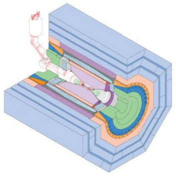

Recent CLEO results on quarkonium spectroscopy

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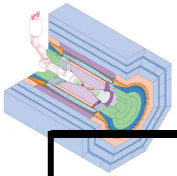

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FORCES			System	**Ground triplet state 1^3S_1**			**$(v/c)^2$**	Number of states below dissociation energy	
binding	decay			Name	Γ (MeV)	Mass (GeV)		n^3S_1	all
POSITRONIUM									
EM	EM		e^+e^-	Ortho-	$5\ 10^{-15}$	0.001	**~0.0**	2	8
QUARKONIUM									
STRONG	STRONG		$u\bar{u},d\bar{d}$	ρ	150.00	0.8	**~1.0**	0	0
			$s\bar{s}$	ϕ	4.40	1.0	**~0.8**	"1"	"2"
		EM	$c\bar{c}$	ψ	0.09	3.1	**~0.25**	**2**	**8**
			$b\bar{b}$	Υ	0.05	9.5	**~0.08**	**3**	**30**
	weak		$t\bar{t}$		(3000.0)	(360.)	<0.01	0	0

Toponium is not a lab for QCD

Consequences of **large m_Q**:

- velocities of constituents are small v
- strong coupling constant in annihilation and production is small α_s

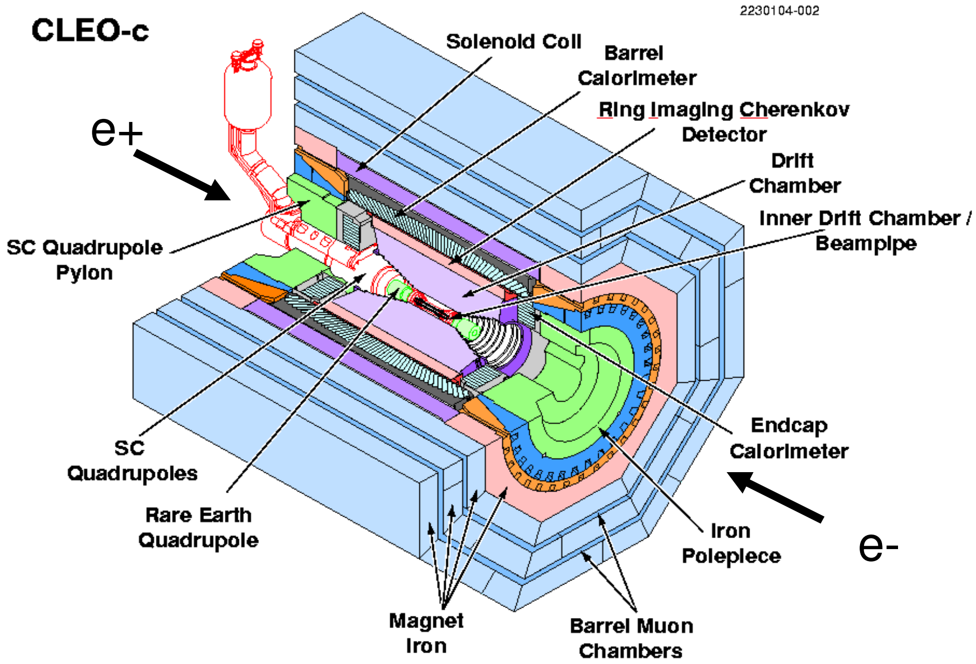
$\left.\begin{matrix} v \\ \alpha_s \end{matrix}\right\}$ Expansion parameters

This opens avenues for **effective theories** of strong interactions:

- purely phenomenological potential models
- more recently NRQCD and much improved QCD on Lattice

Content of this talk

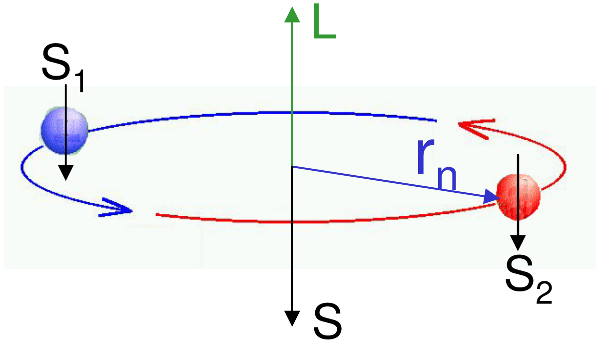
- Report on two recent measurements with the CLEO-III and CLEO-c detectors:
  - Measurement of the $\eta_b(1S)$ mass and the branching fraction for $\Upsilon(3S) \rightarrow \gamma\, \eta_b(1S)$ [arXiv:0909.5474]
  - Higher-order multipole amplitudes in charmonium radiative transitions [Phys.Rev.D80:112003,2009].



- CLEO-c detector ($c\bar{c}$ data):
  - Charged particle detection (1T): σ_p/p=0.6% at 1 GeV
  - Photon detection: σ_E/E=4.8% at 100 MeV, 2.2% at 1 GeV
  - Hadron ID: dE/dX+RICH (fake rates at a few % level)
- CLEO-III detector ($b\bar{b}$ data):
  - The same detector except for inner vertex detector (silicon) and magnetic field (1.5T)

Hyperfine splitting $\vec{S_1}\cdot\vec{S_2}$

$$n\;^{2S+1}L_J$$



$$\vec{J}=\vec{L}+\vec{S}$$

$$\vec{S}=\vec{S}_1+\vec{S}_2$$

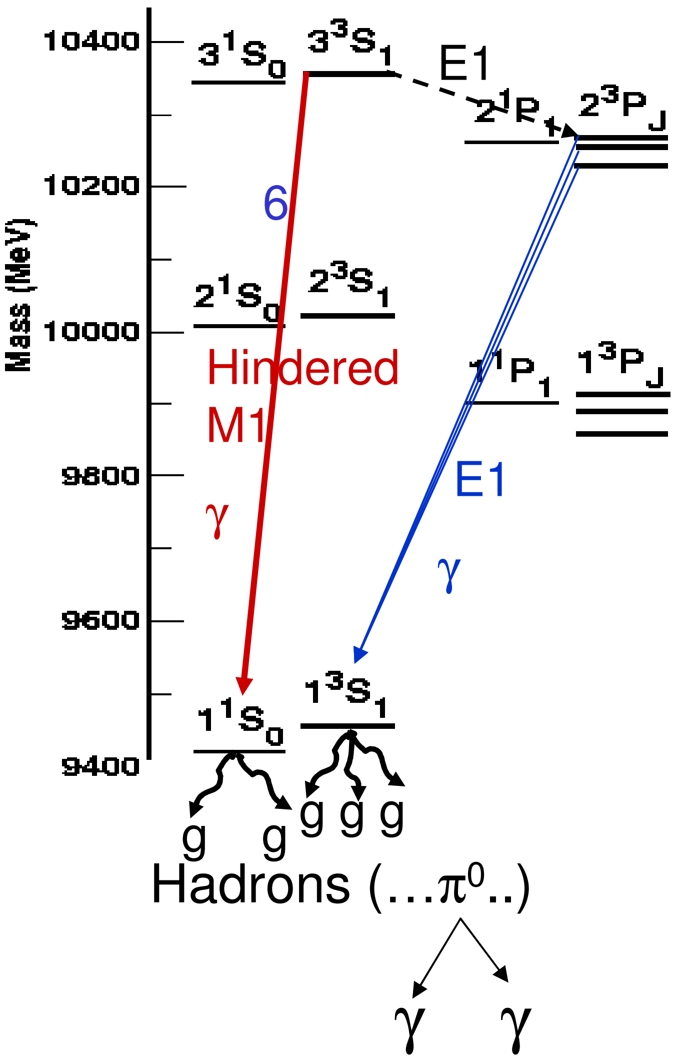
- Expected to be significant only for S states (L=0)
- Hyperfine splitting of the ground state of $b\bar{b}$ (n=1) a good place to test lattice QCD calculations:

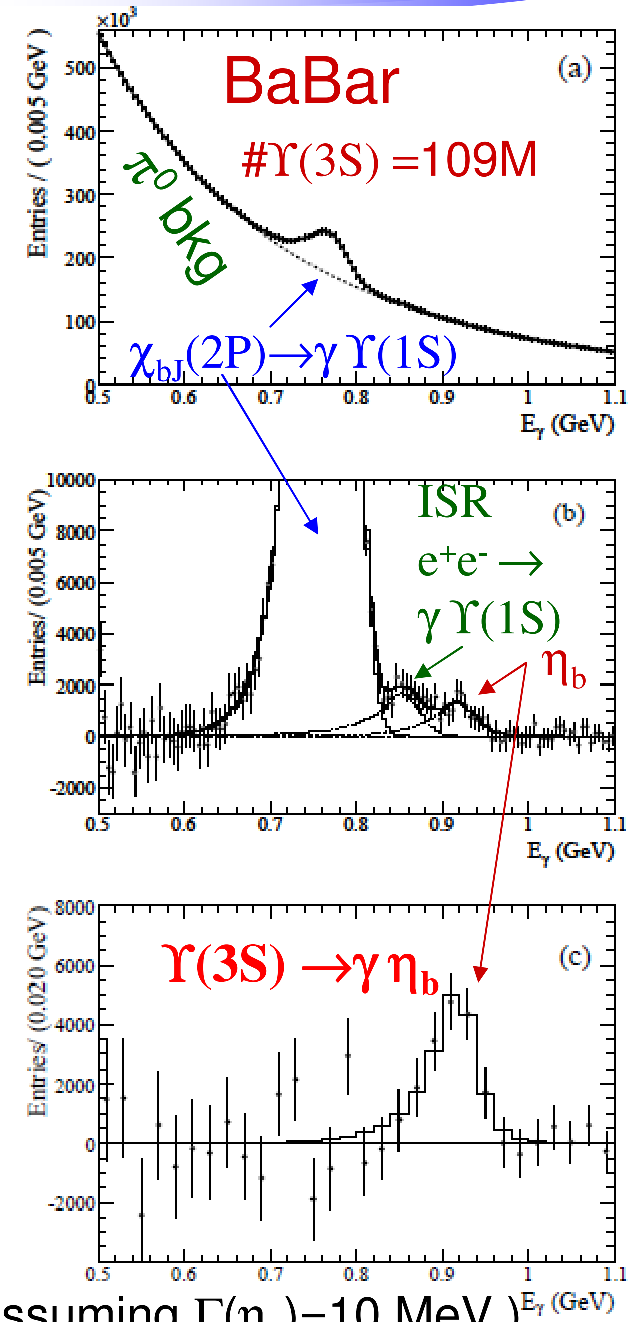
$$\Delta M_{hf}(1S)_{b\bar{b}}= M(1^3S_1) - M(1^1S_0) = M(\Upsilon) - M(\eta_b)$$

- Only recently measured experimentally thanks to the first observation of η_b by BaBar

First observation of η_b by BaBar

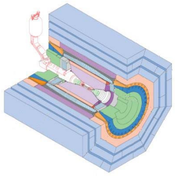
BaBar PRL 101, 071801, 2008





(Assuming $\Gamma(\eta_b)$=10 MeV)

- Statistical significance >10σ



Confirmation from the CLEO data?

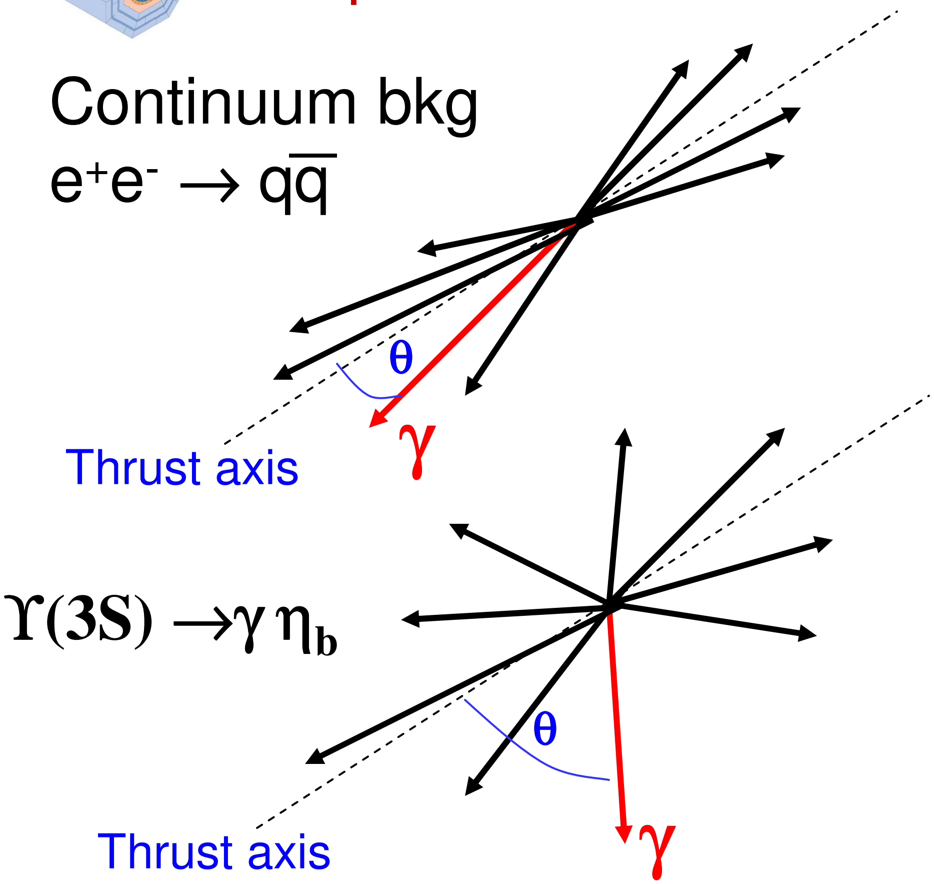
- The CLEO $\Upsilon(3S)$ data samples is ~18 times smaller than the BaBar's
- We published the upper limit on $BR(\Upsilon(3S) \to \gamma\eta_b) < 4.3\times10^{-4}$ (90% C.L.) in 2005 [vs BaBar $(4.8\pm0.5 \pm 0.6)\times10^{-4}$] , but:
  - We did not include the ISR peak in the background fit which biased the BR down;
  - We assumed $\Gamma(\eta_b)=0$, while 4-20 MeV is predicted (not completely negligible compared to the resolution).
  - We did not use continuum background suppression cuts, which BaBar proved to be beneficial for this channel (our analysis was optimized to lower energy E1 transitions where continuum backgrounds were insignificant)
- Today present re-analysis of the CLEO data, optimized for $\Upsilon(3S) \to \gamma\,\eta_b$ sensitivity

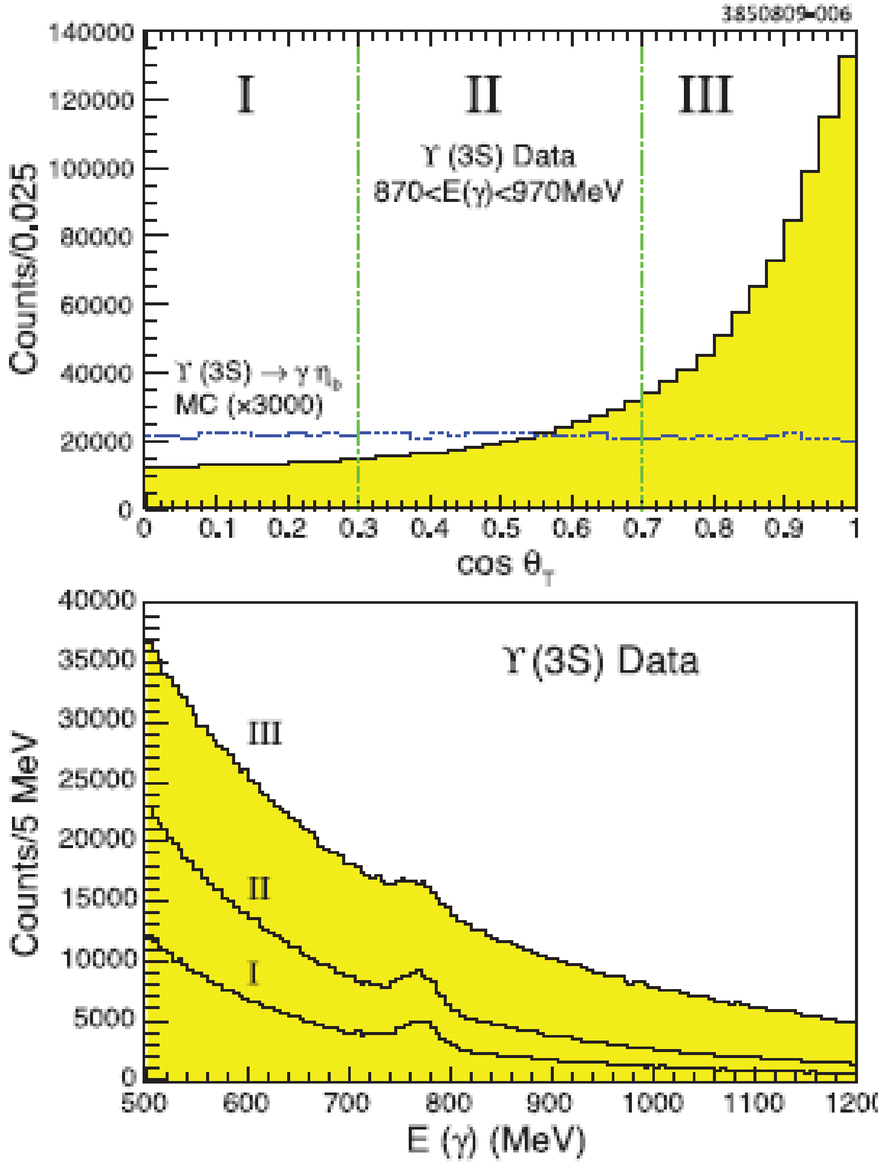
Improved thrust axis analysis

Continuum bkg

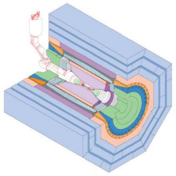
$e^+e^- \to q\bar{q}$

$\Upsilon(3S) \to \gamma\, \eta_b$





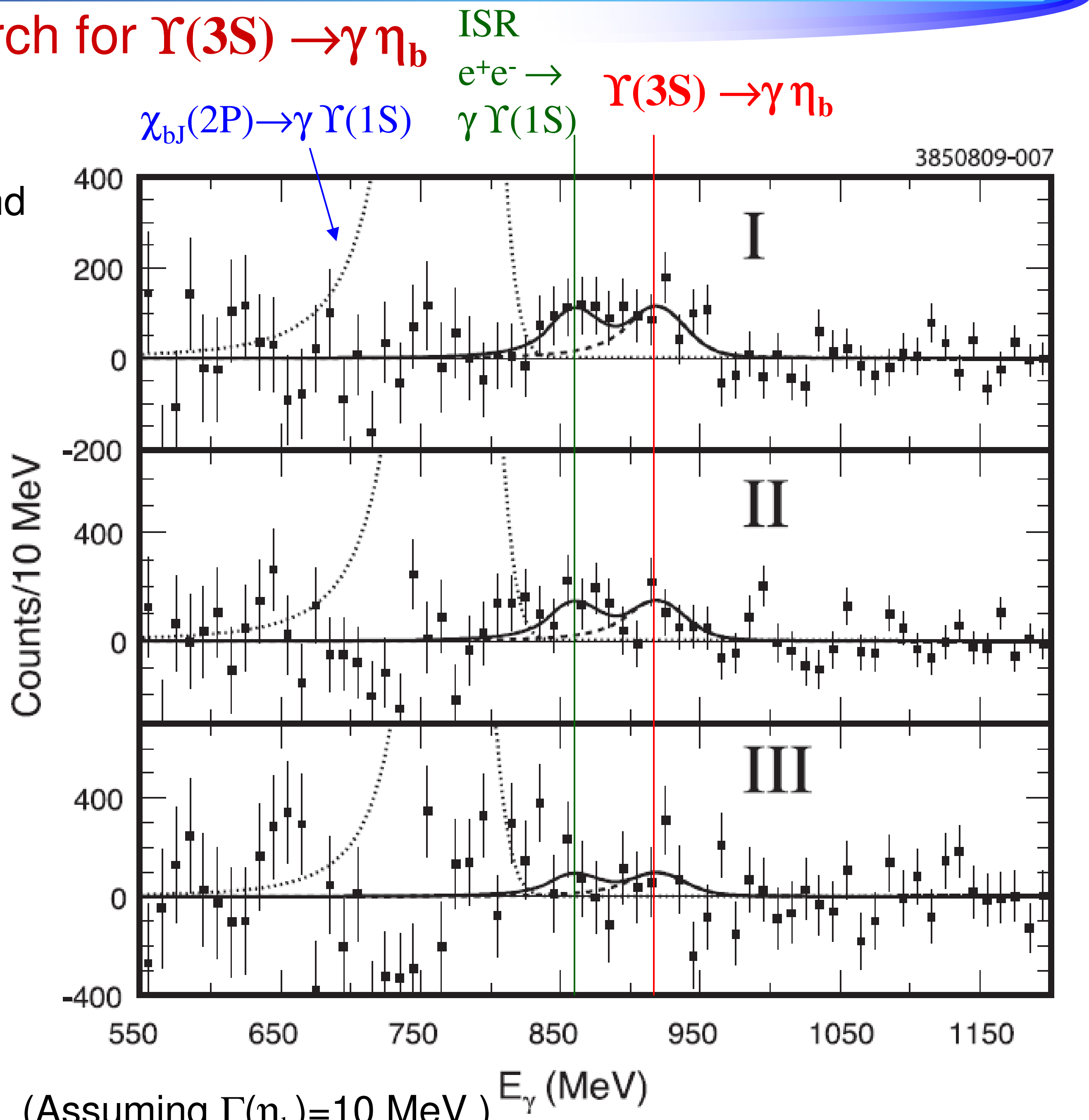
- BaBar used $|\cos\theta|<0.7$
- We split <0.7 into 2 bins (the main improvement) and keep >0.7 data
- We perform simultaneous fit to all 3 photon spectra



CLEO search for $\Upsilon(3S) \to \gamma\, \eta_b$

The smooth background and $\chi_{bJ}(2P) \to \gamma\, \Upsilon(1S)$ subtracted.

- Statistical significance ~4σ

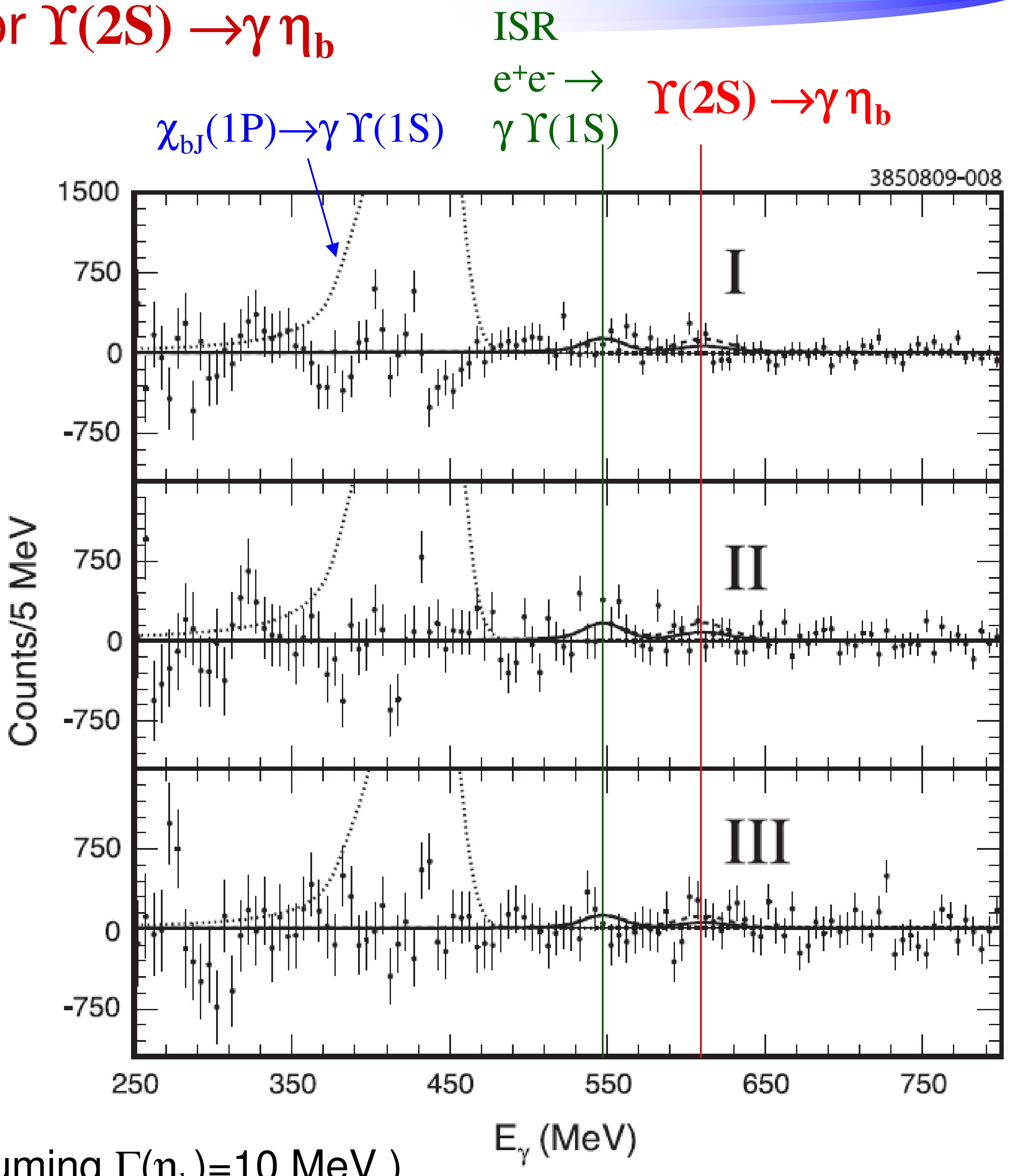


(Assuming $\Gamma(\eta_b)$=10 MeV)

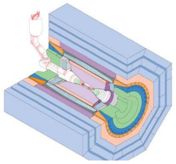
CLEO search for $\Upsilon(2S) \to \gamma\, \eta_b$

The smooth background and $\chi_{bJ}(2P) \to \gamma\, \Upsilon(1S)$ subtracted.

- No signal detected (much higher resonant backgrounds)
- BaBar detected ~3.5σ signal in ~10 times more data



(Assuming $\Gamma(\eta_b)$=10 MeV)



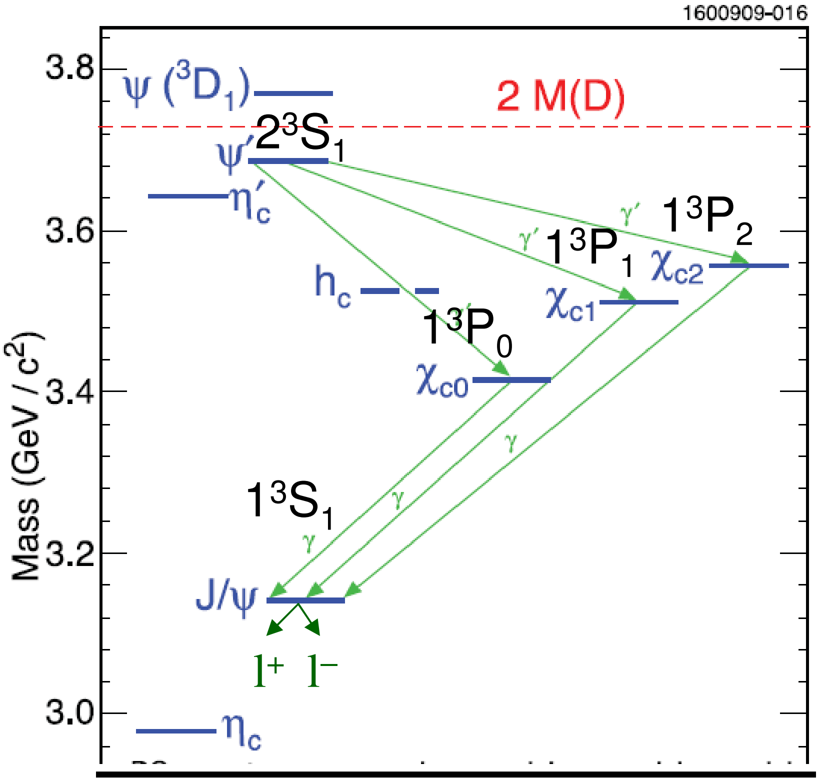
CLEO vs BaBar vs theory

(Assuming $\Gamma(\eta_b)$=10 MeV)

		$\Delta M_{hf}(1S)_{b\bar{b}}$, (MeV)	$\mathcal{B}(\Upsilon(nS) \to \gamma\eta_b) \times 10^4$	significance
$\Upsilon(3S) \to \gamma\eta_b$	(CLEO)	$68.5 \pm 6.6 \pm 2.0$	$7.1 \pm 1.8 \pm 1.1$	4σ
	(BaBar)	$71.4^{+3.1}_{-2.3} \pm 2.7$	$4.8 \pm 0.5 \pm 0.6$	$\geq 10\sigma$
$\Upsilon(2S) \to \gamma\eta_b$	(CLEO)	—	< 8.4 (90% CL)	—
	(BaBar)	$67.4^{+4.8}_{-4.6} \pm 2.0$	$3.9^{+1.1}_{-1.0} \pm 0.9$	3.5σ
Lattice (UKQCD+HPQCD)		61 ± 14	} Unquenched	
	(TWQCD)	70 ± 5		
	(Ehrman)	37 ± 8		
pQCD (various)		$35 - 100$	$0.05 - 25$ $(\Upsilon(3S))$	
			$0.05 - 15$ $(\Upsilon(2S))$	

- The experimental results for hyperfine mass splitting agree with the unquenched lattice QCD calculations
- BaBar has the best measurements
- Significance of the CLEO measurement is in independent confirmation of the BaBar results

Higher-order mutipole amplitudes in charmonium radiative transitions



- Wavelength of the radiated photon large compared to the radiating system, thus lowest multipole amplitude dominates: E1
- Allowed higher order mutipoles:
  - For 1^3P_1: M2
  - For 1^3P_2: M2, E3
- To the first order in $E\gamma/m_c$, a fraction of M2 amplitude is expected to be:

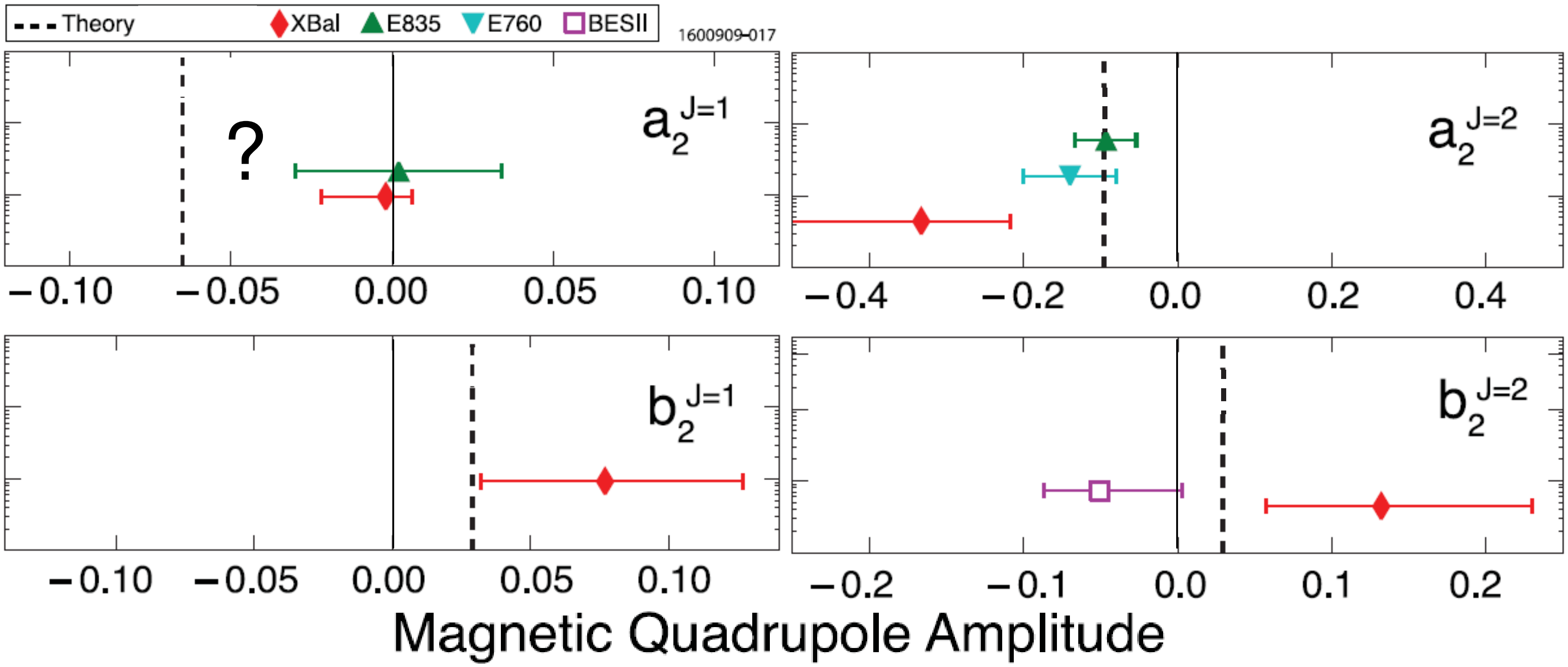
$$1^3P_1 \quad \frac{M2}{\sqrt{E1^2+M2^2}} = -\frac{E_\gamma}{4m_c}(1+\kappa_c)$$

$$1^3P_2 \quad \frac{M2}{\sqrt{E1^2+M2^2+E3^2}} = -\frac{3}{\sqrt{5}}\frac{E_\gamma}{4m_c}(1+\kappa_c)$$

- Denote these fractions as:
  - b_2^J for $\psi(2S) \rightarrow \gamma\, \chi_{cJ}(1P_J)$
  - a_2^J for $\chi_{cJ}(1P_J) \rightarrow \gamma J/\psi(1S)$

κ_c – anomalous magnetic moment of c-quark (expect κ_c=0)

Previous measurements



The ratios are independent of m_c , κ_c (in the 1st order)

$$\left(\frac{a_2^{J=1}}{a_2^{J=2}}\right)_{\rm th} = \frac{E_\gamma^{J=1}}{E_\gamma^{J=2}}\frac{\sqrt{5}}{3} = 0.676\pm0.071\,,$$

$$\left(\frac{a_2^{J=1}}{b_2^{J=1}}\right)_{\rm th} = -\frac{E_\gamma^{J=1}}{E_{\gamma'}^{J=1}} = -2.27\pm0.16\,,$$

$$\left(\frac{b_2^{J=2}}{b_2^{J=1}}\right)_{\rm th} = \frac{E_{\gamma'}^{J=2}}{E_{\gamma'}^{J=1}}\frac{3}{\sqrt{5}} = 1.000\pm0.015\,,$$

$$\left(\frac{b_2^{J=2}}{a_2^{J=2}}\right)_{\rm th} = -\frac{E_{\gamma'}^{J=2}}{E_\gamma^{J=2}} = -0.297\pm0.025\,.$$

?

?

$$\left(\frac{a_2^{J=1}}{a_2^{J=2}}\right)_{\rm exp} = \frac{-0.002\pm0.020}{-0.13\pm0.05} = 0.02^{+0.17}_{-0.16}$$

$$\left(\frac{a_2^{J=1}}{b_2^{J=1}}\right)_{\rm exp} = \frac{-0.002\pm0.020}{0.077\pm0.050} = -0.02^{+0.30}_{-0.32}$$

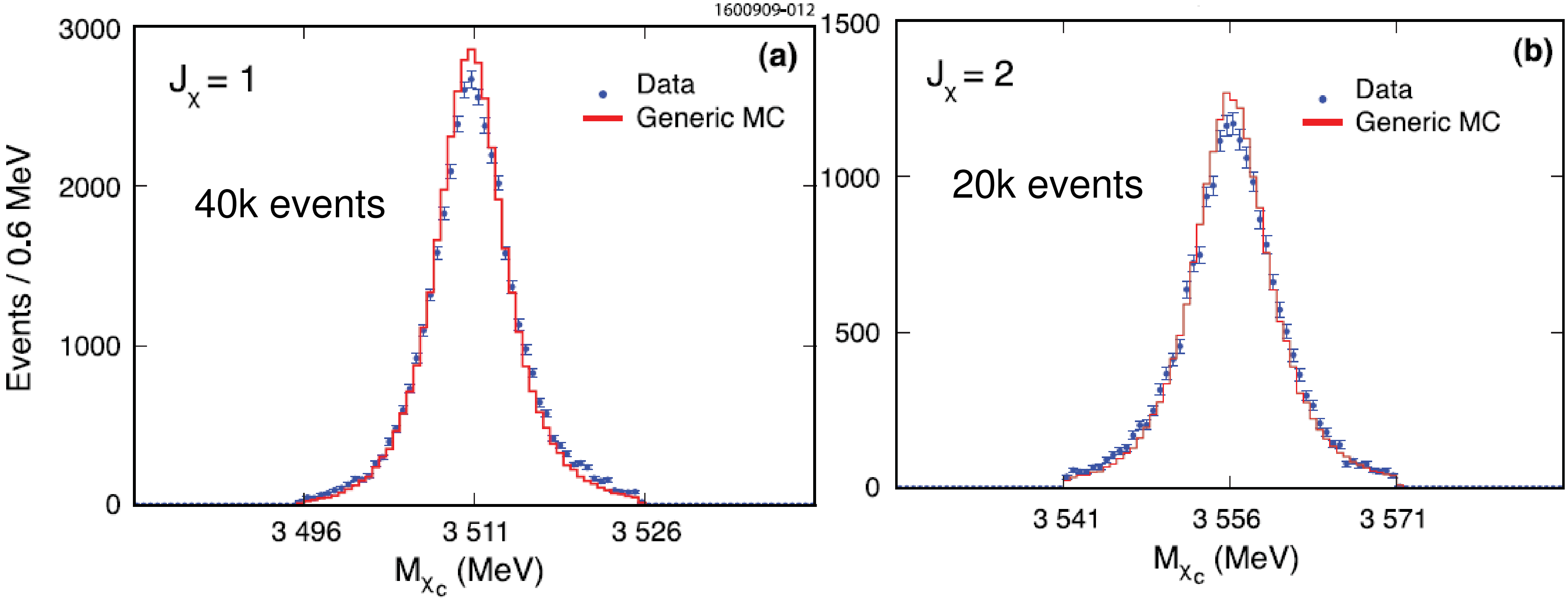
$$\left(\frac{b_2^{J=2}}{b_2^{J=1}}\right)_{\rm exp} = \frac{0.132\pm0.075}{0.077\pm0.050} = 1.5^{+2.2}_{-1.1}$$

$$\left(\frac{b_2^{J=2}}{a_2^{J=2}}\right)_{\rm exp} = \frac{0.132\pm0.075}{-0.13\pm0.05} = -1.01^{+0.60}_{-0.93}$$

- Inconsistencies between data and theory

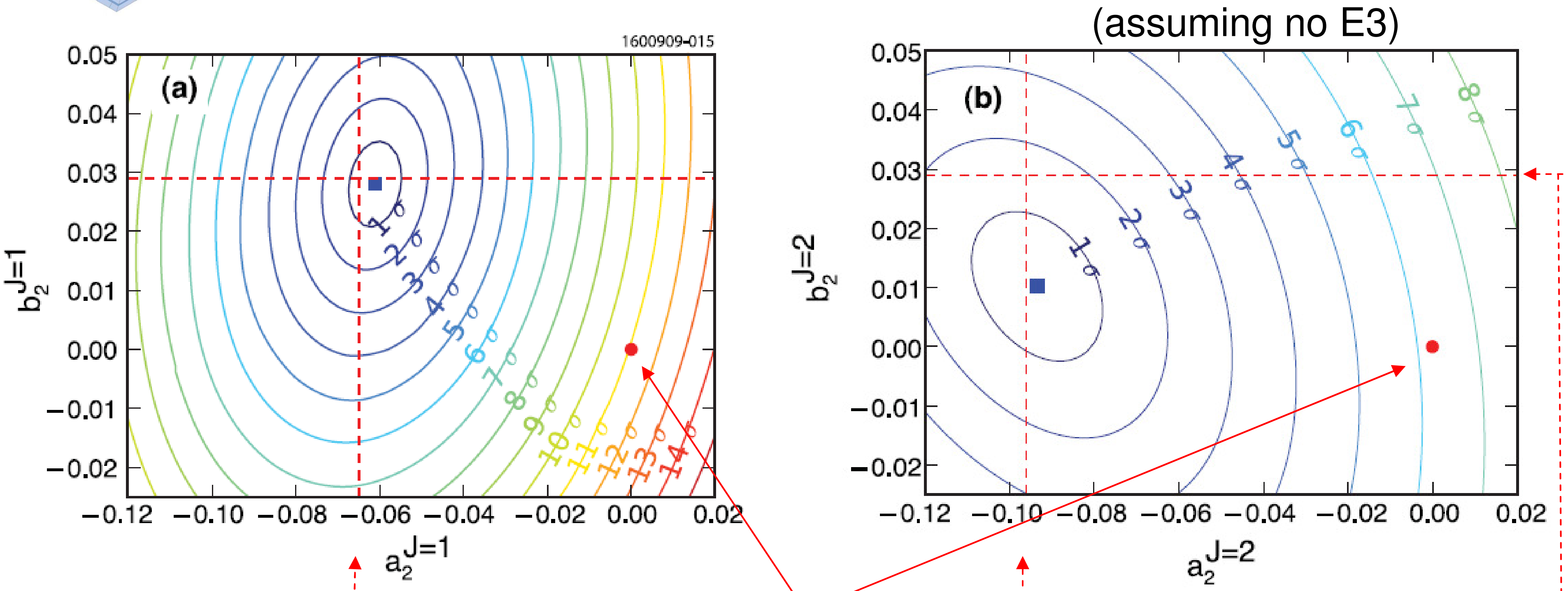
CLEOc data

- Select $\gamma\gamma\mu^+\mu^-$ or $\gamma\gamma e^+e^-$ events. Backgrounds are small and under control. The χ_{c1} and χ_{c2} are well separated.



- By an order of magnitude larger statistics than in the previous experiments.

CLEOc results



(assuming no E3)

Presence of quadrupole amplitudes established at 11.1σ (6.2σ) for J=1 (2).

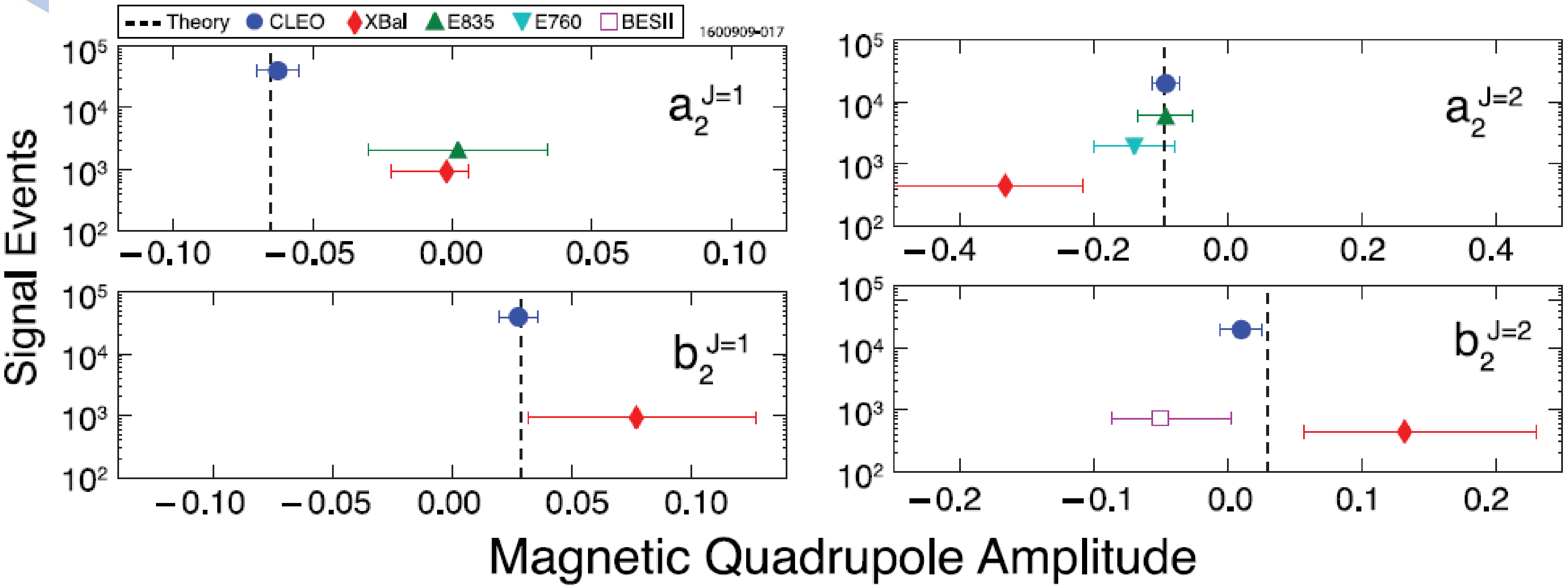
- Good agreement with the theoretical predictions (m_c=1.5 GeV, κ_c=0)

Allowing electric octupole (E3) amplitude for J=2 data:

$$a_3^{J=2} = (1.7 \pm 1.4 \pm 0.3)\ 10^{-3} \quad b_3^{J=2} = (-0.8 \pm 1.2 \pm 0.2)\ 10^{-3}$$

(the results for $a_2^{J=2}$, $b_2^{J=2}$ change within the errors)

CLEOc results



$$\left(\frac{a_2^{J=1}}{a_2^{J=2}}\right)_{\rm th} = \frac{E_\gamma^{J=1}}{E_\gamma^{J=2}}\frac{\sqrt{5}}{3} = 0.676 \pm 0.071\ ,$$

$$\left(\frac{a_2^{J=1}}{b_2^{J=1}}\right)_{\rm th} = -\frac{E_\gamma^{J=1}}{E_{\gamma'}^{J=1}} = -2.27 \pm 0.16\ ,$$

$$\left(\frac{b_2^{J=2}}{b_2^{J=1}}\right)_{\rm th} = \frac{E_{\gamma'}^{J=2}}{E_{\gamma'}^{J=1}}\frac{3}{\sqrt{5}} = 1.000 \pm 0.015\ ,$$

$$\left(\frac{b_2^{J=2}}{a_2^{J=2}}\right)_{\rm th} = -\frac{E_{\gamma'}^{J=2}}{E_\gamma^{J=2}} = -0.297 \pm 0.025\ .$$

$$\left(\frac{a_2^{J=1}}{a_2^{J=2}}\right)_{\rm CLEO} = 0.67^{+0.19}_{-0.13}$$

$$\left(\frac{a_2^{J=1}}{b_2^{J=1}}\right)_{\rm CLEO} = -2.27^{+0.57}_{-0.99}$$

$$\left(\frac{b_2^{J=2}}{b_2^{J=1}}\right)_{\rm CLEO} = 0.37^{+0.53}_{-0.47}$$

$$\left(\frac{b_2^{J=2}}{a_2^{J=2}}\right)_{\rm CLEO} = -0.11^{+0.14}_{-0.15}$$

- The inconsistencies with the theory has been resolved

$\kappa_c = -0.123 \pm 0.088 \pm 0.034 \pm 0.175$ (last error due to $m_c = 1.5 \pm 0.3$ GeV)

Conclusions

- BaBar's observation of the $\Upsilon(3S) \to \gamma\, \eta_b$ confirmed by the CLEO data:
  - The experimental results for hyperfine mass splitting agree with the lattice QCD calculations
- Admixture of the magnetic quadrupole amplitude to predominantly electric dipole transitions $2^3S_1 \to 1^3P_{1,2} \to 1^3S_1$ in charmonium well established by the CLEOc data:
  - No inconsistencies with the expectations, unlike in the previous experiments
  - No evidence for anomalous magnetic moment of c-quark