Recent $\psi(2S)$ results from CLEOc

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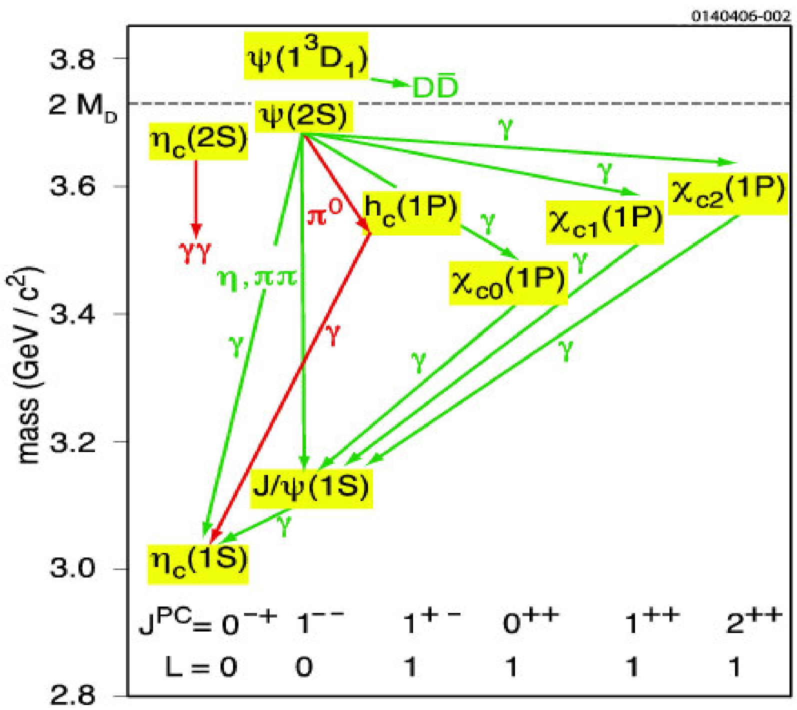
Introduction



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

These are:

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

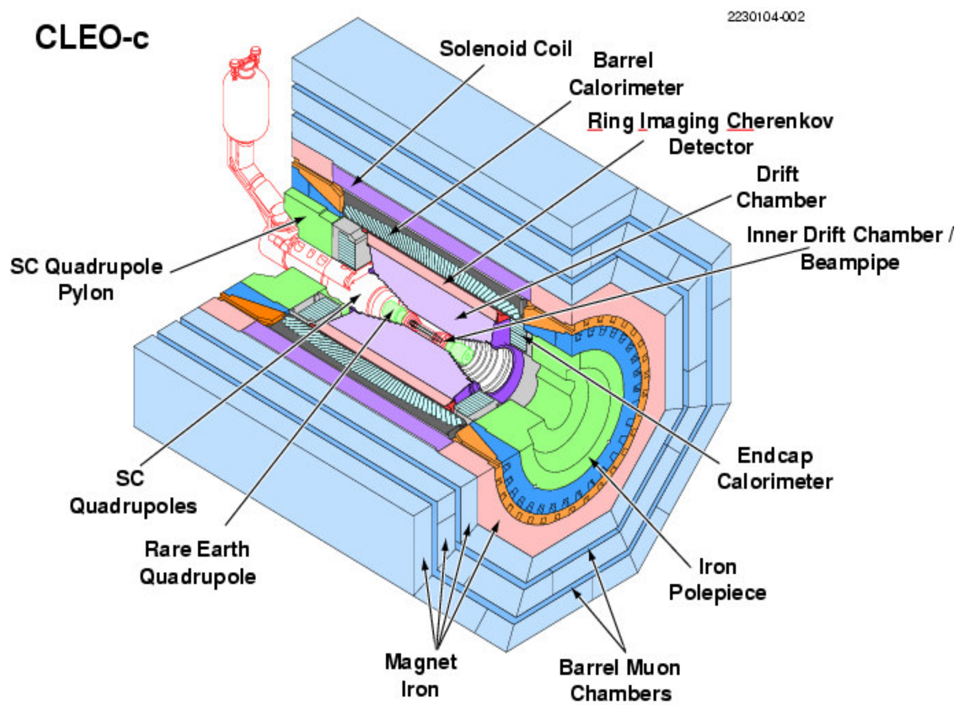
spin singlets - $\eta_c(1^3S_0)$, $\eta_c'(2^3S_0)$, $h_c(1^1P_1)$.

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

All states below $\psi(2S)$ can be produced from $\psi(2S)$ through radiative and hadronic transitions.

Thus, $\psi(2S)$ data provides an excellent source for the studies of charmonium physics below the $D\bar{D}$ breakup threshold.

CLEOc Detector



- 93% of 4π coverage.
- Calorimeter: 7800 Tl(Csi) crystals:

  $\sigma_E/E=2.2\%$ at 1 GeV,
  $\sigma_E/E=5.0\%$ at 100 MeV.

- Tracking: inner (ZD) and outer (DR) drift chambers:

  $\sigma_p/p=0.6\%$ at 1 GeV.

- Particle ID: dE/dx and RICH.

Data sets: 5.63 pb^{-1}, 3.08×10^6 events at $\psi(2S)$ (CLEO III and CLEOc);
20.70 pb^{-1} continuum at 3670 MeV.

Scope of Talk

I will talk about the results obtained with $\psi(2S)$ data from CLEOc.

- <u>Discovery</u>:

  - Observation of $h_c(1^1P_1)$ state of charmonium;

- <u>Precision measurements</u>:

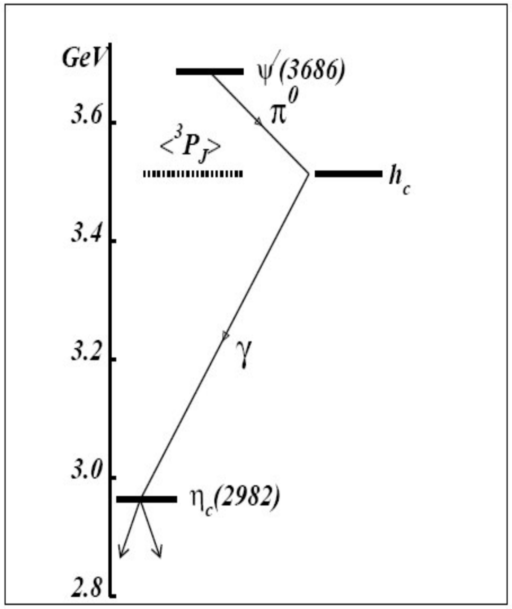
  - Photon transitions in $\psi(2S)$ decays to χ_J and η_c;
  - $\psi(2S)$ transitions to J/ψ;
  - J/ψ decays to lepton pairs;
  - Hadronic decays of the $\psi(2S)$:
    - Baryon-Antibaryon decays of $\psi(2S)$;
    - Two-body and multi-body meson decays of $\psi(2S)$;
    - $\psi(2S)$ decays to pseudoscalar pairs - $\pi^+\pi^-$, K^+K^- and $K_S^0K_L^0$;
    - $\psi(2S)$ decay to $\eta_c 3\pi$.
  - Electromagnetic form factors of the Pion, Kaon and Proton.

Observation of $h_c(1^1P_1)$

PRL 95(2005)102003

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:

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



The data have been analyzed for

3.08x10[6] ψ(2S) events

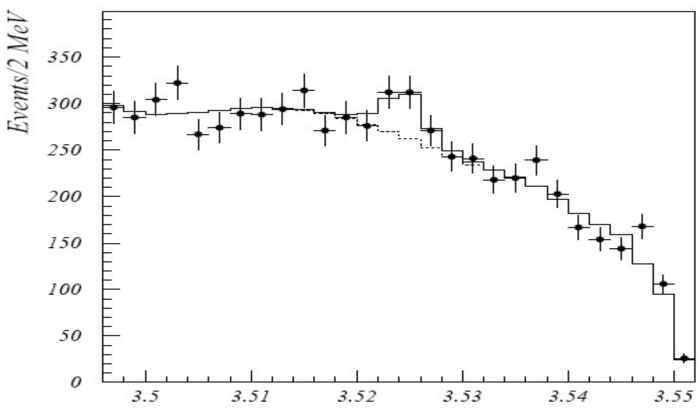
$$\psi(2S)\to\pi^0 h_c,\ h_c\to\gamma\eta_c$$

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.

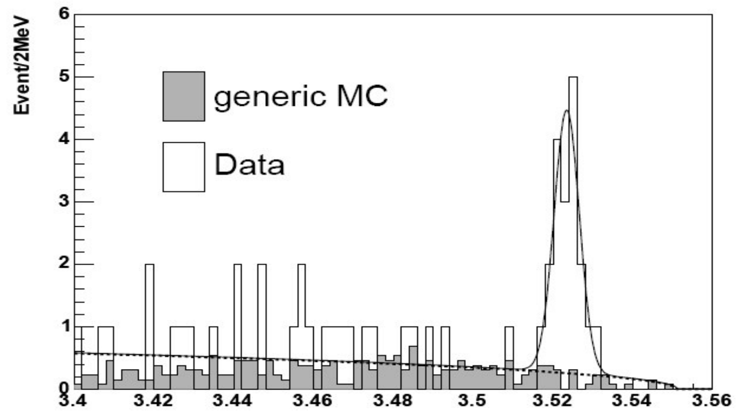
Observation of $h_c(1^1P_1)$, cont'd.



π^0 recoil mass in GeV

INCLUSIVE

Significance = 3.8σ



π^0 recoil mass in GeV

EXCLUSIVE

Significance = 5.2σ

$$B(\psi(2S)\to\pi^0 h_c)\times B(h_c\to\gamma\eta_c)=(4.0 \pm 0.8 \pm 0.7)\times 10^{-4}$$

$$M(h_c)=(3524.4 \pm 0.6 \pm 0.4)\ \text{MeV}$$

$$\Delta M_{hf}(1P)=M(\chi_{cJ})-M(h_c)=(+1.0 \pm 0.6 \pm 0.4)\ \text{MeV}$$

using $\langle M(\chi_{cJ})\rangle=(3525.4 \pm 0.1)$ MeV

Two conclusions follow:

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

Photon transitions in $\psi(2S)$ decays to χ_{cJ} and η_c

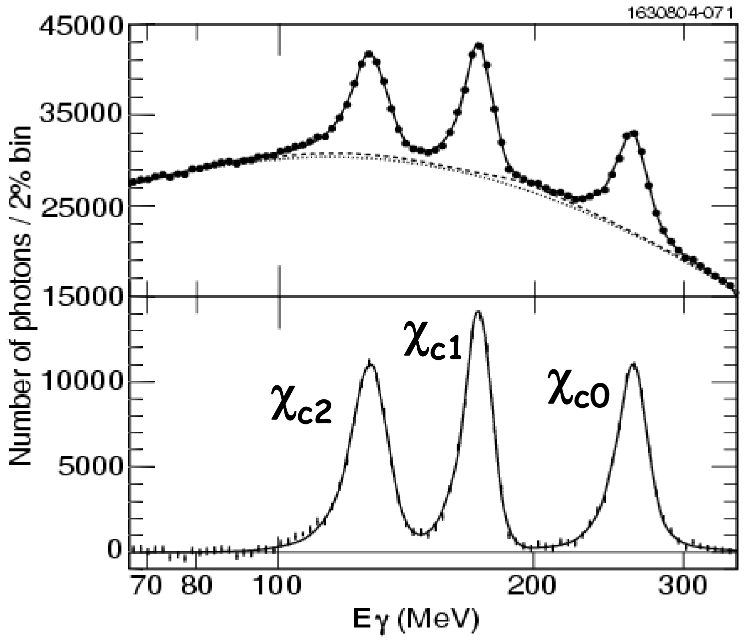
PRD 70(2004)112002

CLEO has recently made precision measurements of the

- radiative transitions:

  $\psi(2S)\rightarrow\gamma\,\chi_{cJ}$ (E1 transitions)
  $\psi(2S)\rightarrow\gamma\,\eta_c$ (M1 transition)

The result for $B(\psi(2S)\rightarrow\gamma\,\chi_{c2})$ is different from PDG 2004 - central value is higher by 45%.



	PDG(04) %	CLEO %
$B(\psi(2S)\rightarrow\gamma\,\chi_{c0})$	8.6 ± 0.7	9.22 ± 0.47
$B(\psi(2S)\rightarrow\gamma\,\chi_{c1})$	8.4 ± 0.8	9.07 ± 0.55
$B(\psi(2S)\rightarrow\gamma\,\chi_{c2})$	**6.4 ± 0.6**	**9.33 ± 0.63**
$B(\psi(2S)\rightarrow\gamma\,\eta_c)$	0.28 ± 0.08	0.32 ± 0.07

$\psi(2S)$ transitions to J/ψ

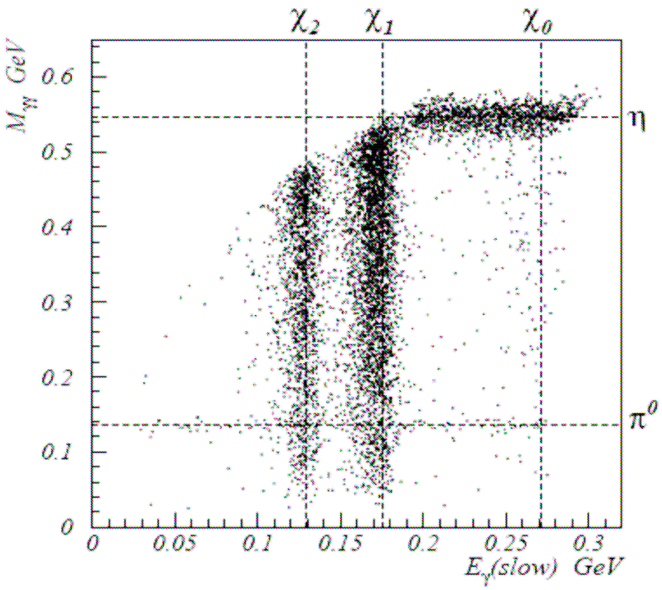
PRL 94(2005)232002

In another recent measurement, CLEO has measured:

- double radiative transitions

$$\psi(2S)\to\gamma\,\chi_{cJ}(1P)\to\gamma\gamma\,J/\psi$$

with $J/\psi\to e^+e^-$, $\mu^+\mu^-$.



	CB %	BES %	CLEO %
$\mathcal{B}(\psi'\to\gamma\chi_{c0})\times\mathcal{B}(\chi_{c0}\to\gamma J/\psi)$	0.069 ± 0.018	–	0.18 ± 0.02
$\mathcal{B}(\psi'\to\gamma\chi_{c1})\times\mathcal{B}(\chi_{c1}\to\gamma J/\psi)$	2.56 ± 0.23	2.81 ± 0.24	3.44 ± 0.14
$\mathcal{B}(\psi'\to\gamma\chi_{c2})\times\mathcal{B}(\chi_{c2}\to\gamma J/\psi)$	0.99 ± 0.13	1.62 ± 0.13	1.85 ± 0.08

Using CLEO results for $\psi(2S)\to\gamma\,\chi_{cJ}$, we get:

	CB %	CLEO %
$B(\chi_{c0}\to\gamma J/\psi)$	0.6 ± 0.2	2.0 ± 0.3
$B(\chi_{c1}\to\gamma J/\psi)$	28.4 ± 2.1	37.9 ± 2.2
$B(\chi_{c2}\to\gamma J/\psi)$	12.4 ± 1.5	19.9 ± 1.3

$\psi(2S)$ transitions to J/ψ cont'd.

- **exclusive hadronic transitions:**

– $\psi(2S)\to\eta J/\psi\to\gamma\gamma\, J/\psi$ $\quad B(\psi(2S)\to\eta J/\psi) = (3.25 \pm 0.06 \pm 0.11)\ \%$

– $\psi(2S)\to\pi^0 J/\psi\to\gamma\gamma\, J/\psi$ $\quad B(\psi(2S)\to\pi^0 J/\psi) = (0.13 \pm 0.01 \pm 0.01)\ \%$

$$[B(\psi(2S)\to\pi^0 J/\psi)/B(\psi(2S)\to\eta J/\psi)] = 0.040 \pm 0.004$$

With the factor 11 smaller phase space for the η transition, this implies Isospin Violation at a ± 0.4 % level.

– $\psi(2S)\to\pi^+\pi^- J/\psi$ $\quad B(\psi(2S)\to\pi^+\pi^- J/\psi) = (33.54 \pm 0.14 \pm 1.10)\ \%$

– $\psi(2S)\to\pi^0\pi^0 J/\psi$ $\quad B(\psi(2S)\to\pi^0\pi^0 J/\psi) = (16.52 \pm 0.14 \pm 0.58)\ \%$

$$[B(\psi(2S)\to\pi^+\pi^- J/\psi)\ /\ B(\psi(2S)\to\pi^0\pi^0 J/\psi)\ ] = 2.03 \pm 0.04$$

$$1.69 \pm 0.12 \text{ (PDG04)}$$

This establishes Isospin Conservation at a ± 2 % level.

$\psi(2S)$ transitions to J/ψ cont'd.

Difference from the unity of the sum of exclusive CLEO measured branching fractions $\Sigma[\psi(2S)\to h\, J/\psi]$, branching fractions of radiative decays $\psi(2S)\to\gamma\,\chi_{cJ}$ and $\psi(2S)\to\gamma\,\eta_c$, and the dilepton branching fractions from the PDG04 is

$$B(\psi(2S)\to \text{light hadrons}) = (16.9 \pm 2.6)\%$$

It can be compared with that of J/ψ:

$$B(J/\psi \to \text{light hadrons}) = (87.7 \pm 0.5)\% \quad \text{(PDG04)}$$

yielding a ratio of $(19.2 \pm 3.0)\%$, ~2.1σ above of $B(\psi(2S)\to l^+l^-)/B(J/\psi\to l^+l^-)=(12.7 \pm 0.5)\%$ (PDG04).

What can precision measurements do

PRD 73(2006)071101

The old controversy in measurement of $\Gamma(\chi_{c2}\to\gamma\gamma)$ is resolved when the CLEO measurement of $B(\chi_{c2}\to\gamma J/\psi)$ is used.

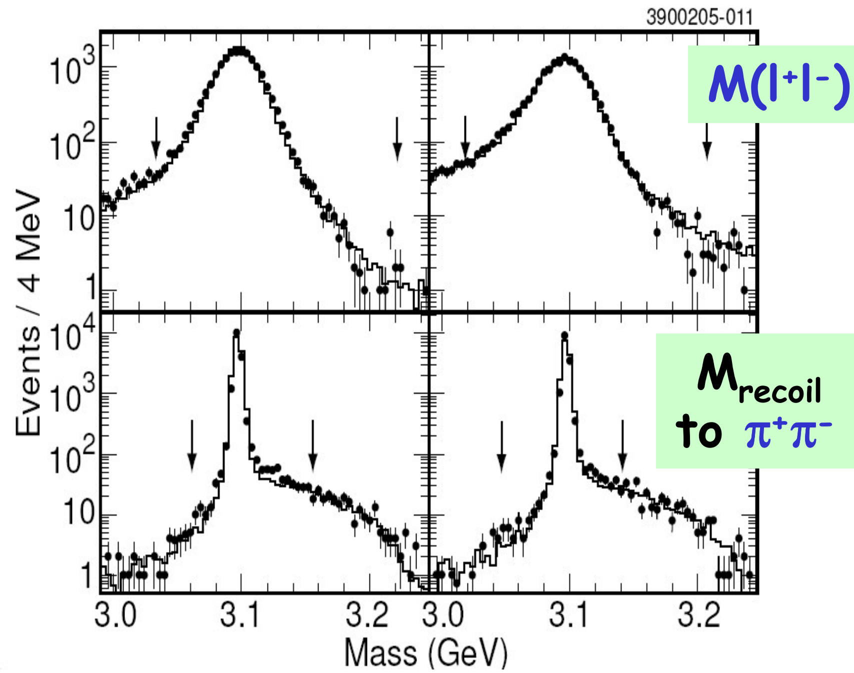
Measurement	$\Gamma_{\gamma\gamma}(\chi_{c2})$ (eV) (as published)	$\Gamma_{\gamma\gamma}(\chi_{c2})$ (eV) (as reevaluated)
E835 (2002) $\frac{\bar{p}p\to\chi_{c2}\to\gamma\gamma}{\bar{p}p\to\chi_{c2}\to\gamma J/\psi}$	270 ± 59	384 ± 83
Belle (2002) $\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$	850 ± 127	570 ± 81
CLEO (2005) $\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$		559 ± 81

Average
506 ± 60
(Sc. Fact.=1.3)

J/ψ decays to lepton pairs

PRD 71(2005)111103

- $B(J/\psi \to l^+l^-)$ is used in determination of $\Gamma_{tot}(J/\psi)$ and $\Gamma_{ee}(J/\psi)$ from $\sigma(e^+e^- \to J/\psi \to hadrons)$.
- Tests lepton universality.



<u>Method</u>: use $\psi(2S) \to \pi^+\pi^- J/\psi$ and measure $N(J/\psi \to l^+l^-)$ [from $M(l^+l^-)$] and $N(J/\psi \to X)$ (from $\pi^+\pi^-$ recoil).

$B(J/\psi \to e^+e^-) = (5.945 \pm 0.067 \pm 0.042)\,\%$

$B(J/\psi \to \mu^+\mu^-) = (5.960 \pm 0.065 \pm 0.050)\,\%$

or $[B(J/\psi \to e^+e^-)/B(J/\psi \to \mu^+\mu^-)] = 0.997 \pm 0.013$

This establishes <u>Lepton Universality</u> at a $\pm 1\%$ level.

Hadronic decays of the $\psi(2S)$

- According to pQCD

$$Q_{e+e-} = \Gamma(\psi(2S)\to e^+e^-) / \Gamma(J/\psi \to e^+e^-) =$$
$$= \alpha_{em}^2|R_{\psi(2S)}(0)|^2 / \alpha_{em}^2|R_{J/\psi}(0)|^2 = (12.7 \pm 0.5)\ \%$$

$$Q_{ggg} = \Gamma(\psi(2S)\to ggg) / \Gamma(J/\psi \to ggg) =$$
$$= \alpha_s^2|R_{\psi(2S)}(0)|^2 / \alpha_s^2|R_{J/\psi}(0)|^2$$

- If $\alpha_s(\psi(2S)) = \alpha_s(J/\psi)$ is assumed, then

$$Q = B(\psi(2S)\to ggg)/B(J/\psi \to ggg) = (12.7 \pm 0.5)\ \%$$

- Indeed

(see page 10)

$$Q = B(\psi(2S)\to \text{light hadrons})/B(J/\psi \to \text{light hadrons}) = (19.2 \pm 3.0)\%,$$

- How do individual decays behave with respect to "12% rule"?

- Over the years BES has measured many $\psi(2S)$ decays.

- CLEO has recently measured many individual decays of $\psi(2S)$ to Baryon-Antibaryon, two-body and multi-body meson final states, many of them for the first time and many of them with highest precision.

Baryon-Antibaryon decays of $\psi(2S)$

PRD 72(2005)051108

- Very few decays of charmonia to baryon-antibaryon pairs have been measured.

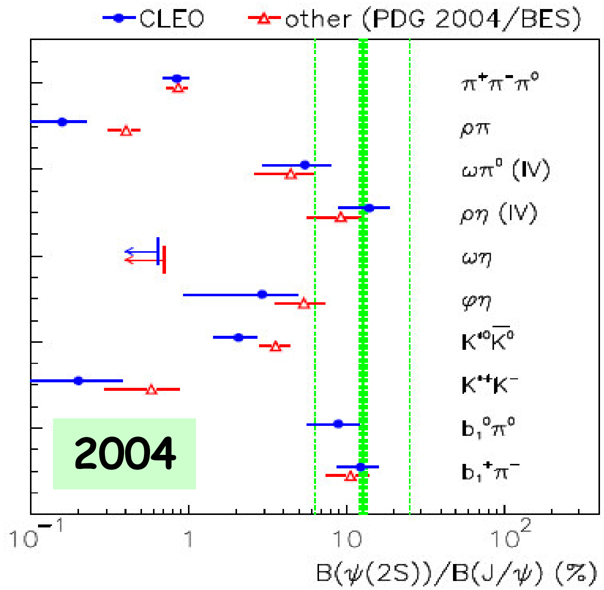
- CLEO has measured the following decays:
  $\psi(2S) \to$ baryon-antibaryon with baryons: p, Λ, Σ^+, Σ^0, Ξ^0, Ξ^{*0} and Ω^-, most of them for the first time.

- A rather interesting feature is that all branching fractions are nearly the same ~$(2-3)\times10^{-4}$, which is surprising considering that phase space is quite different for each of them.

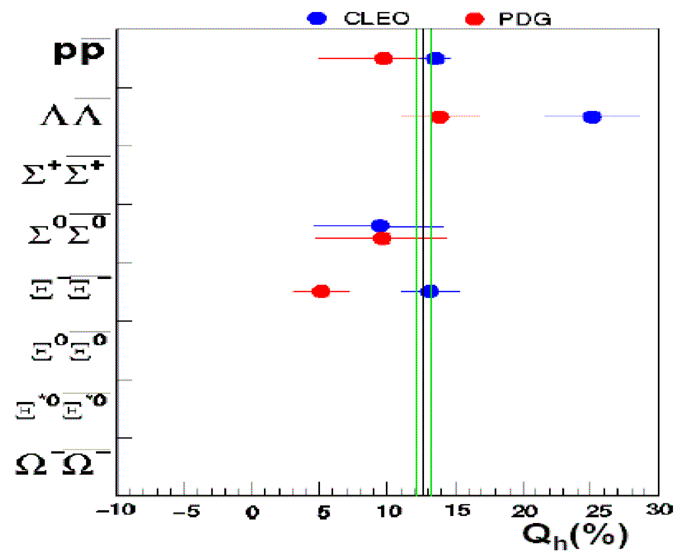
Modes	$M(B+\bar{B})$ MeV	evts	$\mathcal{B}$(CLEO) in 10^{-4}	$\mathcal{B}$(PDG04) in 10^{-4}
$p\overline{p}$	1876	552	2.87±0.12±0.15	2.07±0.31
$\Lambda\overline{\Lambda}$	2231	203	3.28±0.23±0.25	1.81±0.34
$\Sigma^+\overline{\Sigma^+}$	2378	34	2.57±0.44±0.68	–
$\Sigma^0\overline{\Sigma^0}$	2385	58	2.63±0.35±0.21	1.2±0.6
$\Xi^-\overline{\Xi^-}$	2643	62	2.38±0.30±0.21	0.94±0.31
$\Xi^0\overline{\Xi^0}$	2639	18	2.75±0.64±0.61	–
$\Xi^{*0}\overline{\Xi^{*0}}$		2	(<3.2 @90 CL)	< 0.81
$\Omega^-\overline{\Omega^-}$		4	(<1.6 @90 CL)	< 0.73

Two-body and multi-body meson decays of $\psi(2S)$

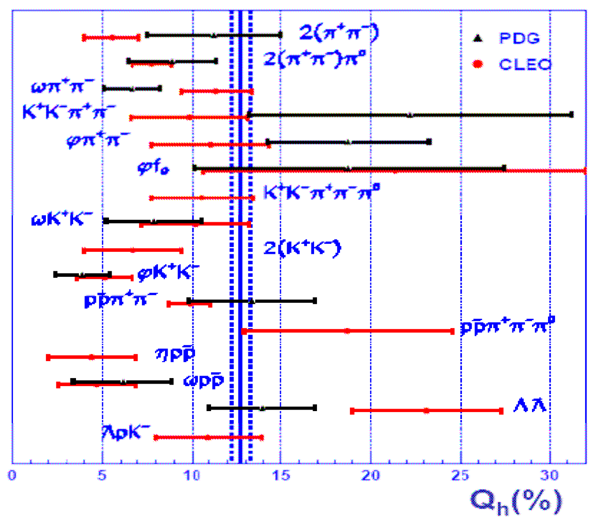
PRL 94(2005)012005
PRL 95(2005)062001



Q for Two-body Decays



Q for Baryon Decays



Q for Multibody Decays

- For two-body meson decays Q varies all over the map
  e.g. Q(ρπ) = (0.2 ± 0.1)%.
- For multibody meson decays Q=(4-20)%.
- For baryon decays Q = (5 – 25)%.
- Needs to be explained.

$\psi(2S)$ decays to pseudoscalar pairs - $\pi^+\pi^-$, K^+K^- and $K_S^0K_L^0$ - Interference between Electromagnetic and Strong amplitudes

hep-ex/0603020

- CLEO has measured the branching fractions for $\psi(2S)$ decays to pseudoscalar pairs - $\pi^+\pi^-$, K^+K^- and $K_s^0K_L^0$.
- $\psi(2S)\to\pi^+\pi^-$ - dominantly virtual photon;
- $\psi(2S)\to K_s^0K_L^0$ - dominantly three gluons;
- $\psi(2S)\to K^+K^-$ - both with phase difference $\Delta\sim90^0$ (Suzuki, Rosner).

$B(\psi(2S)\to\pi^+\pi^-) < 2.1\times10^{-5}$ (90% C.L.)

$B(\psi(2S)\to K^+K^-) = (6.3\pm0.6\pm0.3)\,\%$

$B(\psi(2S)\to K_s^0K_L^0) = (5.8\pm0.8\pm0.4)\,\%$

$R = A(ggg)/A(\gamma^*) = 2.8\pm1.4$

$\Delta = (93\pm20)^0$

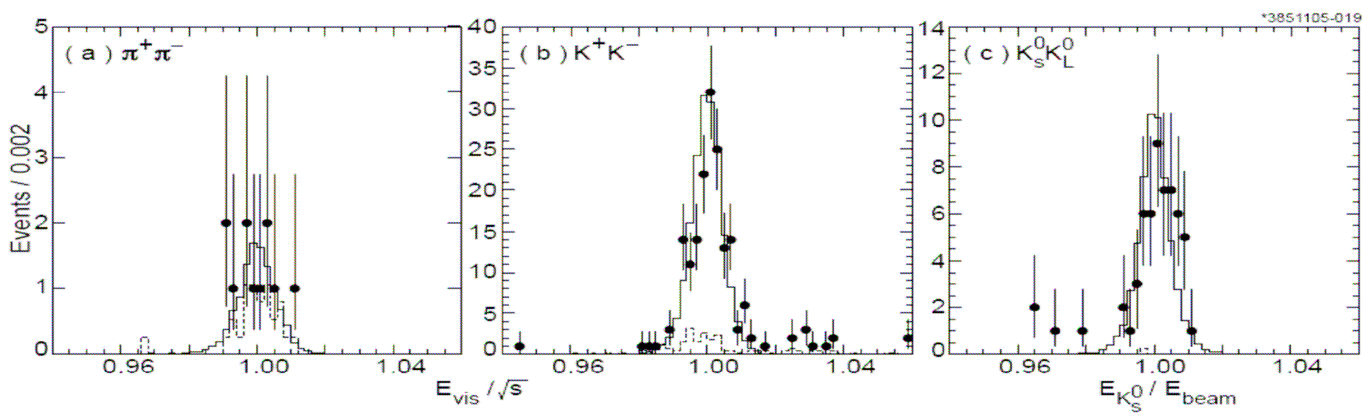
	DASP [15]	BES [6, 16]	CLEO	World Avg.
$\mathcal{B}_{\pi^+\pi^-}$	8±5	0.84±0.65	0.8±0.8	0.9±0.5
$\mathcal{B}_{K^+K^-}$	10±7	6.1±2.1	6.3±0.7	6.3±0.7
$\mathcal{B}_{K_S^0K_L^0}$	—	5.24±0.67	5.8±0.9	5.4±0.6
$R(\psi(2S))$	—	2.6±1.0	2.8±1.4	2.6±0.7
$\Delta(\psi(2S))$	—	$(89\pm35)^\circ$	$(93\pm20)^\circ$	$(89\pm14)^\circ$

$Q(\pi^+\pi^-) = 5.4\pm5.6$

$Q(K^+K^-) = 26.6\pm4.5$

$Q(K_s^0K_L^0) = 32.2\pm5.2$

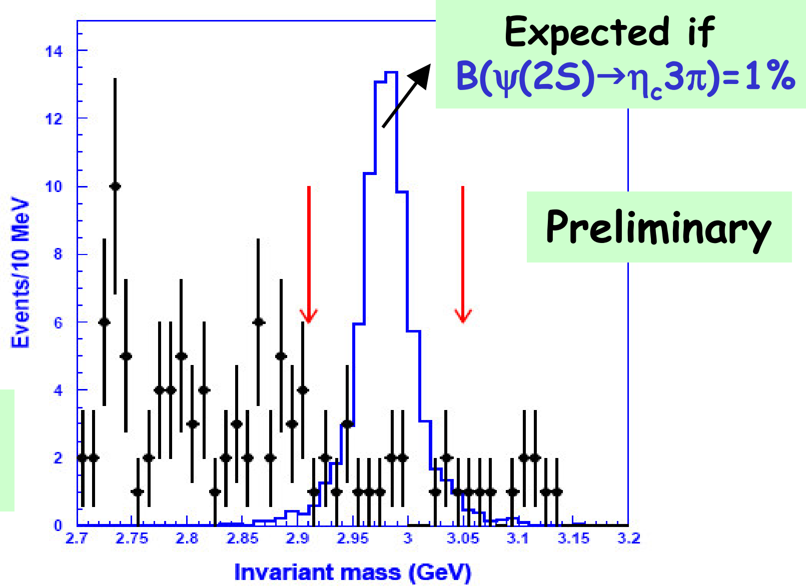
"12% rule"



$\psi(2S)$ decay to $\eta_c 3\pi$

CLEO Preliminary

- "12% rule" is violated for many decay channels – needs theoretical explanations.
- P. Artoisenet et al. [Phys.Lett. B 628, 211 (2005)] proposed mechanism "survival before annihilation" meaning $c\bar{c}$ pair does not annihilate into ggg but rather survives before annihilation.
  One of the predictions: $B(\psi(2S)\to\eta_c 3\pi)$ is expected at ~1% level.
- CLEO has searched for $\psi(2S)\to\eta_c\pi^+\pi^-\pi^0$, when η_c decays into 6 modes with total branching fraction of 9.5%.



- No signal is observed.
- $B(\psi(2S)\to\eta_c 3\pi) < 1.1 \times 10^{-3}$ (90% C.L.)
- This upper limit is order of magnitude below the theoretical expectation of ~1%.

Electromagnetic form factors of the Pion, Kaon and Proton

PRL 95(2005)261803

- **Electromagnetic form factors** provide deep insight into particle structure.

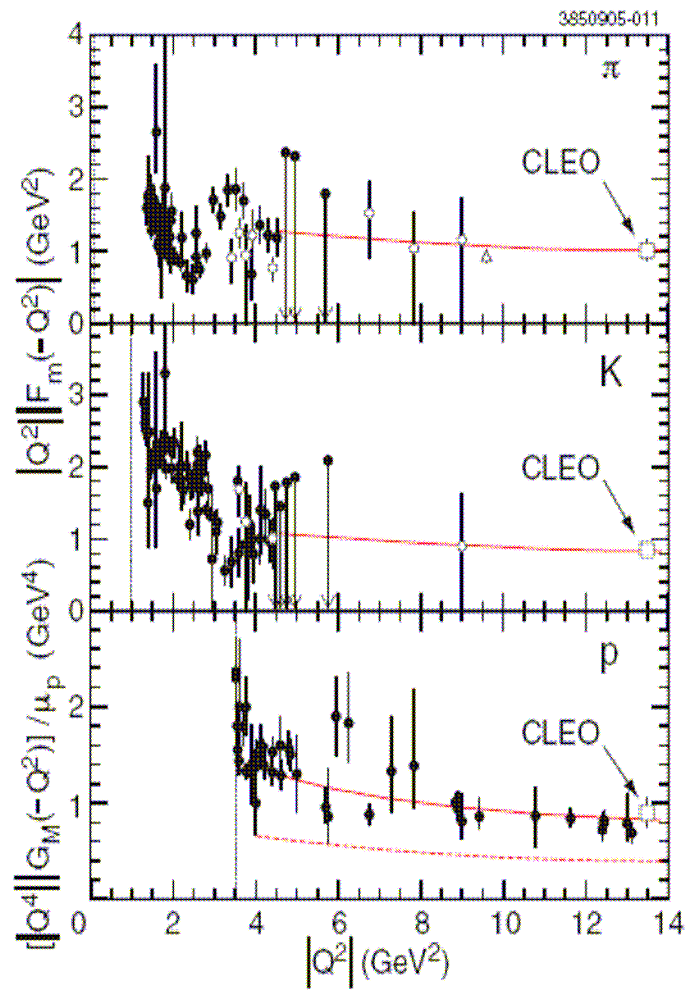
- **CLEO** has measured the **timelike ($Q^2<0$)** form factors of π, K and p, using 20.7 pb^{-1} of data taken at $E_{c.m.}$=3.671 GeV ($|Q^2|$=13.48 GeV^2), by means of the reactions:

$$e^+e^- \to \pi^+\pi^- \;,\; e^+e^- \to K^+K^- \;, \text{ and } \; e^+e^- \to p\bar{p}$$

$|F_\pi(13.48\ GeV^2)|$ = 0.075 ± 0.008 ± 0.005

$|F_K(13.48\ GeV^2)|$ = 0.063 ± 0.004 ± 0.001

$|G_\pi^p(13.48\ GeV^2)|$ = 0.014 ± 0.002 ± 0.001



- **Pion** and **kaon** EM Form Factors are the first direct measurements with $Q^2>4.5$ GeV^2.

- **Proton** EM Form Factor is consistent with existing data.

Summary

- Using the available $\psi(2S)$ data, CLEO Collaboration has provided many interesting results in charmonium spectroscopy and decays, including observation of previously unobserved charmonium state. Most of the results are either first observations or of higher precision than previous measurements.

- CLEO has decided to collect 30 million $\psi(2S)$ data (10 times present statistics).

  Many important new results are expected in the near future.