Observation of spin polarization in $e^+e^- \to \Lambda\bar{\Lambda}$ at BESIII

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Outline

- Electromagnetic Form Factors
- The BESIII experiment
- Observation of spin polarization in $e^+e^- \to \Lambda\bar{\Lambda}$ at BESIII
  - $\Lambda\bar{\Lambda}$ decay asymmetry parameters with J/ψ
  - Time-like Λ electromagnetic form factors with scan data at 2.396 GeV
- Summary

Electromagnetic form factors

- Assuming one-photon exchange ($e^+e^- \to \gamma^* \to B\bar{B}$), the Born cross section of spin 1/2 baryon-antibaryon pair production can be parameterized in terms of G_E and G_M:

$$\sigma_{B\bar{B}}(s) = \frac{4\pi\alpha^2\beta}{3s}\left[|G_M(s)|^2 + \frac{1}{2\tau}|G_E(s)|^2\right]. \quad (1)$$

α=1/137.036 the fine-structure constant, $\beta = \sqrt{1 - 4m_B^2c^4/s}$ the velocity of the produced baryon, c the speed of light, s the square of the c.m. energy, m_B the mass of the baryon and $\tau = s/(4m_B^2)$.

- The effective form factor is defined as

$$|G(s)| \equiv \sqrt{\frac{2\tau|G_M(s)|^2 + |G_E(s)|^2}{2\tau + 1}}. \quad (2)$$

Electromagnetic form factors

- The $|G(s)|$ can be straightly calculated:

$$|G(s)| = \sqrt{\frac{\sigma_{B\bar{B}}(s)}{(1+\frac{1}{2\tau})(\frac{4\pi\alpha^2\beta}{3s})}} \tag{3}$$

- $G_E(s)$ and $G_M(s)$ can be expressed in terms of the effective form factor $G(s)$ and the ratio $R = |G_E(s)/G_M(s)|$:

$$|G_M(s)|^2 = \frac{2\tau+1}{2\tau+R^2}|G(s)|^2, \quad |G_E(s)|^2 = R^2\frac{2\tau+1}{2\tau+R^2}|G(s)|^2. \tag{4}$$

- The ratio R can be extracted from the scattering angle of the baryon:

$$\frac{d\sigma_{Born}(s)}{d\cos\theta} = \frac{2\pi\alpha^2\beta}{4s}[(1+\cos^2\theta) + \frac{1}{\tau}R^2(\sin^2\theta)]. \tag{5}$$

Electromagnetic form factors

- This can be expressed in a simpler form, linear in $\cos^2\theta$

$$\frac{d\sigma}{d\cos\theta} \propto 1 + \eta\cos^2\theta, \tag{6}$$

  where η is the slope and satisfies $-1 < \eta < 1$.

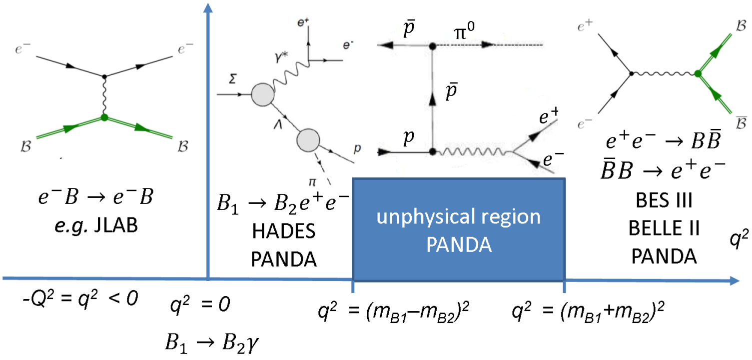
- R can then be extracted from η

$$R = \sqrt{\tau}\sqrt{\frac{1-\eta}{1+\eta}}. \tag{7}$$

- Conversely η can be expressed in terms of R as:

$$\eta = \frac{\tau - R^2}{\tau + R^2}. \tag{8}$$

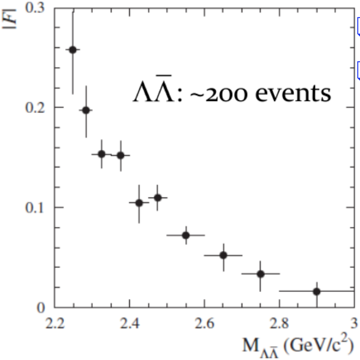
Space-like *versus* Time-like Electromagnetic Form Factors



- Spin 1/2 baryons have magnetic G_M and electric G_E form factors
- Space-like ($q^2 < 0$) G_E and G_M real numbers
- Time-like ($q^2 \geq 4M_B^2 > 0$)
  - $G_E(s) = |G_E(s)|e^{i\Phi_E}$, $G_M(s) = |G_M(s)|e^{i\Phi_M}$
  - Relative phase: $\Delta\Phi = \Phi_E - \Phi_M$

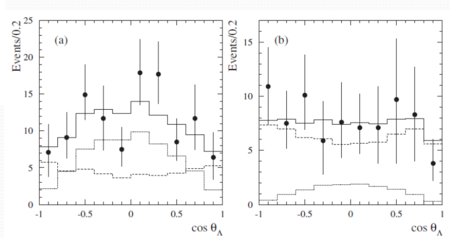
Experimental status

- Babar Collaboration:



Phys. Rev. D76, 092006(2007)

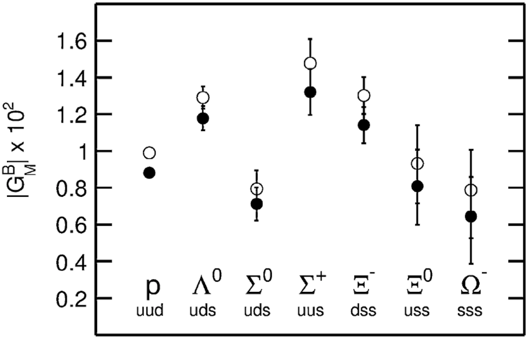
- $e^+e^- \to \gamma\Lambda\bar{\Lambda}$
- Based on very little data.
- Total error on the G_E/G_M ratio 33-100%.



- Λ polarization: $-0.22 < P_n < 0.28$
- Relative phase: $-0.76 < sin\phi < 0.98$

Experimental status

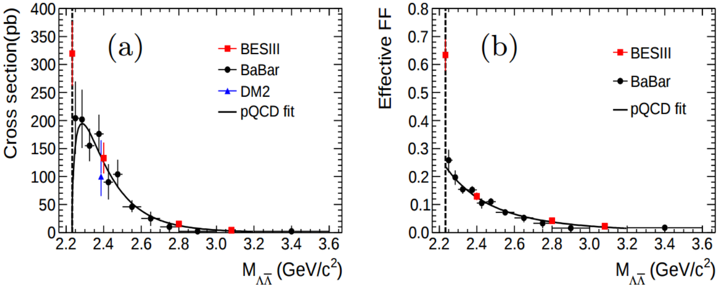
- CLEO-c: very few hyperon events @3.773GeV (15 ∼ 105 events)
  Phy. Lett. B739(2014)



- Far from threshold = low cross sections = small data samples = large uncertainties.
- No angular distributions → no ratio $R = G_E/G_M$ extracted → the EMFFs calculated assuming R=1 or 0.

Experimental status

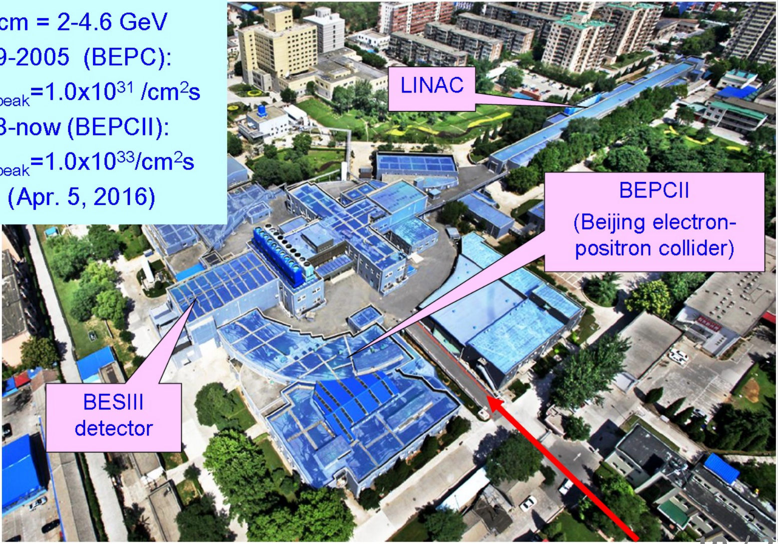
- with data at 2.2324 GeV, 2.4 GeV, 2.8 GeV and 3.065 GeV collected by BESIII in 2011-2012
- The 2.2324 GeV is the closest to the $\Lambda\bar{\Lambda}$ threshold so far.
- The cross section of 319.5 ± 57.6 pb which is larger than theoretical predictions.



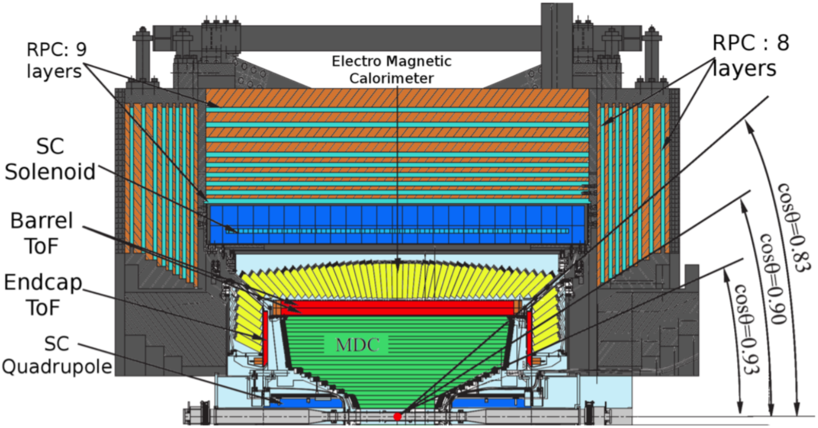
See Liang Yan's talk

Beijing Electron Positron Collider (BEPC)

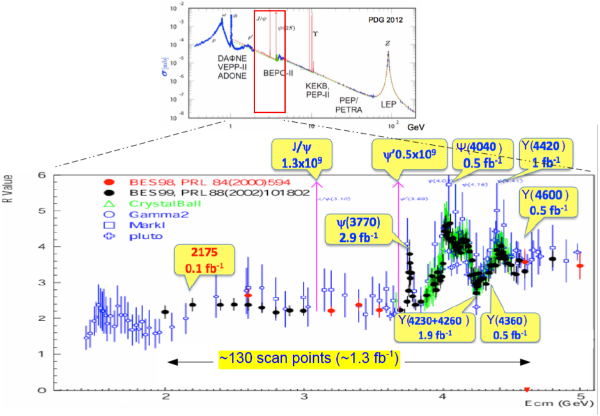
- Founded: 1984
  Ecm = 2-4.6 GeV
- 1989-2005 (BEPC):
  $L_{peak}=1.0\times10^{31}$ /cm^{2}s
- 2008-now (BEPCII):
  $L_{peak}=1.0\times10^{33}$/cm^{2}s
  (Apr. 5, 2016)



BEijing Spectrometer (BES)

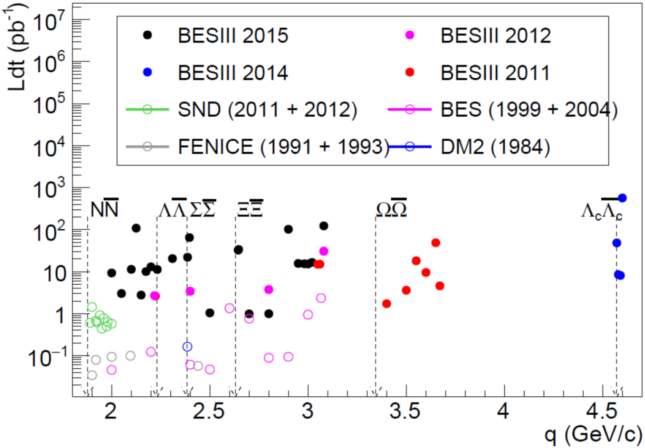


Data collected at BESIII



- World largest data sample of $J/\psi, \psi(2S)$ and $\psi(3770)$
- Unique data sample at XYZ (charmonium-like resonances) region
- Can cover 0-4.6 GeV from annihilation or ISR

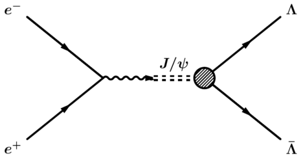
Energy scan 2014-2015 at BESIII



- World leading scan data between 2.0 GeV and 3.08 GeV
- Nucleon and hyperon EMFFs available

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

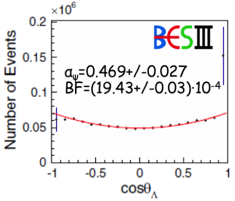
$e^+e^- \to \gamma^* \to J/\psi \to \Lambda\bar{\Lambda}$



- Process described by two complex numbers: magnetic G_M and electric G_E form factors.
- Two real parameters:
  - α_ψ angular distribution
  - $\Delta\Phi = arg(G_E/G_M)$ the phase between the two form factors

Dubnickova, Dubnicka, Rekalo Nuovo Cim. A109 (1996) 241
Gakh, Tomasi-Gustafsson NPA771 (2006) 169
Czyz, Grzelinska, Kuhn PRD75 (2007) 074026
Fäldt EPJ A51 (2015) 74; EPJ A52 (2016)141
Fäldt, Kupsc PLB772 (2017) 16

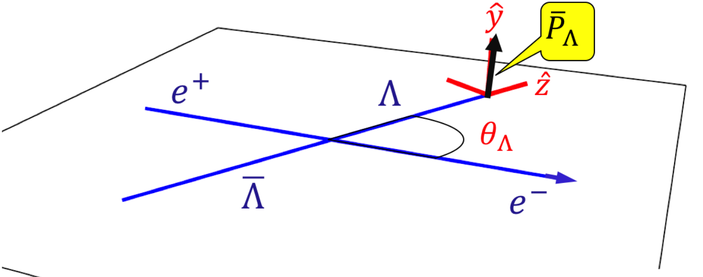
- α_ψ well known
- $d\Gamma/d\Omega \propto 1 + \alpha_\psi \cos^2\theta$



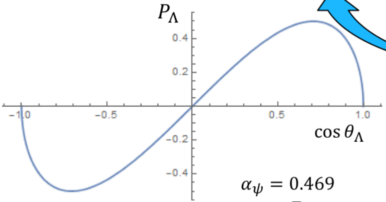
BESIII,PRD 95, 052003 (2017)

- $\Delta\Phi$ never considered before

Baryon polarization in e^+e^- annihilation



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

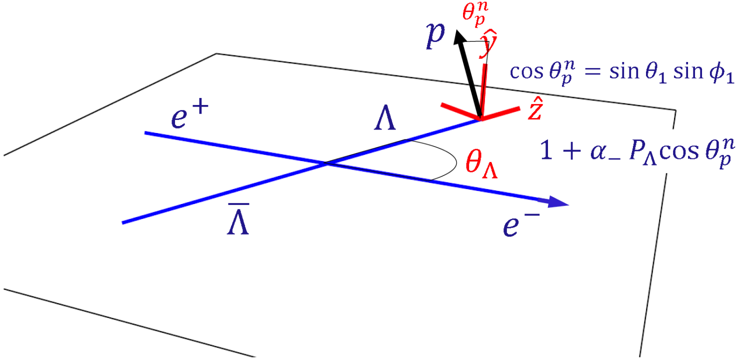


$\alpha_\psi = 0.469$

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

$\Delta\Phi \neq 0$

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



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

- Hyperon polarization can be determined using the angular distribution of the daughter particle.

Exclusive decay distributions for

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

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

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

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

$$\bar{\Lambda} \to \bar{n}\pi^0 : \alpha_2 \to \bar{\alpha}_0 \qquad \bar{\Lambda} \to \bar{p}\pi^+ : \alpha_2 \to \alpha_+$$

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

Spin correlations

Spin polarization

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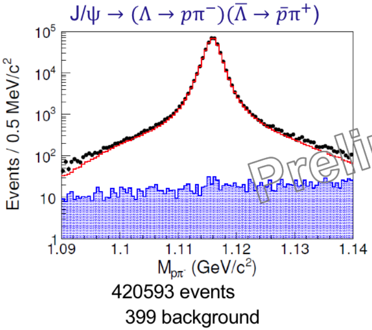
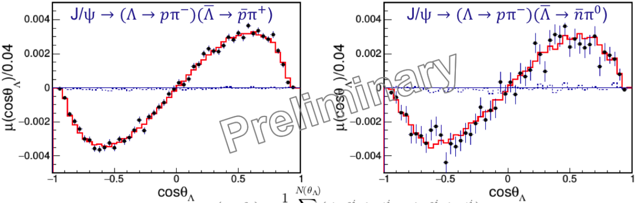
$J/\psi \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+/\bar{n}\pi^0)$



- A simultaneous maximum likelihood fit is performed to two data sets.
- Background events subtracted.

Fit results

ΔΦ=42.3°±0.6°±0.5°



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

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

CP asymmetry:

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

- The result of α_ψ is consistent with previous BESIII measurement.
- Spin polarization of Λ and $\bar{\Lambda}$ are observed.
- The result of α_- is ~5σ larger than the PDG value.

$$e^+e^- \to \gamma^* \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+) \text{ @ } 2.396\ \text{GeV}$$

The $\bar{p}p \to \bar{\Lambda}\Lambda$ at the PS185

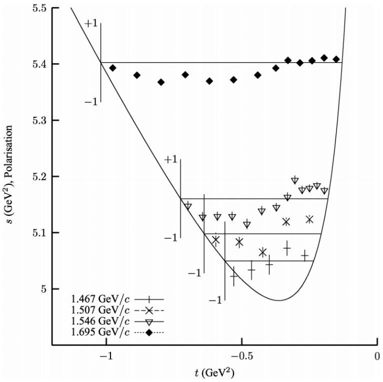


Fig. 4.30. Polarisation for $\bar{p}p \to \bar{\Lambda}\Lambda$ at various energies.

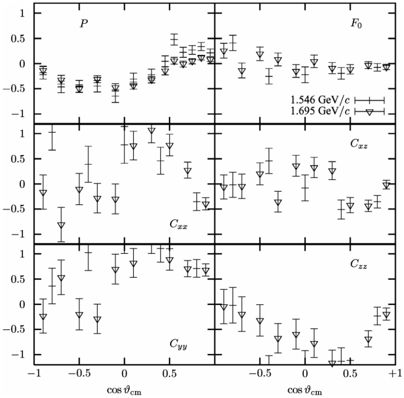
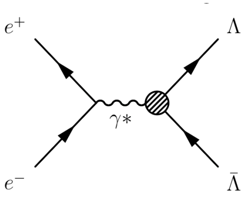


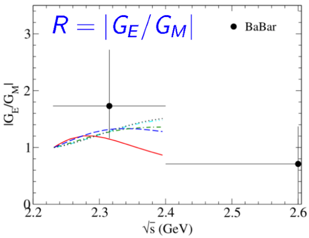
Fig. 4.31. Spin observables for $\bar{p}p \to \bar{\Lambda}\Lambda$ at 1546 and 1695 MeV/c.

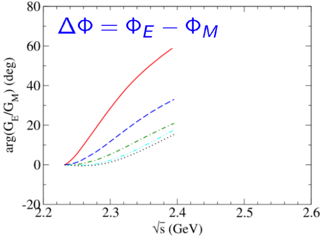
- Polarization and spin-correlation are observed. (Phys Rep 368 (2002) 119)
- Theoretical model of meson-exchange describes PS185 data well. (PRC 45, 931(1992); PRC46, 2158(1992))

Theoretical prediction of Time-like Λ form factors

Time-like Λ EMFFs studied by Haidenbauer and Meissner (PLB 761 (2016) 456-461)





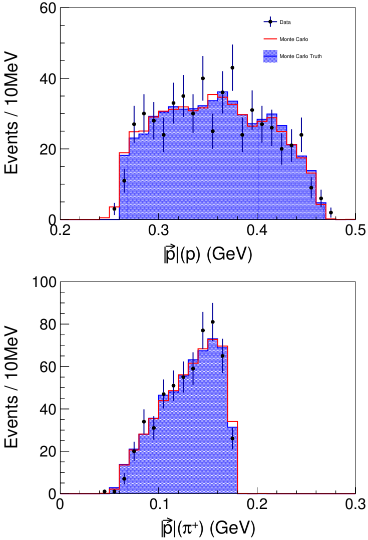


- Restrict to one-photon exchange
- PS185 data $p\bar{p} \to \Lambda\bar{\Lambda}$ used as input to fit $\Lambda\bar{\Lambda}$ potentials (Phys Rep 368 (2002) 119)
- The ratio R and the phase $\Delta\Phi$ are model dependent
- Inconclusive BaBar results (PRD 76 (2007) 092006)

Event selection of $e^+e^- \to \Lambda\bar{\Lambda}$

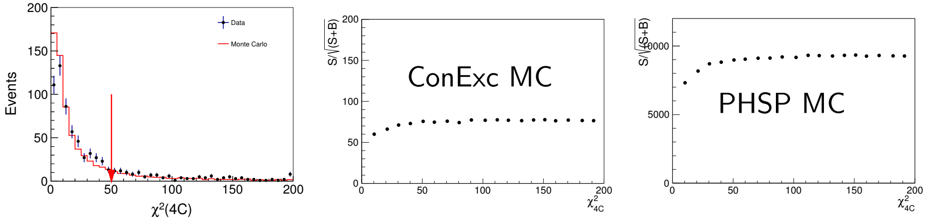
- Track level
  - Polar angle: $|cos\theta|$ <0.93
  - Momentum should be less than 0.5 GeV
  - At least 4 tracks
- Tracks with $p < 0.2$GeV are assigned to be pions, $p > 0.2$ GeV $p\bar{p}$
- Secondary vertex fit to reconstruct Λ and $\bar{\Lambda}$
- Four constraint Kinematic fit to Λ and $\bar{\Lambda}$

Momentum distribution of final states

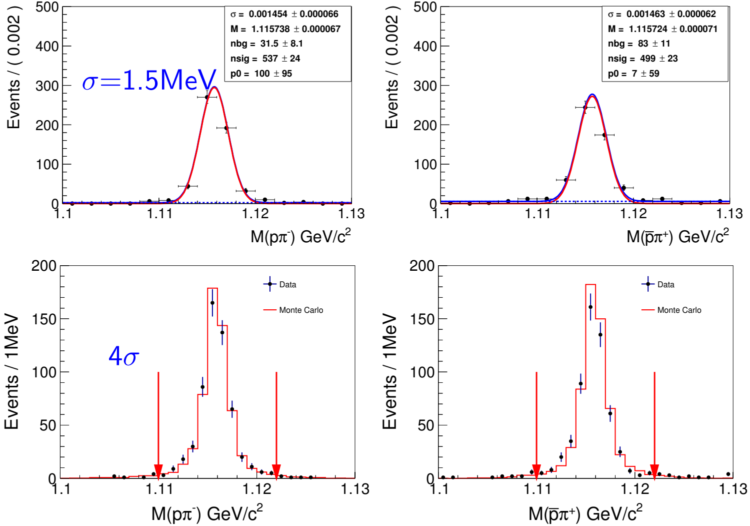


Distribution of χ^2(4C)

- $\chi^2(4C) < 50$
- Optimized by the value of figure of merit (FOM), $\frac{S}{\sqrt{S+B}}$
- S is signal MC sample, $S+B$ is data
- The FOM is not sensitive to the EMFFs and phase.

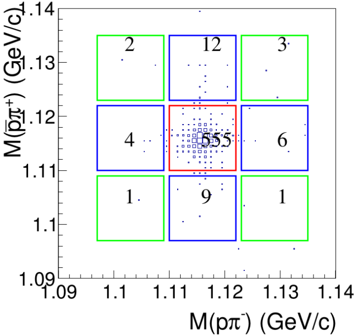


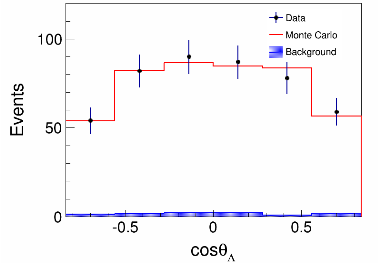
Invariant mass of $p\pi^-$ and $\bar{p}\pi^+$



- $|M(p\pi^-/\bar{p}\pi^+) - m_\Lambda| < 0.006$ GeV, m_Λ is the mass of Λ from PDG.

Background study by sideband method





- $N_{BG} = \frac{1}{2} N_{blue} - \frac{1}{4} N_{green} = 14 \pm 4$
- Background level is 2.5%.

Decay distribution

- Assume CP symmetry in this case $\alpha_\Lambda = -\alpha_{\bar{\Lambda}}$
- The decay distribution described in a simpler form

$$
\begin{aligned}
\mathcal{W}(\xi) =& \mathcal{T}_0(\xi) + \eta \mathcal{T}_5(\xi) \\
& -\alpha_\Lambda^2 \left(\mathcal{T}_1(\xi) + \sqrt{1-\eta^2} \cos(\Delta\Phi) \mathcal{T}_2(\xi) + \eta \mathcal{T}_6(\xi) \right) \\
& +\alpha_\Lambda \sqrt{1-\eta^2} \sin(\Delta\Phi) \left(\mathcal{T}_3(\xi) - \mathcal{T}_4(\xi) \right).
\end{aligned}
$$

$\mathcal{T}_i$ are known functions of the five-dimensional $\xi(\theta, \Omega_1(\theta_1, \phi_1), \Omega_2(\theta_2, \phi_2))$

$R = |G_E/G_M|$

$$\eta = \frac{\tau - R^2}{\tau + R^2}$$

$\Delta\Phi = \Phi_E - \Phi_M$

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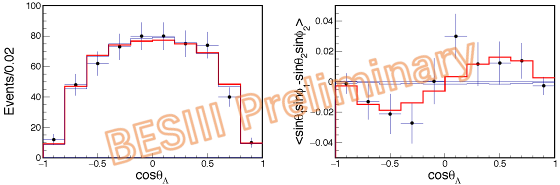
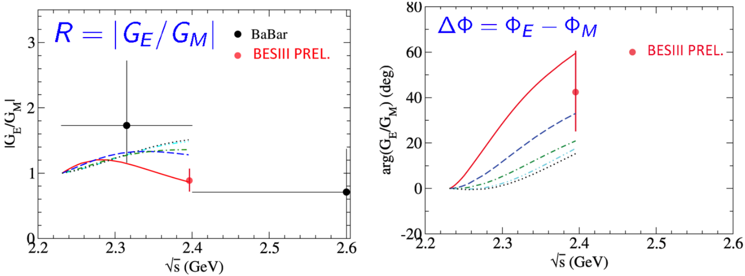
Fit results

- A maximum likelihood fit is performed to the data set.
- With PDG value $\alpha_\Lambda = 0.642$
  - $R = |G_E/G_M| = 0.94 \pm 0.16 \pm 0.03$
  - $\Delta\Phi = 42^o \pm 16^o \pm 8^o$.
- With BESIII value $\alpha_\Lambda = 0.75 \pm 0.01$
  - $R = 0.96 \pm 0.14 \pm 0.02$
  - $\Delta\Phi = 37^o \pm 12^o \pm 6^o$



- Spin polarization of Λ and $\bar{\Lambda}$ are observed.

Comparison of $|G_E/G_M|$ and $\Delta\Phi$



❑ Results of data support the $\Lambda\bar{\Lambda}$ model I (Red line) PRC 45, 931(1992)

Results of the cross section and effective EMFFs

- The cross section $\sigma = \frac{N_{signal}}{L\epsilon(1+\delta)Br(\Lambda\to p\pi^-)Br(\bar{\Lambda}\to\bar{p}\pi^+)}$
  - ISR and vacuum polarization factor $1+\delta$ is from ConExc
  - ϵ is the detection efficiency, L is the luminosity
  - $\sigma = 119.0 \pm 5.3(stat.) \pm 5.1(sys.)$ pb
- Effective form factors are related to σ, $|G(q^2)| = \sqrt{\frac{\sigma(q^2)}{(1+\frac{1}{2\tau})(\frac{4\pi\alpha^2\beta}{3q^2})}}$
  - $|G| = 0.123 \pm 0.003(stat.) \pm 0.003(sys.)$

$\alpha \approx \frac{1}{137}$ is the fine structure constant,

$\beta = \sqrt{1-\frac{1}{\tau}}$ is the velocity, $\tau = \frac{q^2}{4m_\Lambda^2}$.

Previous measurements

	σ(pb)	$\lvert G\rvert$	Reference
BESIII $\sqrt{s}$ =2.40GeV	128±19±18	0.127±0.009±0.009	Phys. Rev. D **97**, 032013 (2018)
BaBar $\sqrt{s}$ =2.35-2.40 GeV	176±34	0.152±0.016	Phys. Rev. D **76**, 092006 (2007)

Summary

- Hyperon spin polarization is observed in $e^+e^- \to \Lambda\bar{\Lambda}$
- The phase is measured for the first time.
- With J/ψ
  - The phase determined to be $42.3^o \pm 0.62^o \pm 0.5^o$
  - Decay asymmetry parameter of $\Lambda \to p\pi^-$ obtained to be $0.750 \pm 0.009 \pm 0.004$
  - The CP odd observable $A_{CP} = -0.006 \pm 0.012 \pm 0.007$
- With scan data at 2.396 GeV

PDG value $\alpha_\Lambda = 0.642$
- $R = |G_E/G_M| = 0.94 \pm 0.16 \pm 0.03$
- $\Delta\Phi = 42^o \pm 16^o \pm 8^o$.

BESIII value $\alpha_\Lambda = 0.75 \pm 0.01$
- $R = |G_E/G_M| = 0.96 \pm 0.14 \pm 0.02$
- $\Delta\Phi = 37^o \pm 12^o \pm 6^o$

Thank you for your attention!

Check contribution from two-photon exchange

- Significant involvement of two-photon exchange would result in an asymmetric Λ angular distribution(PLB 659 197-200 (2008)):

$$A = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}. \tag{9}$$

- In the formula of decay distribution, an additional term $\kappa\cos\theta\sin^2\theta$ due to interference of the single and two photon amplitudes.
- The asymmetry A can be determined from κ in the following way:

$$A = \frac{3}{4}\frac{\kappa}{3+\eta}. \tag{10}$$

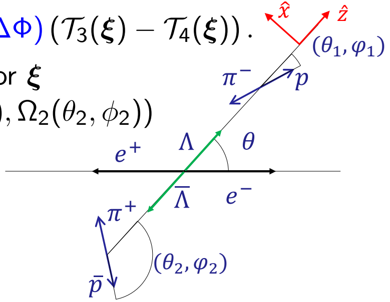
- The asymmetry is found to be $A = 0.001 \pm 0.037$
- This result indicates a negligible contribution from two-photon exchange.

The method of Maximum Log Likelihood

- A simpler form of $\frac{d\sigma}{d\cos\theta} \propto 1 + \eta\cos^2\theta$
- R can then be extracted by $R = \sqrt{\tau}\sqrt{\frac{1-\eta}{1+\eta}}$
- The decay distribution could be expressed as:

$$
\begin{aligned}
\mathcal{W}(\boldsymbol{\xi}) =& \mathcal{T}_0(\boldsymbol{\xi}) + \eta\mathcal{T}_5(\boldsymbol{\xi}) \\
& -\alpha_\Lambda^2\left(\mathcal{T}_1(\boldsymbol{\xi}) + \sqrt{1-\eta^2}\cos(\Delta\Phi)\mathcal{T}_2(\boldsymbol{\xi}) + \eta\mathcal{T}_6(\boldsymbol{\xi})\right) \\
& +\alpha_\Lambda\sqrt{1-\eta^2}\sin(\Delta\Phi)\left(\mathcal{T}_3(\boldsymbol{\xi}) - \mathcal{T}_4(\boldsymbol{\xi})\right).
\end{aligned}
\tag{11}
$$

- $\mathcal{T}_i$ are known functions as vector $\boldsymbol{\xi}$
- five-dimensional $\boldsymbol{\xi}(\theta, \Omega_1(\theta_1, \phi_1), \Omega_2(\theta_2, \phi_2))$



The method of Maximum Log Likelihood

- The probability distribution function of the i:th event by the vector $\boldsymbol{\xi}(\theta, \Omega_1, \Omega_2)$:

$$\mathcal{P}(\boldsymbol{\xi}_i; \eta, \Delta\Phi) = \mathcal{W}(\boldsymbol{\xi}_i; \eta, \Delta\Phi)\epsilon(\boldsymbol{\xi}_i)/\mathcal{N}(\eta, \Delta\Phi) \tag{12}$$

  where $\epsilon(\boldsymbol{\xi})$ is the efficiency.
- The joint probability density for observing the N events in the data sample is:

$$\mathcal{P}(\boldsymbol{\xi}_1, \boldsymbol{\xi}_2, ..., \boldsymbol{\xi}_N; \eta, \Delta\Phi) = \prod_{i=1}^{N} \mathcal{P}(\boldsymbol{\xi}_i; \eta, \Delta\Phi) = \prod_{i=1}^{N} \frac{\mathcal{W}(\boldsymbol{\xi}_i; \eta, \Delta\Phi)\epsilon(\boldsymbol{\xi}_i)}{\mathcal{N}(\eta, \Delta\Phi)} \tag{13}$$

- $\mathcal{N}(\eta, \Delta\Phi)$ is calculated with a PHSP MC sample

The method of Maximum Log Likelihood

- By taking the natural logarithm of the joint probability density, the efficiency function can be separated

$$\ln \mathcal{P}(\boldsymbol{\xi}_1, \boldsymbol{\xi}_2, ..., \boldsymbol{\xi}_N; \eta, \Delta\Phi) = \sum_{i=1}^{N} \ln \frac{\mathcal{W}(\boldsymbol{\xi}_i; \eta, \Delta\Phi)}{\mathcal{N}(\eta, \Delta\Phi)} + \sum_{i=1}^{N} \ln \epsilon(\boldsymbol{\xi}_i), \quad (14)$$

- Technically, minimization $\mathcal{S} = -\ln \mathcal{L}$ instead of maximization is performed using MINUIT.

$$\mathcal{S} = -\ln \mathcal{L} = -\sum_{i=1}^{N} \ln \frac{\mathcal{W}(\boldsymbol{\xi}_i; \eta, \Delta\Phi)}{\mathcal{N}(\eta, \Delta\Phi)} \quad (15)$$

- By a fit, η and $\Delta\Phi$ are given.