Measurement of di-lepton widths and branching fractions of heavy quarkonia at CLEO

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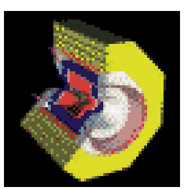
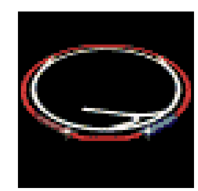


for the CLEO Collaboration



4th International Workshop on Heavy Quarkonium

Brookhaven National Lab

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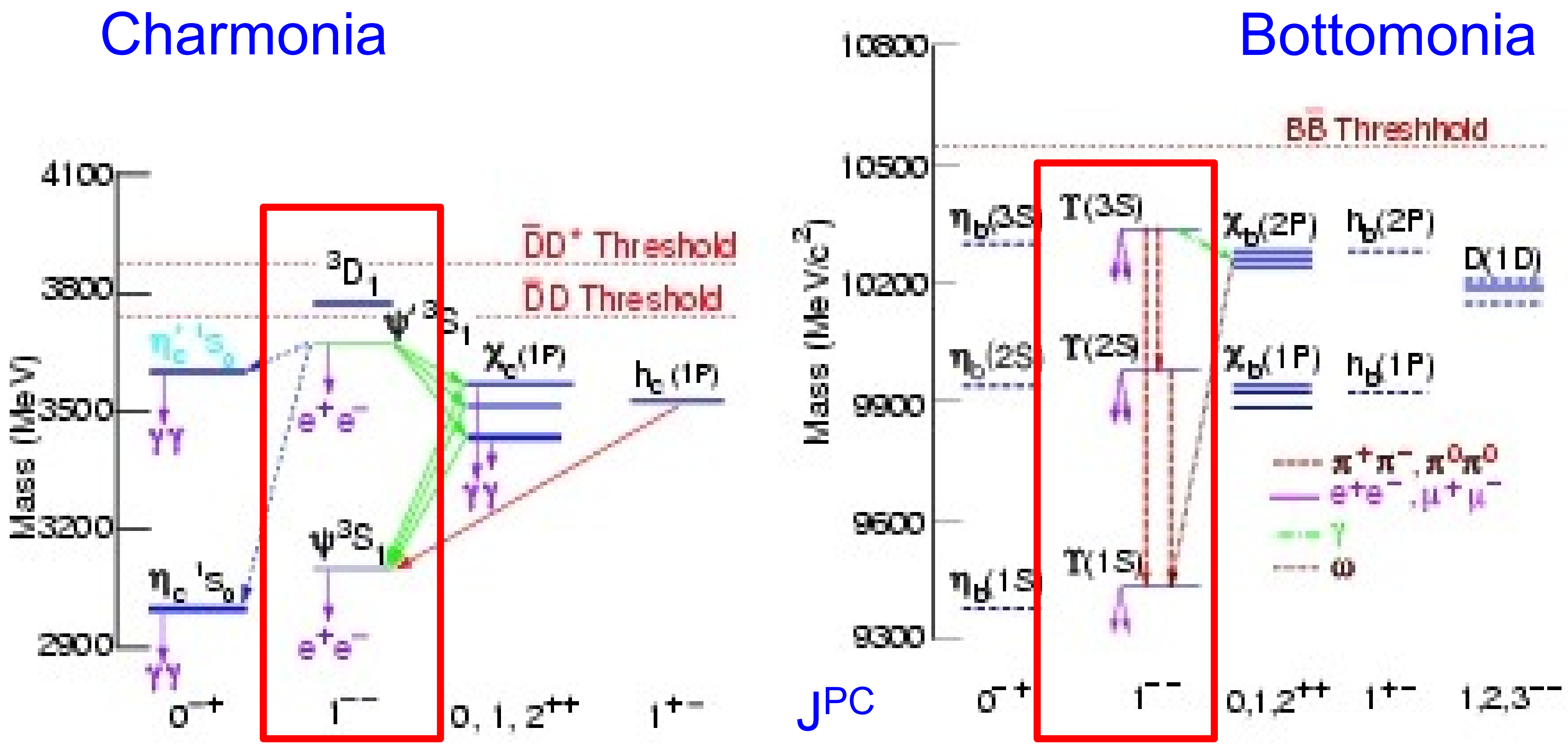
Topics covered

- In the last two years CLEO has measured Γ_{ee} and $B_{\ell\ell}$ (as well as Γ) for several 1^{--} bb (Y) and cc (ψ) states
- Bottominia:
  - $B_{\mu\mu}(Y) = B(Y(nS)\to\mu^+\mu^-)$ for n=1,2,3 PRL 94, 012001 (2005)
  - $\Gamma_{ee}(Y) = \Gamma(Y(nS)\to e^+e^-)$ for n=1,2,3 PRL 96, 092003 (2006)
- Charmonia:
  - $B_{\ell\ell}(J/\psi) = B(J/\psi\to\ell^+\ell^-)$ for ℓ=e,μ PRD 71, 111103(R) (2005)
  - $\Gamma_{ee}(J/\psi) = \Gamma(J/\psi\to e^+e^-)$ PRD 73, 051103(R) (2006)
  - $\Gamma_{ee}[\psi(2S)] = \Gamma(\psi(2S)\to e^+e^-)$ PRL 96, 082004 (2006)
  - $\Gamma_{ee}[\psi(3770)] = \Gamma(\psi(3770)\to e^+e^-)$ PRL 96, 092002 (2006)
- Left out:
  - $B_{\tau\tau}(Y) = B(Y(nS)\to\tau^+\tau^-)$ for n=1,2,3 See talk by J. E. Duboscq Friday morning (session BSM)!

Motivation

- In general, Heavy Quarkonia play the same role in study of the strong interaction as positronium played in the study of QED
- In particular, the fundamental resonance parameters such as the di-electron widths and di-lepton branching fractions, as well as total widths of the Υ and ψ are important for several reason:
  - Γ_{ee} (Γ):
    - test potential models
    - test Lattice QCD calculations (validate high precision unquenched results)
  - $B_{\ell\ell}$:
    - the clean signature of the di-lepton decays are used to measure transition rates between the resonances (and also the production rate of heavy quarkonia at existing and future hadron colliders: Tevatron, RHIC, LHC)
    - test lepton universality and search for possible new physics beyond the SM

Heavy Quarkonia ($Q\bar{Q}$) landscape

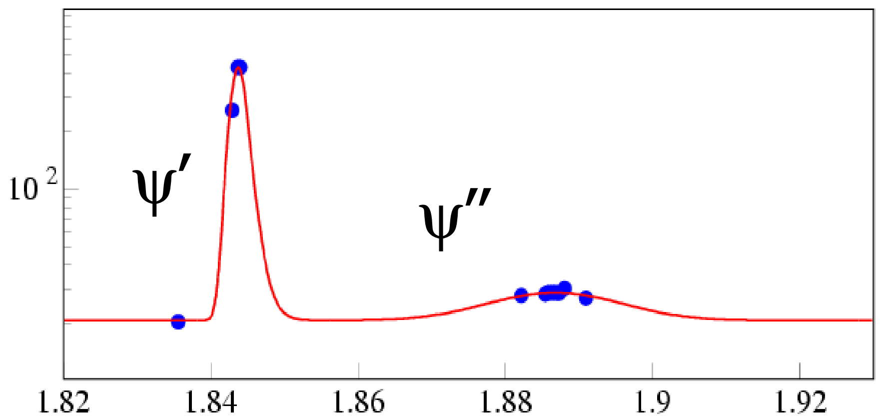


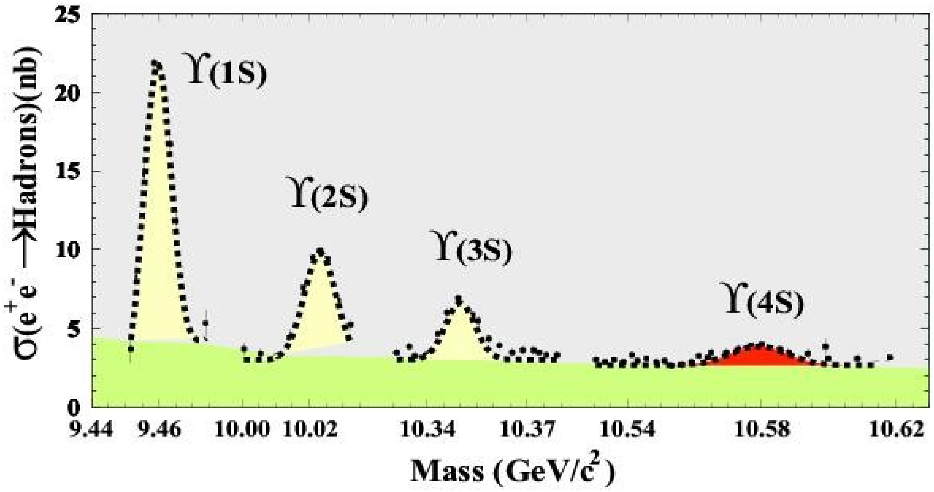
Production of $J^{PC}=1^{--}$ $Q\bar{Q}$ states:

- directly in annihilation: $e^+e^-\rightarrow\gamma^*\rightarrow Q\bar{Q}$,
- after initial state radiation: $e^+e^-\rightarrow\gamma e^+e^-\rightarrow\gamma Q\bar{Q}$,
- populate from higher level states: e.g. $\psi(2S)\rightarrow\pi^+\pi^- J/\psi$

CLEO data on Υ and ψ resonances

- The measurements were carried out at the CESR symmetric e^+e^- collider
- Data were collected by the CLEO III and CLEO-c detector configurations from 2001-2005





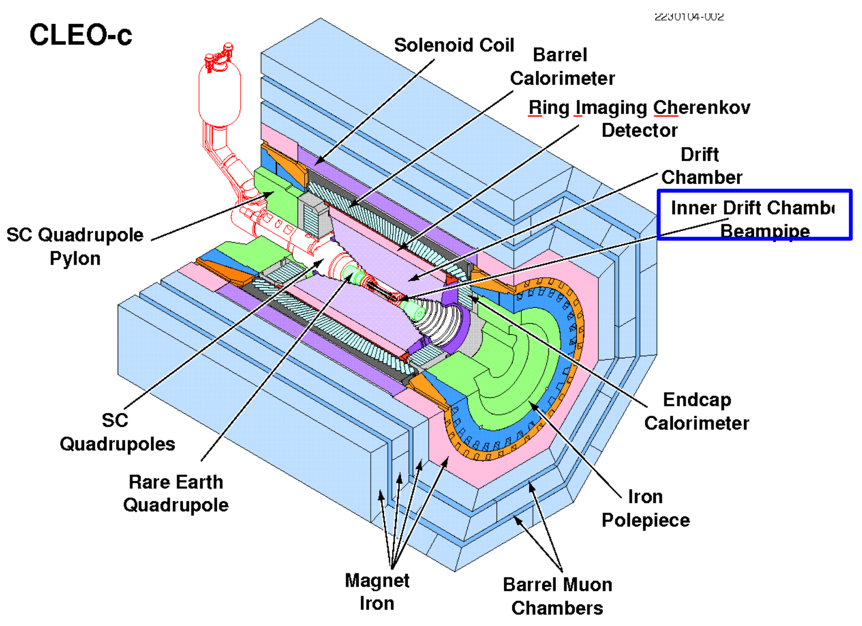
CLEO III + c:

ψ(2S): ~3 M decays

CLEO-c:

ψ(3770): 281 pb-1

off-resonance: 21 pb-1



CLEO III:

Υ(1S): ~22 M decays

Υ(2S): ~10 M decays

Υ(3S): ~6 M decays

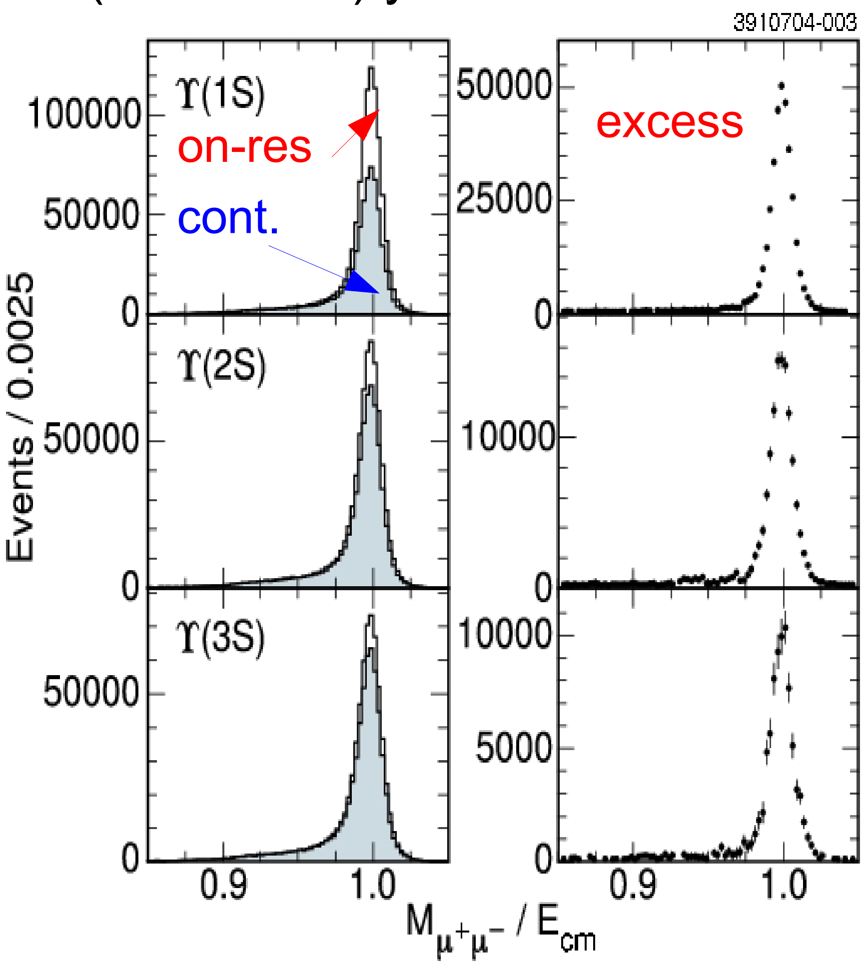
scan data

off-resonance data

B(Υ(1S,2S,3S)→μ⁺μ⁻)

CLEO: PRL 94, 012001 (2005)

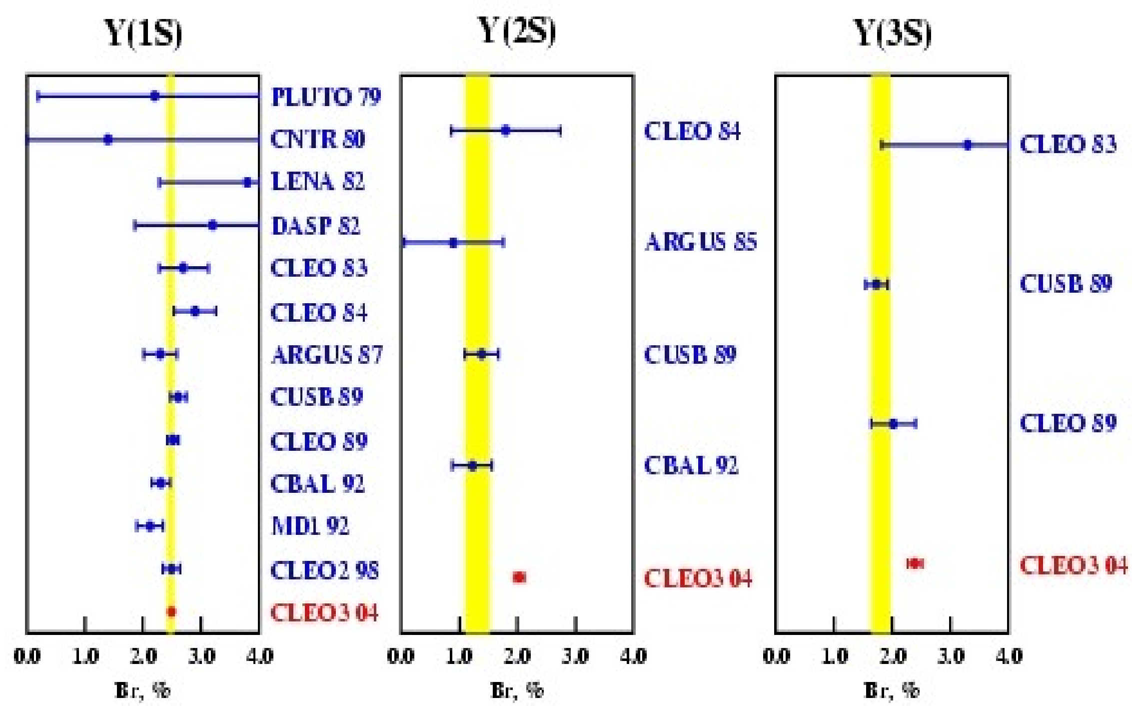
- $B_{\mu\mu}$ is measured from the resonance mu-pair and hadron yields after subtracting off-resonance (continuum) yields



- Final results:

	δB/B
B(1S): (2.49 ± 0.02 ± 0.07)%	2.8%
B(2S): (2.03 ± 0.03 ± 0.08)%	4.0%
B(3S): (2.39 ± 0.07 ± 0.10)%	5.1%

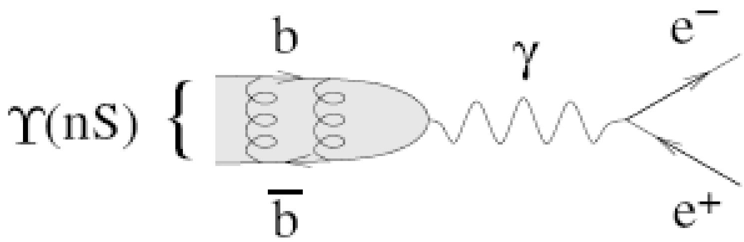
- 3-5% relative precision
- $B_{\mu\mu}$ for Υ(2S) and Υ(3S) is significantly larger than previous measurements



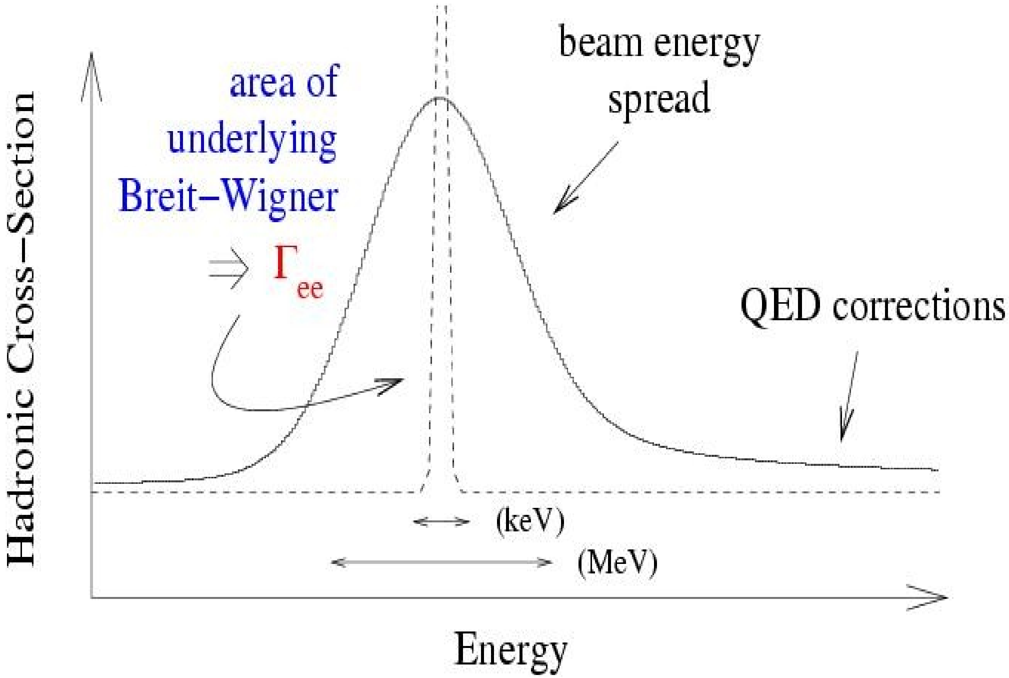
Γ_{ee}[Y(1S,2S,3S)]

CLEO: PRL 96, 092003 (2006)

- Γ_{ee} is the partial decay width of the resonance to di-electrons (it is hard to measure directly due to the large $e^+e^- \to e^+e^-$ background)
- CLEO measured Γ_{ee} using the time-reversed process ($e^+e^- \to$ Y) instead of the decay (Y$\to e^+e^-$)
- The integrated production cross section is proportional to $\Gamma_{ee}=\Gamma(Y(nS)\to e^+e^-)$



$$\Gamma_{ee} = \frac{M_{\Upsilon}^{2}}{6\pi^{2}} \int \sigma(e^+e^- \to \Upsilon)\, dE$$



- Observed line shape is a convolution of
  - BW resonance (including interference between Y $\to$ qq and $e^+e^- \to$ qq)
  - Gaussian c.o.m. energy spread
  - Radiative tail due to ISR
- Area is preserved

Γ_{ee}[Υ(1S,2S,3S)]

- Scan the resonance shape as a function of c.o.m. energy (in several short independent scans – to eliminate beam energy drift):

  1S: 11 scans – 0.27 fb-1

  2S: 6 scans – 0.08 fb-1

  3S: 7 scans – 0.22 fb-1

- plus 0.19 fb-1, 0.41 fb-1 and 0.14fb-1 off-resonance data to constrain background

- From fit to the data extract integrated hadronic cross section

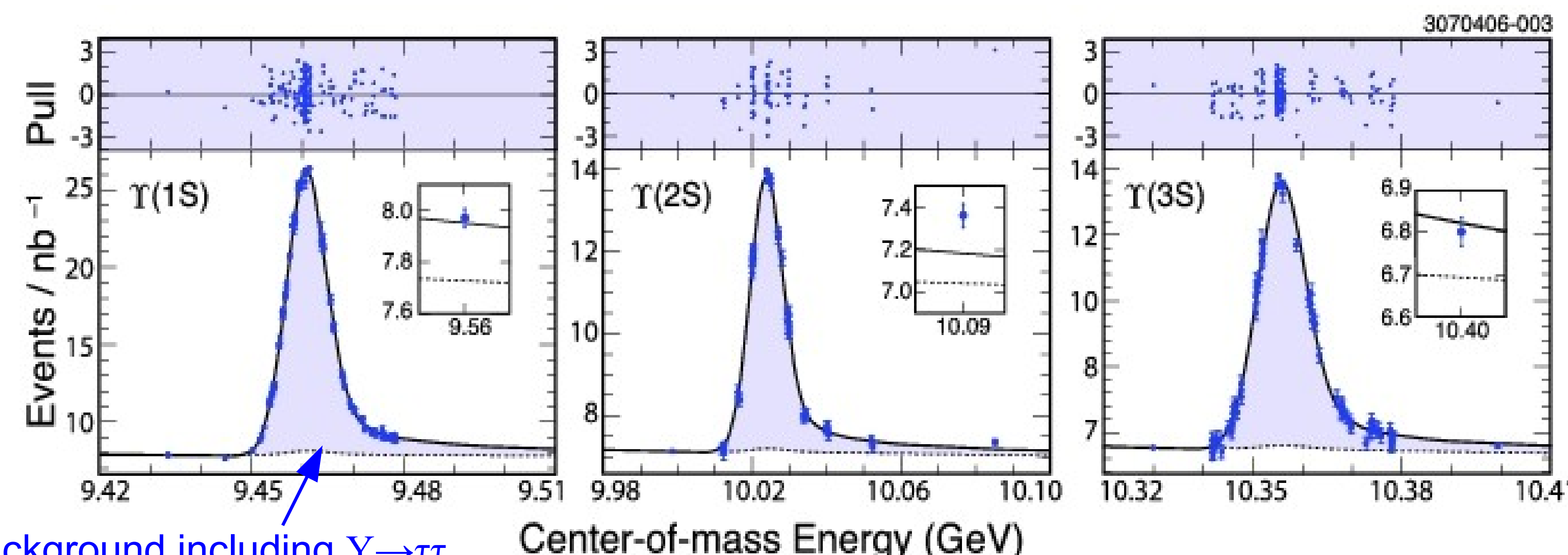
  ⇨ $\Gamma_{ee}\Gamma_{had}/\Gamma$

- Assuming lepton universality:

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

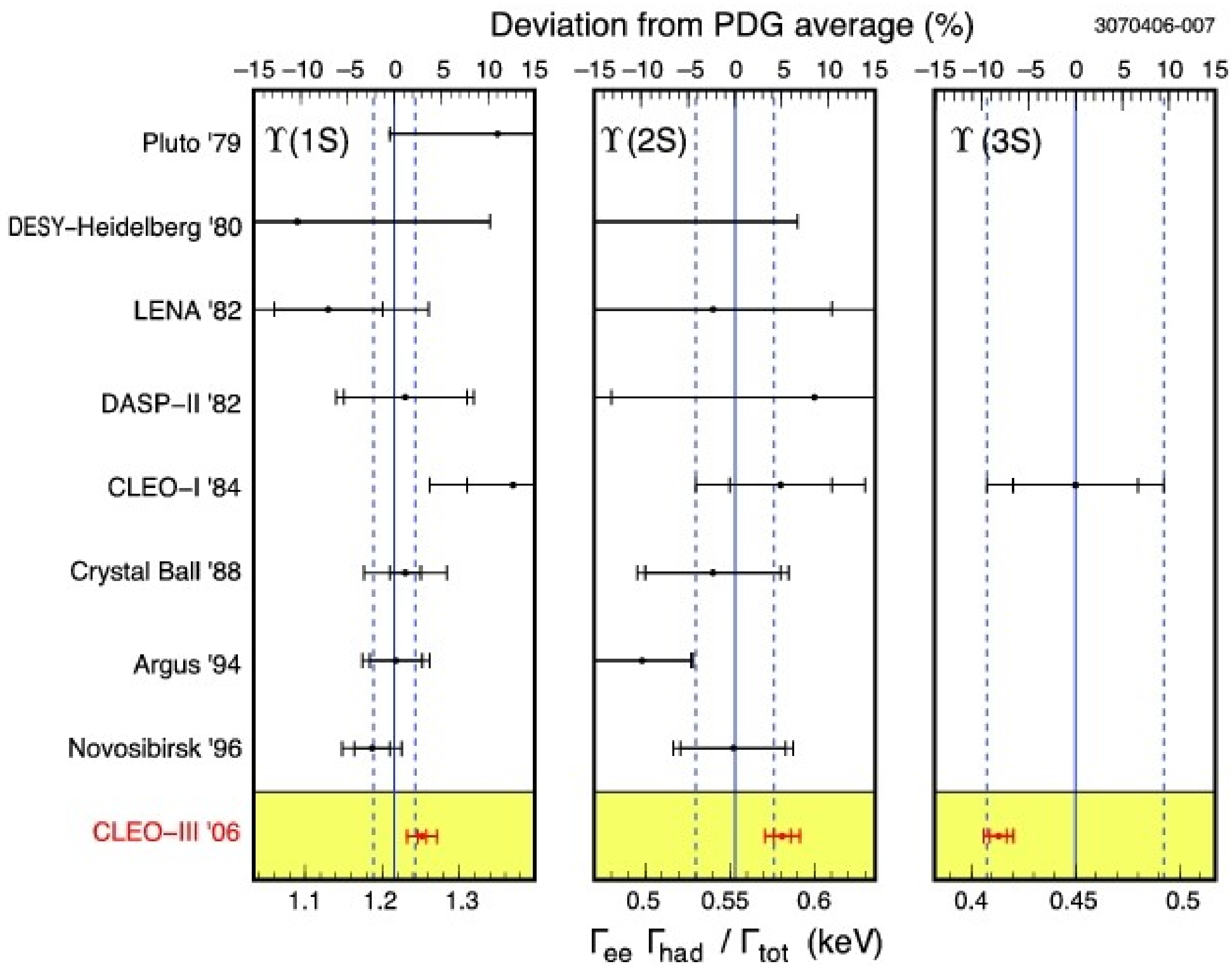
- Then the total width:

  ⇨ $\Gamma = \Gamma_{ee}/B_{\mu\mu}$



Background including $\Upsilon \rightarrow \tau\tau$

$\Gamma_{ee}[\Upsilon(1S,2S,3S)]$



Statistical error:

0.3%, 0.7%, 1.0%

Dominant systematic error:

luminosity: 1.3%

efficiency: 0.5%

Results are consistent with, but more precise than, the PDG average

	$\delta\Gamma_{ee}/\Gamma_{ee}$
$\Gamma_{ee}(1S) = 1.354 \pm 0.004 \pm 0.020$ keV	1.5%
$\Gamma_{ee}(2S) = 0.619 \pm 0.004 \pm 0.010$ keV	1.8%
$\Gamma_{ee}(3S) = 0.446 \pm 0.004 \pm 0.007$ keV	1.8%

$B_{\mu\mu}$ →

stat syst. $B_{\mu\mu}$	$\delta\Gamma/\Gamma$
$\Gamma(1S) = 54.4 \pm 0.2 \pm 0.8 \pm 1.6$ keV	3.3%
$\Gamma(2S) = 30.5 \pm 0.2 \pm 0.5 \pm 1.3$ keV	4.6%
$\Gamma(3S) = 18.6 \pm 0.2 \pm 0.3 \pm 0.9$ keV	5.2%

$\Gamma_{ee}[\Upsilon(1S,2S,3S)]$

The ratio of di-electron widths:

$\Gamma_{ee}(2S)/\Gamma_{ee}(1S)$	$0.457 \pm 0.004 \pm 0.004$
$\Gamma_{ee}(3S)/\Gamma_{ee}(1S)$	$0.329 \pm 0.003 \pm 0.003$
$\Gamma_{ee}(3S)/\Gamma_{ee}(2S)$	$0.720 \pm 0.009 \pm 0.007$

- For comparison with unquenched Lattice QCD calculations the most precise parameter is

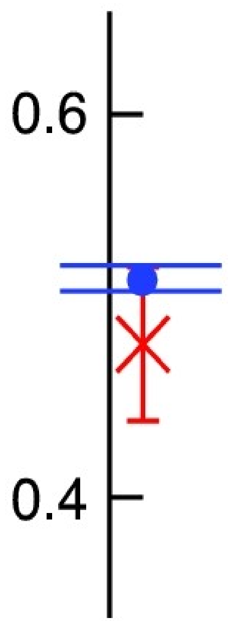
$$(\Gamma_{ee}(2S)M^2(2S))/(\Gamma_{ee}(1S)M^2(1S))$$

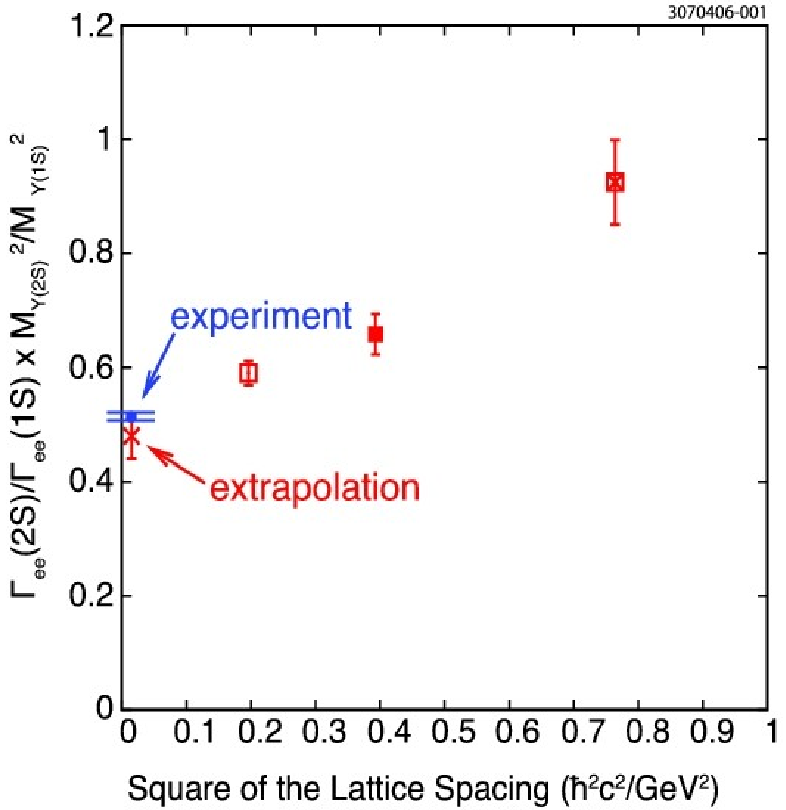
CLEO: 0.514 ± 0.007

LQCD: 0.48 ± 0.05

A. Gray et al. PRD 72, 094507 (2005)

- They are consistent but LQCD has large (10%) error due to extrapolation





The final LQCD results are expected to have a a few percent error on the ratio and 10% error on Γ_{ee}.

B(J/ψ→ℓ+ℓ-)

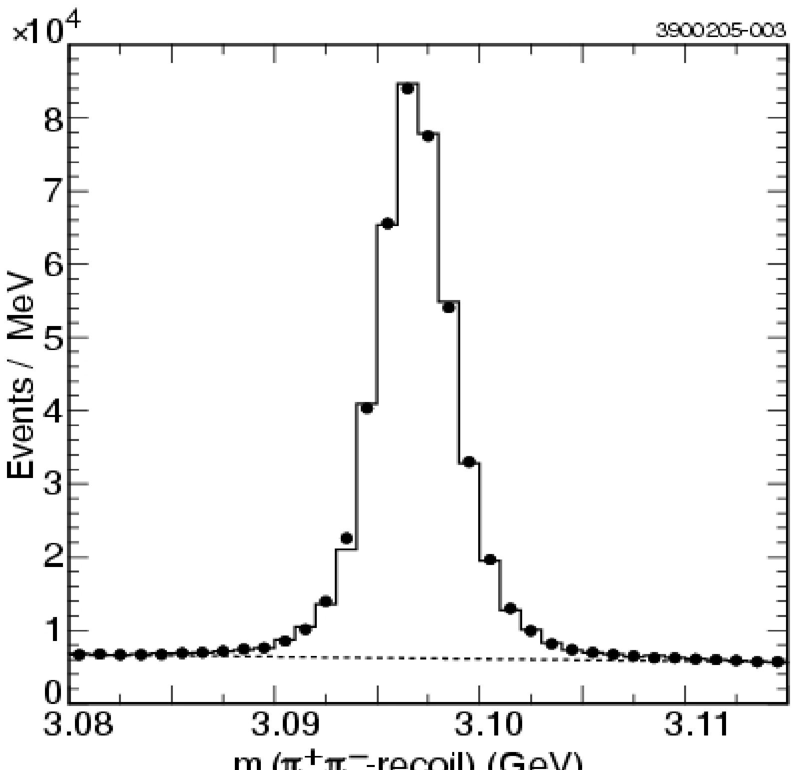
CLEO, PRD 71, 111103(R) (2005)

- Method: use 3M ψ(2S) decays to isolate $\pi^+\pi^- J/\psi$ signal by tagging the soft pions, then

  $B = N(\pi^+\pi^- J/\psi,\ J/\psi \to \ell^+\ell^-) / N(\pi^+\pi^- J/\psi,\ J/\psi \to X)$

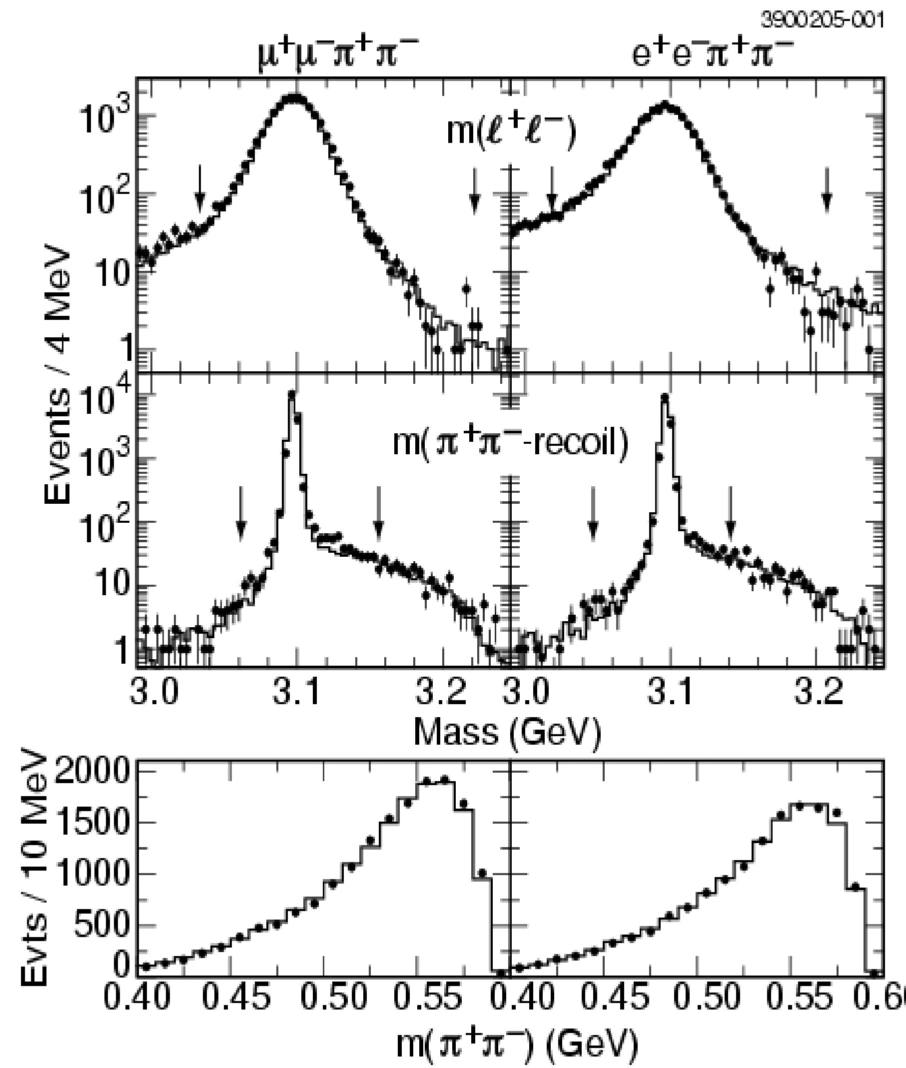
  $\pi^+\pi^-$ systematics mostly cancels

- Denominator: from fit to inclusive recoil mass $m(\pi+\pi-$ -recoil$)$ – $\varepsilon \approx 40\%$



- Numerator: count events after additional $J/\psi \to \ell^+\ell^-$ selection

  $\varepsilon \approx 25\%\ (\pi^+\pi^- e^+e^-)$ $\quad 28\%\ (\pi^+\pi^-\mu^+\mu^-)$



$B(J/\psi \to \ell^+\ell^-)$

- Results:

$B(J/\psi \to e^+e^-) = (5.945 \pm 0.067 \pm 0.042)\%$
$B(J/\psi \to \mu^+\mu^-) = (5.960 \pm 0.065 \pm 0.050)\%$

- The ratio of the ee and $\mu\mu$ branching fractions:

$B(J/\psi \to \mu^+\mu^-)/B(J/\psi \to e^+e^-) = (99.7 \pm 1.2 \pm 0.6)\ \%$

consistent with lepton universality within 1.3%

- Assuming lepton universality, the average:

$B(J/\psi \to \ell^+\ell^-) = (5.953 \pm 0.056 \pm 0.042)\%$

$\delta B/B = 1.18\%$

$\Gamma_{ee}(J/\psi)$

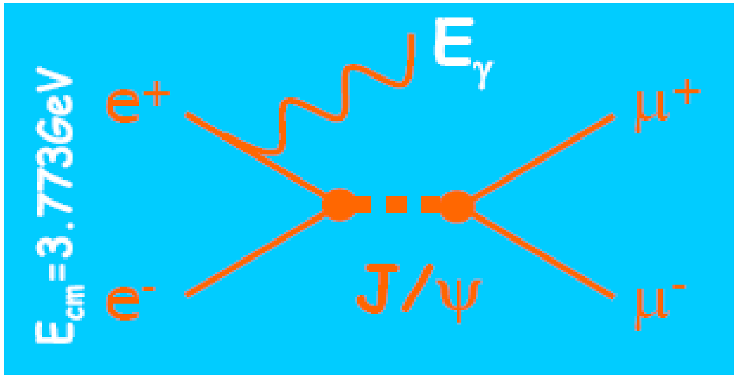
CLEO: PRD 73, 051103(R) (2006)

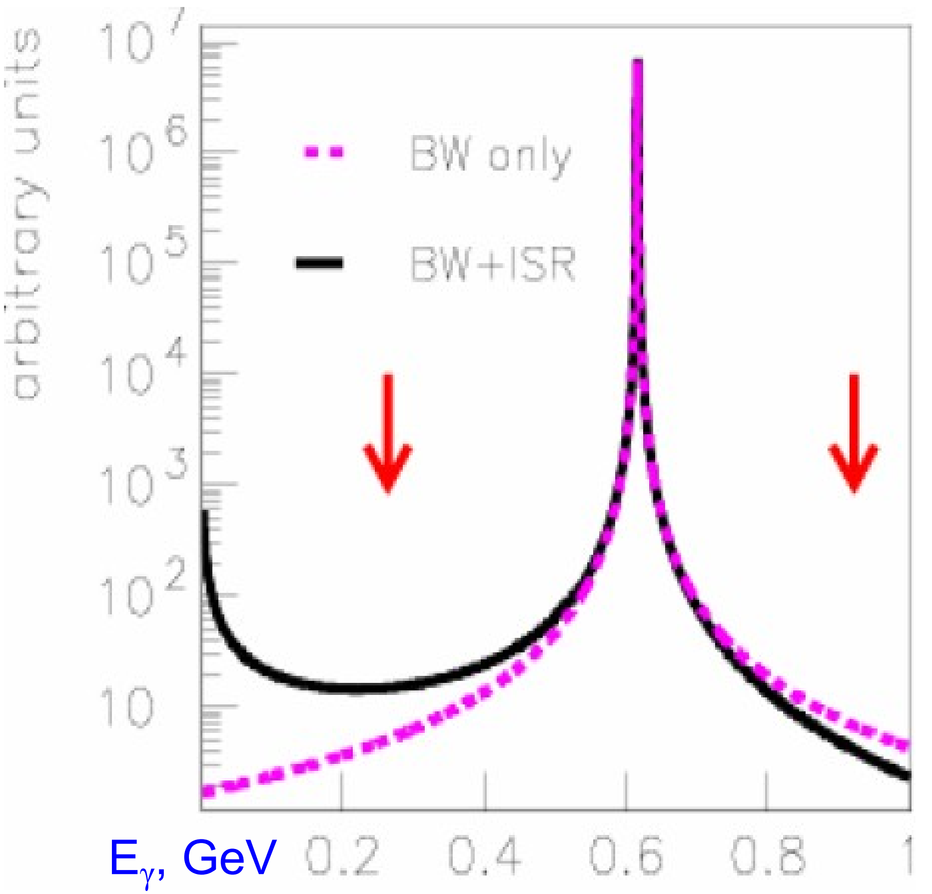
- Using radiative return to J/ψ in data collected at $\psi(3770)$
- Select $\mu^+\mu^-(\gamma)$ events with $M_{\mu\mu} \approx M_{J/\psi}$
- Count excess events over the non-resonant QED background
- Cross section is proportional to $B_{\mu\mu} * \Gamma_{ee}(J/\psi)$:

$$\sigma = N_{J/\psi}/(\varepsilon L) = \Gamma_{ee} * B_{\mu\mu} \int W(s,x) b(s') dx$$

  - W(s,x): ISR kernel (including higher corrections), $x=1-s'/s$
  - b(s'): BW shape (including interference with QED background), $s'=(M_{\mu\mu})^2$

- Integral is evaluated numerically using toy MC





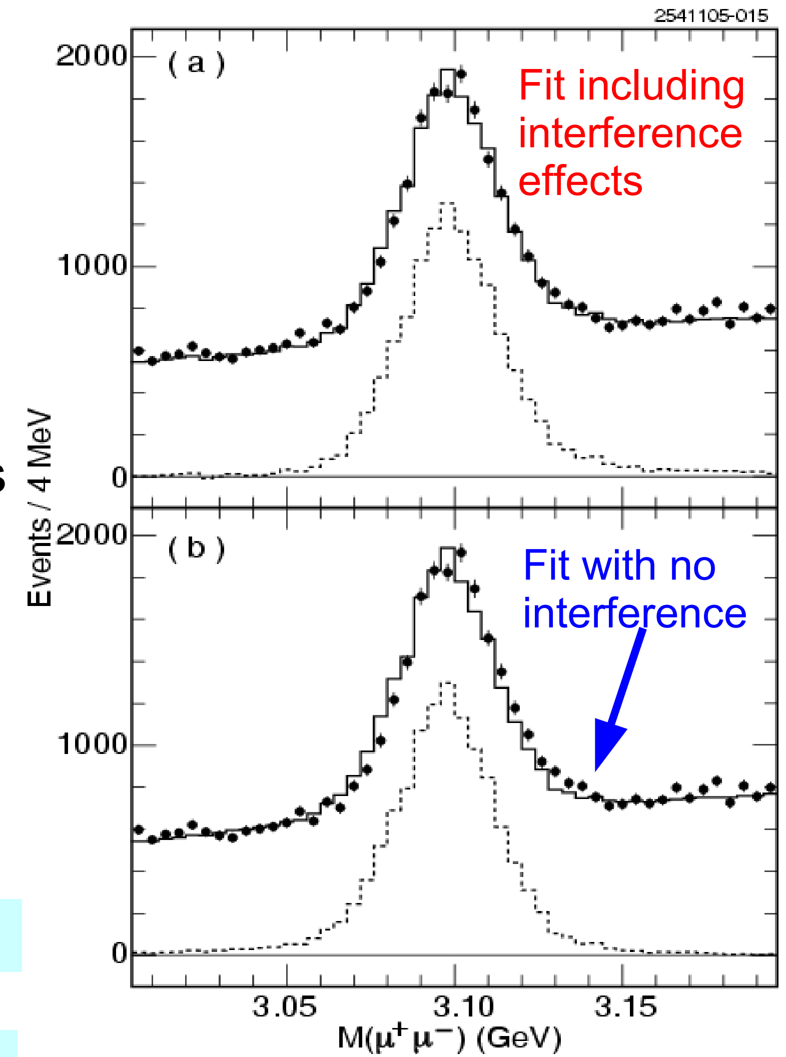
$\Gamma_{ee}(J/\psi)$

- Signal yield is extracted from fitting the invariant mass distribution of muon pairs
  - Signal ($\gamma J/\psi$) shape is derived from toy MC which convolves the measured mass resolution from data (radiative return to $\psi(2S)$, $\psi(2S)\rightarrow\pi\pi J/\psi$, $J/\psi\rightarrow\mu^+\mu^-$) with the expected effects from interference
  - Non-resonant QED background ($e^+e^-\rightarrow\gamma\mu^+\mu^-$) is parametrized by polynomial (order 1-3)
- Fit is sensitive to interference: confidence level increases when interference is included in signal shape
- Results:

$B_{\mu\mu}\Gamma_{ee} = 0.3384 \pm 0.0058 \pm 0.0071$ keV	2.7%

using $B_{\ell\ell}$:

$\Gamma_{ee} = 5.68 \pm 0.11 \pm 0.13$ keV	3.0%
$\Gamma = 95.5 \pm 2.4 \pm 2.4$ keV	3.6%

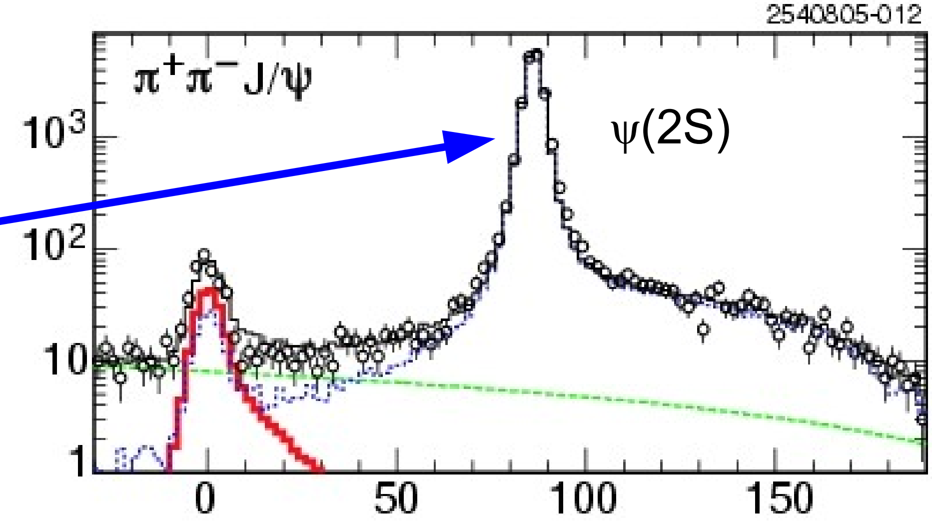


data: circles
solid lines: fit (signal+bckg)
dashed line: signal shape

$\Gamma_{ee}[\psi(2S)]$

- By-product of the search for non-DD bar decays of the $\psi(3770)$ into exclusive XJ/ψ final states (where $X=\pi^+\pi^-$, $\pi^0\pi^0$, η, π^0, and $J/\psi\rightarrow\ell^+\ell^-$)
- The sample is dominated by radiative return to the $\psi(2S)$: $e^+e^-\rightarrow\gamma\psi(2S)$ $(\psi(2S)\rightarrow XJ/\psi)$
- The cross section $e^+e^-\rightarrow\gamma\psi(2S)\rightarrow\gamma XJ/\psi$ is proportional to $B_X*\Gamma_{ee}(\psi(2S))$
- Fit missing momentum spectrum with
  - Signal shape for direct $\psi(3770)$ decay (from MC) – red line
  - Radiative return to $\psi(2S)$ (from MC) – dotted line
  - Background linear in k – dashed line
- $\Gamma_{ee}(\psi(2S))$: obtained from the combined $X=\pi^+\pi^-$, $\pi^0\pi^0$, η results and using B_X

CLEO: PRL 96, 082004 (2006)



$\Gamma_{ee}[\psi(2S)] = (2.54 \pm 0.03 \pm 0.11)$ keV

$\delta\Gamma_{ee}/\Gamma_{ee}=4.4\%$

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

5.0%

$\Gamma_{ee}[\psi(3770)]$

CLEO: PRL 96, 092002 (2006)

- CLEO measured the total hadronic cross section of the $\psi(3770)$ in order to explore the possible gap between DD and total hadronic cross section:

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

consistent with DD cross section (not much room for non-DD decays):

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

- From the observed $\sigma_{\psi(3770)}$ as well as M and Γ from the PDG we can get the Born level cross section at the peak of the resonance ($\sqrt{s}$=M) and then Γ_{ee} from the relativistic B-W resonance shape:

$$\Gamma_{ee} = [\sigma^{obs}(\sqrt{s}=3773)/f] * h * M^2 * \Gamma / (12\pi)$$

$$h = 1.078 \,^{+0.152}_{-0.006} \,^{+0.055}_{-0.038} \qquad \text{and} \qquad f = 0.77 \pm 0.03$$

$$\Gamma_{ee} = (204 \pm 3 \,^{+41}_{-27})\ \text{eV} \quad \text{(CLEO)}$$

$\Gamma_{ee} = (260 \pm 40)$ eV (PDG'04)

$\Gamma_{ee} = (251 \pm 26 \pm 11)$ eV (BES: hep-ex/0605107)

Summary of di-lepton results from CLEO

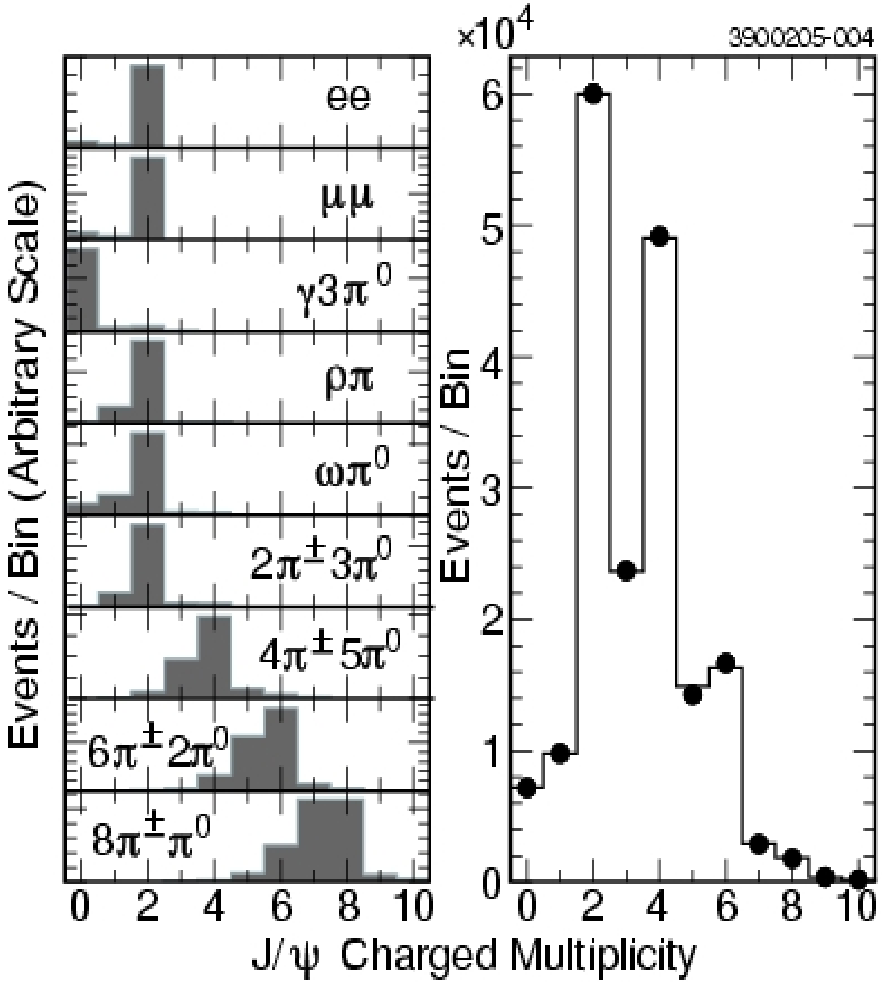
- Lots of new measurements of di-lepton widths and branching fractions from CLEO

	$B_{\mu\mu}$ ($B_{\ell\ell}$) [%]	Γ_{ee} [keV]	$\Gamma = \Gamma_{ee}/B_{\ell\ell}$ [keV]
J/ψ	5.953 ± 0.056 ± 0.042	5.68 ± 0.11 ± 0.13	95.5 ± 2.4 ± 2.4
$\psi(2S)$		2.54 ± 0.03 ± 0.11	
$\Psi(3770)$		$0.204 \pm 0.003\,^{+0.041}_{-0.027}$	
Υ(1S)	2.49 ± 0.02 ± 0.07	1.354 ± 0.004 ± 0.020	54.4 ± 0.2 ± 0.8 ± 1.6
Υ(2S)	2.03 ± 0.03 ± 0.08	0.619 ± 0.004 ± 0.010	30.5 ± 0.2 ± 0.5 ± 1.3
Υ(3S)	2.39 ± 0.07 ± 0.10	0.446 ± 0.004 ± 0.007	18.6 ± 0.2 ± 0.3 ± 0.9

Backup Slides

$B(J/\psi \to \ell^+\ell^-)$

- Fitting $\pi^+\pi^-$ recoil mass from $\pi^+\pi^-X$:
  - signal shape from clean $\pi^+\pi^-\ell^+\ell^-$ final state is used (to get the right momentum resolution)
  - background: 2nd order polynomial
- Efficiency ε_X: ~40%
  - depends slightly on charged and neutral multiplicity of J/ψ final state (X)
  - variation is ~2% (relative)
- Create a mixture of MC using specific exclusive final states to reproduce the charged multiplicity observed in data (dots)
  - BF of ee, μμ, ρπ is fixed in the mixture
  - BF of other modes are let to float in the fit to the multiplicity distribution



- Fit the recoil mass of this mixed MC with shape from the shape from $\pi^+\pi^-\ell^+\ell^-$ MC to get ε_X.

$\Gamma_{ee}[\psi(3770)]$

- The Born-level cross section at the √s=M mass is related to that at √s=3773 MeV via the relativistic Breit-Wigner formula

$$\sigma_{Born}(\sqrt{s}) = 12\pi\Gamma_{ee}\Gamma / [(s-M^2)^2 + M^2\Gamma^2]$$

i.e. $\sigma_{Born}(\sqrt{s}=M)/\sigma_{Born}(\sqrt{s}=3770) = h = 1.078\ ^{+0.152}_{-0.006}\ ^{+0.055}_{-0.038}$

$\Delta M, \Delta\Gamma$ $\Delta\sqrt{s}$ = 1 MeV

- In addition, the observed cross section is smaller than the Born-level cross section due to radiative corrections (except vacuum polarization which is absorbed into Γee):

$$\sigma^{obs}(\sqrt{s}=3773)/\sigma_{Born}(\sqrt{s}=3773) = f = 0.77 \pm 0.03$$ (Particle Data Group)

- Then $\Gamma_{ee}[\psi(3770)]$ can be extracted using the Breit-Wigner formula applied at √s=M:

$$\Gamma_{ee} = [\sigma^{obs}(\sqrt{s}=3773)/f] * h * M^2 * \Gamma / (12\pi)$$