



UPPSALA
UNIVERSITET



Hyperon decay studies

Nora Salone, Patrik Adlarson, Varvara Batozskaya,
Andrzej Kupsc, Stefan Leupold, Jusak Tandean

arXiv:2203.03035

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

BESIII $J/\psi \rightarrow \Xi \bar{\Xi}$

Nature Phys. 15 (2019) 631
arXiv:2204.11058

arXiv:2105.11155

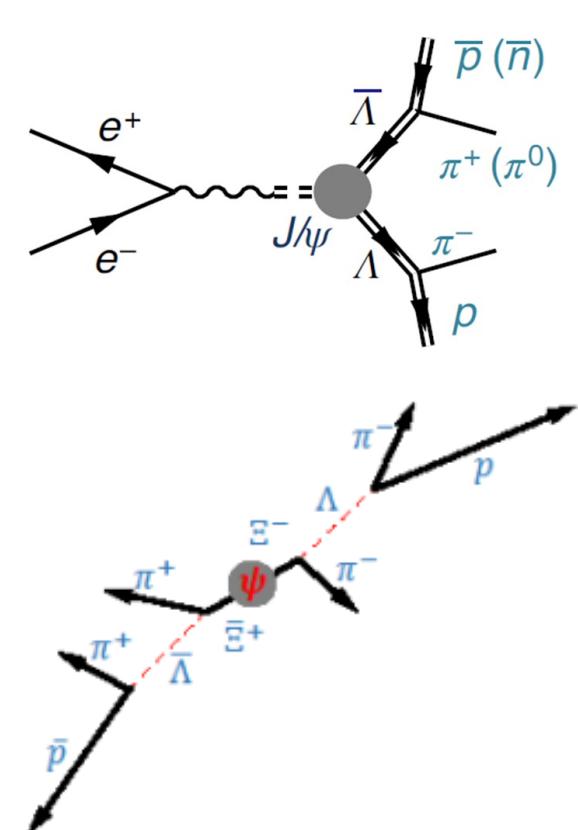
Hyperon non-leptonic decays
Determination of hyperon decay parameters
CP tests

Methods:

Phys. Rev. D 100 (2019) 114005

Phys. Lett. B 772 (2017) 16

Phys. Rev. D 99 (2019) 056008



Strategies for new physics searches

(CP) asymmetries [vs Rare decays]

$$\sigma(A) \approx \frac{\mathcal{O}(1)}{\sqrt{N}} \equiv \frac{\sigma_c}{\sqrt{N}}$$

$\sigma(A) \sim 10^{-4}$ requires $N \sim 10^8$

Goal: optimize (minimize!) σ_c eg 4 \downarrow 1 reduction implies 16 \times less data needed

CP violation in nonleptonic hyperon decays

Polarization vs spin correlations

Experiments:

BESIII super tau-charm factory (elegant method)

HyperCP LHCb (robust, sustainable)

Decay amplitudes in hyperon decays

$K \rightarrow \pi\pi$ interference $|\Delta I| = 1/2$ and $3/2$

Hyperons:

$$\Lambda \rightarrow p\pi^-$$

$$\Xi^- \rightarrow \Lambda\pi^-$$

P and S amplitudes

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

weak CP-odd phases

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

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

$$|\Delta I| = 1/2$$

strong phases

Measurable: BF and two decay parameters

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

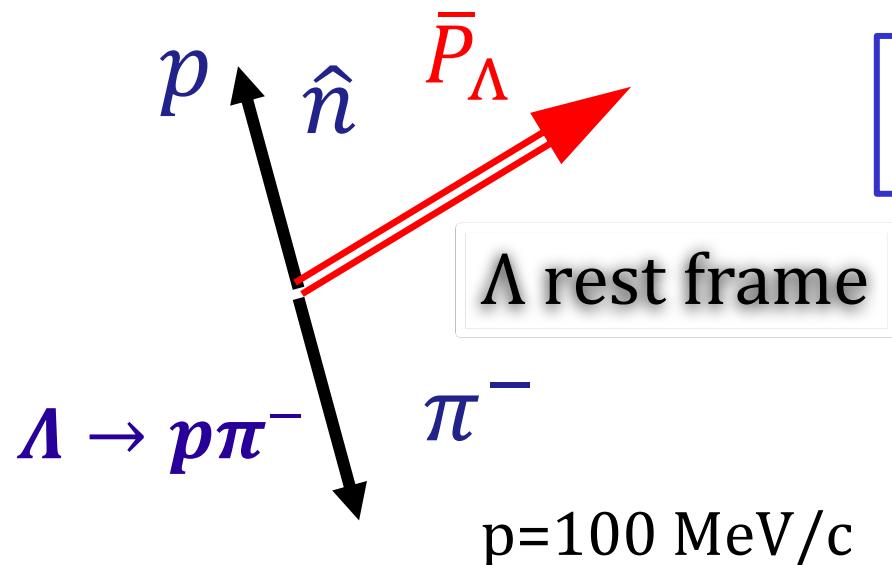
$$\beta = \frac{2\operatorname{Im}(S^* P)}{|P|^2 + |S|^2}$$

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

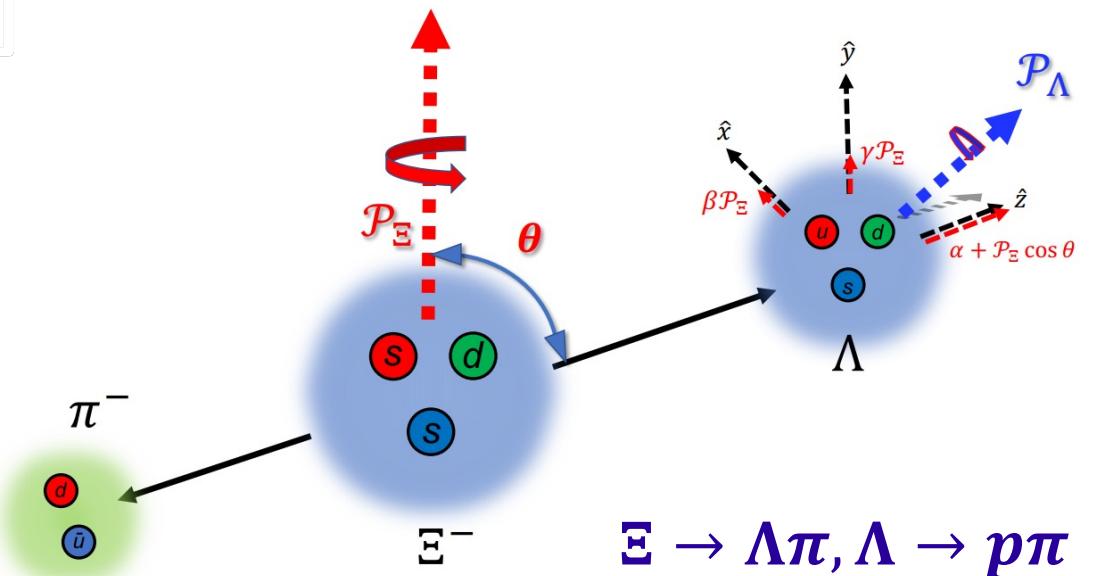
$$\gamma = \sqrt{1 - \alpha^2} \cos \phi$$

For $\Lambda \rightarrow p\pi^-$ $|\Delta I| = 3/2$ contribution $\sim 5\%$

Measuring hyperon decay parameters



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



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

Testing CP violation in hyperon decays

Compare the two decay parameters for c.c. decay modes:

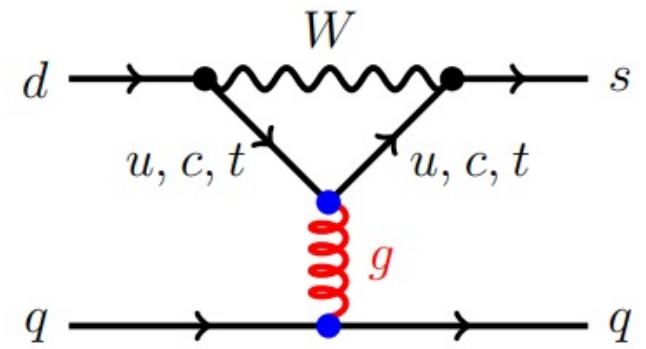
$$A_{CP} = - \tan(\xi_P - \xi_S) \frac{\beta}{\alpha}$$

$$= - \tan(\xi_P - \xi_S) \tan(\delta_P - \delta_S)$$

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

weak P-S phase diff.

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



	$\xi_P - \xi_S$ $(\eta \lambda^5 A^2)$	C_B	C'_B
	SM	BSM	
$\Lambda \rightarrow p \pi^-$	-0.1 ± 1.5	-0.2 ± 2.2	0.9 ± 1.8
$\Xi^- \rightarrow \Lambda \pi^-$	-1.5 ± 1.2	-2.1 ± 1.7	-0.5 ± 1.0

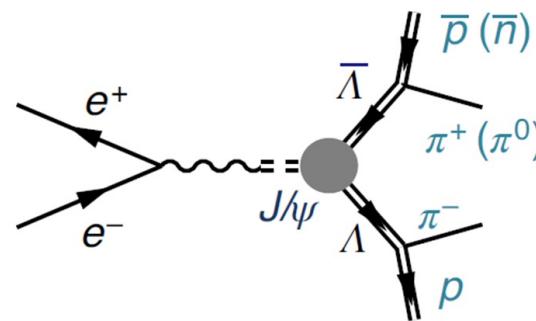
$$(\xi_P - \xi_S)_{BSM} = \frac{C'_B}{B_G} \left(\frac{\epsilon'}{\epsilon} \right)_{BSM} + \frac{C_B}{\kappa} \epsilon_{BSM}$$

Kaon bounds for CPV in hyperon decays assuming chromomagnetic penguin

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

#events at BESIII (estimate)

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



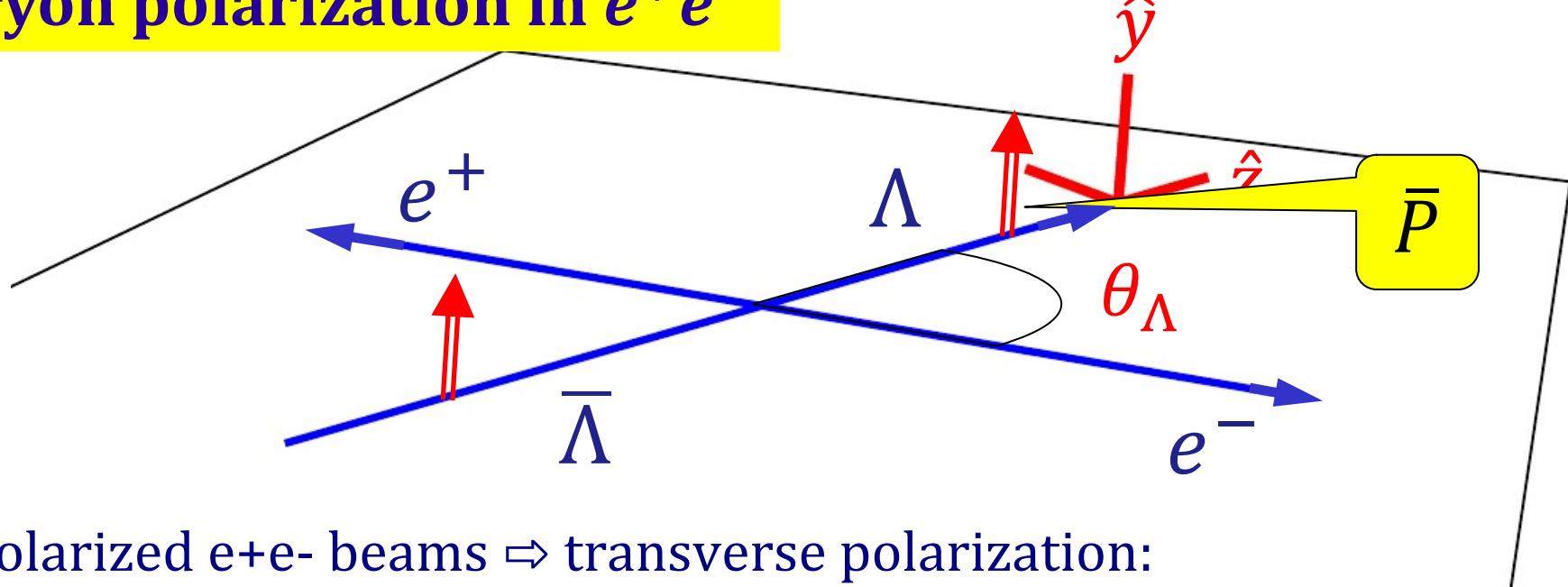
PRD 93, 072003 (2016)

PLB770,217 (2017)

PRD 95, 052003 (2017)

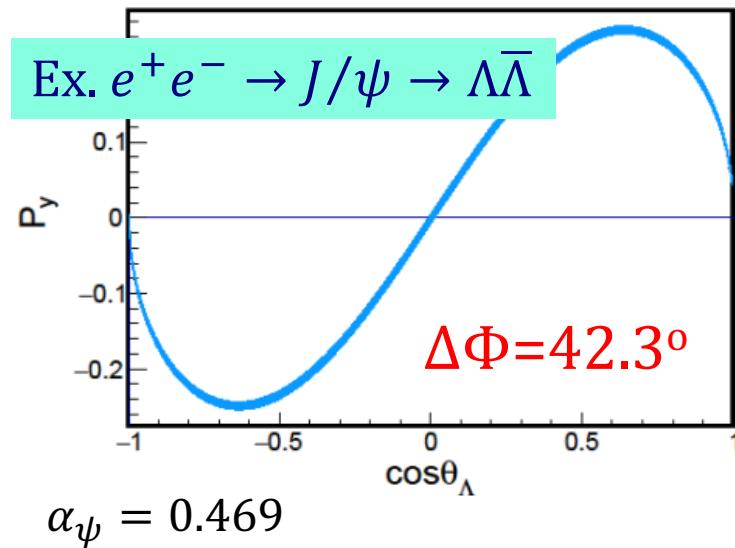
BESIII proposal: $3.2 \times 10^9 \psi(2S)$

Baryon polarization in e^+e^-



Unpolarized e^+e^- beams \Rightarrow transverse polarization:

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



$$\Delta\Phi \neq 0$$

Angular distribution:

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

$$-1 \leq \alpha_\psi \leq 1$$

DT - joint angular distribution (modular form)

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

General two spin 1/2 particle state: $\rho_{1/2,1/2} = \frac{1}{4} \sum_{\mu\bar{\nu}} C_{\mu\bar{\nu}} \sigma_\mu^\Lambda \otimes \sigma_{\bar{\nu}}^{\bar{\Lambda}}$

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

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

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

Apply decay matrices:

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

The angular distribution:

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

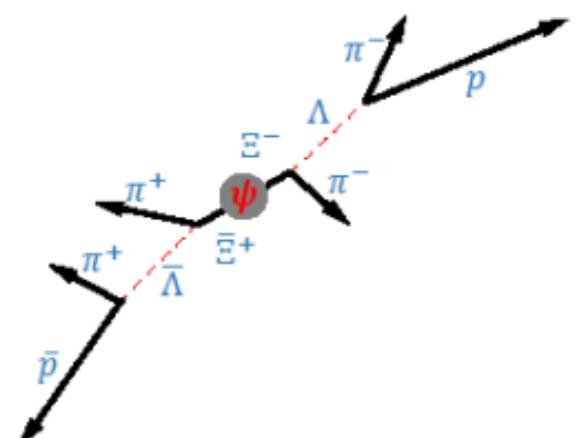
$$e^+ e^- \rightarrow J/\psi \rightarrow \Xi^- \bar{\Xi}^+ \rightarrow \Lambda \pi^- \bar{\Lambda} \pi^+ \rightarrow p \pi^- \pi^- \bar{p} \pi^+ \pi^+$$

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

Parameters: 2 production + 6 for decay chains

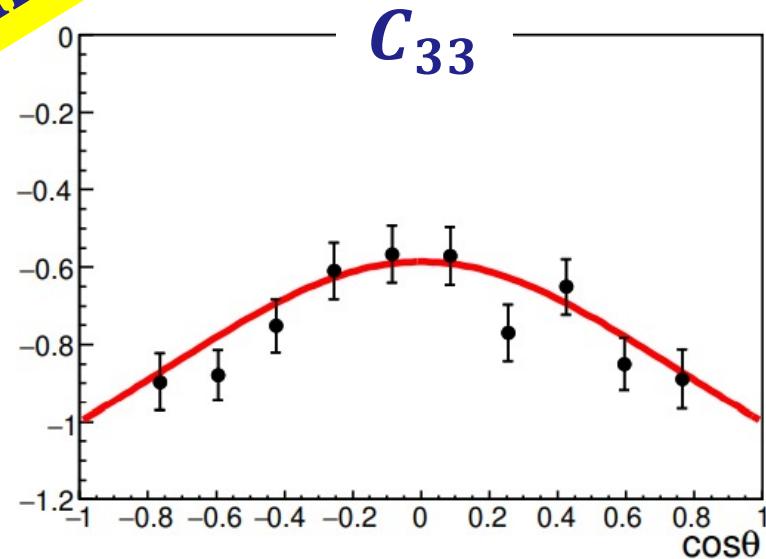
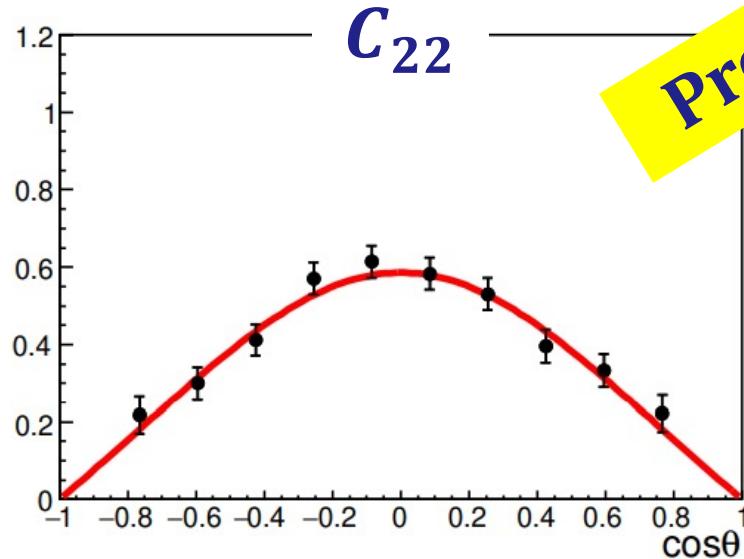
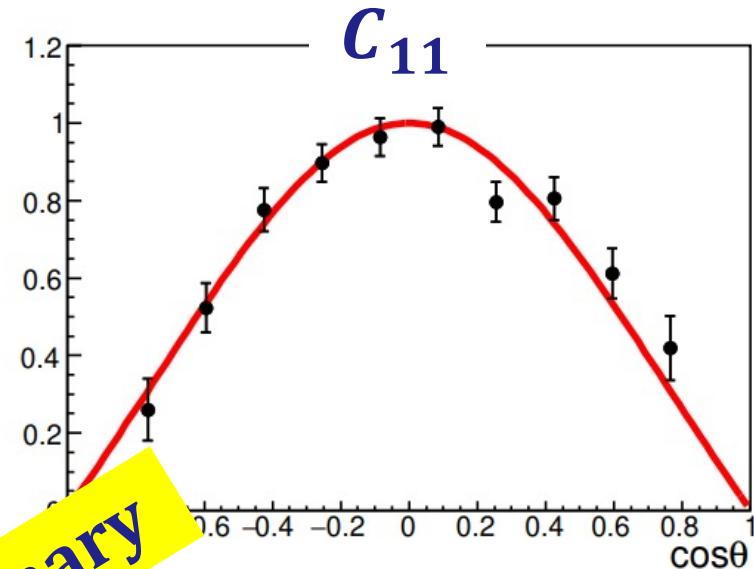
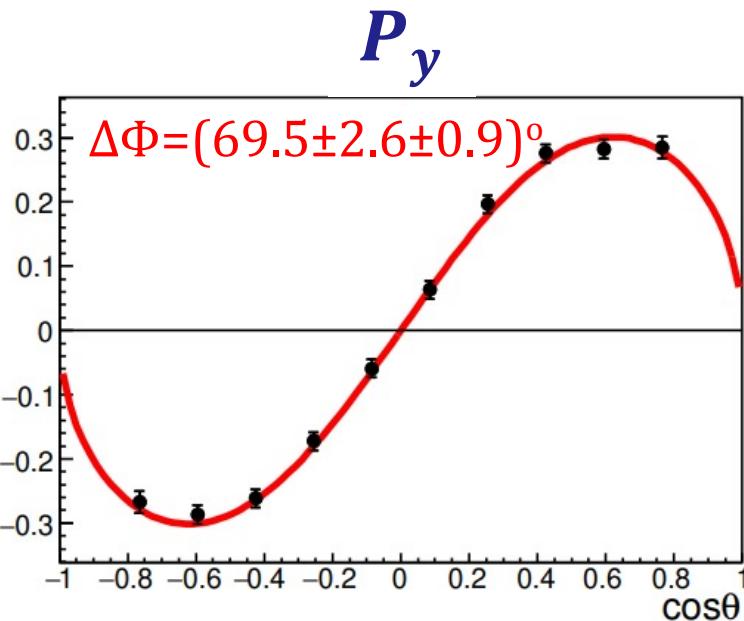
$$\omega = (\alpha_\psi, \Delta\Phi, \alpha_\Xi, \phi_\Xi, \alpha_\Lambda, \bar{\alpha}_\Xi, \bar{\phi}_\Xi, \bar{\alpha}_\Lambda)$$

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

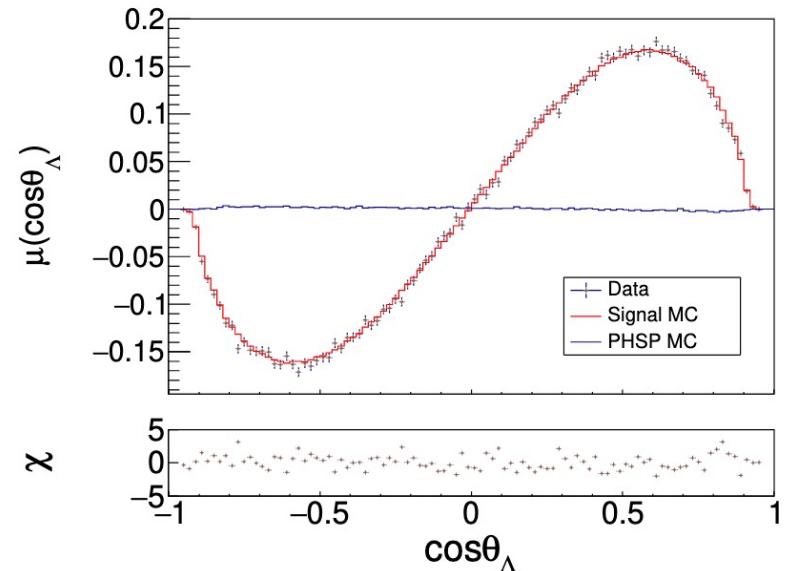
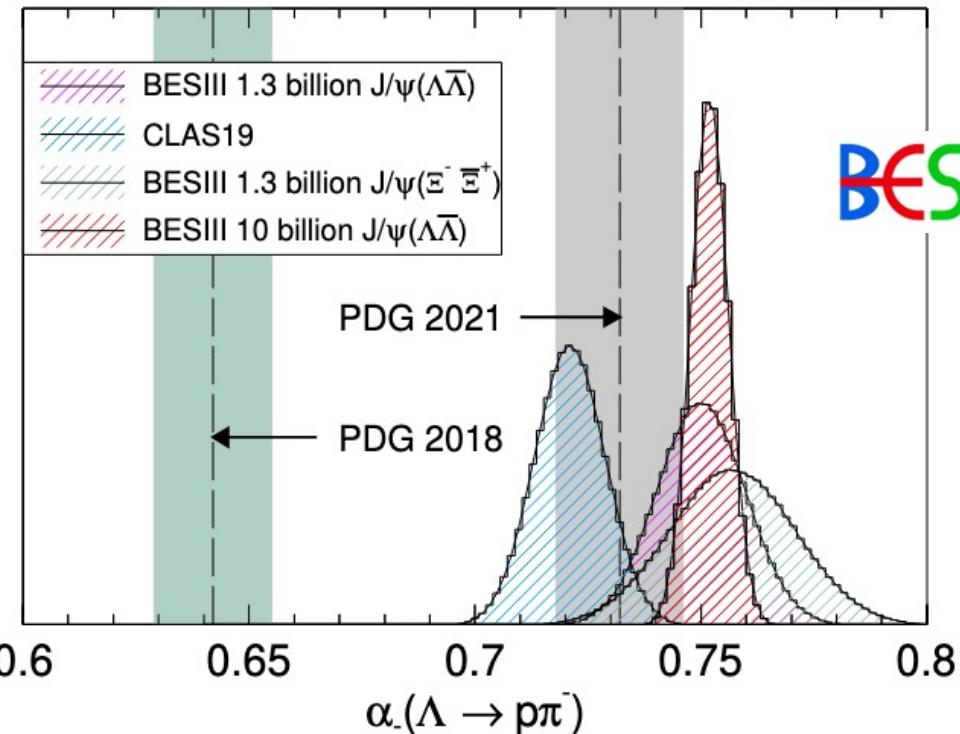


Polarization and C_{ii} for $e^+e^- \rightarrow J/\psi \rightarrow \Xi^-\bar{\Xi}^+$

BESIII



Preliminary



arXiv:2204.11058

	$\sigma(A_{CP}^{[\Lambda p]})$	$\sigma(A_{CP}^{[\Xi^-]})$	$\sigma(B_{CP}^{[\Xi^-]})$	Comment
BESIII	1.0×10^{-2} ^a	1.3×10^{-2}	3.5×10^{-2}	$1.3 \times 10^9 J/\psi$ [28, 29]
BESIII	3.6×10^{-3}	4.8×10^{-3}	1.3×10^{-2}	$1.0 \times 10^{10} J/\psi$ (projection)
SCTF	2.0×10^{-4}	2.6×10^{-4}	6.8×10^{-4}	$3.4 \times 10^{12} J/\psi$ (projection)

$$\Phi_\Xi = \frac{\phi_\Xi + \bar{\phi}_\Xi}{2} = \frac{\alpha_\Xi}{\sqrt{1 - \alpha_\Xi^2}} \cos \phi_\Xi B_{CP}^\Xi$$

Polarized e^- beam

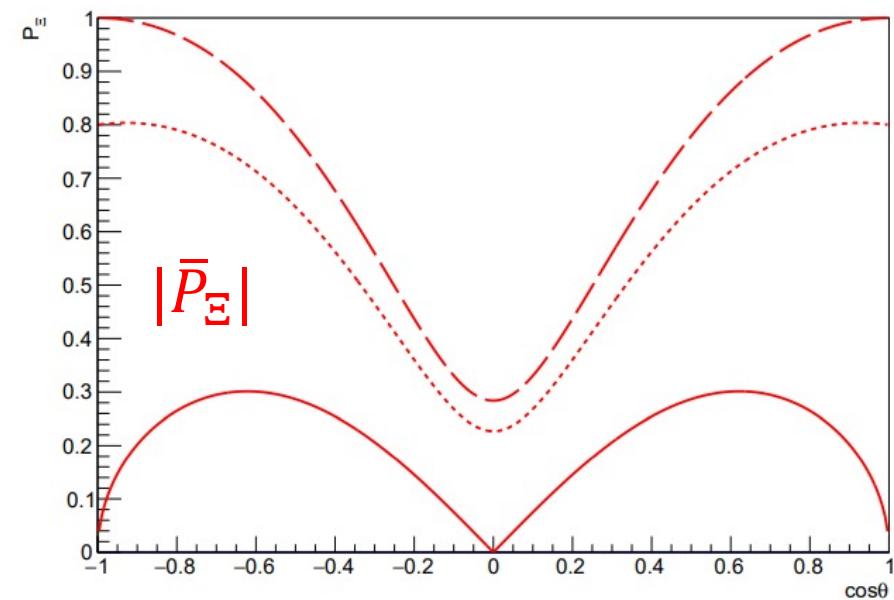
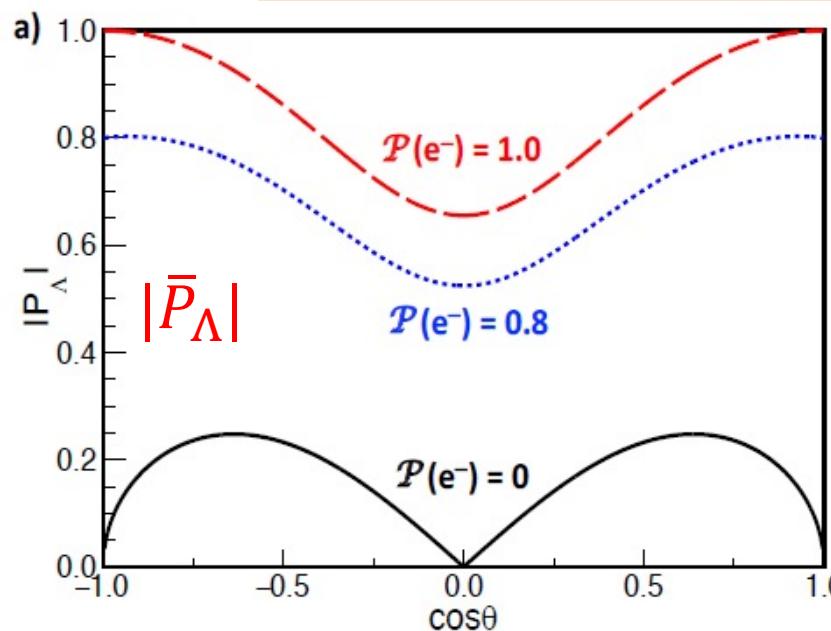
$$e^+ e^- \rightarrow J/\psi \rightarrow \Lambda \bar{\Lambda}, \Xi \bar{\Xi}$$

+ 80% longitudinal e^- polarization Bondar et al. JHEP 03 (2020) 076

$$\langle \mathbb{P}_{\Xi}^2 \rangle \quad \bar{P}_{\Lambda, \Xi}$$

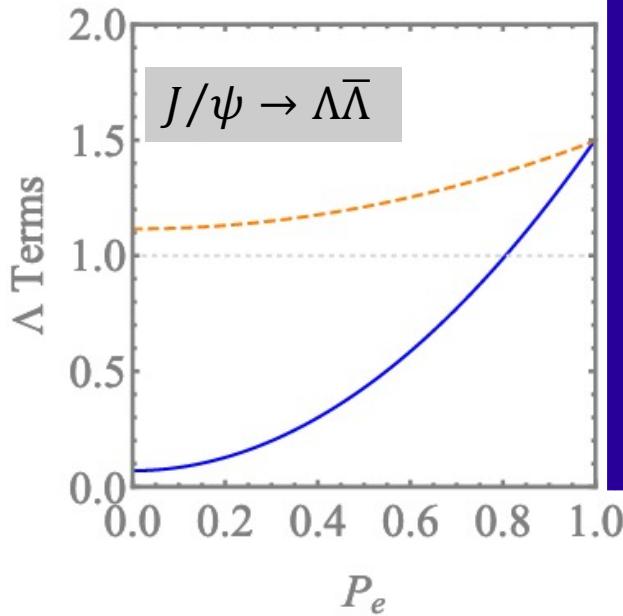
arXiv:2203.03035

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



Information \equiv (covariance matrix) $^{-1}$

$$I(A_\Lambda) = N \frac{1}{3} \alpha_\Lambda^2 \langle \mathbb{P}_\Xi^2 \rangle$$

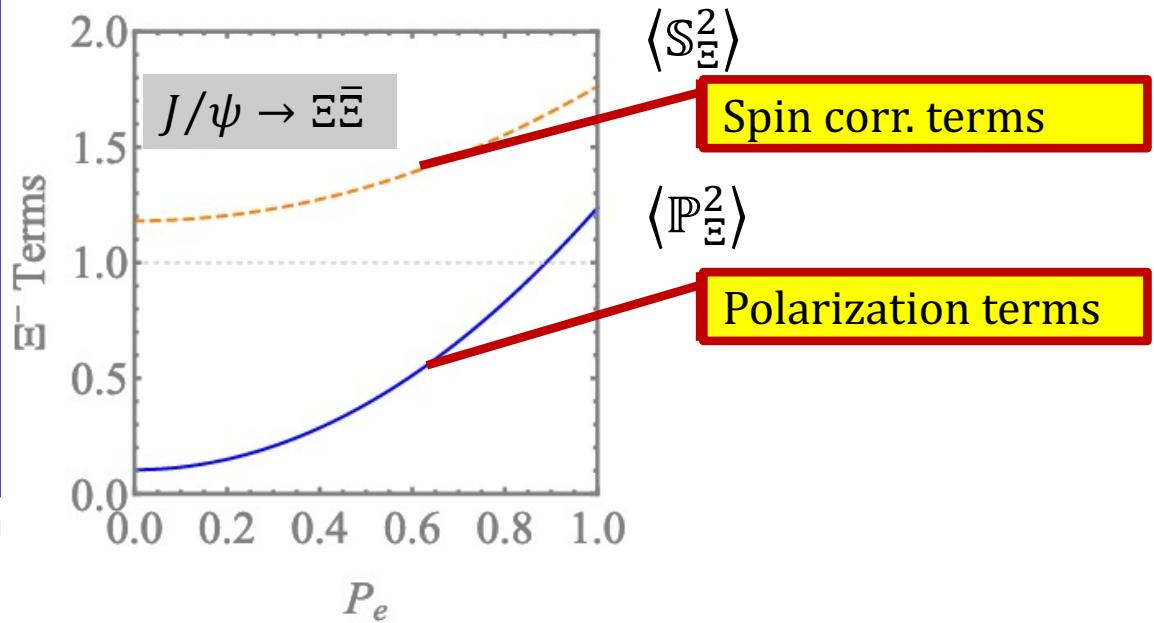


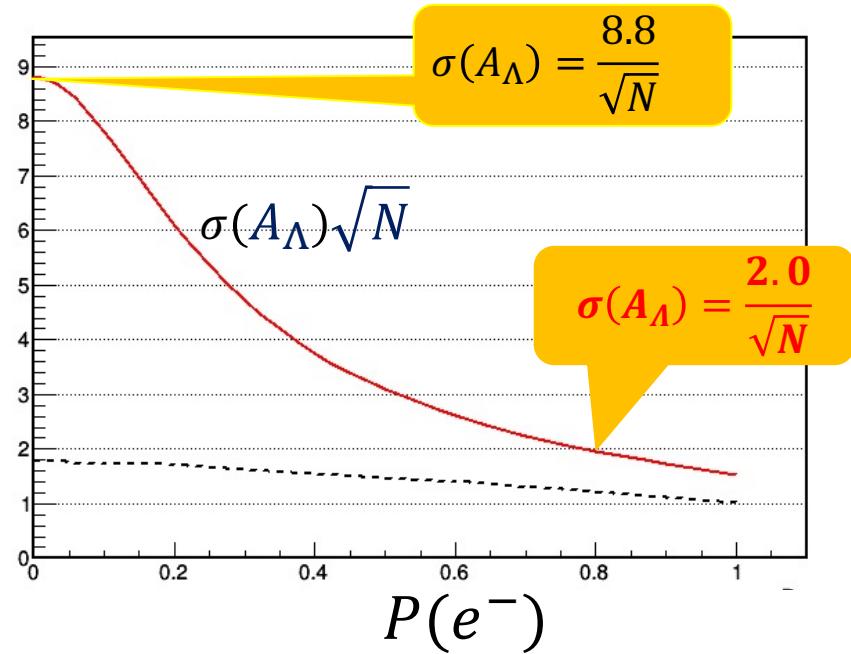
$$I(\Phi_\Xi) = N \frac{2}{27} (1 - \alpha_\Xi^2) \alpha_\Lambda^2 [3.08 \langle \mathbb{P}_\Xi^2 \rangle + 1.30 \langle \mathbb{S}_\Xi^2 \rangle]$$

$$I(A_\Xi) = N \frac{2}{3} \alpha_\Xi^2 \alpha_\Lambda^2 (1 + 1.05 \langle \mathbb{P}_\Xi^2 \rangle + 0.38 \langle \mathbb{S}_\Xi^2 \rangle)$$

$$I(A_\Lambda) = N \frac{2}{3} \alpha_\Xi^2 \alpha_\Lambda^2 (1 + 3.28 \langle \mathbb{P}_\Xi^2 \rangle + 0.30 \langle \mathbb{S}_\Xi^2 \rangle)$$

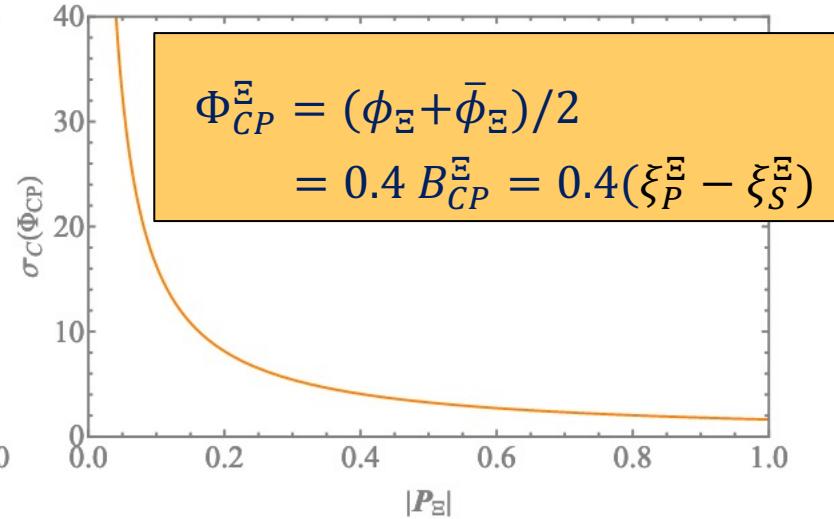
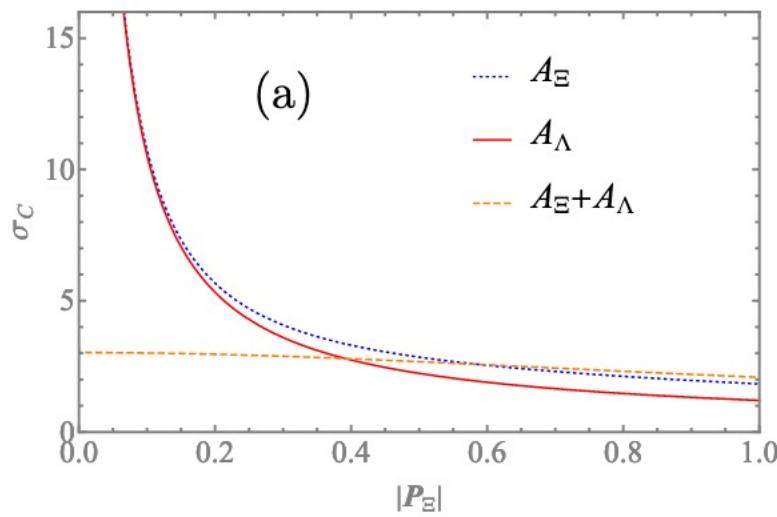
$$I(A_\Xi, A_\Lambda) = N \frac{2}{3} \alpha_\Xi^2 \alpha_\Lambda^2 (1 - \frac{1}{3} \langle \mathbb{P}_\Xi^2 \rangle - \frac{1}{3} \langle \mathbb{S}_\Xi^2 \rangle)$$





Electron beam polarization 80%
Equiv. to $\times 16$ more $J/\psi \rightarrow \Lambda\bar{\Lambda}$ data for A_{CP}^Λ

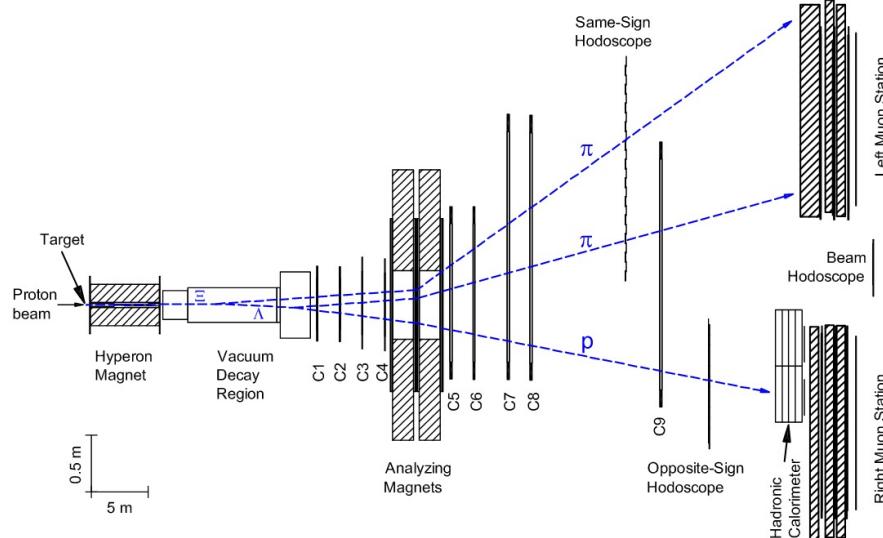
$$\Xi^- \rightarrow \Lambda\pi^- \rightarrow p\pi^-\pi^- + \text{C.C}$$



$$A_\Xi + A_\Lambda = (0.0 \pm 5.1 \pm 4.4) \times 10^{-4}$$

HyperCP PRL 93 (2004) 262001

$$1.2 \times 10^8 \Xi^- \quad \textcolor{red}{4.1 \times 10^7 \Xi^+}$$



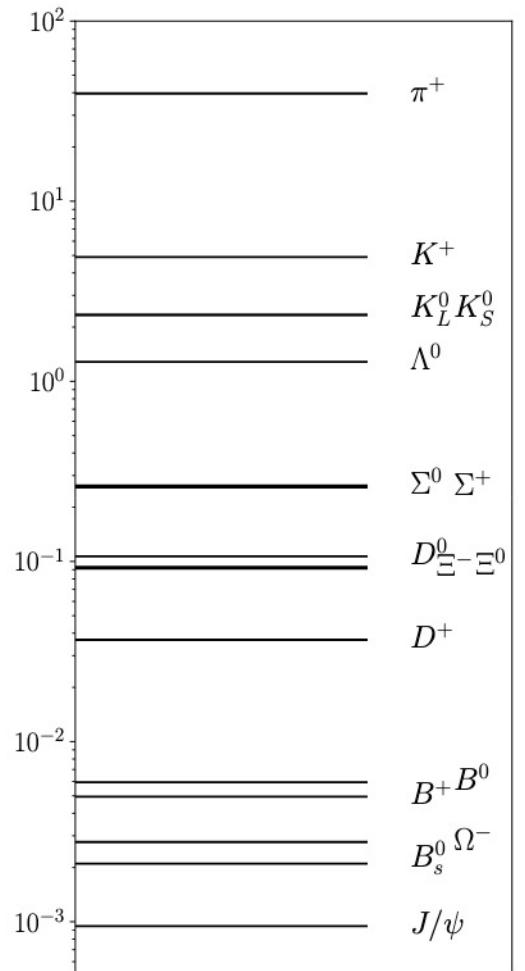
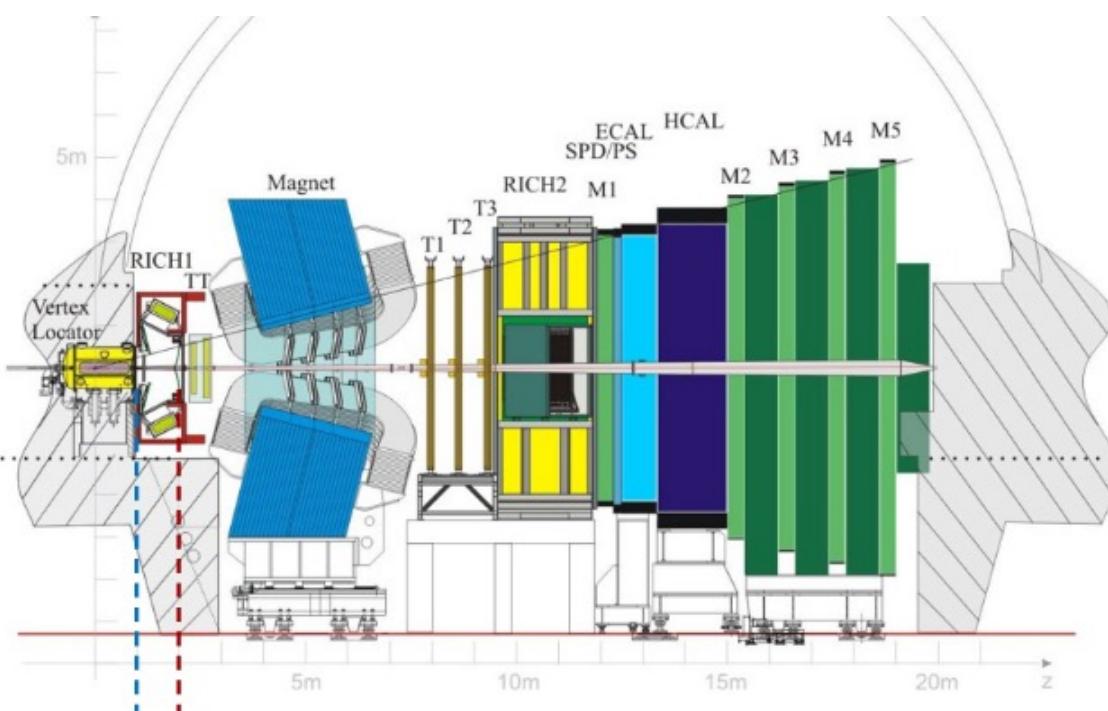
Ξ^- Polarization (3.7%)

HyperCP → LHCb?

$$\Xi^- \rightarrow \Lambda\pi^- \rightarrow p\pi^-\pi^- + \text{c.c}$$

$\Xi^-(\Xi^+)$ Polarization (60%)
simultaneous data
nearly symmetric acceptance

LHCb



#particles per pp interaction
($\sqrt{s} = 13$ TeV at LHCb)

Conclusions:

- J/ψ and ψ' decays into hyperon-antihyperon: unique spin entangled system for CP tests and for determination of (anti-)hyperon decay parameters
- Polarization observed for $J/\psi, (\psi') \rightarrow \Lambda\bar{\Lambda}, \Sigma^+\bar{\Sigma}^-, \Xi^-\bar{\Xi}^+, \Omega^-\bar{\Omega}^+$

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

$$\langle \alpha_{\Xi} \rangle = 0.373(5)(2) \text{ prel } J/\psi \rightarrow \Xi\bar{\Xi}$$

three independent CP tests

measurement of ϕ_{Ξ}

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

BESIII : $10^{10} J/\psi$

SCTF: $2 \times 10^{12} J/\psi$

+ polarization spin correlations

$$A_{CP}^{\Lambda} = 0.12 (\xi_P^{\Lambda} - \xi_S^{\Lambda})$$

$$A_{CP}^{\Xi} = ?? (\xi_P^{\Xi} - \xi_S^{\Xi})$$

$$\Phi_{CP}^{\Xi} = 0.40 (\xi_P^{\Xi} - \xi_S^{\Xi})$$

Improved **HyperCP** measurement at LHCb?