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

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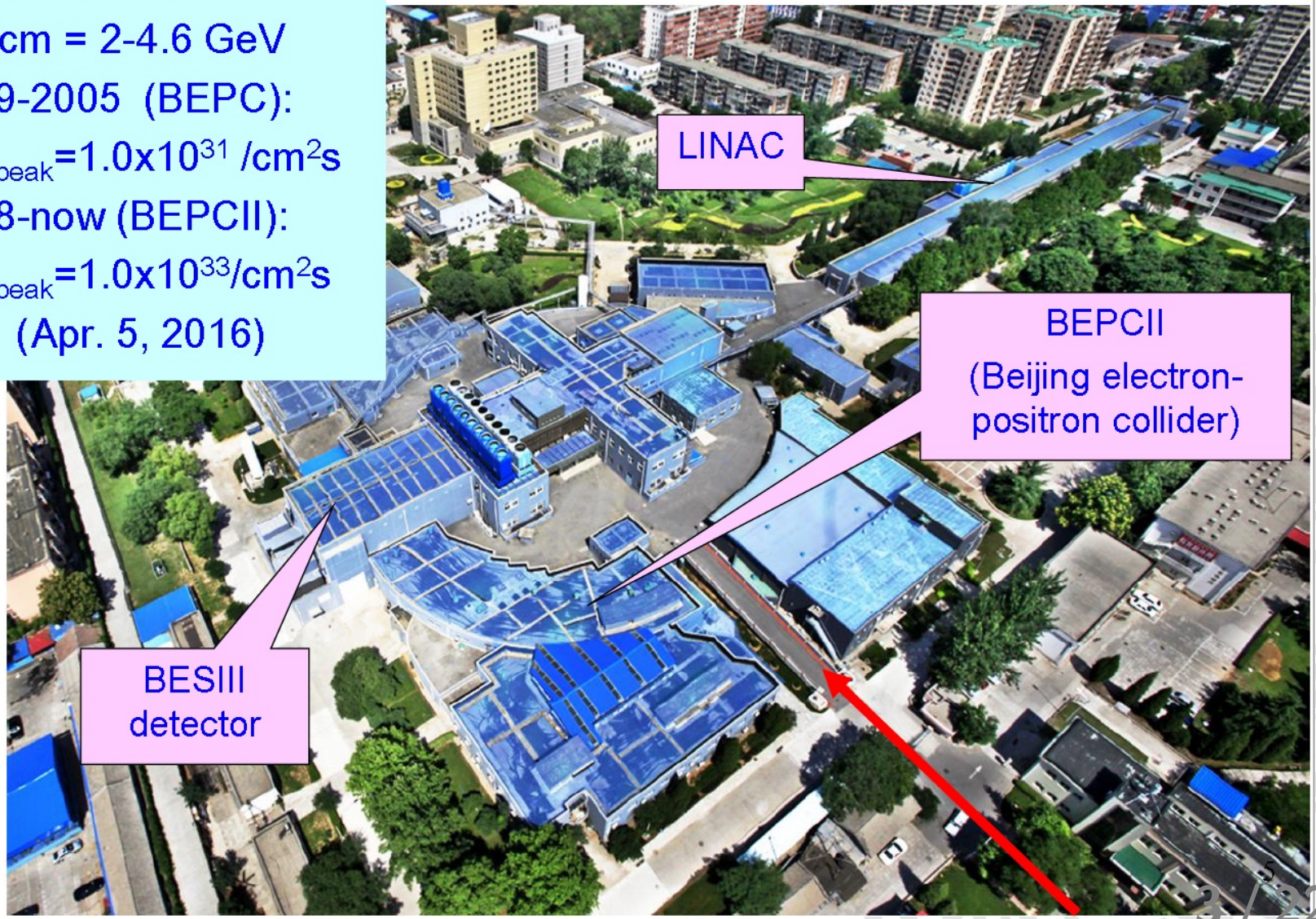
Outline

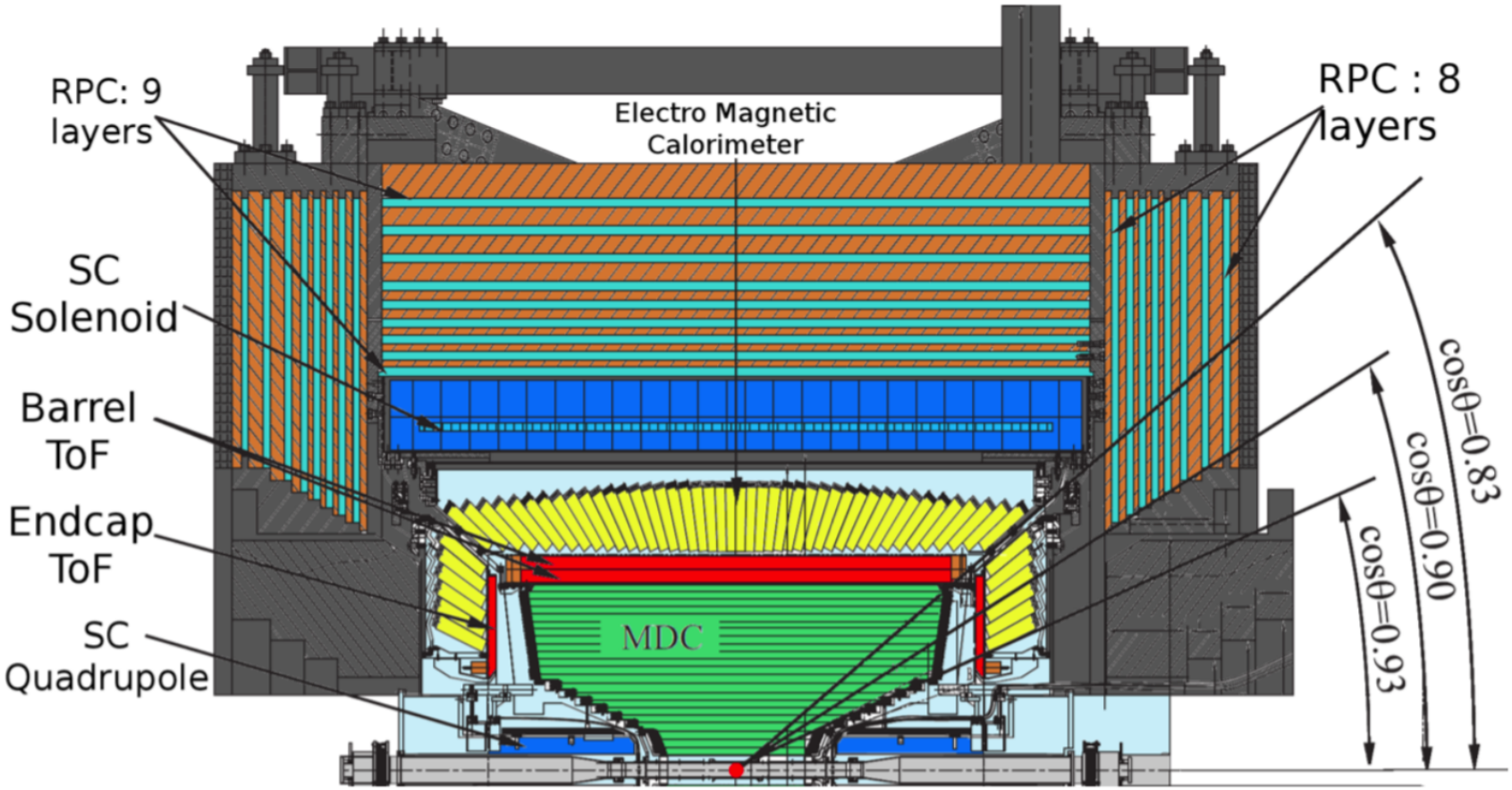
- The BESIII experiment
- Observation of spin polarization in $e^+e^- \to \Lambda\bar{\Lambda}$ at BESIII
  - $\Lambda\bar{\Lambda}$ decay asymmetry parameters
  - Time-like Λ electromagnetic form factors
- Summary

Beijing Electron Positron Collider (BEPC)

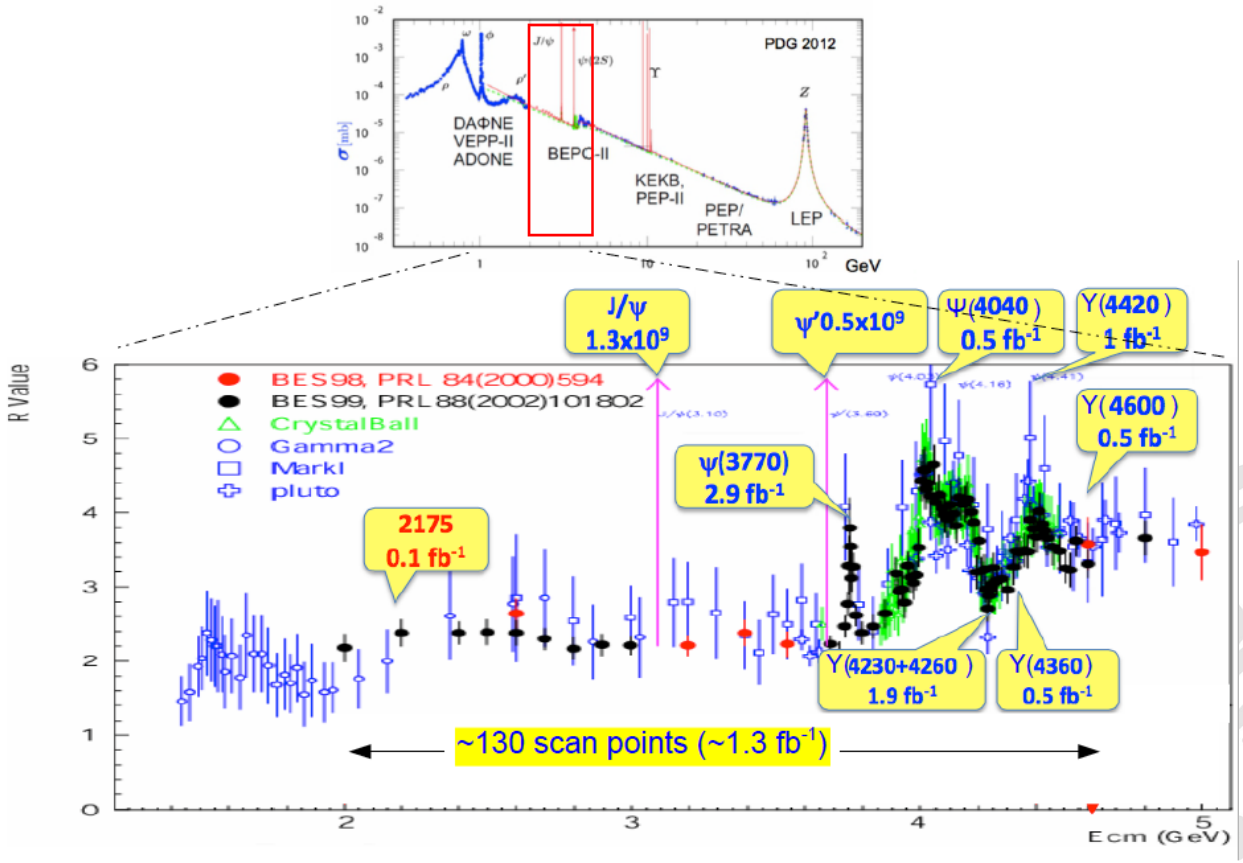
- Founded: 1984
  Ecm = 2-4.6 GeV
- 1989-2005 (BEPC):
  L_{peak}=1.0x10^{31} /cm^{2}s
- 2008-now (BEPCII):
  L_{peak}=1.0x10^{33}/cm^{2}s
  (Apr. 5, 2016)



BEijing Spectrometer (BES)

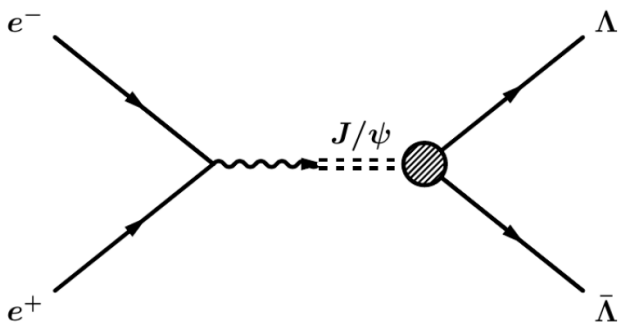


Data collected at BESIII



- 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

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



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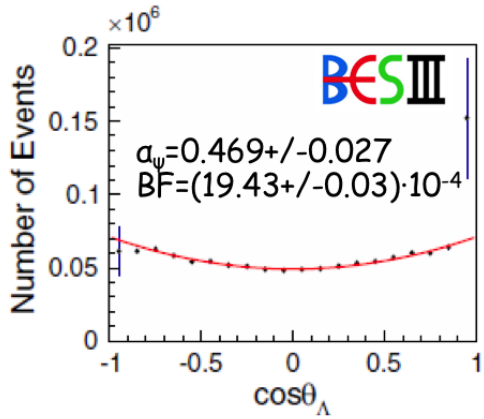
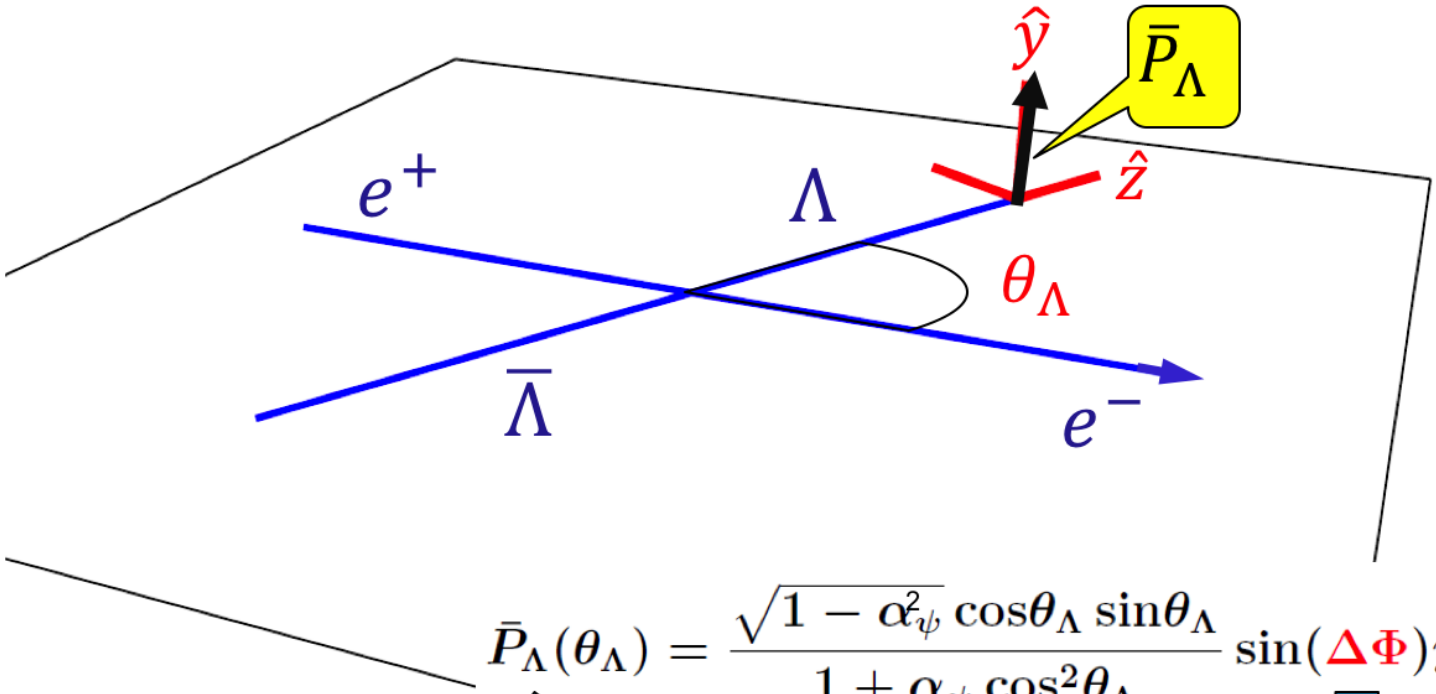
- α_ψ well known
- $d\Gamma/d\Omega \propto 1+\alpha_\psi \cos^2\theta$



BESIII,PRD 95, 052003 (2017)

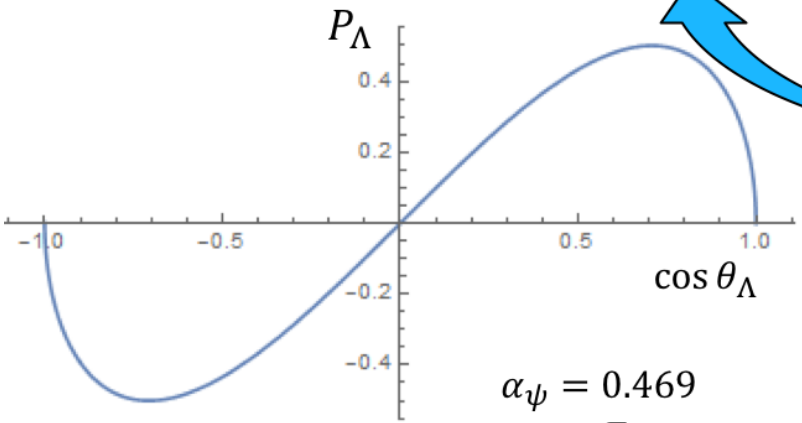
- $\Delta\Phi$ never considered before

Baryon polarization in e^+e^- annihilation



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

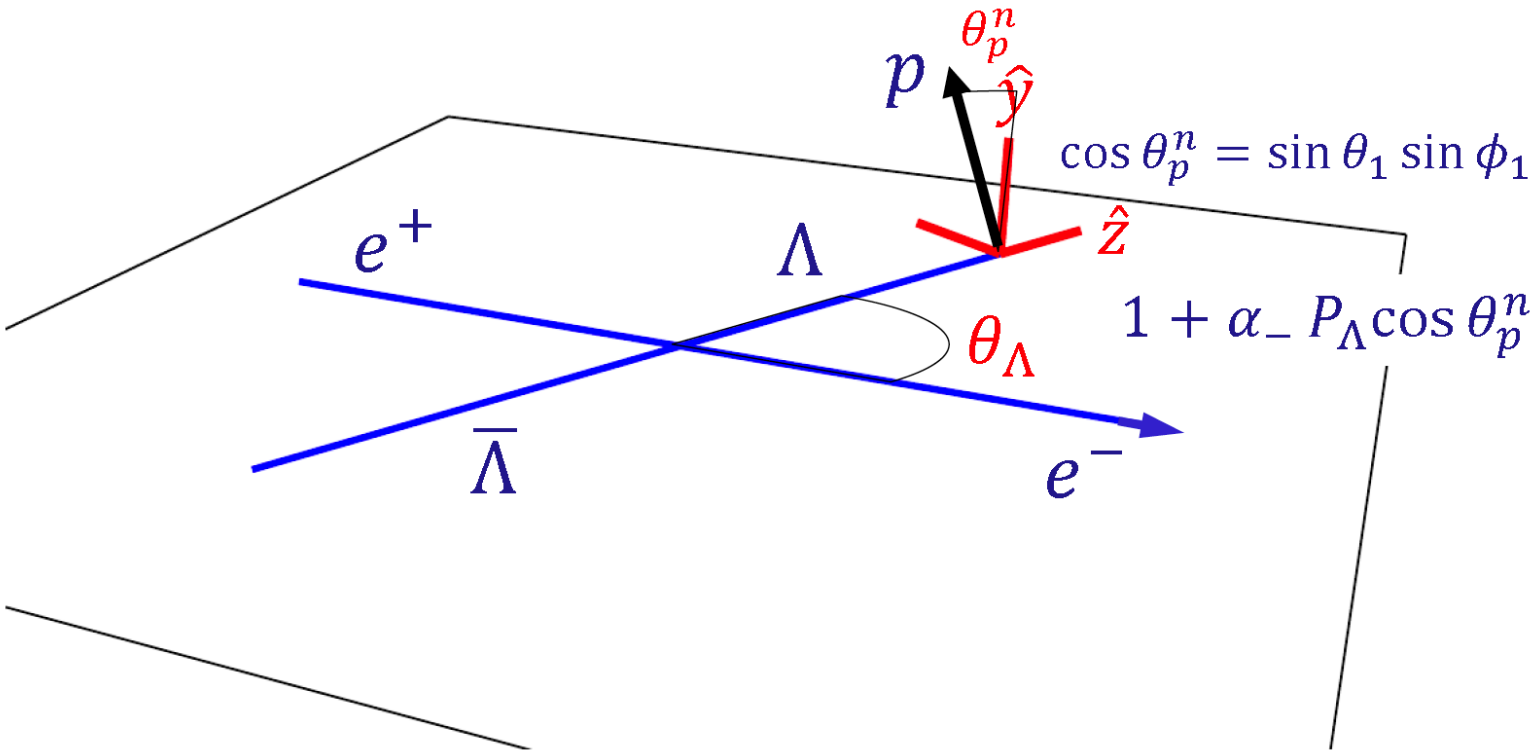
$\Delta\Phi \neq 0$



$\alpha_\psi = 0.469$

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

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



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

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

Exclusive decay distributions for

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

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

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

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

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

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

Spin correlations

Spin polarization

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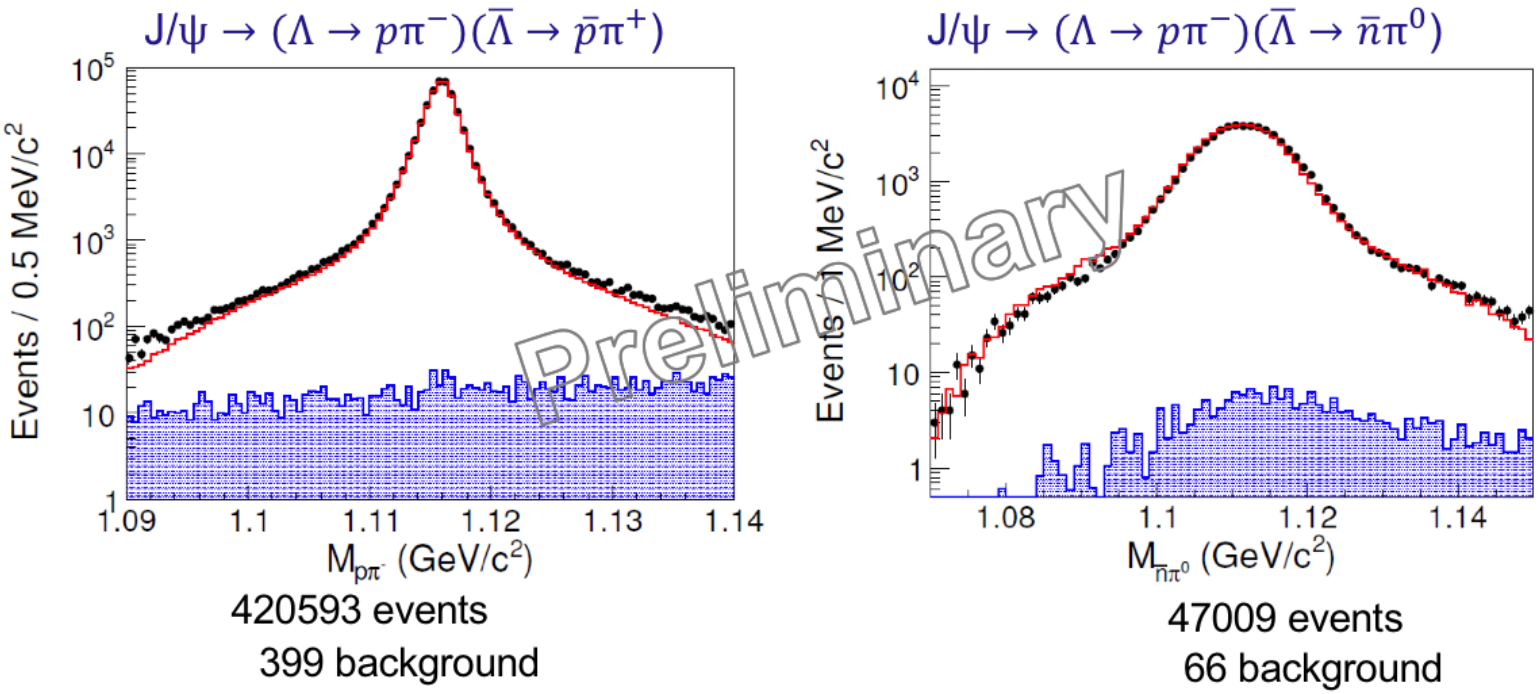
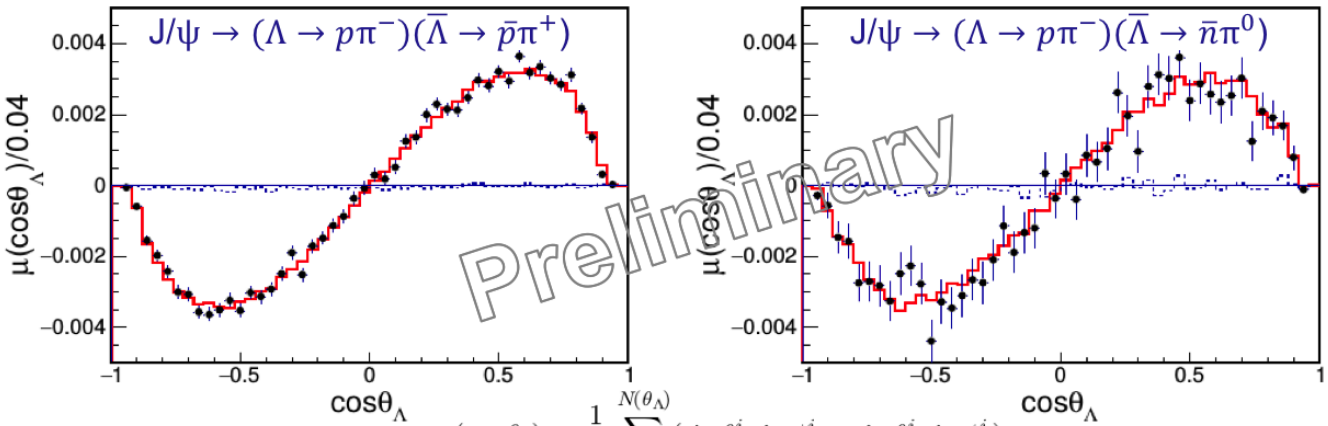
$J/\psi \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+/\bar{n}\pi^0)$



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

Fit results

$\Delta\Phi = 42.3^{o} \pm 0.6^{o} \pm 0.5^{o}$



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

Parameters	This work	Previous results	
α_ψ	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027	BESIII
$\Delta\Phi$ (rad)	$0.740 \pm 0.010 \pm 0.008$	–	
α_-	$0.750 \pm 0.009 \pm 0.004$	0.642 ± 0.013	PDG
α_+	$-0.758 \pm 0.010 \pm 0.007$	-0.71 ± 0.08	PDG
$\bar{\alpha}_0$	$-0.692 \pm 0.016 \pm 0.006$	–	
A_{CP}	$-0.006 \pm 0.012 \pm 0.007$	0.006 ± 0.021	PDG
$\bar{\alpha}_0/\alpha_+$	$0.913 \pm 0.028 \pm 0.012$	–	

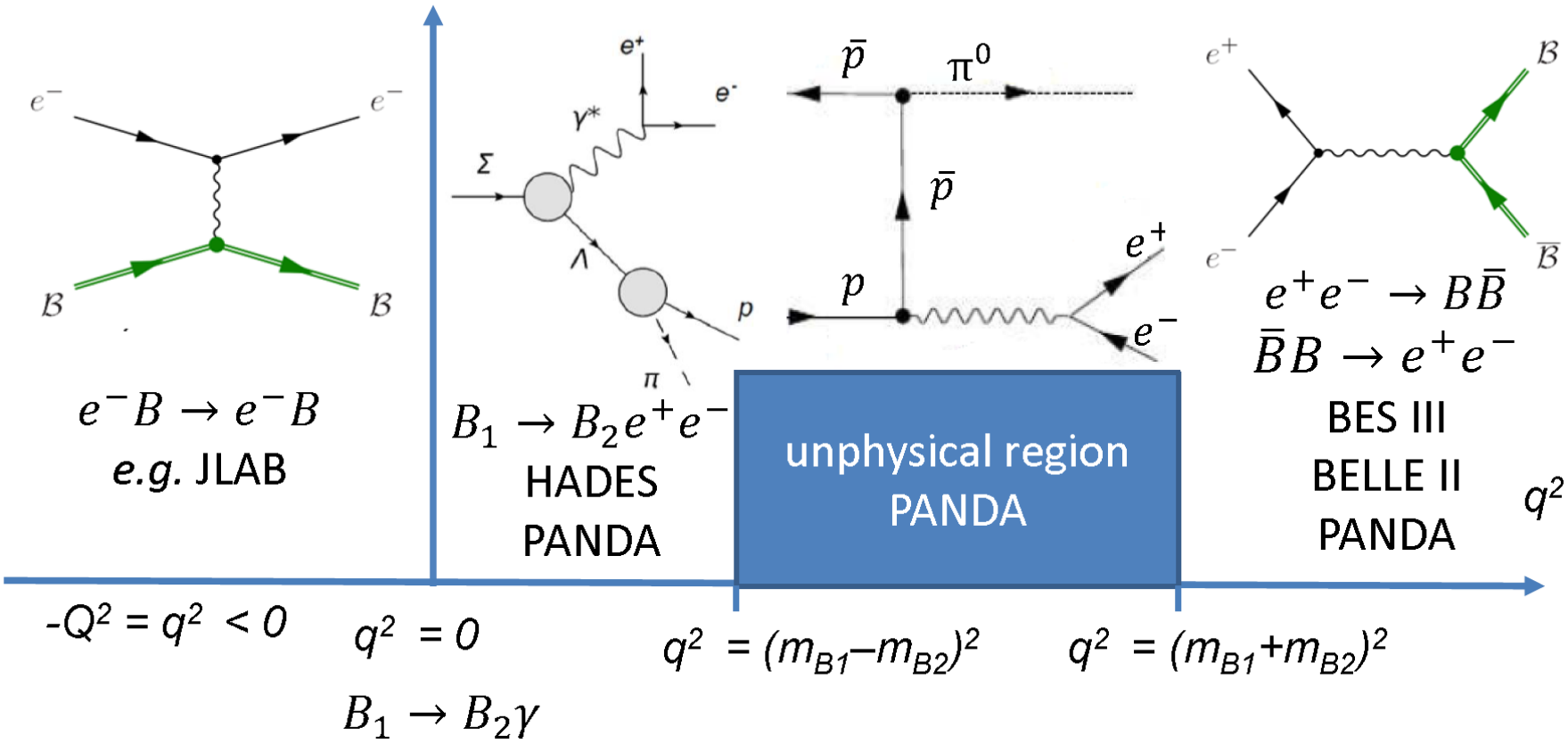
Preliminary

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 $\sim 5\sigma$ larger than the PDG value.

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



- Spin 1/2 baryons have magnetic G_M and electric G_E form factors
- Space-like EMFFs are real numbers
- Time-like EMFFs are complex numbers

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

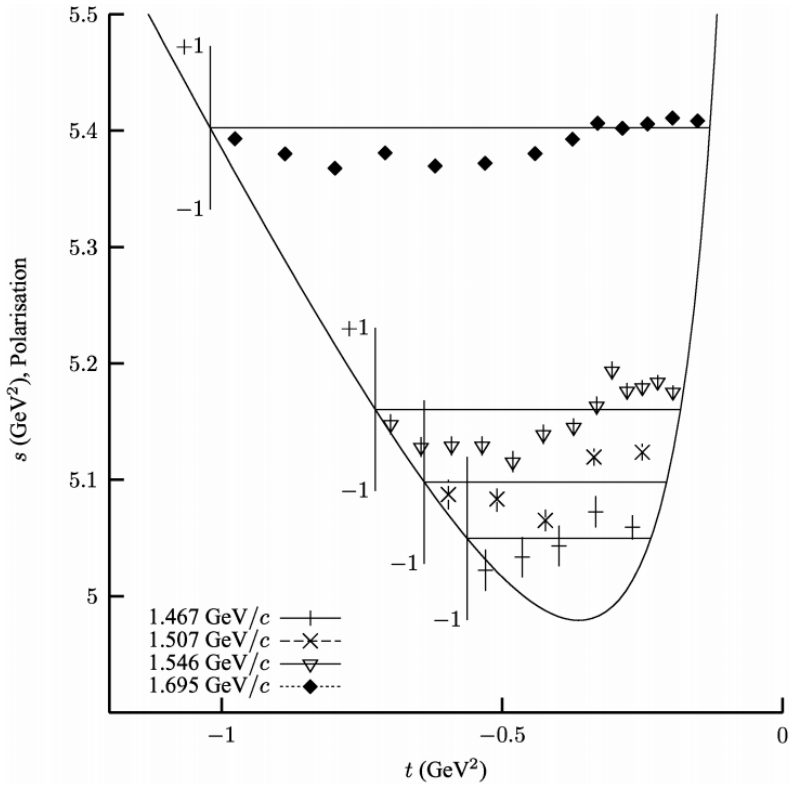


Fig. 4.30. Polarisation for $\bar{p}p \to \bar{\Lambda}\Lambda$ at various energies.

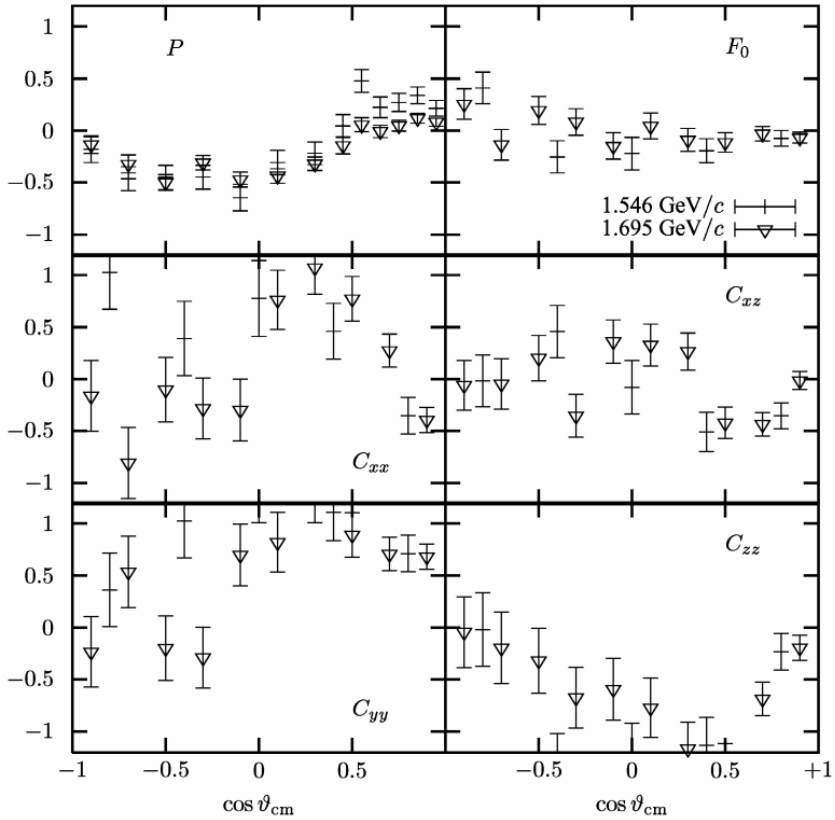
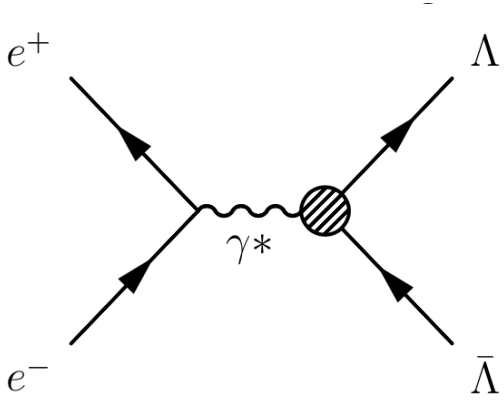


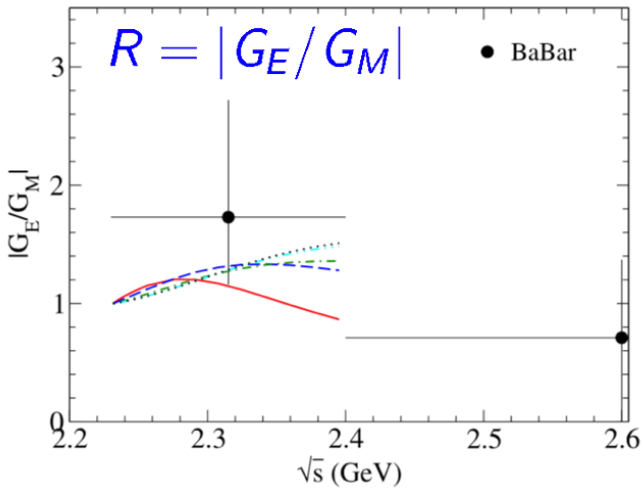
Fig. 4.31. Spin observables for $\bar{p}p \to \bar{\Lambda}\Lambda$ at 1546 and 1695 MeV/c.

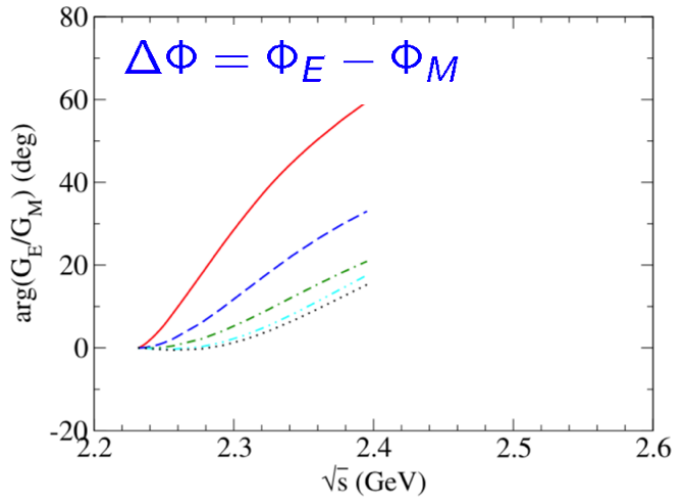
- Polarization and spin-correlation are observed. (Phys Rep 368 (2002) 119)
- Theoretical model of meson-exchange describes PS185 data well. (PRC 45, 931(1992); PRC46, 2158(1992))

Theoretical prediction of Time-like Λ form factors

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

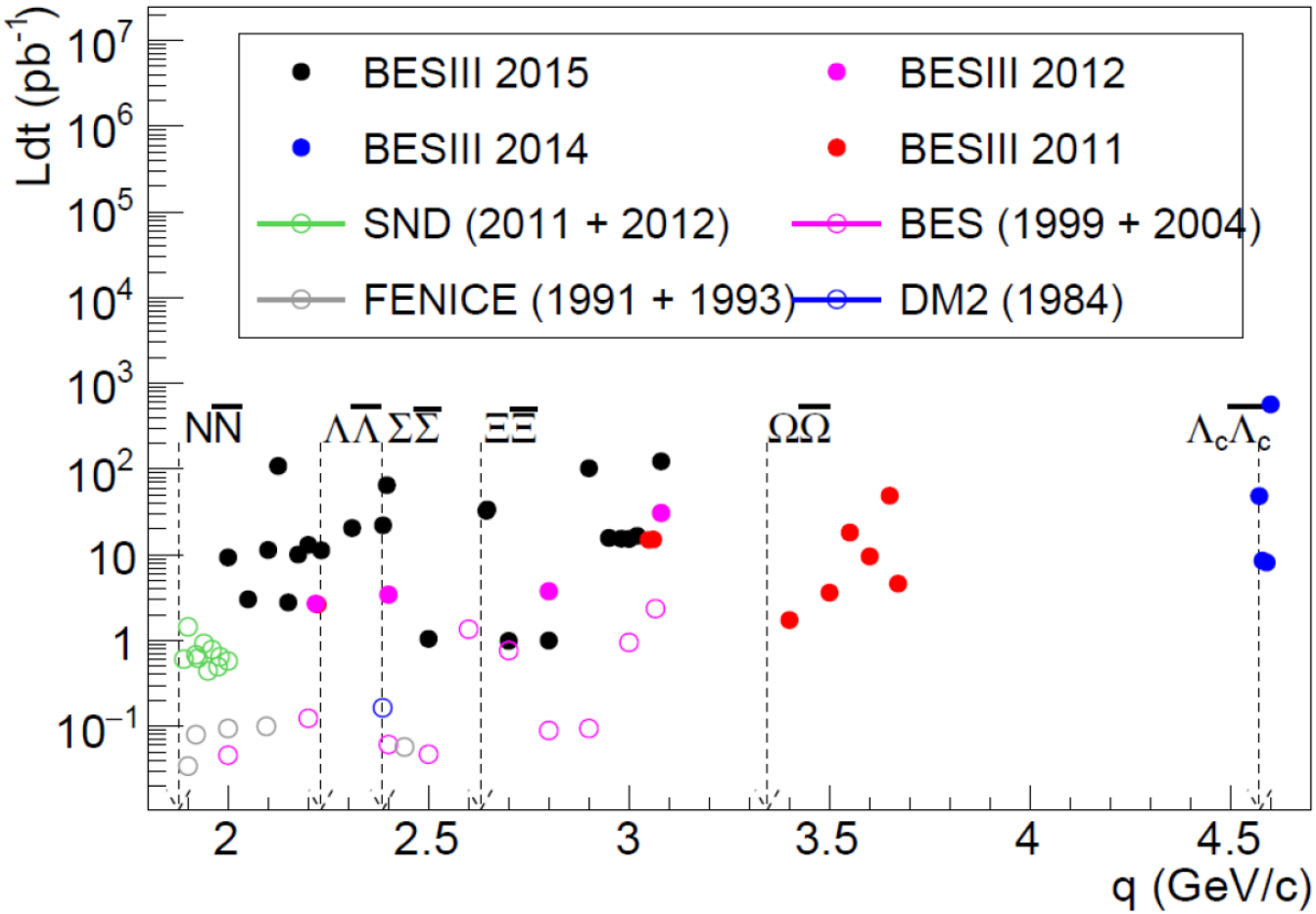






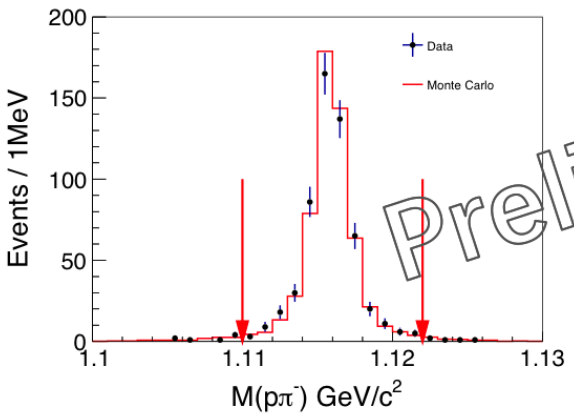
- Restrict to one-photon exchange
- PS185 data $p\bar{p} \to \Lambda\bar{\Lambda}$ used as input to fit $\Lambda\bar{\Lambda}$ potentials (Phys Rep 368 (2002) 119)
- The ratio R and the phase $\Delta\Phi$ are model dependent
- Inconclusive BaBar results (PRD 76 (2007) 092006)

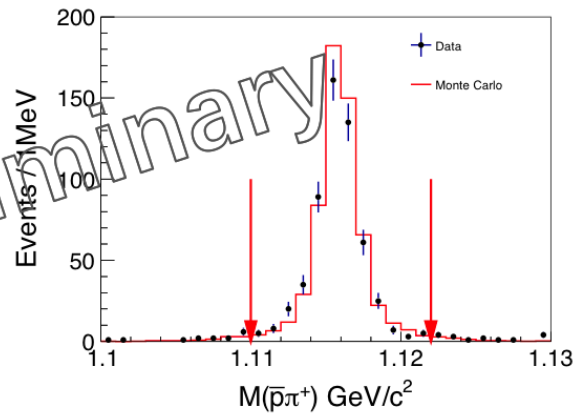
Energy scan 2014-2015 at BESIII

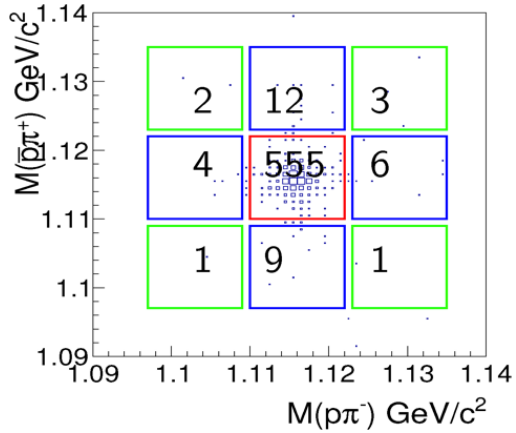


- World leading scan data between 2.0 GeV and 3.08 GeV
- Nucleon and hyperon EMFFs available

$e^+e^- \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$ at $\sqrt{s}$ =2.396 GeV







- Large data sample for scan data
- 555 events with 14±4 background

$e^+e^- \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$ at $\sqrt{s}$ =2.396 GeV

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

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

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

$R = |G_E/G_M|$

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

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

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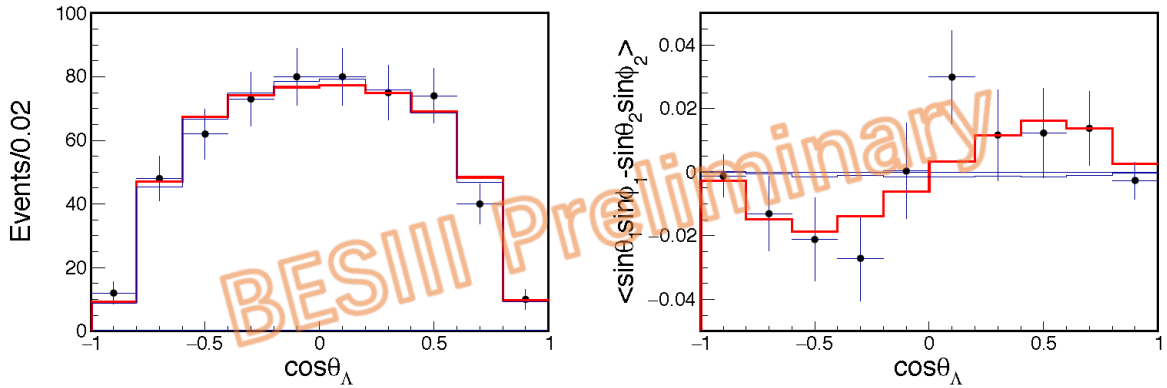
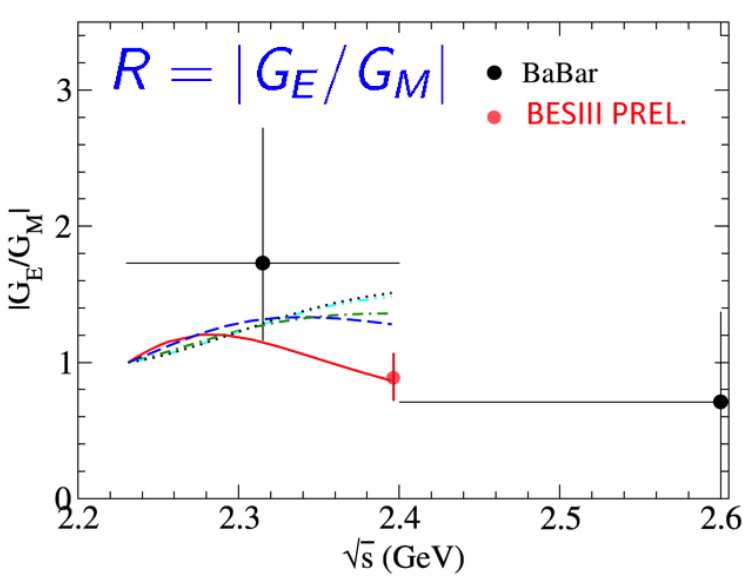
Fit results for $\sqrt{s}$ =2.396 GeV

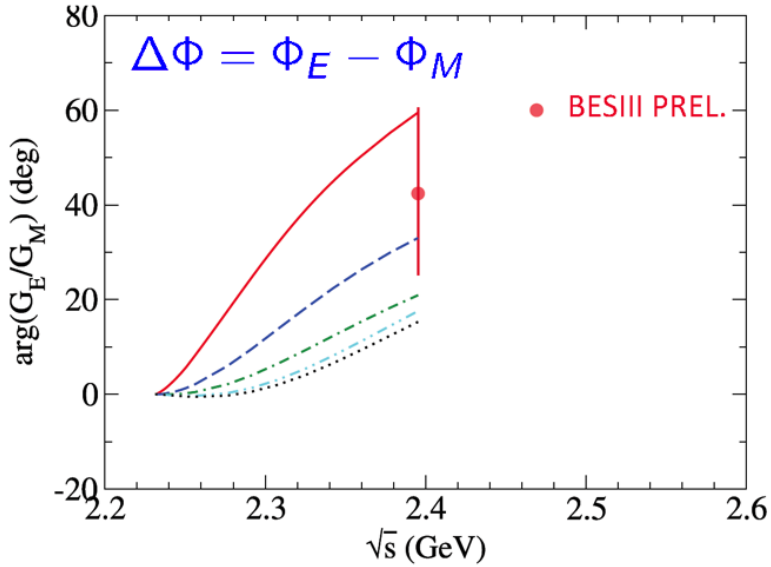
- A maximum likelihood fit is performed to the data set.
- With PDG value $\alpha_\Lambda = 0.642$
  - $R = |G_E/G_M| = 0.94 \pm 0.16 \pm 0.03$
  - $\Delta\Phi = 42^o \pm 16^o \pm 8^o$.
- With BESIII value $\alpha_\Lambda = 0.75 \pm 0.01$
  - $R = 0.96 \pm 0.14 \pm 0.02$
  - $\Delta\Phi = 37^o \pm 12^o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



- 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, $|G(q^2)| = \sqrt{\frac{\sigma(q^2)}{(1+\frac{1}{2\tau})(\frac{4\pi\alpha^2\beta}{3q^2})}}$
  - $|G| = 0.123 \pm 0.003(stat.) \pm 0.003(sys.)$

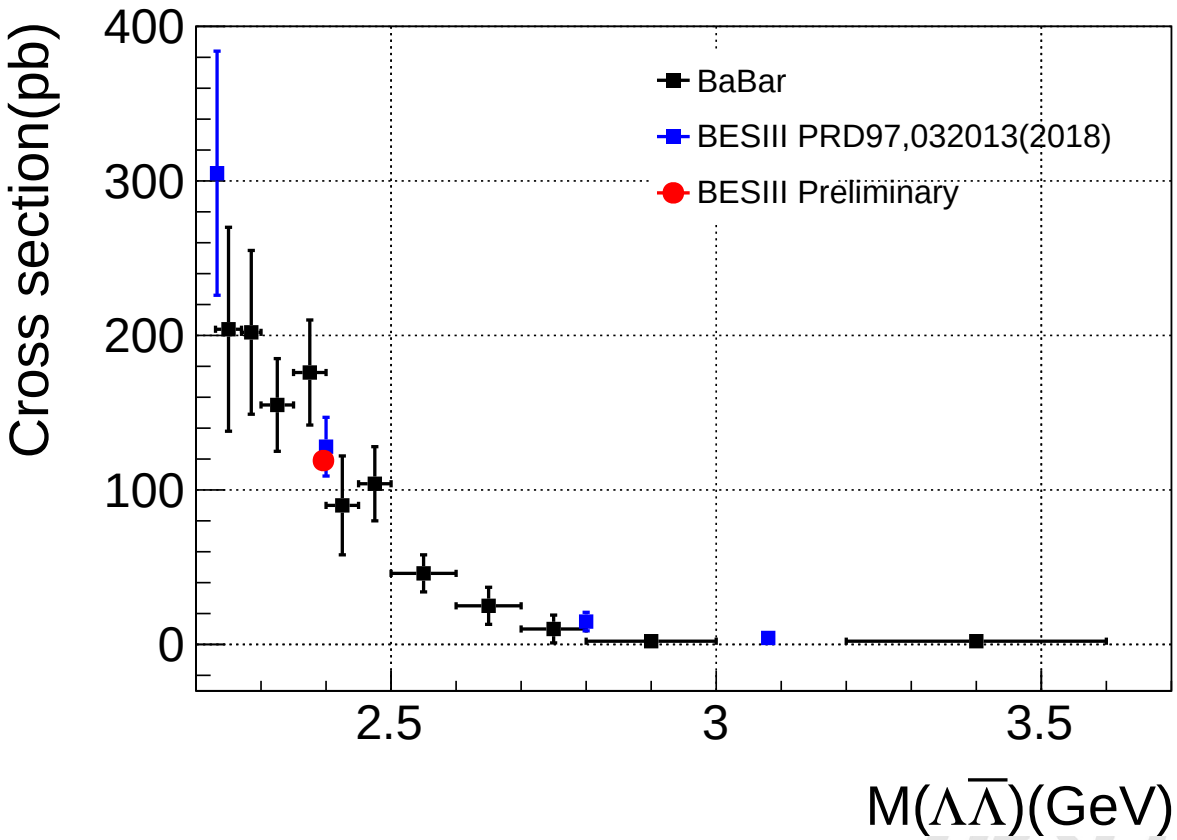
$\alpha \approx \frac{1}{137}$ is the fine structure constant,

$\beta = \sqrt{1-\frac{1}{\tau}}$ 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)

Comparison of cross section



- A novel and interesting enhancement at the kinematic threshold was observed by BESIII.
- Results are consistent.

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!