Polarization and entanglement in $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$

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Outline

- BEPCII and BESIII
- Polarization and CP violation
- Event selection
- Data analysis method
- Results
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BEPCII and BESIII

- **BEPCII** is a e^+e^- collider for the studies of light and charm quarks physics and τ-charm physics, which designed peak luminosity is $10^{33}\text{cm}^{-2}\text{s}^{-1}$ at about 3.7 GeV.

- The **BESIII** detector with a geometrical acceptance of 93% of 4π, consists of: main drift chamber(**MDC**), electromagnetic calorimeter(**EMC**), Time-Of-Flight system(**TOF**), and muon chamber system(**MUC**)

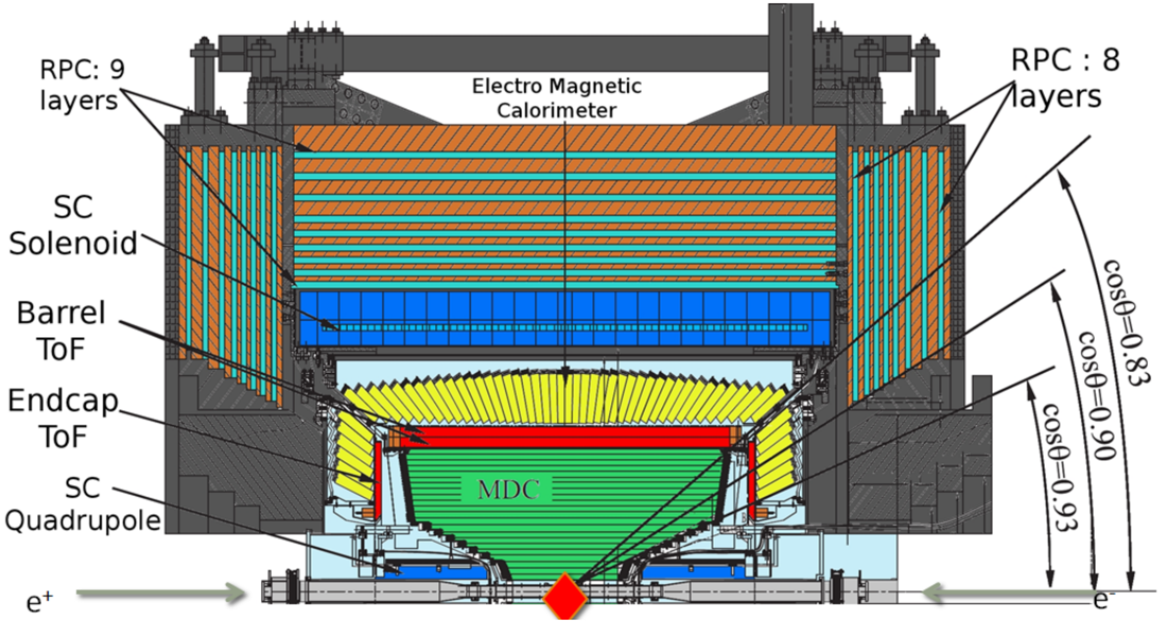

Fig. 1: Structure of BESIII detector

$\Lambda\bar{\Lambda}$ pair produced

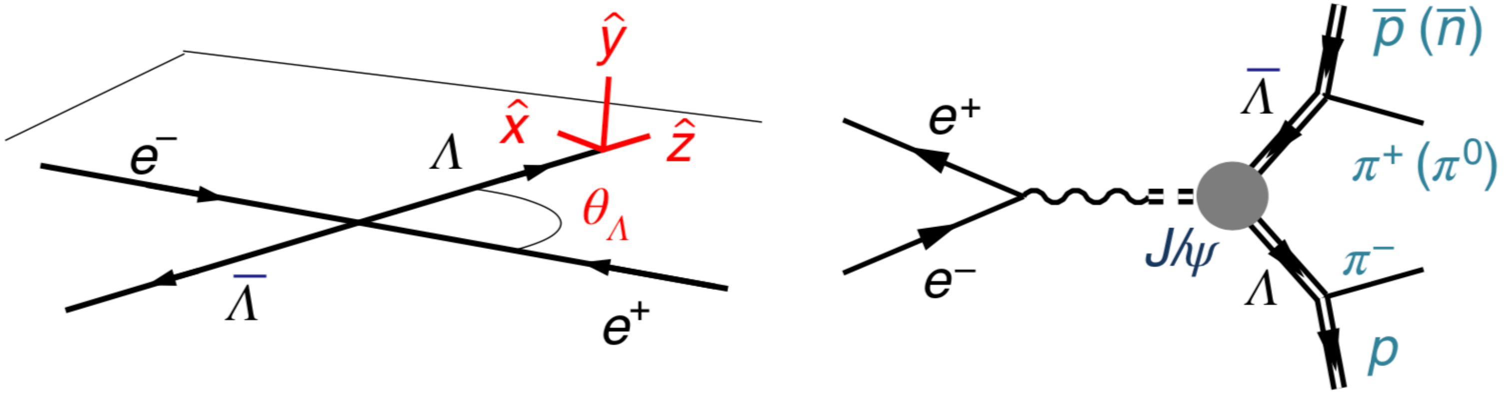

Fig. 2: Illustration of the $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$ process.
In the CMS, Λ particle is emitted in the $\hat{z}$ direction at an angle θ_Λ between the e^- beam direction. The hyperons are polarized in the direction perpendicular to the production plane ($\hat{y}$).

Polarization

- For a spin $\hat{s}$ particle, the component of polarization is $p_i =< \widehat{s_i} >$
- The decay of Λ, the amplitude and angular distribution are:
  - $|M|^2 \sim 1 + \alpha\_\hat{s}_\Lambda \cdot n_p$
  - $\frac{dN}{d\Omega} \sim 1 + \alpha\_P_\Lambda \cdot n_p$
  - $< n_p^i n_p^j > = \delta^{ij}$
- So the n_p^x, n_p^y, n_p^z are the observables of $P_\Lambda^x, P_\Lambda^y, P_\Lambda^z$

Polarized Λ produced in e^+e^- annihilation

Phys. Rev.185 D 75, 074026 (2007)

Nucl. Phys. A190 771, 169 (2006) [hep-ph/0511240]

- Joint amplitude:

$$M = \frac{ie^2}{q^2} j_\mu \bar{u}(p_1)\left(F_1\gamma_\mu + \frac{F_2}{2m} p_\nu \sigma^{\nu\mu}\gamma_5\right) v(p_2)$$

- Differential cross section:

$$d\sigma \sim 1 + \alpha_\psi \cos^2\theta_\Lambda + (\alpha_\psi + \cos^2\theta_\Lambda) s_\Lambda^z s_{\bar{\Lambda}}^z + \sin^2\theta_\Lambda s_\Lambda^x s_{\bar{\Lambda}}^x - \alpha_\psi \sin^2\theta_\Lambda s_\Lambda^y s_{\bar{\Lambda}}^y + \sqrt{1-\alpha_\psi^2}\cos\Delta\Phi \sin\theta_\Lambda \cos\theta_\Lambda (s_\Lambda^x s_{\bar{\Lambda}}^z + s_\Lambda^z s_{\bar{\Lambda}}^x) + \sqrt{1-\alpha_\psi^2}\sin\Delta\Phi \sin\theta_\Lambda \cos\theta_\Lambda (s_\Lambda^y + s_{\bar{\Lambda}}^y)$$

- Only $< s^y >$ could be non-zero, if $\sin\Delta\Phi \neq 0$

Joint angular distribution

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The differential-cross-section distribution: $d\sigma \propto \mathcal{W}(\xi)\, d\cos\theta\; d\Omega_1 d\Omega_2.$

$$
\begin{aligned}
W(\xi; \alpha_{J/\psi}, \Delta\Phi, \alpha_-, \alpha_+) &= 1 + \alpha_{J/\psi}\cos^2\theta_\Lambda \\
&+ \alpha_-\alpha_+ \left[\sin^2\theta_\Lambda \left(n_{1,x}n_{2,x} - \alpha_{J/\psi} n_{1,y}n_{2,y}\right) + \left(\cos^2\theta_\Lambda + \alpha_{J/\psi}\right) n_{1,z}n_{2,z}\right] \\
&+ \alpha_-\alpha_+ \sqrt{1-\alpha_{J/\psi}^2}\cos(\Delta\Phi)\sin\theta_\Lambda\cos\theta_\Lambda \left(n_{1,x}n_{2,z} + n_{1,z}n_{2,x}\right) \\
&+ \sqrt{1-\alpha_{J/\psi}^2}\sin(\Delta\Phi)\sin\theta_\Lambda\cos\theta_\Lambda \left(\alpha_- n_{1,y} + \alpha_+ n_{2,y}\right)
\end{aligned}
$$

$\xi = (\hat{n}_1, \hat{n}_2)$ $\alpha_- = \alpha(\Lambda \to p\pi^-)$ $\alpha_+ = \alpha(\bar{\Lambda} \to \bar{p}\pi^+)$

For $\Lambda \to p\pi^-$, $\bar{\Lambda} \to \bar{n}\pi^0$: $\alpha_+ \to \bar{\alpha}_0(\bar{\Lambda} \to \bar{n}\pi^0)$

Polarization and CP violation

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

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

Event selection

For $\Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$:

- Using four charged track to reconstruct $\Lambda\bar{\Lambda}$
- Applying a four-constraint kinematic fit on $\Lambda\bar{\Lambda}$ hypothesis

For $\Lambda \to p\pi^-, \bar{\Lambda} \to \bar{n}\pi^0$:

- $\bar{\Lambda}$ is reconstructed by $\bar{n}\pi^0$
- A one-constraint kinematic fit is performed because the momentum of $\bar{n}$ is unmeasured.

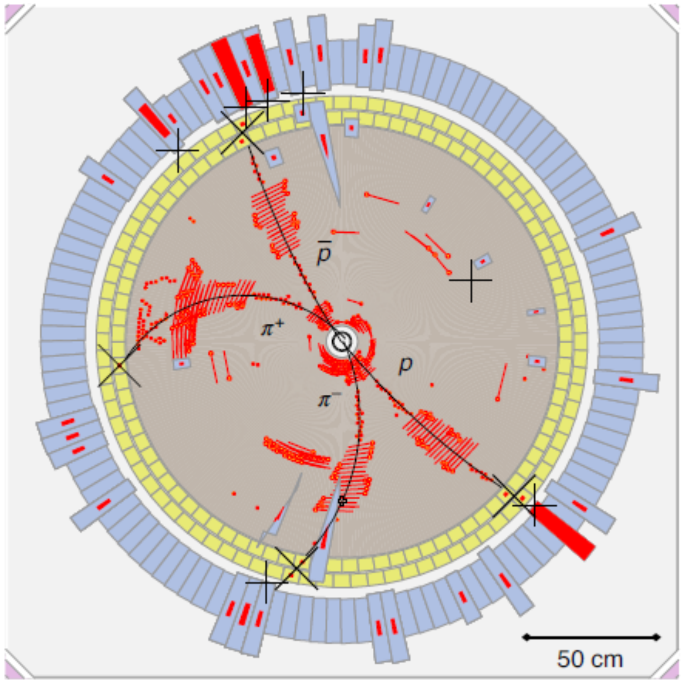

Fig. 3: An example $J/\psi \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$ event in the BESIII detector.

Data analysis method

Maximum likelihood fit:

- Likelihood function: $$\mathcal{L} = \prod_{i=1}^{N} \mathcal{P}(\xi^i; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_+) = \prod_{i=1}^{N} \mathcal{C}\mathcal{W}(\xi^i; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_+)\epsilon(\xi^i),$$
- Normalization factor: $$\mathcal{C}^{-1} = \frac{1}{N_{MC}} \sum_{j=1}^{N_{MC}} \mathcal{W}(\xi^j; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_+)\epsilon(\xi^j)$$
- Minimum function: $$\mathcal{S} = -\ln\mathcal{L}_{\rm data} + \ln\mathcal{L}_{\rm bg}$$

Analysis results

- A clear polarization:

$$\mu(\cos\theta_\Lambda) = \frac{m}{N}\sum_{i=1}^{N_k}(n_{1,y}^{(i)} - n_{2,y}^{(i)}) = \frac{\alpha_- - \alpha_2}{2}\frac{1+\alpha_\psi\cos^2\theta_\Lambda}{3+\alpha_\psi}P_y(\theta_\Lambda)$$

$$\Delta\Phi = (42.4 \pm 0.6 \pm 0.5)°$$

- CP violation:

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

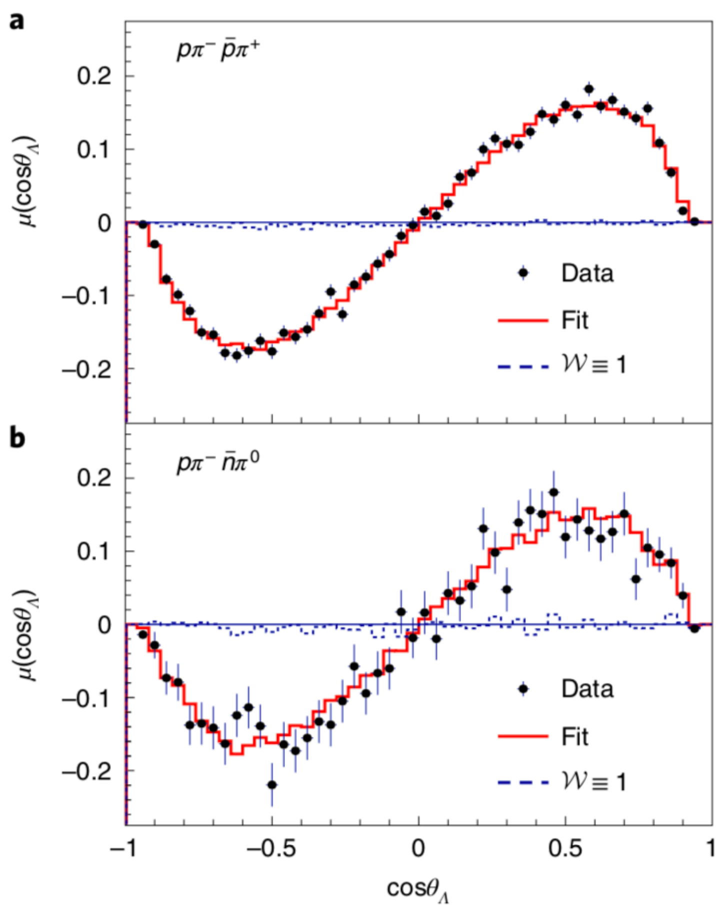

Fig. 4: The polarization signal for $\Lambda(\Lambda)$ in $e^+e^- \rightarrow J/\psi \rightarrow \Lambda\bar{\Lambda}$

Analysis results

Table 1 | Summary of the results

Parameters	This work	Previous results
α_ψ	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027 (ref. [14])
$\Delta\Phi$	$42.4 \pm 0.6 \pm 0.5°$	-
α_-	$0.750 \pm 0.009 \pm 0.004$	0.642 ± 0.013 (ref. [6])
α_+	$-0.758 \pm 0.010 \pm 0.007$	-0.71 ± 0.08 (ref. [6])
$\bar{\alpha}_0$	$-0.692 \pm 0.016 \pm 0.006$	-
A_{CP}	$-0.006 \pm 0.012 \pm 0.007$	0.006 ± 0.021 (ref. [6])
$\bar{\alpha}_0/\alpha_+$	$0.913 \pm 0.028 \pm 0.012$	-

Parameters: $J/\psi \to \Lambda\bar{\Lambda}$ angular distribution parameter α_ψ, helicity phase $\Delta\Phi$, asymmetry parameters for the $\Lambda \to p\pi^-$ (α_-), $\bar{\Lambda} \to \bar{p}\pi^+$ (α_+) and $\bar{\Lambda} \to \bar{n}\pi^0$ ($\bar{\alpha}_0$) decays, CP asymmetry A_{CP} and ratio $\bar{\alpha}_0/\alpha_+$. The first uncertainty is 1s.d. statistical, and the second is systematic, calculated as described in the Methods.

The measurement of helicity phase $\Delta\Phi$ is firstly.

The value of α_- is $17 \pm 3\%$ higher than the current world average.

Supplementary

Background analysis

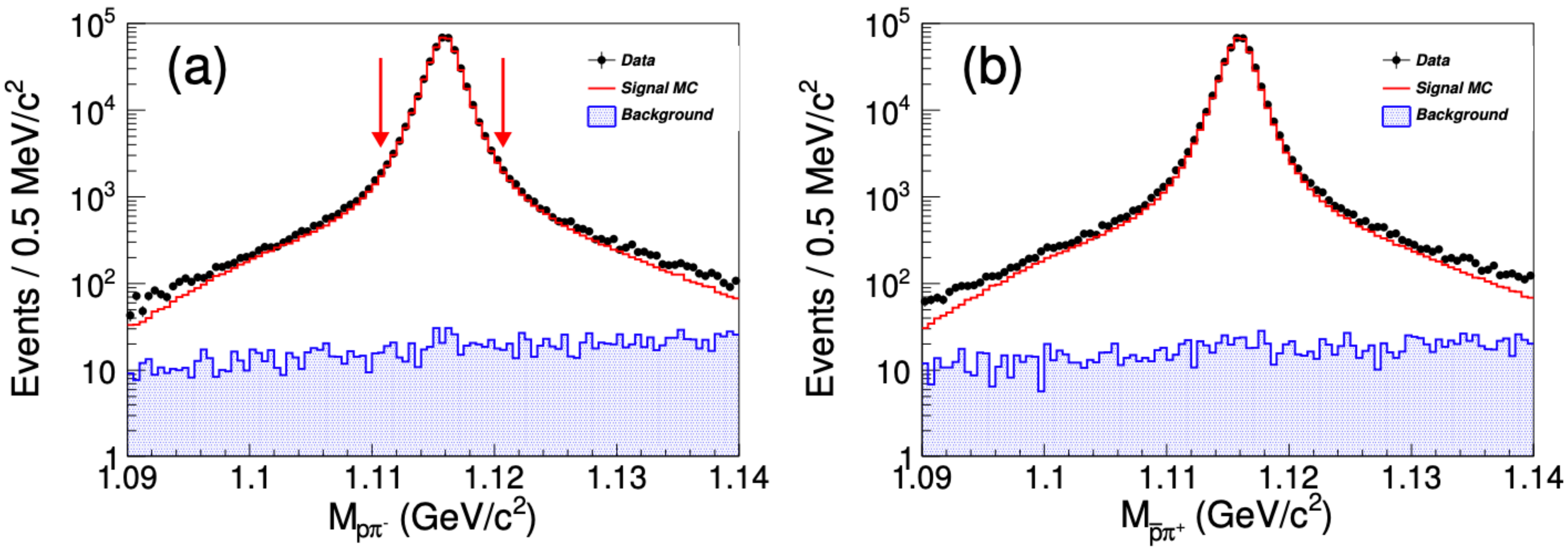

Fig (supplementary) 1: Identification of $J/\psi \to \Lambda\bar{\Lambda},\ \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$

Background analysis

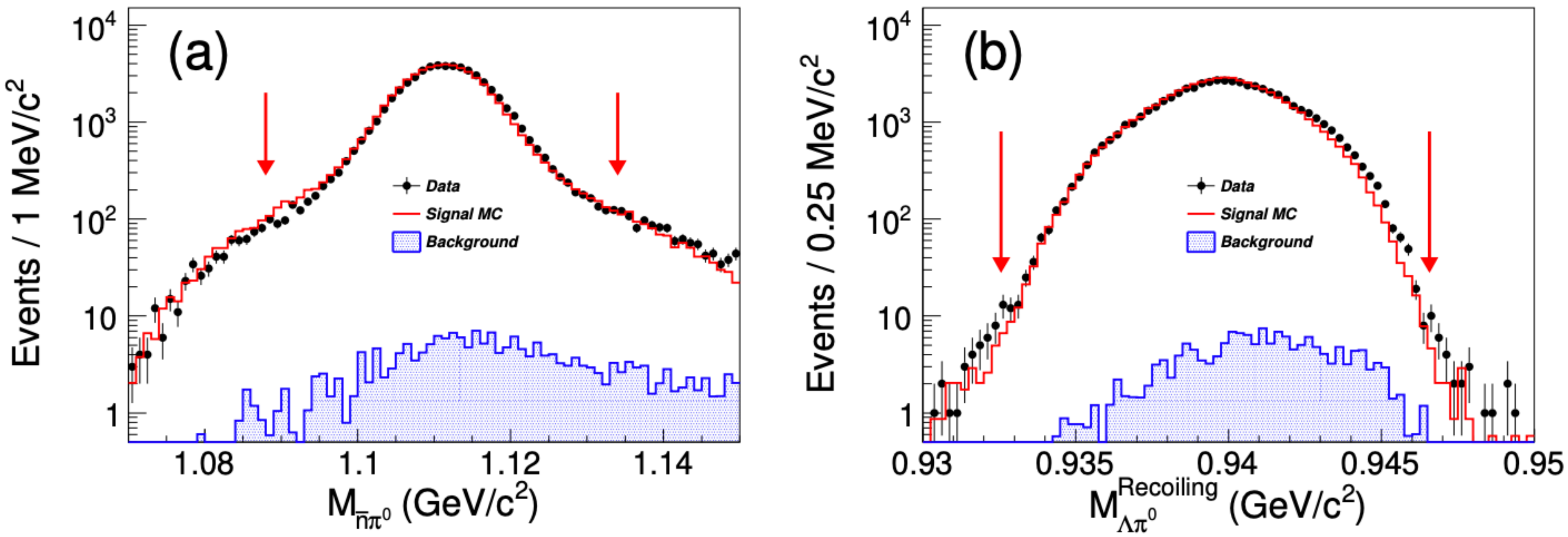

Fig (supplementary) 2: Identification of $J/\psi \to \Lambda\bar{\Lambda},\ \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{n}\pi^0$

Systematic uncertainties

Source	α_ψ	α_-	α_+	$\bar{\alpha}_0$	$\Delta\Phi$
Tracking, π^0, $\bar{n}$	1.5	0.1	0.3	0.6	1.1
Kinematic fit	0.2	0.1	0.8	0.6	0.0
Fit method	0.0	0.5	0.4	0.4	0.1
Total	1.5	0.5	0.9	0.8	1.1

Table (supplementary) 1: Relative systematic uncertainties (in %) for the measurements of parameters $\alpha_\psi, \alpha_-, \alpha_+, \overline{\alpha_0}$, and $\Delta\Phi$.