CLEO Results on Quarkonium Transitions

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Quarkonia Transitions

- $\psi(2S) \rightarrow J/\psi$ + hadrons (NEW!)
  - X J/ψ, $\pi^+\pi^-$ J/ψ, $\pi^0\pi^0$ J/ψ, η J/ψ , π^0 J/ψ (complete set)
- Radiative transitions in charmonium & bottomonium
  - $n^3S_1 \rightarrow \gamma\ (n-1)^3P_J$ (χ_J)
  - $n^3P_J \rightarrow \gamma\ (n,n-1)^3S_1$
  - $n^3S_1 \rightarrow \gamma\ (n-1,n-2)\ ^1S_0$ (η_Q)
- 1st Observation of $\Upsilon(1^3D_2)$ (Review)
  - $\Upsilon(1^3D_2) \rightarrow \pi^+\pi^-\ \Upsilon(1S)$?

$\psi(2S) \to XJ/\psi$

$\psi(2S)$ decays:

Transitions:

- $J/\psi\ \pi^+\pi^-$
- $J/\psi\ \pi^0\pi^0$
- $J/\psi\ \eta$
- $J/\psi\ \pi^0$

} Σ_{excl}

Radiative Decays:

- $\gamma\chi_{cJ}$ (E1)
- $\gamma\eta_c$ (M1)
- $\gamma\eta_c'$ (M1)

Annhilation:

- Dileptons
- direct decay →light hadrons

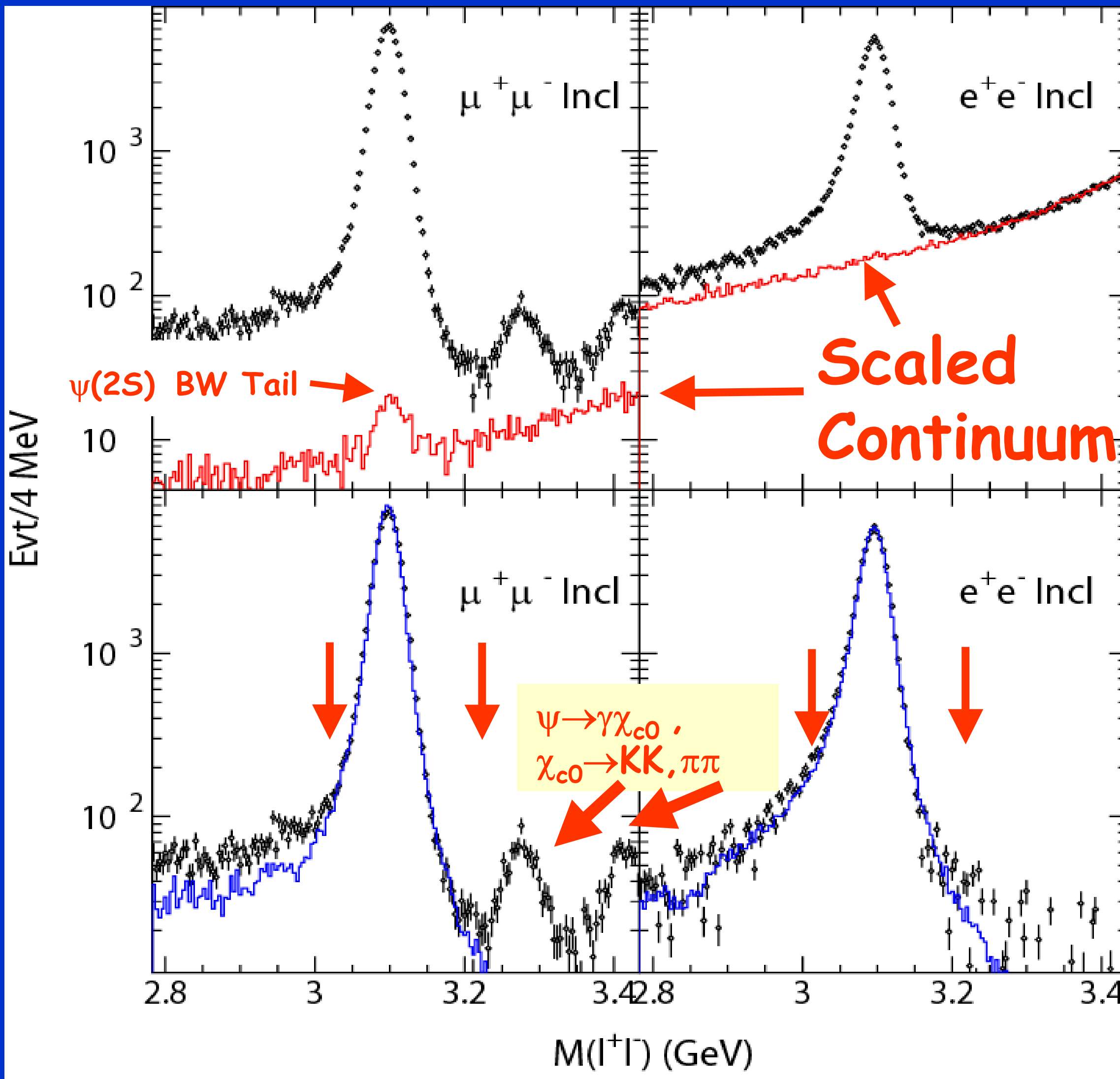
- BRs for XJ/ψ, $\pi^+\pi^- J/\psi$ serve as normalizing modes
- Many relative msmts, few absolute
- PDG fit takes input from different expmts & eras
- A 1st: precision, totality of channels, internal ratios w/ correlations handled
- Questions:
  - $\pi^0\pi^0 J/\psi$: $\pi^+\pi^- J/\psi$?
  - $B(\psi(2S) \to$ light hadrons) ?
  - $XJ/\psi - \Sigma_{excl}$? ($\Rightarrow \Sigma\ \gamma\chi_{cJ} \to \gamma\gamma J/\psi$)

Strategy

- Fully reconstruct
- $J/\psi \to ee, \mu\mu$
  - Use E/p only as ID
- $\eta \to \gamma\gamma$ & $\pi^+\pi^-\pi^0$
- Loose selection to minimize systematics
- Small bgd, mostly cross-feed among themselves
- Trigger eff>98.6%
- $\#\psi(2S)$: ±3%
  - Robust against cut variation: ε=~50-85%
- Add bremsstrahlung γ's to lepton momenta within 100mr cone
- $ee/\mu\mu$ = 1 ?

$\psi(2S)$: 3.08M decays
Continuum: ~20 pb^{-1} GeV

$\psi(2S) \rightarrow X\ J/\psi$, $J/\psi \rightarrow l^+l^-$



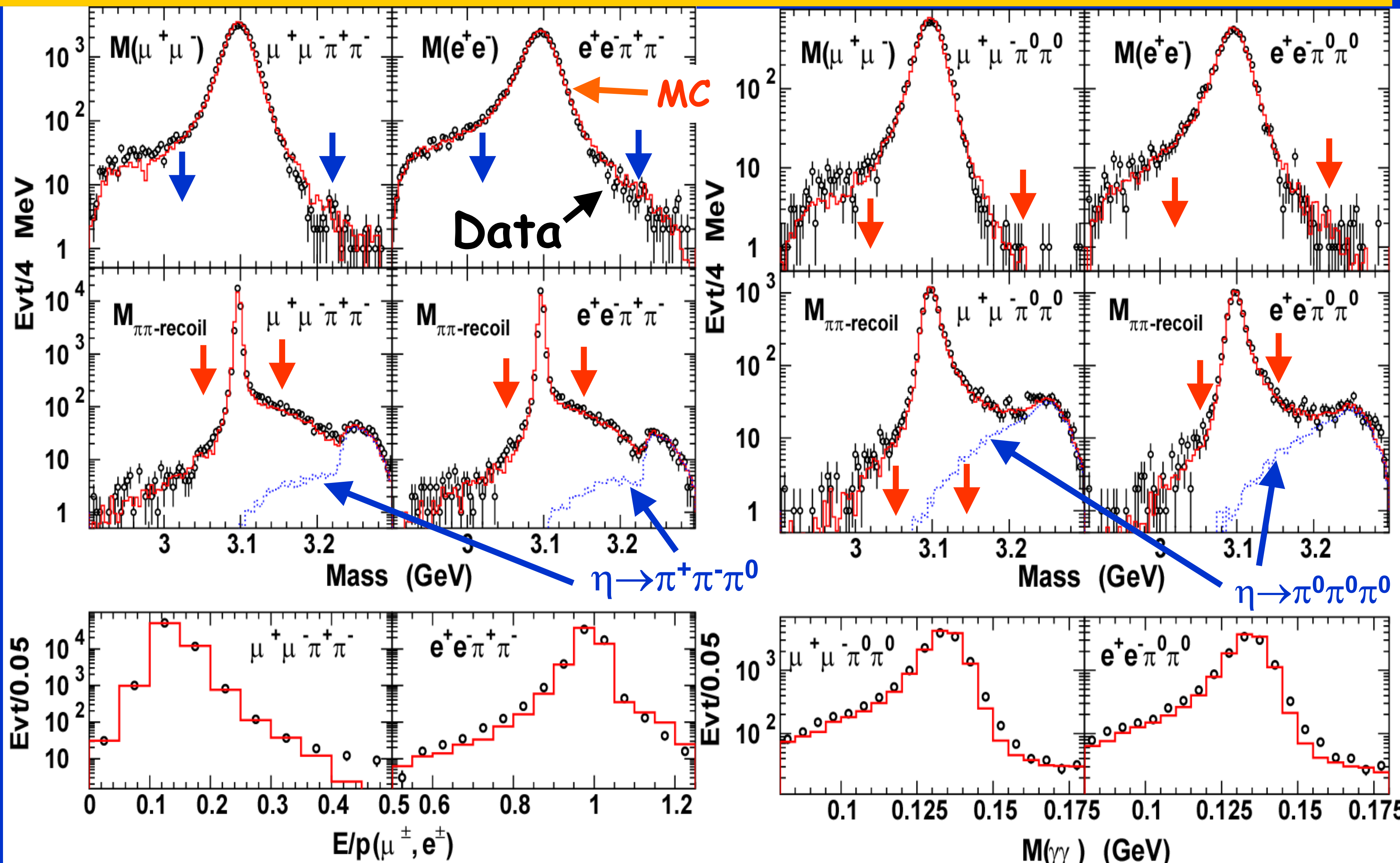
Subtract scaled continuum

ϵ=69% (μ), 61% (e) (wtd by BR)

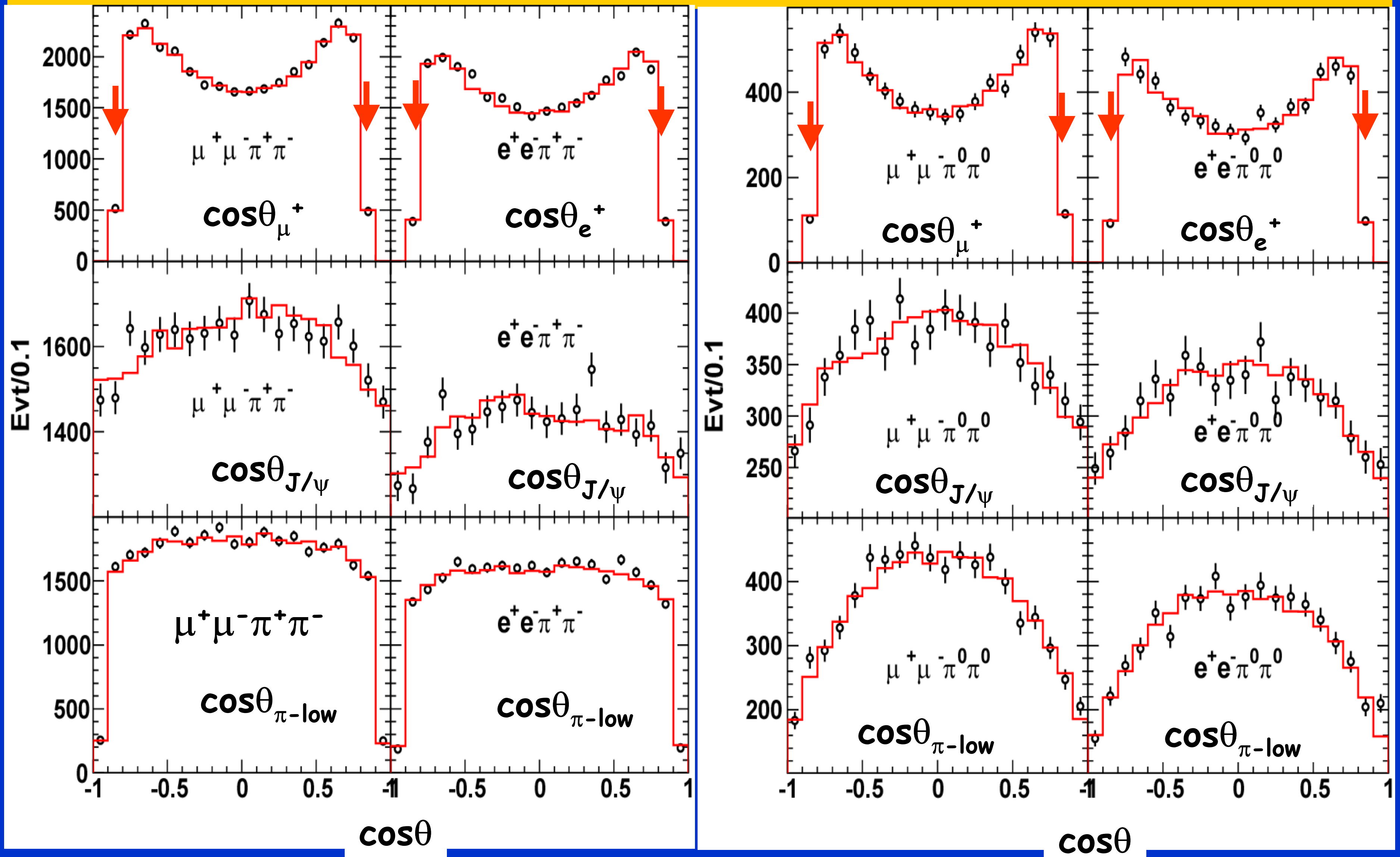
Excellent Data/MC agreement

- $M(l^+l^-)$, $M(\pi\pi)$
- $M(\pi\pi$-recoil$)$
- E/p of leptons
- $M(\pi^0,\ \eta\to\gamma\gamma,\ \eta\to\ \pi^+\pi^-\pi^0)$
- $\cos\ \theta$
- $p(J/\psi)$
- $p(\pi^\pm,\pi^0)$ at all momenta
- See supplemental slides

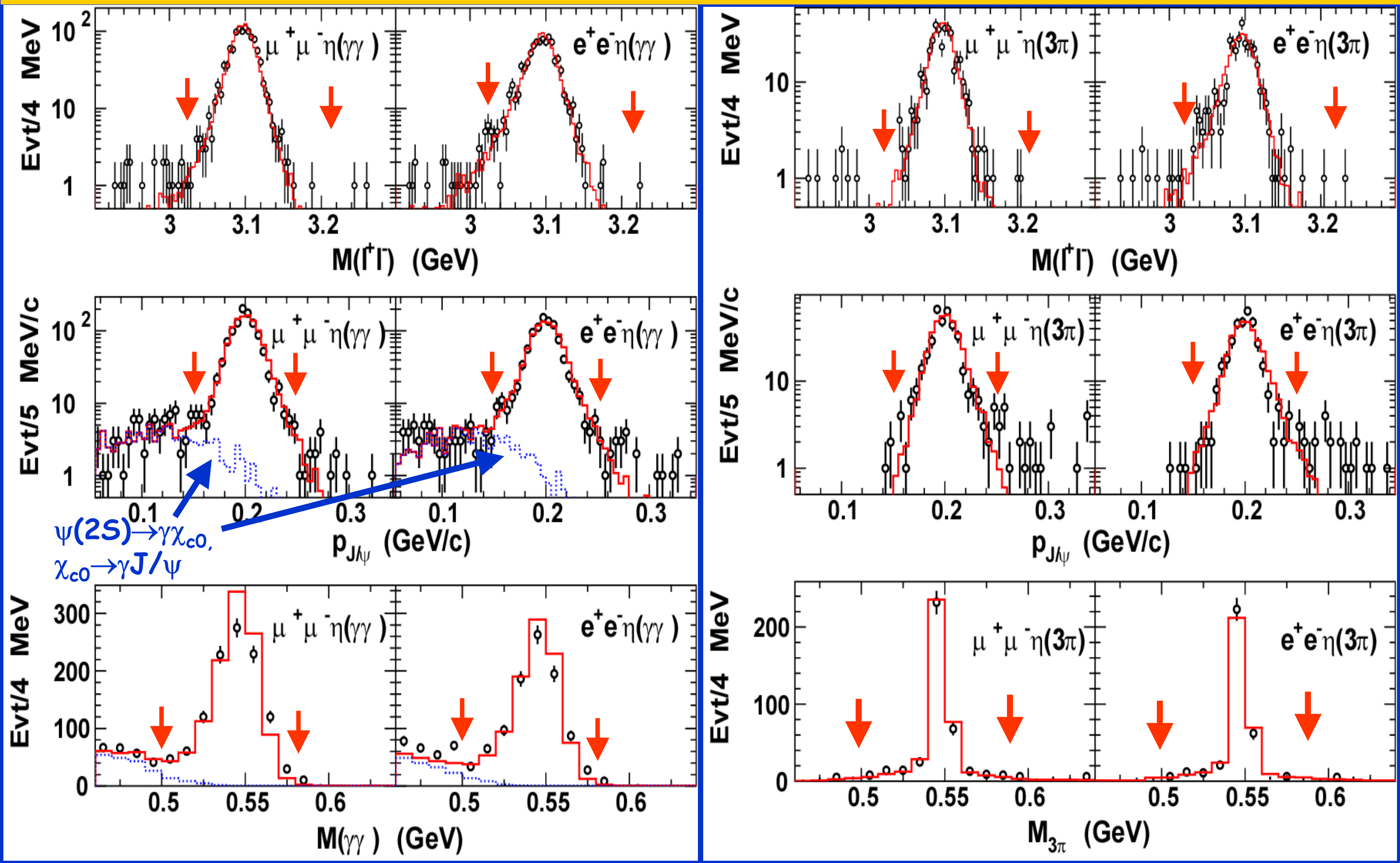
$\psi(2S)\to\pi\pi\ J/\psi,\ J/\psi\to l^+l^-$



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



$\psi(2S)\to\eta\ J/\psi,\ \eta\to\gamma\gamma,\ 3\pi$



Uncertainties (relative, %)

Channel	Stat(%)	2 biggest syst (%)		Total*(%)
$\pi^+\pi^- J/\psi$	0.4	4 ($\pi^\pm$)	0.5 (dec rad)	5.3
$\pi^0\pi^0 J/\psi$	0.9	2 ($\pi^\pm$)	2 (π^0)	4.6
$\eta(\gamma\gamma) J/\psi$	2.2	2 ($\pi^\pm$)	1 (π^0, xfeed)	4.9
$\eta(3\pi) J/\psi$	3.7	4 ($\pi^\pm$)	1.5 (xfeed)	6.9
$\pi^0 J/\psi$	11.9	5 (xfeed)	2 ($\pi^\pm$)	13.7
$X J/\psi$	0.3	2 ($\pi^\pm$)	0.5 (dec rad)	4.1

*Total includes #ψ(2S) normalization error of ±3%

We assign a sys error of 1% per $\pi^\pm$ &
add linearly over $\pi^\pm$'s per event.
Similarly, 1% per π^0.

CLEO Preliminary: BR in % relerror in %

	B	$B/B_{XJ/\psi}$	$B/B_{\pi^+\pi^- J/\psi}$
$X\ J/\psi$	$59.6 \pm 0.2 \pm 2.4^{4.1\%}$	CLEO Prelim	
	PDG $55 \pm 7^{12.7\%}$	PDG avg, not fit	
$\pi^+\pi^-\ J/\psi$	$33.3 \pm 0.1 \pm 1.8^{5.3\%}$	$55.8 \pm 0.3 \pm 1.1^{2.1\%}$	
	$32.3 \pm 1.4^{4.3\%}$	$53.5 \pm 0.7 \pm 1.6^{3.3\%}$	BES
$\pi^0\pi^0\ J/\psi$	$16.9 \pm 0.2 \pm 0.8^{4.6\%}$	$28.3 \pm 0.3 \pm 0.6^{2.2\%}$	$50.7 \pm 0.5 \pm 1.5^{3.0\%}$
		PDG $32.7 \pm 1.4^{4.3\%}$	$57.0 \pm 0.9 \pm 2.6^{4.8\%}$
$\eta(\gamma\gamma)\ J/\psi$	$3.3 \pm 0.1 \pm 0.1^{4.9\%}$	$5.5 \pm 0.1 \pm 0.1^{2.7\%}$	$9.9 \pm 0.2 \pm 0.2^{3.3\%}$
	$3.0 \pm 0.1 \pm 0.2^{8.3\%}$	PDG $6.9 \pm 0.8^{12\%}$	$9.8 \pm 0.5 \pm 1.0^{11.4\%}$
$\eta(3\pi)\ J/\psi$	$3.3 \pm 0.1 \pm 0.2^{6.9\%}$	$5.5 \pm 0.2 \pm 0.2^{4.6\%}$	$9.9 \pm 0.4 \pm 0.2^{4.2\%}$
$\pi^0\ J/\psi$	$0.15 \pm 0.02 \pm 0.01^{14\%}$	$0.26 \pm 0.03 \pm 0.01^{13\%}$	$0.46 \pm 0.05 \pm 0.03^{13\%}$
	$0.143 \pm 0.013 \pm 0.011^{13\%}$		

Further Results

CLEO Preliminary

- $B(J/\psi \to ee)/B(J/\psi \to \mu\mu)=$ 0.9872 ± 0.0093 (1.4σ < 1)
  - BES: 1.011 ± 0.021
- $B(\psi(2S) \to$ light hadrons$)$ = $1 - \Sigma$excl $- \Sigma\gamma\chi_{cj} - \gamma\eta_c - \Sigma\ell\ell$ = **$17.2 \pm 3.6\%$**
  - CLEO results for all terms except $\Sigma\ell\ell$
  - $Q(l.h.)=B(\psi(2S) \to l.h.)/ B(J/\psi \to l.h.)$= **$19.8 \pm 4.1\%$**
- Incl-Excl= **$6.2 \pm 1.1\%$**
  - =? indirect $\Sigma B(\psi(2S) \to \gamma\chi_{cj}) \times B(\chi_{cj} \to \gamma\ J/\psi)$)
  - 1.5σ>BES ($4.5 \pm 0.2\%$), 2σ>PDG(CBAL) ($3.9 \pm 0.3\%$)

Summary: $\psi(2S) \to XJ/\psi$

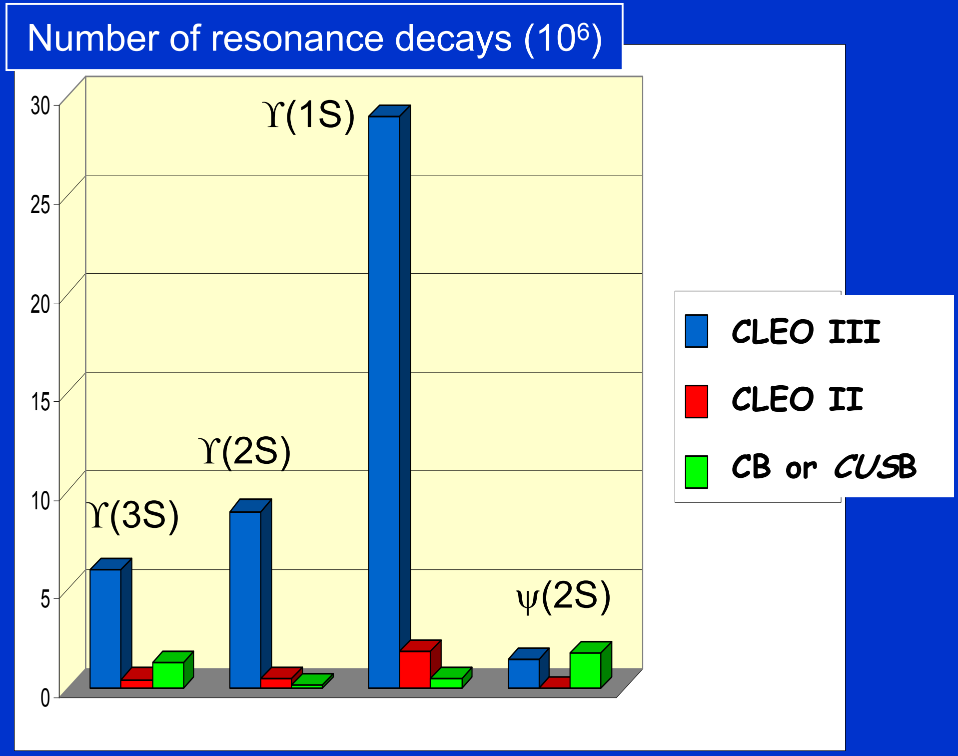
- NEW, PRELIMINARY CLEO msmts of all J/ψ excl hadronic BRs & incl J/ψ as well
  - Systematics limited, many cross checks performed
- Most precise, or comparable to previous
- $\pi^0\pi^0$ absolute rate msd for 1st time
  - Full reconstruction of both π^0's
  - Lower ratios of BR's than BES, E835, E760
  - $\pi^0\pi^0/\pi^+\pi^-$ ratio ~1/2 as expected from isospin
- (Incl-Excl) provides BR cross check
- 1st single-experiment test of inclusive "12% rule"

CLEO Υ & $\psi(2S)$ Data

Reso-nance	Lumi (pb^{-1})	# decays (10^6) CLEO III	CLEO II	Crystal Ball *(CUSB)*
$\Upsilon(3S)$	1460	6.0	0.46	*(1.3)*
$\Upsilon(2S)$	1380	9.0	0.49	0.19
$\Upsilon(1S)$	1210	29.0	1.9	0.48
$\psi(2S)$	2.6	1.5	-	1.8

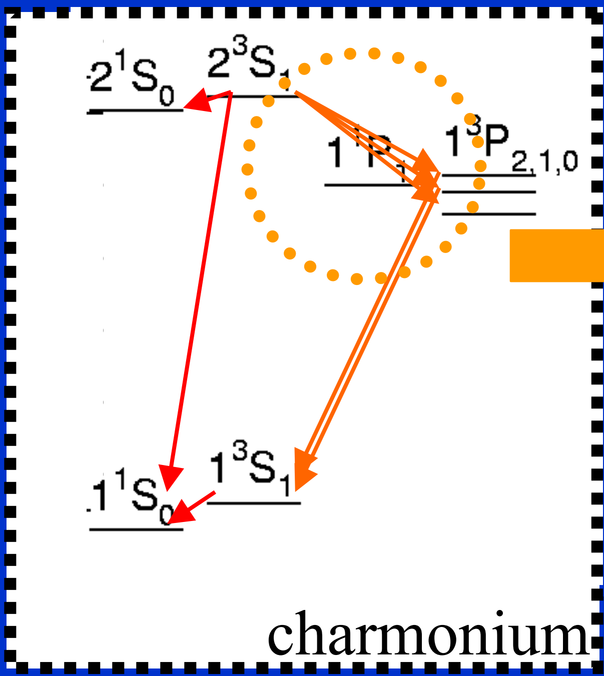
1st half of total CLEO sample

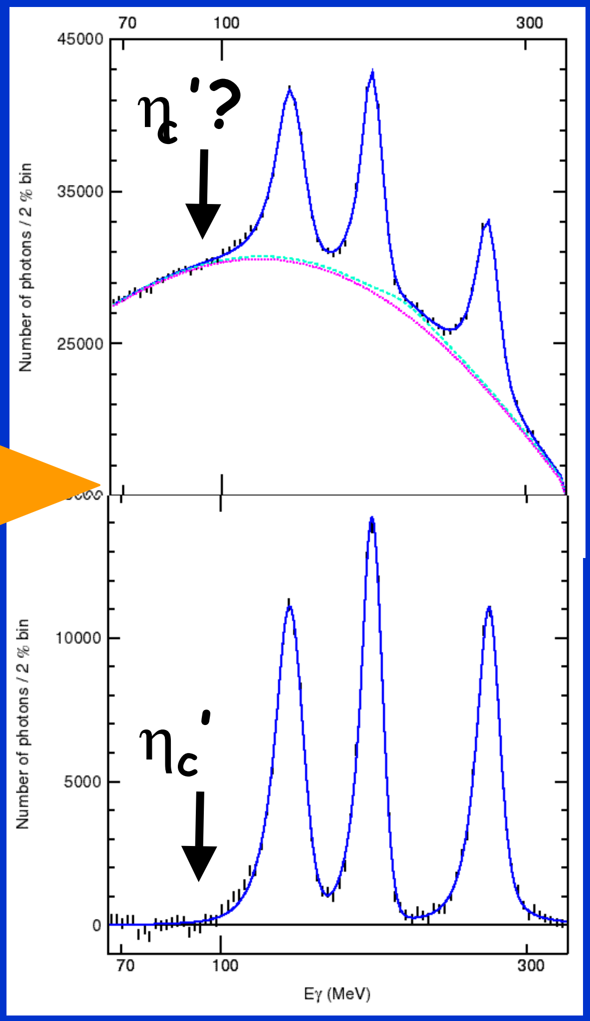
[$\psi(2S)$ BES-II 14.0]



- >10-fold increase for the narrow Υ resonances
- 1st experiment to match Crystal Ball sensitivity for photon transitions from $\psi(2S)$

ψ(2S) Inclusive γ Spectrum



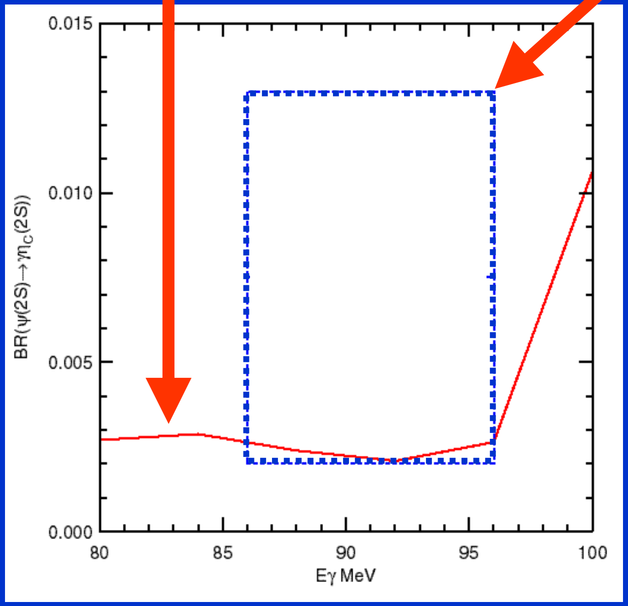


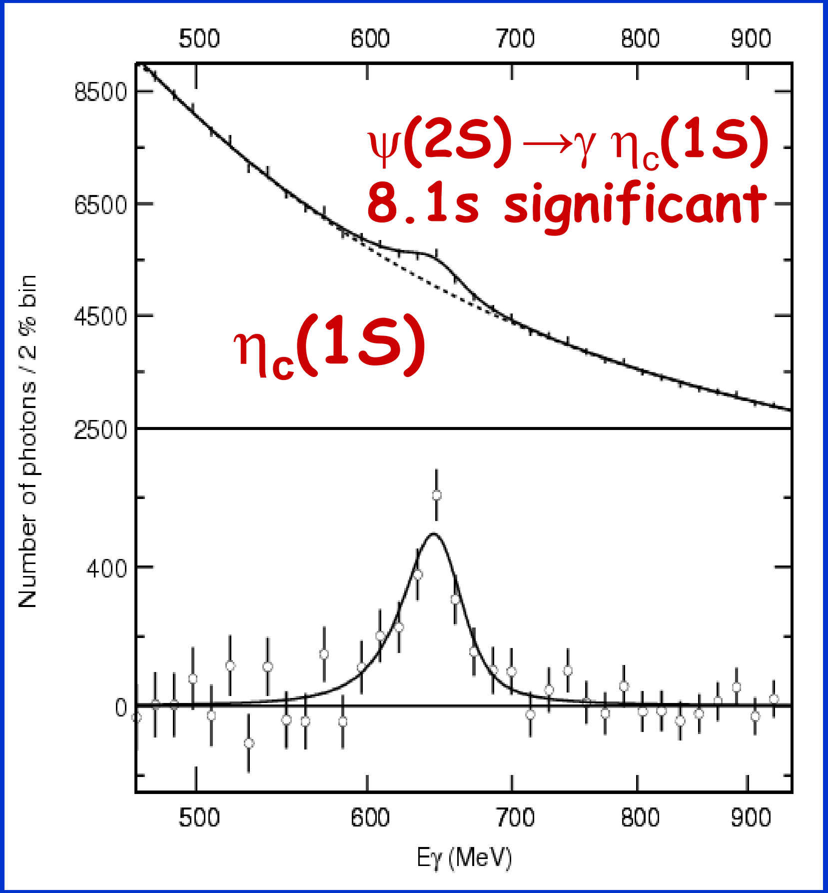
$\eta_c(1S)$ & $\eta_c(2S)$

BR($\psi(2S) \to \gamma\eta_c(2S)$)

CLEO-c 2003
90% CL U.L.

C.Ball 1982
95% CL interval





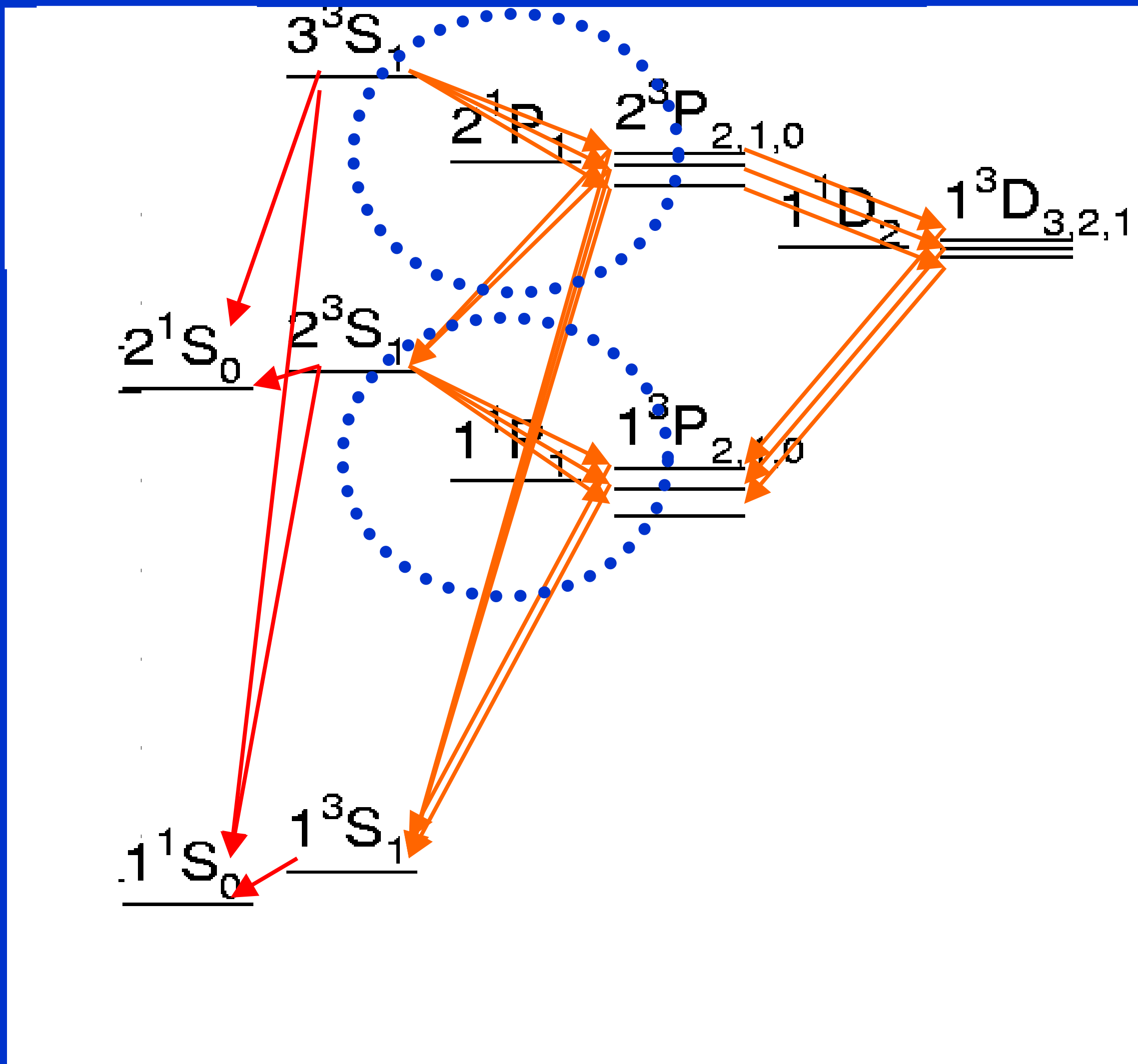
$\psi(2S)$ E1 & M1 transitions

$B(\psi(2S)\rightarrow\gamma X)$ in %	E1 Lines: Branching Ratios			Hindered M1 Line
	J=2	J=1	J=0	J=0
CLEO	9.33±0.14±0.61	9.07±0.11±0.54	9.22±0.11±0.46	0.32±0.04±0.06±0.03
C.Ball	8.0±0.5±0.7	9.0±0.5±0.7	9.9±0.5±0.8	0.28±0.06
PDG	7.8±0.8	8.7±0.8	9.3±0.8	0.28±0.06
ratio	1.20±0.15	1.04±0.11	0.99±0.10	1.21±0.38

$E\gamma$ in MeV	E1 Lines: Photon energies			Hindered M1 Line
	J=2	J=1	J=0	J=0
CLEO	128.00±0.13±0.64	172.05±0.19±0.86	261.99±0.37±1.31	646.2±2.6±3.23
PDG	127.52 ± 0.13	171.21 ± 0.12	260.72 ±0.38	638.44±0.81
Ratio	1.0038±0.0014±0.0050	1.0049±0.0013±0.0050	1.0049±0.0020±0.0050	1.012±0.009

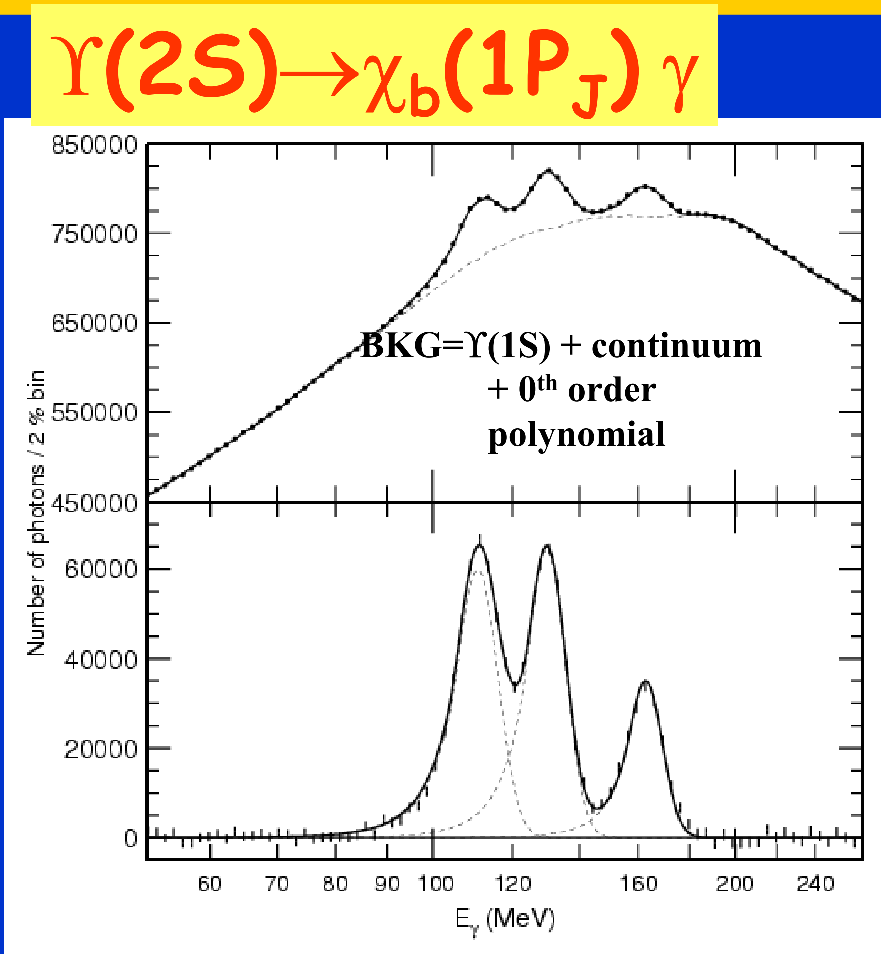
- *Good agreement on branching ratios, ~smallest errors*
- *Hindered M1 transition confirmed!*
- *Use results to recalibrate calorimeter energy scale for Υ's*

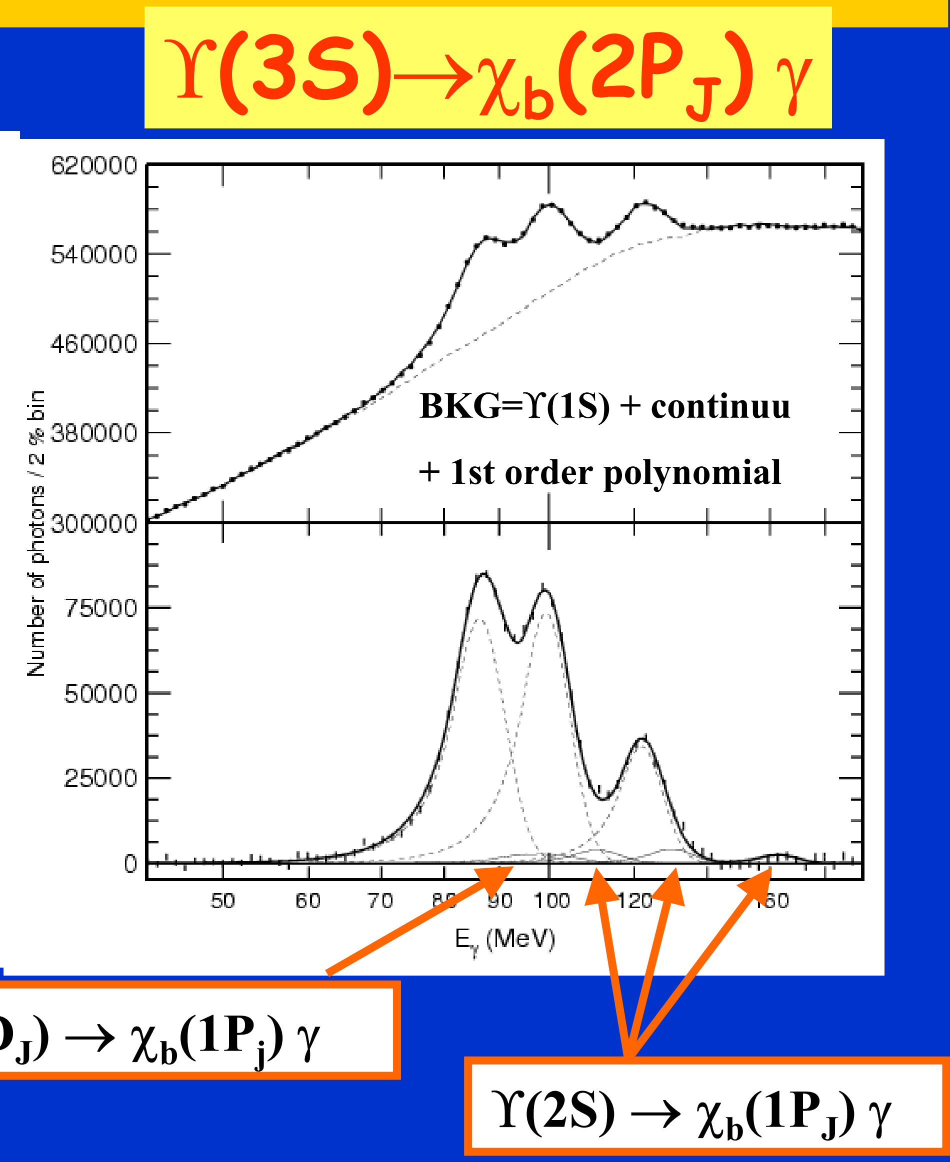
Bottomonium transitions



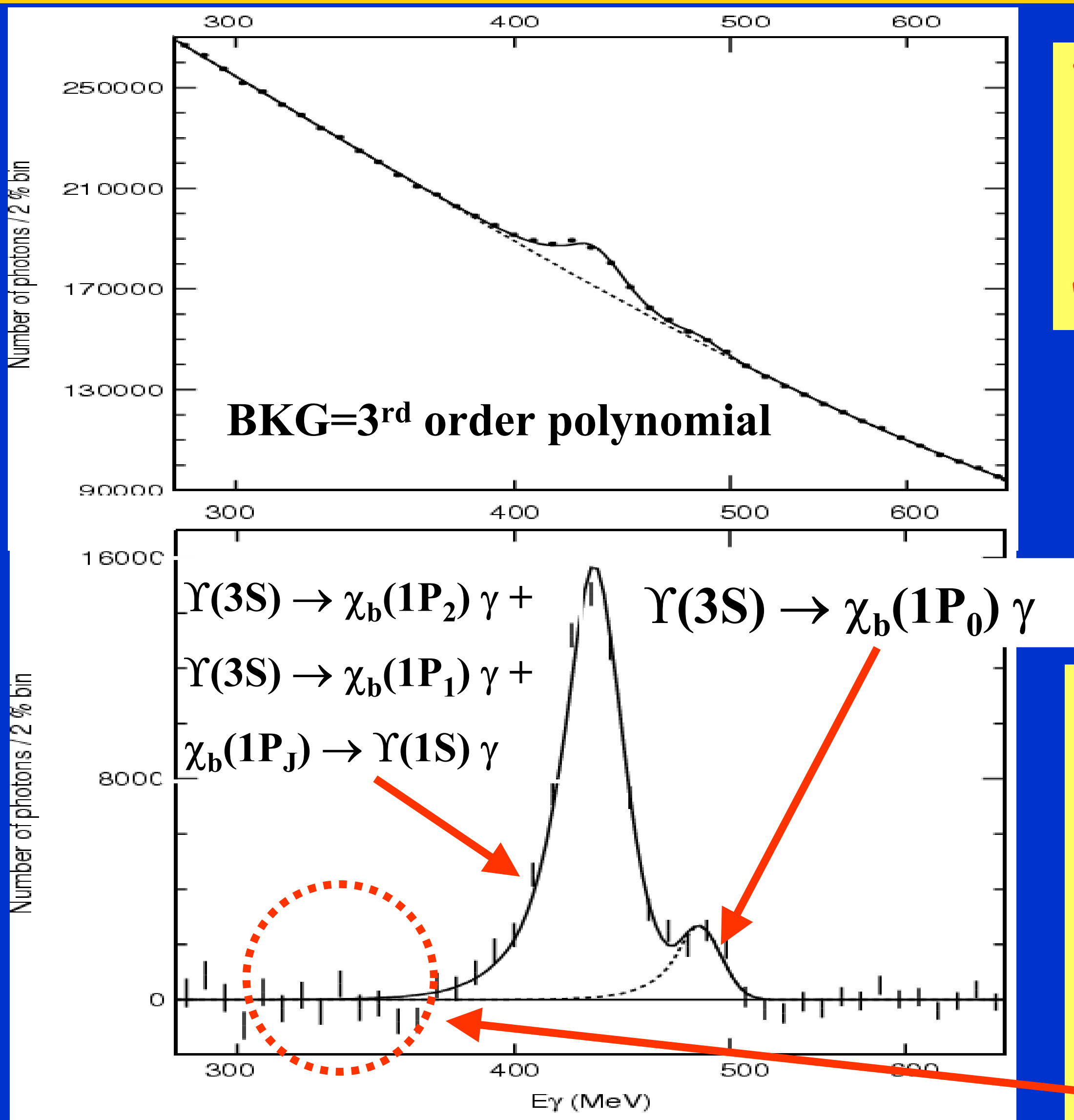
2 sets of lines to P states

$\Upsilon(nS) \rightarrow \gamma\ \chi_b$





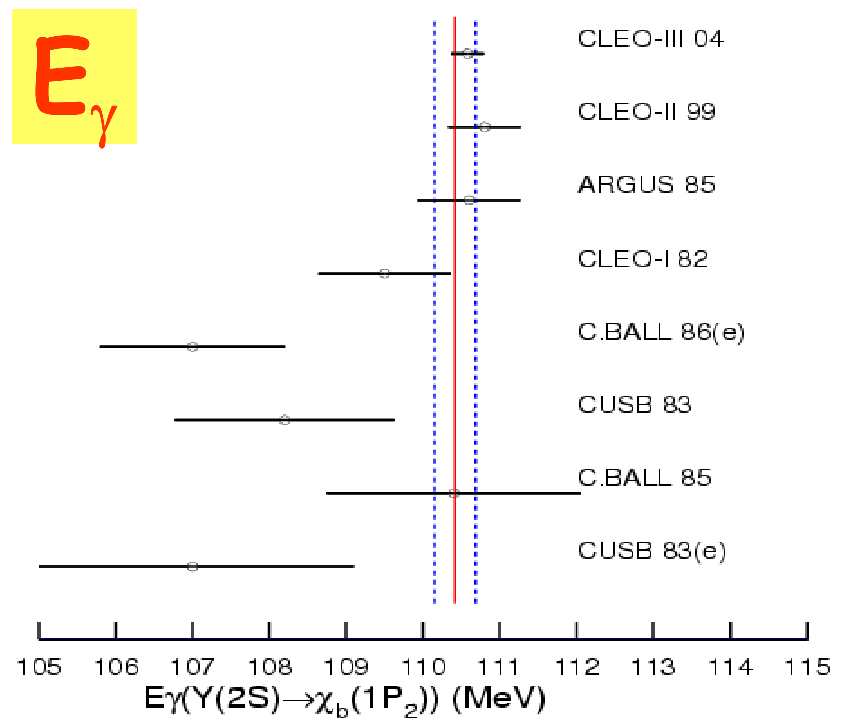
$\Upsilon(3S) \to \chi_{bJ}(1P_J)\,\gamma$

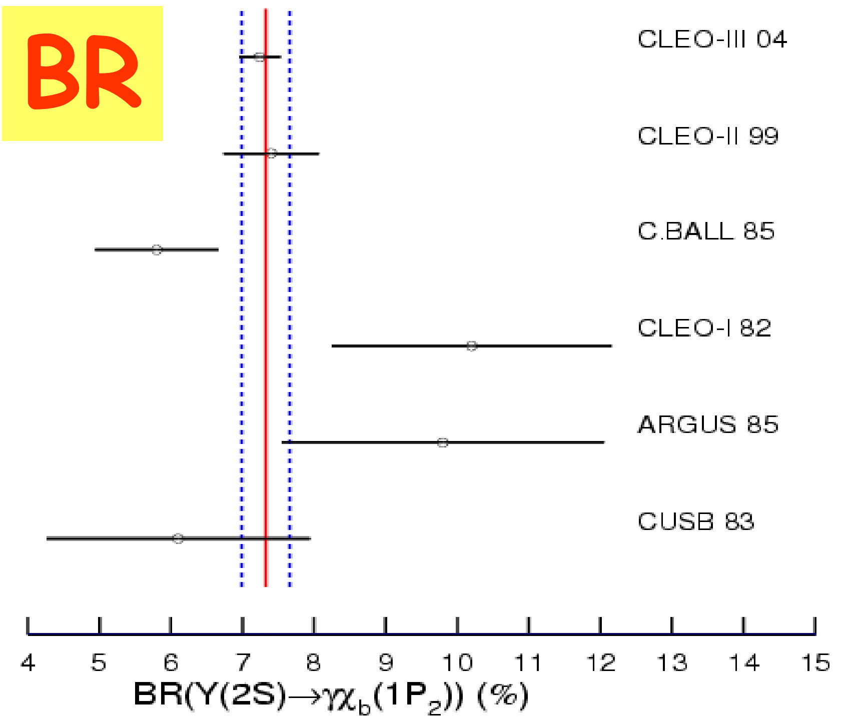


We were able to extract BR($\Upsilon(3S) \to \chi_b(1P_0)\,\gamma$) whose peak is isolated

No significant enhancement around E~350MeV which would correspond to $\Upsilon(3S) \to \eta_b(2S)\,\gamma$

$\Upsilon(2S) \rightarrow \chi_{b2}\,\gamma$





Significantly improved errors (systematics dominated)

Excellent agreement between CLEO3 and previous msts of photon energies and branching ratios

See supplemental slides for complete set of plots like this; also tables w/#s

χ_b, χ_b' Masses

Υ State	Mass (MeV)	
2S	10023.26±0.31	PDG input
3S	10355.2 ± 0.5	
$2P_2$	10268.80±0.06±0.57	CLEO ONLY
$2P_1$	10255.58±0.07±0.56	
$2P_0$	10232.94±0.16±0.68	
$1P_2$	9912.06±0.08±0.43	CLEO ONLY
$1P_1$	9892.83±0.09±0.43	
$1P_0$	9859.36±0.19±0.53	

Electric Dipole Transitions

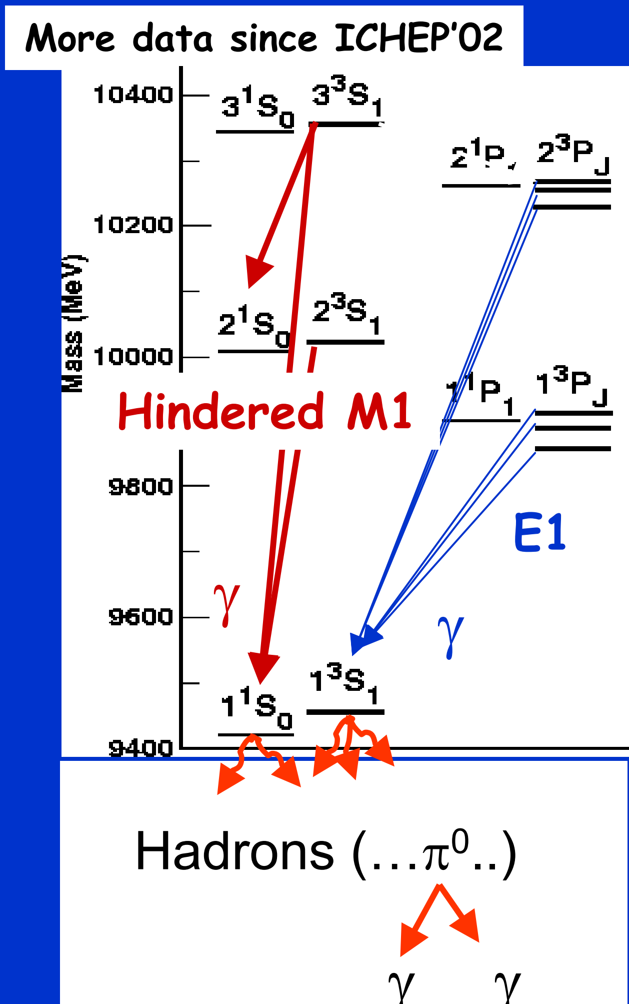
$$\Gamma_{E1}(n_i S \rightarrow n_f P) = \frac{4}{27}\alpha e_Q^2 (2J+1) E_\gamma^3 \langle n_f P | r | n_i S \rangle^2$$

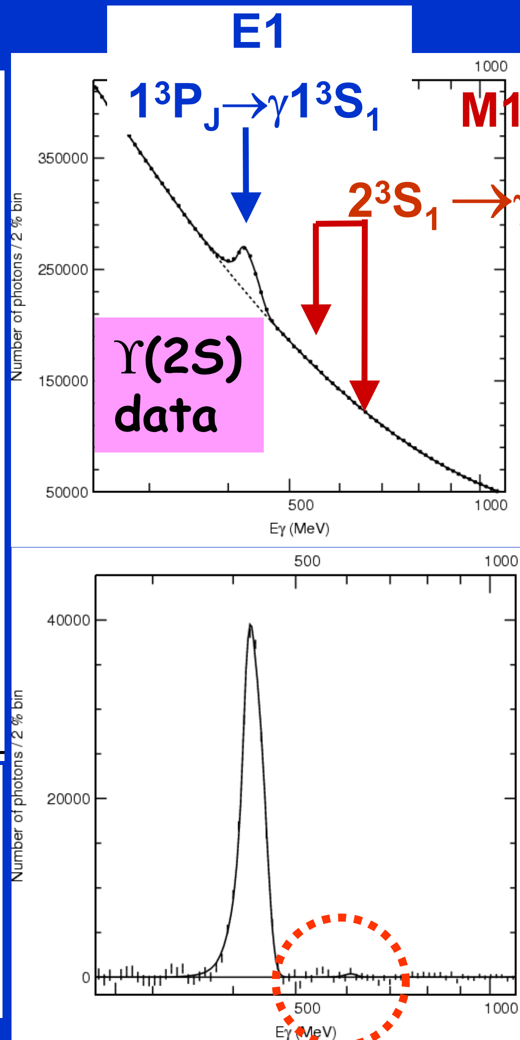
- E1 matrix element is spin independent in NR limit
- Below, ratio of Γ_{E1}'s normalized to $(2J+1)E_\gamma^3$.
- Also results from $\psi' \rightarrow \chi_{cJ}\gamma$ analysis are shown.

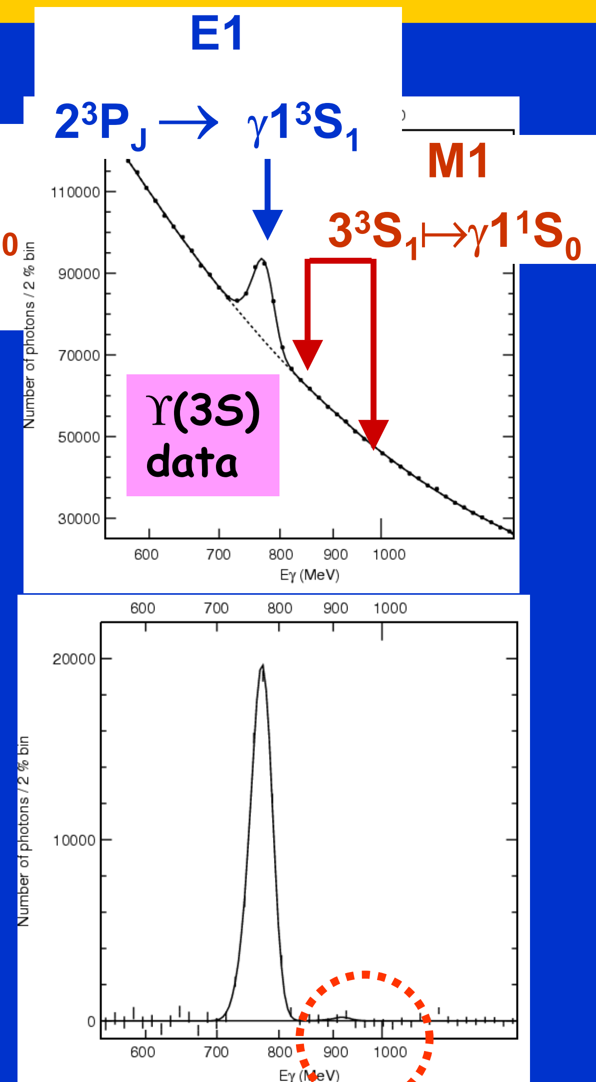
$\chi_b(2P)$:	(J=2)/(J=1)	1.00±0.01±0.05
	(J=0)/(J=1)	0.76±0.02±0.07
	(J=0)/(J=2)	0.76±0.02±0.09
$\chi_b(1P)$:	(J=2)/(J=1)	1.01±0.02±0.08
	(J=0)/(J=1)	0.82±0.02±0.06
	(J=0)/(J=2)	0.81±0.02±0.11
$\chi_c(1P)$:	(J=2)/(J=1)	1.50±0.02±0.05
	(J=0)/(J=1)	0.86±0.01±0.06
	(J=0)/(J=2)	0.59±0.01±0.05

- In bb, (J=2)/(J=1) ~ 1 consistent with NR expectation.
- In cc, (J=2)/(J=1) > 1 due to smaller quark mass.
- Transitions to J=0 indicate relativistic effect at ~20% even for bb.

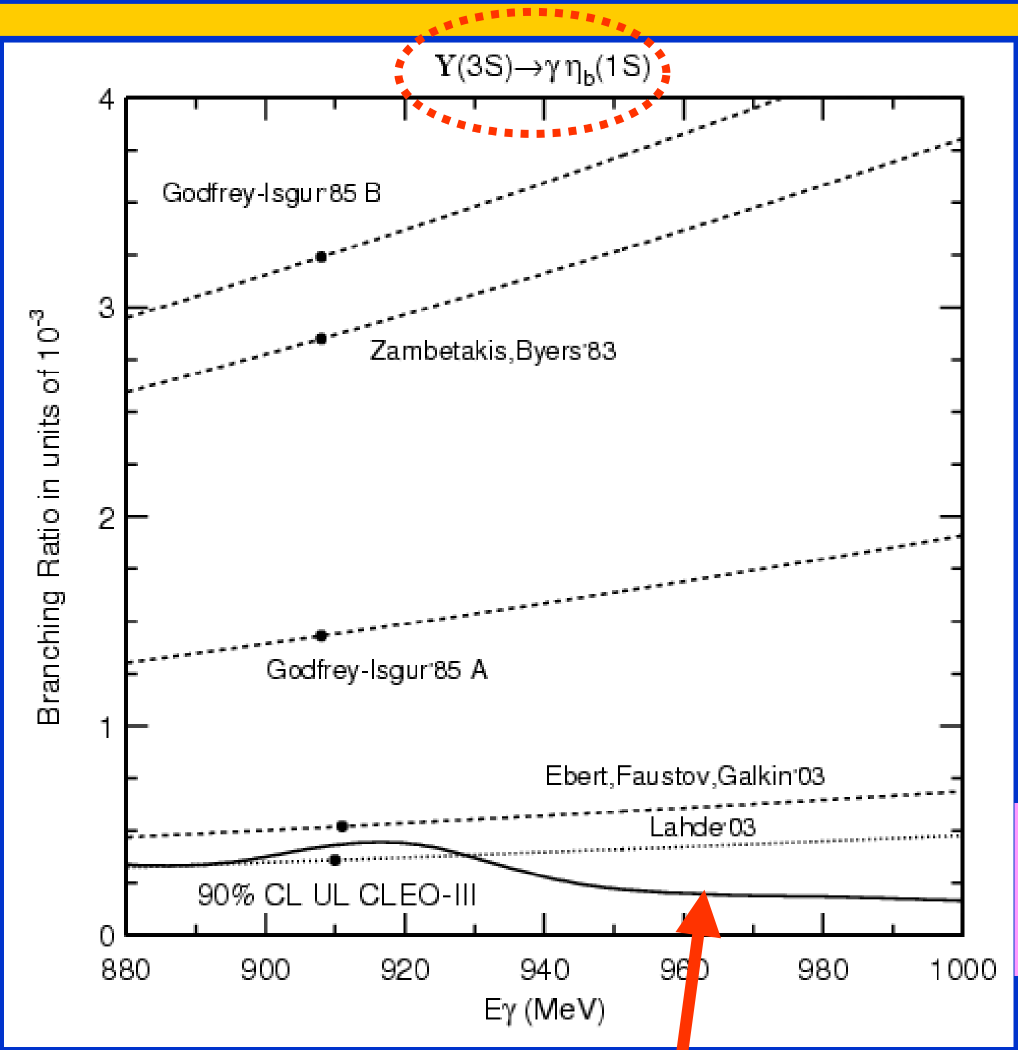
$\Upsilon(3S)\rightarrow\eta_b(1S)\ \gamma$ & $\Upsilon(2S)\rightarrow\eta_b(1S)\ \gamma$







Test potential models Γ_{M1}

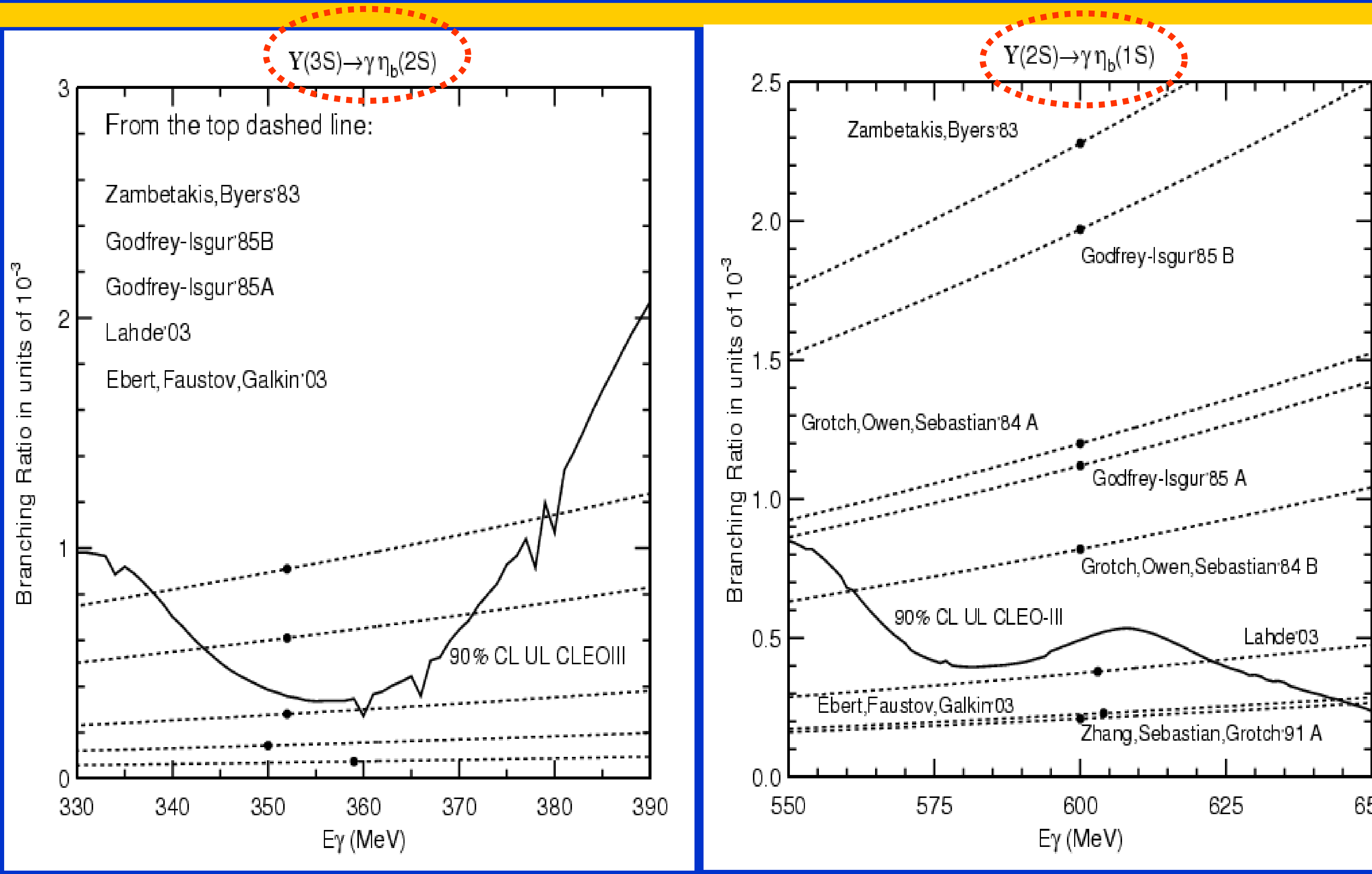


Models from the compilation by Godfrey&Rosner PR D64, 074011 (2001); Ebert,Faustov, and Galkin, PRD67, 014027(2003); Lahde NP A714, 183(2003) [scaled here by phase-space]

Limits are best here at high E where lower bgd

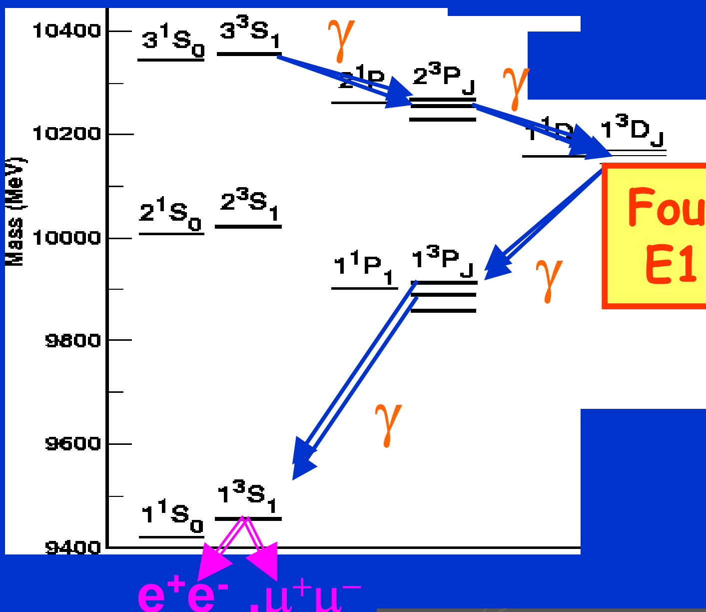
- **Data rule out many predictions!**

Test potential models Γ_{M1}

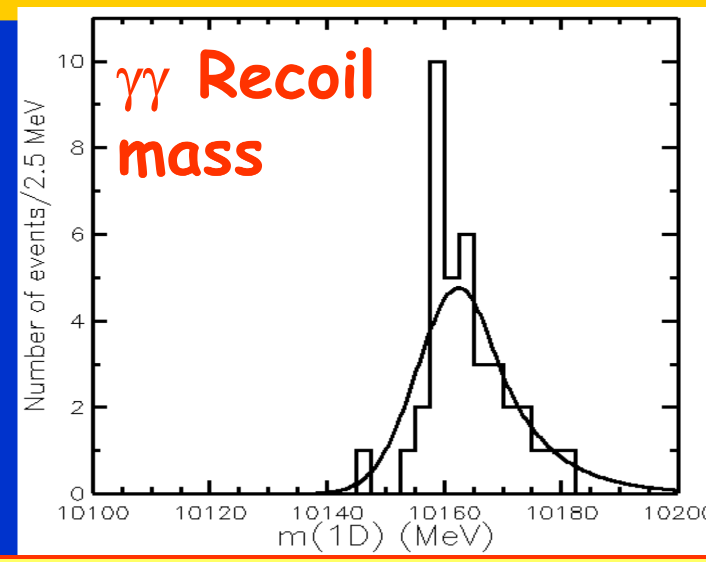


1st Observation of $\Upsilon(1^3D_2)$

- PRD70, 032001 (2004)

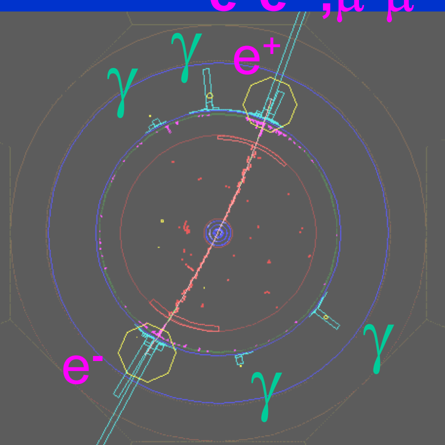


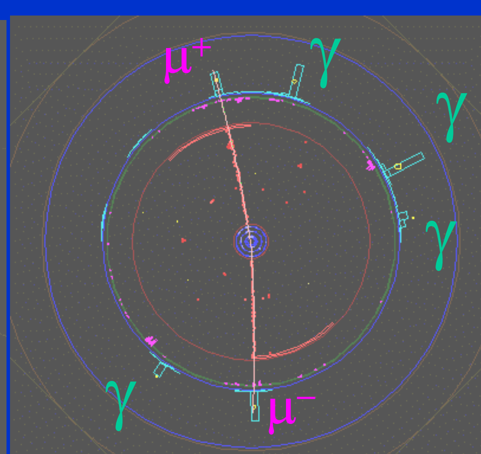
Four successive E1 transitions



$M(\Upsilon(1^3D_2))$ = 10161.1±0.6±1.6 MeV

$B(\Upsilon(3S) \to \gamma\gamma\Upsilon(1D) \to \gamma\gamma\gamma\gamma\, \Upsilon(1S) \to \gamma\gamma\gamma\gamma\, l^+l^-)$
$=(2.6 \pm 0.5 \pm 0.5)\, 10^{-5}$





3.8×10^{-5}
Godfrey&Rosner PRD64,097501(2001)

1st new long-lived heavy quarkonium state in 20 yrs

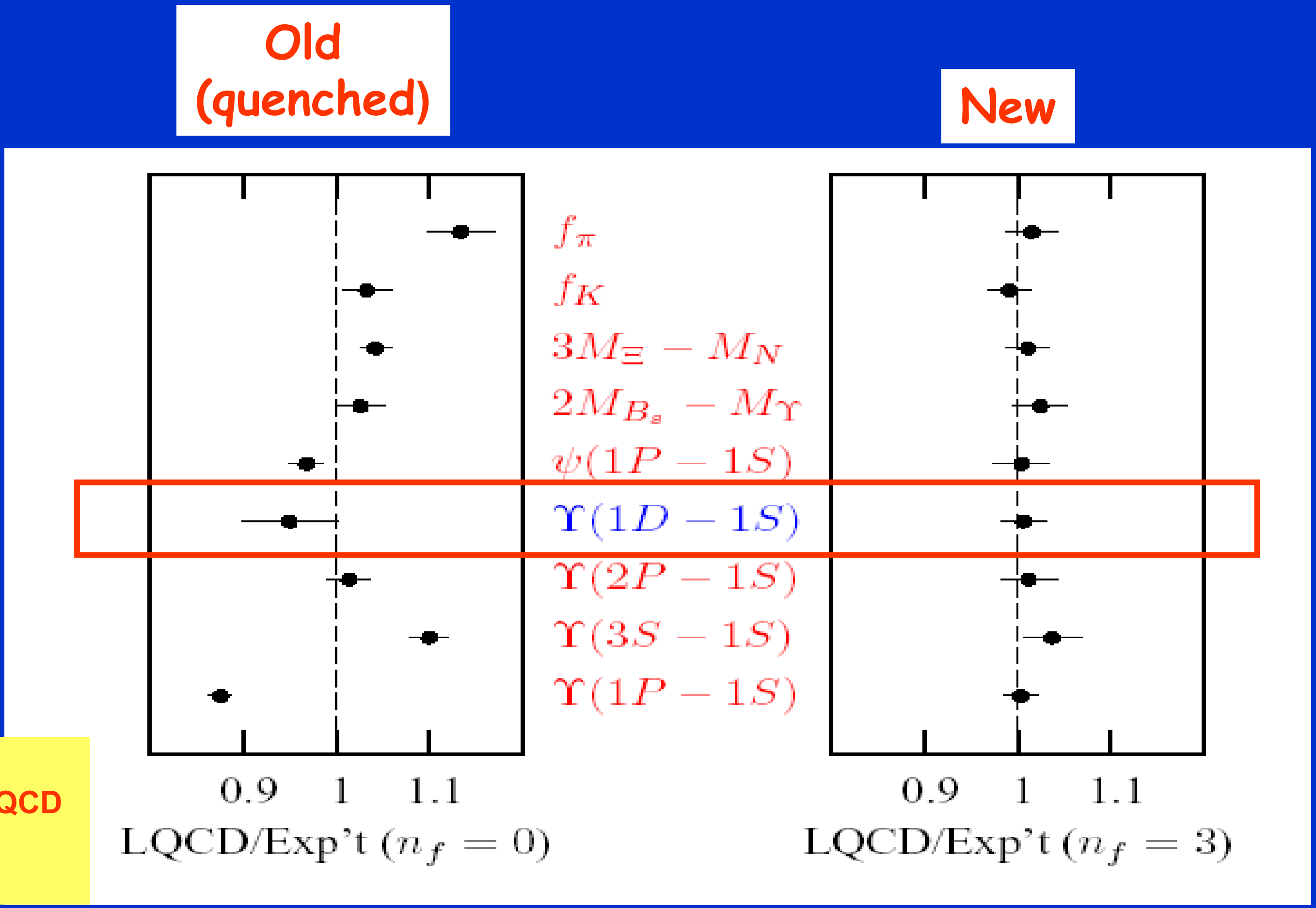
Potential models: $M(\Upsilon(1D))$=?

- Models which have success with other Υ masses

  $\Rightarrow$success w/mass of $\Upsilon(1^3D_2)$
- Fits to quarkonia masses possible with as few free parameters as one (accuracy ~0.2% of mass, 2% of excitation energy) - perhaps the most convincing proof for quark structure of hadrons
- Several potential models consistent w/data

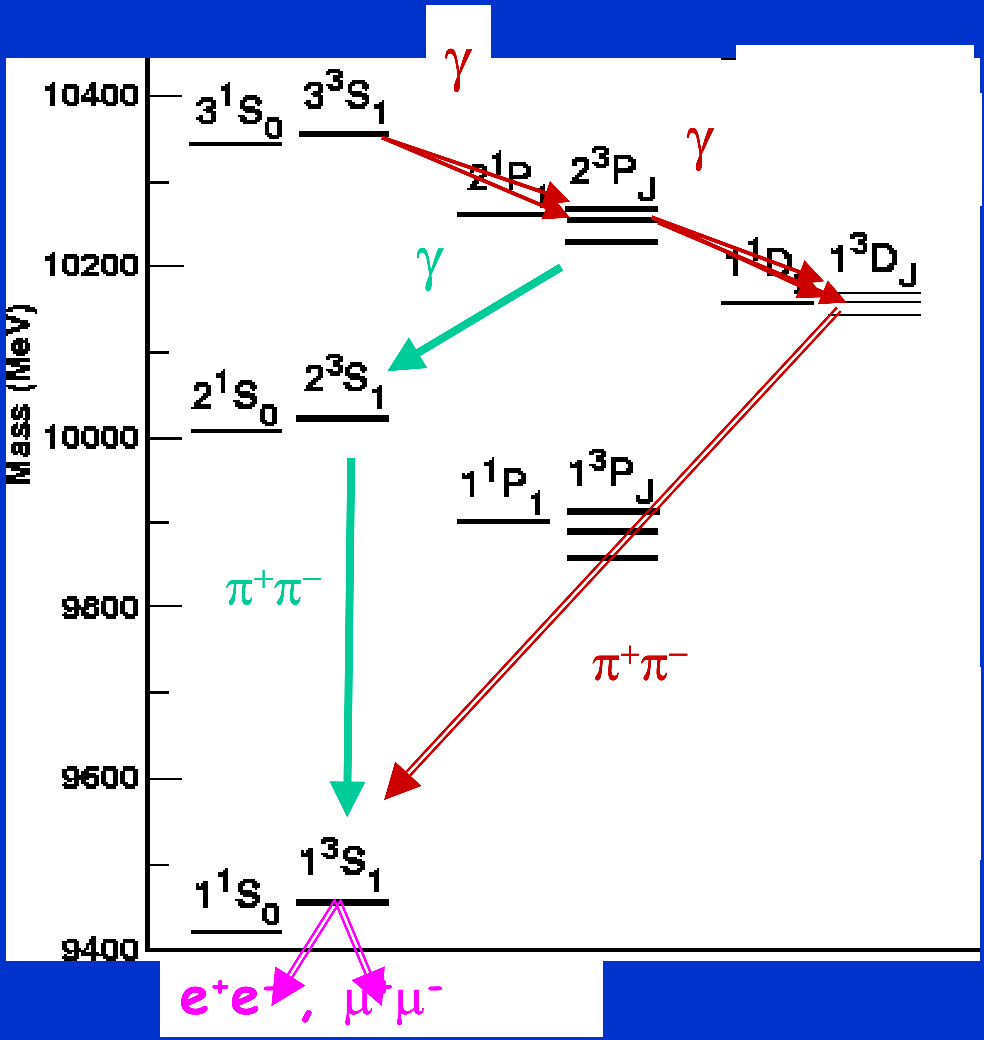
Beyond potential models

Advances in lattice QCD calculations:



G.P. Lepage,
High Precision Nonperturbative QCD
at the *SLAC Summer Institute*
(August 2002; Update May 2003)

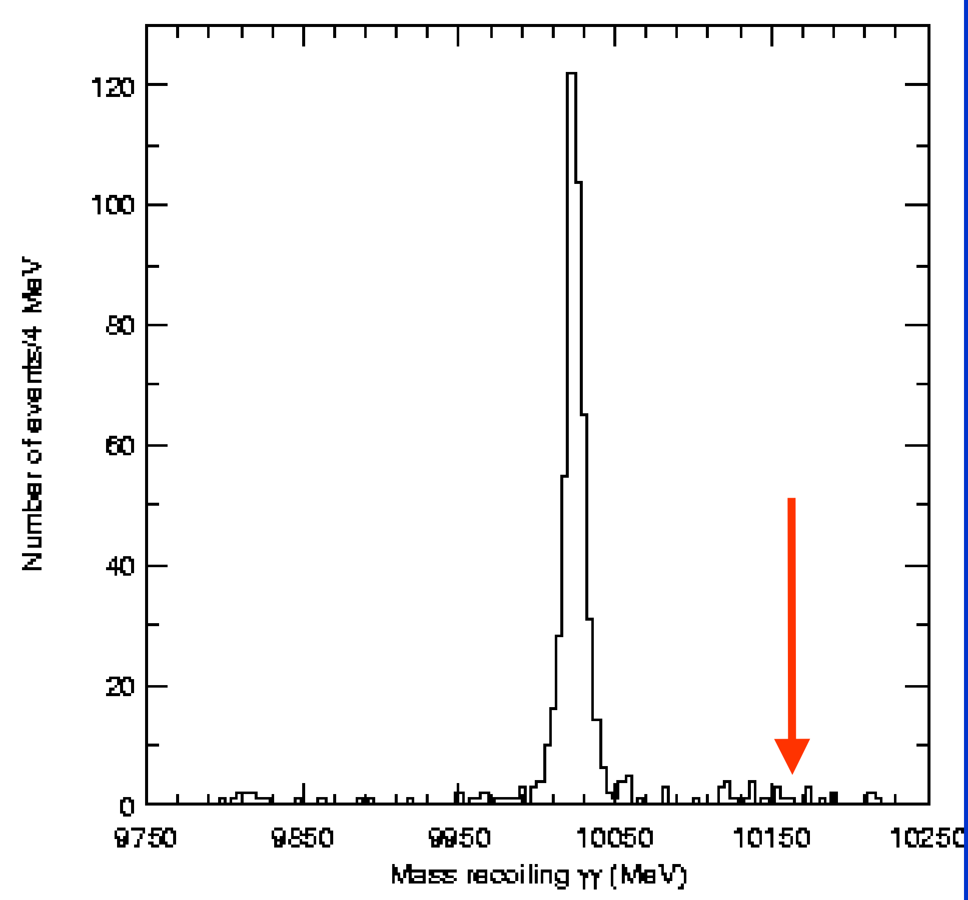
$\Upsilon(1^3D_2) \rightarrow \pi^+\pi^- \Upsilon(1S)$??



Could X(3872) be a 1D state? Let's see how a D state in the Υ system behaves.

$\Upsilon(3S) \rightarrow \gamma\gamma\ \pi^+\pi^-\ \Upsilon(1S)$,
$\Upsilon(1S) \rightarrow l^+l^-$
is our calibration signal

$\Upsilon(1^3D_2)\rightarrow\pi^+\pi^-\Upsilon(1S)$? No.



Limit on product BRs $B(\Upsilon(3S)\rightarrow\gamma\gamma\Upsilon(1D_2)) \times B(\Upsilon(1D_2)\rightarrow\pi^+\pi^-\Upsilon(1S))$, units of 10^{-4}.

	CLEO 90% CL	Kuang-Yan	Moxhay	Ko
$\Upsilon(1D_2)$	<1.1	9.2	0.049	0.39
$\Upsilon(1D_J)$	<2.7	17.7	0.094	0.75

With Rosner's production rates

Kuang-Yan predictions ruled out

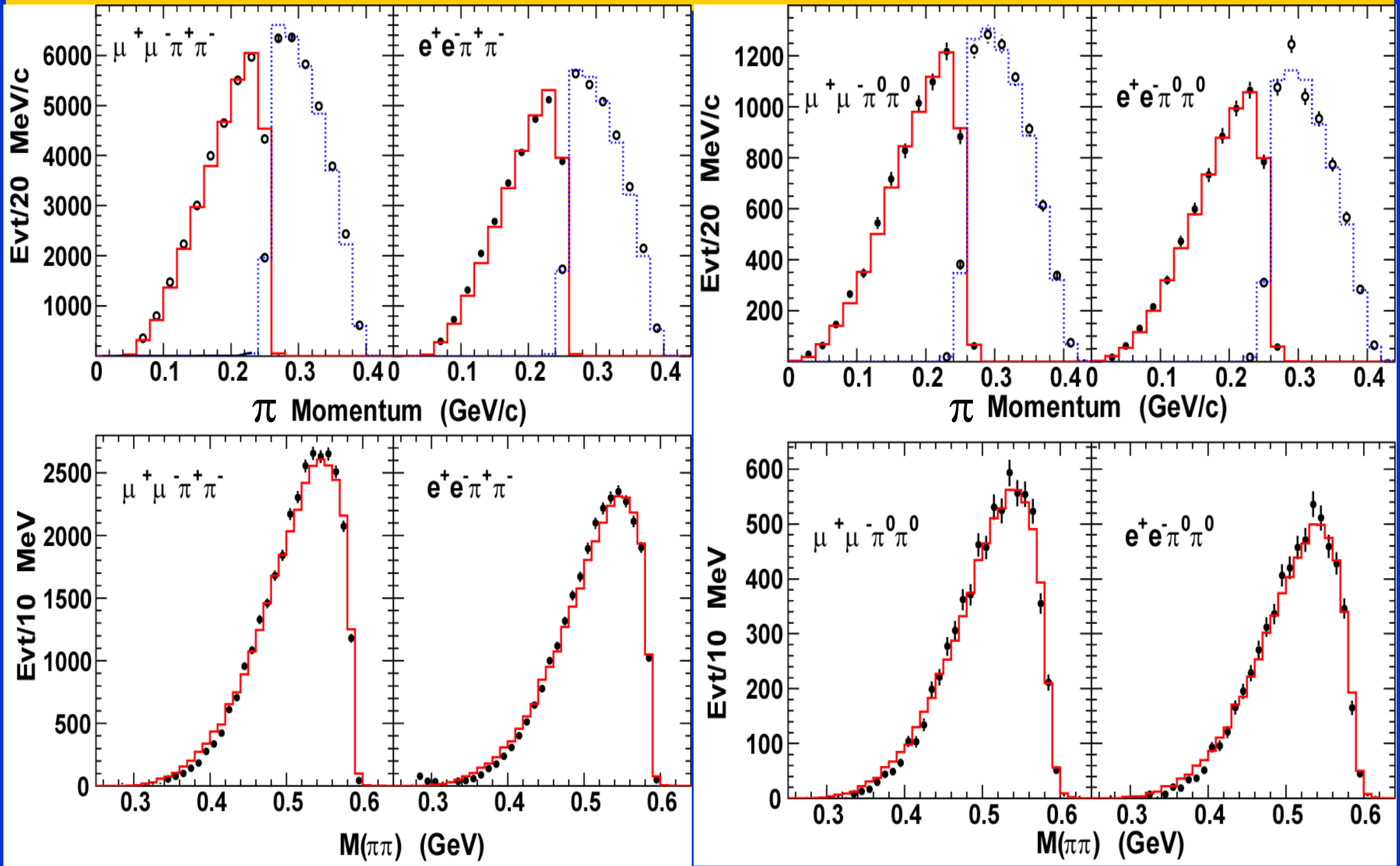
$\eta\ \Upsilon(1S)$ also ruled out at 2.3×10^{-4}

Conclusions

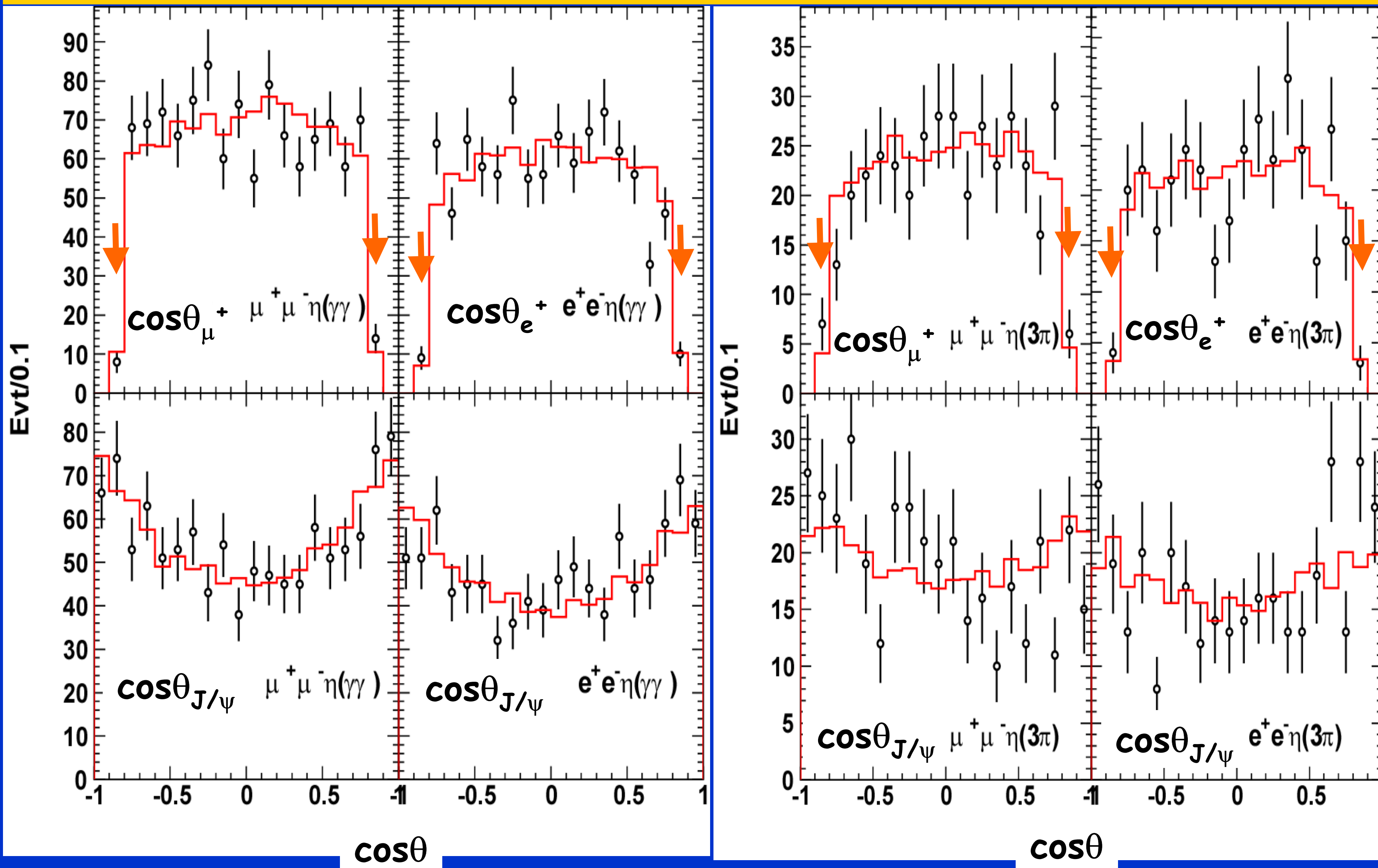
- CLEO has new, preliminary results on transitions to a J/ψ w/1 or more hadrons
  - Complete set, improved precision
- CLEO has final results (E_γ, BR) on radiative transitions from the $\psi(2S)$ & $\Upsilon(nS)$ system
  - η_b's not yet seen, some potential models ruled out
  - η_c confirmed
  - Old η_c' from CBAL ruled out
    - At current known η_c' mass, γ too soft, broad for CLEO
  - Relativistic effects seen for BOTH cc & bb
  - $\Upsilon(1^3D_2)$ seen
- $\Upsilon(1^3D_2)$ observed in photon transitions from $\Upsilon(3S)$, not in $\rightarrow\pi^+\pi^-\Upsilon(1S)$

Supplemental Slides

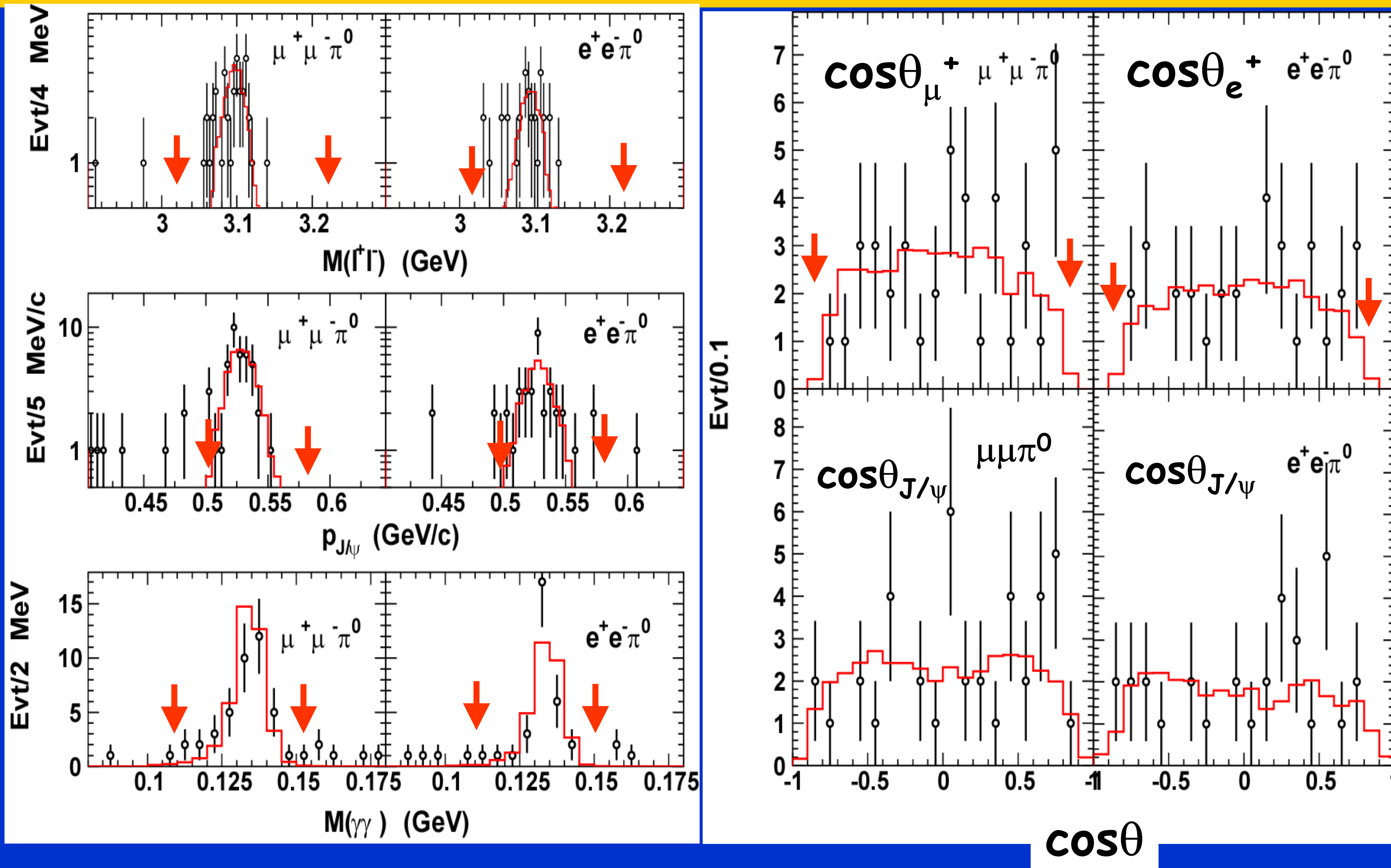
$\psi(2S) \to \pi\pi\ J/\psi,\ J/\psi \to l^+l^-$



ψ(2S)→η J/ψ

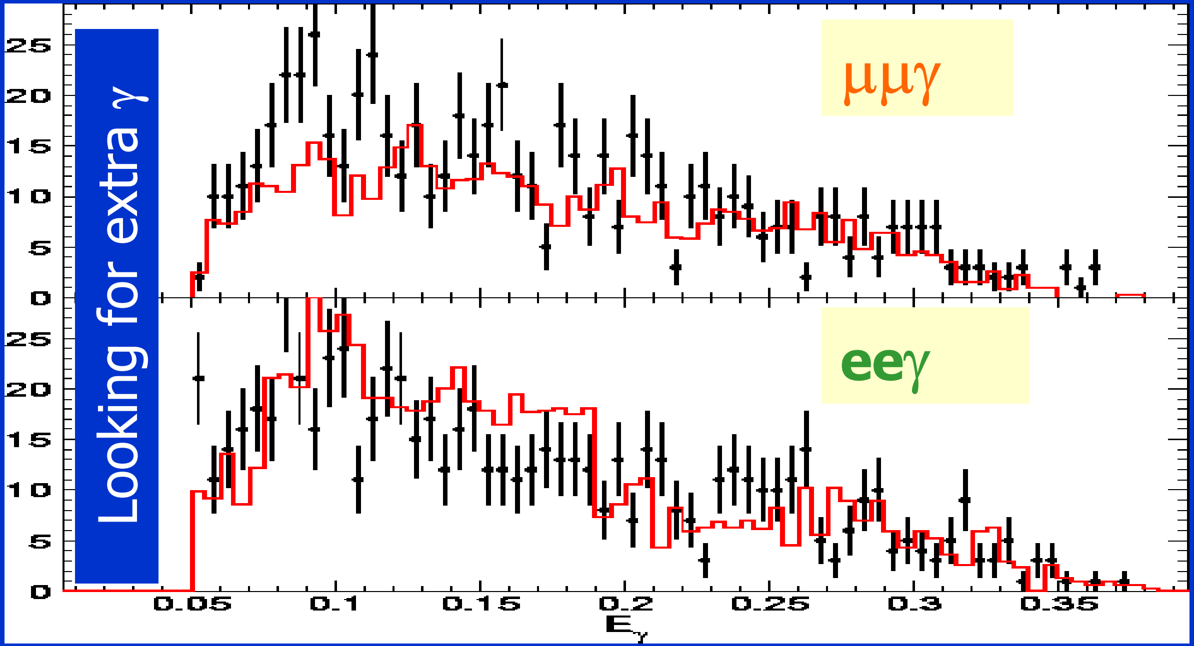

Evt/0.1
$\cos\theta_{\mu^+}$ $\mu^+\mu^-\eta(\gamma\gamma)$
$\cos\theta_{e^+}$ $e^+e^-\eta(\gamma\gamma)$
$\cos\theta_{J/\psi}$ $\mu^+\mu^-\eta(\gamma\gamma)$
$\cos\theta_{J/\psi}$ $e^+e^-\eta(\gamma\gamma)$
$\cos\theta_{\mu^+}$ $\mu^+\mu^-\eta(3\pi)$
$\cos\theta_{e^+}$ $e^+e^-\eta(3\pi)$
$\cos\theta_{J/\psi}$ $\mu^+\mu^-\eta(3\pi)$
$\cos\theta_{J/\psi}$ $e^+e^-\eta(3\pi)$
cosθ
cosθ

$\psi(2S)\to\pi^0 J/\psi,\ \pi^0\to\gamma\gamma$



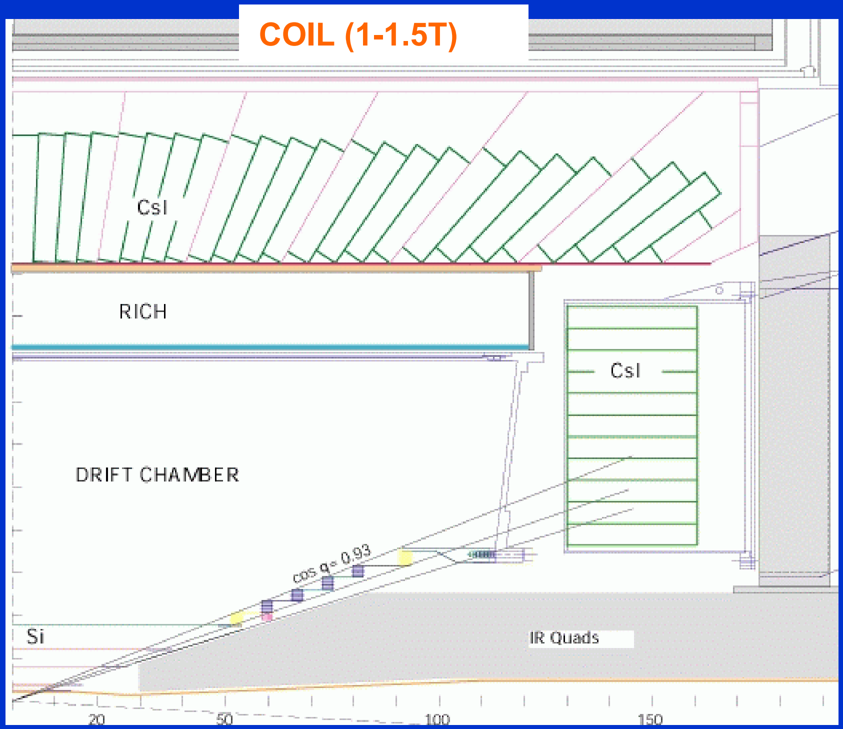
Decay Radiation

- Model with PHOTOS
- Also search for explicit radiation as below
- Reasonable but not perfect agreement
- Assign 0.5% error, separately for e, μ



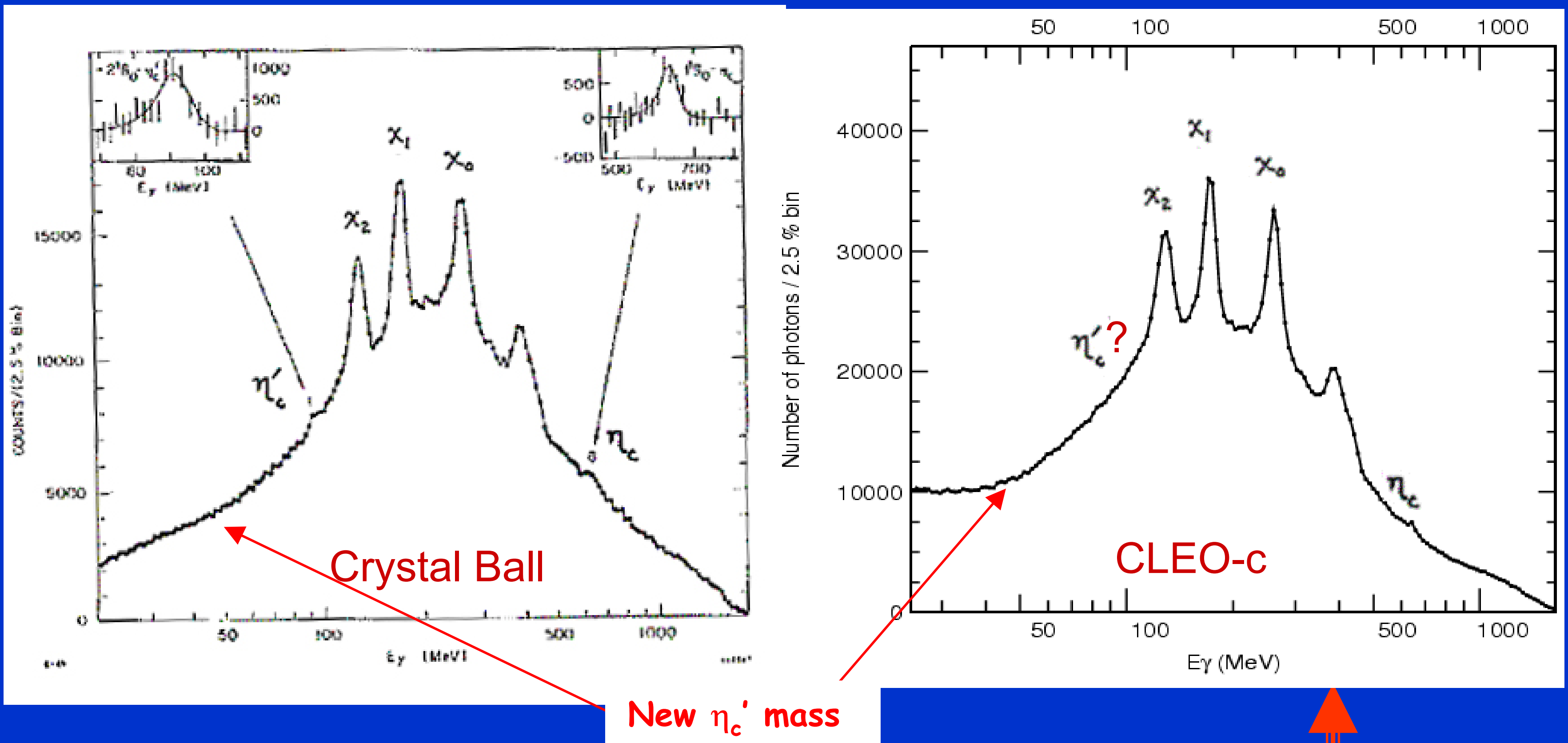
γ Transitions: Detector

- Excellent charged particle detection
- EM calorimeter- Essential for γ spectrocopy
  - ~8000 CsI(Tl) crystals + photo-diodes
  - First crystal calorimeter in magnetic field



Detector	Calorimeter crystals	$\sigma_{E\gamma}$ resolution at $E\gamma$=100 MeV
CLEO-III	CsI(Tl)	4.5 MeV
CUSB-II	BGO	4.2 MeV
Crystal Ball	NaI(Tl)	4.8 MeV
BES-II	Not a crystal calorimeter	70 MeV

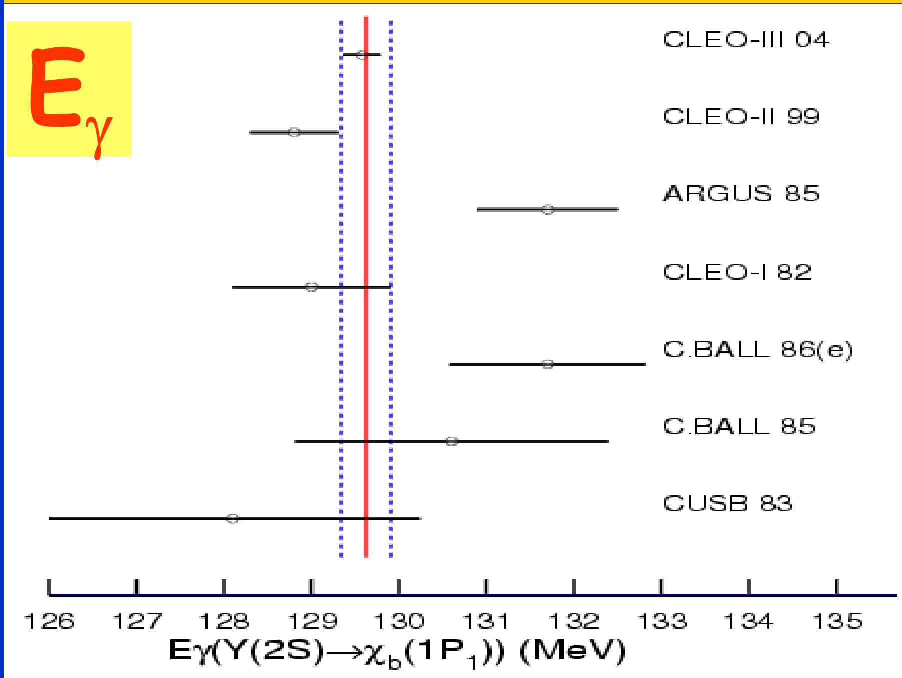
$\psi(2S)$ Photon Spectrum

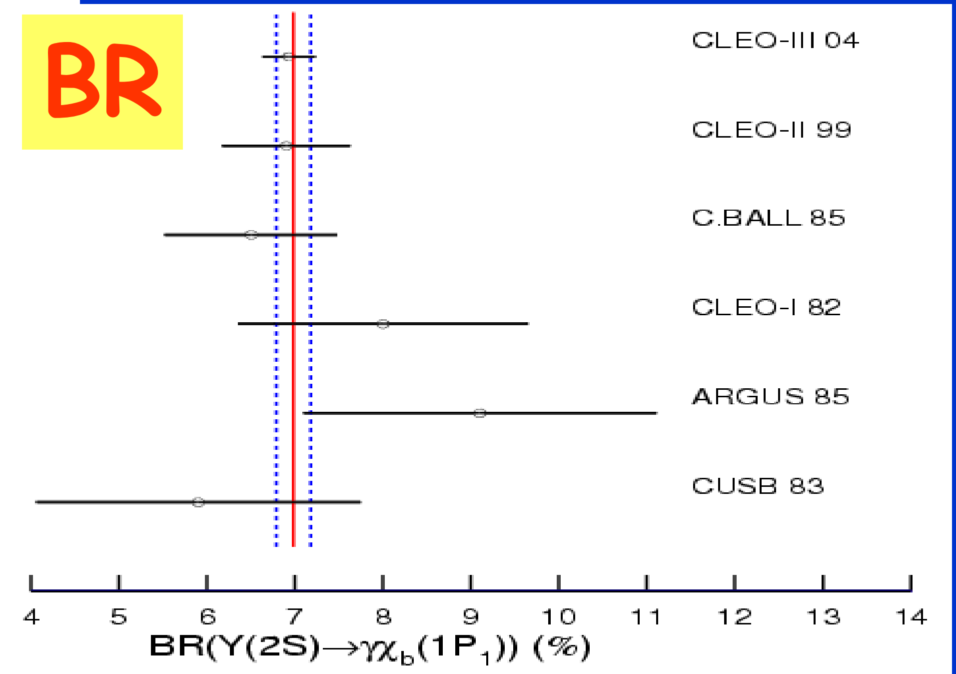


- **More data, comparable resolution**

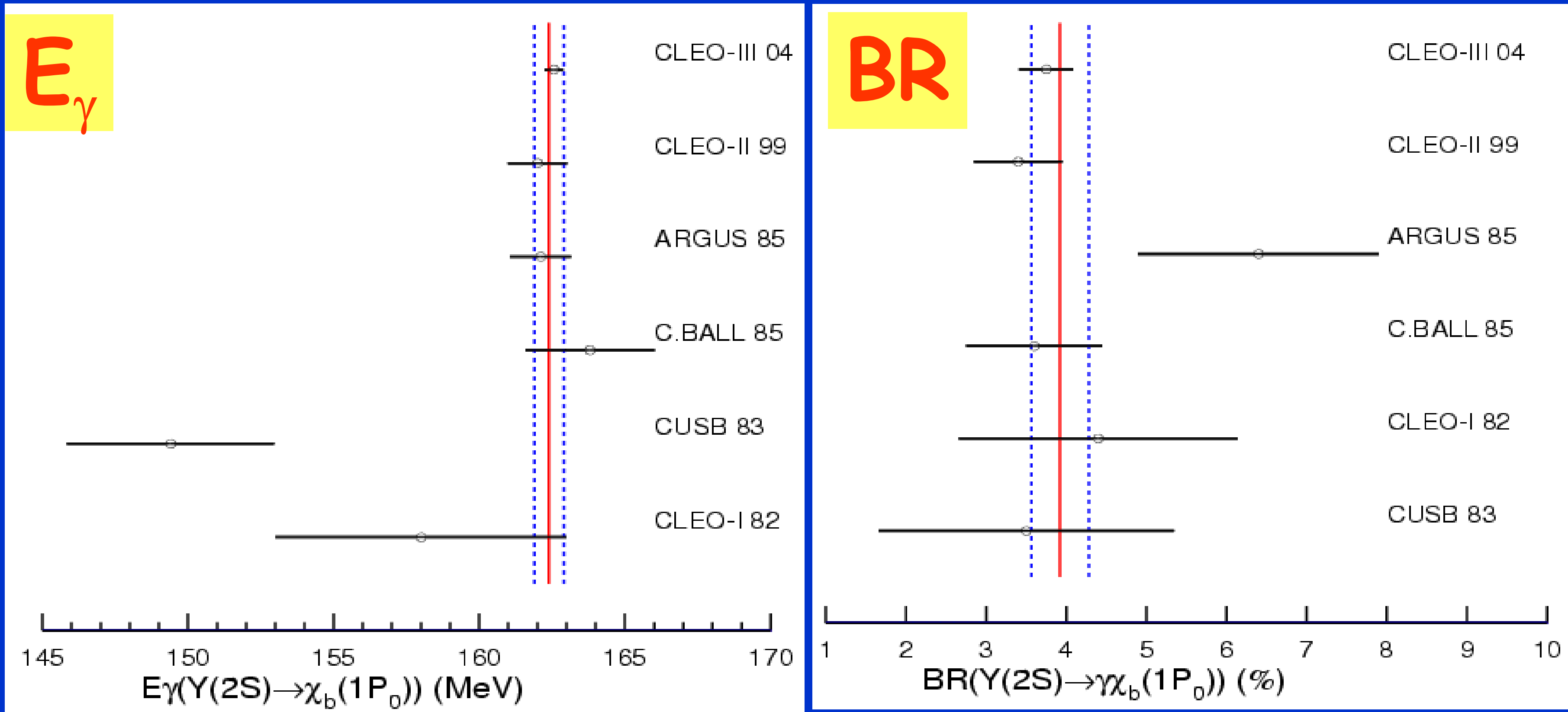
With maximal suppression of the π^0 background – for comparison with C.Ball only (harmful at low photon energies)

$\Upsilon' \rightarrow \chi_{b1}\, \gamma$

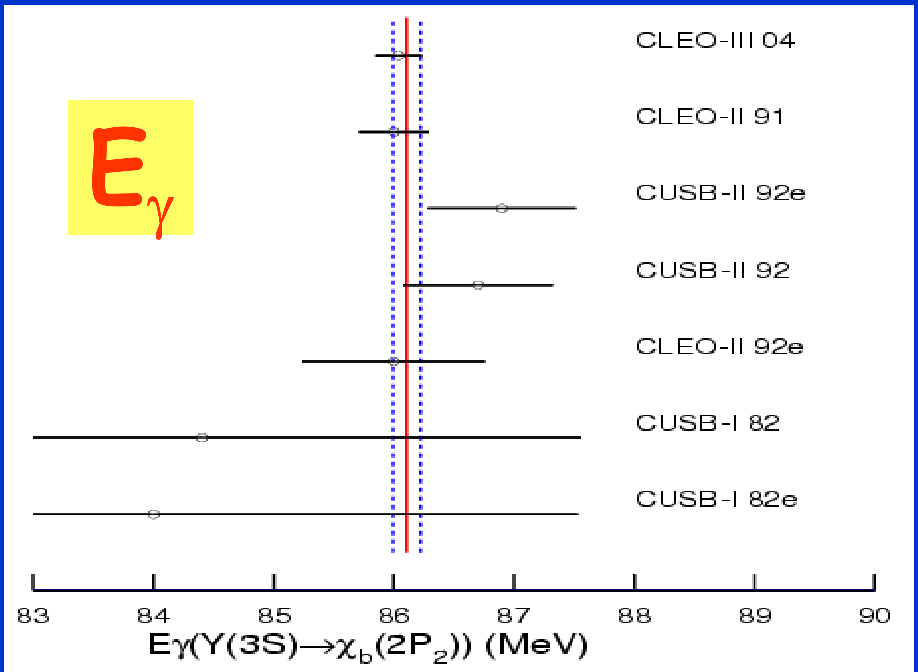


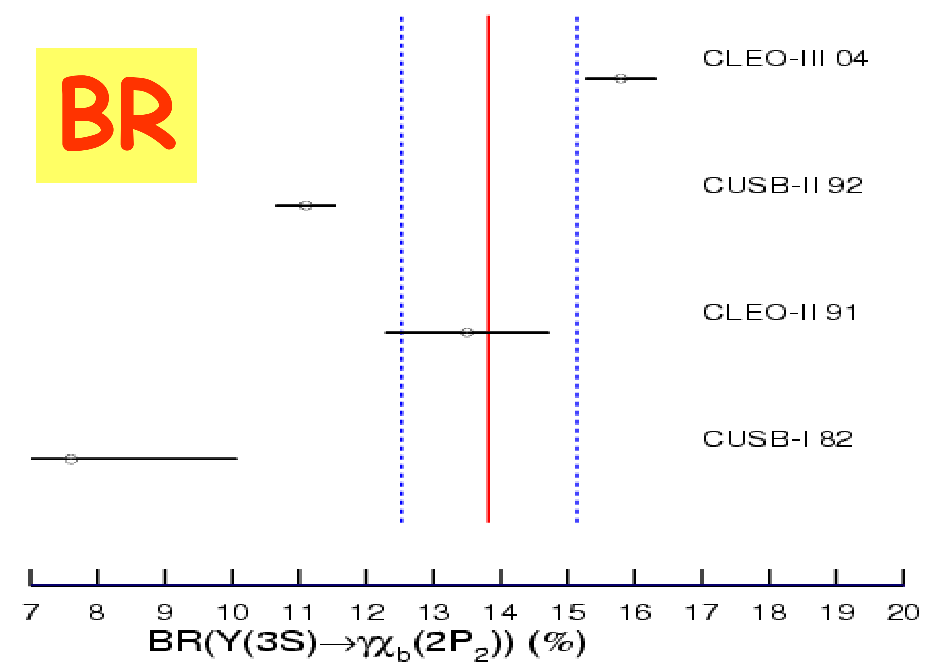


$\Upsilon' \rightarrow \chi_{b0}\, \gamma$

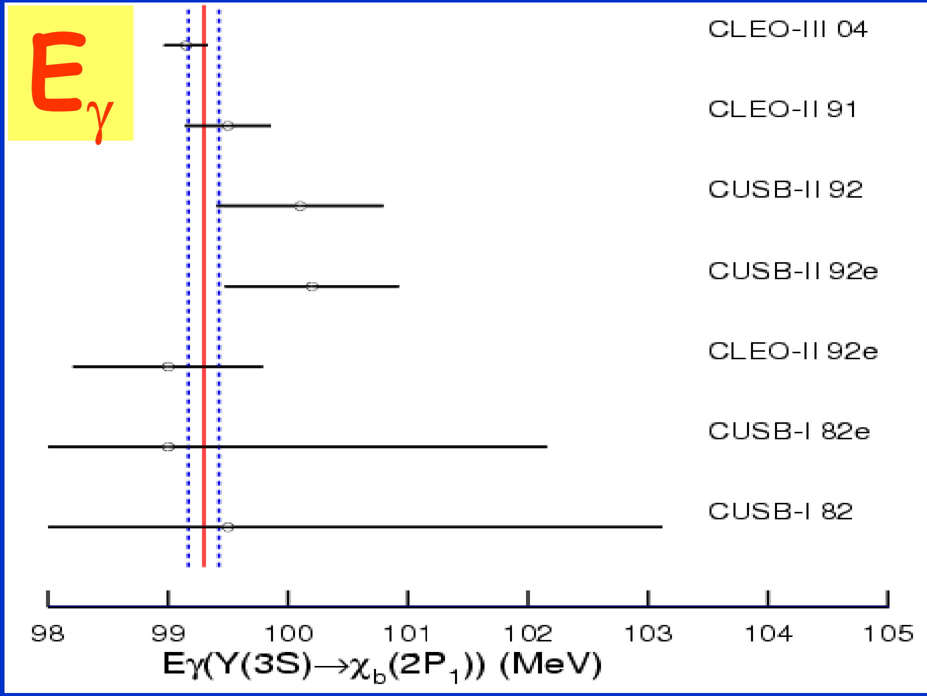


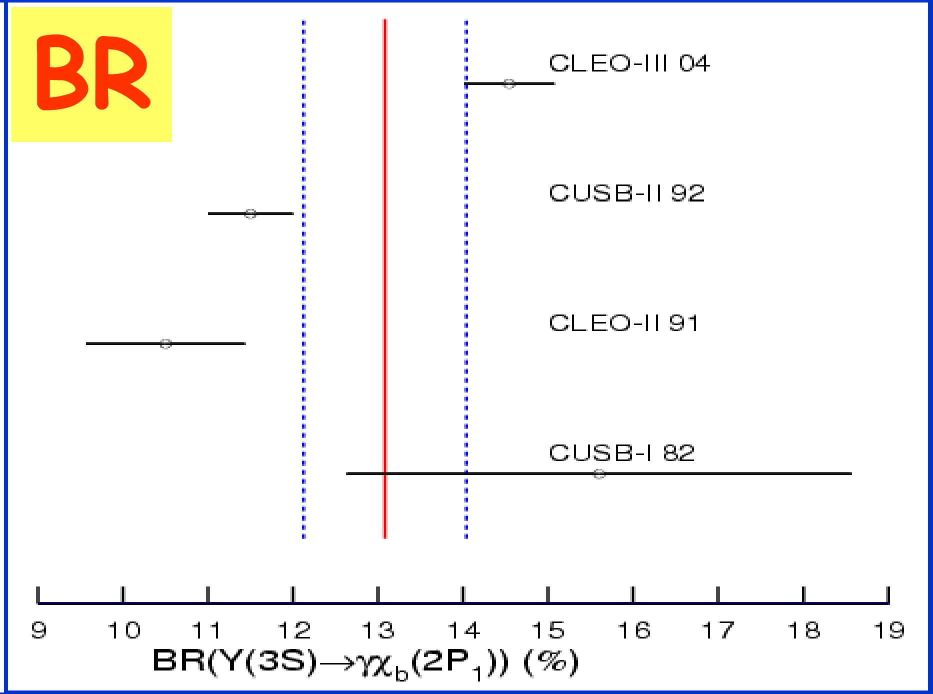
$\Upsilon'' \to \chi_{b2}' \gamma$



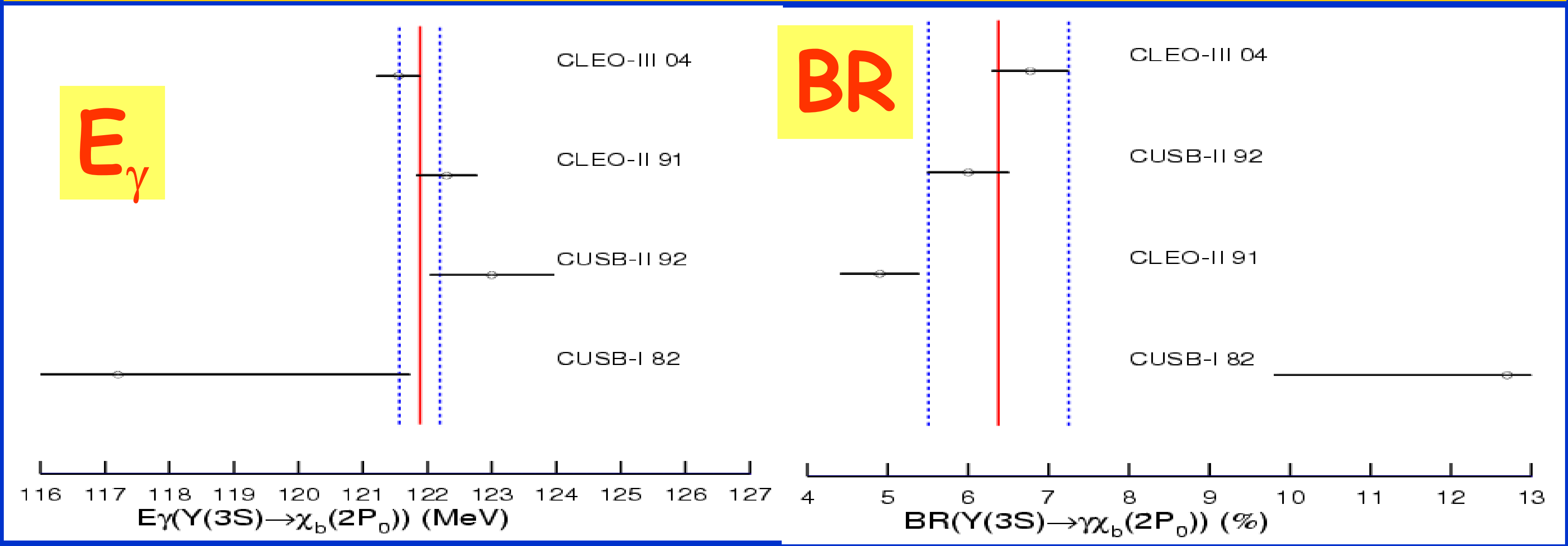


$\Upsilon'' \to \chi_{b1}' \gamma$





$\Upsilon'' \to \chi_{b0}' \gamma$



Tables of Results

	This msmt	CLEO2 (1998)	PDG
$BR(\Upsilon' \to \chi_{b0}\ \gamma)$	3.75±0.12±0.47%	3.4±0.5±0.6 %	3.8±0.6 %
$BR(\Upsilon' \to \chi_{b1}\ \gamma)$	6.93±0.12±0.41%	6.9±0.5±0.9 %	6.8±0.7 %
$BR(\Upsilon' \to \chi_{b2}\ \gamma)$	7.24±0.11±0.40%	7.4±0.5±0.8 %	7.0±0.6 %
$E_\gamma(\Upsilon' \to \chi_{b0}\ \gamma)$	162.56±0.19±0.42MeV	162.0±0.8±1.2 MeV	162.1±1.0 MeV
$E_\gamma(\Upsilon' \to \chi_{b1}\ \gamma)$	129.58±0.09±0.29MeV	128.8±0.4±0.6 MeV	129.8±0.5 MeV
$E_\gamma(\Upsilon' \to \chi_{b2}\ \gamma)$	110.58±0.08±0.30MeV	110.8±0.3±0.6 MeV	110.1±0.5 MeV

	This msmt	CLEO2 (1991)	PDG
$BR(\Upsilon'' \to \chi_{b0}'\ \gamma)$	6.77±0.20±0.65%	$4.9^{+0.3}_{-0.4}$±0.6 %	5.4±0.6 %
$BR(\Upsilon'' \to \chi_{b1}'\ \gamma)$	14.54±0.18±0.73%	$10.5^{+0.3}_{-0.2}$±1.3 %	11.3±0.6 %
$BR(\Upsilon'' \to \chi_{b2}'\ \gamma)$	15.79±0.17±0.73%	13.5±0.3±1.7 %	11.4±0.8 %
$BR(\Upsilon'' \to \chi_{b0}\ \gamma)$	0.30±0.04±0.10%	-	-
$E_\gamma(\Upsilon'' \to \chi_{b0}'\ \gamma)$	121.55±0.16±0.46MeV	122.3±0.3±0.6 MeV	122.8±0.5 MeV
$E_\gamma(\Upsilon'' \to \chi_{b1}'\ \gamma)$	99.15±0.07±0.25MeV	99.5±0.1±0.5 MeV	99.90±0.26 MeV
$E_\gamma(\Upsilon'' \to \chi_{b2}'\ \gamma)$	86.04±0.06±0.27MeV	86.4±0.1±0.4 MeV	86.64±0.23 MeV

χ_b Systematic Errors

Table 6: Systematic errors on the rate measurements.

initial state	$\Upsilon(2S)$			$\Upsilon(3S)$			
final state	$\chi_b(1P_0)$	$\chi_b(1P_1)$	$\chi_b(1P_2)$	$\chi_b(2P_0)$	$\chi_b(2P_1)$	$\chi_b(2P_2)$	$\chi_b(1P_0)$
number of $\Upsilon(nS)$	1.5%			1.7%			
mc stat	0.9%	1.0%	1.1%	0.9%	1.1%	1.1%	0.5%
order of bkg polynomial	0.1%	0.1%	0.1%	6.1%	1.9%	1.4%	16.3%
fitting range (signal)	2.6%	1.0%	0.6%	2.7%	0.9%	0.6%	8.6%
fitting range (background)	0.3%	$< 0.1\%$	$< 0.1\%$	0.1%	0.1%	0.1%	
background shape (continuum)	1.3%	0.4%	1.1%	3.0%	0.3%	0.9%	
MIP				3.0%	1.0%	0.6%	
σ_0							3.3%
E_{scale}							3.6%
π^0 suppression							17.4%
shower simulation	9.9%	5.1%	2.0%	1.5%	3.1%	2.5%	16.5%
E vs lnE	5.6%	0.7%	4.4%	3.5%	0.5%	1.8%	
signal shape	3.7%	2.0%	1.5%	2.9%	1.0%	1.2%	8.0%
$\Upsilon(2S)X$ and $\Upsilon(1D)$				1.4%	1.5%	1.2%	5.1%
Total	12.4%	5.9%	5.5%	9.6%	5.0%	4.6%	32.1%

χ_b Systematic Errors

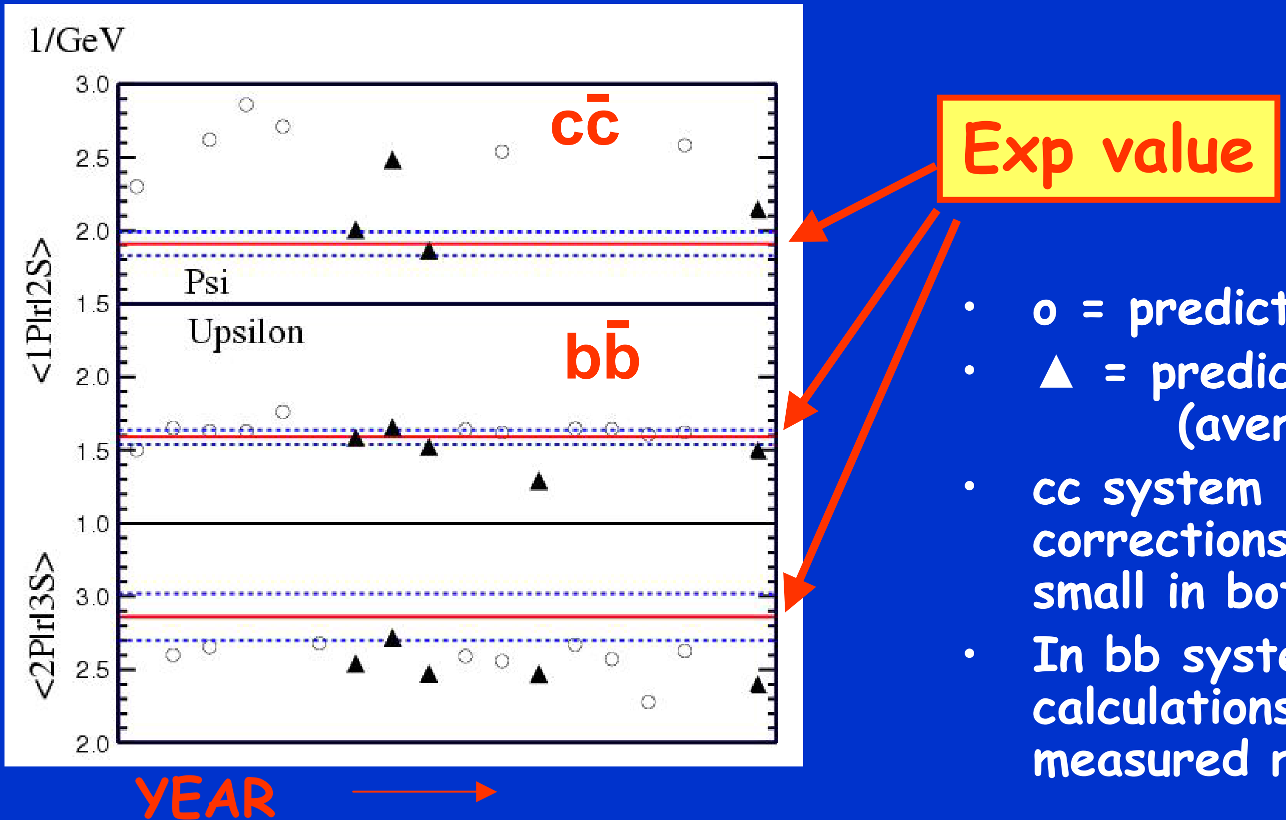
Table 8: Systematic Errors on the photon energy measurements.

initial state	$\Upsilon(2S)$				$\Upsilon(3S)$			
final state	$\chi_b(1P_0)$	$\chi_b(1P_1)$	$\chi_b(1P_2)$	$r(1P)$	$\chi_b(2P_0)$	$\chi_b(2P_1)$	$\chi_b(2P_2)$	$r(2P)$
shower simulation	0.07%	0.05%	0.14%	1.66%	0.29%	0.04%	0.02%	1.08%
E vs lnE	0.07%	0.07%	0.04%	0.06%	0.04%	0.06%	0.01%	0.43%
order of bkg polynomial	<0.01%	0.00%	<0.01%	0.01%	0.01%	0.05%	0.02%	0.63%
fitting range (signal)	0.01%	0.01%	0.01%	0.06%	0.02%	0.02%	0.01%	0.42%
fitting range (background)	0.02%	<0.01%	<0.01%	0.02%	0.01%	<0.01%	<0.01%	0.07%
background shape (continuum)	0.08%	<0.01%	0.11%	0.98%	0.10%	0.01%	0.04%	0.64%
signal shape	0.10%	0.02%	0.01%	0.38%	0.04%	<0.01%	0.03%	0.45%
MIP					0.03%	0.03%	<0.01%	0.89%
$\Upsilon(2S)X$ and $\Upsilon(1D)$					0.08%	0.09%	0.03%	1.25%
sub total	0.16%	0.09%	0.18%	0.38%	0.32%	0.13%	0.07%	2.22%
CC calibration	0.20%			0.00%	0.20%	0.21%	0.30%	0.54%
Total	0.26%	0.22%	0.27%	1.97%	0.38%	0.25%	0.31%	2.28%

Electric Dipole Transitions II

$$\Gamma_{E1}(n_i S \to n_f P) = \frac{4}{27}\alpha e_Q^2 (2J+1) E_\gamma^3 \langle n_f P | r | n_i S \rangle^2$$

- Extract the above E1 matrix element by $\Gamma_{E1}=BR(n_iS\to n_fP)\cdot\Gamma_{total}(\Upsilon(nS))$ for each J's and using the latest CLEO measurements of $\Gamma_{total}(\Upsilon(2S))$ and $\Gamma_{total}(\Upsilon(3S))$.
- Matrix elements averaged over spins are shown below along with various predictions.
- Also result from $\psi'\to\chi_{cJ}\gamma$ analysis is shown using $\Gamma_{total}(\psi(2S))$=277±22keV (PDG)



- o = predictions (non-relativistic)
- ▲ = predictions (relativistic) (averaged over spins)
- cc system is calling for relativistic corrections. The correction is small in bottomonium.
- In bb system, non-relativistic calculations seem to reproduce the measured rates.