QUARKONIUM SPECTROSCOPY FROM CLEO-c DATA

by the

Northwestern University Group

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PREAMBLE

- I have explain the title of my talk. The title is:
  "Quarkonium Spectroscopy from CLEO-c data"
  This is a somewhat peculiar title for the following reason.
- As a formal collaboration CLEO ended exactly a year ago, four years after the end of data taking.
- However, as is true of many experiments, a large quantity of valuable CLEO data remained unanalyzed. It was decided that individual past CLEO groups may continue analyzing and publishing CLEO data under their own authorship and responsibility. The Northwestern group has been doing that with many interesting results.
- Hence this title, with which I want to report a few of the recent interesting results that the Northwestern group has obtained relating to **heavy quarkonium**, which is the defined domain of QWG.
- I will not talk about some very interesting form factor results for **pions**, **kaons**, and **protons**, because they unfortunately contain light quarks.

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CLEO-c

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4. Width Measurement of D^{*0}
5. **STOP PRESS:** Confirmation of Charged State $Z_c(3900)$

Non CLEO-c Results

- The title given to me in the invitation said CLEO-c, but in parentheses it mentioned $\eta_b(2S)$ and $\Upsilon(nS)$ decays, two recent publications of ours which are based on older non-CLEO-c data. So let me describe them first. They are

1. "Observation of $\eta_b(2S)$ Meson in $\Upsilon(2S) \to \gamma\eta_b(2S)$, $\eta_b(2S) \to$ Hadrons and Confirmation of the $\eta_b(1S)$ Meson."
   Phys. Rev. Lett. 109, 082001 (2012)

2. "First Measurements of Exclusive Hadronic Decays of $\Upsilon(1S)$ and $\Upsilon(2S)$"
   Phys. Rev. D 86, 052003 (2012)

Observation of η_b (2S)

S. Dobbs et al., Phys. Rev. Lett. 109, 082001 (2012)

- The ground state of the $|b\,\bar{b}>$ bottomonium family, η_b(1S), was first identified by BaBar in 2008 in the M1 radiative decay, by observing the 920 MeV photon in the reaction $\Upsilon(3S) \rightarrow \gamma\, \eta_b$ (1S), and was confirmed by CLEO in 2010 in the same reaction. These led to

  $$\Delta\, M_{hf}(1S) = M(\Upsilon(1S)) – M(\eta_b(nS)) = 69.3 \pm 2.8 \text{ MeV}$$

  It is well known that the M1 radiative transitions, like $\Upsilon(nS) \rightarrow \gamma\, \eta_b(n'S)$, between states of different principle quantum numbers are difficult to understand theoretically. In contrast, $\Upsilon(nS) \rightarrow \gamma\, \eta_b(nS)$ transitions are well understood, although difficult to observe because they are weak (by E_γ^3) and it is difficult to identify the low energy radiative photons.

- So, even before the discovery of η_b (1S) by BaBar, we were already deeply involved in analyzing CLEO data for $\Upsilon(1S,2S) \rightarrow \gamma\, \eta_b(1S,2S)$ by tagging the low energy (30 – 80 MeV) photons by exclusive hadronic decays of η_b(1S,2S) . It is the results of these analyses which we finally published in 2012.

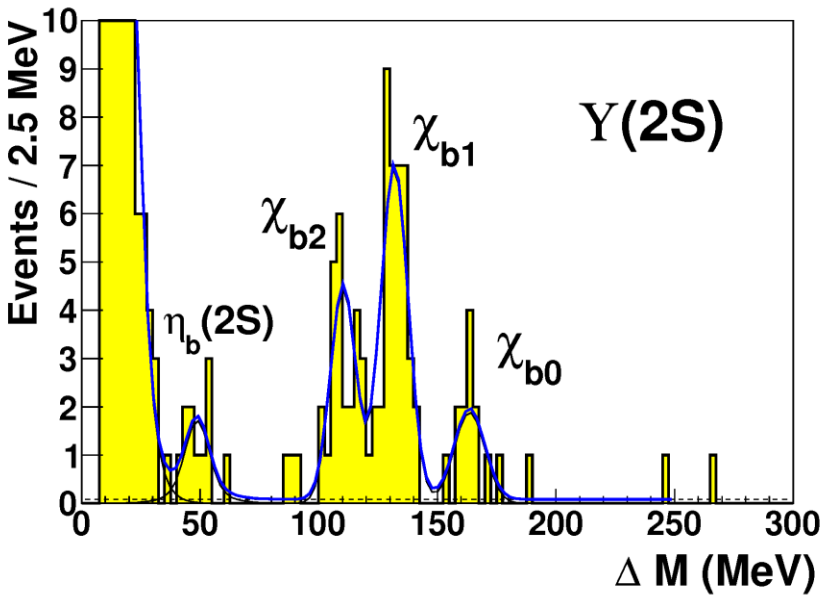
We measured the reactions

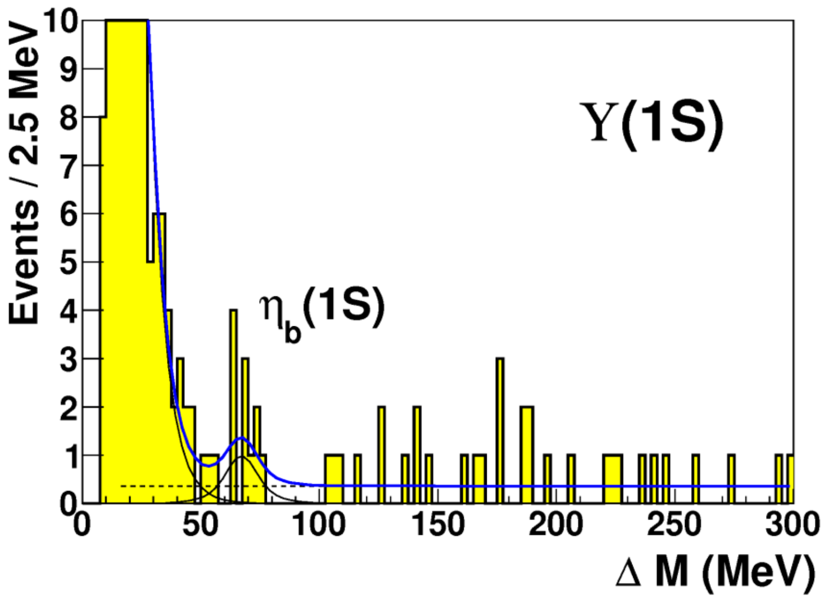
$\Upsilon(1S) \rightarrow \gamma\, \eta_b(1S)$ for 20.8 million $\Upsilon(1S)$, and

$\Upsilon(2S) \rightarrow \gamma\, \eta_b(2S)$ for 9.3 million $\Upsilon(2S)$

and tagged $\eta_b(1S,2S)$ into 26 different decay modes each, into charged hadrons, consisting of $\pi^{\pm}$, $K^{\pm}$, K_S and $p\bar{p}$. The resulting distributions of

$\Delta M = M(\Upsilon(2S,1S) - M(\text{hadrons}))$ are:





Notice the small peaks at $\Delta M \sim 50$ MeV and ~ 70 MeV.

- The low energy peaks (E_γ < 100 MeV) correspond to

  $\Upsilon(2S)$: $\Delta M_{hf}(2S) = 48.7 \pm 3.4$ MeV, (with $11.4^{+4.3}_{-5.5}$ cts, sig. = 4.9 σ)
  $\Upsilon(1S)$: $\Delta M_{hf}(1S) = 67.1 \pm 4.1$ MeV, (with $10.3^{+4.9}_{-4.1}$ cts, sig. = 3.1 σ)

  We satisfied ourselves (and the PRL) that the enhancements were real, that $\Delta M_{hf}(1S)$ agreed with the older BaBar and CLEO results, and published as the first observation of η_b (2S).

- Now a postscript: When we made our measurements the only known way to populate η_b (nS) was by M1 radiative transitions from Υ(nS, n'S). When Belle discovered h_b(1S,2S) a new way opened up by E1 radiative transitions, $h_b(1S,2S) \rightarrow \gamma\, \eta_b(1S,2S)$.
  The Belle result for $M(\eta_b(2S))$ leads to $\Delta M_{hf}(2S) = 24.3^{+4.0}_{-4.5}$ MeV, with $(26 \pm 5) \times 10^3$ counts, a result quite different from ours, and probably right.

- Which leaves open the question: What are the enhancements we observed? CP-odd Higgs?

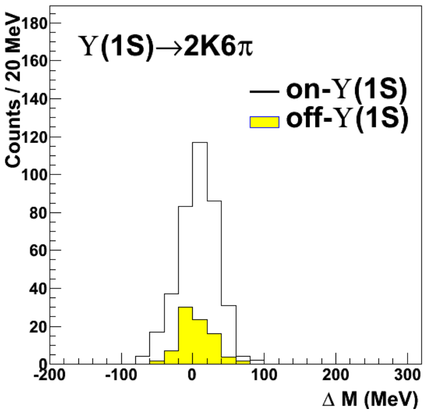
Exclusive Hadronic Decays of Υ(1S,2S)

S. Dobbs et al., Phys. Rev. D 86, 052003 (2012)

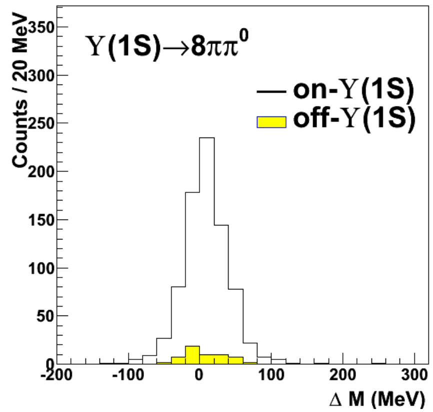
- If you look at PDG 2012, you will find that while J/ψ and $\psi(2S)$ have 97 and 70 exclusive hadronic decays measured, not even a single hadronic decay of Υ(1S,2S) has been measured.

- Since we had developed analysis methods to study a large number of hadronic decays for $\eta_b(1S,2S) \rightarrow$ hadrons, it was natural for us to extend the analysis to $\Upsilon(1S,2S) \rightarrow$ hadrons.

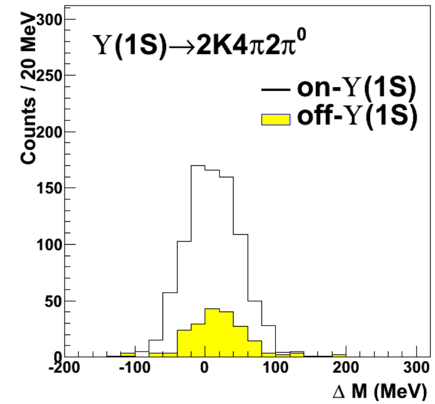
- We analyzed CLEO data for 21.5 million Υ(1S) (1.09 fb^{-1}), and 9.3 million Υ(2S) (1.28 fb^{-1}) for resonance decays, and 0.20 fb^{-1} of data off-Υ(1S) and 0.43 fb^{-1} of data off-Υ(2S) for evaluating continuum backgrounds.
  We measured decays containing 4–10 hadrons, π, K, p, including 0, 1, 2 π^0's. For both Υ(1S) and Υ(2S), one hundred different decays were measured. A few decays are illustrated in the following.



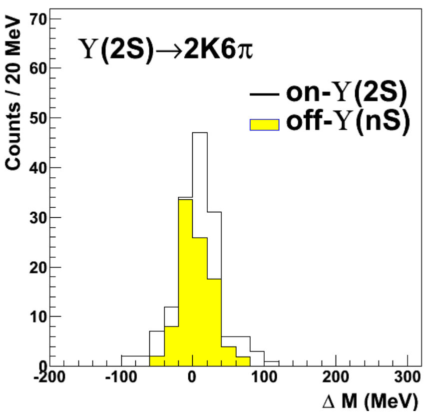
B = (14 ± 2) x 10^{-5}



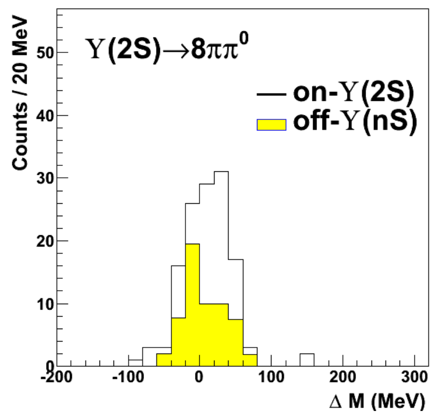
B = (55 ± 9) x 10^{-5}



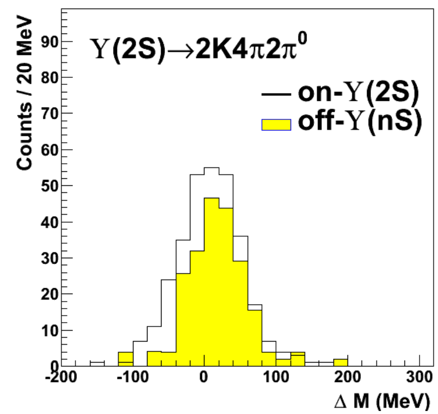
B = (62 ± 11) x 10^{-5}



B = (6 ± 2) x 10^{-5}



B = (12 ± 3) x 10^{-5}



B = (19 ± 4) x 10^{-5}

Y(1S): 73 decays ≥ 3σ, 27 decays – 90% confidence UL

Y(2S): 17 decays ≥ 3σ, 83 decays – 90% confidence UL

To overwhelm you with the results, let me flash a typical table.

TABLE I. Branching fractions for $\Upsilon(1S) \to$ only charged hadrons. $N(1S)_{res} \equiv N(1S)_{on} - N(1S)_{off} \times \mathcal{R}(1S)$, where $\mathcal{R}(1S) = \mathcal{L}_{on}(1S)/\mathcal{L}_{off} = 1.73$, and $\epsilon(1S)$ are the MC-calculated efficiencies. Upper limits (UL) at 90% confidence level are also given for modes with branching fractions that have a significance of $<2\sigma$. The modes marked with asterisks are used to construct the $\Upsilon(1S)/\Upsilon(2S)$ ratio.

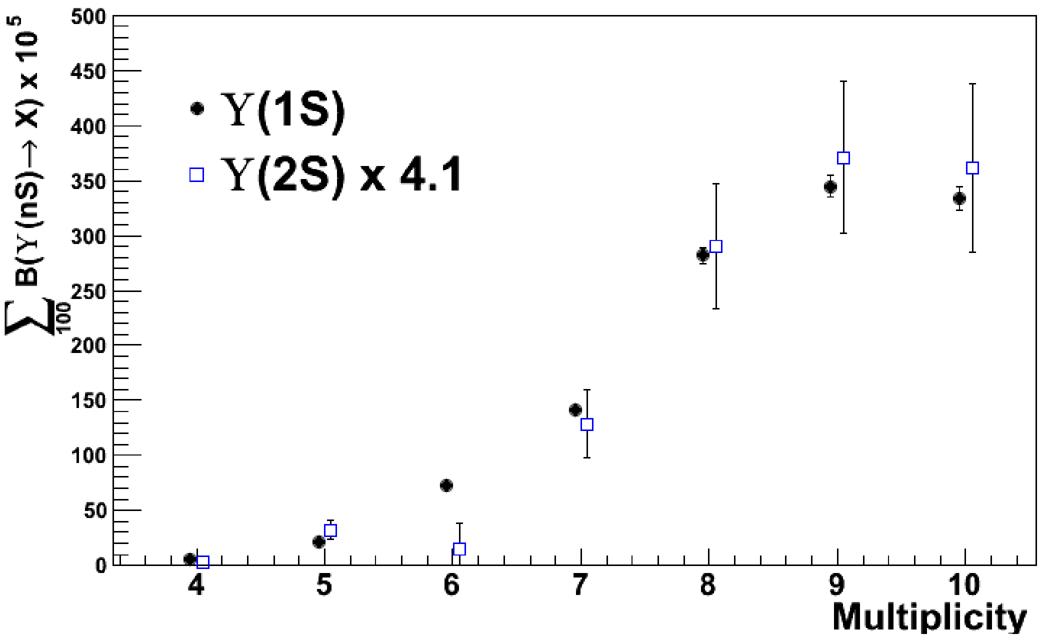
#	Modes	$N(1S)_{on}$	$N(1S)_{off} \times \mathcal{R}(1S)$	$N(1S)_{res}$	$\epsilon(1S)(\%)$	$\mathcal{B}(1S) \times 10^5$	UL $\times 10^5$
1	4π	168 ± 13	92.7 ± 12.7	75.3 ± 18.1	31.56	$1.11 \pm 0.27 \pm 0.13$	···
2	6π	400 ± 20	183.8 ± 17.9	216.2 ± 26.8	19.40	$5.18 \pm 0.64 \pm 0.69$	···
3	8π	377 ± 19	161.5 ± 16.7	215.5 ± 25.6	11.46	$8.74 \pm 1.04 \pm 1.33$	···
4	10π	131 ± 11	48.5 ± 9.2	82.5 ± 14.7	6.19	$6.20 \pm 1.10 \pm 1.08$	···
5	$2K2\pi$	116 ± 11	36.2 ± 7.9	79.8 ± 13.4	26.92	$1.38 \pm 0.23 \pm 0.17$	···
6	$2K4\pi$	414 ± 20	127.8 ± 14.9	286.2 ± 25.2	17.20	$7.74 \pm 0.68 \pm 1.10$	···
*7	$2K6\pi$	381 ± 20	84.0 ± 12.1	297.0 ± 22.9	9.91	$13.93 \pm 1.08 \pm 2.28$	···
8	$2K8\pi$	179 ± 13	31.9 ± 7.4	147.1 ± 15.3	5.14	$13.30 \pm 1.38 \pm 2.48$	···
9	$4K$	36 ± 6	9.4 ± 4.2	26.6 ± 7.3	23.07	$0.54 \pm 0.15 \pm 0.07$	···
10	$4K2\pi$	112 ± 11	33.9 ± 7.7	78.1 ± 13.1	15.01	$2.42 \pm 0.40 \pm 0.37$	···
11	$4K4\pi$	133 ± 12	28.2 ± 7.0	104.8 ± 13.5	8.25	$5.91 \pm 0.76 \pm 1.04$	···
12	$4K6\pi$	59 ± 8	8.7 ± 4.8	50.3 ± 9.1	3.93	$5.94 \pm 1.07 \pm 1.19$	···
13	$6K$	5 ± 3	4.5 ± 2.8	0.5 ± 4.0	13.05	$0.02 \pm 0.14 \pm 0.01$	<0.23
14	$6K2\pi$	13 ± 4	1.7 ± 1.7	11.3 ± 4.0	6.64	$0.79 \pm 0.28 \pm 0.15$	···
15	$6K4\pi$	6 ± 3	1.7 ± 1.7	4.3 ± 3.5	3.03	$0.65 \pm 0.54 \pm 0.14$	<1.90
16	$8K$	1 ± 2	0	1.0 ± 2.8	5.17	$0.09 \pm 0.25 \pm 0.02$	<0.49
17	$8K2\pi$	0	0	···	2.18	···	<0.68
18	$10K$	0	0	···	1.42	···	<1.06
19	$K_SK\pi$	9 ± 4	3.5 ± 3.9	5.5 ± 5.4	18.49	$0.14 \pm 0.14 \pm 0.02$	<0.34
20	$K_SK3\pi$	145 ± 12	41.2 ± 8.5	103.8 ± 14.7	12.36	$3.90 \pm 0.55 \pm 0.53$	···
21	$K_SK5\pi$	231 ± 15	50.5 ± 9.4	180.5 ± 17.8	6.67	$12.58 \pm 1.24 \pm 1.89$	···
22	$K_SK7\pi$	142 ± 12	21.2 ± 6.1	120.8 ± 13.4	3.35	$16.77 \pm 1.86 \pm 3.00$	···
23	$K_S3K\pi$	43 ± 7	9.0 ± 4.5	34.0 ± 8.0	10.97	$1.44 \pm 0.34 \pm 0.21$	···
24	$K_S3K3\pi$	121 ± 11	22.9 ± 6.3	98.1 ± 12.7	5.77	$7.90 \pm 1.02 \pm 1.27$	···
25	$K_S3K5\pi$	71 ± 8	14.1 ± 5.6	56.9 ± 10.1	2.66	$9.94 \pm 1.76 \pm 1.89$	···
26	$K_S5K\pi$	7 ± 3	0	7.0 ± 3.9	4.56	$0.71 \pm 0.40 \pm 0.12$	<1.54
27	$K_S5K3\pi$	13 ± 4	0	13.0 ± 4.2	2.07	$2.92 \pm 0.94 \pm 0.59$	···
28	$K_S7K\pi$	0	0	···	1.44	···	<1.00
29	$2p2\pi$	44 ± 7	14.8 ± 4.8	29.2 ± 8.2	31.49	$0.43 \pm 0.12 \pm 0.05$	···
30	$2p4\pi$	156 ± 12	41.8 ± 8.5	114.2 ± 15.1	19.27	$2.76 \pm 0.36 \pm 0.39$	···
31	$2p6\pi$	212 ± 15	43.7 ± 8.7	168.3 ± 17.0	11.49	$6.81 \pm 0.69 \pm 1.11$	···
*32	$2p8\pi$	109 ± 10	7.2 ± 4.5	101.8 ± 11.4	6.15	$7.69 \pm 0.86 \pm 1.44$	···
33	$2p2K2\pi$	89 ± 9	16.3 ± 5.9	72.7 ± 11.1	17.13	$1.97 \pm 0.30 \pm 0.31$	···
34	$2p2K4\pi$	129 ± 11	12.5 ± 5.3	116.5 ± 12.5	9.50	$5.70 \pm 0.61 \pm 1.01$	···
35	$2p2K6\pi$	66 ± 8	5.4 ± 3.8	60.6 ± 9.0	4.81	$5.86 \pm 0.87 \pm 1.17$	···
36	$2p4K$	2 ± 2	1.7 ± 3.0	0.3 ± 3.8	15.01	$0.01 \pm 0.12 \pm 0.01$	<0.15
37	$2p4K2\pi$	13 ± 4	1.8 ± 3.0	11.2 ± 4.7	7.82	$0.66 \pm 0.28 \pm 0.13$	···
38	$2p4K4\pi$	10 ± 3	0	10.0 ± 3.8	3.59	$1.29 \pm 0.49 \pm 0.28$	···
39	$2p6K$	0	0	···	6.03	···	<0.24
40	$2p6K2\pi$	0	0	···	2.96	···	<0.50
41	$2p8K$	0	0	···	1.54	···	<0.98
42	$4p2\pi$	13 ± 4	0	13.0 ± 4.2	19.70	$0.31 \pm 0.10 \pm 0.04$	···
43	$4p4\pi$	14 ± 4	0	14.0 ± 4.3	11.64	$0.56 \pm 0.17 \pm 0.10$	···
44	$4p6\pi$	5 ± 3	0	5.0 ± 3.5	6.05	$0.38 \pm 0.27 \pm 0.08$	<0.96
Sum						164.68 ± 4.96	

A Few Interesting Results, Υ(1S,2S)→hadrons

Agreement of branching fractions for decays containing multiple pions with isospin-based predictions of Pais (1960).

$\frac{\mathcal{B}((n\text{–}2)\pi^\pm 2\pi^0+X)}{\mathcal{B}(n\pi^\pm+X)}$	$\Upsilon(1S)$	Pais [3]
$K_S K^\mp \pi^\pm 2\pi^0$ / $3\pi^\pm$	0.52 ± 0.17	0.7
$K_S 3K^\mp \pi^\pm 2\pi^0$ / $3\pi^\pm$	0.70 ± 0.18	0.7
$K_S K^\mp 3\pi^\pm 2\pi^0$ / $5\pi^\pm$	2.25 ± 0.31	2.2
$K_S 3K^\mp 3\pi^\pm 2\pi^0$ / $5\pi^\pm$	2.95 ± 0.65	2.2
$2K^\pm 2\pi^\pm 2\pi^0$ / $4\pi^\pm$	1.21 ± 0.17	1.3
$4K^\pm 2\pi^\pm 2\pi^0$ / $4\pi^\pm$	2.16 ± 0.39	1.3
$6K^\pm 2\pi^\pm 2\pi^0$ / $4\pi^\pm$	4.85 ± 4.63	1.3
$p\bar{p} 2\pi^\pm 2\pi^0$ / $4\pi^\pm$	1.50 ± 0.30	1.3
$p\bar{p} 2K^\pm 2\pi^\pm 2\pi^0$ / $4\pi^\pm$	1.19 ± 0.23	1.3
$4\pi^\pm 2\pi^0$ / $6\pi^\pm$	3.48 ± 0.53	3.3
$2K^\pm 4\pi^\pm 2\pi^0$ / $6\pi^\pm$	4.43 ± 0.41	3.3
$4K^\pm 4\pi^\pm 2\pi^0$ / $6\pi^\pm$	4.56 ± 0.97	3.3
$p\bar{p} 4\pi^\pm 2\pi^0$ / $6\pi^\pm$	3.33 ± 0.42	3.3
$p\bar{p} 2K^\pm 4\pi^\pm 2\pi^0$ / $6\pi^\pm$	3.86 ± 0.71	3.3
$K_S K^\mp 5\pi^\pm 2\pi^0$ / $7\pi^\pm$	6.05 ± 0.79	4.7
$6\pi^\pm 2\pi^0$ / $8\pi^\pm$	7.38 ± 0.99	6.3
$2K^\pm 6\pi^\pm 2\pi^0$ / $8\pi^\pm$	8.23 ± 0.96	6.3
$p\bar{p} 6\pi^\pm 2\pi^0$ / $8\pi^\pm$	6.44 ± 0.84	6.3

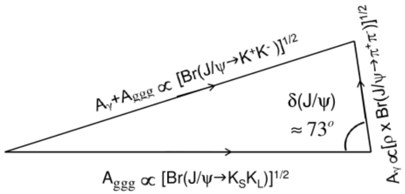
Sums of branching fractions for different multiplicities of hadrons in the exclusive decays of Υ(1S) and Υ(2S)



CLEO-c Results from Northwestern

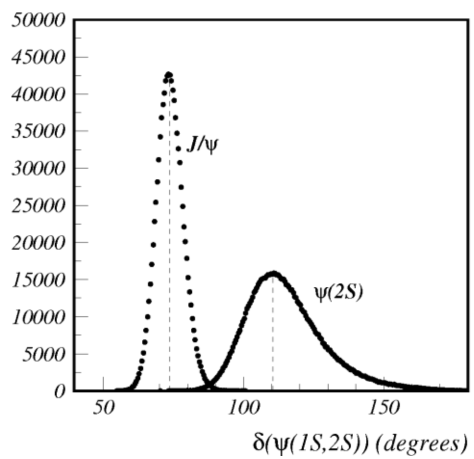
1. Interference Between Electromagnetic and Strong Amplitudes in ψ(2S), and J/ ψ decays to Pseudoscalar Pairs.

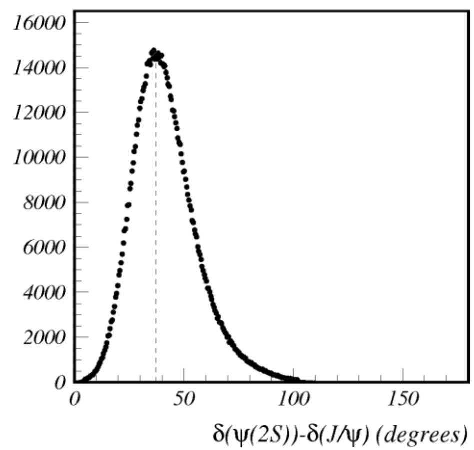
Z. Metreveli et al., Phys. Rev. D 85, 092007 (2012).



	DASP [13] 1979	BES [6,7] 2004	CLEO [8] 2005	This analysis	This analysis MC result
$\mathcal{B}(\psi(2S) \to \pi^+\pi^-) \times 10^6$	80 ± 50	8.4 ± 6.5	8 ± 8	**7.6 ± 2.6**	...
$\mathcal{B}(\psi(2S) \to K^+K^-) \times 10^6$	100 ± 70	61 ± 21	63 ± 7	**74.8 ± 4.5**	...
$\mathcal{B}(\psi(2S) \to K_SK_L) \times 10^6$	...	52.4 ± 6.7	58.0 ± 9.0	**52.8 ± 4.2**	...
$\delta(\psi(2S))$	...	$(91 \pm 35)^\circ$	$(87 \pm 20)^\circ$	$(\mathbf{113.4 \pm 11.5})^\circ$	$(\mathbf{110.5}^{+16.0}_{-9.5})^\circ$

	Mark III [10]	BES [16]	This analysis	This analysis MC result
$\mathcal{B}(J/\psi \to \pi^+\pi^-) \times 10^4$	1.58 ± 0.25	...	**1.47 ± 0.18**	...
$\mathcal{B}(J/\psi \to K^+K^-) \times 10^4$	2.39 ± 0.33	...	**2.86 ± 0.21**	...
$\mathcal{B}(J/\psi \to K_SK_L) \times 10^4$	1.01 ± 0.18	1.82 ± 0.13	**2.62 ± 0.21**	...
$\delta(J/\psi)$	$(88 \pm 11)^\circ$	...	$(\mathbf{73.6 \pm 5.6})^\circ$	$(\mathbf{73.5}^{+5.0}_{-4.5})^\circ$





$$\delta(J/\psi) = (73.5^{+5.0}_{-4.5})^\circ$$

$$\delta(\psi(2S)) = (110.5^{+16.0}_{-9.5})^\circ$$

$$\Delta\delta = \delta(\psi(2S)) - \delta(J/\psi) = (37.0^{+16.5}_{-10.5})^\circ$$

∴ ψ(2S) is not just a simple radial excitation of ψ(1S)

New BES results from BES III (Abstract #61)

CLEO-c Results from Northwestern

2. Our three latest results relate to the mysterious exotic hadron X(3872), and a few other exotics.

   2(a) Search for Radiative Production of the "exotic" mesons X(3872,3915,3930,3940) from $\psi(4160)$

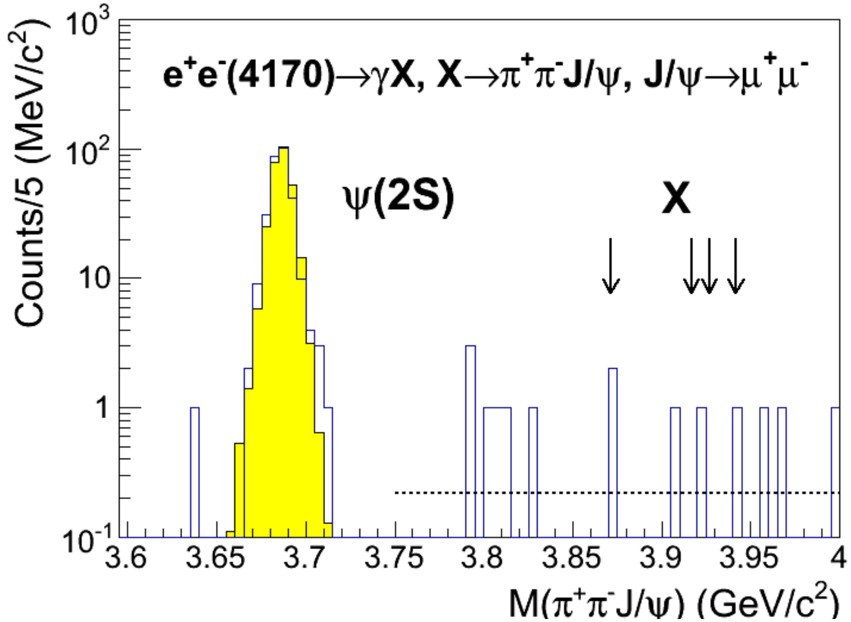
T. Xiao et al., Phys. Rev. D 87, 057501(2013).

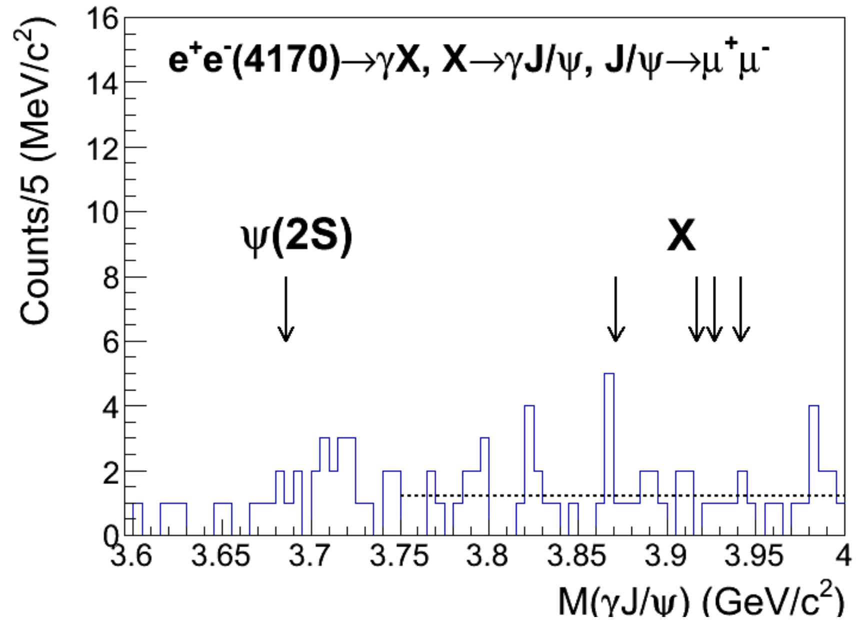
The "exotic" mesons X(3872), X(3915), X(3930) and X(3940), were searched for in their radiative production in the 586 pb^{-1} e^+e^- annihilation data taken with the CLEO-c detector at the $\psi(4160)$ resonance, and their decay in the two modes,

$$\mathbf{X \to \pi^+\pi^- J/\psi, \qquad X \to \gamma J/\psi, \qquad J/\psi \to \mu^+\mu^-.}$$

No evidence for any of the four mesons is found. The limits at 90% confidence level range from

$$B_1(\psi(4160) \to \gamma\, X) \times B_2(X \to \pi^+\pi^-\, J/\psi,\, \gamma J/\psi) = 0.7 \times 10^{-4} \text{ to } 1.8 \times 10^{-4}$$





State	M (MeV/c^2)	Γ_{BW} (MeV/c^2)	Γ_{exp} (MeV/c^2) $\pi^+\pi^-J/\psi$	Γ_{exp} (MeV/c^2) $\gamma J/\psi$	Signal region (MeV/c^2) $\pi^+\pi^-J/\psi$	Signal region (MeV/c^2) $\gamma J/\psi$
$X(3872)$	3871.68 ± 0.17	<1.2	13.4	16.7	3872 ± 13	3872 ± 17
$X(3915)$	3917.5 ± 2.7	27 ± 10	39.2	42.5	3918 ± 39	3918 ± 43
$X(3930)$	3927.2 ± 2.6	24 ± 6	36.2	39.5	3927 ± 36	3927 ± 40
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	49.2	52.5	3942 ± 49	3942 ± 53

Channel	State	$\epsilon(\%)$	Signal region (MeV/c^2)	N_{obs}	N_{bkg}	N_{UL}	$\mathcal{B}_1 \times \mathcal{B}_2 \times 10^4$
$\pi^+\pi^-J/\psi$	$X(3872)$	24.6	3872 ± 13	2	1.1	<4.8	<0.68
	$X(3915)$	20.0	3918 ± 39	3	3.3	<4.1	<1.36
	$X(3930)$	18.0	3927 ± 36	4	3.3	<5.3	<1.18
	$X(3940)$	16.9	3942 ± 49	5	4.2	<5.8	<1.47
$\gamma J/\psi$	$X(3872)$	29.9	3872 ± 17	11	8.5	<9.3	<1.05
	$X(3915)$	30.4	3918 ± 43	20	20.7	<7.8	<1.26
	$X(3930)$	30.1	3927 ± 40	18	18.3	<7.9	<0.88
	$X(3940)$	29.7	3942 ± 53	28	25.6	<12.4	<1.79

CLEO-c Results from Northwestern

2(b) "High Precision Determine of the D0 Mass and the Binding Energy of X(3872) as a D^0D^{*0} Molecule."

(Preliminary, to be published in Phys. Rev. D)

In 2007, the CLEO Collaboration published (C. Cawlfield et al. PRL 98, 092002 (2007)) a precise determination of the mass of the D^0 meson by analyzing 280 pb^{-1} of CLEO-c data taken at $\psi(3770)$ for the decay $D^0 \to K_S\, \phi$, $\phi \to K^+ K^-$. The result, $M(D^0) = 1864.847 \pm 0.178$ MeV led to an uncertainty of $\pm$ 363 keV in the mass of $(M(D^0) + M(D^{*0}))$. At that time M(X(3872)) was known with an uncertainty of $\pm$ 500 keV. This lead to

$$BE(X(3872)) = M(D^0 + D^{*0}) - M(X(3872)) = 600 \pm 600 \text{ keV, or } < 1356 \text{ keV (90\% CL)}$$

Since then several higher precision measurements of the mass of X(3872) have been made, and the present average, M(X(3872))=3871.68 $\pm$ 0.17 MeV, has uncertainty at the level of $\pm$ 170 keV. It has therefore become necessary to improve the $M(D^0)$ measurement. We have done so with the object of improving the precision of D^0 mass measurement by a factor of 3 or 4, i.e., to ~ $\pm$ 50 keV.

- In our old analysis, we analyzed 280 pb^{-1} data taken at $\psi(3770)$. In the present analysis we have analyzed 818 pb^{-1} of $\psi(3770)$ data.

- Previously we analyzed the decay

  $\psi(3770) \to D^0 \bar{D}^0$, $D^0 \to K_S \phi$, with BF = $(0.20 \pm 0.02)\%$.

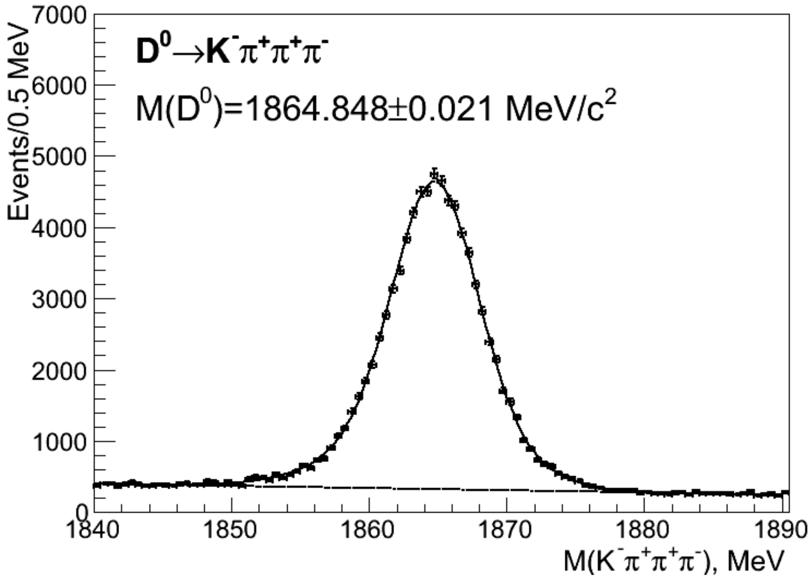
  We now analyze a 40 times more prolific decay,

  $D^0 \to K^{\pm} \pi^{\mp} \pi^{+} \pi^{-}$, with BF = $(8.0 \pm 0.2)\%$.

- The result is that we have nearly 72,000 D^0 decays instead of just 300 in the old paper, and a much higher level of precision.

- In order to get a precision of ~ ± 50 keV in $M(D^0)$ we had to fine tune CLEO-c charged particle energy calibration, which depends on the solenoid magnetic field (value, stability, and uniformity), and the amount of material in the path of the particles. Detailed studies were done to study the nature of these ingredients and to determine the procedure to obtain the desired precision in $M(D^0)$.

- We anchor our calibration on the precision measurements (~ ± 15 keV) of J/ψ and $\psi(2S)$ masses by KEDR and fine tune the magnetic field by using the reaction $\psi(2S) \rightarrow \pi^+ \pi^- J/\psi$.
- With the recalibrated field we analyze the reaction $\psi(2S) \rightarrow K_S + X$, and obtain a precision value of $M(K_S) = 497.600 \pm 0.007 \pm 0.015$ MeV.
- We analyze each individual CLEO-c run for $D^0 \rightarrow K_S + X$, $K_S \rightarrow \pi^+ \pi^-$ and fine tune the magnetic field for each run by requiring that it lead to the measured $M(K_S)$.
- For the decay $D^0 \rightarrow K^\pm \pi^\mp \pi^+ \pi^-$, we use kaons and pions only in the momentum range p < 600 MeV in which the KEDR-based recalibration of the magnetic field was done.



Results for the Mass of D^0

Decay	N(events)	M(D0), MeV
$D^0 \to K\,3\pi$	71,988 ± 388	1864.848 ± 0.021 (stat) ± 0.022 (syst) ± 0.057 (K mass)

Our 2007 value: $M(D^0)$ = 1864.847 ± 0.150 (stat) ± 0.095 (syst + K mass) MeV

or ± 0.178 MeV

Our present value: $M(D^0)$ = 1864.848 ± 0.021 (stat) ± 0.054 (syst + K mass) MeV

or ± 0.061MeV

- With $M(D^0)$ = 1864.848 ± 0.061 MeV, we get
  BE(X(3872)) = 136 ± 220 keV or < 420 keV (90% CL)
- This corresponds to the rms size of X(3872)
  d = 12 fm, or ≥ 7 fm (90% CL)
  ~ twice that of the deuteron !!

CLEO-c Results from Northwestern

2(c) "The Width of the D^{*0} Meson"

(work in progress)

When I mentioned to Eric Braaten how small the binding energy of X(3872) as a $| D^0 \overline{D}^{*0} >$ molecule is (perhaps < 100 keV), he said that it didn't matter, since the width of D^{*0}(2007) was large,
$\Gamma(D^{*0}) < 2.1$ MeV (90% CL), according to PDG 2012.

Indeed, if the width of D^{*0} is one MeV or so, the binding energy of X(3872) being so small does not matter. But, is it really true that
$\Gamma(D^{*0}) \sim 1$ MeV?

There are several reasons to doubt this.

1. The result is based on a 1988 measurement (S. Abachi et al., PLB 212, 533 (1988)), in which not even a single D^{*0} event was observed!!
2. The only hadronic decay of D^{*0}(2007) is $D^{*0} \to D^0 \pi^0$ (B=62%) which has extremely small phase space (2007 MeV $\to$ (1865+135 =) 2000 MeV), which should lead to hadronic width in keVs. A similar contribution can be expected from the electromagnetic decay $D^{*0} \to D^0 \gamma$ (B=38%). So, the total width should be in keVs.
3. Also, the width of $D^{*\pm}$ is known to be 96 ± 22 keV.

- So, we decided to measure $\Gamma(D^{*0})$.
  What is needed for measuring a keV-level width?

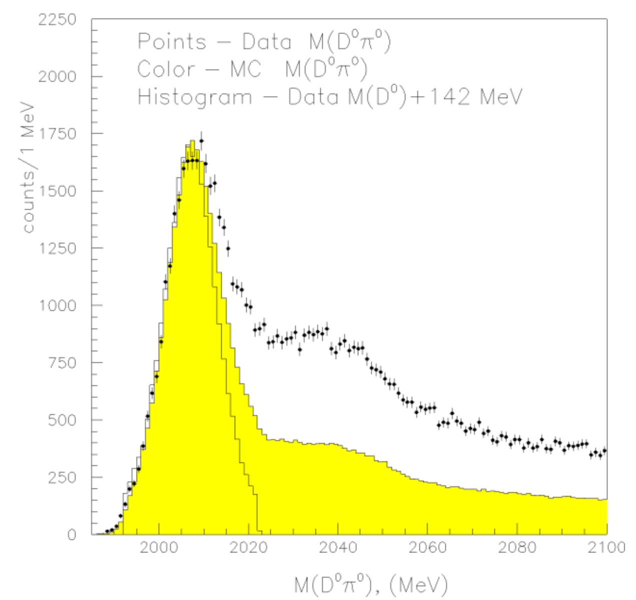
1. Large statistics
2. Narrow mass peak, low background
3. Excellent Monte Carlo calibration

- We use CLEO-c data for $e^+e^- \to \psi(4170)$ with L = 586 pb^{-1}
- We reconstruct the decay chain

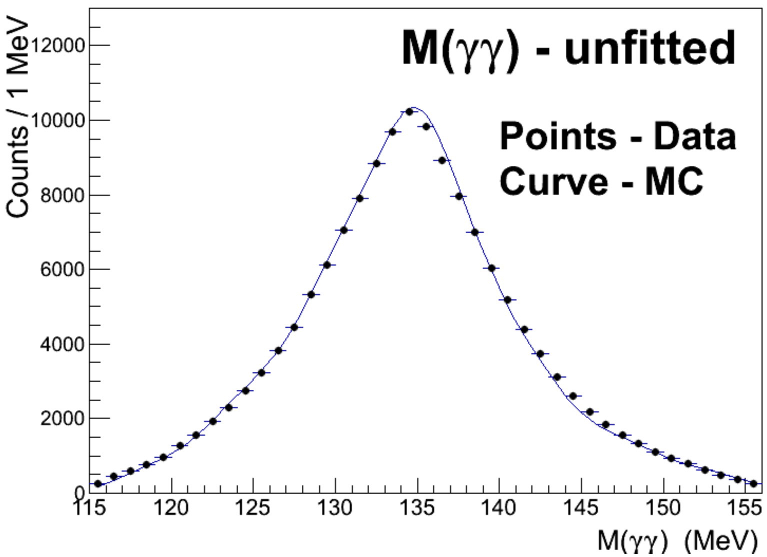
$$\psi(4170) \to D^0 D^{*0},\ D^{*0} D^{*0}, \quad \text{with} \sim 14{,}000\ D^{*0}$$

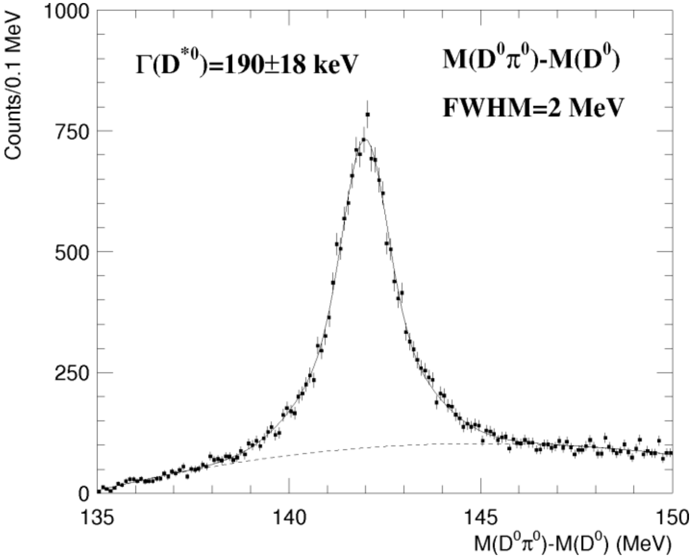
$$D^{*0} \to D^0\pi^0, \quad D^0 \to K^+\pi^-, \quad \pi^0 \to \gamma\gamma$$

- The $M(D^{*0}) = M(D^0\pi^0)$ distribution has a large wdith due to the large width of the $M(D^0 \to K^+\pi^-)$ distribution, FWHM ~ 15 MeV. **That is not good enough** to analyze for a keV's width!



- So we construct
$M(K^+\pi^-\pi^0)$ - $M(K^+\pi^-)$ in order to cancel the $M(K^+\pi^-)$ width and obtain $E(\pi^0)$ from which we can expect to determine a narrow width.





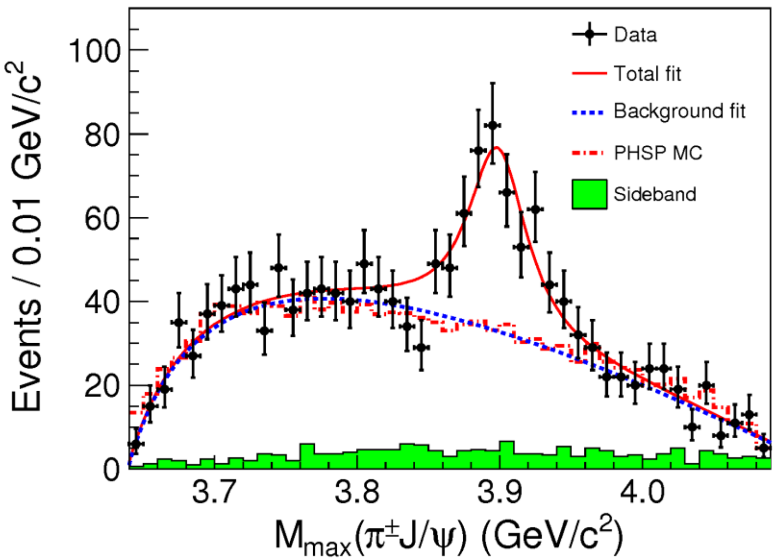
- The unfitted $M(\gamma\gamma)$ agrees very well with MC, and leads to $\Delta\,\Gamma(\pi^0)$ = 20 ± 20 keV, which is a measure of our systematic error in width determination. The $M(K^+\pi^-\pi^0)$ - $M(K^+\pi^-)$ distribution leads to
$M(D^{*0})–M(D^0)$ = 141.99 ± 0.02(stat) ± X(syst) MeV (PDG=142.12 ± 0.07 MeV)
$\Gamma(D^{*0})$ = 190±18(stat)±30(syst) keV (PDG Γ<2.1 MeV, 90% CL)

STOP PRESS

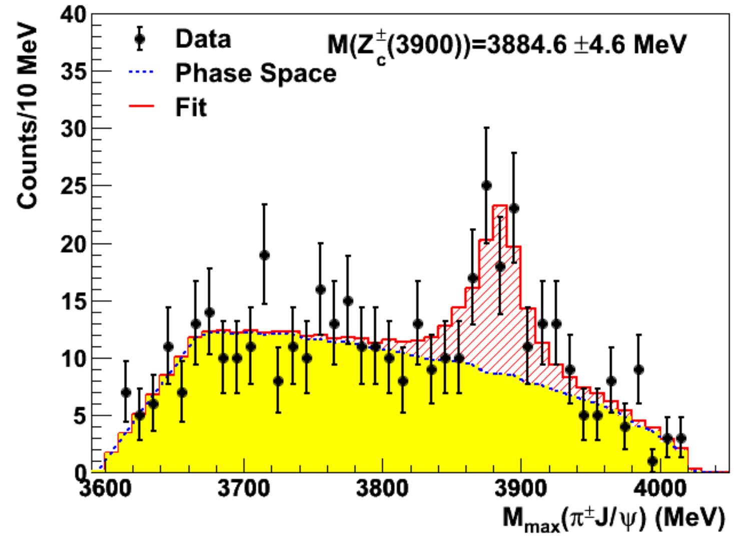
Observation of the Charged $Z_c^{\pm}(3900)$

- Just a few weeks ago, BES III reported (arXiv:1303.5949) an extremely interesting new state, the charged $Z_c^{\pm}(3900)$ in its decay into $\pi^{\pm}$ J/ψ.
- This is a very important finding, because a charged state containing a $c\bar{c}$ pair has to have at least four quarks. If confirmed, it would usher the search for a whole family of charged charmonium-like states.
- We have searched for $Z_c^{\pm}(3900)$ in 586 pb^{-1} of CLEO-c data taken at ψ(4160). We report successful observation of $Z_c^{\pm}(3900)$, confirming the BES III observation, though in data taken at the well-established charmonium resonance ψ(4160), not at the unusual vector state Y(4260) at which the BES observation was made. We believe that this difference is significant.
- We use essentially the same event selection criteria as BES III. We have fewer events, but our results for $Z_c^{\pm}(3900)$ agree very well with those of BES III. We also present evidence for $Z_c^{0}(3900)$

Comparison of BES III and CLEO-c results for charged $Z_c(3930)$



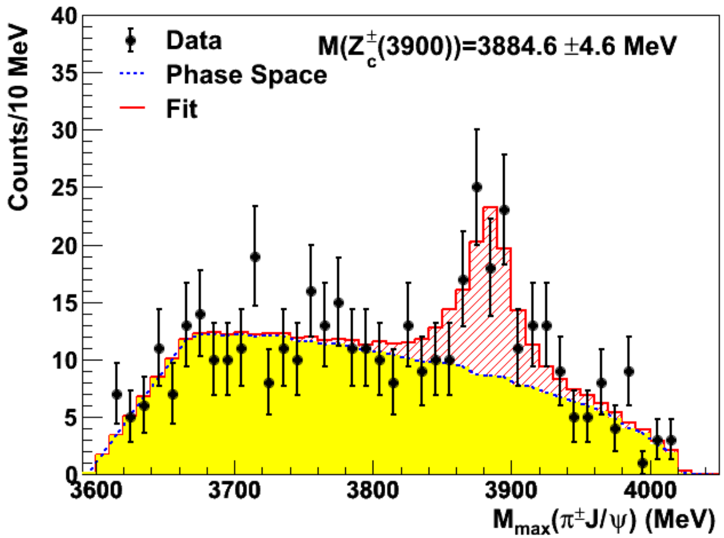
BES III

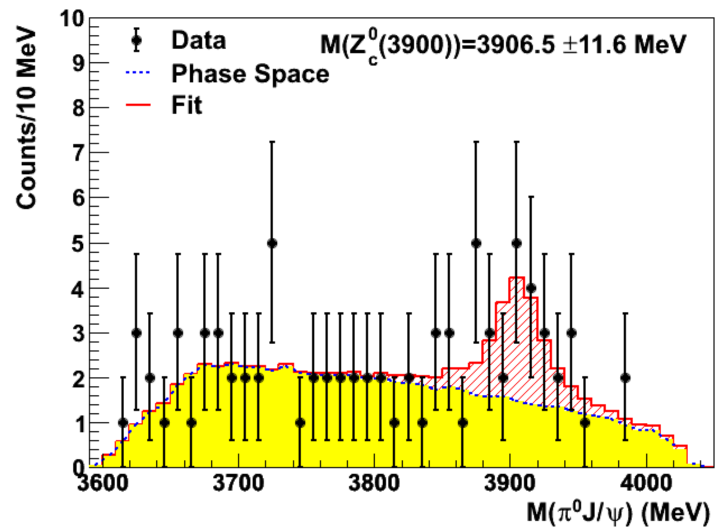


CLEO-c

	√s	L	$N(J/\psi\to e^+e^-)$	$N(J/\psi\to\mu^+\mu^-)$	$\sigma(e^+e^-\to J/\psi\pi\pi)$	$N(Z_c)$	Signif.	$M(Z_c)$	$\Gamma(Z_c)$	R
	GeV	pb^{-1}			pb			MeV	MeV	%
BES III	4.26	525	882±33	595±28	62.9±1.9	307±48	>8	3899±6	46±22	21±3
CLEO-c	4.17	586	137±15	96±11	8.6±0.7	81+20	6.1	3885±5	34±12	35±9
Belle	4.26					159±49	5.2	3895±8	63±35	29±9

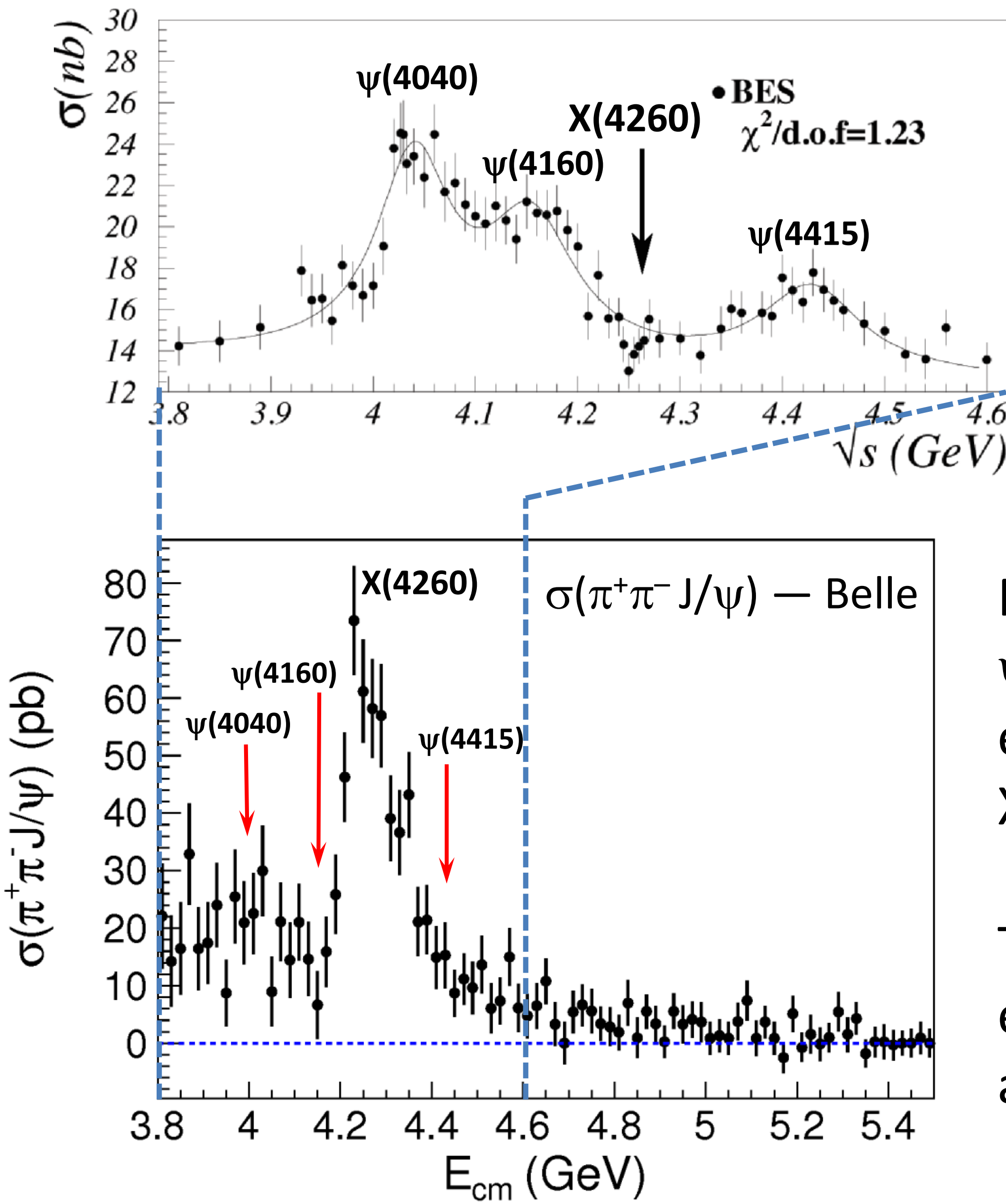
The Neutral $Z_c(3930)$!!





$Z_c^\pm(3900)$ $\quad\quad$ $Z_c^0(3900)$

	√s	L	$N(J/\psi\to e^+e^-)$	$N(J/\psi\to\mu^+\mu^-)$	$\sigma(e^+e^-\to J/\psi\pi\pi)$	$N(Z_c)$	Signif.	$M(Z_c)$	$\Gamma(Z_c)$	R
	GeV	pb^{-1}			pb			MeV	MeV	%
$\pi^+\pi^-$	4.17	586	137±15	96±11	8.6±0.7	81+20	**6.1**	3885±5	34±12	35±9
$\pi^0\pi^0$	4.17	586	40±8	29±5	5.7±0.8	17±10	**3.0**	3907±12	34±29	25±15



Note that **all** 1^{--} states $\psi(4040,4160,4415)$ are strongly excited in $\sigma(e^+e^- \to \gamma^* \to \text{hadrons})$, but X(4260) 1^{--} is not at all excited.

Note that **none** of the 1^{--} states $\psi(4040,4160,4415)$ are appreciably excited in $\sigma(\pi^+\pi^-\ J/\psi)$, but X(4260) is strongly excited

This “orthogonality” in preferential excitation is extremely interesting and provocative