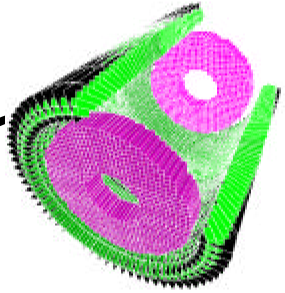


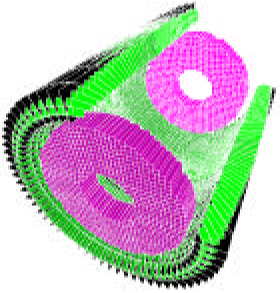
Bottomonium studies via $\Upsilon(3S)$ decays

First observation of $\Upsilon(1D)$

Tomasz Skwarnicki

Representing

the CLEO collaboration

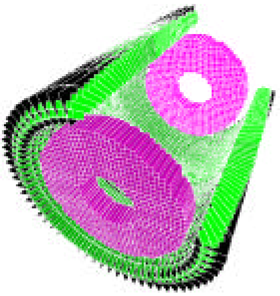


Onia

FORCES			System	$(v/c)^2$	**Ground triplet state 1^3S_1**		Number of states below dissociation energy	
binding	decay				Name	Γ (MeV)	n^3S_1	all
POSITRONIUM								
EM	EM		e^+e^-	~0.0	Ortho-	$5\ 10^{-15}$	2	8
QUARKONIUM								
STRONG	STRONG		$u\bar{u},d\bar{d}$	~1.0	ρ	150.00	0	0
			$s\bar{s}$	~0.8	ϕ	4.40	"1"	"2"
		EM	$c\bar{c}$	~0.25	ψ	0.09	2	8
			$b\bar{b}$	~0.08	Υ	0.05	3	30
	weak		$t\bar{t}$	<0.01		3000.00	0	0

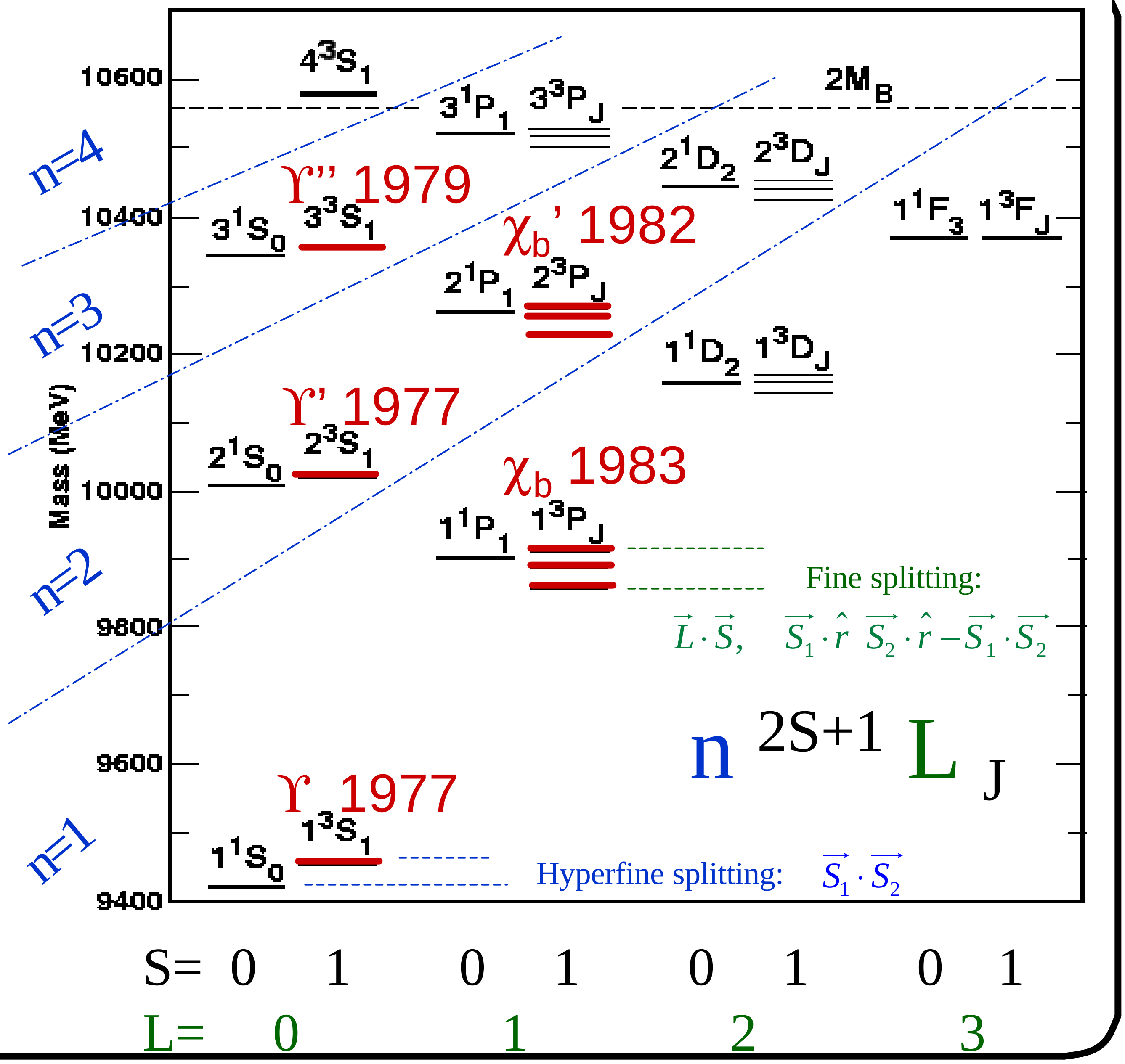
- Heavy quarkonia hold a promise of playing a similar role for QCD as positronium did for QED
- Upsilons are the most non-relativistic (i.e. simplest) states among all long-lived quarkonia states
- The Upsilon system also has the largest number of stable states

↦ Upsilons play a special role in probing the strong interactions (tests of lattice QCD, potential models)

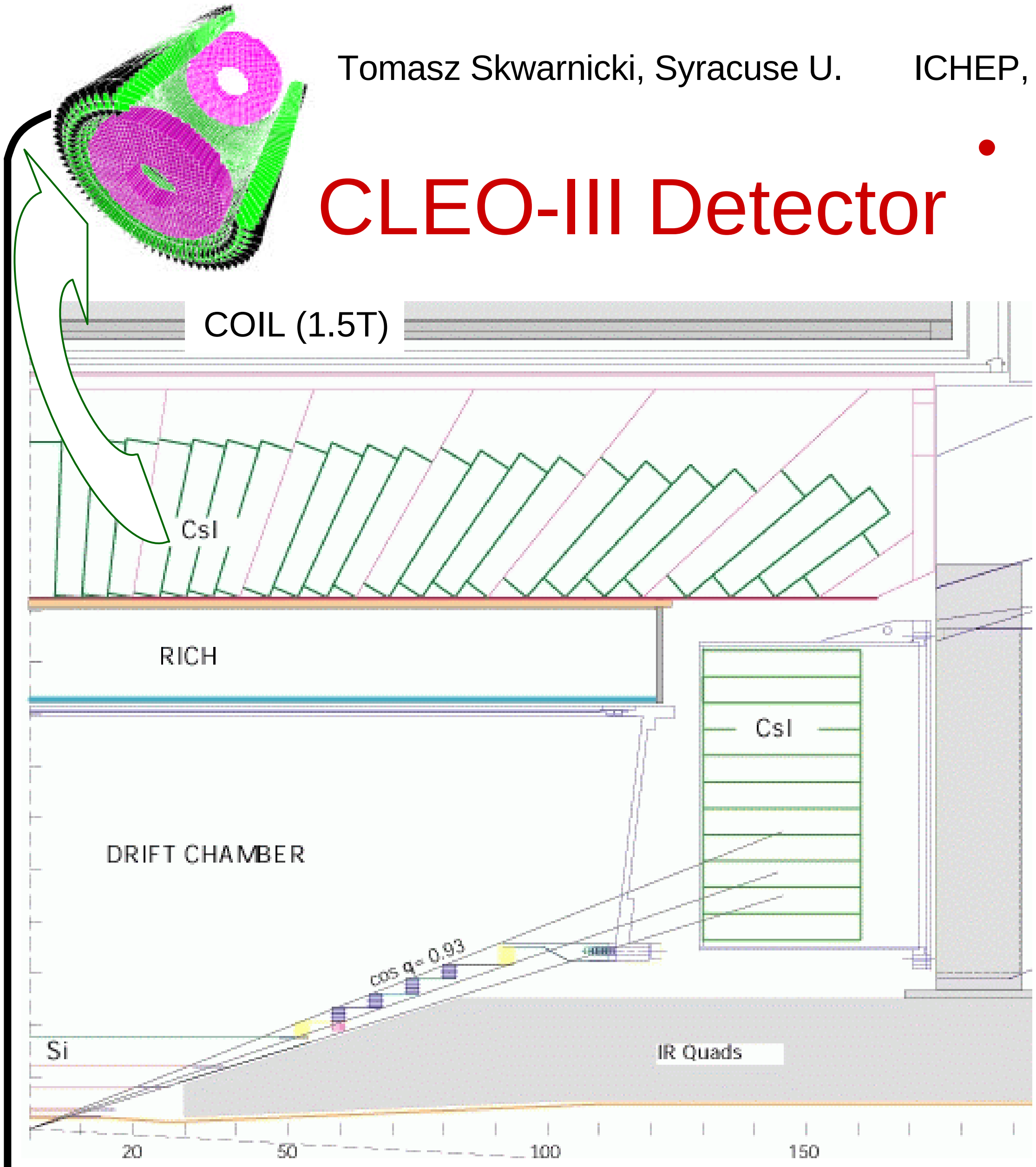


Upsilon States

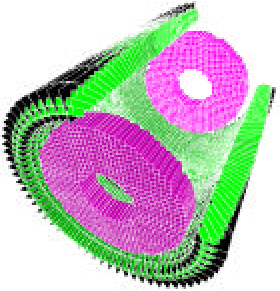
- Only 9 out of 30 narrow states observed so far
- No spin-singlet states observed
- No new states observed in 19 years



CLEO-III Detector

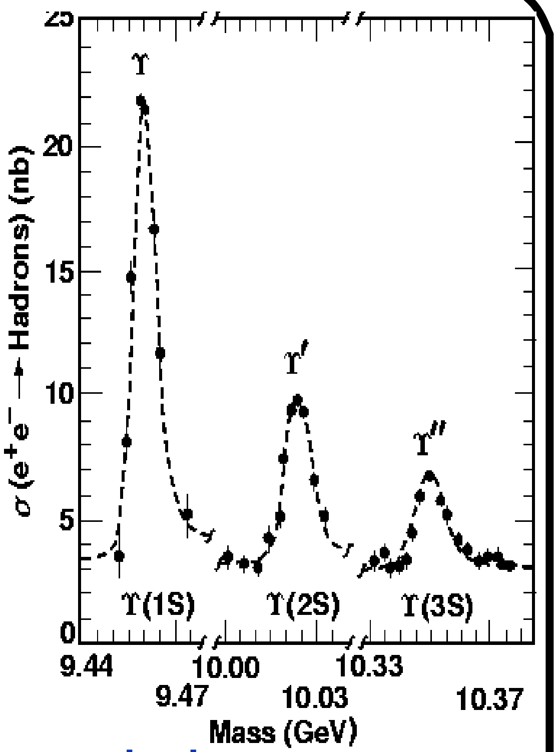


- EM calorimeter - Essential for this work
  - ~8000 CsI(Tl) crystals + photo-diodes
  - First crystal calorimeter in magnetic field
  - Changes since CLEO-II:
    - Low-mass DR endplate!
    - Re-stacked endcaps, moved away
    - New readout electronics
    - Some light loss due to the deteriorating glue used to attach the photo-diodes

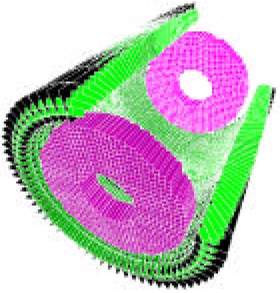


CLEO-III Υ Data

Resonance	CLEO-III Integrated Luminosity (pb^{-1})			Number of resonance decays (10^6)		
	ON	OFF	Scan	CLEOIII	CLEOII	CUSB (C.Ball)
$\Upsilon(3S)$	1150	128	100	4.7	0.46	1.3
$\Upsilon(2S)$	550	150	50	~3.6	0.49	(0.19)
$\Upsilon(1S)$	1230	200	100	~29.0	1.9	(0.48)

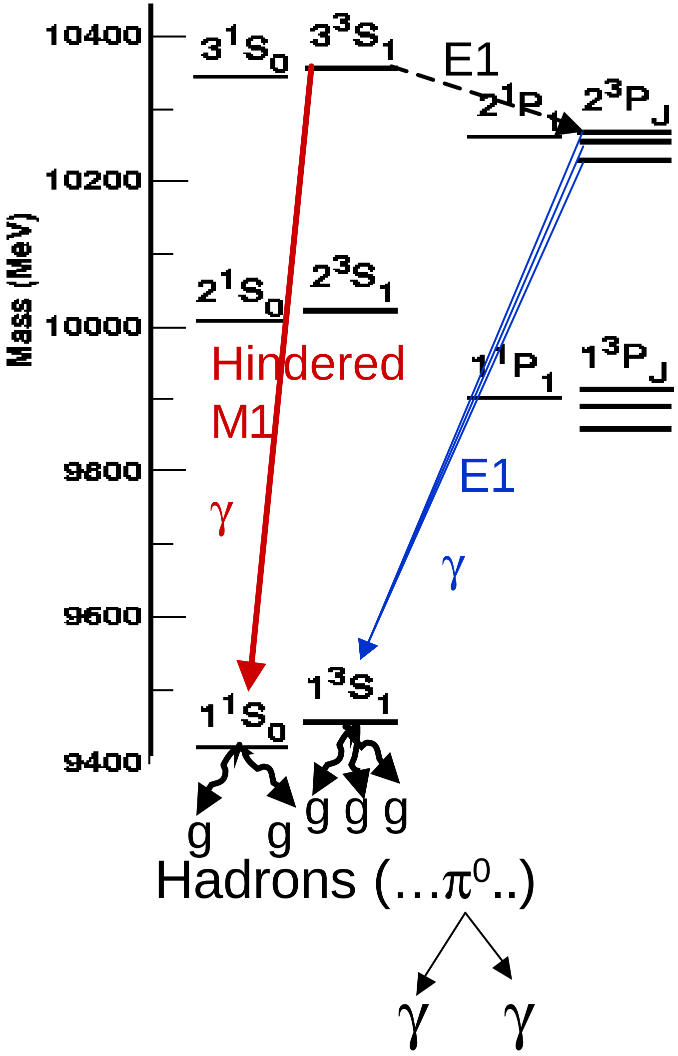


- About 10-fold increase over the CLEO-II statistics
- About 4-times more $\Upsilon(3S)$ data than analyzed by CUSB + 2.5-4.5 times higher efficiency for the final states analyzed here
- The $\Upsilon(3S)$ data already processed off-line
- We will take more Υ data before lowering the beam energy to the charm threshold region next year (↦CLEO-c)



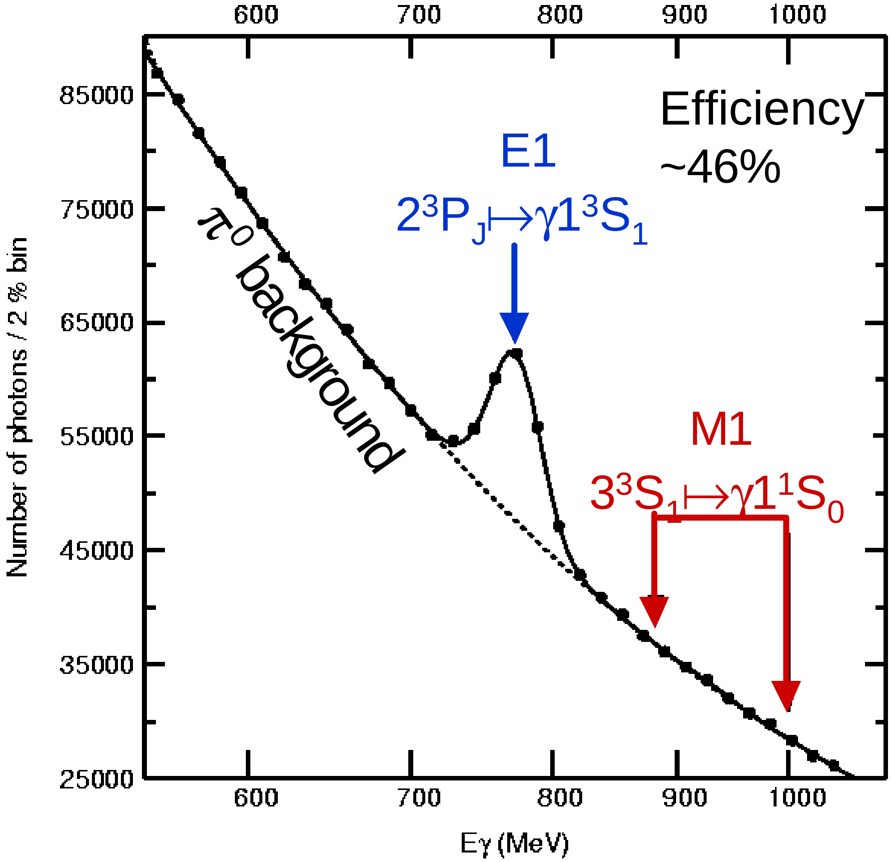
ICHEP ABS947, CLEO CONF 02-05

Search for $\eta_b(1^1S_0)$



Inclusive g spectrum

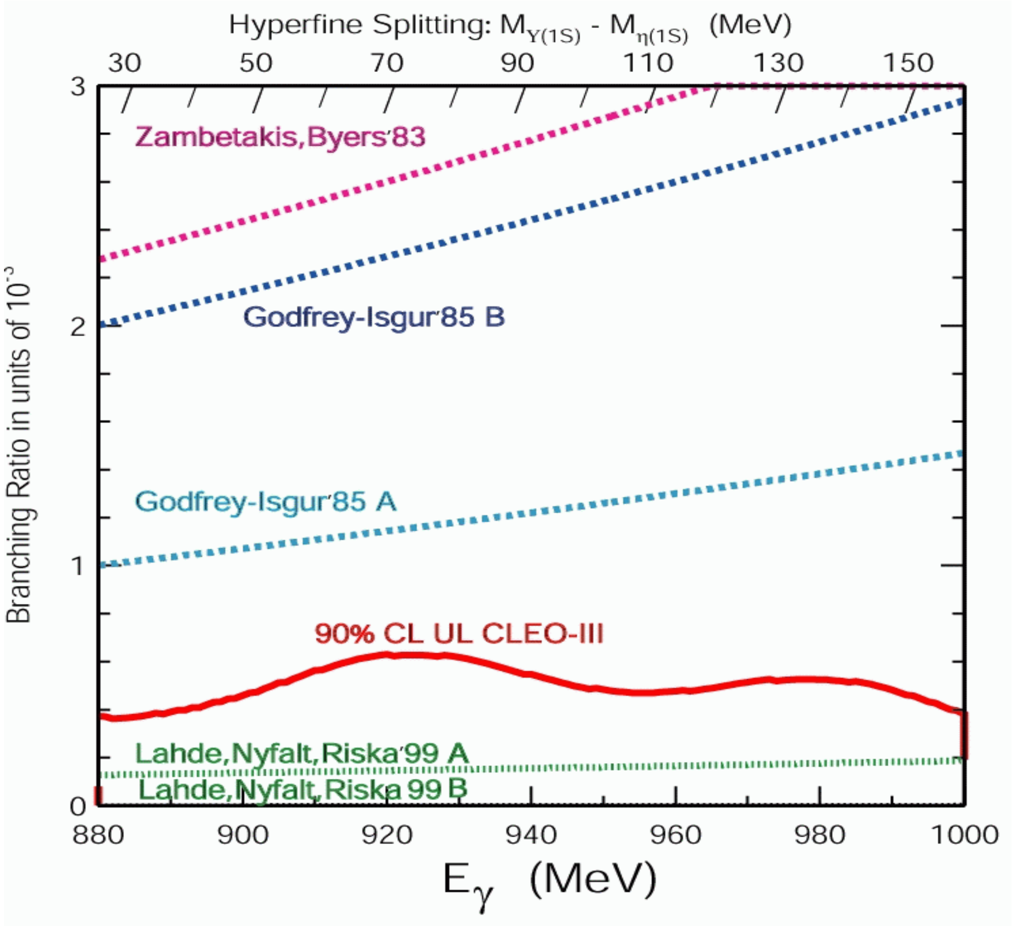
in multi-hadronic events



- No signal found

Search for $\eta_b(1^1S_0)$

- Test potential model predictions for Γ_{M1}



Models from the compilation by Godfrey&Rosner PR D64, 074011 (2001) [scaled here by phase-space]

$$\Gamma_{M1} \propto \frac{e_b^2}{m_b^2} \left| \left\langle n_f L \middle| n_i L \right\rangle \right|^2 E_g{}^3$$

DIRECT $n_i = n_f$

$\langle n_f L | n_i L \rangle = 1$ $E_g{}^3$–tiny

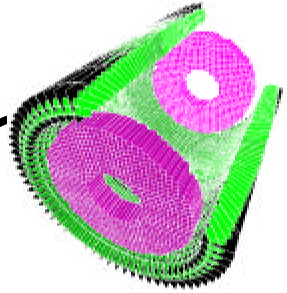
hopeless for $b\bar{b}$

HINDERED $n_i \neq n_f$

$\langle n_f L | n_i L \rangle \approx 0$ $E_g{}^3$–large

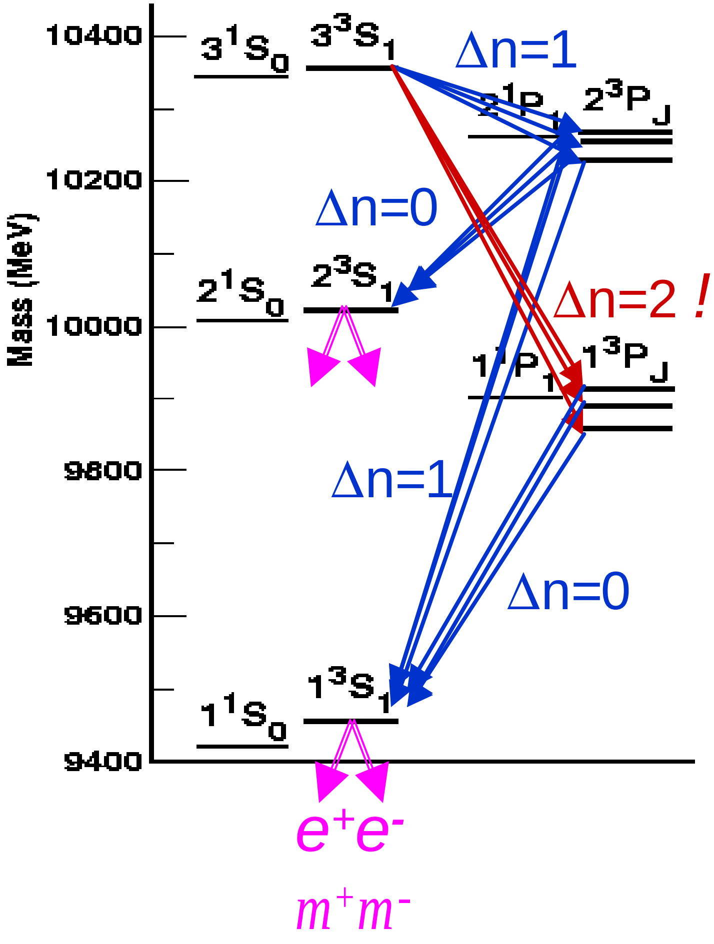
difficult to predict

- Most of the calculations are ruled out!



ICHEP ABS949, CLEO CONF 02-07

Exclusive 2γ-cascades



- $\gamma\gamma\ell^+\ell^-$ final states
- No π^0 backgrounds from gluonic $b\bar{b}$ annihilation
- Low product branching ratio (a few 10^{-4})
- Sensitivity to hadronic widths of triplet P-states:

$$B(P \mapsto \gamma S)=\Gamma_{E1}/(\Gamma_{E1}+\Gamma_{had})$$

- 3S ↦ γ 1P is a Δn=2 transition (rare)

$$\Gamma_{E1} \propto e_b^2 \left| \langle n_f L_f | r | n_i L_i \rangle \right|^2 E_g^{\ 3}$$

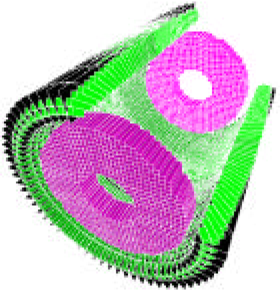
much larger than Γ_{M1} ,since no suppression by $1/m_b^2$

$L_f = L_i \pm 1$

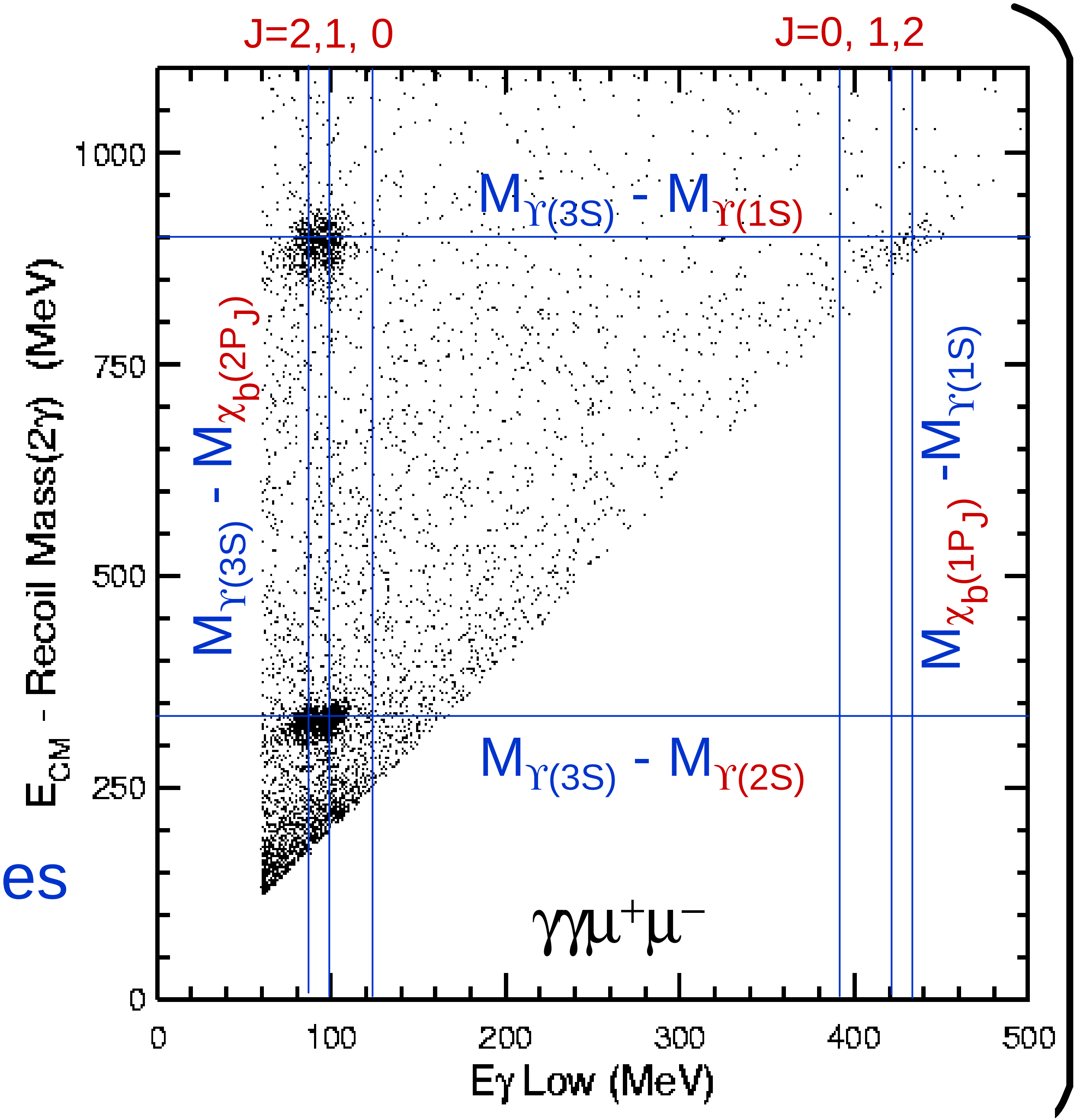
as $\Delta n = n_i - n_f$ increases

$\langle n_f L_f | r | n_i L_i \rangle$ decreases

and Γ_{E1} becomes more difficult to predict

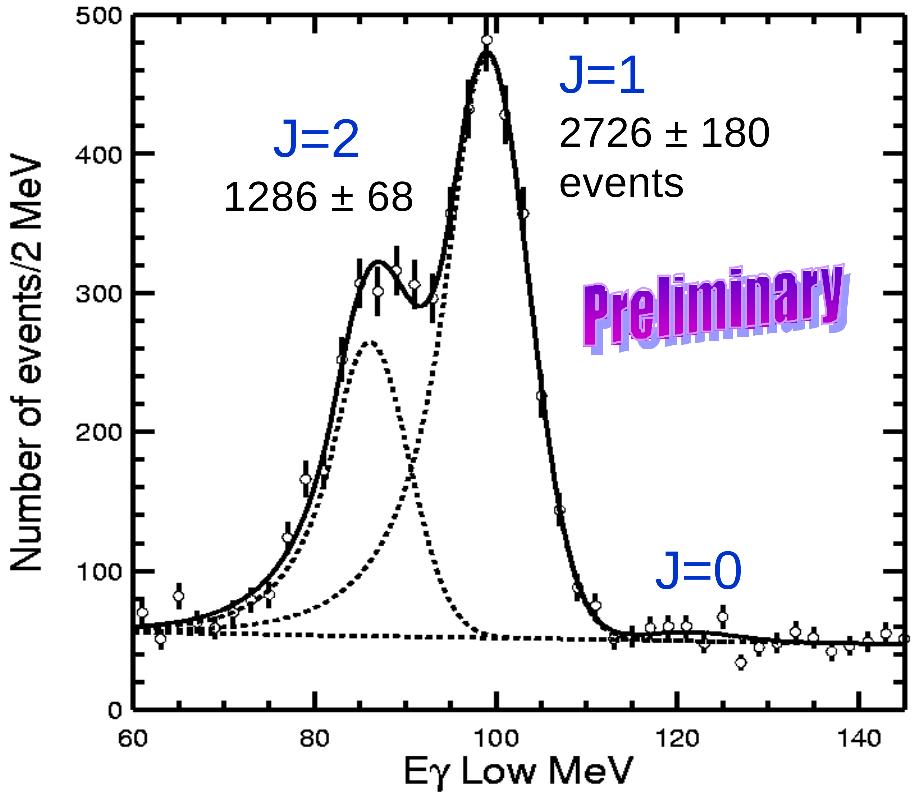


Exclusive 2γ-cascades



- Signal variables

$\Upsilon(3S) \mapsto \gamma\,\chi_b(2P_J) \mapsto \gamma\gamma\ell^+\ell^-$



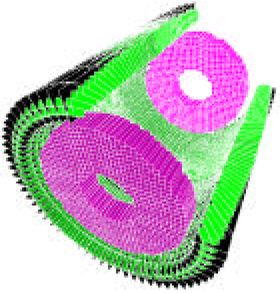
Efficiency
(μμ+ee)/2
~32%

Energy resolution from the fit:
4.6±0.2 MeV @ 100 MeV

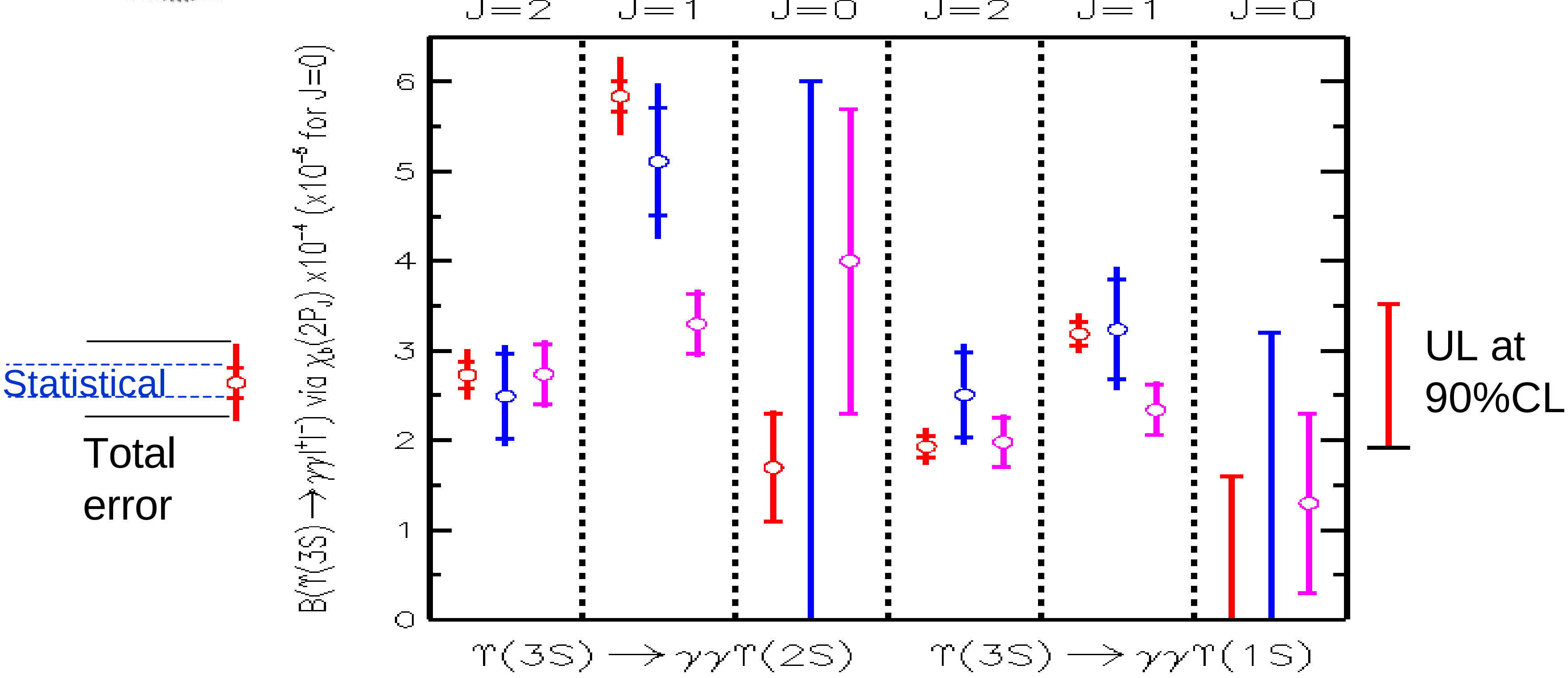
- Energy calibrated to ±0.34% with the photon-recoil mass and known $\Upsilon(nS)$ masses

- Photon-line energies $\mapsto$ $M(\chi_b(2P_J))$
  - $E_{J=2}$ = 86.09±0.30±0.29 MeV
  - $E_{J=1}$ = 99.08±0.17±0.34 MeV

- More precise than previous measurements
- Consistent with CUSB and CLEO-II results

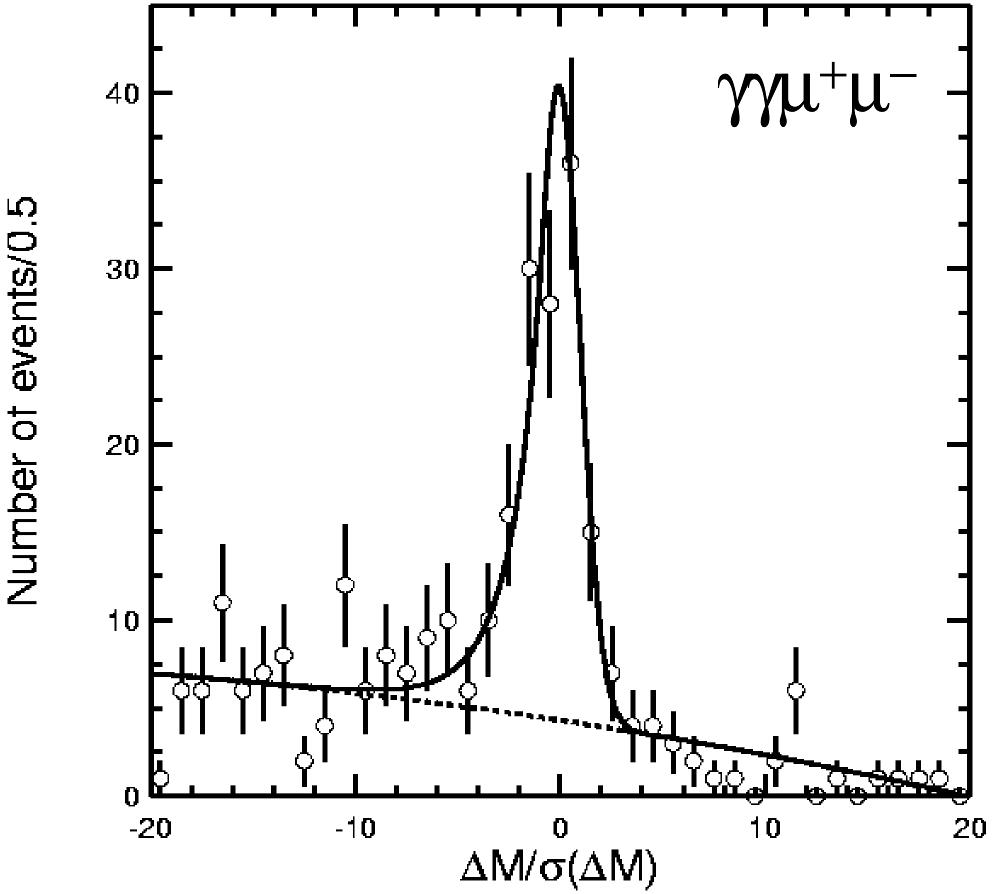


$\Upsilon(3S) \mapsto \gamma\,\chi_b(2P_J) \mapsto \gamma\gamma\ell^+\ell^-$



- Throughout this talk: $B(\gamma\gamma\ell^+\ell^-) = (B(\gamma\gamma\mu^+\mu^-) + B(\gamma\gamma e^+e^-))/2$
- Good agreement with CLEO-II
- CUSB measurements low for J=1
- Much improved errors in CLEO-III

$\Upsilon(3S) \mapsto \gamma\,\chi_b(1P_J) \mapsto \gamma\gamma\ell^+\ell^-$



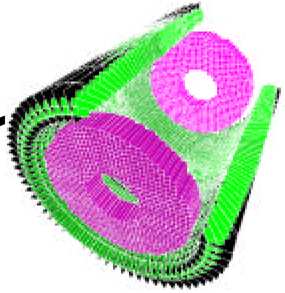
- Since cannot resolve J=2,1,0 states, fit the recoil mass distribution instead

Events (μμ+ee):	167 ± 19 events
Efficiency:	~ 37%

$B(\Upsilon(3S) \mapsto \gamma\chi_b(1P_{2,1}) \mapsto \gamma\gamma\Upsilon(1S) \mapsto \gamma\gamma\ell^+\ell^-) = (5.2 \pm 0.5 \pm 0.5)\ 10^{-5}$

$B(\Upsilon(3S) \mapsto \gamma\chi_b(1P_{2,1}) \mapsto \gamma\gamma\Upsilon(1S)) = (2.1 \pm 0.2 \pm 0.2)\ 10^{-3}$

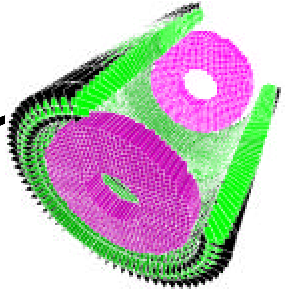
CUSB $(1.2 \pm 0.4 \pm 0.1)\ 10^{-3}$



Comparison of the measured E1 transition rates with the potential models

	$\lvert<2P\lvert r\rvert 3S>\rvert$		$\lvert<1P\lvert r\rvert 2S>\rvert$		$\lvert<1P\lvert r\rvert 3S>\rvert$		$\frac{\lvert<1S\lvert r\rvert 2P>\rvert}{\lvert<2S\lvert r\rvert 2P>\rvert}$	
	GeV^{-1}		GeV^{-1}		GeV^{-1}			
DATA	2.7±0.2		1.9±0.2		0.050±0.006		0.096±0.005	
	World Average				This measurement			
Model	NR	rel	NR	rel	NR	rel	NR	rel
Kwong,Rosner [13]	2.7		1.6		0.023		0.13	
Fulcher [14]	2.6		1.6		0.023		0.13	
Büchmuller et al.[15]	2.7		1.6		0.010		0.12	
Moxhay,Rosner [16]	2.7	2.7	1.6	1.6	0.024	0.044	0.13	0.15
Gupta et al.[17]	2.6		1.6		0.040		0.11	
Gupta et al.[18]	2.6		1.6		0.010		0.12	
Fulcher [19]	2.6		1.6		0.018		0.11	
Danghighian et al.[20]	2.8	2.5	1.7	1.3	0.024	0.037	0.13	0.10
McClary,Byers [21]	2.6	2.5	1.7	1.6			0.15	0.13
Eichten et al.[22]	2.6		1.7		0.110		0.15	
Grotch et al.[23]	2.7	2.5	1.7	1.5	0.011	0.061	0.13	0.19

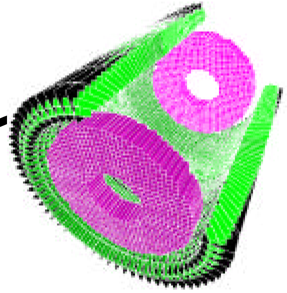
- Potential models:
  - easily reproduce the large E1 matrix elements
  - have trouble predicting small elements (see $\Upsilon(3S) \mapsto \gamma\, \chi_b(1P_J)$ $\Delta n=2$)



Searches for π^0,η transitions

- Also could contribute to $\gamma\gamma\ell^+\ell^-$events
- Suppress photon transitions
- Look at $M\gamma\gamma$
- No signal found

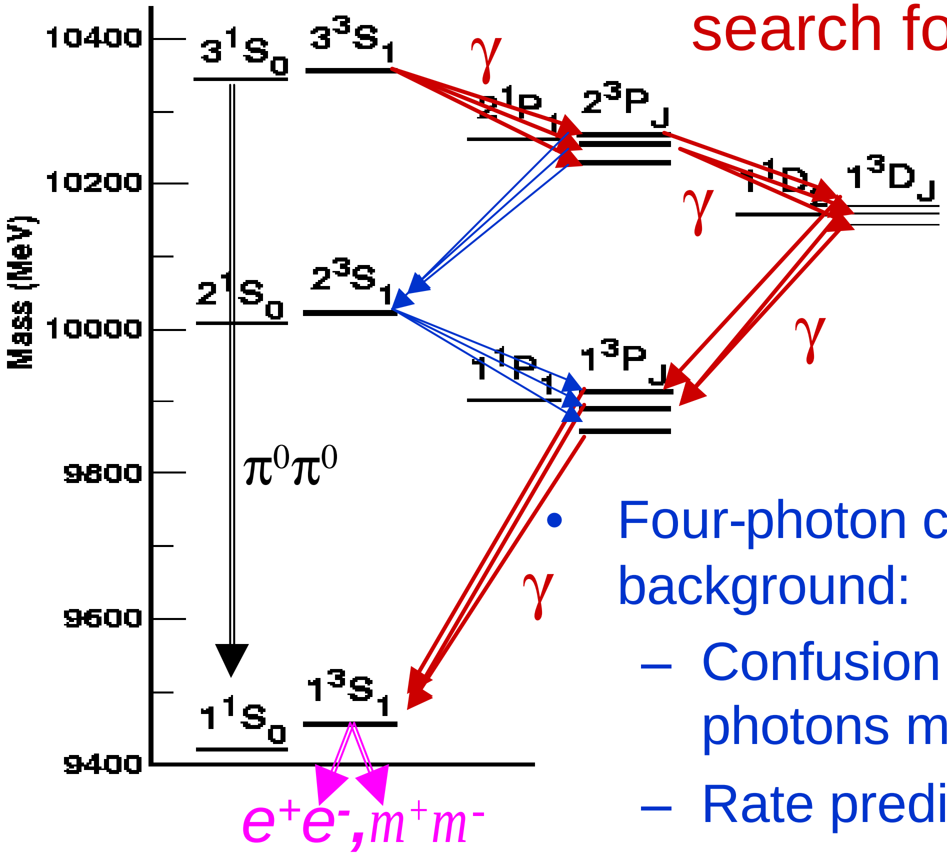
- At 90% C.L.
  - $B(\Upsilon(3S) \mapsto \pi^0\,\Upsilon(1S)) < 0.17\ 10^{-3}$
  - $B(\Upsilon(3S) \mapsto \eta\,\Upsilon(1S)) < 0.9\ 10^{-3}$
  - $B(\Upsilon(3S) \mapsto \pi^0\,\Upsilon(2S)) < 1.2\ 10^{-3}$



ICHEP ABS948, CLEO CONF 02-06

Exclusive 4γ-cascades

- Can use four-photon E1 cascade to search for $\Upsilon(1^3D_J)$!

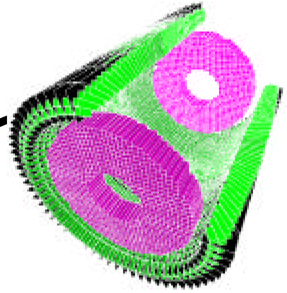


Signal rate predicted by Godfrey&Rosner: 3.76 10^{-5}

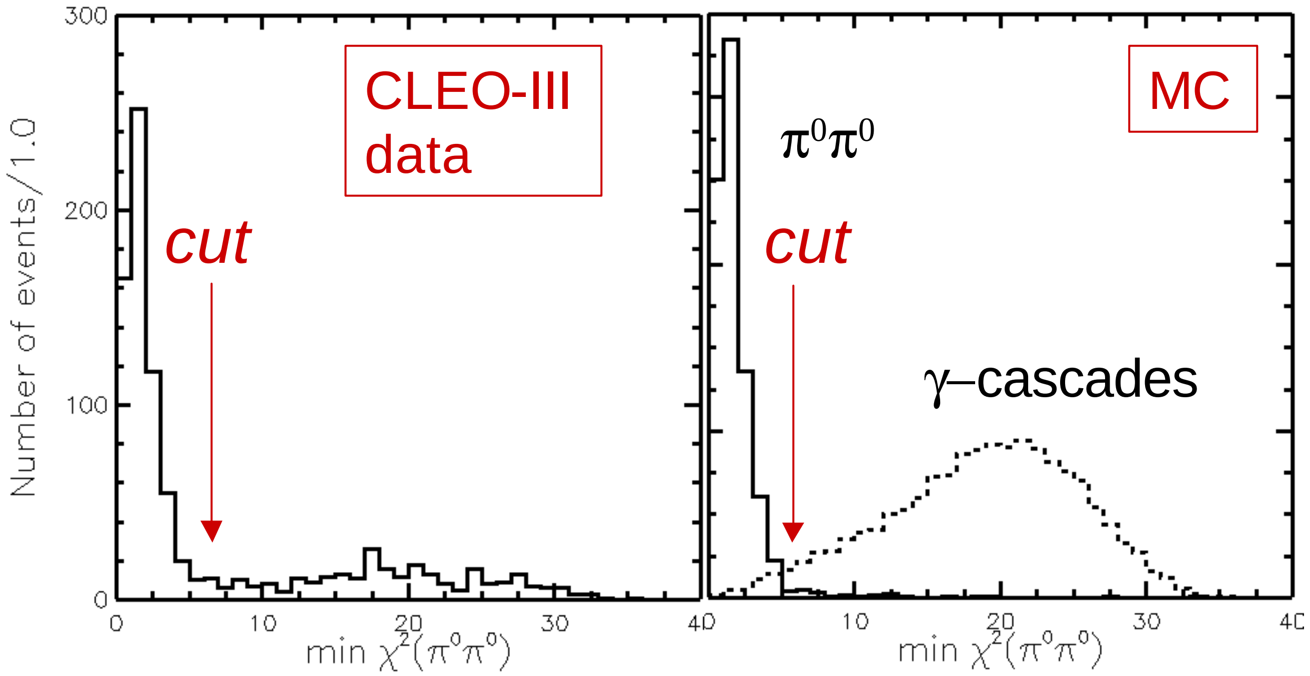
PR D64, 097501 (2001)

- Four-photon cascade via the $\Upsilon(2S)$ – the main background:
  - Confusion in ordering of the observed photons makes these two cascades similar
  - Rate predicted by Godfrey&Rosner: 3.84 10^{-5}

- Also $\Upsilon(3S) \mapsto \pi^0\pi^0\,\Upsilon(1S)$ is a potential background



$\Upsilon(3S) \mapsto \pi^0\pi^0\,\Upsilon(1S)$



- Selection/ rejection of $\Upsilon(3S) \mapsto \pi^0\pi^0\,\Upsilon(1S)$

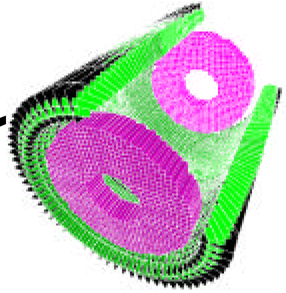
Events ($\mu\mu$+ee):
737 ± 28 events

Efficiency:
~ 14%

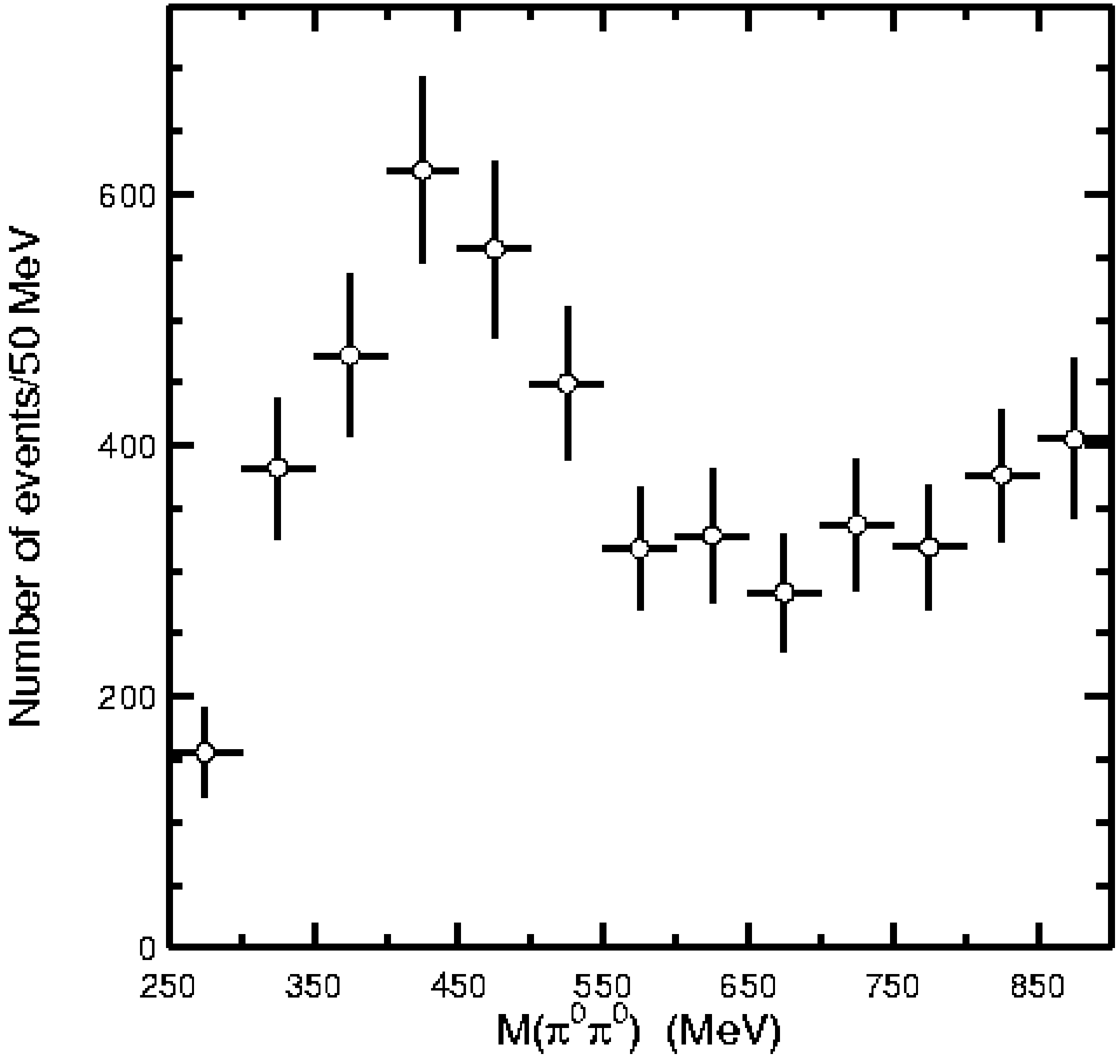
$B(\Upsilon(3S)\mapsto\pi^0\pi^0\Upsilon(1S)\mapsto\gamma\gamma\ell^+\ell^-) = (5.7\pm0.2\pm0.4)\ 10^{-4}$

$B(\Upsilon(3S)\mapsto\pi^0\pi^0\Upsilon(1S)) = (2.33\pm0.09\pm0.16)\ 10^{-2}$

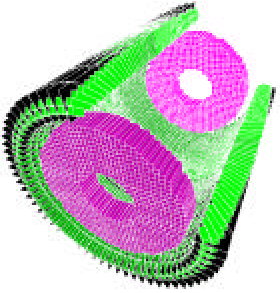
CLEO-II	$(2.03\pm0.28\pm0.19)\ 10^{-2}$
CUSB	$(2.3\ \pm0.4\quad\pm0.3\ )\ 10^{-2}$



$\Upsilon(3S) \mapsto \pi^0\pi^0\,\Upsilon(1S)$



- Double-peak structure in $M(\pi^0\pi^0)$ confirmed here with more data



Selection of ϒ(1D) events

$$c^2_{1D} = \min_{M_{1D},J_{2P},J_{1P}} \sum_{i=1}^{4} \left(\frac{E_{g\,i} - E_{g\,i}^{\text{expected}}(M_{1D}, J_{2P}, J_{1P})}{s\,(E_{g\,i})} \right)^2$$

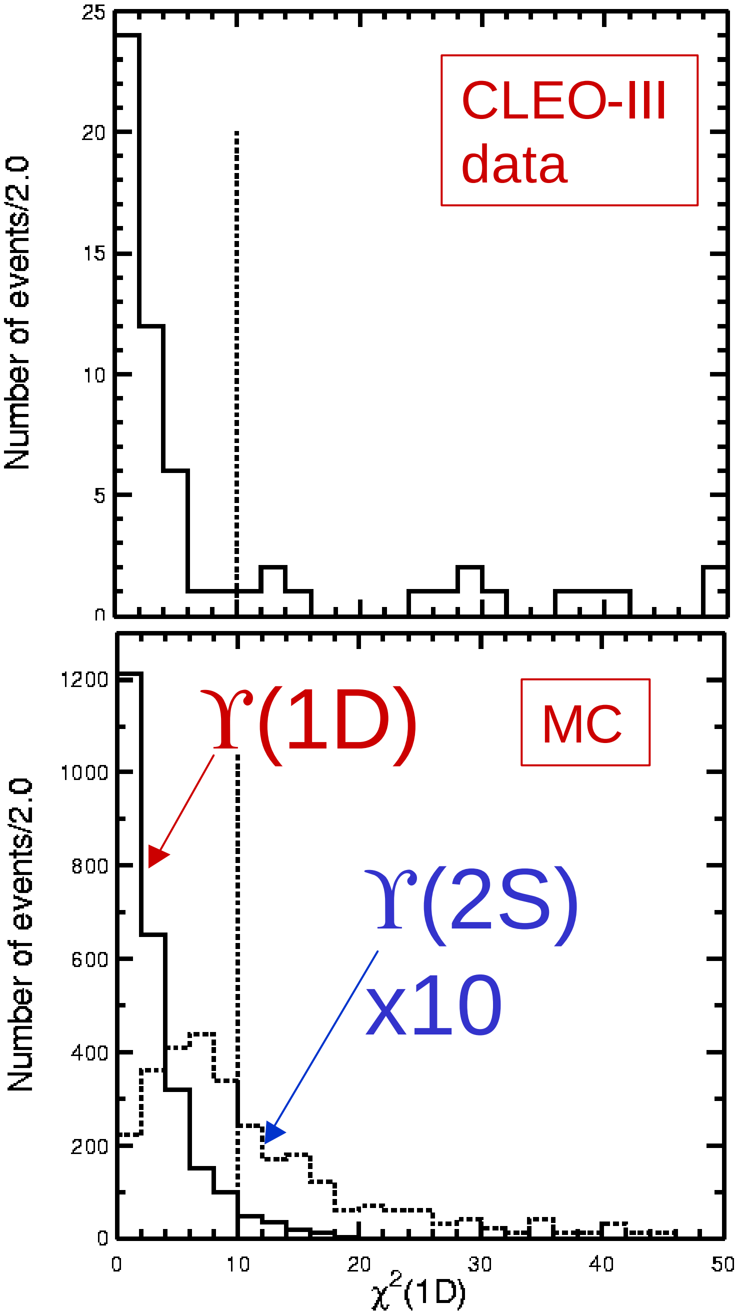
- Implements constraints to the well known masses: M_{3S}, M_{2P_J}, M_{1P_J}, M_{1S}
- In addition to χ^2_{1D} value also obtain “most likely” mass of ϒ(1D) for each event
- To suppress cascades through the ϒ(2S) calculate:

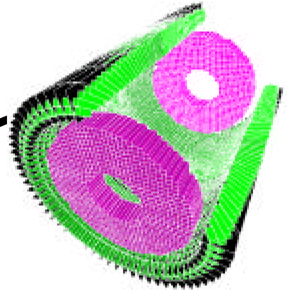
$$c^2_{2S} = \min_{J_{2P},J_{1P}} \sum_{i=1}^{4} \left(\frac{E_{g\,i} - E_{g\,i}^{\text{expected}}(M_{2S}, J_{2P}, J_{1P})}{s\,(E_{g\,i})} \right)^2$$

$$c^2_{2S} > 12$$

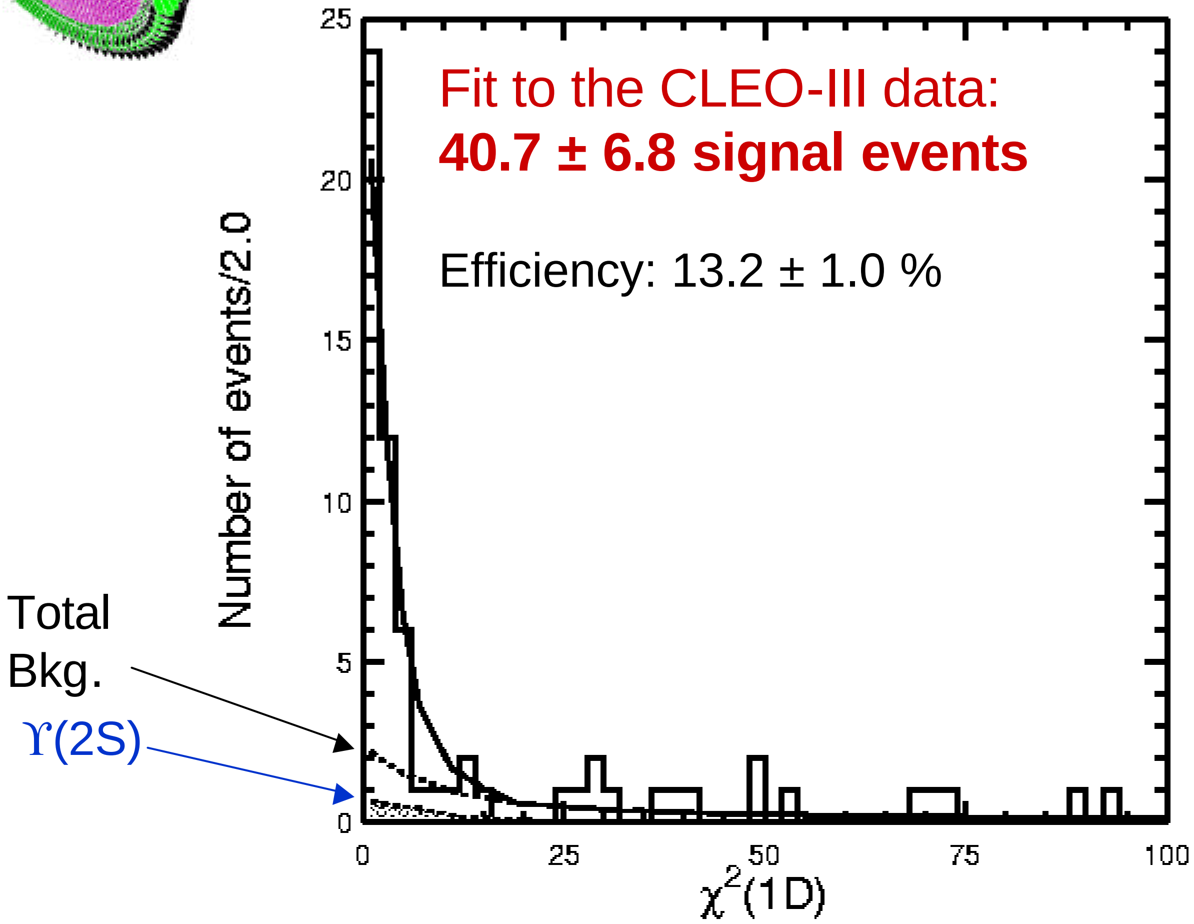
Inclusive Υ(1D) signal

- No background source can produce as narrow a peak as observed in the data
- For $\chi^2_{1D} < 10$:
  - 44 events in the data
  - 1.6-3.0 events due to Υ(2S)
  - 0.8 events due to $\Upsilon(3S) \mapsto \pi^0\pi^0\Upsilon(1S)$
  - 1.8-3.7 of other backgrounds (e.g. radiative Bhabhas and μ–pairs) estimated from the tail of the distribution
  - **Total background 10-14%**





Inclusive ϒ(1D) signal



Fit to the CLEO-III data:
40.7 ± 6.8 signal events

Efficiency: 13.2 ± 1.0 %

The signal significance estimated from the fits with the background contributions alone:

μμ+ee: **9.7**s

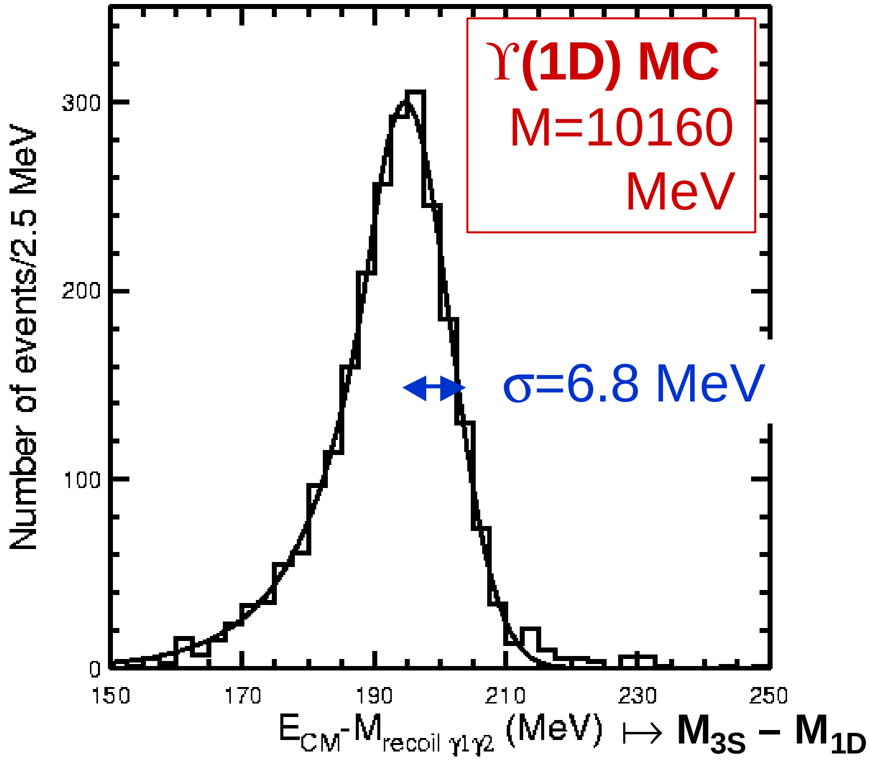
μμ: 8.2σ

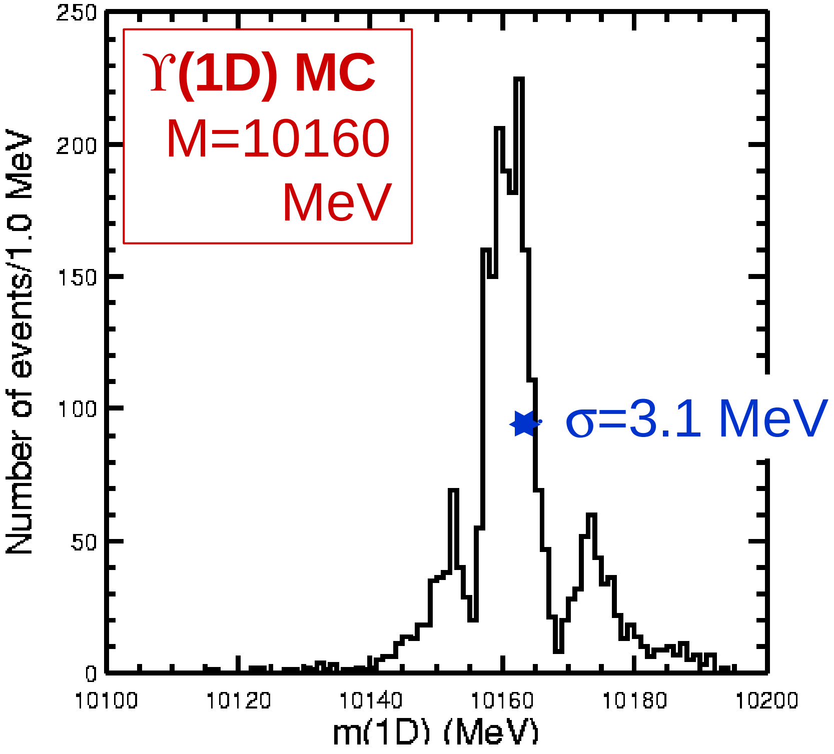
ee: 5.2σ

B(ϒ(3S) $\mapsto gg\Upsilon$**(1D)** $\mapsto gg\gamma\gamma\ \Upsilon$**(1S)** $\mapsto gggg\ell^+\ell^-$**) =(3.3±0.6±0.5) 10^{-5}**

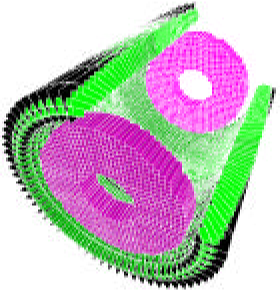
Godfrey&Rosner 3.8 10^{-5}

Υ(1D) mass estimators



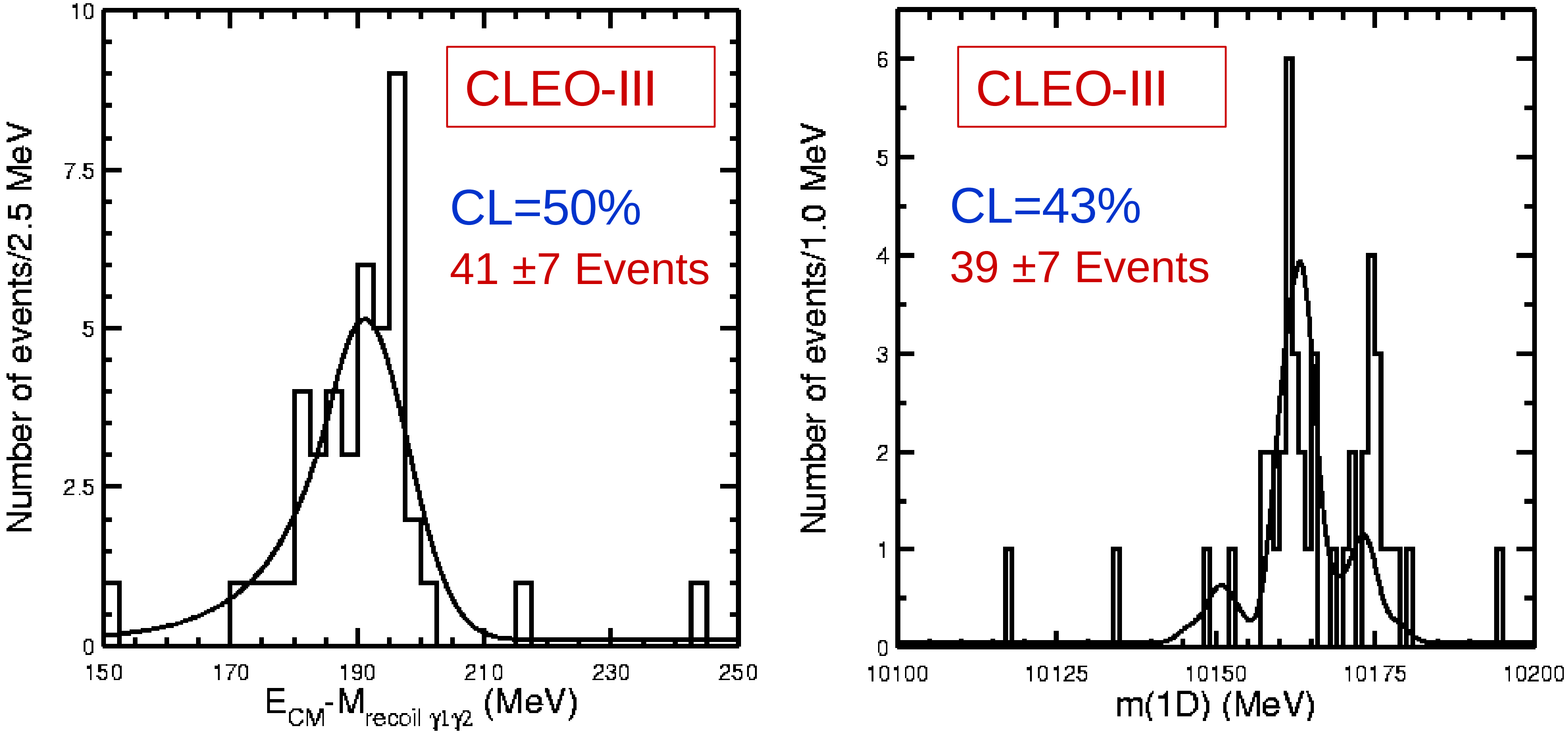


- Recoil mass against the two lowest energy photons:
  - Worse resolution
  - Simple shape
- Most likely mass (constrained to 2P,1P masses):
  - Better resolution
  - Satellite peaks due to wrong J_{2P},J_{1P} minimizing the χ^2_{1D}



Υ**(1D)** mass analysis

- Single-peak fits:

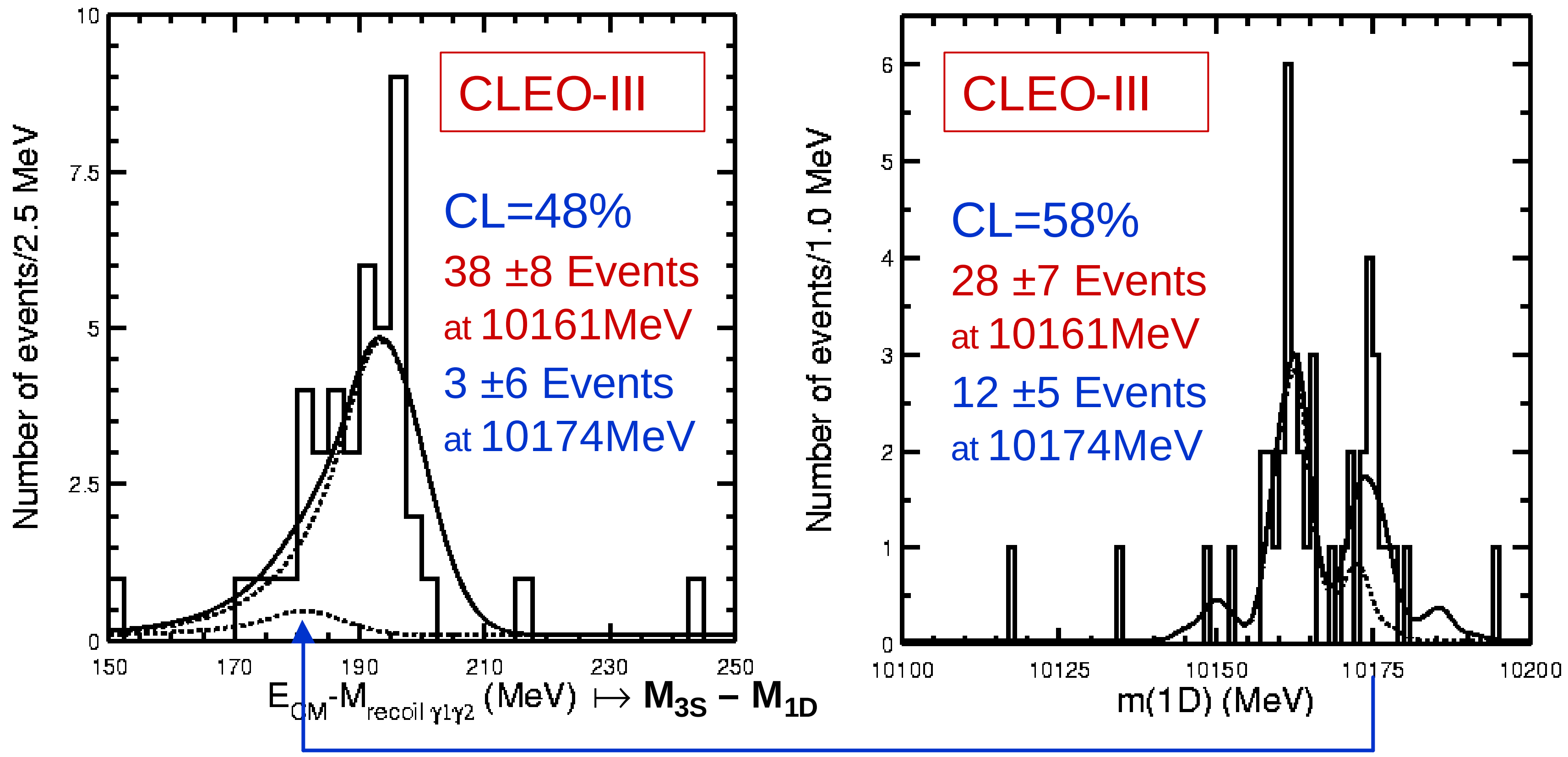


M=10163.4±1.3 MeV

M=10162.0±0.5 MeV

ϒ(1D) mass analysis

- Double-peak fits:



Masses fixed from the fit shown on the right

M=10161.2±0.7 MeV

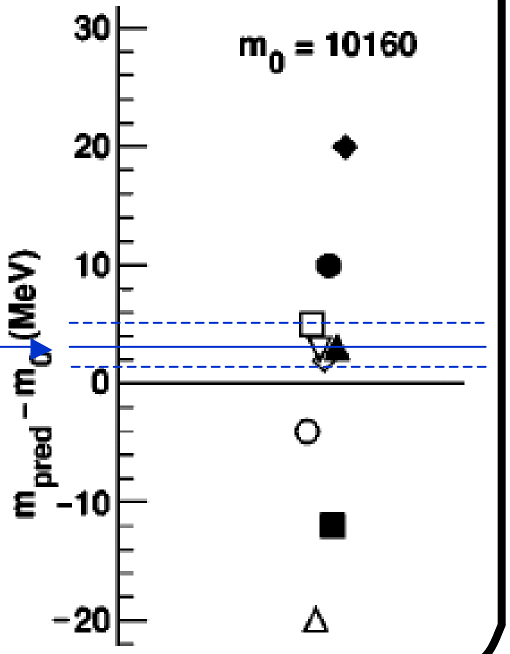
Υ(1D) mass analysis

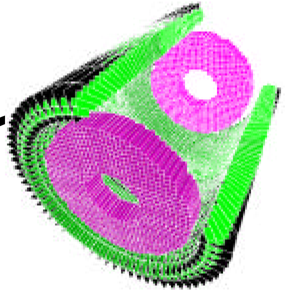
- No compelling evidence for more than one state
- Significance of the peak at 10162: **6.8s**
- Mass averaged over different fits: **10162.2 ±1.6 MeV**
- Inconsistent with the $\Upsilon(1D_3)$
- Could be the $\Upsilon(1D_2)$ or $\Upsilon(1D_1)$
- The theory predicts the rate ratio: $\Upsilon(1D_2)/\ \Upsilon(1D_1)=6$
- **Thus, the $\Upsilon(1D_2)$ is the most likely interpretation**

All calculations of the fine splitting predict the $\Upsilon(1D_2)$ mass from –0.5 to –1.0 MeV below the center-of-gravity of the triplet

↦Our mass measurement is consistent with the c.o.g.~10163 ±2 MeV

Spread in the predictions of the center-of-gravity of the triplet 1D states by various potential models (from Godfrey&Rosner)



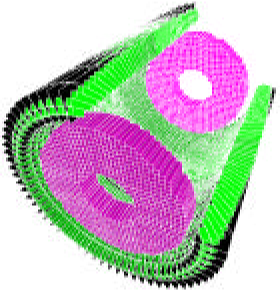


Summary

- **No evidence for hindered M1 transitions $\Upsilon(3S) \mapsto g h_b(1S)$ found in contradiction with many theoretical estimates of the transition width**
- **Much improved results for:**
  - **$B(\Upsilon(3S) \mapsto g c_b(1P_{2,1}) \mapsto g g \Upsilon(1S))$**
  - **$B(\Upsilon(3S) \mapsto g c_b(2P_{2,1,0}) \mapsto g g \Upsilon(2,1S))$**
  - **$B(\Upsilon(3S) \mapsto p^0 p^0 \Upsilon(1S))$**
  - **Upper limits on:**
    - **$B(\Upsilon(3S) \mapsto p^0 \Upsilon(1S))$**
    - **$B(\Upsilon(3S) \mapsto h \Upsilon(1S))$**
    - **$B(\Upsilon(3S) \mapsto p^0 \Upsilon(2S))$**

Summary

- First observation of Υ**(1D)**:
  - **Signal is 9.7σ significant**
  - **Inclusive (i.e. sum over all J) product branching ratio for production in $\gamma\gamma\gamma\gamma\ell^+\ell^-$ (3.3±0.6±0.5) 10^{-5}**
  - **In agreement with the prediction by Godfrey&Rosner (3.8 10^{-5})**
  - **Evidence for a state at 10162.2 ±1.6 MeV**
  - **Likely interpretation: $\Upsilon(1D_2)$**
  - **The mass is consistent with the predictions of some of the potential models**
  - **First new narrow bb state observed in 19 years**
  - **The only long-lived L=2 meson we know**



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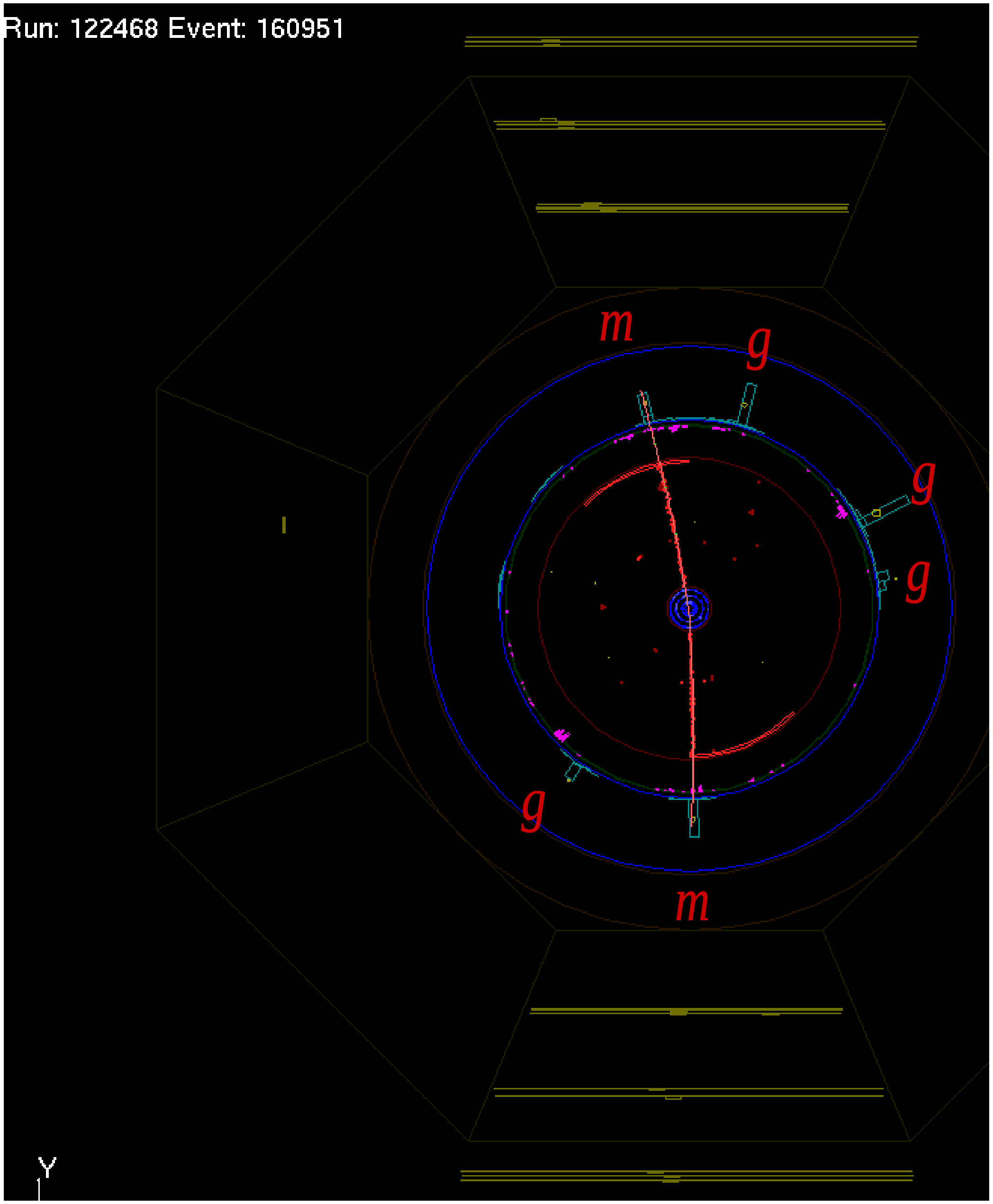
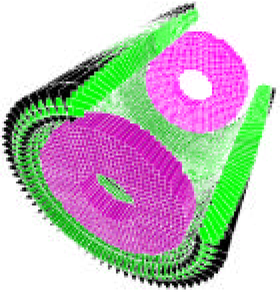


γγγμμ
1D candidate



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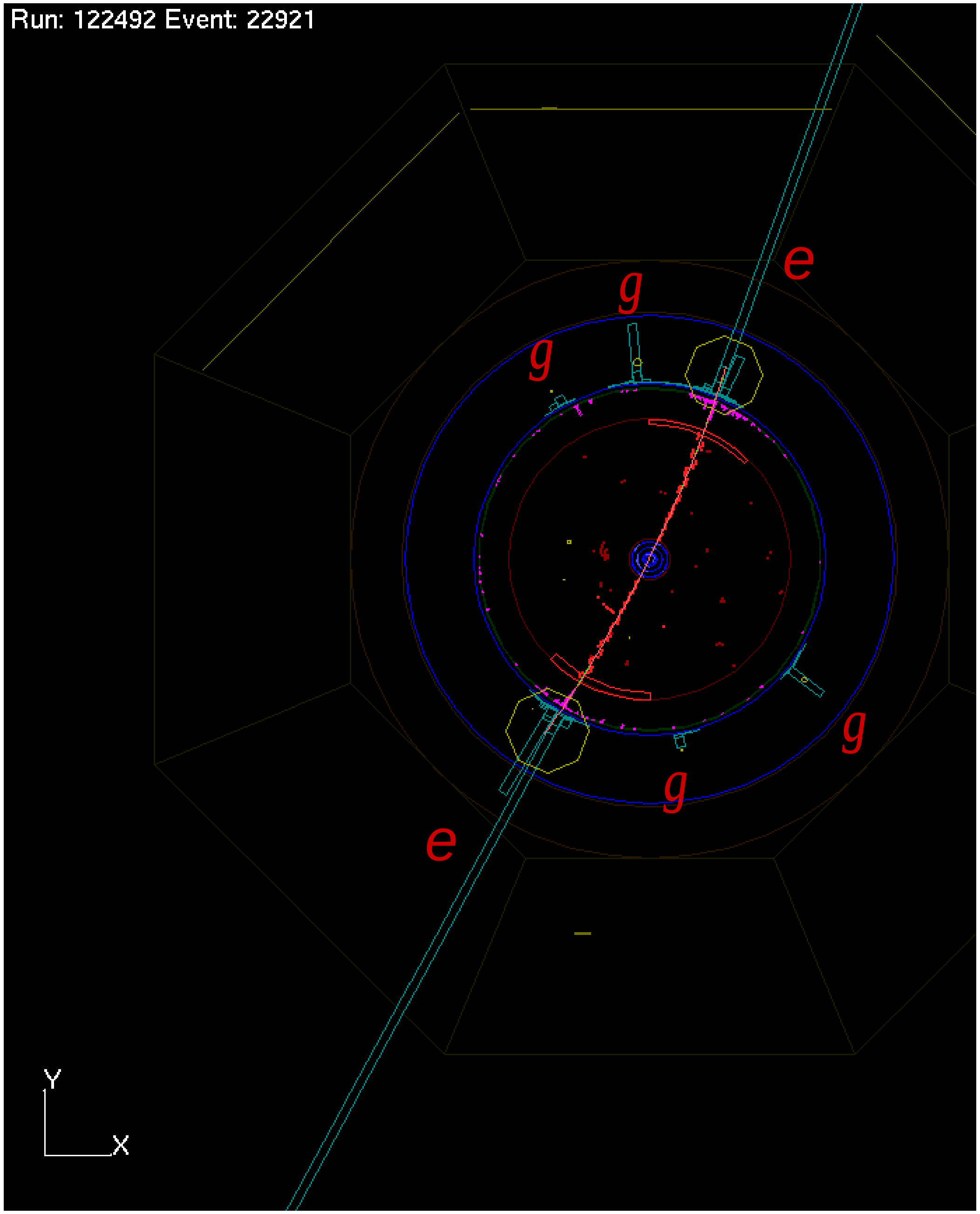

γγγγee 1D candidate

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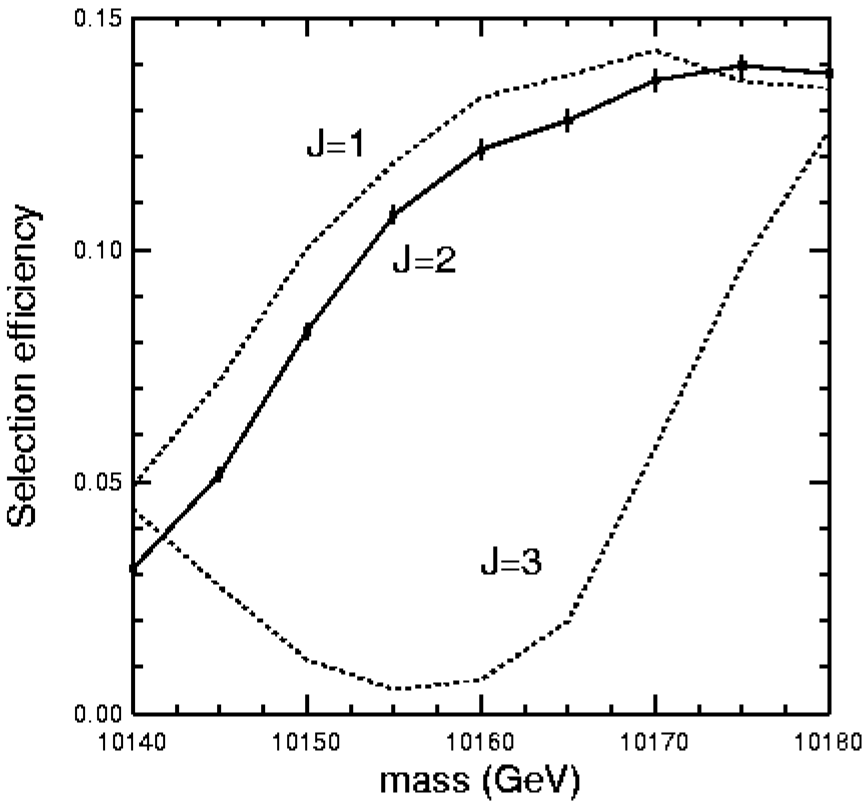
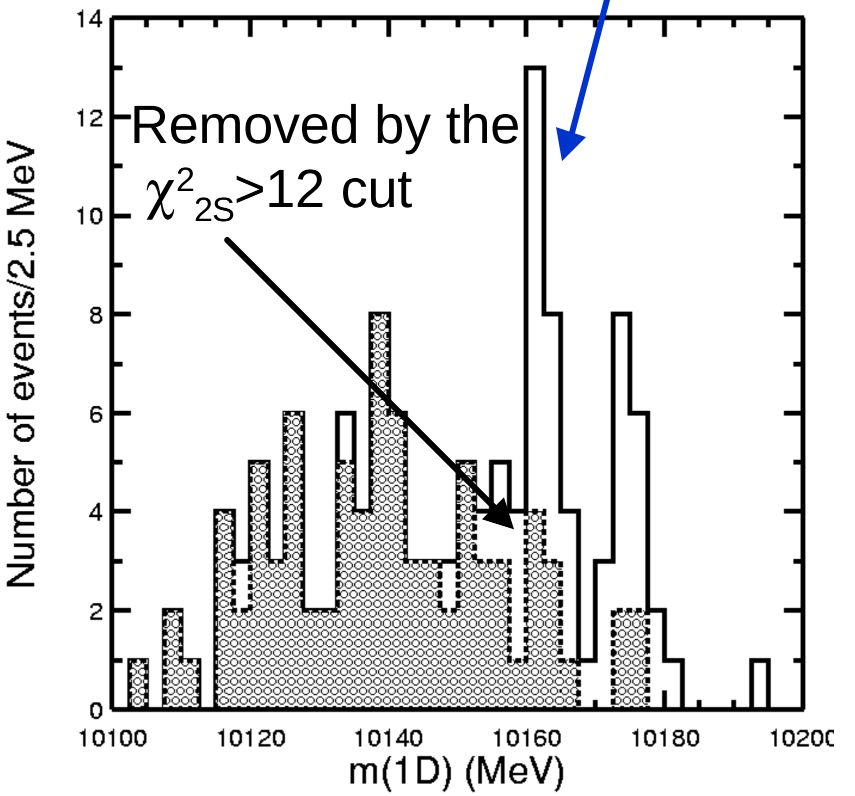
Ruling out $J_{1D}=3$





No $\chi^2_{2S}>12$ cut

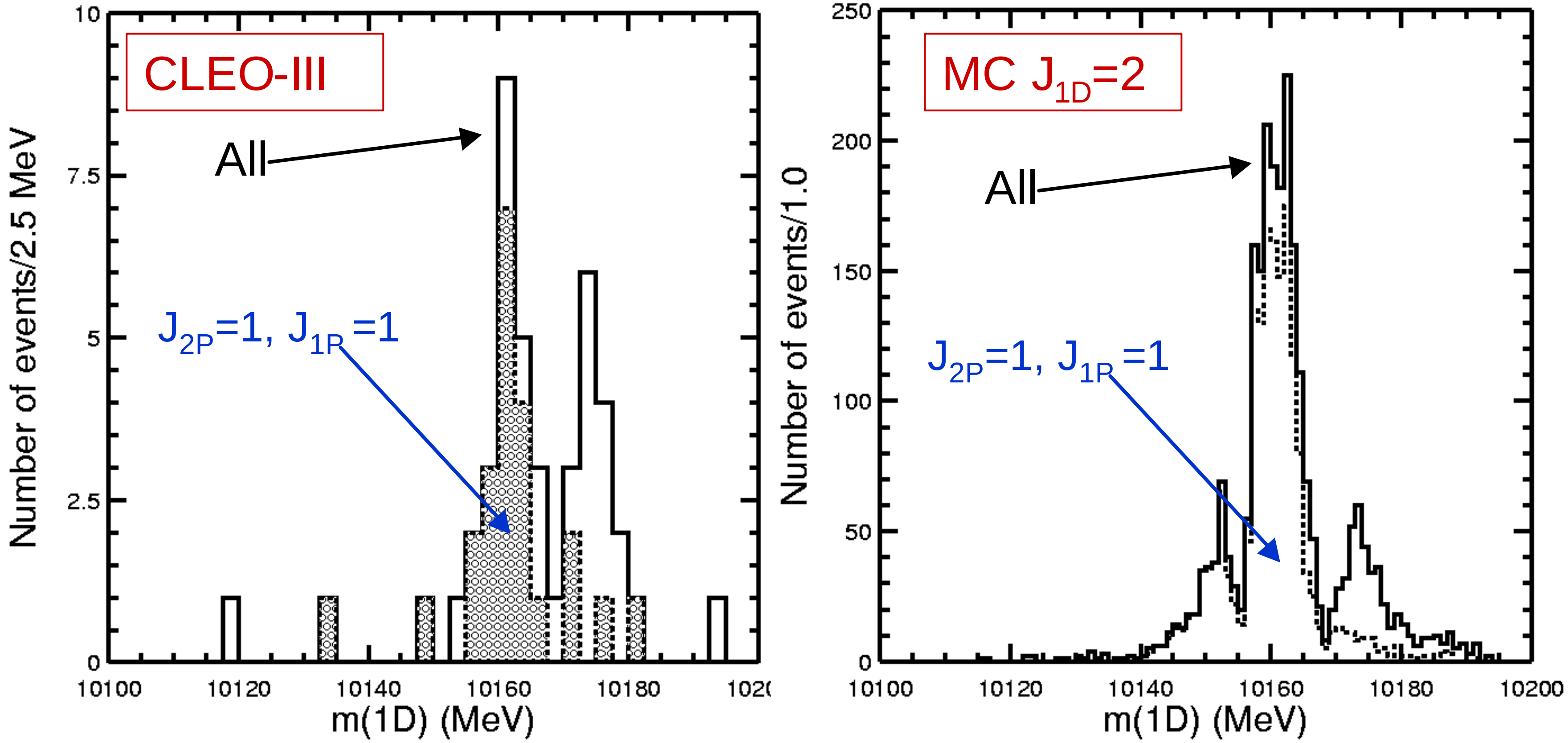
Removed by the $\chi^2_{2S}>12$ cut

- No efficiency for the $\Upsilon(1D_3)$ at 10162 MeV because of the $\chi^2_{2S}>12$ cut
- However the $\chi^2_{2S}>12$ cut does not change the 10162 peak amplitude much

(Extra Slide)

Probing J_{1D} via J_{2P}, J_{1P}

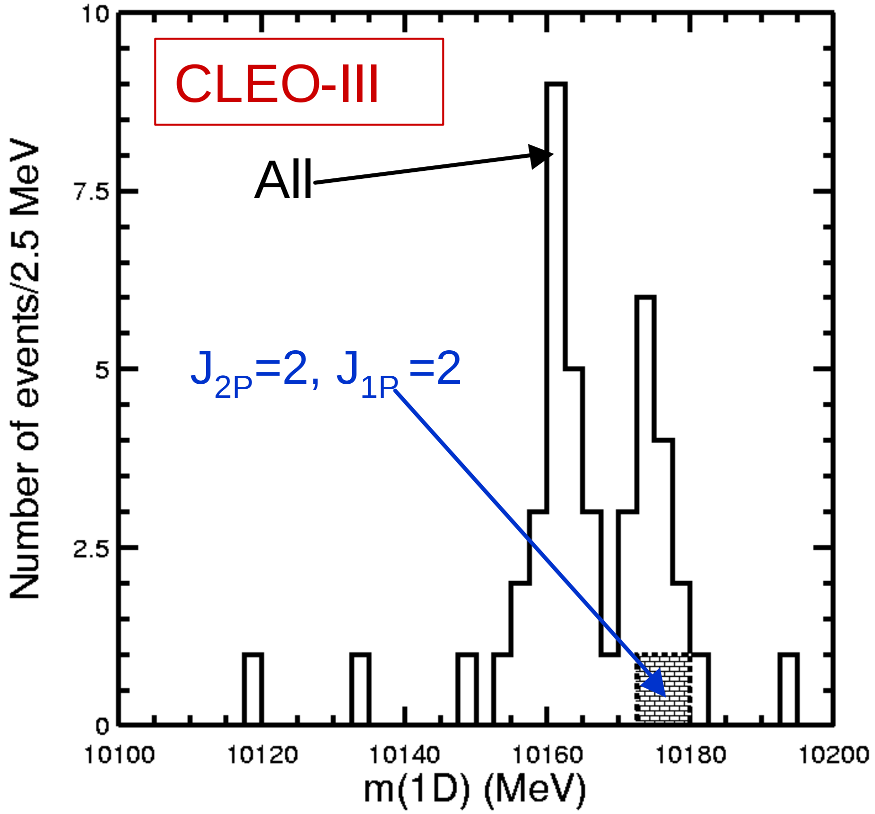
- The peak at 10162 MeV has a large fraction of J_{2P}=1, J_{1P} =1 events, as expected for J_{1D}=1 or 2.

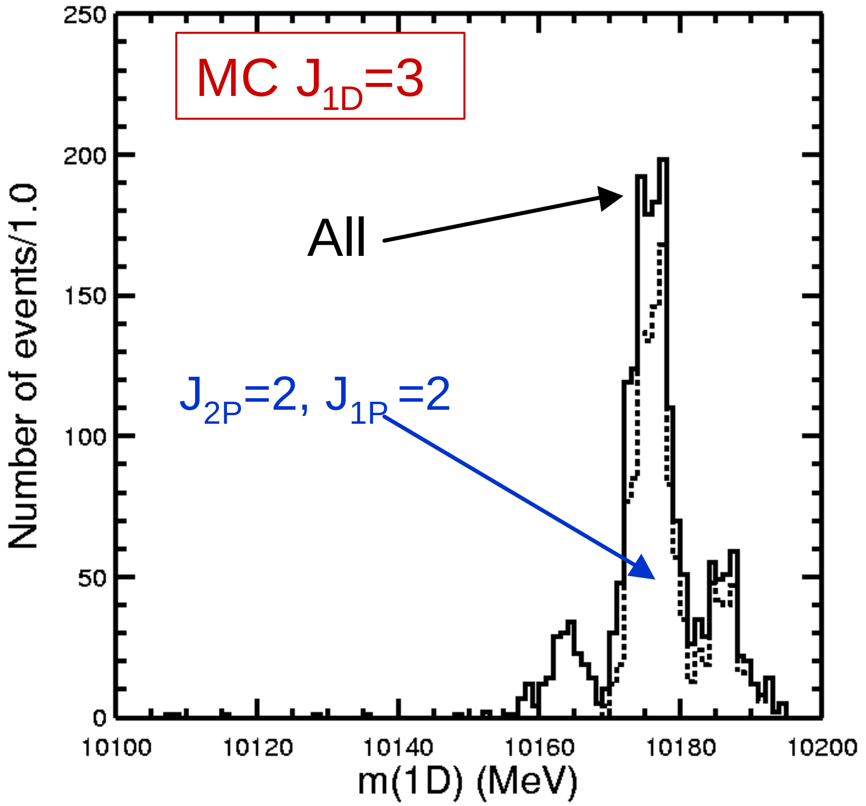


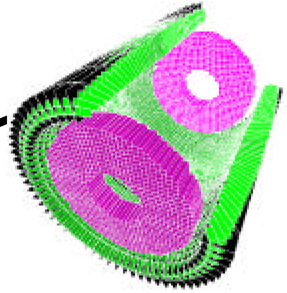
(Extra Slide)

Probing J_{1D} via J_{2P}, J_{1P}

- The peak at 10174 MeV has a too small a fraction of $J_{2P}=2$, $J_{1P}=2$ events, to be $J_{1D}=3$ (in fact a few such events expected due to the satellite from $J_{1D}=2$ at 10162 MeV)







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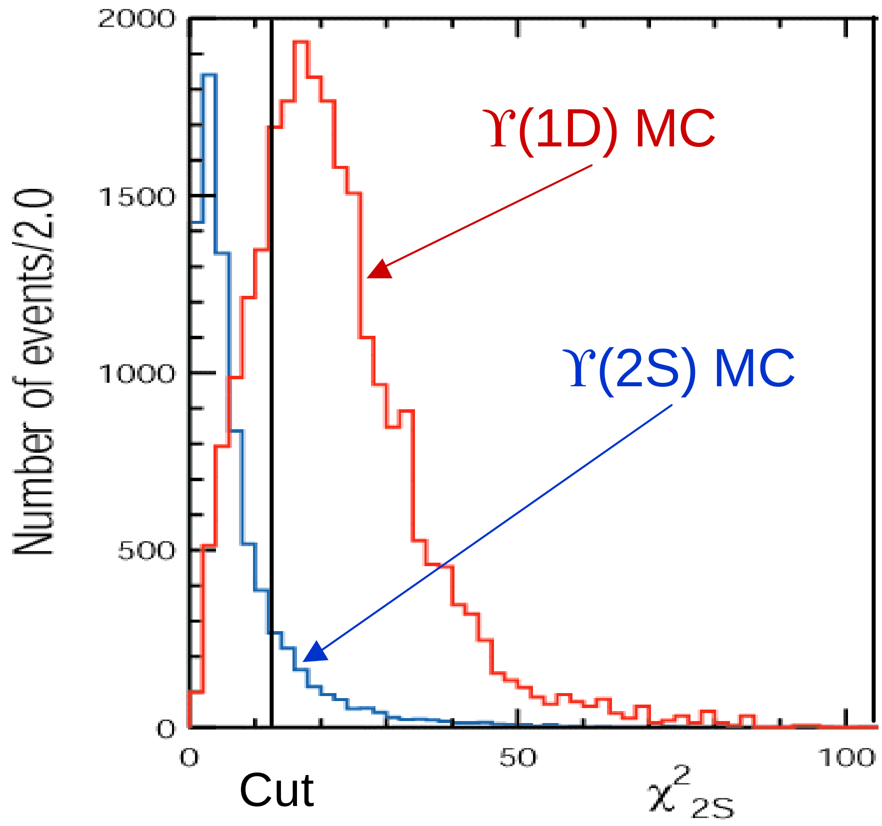
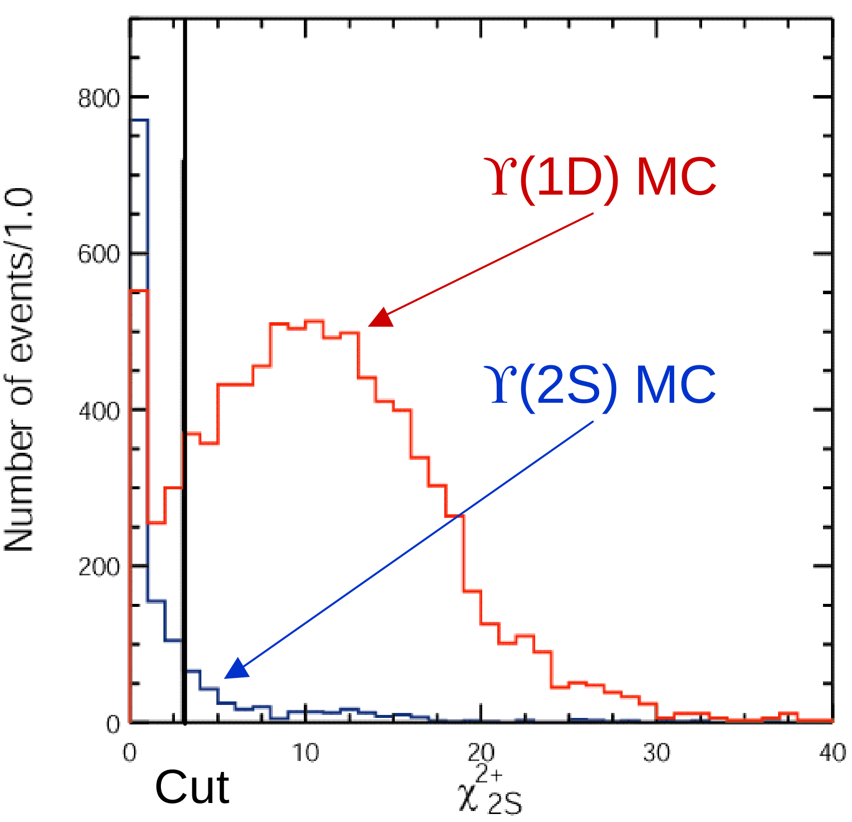
Suppression of the Υ(2S) 4γ-cascades

$$c^{2}_{2S} = \min_{J_{2P},J_{1P}} \sum_{i=1}^{4} \left(\frac{E_{g\,i} - E_{g\,i}^{\text{expected}}(M_{2S}, J_{2P}, J_{1P})}{s\,(E_{g\,i})} \right)^{2} \qquad c^{2+}_{2S} = \min_{J_{2P},J_{1P}} \sum_{i=1}^{4} \left(\frac{\max\{0,\, E_{g\,i} - E_{g\,i}^{\text{expected}}(M_{2S}, J_{2P}, J_{1P})\}}{s\,(E_{g\,i})} \right)^{2}$$

$c^{2}_{2S} > 12$

$c^{2+}_{2S} > 3$





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Signal for $\Upsilon(3S)\mapsto\gamma\chi_b(2P_0)\mapsto\gamma\gamma\,\Upsilon(2S)$

- Projection of 2D-fit to δ=(Recoil Mass(2γ)-$M_{\Upsilon(2S)}$)/σ vs. $E\gamma_{\text{Low}}$ onto $E\gamma_{\text{Low}}$ with the $\exp(-\delta^2/2)$ as weight