Recent Results from CLEO

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MENU

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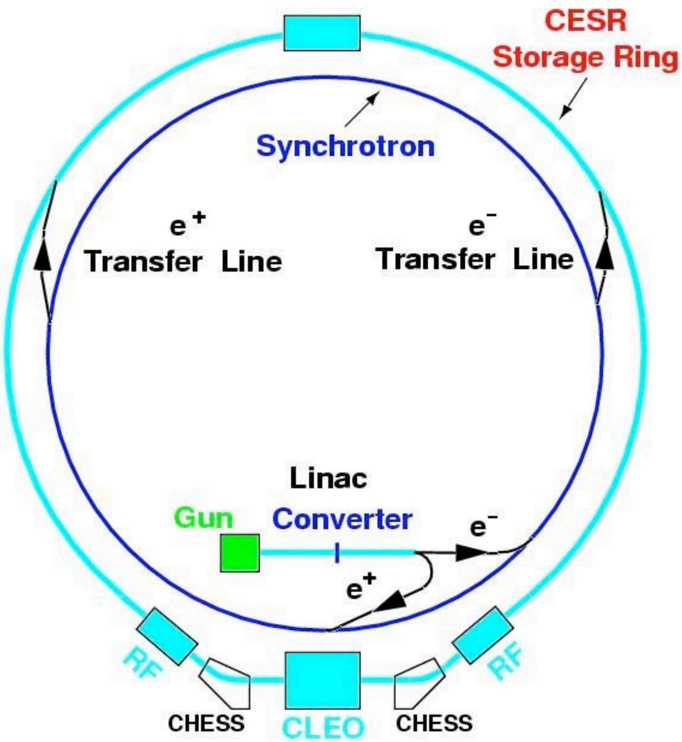
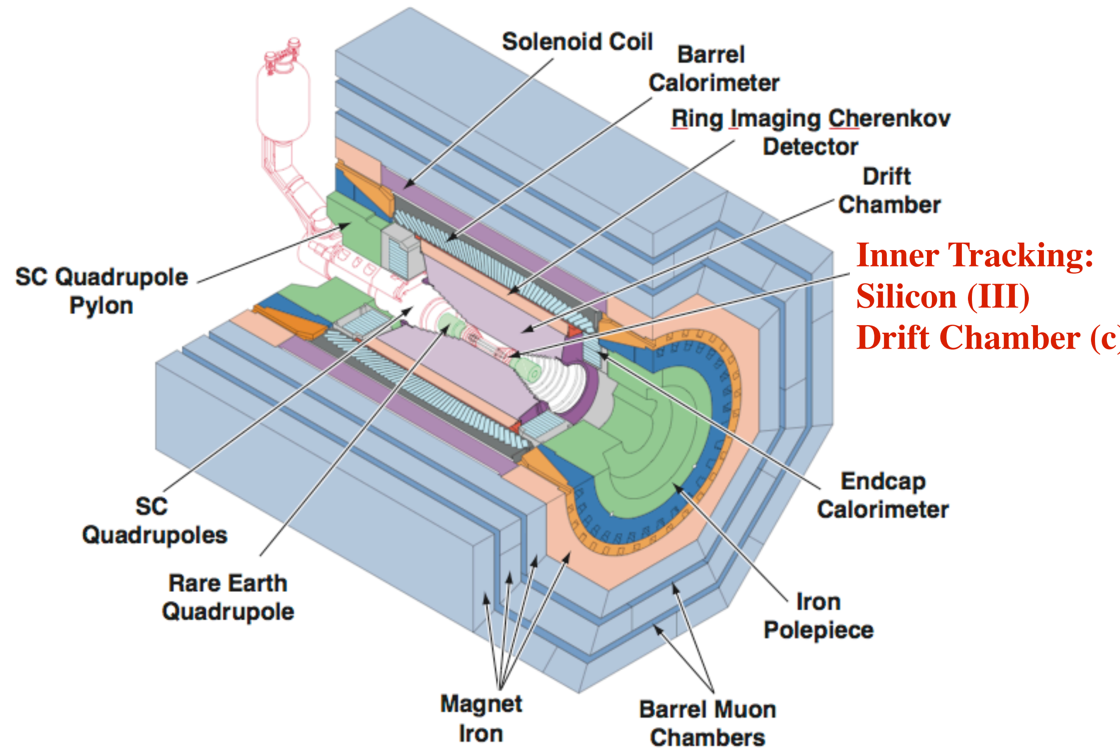
Overview of the CLEO Experiment

CESR at Cornell University: symmetric e^+e^- collisions at bottomonium (III) and charmonium (c) energies





CLEO III (2000 - 2003)

Select Data Samples:

- $\Upsilon(4S) \sim 15.5\ fb^{-1}$
- $\Upsilon(3S) \sim$ 6M events
- $\Upsilon(2S) \sim$ 9M events
- $\Upsilon(1S) \sim$ 22M events

CLEO-c (2003 - 2008)

Select Data Samples:

- 4.17 GeV $\sim 586\ pb^{-1}$
- $\psi(3770)$ $\sim 818\ pb^{-1}$
- $\psi(2S)$ $\sim$ 26M (+1.5M CLEO-III)

1980-2010:
> 500 publications
(weak, em, strong, exotic, etc. physics)

Recent News from CLEO from Light to Heavy

(lightest)

1. Observation of
   $\eta' \to \pi^+\pi^-\pi^0$ and $\eta' \to \pi^+\pi^- e^+e^-$

(heavy decaying to light)

2. J/ψ and $\psi(2S)$ Radiative Decays to η and η'

(half heavy)

3. D and D_s Decay Constants: f_D and f_{D_s}

(heavy)

4. Higher-Order Multipoles in
   $\psi(2S) \to \gamma\chi_{c1,2}$ and $\chi_{c1,2} \to \gamma J/\psi$

(heaviest)

5. Confirming Evidence for $\Upsilon(3S) \to \gamma\eta_b$

(many other results are available but not covered…)

1.

(lightest)

Observation of

$\eta' \to \pi^+\pi^-\pi^0$

and

$\eta' \to \pi^+\pi^- e^+e^-$

PRL 102, 061801 (2009)

Observation of $\eta' \to \pi^+\pi^-\pi^0$ and $\eta' \to \pi^+\pi^-e^+e^-$

- Look for:

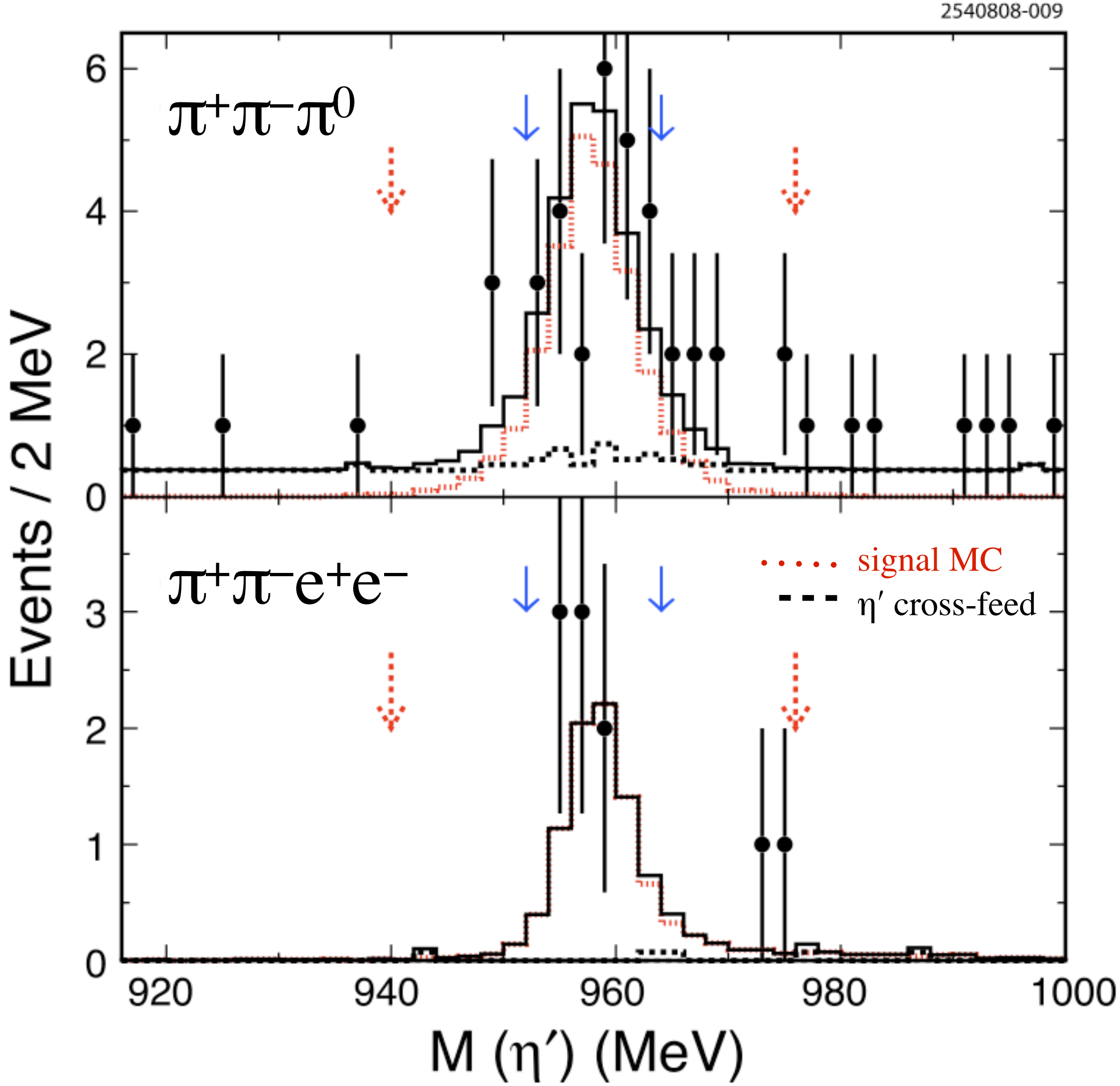
  $\psi(2S) \to \pi^+\pi^- J/\psi$

  $J/\psi \to \gamma\eta'$

  $\eta' \to X$

- Use $\pi^+\pi^-$ to select the **J/ψ**
- Perform a **kinematic fit** of all decay products to the $\psi(2S)$ 4-momentum
- Measure **rates** relative to $\eta' \to \pi^+\pi^-\eta;\ \eta \to \gamma\gamma$
- **Backgrounds**:
  - *Linear backgrounds:* Use sidebands in M(X)
  - *Peaking backgrounds:* Estimate η' cross-feed from MC

Both have significance > 6σ.



Observation of $\eta' \to \pi^+\pi^-\pi^0$ and $\eta' \to \pi^+\pi^-e^+e^-$

$\eta' \to \pi^+\pi^-\pi^0$

24 events observed
- 2.5 bg from sidebands
- 1.3 bg from MC

$20.2^{+6.1}_{-4.8}$ events

$\Rightarrow$ BF = $(37^{+11}_{-9} \pm 4) \times 10^{-4}$

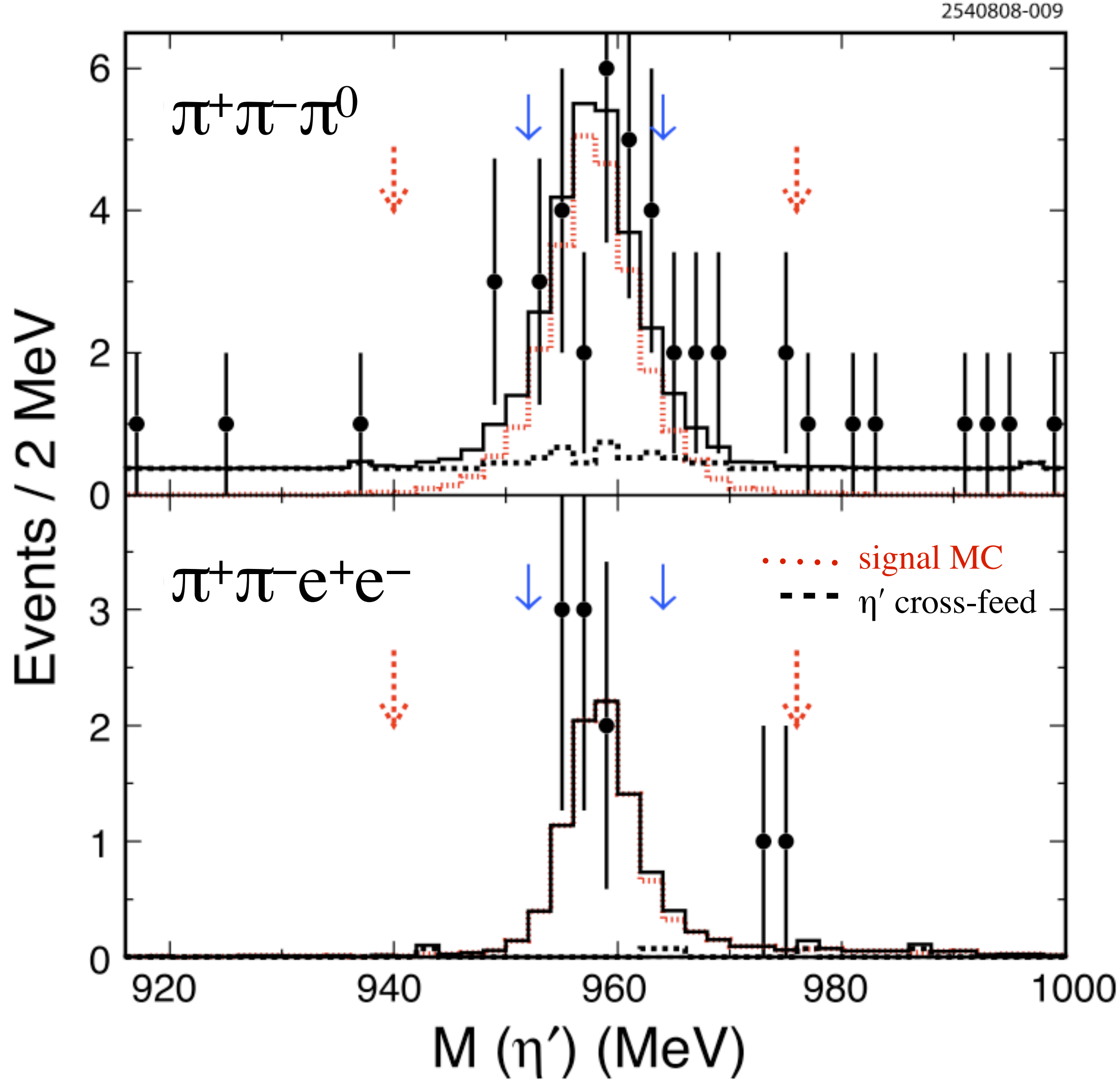
$\eta' \to \pi^+\pi^-e^+e^-$

8 events observed
- 0 bg from sidebands
- 0.14 bg from MC

$7.9^{+3.9}_{-2.7}$ events

$\Rightarrow$ BF = $(25^{+12}_{-9} \pm 5) \times 10^{-4}$

Both have significance > 6σ.



Observation of $\eta' \to \pi^+\pi^-\pi^0$ and $\eta' \to \pi^+\pi^-e^+e^-$

$B(\eta' \to \pi^+\pi^-\pi^0)$ is the last piece needed for the ratio "$r_\pm/r_0$":

$$\frac{r_\pm \equiv \dfrac{\mathcal{B}(\eta' \to \pi^+\pi^-\pi^0)}{\mathcal{B}(\eta' \to \pi^+\pi^-\eta)}}{r_0 \equiv \dfrac{\mathcal{B}(\eta' \to 3\pi^0)}{\mathcal{B}(\eta' \to \pi^0\pi^0\eta)}} = 1.11 \pm 0.35$$

Predictions for $\mathbf{r_\pm/r_0}$ range from:

0.37 (η-π^0 mixing, $\propto(m_u-m_d)$) to

5 ($\pi^+\pi^-\pi^0$ rescattering through ρ, with non-trivial Dalitz structure).

PLB 643, 41 (2006)

R = BF relative to $\eta'\to\pi^+\pi^-\eta[\gamma\gamma]$; **B** = $B(\eta'\to X)$; **P** = previous measurement of B

also many upper limits

Mode X	ϵ/ϵ_0	N	$R(10^{-3})$	$B(10^{-4})$	$P(10^{-4})$
$\pi^+\pi^-\eta[\gamma\gamma]$	1.00	1756 ± 42	-	-	-
$\pi^+\pi^-\pi^0$	0.55	$20.2^{+6.1}_{-4.8}$	$21^{+6}_{-5}\pm2$	$37^{+11}_{-9}\pm4$	<500
$\pi^+\pi^-e^+e^-$	0.31	$7.9^{+3.9}_{-2.7}$	$14^{+7}_{-5}\pm3$	$25^{+12}_{-9}\pm5$	<60
$\pi^+\pi^-\mu^+\mu^-$	2.14	<4.8	<1.3	<2.4	-
$2(\pi^+\pi^-)$	1.02	<2.3	<1.4	<2.4	<100
$\pi^+\pi^-2\pi^0$	0.18	<4.1	<15	<27	-
$2(\pi^+\pi^-)\pi^0$	0.21	<3.6	<11	<20	<100
$3(\pi^+\pi^-)$	0.47	<2.3	<3.0	<5.3	<100
Invisible	0.74	<5.8	<5.4	<9.5	<14

2.

J/ψ and $\psi(2S)$ Radiative Decays to η and η'

(heavy decaying to light)

PRD 79, 111101(R) (2009)

J/ψ and ψ(2S) Radiative Decays to η and η′

- Look for:

  $\psi(2S) \to \pi^+\pi^- J/\psi$

  $J/\psi \to \gamma\eta^{(\prime)}$

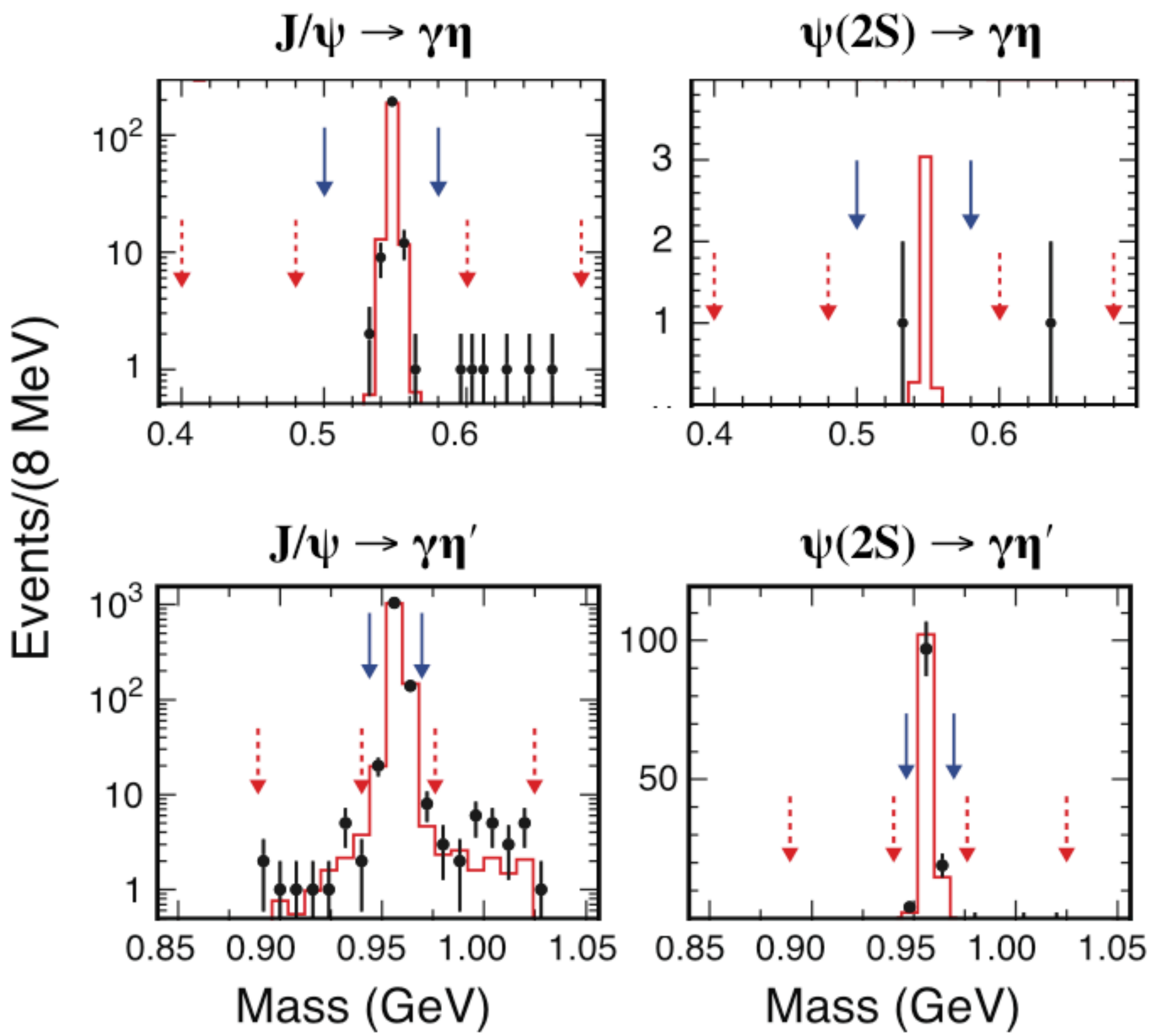
  $\eta^{(\prime)} \to X$

  and

  $\psi(2S) \to \gamma\eta^{(\prime)}$

  $\eta^{(\prime)} \to X$

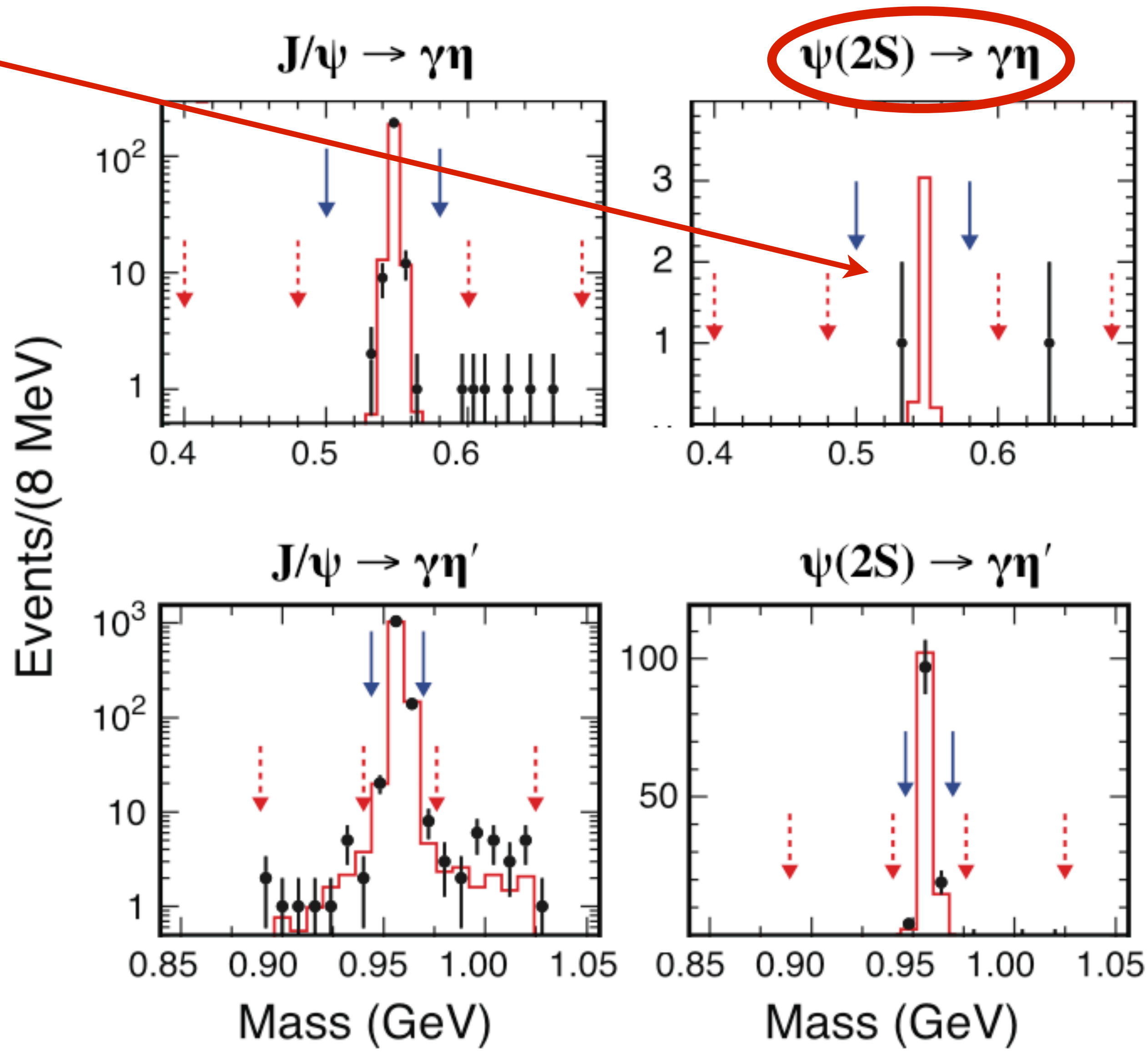
- Use $\pi^+\pi^-$ to select the **J/ψ**
- Use many different **decay modes** of the η and $\eta^{(\prime)}$
- Perform a **kinematic fit** of all decay products to the ψ(2S) 4-momentum
- **Count events** in the signal regions.



(only representative η and η′ decay modes are shown)

J/ψ and ψ(2S) Radiative Decays to η and η′

There is a strange depletion in ψ(2S) → γη !?!



$$\frac{B(J/\psi \to \gamma\eta)}{B(J/\psi \to \gamma\eta')} = (21.1 \pm 0.9)\%$$

but

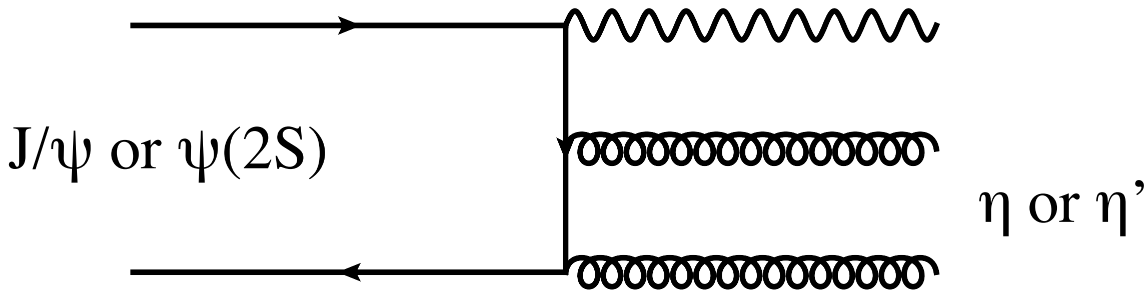
$$\frac{B(\psi(2S) \to \gamma\eta)}{B(\psi(2S) \to \gamma\eta')} < 1.8\%$$

Why are these ratios so different?

(only representative η and η′ decay modes are shown)

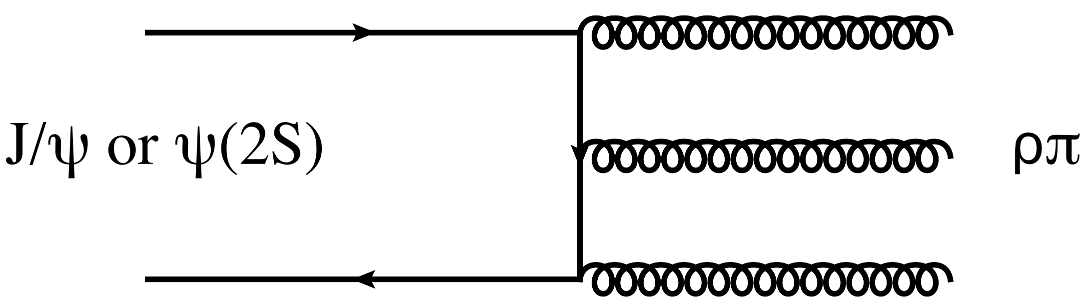
J/ψ and ψ(2S) Radiative Decays to η and η′

There must be something beyond this simple picture:



$$\frac{B(J/\psi \to \gamma\eta)}{B(J/\psi \to \gamma\eta')} >> \frac{B(\psi(2S) \to \gamma\eta)}{B(\psi(2S) \to \gamma\eta')}$$

Perhaps this is related to the classic “ρπ” puzzle:



$$\frac{B(\psi(2S) \to \rho\pi)}{B(J/\psi \to \rho\pi)} << 12\%$$

3.

D and D_s Decay Constants: f_D and f_{Ds}

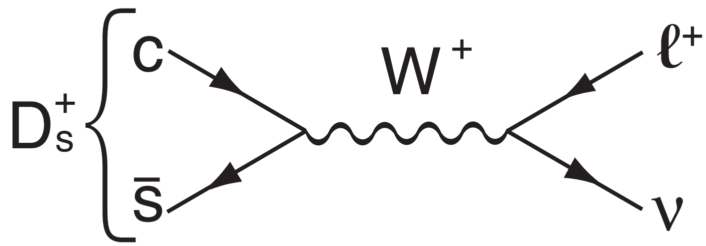
(half heavy)

will show plots from this one… →

PRD 78, 052003 (2008)	*[$D \to \mu\nu$]*
PRD 79, 052001 (2009)	*[$D_s \to \mu\nu, \tau(\pi\nu)\nu$]*
PRD 79, 052002 (2009)	*[$D_s \to \tau(e\nu\nu)\nu$]*
PRD 80, 112004 (2009)	*[$D_s \to \tau(\rho\nu)\nu$]*

D and D$_s$ Decay Constants

- **Leptonic decay** of the D_s^+ (for D^+, swap s for d):



- The **QCD part** of the rate can be factored into a constant, **f_{Ds}** (**f_D** for D^+):

$$\Gamma(D_s^+ \to \ell^+\nu) = \frac{G_F^2}{8\pi} f_{D_s^+}^2 m_\ell^2 M_{D_s^+} \left(1 - \frac{m_\ell^2}{M_{D_s^+}^2}\right)^2 |V_{cs}|^2$$

- Since f_D and f_{Ds} can be calculated in **lattice QCD**, leptonic decays allow comparison between theory and experiment.

- With ~1/2 of the final CLEO-c data set there were **hints of disagreement with lattice QCD (>2σ) for f_{Ds}**, but good agreement for f_D.

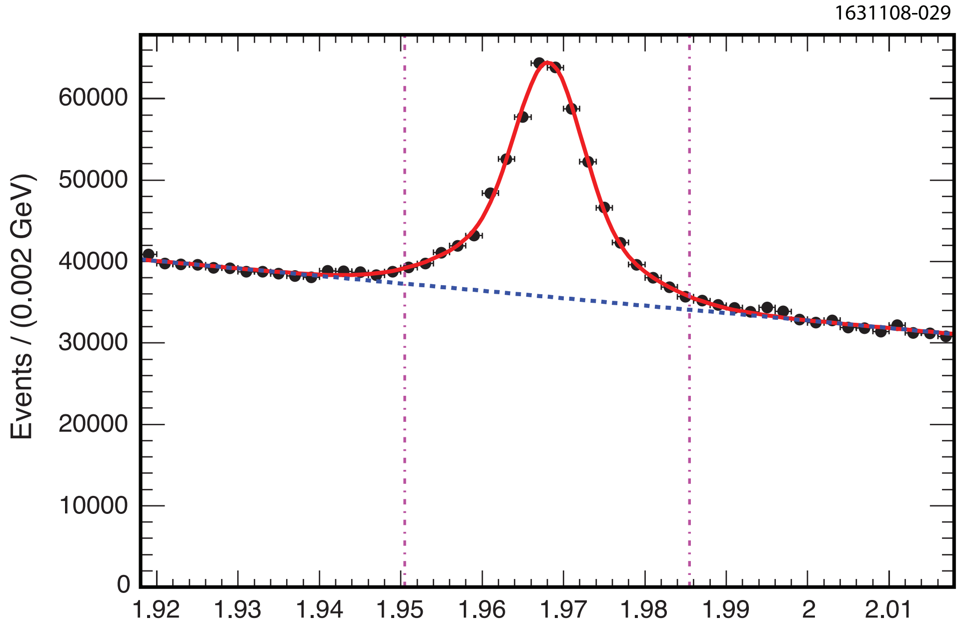
- CLEO-c now has results with the **final data sets** (**586 pb^{-1}** at 4170 MeV and **818 pb^{-1}** at ψ(3770))

D and D_s Decay Constants

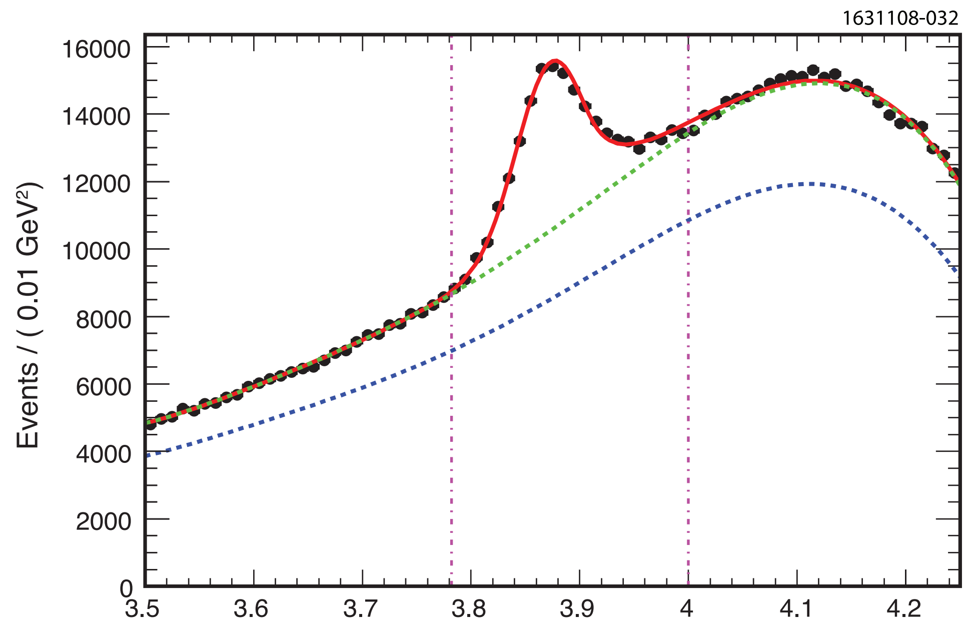
PRD 79, 052001 (2009)

Look at one set of measurements of f_{D_s} as an example…

e^+e^- (at 4170 MeV) **$\rightarrow D_s^{+*}D_s^-$** (or $D_s^{-*}D_s^+$) **$\rightarrow \gamma D_s^+ D_s^- \rightarrow \gamma(D_s)(\mu\nu$ or $\tau\nu$** ($\tau \rightarrow \pi\nu$)**)**



Mass (D_s Tag Modes)



Missing Mass Squared Against D_s Tag Modes and γ

1. Fully reconstruct one D_s using 9 different "tag modes"
2. Require a second D_s using the first D_s and a photon

D and D_s Decay Constants

3. Now look for the second D_s decaying to $\mu\nu$ or $\tau\nu$ (in $\pi\nu\nu$) using the first D_s, the photon, and a μ or π candidate.

4. Separate the μ and the π using energy deposited in the calorimeter.

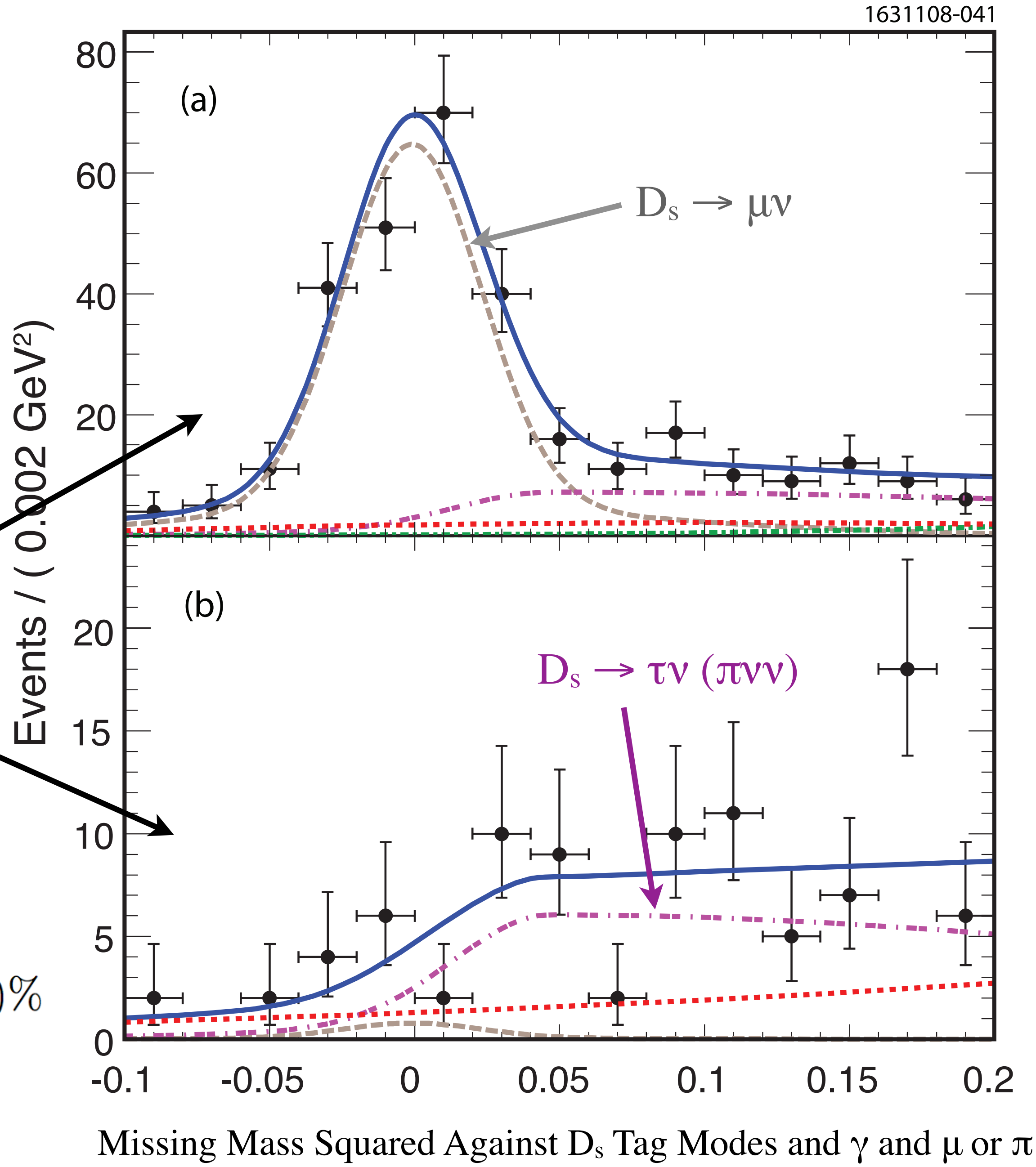
   case i: $E_{calorimeter} < 300$ MeV

   case ii: $E_{calorimeter} > 300$ MeV

5. Find branching fractions:

$$\mathcal{B}(D_s^+ \to \mu^+\nu) = (0.565 \pm 0.045 \pm 0.017)\%$$

$$\mathcal{B}(D_s^+ \to \tau^+\nu) = (6.42 \pm 0.81 \pm 0.18)\%$$



D and D_s Decay Constants

Tabulation of final measurements of D_s leptonic decays from CLEO-c:

	Mode	$\mathcal{B}$ (%)	f_{D_s} (MeV)
PRD 80, 112004 (2009)	$\tau^+\nu$ $(\rho^+\bar{\nu})$	$(5.52 \pm 0.57 \pm 0.21)$	$257.8 \pm 13.3 \pm 5.2$
PRD 79, 052001 (2009)	$\tau^+\nu,$ $(\pi^+\bar{\nu})$	$(6.42 \pm 0.81 \pm 0.18)$	$278.0 \pm 17.5 \pm 4.4$
PRD 79, 052002 (2009)	$\tau^+\nu$ $(e^+\nu\bar{\nu})$	$(5.30 \pm 0.47 \pm 0.22)$	$252.6 \pm 11.2 \pm 5.6$
AVERAGE for τν	$\tau^+\nu$	$(5.58 \pm 0.33 \pm 0.13)$	$259.7 \pm 7.8 \pm 3.4$
PRD 79, 052001 (2009)	$\mu^+\nu$	$(0.565 \pm 0.045 \pm 0.017)$	$257.6 \pm 10.3 \pm 4.3$
FINAL AVERAGE	$\tau^+\nu+\mu^+\nu$		$259.0 \pm 6.2 \pm 3.0$

Compare to lattice calculations of f_{Ds}:

f_{Ds} = 241 ± 3 MeV *(HPQCD, UKQCD)* **PRL 100, 062002 (2008)**

2010 Update: **f_{Ds} = 247 ± 2 MeV**

f_{Ds} = 249 ± 3 ± 16 MeV *(FNAL, MILC, HPQCD)* **PRL 95, 122002 (2005), arXiv:0904.1895**

2010 Update: **f_{Ds} = 261.4 ± 7.7 ± 5.0 MeV**

For f_{Ds}, lattice calculations have risen and experimental values have fallen: discrepancy now < 2σ.

Notes: There is no disagreement for f_D. Belle, BaBar measurements are consistent with CLEO (with larger errors) for f_{Ds}.

4.

(heavy)

Higher-Order Multipoles in

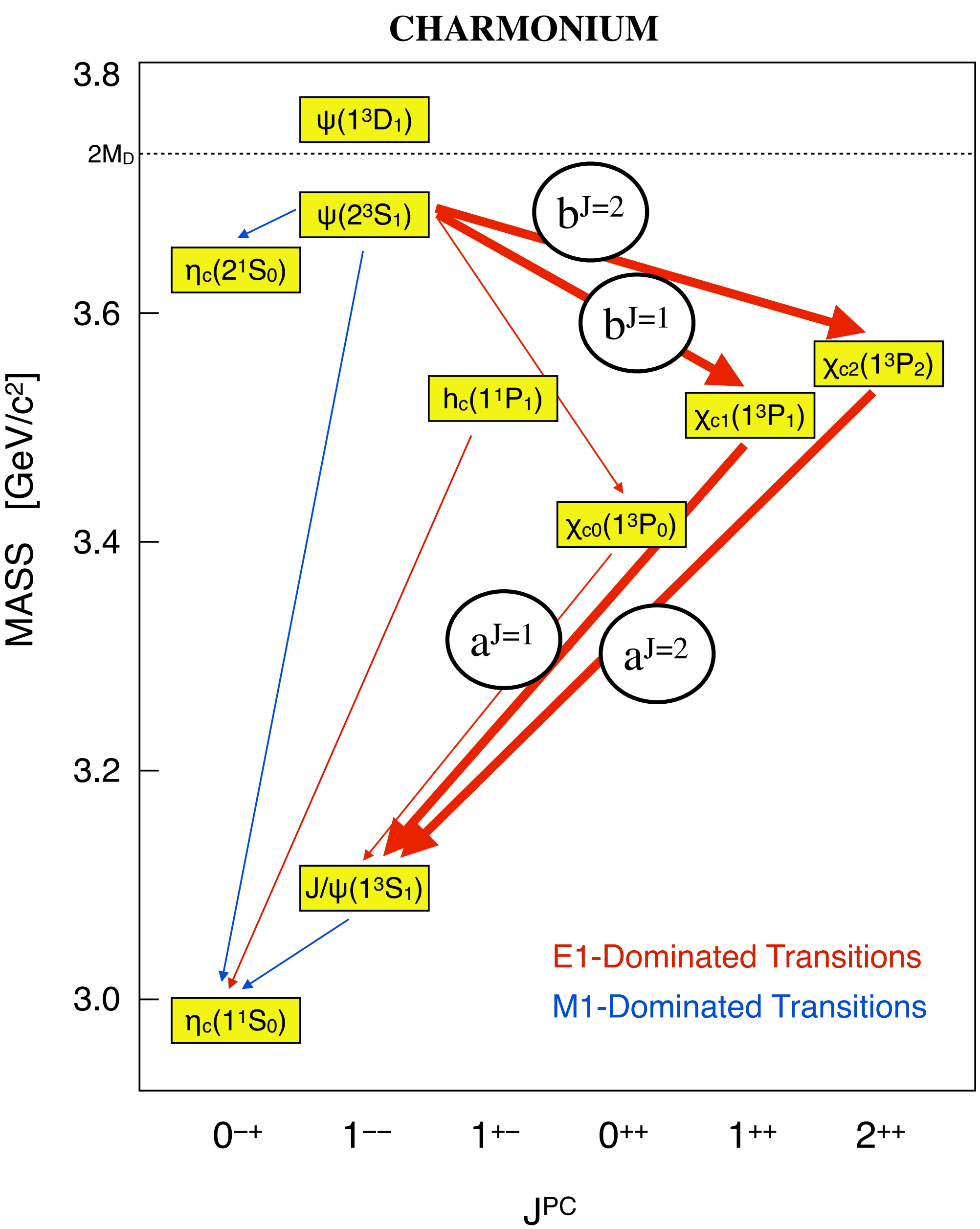
$\psi(2S) \rightarrow \gamma\chi_{c1,2}$

and

$\chi_{c1,2} \rightarrow \gamma J/\psi$

PRD 80, 112003 (2009)

Higher-Order Multipoles in ψ(2S) → γχc1,2; χc1,2 → γJ/ψ



E1 amplitudes are dominant,
but M2 amplitudes are expected:

$$b_2^{J=1} \equiv \frac{M2}{\sqrt{E1^2 + M2^2}} = \frac{E_{\gamma'}}{4m_c}(1+\kappa_c)$$

$$b_2^{J=2} \equiv \frac{M2}{\sqrt{E1^2 + M2^2 + E3^2}} = \frac{3}{\sqrt{5}}\frac{E_{\gamma'}}{4m_c}(1+\kappa_c)$$

$$a_2^{J=1} \equiv \frac{M2}{\sqrt{E1^2 + M2^2}} = -\frac{E_{\gamma}}{4m_c}(1+\kappa_c)$$

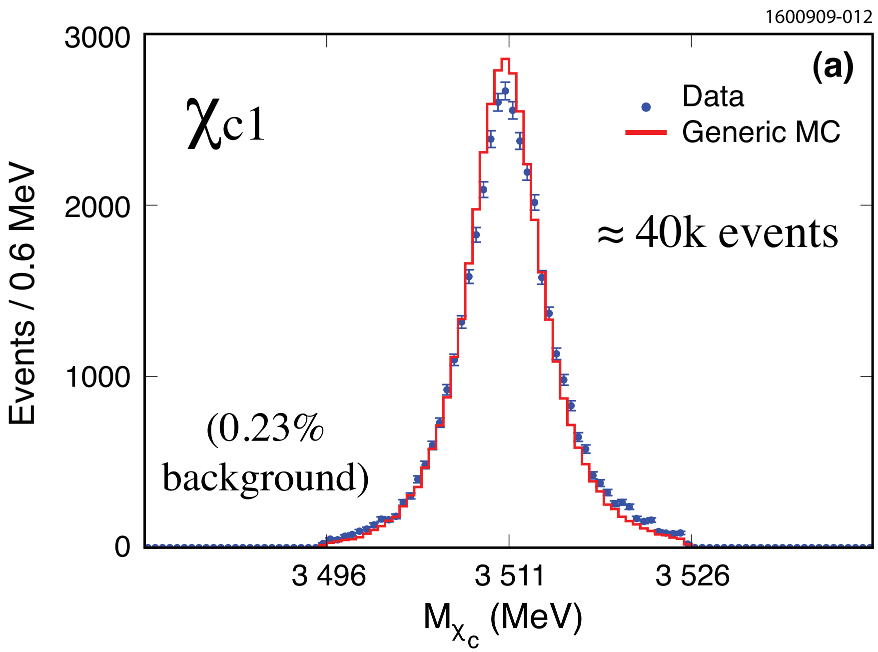
$$a_2^{J=2} \equiv \frac{M2}{\sqrt{E1^2 + M2^2 + E3^2}} = -\frac{3}{\sqrt{5}}\frac{E_{\gamma}}{4m_c}(1+\kappa_c)$$

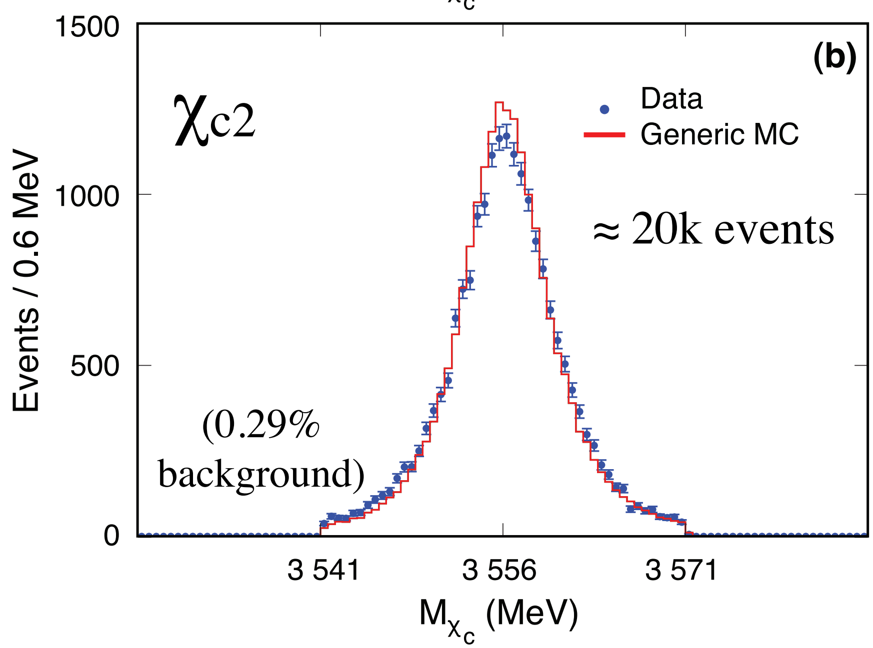
Note that:

- **M2** has sensitivity to the anomalous magnetic moment of the charm quark (κ_c)
- **E3** is expected to be zero, but is allowed if there is S-D (ψ(2S)) or P-F (χ(1P)) mixing
- There are also recent **lattice calculations**:

(Dudek et al., PRD73, 074507 (2006), PRD79, 094504 (2009))

Higher-Order Multipoles in $\psi(2S) \to \gamma\chi_{c1,2}$; $\chi_{c1,2} \to \gamma J/\psi$





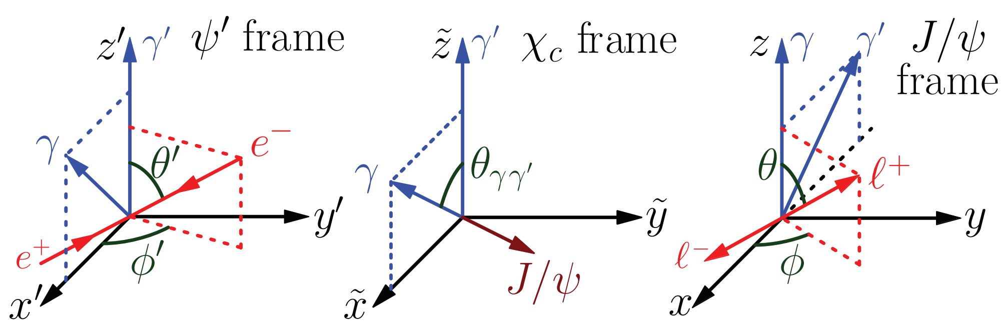
Procedure:

- Select samples of:

$\psi(2S) \to \gamma\chi_{cJ}$;
$\chi_{cJ} \to \gamma J/\psi$;
$J/\psi \to e^+e^-, \mu^+\mu^-$

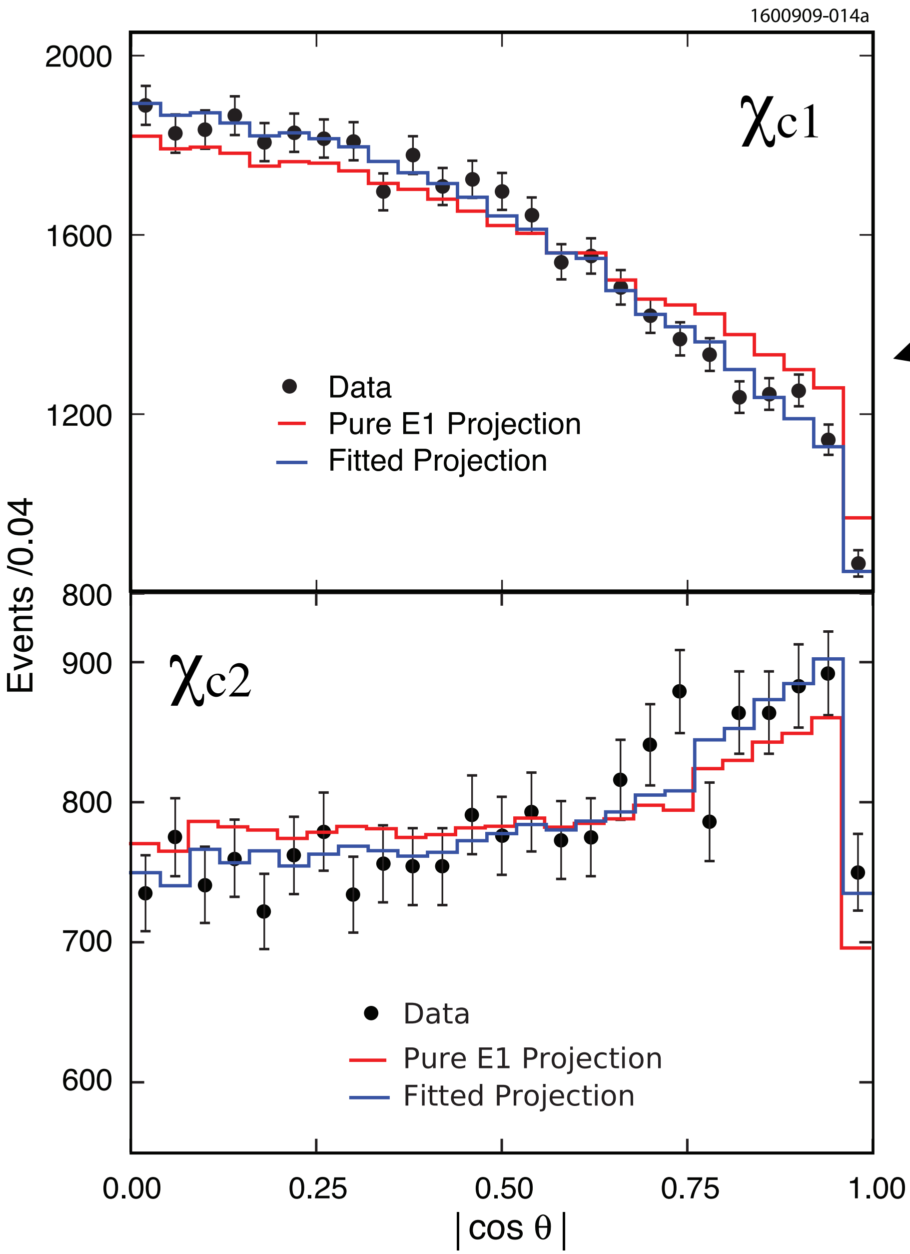
clean samples well-described by MC

- Use 5-dimensional angular distributions to differentiate multipole amplitudes.



- Fit the χ_{c1} and χ_{c2} decay chains separately.

Higher-Order Multipoles in $\psi(2S) \rightarrow \gamma\chi_{c1,2};\ \chi_{c1,2} \rightarrow \gamma J/\psi$



Sample Fit Projections

(projection of cosine of angle between l^+ and γ from χ_{cJ} decay in J/ψ frame)

⇒ Fits are poor when only E1 amplitudes are used.

⇒ There is clear evidence for non-zero M2 amplitudes.

⇒ E3 amplitudes are consistent with zero.

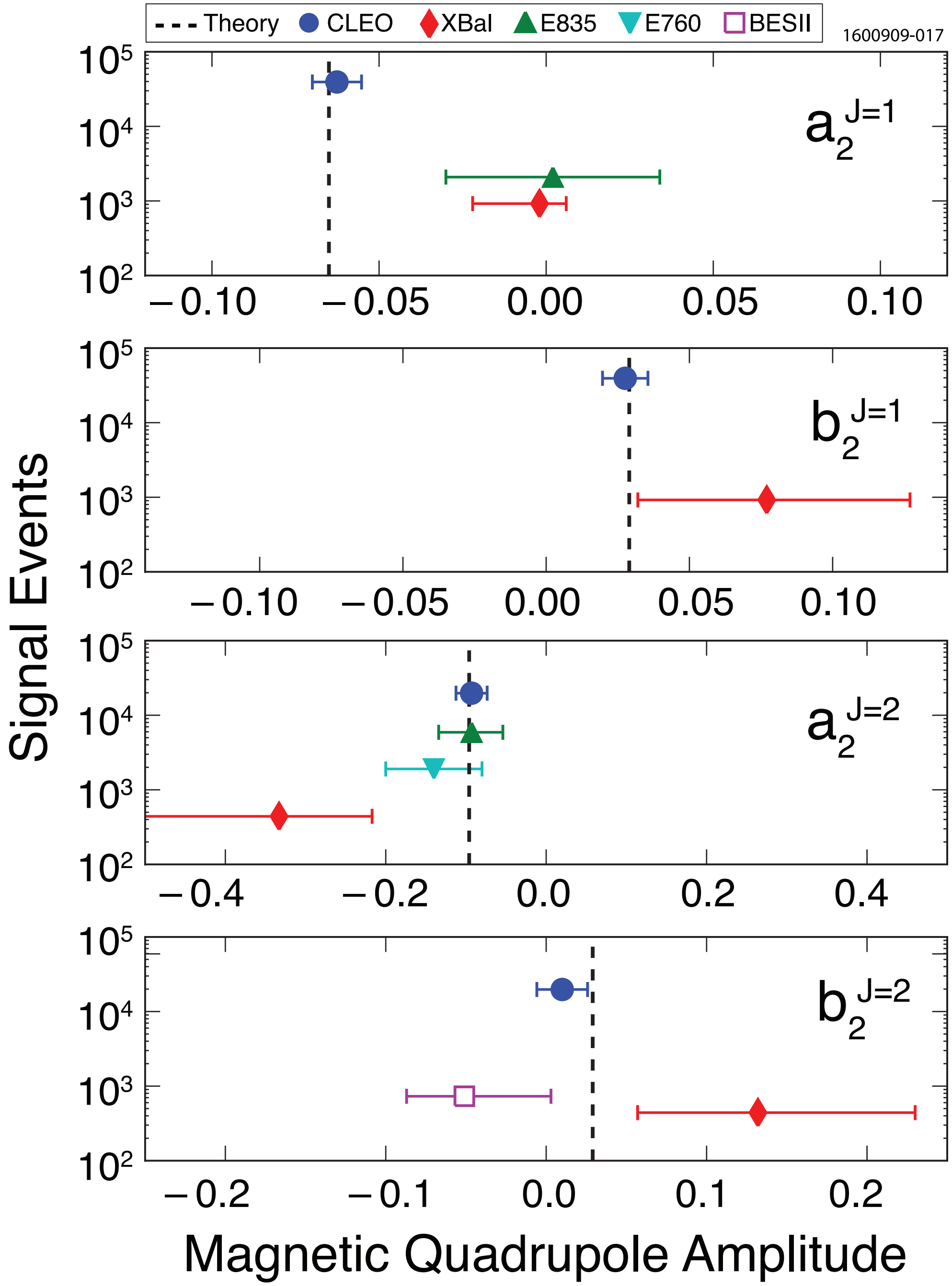
Higher-Order Multipoles in $\psi(2S) \to \gamma\chi_{c1,2}$; $\chi_{c1,2} \to \gamma J/\psi$

$\chi_{c1} \to \gamma J/\psi$

$\psi(2S) \to \gamma\chi_{c1}$

$\chi_{c2} \to \gamma J/\psi$

$\psi(2S) \to \gamma\chi_{c2}$



- There is good agreement with theory when:

  $m_c = 1.5$ GeV/c^2

  and

  $\kappa_c = 0$

  i.e., there is no evidence for a non-zero anomalous magnetic moment of the charm quark.

- Old apparent theory-experiment discrepancies are resolved.

- *(see PRD 80, 112003 (2009) for numerical results)*

5.

(heaviest)

Confirming Evidence for

$\Upsilon(3S) \rightarrow \gamma\eta_b$

PRD 81, 031104(R) (2010)

Confirming Evidence for $\Upsilon(3S) \to \gamma\eta_b$

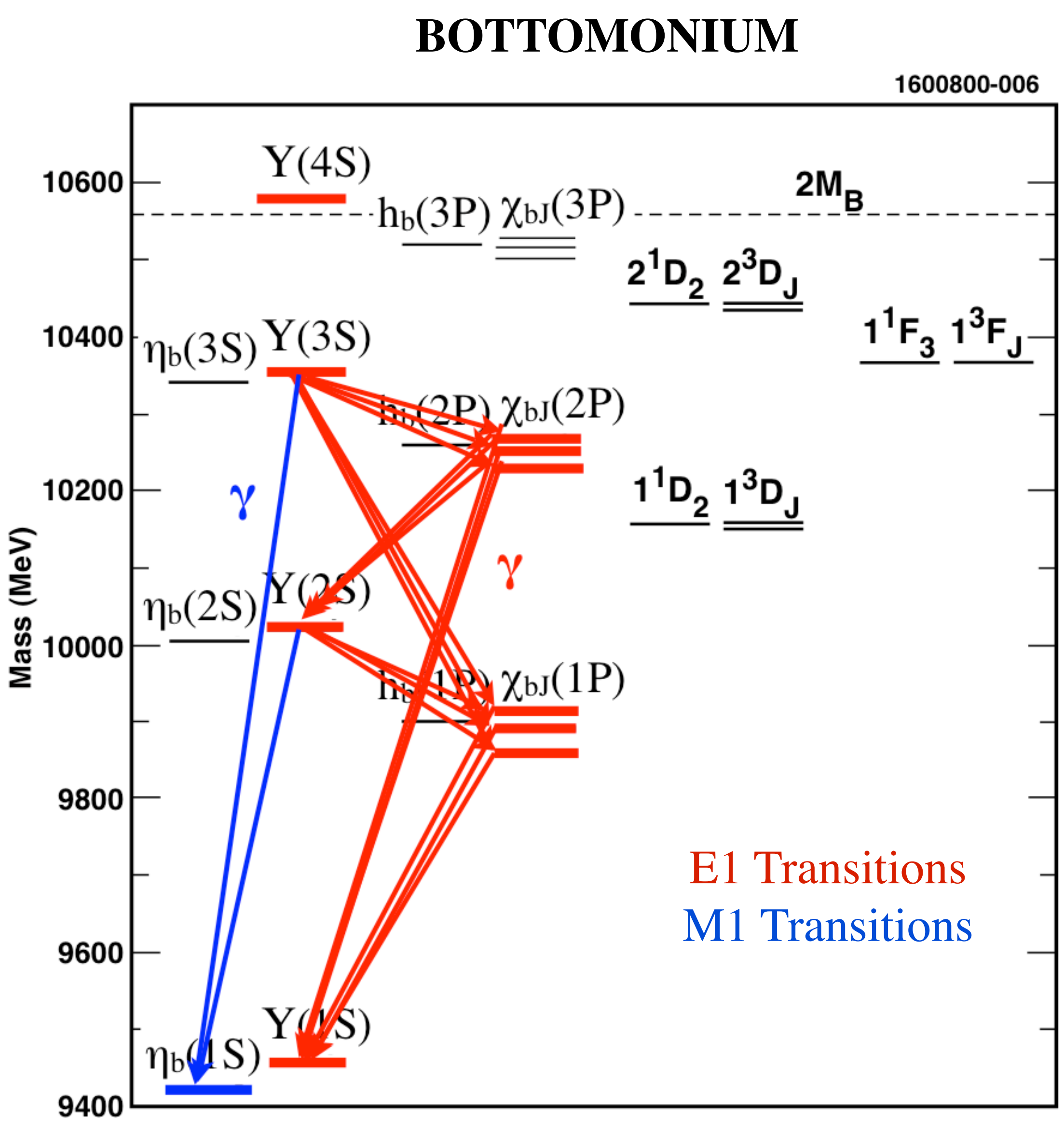
- The η_b is the **ground state of bottomonium**. (Bottomonium was discovered >30 years ago.)

- The η_b was recently **discovered by BaBar** in $\Upsilon(3S) \to \gamma\eta_b$ and has since also been reported in $\Upsilon(2S) \to \gamma\eta_b$.

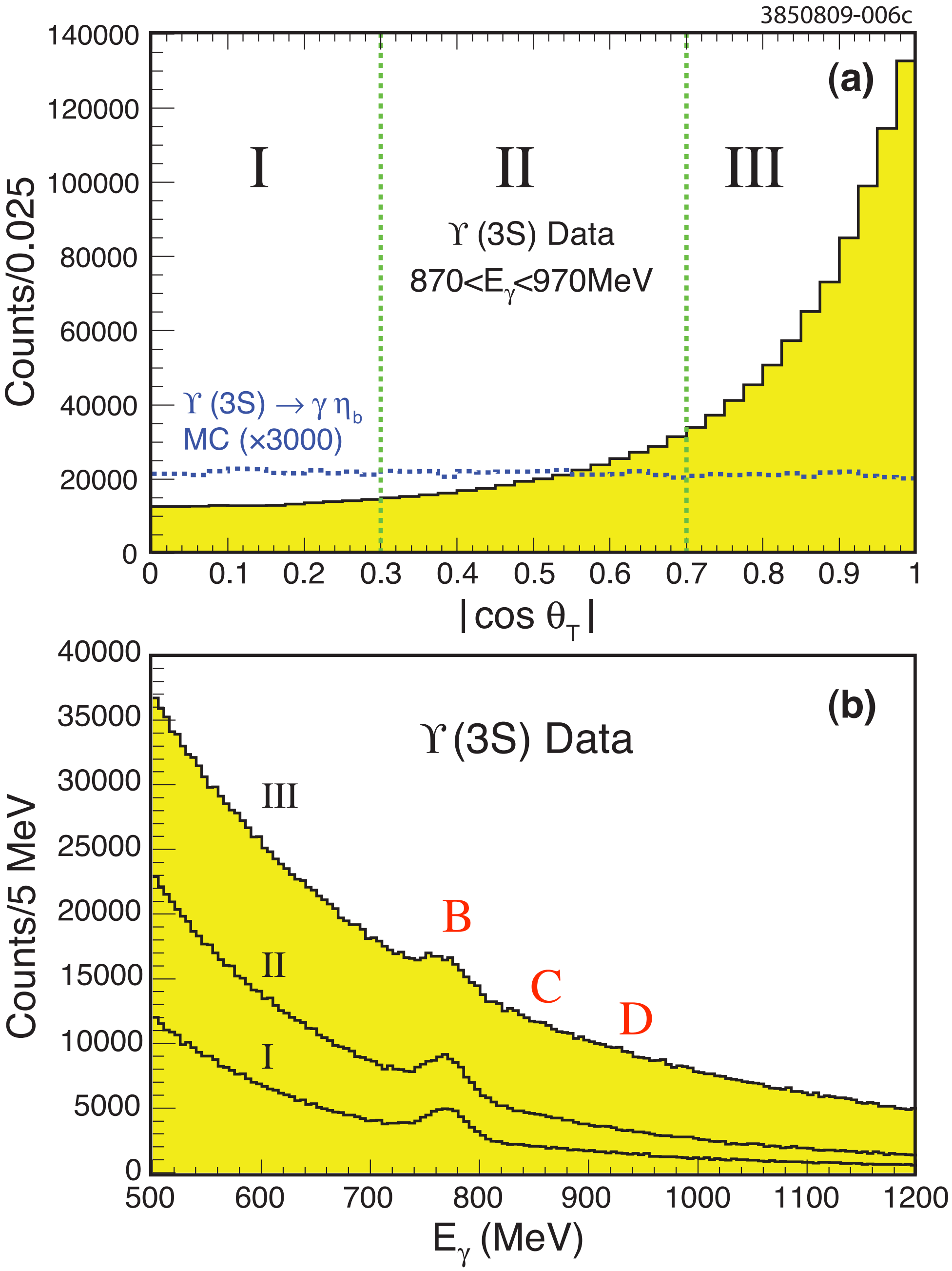
- The η_b mass provides a first look at **hyperfine splitting** in bottomonium (recently calculated in lattice QCD).

- The $\Upsilon(nS) \to \gamma\eta_b$ decays are the only observed **M1 radiative transitions** in bottomonium.

- *CLEO recently reanalyzed $\Upsilon(3S)$ data to search for $\Upsilon(3S) \to \gamma\eta_b$...*



Confirming Evidence for $\Upsilon(3S) \to \gamma\eta_b$



- Use the angle between the photon and the "thrust axis" of the rest of the event to form three bins with different levels of continuum background.

- Simultaneously fit the thrust bins with four components:

  A. *Non-peaking background*

  * different polynomial for each thrust bin

  B. *$\chi_{bJ}(2P) \to \gamma\Upsilon(1S)$ lines*

  * shapes fixed from independent studies

  * normalization, energy resolution, and energy offset floated

  C. *Initial State Radiation (ISR) to $\Upsilon(1S)$*

  * fixed using $\Upsilon(4S)$ data

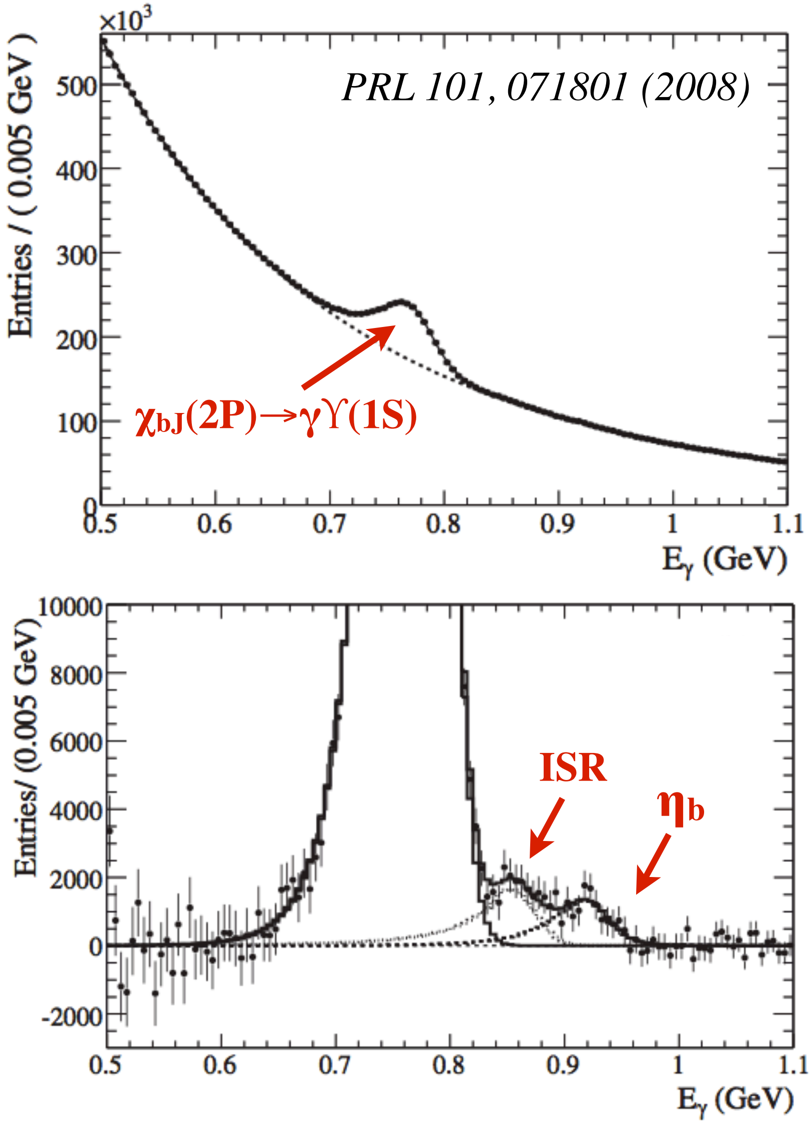
  D. *$\Upsilon(3S) \to \gamma\eta_b$ signal*

  * shape constrained by $\chi_{bJ}(2P)$ lines

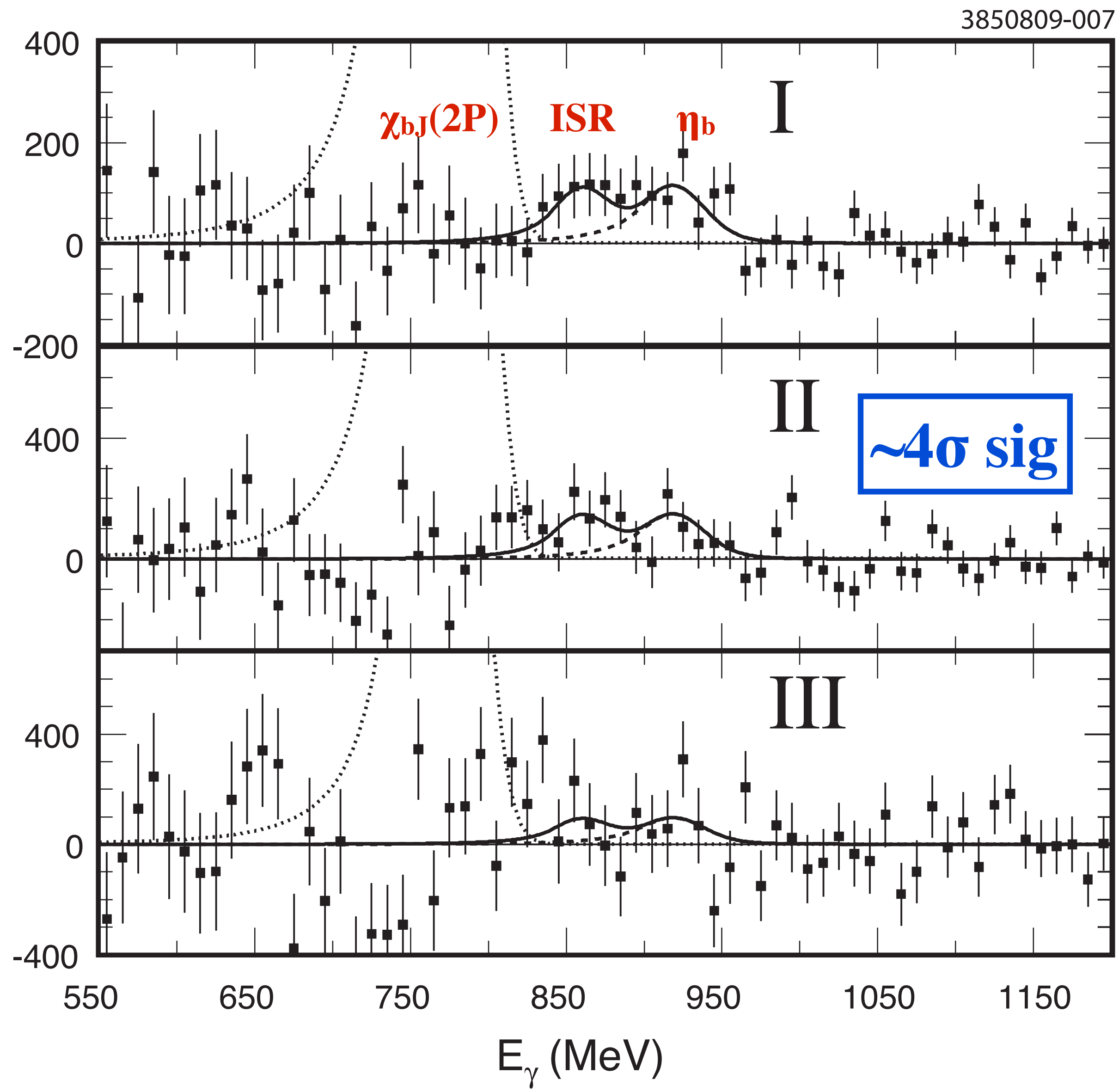
  * width fixed at 10 MeV

Confirming Evidence for $\Upsilon(3S) \rightarrow \gamma\eta_b$

BaBar -- 109M $\Upsilon(3S)$



CLEO -- 6M $\Upsilon(3S)$



Confirming Evidence for $\Upsilon(3S) \to \gamma\eta_b$

- CLEO's new $\Upsilon(3S) \to \gamma\eta_b$ branching fraction measurement is:

  $$\mathcal{B}(\Upsilon(3S) \to \gamma\eta_b) = (7.1 \pm 1.8(\text{stat}) \pm 1.3(\text{syst})) \times 10^{-4}$$

  (assuming the η_b width is 10 MeV), compared to BaBar's **$(4.8 \pm 0.5 \pm 0.6) \times 10^{-4}$** and replaces CLEO's old UL: **$< 4.3 \times 10^{-4}$**.

- The η_b signal has a mass of:

  $$M(\eta_b) = 9391.8 \pm 6.6 \pm 2.0 \text{ MeV}/c^2,$$

  or a hyperfine splitting of:

  $$M(\Upsilon(1S)) - M(\eta_b) = 68.5 \pm 6.6 \pm 2.0 \text{ MeV}/c^2$$

  which is consistent with BaBar's mass of **9390.4 ± 3.1 MeV/c^2**.

- A new upper limit for $\Upsilon(2S) \to \gamma\eta_b$ is found:

  $$\mathcal{B}(\Upsilon(2S) \to \gamma\eta_b) < 8.4 \times 10^{-4},$$

  compared to BaBar's **$(4.2\,^{+1.1}_{-1.0} \pm 0.9) \times 10^{-4}$** and replaces CLEO's UL: **$< 5.1 \times 10^{-4}$**.

Summary of News from CLEO from Light to Heavy

(lightest)	1. Observation of $\eta' \to \pi^+\pi^-\pi^0$ and $\eta' \to \pi^+\pi^-e^+e^-$
(heavy decaying to light)	2. J/ψ and $\psi(2S)$ Radiative Decays to η and η'
(half heavy)	3. D and D_s Decay Constants: f_D and f_{Ds}
(heavy)	4. Higher-Order Multipoles in $\psi(2S) \to \gamma\chi_{c1,2}$ and $\chi_{c1,2} \to \gamma J/\psi$
(heaviest)	5. Confirming Evidence for $\Upsilon(3S) \to \gamma\eta_b$

(many other results are available but not covered…)