Precision Measurement of J/ψ Leptonic Branching Fraction — analysis memo

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Abstract

A comparison of the rates for $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow \ell^+\ell^-$ and $J/\psi \rightarrow$ *anything* is used to determine the J/ψ leptonic branching fractions. The results are $B(J/\psi \rightarrow e^+e^-) = (5.90 \pm 0.07 \pm 0.16)\%$ and $B(J/\psi \rightarrow \mu^+\mu^-) = (5.96 \pm 0.08 \pm 0.16)\%$, where the first error is statistical and the second is systematic. Assuming lepton universality, the leptonic branching fraction of the J/ψ is $B(J/\psi \rightarrow \ell^+\ell^-) = (5.93 \pm 0.05 \pm 0.16)\%$. This result is used to estimate the QCD scale factor $\Lambda^{(4)}_{\overline{MS}}$ and the strong coupling constant α_s.

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I. INTRODUCTION

The precision measurement of the J/ψ leptonic branching fractions is of interest to both experimentalists and theorists. Knowledge of these parameters is necessary in order to determine the total number of produced J/ψ events in most experiments that require to identify heavy flavors such as charm and beauty. It is also important for quantitative quantum chromodynamics (QCD). One may use the J/ψ leptonic branching fractions to estimate the strong coupling constant α_s and the corresponding QCD subtraction parameter $\Lambda^{(n_f)}_{\overline{MS}}$, where n_f is the number of effective quark flavors and $\overline{MS}$ denotes the modified minimum subtraction scheme [1,2].

The first reported measurement of the J/ψ leptonic branching fractions has a precision of about 15% and is based on an energy scan across the resonance performed by the Mark-I group [3]. A subsequent measurement by the Mark-III group [4] is based on a comparison of the rates for $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$,$J/\psi \rightarrow \ell^+\ell^-$ and $J/\psi \rightarrow$ *anything* and is, thus, independent of the luminosity determination. The Mark-III measurement has a precision of 4% and is about five (Mark III) standard deviation below the Mark-I result. In this paper we present a new measurement of the J/ψ leptonic branching fractions applying a technique similar to that used by the Mark-III group to a larger data sample.

II. DETECTOR

The data used in this analysis were collected with the BES (Beijing Spectrometer) detector operating at BEPC (Beijing Electron Positron Collider). The BES is a conventional cylindrical detector that is described in detail in Ref. [5]. A four-layer central drift chamber (CDC) surrounding the beampipe provides trigger information. A forty-layer main drift chamber (MDC), located radially outside the CDC, provides trajectory and energy loss (dE/dx) information on charged tracks over 85% of the total solid angle. The momentum resolution is $\sigma_p/p = 0.017\sqrt{1+p^2}$ (p in GeV/c), and the dE/dx resolution for hadron tracks is $\sim$ 11%. An array of 48 scintillation counters surrounding the MDC measures the time-of-flight (TOF) of charged tracks with a resolution of $\sim$ 450 ps for hadrons. Outside the TOF system, a 12 radiation length, lead-gas barrel shower counter (BSC), operating in self-quenching streamer mode, measures the energies of electrons and photons over $\sim$ 80% of the total solid angle with an energy resolution of $\sigma_E/E = 22\%/\sqrt{E}$ (E in GeV), and spatial resolutions of $\sigma_\phi = 7.9$ mrad, $\sigma_z = 3.6$ cm. Surrounding the BSC is a solenoidal magnet coil that provides a 0.4 Tesla magnetic field throughout the central tracking region of the detector. Three double layers of muon counters instrument the magnet flux return and serve to identify muons of momentum greater than 0.5 GeV/c. Endcap time-of-flight and shower counters extend coverage to the forward and backward regions.

III. TECHNIQUE

Our measurement is based on a data sample corresponding to an integrated luminosity of 2.25 pb^{-1} accumulated at the $\psi(2S)$ resonance in 1993-1994 running, filtered and reconstructed under version 85 of BES library, and only the RUNs with $STATUS > 0$ (see PPRUNS.for in BES library for the defination of the $STATUS$) is used in the analysis. $\psi(2S) \to \pi^+\pi^- J/\psi$, with the branching fraction of 0.324 ± 0.026 [7], is the largest single $\psi(2S)$ decay channel. By using the exclusive and inclusive processes

$$\begin{array}{llr} \psi(2S) \to \pi^+\pi^- \; J/\psi & & \\ & \hookrightarrow \ell^+\ell^- & (I) \\ \text{and} & \hookrightarrow anything & (II) \end{array}$$

the J/ψ leptonic branching fraction is determined as

$$B(J/\psi \to \ell^+\ell^-) = \frac{N_\ell^{obs}/\varepsilon_\ell^{MC}}{N_J^{obs}/\varepsilon_J^{MC}},$$

where N_ℓ^{obs} and N_J^{obs} are observed numbers of events for process I and process II, respectively, and ε_ℓ and ε_J/ψ are the detection efficiencies for each process.

IV. EVENT SELECTION

For both processes I and II, we require at least two oppositely charged candidate pion tracks that each satisfies the following criteria:

1. $P_\pi < 0.60\mathrm{GeV}/c$, where P_π is the pion momentum. The maximum momentum of the cascade pions from $J/\psi \to \pi^+\pi^-$ is 0.40 GeV/c, 0.60GeV/c is used to get a smooth background in inclusive $\pi^+\pi^-$ recoil mass distribution.

2. $P_{\pi xy} > 0.10\mathrm{GeV}/c$, where $P_{\pi xy}$ is the momentum of the pion transverse to the beam direction. This removes tracks that circle in the Main Drift Chamber.

3. $|Xspi| < 3.0$. Here $Xspi$ is defined as

$$Xspi = \frac{(dE/dx)_{meas} - (dE/dx)_{exp}}{\sigma},$$

where $(dE/dx)_{meas}$ and $(dE/dx)_{exp}$ are the measured and expected dE/dx energy losses for pions, respectively, and σ is the experimental dE/dx resolution.

Instead of using the $Xspi$ from $TRKLST$ directly, we renormalized it according to the distribution of real data ($\pi^+\pi^-\ell^+\ell^-$ events), because $Xspi$ is not a standard Gaussian distribution as expected. Fitting the $Xspi$ from $TRKLST$ with an asymmetric Guassian to get the mean value and the standard deviation of each side for π^+ and π^- respectively. Results can be seen in table I and figure 1. Real data and Monte carlo simulated data are treated differently.

4. $|\cos\theta_\pi| < 0.8$, where θ is the polar angle of π in laboratory system. $|\cos\theta_\pi| = 0.8$ corresponds to the coverage of the seventh MDC layer.

5. The invariant mass recoiling against the candidate $\pi^+\pi^-$ pair is required to be in the range $3.0 \leq M^{recoil}_{\pi^+\pi^-} \leq 3.2$ GeV/c^2.

A. $J/\psi \to \ell^+\ell^-$

For leptonic decay candidate events (process-I), the number of charged tracks is required to be four with net charge zero. Lepton pair candidates are required to satisfy the following selection criteria:

1. $|P_\pm| > 0.45\mathrm{GeV}/c$ and $|P_\mp| > 1.40\mathrm{GeV}/c$ or $|P_+| + |P_-| > 2.60\mathrm{GeV}/c$, $|P|$ is the three-momenta of the candidate lepton track;

2. $|\cos\theta_e| < 0.75$, $|\cos\theta_\mu| < 0.60$, θ_e and θ_μ are the polar angles of the electron and muon, respectively. This cut ensures that electrons are contained in the BSC and muons in muon counters;

3. for e^+e^- candidate pairs: $SCE_\pm > 0.70\mathrm{GeV}$ or $SCE_+ + SCE_- > 1.5\mathrm{GeV}$ (for Monte Carlo, since the simulation cannot represent data very well, 0.815 and 1.962 are used instead of 0.70 and 1.5 according to the distribution of SCE), where SCE is the energy deposited in the BSC; and

4. for $\mu^+\mu^-$ candidate pairs: $N^{hit}_+ + N^{hit}_- \geq 4$, where $N^{hit}_\pm$ is the number of the layers of muon counters with matched hits and ranges from 0 to 3 for each track.

The value of N^{hit} is determined according to the hit position and the number of hit layers of the track in μ-counter. To determine whether the μ-counter hits match the extrapolation from inner sub-detector, $DZNORM$ and $DVNORM$ from $TRKLST$ is renormalized according to table II to a standard Gaussian distribution (refer to figure 2 for $DZNORM$

and $DVNORM$ distribution), if the hit position lies within 3 standard deviations from the extrapolated position in both V- and Z-plane, we define this track with a good hit in this layer. N^{hit} is then determined based on table III.

The distribution of $\pi^+\pi^-$ invariant masses, $M_{\pi^+\pi^-}$, for selected process-I events is shown in Fig. 3. We require $M_{\pi^+\pi^-} > 0.36$ GeV/c^2 for both process-I and process-II to eliminate a contamination from misidentified e^+e^- pairs from γ conversions. A total of 5700 $\mu^+\mu^-$ events and 7137 e^+e^- pass all these criteria. Figure 4a shows the $M^{recoil}_{\pi^+\pi^-}$ distribution for these events.

To include those events with one or more tracks interact with the TOF or SC merterial, which cannot simulated by current BES Monte Carlo, we also select events with more than four prongs, looping over all charged tracks to see whether at least one of the four tracks combination meet the requirement of a good $\pi^+\pi^-\ell^+\ell^-$ event, and then confirm them via hard scan. 34 $\mu^+\mu^-$ and 37 e^+e^- events are found in this way to increase the $\mu^+\mu^-$ events to 5734 and e^+e^- events to 7174.

B. $J/\psi \to anything$

The number of process-II events ($J/\psi \to anything$) is determined from a fit to the $\pi^+\pi^-$ recoil mass spectrum (Fig. 4b) using a J/ψ line shape that is determined from the recoil mass spectrum for the leptonic decays (Fig. 4a). This is fitted with a Breit-Wigner function folded with a Gaussian and a quadratic polynomial. The parameters thus obtained are used together with a third order polynomial background to fit the $\pi^+\pi^-$ recoil mass for the $J/\psi \to anything$ decays. The resulting number of inclusive decays is

$$N_J^{obs} = 199840 \pm 642$$

where the error is statistical, determined from the uncertainty of the fitted peak region.

V. ACCEPTANCE

The acceptance is obtained from Monte Carlo simulations. According to ref. [6], the orbital angular momenta between the $\pi^+\pi^-$ system and the J/ψ, as well as that between the π^+ and π^- is zero, and the $\pi^+\pi^-$ mass distribution is

$$\begin{aligned}\frac{d\sigma}{dm_X} &\propto Phase\quad Space \times (M_X^2 - 4m_\pi^2)^2 \\ &\propto (M_X^2 - 4m_\pi^2)^2 (M_X^2 - 4m_\pi^2)^{1/2} \\ &\quad [(M^2_{\psi(2S)} - m^2_{J/\psi} - m_X^2)^2 - 4m^2_{J/\psi} m_X^2]^{1/2}.\end{aligned}$$

We generate process-I as sequential two-body decays $\psi(2S) \to X + J/\psi$, $X \to \pi^+\pi^-$, and $J/\psi \to \ell^+\ell^-$. The generated events have the following characteristics:

1. $\frac{dN}{d\cos\theta_X}$ is uniform;

2. $\frac{dN}{d\cos\theta_{\pi^+}}$ is uniform, where $\cos\theta_{\pi^+}$ is the π^+ polar angle in the X rest frame;

3. the π^+ and π^- decay in the detector according to the PDG [7] life time and branching ratios;

4. $\frac{dN}{d\cos\theta_{\ell^+}} \propto 1+\cos^2\theta$ in the J/ψ rest frame, with α^3 order final state radiative corrections [8].

Initial state radiation is not included in the $\psi(2S)$ generation for data taken at the $\psi(2S)$ peak energy.

Monte Carlo samples of about the number of events produced in our data samples via process-I are generated with $E_{\gamma min} = 0.01 E_b$, where $E_b = \frac{m_{J/\psi}}{2}$. After application of the selection criteria mentioned above, we get $\varepsilon_\mu = 23.35\%$ and $\varepsilon_e = 29.51\%$[1].

For process-II, n_i^{obs}, the total number of events observed with charged multiplicity i, is related to the N_k^{prod}, the number generated with charged multiplicity k, by the relation

$$n_i^{obs} = \sum_k \varepsilon_{ki} N_k^{prod}$$

$$k = 0, 2, 4, \ldots, \quad i = 0, 1, 2, 3, \ldots,$$

where the matrix element ε_{ki} is the probability of an observed *i-prong* event coming from a *k-type* event.

Summing over i and using

$$\frac{n^{obs}}{N^{prod}} = \varepsilon_{J/\psi},$$

we have

$$\varepsilon_{J/\psi} = \sum_k \varepsilon_k \omega_k$$

where ε_k is the acceptance for and ω_k the fraction of multiplicity-k events.

The ε_k obtained from generating different multiplicity J/ψ decay events are listed in Table IV.

We take ω_k from results reported in refs. [9] and obtain $\varepsilon_{J/\psi} = (48.52 \pm 0.17)\%$.

VI. ERROR ESTIMATION

The statistical branching fraction errors, propagated from the statistical errors on N_ℓ^{obs} and N_J^{obs}, are $\sigma_{B_e} = 0.0008$ and $\sigma_{B_\mu} = 0.0007$.

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[1] A factor of $\frac{1}{1-1.37\%}$ is included because of the hole in Monte Carlo simulation of the rib in BSC.

We estimate systematic errors associated with the event selection from the variation of our results when the selection criteria are changed. Using $|\cos\theta_\pi| < 0.7$ and 0.60; $|Xspi| < 2.0$; $P_{\pi xy} < 0.06$ GeV/c and $M_{\pi+\pi-} > 0.32$ or $0.40\mathrm{GeV}/c^2$, results in fractional changes of 2.2% for B_e and 1.9% for B_μ. For the leptonic decays, changing to $|\cos\theta_e| < 0.70$ or 0.65, and $|\cos\theta_\mu| < 0.65$, 0.55 or 0.50; variations of the minimum allowed momenta; using $SCE > 0.8$ or $SCE_+ + SCE_- > 1.7\mathrm{GeV}$ for e^+e^- candidates and $N_+^{hit} + N_-^{hit} \geq 5$ or ≥ 6 for $\mu^+\mu^-$ candidates, result in fractional changes of 1.3% for B_e and 1.6% for B_μ. The uncertainties of $\varepsilon_{J/\psi}$ and ε_ℓ change B_μ and B_e by 0.4%. Fitting the inclusive $M_{\pi^+\pi^-}^{recoil}$ spectra with input parameters differing by one standard deviations from the fit values to the exclusive recoil spectrum results in 0.8% changes in both B_e and B_μ.

The simulations indicate that the acceptance determination is not very sensitive to the numbers of π^0 and kaons in selected multiplicity-k J/ψ decays or on the interchange of $\pi^\pm$ with $K^\pm$ at the generator level. The variations B_ℓ due to the selection of specific Monte Carlo channels is negligible. In addition, a simulation of the potential background process $\psi(2S) \to \eta J/\psi$ with η going to $\pi^+\pi^-\pi^0$ or $\pi^+\pi^-\gamma$ indicate a negligible contribution. The Monte Carlo samples used in this analysis corresponds to four times the integrated luminosity of the data set.

The events we analised in this paper contain at least two charged tracks, and the fraction of this kind of events is very small, based on the typical trigger efficiency at BES, the deviation of the branching fractions due to the trigger efficiency is estimated to be negligible.

The data sample we used in this analysis is filtered before reconstruction, to estimate the filter efficiency, six RUNs (5743, 5816, 5897, 5952, 6011 and 6012) selected randomly from the data set are fully reconstructed, no event of process I is found and 8 ± 5 events of process II are fitted out (Fig. 5), so causes an increasement of the branching fractions of about 0.2% relatively, which is small compared with the errors already quoted and not corrected in the results.

The assumption of the polynomial like background in the inclusive $\pi^+\pi^-$ recoil mass spectrum is checked with J/ψ scan data (RUN4714–4749, $79.28nb^-1$), from figure 6, no peak can be seen explicitly, fittling with a 2nd order or third order polynomial gives the maximum χ in each bin about 2. The J/ψ data include all sources of background except the one with one π comes from ψ' directly and another one from J/ψ of process II, Monte Carlo simulation shows the background from this combination is smooth too, so the selection of the form of the background is resonable.

The systematic error is taken as the quadrature sum of all the variations indicated above. The relative systematic errors on both the $J/\psi \to e^+e^-$ and $\mu^+\mu^-$ branching fractions are 2.7%.

VII. RESULTS AND DISCUSSION

Combining the preceding analyses, the results are listed in Table V [10], and the final results for the branching fractions are:

$$B(J/\psi \to e^+e^-) = (5.90 \pm 0.07 \pm 0.16)\%$$

and

$$B(J/\psi \to \mu^+\mu^-) = (5.96 \pm 0.08 \pm 0.16)\%.$$

The close equality of B_μ and B_e is a verification of e-μ universality:

$$\frac{B(J/\psi \to e^+e^-)}{B(J/\psi \to \mu^+\mu^-)} = 0.990 \pm 0.018 \pm 0.024.$$

Assuming $B_\mu = B_e$, we find a combined leptonic branching fraction of

$$B(J/\psi \to \ell^+\ell^-) = (5.93 \pm 0.05 \pm 0.16)\%$$

These results are consistent with and improve on the precision of the MARK-III measurement [4]. They are also consistent with the recently published BES results determined from e^+e^- cross section measurements in the vicinity of J/ψ resonance [11]. Combining these three measurements with the original Mark-I result [3], we find a new world average of $(5.97 \pm 0.12)\%$; here the error is half that of the 1994 PDG listing [7].

The experimental ratio of the quarkonium annihilation rates

$$R_2 = \frac{\Gamma(quarkonium \to ggg)}{\Gamma(quarkonium \to \mu^+\mu^-)}$$

allows the determination of the strong coupling constant α_s or, equivalently, the QCD scale parameter $\Lambda_{\overline{MS}}^{(n_f)}$ [2,12]. Following the notation of ref. [12], one obtains

$$(1+R_1)R_2 = \frac{1 - (2B(J/\psi \to \ell^+\ell^-) + B(J/\psi \to \gamma^* \to q\bar{q}) + B(J/\psi \to \gamma\eta_c))}{B(J/\psi \to \ell^+\ell^-)},$$

where

$$R_1 = \frac{\Gamma(J/\psi \to \gamma gg)}{\Gamma(J/\psi \to ggg)} = \frac{16\alpha}{5\alpha_s}(1 - 3.0\frac{\alpha_s}{\pi}),$$

$$R_2 = \frac{\Gamma(J/\psi \to ggg)}{\Gamma(J/\psi \to \ell^+\ell^-)} = \frac{5(\pi^2-9)\alpha_s^3}{18\pi\alpha^2}(1 + 1.59\frac{\alpha_s}{\pi})\gamma_\psi,$$

and

$$\gamma_\psi = \frac{\Gamma(c\bar{c} \to ggg)}{\Gamma^0(c\bar{c} \to ggg)} = 0.31 \pm 0.03.$$

The factor γ_ψ is the reduction factor of the three gluon decay caused by the finite size effect in the matrix element. For R_1, we use the theoretically calculated rather than the measured value because of the large error associated with the latter [13].

Combining the above J/ψ decay parameters and the values for $B(J/\psi \to \gamma^* \to q\bar{q})$, $B(J/\psi \to \gamma\eta_c)$ listed in PDG [7], we obtain

$$\alpha_s(m_c = 1.5\mathrm{GeV}/c^2) = 0.28 \pm 0.01 \quad \text{and } \Lambda_{\overline{MS}}^{(4)} = (209 \pm 16)\mathrm{MeV},$$

where only the experimental errors are included. Our results are in good agreement with the PDG [7] values.

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From process II described in the text, by solving the overdetermined equations in section 3, we estimated J/ψ charged-track-multiplicity distribution to be 1.4%, 35.2%, 38.5%, 22.4% and 2.5%.

[10] The data listed in table V are used for $\psi(2S)$ events number estimation, with the branching ratio of $\psi(2S) \to \pi^+\pi^- J/\psi$ given by PDG, produced $\psi(2S)$ events number is estimated to be $1.27(1 \pm 8.7\%) \times 10^6$.

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TABLES

TABLE I. Correction parameters for $Xspi$.

	Mean_{π^+}	$\sigma^-_{\pi^+}$	$\sigma^+_{\pi^+}$	Mean_{π^-}	$\sigma^-_{\pi^-}$	$\sigma^+_{\pi^-}$
Data93-94	0.398	1.291	1.008	0.263	1.228	0.995
MC_V153	0.150	1.379	0.911	0.247	1.428	0.837

TABLE II. Correction parameters for MUID

	Data						Monte Carlo					
	DZNORM		DVNORM				DZNORM		DVNORM			
	$Mean_{\mu^\pm}$	$\sigma_{\mu^\pm}$	$Mean_{\mu^+}$	σ_{μ^+}	$Mean_{\mu^-}$	σ_{μ^-}	$Mean_{\mu^\pm}$	$\sigma_{\mu^\pm}$	$Mean_{\mu^+}$	σ_{μ^+}	$Mean_{\mu^-}$	σ_{μ^-}
Lay 1	0.20	1.01	0.29	1.27	-0.30	1.27	0.04	0.79	0.09	1.18	-0.09	1.17
Lay 2	0.25	1.34	0.19	1.20	-0.24	1.21	0.02	0.96	0.42	1.16	-0.44	1.15
Lay 3	0.18	1.28	0.03	1.14	-0.19	1.15	0.03	1.02	0.55	1.10	-0.55	1.10

TABLE III. Determination of N^{hit}

$MULEVP$	GOOD HIT LAYER NUMBER	TWO TUBES HIT?	N^{hit}
1	1st	N	2
	1st	Y	3
2	1st	N	1
	1st	Y	2
	2nd	N	2
	2nd	Y	3
	1st and 2nd	-	3
3	1st	Y	1
	2nd	Y	2
	3rd	Y	2
	at least two layers	-	3

TABLE IV. Acceptance for different charged multiplicities

J/ψ decay channel	$\varepsilon_k(\%)$	events generated
all neutrals	51.48	5000
$\ell^+\ell^-$	50.32	40000
$\pi^+\pi^-\pi^0$	49.16	10000
$2(\pi^+\pi^-)\pi^0$	48.70	10000
$3(\pi^+\pi^-)$	46.45	10000
$4(\pi^+\pi^-)$	44.82	5000

TABLE V. Summary of Results

	$J/\psi \to anything$	$J/\psi \to e^+e^-$	$J/\psi \to \mu^+\mu^-$
N^{obs}	199840	7174	5734
ϵ^{MC}	48.52%	29.51%	23.35%
N^{prod}	411855	24310	24557

FIGURES

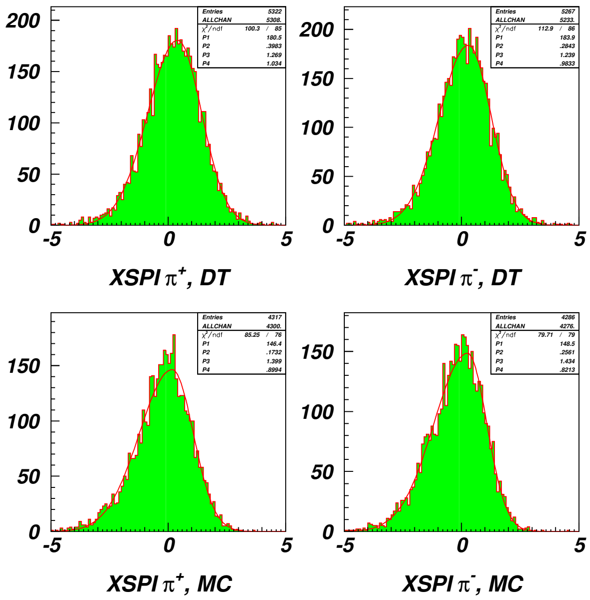
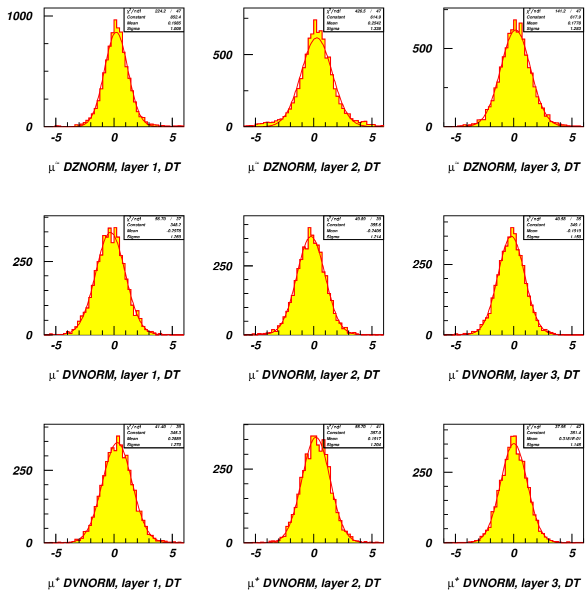


FIG. 1. Distributions of $Xspi$ and fitted results with asymmetry Gaussian



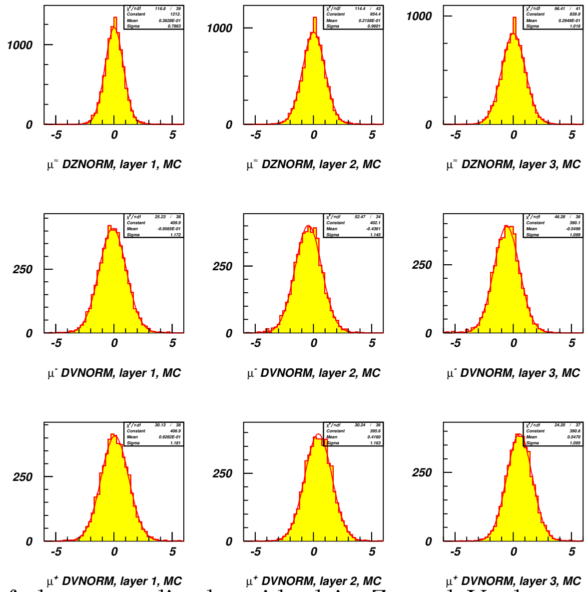


FIG. 2. Distribution of the normalized residuel in Z- and V-plane of μ-counter for both data and Monte Carlo.

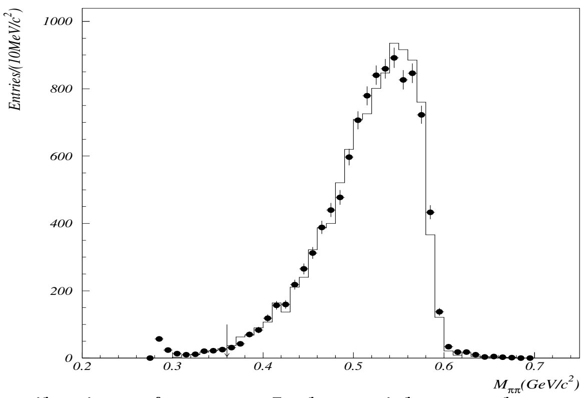


FIG. 3. $\pi^+\pi^-$ mass distribution of process I. dots with error bars are for data; the histogram is for Monte Carlo; the arrow shows the position of the cut.

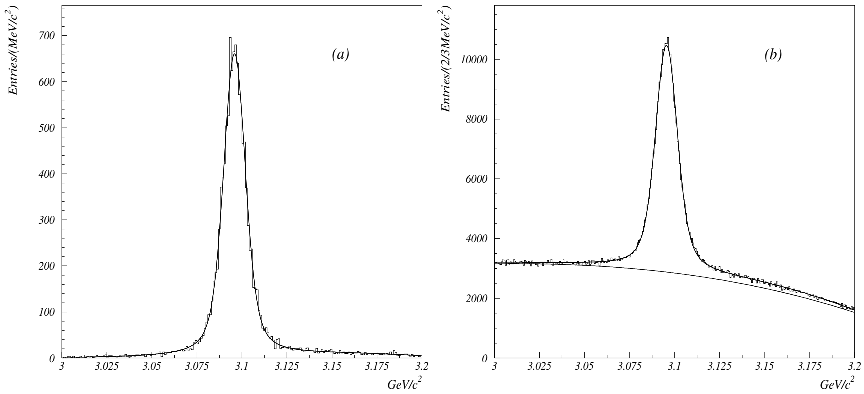


FIG. 4. $\pi^+\pi^-$ recoil mass distribution: (a) process I; (b) process II.

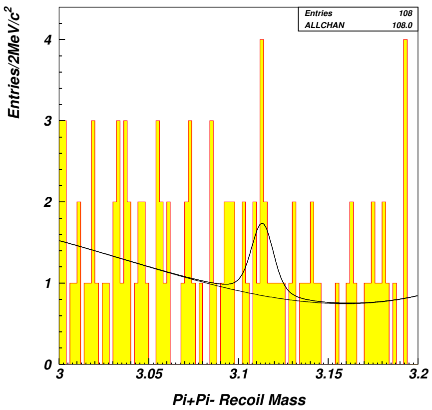


FIG. 5. $\pi^+\pi^-$ recoil mass distribution of bad filter events.

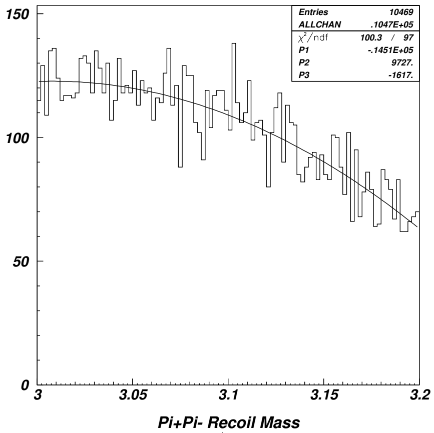


FIG. 6. $\pi^+\pi^-$ recoil mass distribution of J/ψ scan data, no peak can be seen in J/ψ mass region.