

Improve measurement of decay parameters of Λ in $J/\psi \rightarrow \Lambda \bar{\Lambda}$

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Nov-1, 2018

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Motivation I

The differential-cross-section distribution

$$d\sigma \propto \mathcal{W}(\boldsymbol{\xi}) d\cos\theta d\Omega_1 d\Omega_2.$$

The differential-distribution function $\mathcal{W}(\boldsymbol{\xi})$ can be expressed as,

$$\begin{aligned} \mathcal{W}(\boldsymbol{\xi}) = & \mathcal{F}_0(\boldsymbol{\xi}) + \alpha\mathcal{F}_5(\boldsymbol{\xi}) \\ & + \alpha_1\alpha_2 \left(\mathcal{F}_1(\boldsymbol{\xi}) + \sqrt{1-\alpha^2} \cos(\Delta\Phi)\mathcal{F}_2(\boldsymbol{\xi}) + \alpha\mathcal{F}_6(\boldsymbol{\xi}) \right) \\ & + \sqrt{1-\alpha^2} \sin(\Delta\Phi) (\alpha_1\mathcal{F}_3(\boldsymbol{\xi}) + \alpha_2\mathcal{F}_4(\boldsymbol{\xi})), \end{aligned}$$

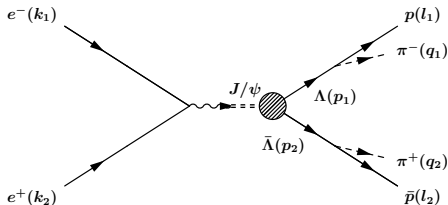


Figure: Graph describing the reaction $e^+e^- \rightarrow \Lambda(\rightarrow p\pi^-)\bar{\Lambda}(\rightarrow \bar{p}\pi^+)$.

Motivation II

$$\mathcal{F}_0(\xi) = 1$$

$$\mathcal{F}_1(\xi) = \sin^2\theta \sin\theta_1 \sin\theta_2 \cos\phi_1 \cos\phi_2 + \cos^2\theta \cos\theta_1 \cos\theta_2$$

$$\mathcal{F}_2(\xi) = \sin\theta \cos\theta (\sin\theta_1 \cos\theta_2 \cos\phi_1 + \cos\theta_1 \sin\theta_2 \cos\phi_2)$$

$$\mathcal{F}_3(\xi) = \sin\theta \cos\theta \sin\theta_1 \sin\phi_1$$

$$\mathcal{F}_4(\xi) = \sin\theta \cos\theta \sin\theta_2 \sin\phi_2$$

$$\mathcal{F}_5(\xi) = \cos^2\theta$$

$$\mathcal{F}_6(\xi) = \cos\theta_1 \cos\theta_2 - \sin^2\theta \sin\theta_1 \sin\theta_2 \sin\phi_1 \sin\phi_2.$$

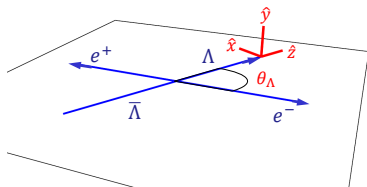


Figure: Kinematics of the reaction $e^+e^- \rightarrow \Lambda \bar{\Lambda}$ in the overall center-of-mass system.

- High precise measurements of hyperon and anti-hyperon decay parameters provide a test of CP symmetry.
[A. Pais, Phys. Rev. Lett. 3, 242 \(1959\).](#)
- The observable of CP asymmetry is defined by $A_Y = \frac{\alpha_Y + \alpha_{\bar{Y}}}{\alpha_Y - \alpha_{\bar{Y}}}$. None zero value of A_Y represents CP Violation.

- Analysis BOSS Version : 6.6.4.p01
- Data Sample : 1.310×10^9 J/ψ @ $\sqrt{s} = 3.097$ GeV in 2009 (0.224×10^9) and 2012 (1.086×10^9)
- Inclusive Monte Carlo Sample : (1.225×10^9) inclusive MC for J/ψ decay
- Signal Monte Carlo Sample (PHSP Model) :

10×10^6 events for $J/\psi \rightarrow \Lambda\bar{\Lambda}, \Lambda \rightarrow p\pi^-, \bar{\Lambda} \rightarrow \bar{p}\pi^+$

Event Selection I

- (1) Good charged tracks selection:
 - polar angle $|\cos \theta| < 0.93$
 - good charged tracks equal or larger than 4
- (2) Proton candidate: $p_p > 0.5\text{GeV}/c$
- (3) Pion candidate: $p_\pi < 0.5\text{GeV}/c$
- (4) Lambda(bar) candidate:
 - primary vertex fit $\chi^2 < 200$
 - $M_{p\pi^-} \in (1.111, 1.121)$
 - $M_{\bar{p}\pi^+} \in (1.111, 1.121)$
- (5) J/ψ candidate: $\chi_{4C}^2 < 60$

Event Selection II

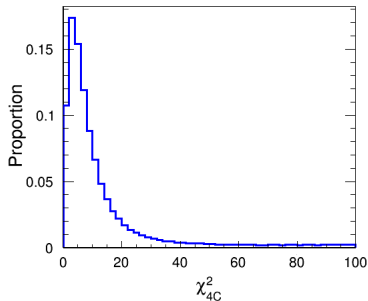


Figure: χ_{4C}^2 distribution of inclusive Monte Carlo

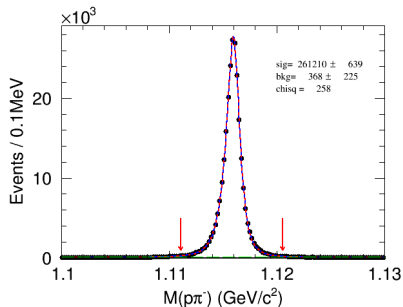


Figure: $M_{p\pi^-}$ distribution of inclusive Monte Carlo

Background Study

There are approximately 0.7 % peak background events and 0.08 % other background events pass the selection.

No.	decay chain	final states	iTopology	nEvt	nTot
0	$J/\psi \rightarrow \Lambda\bar{\Lambda}, \Lambda \rightarrow p\pi^-, \bar{\Lambda} \rightarrow \pi^+\bar{p}$	$\pi^-\bar{p}\pi^+p$	0	254133	254133
1	$J/\psi \rightarrow \Lambda\Sigma^0, \Lambda \rightarrow p\pi^-, \Sigma^0 \rightarrow \gamma\bar{\Lambda}, \bar{\Lambda} \rightarrow \pi^+\bar{p}$	$\pi^-\bar{p}\pi^+\gamma p$	2	801	254934
2	$J/\psi \rightarrow \Sigma^0\bar{\Lambda}, \Sigma^0 \rightarrow \Lambda\gamma, \bar{\Lambda} \rightarrow \pi^+\bar{p}, \Lambda \rightarrow p\pi^-$	$\pi^-\bar{p}\pi^+\gamma p$	1	784	255718
3	$J/\psi \rightarrow \Lambda\gamma\bar{\Lambda}, \Lambda \rightarrow p\pi^-, \bar{\Lambda} \rightarrow \pi^+\bar{p}$	$\pi^-\bar{p}\pi^+\gamma p$	7	307	256025
4	$J/\psi \rightarrow p\pi^+\pi^-\bar{p}$	$\pi^-\bar{p}\pi^+p$	5	116	256141
5	$J/\psi \rightarrow \Delta^{++}\pi^-\bar{p}, \Delta^{++} \rightarrow p\pi^+$	$\pi^-\bar{p}\pi^+p$	6	35	256176
6	$J/\psi \rightarrow \Delta^{++}\bar{\Delta}^{--}, \Delta^{++} \rightarrow p\pi^+, \bar{\Delta}^{--} \rightarrow \pi^-\bar{p}$	$\pi^-\bar{p}\pi^+p$	4	23	256199
7	$J/\psi \rightarrow \eta_c\gamma, \eta_c \rightarrow \Lambda\bar{\Lambda}, \Lambda \rightarrow p\pi^-, \bar{\Lambda} \rightarrow \pi^+\bar{p}$	$\pi^-\bar{p}\pi^+\gamma p$	10	16	256215
8	$J/\psi \rightarrow p\pi^+\bar{\Delta}^{--}, \bar{\Delta}^{--} \rightarrow \pi^-\bar{p}$	$\pi^-\bar{p}\pi^+p$	16	12	256227
9	$J/\psi \rightarrow \Lambda\bar{\Lambda}, \Lambda \rightarrow p\gamma_{FSR}\pi^-, \bar{\Lambda} \rightarrow \pi^+\bar{p}$	$\pi^-\bar{p}\pi^+p$	12	8	256235
10	$J/\psi \rightarrow \Lambda\bar{\Lambda}, \Lambda \rightarrow p\pi^-, \bar{\Lambda} \rightarrow \pi^+\bar{p}$	$\pi^-\bar{p}\pi^+\gamma p$	3	8	256243
11	$J/\psi \rightarrow \Lambda\bar{\Lambda}, \Lambda \rightarrow p\gamma\pi^-, \bar{\Lambda} \rightarrow \pi^+\bar{p}$	$\pi^-\bar{p}\pi^+\gamma p$	9	6	256249
12	$J/\psi \rightarrow \Lambda\bar{\Lambda}, \Lambda \rightarrow p\pi^-, \bar{\Lambda} \rightarrow \pi^+\gamma_{FSR}\bar{p}$	$\pi^-\bar{p}\pi^+p$	14	5	256254
13	$J/\psi \rightarrow \Delta^0\bar{\Delta}^0, \Delta^0 \rightarrow p\pi^-, \bar{\Delta}^0 \rightarrow \pi^+\bar{p}$	$\pi^-\bar{p}\pi^+p$	15	5	256259
14	$J/\psi \rightarrow \Lambda\bar{\Lambda}, \Lambda \rightarrow p\pi^-, \bar{\Lambda} \rightarrow \nu_\mu\mu^+\bar{p}$	$\mu^+\pi^-\bar{p}\nu_\mu p$	11	4	256263
15	$J/\psi \rightarrow \Lambda\bar{\Lambda}, \Lambda \rightarrow p\mu^-\bar{\nu}_\mu, \bar{\Lambda} \rightarrow \pi^+\bar{p}$	$\bar{\nu}_\mu\bar{p}\mu^-\pi^+p$	13	4	256267
16	$J/\psi \rightarrow b_1^+\pi^-, b_1^+ \rightarrow \pi^+\gamma$	$\pi^-\pi^+\gamma$	21	1	256268
17	$J/\psi \rightarrow \Lambda\bar{\Lambda}, \Lambda \rightarrow p\pi^-, \bar{\Lambda} \rightarrow \nu_e e^+\bar{p}$	$e^+\pi^-\bar{p}\nu_e p$	19	1	256269
18	$J/\psi \rightarrow \Delta^{++}\gamma_{FSR}\pi^-\bar{p}, \Delta^{++} \rightarrow p\pi^+$	$\pi^-\bar{p}\pi^+p$	17	1	256270
19	$J/\psi \rightarrow p\pi^-\bar{\Delta}^0, \bar{\Delta}^0 \rightarrow \pi^+\bar{p}$	$\pi^-\bar{p}\pi^+p$	20	1	256271
20	$J/\psi \rightarrow \Delta^0\pi^+\bar{p}, \Delta^0 \rightarrow p\pi^-$	$\pi^-\bar{p}\pi^+p$	8	1	256272
21	$J/\psi \rightarrow \Sigma^0\bar{\Lambda}, \Sigma^0 \rightarrow \Lambda\gamma, \bar{\Lambda} \rightarrow \pi^+\bar{p}, \Lambda \rightarrow p\mu^-\bar{\nu}_\mu$	$\bar{\nu}_\mu\bar{p}\mu^-\pi^+\gamma p$	18	1	256273
22	$J/\psi \rightarrow \Sigma^0\bar{\Sigma}^0, \Sigma^0 \rightarrow \Lambda\gamma, \bar{\Sigma}^0 \rightarrow \gamma\bar{\Lambda}, \Lambda \rightarrow p\pi^-, \bar{\Lambda} \rightarrow \pi^+\bar{p}$	$\pi^-\bar{p}\pi^+\gamma p$	22	1	256274

Figure: The topology of remaining background events from 1225 million J/ψ inclusive MC sample

Background Study - exclusive MC

The exclusive MC samples are generated to estimate background events. Background lists for $\bar{\Lambda} \rightarrow \bar{p}\pi^+$. Branching fractions are calculated according to PDG data. The results show background contribution is less than 0.1%.

Decay mode	Branching ratio	$N_{Gen}(10^5)$	N_{Obs}	Normalized
$J/\psi \rightarrow \Delta^{++}\Delta^{--}, \Delta^{++} \rightarrow p\pi^+, \Delta^{--} \rightarrow \bar{p}\pi^-$	$(1.10 \pm 0.29) \times 10^{-3}$	40	115	41.45 ± 10.93
$J/\psi \rightarrow \Delta^{--}p\pi^+, \Delta^{--} \rightarrow \bar{p}\pi^-$	$(1.6 \pm 0.5) \times 10^{-3}$	40	85	44.56 ± 13.93
$J/\psi \rightarrow \Delta^{++}\bar{p}\pi^-, \Delta^{++} \rightarrow p\pi^+$	$(1.6 \pm 0.5) \times 10^{-3}$	40	107	56.09 ± 17.53
$J/\psi \rightarrow \gamma\eta_C, \eta_C \rightarrow \Lambda\bar{\Lambda}$	$(8.08 \pm 1.55) \times 10^{-6}$	10	4044	42.82 ± 8.21
$J/\psi \rightarrow \gamma\Lambda\bar{\Lambda}$	$(5.31 \pm 0.71) \times 10^{-5}$	100	7320	50.94 ± 6.81
$J/\psi \rightarrow p\pi^-\bar{p}\pi^+$	$(6.0 \pm 0.5) \times 10^{-3}$	100	202	158.85 ± 13.23
$J/\psi \rightarrow \bar{\Lambda}\Sigma^0, \Sigma^0 \rightarrow \gamma\Lambda$	$(7.1 \pm 0.9) \times 10^{-6}$	10	1183	11.01 ± 1.40
$J/\psi \rightarrow \bar{\Sigma}^0\Lambda, \bar{\Sigma}^0 \rightarrow \gamma\bar{\Lambda}$	$(5.59 \pm 0.74) \times 10^{-6}$	10	1166	8.54 ± 1.13
$J/\psi \rightarrow \Sigma^0\bar{\Sigma}^0, \Sigma^0 \rightarrow \gamma\bar{\Lambda}, \bar{\Sigma}^0 \rightarrow \gamma\bar{\Lambda}$	$(5.26 \pm 0.37) \times 10^{-4}$	50	10	1.38 ± 0.10

Likelihood

$$\mathcal{L} = \prod_{i=1}^N \mathcal{P}(\xi_i) = \prod_{i=1}^N C \mathcal{W}(\xi_i; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_+),$$

- 1 normalization factor

$$C^{-1} = \frac{1}{N_{MC}} \sum_{j=1}^{N_{MC}} \text{weight} \cdot \mathcal{W}(\xi_j; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_+)$$

- 2 Angle Distribution

$$\mathcal{W}(\xi_i; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_+)$$

Simultaneous Fit and Results II

We use the RooFit package to determine the parameters, the objective function is defined by

$$\mathcal{S} = -\ln\mathcal{L}_{\text{data}} + \ln\mathcal{L}_{\text{bg}}$$

where $\ln\mathcal{L}_{\text{data}}$ and $\ln\mathcal{L}_{\text{bg}}$ are the likelihood functions for the data set and the background events, respectively.

The results are:

$$\alpha_{J/\psi} = 0.462 \pm 0.006$$

$$\alpha_{-} = 0.748 \pm 0.010$$

$$\Delta = 0.738 \pm 0.011 \text{ rad}$$

$$\alpha_{+} = -0.755 \pm 0.010$$

Simultaneous Fit and Results III

The following moments $T_i (i=1, \dots, 5)$ are used to compare fit results with data,

$$T_1 = \frac{4}{9} \pi^2 \alpha_- \alpha_+ (2\alpha \cos(2\theta) + 2\alpha + \cos(4\theta) + 3) \quad (1)$$

$$T_2 = \frac{8}{9} \pi^2 \alpha_- \alpha_+ \sqrt{1 - \alpha^2} \cos(\Delta\Phi) \sin^2(2\theta) \quad (2)$$

$$T_3 = \frac{4}{3} \pi^2 \alpha_- \sqrt{1 - \alpha^2} \sin(\Delta\Phi) \sin^2(2\theta) \quad (3)$$

$$T_4 = \frac{4}{3} \pi^2 \alpha_+ \sqrt{1 - \alpha^2} \sin(\Delta\Phi) \sin^2(2\theta) \quad (4)$$

$$T_5 = \frac{2}{9} \pi^2 \alpha_- \alpha_+ (\alpha \cos(4\theta) - 4(\alpha - 1) \cos(2\theta) + 11\alpha + 4) \quad (5)$$

Simultaneous Fit and Results IV

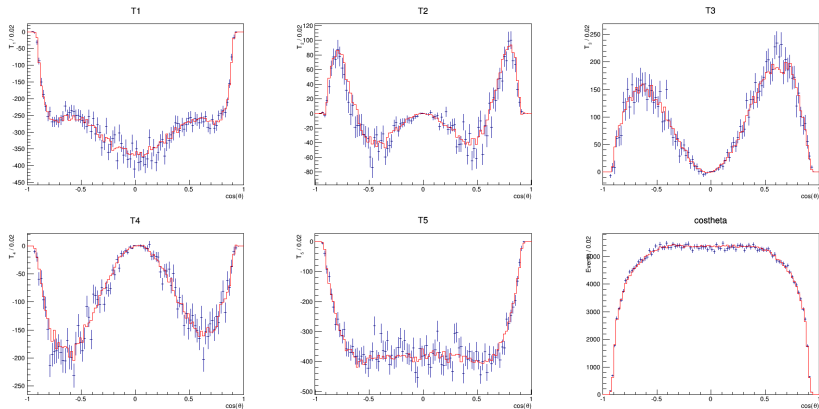


Figure: Distributions of T_i functions in terms of $\cos\theta_\Lambda$. The dots with error bars are the data, and the histograms are the fit results. T_3 and T_4 non-zero value indicate non-zero $\Delta\Phi$.

The systematic uncertainties coming from two categories:

(1) Event selection:

- background estimations
- MDC tracking efficiency
- Λ and $\bar{\Lambda}$ vertex fit
- Kinematic fit
- Λ and $\bar{\Lambda}$ mass window

(2) Fit procedure

Background estimation

Background estimations:

The systematic error from background is calculated by fitting the data with or without considering background contribution. The differences on the parameters are taken as systematic errors. The results without background contribution are:

$$\alpha_{J/\psi} = 0.461 \pm 0.006$$

$$\alpha_{-} = 0.752 \pm 0.010$$

$$\Delta = 0.737 \pm 0.011 \text{ rad}$$

$$\alpha_{+} = -0.760 \pm 0.010$$

① The control sample: $J/\psi \rightarrow p\bar{p}\pi^+\pi^-$

② Correction:

- L:

$$\mathcal{L} = \prod_{i=1}^N \mathcal{P}(\xi_i) = \prod_{i=1}^N \mathcal{C}\mathcal{W}(\xi_i; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_+) \quad (6)$$

- normalization factor:

$$\mathcal{C}^{-1} = \frac{1}{N_{MC}} \sum_{j=1}^{N_{MC}} weight \cdot \mathcal{W}(\xi_j; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_+)$$

- weight:

$$weight = \frac{\prod_{\alpha} \epsilon_{\alpha}^{data}(p_T, \theta)}{\prod_{\alpha} \epsilon_{\alpha}^{MC}(p_T, \theta)}, \alpha = p, \bar{p}, \pi^+, \pi^- \quad (7)$$

where $\epsilon_{p/\bar{p}/\pi^+/\pi^-}$ denote p, \bar{p}, π^+, π^- tracking efficiency, respectively.

MDC tracking

Then looping over all the MC tracks to obtain the efficiency ratio, which will be considered as event weights in the ML fit. The fit results after MDC tracking correction are:

$$\alpha_{J/\psi} = 0.461 \pm 0.006$$

$$\alpha_- = 0.753 \pm 0.010$$

$$\Delta = 0.737 \pm 0.011 \text{ rad}$$

$$\alpha_+ = -0.760 \pm 0.010$$

Using the uncertainty of efficiency ratio as tracking systematic error, the results are:

Source	$\alpha_{J/\psi}$	α_-	α_+	$\Delta\Phi$
Background	0.02	0.10	0.04	0.01
Tracking	1.00	0.10	0.08	0.41

Table: Systematic uncertainties(%) for parameters $\alpha_{J/\psi}$, α_- , α_+ and $\Delta\Phi$

Control sample: $J/\psi \rightarrow p\bar{p}\pi^+\pi^-$ is selected to obtain the kinematic fit efficiency ϵ_{data} and ϵ_{MC} :

$$\epsilon_{data} = \frac{N'_{data}}{N_{data}}, \quad \epsilon_{MC} = \frac{N'_{MC}}{N_{MC}}$$

where N_{data} and N_{MC} are the number of data and MC events before 4C fit, N'_{data} and N'_{MC} are the number of data and MC events after 4C fit, respectively.

The corrections are done with the 4-dimensional variables distributions (10^4 bins): $\theta_p, \theta_{\pi^-}, \theta_{\bar{p}}, \theta_{\pi^+}$, where θ are polar angles. In each bin, correction factor is calculated by $\epsilon_{data}/\epsilon_{MC}$.

The correction factor will be applied on MC events track by track as the fit weight. The results of simultaneous fit with the corrected MC sample are:

$$\alpha_{J/\psi} = 0.565 \pm 0.006$$

$$\alpha_- = 0.709 \pm 0.010$$

$$\Delta = 0.850 \pm 0.010 \text{ rad}$$

$$\alpha_+ = -0.716 \pm 0.010$$