Analysis Note: Number of ψ' Events

F. A. Harris[1] and Wang Meng[2]

[1]University of Hawaii, Honolulu, HI 96822
[2]Inst. of High Energy Physics, Beijing 100039, China

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Introduction

Although the number of ψ' events obtained by BES is important to all ψ' analyses, the analysis of this number is intimately related to the determination of the branching ratio $B(J/\psi \to l^+l^-)$, which is the subject of another analysis note. In this note, the determination of the number of ψ' events found in both the 1993 and the 1995 ψ' data will be summarized.

Actually separate analyses have been done in Hawaii and at IHEP[1]. The analysis done in Hawaii will be described, but at the end, the final results will be compared and the differences included in the systematic errors. This paper is an update of work that was reported at the 1995[2], 1996[3], and 1997[4] BES Annual Meetings.

Method

The idea is to use $\psi' \to \pi^+\pi^- J/\psi, J/\psi \to$ anything. The mass recoiling against the π's is plotted, and the J/ψ peak is used to determine the number of J/ψ events, $N_{J/\psi}$, and the number of ψ' events, $N_{\psi'}$ is obtained from

$$N_{\psi'} = \frac{N_{J/\psi}/\epsilon_{J/\psi}}{B(\psi' \to \pi^+\pi^- J/\psi)}, \tag{1}$$

where $\epsilon_{J/\psi}$ is the acceptance for the π's in $\psi' \to \pi^+\pi^- J/\psi$ and $B(\psi' \to \pi^+\pi^- J/\psi)$ is the branching ratio for this process, $B(\psi' \to \pi^+\pi^- J/\psi) = 32.4 \pm 2.6\%$[5].

Analysis

Reconstruction

The data are reconstructed in Hawaii using version 8.6 of the BES software. No filter is used, but events are required to satisfy:

1. $|z_{min}| < 0.15$ m

2. $r_{min} < 0.015$ m

where z_{min} and r_{min} are the minimum values of z_m and r_m found for all the tracks in the event.

Track Corrections

The track momenta are first corrected by the magnetic field correction (0.9970*p)[6] and then the beam pipe correction (BPCORR). In addition, the dE/dx and TOF corrections of Bill Dunwoodie and Li Xinhua[7] are made.

Cuts

The analysis loops over the $\pi^+\pi^-$ combinations[8] where the two π's have:

1. good run (ppruns: status $>$ 0 or 1).

2. mfit = 2, -9, or -19.

3. $|\cos\theta| < 0.75$. This is the cosine of the π lab angle. See Fig. 1.

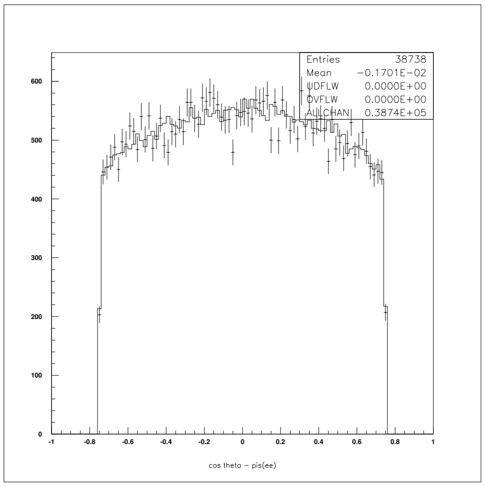

Figure 1: The $\cos\theta$ distribution of the π's in $\psi' \to \pi^+\pi^- J/\psi$, $J/\psi \to e^+e^-$ events (dots with error bars) compared with the distribution of Monte Carlo data (histogram).

4. $p_\pi < 0.5 GeV/c$. p_π is the π momentum. See Fig. 2.

5. $pxy_\pi > 0.1 GeV/c$. pxy_π is the momentum transverse to the beam direction. See Fig. 3.

6. $\cos\theta_{\pi\pi} < 0.9$. $\theta_{\pi\pi}$ is the laboratory angle between the π^+ and π^-. This cut is used to eliminate contamination from misidentified e^+e^- pairs from γ conversions, as shown in Fig. 4.

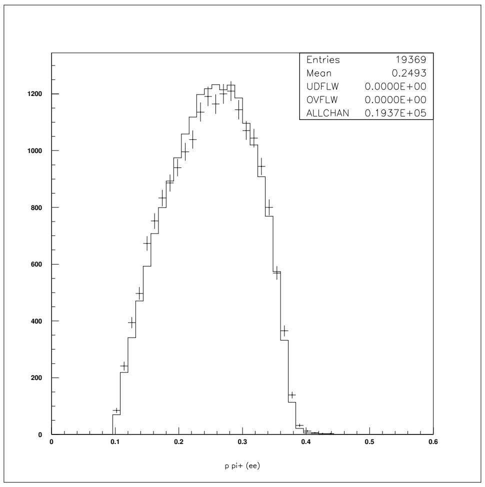

Figure 2: The momentum distribution of the π^+'s in $\psi' \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow e^+e^-$ events (dots with error bars) compared with the distribution of Monte Carlo data (histogram).

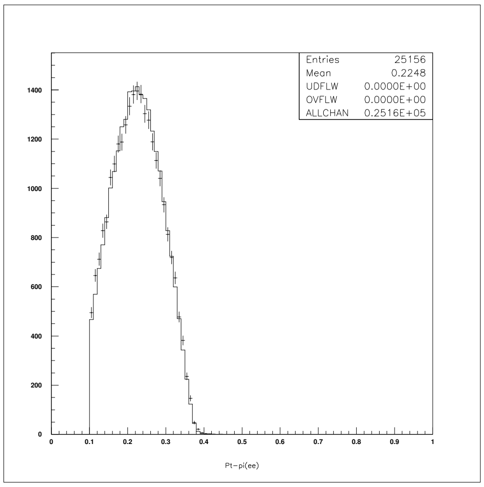

Figure 3: The transverse momentum, pxy_π, distribution of the π^+'s in $\psi' \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow e^+e^-$ events (dots with error bars) compared with the distribution of Monte Carlo data (histogram).

Fitting

For each $\pi^+\pi^-$ combination satisfying cuts, the mass recoiling against the π's, m_{recoil}, is calculated, and the m_{recoil} distribution is fitted using BWFIT to determine the amount of J/ψ signal, as shown in Fig. 5 B. The fit uses a Breit Wigner smeared by a Gaussian (BWG) for the signal plus a 4th order polynomial to describe the background. The BWG parameters used in this fit are obtained from the m_{recoil} distribution for $\psi' \rightarrow \pi^+\pi^- J/\psi$ events, where $J/\psi \rightarrow l^+l^-$[9], as shown in Fig. 5 A. The events in Fig. 5 A are fit with a BWG and a 3rd order polynomial. In this plot, most of the events associated with the polynomial are good $\psi' \rightarrow \pi^+\pi^- J/\psi$ events but where the low energy π's undergo $\pi \rightarrow \mu\nu$ decay. However, using only the BWG curve to describe the signal shape makes us less sensitive to background. The

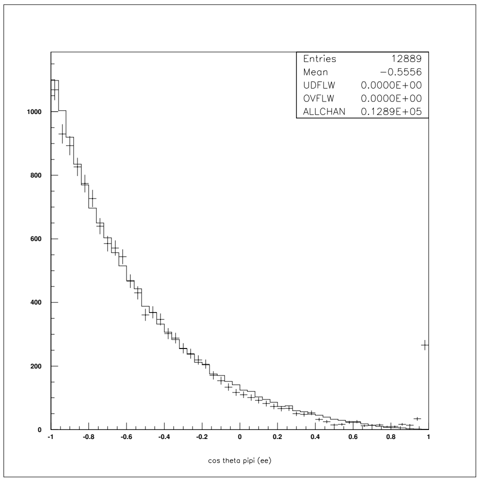

Figure 4: The distribution of the cosine of the angle between the π^+ and π^-,$\cos\theta_{\pi\pi}$, in $\psi^{'} \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow e^+e^-$ events (dots with error bars) compared with the distribution of Monte Carlo data (histogram). The data has background near $\cos\theta_{\pi\pi} = 1$.

fitting is done separately for '93 and '95 data.

Calculation of $\epsilon_{J/\psi}$

For $\psi^{'} \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow$ *anything*, the $\pi\pi$ acceptance, $\epsilon_{J/\psi}$, depends on the charged particle multiplicity produced in the J/ψ decay. For this process, the total number of events observed with charged multiplicity i is related to the N_k^{prod}, the number produced with charged multiplicity k, by the relation

$$n_i^{obs} = \sum_k \epsilon_{ki} N_k^{prod} \tag{2}$$

$$\text{with } k = 0, 2, 4, \ldots, \quad i = 0, 1, 2, 3, \ldots,$$

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

$$\frac{n^{obs}}{N^{prod}} = \epsilon_{J/\psi}, \tag{3}$$

we have

$$\epsilon_{J/\psi} = \sum_k \epsilon_k \omega_k \tag{4}$$

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

To determine the ϵ_{ki}, a modified Howl was used to generate $\psi^{'} \rightarrow \pi^+\pi^- J/\psi$ events with the correct $m_{\pi\pi}$ distribution [11]:

$$\frac{d\sigma}{dm_{\pi\pi}} \propto \text{phasespace} \times (M_{\pi\pi}^2 - 4m_\pi^2)^2$$

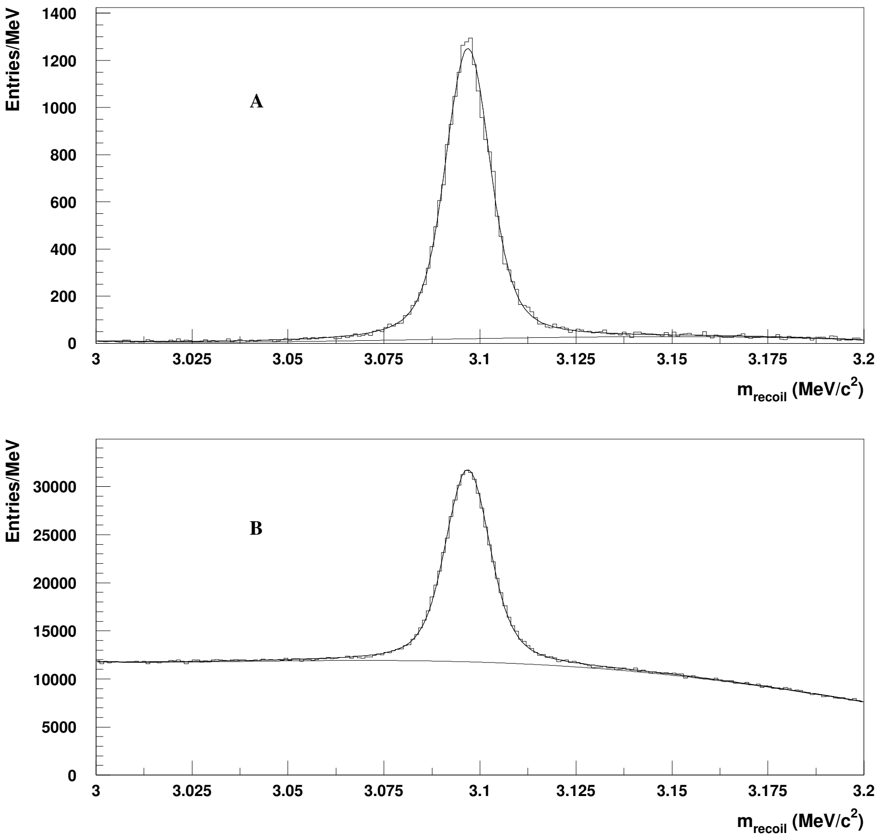

Figure 5: **A)** Number of events versus m_{recoil}, the mass recoiling against the two π's, for $\psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow l^+l^-$ events. The histogram is the 1995 data, and the smooth curve is a BWG ("signal") plus a 3rd order polynomial ("background"). **B)** Number of events versus m_{recoil} for inclusive events. The histogram is the 1995 data, and the smooth curve is a BWG (signal) with parameters determined from A) plus a 4th order polynomial (background).

See Fig. 6 for a comparison of Monte Carlo generated with this distribution and data. Separate samples of events with $J/\psi \rightarrow 0(\pi^+\pi^-), \pi^+\pi^-\pi^o, 2(\pi^+\pi^-)$, etc. are generated, reconstructed with DRUNK, and passed through the same analysis program. For each multiplicity sample, the m_{recoil} distribution is fit with the line shape obtained from Monte Carlo $\psi' \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow l^+l^-$ events plus background, as described in the previous section. This determines the ϵ_{ki}. The overconstrained equation, Eqn. 2, can then be solved to obtain the ω_k. The ω_k and ϵ_k are listed in Tables 1 and 2, along with the values for $\epsilon_{J/\psi}$, which are obtained using Eqn. 4. The ω_k are obtained from the '95 data.

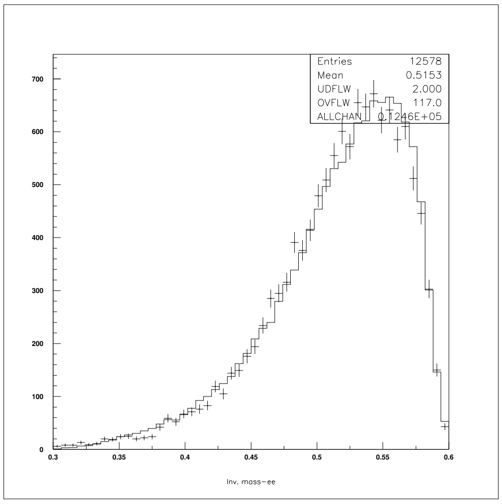

Figure 6: Number of events versus $m_{\pi\pi}$. The points with error bars are data, and the histogram are Monte Carlo data.

Table 1: Efficiency Results for '93 Data

$J/\psi \to n\pi$ Mult.	ω_k (%)	Events Generated	ϵ_k (%)
0	0.5	2×10^4	48.70
2	35.6	5×10^4	46.55
4	40.9	5×10^4	44.23
6	17.7	5×10^4	43.50
8	5.3	2×10^4	40.95
combined ($\epsilon_{J/\psi}$)			44.77

Table 2: Efficiency Results for '95 Data

$J/\psi \to n\pi$ Mult.	ω_k (%)	Events Generated	ϵ_k (%)
0	0.5	1×10^5	47.98
2	35.6	1×10^5	46.38
4	40.9	1×10^5	44.30
6	17.7	1×10^5	42.56
8	5.3	5×10^4	41.68
combined ($\epsilon_{J/\psi}$)			44.61

Background from $\psi' \to \eta J/\psi$.

Sober (HOWL) was used to determine the amount of background expected from $\psi' \to \eta J/\psi$, where $J/\psi \to$ nothing and $\eta \to \pi^+\pi^-\pi^o$ (23.2%) or $\eta \to \pi^+\pi^-\gamma$ (4.78%). For the first case, only 8 events satisfied cuts, including the cut $3.0 < m_{recoil} < 3.2 GeV/c$, out of 5000 events generated. The number of events expected in our final sample from this mode is given by:

$$N_{\psi' \to \eta J/\psi} = N_{\psi'} B(\psi' \to \eta J/\psi) B(\eta \to \pi^+\pi^-\pi^o)(\text{efficiency})$$

$$N_{\psi' \to \eta J/\psi} = (3.7 \times 10^6)(0.027)(0.232)(8/5000) = 37$$

The corresponding number of $\psi' \to \pi^+\pi^- J/\psi$ is

$$N_{\psi' \to \pi^+\pi^- J/\psi} = N_{\psi'} B(\psi' \to \pi^+\pi^- J/\psi) \epsilon_{J/\psi}$$

$$N_{\psi' \to \pi^+\pi^- J/\psi} = (3.7 \times 10^6)(0.324)(0.447) = 5.4 \times 10^5$$

The percentage background is then $37/(5.4 \times 10^5) = 7 \times 10^{-3}\%$. For $\eta \to \pi^+\pi^-\gamma$ with a branching ratio of 4.78%, 1768 events out of 10000 satisfy cuts. Doing the equivalent calculation to the above, the background due to this mode is estimated to be 0.16%. However this is an over estimate because the m_{recoil} distribution peaks at high m_{recoil} (see Fig. 7) unlike the distribution shown in Fig. 5 A. The background obtained by fitting should be much less, which means that the background due to this source is entirely negligible.

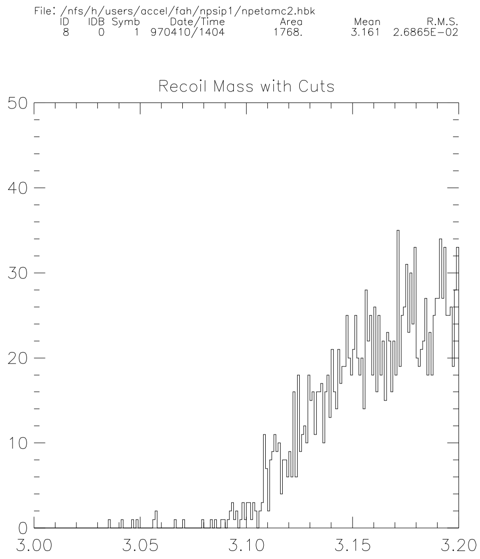

Figure 7: Number of events versus the mass recoiling against the two π's, for $\psi' \to \eta J/\psi, \eta \to \gamma\pi^+\pi^-$ events.

Results

Results for $N_{J/\psi}$, $\epsilon_{J/\psi}$, and $N_{J/\psi}/\epsilon_{J/\psi}$ are given in Table 3 for the 1993 and 1995 data sets and for status > 0 and status > 1. The corresponding values of $N_{\psi'}$ are given in Table 4.

Table 3: $N_{J/\psi}$, $\epsilon_{J/\psi}$, $N_{J/\psi}/\epsilon_{J/\psi}$ Results

Data	Status	$\epsilon_{J/\psi}(\%)$	$N_{J/\psi}$	$N_{J/\psi}/\epsilon_{J/\psi}$
1993	>1	44.77	187342 ± 758	$(418.5 \pm 1.7 \pm 7.4) \times 10^3$
1995	>1	44.61	343081 ± 1019	$(769.1 \pm 2.3 \pm 8.8) \times 10^3$
1993	>0	44.77	192176 ± 766	$(429.3 \pm 1.7 \pm 7.6) \times 10^3$
1995	>0	44.61	356009 ± 1045	$(798.0 \pm 2.3 \pm 9.2) \times 10^3$

Table 4: $N_{\psi'}$ Results

Data	Status	$N_{\psi'}$
1993	>1	$(1.291 \pm 0.005 \pm 0.106) \times 10^6$
1995	>1	$(2.374 \pm 0.007 \pm 0.192) \times 10^6$
1993	>0	$(1.325 \pm 0.005 \pm 0.109) \times 10^6$
1995	>0	$(2.463 \pm 0.007 \pm 0.200) \times 10^6$

The effect of changing the π cuts has been studied. The results are shown in Table 5. There are other potential contributions to the systematic error. For the efficiency calculation, the Monte Carlo program assumes that the cosine of the π^+ angle, $\cos\theta_{\pi^+}$, in the $\pi\pi$ center of mass system is flat (S wave). However, as is predicted in one Heavy Quarkonium Model [12], we find that this distribution is not flat, consistent with a small amount of D-wave. If we assume a $\cos\theta_{\pi^+}$ distribution, consistent with our data, we obtain a slightly different efficiency and a slightly different $N_{\psi'}$, as indicated in Table 5.

Another possible systematic error is due to our fitting procedure, where we fit the $N_{J/\psi}$ "signal" to a BWG. An alternative procedure using MINFIT[13] has also been used in Hawaii. In this method, the inclusive m_{recoil} is fit directly with the exclusive m_{recoil} distribution (histogram), so there is no forcing the data to fit an arbitrary shape. The diffence between the BWG fit and the MINFIT fit is also given in Table 5 and is quite small.

As mentioned previously, similar calculations have been done at Hawaii and IHEP. The methods share a great deal in common but are not completely identical. However there is good agreement between the two calculations. For status > 1, Meng obtains $N_{\psi'} = 1.306 \pm 0.005 \pm 0.111$ for the '93 data and $N_{\psi'} = (2.383 \pm 0.007 \pm 0.198) \times 10^6$ for the '95 data. For more detail, see Ref. [1].

Another contribution comes for the efficiency determination. The efficiency $\epsilon_{J/\psi}$ depends on the produced multiplicity distribution given by ω_k, which we obtain from our data from the fitting procedure. However, the chisquare for the fit is large and the agreement between the predicted observed multiplicity distribution and the actual one is only fair. We can also use ω_k observed in other experiments[10] to obtain other values of $\epsilon_{J/\psi}$ and use the variation in these values to obtain the systematic error in $\Delta\epsilon_{J/\psi} = 0.0013$. Changing the π tracks to be K tracks changes the efficiencies by very little.

Adding the systematic errors in quadrature, we obtain the systematic errors given in Table 3. Combining this result in quadrature with the $B(\psi^{'} \to \pi^+\pi^- J/\psi)$ uncertainty, we obtain the systematic errors given in Table 4. The dominant systematic error here is due to $B(\psi^{'} \to \pi^+\pi^- J/\psi)$, (0.324 ± 0.026) [5].

Table 5: Systematic Studies of $|\Delta N_{\psi'}|/N_{\psi'}$ (Status > 1)

Variable	Variation	'93 Data (%)	'95 Data (%)
$\lvert\cos\theta_\pi\rvert$ cut	$0.75 \to 0.70$	0.91	0.81
$\cos\theta_{\pi\pi}$ cut	$0.9 \to 0.85$	0.19	0.33
pxy_π cut	turn off	0.72	0.02
Non-flat $\cos\theta_{\pi+}$		0.37	0.38
Fitting Method		0.28	0.44
Hawaii/IHEP Difference		1.16	0.13
Efficiency Uncertainty		0.45	0.45
$\Delta B(\psi^{'} \to \pi^+\pi^- J/\psi)$		8.02	8.02
Combined		8.21	8.10

Summary

The number of J/ψ events has been determined for the '93 and '95 data sets. The number does depend on the cuts used. For the cuts used here and for status > 0, the total number of J/ψ events corrected for detection is $(1.227 \pm 0.003 \pm 0.017) \times 10^6$. Dividing by $B(\psi' \to \pi^+\pi^- J/\psi)$, we obtain the total number of $\psi' = (3.788 \pm 0.009 \pm 0.309) \times 10^6$.

References

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[2] Harris, F. A., "Monte Carlo - Data Comparison of $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to l^+l^-$ and the Number of ψ' Events", BES95, 333 (1995).

[3] Harris, F. A., "Study of $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to l^+l^-$", Presented at the 5th Annual BES Meeting (1996).

[4] Harris, F. A., "Analysis Note: Number of ψ' Events", Presented at the 6th Annual BES Meeting (1997).

[5] Particle Data Group.

[6] This magnetic field correction was determined from the distribution for the mass recoiling against the $\pi\pi$ system (m_{recoil}) for $\psi' \to \pi^+\pi^- J/\psi$, $J/\psi \to \mu^+\mu^-$. See http://www.phys.hawaii.edu/~fah/jpsimass.html for more detail.

[7] Bill Dunwoodie and Li Xinhua have studied the dE/dx and TOF information for the ψ' data and have written routines to correct it.

[8] There is a limit to how many combinations are allowed. The limit is 20 combinations satisfying cuts.

[9] The $\psi' \to \pi^+\pi^- J/\psi$, $J/\psi \to l^+l^-$ events are described in another analysis note.

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