$B(\psi(2S) \to \pi^+\pi^- J/\psi)$

Frederick A. Harris
University of Hawaii
Mo Xiaohu
IHEP

July 31, 2000

Introduction

The branching ratio $B(\psi(2S) \to \pi^+\pi^- J/\psi)$, is rather poorly known. The value given by the PDG in 1996 was $B(\psi(2S) \to \pi^+\pi^- J/\psi) = 32.4 \pm 2.6\%$ [1], which has about an 8 % error. In 1998, the PDG gave a value of $B(\psi(2S) \to \pi^+\pi^- J/\psi) = 30.2 \pm 1.9\%$ [2], but it was calculated incorrectly [4]. Now PDG2000 is available on the web [3] and will be published this month. PDG2000 gives $B(\psi(2S) \to \pi^+\pi^- J/\psi) = 31.0 \pm 2.8\%$, which comes from a fit to many branching ratios. In this analysis, we will use the 1999 $\psi(2S)$ scan data to determine it better.

Since $B(\psi(2S) \to \pi^+\pi^- J/\psi)$ is the biggest source of error in the determination of the number of $\psi(2S)$ events required for many results based on our '93 and '95 $\psi(2S)$ data sets, a better measurement will allow us to make better use of our earlier data.

A complete analysis of the scan data is being done by Zhu Yongsheng and Mo Xiaohu; this analysis concentrates only on $B(\psi(2S) \to \pi^+\pi^- J/\psi)$. See the talk by Mo Xiaohu at BES2000 for more details on the complete analysis.

$N_{\pi^+\pi^- J/\psi}$

First we determine the number of $\psi(2S) \to \pi^+\pi^- J/\psi$ events, $N_{\pi^+\pi^- J/\psi}$. The method used is that which was used earlier to determine the number of $\psi(2S)$'s in the '93 and '95 data sets [5] and $B(J/\psi \to l^+l^-)$ [6]. Briefly, the idea is select pairs of low energy pions and to determine the mass recoiling against them, m_{recoil}. The m_{recoil} distribution shows a strong J/ψ peak, which is fit with a signal shape and polynomial background using BWFIT. The very clean $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to l^+l^-$ events are used for the signal shape. The inclusive and exclusive m_{recoil} distributions are shown in Figs. 1 and 2, respectively. For more detail, please refer to Refs. [5] and [6].

To determine acceptances, we use the Monte Carlo programs:

- PPGEN for $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to l^+l^-$.

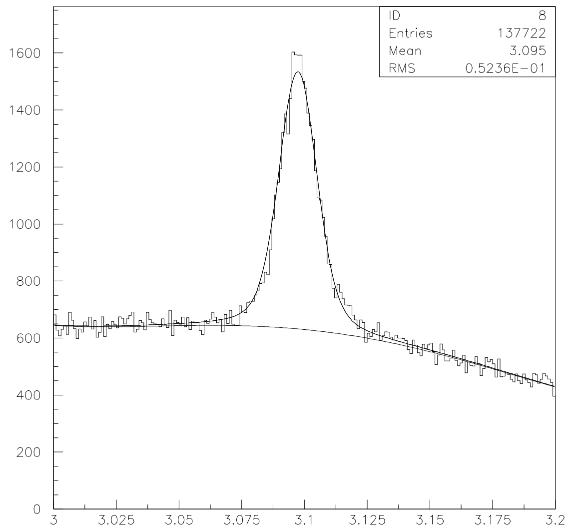

Figure 1: Mass recoiling against $\pi^+\pi^-$ in inclusive scan data events ($\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to$ anything).

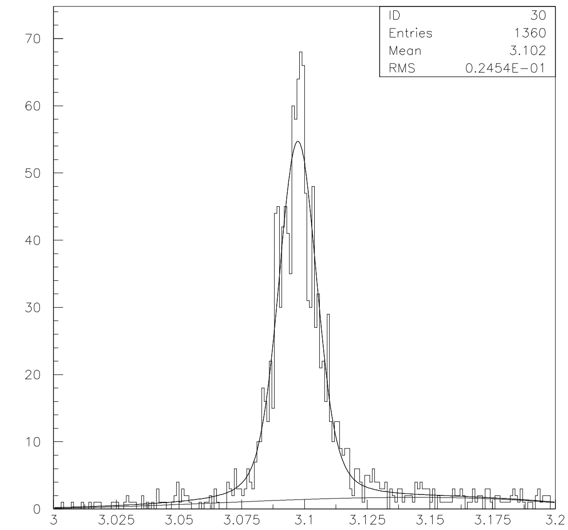

Figure 2: Mass recoiling against $\pi^+\pi^-$ in scan data events containing leptons ($\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to l^+l^-$).

- HOWL for $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to$ hadrons.

For this, HOWL has been modified to yield a $m_{\pi\pi}$ mass distribution which peaks at high mass in better agreement with PPGEN and the data.

$N_{\pi^+\pi^- J/\psi}$ Results

The acceptance for detecting the low energy pions in $\psi(2S) \to \pi^+\pi^- J/\psi$ is given in Table 1 as a function of the multiplicity of the J/ψ final state. Samples of 50, 000 events were generated for each case except for 0-prongs and 8-prongs, where 20, 000 events were generated. For comparison, the acceptances are also given for the '93 and '95 data sets. They are considerably lower now (version 101).

Table 1: Acceptance ($\pi\pi$) for different charged multiplicities.

J/ψ Charged Multiplicity	MC decay channel	Percentage of J/ψ decays	Acceptance (%) earlier	Acceptance (%) Scan Data
0	all neutrals	0.5	48.34	44.88
2	$\pi^+\pi^-\pi^0$	35.6	46.47	42.34
4	$2(\pi^+\pi^-)$	40.9	44.26	39.19
6	$3(\pi^+\pi^-)$	17.7	43.03	37.11
8	$4(\pi^+\pi^-)$	5.3	41.32	34.95
All			44.69	39.74

The acceptances for $\psi(2S) \to \pi^+\pi^- J/\psi,\ J/\psi \to l^+l^-$ events are given in Table 2, and the $J/\psi \to l^+l^-$ branching ratios are given in Table 3, where the errors shown are statistical only. For each case 60,000 Monte Carlo events were generated. Again the acceptances are smaller now. The branching ratios are consistent with our published results, although $B(\mu\mu)$ is about one standard deviation low. Note that these acceptances and the branching ratio results are not required in this analysis; they are only given as a check. We only need the $\psi(2S) \to \pi^+\pi^- J/\psi,\ J/\psi \to l^+l^-$ events to determine the m_{recoil} signal shape.

Table 2: Acceptance for $\psi(2S) \to \pi^+\pi^- J/\psi,\ J/\psi \to l^+l^-$ events.

MC decay channel	Accept. (%) earlier	Accept. (%) Scan Data
$\psi(2S) \to \pi^+\pi^- J/\psi,\ J/\psi \to e^+e^-$	25.85	21.9
$\psi(2S) \to \pi^+\pi^- J/\psi,\ J/\psi \to \mu^+\mu^-$	21.07	17.8

Table 3: Check of $B(J/\psi \to l^+l^-)$ results for scan data.

Decay	$N_{ll}(Detected)$	B (%)
$\psi(2S) \to \pi^+\pi^- J/\psi,\ J/\psi \to e^+e^-$	630	5.96 ± 0.28
$\psi(2S) \to \pi^+\pi^- J/\psi,\ J/\psi \to \mu^+\mu^-$	486	5.67 ± 0.30

Using BWFIT to determine the number of inclusive $N_{\pi^+\pi^- J/\psi}$ decays, we obtain $N_{\pi^+\pi^- J/\psi} = 19174 \pm 263$ and $N^{corr}_{\pi^+\pi^- J/\psi} = 48242 \pm 674$, where the error is statistical and is about 1.4 %.

How to Get $N_{\psi(2S)}$?

Next we need the total number of $\psi(2S)$ events. To find this, we will fit the number of selected hadron events as a function of scan energy with a signal shape determined from the number of $N_{\pi^+\pi^- J/\psi}$ events as a function of energy and a polynomial to describe the background (continuum). Actually we fit by energy bin where the bins are ordered by increasing energy.

Figs. 3 and 4 show the fitting done by BWFIT to determine $N_{\pi^+\pi^- J/\psi}$ by energy (bin). Note that we find almost no J/ψ events below the peak, while we do find some radiative events above the peak.

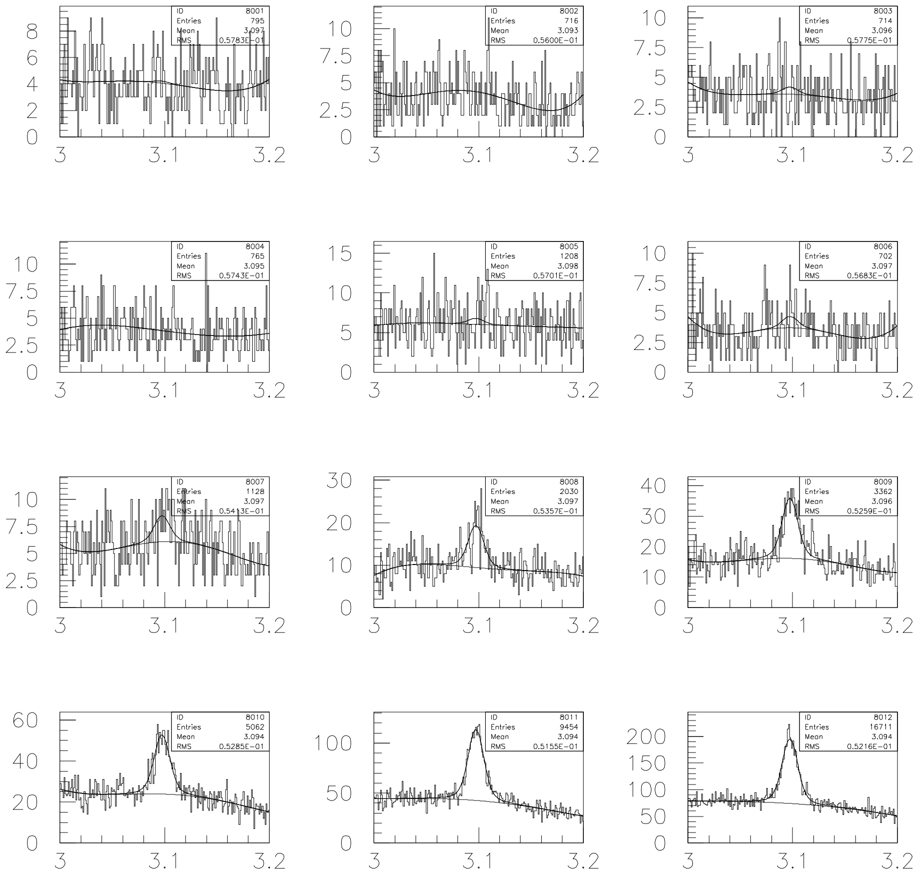

Figure 3: Recoil mass (inclusive) analyzed by energy bin. The bins are ordered by increasing energy.

The results of the fit versus energy are given in Table 4, and Fig. 5 shows $N_{\pi^+\pi^- J/\psi}$ versus energy. This is the $\psi(2S)$ line shape.

To determine the number of hadrons, N_{had}, versus energy bin, the R-group selection routines are used. This makes sense since they have spent a great deal of time studying hadron selection, even though this selection may not be optimized for the $\psi(2S)$ scan data. Since the luminosity is not the same at each scan point, N_{had} and $N_{\pi^+\pi^- J/\psi}$ are normalized

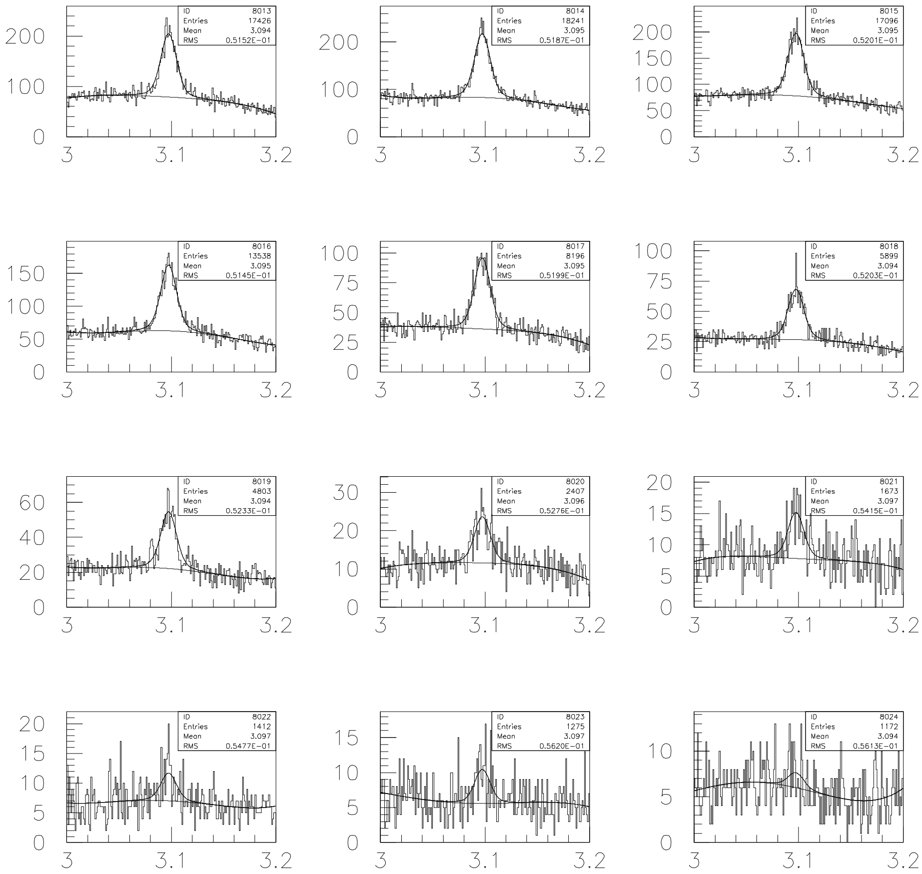

Figure 4: Recoil mass (inclusive) analyzed by energy bin (continued).

according to the number of Bhabha events, N_{Bhabha}, at each point. The number N_{Bhabha} is obtained from Mo Xiaohu. The normalization factor is $2390/N_{Bhabha}$. The numbers N_{had}, N_{Bhabha}, normalized N_{had}, normalized $N_{\pi^+\pi^- J/\psi}$ are given in Table 5. Fig. 6 shows the normalized N_{had} versus energy bin.

The next step is to fit the normalized N_{had} distribution with the normalized $N_{\pi^+\pi^- J/\psi}$ distribution plus polynomial background. Actually we fit normalized N_{had} - normalized $N_{\pi^+\pi^- J/\psi}$ to reduce correlations. The fit with CL = 79 % is shown in Fig. 7. The "background" which is primarily continuum production is essentially flat, as expected over such a narrow energy range. The fit determines the scale factor (NORM) $S = 4.9014 \pm 0.1019$, which can be used to determine $N_{\psi(2S)}$.

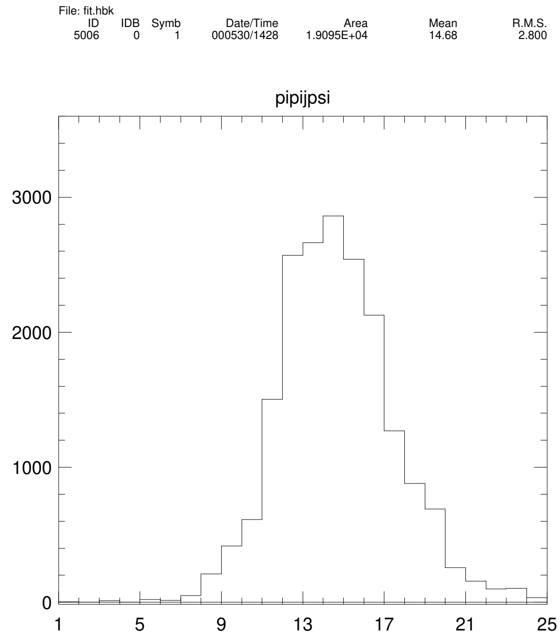

Figure 5: $N_{\pi^+\pi^- J/\psi}$ vs energy bin.

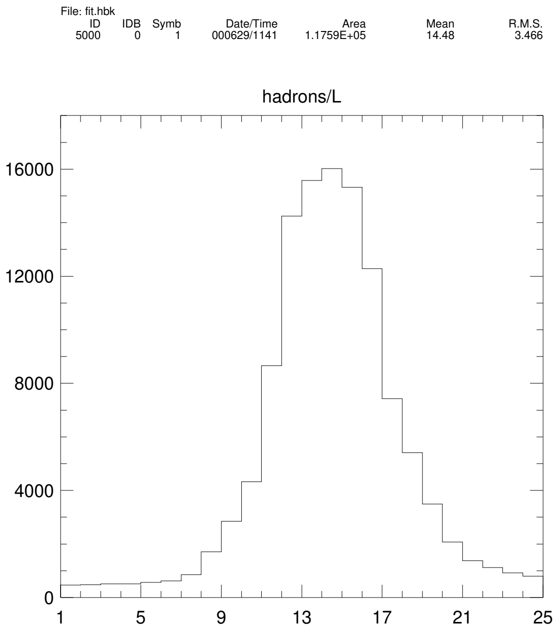

Figure 6: N_{had} normalized by N_{Bhabha} versus energy bin.

Table 4: BWFIT results by energy bin. The bins are ordered in increasing energy.

Bin	$N_{\pi^+\pi^- J/\psi}$	$\Delta(N_{\pi^+\pi^- J/\psi})$	CL (%)	χ^2
1	3.8	15.9	25.9	206.3
2	0.1	0.1	4.7	228.2
3	12.7	16.6	30.0	203.8
4	0.0	0.24	73.5	181.2
5	20.4	18.0	16.2	213.4
6	14.3	19.4	94.2	164.1
7	50.5	21.8	94.5	163.6
8	208.9	30.9	60.0	188.4
9	416.4	41.0	40.8	197.9
10	612.1	50.0	97.3	157.9
11	1503.6	70.1	99.0	150.9
12	2569.3	92.6	48.9	193.9
13	2662.7	94.8	16.6	213.0
14	2860.9	97.6	82.8	175.3
15	2540.8	94.0	42.3	197.2
16	2127.5	84.6	51.5	192.6
17	1269.9	65.2	83.7	174.7
18	881.1	55.0	94.4	163.8
19	690.1	49.0	38.0	199.4
20	256.2	34.2	80.2	177.1
21	156.0	27.6	15.9	213.6
22	99.2	24.4	48.3	194.2
23	103.3	23.0	18.4	211.6
24	34.9	21.0	40.3	198.2

Table 5: N_{Bhabha}, N_{had}, and normalized N_{had} and $N_{\pi^+\pi^- J/\psi}$. N_{Bhabha} is from Mo Xiaohu.

Bin	Energy	N_{Bhabha}	N_{had}	$2390\frac{N_{had}}{N_{Bhabha}}$	$2390\frac{N_{\pi^+\pi^- J/\psi}}{N_{Bhabha}}$
1	3.67000	2284	444	464.6	3.9
2	3.67486	2210	445	481.2	0.2
3	3.67800	2203	471	511.0	13.8
4	3.68100	2273	486	511.0	0.0
5	3.68300	2249	531	564.3	21.7
6	3.68380	2466	646	626.1	13.9
7	3.68496	2292	814	848.8	52.7
8	3.68580	2309	1645	1702.7	216.3
9	3.68620	2352	2803	2848.3	423.1
10	3.68664	2439	4411	4322.4	599.8
11	3.68740	2354	8526	8656.4	1526.7
12	3.68800	2562	15267	14242.1	2396.8
13	3.68850	2410	15710	15579.6	2640.6
14	3.68928	2434	16319	16024.0	2809.2
15	3.68966	2447	15686	15320.6	2481.6
16	3.69044	2358	12116	12280.4	2156.4
17	3.69114	2361	7334	7424.08	1285.5
18	3.69160	2287	5179	5412.3	920.8
19	3.69224	2850	4166	3493.6	578.7
20	3.69386	2296	1987	2068.4	266.7
21	3.69690	2565	1470	1369.7	145.4
22	3.70086	2446	1145	1118.8	96.9
23	3.70464	2403	928	923.0	102.8
24	3.70976	2477	822	793.1	33.6

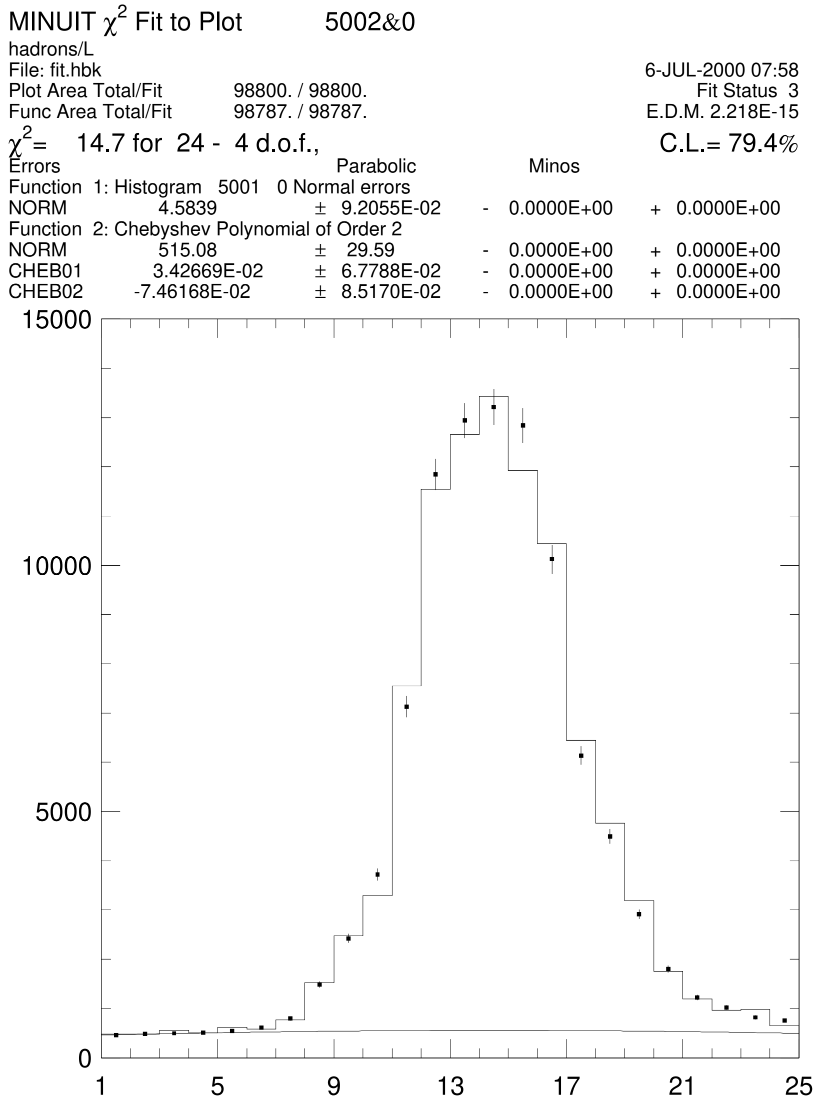

Figure 7: Fit of normalized $N_{had} - N_{\pi^+\pi^- J/\psi}$ distribution with normalized $N_{\pi^+\pi^- J/\psi}$ distribution plus polynomial background. The background function is shown in the plot.

Branching Ratio

To determine the branching ratio, we use

$$B = \frac{\epsilon_{had}}{\epsilon_{\pi^+\pi^- J/\psi}} \frac{N_{\pi^+\pi^- J/\psi}}{N_{had} - C}$$

where ϵ_{had} is the hadron selection efficiency for $\psi(2S)$ events, $\epsilon_{\pi^+\pi^- J/\psi}$ is the acceptance for detecting the two pions in $\psi(2S) \to \pi^+\pi^- J/\psi$ events (given earlier), and $C = \sum(Bkg \times N_{Bhabha})_i/2390$ is the contribution from continuum. Note that ϵ_{had} is the efficiency for passing the hadron selection relative to all $\psi(2S)$ events, including leptons. This efficiency is determined using the Lund-Charm Monte Carlo [7]. The hadron selection selects many $\psi(2S) \to \tau\tau$ events, but the correction for this contribution is small and should be the same for both data and Monte Carlo, so it cancels. The Lund-Charm Monte Carlo assumes $\frac{\Gamma_{had}}{\Gamma} = 98.1 \pm 0.3\%$ [2]. We obtain $\epsilon_{had} = 0.7858$ for 50, 000 generated Monte Carlo events. Assuming constant background versus energy, we obtain 493 background events per energy bin, and the total number of hadrons before background subtraction is 1.19×10^5. Putting in numbers, we obtain

$$B = 0.351 \pm 0.005 \quad (1.4\% \text{ statistical error})$$

Systematic Errors

Many possible sources of systematic errors have been considered. In Table 6 there is a summary of errors excluding those having to do with hadron selection. The uncertainty in the pion acceptance in $\pi\pi J/\psi$ events is what was quoted in Ref. [5]. The uncertainty in the efficiency obtained using the Lund-Charm Monte Carlo is taken to be 2 %, which is confirmed by the R-group. The contribution to the branching ratio from the uncertainty in the number of Bhabha events, which is taken as 3 %, is quite small.

Errors considered in fitting N_{had} as a function of energy are due to the uncertainty in the background, which is determined from the fit, the degree of the polynomial used, and the number of energy bins used in the fit.

Next the errors having to do with the pion cuts are shown. We also know that the $\cos\theta_\pi$ distribution has a small amount of D-wave and is not flat [8]. The angle θ_π is that of the π in the dipion rest frame relative to the J/ψ direction. The systematic error for not using the non flat $\cos\theta_\pi$ is given. Another major contribution comes about when we require that the pion tracks be $mfit = 2$ tracks.

Another important source of error has to do with the shape coming from the $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to l^+l^-$ events used to determine $N_{\pi^+\pi^- J/\psi}$ events. There are not many of these events so this shape is not well determined (see Fig. 2). To check our result, a totally different method was used. Instead of fitting with a Breit-Wigner convoluted with a Gaussian using BWFIT, a double Gaussian was used, and the fitting was done with MN_FIT. But in this case, the shape was not obtained from the $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to l^+l^-$ events but from the inclusive distribution itself. The change between the two approaches was less than 1 %.

Finally errors having to do with the lepton cuts used to select the $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to l^+l^-$ events were studied. Combining the errors in quadrature, we obtain a total error so far of 4.06 %.

Table 6: Systematic Errors Excluding Hadron Selection(%).

Variable	Variation	Error (%)
Pion acceptance - $\epsilon_{\pi^+\pi^- J/\psi}$		0.5
Hadron efficiency - ϵ_{had}		2.0
Bhabha (3 %)		0.33
Fit versus energy errors		
Background uncertainty		0.34
Background fit	Cheb. $0 \to 2$	0.77
Number of bins used	$24 \to 18$	0.1
$\boldsymbol{N_{\pi^+\pi^- J/\psi}}$ **Errors**		
$\cos\theta_\pi$	$0.75 \to 0.70$	0.91
$\cos\theta_{\pi\pi}$	$0.9 \to 0.85$	0.33
p_{xy} cut	off	0.72
Non flat $\cos\theta_\pi$		0.37
Require mfit = 2		2.2
$N_{\pi^+\pi^- J/\psi}$ fitting method		0.80
Lepton Cuts		
p_l cut	$1.3 \to 1.4$	0.13
E/p cut	$0.6/p \to 0.7/p$	0.0
$\cos\theta_\mu$ cut	$0.6 \to 0.65$	1.54
$\cos\theta_e$ cut	$0.75 \to 0.7$	0.55
Back to back cuts	remove	1.27
Total Systematic Error (so far)		4.06

For hadron systematic errors, we got help from Derrick who has written a PERL script (**hadproc**) to run the R-group hadron selection routines over data and Monte Carlo events. Before running all the variations, the script was run to write a subset of the total data to disk using loose cuts. This made the job much faster. The cuts to be studied and the variations to be used are those suggested by the R-group. The summary of systematic errors is given in Table 7. As can be seen, the errors are very small except the error related to for $Ngdmfit$ which is the number of $mfit = 2$ tracks required in the event. Changing from requiring one to requiring two gives a 2 % change.

In Hawaii, we must do reconstruction for Monte Carlo events with V102, since V101 does not work properly. One worry was that V101 and V102 were somehow different. To check this, sober was run both in Hawaii with V102 and at IHEP with V101, and the efficiencies determined from the sober and drunk reconstruction runs were compared. No difference was seen within the statistical errors involved.

Finally $\epsilon_{\pi^+\pi^- J/\psi}$ was determined using the Lund - Charm generator and was compared with that found using the standard approach with a specially modified HOWL. Remember

Table 7: Hadron Selection Systematic Errors (%).

Variable	Variation	Error (%)
had.f		
vr cut	$0.02 \to 0.15$	0.47
$\cos\theta$	$0.84 \to 0.75$	0.01
Ndedx for Mfit = -19	$16 \to 12$	0.32
Ndedx for Mfit = 2	$20 \to 18$	0.01
Pmost	no cut	0.01
TOF cut	no cut	0.24
TOF cut - proton	no cut	0.07
ecut	$0.6 \to 0.05, 1 \to 0.8$	0.32
muhits	$5 \to 0$	0.24
Ngdmfit	$1 \to 2$	2.12
Event energy	$0.5 \to 0.4, 0.28 \to 0.22$	0.12
had2pr.f		
cosacol	$-0.9 \to -0.8$	0.47
Fake photon cut	$0.1 \to 0.06$	0.36
dr	$0.34 \to 0.30$	0.01
dz	$0.6 \to 0.5$	0.01
plots.f		
background fit	2nd degree $\to$ 1st	0.01
balance.f		
egamma	$100 \to 75$ MeV	0.01
eeggzcut.f		
all changes combined		0.10
Total Hadron Selection Systematic Error		2.2

that HOWL puts in the high mass $m_{\pi\pi}$ distribution which better agrees with the data, while Lund-charm uses phase space. Therefore the results might be expected to be different. The two efficiencies agreed within $1.3 \pm 0.9\%$. This error has not been included in the overall systematic error since the results might be expected to be different. More work will be done on this.

Final Result

Combining the hadron selection errors with the other errors in quadrature, we obtain a total systematic error of 4.6 % and a final branching ratio

$$B = (35.1 \pm 0.5 \pm 1.6)\%$$

This gives a total error of 1.7 % and a percentage error of 4.8 %, which is about one half the error given in PDG2000. This result is one and a half PDG2000 standard deviations above the PDG2000 result.

Zhang Liangsheng worked very hard to determine the number of $\psi(2S)$ in the '93 and '95 runs [9]. This is a very complicated analysis. Using his $\psi(2S)$ result along with $N_{\pi^+\pi^- J/\psi}$ [5], he obtains a branching ratio

$$B = (33.9 \pm 0.16 \pm 1.0)\%,$$

which is in good agreement. Although the samples used are independent, the method used to determine $N_{\pi^+\pi^- J/\psi}$ is the same in both cases, so the measurements are not totally independent.

References

[1] R. M. Barnet *et al.*, Phys. Rev. **D54**, 1 (1996).

[2] C. Caso *et al.*, The Eur. Phys. Journal **C3**, 1 (1998).

[3] See http:://pdg.lbl.gov.

[4] Y. Gu and X. Li, Phys. Lett. **B449**, 361 (1999).

[5] F. A. Harris and Wang Meng, "Analysis Note: Number of ψ' Events", March 98;
F. A. Harris and Wang Meng, "Analysis Note: Number of ψ' Events - Update, April 98.

[6] J. Z. Bai *et al.*, Phys. Rev. **D58**, (1998)092006
See also: F. A. Harris and Wang Meng, "Analysis Note: $J/\psi \to l^+l^-$ Branching Ratio", April 98.

[7] J. C. Chen *et al.*, Phys. Rev **D62**, 034003 (2000).

[8] J. Z. Bai *et al.*, Phys. Rev. **D62**, 32002 (2000).

[9] Zhang Liangsheng, "Direct Determination of the Number of $\psi(2S)$ Events", March 20, 2000.