Charmonium Spectroscopy Below Open Flavor Threshold

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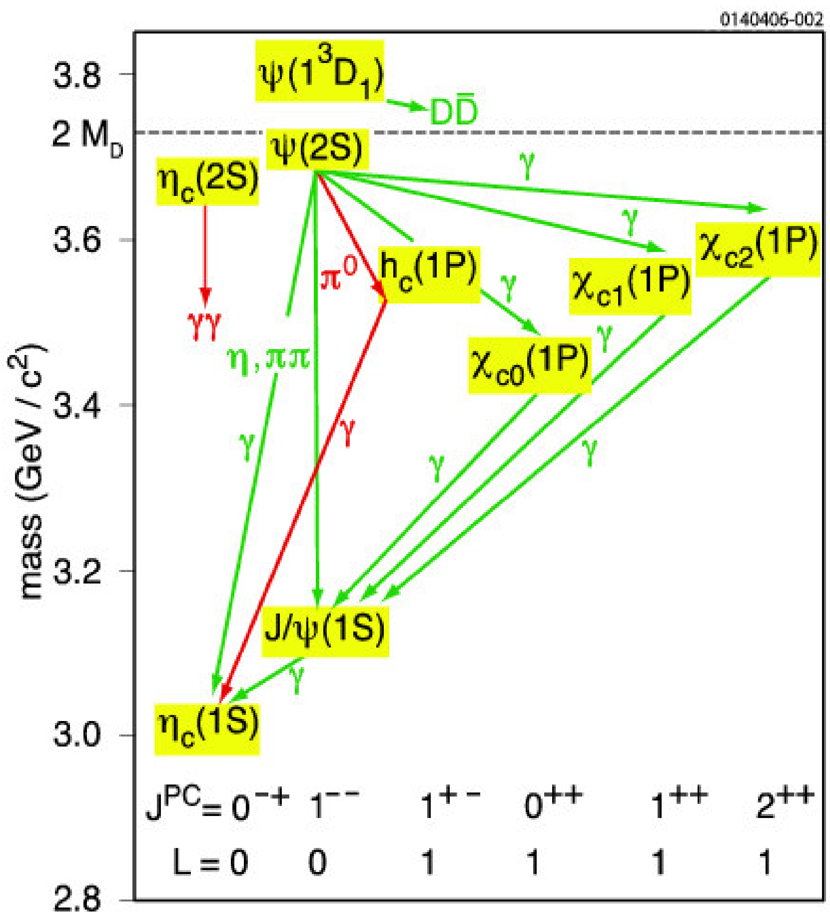
Introduction



- There are 8 bound states of charmonium below the $D\bar{D}$ breakup threshold.

  spin triplets - $J/\psi(1^3S_1)$, $\psi(2^3S_1)$, $\chi_{0,1,2}(1^3P_{0,1,2})$;

  spin singlets - $\eta_c(1^1S_0)$, $\eta_c'(2^1S_0)$, $h_c(1^1P_1)$.

- Only J/ψ, $\psi(2S)$ can be produced directly in e^+e^- annihilation.

  A lot is known about these triplet states.

- Spin singlet states population via radiative transitions from the vector states is either very weak (M1 for $\eta_c(1S)$, $\eta_c(2S)$), or C- forbidden ($h_c(1^1P_1)$).

  Little is known about these singlet states.

Introduction cont'd.

STATUS OF CHARMONIUM STATES

	Mass (MeV) PDG07	Width (MeV) PDG07	Number of Decays (PDG) 2002	2004	2007*
SPIN TRIPLETS					
J/ψ	3096.92(1)	93.4(21)(keV)	134	135	162
$\psi(2S)$	3686.09(3)	327(11) (keV)	51	62	115
χ_{c0}	3414.75(35)	10.4(7)	17	17	51
χ_{c1}	3510.66(7)	0.89(5)	12	13	35
χ_{c2}	3556.20(9)	2.05(12)	18	19	37
SPIN SINGLETS					
$\eta_c(1S)$	2979.8(12)	26.5(35)	20	21	31
$\eta_c(2S)$	3637(4)	14(7)	3	4	4
$h_c(1^1P_1)$	3525.93(27)	<1	3	3	4

- The 2007 PDG entries include some of the developments I am going to talk about.
- Notice the marked improvements after 2004.

Introduction cont'd.

- Charm quark has large mass (~1.5 GeV), compared to the masses of u, d, s quarks;
- Velocity of the charm quarks in hadrons is not too relativistic $(v/c)^2 \sim 0.2$;
- Strong coupling constant $\alpha_s(m_c)$ is small (~ 0.3).

Therefore:

Charmonium spectroscopy is a good testing ground for the theories of strong interactions:

- QCD in both perturbative and nonperturbative regimes;
- QCD inspired purely phenomenological potential models;
- NRQCD and Lattice QCD.

I will review some new and recent experimental results on charmonium spectroscopy below open flavor threshold.

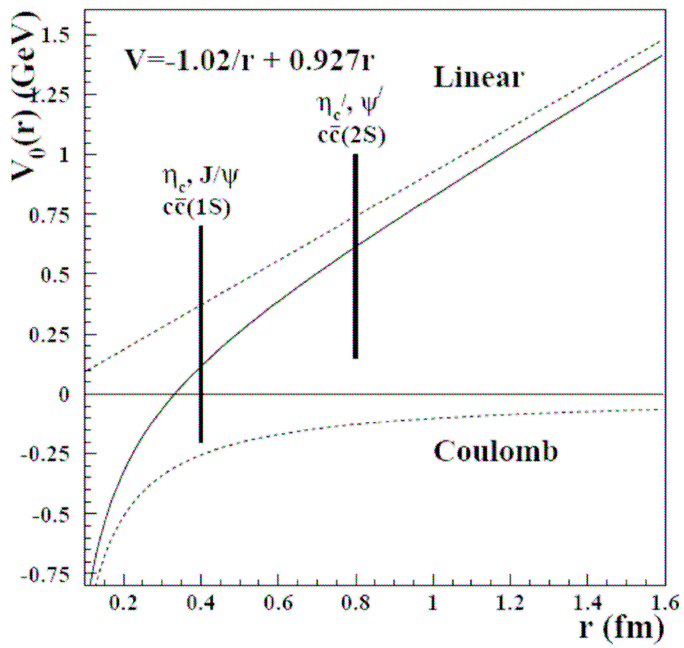
Observation of $\eta_c(2S)$

- Prior to 2002 there were several unsuccessful attempts to identify $\eta_c(2S)$ in $p\bar{p}$, $\gamma\gamma$ fusion, inclusive photon analysis.

- Most potential model calculations predicted $M(\eta_c(2S))$ = 3594 – 3626 (MeV).

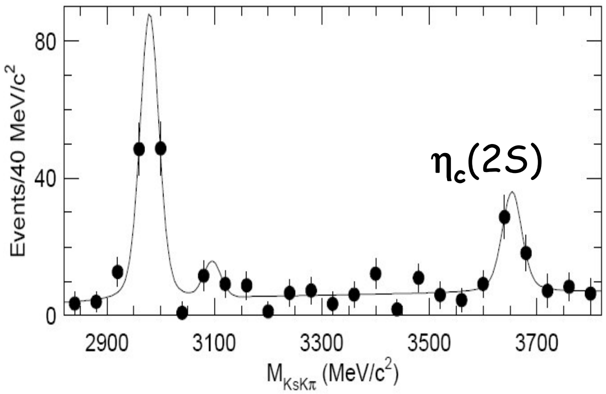
- It is important to identify the singlets in order to determine the hyperfine or spin-spin interaction, which is responsible for singlet-triplet splitting of $q\bar{q}$ states.

- Identification of $\eta_c(2S)$ is important to know the possible variation of spin-spin interaction from Coulombic (J/ψ, $\eta_c(1S)$) to Confinement ($\psi(2S)$, $\eta_c(2S)$) regions of the $q\bar{q}$ interaction.



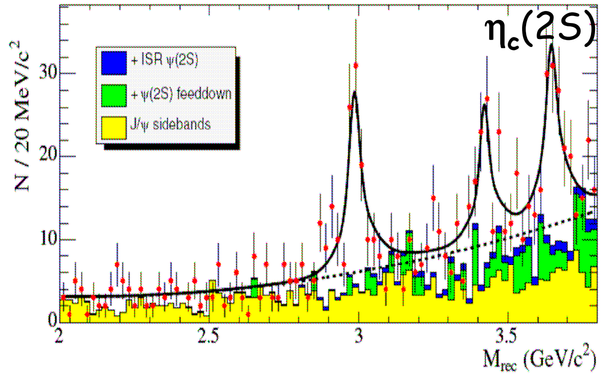
Observation of $\eta_c(2S)$ cont'd.

PRL 89(2002)102001



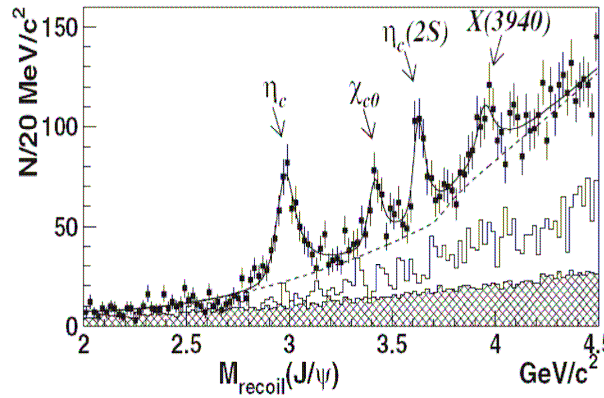
Belle: 42 fb^{-1} [$B \to K(K_S K\pi)$]

PRD 72(2005)031101(R)



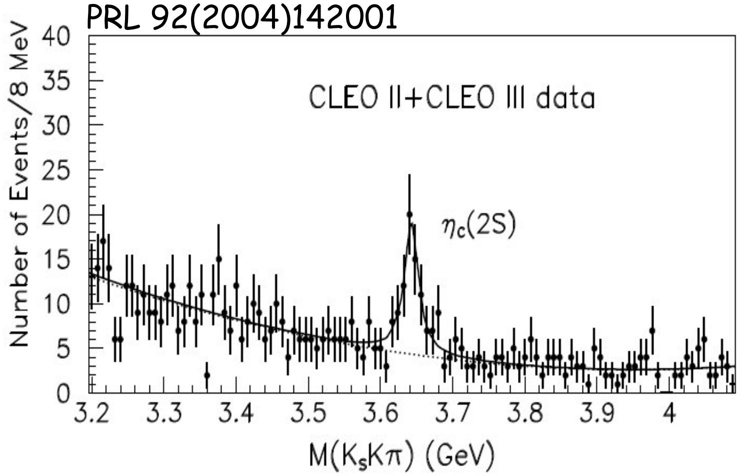
BaBar: 124 fb^{-1} ($e^+e^- \to J/\psi + cc$)

PRL 98(2007)082001



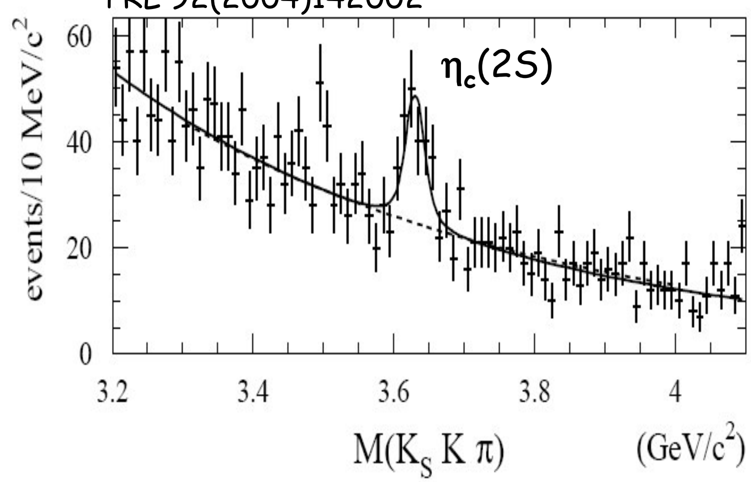
Belle: 357fb^{-1} ($e^+e^- \to J/\psi + cc$)

PRL 92(2004)142001



CLEO II+III: 27 fb^{-1} ($\gamma\gamma \to K_S K\pi$)

PRL 92(2004)142002



BaBar: 86 fb^{-1} ($\gamma\gamma \to K_S K\pi$)

Observation of $\eta_c(2S)$ cont'd.

Experiment	$M(\eta_c(2S))$	$\Gamma(\eta_c(2S))$	Events(reaction)
Belle(2002)	3654 ± 10	< 55	39 ± 11 $[B\to K(K_SK\pi)]$
CLEO(2004)	3643.9 ± 3.4	6.3 ± 13.0	61 ± 15 $(\gamma\gamma\to K_SK\pi)$
BaBar(2004)	3630.8 ± 3.5	17.0 ± 8.7	112 ± 24 $(\gamma\gamma\to K_SK\pi)$
BaBar(2005)	3645.0 ± 8.4	22 ± 14	121 ± 27 $(e^+e^-\to J/\psi+cc)$
Belle(2007)	3626 ± 8	-	311 ± 42 $(e^+e^-\to J/\psi+cc)$

Spread in $M(\eta_c(2S))$ is uncomfortably too large.

- The PDG07 weighted average is $M(\eta_c(2S)) = 3637 \pm 4$ (MeV);
- This leads to the hyperfine splitting $\Delta M_{hf}(2S) = 49 \pm 4$ (MeV) [$\Delta M_{hf}(1S) = 117 \pm 1$ (MeV)];
- Explaining large difference between $\Delta M_{hf}(2S)$ and $\Delta M_{hf}(1S)$ is a challenge for theorists;
- Width of $\eta_c(2S)$ is essentially unmeasured (PDG07 value $\Gamma(\eta_c(2S)) = 14 \pm 7$ (MeV)). Measurement of the width is a challenge to the experimentalists.
- $\eta_c(2S)$ decay is observed only in one decay channel, $\eta_c(2S)\to K_SK\pi$.

A lot remains to be done about $\eta_c(2S)$.

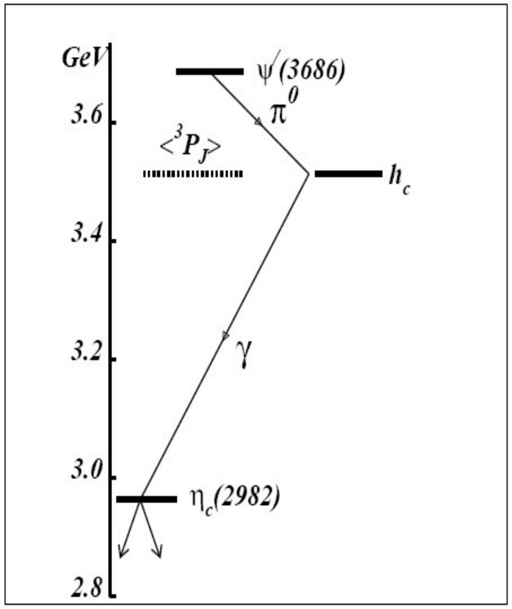
Attempts are being made to identify $\eta_c(2S)$ in the decay $\psi(2S)\to\gamma\,\eta_c(2S)$ from 54 pb^{-1} CLEOc $\psi(2S)$ data. Expect news from CLEOc.

CLEO observation of $h_c(1^1P_1)$

CLEO PRL 95(2005)102003
PRD 72(2005)092004

The observation and the measurement of the parameters of $h_c(1^1P_1)$ are important to determine the hyperfine splitting of P-states, which is expected from simple pQCD to be:

$$\Delta M_{hf}(1P)=M(\langle{}^3P_J\rangle)-M({}^1P_1)=0$$



CLEO has analyzed data for 3.08×10^6 $\psi(2S)$ events

$$\psi(2S)\rightarrow\pi^0 h_c,\ \ h_c\rightarrow\gamma\eta_c$$

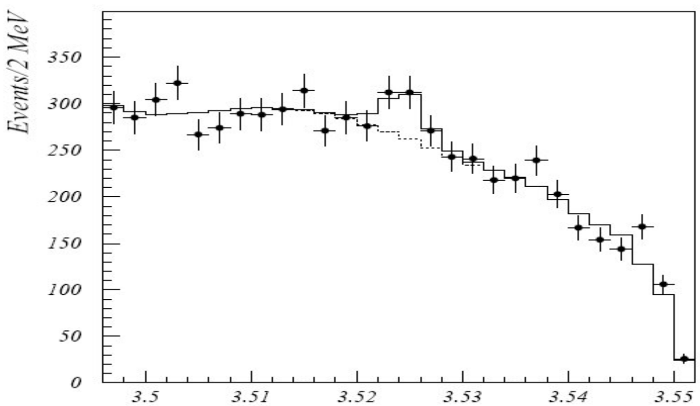
Inclusive analysis: two independent analysis, different in details of event selection. One constrained the photon energy, and the other the η_c mass (recoil against $\pi^0\gamma$).

Exclusive analysis: Instead of constraining E_γ or $M(\eta_c)$, seven known η_c channels with a total branching fraction of ~10% were measured.

Results of inclusive and exclusive analysis are consistent.

CLEO observation of $h_c(1^1P_1)$, cont'd.

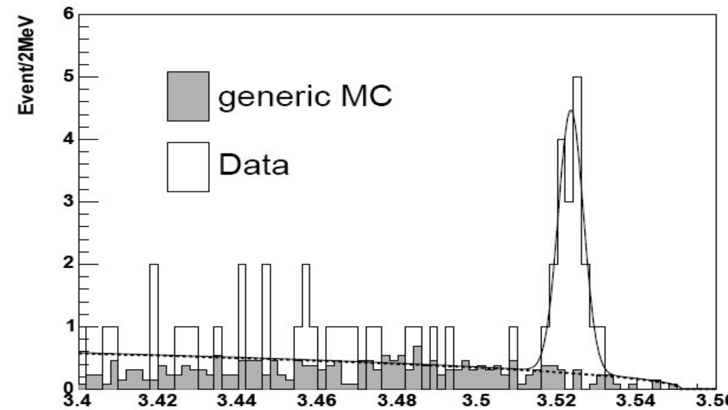
CLEO PRL 95(2005)102003
PRD 72(2005)092004



π^0 recoil mass in GeV

INCLUSIVE

Significance = 3.8σ



π^0 recoil mass in GeV

EXCLUSIVE

Significance = 5.2σ

$$Br(\psi(2S)\to\pi^0 h_c)\times Br(h_c\to\gamma\eta_c)=(4.0\pm0.8\pm0.7)\times10^{-4}$$

$$M(h_c)=(3524.4\pm0.6\pm0.4)\ \text{MeV}$$

$$\Delta M_{hf}(1P)=M(\chi_{cJ})-M(h_c)=(+1.0\pm0.6\pm0.4)\ \text{MeV}$$

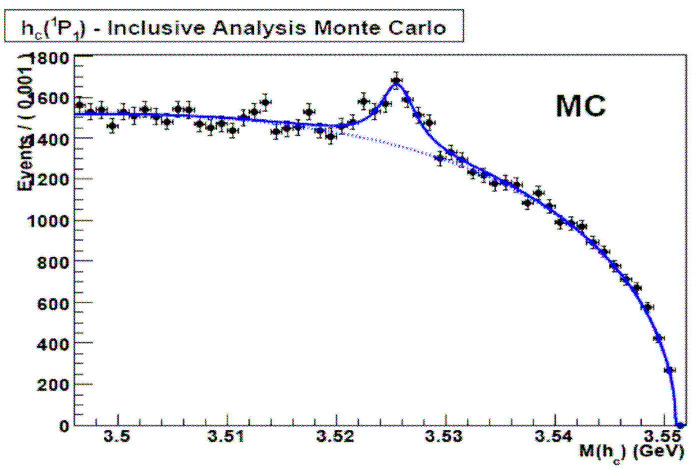
using $\langle M(\chi_{cJ})\rangle=(3525.4\pm0.1)$ MeV

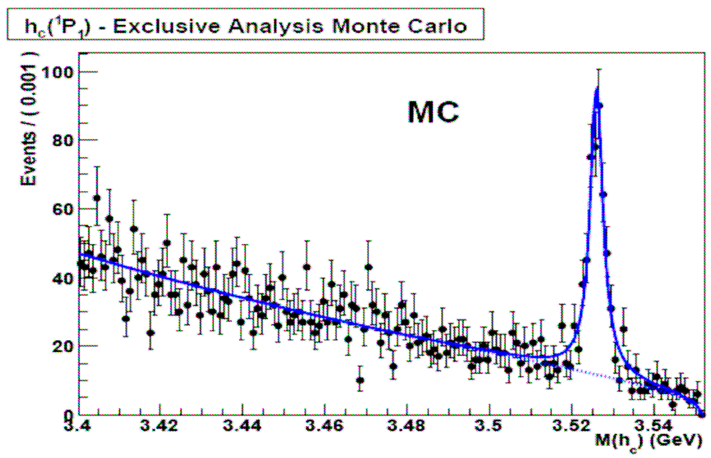
Two conclusions follow:

- Simple pQCD expectation, $\Delta M_{hf}(1P)=0$, is not violated;
- The magnitude and sign of $\Delta M_{hf}(1P)$ is not yet well determined.

More on CLEO $h_c(1^1P_1)$

- CLEOc now has new 48 pb^{-1} $\psi(2S)$ data (24 million $\psi(2S)$ events).
- With these data greatly improved results from both inclusive and exclusive analysis are expected.
- Preliminary analysis show that these expectations will be fully met:
  ~ 1000 h_c are expected in inclusive analysis;
  ~ 250 h_c are expected in exclusive analysis.
- These should lead to $M(h_c)$ and $\Gamma(h_c)$ determinations with uncertainties at the level of ~ ± 0.3 MeV and ~ ± 0.5 MeV respectively.





Monte Carlo simulations for 24 million $\psi(2S)$ based on analysis of 3 million $\psi(2S)$.

E835 evidence for $h_c(1^1P_1)$

E835 PRD 72(2005)032001

Data

45 pb^{-1} of $p\bar{p}$ annihilation scan data in the h_c region, collected by Fermilab E835 in 1997 and 2000.

Channel

$p\bar{p} \rightarrow h_c \rightarrow \gamma\eta_c, \ \eta_c \rightarrow \gamma\gamma$

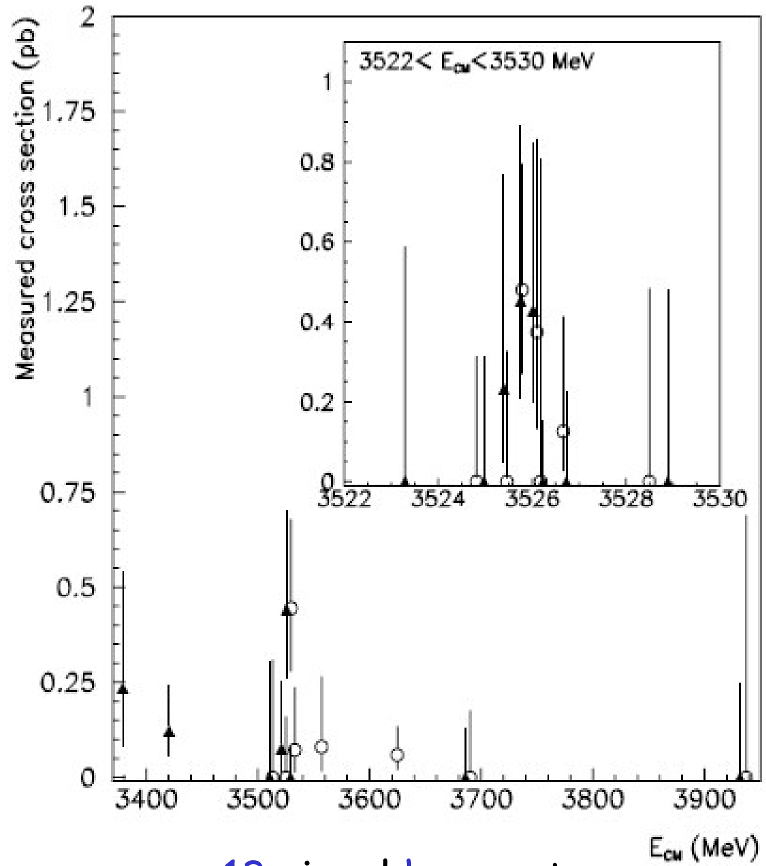
Method

Extract resonance parameters from a maximum-likelihood fit to the cross section curve.

$M(h_c) = (3525.8 \pm 0.2 \pm 0.2)$ MeV

$\Gamma(h_c) < 1$ MeV

$\Delta M_{hf}(1P) = M(\chi_{cJ}) - M(h_c) = (-0.4 \pm 0.2 \pm 0.2)$ MeV



13 signal h_c events

A lot remains to be done about h_c.
Expect news from CLEOc soon.

New Measurements of the ψ(2S) Width

E835, hep-ex/0703012

Data

1.64 pb^{-1} of $\bar{p}p$ annihilation scan data in the ψ(2S) region, collected by Fermilab E835 in 2000.

Channels

$\bar{p}p \to e^+e^-$

$\bar{p}p \to J/\psi + X \to e^+e^- + X$

Advantage to measurements at e^+e^- experiments

$\bar{p}$ beams with FWHM energy spreads of 0.4-0.5 MeV.

Method

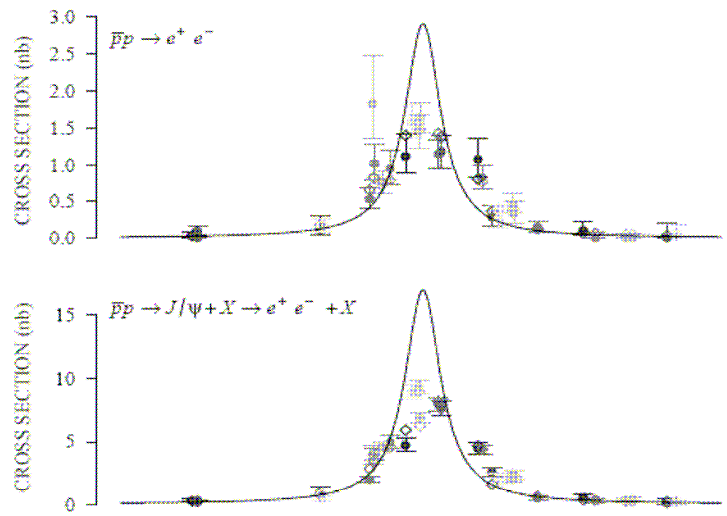
new technique of "complementary scans", based on precise beam revolution-frequency and orbit-length measurements.

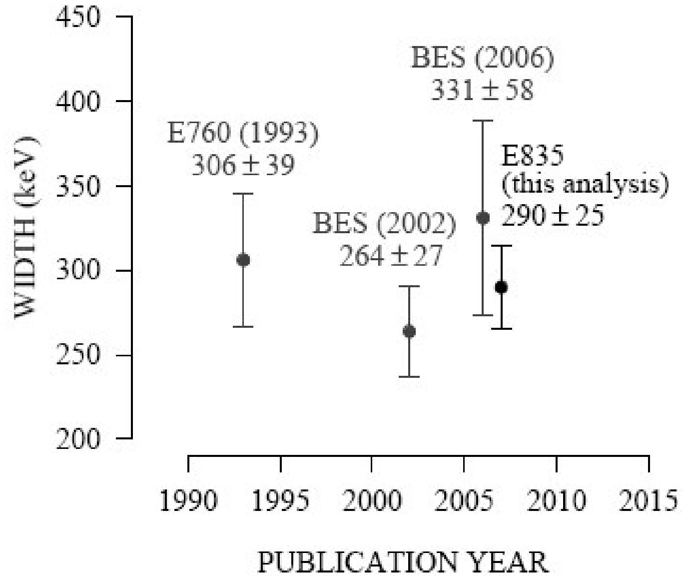
Extract resonance parameters from a maximum-likelihood fit to the excitation curves.

Most precise measurements to date:

$\Gamma_{tot}[(\psi(2S)] = [290 \pm 25(sta) \pm 4(sys)]$ keV

$\Gamma_{ee}\Gamma_{pp}/\Gamma_{tot} = [579 \pm 38(sta) \pm 36(sys)]$ meV





BES, PRL 97(2006)121801

Measurements of the $\psi(2S)$ Width cont'd

Data

The e^+e^- annihilation scan data in the $\psi(2S)$ and $\psi(3770)$ regions, collected by BES II in 2003.

Channel

$e^+e^- \rightarrow hadrons$

Method

Extract resonance parameters from simultaneous fit of cross section curves covering energy ranges of both $\psi(2S)$ and $\psi(3770)$ resonances.

$$\Gamma_{ee}[(\psi(2S)] = [2.330 \pm 0.036(sta) \pm 0.110(sys)] \text{ keV}$$

$$\Gamma_{tot}[(\psi(2S)] = [331 \pm 58(sta) \pm 2(sys)] \text{ keV}$$

PDG 2006 average value is

$$\Gamma_{tot}[(\psi(2S)] = (277 \pm 22) \text{ keV}$$

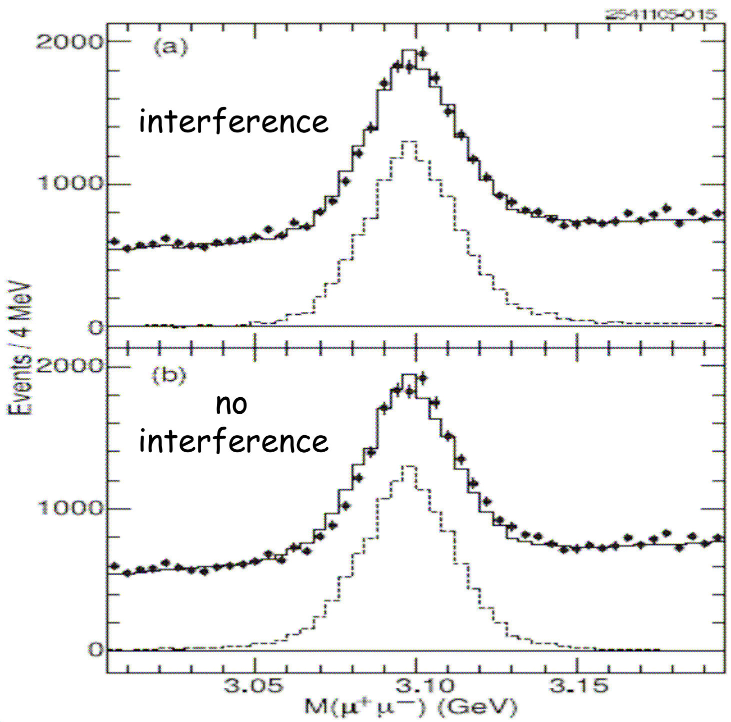
New average value including E835 and BES new results will be

$$\Gamma_{tot}[(\psi(2S)] = (287 \pm 16) \text{ keV}$$

CLEO, PRD 73(2006)051103(R)

Measurements of the J/ψ Widths

- Use 281 pb^{-1} CLEOc $\psi(3770)$ data and look for radiative return events to J/ψ.
- Select $\mu^+\mu^-(\gamma)$ events with a $M(\mu^+\mu^-)=M(J/\psi)$.
- Resulting cross-section is proportional to $Br_{\mu\mu}\times\Gamma_{ee}(J/\psi)$.
- Divide by new CLEOc $Br_{\mu\mu}=(5.953\pm0.056\pm0.042)\%$ (PRD 71(2005)111103(R)) to get $\Gamma_{ee}(J/\psi)$.
- Assume lepton universality $Br_{ee}=Br_{\mu\mu}$, divide by CLEOc $Br_{\mu\mu}$ again to get $\Gamma_{tot}(J/\psi)$.



Most precise measurements to date:

$Br_{\mu\mu}\times\Gamma_{ee}(J/\psi)$ = [0.3384 ± 0.0058(sta) ± 0.0071(sys)] keV

$\Gamma_{ee}(J/\psi)$ = [5.68 ± 0.11(sta) ± 0.13(sys)] keV

$\Gamma_{tot}(J/\psi)$ = [95.5 ± 2.4(sta) ± 2.4(sys)] keV

Measurements of $\eta_c(1S)$, $\chi_{c0}(1P)$, $\chi_{c2}(1P)$ in two-photon fusion processes at Belle

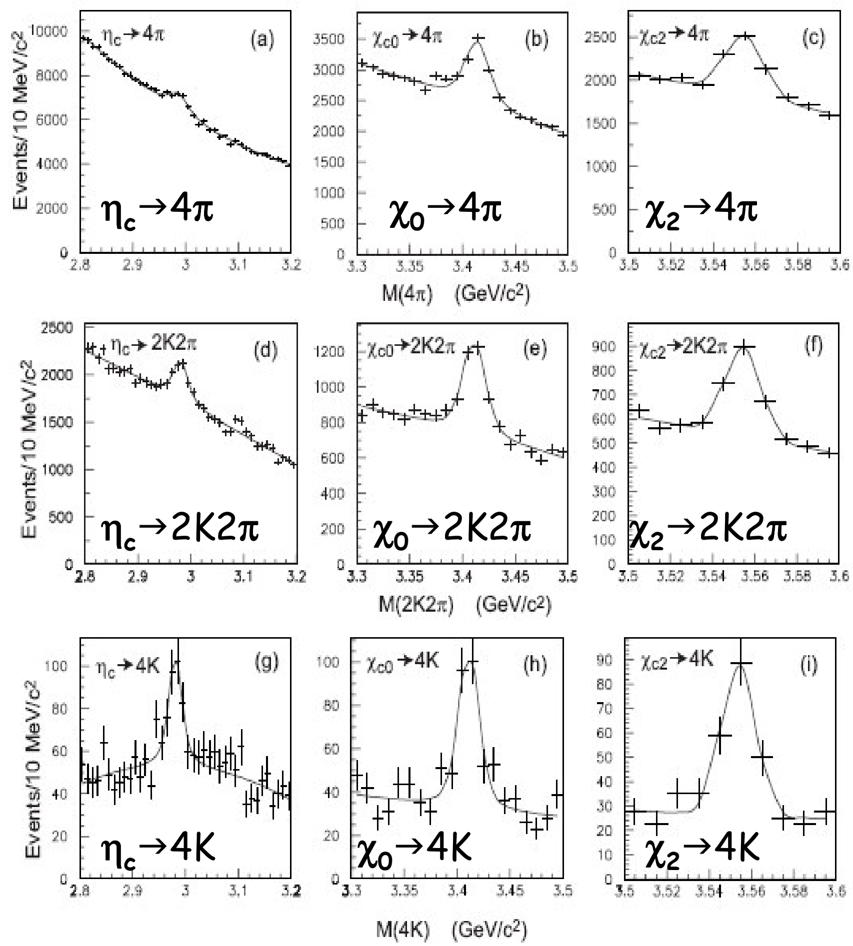
Belle, hep-ex/0706.3955

- Use 395 fb^{-1} Belle data and look for
  4π, $2K2\pi$, $4K$
  final states in two-photon fusion reactions.

- Signals of $\eta_c(1S)$, $\chi_{c0}(1P)$, $\chi_{c2}(1P)$ are observed.

- Measure Masses and Total Widths of
  R = $\eta_c(1S)$, $\chi_{c0}(1P)$, $\chi_{c2}(1P)$
  in the channels R→4π, $2K2\pi$, $4K$.

- Measure $\Gamma_{\gamma\gamma}\times Br$ for $\eta_c(1S)$, $\chi_{c0}(1P)$, $\chi_{c2}(1P)$.



Mass and Width of $\eta_c(1S)$

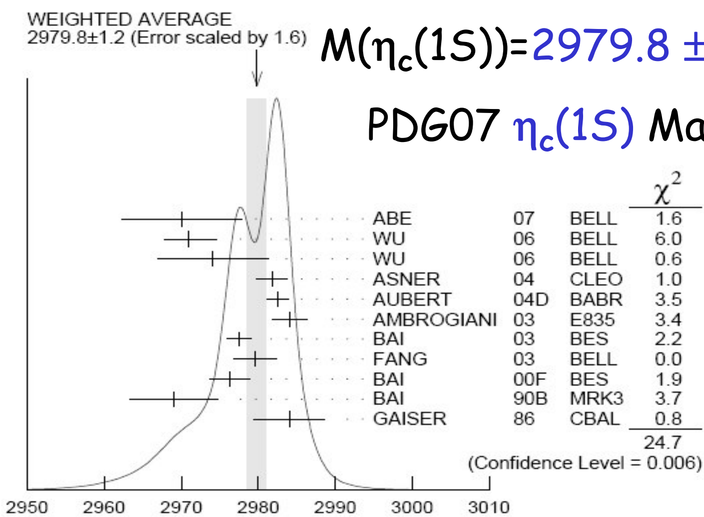
Belle, hep-ex/0706.3955

Resonance	Mass (MeV)	Width (MeV)	N(events)
$\eta_c(1S)$	**2986.1±1.0±2.5**	**28.1±3.2±2.2**	7616±553
$\chi_{c0}(1P)$	3414.2±0.5±2.3	10.6±1.9±2.6	5459±319
$\chi_{c2}(1P)$	3555.3±0.6±2.2	-	2503±158

$M(\eta_c(1S))$ and $\Gamma(\eta_c(1S))$ are known with only ~1 MeV and ~3 MeV precision respectively

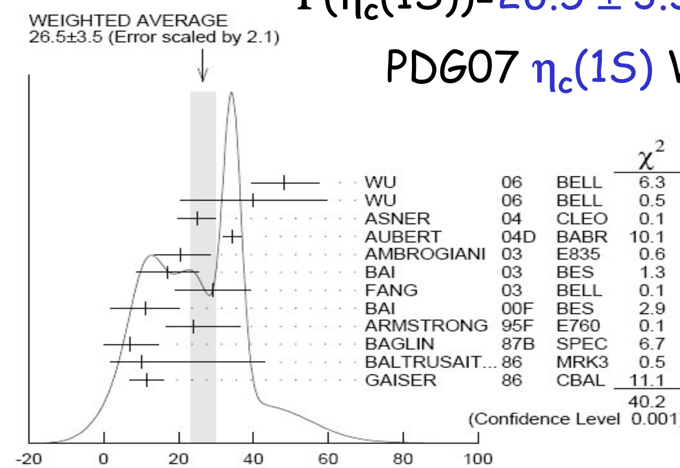
$M(\eta_c(1S)) = 2979.8 \pm 1.2$ (MeV)

PDG07 $\eta_c(1S)$ Mass



$\Gamma(\eta_c(1S)) = 26.5 \pm 3.5$ (MeV)

PDG07 $\eta_c(1S)$ Width



Expect new results from CLEOc with its (48+6) pb^{-1} $\psi(2S)$ data studying the reactions $J/\psi \to \gamma\,\eta_c(1S)$ and $\psi(2S) \to \gamma\,\eta_c(1S)$.

Two photon widths of $\eta_c(1S)$, $\chi_{c0,2}$ (1P)

Belle, hep-ex/0706.3955

$\Gamma_{\gamma\gamma}$ values are evaluated from measured $\Gamma_{\gamma\gamma}\times$ Br using Br from PDG07.
Results of 4π, $2K2\pi$, $4K$ channels are combined.

Resonance	$\Gamma_{\gamma\gamma}$(keV), Belle	$\Gamma_{\gamma\gamma}$(keV), PDG07
$\eta_c(1S)$	2.46±0.60	6.7±0.9
$\chi_{c0}(1P)$	1.98±0.24	2.90±0.43
$\chi_{c2}(1P)$	0.438±0.062	0.539±0.050
$R= \Gamma_{\gamma\gamma}(\chi_{c2})/ \Gamma_{\gamma\gamma}(\chi_{c0})$	0.221±0.041 *	0.186±0.032 *

* These errors in the ratios are overestimated since they do not take account of correlations between the errors for the individual values.

- The ratio R is an interesting quantity because it allows us to evaluate the reliability of the first order radiative corrections, which are often very large, by calculating α_s from them

$$R \equiv \frac{\Gamma_{\gamma\gamma}(\chi_{c2})}{\Gamma_{\gamma\gamma}(\chi_{c0})} = \frac{(4|\Psi'(0)|^2\,\alpha_{em}^2/m_c^4)\times(1-1.7\alpha_s)}{(15|\Psi'(0)|^2\,\alpha_{em}^2/m_c^4)\times(1+0.06\alpha_s)} = 0.267(1-1.76\alpha_s)$$

- The Belle value of $R=0.221\pm0.040$ leads to $\alpha_s=0.098\pm0.085$ which is obviously a gross underestimate of $\alpha_s(m_c)$, which is known to be ~0.3. This clearly illustrates that the nearly factor of two first order correction factor for $\Gamma_{\gamma\gamma}(\chi_{c2})$ is unreliable.

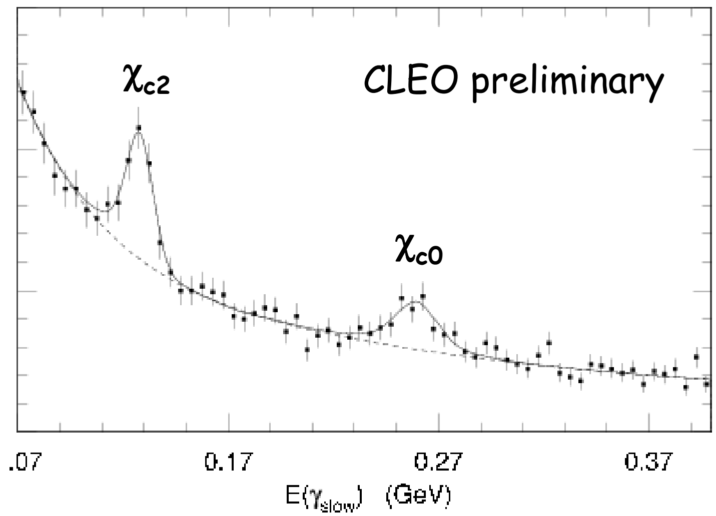
Measurement of $\Gamma_{\gamma\gamma}(\chi_{c0},\chi_{c2})$ at CLEO

- At CLEOc a measurement of $\Gamma_{\gamma\gamma}(\chi_{c0},\chi_{c2})$ has been undertaken by using data for 24×10^6 $\psi(2S)$. The reaction chosen is

  $$\psi(2S) \to \gamma\, \chi_{c0,2}, \quad \chi_{c0,2} \to \gamma\gamma$$

  to take advantage of the very precisely known values of $Br[\psi(2S) \to \gamma\, \chi_{c0,2}]$.

- The CLEO results should be available soon by analysis of the spectra in which χ_{c0} and χ_{c2} are both excited.



Summary

- All charmonium states below open flavor threshold have now been firmly identified.

- The spectroscopy of spin-triplet states is now well in hand, but a lot still needs to be done for spin-singlet states. Masses, widths, particularly of $\eta_c(2S)$ and $h_c(1^1P_1)$ need to be better determined. Many more decay channels need to be investigated for each.

- A large number of investigations, based on the world's largest sample of $\psi(2S)$ acquired by CLEOc, are currently in progress, and results are expected soon.

  These include:

  - Precision results for mass, width and branching fractions of $h_c(1^1P_1)$;
  - Results for many decay channels of $\eta_c(1S)$;
  - Results for attempt to identify $\eta_c(2S)$ in radiative decay of $\psi(2S)$;
  - Results of studies for $p\bar{p}$ threshold enhancement in radiative decays of J/ψ, $\psi(2S)$;
  - Results of search for the tensor glueball, $\xi(2230)$;
  - Hadronic and radiative decays of $\psi(2S)$ and J/ψ ;
  - Two-body and multi-body decays of $\chi_c(1P)$ states;
  - and others.