Parity violation in Λ hyperon nonleptonic weak decays

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Novel method to determine hyperon decay parameters

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

Preliminary result

BESIII

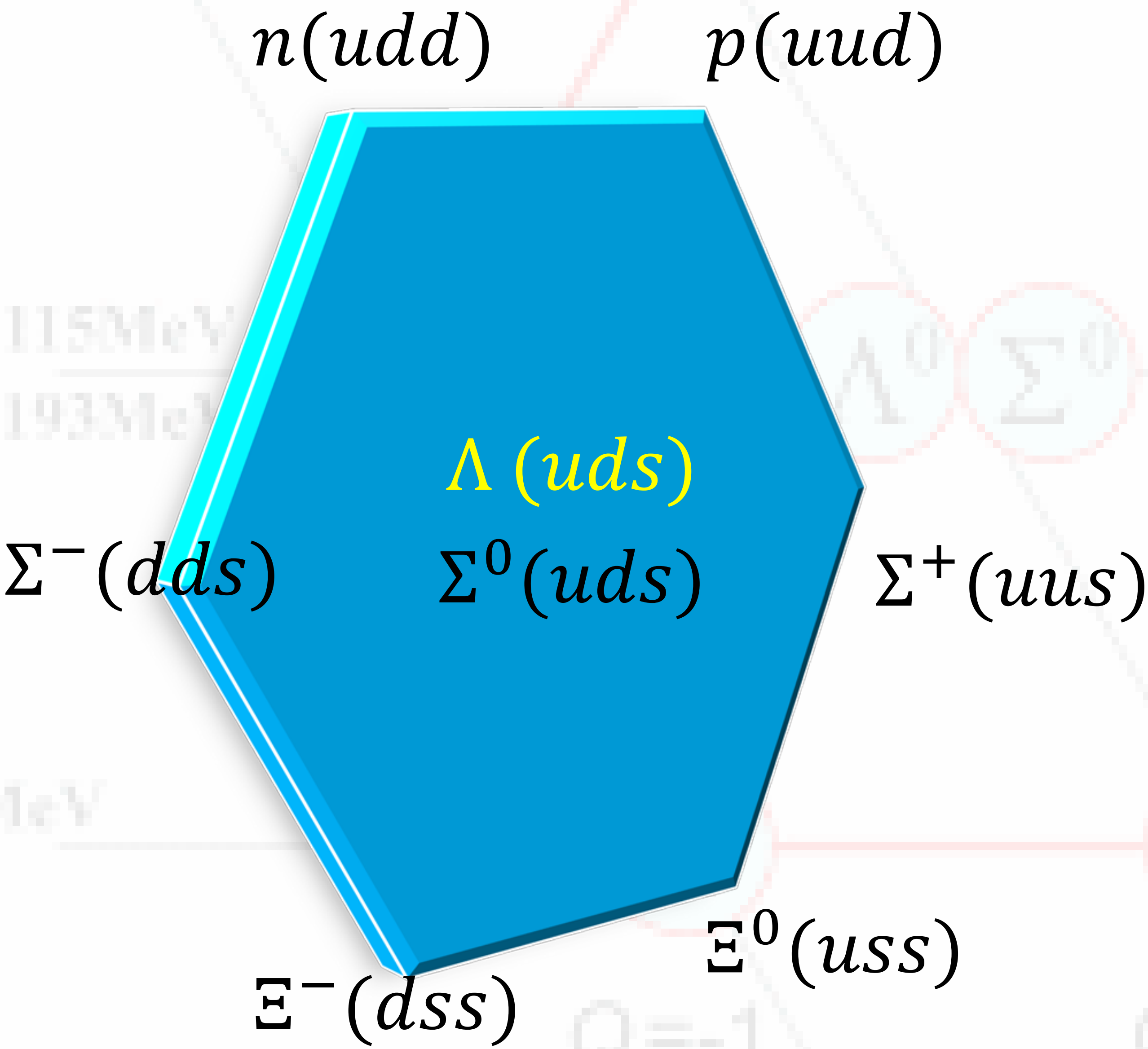
Observation of Λ transverse polarization

⇨ Determination of Λ decay asymmetries and CP test

arXiv:1808.08917

Particle Physics with Neutrons at ESS 10-14 December, Stockholm

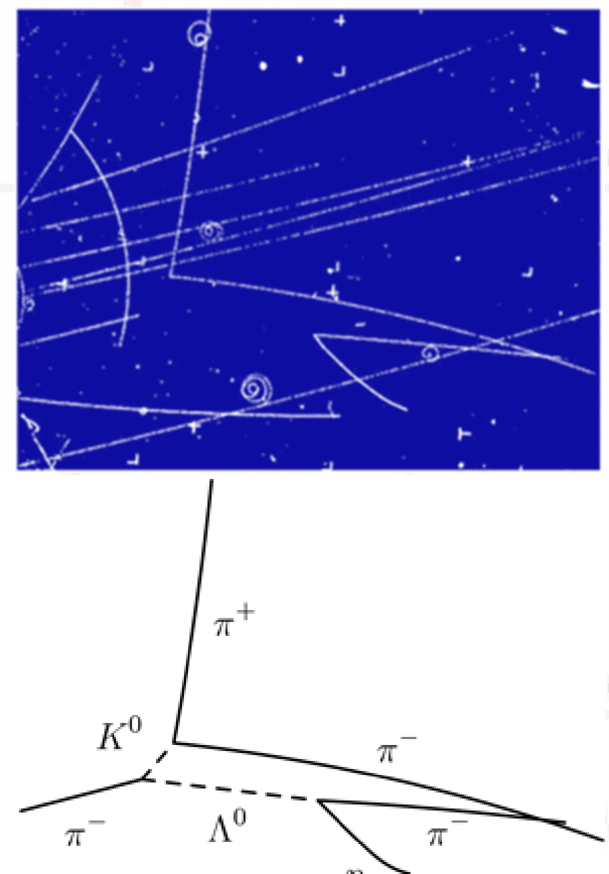
Spin ½ baryon octet:



Λ hyperon:

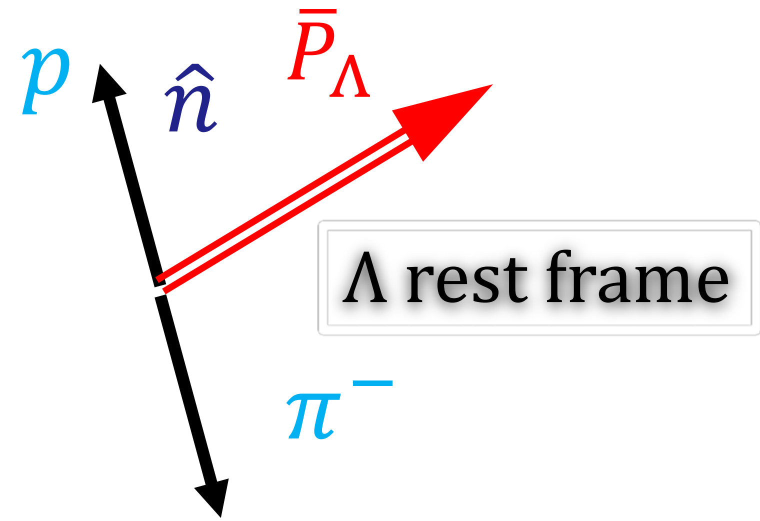
$$M_\Lambda = 1.115\ \mathrm{GeV}/c^2$$

$$c\tau = 7.9\ \mathrm{cm}$$



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

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



p=100 MeV/c

Hyperon polarization is determined from its own decay

If proton polarization could be measured
there is one more decay parameter ϕ ...

$$\alpha_Y = \frac{2\mathrm{Re}(s^*p)}{|s|^2+|p|^2}\,,\ \beta_Y = \frac{2\mathrm{Im}(s^*p)}{|s|^2+|p|^2} = \sqrt{1-\alpha_Y^2}\sin\phi_\Lambda$$

$$\gamma_Y = \frac{|s|^2-|p|^2}{|s|^2+|p|^2} = \sqrt{1-\alpha_Y^2}\cos\phi_Y$$

$$\boldsymbol{P}_B = \frac{(\alpha_Y + \boldsymbol{P}_Y\cdot\hat{\boldsymbol{n}})\hat{\boldsymbol{n}} + \beta_Y\boldsymbol{P}_Y\times\hat{\boldsymbol{n}} + \gamma_Y\hat{\boldsymbol{n}}\times\boldsymbol{P}_Y\times\hat{\boldsymbol{n}}}{1+\alpha_Y\boldsymbol{P}_Y\cdot\hat{\boldsymbol{n}}}$$

Hyperon properties

α_-

hyperon	Mass [GeV/c^2]	$c\tau$ [cm]	decay (BF)	α	ϕ
$\Lambda(uds)$	1.116	7.9	$p\pi^-$ (63.9%)	**0.642 ± 0.013**	$-6.5^\circ \pm 3.5^\circ$
			$n\pi^0$ (35.8%)		
$\bar{\Lambda}(\bar{u}\bar{d}\bar{s})$			$\bar{p}\pi^+$ (63.9%)	**−0.71 ± 0.08**	–
$\Sigma^-(dds)$	1.197	4.4	$n\pi^-$ (99.8%)	-0.068 ± 0.008	$10^\circ \pm 15^\circ$
$\Sigma^+(uus)$	1.189	2.4	$p\pi^0$ (51.6%)	-0.980 ± 0.017	$36^\circ \pm 34^\circ$
			$n\pi^+$ (48.3%)	-0.068 ± 0.013	$167 \pm 20^\circ$
$\Xi^0(uss)$	1.315	8.7	$\Lambda\pi^0$ (99.5%)	-0.406 ± 0.085	$21^\circ \pm 12^\circ$
$\Xi^-(dss)$	1.321	5.1	$\Lambda\pi^-$ (99.8%)	-0.458 ± 0.012	$-2.1^\circ \pm 0.8^\circ$

α_0

α_+

CP violating asymmetries

$$A_{CP} = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}$$

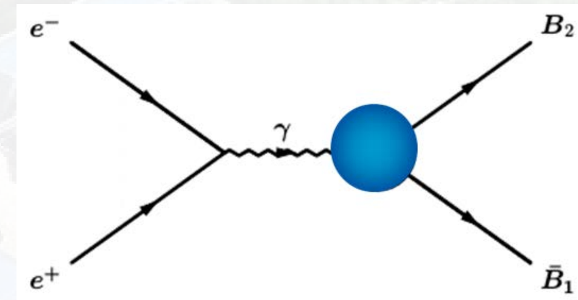
$$\beta = \sqrt{1 - \alpha^2} \sin \phi$$

$$B_{CP} = \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}}$$

In sequential decays also ϕ (β) is accessible

Hyperon-antihyperon production at BESIII

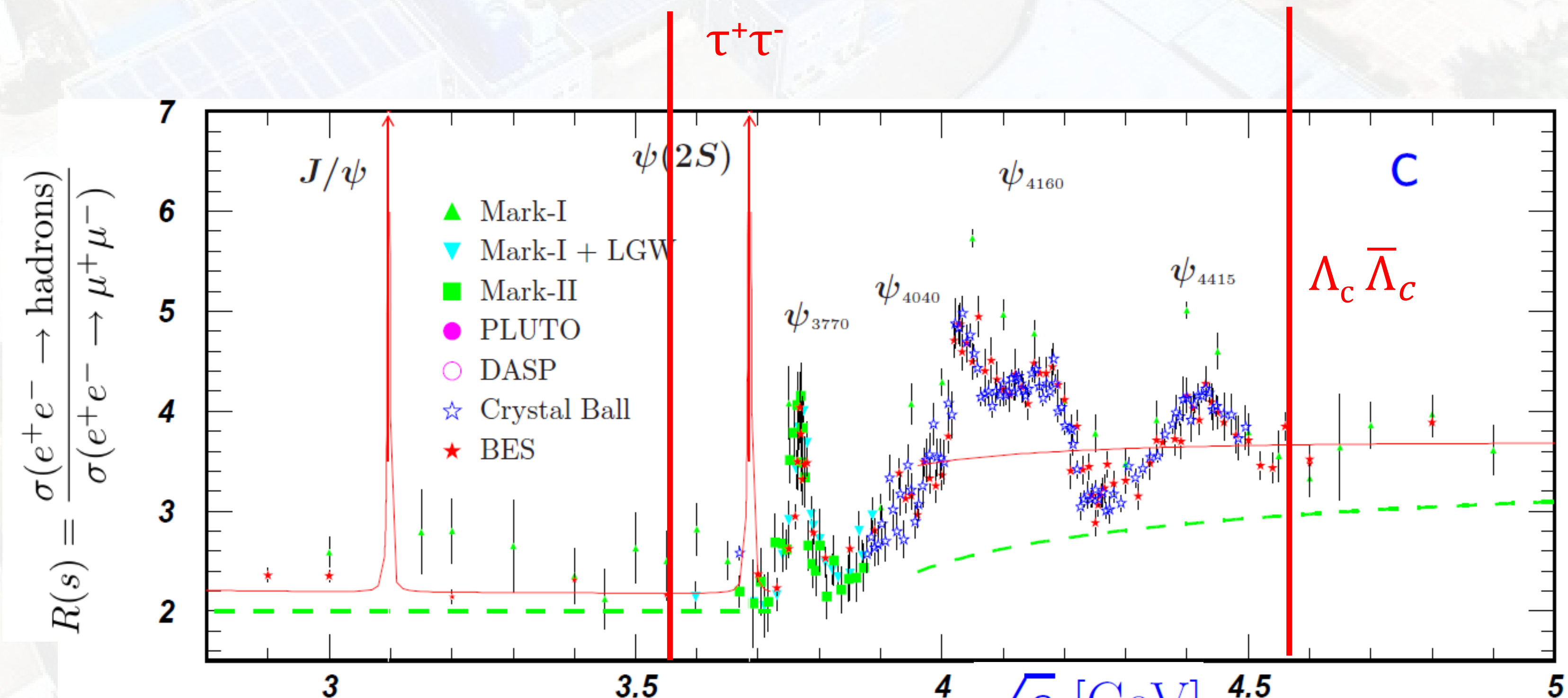
e^+e^- collider: $2.0\ \text{GeV} \leq \sqrt{s} \leq 4.6\ \text{GeV}$



Thresholds:

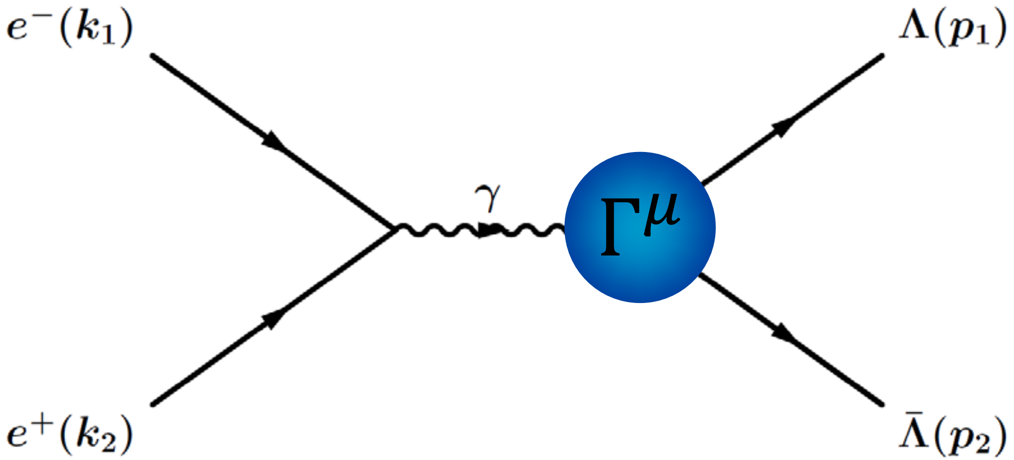
$\Lambda\bar{\Lambda}$:	2.231 GeV	$\Sigma^+\bar{\Sigma}^-$	2.379 GeV
$\Sigma^0\bar{\Sigma}^0$	2.385 GeV	$\Sigma^-\bar{\Sigma}^+$	2.395 GeV
$\Xi^0\bar{\Xi}^0$	2.630 GeV	$\Xi^-\bar{\Xi}^+$	2.643 GeV
$\Lambda\bar{\Sigma}^0$	2.308 GeV		

($\Omega\bar{\Omega}$ 3.345 GeV)



$1.31\text{x}10^9\ J/\Psi$

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



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

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

F_1 (Dirac) and F_2 (Pauli) Form Factors

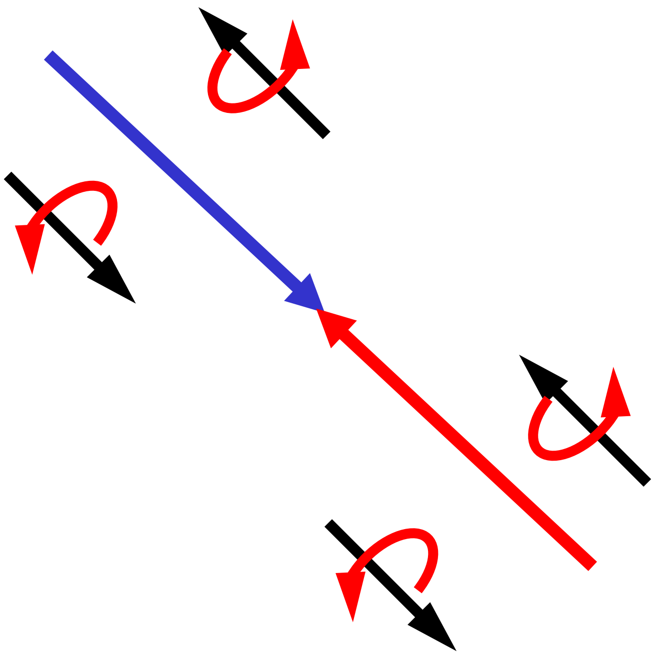
Sachs Form Factors (FFs) ⇔ helicity amplitudes:

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

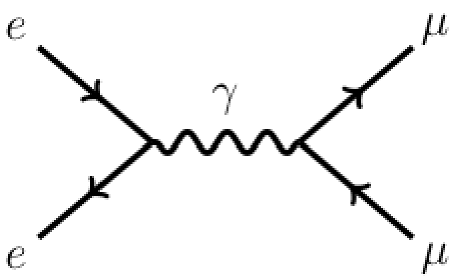
$$\tau = \frac{s}{4M_B^2}$$

Cross-section for e+e− → μ+μ−

At high energies annihilating e+e- have opposite helicities.

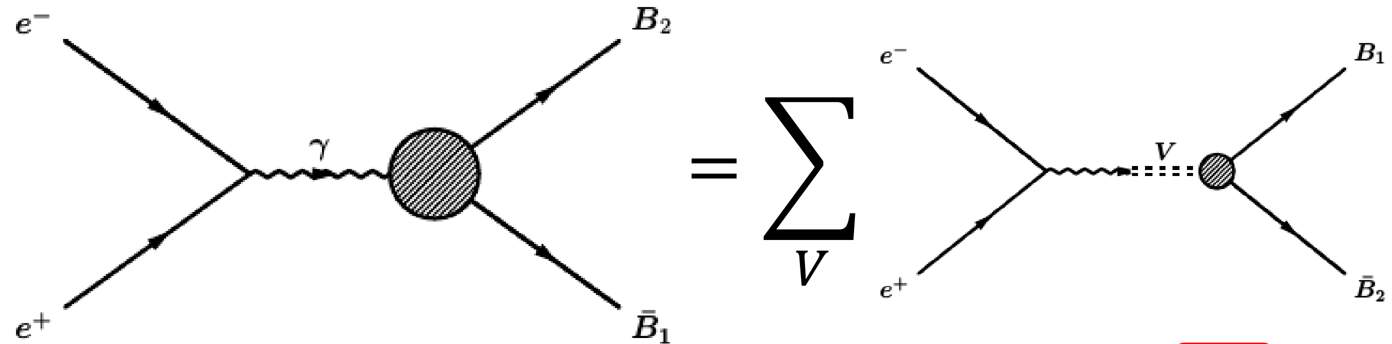


$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}(1 + \cos^2\theta)$$



$$F_1(0) = 1, \quad F_2(0) = a_\mu$$

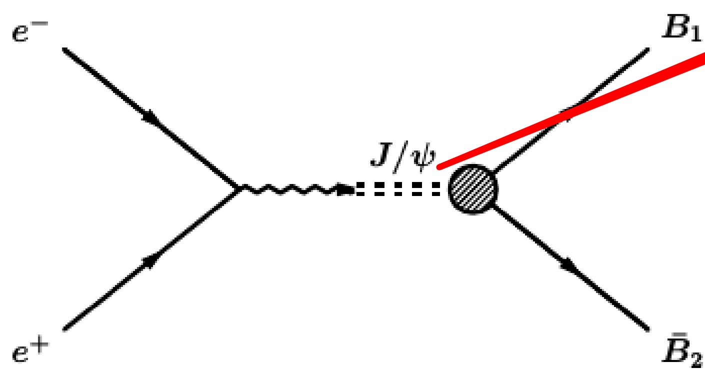
Baryon FFs (continuum):



Baryons B_1 and $\bar{B}_2$
(spin 1/2, 3/2, ...)

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

vs J/ψ decay:



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

Cabibbo, Gatto PR124 (1961)1577

Time like 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

Charmonia decays:
Fäldt, Kupsc PLB772 (2017) 16

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

The process at Born level is described by two complex FFs:
$G_M(s)$, $G_E(s)$

⇨ at given energy $\sqrt{s}$ three real parameters (neglecting overall phase):

- cross section (σ)
- angular distribution parameter (α_ψ) or R
- and relative phase ($\Delta\Phi$)

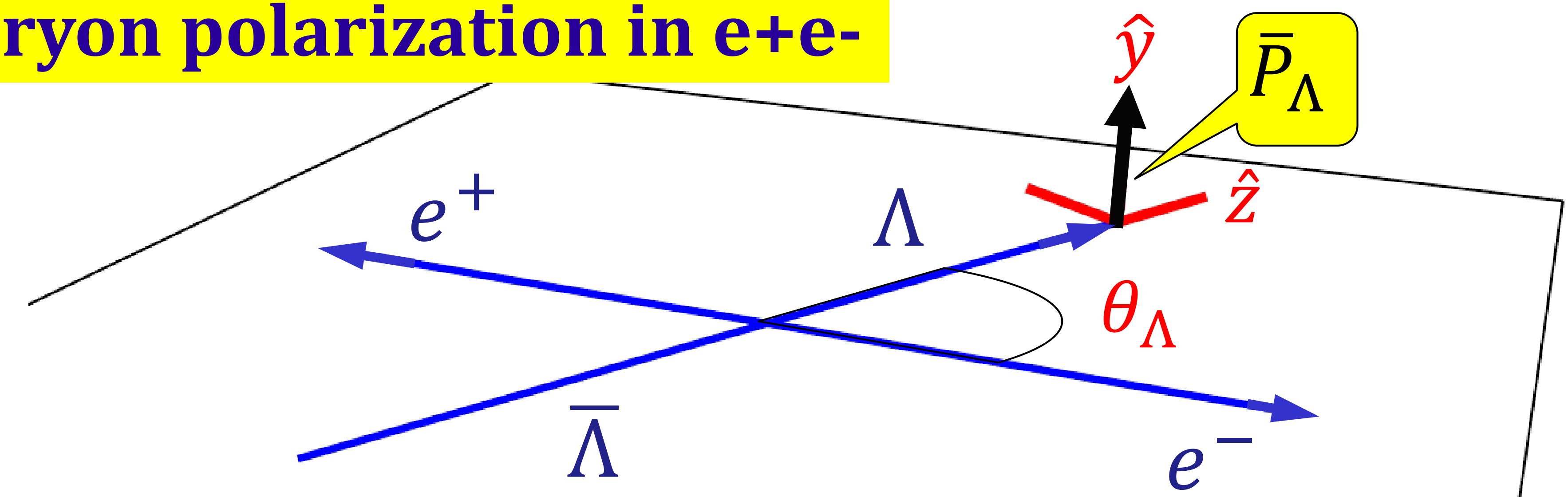
$$\alpha_\psi = \frac{\tau - R^2}{\tau + R^2} \qquad R = \left|\frac{G_E}{G_M}\right| \qquad G_E = R G_M e^{i\Delta\Phi}$$

Baryon angular distribution:
(well known)

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

Phase predicted/expected for continuum
but neglected/not expected for the decays

Baryon polarization in e+e-



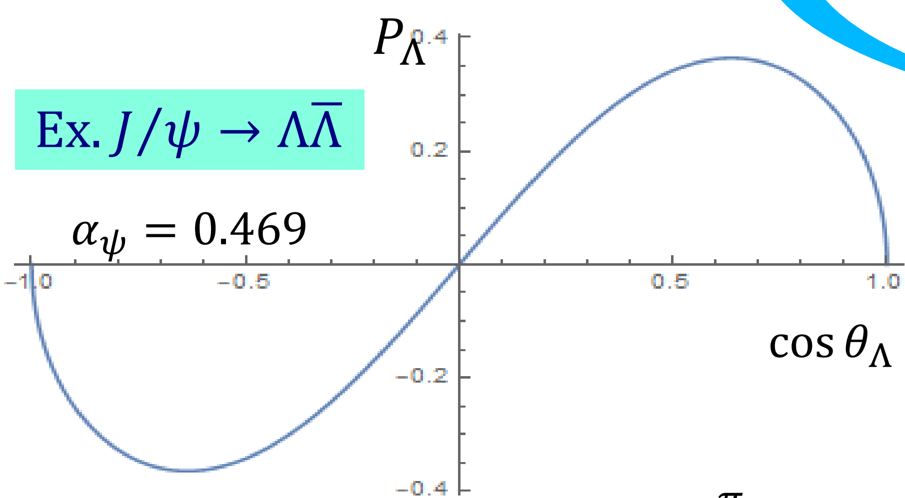
For unpolarized e+e- beams ⇨ transverse polarization:

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

$\Delta\Phi \neq 0$

Ex. $J/\psi \to \Lambda\bar{\Lambda}$

$\alpha_\psi = 0.469$

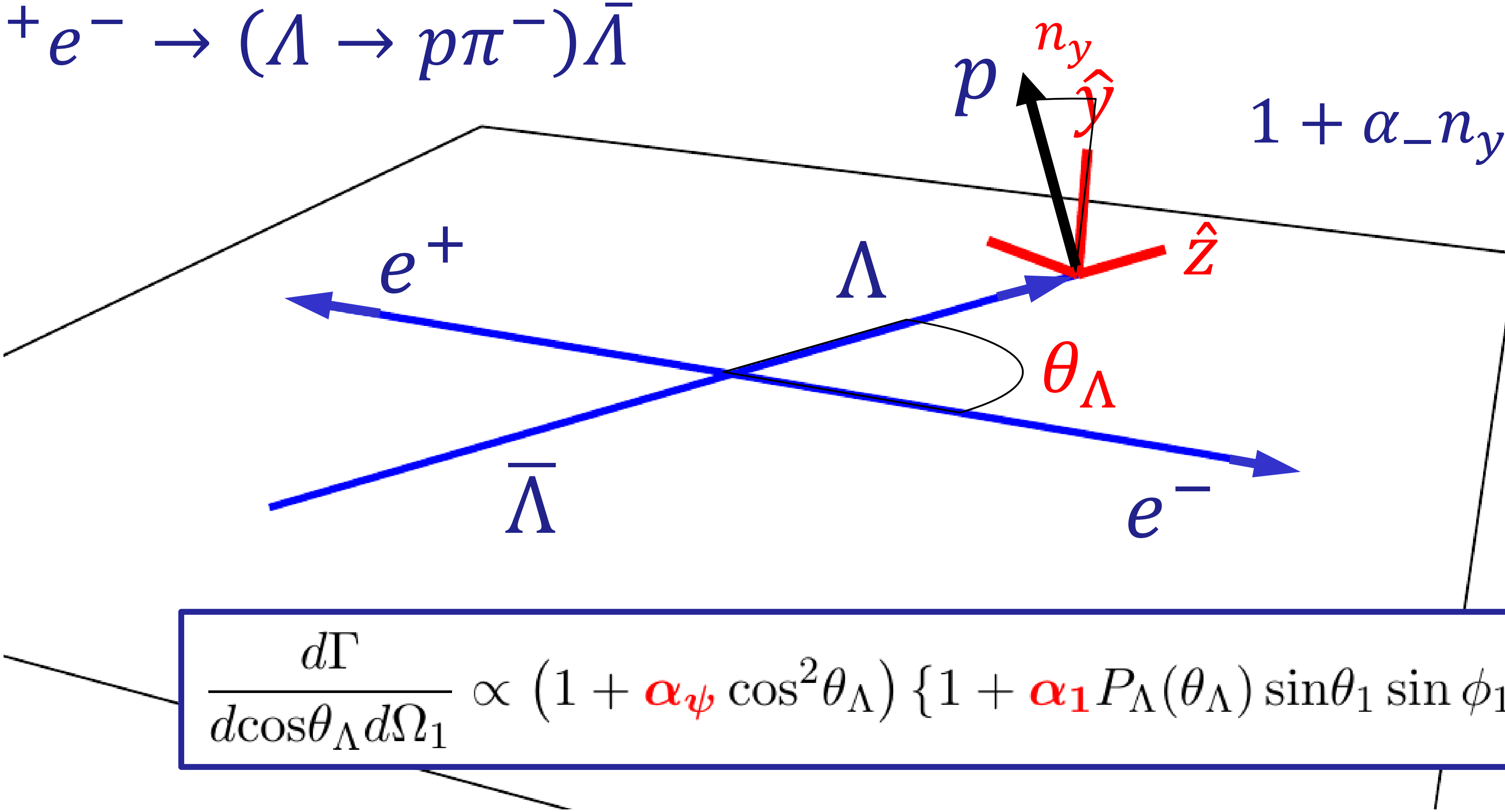


Max P_Λ= 36.4%

if $\Delta\Phi = \frac{\pi}{2}$

Inclusive angular distributions

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



$$1 + \alpha_- n_y P_y$$

$$\frac{d\Gamma}{d\cos\theta_\Lambda d\Omega_1} \propto \left(1 + \alpha_\psi \cos^2\theta_\Lambda\right)\{1 + \alpha_1 P_\Lambda(\theta_\Lambda)\sin\theta_1 \sin\phi_1\}$$

$\Lambda \to p\pi^-$: $\Omega_1 = (\cos\theta_1, \phi_1)$: $\alpha_1 \to \alpha_-$

Hyperon polarization determined from
angular distribution of the nucleon from the weak decay

Exclusive angular distributions

Two decay modes for $\overline{\Lambda}$:

$e^+e^- \to (\Lambda \to p\pi^-)(\overline{\Lambda} \to \bar{p}\pi^+)$ $: \alpha_2 \to \alpha_+$

$e^+e^- \to (\Lambda \to p\pi^-)(\overline{\Lambda} \to \bar{n}\pi^0)$ $: \alpha_2 \to \bar{\alpha}_0$

$\overline{\Lambda} \to \bar{p}\pi^+ (or\ \bar{n}\pi^0)$: $\Omega_2 = (\cos\theta_2, \phi_2)$

$\Lambda \to p\pi^-$: $\Omega_1 = (\cos\theta_1, \phi_1)$ $: \alpha_1 \to \alpha_-$

$d\Gamma \propto \mathcal{W}(\boldsymbol{\xi})d\boldsymbol{\xi} = \mathcal{W}(\boldsymbol{\xi})d\cos\theta_\Lambda d\Omega_1 d\Omega_2$ $\boldsymbol{\xi} : (\cos\theta_\Lambda, \Omega_1, \Omega_2)$ 5D PhSp

Cross section

Spin correlations

Polarizations

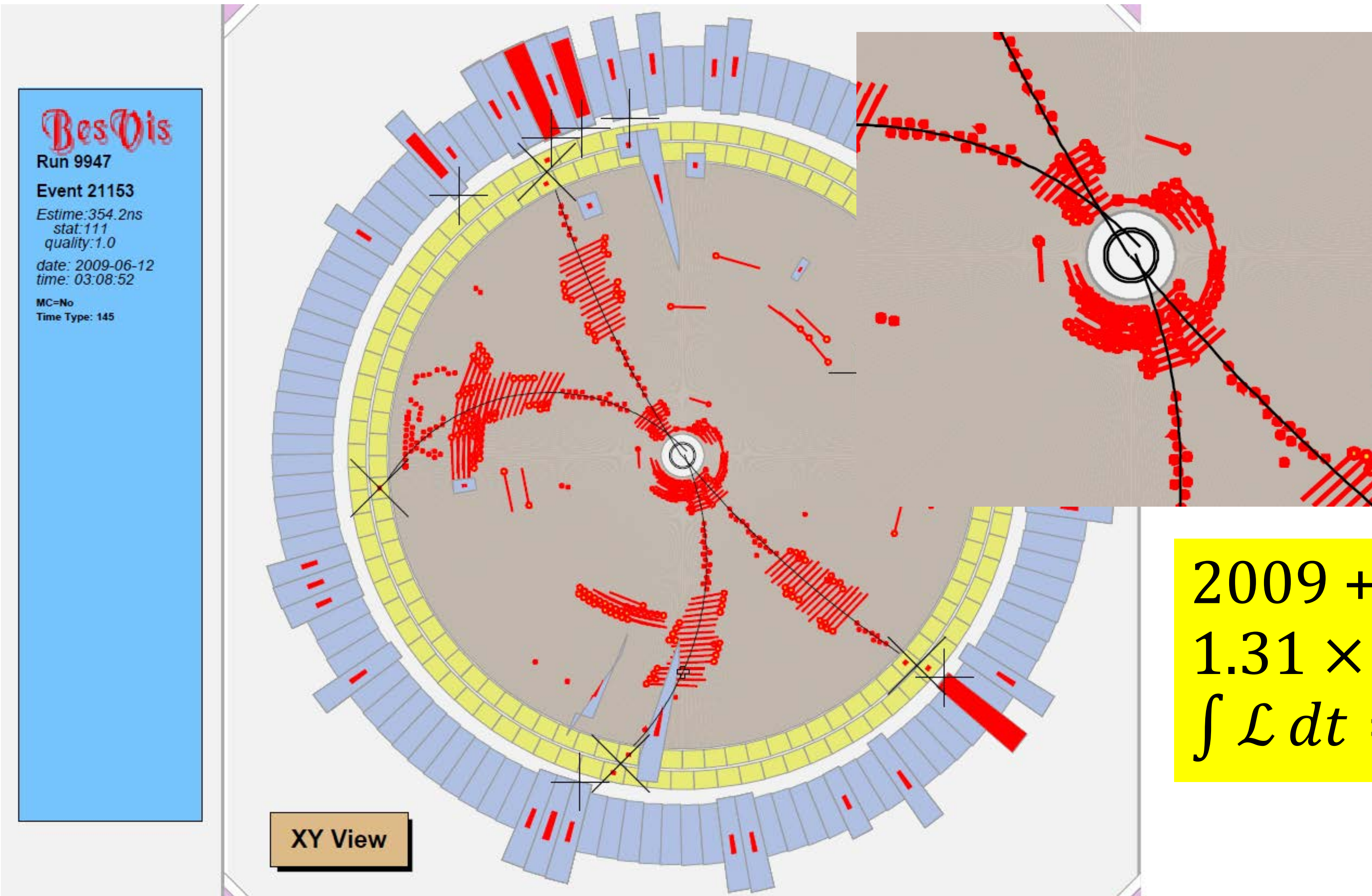
$$
\begin{aligned}
\mathcal{W}(\boldsymbol{\xi}) = 1 &+ \boldsymbol{\alpha_\psi}\cos^2\theta_\Lambda \\
&+ \boldsymbol{\alpha_1\alpha_2}\left(\sin^2\theta_\Lambda \sin\theta_1 \sin\theta_2 \cos\phi_1 \cos\phi_2 + \cos^2\theta_\Lambda \cos\theta_1 \cos\theta_2\right) \\
&+ \boldsymbol{\alpha_1\alpha_2}\sqrt{1-\boldsymbol{\alpha_\psi}^2}\cos(\boldsymbol{\Delta\Phi})\left\{\sin\theta_\Lambda \cos\theta_\Lambda \left(\sin\theta_1 \cos\theta_2 \cos\phi_1 + \cos\theta_1 \sin\theta_2 \cos\phi_2\right)\right\} \\
&+ \boldsymbol{\alpha_1\alpha_2}\,\boldsymbol{\alpha_\psi}\left(\cos\theta_1 \cos\theta_2 - \sin^2\theta_\Lambda \sin\theta_1 \sin\theta_2 \sin\phi_1 \sin\phi_2\right) \\
&+ \sqrt{1-\boldsymbol{\alpha_\psi}^2}\sin(\boldsymbol{\Delta\Phi})\sin\theta_\Lambda \cos\theta_\Lambda \left(\boldsymbol{\alpha_1}\sin\theta_1 \sin\phi_1 + \boldsymbol{\alpha_2}\sin\theta_2 \sin\phi_2\right)
\end{aligned}
$$

$\Delta\Phi \neq 0$ $\Rightarrow$ independent determination of α_1 and α_2!

Fäldt, Kupsc PLB772 (2017) 16

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

event in BESIII detector



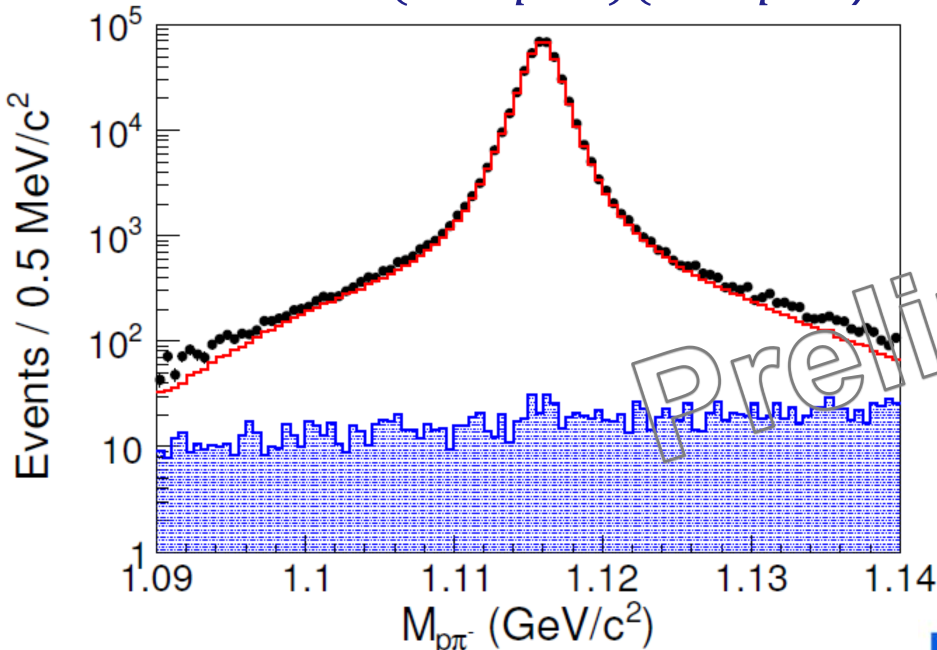
2009 + 2012 Data

1.31×10^9 J/ψ

$\int \mathcal{L}\, dt = 386.0$ pb^{-1}

Jianbin

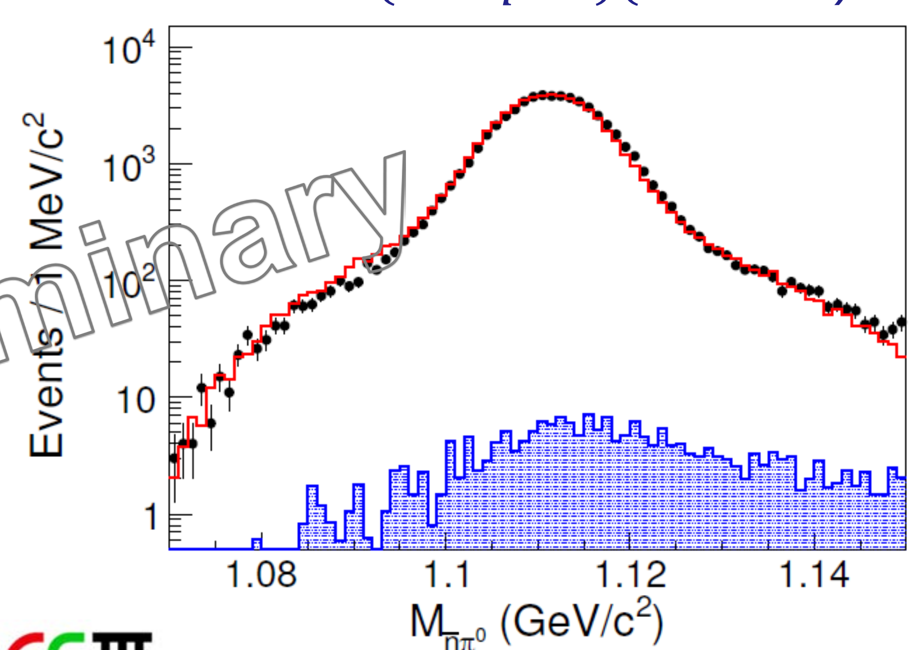
$e^+e^- \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$



420593 events

399 background

$e^+e^- \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{n}\pi^0)$



47009 events

66 background

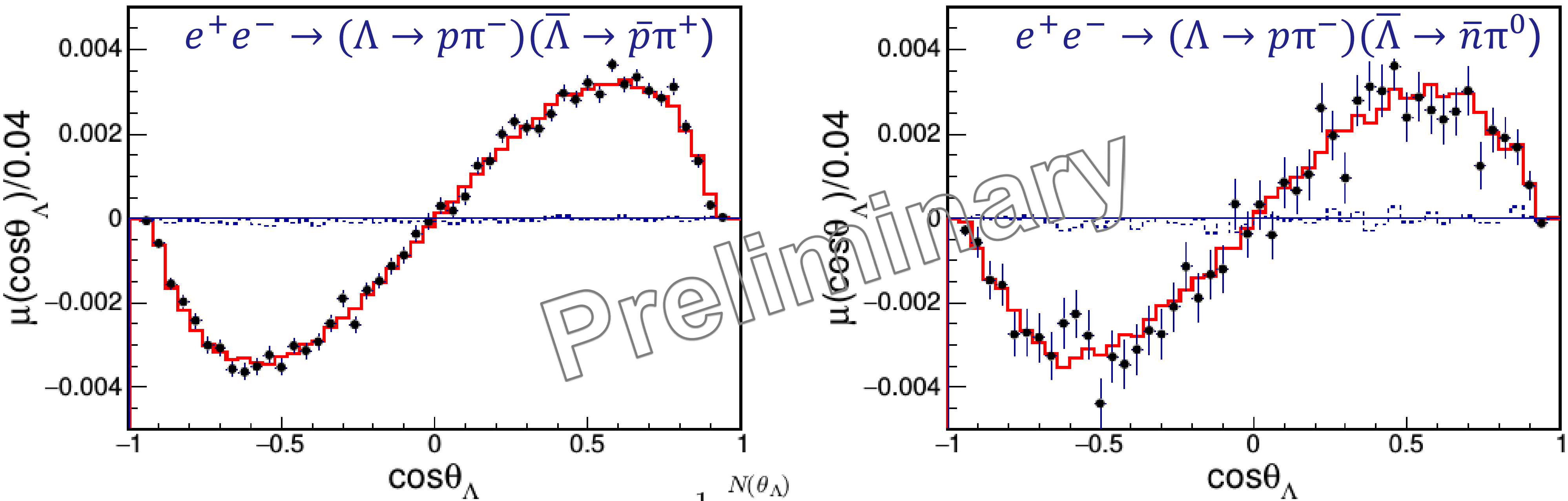
Global unbinned maximum log likelihood fit to the two data sets with the likelihood function constructed from probability function:

$$\mathcal{C}(\alpha_\psi, \Delta\Phi, \alpha_-, \alpha_2)\mathcal{W}(\boldsymbol{\xi}_i; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_2)$$

Where $\mathcal{C}(\alpha_\psi, \Delta\Phi, \alpha_-, \alpha_2)$ is the normalization factor obtained from $\mathcal{W}(\boldsymbol{\xi}_i; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_2)$ weighted sum for flat phase space model MC events after detector reconstruction.

Fit results

ΔΦ=42.3°±0.6°±0.5°



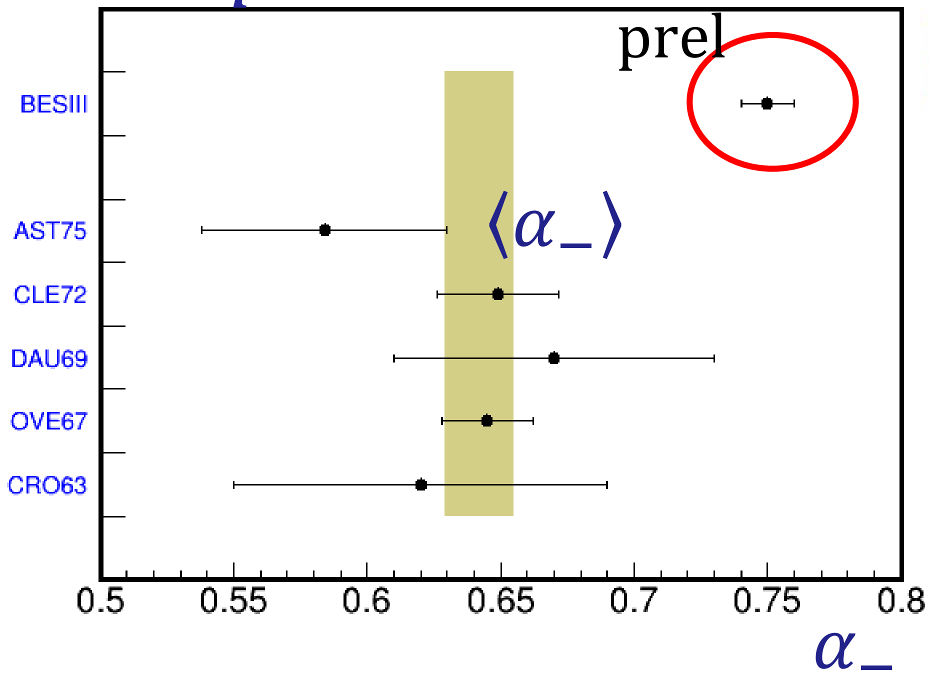
Moment: $\mu(\cos\theta_\Lambda) = \frac{1}{N}\sum_{i}^{N(\theta_\Lambda)}(\sin\theta_1^i \sin\phi_1^i - \sin\theta_2^i \sin\phi_2^i)$

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
$\bar{\alpha}_0$	$\mathbf{-0.692 \pm 0.016 \pm 0.006}$	–
A_{CP}	$\mathbf{-0.006 \pm 0.012 \pm 0.007}$	0.006 ± 0.021 PDG
$\bar{\alpha}_0/\alpha_+$	$\mathbf{0.913 \pm 0.028 \pm 0.012}$	–

Preliminary

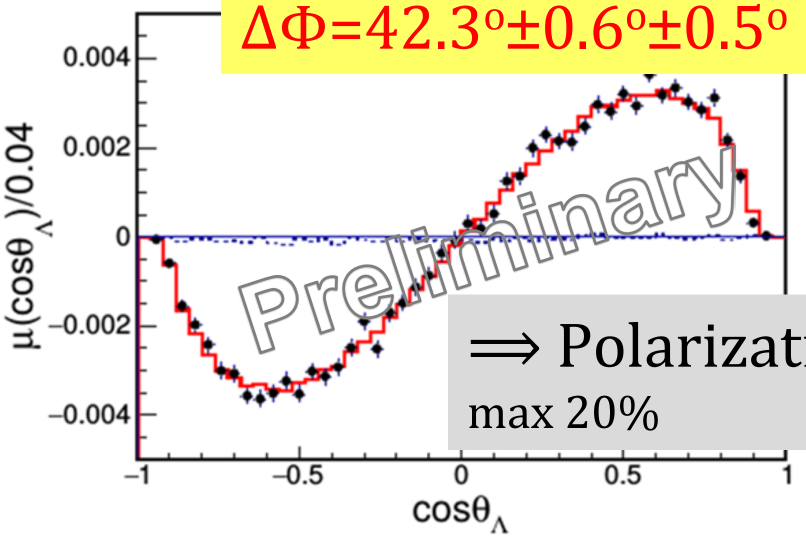
Summary of the $J/\psi \to \Lambda\bar{\Lambda}$ analysis

$\Lambda \to p\pi^-$: $\alpha_-=0.750\pm0.009\pm0.004$



17(3)% larger than PDG average
> 5 σ difference

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



⟹ Polarization: max 20%

CP test: $A_{CP} = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$

$A_{CP} = -0.006 \pm 0.012 \pm 0.007$ prel

Previous result (using αP product):

$A_{CP} = 0.013 \pm 0.021$
PS185 PRC54(96)1877

CKM $A_{CP} \sim 10^{-4}$

Parity conserving / violating amplitudes

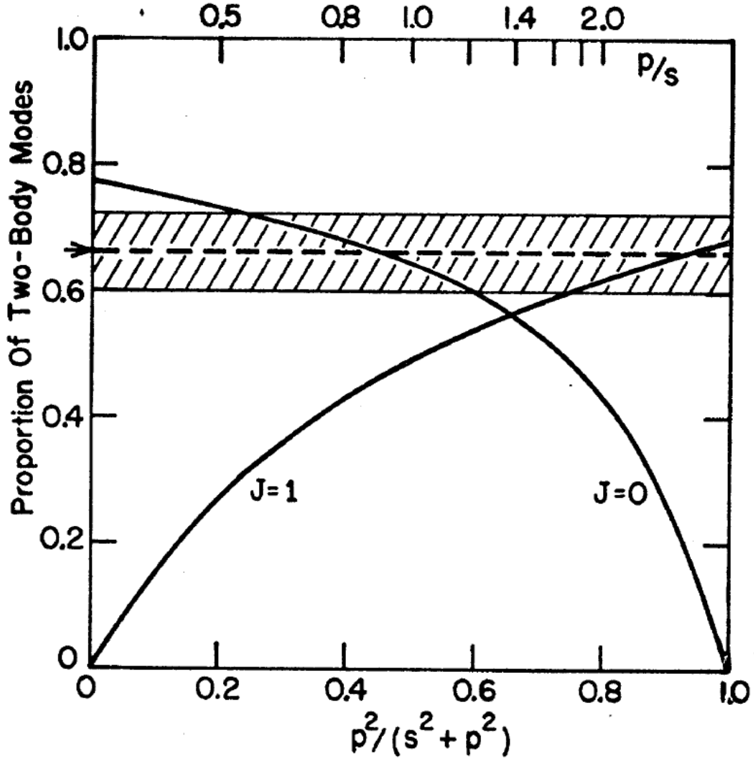
	$\frac{p^2}{p^2+s^2}$	p^2/s^2	p/s
PDG	0.119(6)	0.135(8)	0.368(11)
BESIII	0.171(6)	0.207(9)	0.455(10)

$$\alpha_Y = \frac{2\mathrm{Re}(s^* p)}{|s|^2+|p|^2}, \quad \beta_Y = \frac{2\mathrm{Im}(s^* p)}{|s|^2+|p|^2} = \sqrt{1-\alpha_Y^2}\sin\phi_\Lambda$$

$$\gamma_Y = \frac{|s|^2-|p|^2}{|s|^2+|p|^2} = \sqrt{1-\alpha_Y^2}\cos\phi_Y$$

$${}_\Lambda H^4 \longrightarrow \pi^- + He^4$$

Dalitz,Liu PR116,1312



Test of $|\Delta I| = {}^{1}/_{2}$ rule

$${}^{\alpha_0}/_{\alpha_-} = 0.913 \pm 0.028 \pm 0.013 \quad \text{BESIII}$$

$${}^{\Gamma^0}/_{\Gamma^-} = 0.560 \pm 0.009 \quad \text{PDG}$$

$\Lambda \to p\pi^-$

$$S^- = -(\sqrt{\tfrac{2}{3}})S_{11}e^{i\delta_1} + (\sqrt{\tfrac{1}{3}})S_{33}e^{i\delta_3},$$
$$P^- = -(\sqrt{\tfrac{2}{3}})P_{11}e^{i\delta_{11}} + (\sqrt{\tfrac{1}{3}})P_{33}e^{i\delta_{31}}$$

$\Lambda \to n\pi^0$

$$S^0 = (\sqrt{\tfrac{1}{3}})S_{11}e^{i\delta_1} + (\sqrt{\tfrac{2}{3}})S_{33}e^{i\delta_3},$$
$$P^0 = (\sqrt{\tfrac{1}{3}})P_{11}e^{i\delta_{11}} + (\sqrt{\tfrac{2}{3}})P_{33}e^{i\delta_{31}},$$

$$|\Delta I| = {}^{1}/_{2} \;\Rightarrow\; \Gamma^- = 2\Gamma^0; \alpha_0 = \alpha_-$$

$$\frac{\alpha^0}{\alpha^-} \cong \frac{1}{2}\frac{\Gamma^-}{\Gamma^0}\left(1 + \frac{3}{\sqrt{2}}\frac{S_{33}\cos(\delta_{11}-\delta_3)}{S_{11}\cos(\delta_{11}-\delta_1)} + \frac{3}{\sqrt{2}}\frac{P_{33}\cos(\delta_{31}-\delta_1)}{P_{11}\cos(\delta_{11}-\delta_1)}\right)$$

Corrections: Phase Space, radiative (Coulomb)…

Outlook:

Λ DECAY PARAMETERS

α_- FOR $\Lambda \to p\pi^-$	0.642 ± 0.013
α_+ FOR $\overline{\Lambda} \to \overline{p}\pi^+$	-0.71 ± 0.08
ϕ ANGLE FOR $\Lambda \to p\pi^-$ ($\tan\phi = \beta / \gamma$)	-6.5 ± 3.5 °
$\alpha_0 / \alpha_- = \alpha(\Lambda \to n\pi^0) / \alpha(\Lambda \to p\pi^-)$	1.01 ± 0.07
$(\alpha + \bar{\alpha})/(\alpha - \bar{\alpha})$ in $\Lambda \to p\pi^-$, $\overline{\Lambda} \to \overline{p}\pi^+$	0.006 ± 0.021
g_A / g_V FOR $\Lambda \to pe^-\overline{\nu}_e$	-0.718 ± 0.015

Decay Modes

Mode			Fraction (Γ_i / Γ)
Γ_1	$p\pi^-$		$(63.9 \pm 0.5)\%$
Γ_2	$n\pi^0$		$(35.8 \pm 0.5)\%$
Γ_3	$n\gamma$		$(1.75 \pm 0.15) \times 10^{-3}$
Γ_4	$p\pi^-\gamma$	[1]	$(8.4 \pm 1.4) \times 10^{-4}$
Γ_5	$pe^-\overline{\nu}_e$		$(8.32 \pm 0.14) \times 10^{-4}$
Γ_6	$p\mu^-\overline{\nu}_\mu$		$(1.57 \pm 0.35) \times 10^{-4}$

$\bar{\Lambda} \to \bar{n}\gamma$

PDG18

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

$J/\psi, \psi(2S) \to B\bar{B}$

Decay mode	Events	$\mathcal{B}(\times 10^{-4})$
$J/\psi \to \Lambda\bar{\Lambda}$	440675 ± 670	$19.43 \pm 0.03 \pm 0.33$
$\psi(2S) \to \Lambda\bar{\Lambda}$	31119 ± 187	$3.97 \pm 0.02 \pm 0.12$
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	111026 ± 335	$11.64 \pm 0.04 \pm 0.23$
$\psi(2S) \to \Sigma^0\bar{\Sigma}^0$	6612 ± 82	$2.44 \pm 0.03 \pm 0.11$
$J/\psi \to \Sigma(1385)^0\bar{\Sigma}(1385)^0$	102762 ± 852	10.71 ± 0.09
$J/\psi \to \Xi^0\bar{\Xi}^0$	134846 ± 437	11.65 ± 0.04
$\psi(2S) \to \Sigma(1385)^0\bar{\Sigma}(1385)^0$	2214 ± 148	0.69 ± 0.05
$\psi(2S) \to \Xi^0\bar{\Xi}^0$	10839 ± 123	2.73 ± 0.03
$J/\psi \to \Xi^-\bar{\Xi}^+$	42811 ± 231	10.40 ± 0.06
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}(1385)^+$	42595 ± 467	10.96 ± 0.12
$J/\psi \to \Sigma(1385)^+\bar{\Sigma}(1385)^-$	52523 ± 596	12.58 ± 0.14
$\psi(2S) \to \Xi^-\bar{\Xi}^+$	5337 ± 83	2.78 ± 0.05
$\psi(2S) \to \Sigma(1385)^-\bar{\Sigma}(1385)^+$	1375 ± 98	0.85 ± 0.06
$\psi(2S) \to \Sigma(1385)^+\bar{\Sigma}(1385)^-$	1470 ± 95	0.84 ± 0.05

BESIII

Phys. Rev. D 93, 072003 (2016)
PLB770(2017)217

Phys. Rev. D 95, 052003 (2017)

1.31×10^9 J/ψ and 4.48×10^8 ψ(2S)

J/ψ→ $n\bar{n}$: $\mathfrak{B} = 2.09(16) \times 10^{-3}$

$p_{\rm cm} = 1231$ MeV$/c$

Conclusions:

Polarization in $e^+e^- \to \Lambda\bar{\Lambda}$ observed at J/ψ (unexpected)
[phase close to 40°]

J/ψ and ψ' decays into hyperon-antihyperon:
unique spin correlated system for CP tests and for determination of (anti-)hyperon decay parameters (polarization is essential!)

Presented results use $1.31 \cdot 10^9$ J/ψ but 10^{10} J/ψ are being collected

17(3)% larger value for the $\Lambda \to p\pi^-$ decay asymmetry (α_-)
⇒ calls for reinterpretation of **all** Λ polarization measurements!

α_-: 0.642±0.012 (PDG) ⇨ 0.750±0.009±0.004

Thank you!

BESIII

arXiv:1808.08917

BESIII Prel.