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

Jianyu Zhang[1],Haibo Li[2]

Institute of High Energy Physics

OCT-18, 2018

Outline

- Motivation
- Data Sets
- Event Selection
- Background Study
- Simultaneous Fit and Results
- Systematic Errors

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,

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

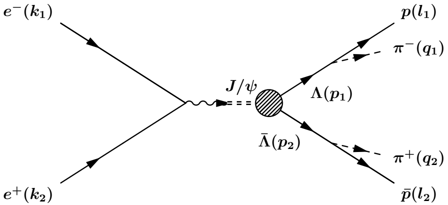

Figure: Graph describing the reaction $e^+e^- \to \Lambda(\to p\pi^-)\bar{\Lambda}(\to \bar{p}\pi^+)$.

Motivation II

$$\mathcal{F}_0(\boldsymbol{\xi}) = 1$$
$$\mathcal{F}_1(\boldsymbol{\xi}) = \sin^2\theta \sin\theta_1 \sin\theta_2 \cos\phi_1 \cos\phi_2 + \cos^2\theta \cos\theta_1 \cos\theta_2$$
$$\mathcal{F}_2(\boldsymbol{\xi}) = \sin\theta \cos\theta \left(\sin\theta_1 \cos\theta_2 \cos\phi_1 + \cos\theta_1 \sin\theta_2 \cos\phi_2\right)$$
$$\mathcal{F}_3(\boldsymbol{\xi}) = \sin\theta \cos\theta \sin\theta_1 \sin\phi_1$$
$$\mathcal{F}_4(\boldsymbol{\xi}) = \sin\theta \cos\theta \sin\theta_2 \sin\phi_2$$
$$\mathcal{F}_5(\boldsymbol{\xi}) = \cos^2\theta$$
$$\mathcal{F}_6(\boldsymbol{\xi}) = \cos\theta_1 \cos\theta_2 - \sin^2\theta \sin\theta_1 \sin\theta_2 \sin\phi_1 \sin\phi_2.$$

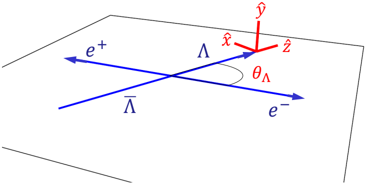

Figure: Kinematics of the reaction $e^+e^- \rightarrow$ in the overall center-of-mass system.

Motivation III

- 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.

Data Sets

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

$$10 \times 10^6 \text{ events for } J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$$

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: $p_p >$ 0.5GeV$/c$

(3) Pion candidate: $p_\pi <$ 0.5GeV$/c$

(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: $\chi^2_{4C} <$ 60

Event Selection II

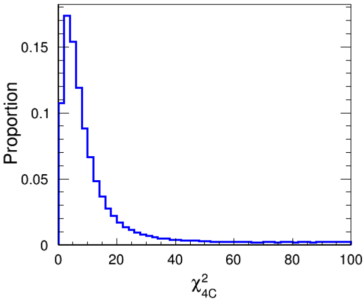

Figure: χ^2_{4C} distribution of inclusive Monte Carlo

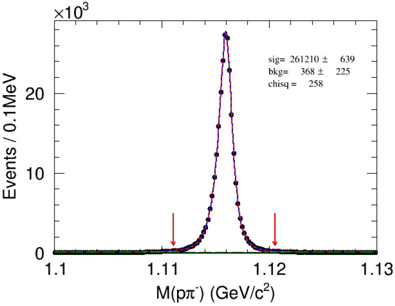

Figure: $M_{p\pi^-}$ distribution of inclusive Monte Carlo

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	$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \pi^+\bar{p}$	$\pi^-\bar{p}\pi^+p$	0	254133	254133
1	$J/\psi \to \Lambda\bar{\Sigma}^0, \Lambda \to p\pi^-, \bar{\Sigma}^0 \to \gamma\bar{\Lambda}, \bar{\Lambda} \to \pi^+\bar{p}$	$\pi^-\bar{p}\pi^+\gamma p$	2	801	254934
2	$J/\psi \to \Sigma^0\bar{\Lambda}, \Sigma^0 \to \Lambda\gamma, \bar{\Lambda} \to \pi^+\bar{p}, \Lambda \to p\pi^-$	$\pi^-\bar{p}\pi^+\gamma p$	1	784	255718
3	$J/\psi \to \Lambda\gamma\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \pi^+\bar{p}$	$\pi^-\bar{p}\pi^+\gamma p$	7	307	256025
4	$J/\psi \to p\pi^+\pi^-\bar{p}$	$\pi^-\bar{p}\pi^+p$	5	116	256141
5	$J/\psi \to \Delta^{++}\pi^-\bar{p}, \Delta^{++} \to p\pi^+$	$\pi^-\bar{p}\pi^+p$	6	35	256176
6	$J/\psi \to \Delta^{++}\bar{\Delta}^{--}, \Delta^{++} \to p\pi^+, \bar{\Delta}^{--} \to \pi^-\bar{p}$	$\pi^-\bar{p}\pi^+p$	4	23	256199
7	$J/\psi \to \eta_c\gamma, \eta_c \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \pi^+\bar{p}$	$\pi^-\bar{p}\pi^+\gamma p$	10	16	256215
8	$J/\psi \to p\pi^+\bar{\Delta}^{--}, \bar{\Delta}^{--} \to \pi^-\bar{p}$	$\pi^-\bar{p}\pi^+p$	16	12	256227
9	$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\gamma_{FSR}\pi^-, \bar{\Lambda} \to \pi^+\bar{p}$	$\pi^-\bar{p}\pi^+p$	12	8	256235
10	$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \pi^+\gamma\bar{p}$	$\pi^-\bar{p}\pi^+\gamma p$	3	8	256243
11	$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\gamma\pi^-, \bar{\Lambda} \to \pi^+\bar{p}$	$\pi^-\bar{p}\pi^+\gamma p$	9	6	256249
12	$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \pi^+\gamma_{FSR}\bar{p}$	$\pi^-\bar{p}\pi^+p$	14	5	256254
13	$J/\psi \to \Delta^0\bar{\Delta}^0, \Delta^0 \to p\pi^-, \bar{\Delta}^0 \to \pi^+\bar{p}$	$\pi^-\bar{p}\pi^+p$	15	5	256259
14	$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \nu_\mu\mu^+\bar{p}$	$\mu^+\pi^-\bar{p}\nu_\mu p$	11	4	256263
15	$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\mu^-\bar{\nu}_\mu, \bar{\Lambda} \to \pi^+\bar{p}$	$\bar{\nu}_\mu\bar{p}\mu^-\pi^+p$	13	4	256267
16	$J/\psi \to b_1^+\pi^-, b_1^+ \to \pi^+\gamma$	$\pi^-\pi^+\gamma$	21	1	256268
17	$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \nu_e e^+\bar{p}$	$e^+\pi^-\bar{p}\nu_e p$	19	1	256269
18	$J/\psi \to \Delta^{++}\gamma_{FSR}\pi^-\bar{p}, \Delta^{++} \to p\pi^+$	$\pi^-\bar{p}\pi^+p$	17	1	256270
19	$J/\psi \to p\pi^-\bar{\Delta}^0, \bar{\Delta}^0 \to \pi^+\bar{p}$	$\pi^-\bar{p}\pi^+p$	20	1	256271
20	$J/\psi \to \Delta^0\pi^+\bar{p}, \Delta^0 \to p\pi^-$	$\pi^-\bar{p}\pi^+p$	8	1	256272
21	$J/\psi \to \Sigma^0\bar{\Lambda}, \Sigma^0 \to \Lambda\gamma, \bar{\Lambda} \to \pi^+\bar{p}, \Lambda \to p\mu^-\bar{\nu}_\mu$	$\bar{\nu}_\mu\bar{p}\mu^-\pi^+\gamma p$	18	1	256273
22	$J/\psi \to \Sigma^0\bar{\Sigma}^0, \Sigma^0 \to \Lambda\gamma, \bar{\Sigma}^0 \to \gamma\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \pi^+\bar{p}$	$\pi^-\bar{p}\pi^+\gamma\gamma p$	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 $\bar{\Lambda} \to \bar{p}\pi^+$. 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
$J/\psi \to \Delta^{++}\Delta^{--}, \Delta^{++} \to p\pi^+, \Delta^{--} \to \bar{p}\pi^-$	$(1.10 \pm 0.29)\ \times 10^{-3}$	40	115	41.45 ± 10.93
$J/\psi \to \Delta^{--}p\pi^+, \Delta^{--} \to \bar{p}\pi^-$	$(1.6 \pm 0.5)\ \times 10^{-3}$	40	85	44.56 ± 13.93
$J/\psi \to \Delta^{++}\bar{p}\pi^-, \Delta^{++} \to p\pi^+$	$(1.6 \pm 0.5)\ \times 10^{-3}$	40	107	56.09 ± 17.53
$J/\psi \to \gamma\eta_C, \eta_C \to \Lambda\bar{\Lambda}$	$(8.08 \pm 1.55)\ \times 10^{-6}$	10	4044	42.82 ± 8.21
$J/\psi \to \gamma\Lambda\bar{\Lambda}$	$(5.31 \pm 0.71)\ \times 10^{-5}$	100	7320	50.94 ± 6.81
$J/\psi \to p\pi^-\bar{p}\pi^+$	$(6.0 \pm 0.5)\ \times 10^{-3}$	100	202	158.85 ± 13.23
$J/\psi \to \bar{\Lambda}\Sigma^0, \Sigma^0 \to \gamma\Lambda$	$(7.1 \pm 0.9)\ \times 10^{-6}$	10	1183	11.01 ± 1.40
$J/\psi \to \bar{\Sigma^0}\Lambda, \bar{\Sigma^0} \to \gamma\bar{\Lambda}$	$(5.59 \pm 0.74)\ \times 10^{-6}$	10	1166	8.54 ± 1.13
$J/\psi \to \Sigma^0\bar{\Sigma^0}, \Sigma^0 \to \gamma\bar{\Lambda}, \bar{\Sigma^0} \to \gamma\bar{\Lambda}$	$(5.26 \pm 0.37)\ \times 10^{-4}$	50	10	1.38 ± 0.10

Simultaneous Fit and Results I

The joint likelihood function is defined as:

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

$\mathcal{P}(\xi_i)$ is the probability density function evaluated for event i.

$\mathcal{W}(\xi_i; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_+)$ is the differential-distribution function for event i

$\mathcal{C}^{-1} = \frac{1}{N_{MC}} \sum_{j=1}^{N_{MC}} \mathcal{W}(\xi_j; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_+)$ is the normalization factor, which calculated by Monte Carlo events generated with phase space model.

Simultaneous Fit and Results II

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

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

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

The results are:

$\alpha_{J/\psi}$ = 0.462 $\pm$ 0.006 Δ = 0.738 $\pm$ 0.011 rad
α_{-} = 0.748 $\pm$ 0.010 α_{+} = -0.755 $\pm$ 0.010

Simultaneous Fit and Results III

The following moments T_i(i=1,...,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

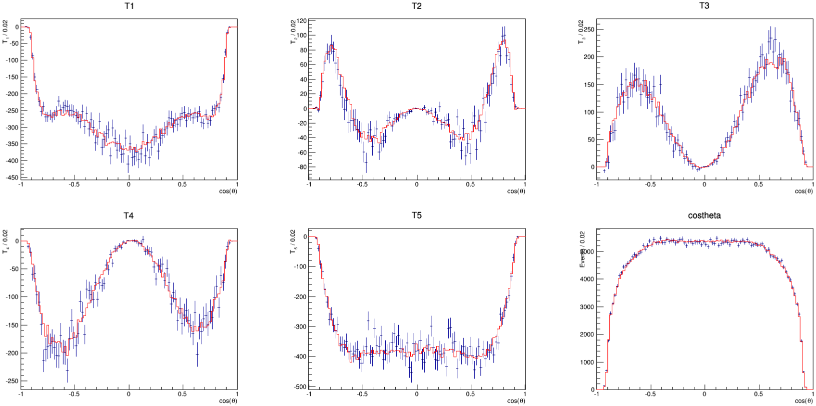

Figure: Distributions of T_i functions in terms of $\cos\theta_\Lambda$. The dots with error bars are the data, and the histograms are the fit results. T_3 and T_4 none-zero value indicate none-zero $\Delta\Phi$.

Systematic Errors

The systematic uncertainties coming from two categories:

(1) Event selection:

- background estimations
- MDC tracking effenciency
- 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 $\quad\quad$ Δ = 0.737 $\pm$ 0.011 rad
α_{-} = 0.752 $\pm$ 0.010 $\quad\quad$ α_{+} = -0.760 $\pm$ 0.010

MDC tracking

The control sample: $J/\psi \to p\bar{p}\pi^+\pi^-$ is selected to study the inconsistency of MC and data tracking efficiency. This correction is related to track's transverse momentum and polar acceptance, which performed based on 2-dimension distribution.

The efficiency ratio of data to MC is calculated with,

$$r_\epsilon = \frac{\epsilon^{data}_{p,track}(p_p)\epsilon^{data}_{\bar{p},track}(p_{\bar{p}})\epsilon^{data}_{\pi^+,track}(p_{\pi^+})\epsilon^{data}_{\pi^-,track}(p_{\pi^-})}{\epsilon^{MC}_{p,track}(p_p)\epsilon^{MC}_{\bar{p},track}(p_{\bar{p}})\epsilon^{MC}_{\pi^+,track}(p_{\pi^+})\epsilon^{MC}_{\pi^-,track}(p_{\pi^-})}$$

where $\epsilon_{p/\bar{p}/\pi^+/\pi^-}$ denote $p, \bar{p}, \pi^+, \pi^-$ 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 Δ = 0.737 $\pm$ 0.011 rad
α_{-} = 0.753 $\pm$ 0.010 α_{+} = -0.760 $\pm$ 0.010

Source	$\alpha_{/\psi}$	α_{-}	α_{+}	$\Delta\Phi$
Background	0.2	1.0	0.4	0.1
Tracking	1.3	7.0	6.6	1.6

Table: Systematic uncertainties(0.1%) for parameters $\alpha_{/\psi}$, α_{-}, α_{+} and $\Delta\Phi$