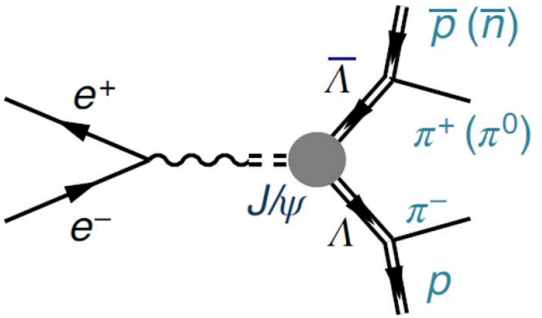
UPPSALA UNIVERSITET

Precision (hyperon) physics at high luminosity (HL) J/ψ factory

Andrzej Kupsc, Hai-Bo Li, and Stephen Lars Olsen

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



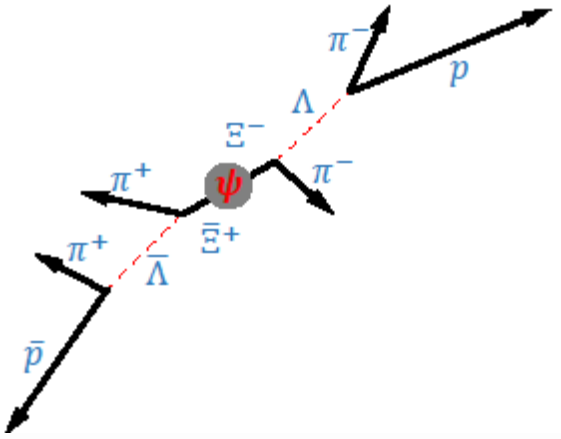
- Experiment at BESIII

nature physics
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*

Nature Phys. 15 (2019) 631



- Prospects at HL J/ψ Factory: polarization, energy compensation
- Bonus: η' super factory …

CP violation in hyperon decays

$\Lambda \rightarrow p\pi^-$

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

VOLUME 55, NUMBER 2 PHYSICAL REVIEW LETTERS 8 JULY 1985

Signals of *CP* Nonconservation in Hyperon Decay

John F. Donoghue
Department of Physics, University of Massachusetts, Amherst, Massachusetts 01002
and
Sandip Pakvasa
Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 96822
(Received 2 May 1985)

$$\mathcal{A}(\Xi^- \rightarrow \Lambda\pi^-) = A_S + A_P \boldsymbol{\sigma}\cdot\hat{\mathbf{q}}$$

S and P transitions

strong phases

$$\mathcal{A}(\Xi^- \rightarrow \Lambda\pi^-) = S\exp(i\delta_s) + P\exp(i\delta_p)\boldsymbol{\sigma}\cdot\hat{\mathbf{q}}$$

$$S = S_1 \exp(i\phi_s^1)$$

$$P = P_1 \exp(i\phi_p^1)$$

weak CP-odd phases for S and P waves

$|\Delta I| = 1/2$

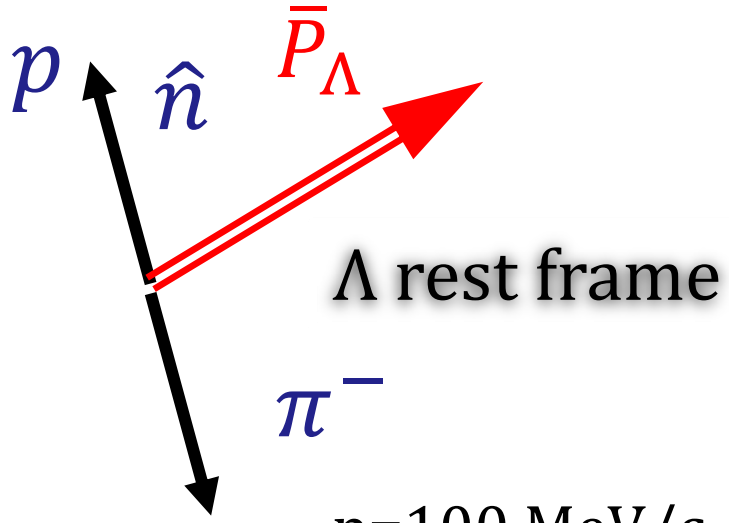
For $\Lambda \rightarrow p\pi^-$ admixture of $|\Delta I| = 3/2$ (~1/22)

Experimentally accessible two decay parameters:

$$\alpha = 2\,\mathrm{Re}S^* P e^{i(\delta p - \delta s)}$$

$$\beta = 2\,\mathrm{Im}S^* P e^{i(\delta p - \delta s)}$$

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



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

α_Λ= **0.750±0.010** β_Λ=**-0.075±0.040**

α_Ξ=**-0.392±0.008** β_Ξ=**-0.034±0.013**

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

Testing CP violation in hyperon decays (say Ξ)

Experimentally accessible two decay parameters:

$$\alpha = 2\,\mathrm{Re}S^{*}Pe^{i(\delta p-\delta s)}$$

$$\beta = 2\,\mathrm{Im}S^{*}Pe^{i(\delta p-\delta s)}$$

In the leading order:

strong *S*-*P* phase diff.

weak *P*-*S* phase diff.

$$A_{CP}^{\Xi} = \frac{\alpha_{\Xi}+\bar{\alpha}_{\Xi}}{\alpha_{\Xi}-\bar{\alpha}_{\Xi}} = \tan(\delta_s-\delta_p)\tan(\phi_p^1-\phi_s^1)$$

$$\approx \frac{\beta_{\Xi}}{\alpha_{\Xi}}\tan(\phi_p^1-\phi_s^1)$$

$$\frac{\beta_{\Xi}+\bar{\beta}_{\Xi}}{\alpha_{\Xi}-\bar{\alpha}_{\Xi}} = \tan(\phi_p^1-\phi_s^1)$$

Can one observe strange baryon CPV?

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

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

$$\frac{[\alpha(\Xi^-)\alpha_-(\Lambda) - \alpha(\bar{\Xi}^+)\alpha_+(\bar{\Lambda})]}{[\alpha(\Xi^-)\alpha_-(\Lambda) + \alpha(\bar{\Xi}^+)\alpha_+(\bar{\Lambda})]}$$

present best limits…

HyperCP PRL 93 (2004) 262001

1.2×10^8 Ξ^- 4.1×10^7 $\bar{\Xi}^+$

$A_\Lambda = -0.006 \pm 0.012 \pm 0.007$

BESIII

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

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

CKM

Tandean,Valencia PRD67 (2003) 056001

$J/\psi, \psi(2S) \to B\bar{B}$ Number of events at BESIII

BESIII
10^{10} J/ψ

decay mode	$\mathcal{B}$(units 10^{-4})	α_ψ	eff	
$J/\psi \to \Lambda\bar{\Lambda}$	$19.43 \pm 0.03 \pm 0.33$	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

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

PRD 95, 052003 (2017)

BESIII

$$\mathcal{B}(\Lambda \to p\pi^-) = 0.639(5)$$

Exclusive joint angular distribution

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

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

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

$$d\Gamma \propto W(\boldsymbol{\xi}; \boldsymbol{\alpha_\psi}, \boldsymbol{\Delta\Phi}, \boldsymbol{\alpha_\Lambda}, \boldsymbol{\bar{\alpha}_\Lambda}) =$$

$$1 + \boldsymbol{\alpha_\psi} \cos^2\theta_\Lambda \quad \text{Cross section}$$

$$+\boldsymbol{\alpha_\Lambda}\boldsymbol{\bar{\alpha}_\Lambda}\{\sin^2\theta_\Lambda(n_{1,x}n_{2,x} - \boldsymbol{\alpha_\psi} n_{1,y}n_{2,y}) + (\cos^2\theta_\Lambda + \boldsymbol{\alpha_\psi})n_{1,z}n_{2,z}\} \quad \text{Spin correlations}$$

$$+\boldsymbol{\alpha_\Lambda}\boldsymbol{\bar{\alpha}_\Lambda}\sqrt{1-\boldsymbol{\alpha_\psi}^2}\cos(\boldsymbol{\Delta\Phi})\sin\theta_\Lambda\cos\theta_\Lambda\,(n_{1,x}n_{2,z} + n_{1,z}n_{1,x})$$

$$+\sqrt{1-\boldsymbol{\alpha_\psi}^2}\sin(\boldsymbol{\Delta\Phi})\sin\theta_\Lambda\cos\theta_\Lambda\,(\boldsymbol{\alpha_\Lambda} n_{1,y} + \boldsymbol{\bar{\alpha}_\Lambda} n_{2,y}) \quad \text{Polarization}$$

$\Delta\Phi \neq 0$ $\Rightarrow$ independent determination of $\boldsymbol{\alpha_\Lambda}$ and $\boldsymbol{\bar{\alpha}_\Lambda}$

Fäldt, Kupsc PLB772 (2017) 16

Baryon-antibaryon spin density matrix

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

General two spin ½ particle state:

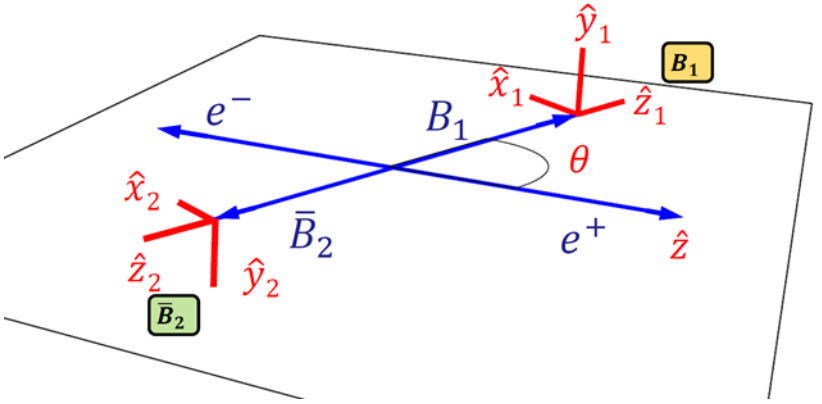
$$\rho_{1/2,\overline{1/2}} = \frac{1}{4}\sum_{\mu\bar{\nu}} C_{\mu\bar{\nu}}\, \sigma_\mu^{B_1} \otimes \sigma_{\bar{\nu}}^{\bar{B}_2}$$

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

P_Λ

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

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



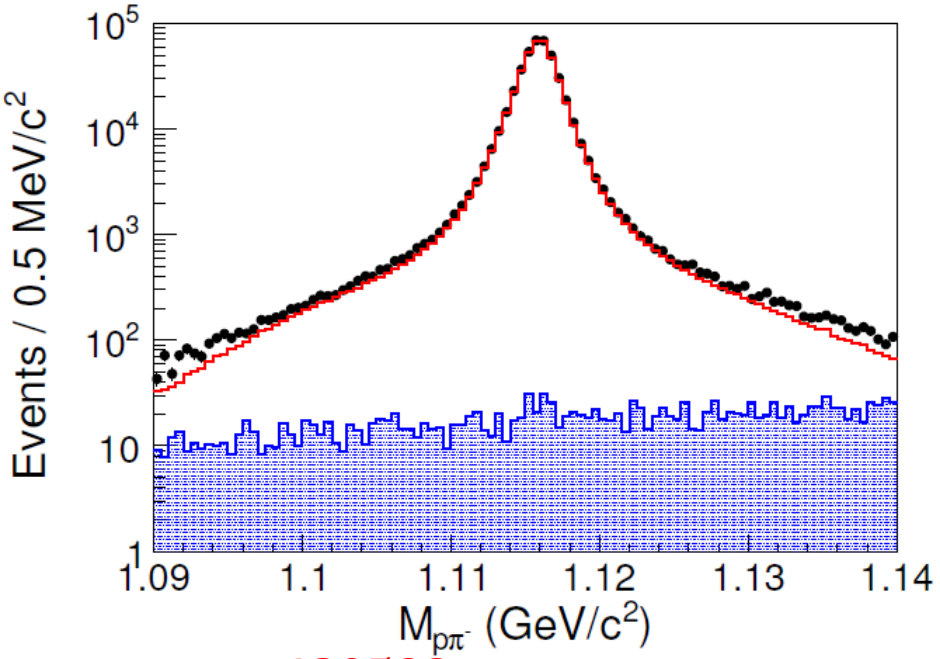
Angular distribution:

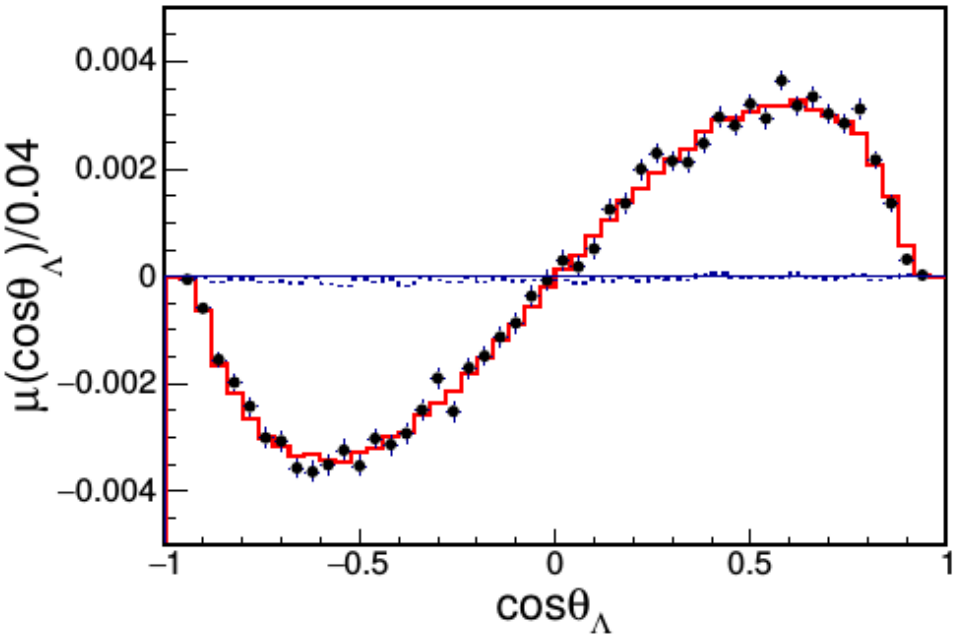
$$\frac{d\Gamma}{d\Omega} \propto 1+\alpha_\psi\cos^2\theta \qquad -1 \le \alpha_\psi \le 1$$

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

BESIII result

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





420593 events

399 background

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_-	$\mathbf{0.750 \pm 0.009 \pm 0.004}$	0.642 ± 0.013 PDG
α_+	$\mathbf{-0.758 \pm 0.010 \pm 0.007}$	-0.71 ± 0.08 PDG
$\bar{\alpha}_0$	$\mathbf{-0.692 \pm 0.016 \pm 0.006}$	–

BESIII Nature Phys. 15 (2019) 631

Prospects for CP tests $J/\psi \to \Lambda\bar{\Lambda}$

CP test: $A_\Lambda = \dfrac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$ $J/\psi \to \Lambda\bar{\Lambda}$

$A_\Lambda = -0.006 \pm 0.012 \pm 0.007$

BESIII

	Events	Stat error A_Λ	
BESIII(2018)	**$4.2 \cdot 10^5$**	**$1.2 \cdot 10^{-2}$**	**1.31 10^9 J/ψ**
BESIII(full stat)	$3.2 \cdot 10^6$	$4.4 \cdot 10^{-3}$	10^{10} J/ψ L=$0.47 \cdot 10^{33}$ $cm^{-2}s^{-1}$
SCTF	$4.5 \cdot 10^8$	$3.1 \cdot 10^{-4}$	$2 \cdot 10^{12}$ J/ψ L=10^{35} $cm^{-2}s^{-1}$

$|A_\Lambda| \leq 4 \times 10^{-5}$ CKM

Tandean,Valencia PRD67 (2003) 056001

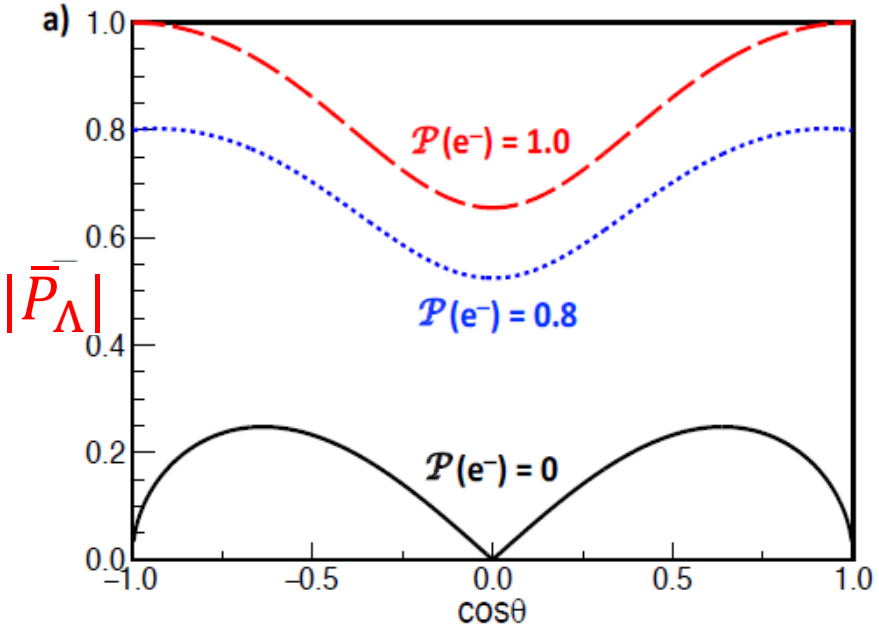
Polarized e^- beam

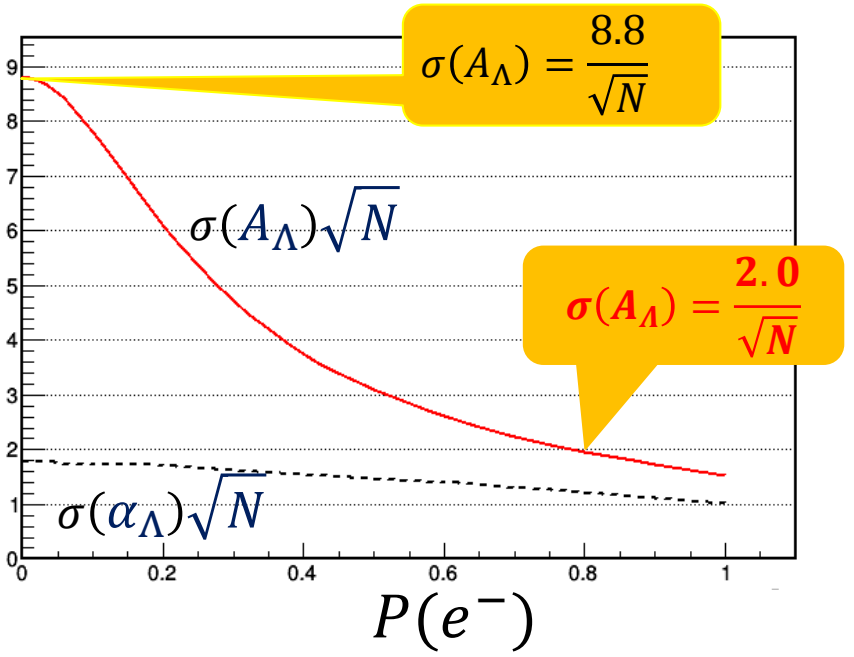
$$e^+e^- \to B_1\bar{B}_2$$

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

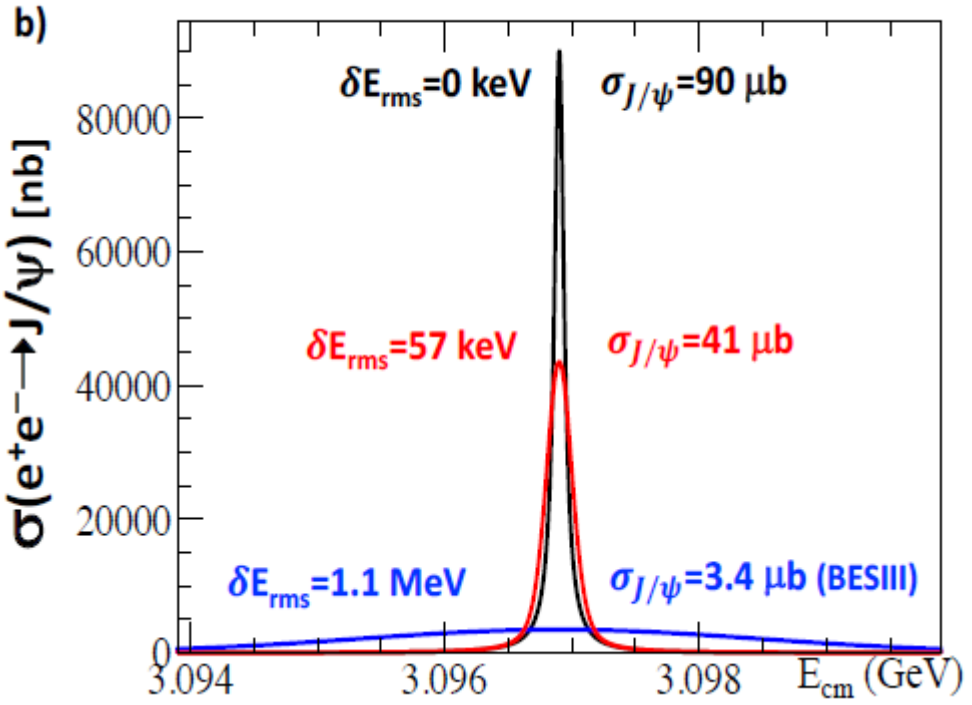
$\bar{P}_\Lambda$

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



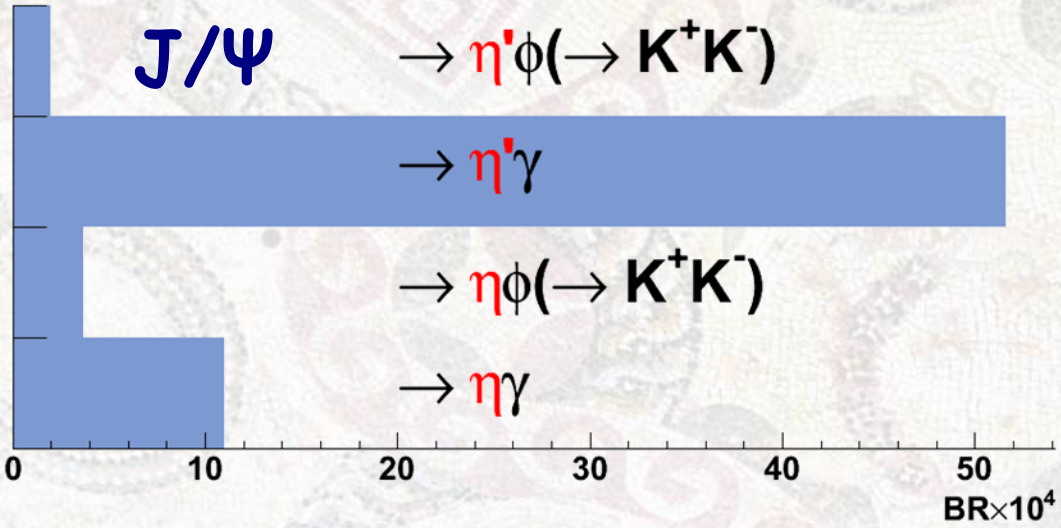


Monochromator



Goal for HL J/ψ Factory: $>10^{13}$ J/Ψ

η' Super Factory



BESIII

10^{10} J/Ψ ➔ 5×10^{7} η'

Decay Mode			ε (%)	$\mathcal{B}$ ($\times10^{-4}$)		
η'	$\to$	$\pi^+\pi^-\pi^0$	25.3	35.91	$\pm$	0.54 ± 1.74
		$(\pi^+\pi^-\pi^0)_S$	26.2	37.63	$\pm$	$0.77\pm2.22\pm4.48$
η'	$\to$	$\pi^0\pi^0\pi^0$	8.8	35.22	$\pm$	0.82 ± 2.60
η'	$\to$	$e^+e^-\gamma$	24.5	4.69	$\pm$	0.20 ± 0.23
η'	$\to$	$e^+e^-\omega$	5.45	1.97	$\pm$	0.34 ± 0.17
η'	$\to$	$\gamma\gamma\pi^0$	15.9	6.16	$\pm$	0.64 ± 0.67
η'	$\to$	$\pi^+\pi^-\pi^+\pi^-$	34.5	0.853	$\pm$	0.069 ± 0.069
η'	$\to$	$\pi^+\pi^-\pi^0\pi^0$	7.0	1.82	$\pm$	0.35 ± 0.18

low background/large acceptance

HL J/ψ factory: $>5\times10^{10}$ η'

Conclusions:

Potential to test CPV in hyperon decays $A_{\Lambda,\Xi} < 10^{-4}$ using $J/\psi \rightarrow B\bar{B}$ decays CKM estimate: (1-5) $\cdot 10^{-5}$

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

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

HL J/ψ Factory: $> 10^{13}\ J/\psi$ (monochromator)

+ polarization

(equivalent to $\times$ 16 more $J/\psi \rightarrow \Lambda\bar{\Lambda}$ data)

$J/\psi \rightarrow \Xi\bar{\Xi}$ measurement of β_{Ξ} and direct measurement of the weak phase difference

P. Adlarsson, AK Phys.Rev.D 100 (2019) 114005

Thank you!

- Work/White book: roadmap for CP violation observation in hyperons, strategy to deal with main syst uncertainties.
- Joint efforts with SCTF (extension, different detector concept)
- Hope for interest from Lattice/theory to calculate SM predictions for CPV in hyperons
- Other physics topics for HL J/ψ Factory