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

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Outline

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- Event Selection
- Background Study
- Simultaneous Fit and Results
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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,

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

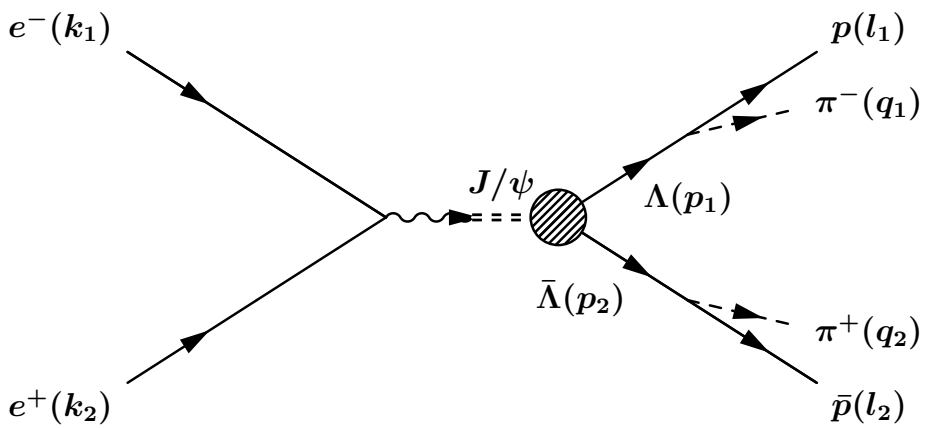


Figure: Graph describing the reaction $e^+e^- \to \Lambda(\to p\pi^-)\bar{\Lambda}(\to \bar{p}\pi^+)$.

Motivation II

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

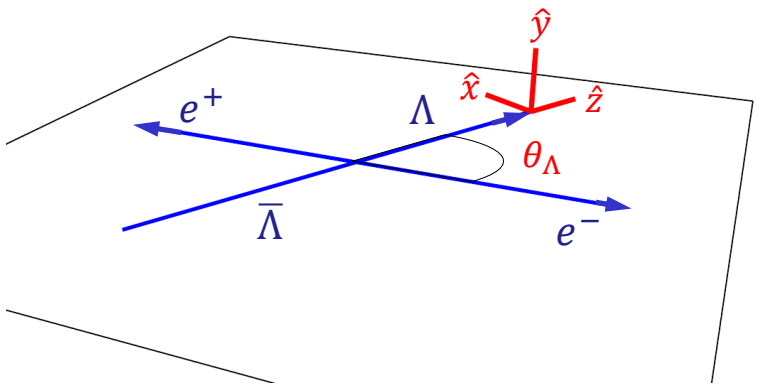


Figure: Kinematics of the reaction $e^+e^- \rightarrow$ in the overall center-of-mass system.

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) :

10×10^6 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

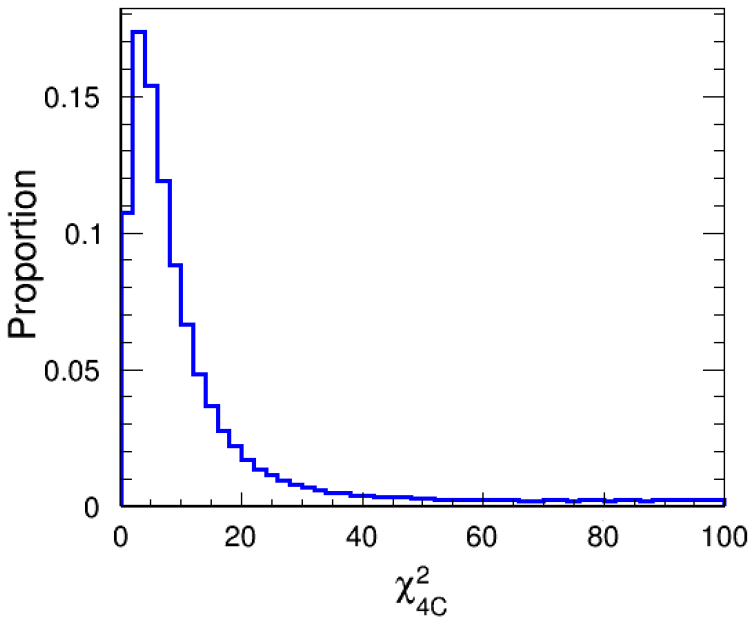


Figure: χ^2_{4C} distribution of inclusive Monte Carlo

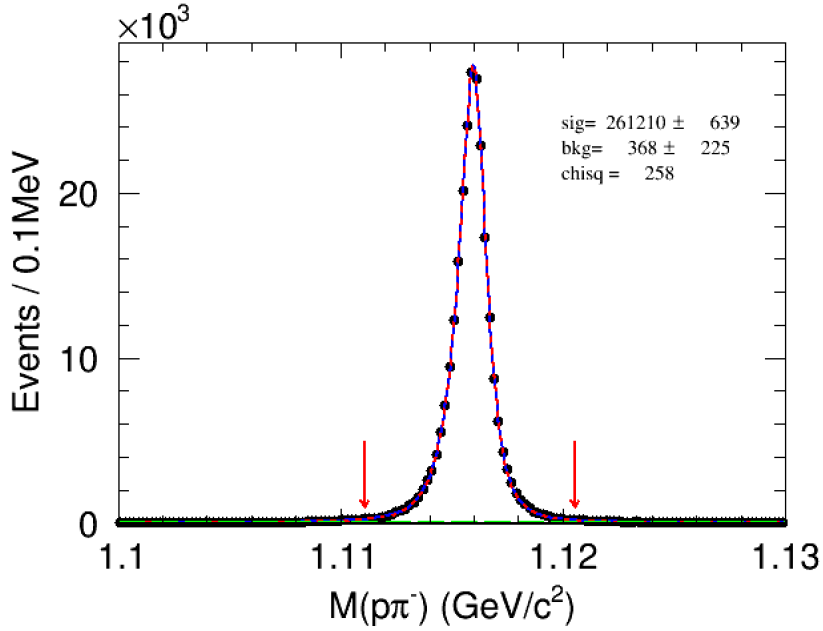


Figure: $M_{p\pi^-}$ distribution of inclusive Monte Carlo

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**
$J/\psi \to \gamma\eta_C, \eta_C \to \Lambda\bar{\Lambda}$	(7.57 $\pm$ 2.44) $\times 10^{-6}$	10	4007	40.08 $\pm$ 12.92
$J/\psi \to \gamma\Lambda\bar{\Lambda}$	(5.31 $\pm$ 0.06) $\times 10^{-5}$	100	7238	50.90 $\pm$ 0.56
$J/\psi \to \bar{\Lambda}\Sigma^0, \Sigma^0 \to \gamma\Lambda$(+ c.c.)	(1.16 $\pm$ 0.09) $\times 10^{-5}$	10	2294	17.73 $\pm$ 1.45
$J/\psi \to \Sigma^0\bar{\Sigma^0}, \Sigma^0 \to \gamma\bar{\Lambda}, \bar{\Sigma^0} \to \gamma\bar{\Lambda}$	(4.78 $\pm$ 0.13) $\times 10^{-4}$	50	9	1.25 $\pm$ 0.03

Simultaneous Fit and Results I

Likelihood

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

1. normalization factor

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

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

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

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 $\quad$ Δ = 0.738 $\pm$ 0.011 rad

α_- = 0.748 $\pm$ 0.010 $\quad$ 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

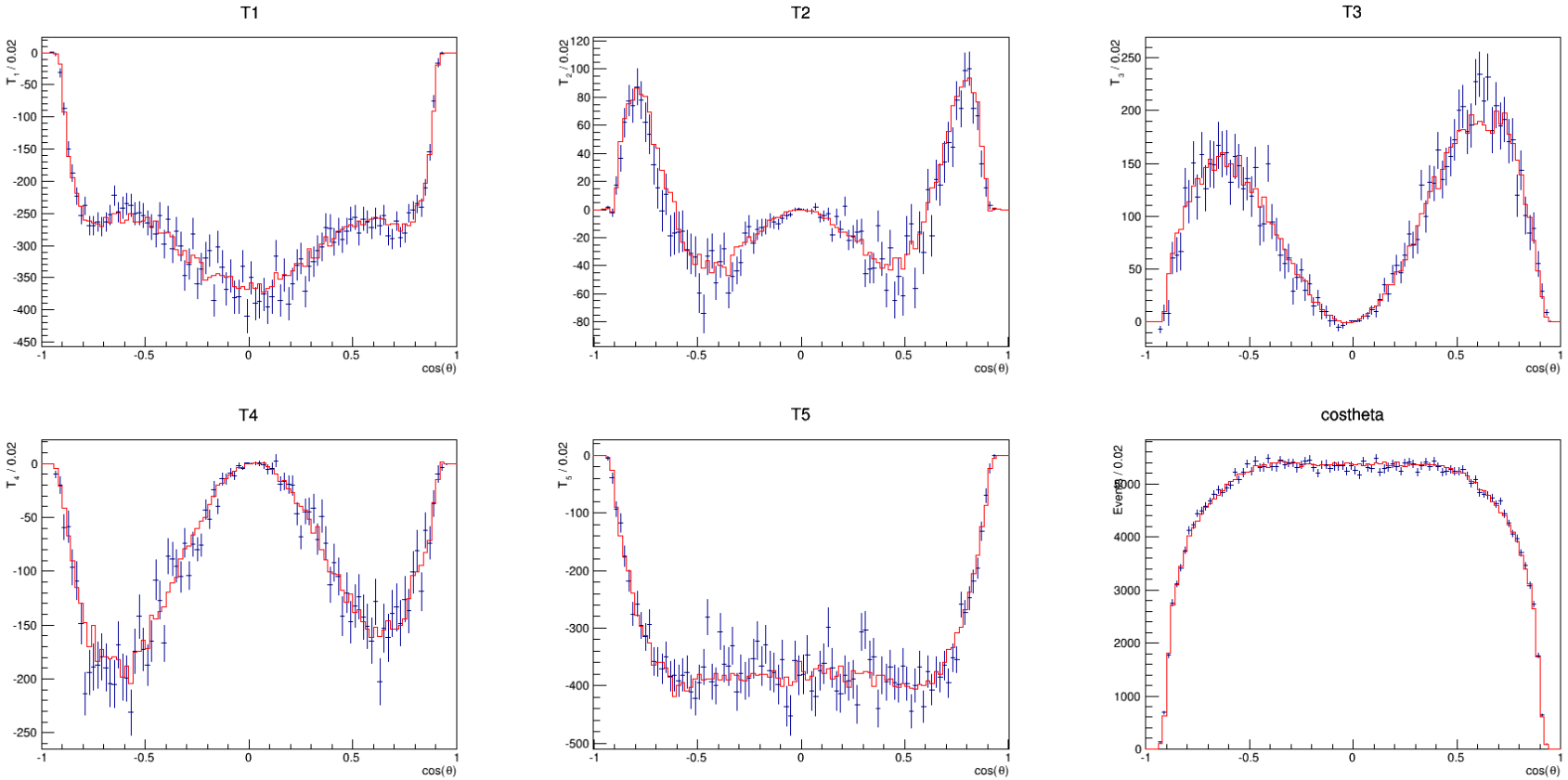


Figure: Distributions of T_i functions in terms of $\cos\theta_\Lambda$. The dots with error bars are the data, and the histograms are the fit results. T_3 and T_4 none-zero value indicate none-zero $\Delta\Phi$.

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:

$\alpha_{J/\psi}$ = 0.462 $\pm$ 0.006 $\quad$ Δ = 0.738 $\pm$ 0.011 rad

α_- = 0.747 $\pm$ 0.010 $\quad$ α_+ = -0.755 $\pm$ 0.010

MDC tracking

1. The control sample: $J/\psi \to p\bar{p}\pi^+\pi^-$
2. Correction:
   - Likelihood:

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

   - 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:

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

   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 $\quad\quad$ Δ = 0.737 $\pm$ 0.011 rad
α_- = 0.753 $\pm$ 0.010 $\quad\quad$ α_+ = -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

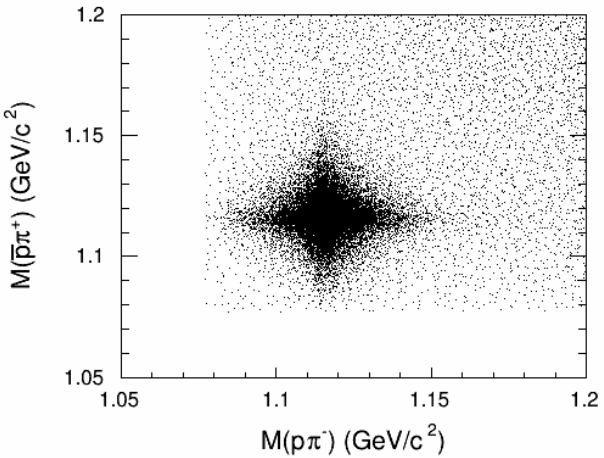
Table: Systematic uncertainties(%) for parameters $\alpha_{J/\psi}$, α_-, α_+ and $\Delta\Phi$

Kinematic fit

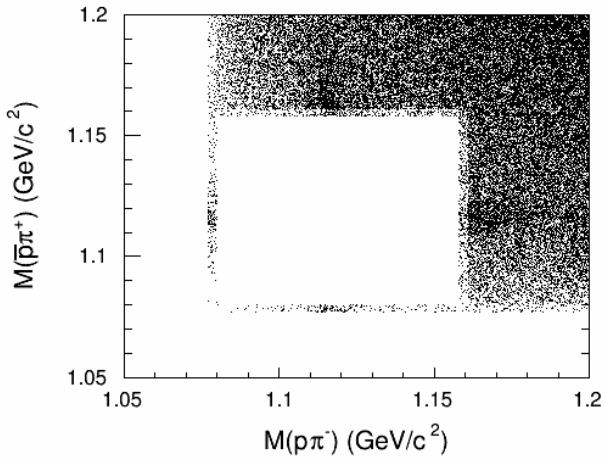
Control sample: $J/\psi \to p\bar{p}\pi^+\pi^-$

Event selection:

1. Good charged tracks selection:
   - polar angle $|\cos\theta| < 0.93$
   - good charged tracks equal or larger than 4
2. Proton candidate: do PID
3. Veto Λ: $M_{p\pi} \notin [1.08, 1.16]\ \mathrm{GeV/c^2}$



(a) $\mathrm{M_{p\pi^-}}$ and $\mathrm{M_{\bar{p}\pi^-}}$ distribution of inclusiveMC



(b) $\mathrm{M_{p\pi^-}}$ and $\mathrm{M_{\bar{p}\pi^-}}$ distribution of inclusiveMC after Veto Λ

Background estimate

No.	decay chain	iTopo	nEvt
	$\pi^-\bar{p}\pi^+p$		
0	$J/\psi \to p\pi^+\pi^-\bar{p}$	2	2983063
1	$J/\psi \to \Delta^{++}\pi^-\bar{p}, \Delta^{++} \to p\pi^+$	3	831070
2	$J/\psi \to p\pi^+\bar{\Delta}^{--}, \bar{\Delta}^{--} \to \pi^-\bar{p}$	4	625165
3	$J/\psi \to \Delta^{++}\bar{\Delta}^{--}, \Delta^{++} \to p\pi^+, \bar{\Delta}^{--} \to \pi^-\bar{p}$	1	609157
4	$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \pi^+\bar{p}$	7	329060
7	$J/\psi \to \Delta^0\pi^+\bar{p}, \Delta^0 \to p\pi^-$	9	120235
8	$J/\psi \to p\pi^-\bar{\Delta}^0, \bar{\Delta}^0 \to \pi^+\bar{p}$	5	116415
9	$J/\psi \to f_0^{'}p\bar{p}, f_0^{'} \to \pi^+\pi^-$	0	115191
10	$J/\psi \to p\rho^0\bar{p}, \rho^0 \to \pi^+\pi^-$	11	41810
11	$J/\psi \to p\pi^+\gamma_{FSR}\pi^-\bar{p}$	8	32560
12	$J/\psi \to \Delta^0\bar{\Delta}^0, \Delta^0 \to p\pi^-, \bar{\Delta}^0 \to \pi^+\bar{p}$	15	27646
16	$J/\psi \to \Delta^{++}\gamma_{FSR}\bar{\Delta}^{--}, \Delta^{++} \to p\pi^+, \bar{\Delta}^{--} \to \pi^-\bar{p}$	32	8157
17	$J/\psi \to p\omega\bar{p}, \omega \to \pi^+\pi^-$	26	7843
19	$J/\psi \to \Delta^{++}\gamma_{FSR}\pi^-\bar{p}, \Delta^{++} \to p\pi^+$	19	7208
20	$J/\psi \to p\pi^+\gamma_{FSR}\bar{\Delta}^{--}, \bar{\Delta}^{--} \to \pi^-\bar{p}$	24	6221
21	$J/\psi \to f_0^{'}p\bar{p}, f_0^{'} \to \pi^+\gamma_{FSR}\pi^-$	20	3588
22	$J/\psi \to \Delta^{++}\pi^-\bar{p}, \Delta^{++} \to p\pi^+\gamma_{FSR}$	14	2740
24	$J/\psi \to \Delta^{++}\bar{\Delta}^{--}, \Delta^{++} \to p\pi^+, \bar{\Delta}^{--} \to \gamma_{FSR}\pi^-\bar{p}$	31	1988
25	$J/\psi \to \Delta^{++}\bar{\Delta}^{--}, \Delta^{++} \to p\pi^+\gamma_{FSR}, \bar{\Delta}^{--} \to \pi^-\bar{p}$	77	1925
26	$J/\psi \to pf_2(1270)\bar{p}, f_2(1270) \to \pi^+\pi^-$	23	1845
28	$J/\psi \to p\pi^+\bar{\Delta}^{--}, \bar{\Delta}^{--} \to \gamma_{FSR}\pi^-\bar{p}$	52	1672
30	$J/\psi \to p\rho^0\bar{p}, \rho^0 \to \pi^+\gamma_{FSR}\pi^-$	44	1123
36	$J/\psi \to \Delta^0\pi^+\gamma_{FSR}\bar{p}, \Delta^0 \to p\pi^-$	83	956
37	$J/\psi \to p\gamma_{FSR}\pi^-\bar{\Delta}^0, \bar{\Delta}^0 \to \pi^+\bar{p}$	45	937
40	$J/\psi \to \Delta^0\pi^+\bar{p}, \Delta^0 \to p\gamma_{FSR}\pi^-$	91	641
41	$J/\psi \to p\pi^-\bar{\Delta}^0, \bar{\Delta}^0 \to \pi^+\gamma_{FSR}\bar{p}$	28	618
45	$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\gamma_{FSR}\pi^-, \bar{\Lambda} \to \pi^+\bar{p}$	65	495
47	$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \pi^+\gamma_{FSR}\bar{p}$	34	438
59	$J/\psi \to p\omega\bar{p}, \omega \to \pi^+\gamma_{FSR}\pi^-$	70	231
	5880885 evts (60 modes)		

Table 1:

No.	decay chain	iTopo	nEvt
	$\pi^-\bar{p}\pi^+\gamma p$		
5	$J/\psi \to \Sigma^0\bar{\Lambda}, \Sigma^0 \to \Lambda\gamma, \bar{\Lambda} \to \pi^+\bar{p}, \Lambda \to p\pi^-$	10	140233
6	$J/\psi \to \Lambda\bar{\Sigma}^0, \Lambda \to p\pi^-, \bar{\Sigma}^0 \to \gamma\bar{\Lambda}, \bar{\Lambda} \to \pi^+\bar{p}$	6	140133
14	$J/\psi \to p\eta\bar{p}, \eta \to \pi^+\gamma\pi^-$	17	10279
15	$J/\psi \to p\eta^{'}\bar{p}, \eta^{'} \to \rho^0\gamma, \rho^0 \to \pi^+\pi^-$	30	10199
18	$J/\psi \to \Lambda\gamma\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \pi^+\bar{p}$	13	7240
23	$J/\psi \to \eta_c\gamma, \eta_c \to p\rho^0\bar{p}, \rho^0 \to \pi^+\pi^-$	25	2282
31	$J/\psi \to \eta_c\gamma, \eta_c \to \Delta^{++}\bar{\Delta}^{--}, \Delta^{++} \to p\pi^+, \bar{\Delta}^{--} \to \pi^-\bar{p}$	71	1025
33	$J/\psi \to p\rho^0\gamma\bar{p}, \rho^0 \to \pi^+\pi^-$	66	979
34	$J/\psi \to \eta_c\gamma, \eta_c \to p\pi^+\bar{\Delta}^{--}, \bar{\Delta}^{--} \to \pi^-\bar{p}$	49	971
35	$J/\psi \to \eta_c\gamma, \eta_c \to \Delta^{++}\pi^-\bar{p}, \Delta^{++} \to p\pi^+$	27	970
43	$J/\psi \to \eta_c\gamma, \eta_c \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \pi^+\bar{p}$	89	554
50	$J/\psi \to \Delta^{++}\gamma\pi^-\bar{p}, \Delta^{++} \to p\pi^+$	96	322
52	$J/\psi \to p\pi^+\gamma\bar{\Delta}^{--}, \bar{\Delta}^{--} \to \pi^-\bar{p}$	123	316
56	$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\gamma\pi^-, \bar{\Lambda} \to \pi^+\bar{p}$	50	270
57	$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \pi^+\gamma\bar{p}$	58	257
60	$J/\psi \to p\eta^{'}\bar{p}, \eta^{'} \to \rho^0\gamma, \rho^0 \to \pi^+\gamma_{FSR}\pi^-$	115	223
62	$J/\psi \to \eta_c\gamma, \eta_c \to p\pi^-\bar{\Delta}^0, \bar{\Delta}^0 \to \pi^+\bar{p}$	122	191
65	$J/\psi \to \Sigma^0\bar{\Lambda}, \Sigma^0 \to \Lambda\gamma, \bar{\Lambda} \to \pi^+\gamma_{FSR}\bar{p}, \Lambda \to p\pi^-$	201	171
68	$J/\psi \to \eta_c\gamma, \eta_c \to \Delta^0\pi^+\bar{p}, \Delta^0 \to p\pi^-$	73	161
70	$J/\psi \to \Lambda\bar{\Sigma}^0, \Lambda \to p\gamma_{FSR}\pi^-, \bar{\Sigma}^0 \to \gamma\bar{\Lambda}, \bar{\Lambda} \to \pi^+\bar{p}$	68	154
71	$J/\psi \to \Lambda\bar{\Sigma}^0, \Lambda \to p\pi^-, \bar{\Sigma}^0 \to \gamma\bar{\Lambda}, \bar{\Lambda} \to \pi^+\gamma_{FSR}\bar{p}$	63	154
75	$J/\psi \to \Sigma^0\bar{\Lambda}, \Sigma^0 \to \Lambda\gamma, \bar{\Lambda} \to \pi^+\bar{p}, \Lambda \to p\gamma_{FSR}\pi^-$	112	114
98	$J/\psi \to p\omega\bar{p}, \omega \to \pi^+\gamma\pi^-$	108	70
101	$J/\psi \to p\gamma\pi^-\bar{\Delta}^0, \bar{\Delta}^0 \to \pi^+\bar{p}$	76	64
104	$J/\psi \to \eta_c\gamma, \eta_c \to p\pi^+\pi^-\bar{p}$	218	57
106	$J/\psi \to p\eta\bar{p}, \eta \to \pi^+\gamma\gamma_{FSR}\pi^-$	356	56
112	$J/\psi \to \eta_c\gamma, \eta_c \to p\rho^0\bar{p}, \rho^0 \to \pi^+\gamma_{FSR}\pi^-$	161	46
114	$J/\psi \to p\rho^0\bar{p}, \rho^0 \to \pi^+\gamma\pi^-$	39	45
116	$J/\psi \to \Delta^0\pi^+\gamma\bar{p}, \Delta^0 \to p\pi^-$	260	45
	317856 evts (67 modes)		

Table 2:

Figure: Topological results before veto Λ

Background estimate

No.	decay chain	iTopo	nEvt
	$\pi^-\bar{p}\pi^+p$		
0	$J/\psi \to p\pi^+\pi^-\bar{p}$	2	2972497
1	$J/\psi \to \Delta^{++}\pi^-\bar{p}, \Delta^{++} \to p\pi^+$	3	827949
2	$J/\psi \to p\pi^+\bar{\Delta}^{--}, \bar{\Delta}^{--} \to \pi^-\bar{p}$	4	624194
3	$J/\psi \to \Delta^{++}\bar{\Delta}^{--}, \Delta^{++} \to p\pi^+, \bar{\Delta}^{--} \to \pi^-\bar{p}$	1	606801
4	$J/\psi \to \Delta^0\pi^+\bar{p}, \Delta^0 \to p\pi^-$	7	120029
5	$J/\psi \to p\pi^-\bar{\Delta}^0, \bar{\Delta}^0 \to \pi^+\bar{p}$	5	116205
6	$J/\psi \to f_0^{'}p\bar{p}, f_0^{'} \to \pi^+\pi^-$	0	115180
7	$J/\psi \to p\rho^0\bar{p}, \rho^0 \to \pi^+\pi^-$	8	41781
8	$J/\psi \to p\pi^+\gamma_{FSR}\pi^-\bar{p}$	6	32453
9	$J/\psi \to \Delta^0\bar{\Delta}^0, \Delta^0 \to p\pi^-, \bar{\Delta}^0 \to \pi^+\bar{p}$	11	27252
12	$J/\psi \to \Delta^{++}\gamma_{FSR}\bar{\Delta}^{--}, \Delta^{++} \to p\pi^+, \bar{\Delta}^{--} \to \pi^-\bar{p}$	29	8117
13	$J/\psi \to p\omega\bar{p}, \omega \to \pi^+\pi^-$	22	7841
14	$J/\psi \to \Delta^{++}\gamma_{FSR}\pi^-\bar{p}, \Delta^{++} \to p\pi^+$	16	7189
15	$J/\psi \to p\pi^+\gamma_{FSR}\bar{\Delta}^{--}, \bar{\Delta}^{--} \to \pi^-\bar{p}$	20	6212
16	$J/\psi \to f_0^{'}p\bar{p}, f_0^{'} \to \pi^+\gamma_{FSR}\pi^-$	17	3588
17	$J/\psi \to \Delta^{++}\pi^-\bar{p}, \Delta^{++} \to p\pi^+\gamma_{FSR}$	10	2726
19	$J/\psi \to \Delta^{++}\bar{\Delta}^{--}, \Delta^{++} \to p\pi^+, \bar{\Delta}^{--} \to \gamma_{FSR}\pi^-\bar{p}$	28	1981
20	$J/\psi \to \Delta^{++}\bar{\Delta}^{--}, \Delta^{++} \to p\pi^+\gamma_{FSR}, \bar{\Delta}^{--} \to \pi^-\bar{p}$	66	1912
21	$J/\psi \to pf_2(1270)\bar{p}, f_2(1270) \to \pi^+\pi^-$	19	1845
23	$J/\psi \to p\pi^+\bar{\Delta}^{--}, \bar{\Delta}^{--} \to \gamma_{FSR}\pi^-\bar{p}$	49	1670
24	$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \pi^+\bar{p}$	12	1531
26	$J/\psi \to p\rho^0\bar{p}, \rho^0 \to \pi^+\gamma_{FSR}\pi^-$	43	1123
32	$J/\psi \to \Delta^0\pi^+\gamma_{FSR}\bar{p}, \Delta^0 \to p\pi^-$	72	955
33	$J/\psi \to p\gamma_{FSR}\pi^-\bar{\Delta}^0, \bar{\Delta}^0 \to \pi^+\bar{p}$	44	936
38	$J/\psi \to \Delta^0\pi^+\bar{p}, \Delta^0 \to p\gamma_{FSR}\pi^-$	78	638
39	$J/\psi \to p\pi^-\bar{\Delta}^0, \bar{\Delta}^0 \to \pi^+\gamma_{FSR}\bar{p}$	24	616
53	$J/\psi \to p\omega\bar{p}, \omega \to \pi^+\gamma_{FSR}\pi^-$	60	231
59	$J/\psi \to \Delta^0\bar{\Delta}^0, \Delta^0 \to p\gamma_{FSR}\pi^-, \bar{\Delta}^0 \to \pi^+\bar{p}$	30	155
64	$J/\psi \to \Delta^0\bar{\Delta}^0, \Delta^0 \to p\pi^-, \bar{\Delta}^0 \to \pi^+\gamma_{FSR}\bar{p}$	121	134
	5534389 evts (59 modes)		

Table 1:

No.	decay chain	iTopo	nEvt
	$\pi^-\bar{p}\pi^+\gamma p$		
10	$J/\psi \to p\eta'\bar{p}, \eta' \to \rho^0\gamma, \rho^0 \to \pi^+\pi^-$	27	10199
11	$J/\psi \to p\eta\bar{p}, \eta \to \pi^+\gamma\pi^-$	14	10191
18	$J/\psi \to \eta_c\gamma, \eta_c \to p\rho^0\bar{p}, \rho^0 \to \pi^+\pi^-$	21	2276
27	$J/\psi \to \eta_c\gamma, \eta_c \to \Delta^{++}\bar{\Delta}^{--}, \Delta^{++} \to p\pi^+, \bar{\Delta}^{--} \to \pi^-\bar{p}$	61	1011
29	$J/\psi \to p\rho^0\gamma\bar{p}, \rho^0 \to \pi^+\pi^-$	58	979
30	$J/\psi \to \eta_c\gamma, \eta_c \to p\pi^+\bar{\Delta}^{--}, \bar{\Delta}^{--} \to \pi^-\bar{p}$	47	967
31	$J/\psi \to \eta_c\gamma, \eta_c \to \Delta^{++}\pi^-\bar{p}, \Delta^{++} \to p\pi^+$	23	962
35	$J/\psi \to \Lambda\bar{\Sigma}^0, \Lambda \to p\pi^-, \bar{\Sigma}^0 \to \gamma\bar{\Lambda}, \bar{\Lambda} \to \pi^+\bar{p}$	26	863
36	$J/\psi \to \Sigma^0\bar{\Lambda}, \Sigma^0 \to \Lambda\gamma, \bar{\Lambda} \to \pi^+\bar{p}, \Lambda \to p\pi^-$	32	803
45	$J/\psi \to \Delta^{++}\gamma\pi^-\bar{p}, \Delta^{++} \to p\pi^+$	83	320
46	$J/\psi \to p\pi^+\gamma\bar{\Delta}^{--}, \bar{\Delta}^{--} \to \pi^-\bar{p}$	106	314
54	$J/\psi \to p\eta'\bar{p}, \eta' \to \rho^0\gamma, \rho^0 \to \pi^+\gamma_{FSR}\pi^-$	98	223
55	$J/\psi \to \eta_c\gamma, \eta_c \to p\pi^-\bar{\Delta}^0, \bar{\Delta}^0 \to \pi^+\bar{p}$	105	190
57	$J/\psi \to \eta_c\gamma, \eta_c \to \Delta^0\pi^+\bar{p}, \Delta^0 \to p\pi^-$	62	161
63	$J/\psi \to \Lambda\gamma\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \pi^+\bar{p}$	110	136
77	$J/\psi \to p\omega\bar{p}, \omega \to \pi^+\gamma\pi^-$	93	70
79	$J/\psi \to p\gamma\pi^-\bar{\Delta}^0, \bar{\Delta}^0 \to \pi^+\bar{p}$	65	64
80	$J/\psi \to \eta_c\gamma, \eta_c \to p\pi^+\pi^-\bar{p}$	195	57
83	$J/\psi \to p\eta\bar{p}, \eta \to \pi^+\gamma\gamma_{FSR}\pi^-$	329	56
90	$J/\psi \to \eta_c\gamma, \eta_c \to p\rho^0\bar{p}, \rho^0 \to \pi^+\gamma_{FSR}\pi^-$	139	46
91	$J/\psi \to \Delta^0\pi^+\gamma\bar{p}, \Delta^0 \to p\pi^-$	237	45
93	$J/\psi \to p\rho^0\bar{p}, \rho^0 \to \pi^+\gamma\pi^-$	38	45
94	$J/\psi \to \eta_c\gamma, \eta_c \to \Delta^0\bar{\Delta}^0, \Delta^0 \to p\pi^-, \bar{\Delta}^0 \to \pi^+\bar{p}$	133	44
96	$J/\psi \to \eta_c\gamma, \eta_c \to f_0^{'}p\bar{p}, f_0^{'} \to \pi^+\pi^-$	95	44
106	$J/\psi \to \eta_c\gamma, \eta_c \to p\omega\bar{p}, \omega \to \pi^+\pi^-$	274	29
115	$J/\psi \to \Delta^{++}\gamma\bar{\Delta}^{--}, \Delta^{++} \to p\pi^+, \bar{\Delta}^{--} \to \pi^-\bar{p}$	253	23
127	$J/\psi \to p\eta\gamma_{FSR}\bar{p}, \eta \to \pi^+\gamma\pi^-$	248	17
129	$J/\psi \to p\omega\gamma\bar{p}, \omega \to \pi^+\pi^-$	205	17
130	$J/\psi \to p\pi^+\gamma\pi^-\bar{p}$	595	17
	30280 evts (63 modes)		

Table 2:

Figure: Topological results after veto Λ

Kinematic fit

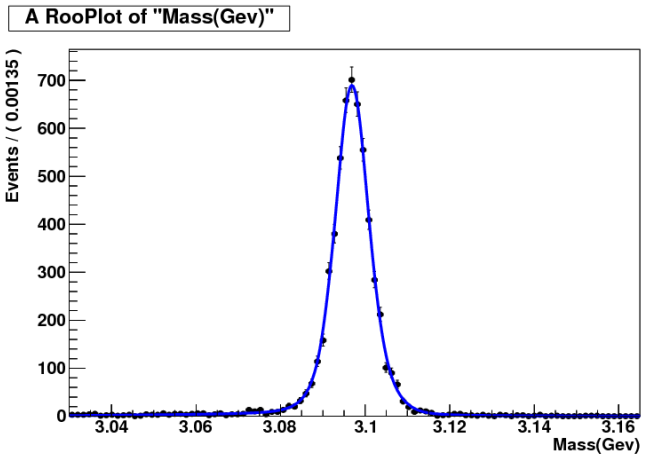
Control sample are analyzed in data and signal Monte Carlo generated in phase space model to get the inconsistency of kinematic fit efficiency.

$$\epsilon^{4C}_{data} = \frac{N^{'}_{data}}{N_{data}}, \qquad \epsilon^{4C}_{MC} = \frac{N^{'}_{MC}}{N_{MC}}$$

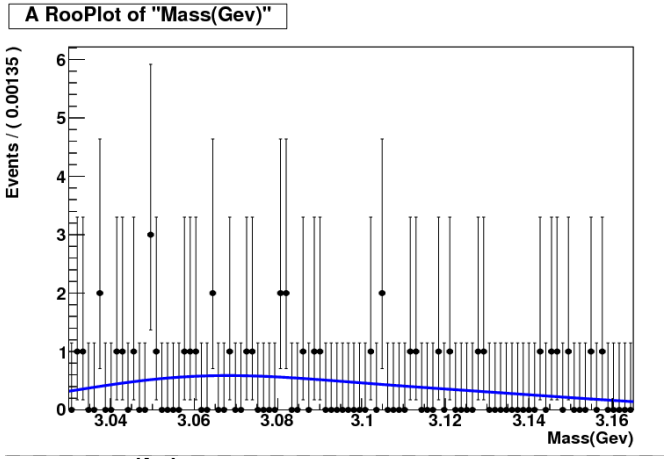
$N^{'}_{data}$ and $N^{'}_{MC}$ is number of events before 4-C fit, estimated by fitting $M_{J/\psi}$

N_{data} and N_{MC} is number of events after 4-C fit, calculated by events in $\chi^2_{4C} < 60$ reduce events in $\chi^2_{4C} \in [300, 360]$

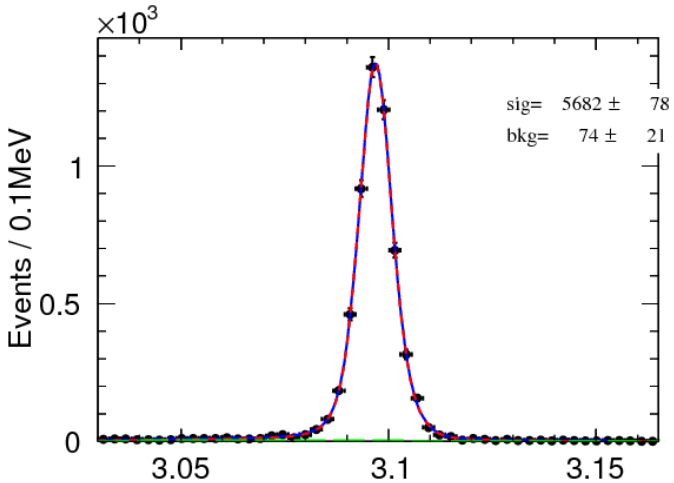
Kinematic fit



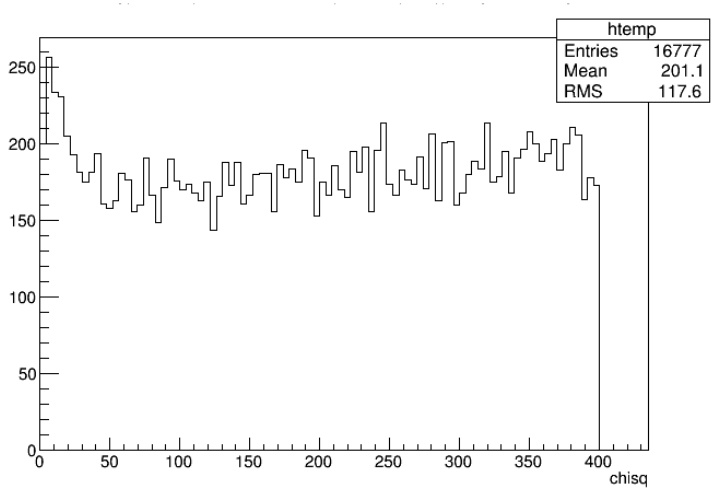
(a) signal PDF



(b) background PDF



(c) fit result of $M_{J/\psi}$



(d) χ^2_{4C} of background events

Kinematic fit

The corrections are done with the 4-dimentional variables distributions (10^4 bins): θ_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:

$\alpha_{J/\psi}$ = 0.465 $\pm$ 0.006 $\quad$ Δ = 0.741 $\pm$ 0.010 rad
α_- = 0.746 $\pm$ 0.010 $\quad$ α_+ = -0.754 $\pm$ 0.010

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
4-C fit	0.80	0.85	0.83	0.48

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

Input and Output check

PHSP MC sampling: 1795364 events.

I/O check	$\alpha_{J/\psi}$	α_-	α_+	$\Delta\Phi$
Input	0.461	0.753	-0.760	0.737
Output	0.457 ± 0.003	0.754 ± 0.005	-0.759 ± 0.005	0.735 ± 0.005
Uncertainty(σ)	1.32	0.15	0.21	0.41

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

Toy MC: 3882919 events.

I/O check	$\alpha_{J/\psi}$	α_-	α_+	$\Delta\Phi$
Input	0.461	0.750	-0.758	0.740
Output	0.459 ± 0.002	0.750 ± 0.003	-0.764 ± 0.003	0.730 ± 0.004
Uncertainty(σ)	1.00	0.00	2.00	2.50

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

Event selection of $\Lambda \to n\pi^0$

(1) Good charged tracks selection:
- polar angle $|\cos\theta| < 0.93$
- good charged tracks equal or larger than 2

(2) Proton candidate: do PID

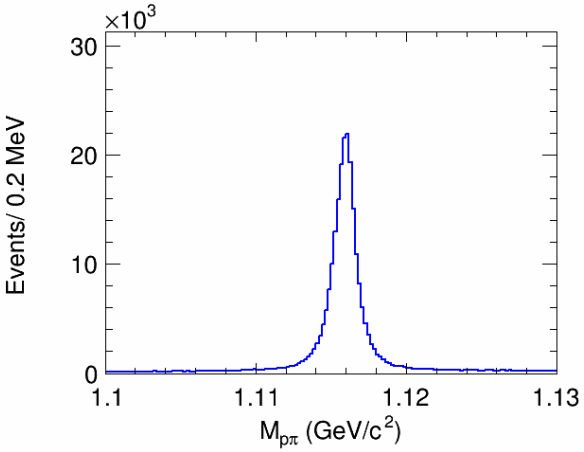
(3) Good shower selection:
- Deposition energy:
  $E_\gamma > 25.0\mathrm{MeV}\ (|\cos_\theta| < 0.80),\ \mathrm{E}_\gamma > 50.0\mathrm{MeV}\ (0.86 < |\cos_\theta| < 0.92)$
- $0 \le TDC \le 14(/50ns)$
- the angle between the position of EMC hited by the charged tracks with gamma direction should larger than 20

(4) π^0 selection: $M_{\gamma\gamma} \in (0.115, 0.150)\mathrm{GeV/c^2}$

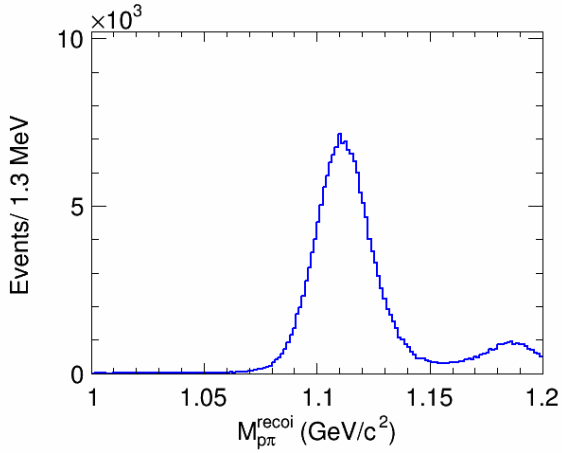
(5) Lambda(bar) candidate:
- primary vertex fit $\chi^2 < 200$
- $M_{\bar{p}\pi+} \in$ (1.095, 1.135) GeV/c^2

(6) 1-C fit: n is treated as missed particle with mass fixed to 0.9396 GeV/c^2

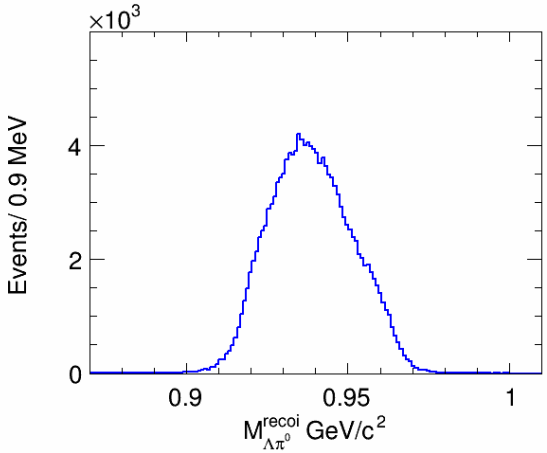
Distribution



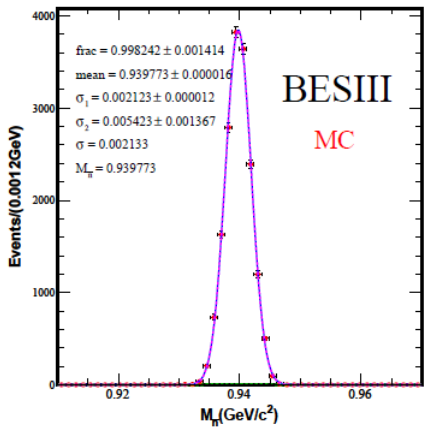
(e) Invariant mass of $p\pi$



(f) Recoiling mass of $p\pi$



(g) Recoiling mass of $p\pi\pi^0$



(c) Recoiling mass of $\Lambda\pi^0$

(h) Recoiling mass of

Efficiency and background

Branching fraction of $J/\psi \to \Sigma^0\bar{\Lambda} + c.c.$
in PDG is: $(2.83 \pm 0.23) \times 10^{-5}$
in Inclusive MC is: 2.84×10^{-3}
The background level is 0.89%

No.	decay chain	final states	iTopology	nEvt	nTot
0	$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \pi^0\bar{n}$	$\pi^-\bar{n}\gamma\gamma p$	0	66904	66904
1	$J/\psi \to \Sigma^0\bar{\Lambda}, \Sigma^0 \to \Lambda\gamma, \bar{\Lambda} \to \pi^0\bar{n}, \Lambda \to p\pi^-$	$\pi^-\bar{n}\gamma\gamma\gamma p$	1	2623	69527
2	$J/\psi \to \Lambda\bar{\Sigma}^0, \Lambda \to p\pi^-, \bar{\Sigma}^0 \to \gamma\bar{\Lambda}, \bar{\Lambda} \to \pi^0\bar{n}$	$\pi^-\bar{n}\gamma\gamma\gamma p$	2	437	69964
3	$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \pi^+\bar{p}$	$\pi^-\bar{p}\pi^+p$	4	176	70140
4	$J/\psi \to \Lambda\gamma\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \pi^0\bar{n}$	$\pi^-\bar{n}\gamma\gamma\gamma p$	5	155	70295
5	$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \pi^0\bar{n}$	$e^+\pi^-\bar{n}e^-\gamma p$	9	57	70352
6	$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \gamma\bar{n}$	$\pi^-\bar{n}\gamma p$	8	54	70406
7	$J/\psi \to \Sigma^+\bar{\Sigma}^-, \Sigma^+ \to p\pi^0, \bar{\Sigma}^- \to \pi^-\bar{n}$	$\pi^-\bar{n}\gamma\gamma p$	6	41	70447
8	$J/\psi \to \Delta^0\bar{\Delta}^0, \Delta^0 \to p\pi^-, \bar{\Delta}^0 \to \pi^0\bar{n}$	$\pi^-\bar{n}\gamma\gamma p$	3	27	70474
9	$J/\psi \to \Sigma^0\bar{\Sigma}^0, \Sigma^0 \to \Lambda\gamma, \bar{\Sigma}^0 \to \gamma\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \pi^0\bar{n}$	$\pi^-\bar{n}\gamma\gamma\gamma\gamma p$	7	18	70492
10	$J/\psi \to p\pi^-\bar{\Delta}^0, \bar{\Delta}^0 \to \pi^0\bar{n}$	$\pi^-\bar{n}\gamma\gamma p$	13	14	70506
11	$J/\psi \to \Sigma^0\bar{\Lambda}, \Sigma^0 \to \Lambda\gamma, \bar{\Lambda} \to \pi^+\bar{p}, \Lambda \to p\pi^-$	$\pi^-\bar{p}\pi^+\gamma p$	15	12	70518
12	$J/\psi \to \Delta^+\bar{\Delta}^+, \Delta^+ \to p\pi^0, \bar{\Delta}^+ \to \pi^-\bar{n}$	$\pi^-\bar{n}\gamma\gamma p$	24	11	70529

Figure: $\bar{\Lambda} \to \bar{n}\pi^0$

Simultaneous Fit and Results

Simultaneous fit is performed to three data sets:

$$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+ \quad (1)$$

$$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to n\pi^0, \bar{\Lambda} \to \bar{p}\pi^+ \quad (2)$$

$$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{n}\pi^0 \quad (3)$$

The joint objective function is

$$\mathcal{S} = -\ln\mathcal{L}^1_{\rm data} - \ln\mathcal{L}^2_{\rm data} - \ln\mathcal{L}^3_{\rm data} + \ln\mathcal{L}^1_{\rm bg} + \ln\mathcal{L}^2_{\rm bg} + \ln\mathcal{L}^3_{\rm bg}$$

The results are:

I/O check	$\alpha_{J/\psi}$	α_-	α_+	α_0	$\bar{\alpha_0}$	$\Delta\Phi$
Joint	0.422 $\pm$ 0.005	0.755 $\pm$ 0.008	-0.756 $\pm$ 0.008	0.623 $\pm$ 0.013	-0.595 $\pm$ 0.012	0.720 $\pm$ 0.009
Charged	0.462 $\pm$ 0.006	0.747 $\pm$ 0.010	-0.755 $\pm$ 0.010			0.738 $\pm$ 0.011
Uncertainty(σ)	8.00	1.00	0.13			2.00

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