Light Hyperon Physics at BESIII

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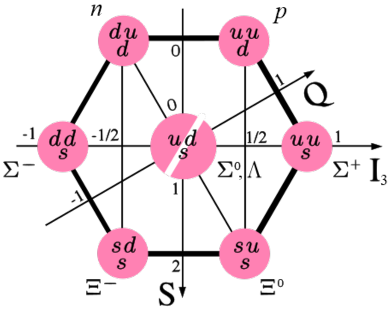
University of Birmingham
Particle physics seminar
2021-11-17

Outline

1. Hyperons and CP-violation
2. Theoretical description. Analysis Methods
3. Recent results from BESIII

Hyperons



Hyperon	Mass [GeV/c^2]	Decay (BF)
Λ	1.116	$p\pi^-$ (63.9%)
		$n\pi^0$ (35.8%)
Σ^-	1.197	$n\pi^-$ (99.8%)
Σ^+	1.189	$p\pi^0$ (51.6%)
		$n\pi^+$ (48.3%)
Ξ^0	1.315	$\Lambda\pi^0$ (99.5%)
Ξ^-	1.321	$\Lambda\pi^-$ (99.8%)
Ω	1.672	ΛK^- (67.8%)
		$\Xi^0\pi^-$ (23.6%)
		$\Xi^-\pi^0$ (8.6%)

$+\,\Omega^-(sss)$ Spin 3/2

Direct CP-Violation: Hyperon vs. Kaon Decays

To see CPV, need ≥ 2 amplitudes

Kaons:

Isospin amplitudes $\mathcal{A}_{\Delta I=1/2}$ and $\mathcal{A}_{\Delta I=3/2}$

Test direct CPV via $\frac{\mathcal{A}(K_L\to\pi^0\pi^0)}{\mathcal{A}(K_S\to\pi^0\pi^0)} \equiv \epsilon - 2\epsilon'$, $\frac{\mathcal{A}(K_L\to\pi^+\pi^-)}{\mathcal{A}(K_S\to\pi^+\pi^-)} \equiv \epsilon + \epsilon'$

Hyperons:

Two amplitudes S, P *even* for $\Delta I = 1/2$:

$\mathcal{A} = S + P\sigma\cdot\hat{n}$

Strong phases

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

Weak CP-odd phases

Admixture of $|\Delta I| = 3/2$ in $\Lambda \to p\pi^- \sim 1/22$

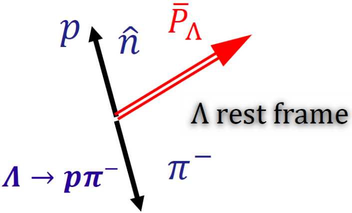
Two Measureable Parameters

$$\alpha = \frac{2Re(S^*P)}{|S|^2+|P|^2}$$

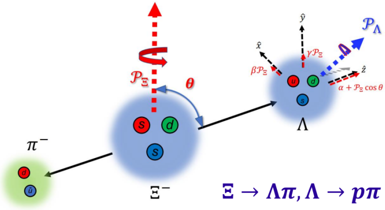
$$\beta = \frac{2IM(S^*P)}{|S|^2+|P|^2}$$

$$= \sqrt{1-\alpha^2}\sin\phi$$

$$\frac{d\Gamma}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda \hat{n}\bar{P}_\Lambda)$$



Experimentally, ϕ accessible when polarization of mother and daughter hyperon measured.



$$\beta = \sqrt{1-\alpha^2}\sin\phi$$

CP Tests in Hyperon Decays

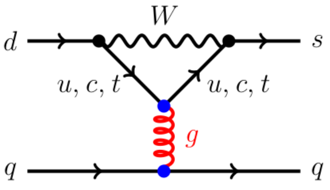
If CP conserved: $\bar{\alpha} = -\alpha$, $\bar{\beta} = -\beta$ (Experimentally $\bar{\phi} = -\phi$)

CP-tests: $A_{CP} = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}}$, $B_{CP} = \frac{\beta+\bar{\beta}}{\alpha-\bar{\alpha}} = (\xi_P - \xi_S)$

SM prediction [1]:

$$-3 \times 10^{-5} \leq A_{\Lambda} \leq 4 \times 10^{-5}$$
$$-2 \times 10^{-5} \leq A_{\Xi} \leq 1 \times 10^{-5}$$

Decay mode	$\xi_S - \xi_P$ (10^{-4} rad.)
$\Lambda \to p\pi^-$	0.3 ± 2.2
$\Xi \to \Lambda\pi^-$	-1.9 ± 1.6



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

$0.5 < B_G < 2$ and $0.2 < |\kappa| < 1$ [3]

Decay	C_B	C'_B
$\Lambda \to p\pi^-$	1.1 ± 2.2	0.4 ± 0.8
$\Xi \to \Lambda\pi^-$	-0.5 ± 1.0	0.4 ± 0.7

HyperCP measurement[2]:

$$A^{\Xi}_{CP} + A^{\Lambda}_{CP} = 0(5)(4) \times 10^{-4}$$

[1] Tandean, Valencia PRD67 (2003) 056001
[2] PRL 93 (2004) 262001
[3] Tandean, PRD69 (2004) 076008

Previous Measurements

PS185: $\Lambda \to p\pi$
$\bar{P}_y = P_y$ $(d\Gamma/d\Omega \propto 1 + \alpha_\Lambda P_y \cos\theta_p)$

$$A_\Lambda = \frac{\alpha P_y + \bar{\alpha}\bar{P}_y}{\alpha P_y - \bar{\alpha}\bar{P}_y} = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}$$

HyperCP: $\Xi \to \Lambda\pi \to p\pi\pi$
No polarization $(d\Gamma/d\Omega \propto 1 + \alpha_\Xi \alpha_\Lambda \cos\theta_p)$

$$A_{\Xi\Lambda} = \frac{\alpha_\Xi \alpha_\Lambda - \bar{\alpha}_\Xi \bar{\alpha}_\Lambda}{\alpha_\Xi \alpha_\Lambda + \bar{\alpha}_\Xi \bar{\alpha}_\Lambda} \approx A_\Xi + A_\Lambda$$

PS185, PRC54(96)1877

HyperCP, PRL 93 (2004) 262001

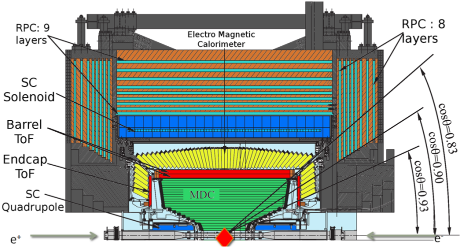
BESIII at BEPCII

Beijing Electron-Positron Collider (BEPCII)

- CMS Energy from 2 to 4.95 GeV/c^2
- Design luminosity 10^{33} cm^{-2}s^{-1}

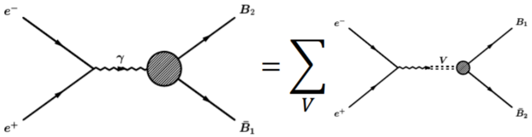
Beijing Spectrometer (BESIII)

- Near 4π coverage
- Helium-gas drift chamber
- CsI(Tl) crystal calorimeter
- MRPC TOF-system
- 1 T super-conducting solenoid
- RPC-based muon chamber
- World's largest datasets at:
  - J/ψ: 10B events (here results from 1.3B)
  - $\psi(2S)$: 3B events (here results from 0.4B)

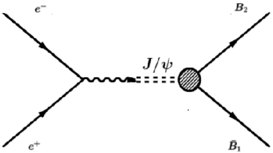


Decay	$\mathcal{B}$ (10^{-5})	Events at BESIII
$J/\psi \to \Lambda\bar{\Lambda}$	189 ± 9	18.9×10^6
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	150 ± 24	15.0×10^6
$J/\psi \to \Xi\bar{\Xi}$	97 ± 8	9.7×10^6
$\psi(2S) \to \Sigma\bar{\Sigma}$	23.2 ± 1.2	696×10^3
$\psi(2S) \to \Omega\bar{\Omega}$	5.66 ± 0.30	170×10^3

$e^+e^- \to \gamma^* \to B\bar{B}$



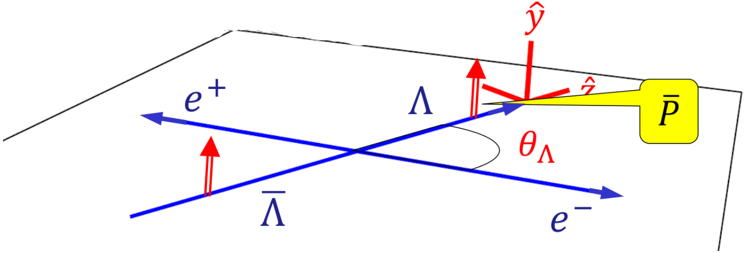
Both processes described by two complex form factors.
Ratio of FFs: α_ψ
Relative phase: $\Delta\Phi$



Timelike spin-1/2 EM FFs
Dubnickova, Dubnicka, Rekalo Nuovo Cim. A109 (1996) 241
Gakh, Tomasi-Gustafsson Nucl.Phys. A771 (2006) 169
Czyz, Grzelinska, Kuhn PRD75 (2007) 074026
Fäldt EPJ A51 (2015) 74; EPJ A52 (2016)141

Charmonium decays:
Fäldt, Kupsc, PLB 772 (2017) 16

$B\bar{B}$ Production in e^+e^--Annihilation



Unpolarized e^+e^- beams $\rightarrow$ Transverse polarization:

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

Angular distibution: $\frac{d\Gamma}{d\Omega} \propto 1 + \alpha_\psi \cos^2\theta_\Lambda,\ -1 \leq \alpha_\psi \leq 1$

$B\bar{B}$ Production in e^+e^--Annihilation: Modular Description

Two spin 1/2 particle state:

$$\rho_{1/2,\overline{1/2}} = \frac{1}{4}\sum_{\mu\bar{\nu}} C_{\mu\bar{\nu}}\, \sigma_{\mu}^{\Lambda} \otimes \sigma_{\bar{\nu}}^{\bar{\Lambda}}$$

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

Spin correlations

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

Include decay via decay matrices:

$$\sigma_\mu^\Lambda \rightarrow \sum_{\mu'=0}^{3} a_{\mu,\mu'}^{\Lambda}\, \sigma_{\mu'}^{p}$$

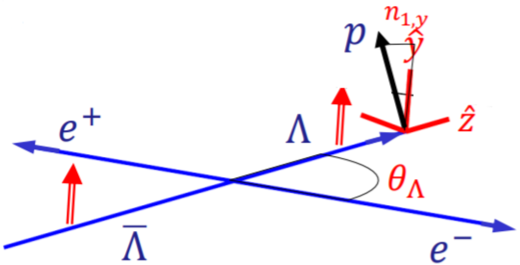
Full angular distribution:

$$W = Tr\rho_{p,\bar{p}} = \sum_{\mu,\bar{\nu}=0}^{3} C_{\mu\bar{\nu}} a_{\mu,0}^{\Lambda} a_{\bar{\nu},0}^{\bar{\Lambda}}$$

E.Perotti, G.Faldt, A. Kupsc, S.Leupold,JJ.Song PRD99 (2019)056008

Inclusive Analysis(Single-Tag) $e^+e^- \to Y\bar{Y}, Y \to BM + c.c.$

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



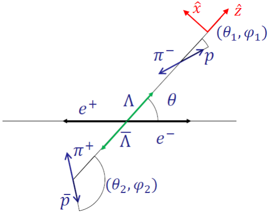
$$\frac{d\Gamma}{d\cos\theta_\Lambda d\Omega} \propto \left(1 + \alpha_\psi \cos^2\theta_\Lambda\right)\left(1 + \alpha_\Lambda P_y n_{1,y}\right)$$

$\Lambda \to p\pi^-$ described by: $\hat{n} \to \Omega = (\cos\theta_1, \phi_1)$, and parameter α_Λ

Can measure product: $\alpha_\Lambda P_y \sim \alpha_\Lambda \sin(\Delta\Phi)$

Exclusive Analysis(Double-Tag) $e^+e^- \to Y\bar{Y}, Y \to BM + c.c.$

Production parameters: α_ψ, $\Delta\Phi$
Decay parameters:
α_Λ $(\Lambda \to p\pi^-)$
$\bar{\alpha}_\Lambda$ $(\bar{\Lambda} \to \bar{p}\pi^+)$
5D phase space $\xi = (\theta, \theta_1, \phi_1, \theta_2, \phi_2)$



spin correlations

$$d\Gamma \propto \mathcal{W}(\xi) = \mathcal{F}_0(\xi) + \alpha_\psi \mathcal{F}_5(\xi) + \boxed{\alpha_\Lambda \bar{\alpha}_\Lambda \left(\mathcal{F}_1(\xi) + \sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)\mathcal{F}_2(\xi) + \alpha_\psi \mathcal{F}_6(\xi)\right)} + \boxed{\sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)(\alpha_\Lambda \mathcal{F}_3(\xi) + \bar{\alpha}_\Lambda \mathcal{F}_4(\xi))}$$

polarization

Non-zero $\Delta\Phi \implies$ independent measurement of α_Λ, $\bar{\alpha}_\Lambda$

Fäldt, Kupsc, PLB 772 (2017) 16

Experimental Method

- Determine angles ξ for each signal event.
- Extract parameters ω with unbinned MLL fit

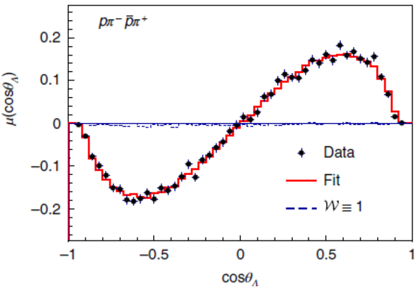
$$\mathcal{L}(\xi_1, ..., \xi_N; \omega) = \prod_{i=1}^{N} \frac{\mathcal{W}(\xi_i; \omega)\epsilon(\xi_i)}{N(\omega)}$$

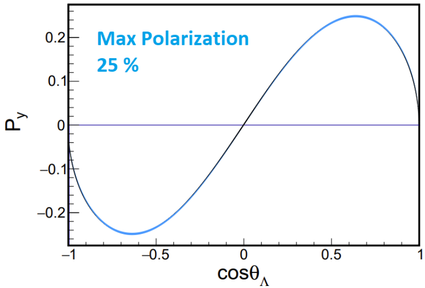
Normalisation N and efficiency ϵ calculated with phase space MC

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

(Based on 1.31×10^9 J/ψ events)

Exclusive analysis. 421k events (399 background)





Parameters	This work	Previous results
α_ψ	$\mathbf{0.461 \pm 0.006 \pm 0.007}$	0.469 ± 0.027 BESIII
$\Delta\Phi$ (rad)	$\mathbf{0.740 \pm 0.010 \pm 0.008}$	–
α_Λ	$\mathbf{0.750 \pm 0.009 \pm 0.004}$	0.642 ± 0.013 PDG
$\bar{\alpha}_\Lambda$	$\mathbf{-0.758 \pm 0.010 \pm 0.007}$	-0.71 ± 0.08 PDG

Nature Phys. 15 (2019) 631

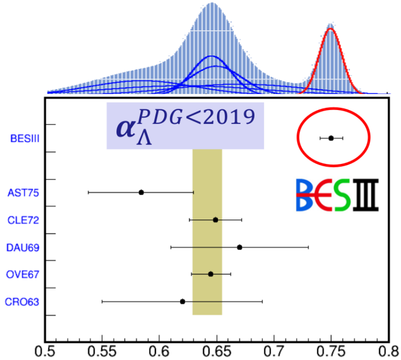
$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda},\ \Lambda \to p\pi^- + c.c.$

$$A_{CP} = \frac{\alpha_\Lambda + \alpha_{\bar{\Lambda}}}{\alpha_\Lambda - \alpha_{\bar{\Lambda}}} = -0.006 \pm 0.012 \pm 0.007$$

PS185: $A_\Lambda = 0.013 \pm 0.021$
PRC54(96)1877

$$< \alpha >= \frac{\alpha - \bar{\alpha}}{2} = 0.754 \pm 0.003 \pm 0.002$$

CLAS: $\alpha_\Lambda = 0.721 \pm 0.006 \pm 0.005$
PRL 123 (2019) 182301
Data on $\Lambda_b \to J/\psi\Lambda$ favor new value
LHCb, JHEP 06 (2020) 110

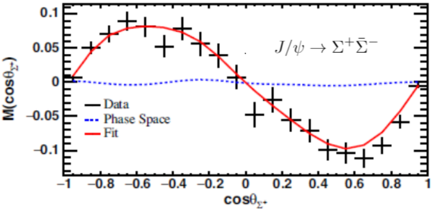


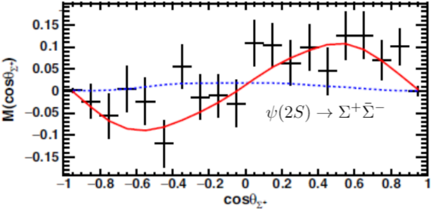
BESIII, Nature Phys. 15 (2019) 631

$e^+e^- \to J/\psi, \psi(2S) \to \Sigma^+\bar{\Sigma}^-$, $\Sigma^+ \to p\pi^0 + c.c.$

Based on 1.31×10^9 J/ψ events, and 0.5×10^9 $\psi(2S)$ events.

Plots acceptance uncorrected





87k events (5% bkg)
$\alpha_{J/\psi} = -0.507 \pm 0.006 \pm 0.002$
$\Delta\Phi(J/\psi) = (-15.4 \pm 0.7 \pm 0.3)^\circ$

$< \alpha >= (\alpha - \bar{\alpha})/2 = -0.994 \pm 0.004 \pm 0.002$
$A_{CP} = -0.004 \pm 0.037 \pm 0.010$
c.f. SM prediction $A_{CP} \sim 3.6 \times 10^{-6}$

BESIII, Phys. Rev. Lett. 125 (2020) 052004

5k events (1% bkg)
$\alpha_{\psi} = 0.676 \pm 0.030 \pm 0.006$
$\Delta\Phi(\psi) = (21.5 \pm 0.4 \pm 0.5)^\circ$

$$W = \sum_{\mu,\bar{\nu}=0}^{3} C_{\mu\bar{\nu}} \sum_{\mu',\bar{\nu}'=0}^{3} a^{\Xi}_{\mu,\mu'} a^{\bar{\Xi}}_{\bar{\nu},\bar{\nu}'} a^{\Lambda}_{\mu',0} a^{\bar{\Lambda}}_{\bar{\nu}',0}$$

$d\Gamma \propto W(\xi,\omega)$, ξ: 9 kin. variables

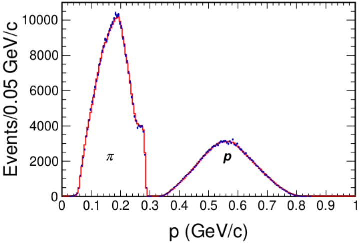
8 parameters:

Production

$$\omega = (\alpha_\Psi, \Delta\Phi, \alpha_\Xi, \phi_\Xi, \alpha_\Lambda, \bar{\alpha}_\Xi, \bar{\phi}_\Xi, \bar{\alpha}_\Lambda)$$

Decay

BESIII



- Exclusive analysis. 73k events (190 bkg)
- Parameters estimated using unbinned MLL fit

E.Perotti, G.Faldt, A. Kupsc, S.Leupold,JJ.Song PRD99 (2019)056008

BESIII, arXiv:2105.11155

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

Parameter	Preliminary	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	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$	***
$\overline{\alpha}$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$	***
$\delta_P - \delta_S$	$(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2}$ rad	$(10.2 \pm 3.9) \times 10^{-2}$ rad	****
$\xi_P - \xi_S$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad	–	
A_{CP}^{Ξ}	$(6.0 \pm 13.4 \pm 5.6) \times 10^{-3}$	–	
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		

8 Fit Parameters

3 CP tests

BESIII

* PRD 93, 072003 (2016)
** PDG 2020
*** Nat. Ph. 15, 631 (2019)
**** PRL 93, 011802 (2004)

BESIII, arXiv:2105.11155

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

First measurement of weak phase difference

* PRD 93, 072003 (2016)
** PDG 2020
*** Nat. Ph. 15, 631 (2019)
**** PRL 93, 011802 (2004)

BESIII, arXiv:2105.11155

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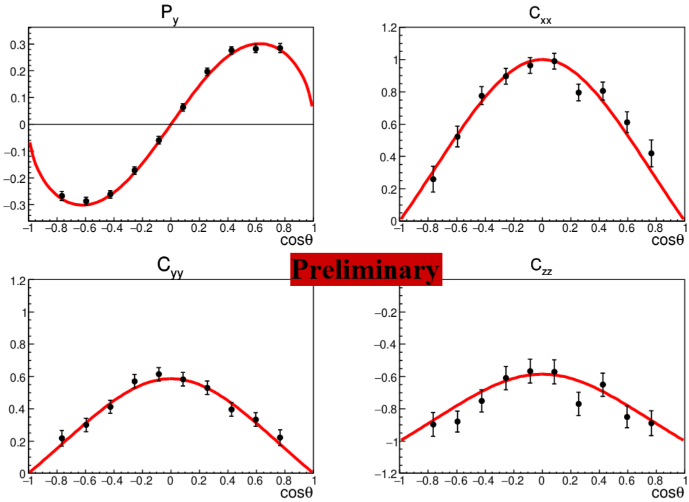
Independent measurement of α_Λ

BESIII

* PRD 93, 072003 (2016)
** PDG 2020
*** Nat. Ph. 15, 631 (2019)
**** PRL 93, 011802 (2004)

BESIII, arXiv:2105.11155

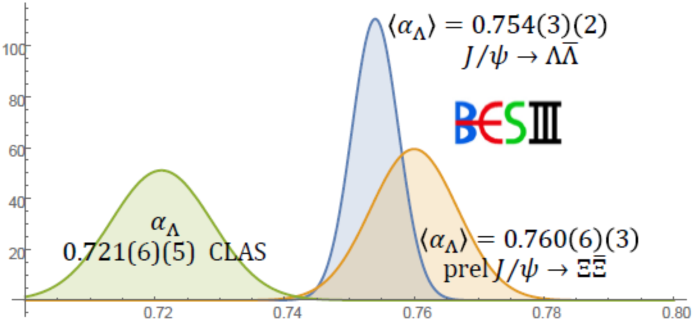
Polarization and C_{ii} for $e^+e^- \to J/\psi, \to \Xi\bar{\Xi}$



(Acceptance corrected)

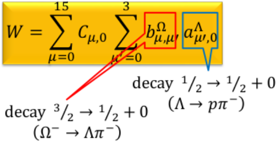
BESIII, arXiv:2105.11155

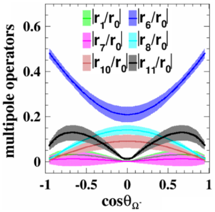
Λ Decay Parameter



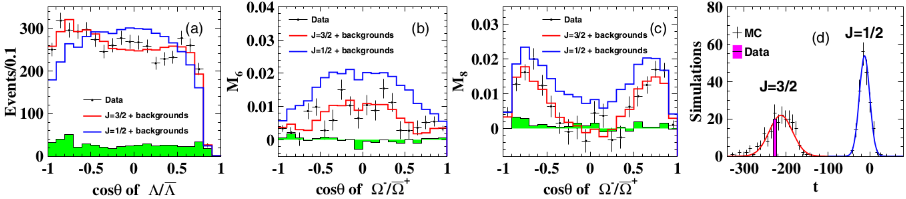
Kupsc, PoS CHARM2020 (2021) 009

$e^+e^- \to \psi(2S) \to \Omega\bar{\Omega},\ \Omega \to \Lambda\pi^-,\ \Lambda \to p\pi^- + c.c.$





- Single-tag analysis of 4.48×10^8 $\psi(2S)$ events $\to$ 2507 Ω^- (298 bkg) and 2238 $\bar{\Omega}^+$ (189 bkg)
- Spin 3/2 confirmed model-indepently for the first time.
- Multipolar polarization measured



E.Perotti, G.Faldt, A. Kupsc, S.Leupold,JJ.Song PRD99 (2019)056008

BESIII, Phys. Rev. Lett. 126, 092002 (2021)

Conclusion

Summary

- Polarization/spin correlations measured in $J/\psi(\psi(2S)) \to \Lambda\bar{\Lambda}, \Sigma\bar{\Sigma}, \Xi\bar{\Xi}, \Omega\bar{\Omega}$
- Hyperon and anti-hyperon decay parameters determined
- CP-tests in decays of Λ,Σ^+, Ξ^-
- Model independent determination of Ω^- spin

Outlook

- At BESIII
  - 10B J/ψ
  - 3B $\psi(2S)$
- Future super charm-tau factory?
  - 2×10^{12} J/ψ
  - Polarized electron beam?