Bottomonium and Charmonium Results from CLEO

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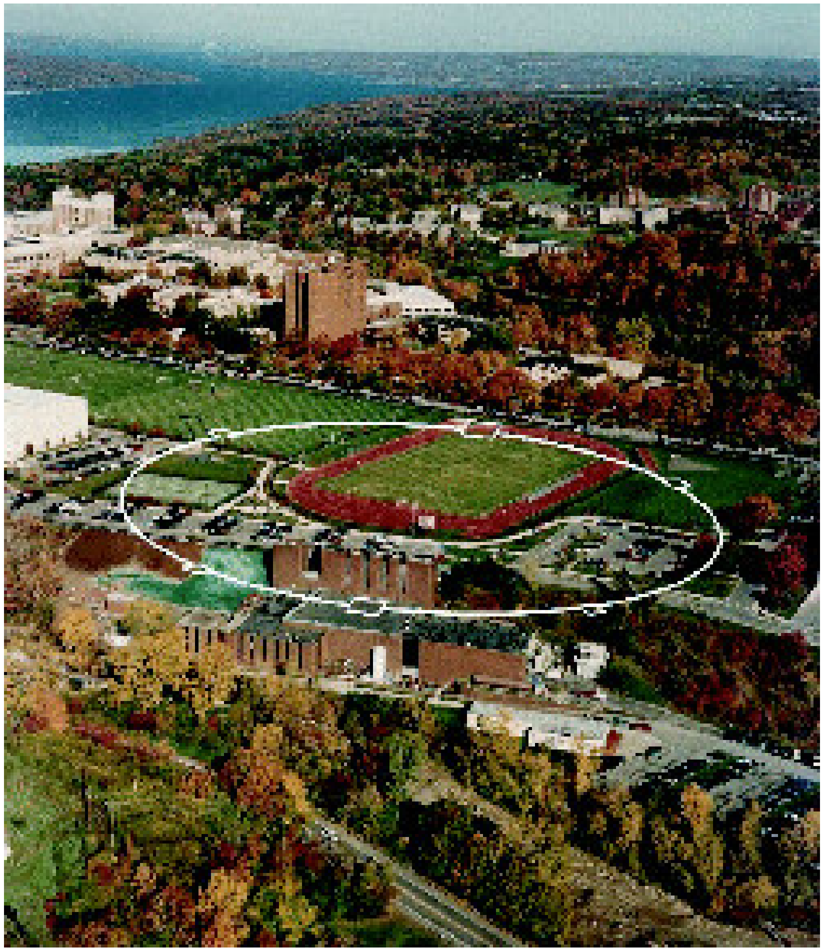
The XLI Rencontres de Moriond
QCD and High Energy Hadronic Interactions

Outline

- The CLEO Detector
- Γ_{ee} of the Υ(1S, 2S, 3S) Resonances
- Measurement of $\Gamma_{ee}(J/\psi)$, $\Gamma_{tot}(J/\psi)$, $\Gamma_{ee}[\psi(2S)]/\Gamma_{ee}(J/\psi)$
- Measurement of $\sigma(\psi(3770) \rightarrow \text{hadrons})$ and $\Gamma_{ee}[\psi(3770)]$
- Charmonium Decays of $\psi(4040)$, $\psi(4160)$ & $\Upsilon(4260)$
- Summary

The CLEO/CESR Experiment

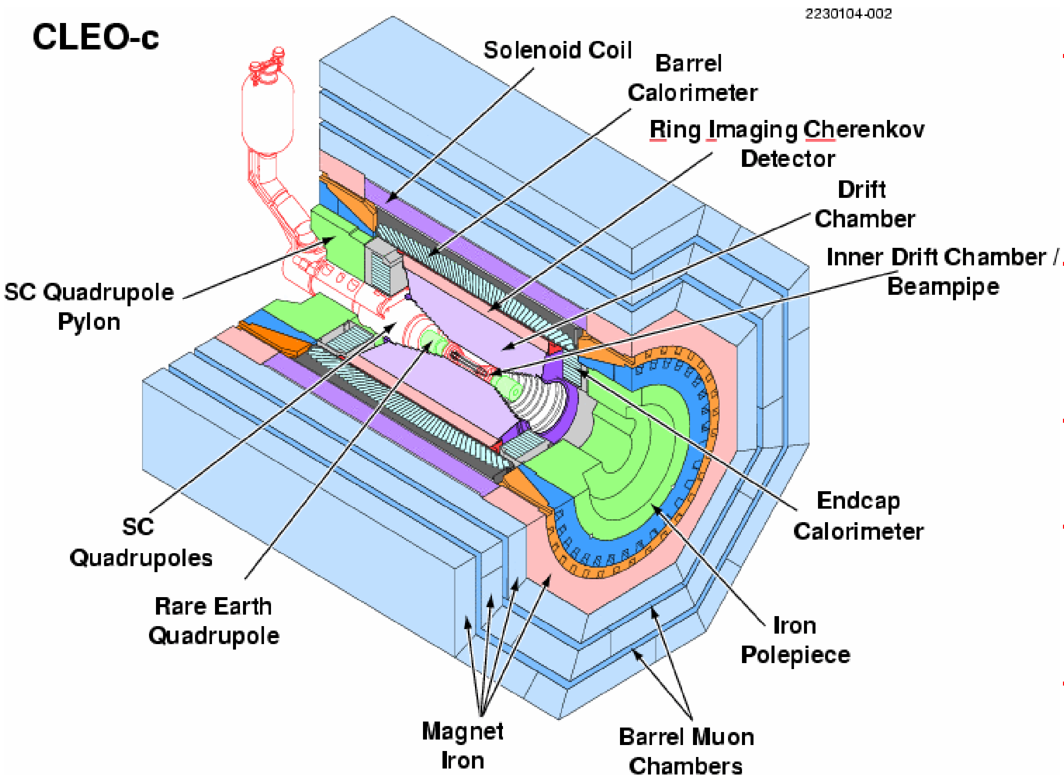


CESR (Cornell Electron Storage Ring) – Symmetric e+e- collider with capability of running at $\sqrt{s}$ = 3-11 GeV

Located at Wilson Synchrotron Laboratory in Ithaca, NY

CLEO and CESR have been producing results in B, Υ, τ, and 2-photon physics for almost 30 years

The CLEO detector



Inner Drift Chamber:

- 6 stereo layers
- 100 μm hit resolution

Drift Chamber:

- 47 layers
- 93% of 4π
- Δp/p = 0.6% @ p=1.0 GeV

CsI Calorimeter:

- 93% of 4π
- ΔE/E = 4% @ E=100 MeV

B field 1.0 T

Muon Chambers:

- 85% of 4π
- Identify muons for p > 1 GeV

Particle Identification:

- RICH detector
- dE/dx in drift chamber
- Combined ε (π or K) > 90%

Di-electron Widths of Υ(1S,2S,3S) Resonances

Di-electron widths (Γ_{ee}) are basic parameters of any onium system. Their measurement can also test new unquenched lattice QCD calculations.

Precision of previously measured Γ_{ee}:

- 2.2% for Υ(1S)
- 4.2% for Υ(2S)
- 9.4% for Υ(3S)

CESR scanned center-of-mass energies in the vicinity of the Υ(1S), Υ(2S) and Υ(3S) resonances.

11 scans @ Υ(1S): $\int \mathcal{L}\, dt = 0.27\ fb^{-1}$
6 scans @ Υ(2S): $\int \mathcal{L}\, dt = 0.08\ fb^{-1}$
7 scans @ Υ(3S): $\int \mathcal{L}\, dt = 0.22\ fb^{-1}$

Data below resonances to constrain backgrounds

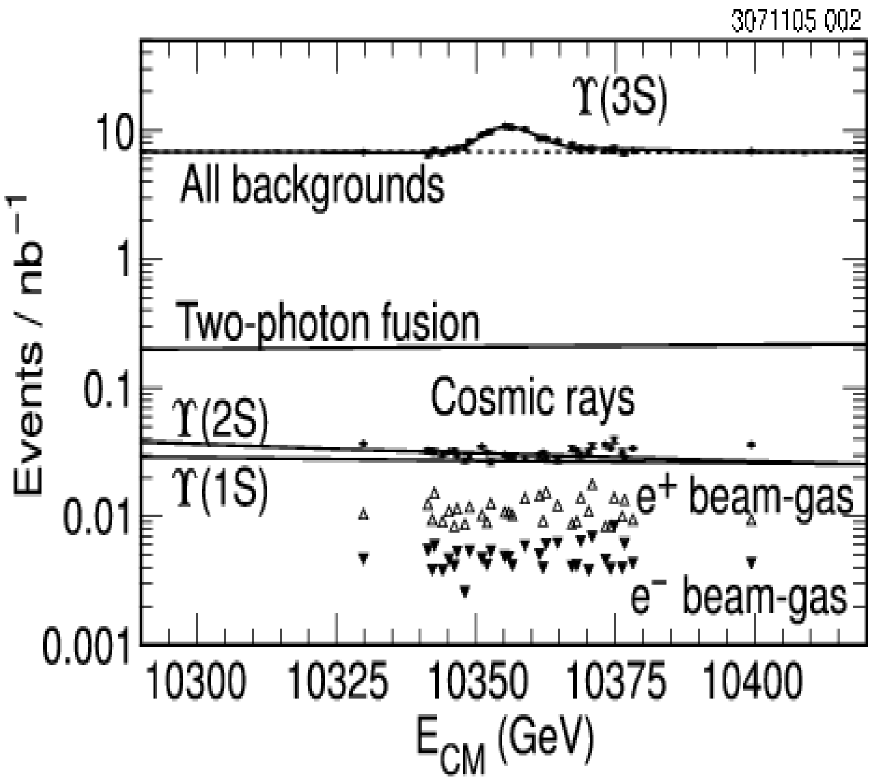
$\int \mathcal{L}\, dt = 0.19\ fb^{-1}$
$\int \mathcal{L}\, dt = 0.41\ fb^{-1}$
$\int \mathcal{L}\, dt = 0.14\ fb^{-1}$

Di-electron Widths of Υ(1S,2S,3S) Resonances

Γ_{ee} measurement method:

- Fit the hadronic cross-section and get $\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$.
- Correct for the missing leptonic modes. Use $B_{\mu\mu}$ to get Γ_{ee} (assuming $B_{ee}=B_{\mu\mu}=B_{\tau\tau}$).

$$\Gamma_{ee} = (\Gamma_{ee}\Gamma_{had}/\Gamma_{tot})/(1-3B_{\mu\mu})$$



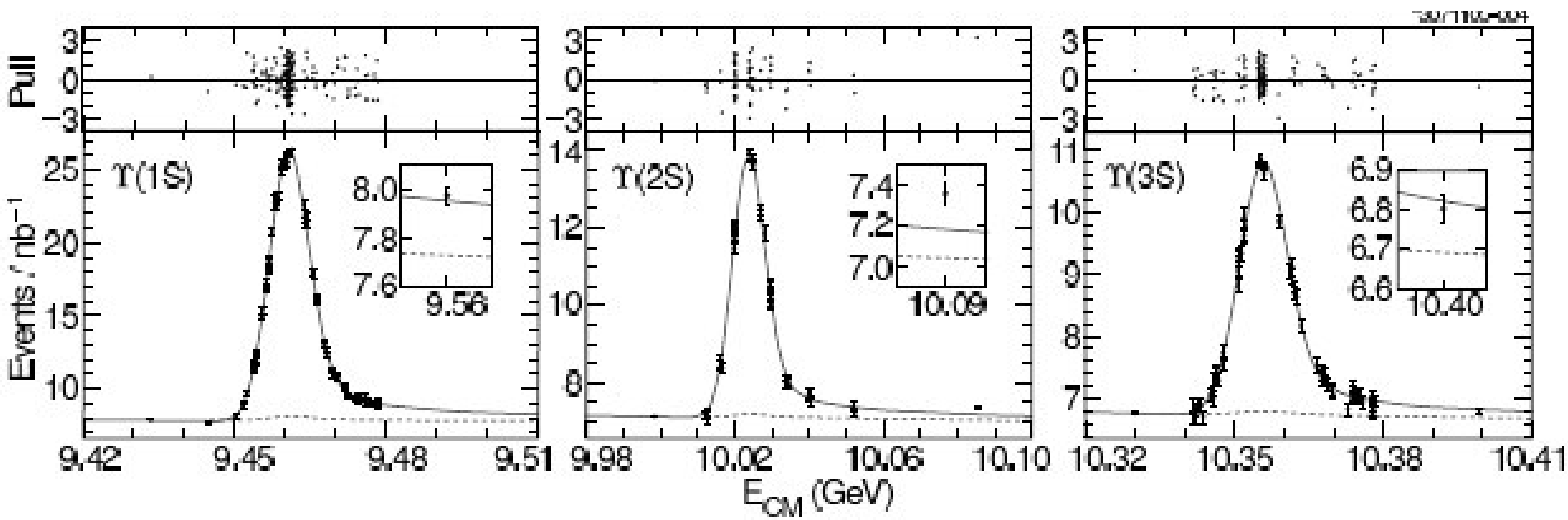
Main backgrounds:

- Two-photon events ($e^+e^- \rightarrow e^+e^-X$). ~ln s.
- Cosmic rays and beam gas interactions.
- Background from the high-energy tails of the Υ(1S) and Υ(2S).

The figure shows the event yields as a function of E_{cm} in the Υ(3S) region.
Top points are data with the fit superimposed.
Dashed curve – the sum of all backgrounds.
The lower points and lines show the individual backgrounds.

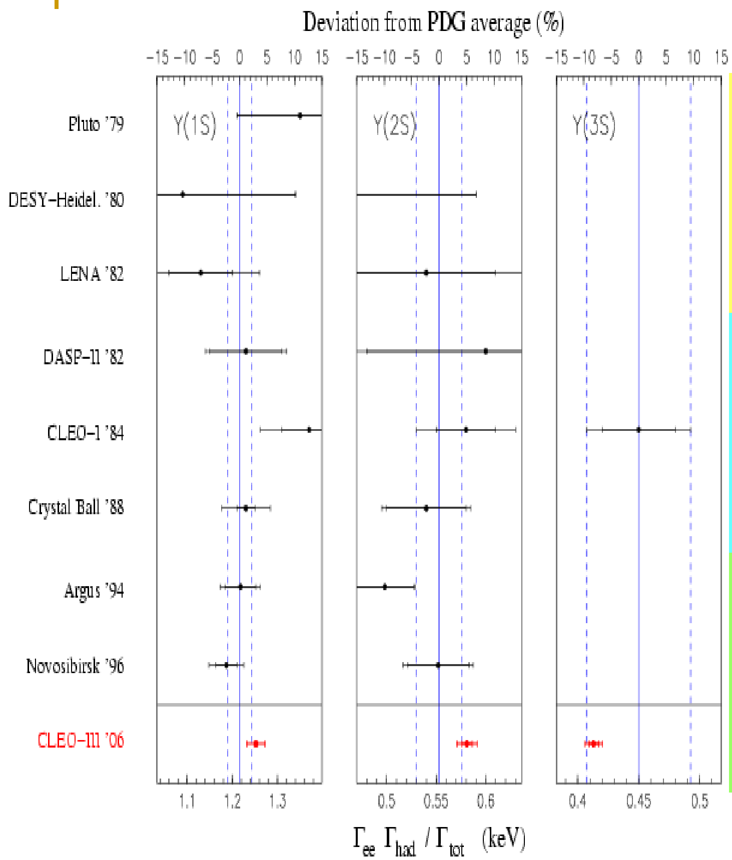
Di-electron Widths of Υ(1S,2S,3S) Resonances

- Subtract cosmic ray and beam-gas backgrounds.
- Fit each resonance to convolution of:
  - Breit-Wigner resonance including interference between $\Upsilon \to q\bar{q}$ and $e^+e^- \to q\bar{q}$
  - Initial-state radiation
  - Gaussian spread in CESR beam energy of (4 MeV)
  - Background terms proportional to 1/s and ln(s)



- Statistical errors: 0.3% (Υ(1S)), 0.7% (Υ(2S)), 1.0% (Υ(3S)).
- Main systematic errors: luminosity measurement (1.3%), hadronic efficiency (0.5%).

Di-electron Widths of Υ(1S,2S,3S) Resonances



		% Error	PDG % Error
$\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}(1S)$	$1.252 \pm 0.004 \pm 0.019$ keV		
$\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}(2S)$	$0.581 \pm 0.004 \pm 0.009$ keV		
$\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}(3S)$	$0.413 \pm 0.004 \pm 0.006$ keV		
$\Gamma_{ee}(1S)$	$1.354 \pm 0.004 \pm 0.020$ keV	1.5	2.2
$\Gamma_{ee}(2S)$	$0.619 \pm 0.004 \pm 0.010$ keV	1.7	4.2
$\Gamma_{ee}(3S)$	$0.446 \pm 0.004 \pm 0.007$ keV	1.8	9.4
$\Gamma_{ee}(2S)/\Gamma_{ee}(1S)$	$0.457 \pm 0.004 \pm 0.004$		
$\Gamma_{ee}(3S)/\Gamma_{ee}(1S)$	$0.329 \pm 0.003 \pm 0.003$		
$\Gamma_{ee}(3S)/\Gamma_{ee}(2S)$	$0.720 \pm 0.009 \pm 0.007$		

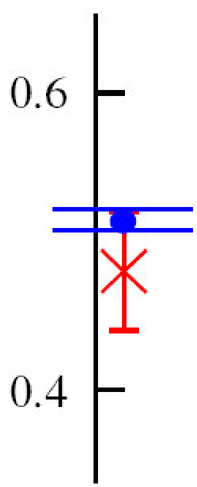
Assuming $B_{ee} = B_{\mu\mu}$ gives:

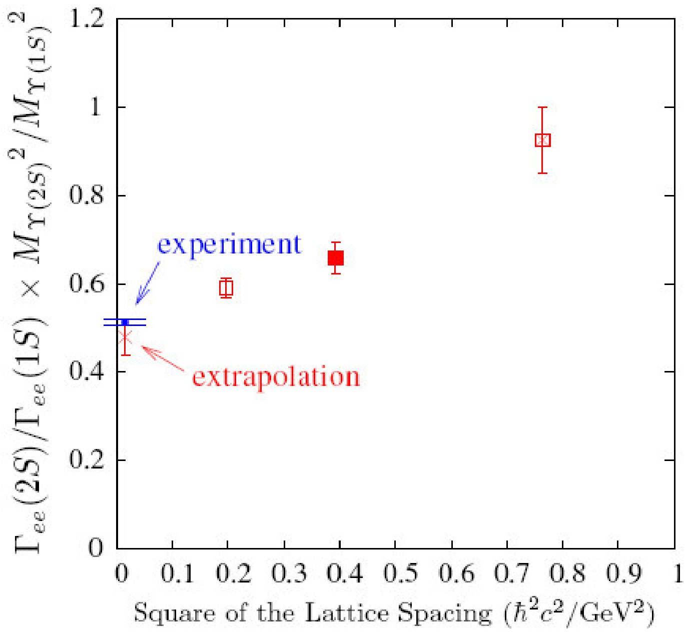
$\Gamma_{tot}[\Upsilon(1S)] = 54.4 \pm 0.2$ (stat.) ± 0.8 (syst.) ± 1.6 ($\sigma_{B\mu\mu}$) keV
$\Gamma_{tot}[\Upsilon(2S)] = 30.5 \pm 0.2$ (stat.) ± 0.5 (syst.) ± 1.3 ($\sigma_{B\mu\mu}$) keV
$\Gamma_{tot}[\Upsilon(3S)] = 18.6 \pm 0.2$ (stat.) ± 0.3 (syst.) ± 0.9 ($\sigma_{B\mu\mu}$) keV

Di-electron Widths of Υ(1S,2S,3S) Resonances

- **Comparison with newest unquenched lattice QCD results,**
- **Most precise parameter =** $$\frac{\Gamma_{ee}(2S)\cdot M^2(2S)}{\Gamma_{ee}(1S)\cdot M^2(1S)}$$

= 0.48 ± 0.05 - Lattice QCD, A.Gray et al., Phys. Rev. D72, 094507 (2005).
= 0.514 ± 0.007 – CLEO, J.L.Rosner et al., Phys. Rev. Lett. 96, 092003 (2006).

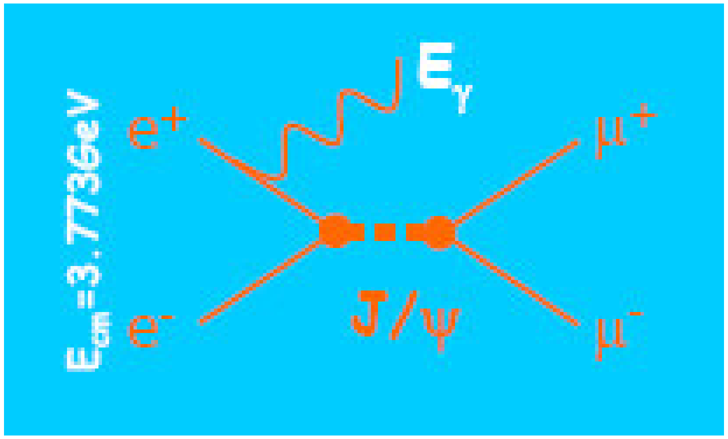




The final lattice QCD results are expected to have a few percent precision in Γ_{ee}(nS)/Γ_{ee}(mS) and ~10% in Γ_{ee}(nS).

Measurement of $\Gamma_{ee}(J/\psi)$, $\Gamma_{tot}(J/\psi)$, $\Gamma_{ee}[\psi(2S)]/\Gamma_{ee}(J/\psi)$

- Use data at $\psi(3770)$, look for radiative return events to J/ψ.
- Select $\mu^+\mu^-(\gamma)$ events with a $M(\mu^+\mu^-) = M(J/\psi)$.
- Resulting cross-section proportional to $\mathcal{B}_{\mu\mu} \times \Gamma_{ee}(J/\psi)$.
- Divide by new CLEO $\mathcal{B}_{\mu\mu}$ (1.2% precision) to get $\Gamma_{ee}(J/\psi)$.
- Assume $\mathcal{B}_{ee} = \mathcal{B}_{\mu\mu}$, divide by again to get $\Gamma_{tot}(J/\psi)$.



R e s u l t s:

$\mathcal{B}(J/\psi \to \mu^+\mu^-) \times \Gamma_{ee}(J/\psi) = 0.3384 \pm 0.0058$ (stat.) ± 0.0071 (syst.) keV
$\Gamma_{ee}(J/\psi) = 5.68 \pm 0.11$ (stat.) ± 0.13 (syst.) keV
$\Gamma_{tot}(J/\psi) = 95.5 \pm 2.4$ (stat.) ± 2.4 (syst.) keV

Measurement of $\Gamma_{ee}(J/\psi)$, $\Gamma_{tot}(J/\psi)$, $\Gamma_{ee}[\psi(2S)]/\Gamma_{ee}(J/\psi)$

- Using a recent CLEO measurement of $\Gamma_{ee}[\psi(2S)]$, $\Gamma_{ee}[\psi(2S)] = 2.54 \pm 0.03 \pm 0.11$ keV, we determine the ratio:

$\Gamma_{ee}[\psi(2S)]/\Gamma_{ee}(J/\psi) = 0.45 \pm 0.01$ (stat.) ± 0.02 (syst.)

	CLEO	Previous World Average
$B_{\mu\mu} \times \Gamma_{ee}$	3.0%	3.2%
Γ_{ee}	3.0%	3.1%
Γ_{tot}	3.4%	3.5%
$\Gamma_{ee}(2S)/\Gamma_{ee}(1S)$	4.9%	6.5%

G.S. Adams et al., Phys. Rev. D73, 051103 (R), (2006).

Measurement of $\sigma(\psi(3770) \to \text{hadrons})$ and $\Gamma_{ee}(\psi(3770))$

- Lead-Glass Wall (1977), Mark II (1981) measured $\sigma(\psi(3770) \to \text{hadrons}) \sim 10$ nb.

- Mark III (1988) using a double-tag technique measured $\sigma(\psi(3770) \to DD) \sim 5$ nb.

- Complete surprise since $\sigma(\psi(3770) \to \text{non-}D\bar{D}) \ll \sigma(\psi(3770) \to D\bar{D})$.

- CLEO repeats Mark III measurement:
  $\sigma(\psi(3770) \to DD) = (6.39 \pm 0.10\ ^{+0.17}_{-0.08})$ nb.
  Q. He et al., Phys. Rev. Lett. 95, 121801 (2005).

- So remeasure $\sigma(\psi(3770) \to \text{hadrons})$ using:

$$\sigma_{\psi(3770)} = \frac{N_{\psi(3770)}}{\varepsilon_{\psi(3770)} \cdot \mathcal{L}_{\psi(3770)}}$$

$N_{\psi(3770)}$ = number of observed hadron events from $\psi(3770)$ decays.
$\varepsilon_{\psi(3770)}$ = hadron event efficiency, = 80%.
$\mathcal{L}_{\psi(3770)}$ = integrated luminosity, = $(281.3 \pm 2.8)\ \text{pb}^{-1}$.

Measurement of $\sigma(\psi(3770) \to \text{hadrons})$ and $\Gamma_{ee}(\psi(3770))$

$$N_{\psi(3770)} = N_{on-\psi(3770)} - N_{q\bar{q}} - N_{\psi(2S)} - N_{J/\psi} - \sum_{l=\tau,\mu,e} N_{l^+l^-}$$

$N_{on-\psi(3770)}$ is the observed number of hadronic events in the $\psi(3770)$ data.
N_{qq} – number of the hadronic events from $e^+e^- \to \gamma^* \to q\bar{q}$.
$N_{\psi(2S)}$ / $N_{J/\psi}$ & $N_{l^+l^-}$ - number of hadronic events from $\psi(2S)$ / J/ψ & from $e^+e^- \to \ell^+\ell^-$.

$\sigma_{\psi(3770)} = (6.38 \pm 0.08 \,^{+0.41}_{-0.30})$ nb

D. Besson et al., hep-ex/0512038

Significantly smaller than Lead-Glass Wall and Mark II measurements.

$\sigma_{\psi(3770)} - \sigma_{\psi(3770)\to D\bar{D}} = (-0.01 \pm 0.08 \,^{+0.41}_{-0.30})$ nb

Consistent with only small $\sigma(\psi(3770) \to \text{non-}D\bar{D})$. Mystery solved.

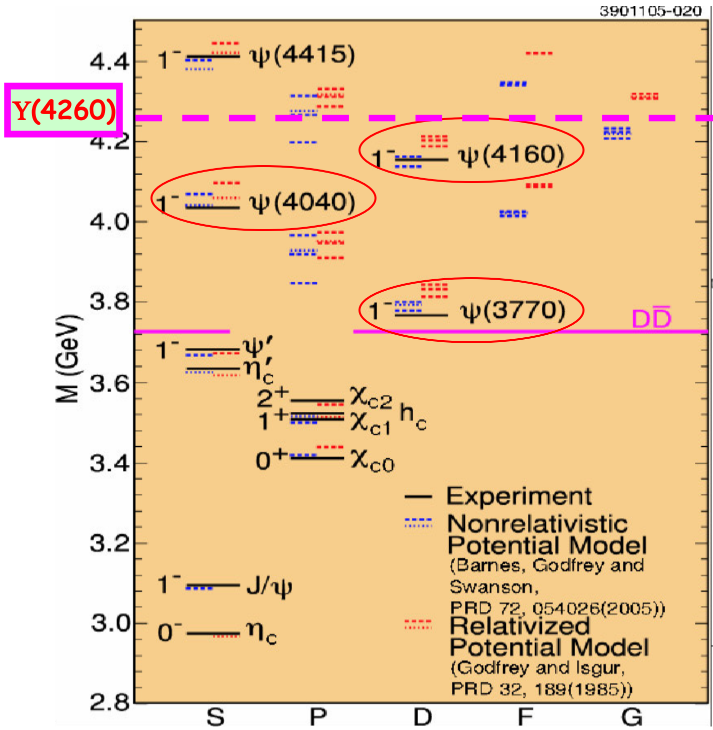
- Using our $\sigma(\psi(3770) \to \text{hadron})$ number and M and Γ_{tot} from PDG, get:

$\Gamma_{ee}(\psi(3770)) = (0.204 \pm 0.003 \,^{+0.041}_{-0.027})$ keV

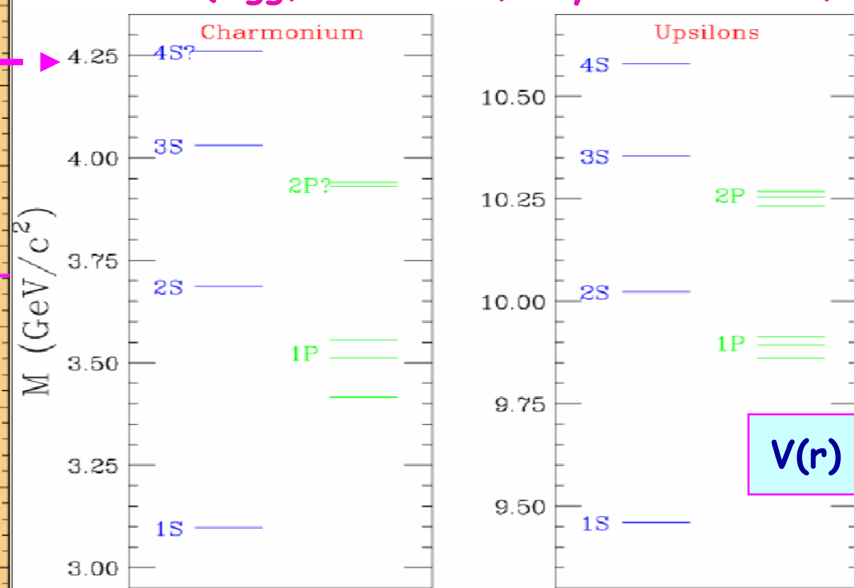
- Consistent with PDG value of 0.26 ± 0.04.

Charmonium decays of ψ(4040), ψ(4160) & Υ(4260)

The region at center-of-mass energies above charmonium open-flavor production threshold is of great theoretical interest due to its richness of $c\bar{c}$ states, the properties of which are not well understood.



C. Quigg, J. Rosner, Phys. Lett. B71, 153 (1977)



$V(r) = C\ln(r/r_0)$

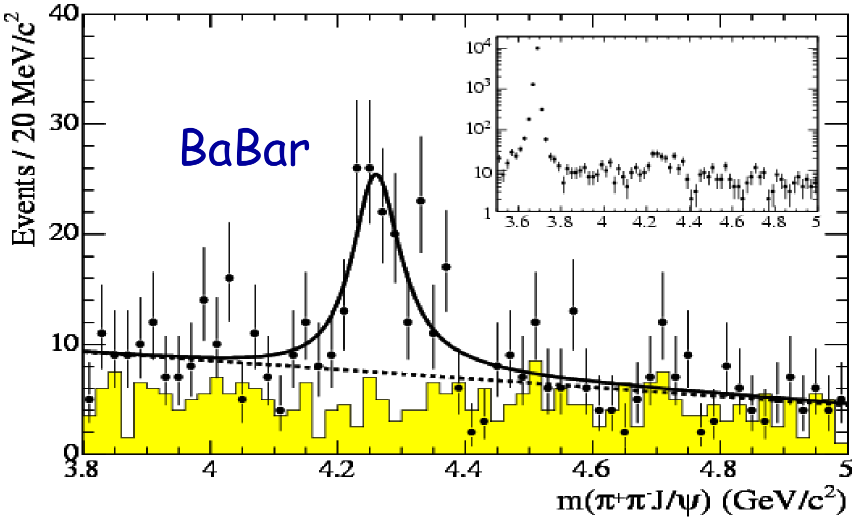
Prominent structures in the hadronic cross-section are the ψ(3770), the ψ(4040) and the ψ(4160).

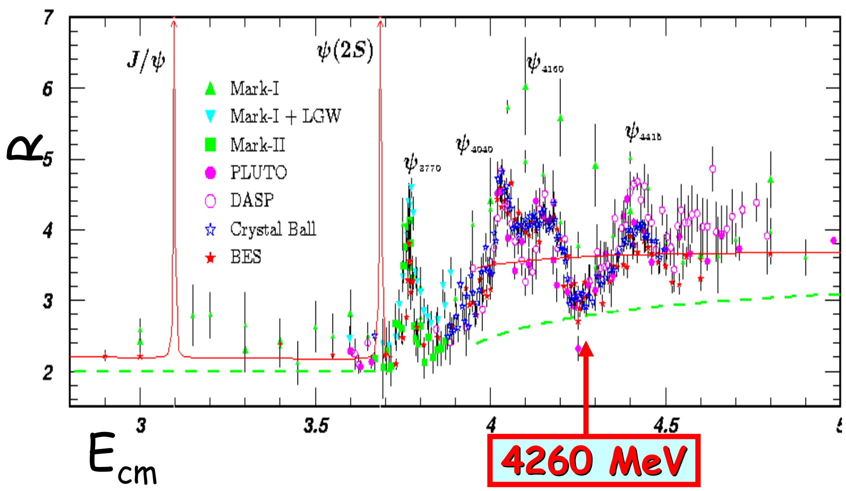
Main characteristics of states above open-charm threshold:

- Large total widths;
- Weaker couplings to leptons than the J/ψ and ψ(2S);
- Decays to closed-charm states are not favored.

Charmonium decays of $\psi(4040)$, $\psi(4160)$ & $\Upsilon(4260)$

BaBar finds enhancement in $e^+e^- \rightarrow \gamma(\pi^+\pi^- J/\psi)$. Not yet confirmed.





B.Aubert et al., Phys. Rev. Lett. 95, 142001 (2005)

Mass: $M = 4259 \pm 8\ ^{+2}_{-6}$ MeV

Width: $\Gamma_{tot} = 88 \pm 23\ ^{+6}_{-4}$ MeV

Coupling: $\Gamma_{ee} \times B(\Upsilon(4260) \rightarrow \pi^+\pi^- J/\psi) = 5.5 \pm 1.0\ ^{+0.8}_{-0.7}$ eV

J^{PC} of $\Upsilon(4260)$ is 1^{--} since it is observed in ISR

$\Upsilon(4260)$ located at a local minimum of the total hadronic cross-section.

Theory explanations of $\Upsilon(4260)$

Hybrid charmonium ($c\bar{c}g$): suppress $D(^*)\bar{D}(^*)$, $D_s(^*)\bar{D}_s(^*)$; $K^+K^- \approx \pi^+\pi^-$?; $\pi^0 J/\psi$? $\pi^+\pi^-$?

$\bar{D}D_1$ as another possible decay of the $\Upsilon(4260)$.

Tetraquark $(cs)(\overline{cs})$: member of nonet along with X(3872) & X(3940). Must decay into $D_s\bar{D}_s$.

$\chi_{cJ}\ \rho^0$ molecule: no decay into $\pi^0\pi^0 J/\psi$.

$\chi_{cJ}\ \omega$ molecule: $\pi^0\pi^0/\pi^+\pi^- \approx 0.5$; $\gamma\chi_{cJ}$, $\gamma\gamma J/\psi$, $\gamma\pi^+\pi^-\pi^0 J/\psi$.

Baryonium molecule: tiny KKJ/ψ; $\pi^0\pi^0/\pi^+\pi^- \approx 1$.

$\psi(4S)$ $c\bar{c}$ state: interference effects produce dip in open-charm. $\psi(4040) \rightarrow \pi^+\pi^- J/\psi$.

Charmonium decays of ψ(4040), ψ(4160) & Υ(4260)

- To confirm and clarify Υ(4260), CLEO performed scan from √s = 3.97 – 4.26 GeV.
- Look for decays to 16 final states containing a J/ψ, ψ(2S), χ_{cJ} or ϕ.

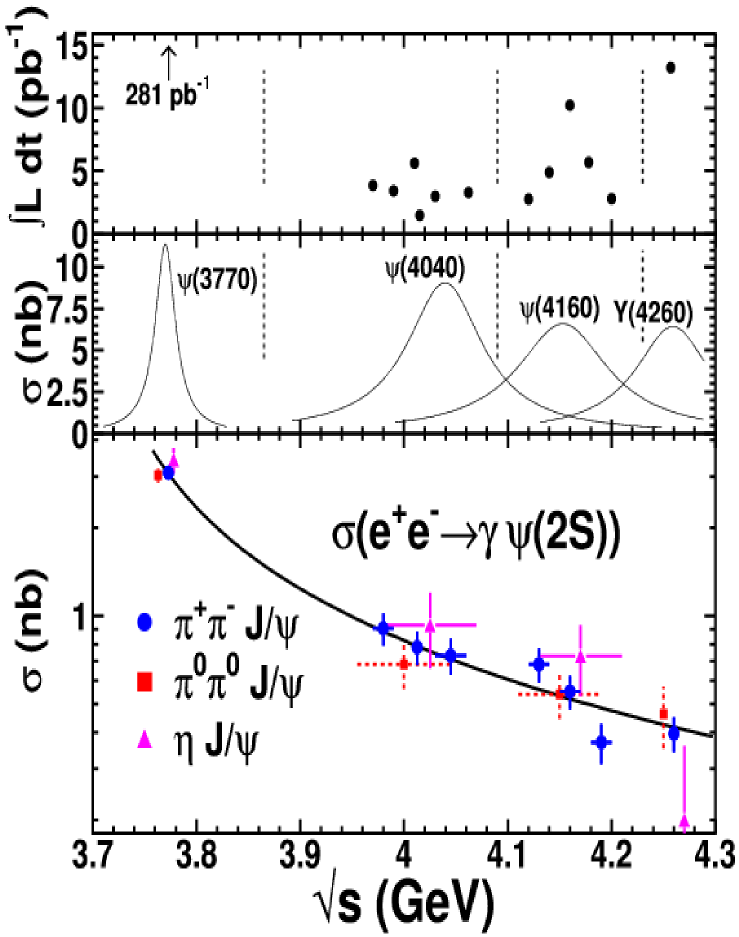
Scan regions:

- ψ(4040): $\int \mathcal{L}\,dt$ = 20.7 pb^{-1} @ √s = 3.97-4.06 GeV
- ψ(4160): $\int \mathcal{L}\,dt$ = 26.3 pb^{-1} @ √s = 4.12-4.20 GeV
- Υ(4260): $\int \mathcal{L}\,dt$ = 13.2 pb^{-1} @ √s = 4.26 GeV

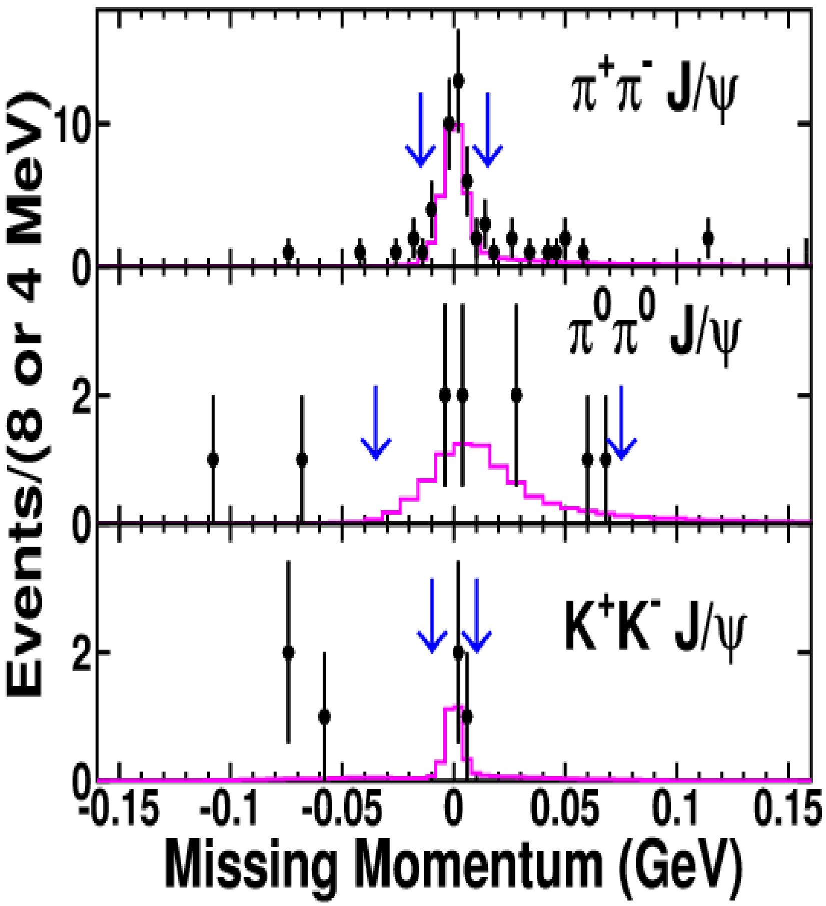
Born-level Breit-Wigner line shapes between √s = 3.97 & 4.4 GeV indicating the grouping of scan points.

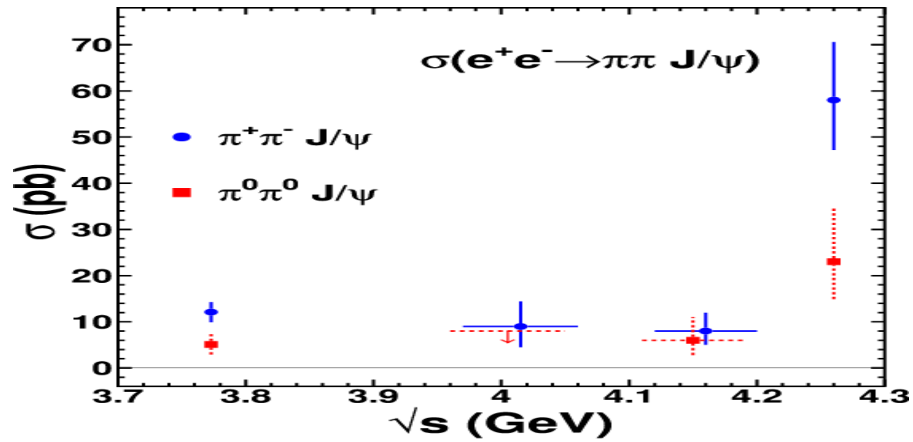
The radiative return (RR) process e^+e^- → γ ψ(2S) → XJ/ψ results in final states which are identical to some of our signal modes.

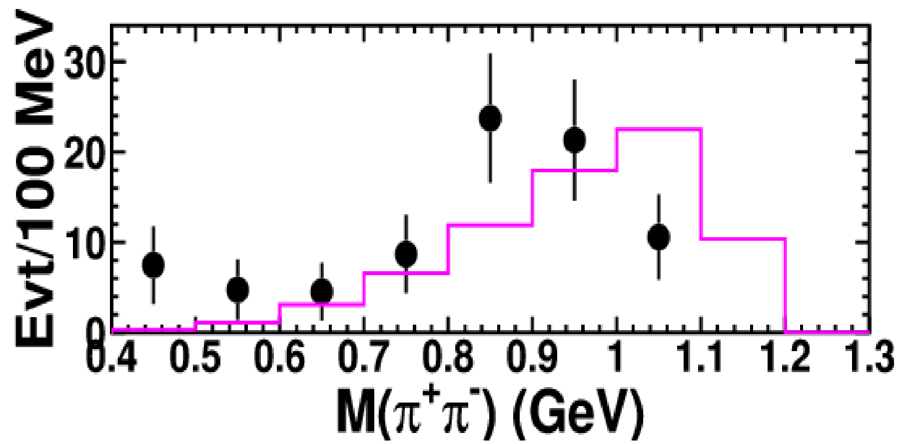
This is one indication that our efficiencies, luminosities and overall normalizations are understood.



Charmonium decays of ψ(4040), ψ(4160) & Υ(4260)







Data taken @ √s = 4.26 GeV.
Solid line histogram from MC simulation.

Efficiency corrected. Solid histogram from ψ(2S)-like MC.

Charmonium decays of $\psi(4040)$, $\psi(4160)$ & $Y(4260)$

- We confirm (@ 11σ significance) the $Y(4260) \to \pi^+\pi^- J/\psi$ discovery.
- First observation of $Y(4260) \to \pi^0\pi^0 J/\psi$ (5.1σ).
- First evidence for $Y(4260) \to K^+K^- J/\psi$ (3.7σ).
- We measure the following production cross-sections @ $\sqrt{s}$ = 4.26 GeV:

$\sigma(\pi^+\pi^- J/\psi) = 58\ ^{+12}_{-10} \pm 4$ pb,
$\sigma(\pi^0\pi^0 J/\psi) = 23\ ^{+12}_{-8} \pm 1$ pb,
$\sigma(K^+K^- J/\psi) = 9\ ^{+9}_{-5} \pm 1$ pb.

T.E. Coan et al., hep-ex/0602034

- No compelling evidence is found for any other decays in the three resonance regions. We find:

  $B(\psi(4040) \to \pi^+\pi^- J/\psi) < 0.4\%$ and $B(\psi(4160) \to \pi^+\pi^- J/\psi) < 0.4\%$

- The observation of the $\pi^0\pi^0 J/\psi$ mode disfavors $\chi_{CJ}\rho^0$ molecular model.
- The fact that the $\pi^0\pi^0 J/\psi$ rate is about half that of $\pi^+\pi^- J/\psi$ disagrees with the prediction of the baryonium model.
- Observation of the KKJ/ψ decay is also incompatible with these 2 models.
- No enhancement for $\psi(4040) \to \pi^+\pi^- J/\psi$. Identification $Y(4260) = \psi(4S)$ less attractive.
- The results are compatible with hybrid-charmonium interpretation.

Summary

- Precise measurement of Γ_{ee} for $\Upsilon(1S, 2S, 3S)$. Good agreement with unquenched lattice QCD result.
- Improved determinations of Γ_{ee} and Γ_{tot} for J/ψ.
- New measurement of $\sigma(\psi(3770) \rightarrow \text{hadrons})$ – mystery of a large $\psi(3770) \rightarrow$ non-$D\bar{D}$ cross-section solved.
- New measurements of closed-charm decays for the $\psi(4040)$, $\psi(4160)$ and $Y(4260)$:
  - Confirm the BaBar discovery of $Y(4260) \rightarrow \pi^+\pi^- J/\psi$.
  - First observation of $Y(4260) \rightarrow \pi^0\pi^0 J/\psi$.
  - First evidence of $Y(4260) \rightarrow K^+K^- J/\psi$.
- Many CLEO heavy-quarkonium results not covered in this talk – see next slide.

Other Recent CLEO Heavy-Quarkonium Results

"Branching Fractions for $\psi(2S)$ to J/ψ Transitions", PRL 94, 232002 (2005);

"Measurement of the Branching Fractions for $J/\psi \to l^+l^-$", PRD 71, 111103 (2005);

"Observation of Thirteen New Exclusive Multi-Body Hadronic Decays of the $\psi(2S)$", PRL 95, 062001 (2005);

"Branching Fraction Measurements of $\psi(2S)$ Decay to Baryon-Antibaryon Final States", PRD 72, 051108 (2005);

"Observation of the $h_c(1P_1)$ State of Charmonium", PRL 95, 102003 (2005), PRD 72, 092004 (2005);

"Search for Exclusive Multi-Body Non-$D\bar{D}$ Decays at the $\psi(3770)$", PRL 96, 032003 (2006);

"Measurement of the Direct Photon Momentum Spectrum in $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ Decays", hep-ex/0512061;

"Radiative Decays of the $\Upsilon(1S)$ to a Pair of Charged Hadrons", PRD 73, 032001 (2006);

"First Observation of $\psi(3770) \to \gamma\chi_{c1} \to \gamma\gamma J/y$", hep-ex/0509030;

"Decay of the $\psi(3770)$ to Light Hadrons", PRD 73, 012002 (2006);

"Two-Photon Width of the χ_{c2}", S. Dobbs et al., hep-ex/0510033;

"Experimental Study of $\chi_b(2P) \to \pi\pi\chi_b(1P)$", PRD 73, 012003 (2006);

"Radiative Decays of the $\Upsilon(1S)$ to $\gamma\pi^0\pi^0$, $\gamma\eta\eta$ and $\gamma\pi^0\eta$", hep-ex/0512003;

"Observation of $\psi(3770) \to \pi\pi J/\psi$ and Measurement of $\Gamma_{ee}[\psi(2S)]$", hep-ex/0508023;

"Measurement of $\psi(2S)$ Decays to two Pseudoscalar Mesons", hep-ex/0603020;

"Search for the non-$D\bar{D}$ decay $y(3770) \to K_S K_L$", hep-ex/0603026.