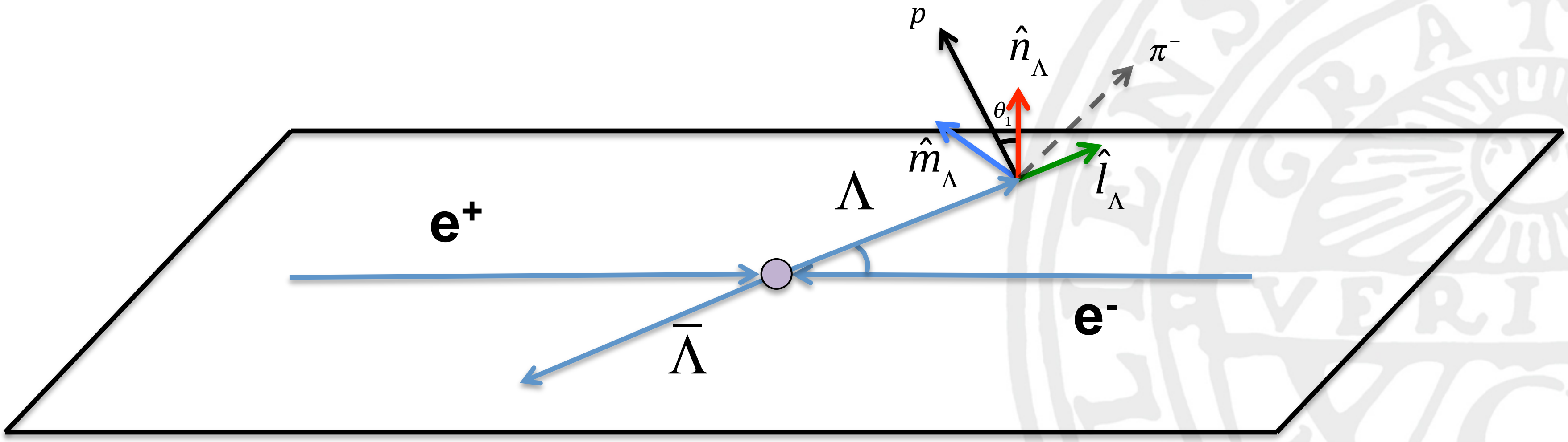
# Hyperon Electromagnetic Structure and CP Tests at BESIII

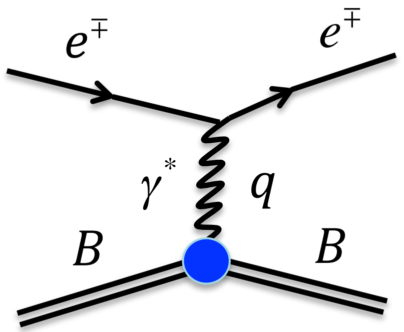
**Patrik Adlarson, Uppsala University**

**for the BESIII collaboration**

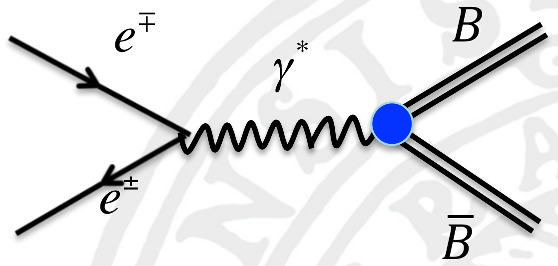


# Space- and Timelike EMFF

- The Electromagnetic Form Factors are hadron structure observables related to the charge and magnetization density
- EMFFs are accessed in kinematical regions of (transfered squared four-momentum) $q^2$ through study of space- and timelike processes



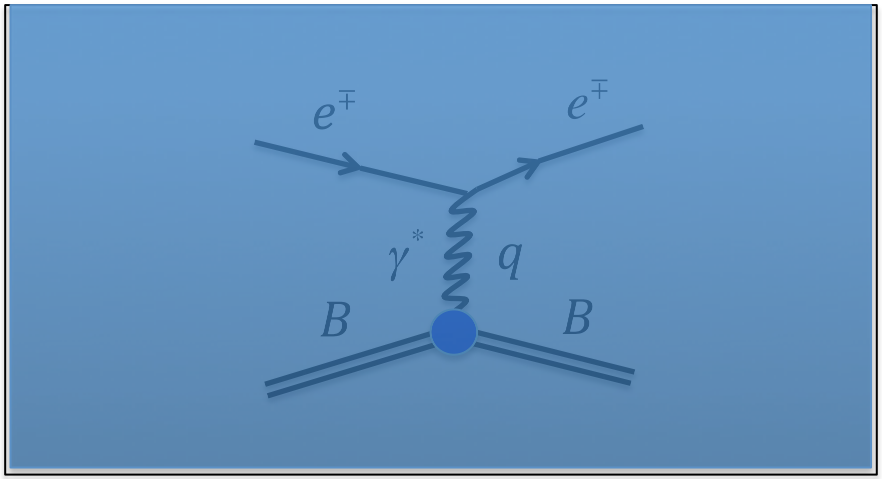

**Space-like $q^2 < 0$**
**Scattering processes**




**Time-like $q^2 > 0$**
**Annihilation processes**
**kin accessible $q^2 > (2M_B)^2$**

# Space- and Timelike EMFF

Focus of this talk on Timelike EMFF of hyperons (*B* = *Y*) as probe




**Space-like $q^2 < 0$**
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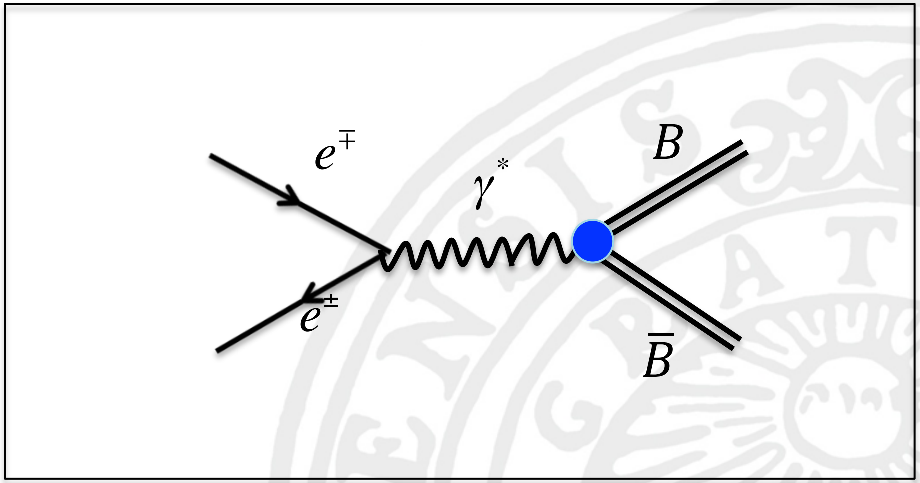


**Time-like $q^2 > 0$**
**Annihilation processes**
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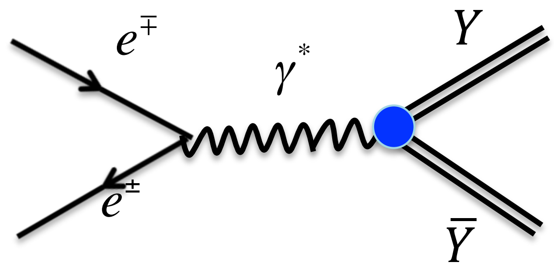
# Timelike EMFF




Assuming one-photon exchange, Born cross section

$$\sigma_{Born}(q^2) = \frac{4\pi\alpha^2\beta}{3q^2}\left[\left|G_M(q^2)\right|^2 + \frac{1}{2\tau}\left|G_E(q^2)\right|^2\right] \qquad \alpha = \frac{1}{137} \quad \beta = \sqrt{1-\frac{1}{\tau}} \quad \tau = \frac{q^2}{4m_B^2}$$

Magnetic FF

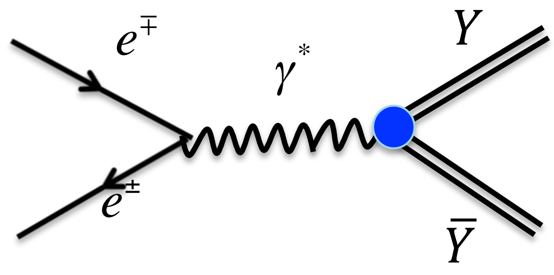
Electric FF

Effective form factor linear combination of electric and magnetic FF squared

Useful observable for low statistics

$$\left|G(q^2)\right|^2 \propto \sigma_{Born}(q^2) = \frac{2\tau\left|G_M(q^2)\right|^2 + \left|G_E(q^2)\right|^2}{2\tau+1}$$

# Timelike EMFF




A peculiarity of Timelike EMFF is that final state baryons/hyperons can be **polarized** *even if* the initial state is unpolarized *Phys Rev 124 (1961) 1577, NuovoCim.A109 (1996) 241*

This is from intermediate (virtual) hadron-antihadron states which can polarize final state

$$G_E(q^2) = |G_E(q^2)| \cdot e^{i\Phi_E} \qquad G_M(q^2) = |G_M(q^2)| \cdot e^{i\Phi_M}$$

Three real numbers used to describe form factors

1) $|G(q^2)|^2$

2) $R = |G_E(q^2)/G_M(q^2)|$

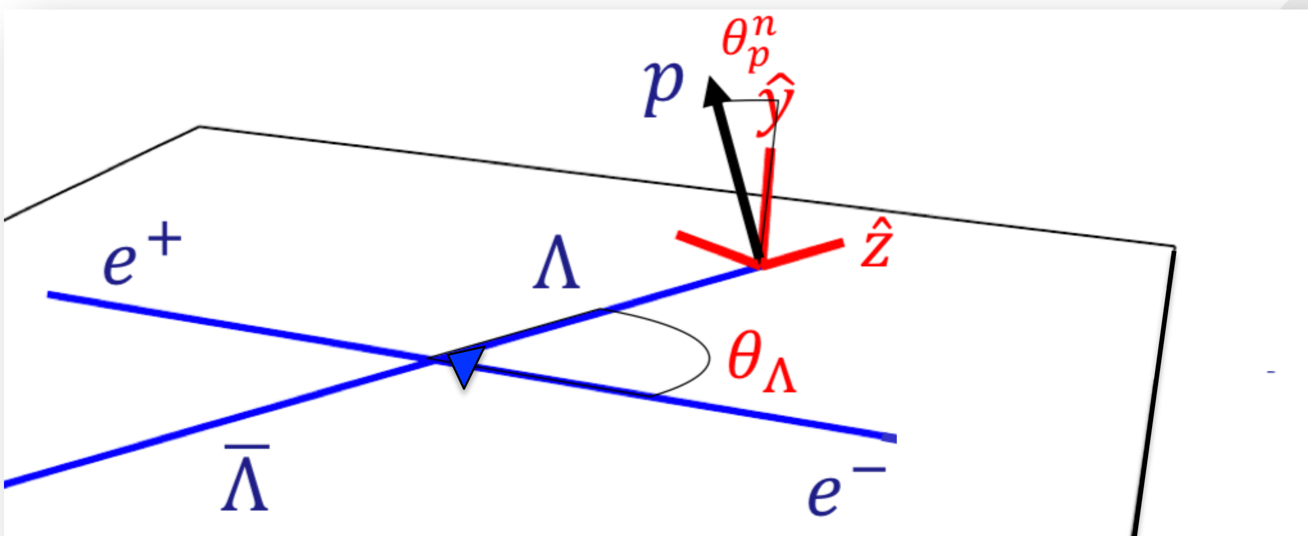
3) $\Delta\Phi = \Phi_E - \Phi_M$

Non-zero rel. phase = polarization

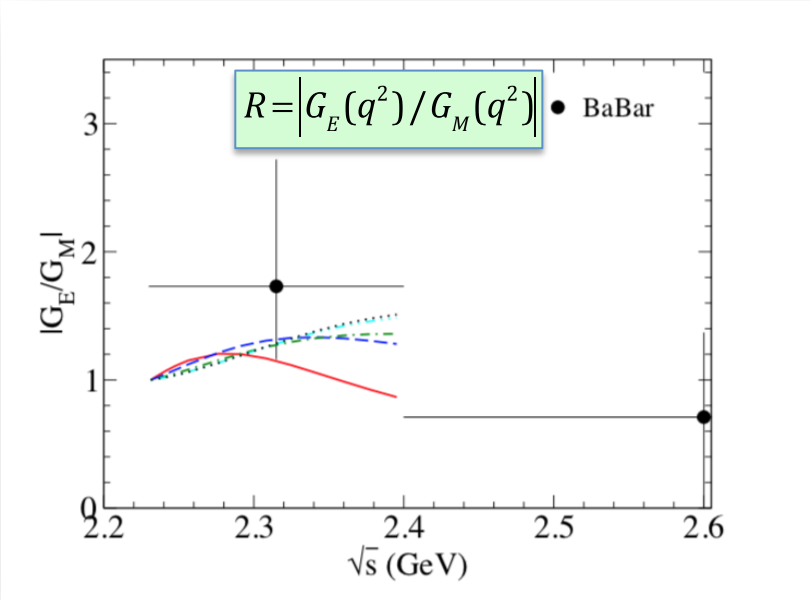
# Polarization

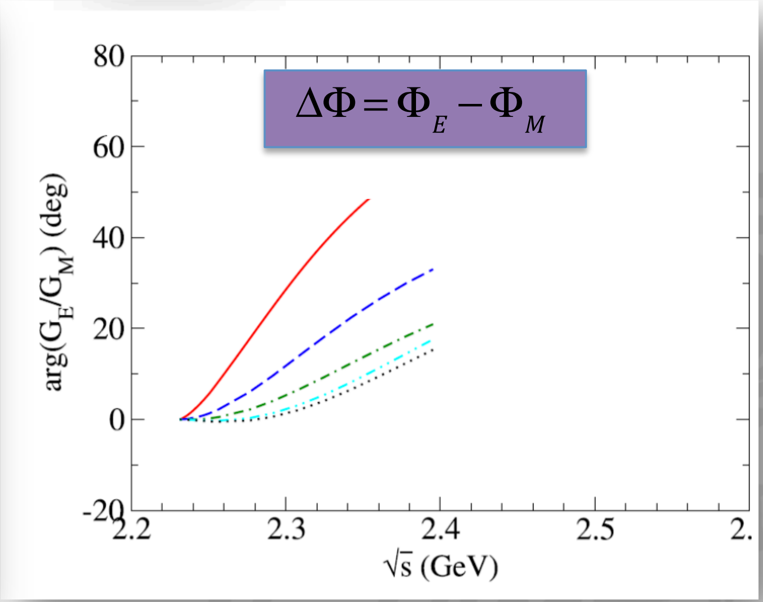
When initial state is unpolarized and process is parity conserving, final state particles polarized perpendicular to production plane

- Phase is production related, depending on CMS energy and scattering angle
- $\Delta\Phi \neq 0$ from interfering amplitudes (e.g. s- and d- waves) ➡ $\Delta\Phi = 0$ threshold
- Analyticity requires that SL FF ~ TL FF as $|q^2|$ approaches $\infty$ ➡ $\Delta\Phi = 0$



# Theoretical predictions



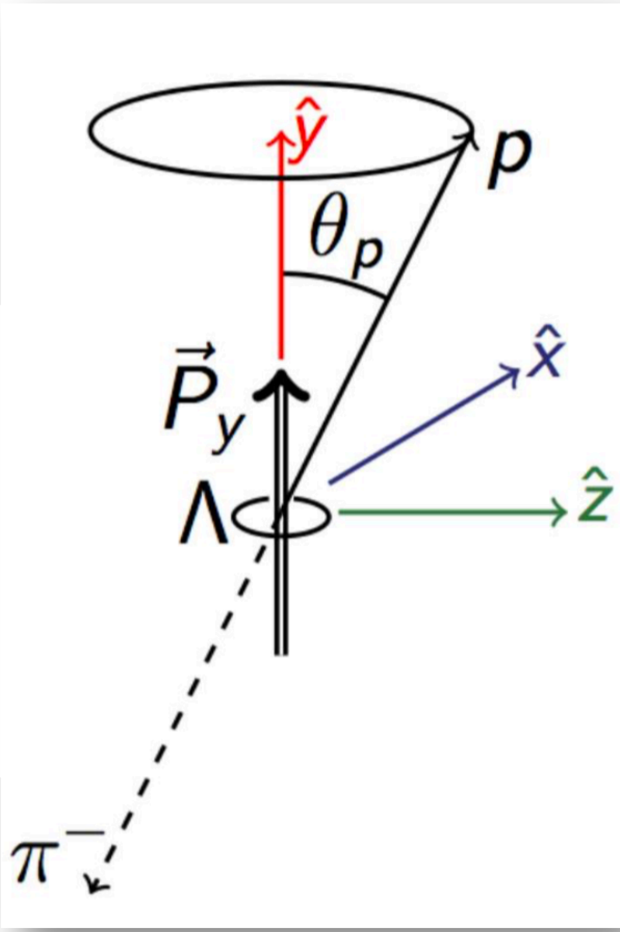

Time-like EMFFs of Λ studied in work by Haidenbauer Meissner *PLB 761 (2016) 456*

Focus on $\Lambda\bar{\Lambda}$ final state interactions

PS185 data for pp $\rightarrow \Lambda\bar{\Lambda}$ used as input to fit $\Lambda\bar{\Lambda}$ potentials *Phys Rep 368 (2002) 119*

Inconclusive BaBar results, more data required *Phys Rev D 76 (2007) 092006*

# Asymmetry parameters




Polarization of hyperons experimentally accessible in weak parity violating decays.

They are *self analyzing*: daughter particles are emitted according to polarization of mother hyperon

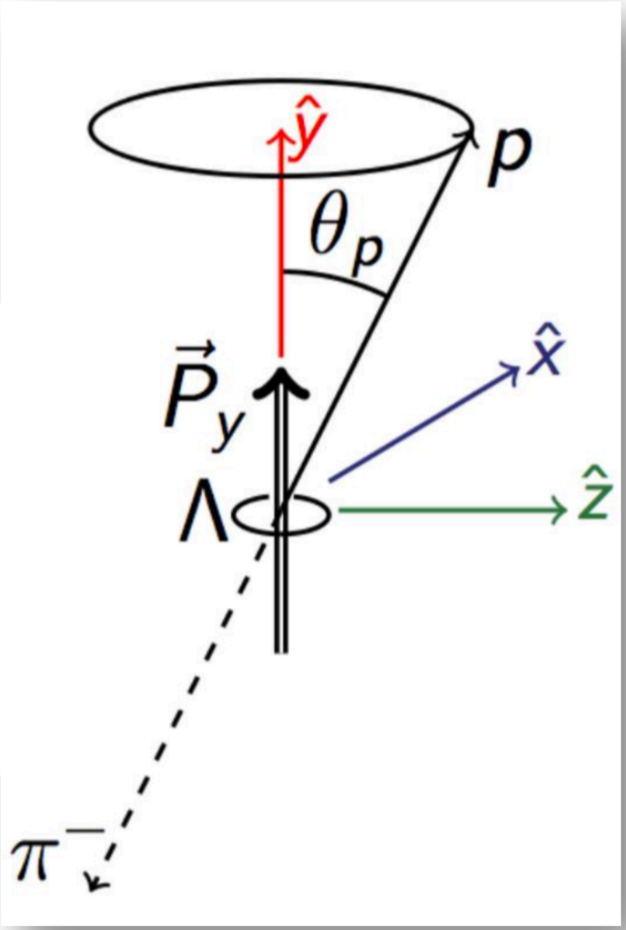
Example: Angular distribution of $\Lambda \rightarrow p\pi^-$

$$I(\cos\theta_p) \propto 1 + \alpha_- P_\Lambda \cos\theta_p$$

Asymmetry parameter
$\alpha_{-,PDG}$= 0.642(13)

Polarization

# Asymmetry parameters




By comparing $\alpha_-$ to CP-odd $\alpha_+$ CP-test

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

**$A_{CP,\ PDG} = 0.006(21)$**

This test not limited to Λ but also all other weakly decaying hyperons

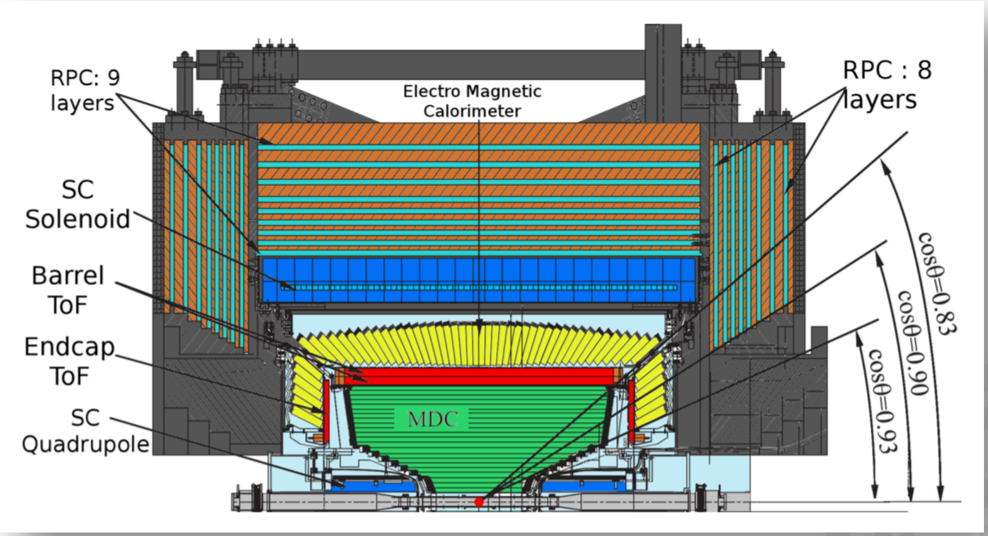
# Beijing Electron Positron Collider BEPC II


***Aerial view of BEPC II and BESIII***

BESIII at BEPC II located in Beijing, China

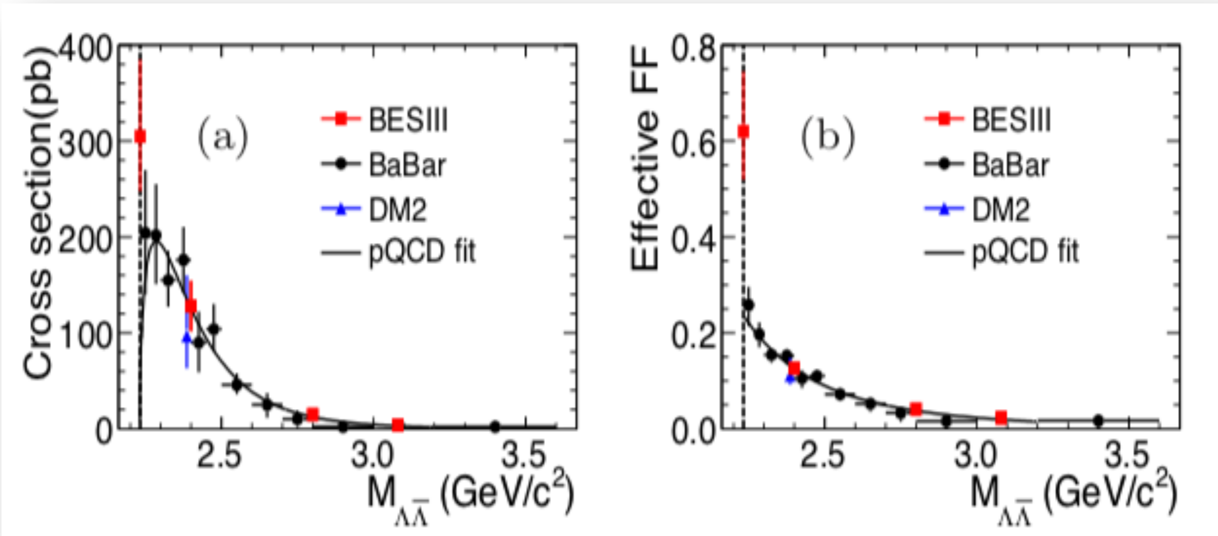
Data taking since 2009, peak luminosity $10^{33}$ $cm^{-2}s^{-1}$

# BESIII ❤ Hyperons




- Multipurpose detector with very good resolution, near 4π angular coverage
- Symmetric particle / anti particle conditions
- $e^+e^-$ experiment ➞ lower hadronic background compared to hadronic experiments
- Controlled systematic uncertainties
- Large data samples

# BESIII results cross section




BESIII PRD 97 (2018) 032013

BaBar PRD 76 (2007) 092006

DM2 Z. Phys. C 48 (1990) 23

$$\sigma_{Born}(q^2) = \frac{4\pi\alpha^2\beta}{3q^2}\left[\left|G_M(q^2)\right|^2 + \frac{1}{2\tau}\left|G_E(q^2)\right|^2\right] \qquad \left|G(q^2)\right|^2 = \frac{2\tau\left|G_M(q^2)\right|^2 + \left|G_E(q^2)\right|^2}{2\tau+1}$$

Recent results: four data points, inclusive $\bar{\Lambda} \to \bar{p}\pi^+ / \bar{n}\pi^0$ close to production threshold, exclusive for other three points

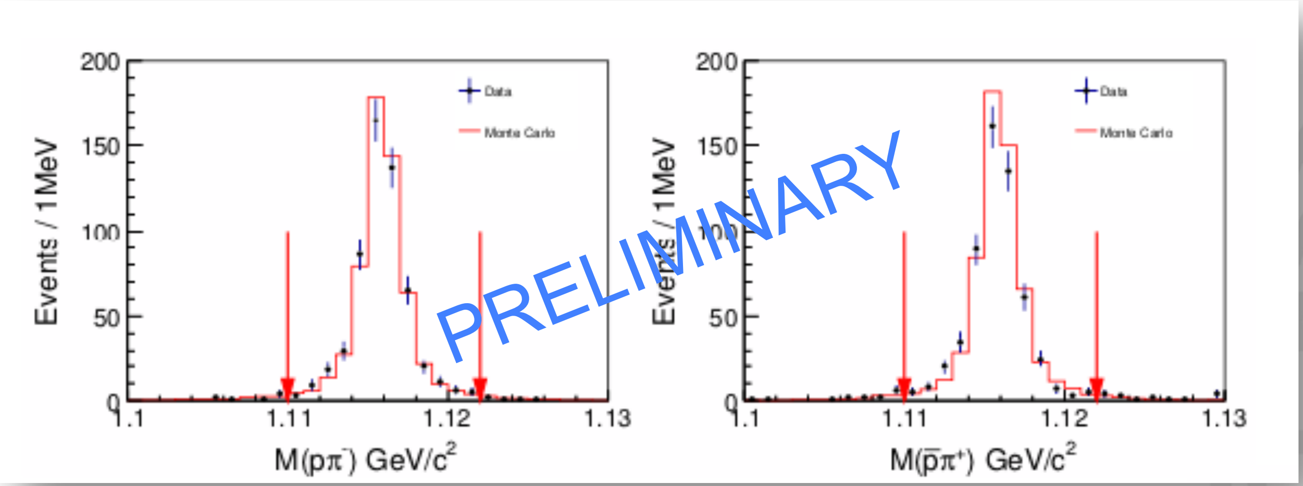
Biggest surprise is large cross section enhancement at CMS energy 2.2324 GeV, 1.0 MeV above production threshold.

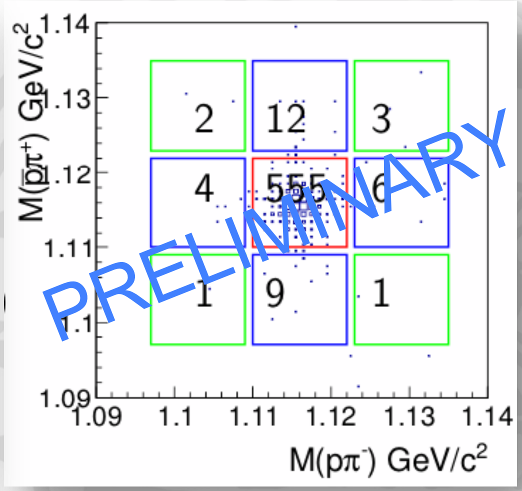
# First complete measurement Λ EMFF

Exclusive measurement using large available data sample at CMS 2.396 GeV

**$N_{exp}$ = 555(24) events**
**Mass resolution Λ 1.5 MeV/$c^2$**

**$N_{background}$ = 14(4) events**



# Λ EMFF analytic distribution

CP symmetry is assumed and $\alpha_{-/+}$ values fixed ➡ decay distribution

$$W(\xi) = \mathrm{T}_0(\xi) + \eta \mathrm{T}_5(\xi)$$
$$-\alpha^2_{-/+}\left(\mathrm{T}_1(\xi) + \sqrt{1-\eta^2}\cos(\Delta\Phi)\mathrm{T}_2(\xi) + \eta \mathrm{T}_6(\xi)\right)$$
$$+\alpha^2_{-/+}\sqrt{1-\eta^2}\sin(\Delta\Phi)\left(\mathrm{T}_3(\xi) - \mathrm{T}_4(\xi)\right)$$

*PLB 772 (2017) 16*

Maximum Log Likelihood method used to estimate two unknown parameters

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*PLB 772 (2017) 16*

ood … o esti … n parameters

Functions of 5D

$$\xi = \left(\theta, \theta_p, \varphi_p, \theta_{\bar{p}}, \varphi_{\bar{p}}\right)$$

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

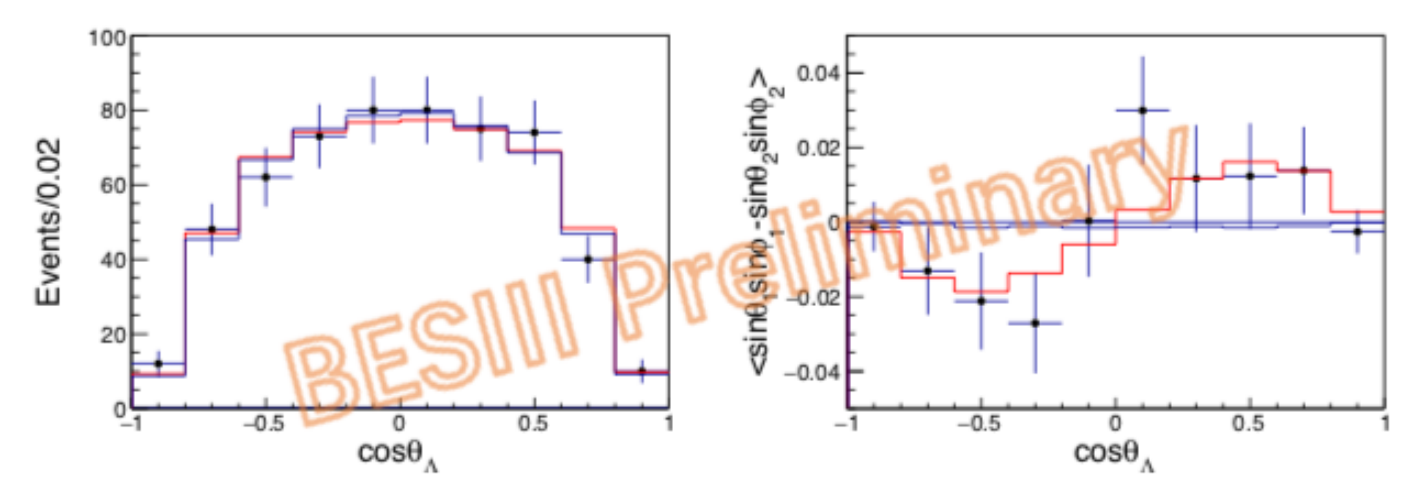
$$\Delta\Phi = \Phi_E - \Phi_M$$

# Results Λ EMFF

PRELIMINARY

$$\sigma = \frac{N_{signal}}{L(1+\varepsilon)Br(\Lambda \to p\pi^-)Br(\bar{\Lambda} \to \bar{p}\pi^+)} = 119.0 \pm (5.3)_{stat}(7.3)_{syst}\ pb^{-1}$$

$$\left|G(q^2)\right|^2 = \frac{2\tau\left|G_M(q^2)\right|^2 + \left|G_E(q^2)\right|^2}{2\tau+1} = 0.123 \pm (3)_{stat}(4)_{syst}$$




PRELIMINARY

$$R = 0.94(16)_{stat}(3)_{syst}(2)_{\alpha_\Lambda}$$

$$\Delta\Phi = 42^\circ(16^\circ)_{stat}(8^\circ)_{syst}(6^\circ)_{\alpha_\Lambda}$$

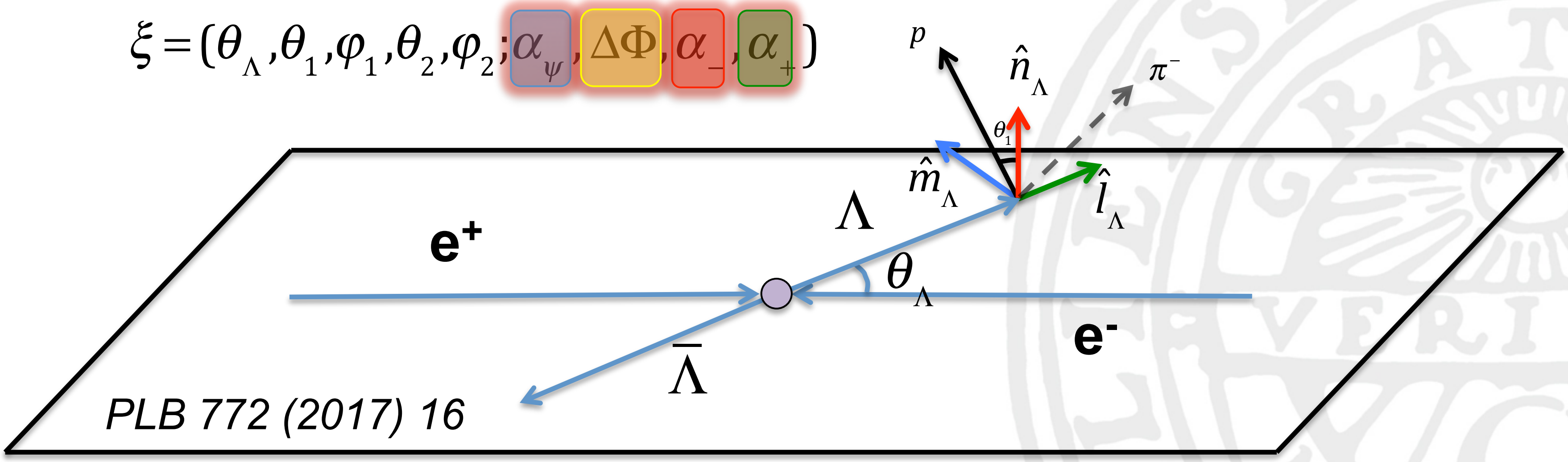
**ΔΦ is determined for the first time for *any* baryon!**

# Exclusive decay distribution

Production and Decay process for $e^+e^- \to J/\psi(\gamma^*) \to \Lambda\bar{\Lambda} \to p\pi^-\bar{p}\pi^+$

$$W(\xi) = 1 + \alpha_\psi \cos^2\theta_\Lambda + \alpha_-\alpha_+(\sin^2\theta_\Lambda \sin\theta_1 \sin\theta_2 \cos\phi_1 \cos\phi_2 + \cos^2\theta_\Lambda \cos\theta_1 \cos\theta_2)$$
$$+\alpha_-\alpha_+\sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)\left[\sin\theta_\Lambda \cos\theta_\Lambda (\sin\theta_1 \cos\theta_2 \cos\phi_1 + \cos\theta_1 \sin\theta_2 \cos\phi_2)\right]$$
$$+\alpha_-\alpha_+\alpha_\psi(\cos\theta_1\cos\theta_2 - \sin^2\theta_\Lambda \sin\theta_1 \sin\theta_2 \sin\phi_1 \sin\phi_2)$$
$$+\sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)\sin\theta_\Lambda\cos\theta_\Lambda(\alpha_-\sin\theta_1\sin\phi_1 + \alpha_+\sin\theta_2\sin\phi_2)$$

$$\xi = (\theta_\Lambda, \theta_1, \varphi_1, \theta_2, \varphi_2; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_+)$$

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# Exclusive decay distribution

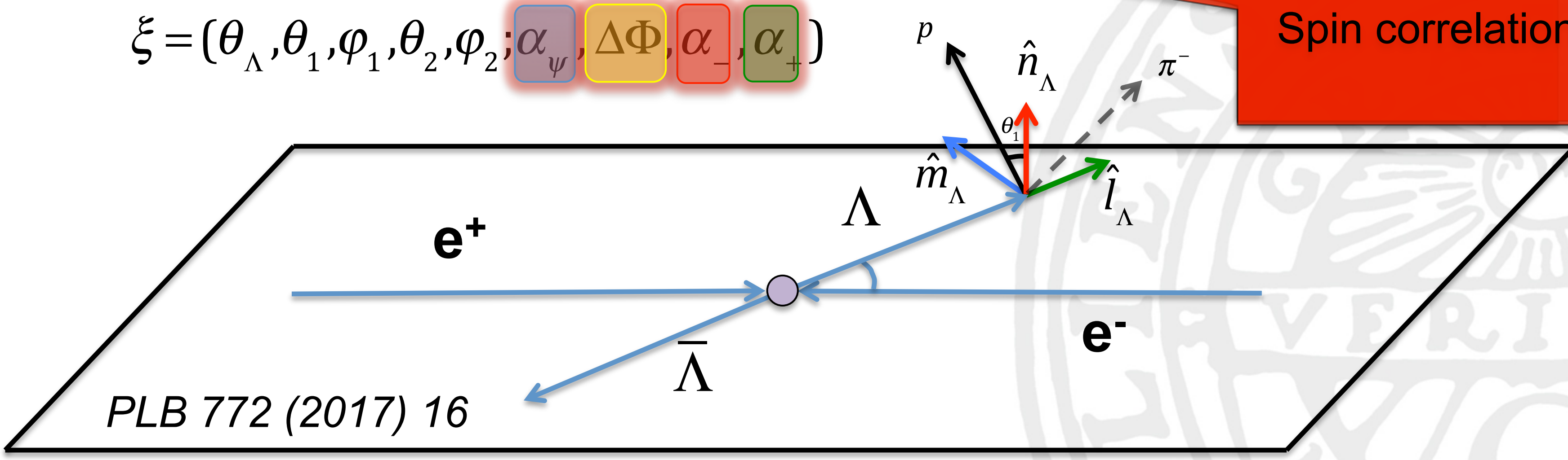
BESIII

Production and Decay process for $e^+e^- \to J/\psi(\gamma^*) \to \Lambda\bar{\Lambda} \to p\pi^-\bar{p}\pi^+$

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

Spin correlation

$$\xi = (\theta_\Lambda, \theta_1, \varphi_1, \theta_2, \varphi_2; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_+)$$

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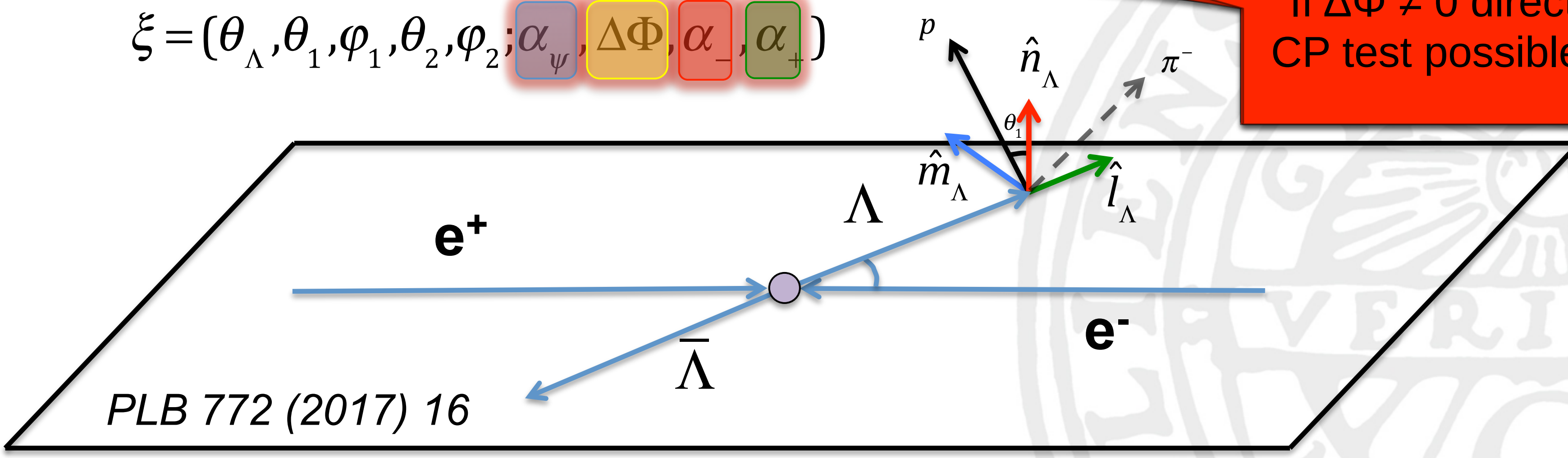
$$+\alpha_-\alpha_+\sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)\left[\sin\theta_\Lambda \cos\theta_\Lambda(\sin\theta_1\cos\theta_2\cos\phi_1 + \cos\theta_1\sin\theta_2\cos\phi_2)\right]$$
$$+\alpha_-\alpha_+\alpha_\psi(\cos\theta_1\cos\theta_2 - \sin^2\theta_\Lambda \sin\theta_1\sin\theta_2\sin\phi_1\sin\phi_2)$$
$$+\sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)\sin\theta_\Lambda\cos\theta_\Lambda(\alpha_-\sin\theta_1\sin\phi_1 + \alpha_+\sin\theta_2\sin\phi_2)$$

$$\xi = (\theta_\Lambda, \theta_1, \varphi_1, \theta_2, \varphi_2; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_+)$$

If $\Delta\Phi \neq 0$ direct CP test possible!

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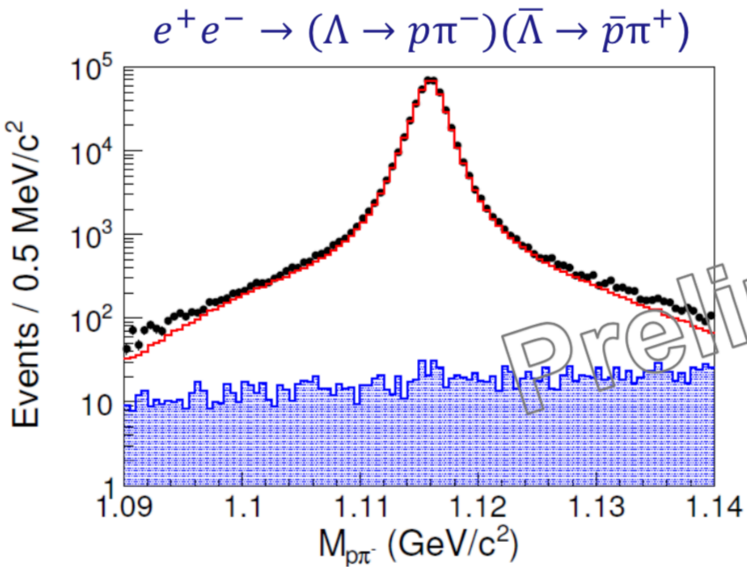
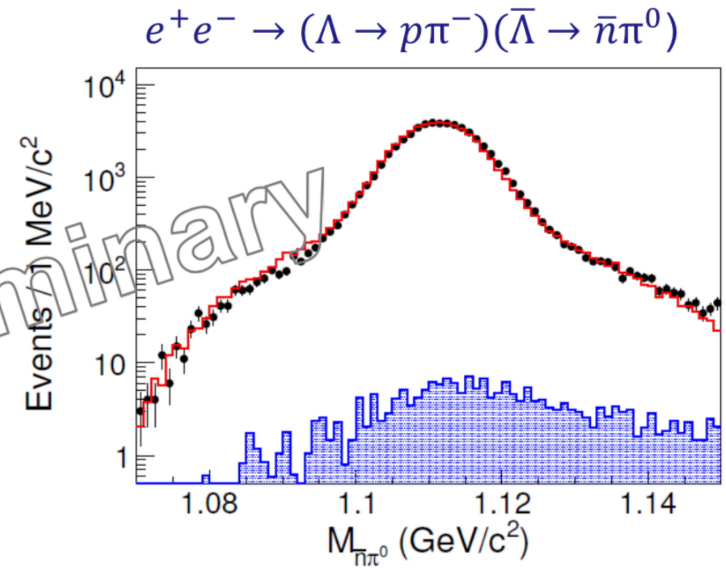
# $e^+e^- \to J/\psi \to \Lambda(\to p\pi^-)\bar{\Lambda}(\to \bar{p}\pi^+ / \bar{n}\pi^0)$




**420 593 events**
**399 background**



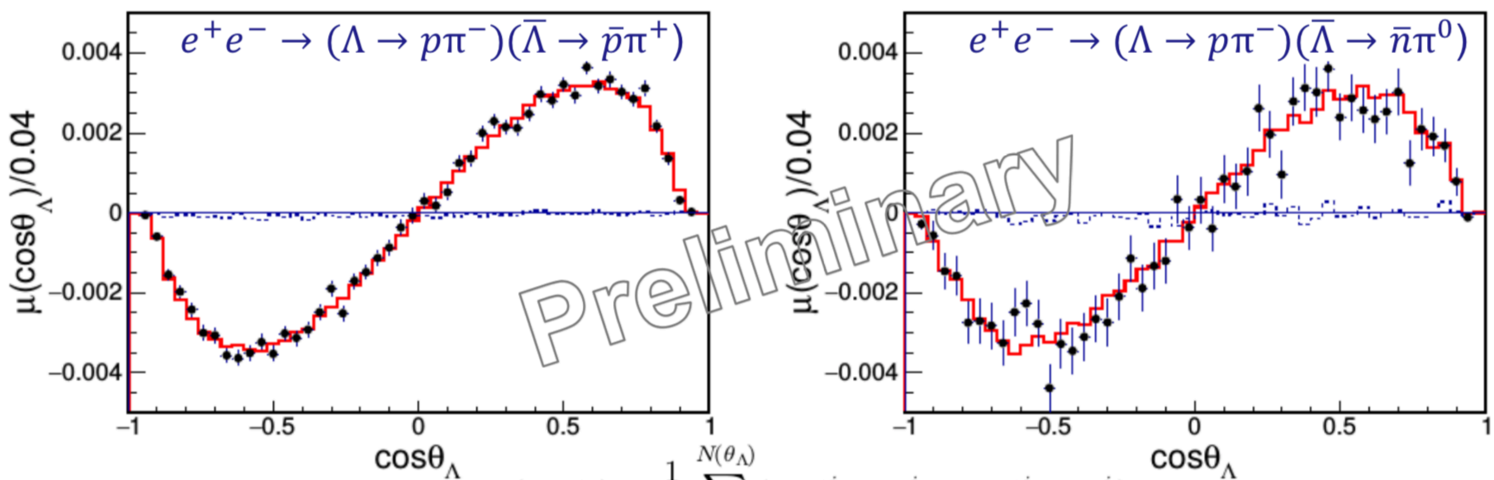

**47 009 events**
**66 background**

Results based on $1.3\times10^9$ J/Ψ events

Excellent agreement between data and simulation with little background

Maximum log likelihood approach used for estimating the parameters

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




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

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

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

**First direct CP test of ΛΛ**

**First measurement of hyperon polarization at J/ψ resonance**

**$\alpha_-$ is 17(3)% larger than quoted PDG value!**

# Summary and Outlook

1) First full measurement of $\Lambda\bar{\Lambda}$ at CMS 2.396 GeV

→ BESIII has the largest available data sample between 2.0-3.08 GeV and more results on hyperon-antihyperons will be available

2) Possible to measure values of decay parameters if ΔΦ≠0. First results on J/ψ → $\Lambda\bar{\Lambda}$ give strongly deviating value of $\alpha_-$ cf. PDG and first direct CP test

→ $1.3 \times 10^{9}$ J/ψ will increase to $1.0 \times 10^{10}$ J/ψ. Analysis ongoing for $\Sigma\bar{\Sigma}$, $\Xi\bar{\Xi}$

**Many interesting results on hyperons in forthcoming years from BESIII. Very little theory input available. Theoretical input highly desirable**

**Thank you!**