BRANCHING RATIOS OF $\psi(2S)$ AND $\chi_{c0,1,2}$

Updated May 2008 by J.J. Hernández-Rey (IFIC, Valencia), S. Navas (University of Granada), and C. Patrignani (INFN, Genova).

Since 2002, the treatment of the branching ratios of the $\psi(2S)$ and $\chi_{c0,1,2}$ has undergone an important restructuring.

When measuring a branching ratio experimentally, it is not always possible to normalize the number of events observed in the corresponding decay mode to the total number of particles produced. Therefore, the experimenters sometimes report the number of observed decays with respect to another decay mode of the same, or another particle in the relevant decay chain. This is actually equivalent to measuring combinations of branching fractions of several decay modes.

To extract the branching ratio of a given decay mode, the collaborations use some previously reported measurements of the required branching ratios. However, the values are frequently taken from the *Review of Particle Physics* (RPP), which in turn uses the branching ratio reported by the experiment in the following edition, giving rise either to correlations or to plain vicious circles.

One of these inconsistencies within the $\psi(2S)$ decays was reported in Ref. 10. To obtain the branching ratios of the decay modes $\psi(2S) \to J/\psi(1S)\,\pi^+\pi^-$, $\psi(2S) \to J/\psi(1S)\,\pi^0\pi^0$, and $\psi(2S) \to J/\psi(1S)\,\eta$, E760 Collaboration [2] used the value of $\mathrm{B}(\psi(2S) \to J/\psi(1S)\ \mathit{anything})$ given in Ref. 6, obtained with a fit that included the above decays. The values obtained in this way in Ref. 2 were subsequently used in the 1998 edition of RPP [7] as new entries in the same fit.

A more subtle correlation, among others, was pointed out in Ref. 5. The BES Collaboration [3] obtained the value of $B(\chi_{c0} \to p\overline{p})$ in e^+e^- collisions from the number of observed decays $\psi(2S) \to \gamma\,\chi_{c0} \to \gamma\,p\,\overline{p}$, and the total number of $\psi(2S)$ produced, which was estimated in turn from the observed number of decays of the type $\psi(2S) \to J/\psi(1S)\,\pi^+\pi^-$ [4]. To this end, they used the values of the branching ratios of $\psi(2S) \to J/\psi(1S)\,\pi^+\pi^-$ and $\psi(2S) \to \gamma\,\chi_{c0}$ given in the 1996 edition of RPP [6]. On the other hand, in $p\,\overline{p}$ collision experiments (*e.g.*, E835 Collaboration [1]) , the value of B($\psi(2S) \rightarrow \gamma\,\chi_{c0}$) was entered inversely in the determination of B($\chi_{c0} \rightarrow p\,\overline{p}$) from a measurement of $\Gamma(\chi_{c0} \rightarrow p\,\overline{p}) \times$ B($\chi_{c0} \rightarrow \gamma\,J/\psi(1S)$), since it was used to derive B($\chi_{c0} \rightarrow \gamma\,J/\psi(1S)$). Therefore, a hidden correlation was introduced in RPP when quoting the values of the corresponding unfolded magnitudes for both types of experiments.

The way to avoid these dependencies and correlations is to extract the branching ratios through a fit that uses the truly measured combinations of branching fractions and partial widths. This fit, in fact, should involve decays from the four concerned particles, $\psi(2S)$, χ_{c0}, χ_{c1}, and χ_{c2}, and occasionally some combinations of branching ratios of more than one of them. This is what is done since the 2002 edition [9].

The PDG policy is to quote the results of the collaborations in a manner as close as possible to what appears in their original publications. However, in order to avoid the problems mentioned above, we had in some cases to work out the values originally measured, using the number of events and detection efficiencies given by the collaborations, or rescaling back the published results. The information was sometimes spread over several articles, and some articles referred to papers still unpublished, which in turn contained the relevant numbers in footnotes.

Even though the experimental collaborations are entitled to extract whatever branching ratios they consider appropriate by using other published results, we would like to encourage them to also quote explicitly in their articles the actual quantities measured, so that they can be used directly in averages and fits of different experimental determinations.

To inform the reader how we computed some of the values used in this edition of RPP, we use footnotes to indicate the branching ratios actually given by the experiments, and the quantities they use to derive them from the true combination of branching ratios actually measured.

None of the branching ratios of the $\chi_{c0,1,2}$ are measured independently of the $\psi(2S)$ radiative decays. We tried to identify those branching ratios which can be correlated in a non-trivial way, and although we cannot preclude the existence of other cases, we are confident that the most relevant correlations have already been removed. Nevertheless, correlations in the errors of different quantities measured by the same experiment have not been taken into account.

FIT INFORMATION

This is an overall fit to 4 total widths, 1 partial width, 24 combinations of partial widths, 8 branching ratios, and 66 combinations of branching ratios. Of the latter, 44 involve decays of more than one particle.

The overall fit uses 190 measurements to determine 44 parameters and has a χ^2 of 268.6 for 146 degrees of freedom

The relatively high χ^2 of the fit, 1.9 per d.o.f., can be traced back to a few specific discrepancies in the data. No rescaling of errors has been applied.

	Mode	Value
1	$\Gamma(\chi_{c_0})$	10.2 ± 0.7 (MeV)
2	$\mathcal{B}(\chi_{c_0} \to J/\psi\gamma)$	$(128 \pm 11) \times 10^{-4}$
3	$\mathcal{B}(\chi_{c_0} \to p\bar{p})$	$(2.14 \pm 0.19) \times 10^{-4}$
4	$\mathcal{B}(\chi_{c_0} \to \gamma\gamma)$	$(2.35 \pm 0.23) \times 10^{-4}$
5	$\mathcal{B}(\chi_{c_0} \to \pi\,\pi)$	$(7.4 \pm 0.6) \times 10^{-3}$
6	$\mathcal{B}(\chi_{c_0} \to \eta\,\eta)$	$(2.4 \pm 0.4) \times 10^{-3}$
7	$\mathcal{B}(\chi_{c_0} \to K^+\,K^-)$	$(5.8 \pm 0.6) \times 10^{-3}$
8	$\mathcal{B}(\chi_{c_0} \to K^0_s\,K^0_s)$	$(2.82 \pm 0.28) \times 10^{-3}$
9	$\mathcal{B}(\chi_{c_0} \to 2(\pi^+\,\pi^-)\,)$	$(2.23 \pm 0.20) \times 10^{-2}$
10	$\mathcal{B}(\chi_{c_0} \to \rho^0\pi^+\,\pi^-)$	$(8.7 \pm 2.8) \times 10^{-3}$
11	$\mathcal{B}(\chi_{c_0} \to K^+\,K^-\pi^+\pi^-\,)$	$(18.0 \pm 1.6) \times 10^{-3}$
12	$\mathcal{B}(\chi_{c_0} \to K^{*0}K^+\pi^-)$	$(7.2 \pm 1.6 \times 10^{-3}$
13	$\mathcal{B}(\chi_{c_0} \to 2(K^+\,K^-)\,)$	$(2.82 \pm 0.30) \times 10^{-3}$
14	$\mathcal{B}(\chi_{c_0} \to \phi\,\phi)$	$(0.93 \pm 0.20) \times 10^{-3}$
15	$\Gamma(\chi_{c_1})$	0.89 ± 0.05 (MeV)
16	$\mathcal{B}(\chi_{c_1} \to \gamma J/\psi)$	0.361 ± 0.019
17	$\mathcal{B}(\chi_{c_1} \to p\bar{p})$	$(0.66 \pm 0.05) \times 10^{-4}$
18	$\mathcal{B}(\chi_{c_1} \to K^0\,K^+\,\pi^-)$	$(7.7 \pm 0.7) \times 10^{-3}$
19	$\mathcal{B}(\chi_{c_1} \to 2\,(K^+\,K^-)\,)$	$(0.58 \pm 0.12) \times 10^{-3}$
20	$\Gamma(\chi_{c_2})$	2.03 ± 0.12 (MeV)
21	$\mathcal{B}(\chi_{c_2} \to J/\psi\gamma)$	0.201 ± 0.010
22	$\mathcal{B}(\chi_{c_2} \to p\bar{p})$	$(0.67 \pm 0.05) \times 10^{-4}$
23	$\mathcal{B}(\chi_{c_2} \to \gamma\gamma)$	$(2.43 \pm 0.18) \times 10^{-4}$
24	$\mathcal{B}(\chi_{c_2} \to \pi\,\pi)$	$(2.18 \pm 0.25) \times 10^{-3}$
25	$\mathcal{B}(\chi_{c_2} \to K^+\,K^-)$	$(0.79 \pm 0.14) \times 10^{-3}$
26	$\mathcal{B}(\chi_{c_2} \to K^0_s\,K^0_s)$	$(0.65 \pm 0.08) \times 10^{-3}$
27	$\mathcal{B}(\chi_{c_2} \to 2(\pi^+\,\pi^-)\,)$	$(1.14 \pm 0.12) \times 10^{-2}$
28	$\mathcal{B}(\chi_{c_2} \to \rho^0\pi^+\pi^-)$	$(41 \pm 18) \times 10^{-4}$
29	$\mathcal{B}(\chi_{c_2} \to K^+K^-\pi^+\pi^-)$	$(9.4 \pm 1.1) \times 10^{-3}$
30	$\mathcal{B}(\chi_{c_2} \to K^{*0}K^+\pi^-)$	$(24 \pm 13) \times 10^{-4}$
31	$\mathcal{B}(\chi_{c_2} \to K^{*0}\bar{K}^{*0})$	$(2.6 \pm 0.5) \times 10^{-3}$
32	$\mathcal{B}(\chi_{c_2} \to 2(K^+\,K^-)\,)$	$(1.85 \pm 0.24) \times 10^{-3}$
33	$\mathcal{B}(\chi_{c_2} \to \phi\,\phi)$	$(1.54 \pm 0.30) \times 10^{-3}$

	Mode	Value
34	$\Gamma(\psi')$	(317 ± 10) eV
35	$\mathcal{B}(\psi' \to J/\psi\pi^+\pi^-)$	0.328 ± 0.005
36	$\mathcal{B}(\psi' \to J/\psi\pi^0\pi^0)$	0.1689 ± 0.0033
37	$\mathcal{B}(\psi' \to J/\psi\eta)$	$(3.17 \pm 0.07) \times 10^{-2}$
38	$\mathcal{B}(\psi' \to \chi_{c_0}\gamma)$	$(9.4 \pm 0.4) \times 10^{-2}$
39	$\mathcal{B}(\psi' \to \chi_{c_1}\gamma)$	$(8.8 \pm 0.4) \times 10^{-2}$
40	$\mathcal{B}(\psi' \to \chi_{c_2}\gamma)$	$(8.3 \pm 0.4) \times 10^{-2}$
41	$\mathcal{B}(\psi' \to e^+ e^-)$	$(75.5 \pm 1.7) \times 10^{-4}$
42	$\mathcal{B}(\psi' \to \mu^+ \mu^-)$	$(75 \pm 8) \times 10^{-4}$
43	$\mathcal{B}(\psi' \to \tau^+ \tau^-)$	$(30 \pm 4) \times 10^{-4}$
44	$\mathcal{B}(\psi' \to p\,\bar{p})$	$(2.61 \pm 0.10) \times 10^{-4}$

The following *off-diagonal* array elements are the correlation coefficients $< \delta x_i \delta x_j > / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the corresponding parameter x_i.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
2	−12													
3	8	−68												
4	−58	9	−5											
5	−5	23	−29	−13										
6	−3	21	−29	−2	12									
7	−4	7	−6	−21	17	5								
8	−6	5	−5	−30	17	5	18							
9	−7	5	−5	−41	20	5	22	27						
10	−2	1	−1	−11	6	2	6	8	28					
11	−6	6	−6	−32	19	6	20	24	30	8				
12	−3	2	−2	−17	8	2	9	11	14	4	33			
13	−4	7	−6	−16	16	5	15	16	19	5	18	7		
14	−2	3	−3	−10	8	3	8	9	10	3	10	4	7	
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	−1	2	0	2	1	2	0	1	0	1	0
17	0	0	0	1	−1	0	−1	−1	−1	0	−1	0	−1	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	−1	1	0	1	0	1	0	1	0	1	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	−1	1	0	1	1	1	0	1	0	1	0
25	0	0	0	0	1	0	1	0	1	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	−1	1	0	1	0	1	0	0	0	1	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	1	0	1	0	1	0	0	0	1	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	1	0	1	0	1	0	0	0	0	0

16	−11													
17	−59	−56												
18	−5	45	−25											
19	−2	20	−11	12										
20	0	−1	0	0	0									
21	0	2	−1	0	0	−36								
22	0	−1	0	0	0	−47	−34							
23	0	0	0	0	0	−43	−9	31						
24	0	1	−1	0	0	−16	35	−9	−12					
25	0	1	0	0	0	−11	22	−5	−9	11				
26	0	0	0	0	0	−16	27	−4	−19	14	10			
27	0	1	−1	0	0	−22	32	−2	−31	18	12	19		
28	0	0	0	0	0	−5	7	0	−8	4	3	5	23	
29	0	1	−1	0	0	−18	28	−3	−26	16	11	16	23	6
30	0	0	0	0	0	−4	6	−1	−6	4	2	4	5	1
31	0	0	0	0	0	−12	16	0	−20	9	6	11	16	4
32	0	1	0	0	0	−14	31	−8	−10	15	10	13	16	4
	15	16	17	18	19	20	21	22	23	24	25	26	27	28

1	0	1	−1	−1	−1	8	0	0	−1	0	0	0
2	0	−1	1	1	1	−23	0	0	1	0	0	0
3	0	1	−2	−2	−1	18	0	0	−1	0	0	0
4	0	4	−7	−4	−4	27	0	−1	−3	−1	0	−1
5	0	−8	14	9	7	−41	0	1	7	2	1	3
6	0	−1	2	1	1	−15	0	0	1	0	0	0
7	0	−7	12	8	6	−35	0	1	6	2	0	2
8	0	−4	7	4	3	−36	0	0	3	1	0	1
9	0	−7	12	8	6	−39	0	1	6	2	0	2
10	0	−2	3	2	2	−11	0	0	2	0	0	1
11	0	−4	7	4	3	−41	0	0	3	1	0	1
12	0	−2	3	2	1	−16	0	0	1	0	0	1
13	0	−4	8	5	4	−35	0	1	4	1	0	2
14	0	−1	1	1	1	−18	0	0	1	0	0	0
15	0	1	−1	−1	−1	0	11	0	−1	0	0	0
16	0	−10	14	11	9	1	−88	1	9	2	1	3
17	0	6	−8	−7	−5	0	48	−1	−5	−1	0	−2
18	0	−1	3	2	1	0	−51	0	1	0	0	1
19	0	−2	3	2	2	0	−22	0	2	0	0	1
20	−11	2	−3	−2	−2	0	0	34	−2	0	0	−1
21	18	−5	7	7	5	0	0	−85	5	1	0	1
22	−3	2	−2	−2	−2	0	0	26	−2	0	0	0
23	−13	2	−3	−2	−1	0	0	13	−1	0	0	−1
24	10	−5	10	6	5	0	0	−38	4	1	0	2
25	6	−3	6	4	3	0	0	−25	3	1	0	1
26	10	−1	2	1	1	0	0	−30	1	0	0	0
27	13	−4	7	4	3	0	0	−35	3	1	0	1
28	3	−1	2	1	1	0	0	−8	1	0	0	0
	33	34	35	36	37	38	39	40	41	42	43	44

30	23														
31	13	3													
32	14	3	8												
33	11	2	7	8											
34	−4	−1	−1	−2	0										
35	7	1	1	5	1	−56									
36	4	1	1	3	0	−49	63								
37	3	1	1	2	0	−34	49	41							
38	0	0	0	0	0	−2	4	3	2						
39	0	0	0	0	0	−1	2	2	1	0					
40	−30	−7	−17	−35	−21	−4	7	5	4	0	0				
41	3	1	1	2	0	−76	47	42	29	2	1	4			
42	1	0	0	1	0	−8	14	9	7	1	0	1	7		
43	0	0	0	0	0	−2	4	2	2	0	0	0	2	1	
44	1	0	0	1	0	−17	20	13	10	1	0	1	8	3	1
	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43

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