CP-symmetry tests in sequential decays of entangled strange baryons

Andrzej Kupsc (UU&NCBJ)

Precision hyperon physics at J/ψ and ψ' factories:

$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$ Nature Phys. 15 (2019) 631

$J/\psi(\psi') \to \Sigma^+\bar{\Sigma}^-$ PRL125 (2020) 052004

$J/\psi \to \Xi\bar{\Xi}$ **arXiv:2105.11155**

$\psi' \to \Omega^-\bar{\Omega}^+$ PRL126 (2021) 092002

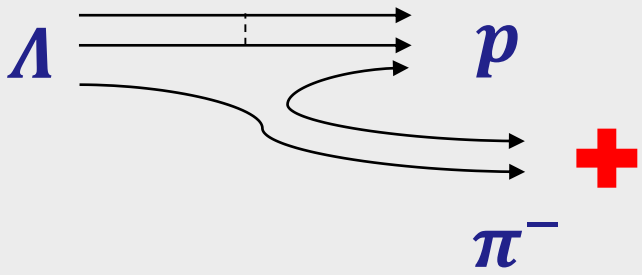
Polarization and spin correlations
Sequential decays
Determination of hyperon decay parameters
CP tests

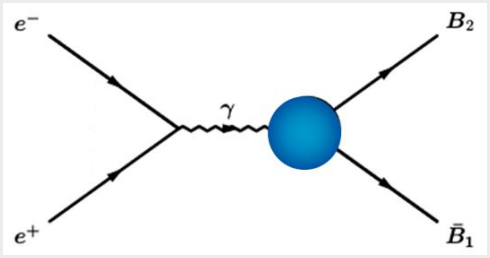
NCBJ from 30/6:
V. Batozskaja*
M. Berłowski
A. Kupść*
A. Ukleja
N. Salone

Methods (UU&NCBJ):

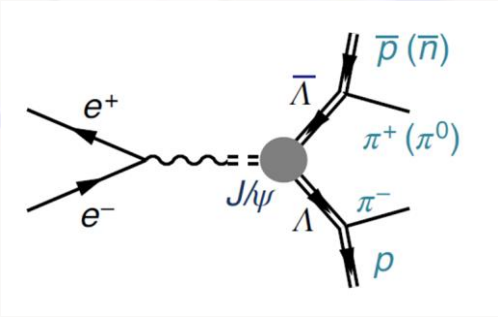
1. G.Fäldt, AK PLB772 (2017) 16
2. E.Perotti,G.Fäldt,AK,S.Leupold,JJ.Song PRD99 (2019)056008
3. P.Adlarson, AK PRD100 (2019) 114005
4. P.Adlarson,V.Batozskaya,AK,N.Salone, S.Leupold, J. Tandean in preparation

NCBJ, 20 December 2021

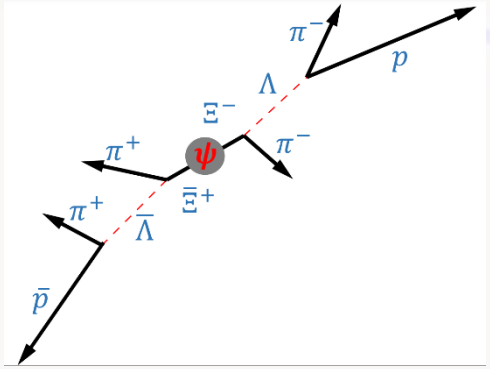




$\Lambda \to p\pi^-$ $e^+e^- \to J/\psi \to B\bar{B}$



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



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

nature physics
Nature Phys. 15 (2019) 631 LETTERS
https://doi.org/10.1038/s41567-019-0494-8

Polarization and entanglement in baryon–antibaryon pair production in electron–positron annihilation

The BESIII Collaboration*

#94 citations

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

Introduction: Direct CP violation in kaon decays

$$\frac{\mathcal{A}(K_L \to \pi^+\pi^-)}{\mathcal{A}(K_S \to \pi^+\pi^-)} := \epsilon + \epsilon' \quad \text{and} \quad \frac{\mathcal{A}(K_L \to \pi^0\pi^0)}{\mathcal{A}(K_S \to \pi^0\pi^0)} := \epsilon - 2\epsilon'$$

$\Delta I = 1/2$ and $3/2$ amplitudes

$$\mathcal{A}(K^0 \to \pi^+\pi^-) = \sqrt{\frac{1}{3}} A_{3,2} \exp(i\xi_{3,2} + i\delta_2) + \sqrt{\frac{2}{3}} A_{1,0} \exp(i\xi_{1,0} + i\delta_0)$$

$$\mathcal{A}(K^0 \to \pi^0\pi^0) = \sqrt{\frac{2}{3}} A_{3,2} \exp(i\xi_{3,2} + i\delta_2) - \sqrt{\frac{2}{3}} A_{1,0} \exp(i\xi_{1,0} + i\delta_0)$$

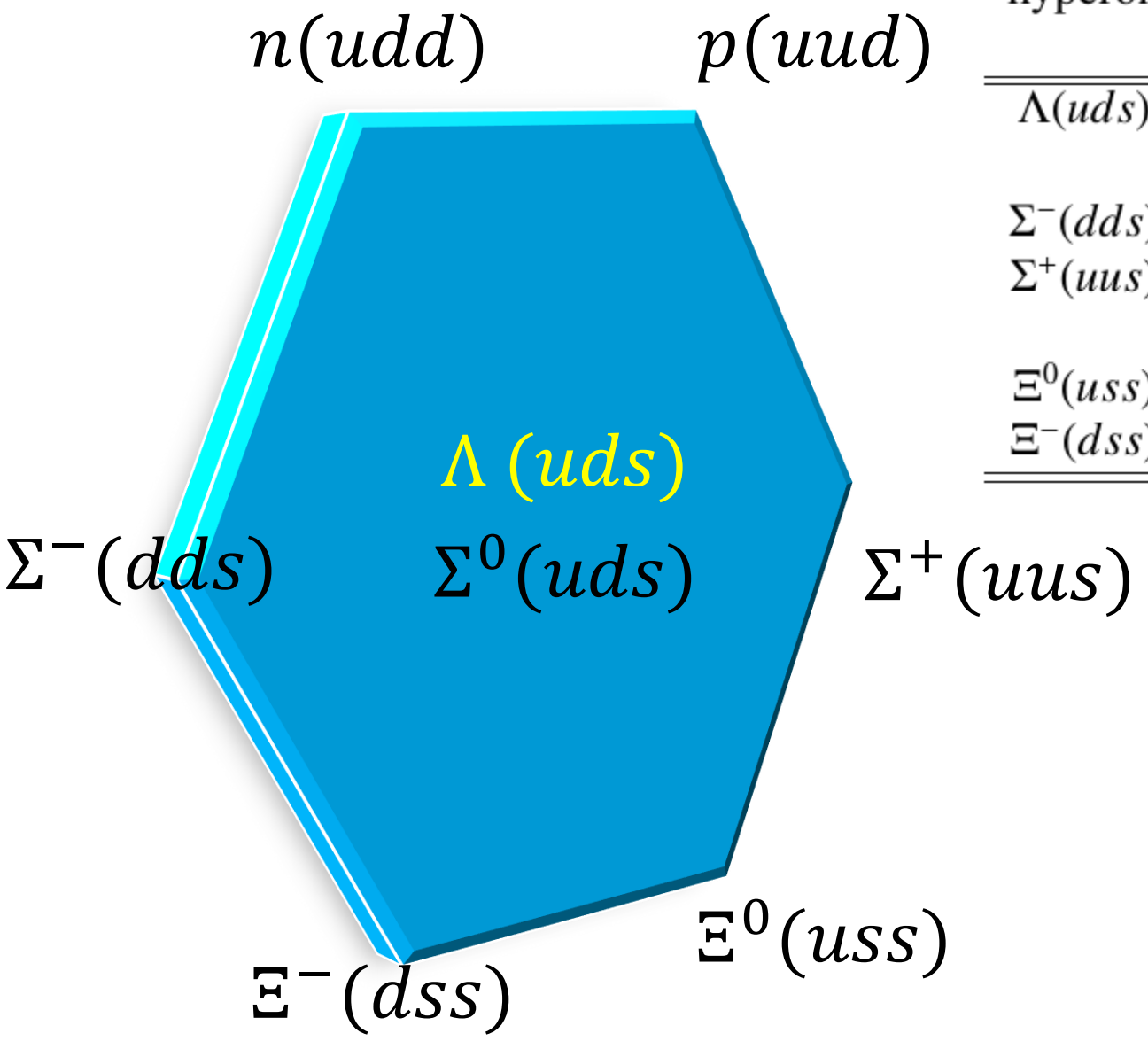
Notation: $\mathcal{A}_{2\Delta I, I}$

ΔI 1/2 , 3/2 CPV phases

$$\epsilon' \simeq -\frac{i}{\sqrt{2}} \exp(i\delta_2 - i\delta_0) \frac{A_{3,2}}{A_{1,0}} (\xi_{1,0} - \xi_{3,2})$$

Ground-state strange baryons

Spin ½ baryon octet



hyperon	Mass [GeV/c^2]	$c\tau$ [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%)

$+\ \Omega^-(sss)$

Spin $^3/_2$

Decay amplitudes in hyperon decays

$\Lambda \to p\pi^-$

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

P and S transitions

$$\mathcal{A}(\Xi^- \to \Lambda\pi^-) = S + P\boldsymbol{\sigma}\cdot\hat{\mathbf{n}}$$

weak CP-odd phases

$$S = |S|\exp(i\xi_S)\exp(i\delta_S)$$

$$P = |P|\exp(i\xi_P)\exp(i\delta_P)$$

strong phases

$|\Delta I| = 1/2$

Admixture of $|\Delta I| = 3/2$ (~1/22)

Measurable: BF and two decay parameters

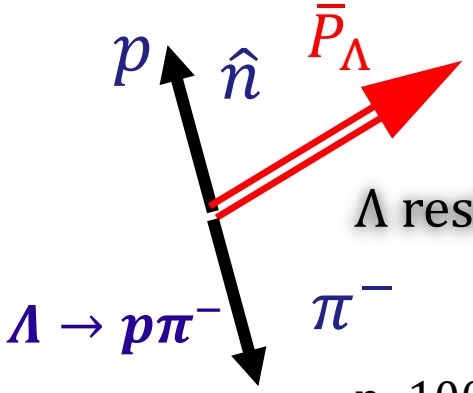
$$\alpha = \frac{2\ \mathrm{Re}(S^*P)}{|S|^2 + |P|^2}$$

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

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

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

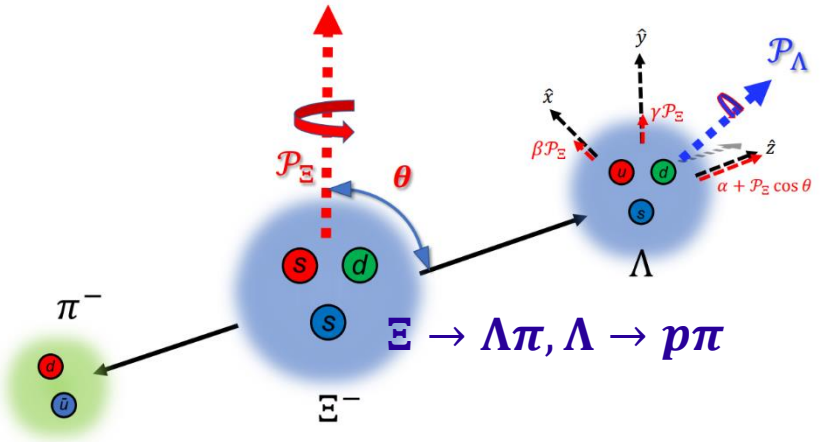
Measurement of hyperon decay parameters



Λ rest frame

p=100 MeV/c

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



α_Λ= 0.750(10)

α_Ξ=-0.392(8)

ϕ_Λ=-0.113(61)

ϕ_Ξ=-0.042(16)

$$\mathbf{P}_p = \frac{(\alpha + P_\Lambda \cos\theta)\,\hat{\mathbf{z}} + \beta P_\Lambda \hat{\mathbf{x}} + \gamma P_\Lambda \hat{\mathbf{y}}}{1 + \alpha P_\Lambda \cos\theta}$$

Accesible if daughter baryon polarization measured eg in decay sequence:
$\Xi \rightarrow \Lambda\pi, \Lambda \rightarrow p\pi$

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

CP violation observables in hyperon decays

for c.c. decay modes if CP conserved: $\bar{\alpha} = -\alpha$ and $\bar{\beta} = -\beta$

CP-test : $A_{CP} := \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}$ and $B_{CP} := \frac{\beta + \bar{\beta}}{\alpha - \bar{\alpha}}$

Leading order ($|\Delta I| = {}^1/_2$):

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

$$B_{\rm CP} = \tan(\xi_P - \xi_S)\,,$$

weak *P-S* phase diff.

	$\xi_P - \xi_S$			C_B	C'_B
	$(\eta\lambda^5 A^2)$	$[10^{-4}$ rad$]$	$[10^{-2}$ rad$]$		
	SM ref *		Exp	BSM ref **	
$\Lambda \to p\pi^-$	0.2 ± 1.6	0.3 ± 2.2	4.7 ± 9.4	1.1 ± 2.2	0.4 ± 0.8
$\Xi^- \to \Lambda\pi^-$	-1.4 ± 1.2	-1.9 ± 1.6	1.2 ± 3.5	-0.5 ± 1.0	0.4 ± 0.7

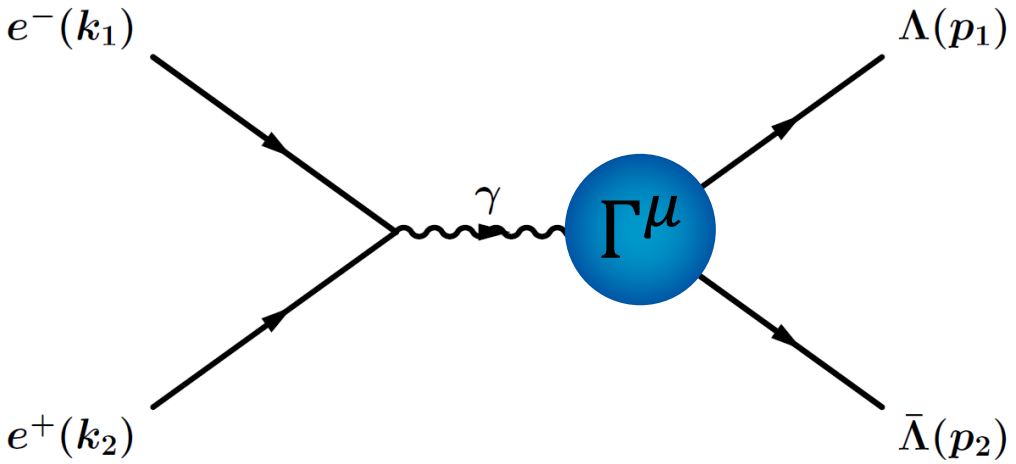
$$(\xi_P - \xi_S)_{BSM} = \frac{C'_B}{B_G}\left(\frac{\epsilon'}{\epsilon}\right)_{BSM} + \frac{C_B}{\kappa}\epsilon_{BSM}$$

$0.5 < B_G < 2$ and $0.2 < |\kappa| < 1$

* Tandean,Valencia PRD67 (2003) 056001

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

$e^+e^- \to \gamma^* \to B\bar{B}$ (spin 1/2)



$$s = (p_1 + p_2)^2$$
$$q = p_1 - p_2$$

$$\Gamma^\mu(p_1, p_2) = -ie\left[\gamma^\mu F_1(s) + i\frac{\sigma^{\mu\nu}}{2M_B}q_\nu F_2(s)\right]$$

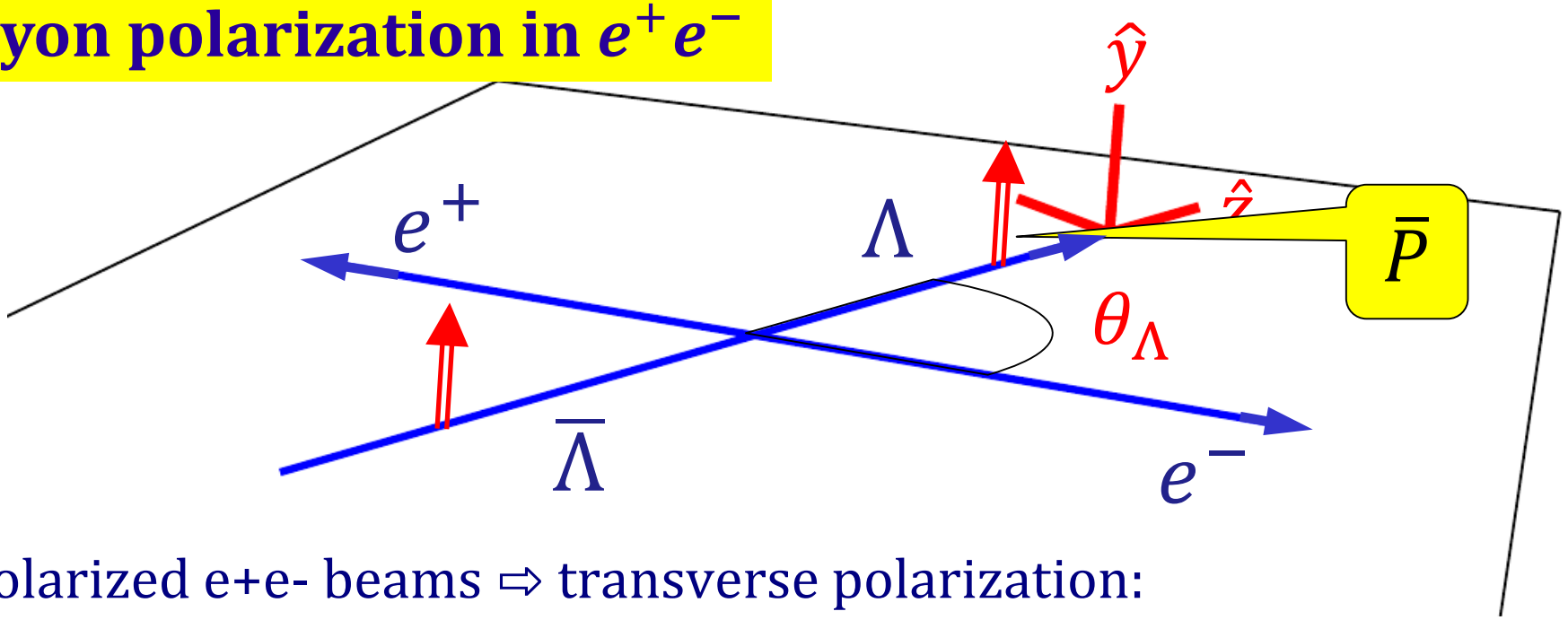
F_1 (Dirac) and F_2 (Pauli) Form Factors

Sachs Form Factors (FFs) ⇔ helicity amplitudes:

$$G_M(s) = F_1(s) + F_2(s), \quad G_E(s) = F_1(s) + \tau F_2(s)$$

helicity non-flip helicity flip

Baryon polarization in e^+e^-

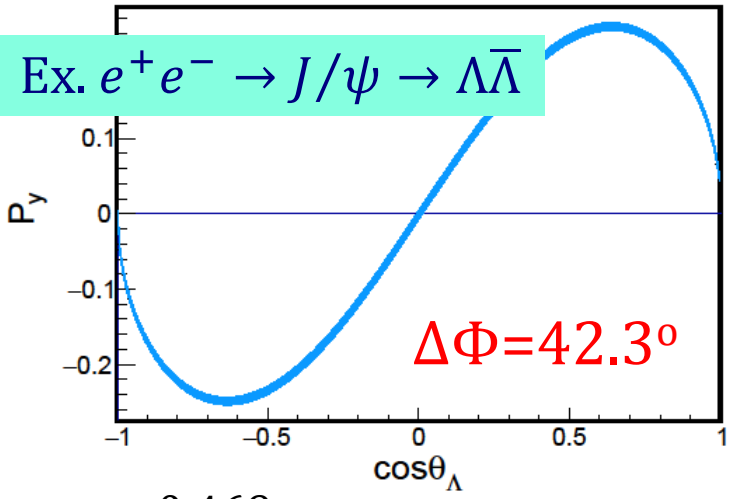


Unpolarized e+e- beams ⇨ transverse polarization:

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

$\Delta\Phi \neq 0$

Ex. $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$



$\alpha_\psi = 0.469$

Angular distribution:

$$\frac{d\Gamma}{d\Omega} \propto 1+\alpha_\psi\cos^2\theta \qquad -1 \le \alpha_\psi \le 1$$

Baryon-antibaryon spin density matrix

$$e^+e^- \to B_1\bar{B}_2$$

General two spin ½ particle state:

$$\rho_{1/2,\overline{1/2}} = \frac{1}{4}\sum_{\mu\bar{\nu}} C_{\mu\bar{\nu}}\, \sigma_\mu^{B_1} \otimes \sigma_{\bar{\nu}}^{\bar{B}_2}$$

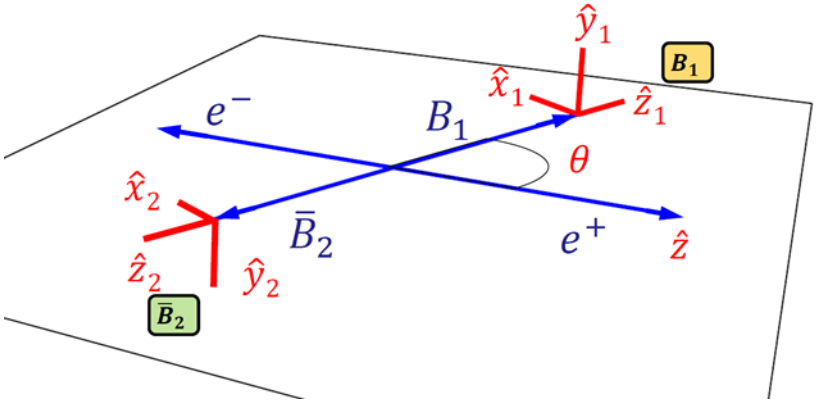
$(\sigma_0 = \mathbf{1}_2, \sigma_1 = \sigma_x, \sigma_2 = \sigma_y, \sigma_3 = \sigma_z)$

$\propto P_y$

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

$\propto C_{i\bar{j}}$

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



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

$e^+e^- \to J/\psi, \psi(2S) \to B\bar{B}$

#events at BESIII (estimate)

BESIII 10^{10} J/ψ

decay mode	$\mathcal{B}$(units 10^{-4})	α_ψ	eff ST	
$J/\psi \to \Lambda\bar{\Lambda}$	$19.43 \pm 0.03 \pm 0.33$	0.469 ± 0.026	40%	3200×10^3
$\psi(2S) \to \Lambda\bar{\Lambda}$	$3.97 \pm 0.02 \pm 0.12$	0.824 ± 0.074	40%	650×10^3
$J/\psi \to \Xi^0\bar{\Xi}^0$	11.65 ± 0.04	0.66 ± 0.03	14%	670×10^3
$\psi(2S) \to \Xi^0\bar{\Xi}^0$	2.73 ± 0.03	0.65 ± 0.09	14%	160×10^3
$J/\psi \to \Xi^-\bar{\Xi}^+$	10.40 ± 0.06	0.58 ± 0.04	19%	810×10^3
$\psi(2S) \to \Xi^-\bar{\Xi}^+$	2.78 ± 0.05	0.91 ± 0.13	19%	210×10^3

$\mathcal{B}(J/\psi \to p\bar{p}) = (21.21 \pm 0.29) \times 10^{-4}$

PRD 93, 072003 (2016)
PLB770,217 (2017)

PRD 95, 052003 (2017)

BESIII

Exclusive (Double Tag - DT)

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

$\Lambda \to p\pi^-$: $\hat{\mathbf{n}}_1 \to (\cos\theta_1, \phi_1)$: $\boldsymbol{\alpha_\Lambda}$ $\quad$ $\bar{\Lambda} \to \bar{p}\pi^+$: $\hat{\mathbf{n}}_2 \to (\cos\theta_2, \phi_2)$: $\bar{\boldsymbol{\alpha}}_\Lambda$

$\xi : (\cos\theta_\Lambda, \hat{\mathbf{n}}_1, \hat{\mathbf{n}}_2)$ 5D PhSp

$$d\Gamma \propto W(\xi; \alpha_\psi, \Delta\Phi, \alpha_\Lambda, \bar{\alpha}_\Lambda) = 1 + \alpha_\psi \cos^2\theta_\Lambda$$ Cross section

$$+\alpha_\Lambda\bar{\alpha}_\Lambda \sum_{i,\bar{j}=1}^{3} C_{i\bar{j}}\, n_{1,z} n_{2,z}$$ Spin correlations

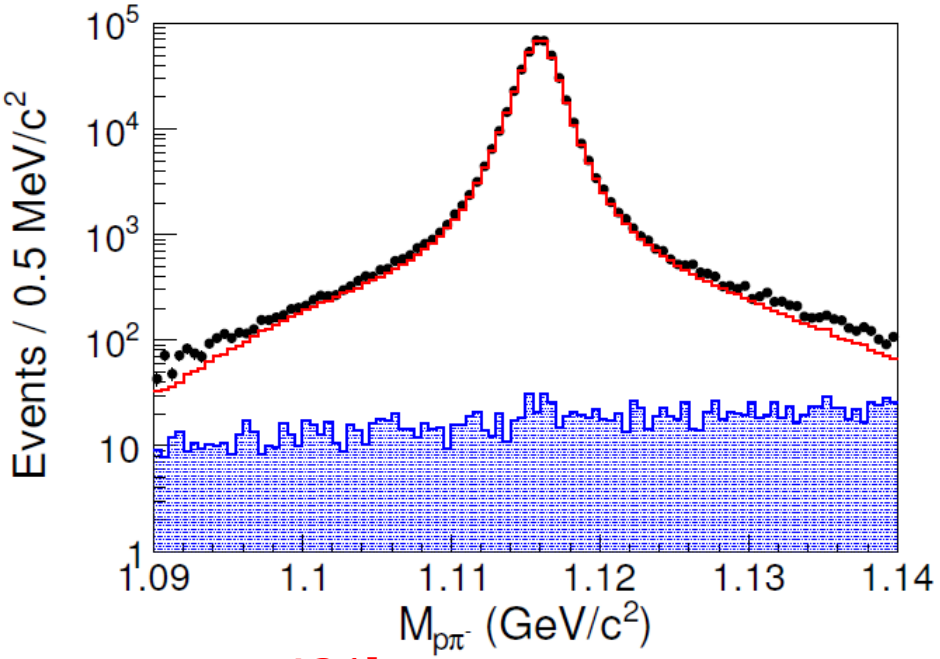
$$+(\alpha_\Lambda n_{1,y} - \bar{\alpha}_\Lambda n_{2,y}) P_y$$ Polarization

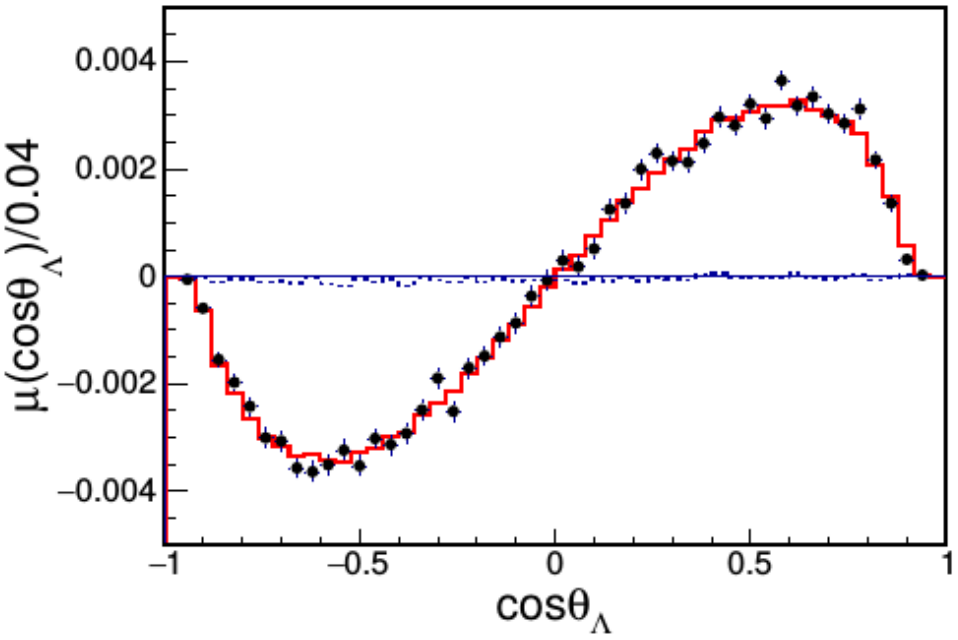
Modular angular distribution:

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

Fäldt, Kupsc PLB772 (2017) 16

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





421k events

399 background

based on 1.31×10^9 J/ψ

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

4 fit parameters

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

BESIII Nature Phys. 15 (2019) 631

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

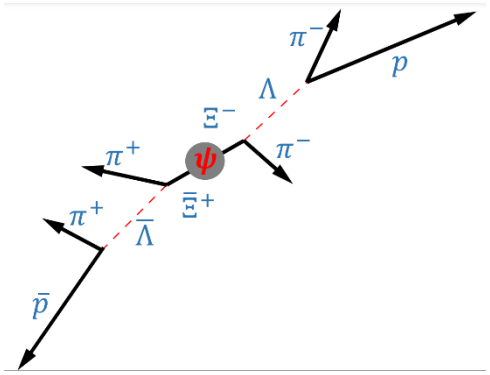
$d\Gamma \propto W(\xi;\omega)$ ξ **9 kinematical variables, 9D PhSp**

Parameters: 2 production + 6 for decay chains

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

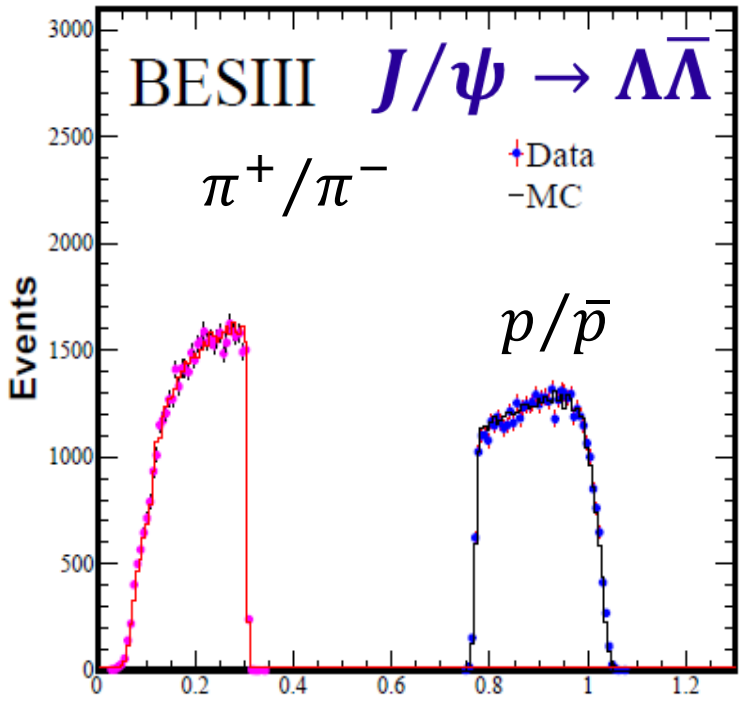
Modular angular distribution:

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



E.Perotti, G.Faldt, AK, S.Leupold,JJ.Song PRD99 (2019)056008
P.Adlarson, AK PRD100 (2019) 114005

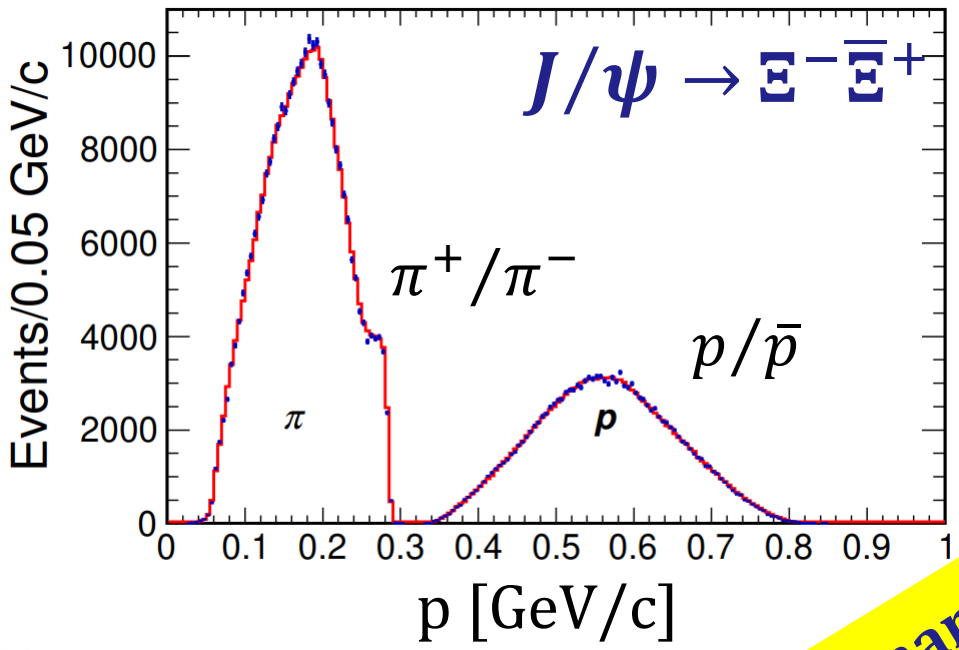
Exclusive (DT) analyses based on 1.31×10^9 J/ψ



421k events

399 bkg

5D PhSp



73k events

190 bkg

9D PhSp

Preliminary

Unbinned MLL fit

4 parameters

8 parameters

Nature Phys. 15 (2019) 631

arXiv:2105.11155

BESIII

Preliminary

		Previous result	
α_ψ	$0.586 \pm 0.012 \pm 0.010$	$0.58 \pm 0.04 \pm 0.08$	[39]
$\Delta\Phi$	$1.213 \pm 0.046 \pm 0.016$ 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	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$	[4]
$\overline{\alpha}_\Lambda$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$	[4]
$\xi_P - \xi_S$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ 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	[3]
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		

8 fit parameters

3 CP tests

arXiv:2105.11155

Conclusions

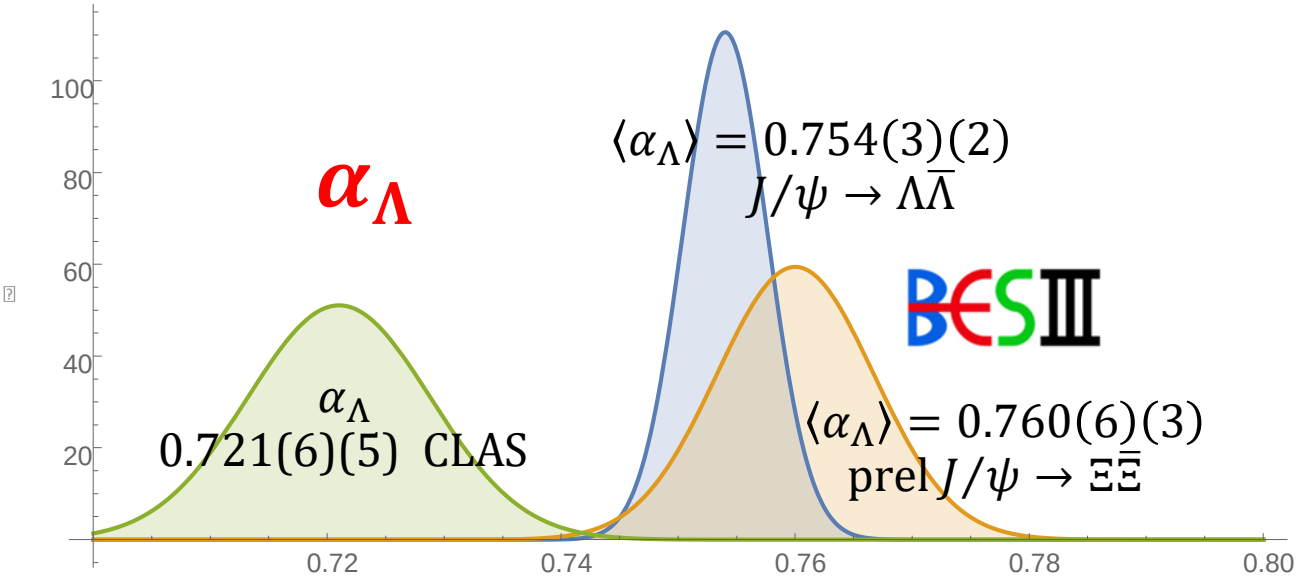
J/ψ and ψ' decays into hyperon-antihyperon unique spin entangled system:

- determination of (anti-)hyperon decay parameters
- CP tests
- polarization observed for $J/\psi,(\psi') \rightarrow \Lambda\bar{\Lambda}, \Sigma^+\bar{\Sigma}^-, \Xi^-\bar{\Xi}^+, \Omega^-\bar{\Omega}^+$

Results using:
1.3×10^9 J/ψ
4.5×10^8 ψ(2S)

BESIII

More data: 10^{10} J/ψ
$3\text{x}10^9$ ψ(2S)



$J/\psi \rightarrow \Xi\bar{\Xi}$ (prel.)

$\langle\alpha_\Xi\rangle = 0.373(5)(2)$

three independent CP tests

first direct measurement of weak phase difference: $(\xi_P - \xi_S)$

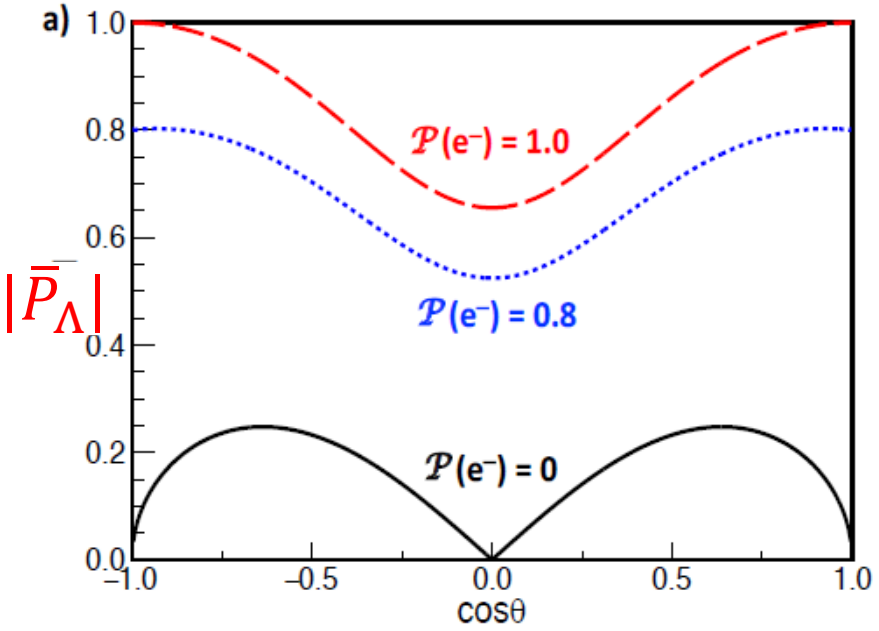
Outlook I:Polarized e^- beam

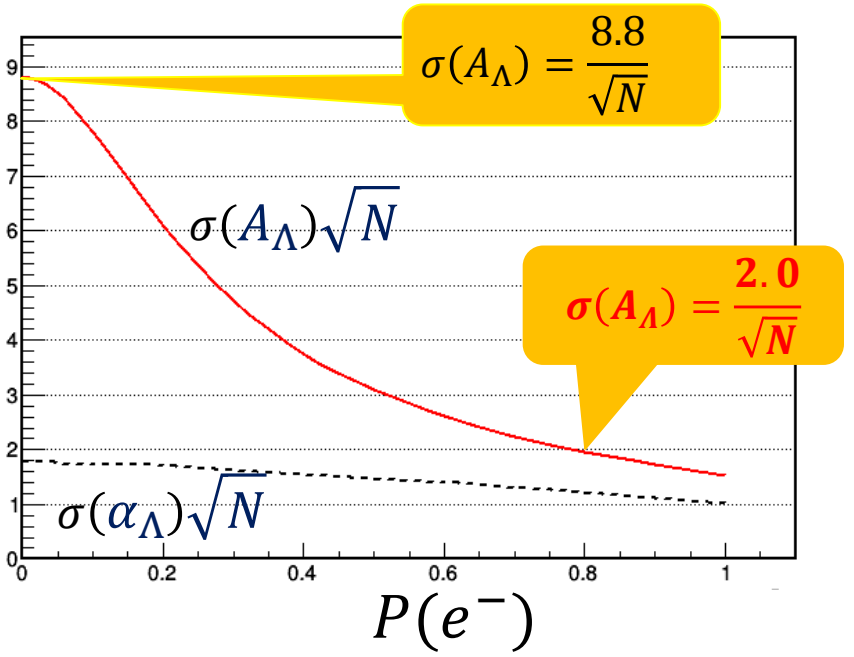
$$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$$

+ 80% longitudinal e^- polarization

$\bar{P}_\Lambda$

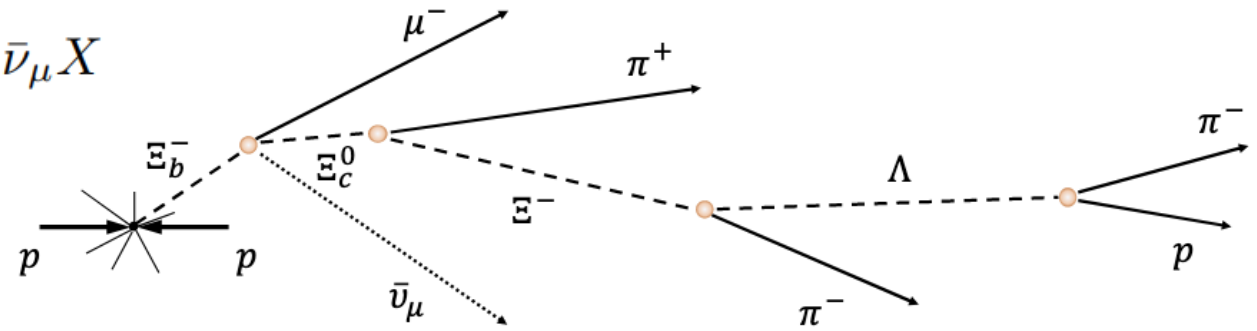
$$C_{\mu\bar{\nu}} = \begin{pmatrix} 1+\alpha_\psi\cos^2\theta & \gamma_\psi P_z \sin\theta & \beta_\psi \sin\theta\cos\theta & (1+\alpha_\psi)P_z\cos\theta \\ \gamma_\psi P_z \sin\theta & \sin^2\theta & 0 & \gamma_\psi \sin\theta\cos\theta \\ -\beta_\psi \sin\theta\cos\theta & 0 & \alpha_\psi \sin^2\theta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





Outlook II: Sequential decays of charmed baryons at LHCb

$\Xi_b^- \to \Xi_c^0 \mu^- \bar{\nu}_\mu X$

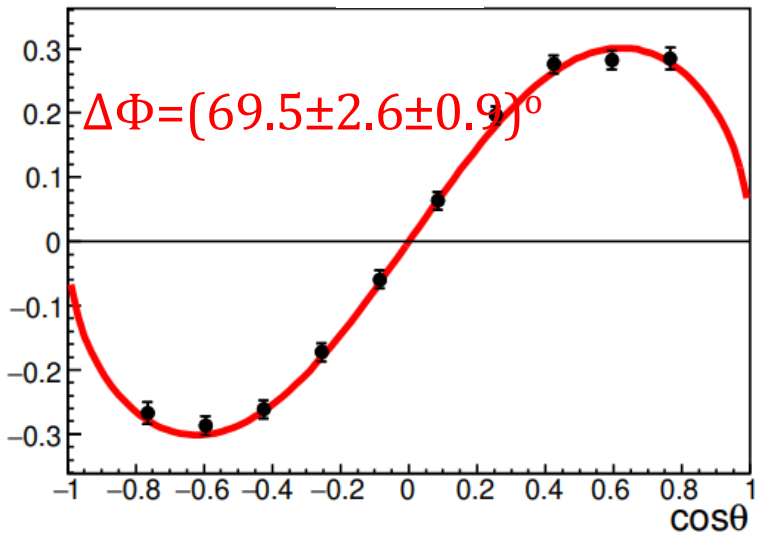


1. $\Xi_c^0 \to \Xi^-\pi^+ \to \Lambda\pi^-\pi^+ \to p\pi^-\pi^-\pi^+$ (Cabibbo favoured)
2. $\Xi_c^0 \to \Xi^-K^+ \to \Lambda\pi^-K^+ \to p\pi^-\pi^-K^+$ (Cabibbo suppressed)
3. $\Omega_c \to \Omega^-\pi^+ \to \Lambda K^-\pi^+ \to p\pi^-K^-\pi^+$ (Cabibbo favoured)
4. $\Omega_c \to \Xi^-\pi^+ \to \Lambda\pi^-\pi^+ \to p\pi^-\pi^-\pi^+$ (Cabibbo suppressed)
5. $\Omega_c \to \Xi^-K^+ \to \Lambda\pi^-K^+ \to p\pi^-\pi^-K^+$ (doubly Cabibbo suppressed)

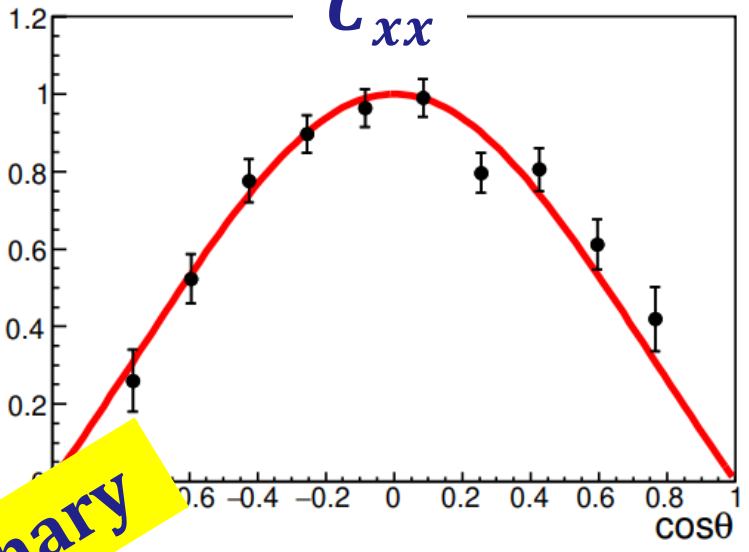
Precision values of hyperon decay parameters fixed from our BESIII measurements.

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

P_y

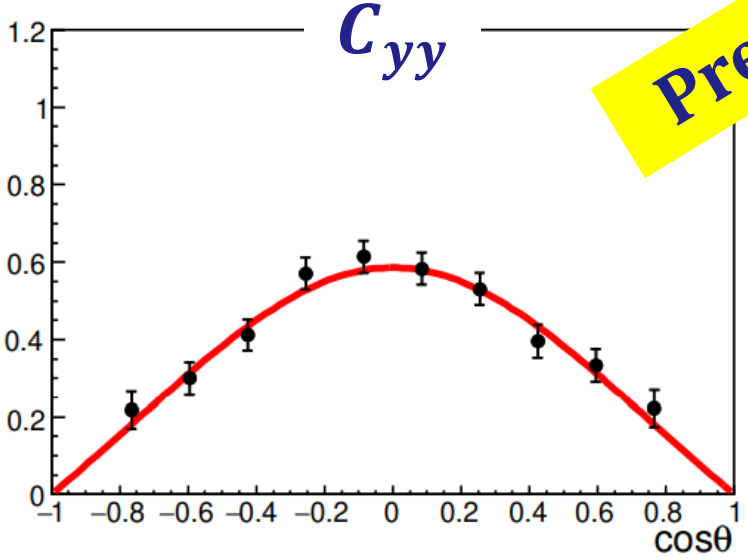


C_{xx}

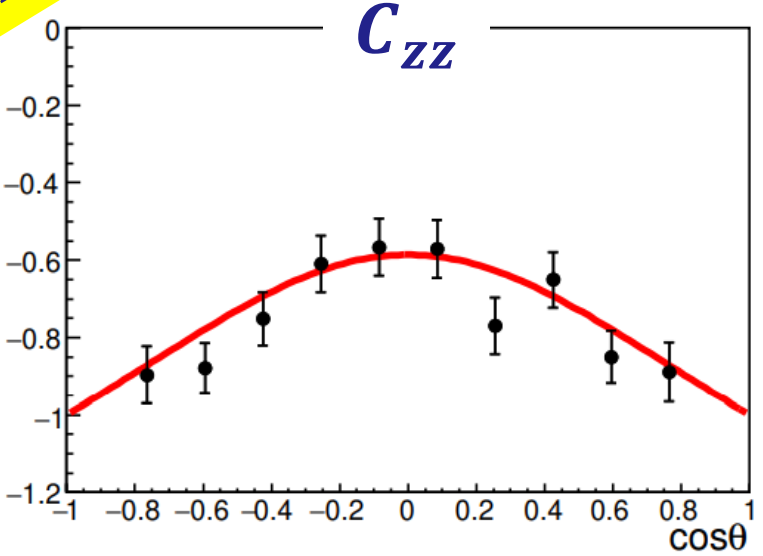


Preliminary

C_{yy}



C_{zz}



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