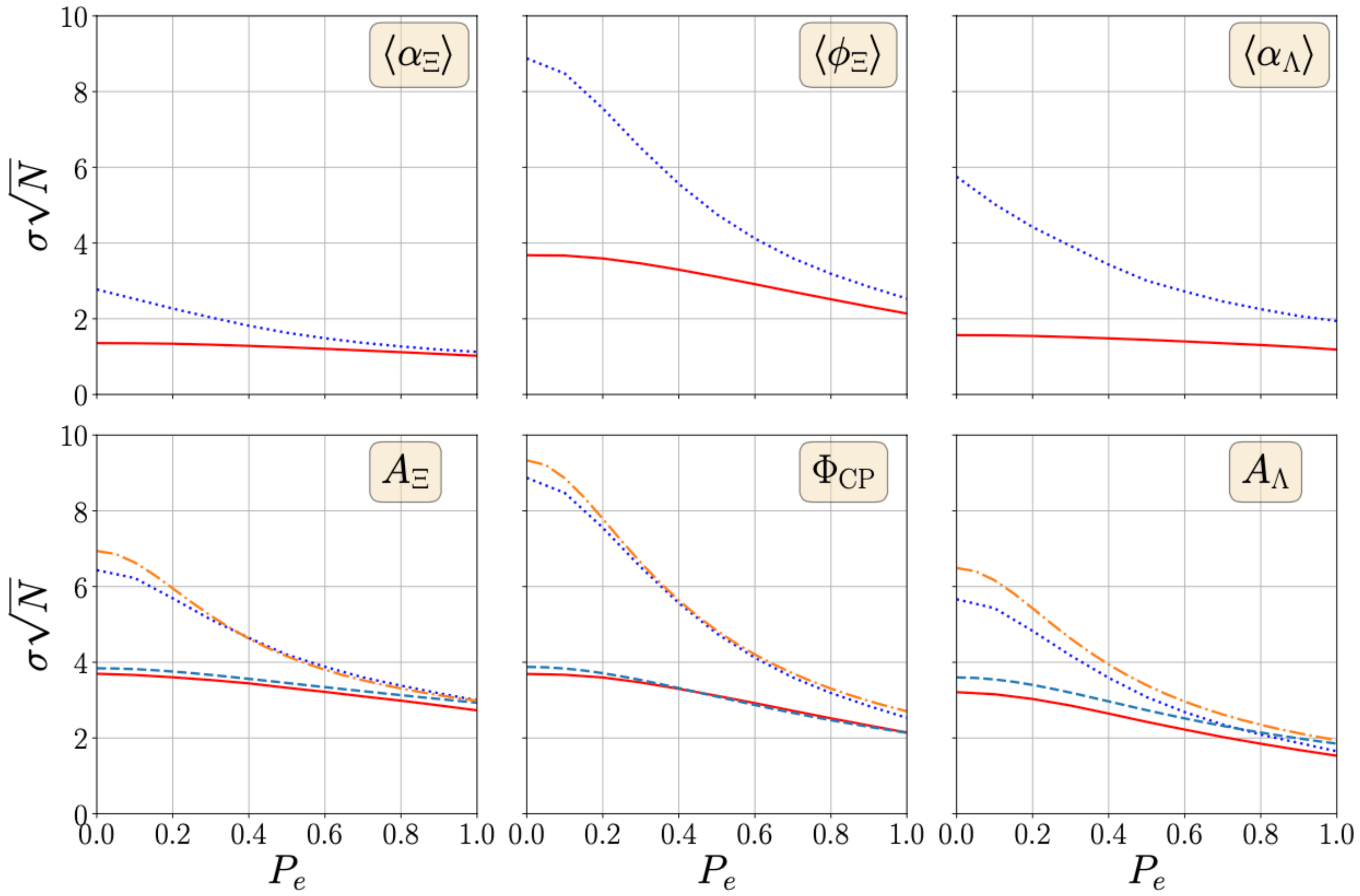
Bkg % level

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



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





arXiv 2203:03035

BESIII

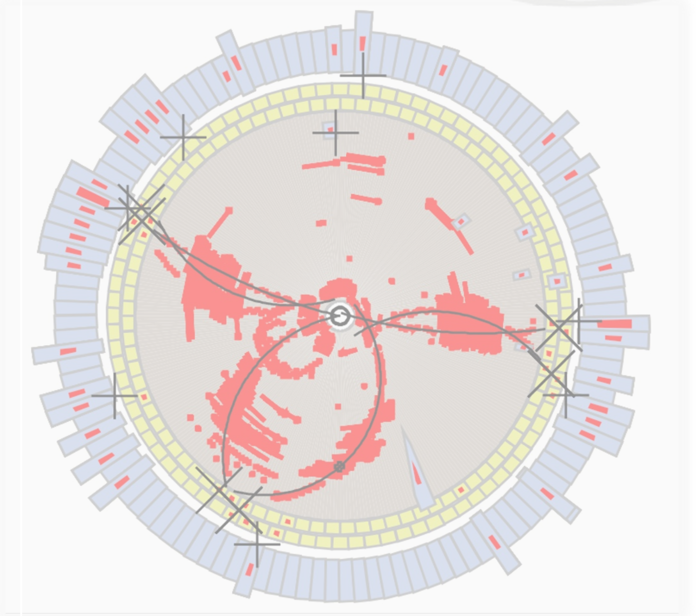
Summary & Outlook

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

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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