BES Analysis Memo

September 17, 1997

$\psi_{2S} \to$ vector- plus pseudoscalar-mesons: the "other" modes

Stephen L. Olsen

University of Hawaii

-ABSTRACT-

I report measurements of $\psi_{2S} \to$ vector- plus pseudoscalar-mesons, other than the well studied $\rho\pi$ and K^*K channels, using the 3.6 million ψ_{2S} event sample collected by the BES detector. I confirm Ye Shuwei's observation of the i-spin violating decay $\psi_{2S} \to \omega\pi^0$ and determine a branching fraction $\mathcal{B}(\psi_{2S} \to \omega\pi^0) = 3.6 \pm 1.6 \pm 0.6 \times 10^{-5}$, which is larger than that for its i-spin conserving counterpart $\psi_{2S} \to \rho\pi^0$. I present first measurements of branching fractions for the decays $\psi_{2S} \to \omega\eta'$, and $\psi_{2S} \to \phi\eta$, and 90% Cl upper limits for the $\rho\eta$, $\rho\eta'$, $\omega\eta$, $\phi\pi^0$, and $\phi\eta'$ decay channels

1 Introduction

The strong suppression of $\psi_{2S} \to \rho\pi$ and $K^*\overline{K}$ decays is well known and has been a subject for considerable experimental [1] and theoretical [2, 3] activity. No evidence is seen for $\psi_{2S} \to \rho\pi$ decays in the BES group's 3.6M ψ_{2S} event sample [4], in striking contrast to the case for the J/ψ, where $J/\psi \to \rho\pi$ is the dominant decay [5]. This conundrum is referred to as the "$\rho\pi$ puzzle" [3] and remains one of the most intriguing mysteries in quarkonium physics.

The BES group's large event sample of ψ_{2S} decays affords the opportunity to undertake a systematic investigation of ψ_{2S} decays to all of the lowest-lying vector- plus pseudoscalar-meson (VP) final states. Comparisons with the corresponding J/ψ decays may provide clues that ultimately lead to an explanation of the $\rho\pi$ puzzle.

2 $\psi_{2S} \to VP$; the current status.

Table 1 lists the existing information (i.e. prior to the results reported here) on J/ψ and ψ_{2S} decays to the lowest lying vector- plus pseudoscalar-meson states. Here, the

ψ_{2S} results come from BES [4] and the J/ψ results are taken from the PDG listings [5]. In the fourth column, I indicate the extent to which the decay is suppressed by a "suppression factor" $\mathcal{S}$, defined as

$$\mathcal{S} \equiv \frac{0.147 \times \mathcal{B}(J/\psi \to VP)}{\mathcal{B}(\psi_{2S} \to VP)}. \quad (1)$$

Here the factor 0.147 is the ratio of the $\psi_{2S} \to \ell^+\ell^-$ and $J/\psi \to \ell^+\ell^-$ branching ratios. Decay branching ratios that scale like the dileptons, i.e. those that obey the "14% rule," will have $\mathcal{S} \simeq 1$; those, like $\psi_{2S} \to \rho\pi$, that are suppressed have $\mathcal{S} > 1$, etc. Included in Table 1 for completeness are the branching fractions for the radiative VP transitions to $\gamma\eta$ and $\gamma\eta'$, which were recently determined by Ye and myself [6].

A decay channel of particular interest is the i-spin violating process $\psi_{2S} \to \omega\pi^0$, which was recently measured by Ye [7] to be larger than its i-spin conserving counterpart $\psi_{2S} \to \rho\pi^0$. Moreover, of all the entries in Table 1, this is the only one that does not appear to be suppressed.

In the following, I describe analyses that try to reproduce Ye's results for the $\omega\eta$ and $\omega\pi^0$ channels as well as first measurements of all of the other entries is Table 1, with the exception of $\gamma\pi^0$, which is a difficult mode for the BES detector.

3 Event Preselection

For the analyses reported here, I use the ψ_{2S} event samples on the two-prong and and four-prong data summary tapes. I only use charged tracks and gammas that are in the $|\cos\theta| < 0.8$ polar angle region. I veto events where the highest momentum positive *and* negative tracks are *both* identified either as muons or electrons. This eliminates most of the $\psi_{2S} \to J/\psi$ cascade events where the J/ψ decays to lepton pairs. For each final state studied, events are required to have the appropriate number of tracks with zero net charge. Gammas are associated with neutral clusters in the BSC with energies greater than 50 MeV. In the event that the number of neutral clusters exceeds the minimum number needed for a given hypothesis, the "best" combination is selected by means of a four-constraint kinematic fit. In the following tables, these criteria are included in the category labeled "preselection."

For the number of ψ_{2S} events in the data sample I use the number $N_{\psi_{2S}} = (3.44 \pm 0.31) \times 10^6$ that was determined from the number of $\psi_{2S} \to \pi^+\pi^- J/\psi$; $J/\psi \to \mu^+\mu^-$ events found on the four-prong data summary tapes [8]. This number is determined

Table 1: A tabulation of existing measurements for $J/\psi \rightarrow$ and $\psi_{2S} \rightarrow$ lowest lying vector- plus pseudoscalar-mesons.

VP mode	$\mathcal{B}(\psi' \rightarrow VP)$ (10^{-4})	$\mathcal{B}(J\psi \rightarrow VP)$ (10^{-3})	$\mathcal{S}$ $(= \frac{0.14\mathcal{B}_{J/\psi}}{\mathcal{B}_{\psi'}})$
$\rho\pi$	< 0.28	12.8 ± 1.0	> 64
$K^{*+}K^-$	< 0.3	5.0 ± 0.4	> 23
$K^{*0}\bar{K}^0$	$0.81 \pm 0.24 \pm 0.16$	4.2 ± 0.4	7.3 ± 2.7
$\omega\pi^0$	$0.44 \pm 0.17 \pm 0.09$	0.42 ± 0.06	1.4 ± 0.6
$\omega\eta$	< 0.71	1.58 ± 0.16	> 3.3
$\omega\eta'$		0.167 ± 0.025	
$\phi\pi^0$		< 0.0068	
$\phi\eta$		0.65 ± 0.07	
$\phi\eta'$		0.33 ± 0.04	
$\rho\eta$		0.193 ± 0.023	
$\rho\eta'$		0.105 ± 0.023	
$\gamma\pi^0$		0.039 ± 0.013	
$\gamma\eta$	$0.5 \pm 0.3 \pm 0.1$	0.86 ± 0.08	2.5 ± 1.5
$\gamma\eta'$	$1.4 \pm 0.3 \pm 0.3$	4.31 ± 0.30	4.3 ± 1.3

using similar charged-track requirements as is used in the analysis reported here, which will tend to cancel errors associated with extra "ghost" tracks, etc.

4 $\psi_{2S} \to \omega\pi^0$, $\omega\eta$, $\omega\eta'$ decays

4.1 $\psi_{2S} \to \omega\pi^0$

For $\psi_{2S} \to \omega\pi^0$, the topology of interest is $\pi^+\pi^-\pi^0\pi^0 \to \pi^+\pi^-4\gamma$. I select events with two charged tracks and four or more candidate gammas. For events with more than four candidate gammas, I select the four gamma combination that produces the best χ^2 value from a 4-c kinematic fit to the hypothesis $\psi_{2S} \to \pi^+\pi^-4\gamma$. Since the charged $\pi^+\pi^-$ pair must come from the decay $\omega \to \pi^+\pi^-\pi^0$, I require $M_{\pi^+\pi^-} < 0.62$ GeV. Cascade $\psi_{2S} \to \pi^+\pi^- J/\psi$ events are removed by eliminating events where the mass recoiling against the $\pi^+\pi^-$ pair is within 50 MeV of the J/ψ. QED backgrounds are reduced by requiring the opening angle between the charged track and the nearest gamma to be $\theta_{\pi\gamma} > 11.5^0$.

I used 1000 simulated $\psi_{2S} \to \omega\pi^0$ events generated by the HOWL Monte Carlo simulator the develop the final selection criteria: $|M_{\gamma_i\gamma_j} - M_{\pi^0}| < 0.035$ GeV. A total of 71 events survive the selection proceedure, indicating an acceptance of $acc_{\omega\pi} = 0.07 \pm 0.01$.

Figures 1a through 1e show the results from the application of the selection criteria to the data. Fig. 1e shows the invaraiant mass distribution for $\pi^+\pi^-\pi^0$ combinations recoiling against a $\gamma\gamma$ pair with invariant mass within 35 MeV of M_{π^0}. A peak is evident at M_ω. A fit to this distribution using a gaussian signal function with mass fixed at M_ω and width fixed at the MC expectation $\sigma = 0.02$ GeV plus a smooth background yields the number of signal events $N^{evt}_{\omega\pi^0} = 7.9 \pm 3.6$. Figure 1d shows the $\gamma\gamma$ mass distribution recoiling against $\pi^+\pi^-\pi^0$ combinations with invariant masses within 50 MeV of M_ω, where a π^0 peak is apparent. A fit to this distribution yields 8.2 ± 3.8 π^0s, in good agreement with the fit to the ω peak. A summary of the cuts and the number of events that survive them is presented in Table 2

I determine the $\psi_{2S} \to \omega\pi^0$ branching fraction from the relation

$$\mathcal{B}(\psi_{2S} \to \omega\pi^0) = \frac{N^{evt}_{\omega\pi^0}}{N_{\psi_{2S}} \mathcal{B}^{\omega}_{\pi^+\pi^-\pi^0} (\mathcal{B}^{\pi^0}_{\gamma\gamma})^2 acc_{\omega\pi}} = (3.8 \pm 1.7 \pm 0.6) \times 10^{-5}, \qquad (2)$$

which is in good agreement with Ye's result given above in Table 1.

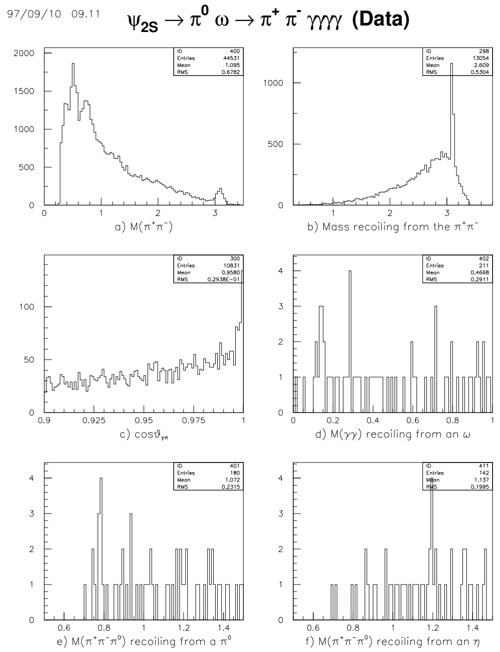

Figure 1: Distributions for events that satisfy the 4-c fit to the hypothesis $\psi_{2S} \to \pi^+\pi^-4\gamma$ with a confidence level of better than 5%: **a)** $M_{\pi^+\pi^-}$; **b)** the mass recoiling against the $\pi^+\pi^-$ pair; **c)** $\cos\theta_{\pi\gamma}$; **d)** $M_{\gamma\gamma}$ recoiling against a $\pi^+\pi^-\pi^0$ combination with an invariant mass within 50 MeV of M_ω; **e)** $M_{\pi^+\pi^-\pi^0}$ recoiling against a $\gamma\gamma$ with invariant mass within 35 MeV M_{π^0}. **f)** $M_{\pi^+\pi^-\pi^0}$ recoiling against a $\gamma\gamma$ pair with an invariant mass within 35 MeV of M_η.

4.2 $\psi_{2S} \to \omega\eta$

For the $\psi_{2S} \to \omega\eta$ analysis, I use the $\eta \to \gamma\gamma$ ($\mathcal{B}^\eta_{\gamma\gamma} = 0.393 \pm 0.003$) and $\eta \to \pi^+\pi^-\pi^0$ ($\mathcal{B}^\eta_{\pi^+\pi^-\pi^0} = 0.232 \pm 0.005$) decay modes.

4.2.1 $\psi_{2S} \to \omega\eta$ using the $\eta \to \gamma\gamma$ mode

For $\psi_{2S} \to \omega\eta$; $\eta \to \gamma\gamma$, the $\pi^+\pi^-4\gamma$ final state is very similar to that for the $\omega\pi$ analysis and the same selection criteria are used, with the exception that the invariant mass of the $\gamma\gamma$ pair recoiling from the ω should be M_η rather than M_{π^0}. Figure 1d shows the distribution of $\gamma\gamma$ invariant masses recoiling from a $\pi^+\pi^-\pi^0$ combination with invariant mass within 50 MeV of the ω. No signal is apparent near the mass of the η. Figure 1f shows the $\pi^+\pi^-\pi^0$ invariant mass distribution recoiling against $\gamma\gamma$ pairs with invariant mass within 35 MeV of M_η. There is one event within 2σ of M_ω, consistent with background.

Table 2: A tabulation of the $\psi_{2S} \to \omega\pi^0$ selection cuts.

The number of events surviving each requirement

	data	Monte Carlo
Generated		1000
Preselection	215370	192
$CL_{4c} > 0.05$	44531	112
$M_{\pi^+\pi^-} < 0.62$ GeV	13054	112
$\lvert MM_{\pi^+\pi^-} - M_{J/\psi}\rvert > 0.05$ GeV	10831	108
$\cos\theta_{\pi\gamma} < 0.98$	9627	99
$\lvert M_{\gamma_i\gamma_j} - M_{\pi^0}\rvert < 0.035$ GeV		
$\lvert M_{\gamma_k\gamma_l} - M_{\pi^0}\rvert < 0.035$ GeV	90	71
$M_{\pi^+\pi^-\pi^0} = M_\omega$	8	71

4.2.2 $\psi_{2S} \to \omega\eta$ using the $\eta \to \pi^+\pi^-\pi^0$ mode

For $\psi_{2S} \to \omega\eta$ followed by $\eta \to \pi^+\pi^-\pi^0$, the event topology is $\psi_{2S} \to 2(\pi^+\pi^-)4\gamma$. I select events with four charged tracks and four or more candidate gammas. I select the four gamma combination that produces the best χ^2 value from a 4-c kinematic fit to the hypothesis $\psi_{2S} \to 2(\pi^+\pi^-)\gamma\gamma\gamma\gamma$. The $\pi^0 \to \gamma\gamma$ pairings are selected by a 6-c fit where the fifth and sixth constraints are $M_{\gamma\gamma} = M_{\pi^0}$. A $\pi^+\pi^-\pi^0$ combination with invariant mass within 40 MeV of M_η (M_ω) is considered to be an η (ω) candidate. The are no $\pi^+\pi^-\pi^0$ combinations recoiling against an η candidate that have an invariant mass within 40 MeV of M_ω. The results of the selection cuts for data and MC are presented in Table 3.

4.2.3 The limit on the $\psi_{2S} \to \omega\eta$ branching fraction

In the combined sample of $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$ decays, only one event satisfies the $\psi_{2S} \to \omega\eta$ selection criteria, and this is consistent with background. Translating this single event to a 90% CL upper limit of $N^{Lim}_{\omega\eta} = 3.9$, I determine a limit on the $\psi_{2S} \to \omega\eta$ branching fraction using the relation

$$\begin{aligned} \mathcal{B}(\psi_{2S} \to \omega\eta) &< \frac{N^{Lim}_{\omega\eta}}{N_{\psi_{2S}} \mathcal{B}^{\omega}_{\pi^+\pi^-\pi^0} \mathcal{B}^{\pi^0}_{\gamma\gamma} [\mathcal{B}^{\eta}_{\gamma\gamma} acc_{\gamma\gamma} + \mathcal{B}^{\eta}_{\pi^+\pi^-\pi^0} \mathcal{B}^{\pi^0}_{\gamma\gamma} acc_{3\pi}]} \\ &= 3.3 \times 10^{-5}. \end{aligned} \tag{3}$$

Table 3: A tabulation of the $\psi_{2S} \to \omega\eta$ selection cuts.

The number of events surviving each requirement

	data	Monte Carlo
Generated		1000
Preselection	280975	136
$\chi^2_{4c} \leq 50$	135906	106
$CL_{6c} > 0.05$	5231	53
$\lvert MM_{\pi^+\pi^-} - M_{J/\psi}\rvert > 0.05$ GeV	1296	50
$M_{\pi_a^+\pi_b^-} < 0.42$ GeV		
$M_{\pi_c^+\pi_d^-} < 0.62$ GeV		
$\lvert M_{\pi_a^+\pi_b^-\pi^0} - M_\eta\rvert < 0.04$ GeV	57	50
$\lvert M_{\pi_c^+\pi_d^-\pi^0} - M_\omega\rvert < 0.04$ GeV	0	47

This is a factor of two more stringent than Ye's limit of 7.1×10^{-5}, listed in Table 1 above.

4.3 $\psi_{2S} \to \omega\eta'(958)$

Here I looked for both the $\eta' \to \pi^+\pi^-\eta$ ($\mathcal{B}^{\eta'}_{\pi^+\pi^-\eta} = 0.437 \pm 0.015$) and $\eta' \to \rho\gamma$ ($\mathcal{B}^{\eta'}_{\rho\gamma} = 0.302 \pm 0.013$) decay modes.

4.3.1 $\psi_{2S} \to \omega\eta'(958)$ using the $\eta' \to \pi^+\pi^-\eta$ decay mode

For the $\eta' \to \pi^+\pi^-\eta$ decay mode, I only use $\eta \to \gamma\gamma$ decays, which makes the analysis similar to the $\psi_{2S} \to \omega\eta;\ \eta \to \pi^+\pi^-\pi^0$ measurement described in Section 4.2.2 above. The only exception is that the 5-c fit requires $M_{\gamma\gamma} = M_\eta$ and I look for an $\eta'(958)$ signal in the selected $\pi^+\pi^-\eta$ mass distribution. To reduce background, I make cuts on the $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ masses that come from the 4-c fit.

The results are shown in Figs. 2a through 2d. There are three events with $M_{\pi^+\pi^-\pi^0}$ within 40 MeV of M_ω and $M_{\pi^+\pi^-\eta}$ within 40 MeV of $M_{\eta'}$. The MC and data event yields after each of the cuts are tabulated in Table 4.

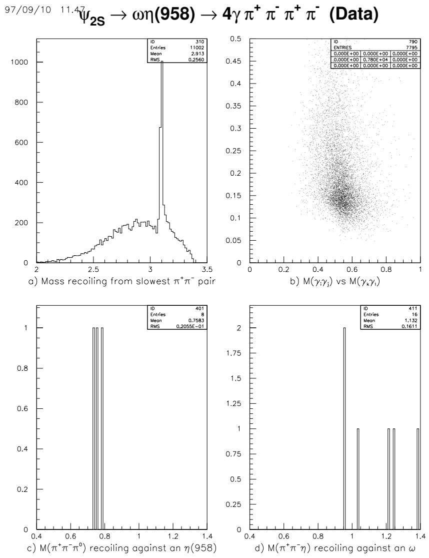

Figure 2: Distributions for events that satisfy a 6-c fit to the hypothesis $\psi_{2S} \rightarrow 2(\pi^+\pi^-)\eta$ with a confidence level better than 5%: **a)** The mass recoiling from the slowest $\pi^+\pi^-$ pair; **b)** $y = M_{\gamma_i\gamma_j}$ *vs* $x = M_{\gamma_k\gamma_l}$ from the 4-c fit where $\gamma_i\gamma_j$ ($\gamma_k\gamma_l$) is the combination that is constrained to be a π^0 (η) in the 6-c fit; **c)** $M_{\pi_a^+\pi_b^-\pi^0}$ for combinations where $M_{\pi_a^+\pi_b^-} < 0.62$ GeV, $M_{\pi_c^+\pi_d^-} < 0.42$ GeV, and $M_{\pi_c^+\pi_d^-\eta}$ is within 40 MeV of $M_{\eta'}$. **d)** $M_{\pi_c^+\pi_d^-\eta}$ for combinations where $M_{\pi_a^+\pi_b^-\pi^0}$ is within 40 MeV of M_ω.

4.3.2 $\psi_{2S} \rightarrow \omega\eta'(958)$ using the $\eta' \rightarrow \rho\gamma$ decay mode

In the $\eta' \rightarrow \rho\gamma$ decay channel, the final states of interest is $\psi_{2S} \rightarrow 2(\pi^+\pi^-)\pi^0\gamma$, where the bachelor γ is in the energy range $0 \sim 1$ GeV. I subject events with four charged tracks and at least 3 gammas to a 4-c fit and select the three gammas based on the best χ^2 value. I subsequently use a 5-c fit, where the fifth constraint is $M_{\gamma\gamma} = M_{\pi^0}$ to identify the two gammas from the π^0. Here there is some background from $\psi_{2S} \rightarrow \gamma\chi_{c0,1,2}$ with the subsequent decay $\chi_{c0,1,2} \rightarrow 2(\pi^+\pi^-)\pi^0$. To reduce this background I eliminate events where the the energy of the bachelor gamma is within 10 MeV of either of the three $\psi_{2S} - \chi_c$ mass differences, a cut that loses about 30% of the signal. The results of the data selection are shown in Figs. 3a through 3d, which show the distributions of some of the cut variables before the cut is applied. There are 6 events with $M_{\pi^+\pi^-\pi^0}$ within 40 MeV of $M_\omega$and $M_{\pi^+\pi^-\gamma}$ within 40 MeV of $M_{\eta'}$. The MC and data event yields after each of the cuts are tabulated in Table 5.

Table 4: A tabulation of the $\psi_{2S} \to \omega\eta'$: $\eta'\pi^+\pi^-\eta$ selection cuts.

The number of events surviving each requirement

	data	Monte Carlo
Generated		1000
Preselection	280975	165
$\chi^2_{4c} \leq 50$	135906	129
$CL_{6c} > 0.05$	11002	63
$\|MM_{\pi^+\pi^-} - M_{J/\psi}\| > 0.05$ GeV	7795	52
$\|M^{4c}_{\gamma_i\gamma_j} - M_{\pi^0}\| < 0.035$ GeV		
$\|M^{4c}_{\gamma_k\gamma_l} - M_{\eta}\| < 0.035$ GeV	2471	41
$\|M_{\pi_a^+\pi_b^-}\| < 0.15$ GeV		
$M_{\pi_c^+\pi_d^-} < 0.42$ GeV		147
$\|M_{\pi_c^+\pi_d^-\eta} - M_{\eta'}\| < 0.04$ GeV	8	37
$\|M_{\pi_c^+\pi_d^-\pi^0} - M_{\eta'}\| < 0.03$ GeV	3	31

Table 5: A tabulation of the $\psi_{2S} \to \omega\eta'$; $\eta' \to \rho\gamma$ selection cuts.

The number of events surviving each requirement

	data	Monte Carlo
Generated		1000
Preselection	374392	162
$\chi^2_{4c} < 50$	122280	134
$CL_{5c} > 0.05$	11254	91
$\|M_{\pi^+\pi^-\pi^0} - M_{J/\psi}\| > 0.05$ GeV	7542	84
$\|E_\gamma - 0.130\| > 0.01$ GeV		
$\|E_\gamma - 0.176\| > 0.01$ GeV		
$\|E_\gamma - 0.271\| > 0.01$ GeV	5380	58
$M_{\pi_a^+\pi_b^-} < 0.62$ GeV		
$\|M_{\pi_c^+\pi_d^-} - M_\rho\| < 0.15$ GeV		
$\|M_{\pi_c^+\pi_d^-\gamma} - M_{\eta'}\| < 0.04$ GeV	66	43
$\|M_{\pi_a^+\pi_b^-\pi^0} - M_\omega\| < 0.04$ GeV	6	41

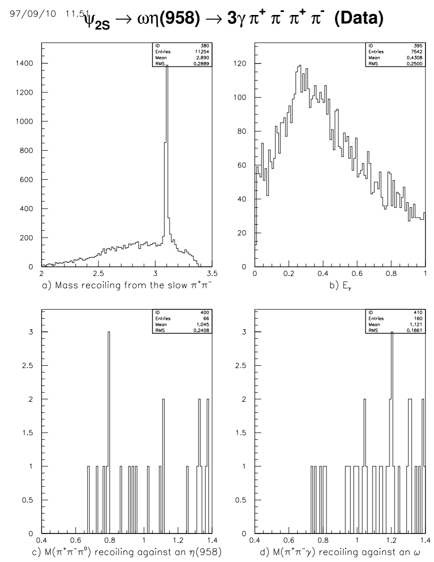

Figure 3: Distributions for events that satisfy a 5-c fit to the hypothesis $\psi_{2S} \to 2(\pi^+\pi^-)\pi^0\gamma$ with a confidence level better than 5%: **a)** The mass recoiling from the slowest $\pi^+\pi^-$ pair; **b)** the bachelor gamma energy; **c)** $M_{\pi_a^+\pi_b^-\pi^0}$ for combinations where $M_{\pi_a^+\pi_b^-} < 0.62$ GeV, $|M_{\pi_c^+\pi_d^-} - M_\rho| < 0.15$ GeV and $|M_{\pi_c^+\pi_d^-\gamma} - M_{\eta'}| < 0.04$ GeV; **d)** $M_{\pi_c^+\pi_d^-\gamma}$ for combinations where $|M_{\pi_c^+\pi_d^-} - M_\rho| < 0.15$ GeV and $M_{\pi_a^+\pi_b^-\pi^0}$ is within 40 MeV of M_ω.

4.3.3 The $\psi_{2S} \to \omega\eta'$ branching fraction

Figure 4 shows the combined $\pi^+\pi^-\pi^0$ mass distribution from the two η' decay modes (the sum of the histograms shown in Figs. 2c and 3c). The smooth curve is the results of a fit using a gaussian function with mass set at M_ω and width fixed at the MC value $\sigma = 15$ MeV, and a smooth background. The fit gives gives $N_\omega = 4.4 \pm 2.4$ events. Although the ω peak in Fig. 4 has only about $\sim 2\sigma$ significance, it is confirmed by a corresponding peak with similar significance in the combined η' mass plot, shown in Fig. 5: here a fit to the sum the histograms shown in Figs. 2d and 3d yields $N_{\eta'} = 3.7 \pm 2.3$ events. Since the signal shows up with similar strength in both the ω and η' plots, I consider this a valid signal and use it to determine a branching fraction.

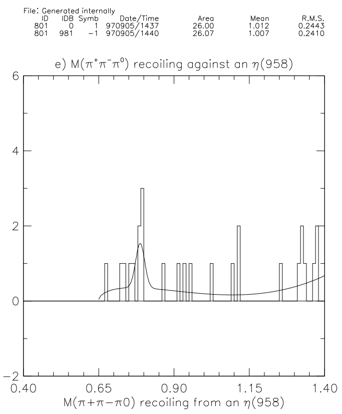

Figure 4: The combined $\pi^+\pi^-\pi^0$ mass distribution for both η' decay modes with a fit to an ω signal superimposed.

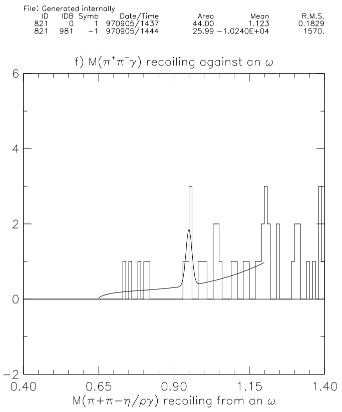

Figure 5: The combined $\pi^+\pi^-\eta$ and $\rho\gamma$ mass distributions where the recoiling $\pi^+\pi^-\pi^0$ system has an inavariant mass within 40 MeV of M_ω, with a fit to an η' signal superimposed.

I infer the $\psi_{2S} \to \omega\eta'$ branching fraction from the relation

$$\begin{aligned}
\mathcal{B}(\psi_{2S} \to \omega\eta') &= \frac{N^{evt}_{\omega\eta'}}{N_{\psi_{2S}} \mathcal{B}^{\omega}_{\pi^+\pi^-\pi^0} \mathcal{B}^{\pi^0}_{\gamma\gamma} [\mathcal{B}^{\eta'}_{\pi^+\pi^-\eta} \mathcal{B}^{\eta}_{\gamma\gamma} acc_{\pi\pi\eta} + \mathcal{B}^{\eta'}_{\gamma\rho} acc_{\gamma\rho}]} \\
&= (7.6 \pm 4.4 \pm 1.8) \times 10^{-5}, \qquad (4)
\end{aligned}$$

where, for $N^{evt}_{\omega\eta'}$, I use the average of N_ω and $N_{\eta'}$ given above.

Table 6: A tabulation of the $\psi_{2S} \to \phi\pi^0$ selection cuts.

The number of events surviving each requirement

	data	Monte Carlo
Generated		1000
Preselection	461431	467
$CL_{4c} > 0.05$	23621	195
$\cos\theta_{K\gamma} < 0.95$	8902	189
$\lvert p_{K^+} - p_{K^-}\rvert < 0.5$ GeV/c	5799	185
$\lvert M_{\gamma\gamma} - M_{\pi^0}\rvert < 0.035$ GeV	431	161
$\lvert M_{K^+K^-} - M_\phi\rvert < 0.015$ GeV	1	160

5 $\psi_{2S} \to \phi\pi^0$, $\phi\eta$, $\phi\eta'$ decays

5.1 $\psi_{2S} \to \phi\pi^0$

For $\psi_{2S} \to \phi\pi^0$, I only use $\phi \to K^+K^-$ decays ($\mathcal{B}^{\phi}_{K^+K^-} = 0.491 \pm 0.006$) and the topology of interest is $K^+K^-\pi^0$. I select events with two charged tracks and two or more candidate gammas. For events with more than two candidate gammas, I select the $\gamma\gamma$ pair that produces the best χ^2 value from a 4-c kinematic fit to the hypothesis $\psi_{2S} \to K^+K^-\gamma\gamma$. I require all $K-\gamma$ opening angles to be greater than 18^0 degrees Since the charged K^+K^- pair must come from the decay $\phi \to K^+K^-$, which has a very low Q value, the K^+ and K^- have nearly equal three-momenta: I require $|p_{K^+} - p_{K^-}| < 0.5 GeV$. I define a $\gamma\gamma$ pair with invariant mass $|M_{\gamma_i\gamma_j} - M_{\pi^0}| < 0.035$ GeV as a candidate π^0.

I used 1000 simulated $\psi_{2S} \to \phi\pi^0$ events generated by the HOWL Monte Carlo simulator the develop the selection criteria. A total of 160 events pass the $\psi_{2S} \to \phi\pi^0$ selection criteria, indicating an acceptance of $acc_{\phi\pi} = 0.16 \pm 0.01$. In the data, only one event surviving the selection cuts is within 15 MeV of M_ϕ (i.e. $\pm 3\sigma$). A summary of the cuts and the number of events that survive them is presented in Table 6

The single event corresponds to a 90% CL upper limit of $N^{Lim}_{\phi\pi^0} = 3.9$, which I use to determine a limit on the branching fraction for $\psi_{2S} \to \phi\pi^0$ from the relation

$$\mathcal{B}(\psi_{2S} \to \phi\pi^0) < \frac{N^{Lim}_{\phi\pi^0}}{N_{\psi_{2S}} \mathcal{B}^{\phi}_{K^+K^-} \mathcal{B}^{\pi^0}_{\gamma\gamma} acc_{\phi\pi}} = 1.5 \times 10^{-5}. \tag{5}$$

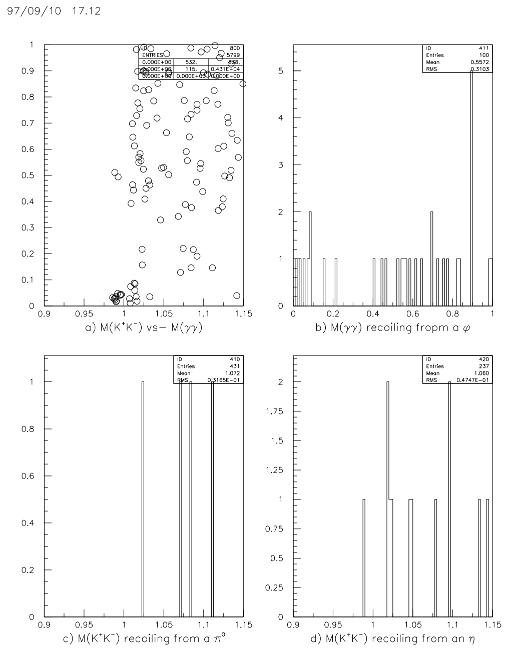

Figure 6: Distributions for selected data events that satisfy a 4-c fit to the hypothesis $\psi_{2S} \to K^+K^-\gamma\gamma$ with a confidence level better than 5%: **a)** $y = M_{\gamma\gamma}$ *vs* $x = M_{K^+K^-}$; **b)** $M_{\gamma\gamma}$ reoiling against a K^+K^- pair with invariant mass within 30 MeV of M_ϕ; **c)**$M_{K^+K^-}$ distribution recoiling against a $\gamma\gamma$ pair with invariant mass within 35 MeV of M_{π^0}; **d)**$M_{K^+K^-}$ distribution recoiling against a $\gamma\gamma$ pair with invariant mass within 35 MeV of M_η.

5.2 $\psi_{2S} \to \phi\eta$

For the $\psi_{2S} \to \phi\eta$ analysis, I use the $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$ decay modes.

5.2.1 $\psi_{2S} \to \phi\eta$ using the $\eta \to \gamma\gamma$ mode

For $\psi_{2S} \to \phi\eta$; $\eta \to \gamma\gamma$ the final $K^+K^-\gamma\gamma$ state is very similar to that for the $\phi\pi^0$ analysis and the same selection criteria are used, with the exception that the invariant mass of the $\gamma\gamma$ pair recoiling from the ω should be M_η rather than M_{π^0}. Figure 6d shows the the invariant mass distribution for K^+K^- pairs recoiling against a $\gamma\gamma$ pair with invariant mass within 35 MeV of M_η. Four events are clustered around M_ϕ.

5.2.2 $\psi_{2S} \to \phi\eta$ using the $\eta \to \pi^+\pi^-\pi^0$ mode

For $\psi_{2S} \to \phi\eta$ followed by $\eta \to \pi^+\pi^-\pi^0$, the event topology is $\psi_{2S} \to K^+K^-\pi^+\pi^-\gamma\gamma$. I select events with four charged tracks and two or more candidate gammas. I select the two gamma combination that produces the best χ^2 value from a 5-c kinematic fit to the hypothesis $\psi_{2S} \to K^+K^-\pi^+\pi^-\pi^0$; $\pi^0 \to \gamma\gamma$. I reject events where the mass recoiling against the $\pi^+\pi^-$ pair is within 50 MeV of $M_{J/\psi}$. The $\pi^+\pi^-$ pairs coming from the decay $\eta \to \pi^+\pi^-\pi^0$ will have low invariant mass: I require $M_{\pi^+\pi^-} < 0.42$ GeV.

Figures 7a through 7d show distributions from the data. In particular, Fig. 7c (7d) shows the selected $\pi^+\pi^-\pi^0$ (K^+K^-) invariant mass distribution for combinations recoiling against ϕ (η) candidates. There is one event with $M_{K^+K^-}$ within 20 MeV ($\pm3\sigma$) of M_ϕ and $M_{\pi^+\pi^-\pi^0}$ within 30 MeV of M_η. The results of the selection cuts for data and MC are presented in Table 7.

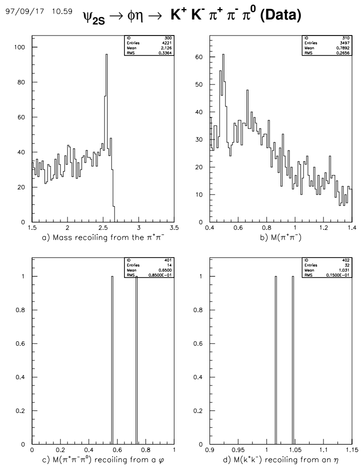

Figure 7: Distributions for selected events that satisfy a 5-c fit to the hypothesis $\psi_{2S} \to K^+K^-\pi^+\pi^-\pi^0$; $\pi^0 \to \gamma\gamma$ with a confidence level better than 5%: **a)** $M_{K^+K^-\pi^0}$ recoiling from the $\pi^+\pi^-$ pair; **b)** $M_{\pi^+\pi^-}$; **c)** $M_{\pi^+\pi^-\pi^0}$ recoiling against K^+K^- pairs with invariant mass within 20 MeV of M_ϕ; **d)** $M_{K^+K^-}$ recoiling against $\pi^+\pi^-\pi^0$ combinations with invariant mass within 30 MeV of M_η.

5.2.3 The $\psi_{2S} \to \phi\eta$ branching fraction

In Fig. 8, I show the sum of the invariant mass distributions for K^+K^- combinations recoiling against η candidates for both η decay modes that are considered, namely the sum of the histograms in Figs. 6f and 7d. Superimposed on the plot is a fit to a gaussian with a mass near M_ϕ and a width fixed at the MC expectation of $\sigma = 0.004$ GeV, together with a smooth function to represent the background. The fit gives $N_\phi = 4.3 \pm 2.3$ events.

The combined $M_{\gamma\gamma}$ and $M_{\pi^+\pi^-\pi^0}$ distributions recoiling against a ϕ—the sum of the histograms in Figs. 6d and 7c—has a corresponding cluster near M_η. Fitting this

Table 7: A tabulation of the $\psi_{2S} \to \phi\eta$ selection cuts.

The number of events surviving each requirement

	data	Monte Carlo
Generated		1000
Preselection	474686	290
$CL_{5c} > 0.05$	4221	107
$\lvert M_{K^+K^-\pi^0} - M_{J/\psi}\rvert > 0.05$ GeV	3497	106
$M_{\pi^+\pi^-} < 0.42$ GeV	386	75
$\lvert M_{K^+K^-} - M_\phi\rvert < 0.02$ GeV	14	69
$\lvert M_{\pi^+\pi^-\pi^0} - M_\eta\rvert < 0.03$ GeV	1	60

distribution with a gaussian plus a smooth background function gives a peak at M_η with a width consistent with MC expectations and $N_\eta = 4.4 \pm 2.6$ events.

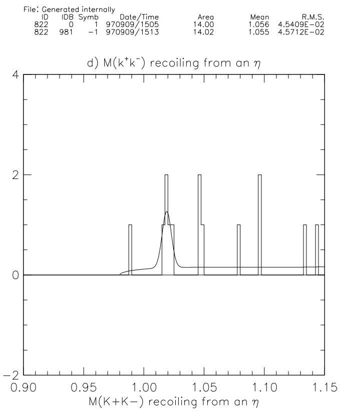

Figure 8: The combined invariant mass distribution of K^+K^- pairs recoiling against η candidates for both the $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$ modes. A fit to a gaussian ϕ signal plus a smooth background is superimposed.

Table 8: A tabulation of the $\psi_{2S} \to \phi\eta'$; $\eta' \to \rho\gamma$ selection cuts.

The number of events surviving each requirement

	data	Monte Carlo
Generated		1000
Preselection	374392	
$CL_{4c} > 0.05$	5624	173
$\|M_{\pi^+\pi^-} - M_\rho\| < 0.15$ GeV	1339	68
$\|M_{K^+K^-} - M_\phi\| < 0.03$ GeV	43	63
$\|M_{\pi^+\pi^-\gamma} - M_{\eta'}\| < 0.03$ GeV	0	60

Since there are consistent $\simeq 2\sigma$ signals in both the $M_{K^+K^-}$ and $M_{\gamma\gamma/\pi^+\pi^-\pi^0}$ distributions, I use the results to determine the the $\psi_{2S} \to \phi\eta$ branching fraction via the relation

$$\begin{aligned} \mathcal{B}(\psi_{2S} \to \phi\eta) &= \frac{N_{\phi\eta}^{evt}}{N_{\psi_{2S}}\mathcal{B}^{\phi}_{K^+K^-}[\mathcal{B}^{\eta}_{\gamma\gamma}acc_{\gamma\gamma} + \mathcal{B}^{\eta}_{\pi^+\pi^-\pi^0}\mathcal{B}^{\pi^0}_{\gamma\gamma}acc_{3\pi}]} \\ &= (3.5 \pm 1.9 \pm 0.7) \times 10^{-5}, \end{aligned} \tag{6}$$

where for $N_{\phi\eta}^{evt}$, I use the average of N_ϕ and N_η given above.

5.3 $\psi_{2S} \to \phi\eta'(958)$

Here I looked for the $\eta' \to \rho\gamma$ decay channel. The final state of interest is $\psi_{2S} \to K^+K^-\pi^+\pi^-\gamma$, where the γ is in the energy range $0 \sim 1$ GeV. I subject events with four charged tracks and at least 1 gamma to a 4-c fit select the gamma based on the best χ^2 value. For the ρ selection, I require the $\pi^+\pi^-$ pair to have an invariant mass that is within 0.15 GeV of M_ρ. For the ϕ selection, I require $M_{K^+K^-}$ to be within 30 MeV of M_ϕ. The results of the data selection are shown in Figs. 9a through 9d, which show the distributions of cut variables before the cut is applied. There are no surviving events consistent with $\psi_{2S} \to \phi\eta'$. The MC and data event yields after each of the cuts are tabulated in Table 8.

I determine a 90% confidence level upper limit on the $\psi_{2S} \to \phi\eta'$ branching fraction from the relation

$$\mathcal{B}(\psi_{2S} \to \phi\eta') < \frac{N_{\phi\eta'}^{Lim}}{N_{\psi_{2S}}\mathcal{B}^{\phi}_{K^+K^-}\mathcal{B}^{\eta'}_{\rho\gamma}acc_{\phi\rho\gamma}} = 7.5 \times 10^{-5}, \tag{7}$$

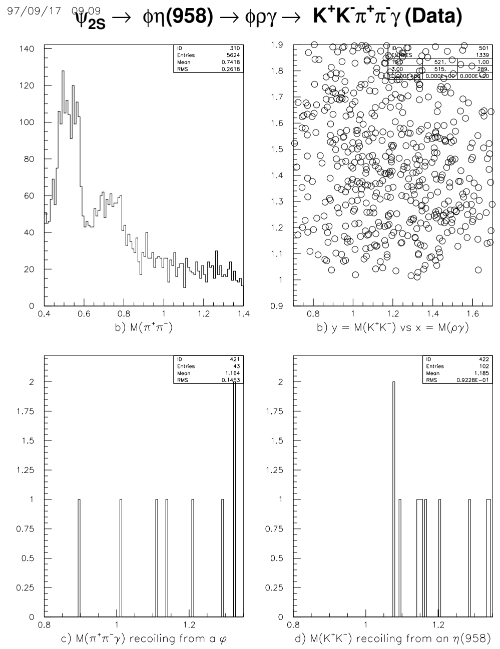

Figure 9: Distributions for events that satisfy a 4-c fit to the hypothesis $\psi_{2S} \to K^+K^-\pi^+\pi^-\gamma$ with a confidence level better than 5%: **a)** $M_{\pi^+\pi^-}$; **b)** $y = M_{K^+K^-}$ vs $x = M_{\pi^+\pi^-\gamma}$ where $M_{\pi^+\pi^-}$ is within 0.15 GeV of M_ρ; **c)** $M_{\rho\gamma}$ recoiling against a K^+K^- pair with invariant mass within 30 MeV of M_ϕ; **d)** $M_{K^+K^-}$ recoiling against a $\rho\gamma$ combination with an invariant mass within 30 MeV of $M_{\eta'}$.

where I used $N^{Lim}_{\phi\eta'} = 2.3$ and $acc_{\phi\rho\gamma} = 0.06$.

6 $\psi_{2S} \to \rho\,\eta,\ \rho\eta'$ decays

6.1 $\psi_{2S} \to \rho\eta$

For $\psi_{2S} \to \rho\eta$, I found considerable background for the $\eta \to \gamma\gamma$ decay channel so I concentrated on the $\eta \to \pi^+\pi^-\pi^0$ mode. The topology of interest is, thus, $2(\pi^+\pi^-)\pi^0$. I select events with four charged tracks and two or more candidate gammas. I select the two gamma combination that produces the best χ^2 value from a 4-c kinematic fit to the hypothesis $\psi_{2S} \to 2(\pi^+\pi^-)\gamma\gamma$. This combination is required to pass a 5-c fit with a confidence level of better than 5%, where the fifth constraint is $M_{\gamma\gamma} = M_{\pi^0}$. Cascade $\psi_{2S} \to \pi^+\pi^- J/\psi$ events are removed by eliminating events where the mass recoiling against any $\pi^+\pi^-$ pair is within 50 MeV of the J/ψ.

I used 1000 simulated $\psi_{2S} \to \rho\eta$; $\eta \to \pi^+\pi^-\pi^0$ events generated by the HOWL Monte Carlo simulator the develop final selection criteria:

$|M_{\pi_a^+\pi_b^-} - M_\rho| < 0.15$ GeV, and

$M_{\pi_c^+\pi_d^-} < 0.42$ GeV,

where $\pi_a^+\pi_b^-\pi_c^+\pi_d^-$ are any of the four combinations of the charged pions in the event. There are 89 surviving MC events that have $\pi^+\pi^-\pi^0$ combinations with an invariant mass peak at M_η, indicating an acceptance of $acc_{\rho\eta} = 0.09$.

Figures 10a through 10d show the distributions of the cut variables for the data. Here, as can be seen in Fig. 10c, there are no surviving events consistent with the $\psi_{2S} \to \rho\eta$ hypothesis. A summary of the cuts and the number of events that survive them is presented in Table 9

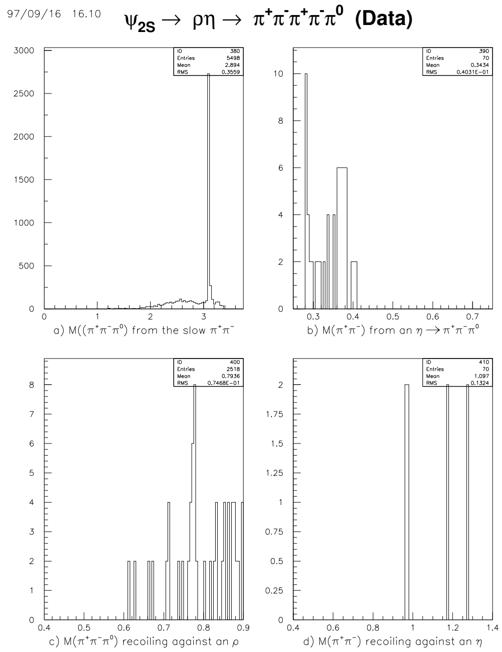

Figure 10: Distributions for events that satisfy a 5-c fit to the hypothesis $\psi_{2S} \to 2(\pi^+\pi^-)\pi^0$ with a confidence level better than 5%: **a)** $M_{\pi^+\pi^-\pi^0}$ recoiling against the slowest $\pi^+\pi^-$ pair; **b)** $M_{\pi^+\pi^-}$ from candidate $\eta \to \pi^+\pi^-\pi^0$ decays; **c)** $M_{\pi^+\pi^-\pi^0}$ recoiling against a $\pi^+\pi^-$ pair with an invariant mass within 0.15 GeV of M_ρ; **c)** $M_{\pi^+\pi^-}$ recoiling against a $\pi^+\pi^-\pi^0$ combination with an invariant mass within 30 MeV of M_η.

In the absence of any events I infer a 90% CL upper limit on the $\psi_{2S} \to \rho\eta$ branching fraction from the relation

$$\mathcal{B}(\psi_{2S} \to \rho\eta) < \frac{N_{\rho\eta}^{Lim}}{N_{\psi_{2S}} \mathcal{B}^{\eta}_{\pi^+\pi^-\pi^0} \mathcal{B}^{\pi^0}_{\gamma\gamma} acc_{\rho\eta}} = 3.2 \times 10^{-5}, \qquad (8)$$

where I used $N_{\rho\eta}^{Lim} = 2.3$.

Table 9: A tabulation of the $\psi_{2S} \to \rho\eta$ selection cuts.

The number of events surviving each requirement

	data	Monte Carlo
Generated		1000
Preselection	456341	242
$\chi^2_{4c} \leq 50$	49511	200
$CL_{5c} > 0.05$	4321	125
$\lvert M_{\pi^+\pi^-\pi^0} - M_{J/\psi}\rvert > 0.05$ GeV	1545	117
$\lvert M_{\pi_a^+\pi_b^-} - M_\rho\rvert < 0.15$ GeV		
$M_{\pi_c^+\pi_d^-} < 0.42$ GeV	1648	127
$\lvert M_{\pi_c^+\pi_d^-\pi^0} - M_\eta\rvert < 0.03$ GeV	0	89

6.2 $\psi_{2S} \to \rho\eta'(958)$

Here I looked for both the $\eta' \to \pi^+\pi^-\eta$ ($\mathcal{B}^{\eta'}_{\pi^+\pi^-\eta} = 0.437 \pm 0.015$) and $\eta' \to \rho\gamma$ ($\mathcal{B}^{\eta'}_{\rho\gamma} = 0.302 \pm 0.013$) decay modes.

6.2.1 $\psi_{2S} \to \rho\eta'(958)$ using the $\eta' \to \pi^+\pi^-\eta$ decay mode

I only use the $\eta \to \gamma\gamma$ decay channel and the analysis is essentially identical to the $\psi_{2S} \to \rho\eta$ measurement described above. The only exception is that the 5-c fit requires $M_{\gamma\gamma} = M_\eta$ and I look for an $\eta'(958)$ signal in the selected $\pi^+\pi^-\eta$ mass distribution. Monte Carlo studies indicate that the effects of the cuts and the acceptance are the same as for the $\rho\eta$ analysis. Distributions of some of the selection variables are shown in Figs. 11a through 11d. The MC and data event yield after each of the cuts is tabulated in Table 10. The two events that satisfy the $\psi_{2S} \to \rho\eta'$ criteria are consistent with background.

6.2.2 $\psi_{2S} \to \rho\eta'(958)$ using the $\eta' \to \rho\gamma$ decay mode

In the $\eta' \to \rho\gamma$ decay channel, the final states of interest is $\psi_{2S} \to 2(\pi^+\pi^-)\gamma$, where the γ is in the energy range $0 \sim 1$ GeV. Here there is considerable background from $\psi_{2S} \to \gamma\chi_{c0,1,2}$ with the subsequent decay $\chi_{c0,1,2} \to 2(\pi^+\pi^-)$. To eliminate this background I eliminate events where the $2(\pi^+\pi^-)$ mass is consistent with one of the three χ_c states, a cut that loses about 30% of the signal. In addition, I make tight ρ mass cuts:

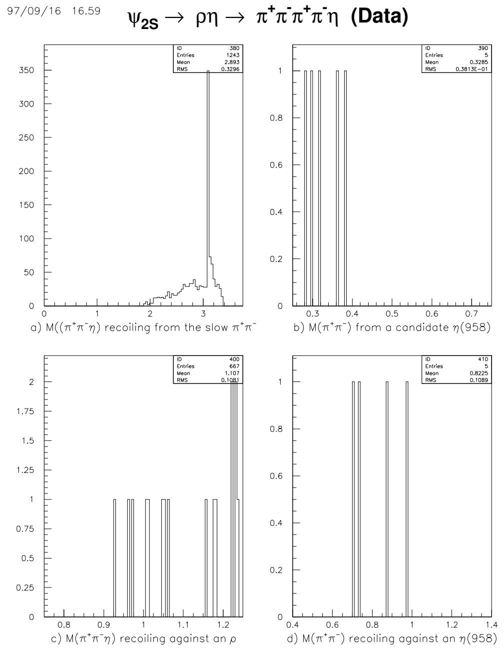

Figure 11: Distributions for events that pass a 5-c fit to the hypothesis $\psi_{2S} \to 2(\pi^+\pi^-)\eta;\ \eta\gamma\gamma$ with a confidence level better than 5%: **a)** $M_{\pi^+\pi^-\eta}$ recoiling from the slowest $\pi^+\pi^-$ pair; **b)** $M_{\pi^+\pi^-}$ for pions where $|M_{\pi^+\pi^-\eta} - M_{\eta'}| < 30$ MeV; **c)** $M_{\pi_c^+\pi_d^-\eta}$ for combinations where $M_{\pi_c^+\pi_d^-} < 0.42$ GeV and $|M_{\pi_a^+\pi_b^-} - M_\rho| < 0.15$ GeV. **d)** The $M_{\pi_a^+\pi_b^-}$ distribution for combinations where $M_{\pi_c^+\pi_d^-\eta}$ is within 30 MeV of $M_{\eta'}$.

$|M_{\pi^+\pi^-} - M_\rho| < 0.1$ GeV. The results are shown in Figs. 12a through 12d, which show the distributions of some of the cut variables before the cut is applied. The MC and data event yield after each of the cuts is tabulated in Table 11. The three events that satisfy the $\psi_{2S} \to \rho\eta'$ criteria are consistent with the background level.

6.2.3 The limit on the $\psi_{2S} \to \rho\eta'$ branching fraction

In Fig. 13, I show the sum of the $\pi^+\pi^-\eta$ mass distribution of Fig. 11e and the $\rho\gamma$ mass distribution of Fig. 12e. There is no obvious signal in the region of the $\eta'(958)$. Superimposed on the plot is the results of a fit using a gaussian with a mass constrained to be within ± 10 MeV of $M_{\eta'}$ and a width $\sigma = 12$ MeV that is consistent with MC expectations, plus a third-order polynomial background function. The fit gives 3.1 ± 3.0 η' events, which corresponds to a 90% CL upper limit of $N_{\rho\eta'}^{Lim} = 7$ events.

Table 10: A tabulation of the $\psi_{2S} \rightarrow \rho\eta'$: $\eta' \rightarrow \pi^+\pi^-\eta$ selection cuts.

The number of events surviving each requirement

	data	Monte Carlo
Generated		1000
Preselection	456341	321
$\chi^2_{4c} \leq 50$	49511	276
$CL_{5c} > 0.05$	1243	177
$\lvert M_{\pi^+\pi^-\pi^0} - M_{J/\psi}\rvert > 0.05$ GeV	562	117
$\lvert M_{\pi_a^+\pi_b^-} - M_\rho\rvert < 0.15$ GeV		
$M_{\pi_c^+\pi_d^-} < 0.42$ GeV	667	147
$\lvert M_{\pi_c^+\pi_d^-\pi^0} - M_{\eta'}\rvert < 0.03$ GeV	2	89

Table 11: A tabulation of the $\psi_{2S} \rightarrow \rho\eta'$; $\eta' \rightarrow \rho\gamma$ selection cuts.

The number of events surviving each requirement

	data	Monte Carlo
Generated		1000
Preselection	530147	344
$CL_{4c} > 0.05$	6081	201
$\lvert M_{\pi^+\pi^-\pi^0} - M_{J/\psi}\rvert > 0.05$ GeV	3629	196
$\lvert M_{4\pi} - M_{\chi_{c0}}\rvert > 0.035$ GeV		
$\lvert M_{4\pi} - M_{\chi_{c1}}\rvert > 0.025$ GeV		
$\lvert M_{4\pi} - M_{\chi_{c2}}\rvert > 0.025$ GeV	1555	135
$\lvert M_{\pi_a^+\pi_b^-} - M_\rho\rvert < 0.10$ GeV		
$\lvert M_{\pi_c^+\pi_d^-} - M_\rho\rvert < 0.10$ GeV	250	124
$\lvert M_{\pi_c^+\pi_d^-\pi^0} - M_{\eta'}\rvert < 0.03$ GeV	3	62

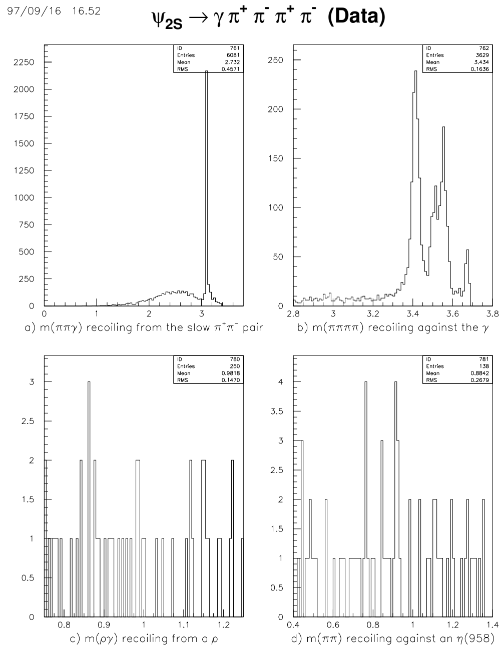

Figure 12: Distributions for events that pass a 4-c fit to the hypotheis $\psi_{2S} \to 2(\pi^+\pi^-)\gamma$ events with a confidence level better than 5%: **a)** $M_{\pi^+\pi^-\eta}$ recoiling from the slowest $\pi^+\pi^-$ pair; **b)** $M_{\pi^+\pi^-\pi^+\pi^-}$; **c)** $M_{\pi_c^+\pi_d^-\gamma}$ for combinations where $|M_{\pi_a^+\pi_b^-} - M_\rho| < 0.10$ GeV and $|M_{\pi_c^+\pi_d^-} - M_\rho| < 0.10$ GeV. **d)** The $M_{\pi_a^+\pi_b^-}$ distribution for combinations where $|M_{\pi_c^+\pi_d^-} - M_\rho| < 0.10$ GeV and $M_{\pi_c^+\pi_d^-\gamma}$ is within 30 MeV of $M_{\eta'}$.

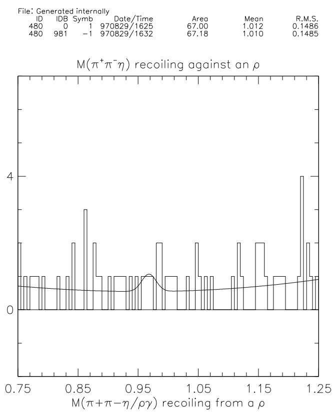

Figure 13: The sum of the $M_{\pi^+\pi^-\eta}$ and $M_{\rho\gamma}$ mass distributions (Fig. 11c and Fig. 12c) with a fit to a possible η' signal superimposed.

I infer a 90% CL upper limit on the $\psi_{2S} \to \rho\eta'$ branching fraction from the relation

$$\mathcal{B}(\psi_{2S} \to \rho\eta') \; < \; \frac{N^{Lim}_{\rho\eta'}}{N_{\psi_{2S}}[\mathcal{B}^{\eta'}_{\pi^+\pi^-\eta}\mathcal{B}^{\eta}_{\gamma\gamma}acc_{\pi\pi\eta} + \mathcal{B}^{\eta'}_{\gamma\rho}acc_{\gamma\rho}]} \; = \; 6.2 \times 10^{-5}. \qquad (9)$$

7 Discussion

The results of this analysis are tabulated in Table 12. Of the modes studied here, the clearest non-zero signal signal is that for the i-spin-violating $\psi_{2S} \to \omega\pi^0$ decay. My result for this branching fraction agrees well with that determined by Ye. This process, which is electromagnetic, has a branching fraction that is larger than the upper limit of the strong-interaction-allowed $\psi_{2S} \to \rho\pi$ decay. For some reason the strong-interaction-allowed $\psi_{2S} \to VP$ is suppressed below the level of electromagnetic contributions. Hadron-helicity conservation, to which the authors of ref. [3] attribute the suppression of $\psi_{2S} \to \rho\pi$, should also suppress the electromagnetic processes $\psi_{2S} \to \omega\pi^0$ [9].

Also of interest, but with only a $2 \sim 3\sigma$ statistical significance, is the relative strength of the $\psi_{2S} \to \omega\eta$ and $\omega\eta'$ decays. In the case of the J/ψ, the $\omega\eta$ channel has a branching fraction that is an order-of-magnitude larger than that for $\omega\eta'$, a result that has been attributed to the value of the η-η' mixing angle [10]. It appears that for ψ_{2S} decays the $\omega\eta'$ mode is the stronger, contrary to what is expected from η-η' mixing. The $\omega\eta$ channel is supressed relative to 14%-rule expectations, while the $\omega\eta'$ channel is not.

8 Conclusion

Something is suppressing the strong interaction $\psi_{2S} \to VP$ processes to at least the level of the electromagnetic processes. This suppression does not occur for J/ψ decays. The $\rho\pi$ puzzle is indeed a puzzle.

9 Acknowledgements

This research is supported by the U.S. Department of Energy research grant number DE-FG03-94ER40833. This work was aided by my colleagues in the Hawaii BES group.

Table 12: A tabulation of measurements from this analysis for $J/\psi \to$ and $\psi_{2S} \to$ lowest lying vector- plus pseudoscalar-mesons.

VP mode	$\mathcal{B}(\psi' \to VP)$ (10^{-4})	$\mathcal{B}(J\psi \to VP)$ (10^{-3})	$\mathcal{S}$ $(= \frac{0.14\mathcal{B}_{J/\psi}}{\mathcal{B}_{\psi'}})$
$\rho\pi$	< 0.28	12.8 ± 1.0	> 64
$K^{*+}K^-$	< 0.3	5.0 ± 0.4	> 23
$K^{*0}\bar{K}^0$	$0.81 \pm 0.24 \pm 0.16$	4.2 ± 0.4	7.3 ± 2.7
$\omega\pi^0$	$0.37 \pm 0.17 \pm 0.06$	0.42 ± 0.06	1.7 ± 0.8
$\omega\eta$	< 0.33	1.58 ± 0.16	> 7.0
$\omega\eta'$	$0.76 \pm 0.44 \pm 0.18$	0.167 ± 0.025	0.32 ± 0.2
$\phi\pi^0$	< 0.15	< 0.0068	
$\phi\eta$	$0.35 \pm 0.19 \pm 0.07$	0.65 ± 0.07	4.3 ± 2.5
$\phi\eta'$	< 0.75	0.33 ± 0.04	> 0.6
$\rho\eta$	< 0.32	0.193 ± 0.023	> 0.9
$\rho\eta'$	< 0.62	0.105 ± 0.023	> 0.2
$\gamma\pi^0$		0.039 ± 0.013	–
$\gamma\eta$	$0.5 \pm 0.3 \pm 0.1$	0.86 ± 0.08	2.5 ± 1.5
$\gamma\eta'$	$1.4 \pm 0.3 \pm 0.3$	4.31 ± 0.30	4.3 ± 1.3

References

[1] M.E.B. Franklin *et al.* (Mark II Collaboration), Phys. Rev. Lett. **51**, 963 (1983).

[2] W-S. Hou, and A. Soni, Phys. Rev. Lett. **50**, 569 (1983); S.S. Pinsky, Phys. Lett **B236**, 479 (1990); M. Anselimo *et al.* , Phys. Rev. **D50**, 595 (1994); W-S. Hou, Phys. Rev. **D55**, 6952 (1997); S.J. Brodsky and M. Karliner, Phys. Rev. **78**, 4682 (1997).

[3] S.J. Brodsky, G.P. LePage, and S.F. Tuan, Phys. Rev. Lett. **59**, 59 (1987).

[4] J.Z. Bai *et al.* (BES Collaboration), Phys. Rev. **D54**, 1221 (1996); J.Z. Bai *et al.* (BES Collaboration), *Search for* $\psi' \to$ *Vector + Pseudoscalar Decays*, paper submitted to the 1995 International Symposium on Lepton and Photon Interactions at High Energies, Beijing, China.

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

[6] S.W. Ye *Analysis memo of* $\psi(2S) \to \gamma\eta'(958)$, June 1997; S.L. Olsen, BES Analysis Memo: *Observation of* $\psi' \to \gamma\eta'(958)$, October 24, 1996 (revised November 26, 1996).

[7] S.W. Ye, private communication. The results for $\psi_{2S} \to \omega\pi^0$ and $\omega\eta$ were presented by Y.F. Gu at the 1997 BES Annual Meeting.

[8] J.Z. Bai *et al.* (BES Collaboration), *Branching fractions for* ψ_{2S} *decays to octet-baryon pairs*, paper submitted to the 1995 International Symposium on Lepton and Photon Interactions at High Energies, Beijing, China.

[9] S.F. Tuan, private communication.

[10] D. Coffman *et al.* (Mark III Collaboration), Phys. Rev. **D38**, 2695 (1988); A. Seiden, H.F-W. Sadrozinski, and H.E. Haber, Phys. Rev. **D38**, 824 (1988); A. Bramon, R. Escribano, and M.D. Scadron, Phys. Lett. **B403**, 339 (1997).