Precision hyperon physics at J/ψ and ψ' factories

Andrzej Kupsc (UU&NCBJ)

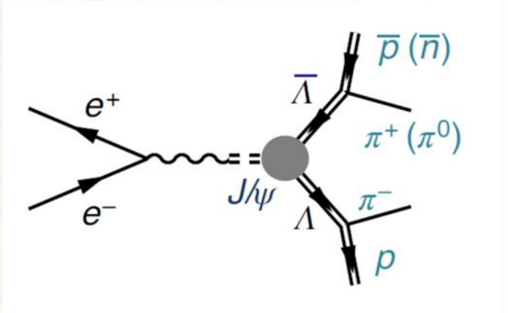
BESIII

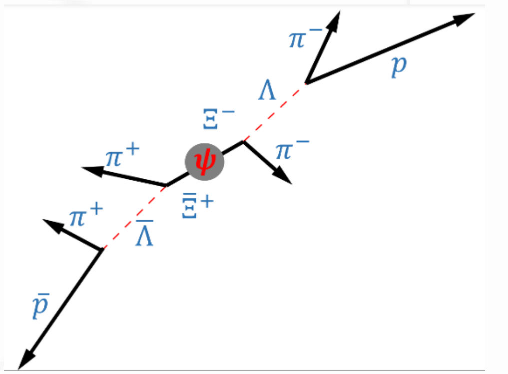
$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$ Nature Phys. 15 (2019) 631

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

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

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



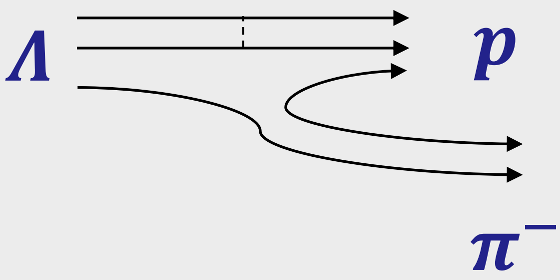


Polarization and spin correlations
Sequential decays
Determination of hyperon decay parameters
CP tests

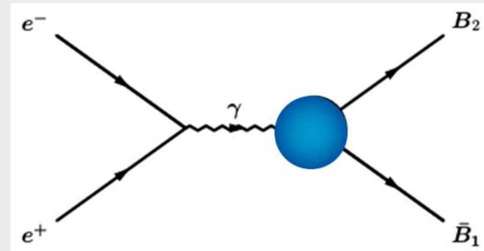
Methods (UU&NCBJ):

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 in preparation

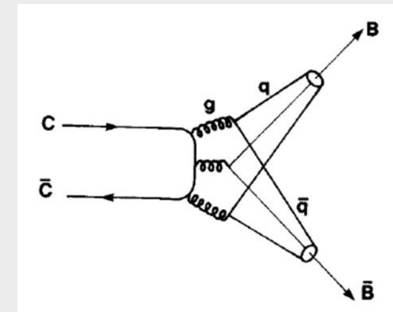
CHARM20,Mexico(zoom), 1 June 2021



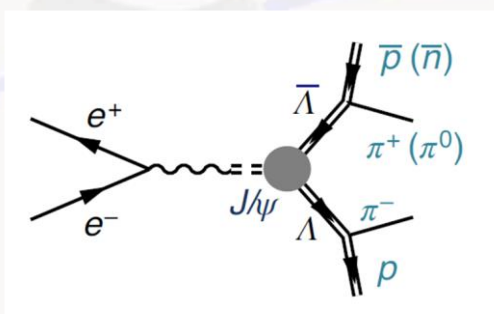
$\Lambda \to p\pi^-$



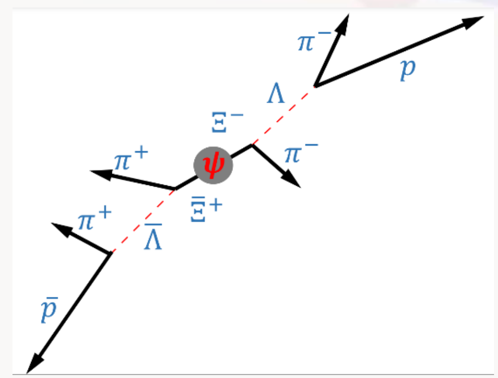
$e^+e^- \to f\bar{f}, \mathrm{B_1\bar{B}_2}$



$\mathrm{J/\psi \to B_1\bar{B}_2}$



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



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

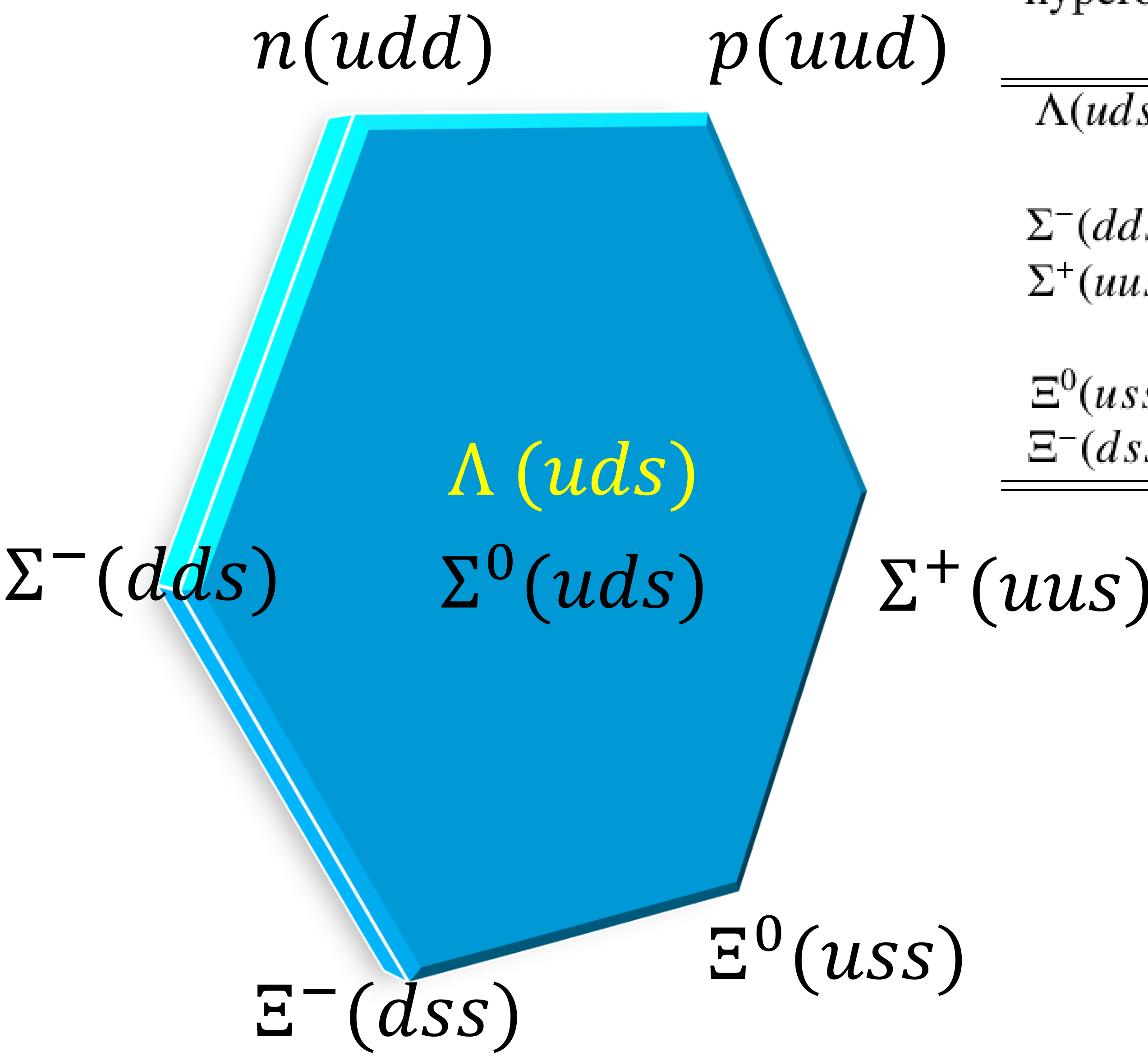
$\mathrm{J}/\psi(\psi') \to \Sigma^+\bar{\Sigma}^-$

$\psi' \to \Omega^-\bar{\Omega}^+$

CP tests:
Prospects at 10^{13} J/ψ factory

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

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

P and S transitions

P and D in $\overline{\Omega}^- \to \Lambda K^-$

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

weak CP-odd phases

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

strong phases

$|\Delta I| = 1/2$

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

Measurable: BF and two decay parameters

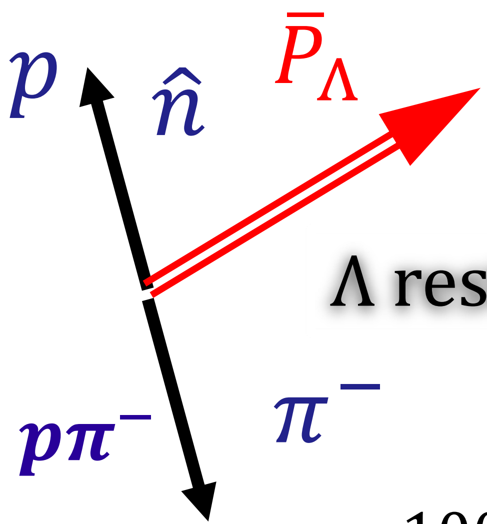
$$\alpha = \frac{2\,\mathrm{Re}(S^*P)}{|S|^2+|P|^2}$$

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

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

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

Measuring hyperon decay parameters

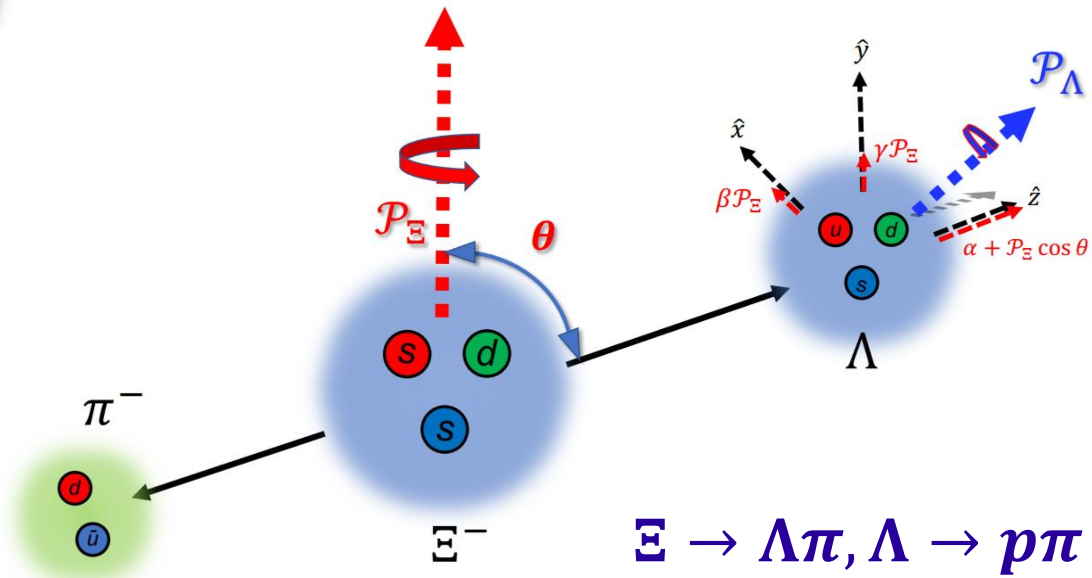


$$\frac{d\Gamma}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda \hat{n}\,\bar{P}_\Lambda)$$

Λ rest frame

$\boldsymbol{\Lambda \to p\pi^-}$

p=100 MeV/c



$\boldsymbol{\Xi \to \Lambda\pi, \Lambda \to p\pi}$

α_Λ= 0.750(10)

α_Ξ=-0.392(8)

ϕ_Λ=-0.113(61)

ϕ_Ξ=-0.042(16)

Accesible if daughter baryon polarization measured eg in decay sequence:
$\boldsymbol{\Xi \to \Lambda\pi, \Lambda \to p\pi}$

Measuring α, β, γ in the 20th century

James Cronin
1931-2016

Oliver Overseth
1928-2008

PHYSICAL REVIEW VOLUME 129, NUMBER 4 15 FEBRUARY 1963

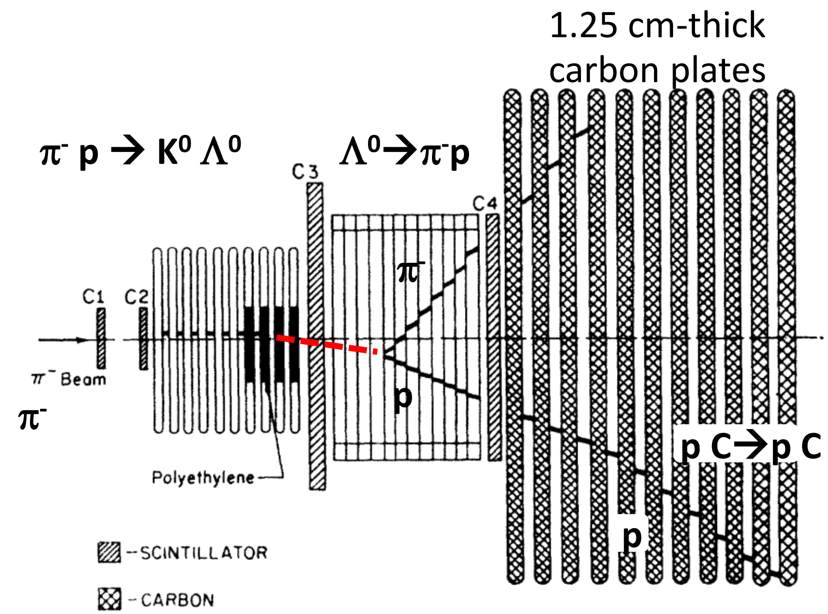
Measurement of the Decay Parameters of the Λ^0 Particle*

JAMES W. CRONIN AND OLIVER E. OVERSETH†
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received 26 September 1962)

The decay parameters of $\Lambda^0 \to \pi^- + p$ have been measured by observing the polarization of the decay protons by scattering in a carbon-plate spark chamber. The experimental procedure is discussed in some detail. A total of 1156 decays with useful proton scatters was obtained. The results are expressed in terms of polarization parameters, α, β, and γ given below:

$$\alpha = 2\,\mathrm{Re}\,sp^*/(|s|^2+|p|^2) = +0.62\pm0.07,$$
$$\beta = 2\,\mathrm{Im}\,sp^*/(|s|^2+|p|^2) = +0.18\pm0.24,$$
$$\gamma = |s|^2-|p|^2/(|s|^2+|p|^2) = +0.78\pm0.06,$$

where s and p are the s- and p-wave decay amplitudes in an effective Hamiltonian $s+p\boldsymbol{\sigma}\cdot\mathbf{p}/|\mathbf{p}|$, where $\mathbf{p}$ is the momentum of the decay proton in the center-of-mass system of the Λ^0, and $\boldsymbol{\sigma}$ is the Pauli spin operator. The helicity of the decay proton is positive. The ratio $|p|/|s|$ is $0.36_{-0.06}^{+0.05}$ which supports the conclusion that the $K\Lambda N$ parity is odd. The result $\beta=0.18\pm0.24$ is consistent with the value $\beta=0.08$ expected on the basis of time-reversal invariance.



no H_2 target, no magnet; use kinematics and proton's range in carbon to infer E_p

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

T. D. Lee, C.-N. Yang, PR 108 (1957) 1645

Slide from Steve Olsen

Testing CP violation in hyperon decays

for c.c. decay modes
if CP conserved:

$$\overline{\alpha} = -\alpha \text{ and } \overline{\phi} = -\phi$$

CP-test :

$$A_{\mathrm{CP}} = \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}}, \quad B_{\mathrm{CP}} = \frac{\phi + \overline{\phi}}{2}$$

Leading order ($|\Delta I| = 1/2$):

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

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

weak *P*-*S*
phase diff.

HyperCP:

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

	ξ_S $(\eta\lambda^5 A^2)$	ξ_P $(\eta\lambda^5 A^2)$	C_B	C'_B
	SM Ref. [13]		BSM Ref. [21]	
$\Lambda \to p\pi^-$	1.0 ± 1.0	1.2 ± 0.6	1.1 ± 2.2	0.4 ± 0.8
$\Xi^- \to \Lambda\pi^-$	0.9 ± 0.9	-0.5 ± 0.3	-0.5 ± 1.0	0.4 ± 0.7

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

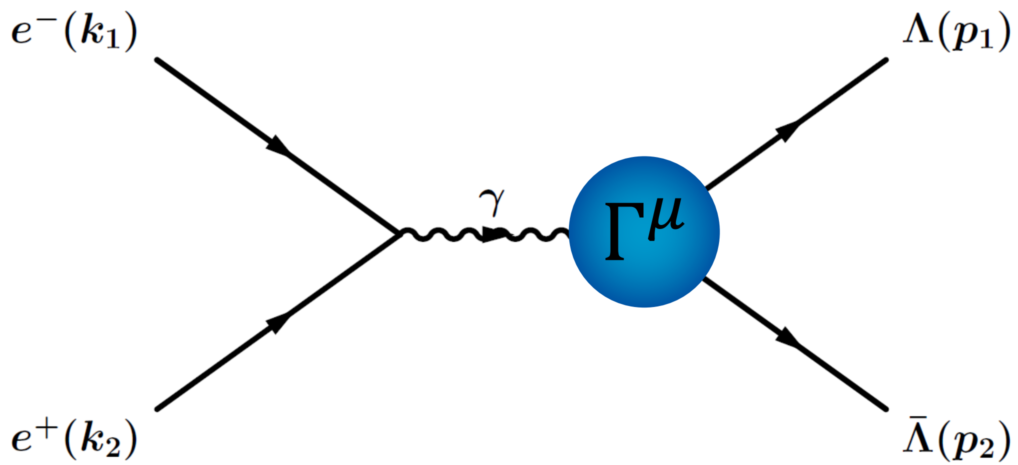
SM

Tandean,Valencia PRD67 (2003) 056001

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

$$0.5 < B_G < 2 \text{ and } 0.2 < |\kappa| < 1$$

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

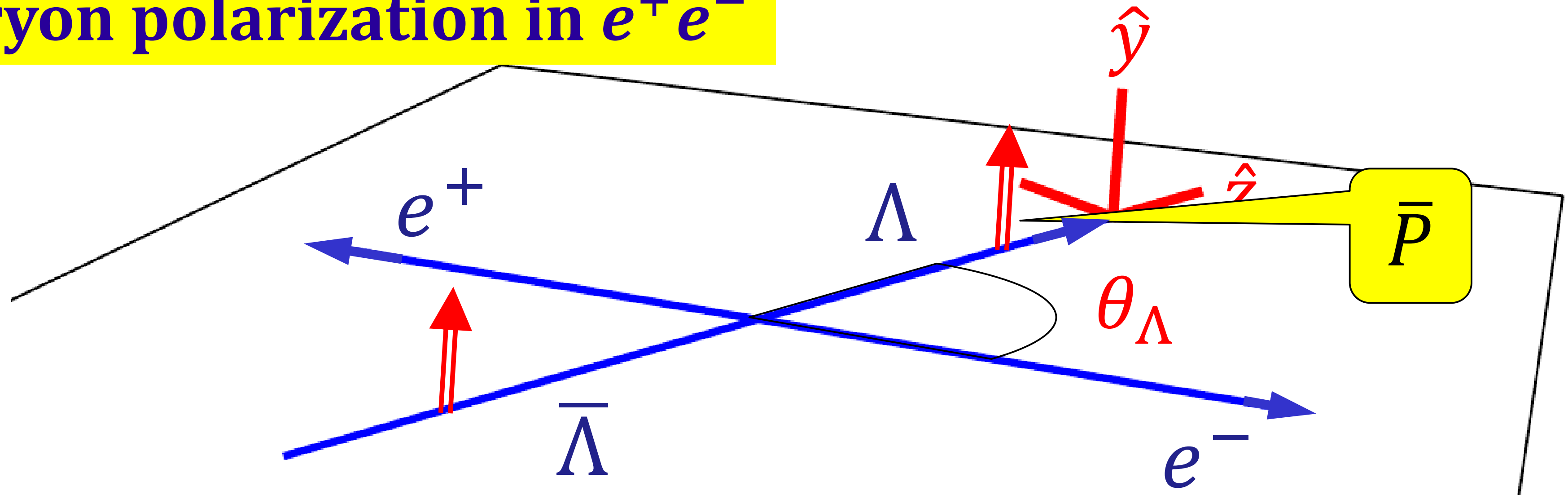
Sachs Form Factors (FFs) ⇔ helicity amplitudes:

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

helicity non-flip helicity flip

$$\tau = \frac{s}{4M_B^2}$$

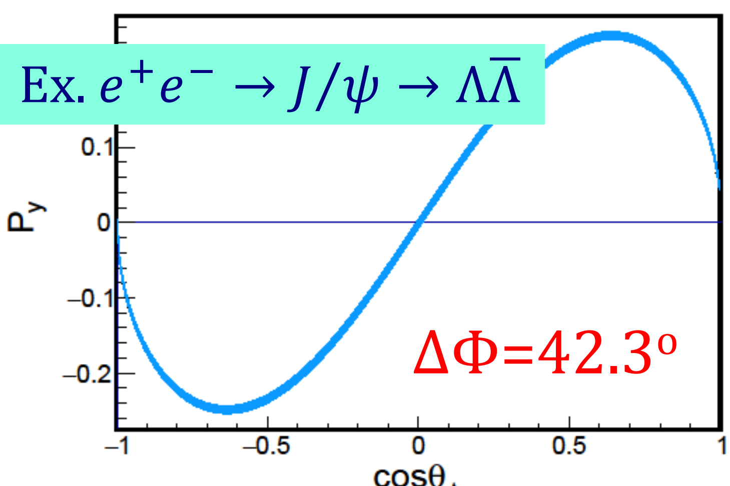
Baryon polarization in e^+e^-



Unpolarized e+e- beams ⇨ transverse polarization:

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

$\Delta\Phi \neq 0$



$\alpha_\psi = 0.469$

Angular distribution:

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

Baryon-antibaryon spin density matrix

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

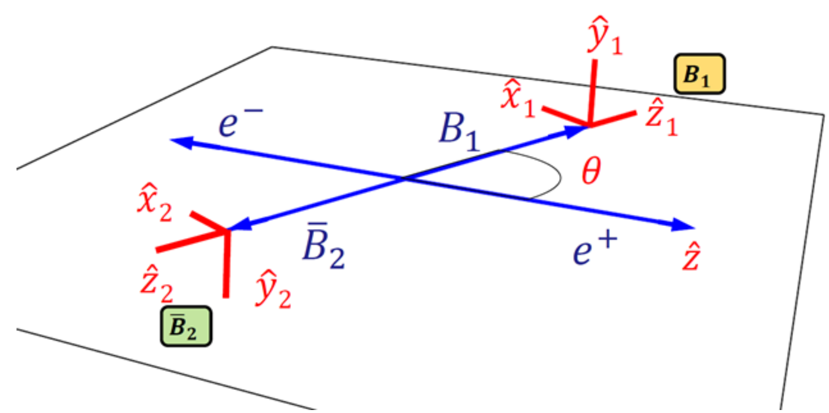
General two spin ½ particle state: $$\rho_{1/2,\overline{1/2}} = \frac{1}{4}\sum_{\mu\bar{\nu}} C_{\mu\bar{\nu}}\, \sigma_{\mu}^{B_1} \otimes \sigma_{\bar{\nu}}^{\bar{B}_2}$$

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

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

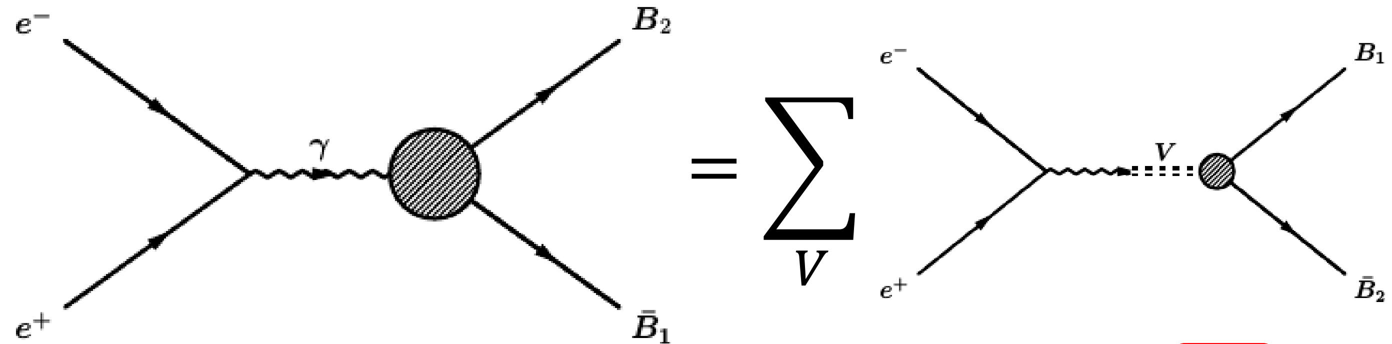
P_y

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



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

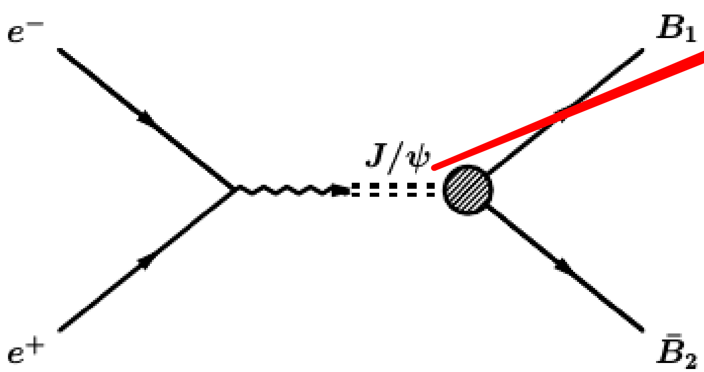
Baryon FFs (continuum):



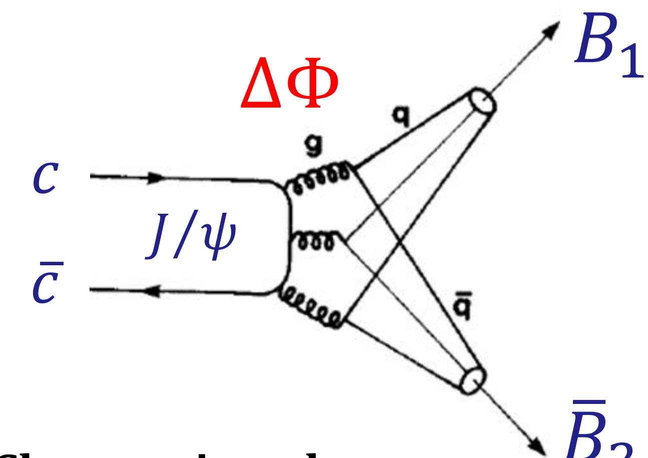
Baryons B_1 and $\bar{B}_2$
(spin 1/2, ...)

$V = \gamma, \rho, \omega, \varphi, \ldots, \boxed{J/\psi}, \psi(2S), \ldots$

vs J/ψ decay:



Both processes described by two complex FFs: relative phase $\Delta\Phi$



Time like spin ½ baryon 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 PLB772 (2017) 16

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

#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)

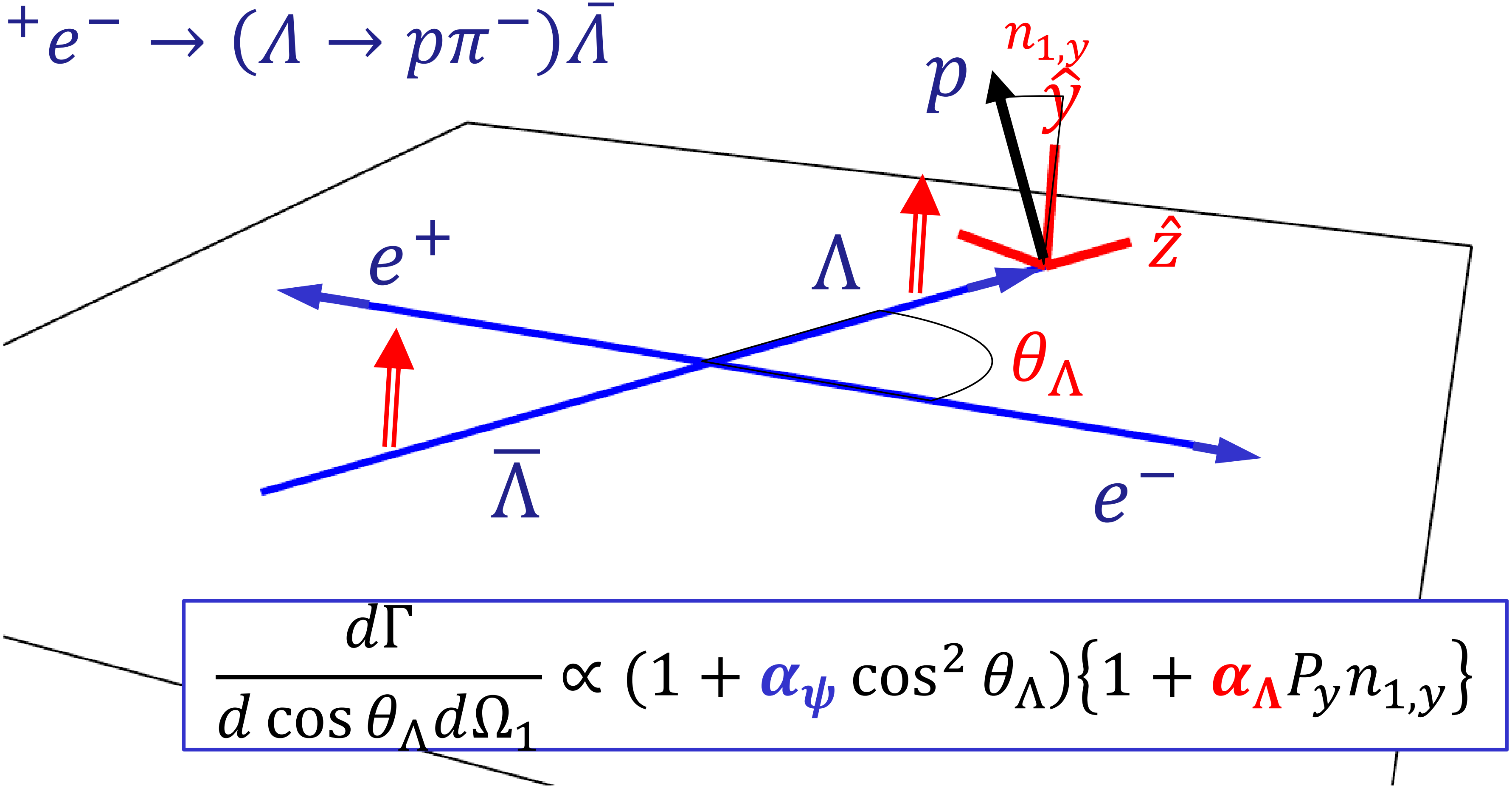
PRD 95, 052003 (2017)

BESIII proposal: $3.2\text{x}10^9$ ψ(2S)

$$\mathcal{B}(\psi(2S) \to \Omega^-\bar{\Omega}^+) = 5.85(28) \times 10^{-5}$$

Inclusive experiment (Single Tag - ST)

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



$$\frac{d\Gamma}{d\cos\theta_\Lambda d\Omega_1} \propto (1 + \boldsymbol{\alpha_\psi} \cos^2\theta_\Lambda)\{1 + \boldsymbol{\alpha_\Lambda} P_y n_{1,y}\}$$

$\Lambda \to p\pi^-$: $\hat{\mathbf{n}}_1 \to \Omega_1 = (\cos\theta_1, \phi_1)$: α_Λ

⇒Determine product: $\alpha_\Lambda P_y \sim \alpha_\Lambda \sin(\Delta\Phi)$

Exclusive **(Double Tag - DT)**

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

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

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

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

$$1 + \alpha_\psi \cos^2\theta_\Lambda$$

Cross section

Spin correlations

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

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

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

Polarization

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

Fäldt, Kupsc PLB772 (2017) 16

DT - joint angular distribution (modular form)

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

General two spin ½ particle state: $$\rho_{1/2,\overline{1/2}} = \frac{1}{4}\sum_{\mu\bar{\nu}} C_{\mu\bar{\nu}}\, \sigma_\mu^\Lambda \otimes \sigma_{\bar{\nu}}^{\bar{\Lambda}}$$

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

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

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

Apply decay matrices:

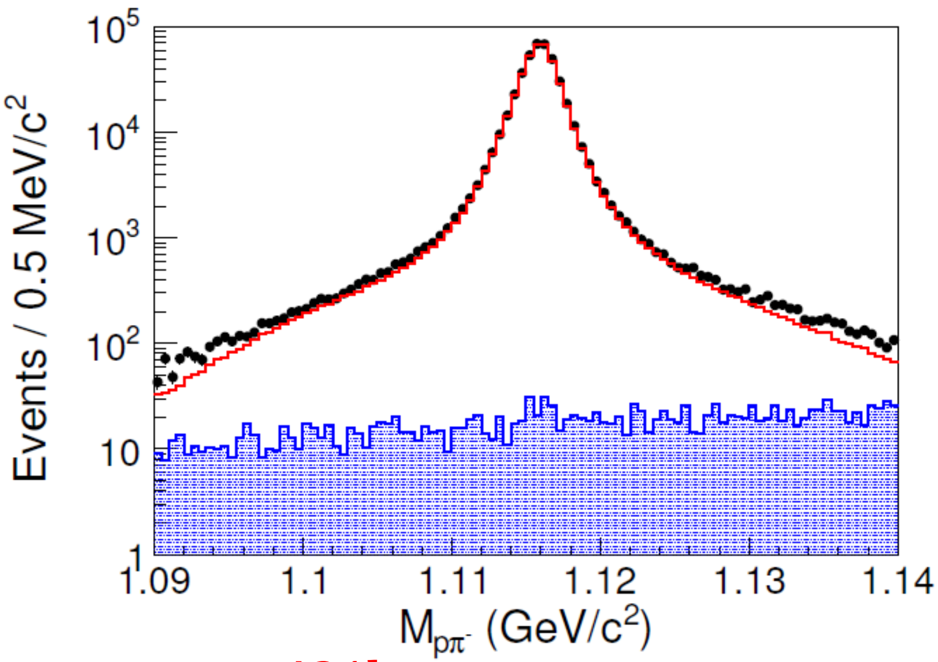
$$\sigma_\mu^\Lambda \to \sum_{\mu'=0}^{3} a_{\mu,\mu'}^\Lambda\, \sigma_{\mu'}^p$$

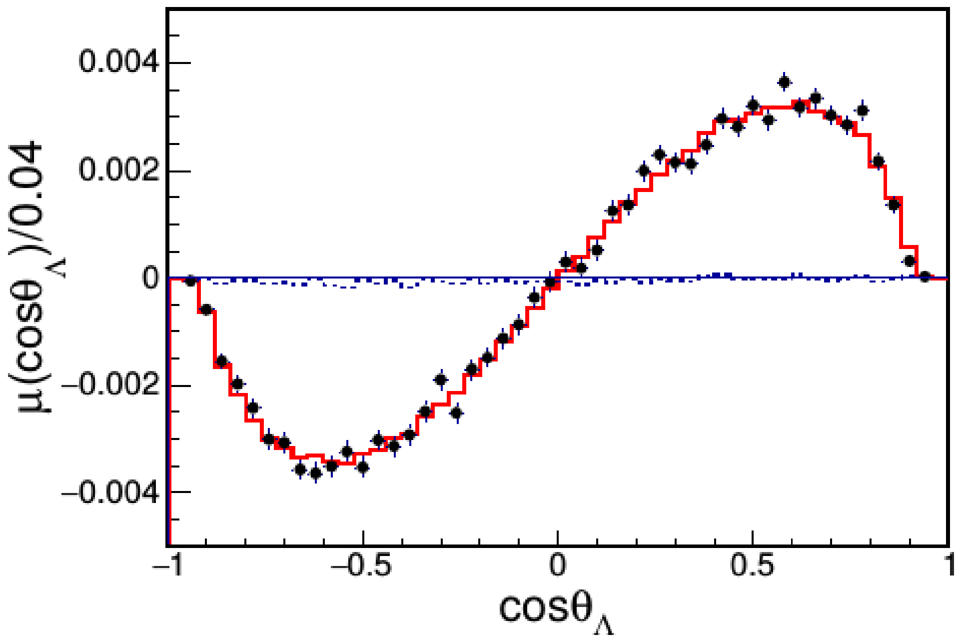
Modular angular distribution:

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

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

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

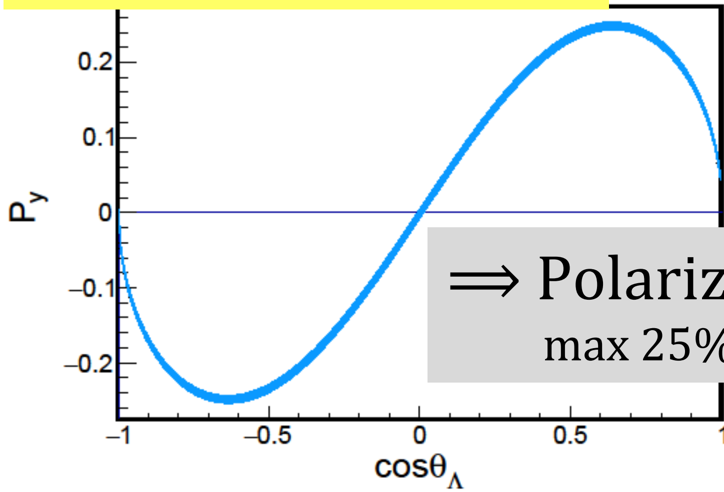
Parameters	This work	Previous results
α_ψ	$\mathbf{0.461 \pm 0.006 \pm 0.007}$	0.469 ± 0.027 BESIII
$\Delta\Phi$ (rad)	$\mathbf{0.740 \pm 0.010 \pm 0.008}$	–
α_Λ	$\mathbf{0.750 \pm 0.009 \pm 0.004}$	0.642 ± 0.013 PDG
$\bar{\alpha}_\Lambda$	$\mathbf{-0.758 \pm 0.010 \pm 0.007}$	-0.71 ± 0.08 PDG

4 fit parameters

BESIII Nature Phys. 15 (2019) 631

Implications of the BESIII $\Lambda\bar{\Lambda}$ result

$\Delta\Phi=42.3^{o}\pm0.6^{o}\pm0.5^{o}$



$\Longrightarrow$ Polarization:
max 25%

$\bar{\alpha}_0/\alpha_+$	$0.913\pm0.028\pm0.012$

$\Delta I=\frac{1}{2}$ **rule violation**

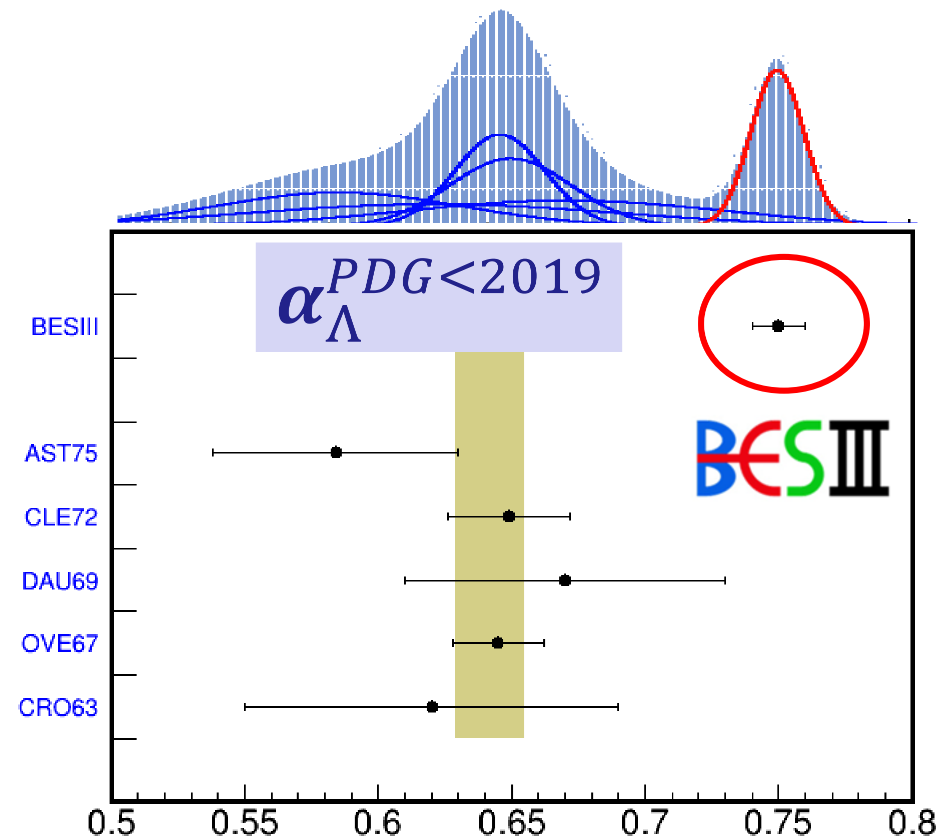
CP test:

$$A_{CP}(\Lambda)=\frac{\alpha_\Lambda+\bar{\alpha}_\Lambda}{\alpha_\Lambda-\bar{\alpha}_\Lambda}$$

A_{CP} = -0.006 ± 0.012± 0.007

A_Λ= 0.013 ± 0.021
PS185 PRC54(96)1877

$\Lambda\to p\pi^-$: $\langle\alpha\rangle=\frac{\alpha-\bar{\alpha}}{2}=0.754(3)(2)$



$\alpha_\Lambda^{PDG<2019}$

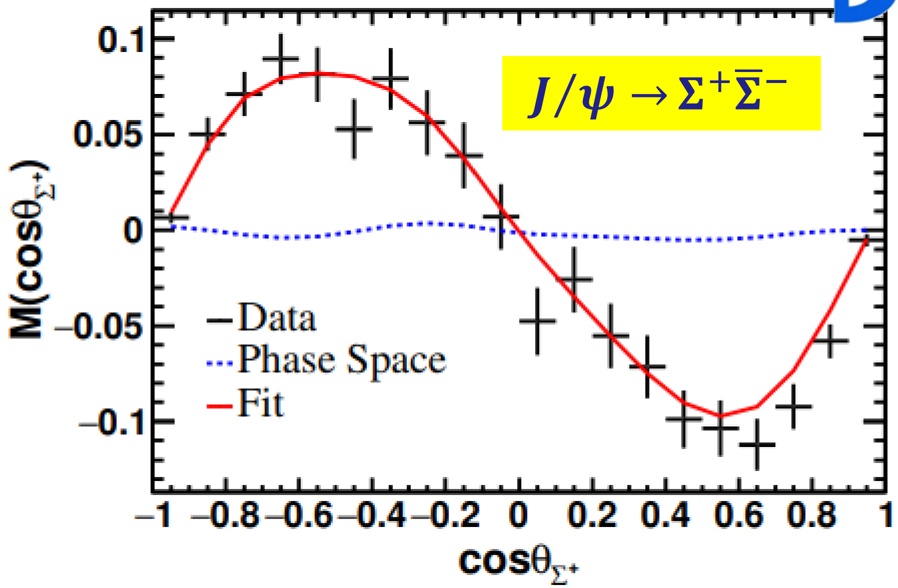
α_Λ

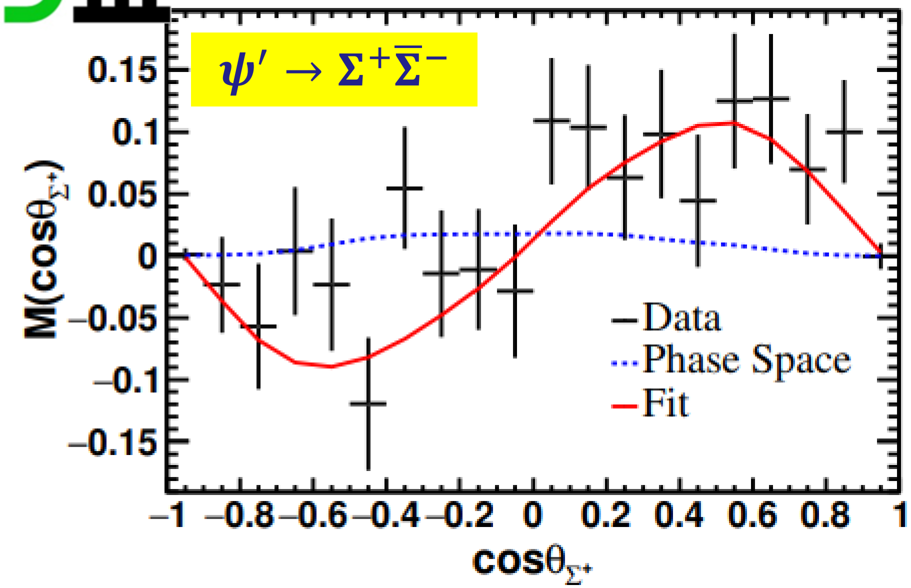
α_Λ =0.721(6)(5)

CLAS, *PRL* 123 (2019) 182301

$e^+e^- \to J/\psi, \psi' \to \Sigma^+\bar{\Sigma}^- \to p\pi^-\bar{p}\pi^+$

(same formalism as for $J/\psi \to \Lambda\bar{\Lambda}$)





$\alpha_{J/\psi}/\alpha_{\psi}$ = -0.507±0.006±0.002   0.676±0.030±0.006

$\Delta\Phi(J/\psi, \psi)$ = (-15.4±0.7±0.3)°   (21.5 ± 0.4 ± 0.5)°

PRL 125 (2020) 052004

$\langle\alpha\rangle = (\alpha - \bar{\alpha})/2 = -0.994(4)(2)$

A_{CP} = -0.004±0.037±0.010

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

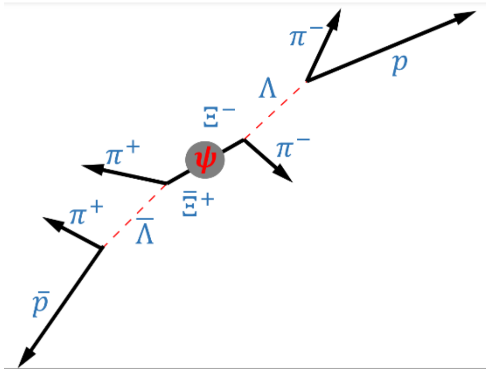
$d\Gamma \propto W(\xi;\boldsymbol{\omega})$ $\quad\xi$ **9 kinematical variables, 9D PhSp**

Parameters: 2 production + 6 for decay chains

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

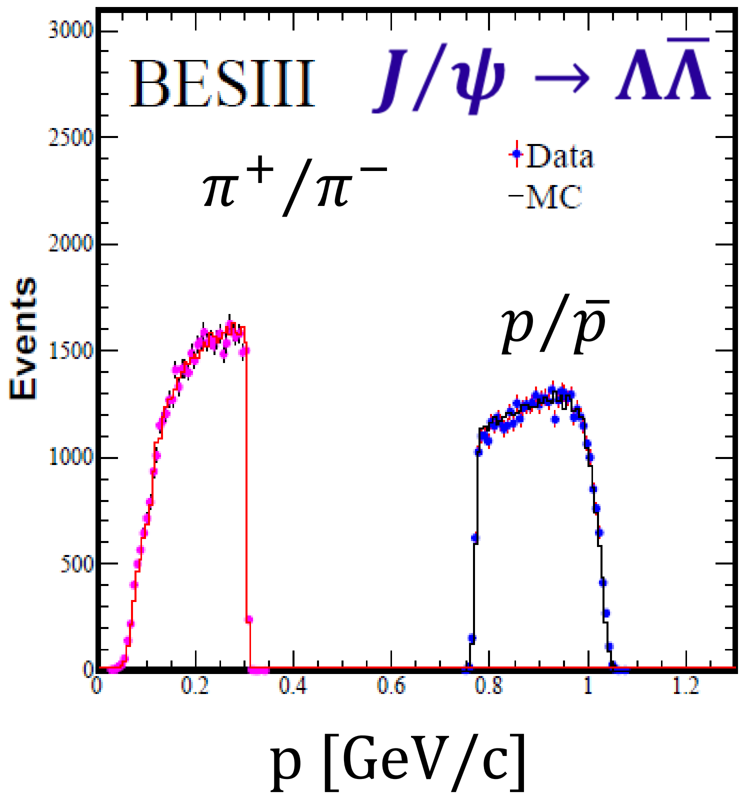
Modular angular distribution:

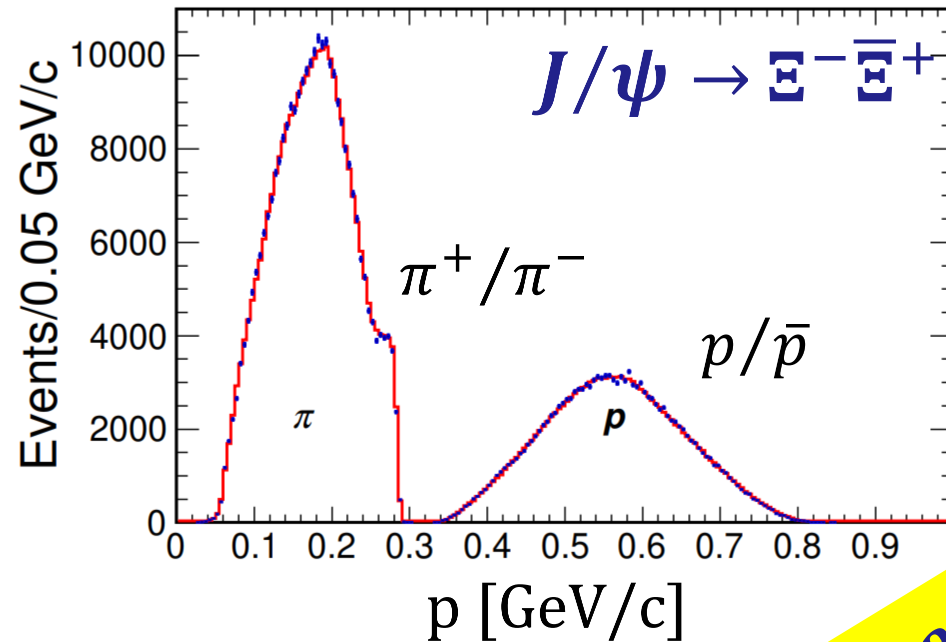
$$W = \sum_{\mu,\overline{\nu}=0}^{3} C_{\mu\overline{\nu}} \sum_{\mu',\overline{\nu}'=0}^{3} a^{\Xi}_{\mu,\mu'} a^{\overline{\Xi}}_{\overline{\nu},\overline{\nu}'} a^{\Lambda}_{\mu',0} a^{\overline{\Lambda}}_{\overline{\nu}',0}$$



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





Preliminary

421k events	**73k** events
399 bkg	190 bkg
5D PhSp	**9D PhSp**

Unbinned MLL

4 parameters	**8 parameters**

Nature Phys. 15 (2019) 631

arXiv:2105.11155

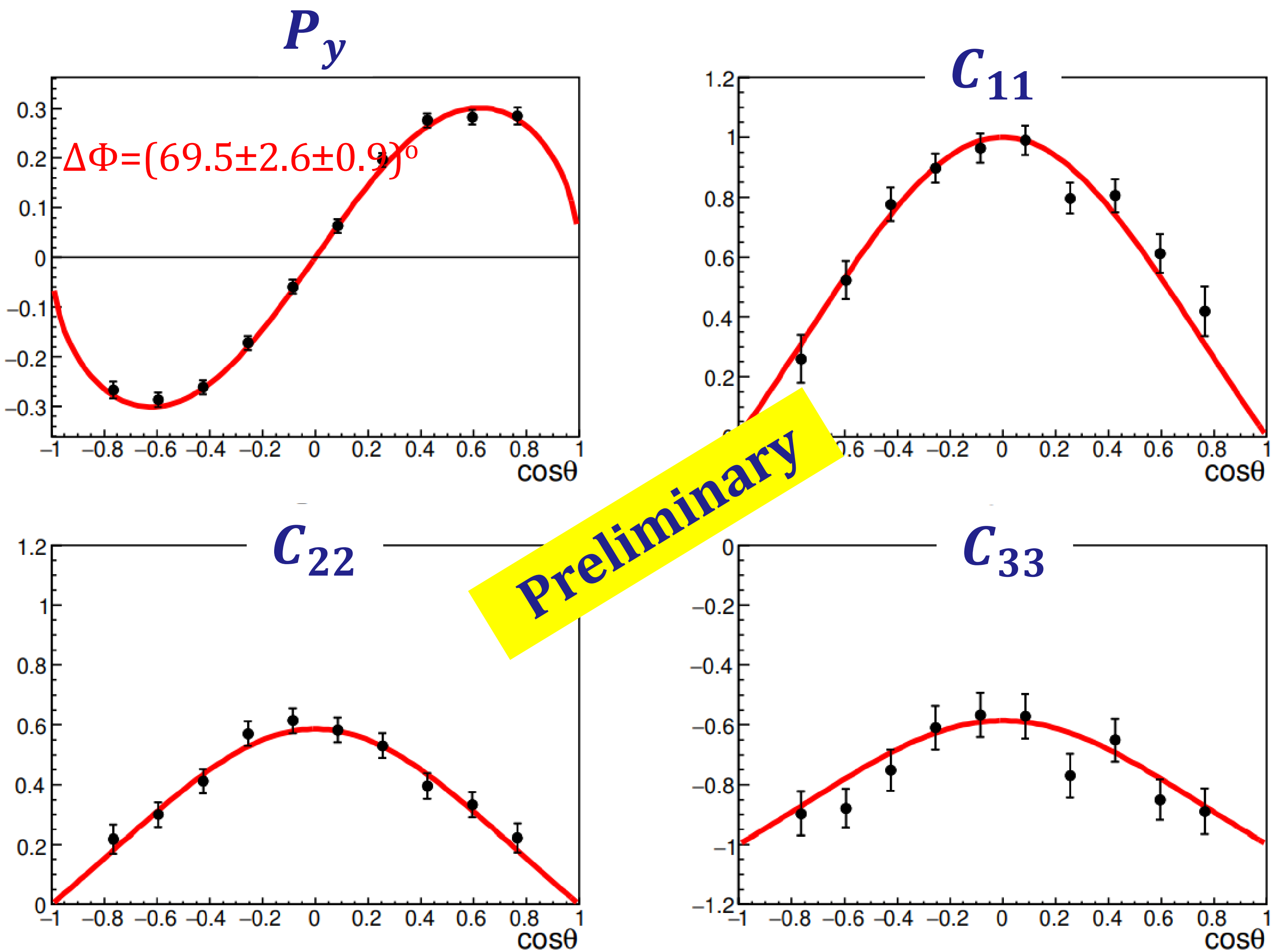
	Preliminary	Previous result
α_ψ	$0.586 \pm 0.012 \pm 0.010$	$0.58 \pm 0.04 \pm 0.08$ [39]
$\Delta\Phi$	$1.213 \pm 0.046 \pm 0.016$ rad	–
α_Ξ	$-0.376 \pm 0.007 \pm 0.003$	-0.401 ± 0.010
ϕ_Ξ	$0.011 \pm 0.019 \pm 0.009$ rad	-0.037 ± 0.014 rad
$\overline{\alpha}_\Xi$	$0.371 \pm 0.007 \pm 0.002$	–
$\overline{\phi}_\Xi$	$-0.021 \pm 0.019 \pm 0.007$ 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^{Ξ}_{CP}	$(6.0 \pm 13.4 \pm 5.6) \times 10^{-3}$	–
$\Delta\phi^{\Xi}_{\mathrm{CP}}$	$(-4.8 \pm 13.7 \pm 2.9) \times 10^{-3}$ rad	–
$A^{\Lambda}_{\mathrm{CP}}$	$(-3.7 \pm 11.7 \pm 9.0) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$
$\langle \phi_\Xi \rangle$	$0.016 \pm 0.014 \pm 0.007$ rad	

8 fit parameters

3 CP tests

arXiv:2105.11155

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



$e^+e^- \to \psi' \to \Omega^-\bar{\Omega}^+$

$e^+e^- \to \gamma^* \to \psi' \to B\bar{B}$ (spin 3/2)

$$A = \begin{pmatrix} \mathbf{h}_4 & \mathbf{h}_3 & 0 & 0 \\ \mathbf{h}_3 & \mathbf{h}_1 & \mathbf{h}_2 & 0 \\ 0 & \mathbf{h}_2 & \mathbf{h}_1 & \mathbf{h}_3 \\ 0 & 0 & \mathbf{h}_3 & \mathbf{h}_4 \end{pmatrix}$$

Four (Complex) Form Factors

Using base 3/2 spin matrices Q:

Nucl. Phys. B38, 477(1972)

$$\rho_{3/2,\overline{3/2}} = \sum_{\mu=0}^{15}\sum_{\bar{\nu}=0}^{15} C_{\mu,\bar{\nu}}\, Q_\mu \otimes Q_{\bar{\nu}}$$

DT Experiment

$$\rho_{3/2} = \sum_{\mu=0}^{15} r_\mu Q_\mu$$

ST Experiment

$$\rho_{3/2} = r_0 \left(Q_0 + \frac{3}{4} \overbrace{\sum_{M=-1}^{1} r_M^1 Q_M^1}^{r^1_{-1} \to P_y \;\; r^1_0 \to P_x \;\; r^1_1 \to P_z} + \frac{3}{4}\sum_{M=-2}^{2} r_M^2 Q_M^2 + \frac{3}{4}\sum_{M=-3}^{3} r_M^3 Q_M^3 \right)$$

$$Q_0 = \frac{1}{4} I \qquad \frac{3}{4} Q_M^L \to Q_\mu \,, \mu = 1, \ldots, 15$$

Single tag $e^+e^- \to \Omega^-\overline{\Omega}^+$

Single 3/2-spin baryon density matrix is

$$\rho_{3/2} = \sum_{\mu=0}^{15} r_\mu Q_\mu = \sum_{\mu=0}^{15} C_{\mu,0} Q_\mu$$

ST angular distribution:

$$W = \sum_{\mu=0}^{15} C_{\mu,0} \sum_{\mu'=0}^{3} \boxed{b^{\Omega}_{\mu,\mu'}}\, \boxed{a^{\Lambda}_{\mu',0}}$$

decay ${}^{1}/_{2} \to {}^{1}/_{2} + 0$
$(\Lambda \to p\pi^-)$

decay ${}^{3}/_{2} \to {}^{1}/_{2} + 0$
$(\Omega^- \to \Lambda\pi^-)$

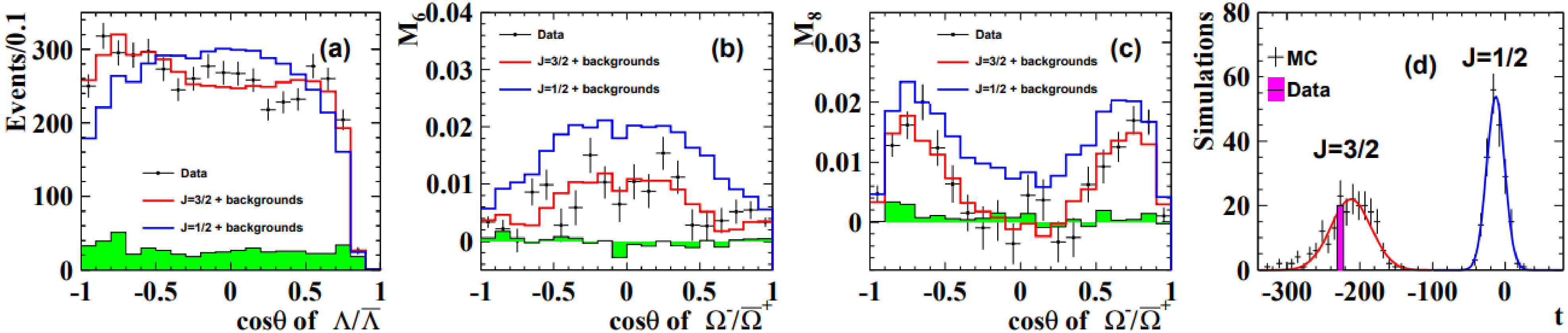
Degree of polarization

$$d(\rho_{3/2}) = \sqrt{\sum_{L=1}^{3} \sum_{M=-L}^{L} \left(r_M^L\right)^2}$$

At threshold: d(3/2)=23%

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

Single tag $e^+e^- \to \psi' \to \Omega^- \bar{\Omega}^+$

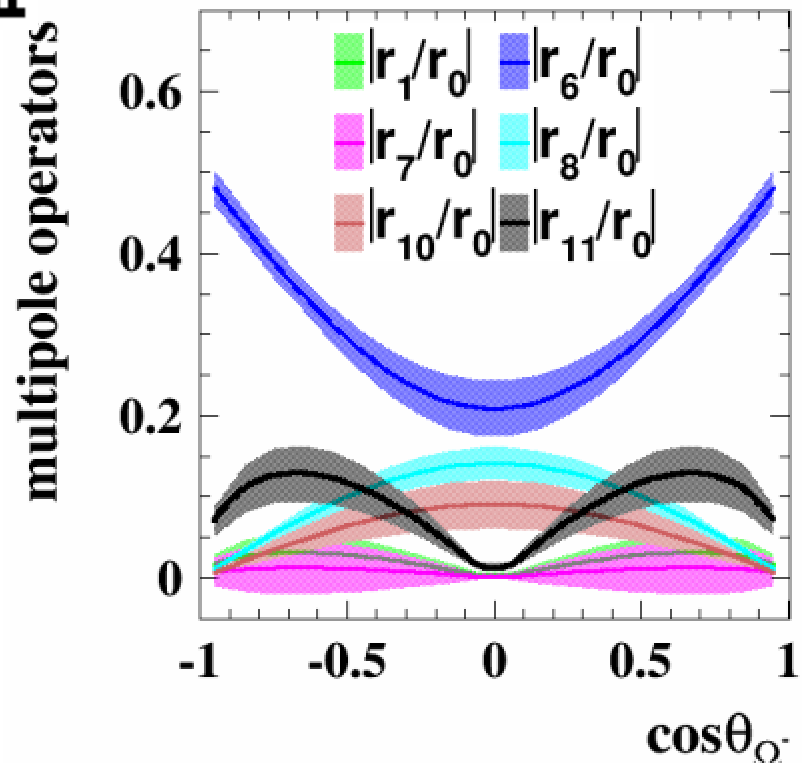


Data: $4.48 \times 10^8 \psi(2S)$

Model independent Ω spin determination
Four production form-factors

ST analysis: $2507\Omega^- + 2238\ \bar{\Omega}^+$

Phys.Rev.Lett. 126 (2021) 092002



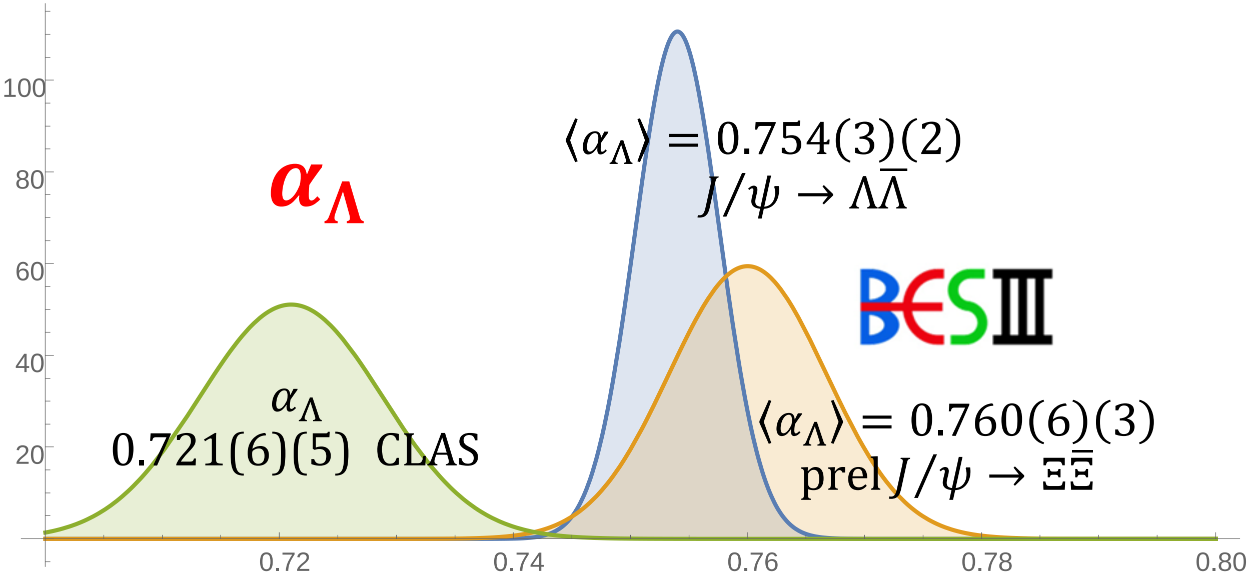
Conclusions I

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

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

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

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



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

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

three independent CP tests
measurement of $\phi_\Xi, \bar{\phi}_\Xi$
first direct measurement of weak phase difference: $(\xi_P - \xi_S)$

Outlook: high luminosity (HL) J/ψ factory

AK, Hai-Bo Li, and Steve Olsen

CP test: $A_{CP}(\Lambda) = \frac{\alpha_\Lambda + \bar{\alpha}_\Lambda}{\alpha_\Lambda - \bar{\alpha}_\Lambda}$

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

$A_\Lambda = -0.004 \pm 0.012 \pm 0.009$

BESIII

$J/\psi \to \Lambda\bar{\Lambda}, \Xi\bar{\Xi}$

	Events	Stat error A_Λ	
BESIII(2018)	**4.2×10^5**	**1.2×10^{-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

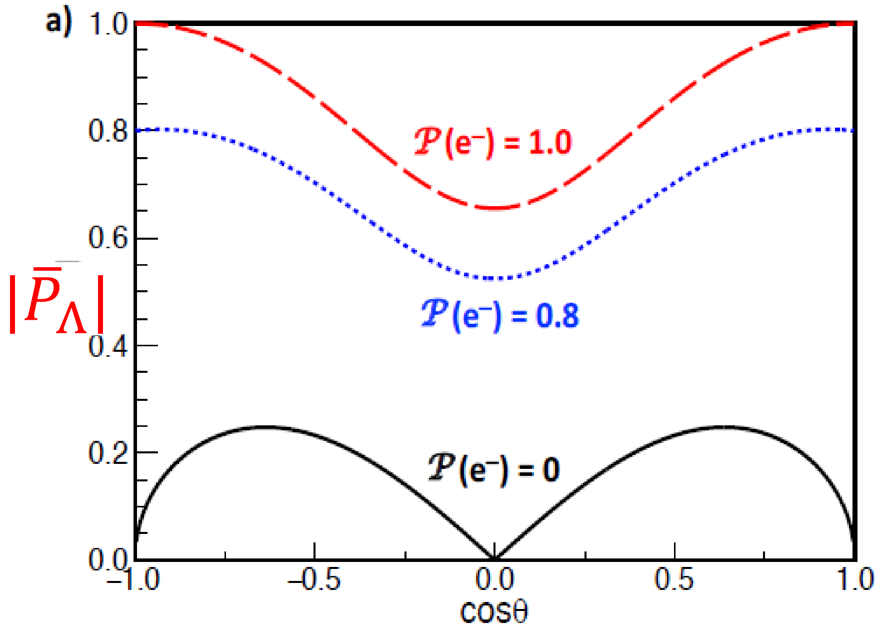
$$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$$

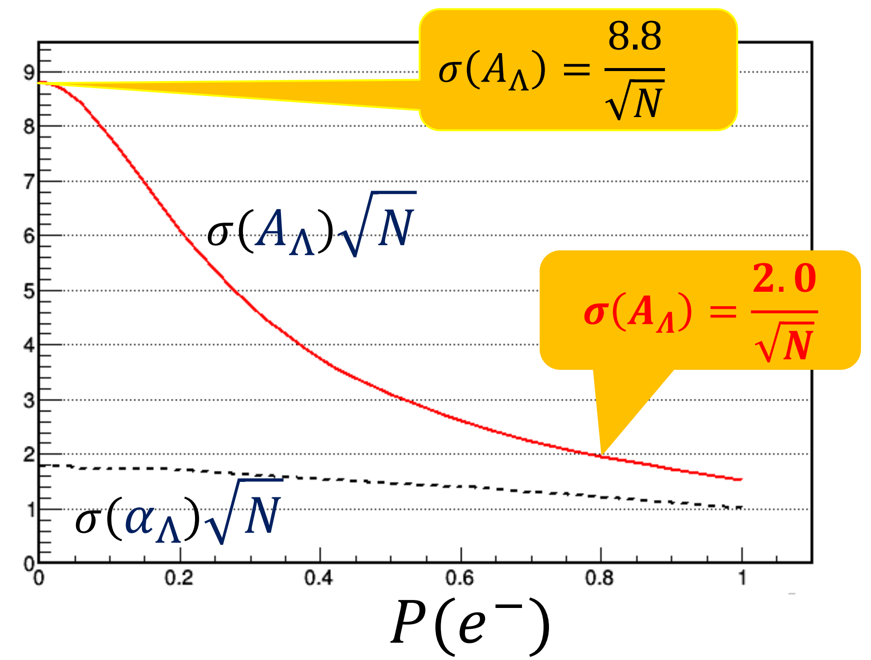
$+$ 80% longitudinal e^- polarization

Bondar et al. JHEP 03 (2020) 076

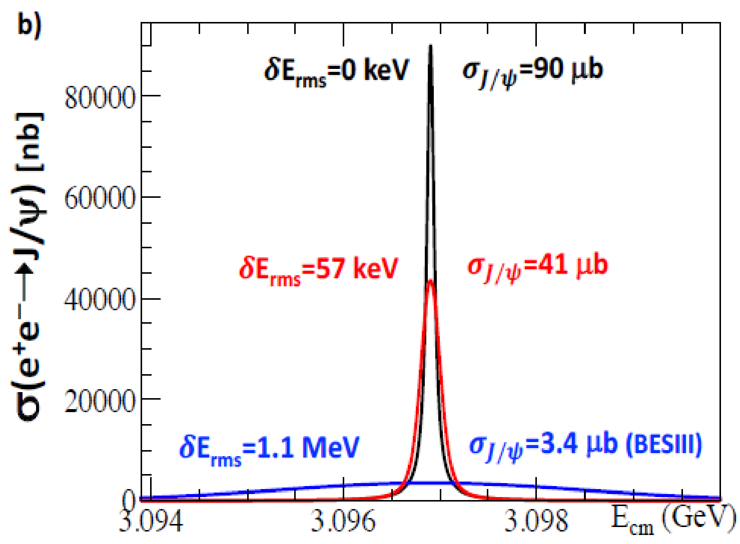
$\bar{P}_\Lambda$

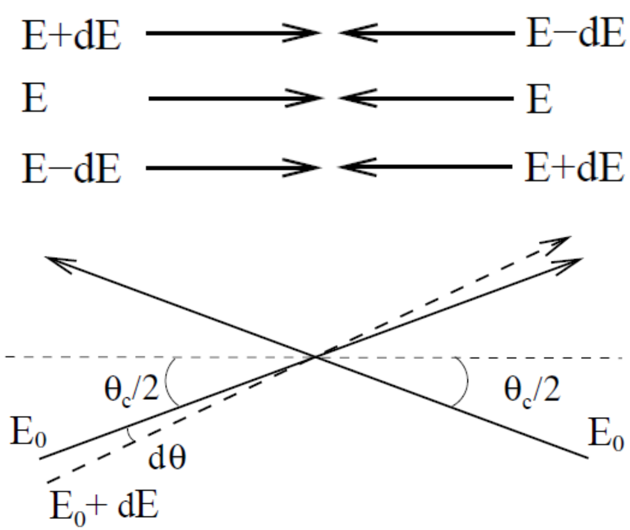
$$C_{\mu\bar{\nu}} = \begin{pmatrix} 1+\alpha_\psi\cos^2\theta & \boxed{\gamma_\psi P_z\sin\theta & \beta_\psi\sin\theta\cos\theta & (1+\alpha_\psi)P_z\cos\theta} \\ \gamma_\psi P_z\sin\theta & \sin^2\theta & 0 & \gamma_\psi\sin\theta\cos\theta \\ -\beta_\psi\sin\theta\cos\theta & 0 & \alpha_\psi\sin^2\theta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





+ monochromator





V.Telenov arXiv:2008.13668

Goal for HL Factory: $>10^{13}\ J/\psi$

+ polarization (equivalent to 16 × more $J/\psi \to \Lambda\bar{\Lambda}$ data)

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