Heavy Quarkonia Spectroscopy and Decay

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Physics in Collision 2003

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1a What are Heavy Onia
1b Theory
1c Experimental Data

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2a Transition options
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2d Searches

3 Decays
3a Scans
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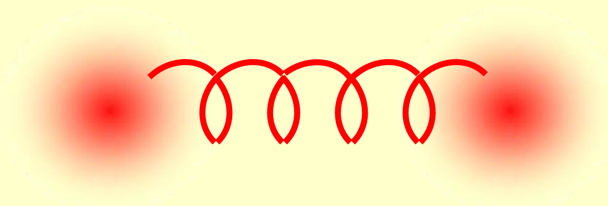
4 What next?

Onia



- Strongly bound $q\bar{q}$ states
- Non-relativistic QM applicable (Appelquist, Politzer)
  - QCD analog to positronium
  - Provide insight into QCD
- Low Q^2, non-perturbative

System	$(v/c)^2$	Ground Triplet State 1^3S_1			Forces: Binding		Forces: Decay		
		Name	Γ(MeV)	m(GeV)	EM	strong	EM	strong	weak
Positronium									
e^+e^-	~0.01		5×10^{-15}		✓		✓		
Quarkonium									
$u\bar{u}$,$d\bar{d}$	~1.0	ρ	150	0.77		✓		✓	
$s\bar{s}$	~0.8	ϕ	4.4	1.02		✓		✓	
$c\bar{c}$	~0.25	ψ	0.09	3.1		✓	✓	✓	
$b\bar{b}$	~0.08	Υ	0.05	9.46		✓	✓	✓	
$t\bar{t}$	<0.01		3000			✓			✓

Onia states

- **Masses**
- **Widths**
- **Production and decay dynamics**

Notation:

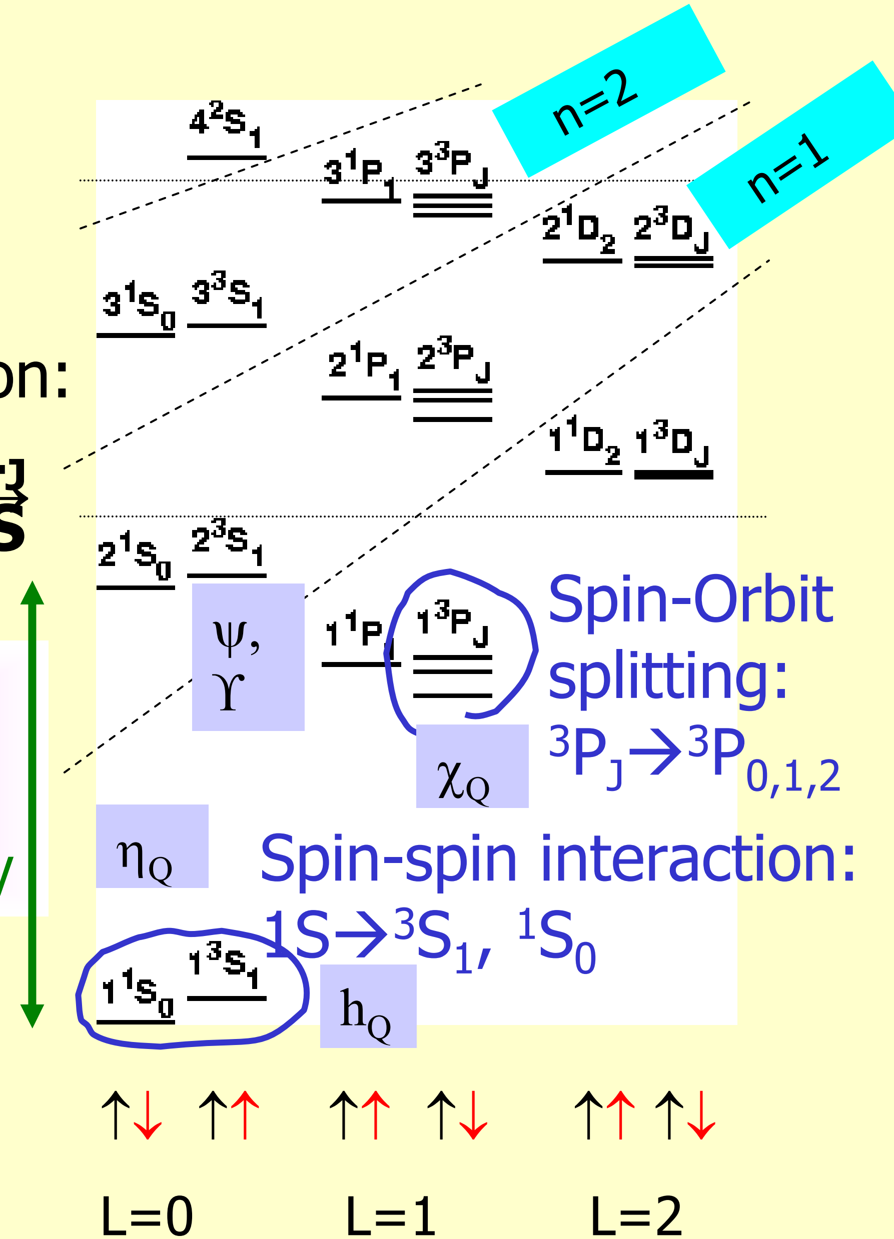
$n^{2S+1}L_J$

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

$b\bar{b}$: 560MeV

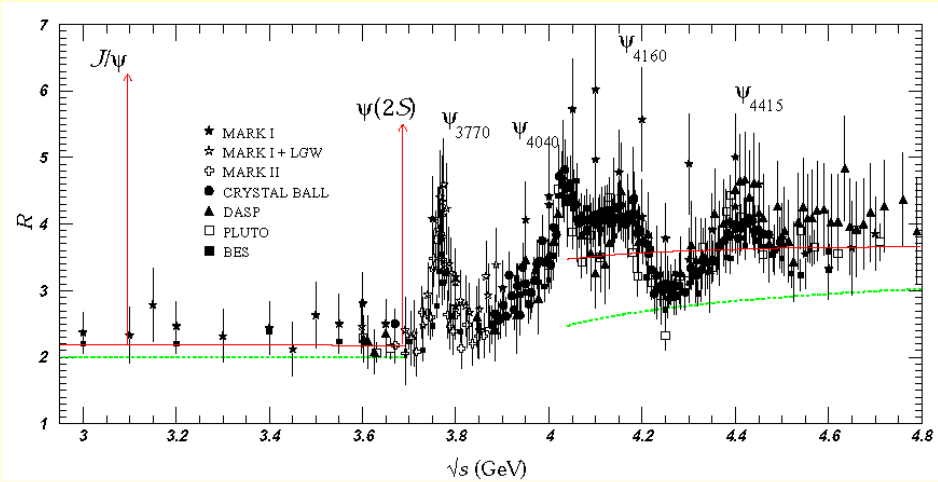
$c\bar{c}$: 589MeV

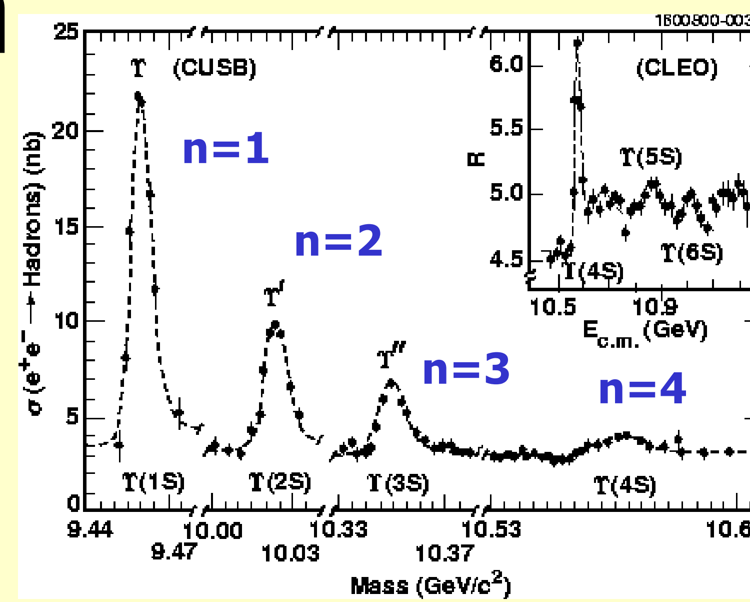
e^+e^-:5×10^{-6}MeV



Partly discovery, partly precision measurements

Producing quarkonia





- **e^+e^- colliders,** $e^+e^- \rightarrow \gamma^* \rightarrow q\bar{q}$:
  can only directly produce states coupling to γ^*, i.e. n^3S_1 (J/ψ, ϒ) with a tiny admixture of n^3D_1
- **two photon collisions:** J=0,2 ($\eta_{[b,c]}$, $\chi_{[b,c][0,2]}$)
- **hadron colliders** can do any energy, but not as clean
- **transition** from higher up, e.g. $\psi(2S) \rightarrow \gamma\chi_{c0}$

Potential Models

- Hydrogen: Coulomb, $V(r)=-\alpha_{em}/r$

Short distance,1g exchange long distance

- Heavy Onia: $V(r)= -\, 4/3\ \alpha_s/r + kr$

Color factor

Strong coupling between q and g

Energy density per distance between q and $\bar{q}$, ~1GeV/fm

- Potential well much deeper!
- Cf positronium: measurement of energy levels, spacing and decay rates can be used to fine-tune the parameters of QED – here: QCD.

The rôle of lattice QCD

- The only complete definition of QCD, both perturbative and non-perturbative
- Made possible through effective field theories for heavy quarks (non-relativistic QCD, HQET)

❖ Recent breakthrough in lattice gauge theory: unquenched calculations became affordable

- Charmonium and bottomonium spectra test LQCD's ability to **calculate** strong phenomena, relevant to many aspects of heavy flavour physics (e.g. $B\bar{B}$ mixing)
- Need experimental results at the % level

Recent Progress in LQCD

Parameters:

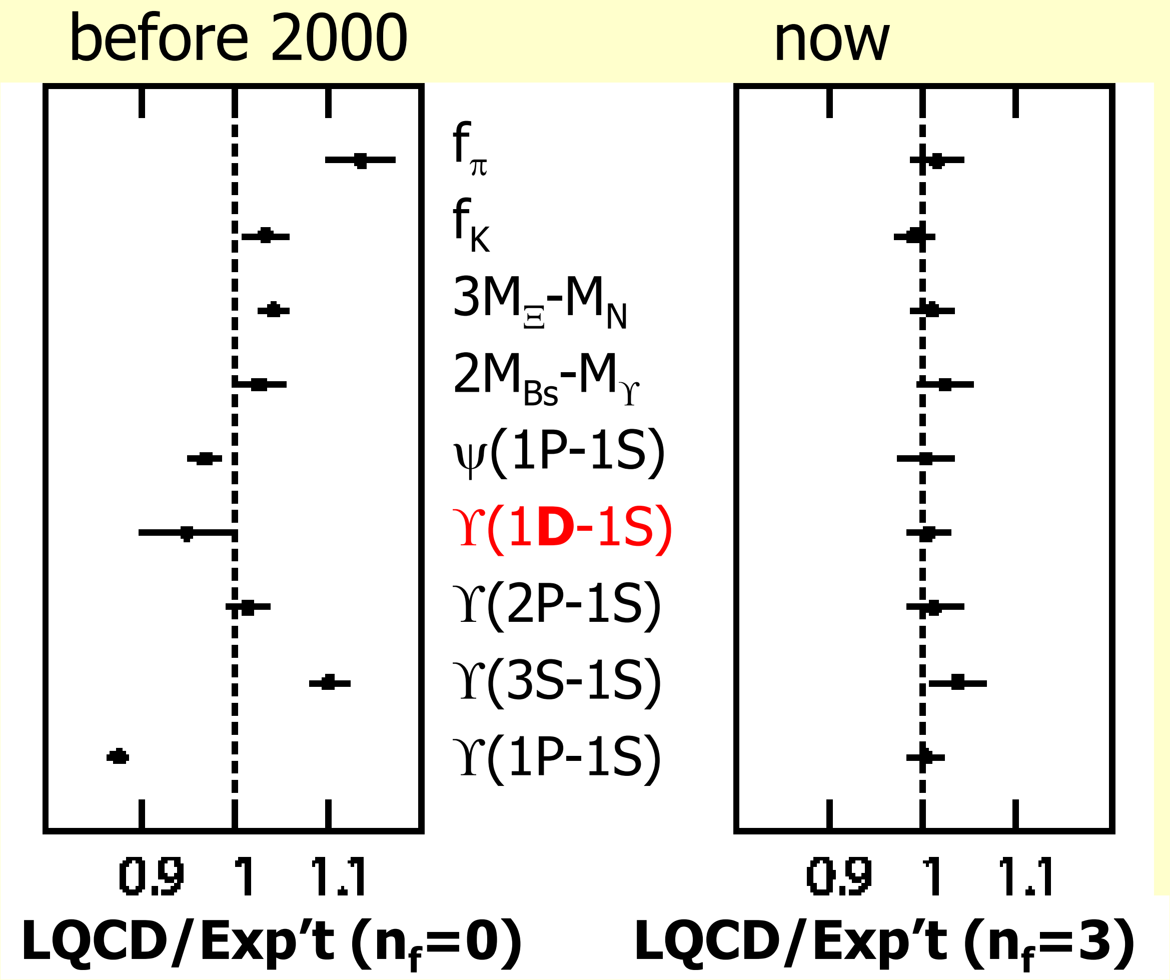
Tune

α_S, $m_u=m_d$, m_S, m_C, and m_b

on

m_π, m_K, m_{Ds}, m_Υ, and ΔE_Υ (2S-1S)

New level of precision achieved



HPQCD&MILC, hep-lat/0304004

Why Investigate Heavy Quarkonia

Simplest strongly interacting systems

Fairly non-relativistic

Excellent place to study an important region of the Standard Model

Gain insight to underlying interaction, QCD

More convenient to handle than glueballs

Data Modern Datasets

- Smaller data samples from MarkI,II,III, DM2, CLEOIII (ψ')
- Cross section falls as n increases
- Both CLEO and BES have additional data samples for special purposes

E_{cm}(GeV)	Physics	Datataking completed	#events
3.10	J/ψ	1990's	8M BES
		2001	58M BESII
3.69	$\psi(2S)$	1990's	4M BES
		2002	14M BESII
9.46	$\Upsilon(1S)$	1990's	2M CleoII
		2003	20M CleoIII
10.02	$\Upsilon(2S)$	1990's	0.5M CleoII
		2003	10M CleoIII
10.36	$\Upsilon(3S)$	1990's	0.5M CleoII
		2003	5M CleoIII
(10.58)	($\Upsilon(4S)$)	(2002)	

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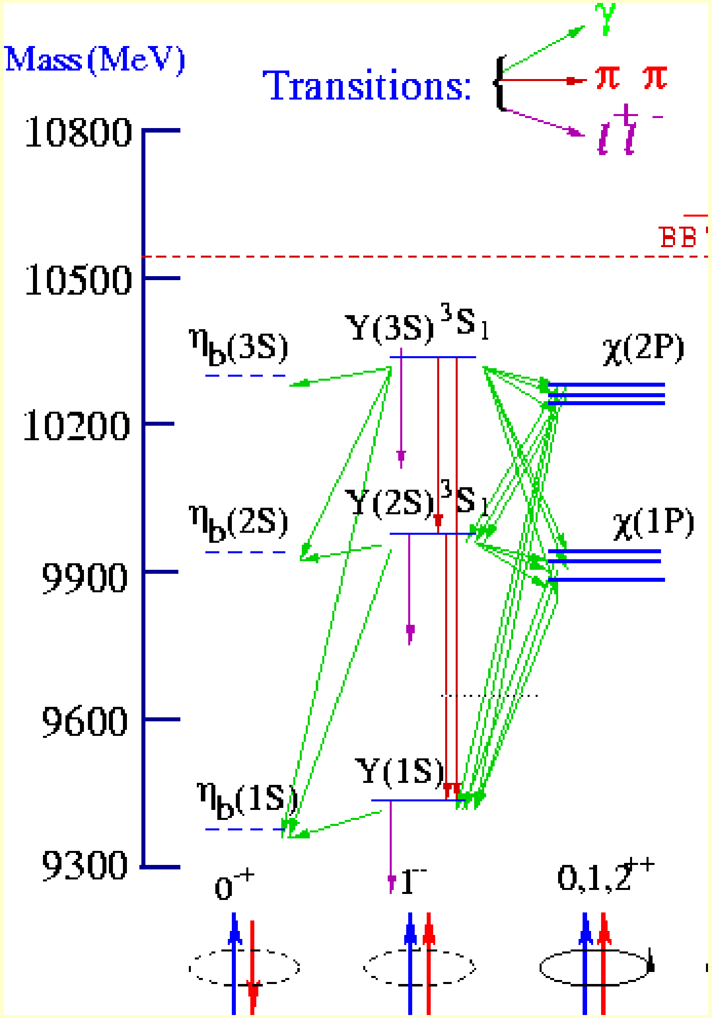
Transition options

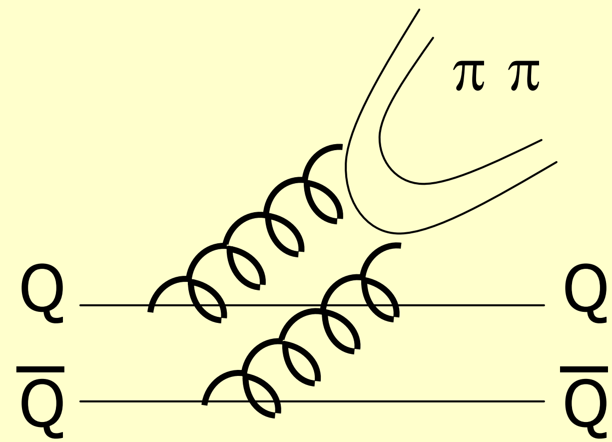


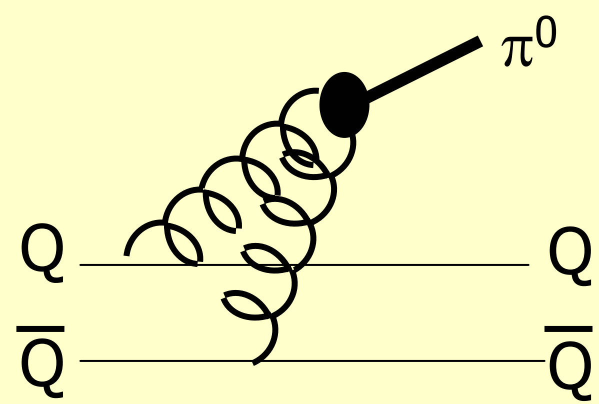
- Hadronic:
  - π^0, η, ω, $\pi^+\pi^-$ - no Ks; splitting too small
- Electromagnetic (photon; $\Delta S=0$)
  - E1: $\Delta L=1$
  - M1: $\Delta L=0$

Hadronic Transitions

No charge involved:

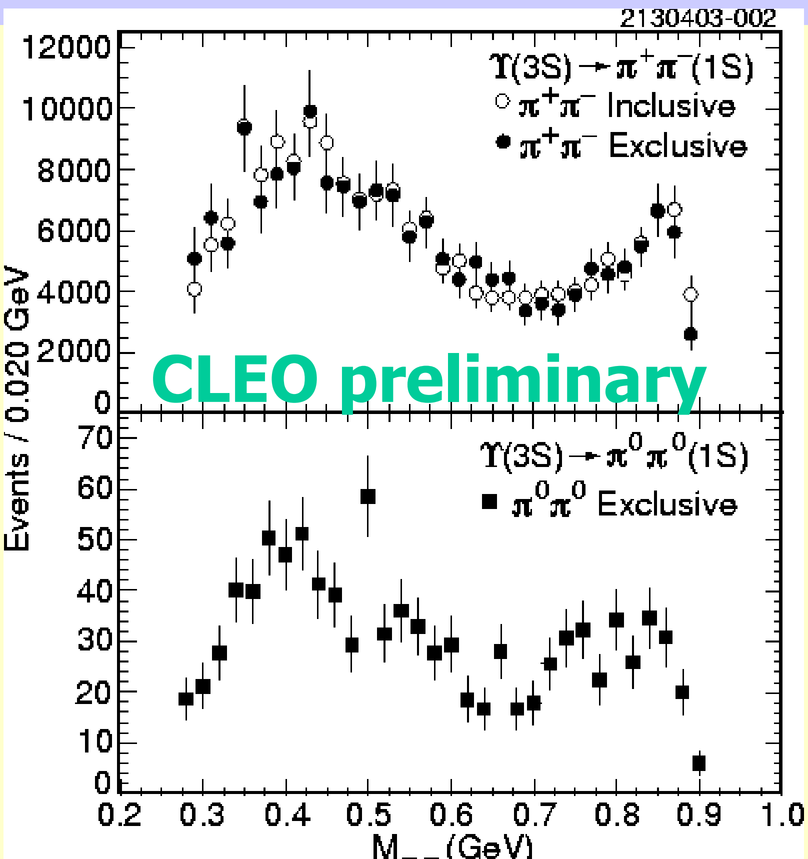
- two charged pions
  or
- neutral particles
  - $\pi^0 \pi^0$
  - Single π^0 transitions isospin **suppressed**
  - η, ω are rare



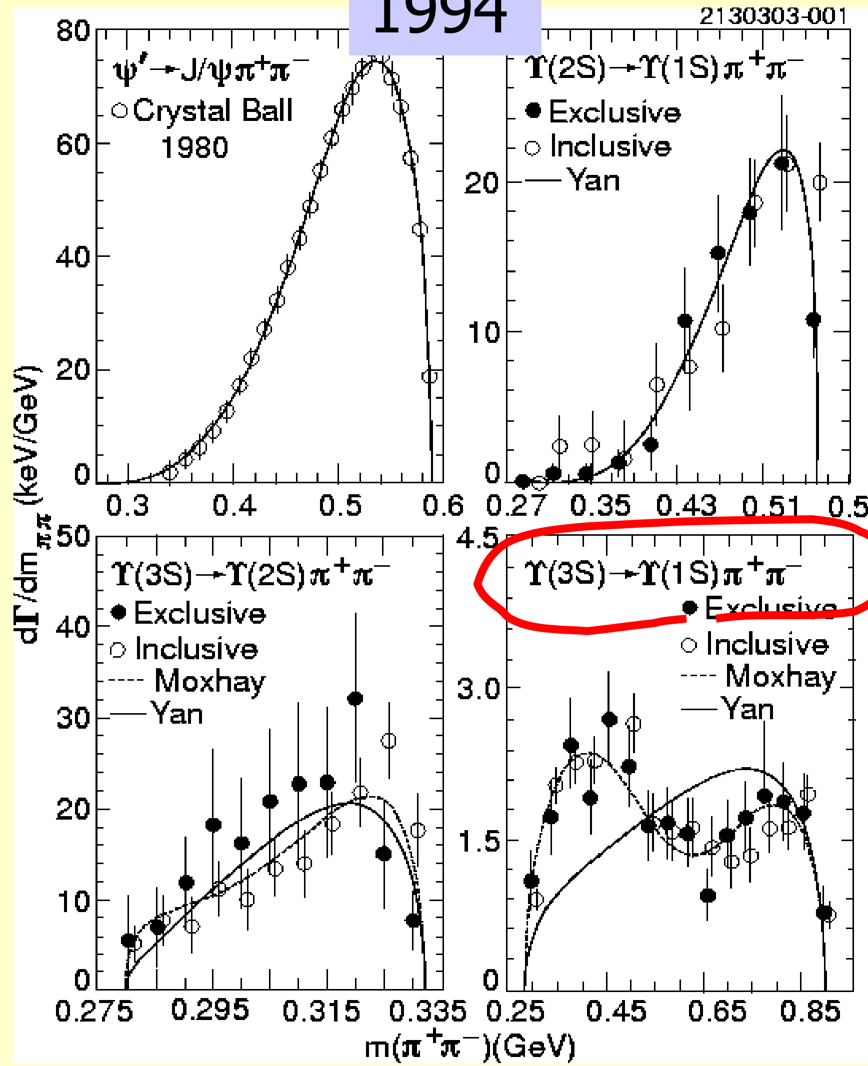


ϒ Dipion transitions

New ϒ(3S)→ϒ(1S)ππ data:



1994



Moxhay, PRD39(1980)3497: generic, constant, complex amplitude coupling to $B\bar{B}^*$ states and interfering with the multipole expansion amplitude

Υ(3S) rare hadronic transitions

$\Upsilon(3S) \to \pi\pi\pi\ \Upsilon(1S) + X$

- $\pi^+\pi^-\pi^0$ distribution peaks at ω, X is photon
- Data consistent with $\Upsilon(3S) \to \gamma\chi_{b1}'$, $\chi_{b1}' \to \omega\Upsilon(1S)$. Small χ_{b2}' admix not excluded

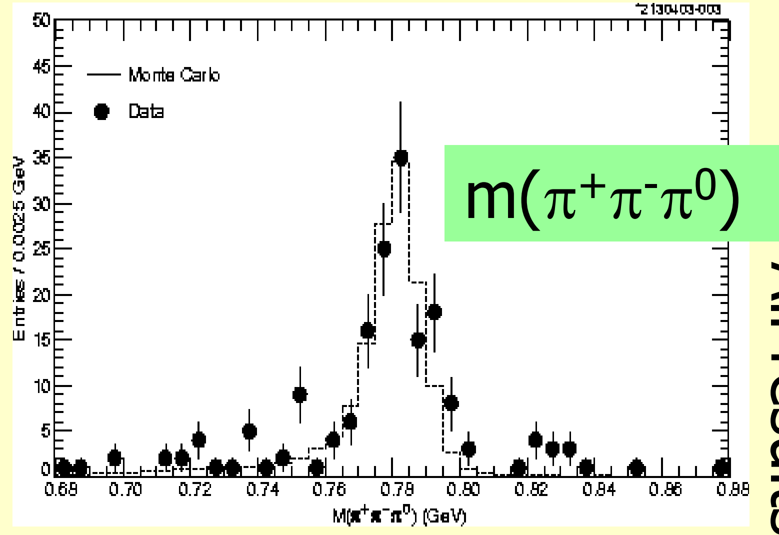
- $B(\chi_{b1}' \to \omega\Upsilon(1S)) = (2.3 \pm 0.4(\text{stat}))\%$

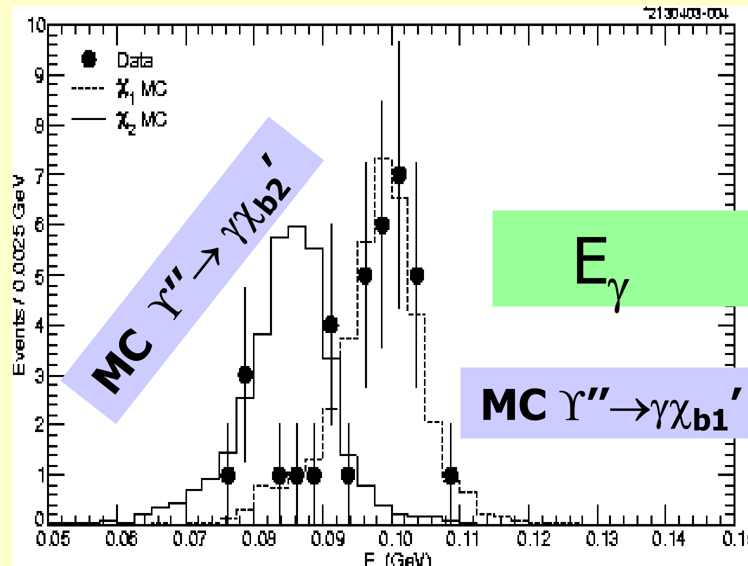
  Substantial!

$\Upsilon(3S) \to \gamma\gamma\ell^+\ell^-$: $\gamma\gamma$ from π^0/η?

- $B(\Upsilon'' \to \pi^0\Upsilon) < 0.17 \times 10^{-3}$
- $B(\Upsilon'' \to \eta\Upsilon) < 0.9 \times 10^{-3}$
- $B(\Upsilon'' \to \pi^0\Upsilon') < 1.2 \times 10^{-3}$

  $\psi' \to \eta J/\psi \sim 3\%$,
  $\psi' \to \pi^0 J/\psi \sim 0.1\%$



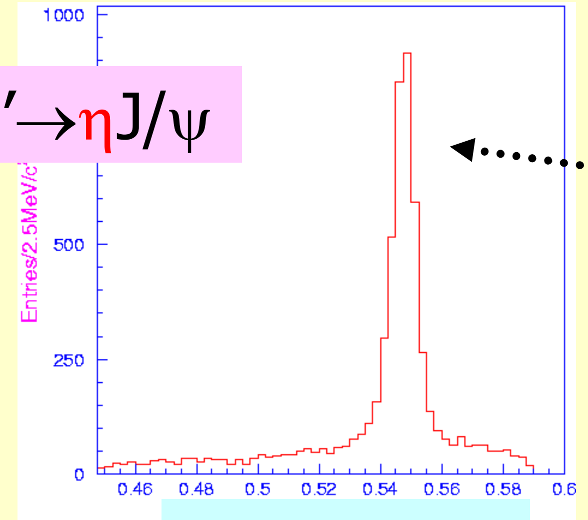


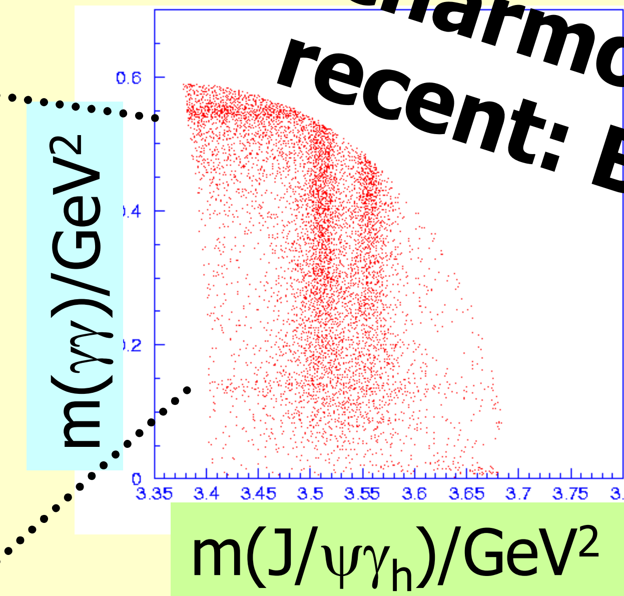
All results CLEO preliminary

First hadronic non-pionic transition in bottomonium!

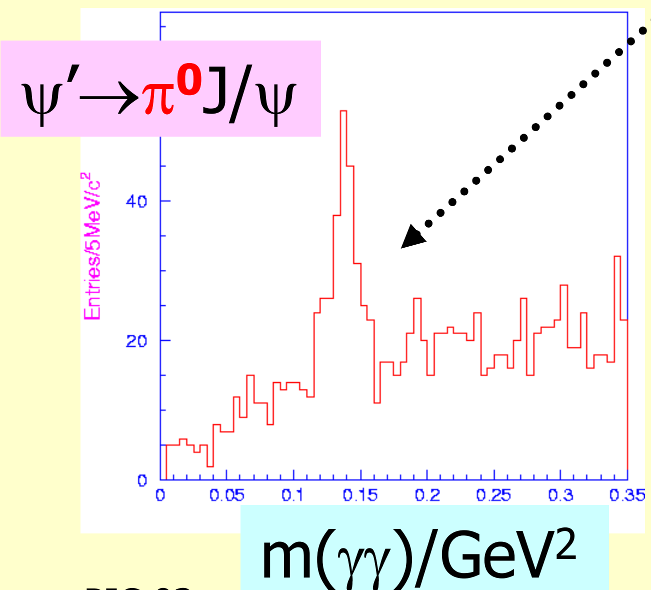
First non-radiative decay of χ_b'

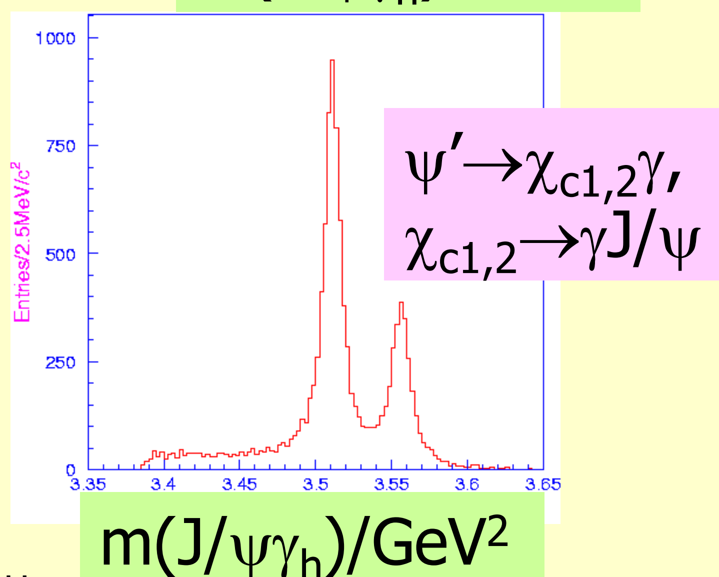
η, π^0 transitions in charmonium (most recent: BES, 14M ψ')





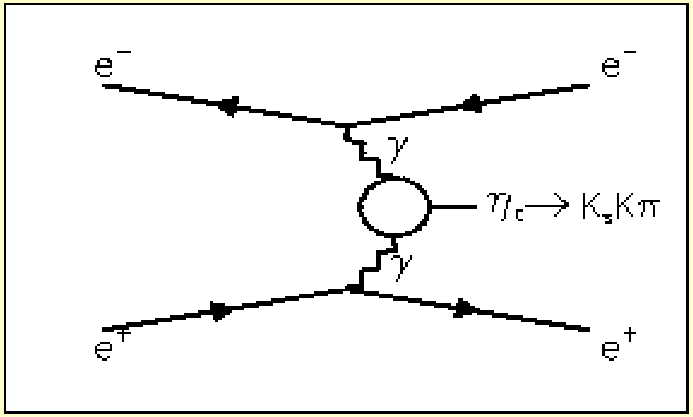
$\psi(2S)\to\gamma\gamma J/\psi$,
$J/\psi\to \ell^+\ell^-$

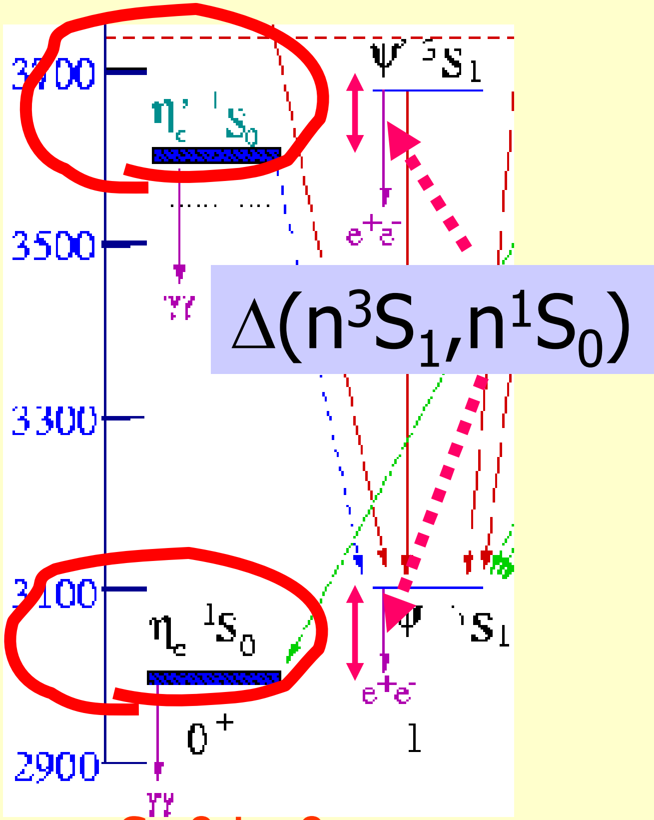




BES prelim, CERN Courier 12/2002

n^1S_0 (η_c, η_c'): what 'n' why

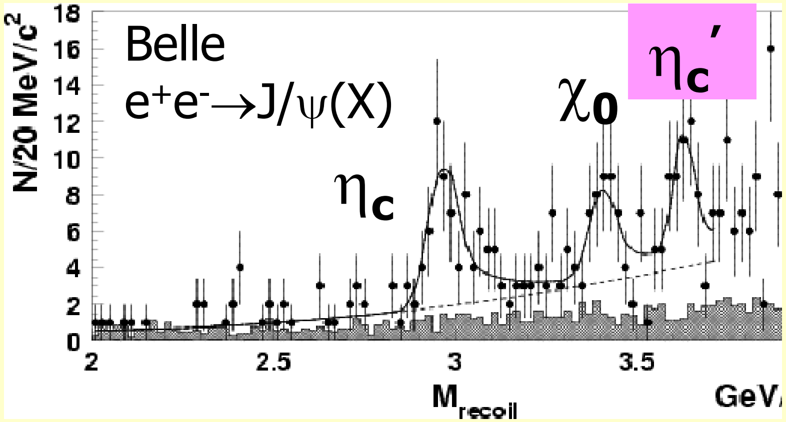


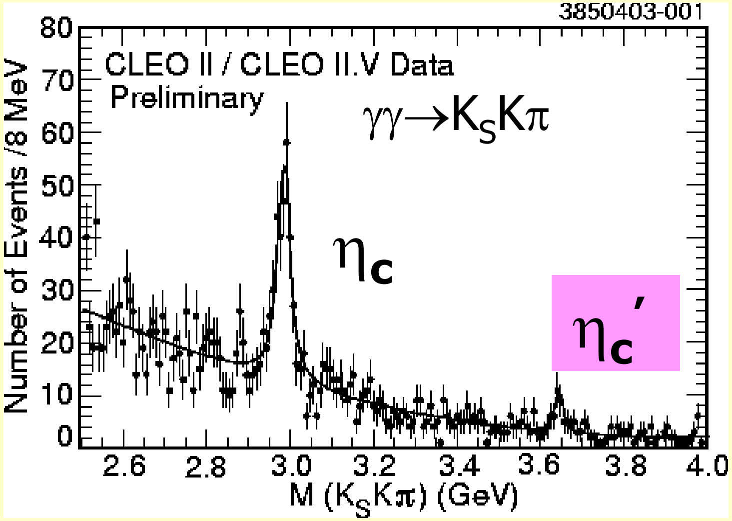


S=0,L=0

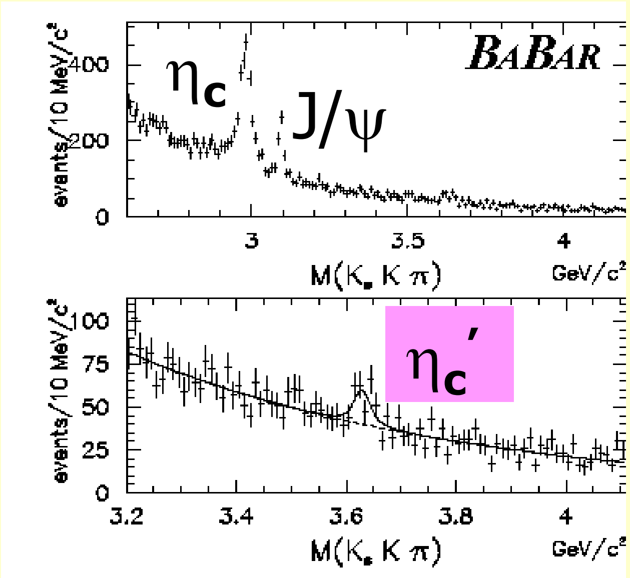
- Produced in γγ collisions
- η_c well established, η_c' confirmed
- ❖ Potential Models predict $m(\eta_c')$=3594..3629MeV

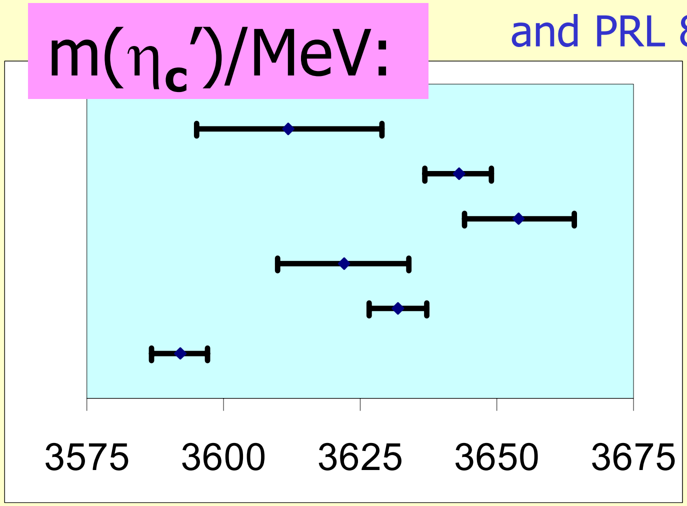
Recent Experimental Information on η_c'



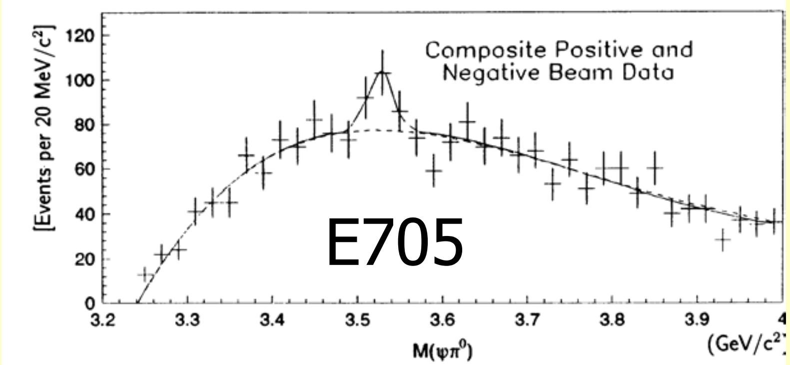


CBAL PRL48(1982)70,
BaBar hep-ex/0305083,
Belle PRL89(2002)102001
and PRL 89(2002)142001



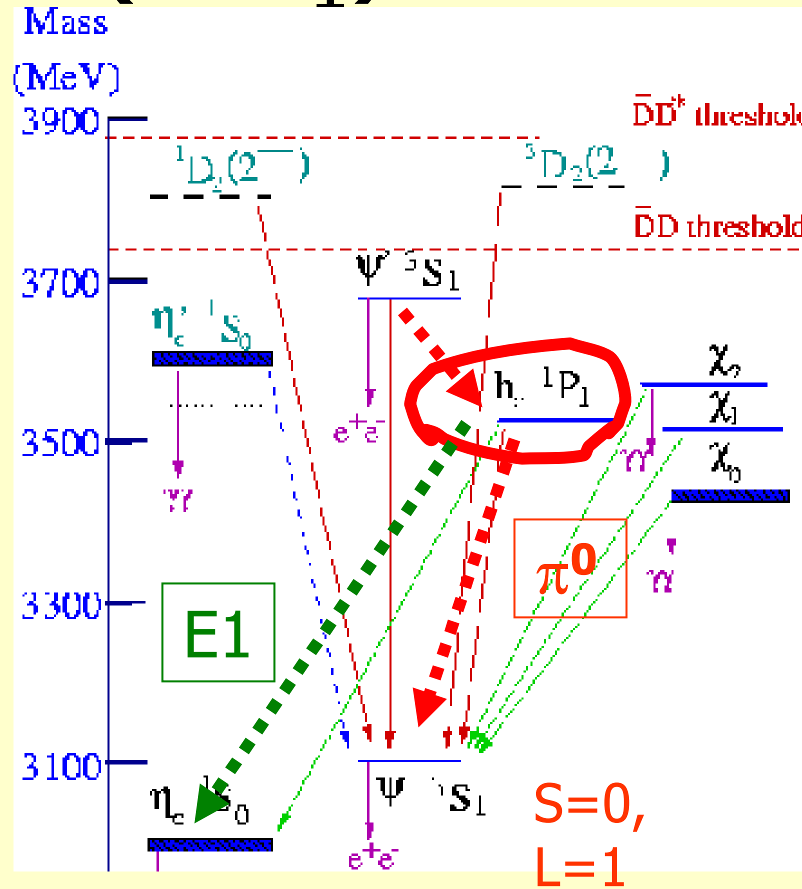


Potential models
CLEO $\gamma\gamma \to K_S K\pi$
Belle $B \to K(K_S K\pi)$
Belle e+e-$\to J/\psi(X)$
BaBar $\gamma\gamma \to K_S K\pi$
Crystal Ball 1982

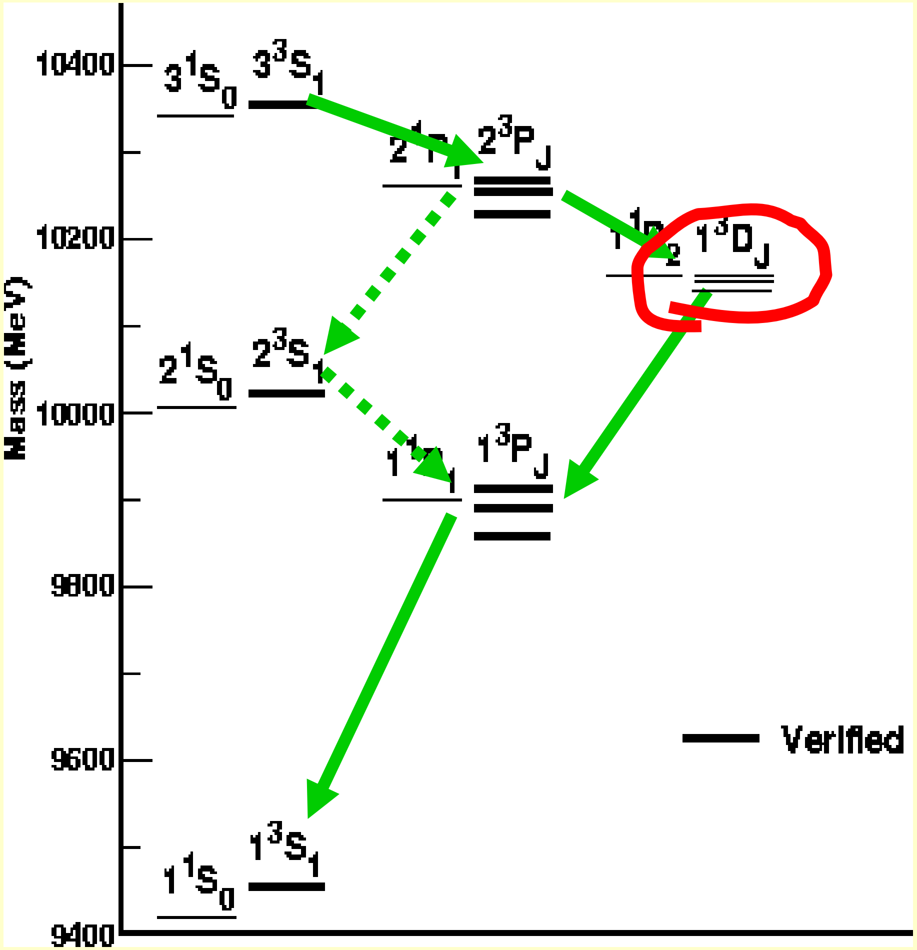


Where is the h_c (1^1P_1) ?

- PDG: "needs confirmation"
- E705: 2.5σ enhancement at 3.527GeV PRD50(1994)4258
- E760: bump around 3.526GeV PRL69(1992)2337
- **Prediction:** PRD37(1988)1210 $B(\psi' \to h_c \pi^0) \sim 3.7 \times 10^{-3}$, $B(h_c \to \gamma \eta_c) \geq 50\%$



Discovery: $\Upsilon(1D)$ states

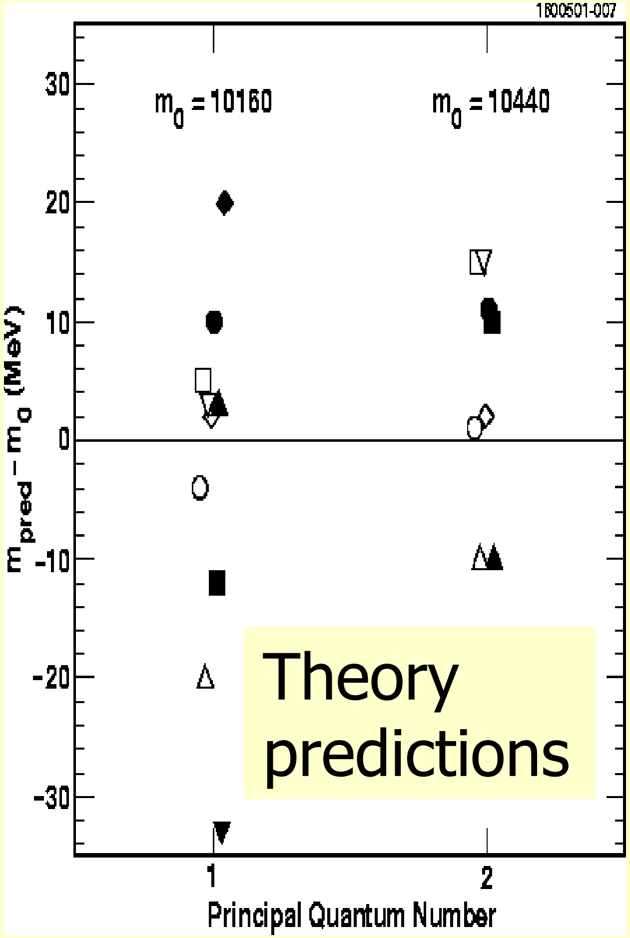


- Unique (L=2 and stable)
- Decays: electromagnetic (dominant, exception!) or via gluon annihilation (tiny)
- Look for $\Upsilon(3S) \rightarrow 4\gamma\Upsilon(1S)$
- Theory check: LCSR, LQCD predict masses; models tuned on L=0,1 states
  - LQCD gets this new state right!

CLEO $\Upsilon(1^3D_J)$ measurement

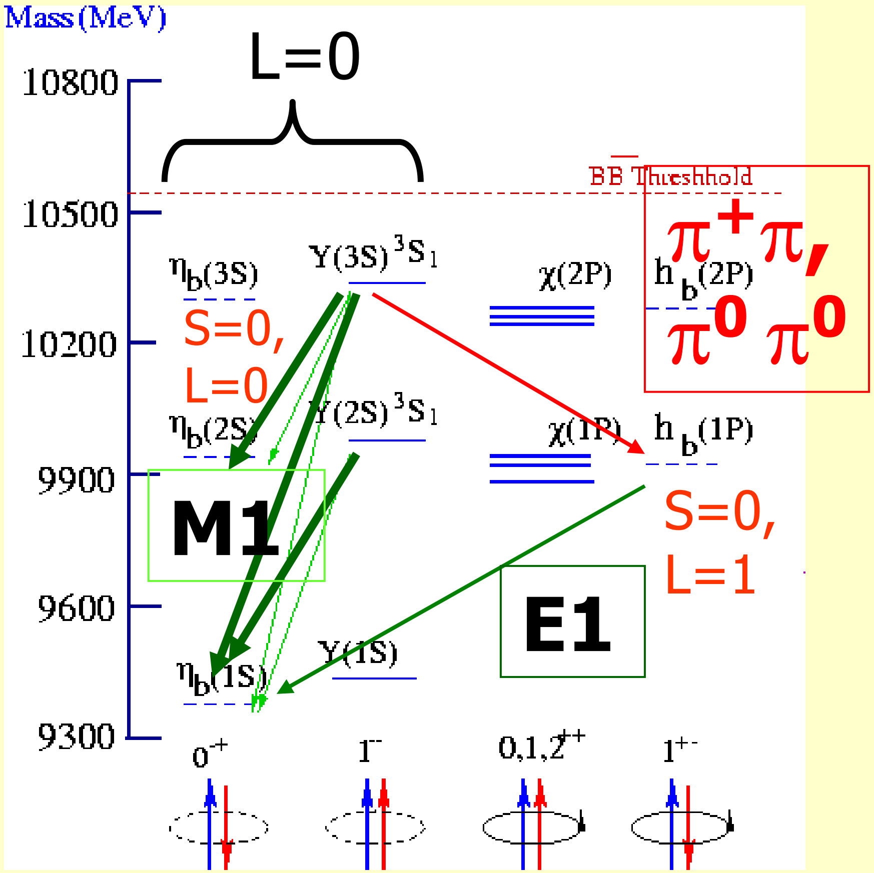
- See state at 10162.2±1.6MeV at 6.8σ: J=1,2,3?
  - inconsistent with J=3
  - Theory: $\Upsilon(1^3D_2)/\ \Upsilon(1^3D_1)=6$
  - $\Upsilon(1^3D_2)$ most likely
- Consistent with predictions for $\Upsilon(1^3D_2)$ to lie 0.5..1MeV below multiplet c.o.g.
- **First new $b\bar{b}$ state in 19 years!**

n^3D_J c.o.g. – m_0 (MeV)



Υ singlet states: $\eta_b(')$, h_b

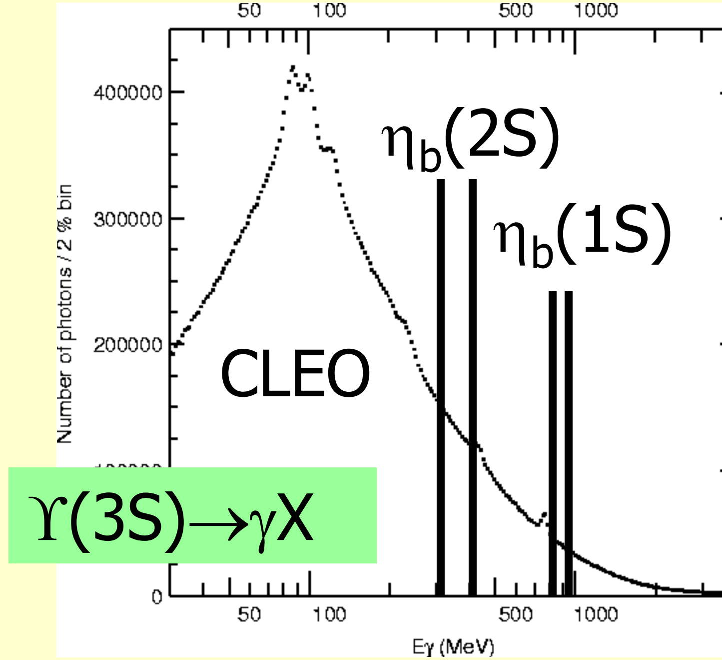
- Singlet states (n^1S_0, n^1P_1) not yet seen in $b\bar{b}$ (n^1S_0 seen in $c\bar{c}$)
- Hyperfine splitting ($n^1S_0 \leftrightarrow n^1S_1 = \Upsilon(nS)$; $n^1P_1 \leftrightarrow n^1P_{1,2,3} = \chi_{b1,2,3}$) predicted by LQCD and potential models
- η_b quasi-stable ($b\bar{b} \rightarrow gg$)
- E1 transitions well known
- Use hindered M1 transitions (ΔE larger)

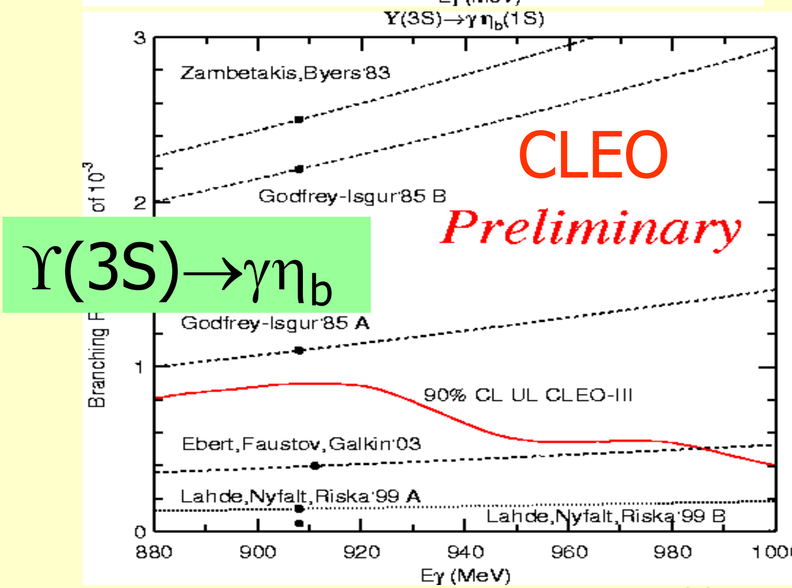


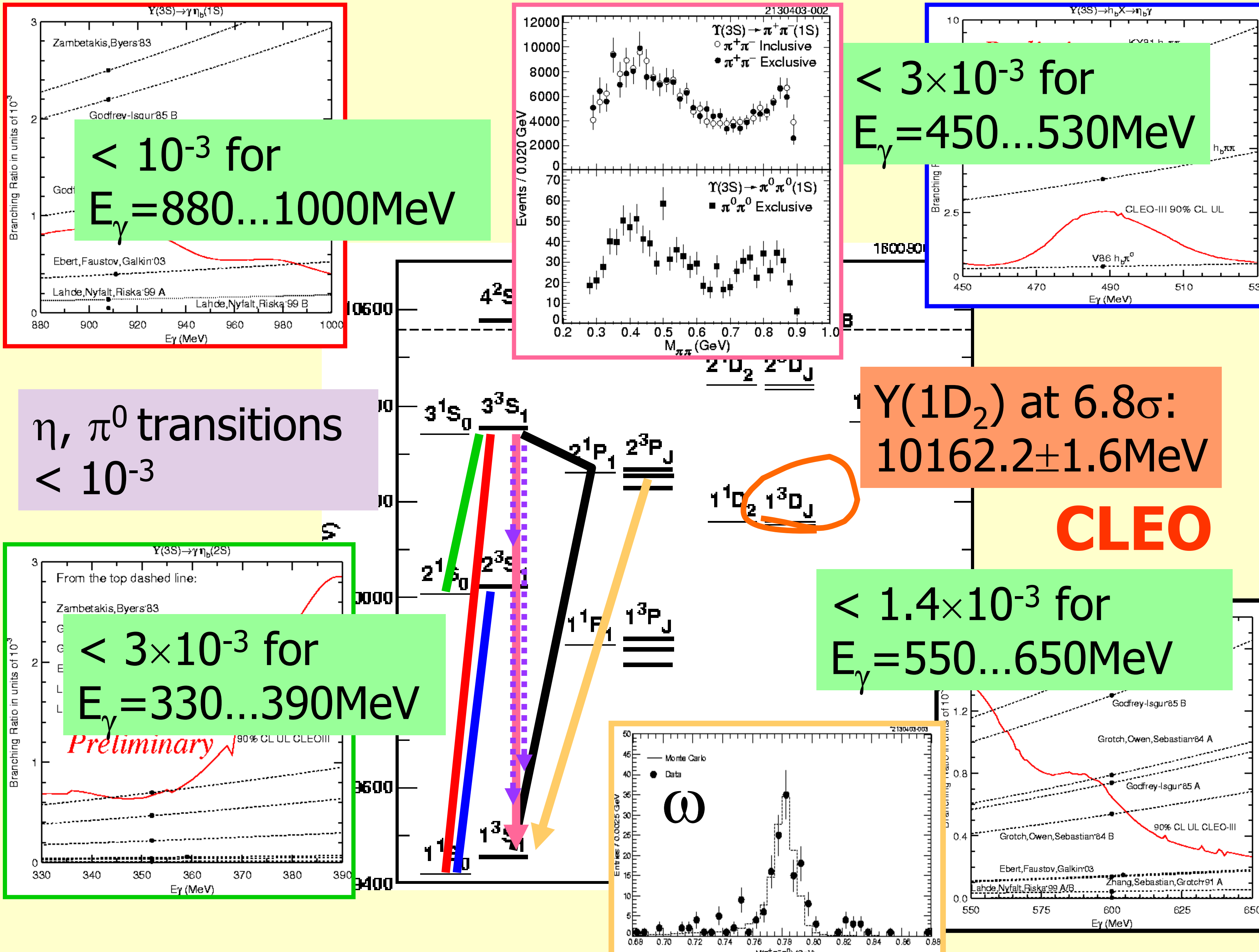
η_b, η_b' searches through hindered M1 transitions

E_γ peaks in $\Upsilon(2,3S)\rightarrow\gamma X$:
mass → level splitting,
amplitude → transition BR

- $1fb^{-1}$ $\Upsilon(3S)$, $0.5fb^{-1}$ $\Upsilon(1S)$ CLEOIII data
- E1 transitions in that region well known
- No significant signal found, upper limits computed as function of photon energy






Υ(3S)→γη_b(1S)
Zambetakis,Byers'83
Godfrey-Isgur'85 B
Ebert,Faustov,Galkin'03
Lahde,Nyfalt,Riska'99 A
Lahde,Nyfalt,Riska'99 B
Branching Ratio in units of 10^-3
Eγ (MeV)
< 10^-3 for
Eγ=880…1000MeV
2130403-002
Υ(3S)→π+π−(1S)
π+π− Inclusive
π+π− Exclusive
Υ(3S)→π0π0(1S)
π0π0 Exclusive
Events / 0.020 GeV
Mππ (GeV)
Υ(3S)→h_bX→η_bγ
< 3×10^-3 for
Eγ=450…530MeV
CLEO-III 90% CL UL
Eγ (MeV)
η, π0 transitions
< 10^-3
Υ(1D2) at 6.8σ:
10162.2±1.6MeV
CLEO
Υ(3S)→γη_b(2S)
From the top dashed line:
Zambetakis,Byers'83
< 3×10^-3 for
Eγ=330…390MeV
Preliminary
90% CL UL CLEOIII
Eγ (MeV)
< 1.4×10^-3 for
Eγ=550…650MeV
Godfrey-Isgur'85 B
Grotch,Owen,Sebastian'84 A
Godfrey-Isgur'85 A
90% CL UL CLEO-III
Grotch,Owen,Sebastian'84 B
Ebert,Faustov,Galkin'03
Zhang,Sebastian,Grotch'91 A
Lahde,Nyfalt,Riska'99 A/B
Monte Carlo
Data
ω
M(π+π−π0) (GeV)

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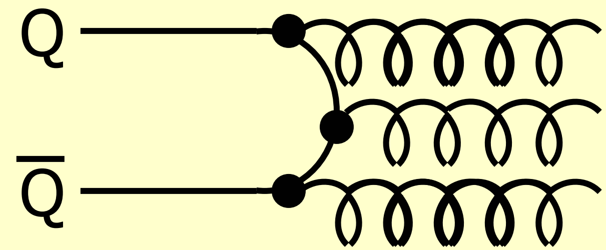
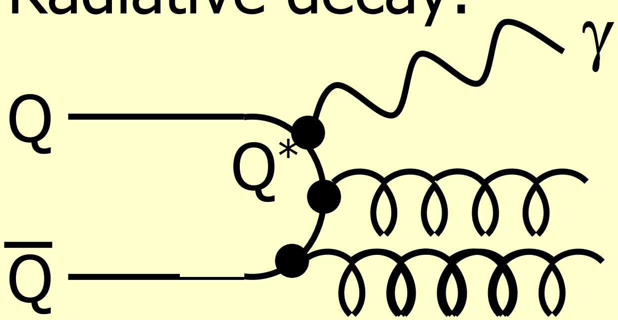
$Q\bar{Q}$ decays into light hadrons

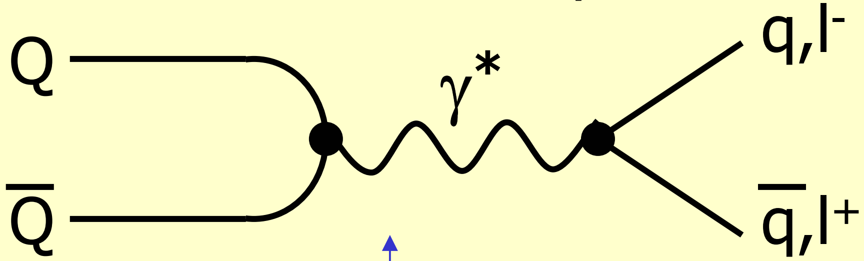
Annihilation into 3g:

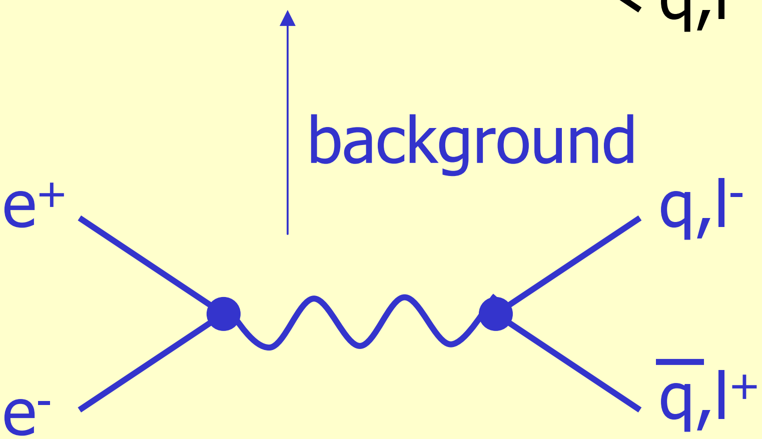


Radiative decay:

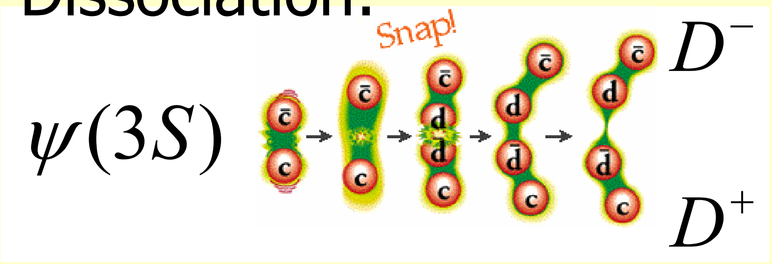


Annihilation into a photon:





Dissociation:



Continuum interference

P.Wang, CZ.Yuan, XH.Mo, DH.Zhang, hep-ph/0212139, Phys.Lett.B557(2003)192

A problem in e^+e^-: $e^+e^- \to \gamma^* \to$ light hadrons
interferes with $e^+e^- \to Q\bar{Q} \to$ light hadrons

- ➢ Resonance + continuum + interference terms

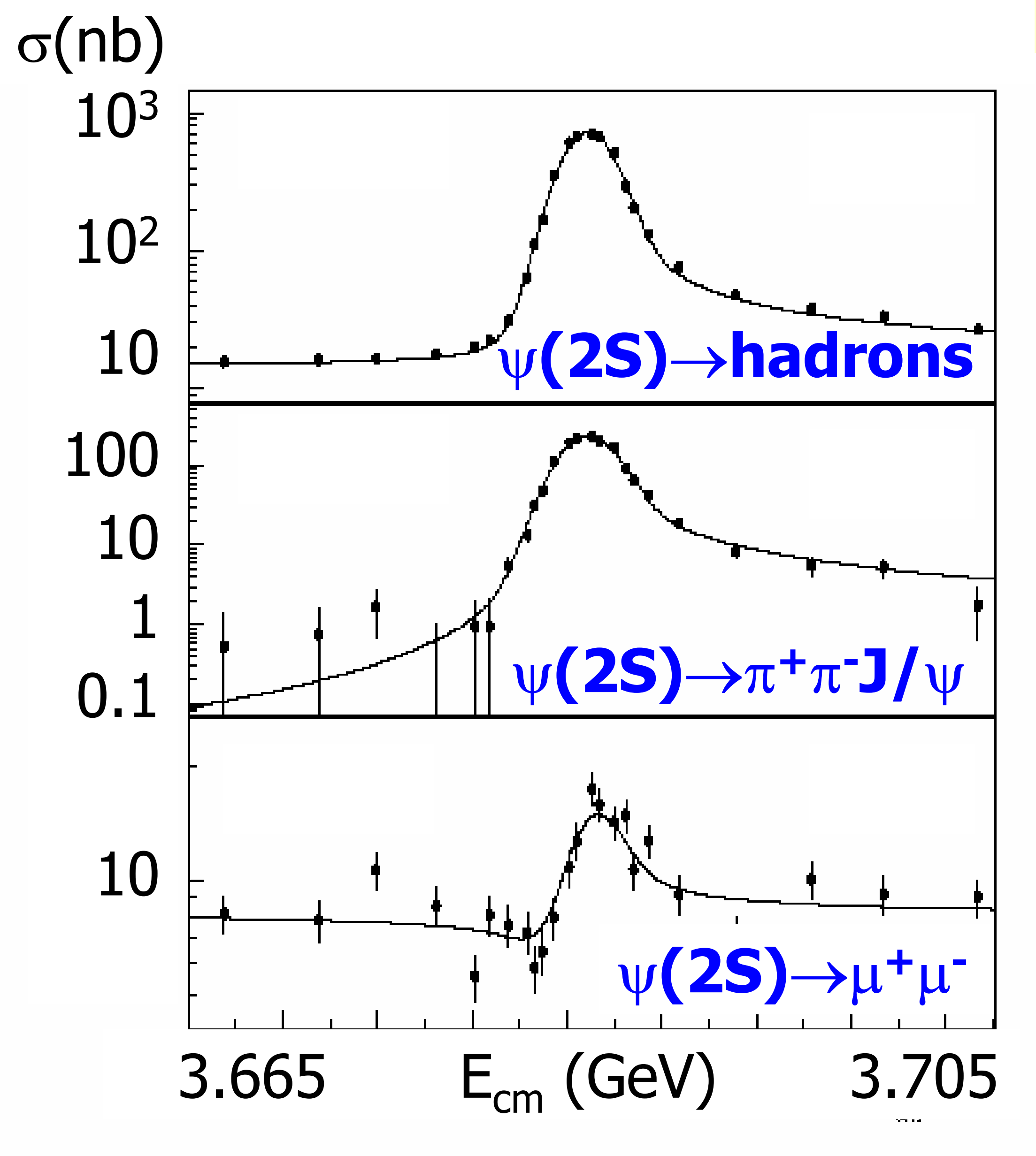
- Recent work suggests substantial corrections to get from measured to desired quantity, e.g. $B(\psi(2S) \to \omega\pi^0) = (3.8 \pm 1.7 \pm 1.1) \times 10^{-5}$ → -58%!
- Dependence on experimental conditions:
  large beam energy spread allows more continuum+interference in;
  tight FS invariant mass requirements prevent ISR $q\bar{q}$ contamination
- Not the same for every channel

➢ **Off-resonance data is costly but necessary.**

BES ψ′ Scan

PLB550(2002)24

- Precision improvement
- BR's as input to other experiments
- **Measure** Γ_{tot}, $\Gamma_{\ell\ell}$, $\Gamma_{J/\psi\pi\pi}$, infer Γ_{had}, $B_{\ell\ell}$, $B_{J/\psi\pi\pi}$

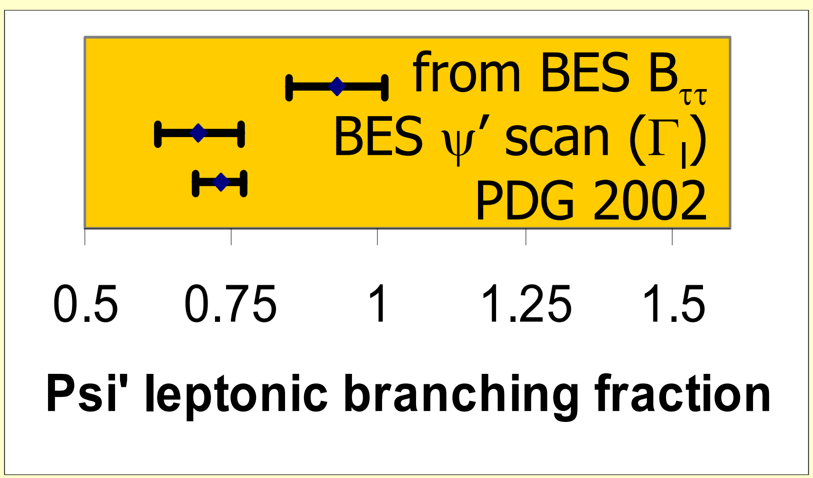


BES ψ' scan and τ data

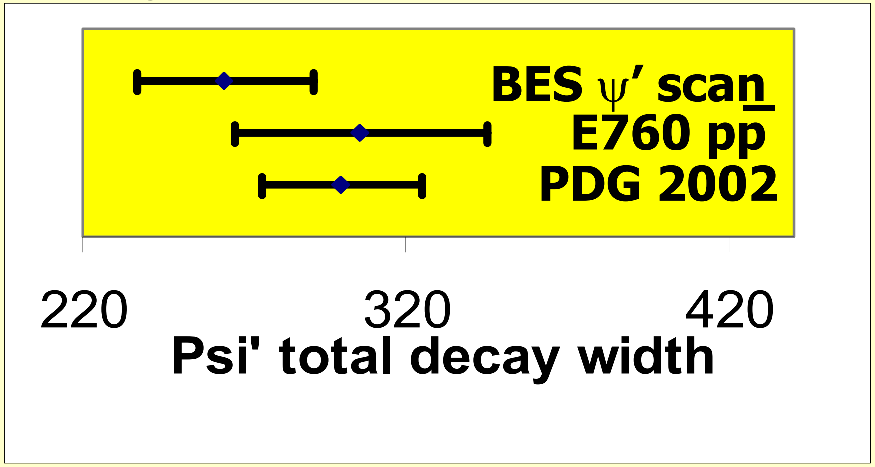
PLB550(2002)24 (BES scan)
PRD65(2002)052004 ($B_{\tau\tau}$)
PRD47(1993)772 (E760 scan)

$$\frac{B_{ll}}{\beta_l\left(\frac{3}{2}-\frac{1}{2}\beta_l^2\right)} = \text{const}, \beta_l = \left(1-\frac{4m_l^2}{M_{\psi'}^2}\right)^{1/2}$$

$B_{ee} \approx B_{\mu\mu} \approx B_{\tau\tau}/0.3885$:



Γ_{tot}:

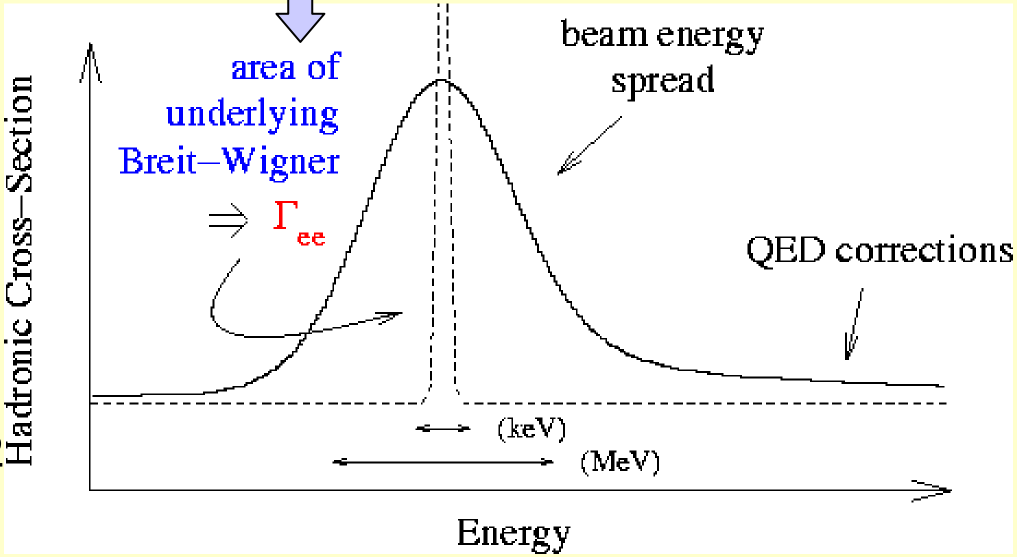


Leptonic $\Upsilon(1,2,3S)$ Width Γ_{ee}

- High precision test for LQCD!
- Strategy:

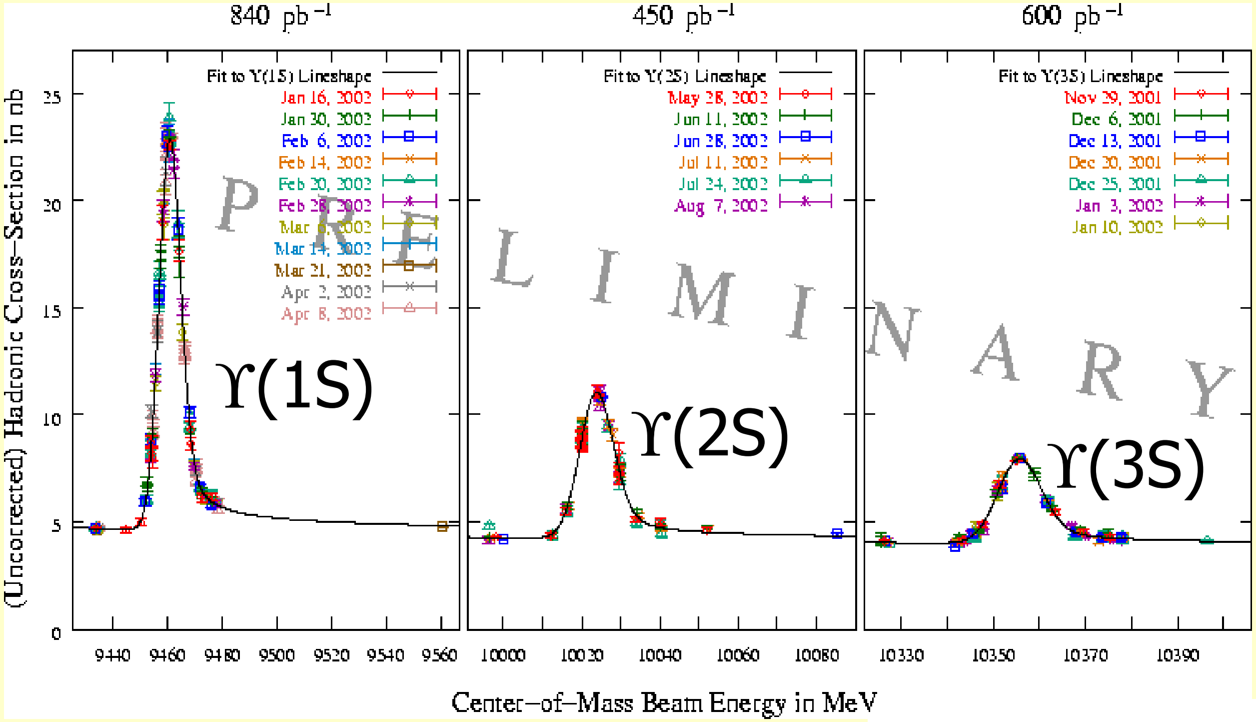
$$\Gamma\left(Y \rightarrow e^+e^-\right) = \frac{M_Y^2}{6\pi^2} \underbrace{\frac{\Gamma_{total}}{\Gamma_{hadrons}}}_{\text{External input}} \int dEnergy\ \sigma\left(e^+e^- \rightarrow Y \rightarrow hadrons\right)$$

Hope to improve from 2/4/9% to better than 2%. Correct for higher orders $\rightarrow \Gamma_{ee}^{(0)}$ to compare with theory – challenge: $|\psi(0)|^2$



CLEO
ϒ scan

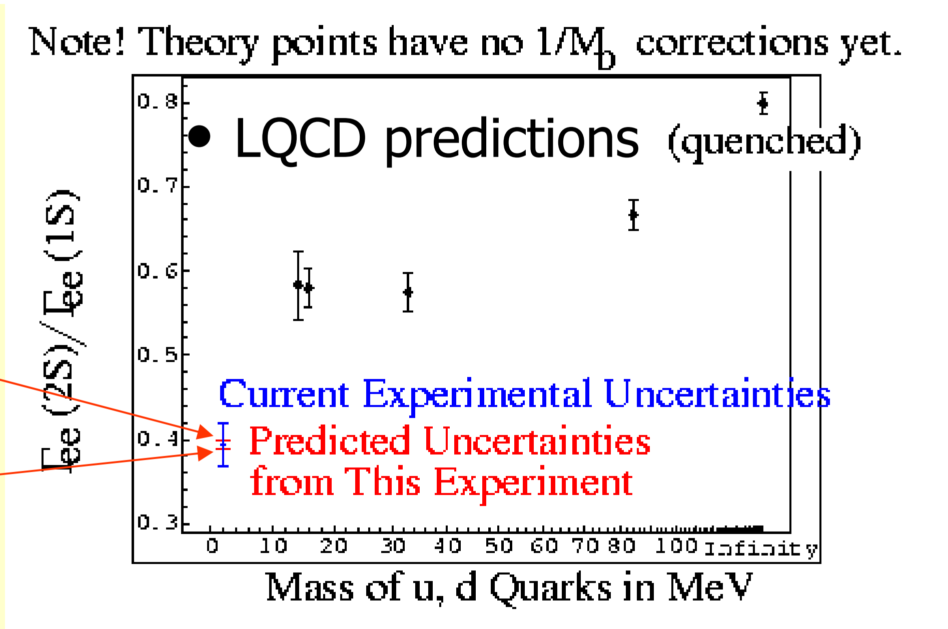
$$\frac{\Gamma_{ee}(2S)}{\Gamma_{ee}(1S)}$$



Statistical precision:

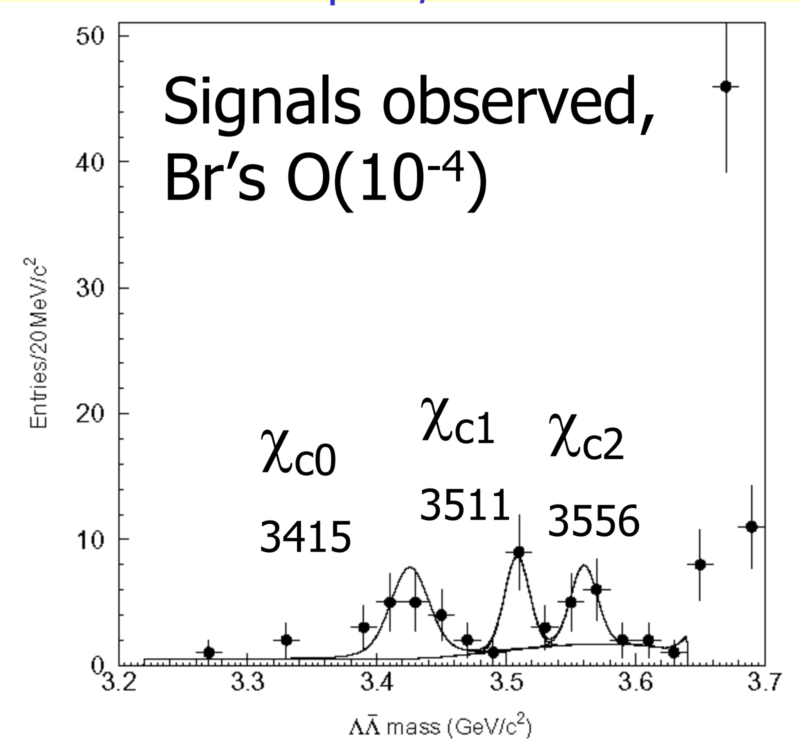
0.1/0.3/0.5%

!



Radiative Decays

hep-ex/0304012

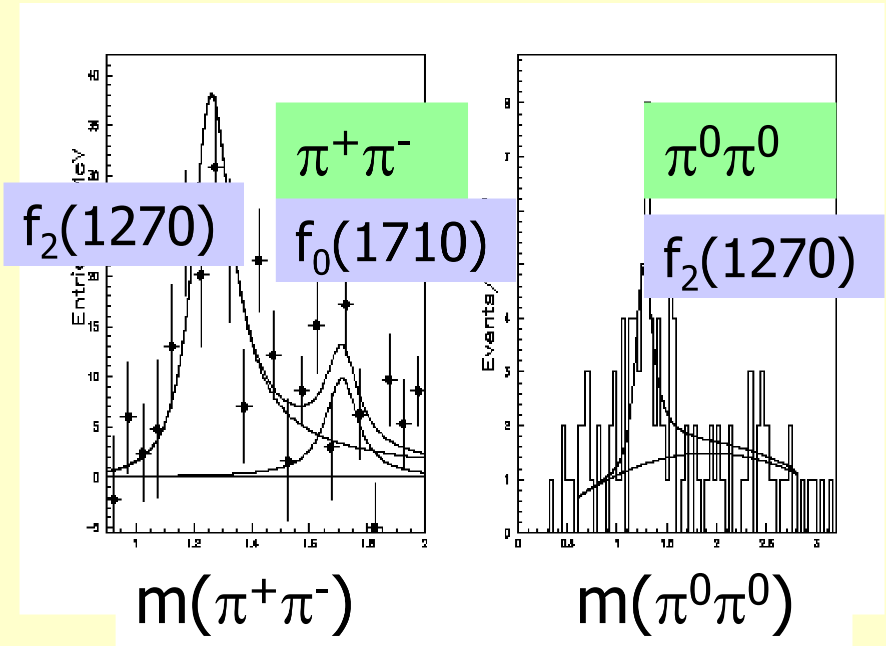


$$\chi_c \to \Lambda\bar{\Lambda},\ J=0,1,2$$

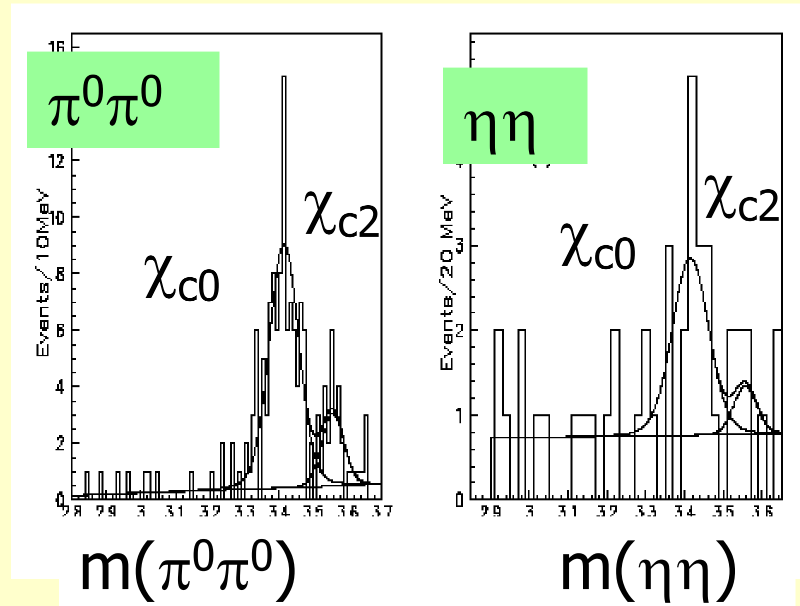
- Color Singlet Model found to be insufficient to describe P-wave quarkonium decays, need Color Octet Model.
- $\Gamma(\chi_c \to p\bar{p}$, Color Octet Model) $\approx$ $\Gamma(\chi_c \to p\bar{p}$, experiment)
- COM: $\Gamma(\chi_{c1,2} \to \Lambda\bar{\Lambda})/\Gamma(\chi_{c1,2} \to p\bar{p}) = 1/2$.

	χ_{c0}	χ_{c1}	χ_{c2}
$B(\chi_{cJ} \to \Lambda\bar{\Lambda})$, 10^{-4}	4.7±35%	2.6±45%	3.3±50%
$B(\chi_{cJ} \to \Lambda\bar{\Lambda})/B(\chi_{cJ} \to p\bar{p})$	2.2±1.2	3.7±2.3	4.7±3.0

$\psi' \to \gamma P\bar{P}$, $P=\pi, K, \eta$



BES, Phys.Rev.D67:032004,2003

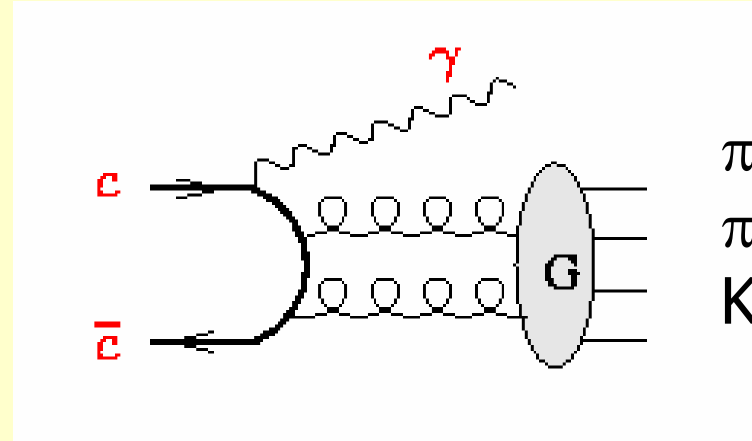


$B(\psi' \to \gamma f_2(1270))$
$= (2.27 \pm 0.26 \pm 0.39) \times 10^{-4}$ (21%)

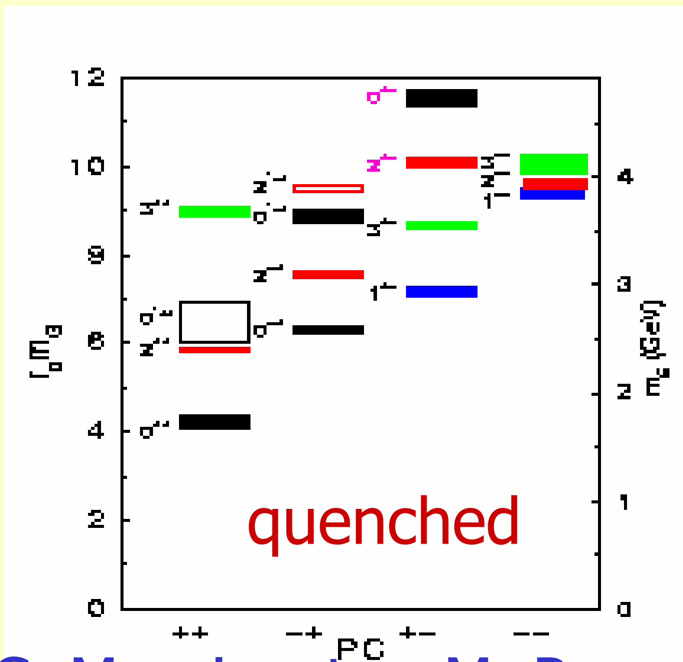
$B(\psi' \to \gamma f_0(1710))$
$\times B(f_0(1710) \to KK, \pi\pi)$
$\leq 10^{-5}$ (90%CL)

$BR \times 10^{-3}$	J=0	J=2
$\chi_{cJ} \to \pi^0\pi^0$	**2.65±25%**	**0.87±64%**
$\chi_{cJ} \to \eta\eta$	**1.94±52%**	**<1.22(90%CL)**
$\frac{\chi_{cJ} \to \eta\eta}{\chi_{cJ} \to \pi^0\pi^0}$	**0.73±60%** **SU(3): 0.95**	

Radiative decays to glueballs: $J/\psi \to \gamma gg$



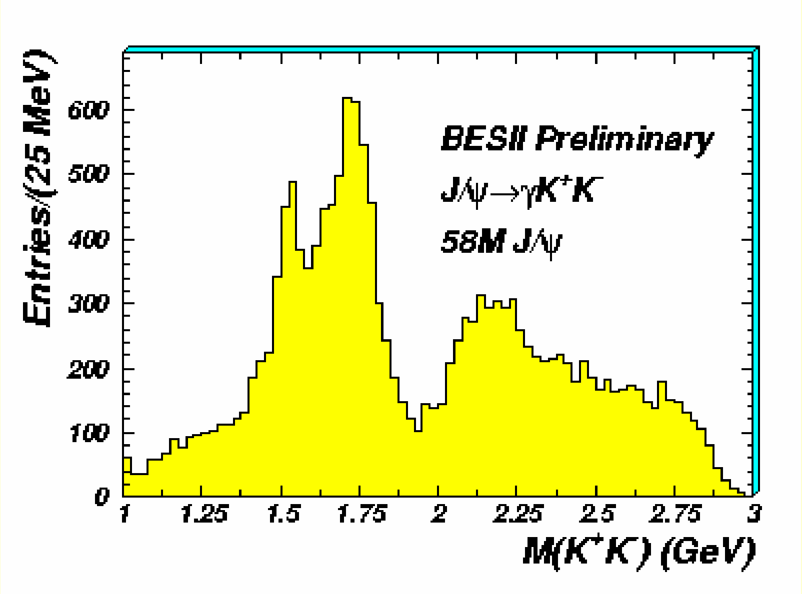
$\pi^+\pi^-$, $\pi^0\pi^0$, $K\bar{K}$, …



C. Morningstar, M. Peardon, hep-lat/9901004

- Lowest candidate (0^{++}) around 1700 MeV, lowest 2^{++} around 2220MeV
- Perform PWA to learn quantum numbers
- If glueball, then $\gamma\gamma$ should not show it (antisearch)

The $f_J(222[3]0)$



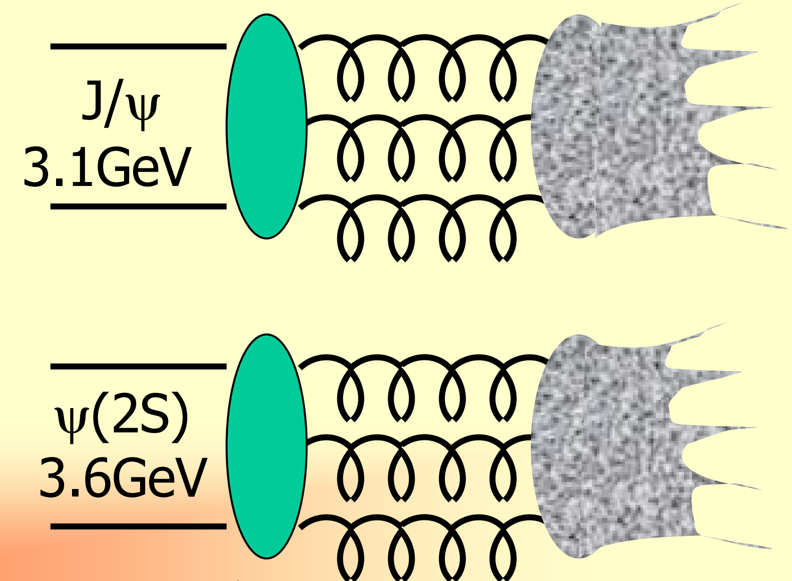
Wait for Cleo-c!

lowest tensor glueball near 2.2GeV, quite narrow:

- 1996: BES candidates in $\pi^+\pi^-, K^+K^-, K_S K_S, p\bar{p}$ modes
- Not confirmed by CBAL, JETSET
- BES is reinvestigating with 58M J/ψ
- At present no signal for a narrow state
- CLEO, LEP antisearched ✓
- CLEO: $\Upsilon(1S) \rightarrow \gamma f_J(2220)$

14/12/15%

"The 14% puzzle"



- If mechanism is $c\bar{c} \to ggg$
  $\Rightarrow$ decay rate ~ $|\Psi(0)|^2$

$$Q_h = \frac{B(\psi(2S) \to H)}{B(J/\psi \to H)} = \frac{\alpha_S^3(\psi(2S))}{\alpha_S^3(J/\psi)} \frac{B(\psi(2S) \to e^+e^-)}{B(J/\psi \to e^+e^-)} \approx (15 \pm 2)\%$$

known

- B(ggg)+B(γgg)+$\underbrace{\text{B}(\gamma^* \to ee,\mu\mu,\tau\tau,\text{hadrons})+\text{B}(c\bar{c}X)}_{\text{known}}$=1:

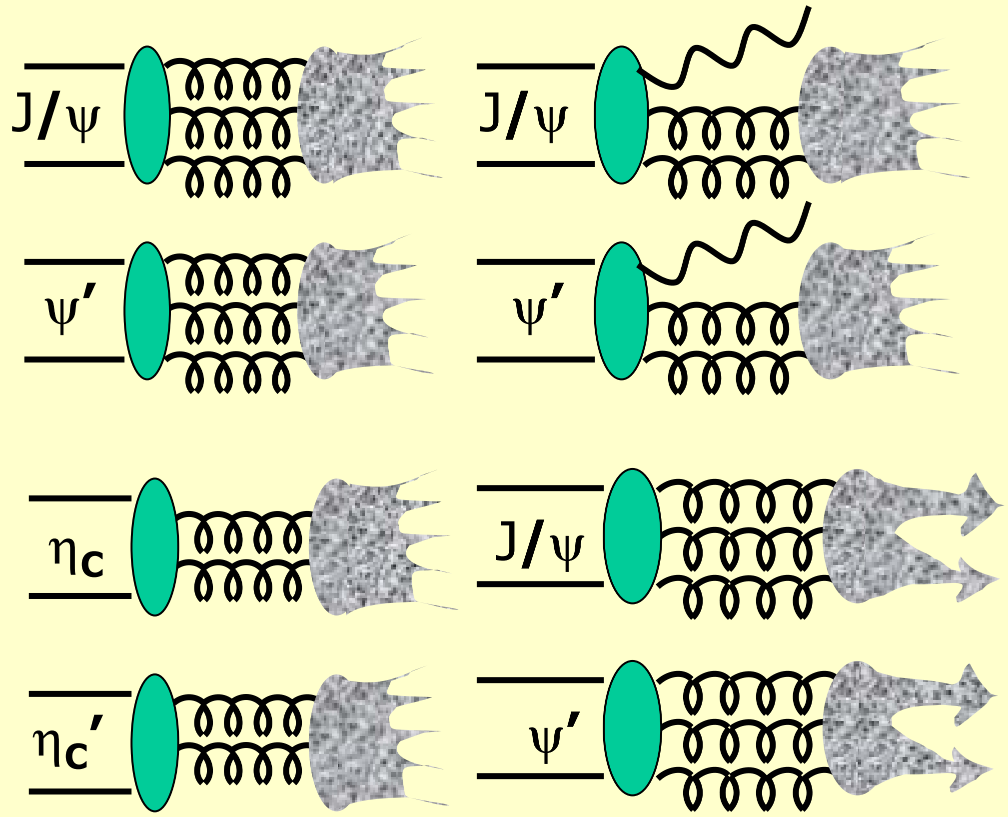
$$Q_h = \frac{B(\psi(2S) \to ggg) + B(\psi(2S) \to \gamma gg)}{B(J/\psi \to ggg) + B(J/\psi \to \gamma gg)} = (24.0 \pm 5.6)\%$$

(Gu, Li, hep-ph/9910406)

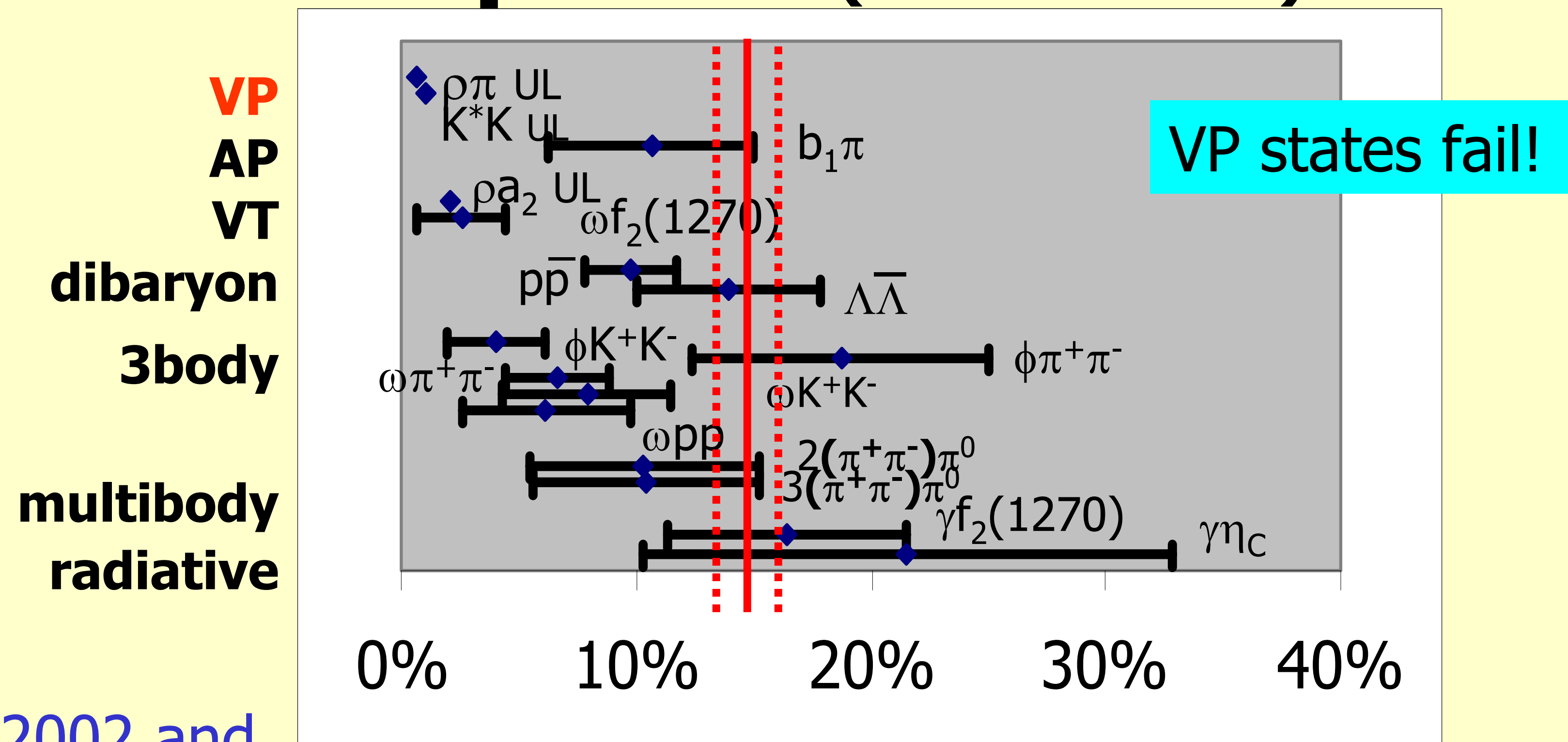
- **Deviations indicate presence of other mechanisms**

Applicability of the "14% rule"

- Should work for other singlet states
- Should work for radiative decays
- Sum or individual channels?
- Next: experimental data



Selected n^3S_1 data on the 14% puzzle (there is more)



PDG2002 and PhysRevD67(2003)0520002

Hadron Helicity Conservation (Brodsky, Lepage, Tuan)

Color-octet ccbar production (Chen and Braaten)

Intrinsic charm (Brodsky, Karliner)

$\psi' \rightarrow VP$ hindered M1 transitions (Pinsky)

Glueball mixing with J/ψ (Freund and Nambu, Hou and Soni)

Final State Interactions (Li, Bugg, Zou)

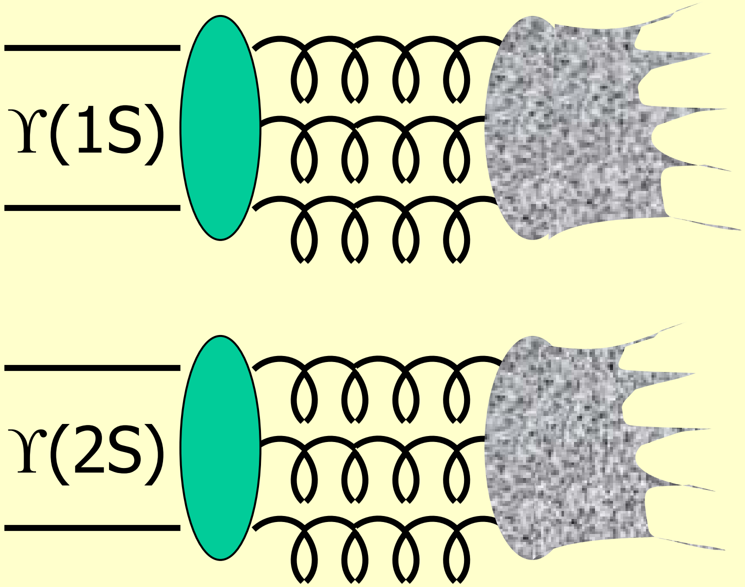
Glueball mixing with ψ' (Suzuki)

Intrinsic charm (Brodsky, Karliner)

Form factor suppresses all 2body meson modes (Chaichian, Tornquist)

Exclusive hadronic Bottomonium decays, or the 14% puzzle for Υ

- Depending on model, $O(10^{-4..5})$ is expected for $\Upsilon \to \rho\pi$
- $\Gamma_{ll}(\Upsilon(2S))/\ \Gamma_{ll}(\Upsilon(1S)) = 0.5/1.3 = 38\%$!
- CLEO is analyzing 20M $\Upsilon(1S)$, 10M $\Upsilon(2)$, 5M $\Upsilon(3S)$, searching for signals in PV final states



CLEO Preliminary $\Upsilon \to h_1 h_2$ Branching Fractions

Upper Limits at 90% CL in 10^{-5}

Mode/Region	1S	2S	3S
$\rho\ \pi$	0.5	1	2
$K^*(892)\ \bar{K}$	1	0.9	2
$\rho\ a_2(1320)$	2	2	3
$K^*(892)\ \bar{K}_2^*(1430)$	2	4	3
$\omega\ f_2(1270)$	0.7	1	0.8
$b_1(1235)\pi$	0.8	1	2
$K_1(1400)\ \bar{K}$	3	4	2

1 Introduction

2 Spectroscopy

2a Transition options

2b Υ pionic transitions

2c Rare transitions

2d Searches

3 Decays

3a Scans

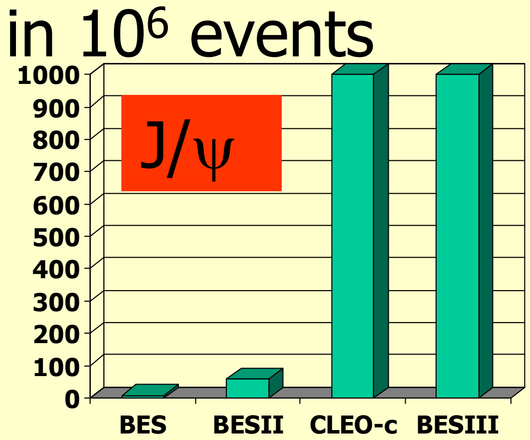
3b Radiative decays

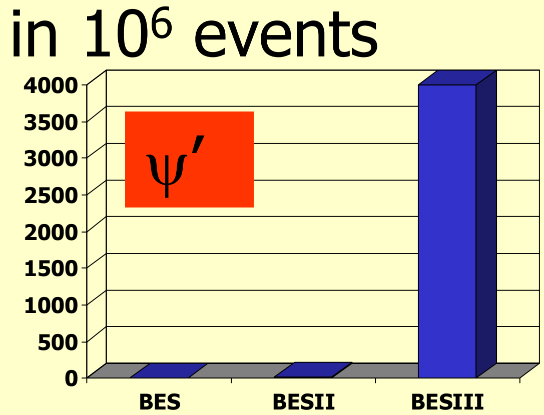
3c 14% puzzle

4 What next?

Upgrades, datasets

- CLEO $\Upsilon(1,2,3S)$ data taking over
- CLEO-c start-up right now, $\sqrt{s}$= 3..5GeV, lumi $1\times10^{-32}s^{-2}cm^{-1}$ at 3.1GeV
- BES/BEPC upgrade, $\sqrt{s}$=2..5GeV, lumi $1\times10^{-33}s^{-2}cm^{-1}$ at 1.89GeV, data taking in 2006?





Puzzles

1 Introduction

2 Spectroscopy

- h_c, h_b, η_b
- $\Delta m(\psi,\eta_c)$, n=1,2
- rare π,η transitions
- E1 such as from χ_{b0}
- …

3 Decays

- η_c' decays
- 14% puzzle in $c\bar{c}$
- 14% puzzle in $b\bar{b}$
- $f_J(2220)$
- …

4 What next?

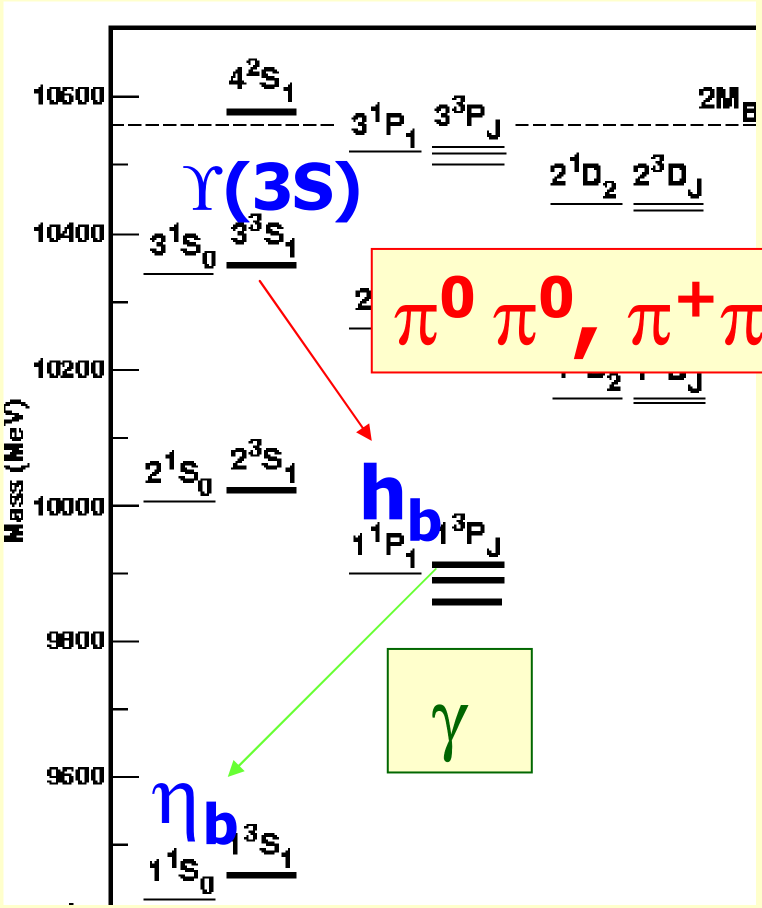
… and there are many more!

Summary

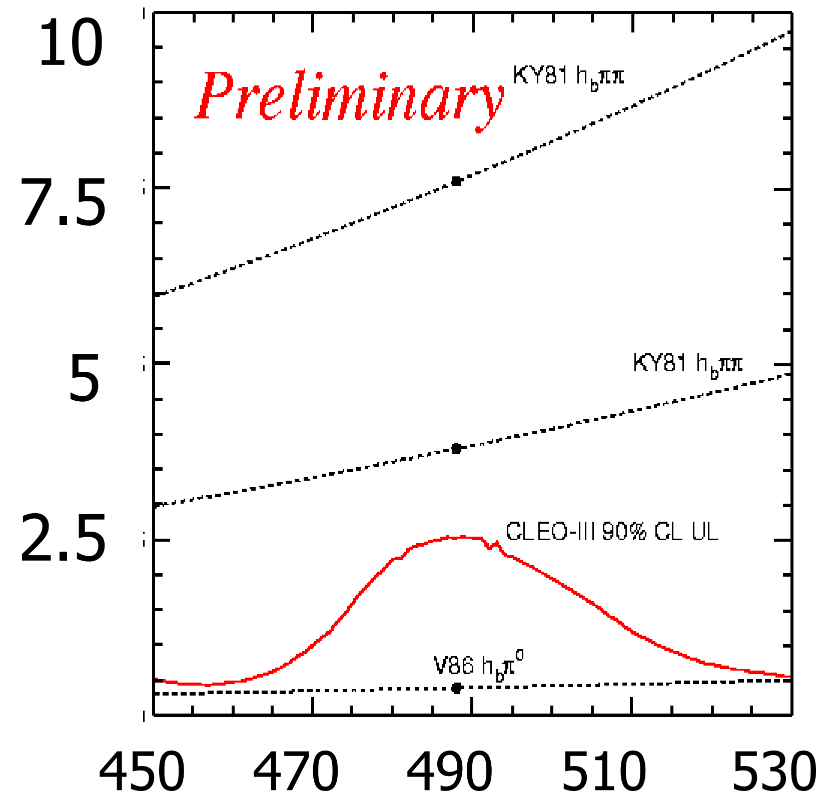
- Progress! Heavy onia spectroscopy is an active field, with many things mapped out
- Theory coming along
- Close data and theory cooperation in a new regime of precision is crucial

➢ More at "Workshop on Quarkonium", September 20-22, 2003, Fermilab

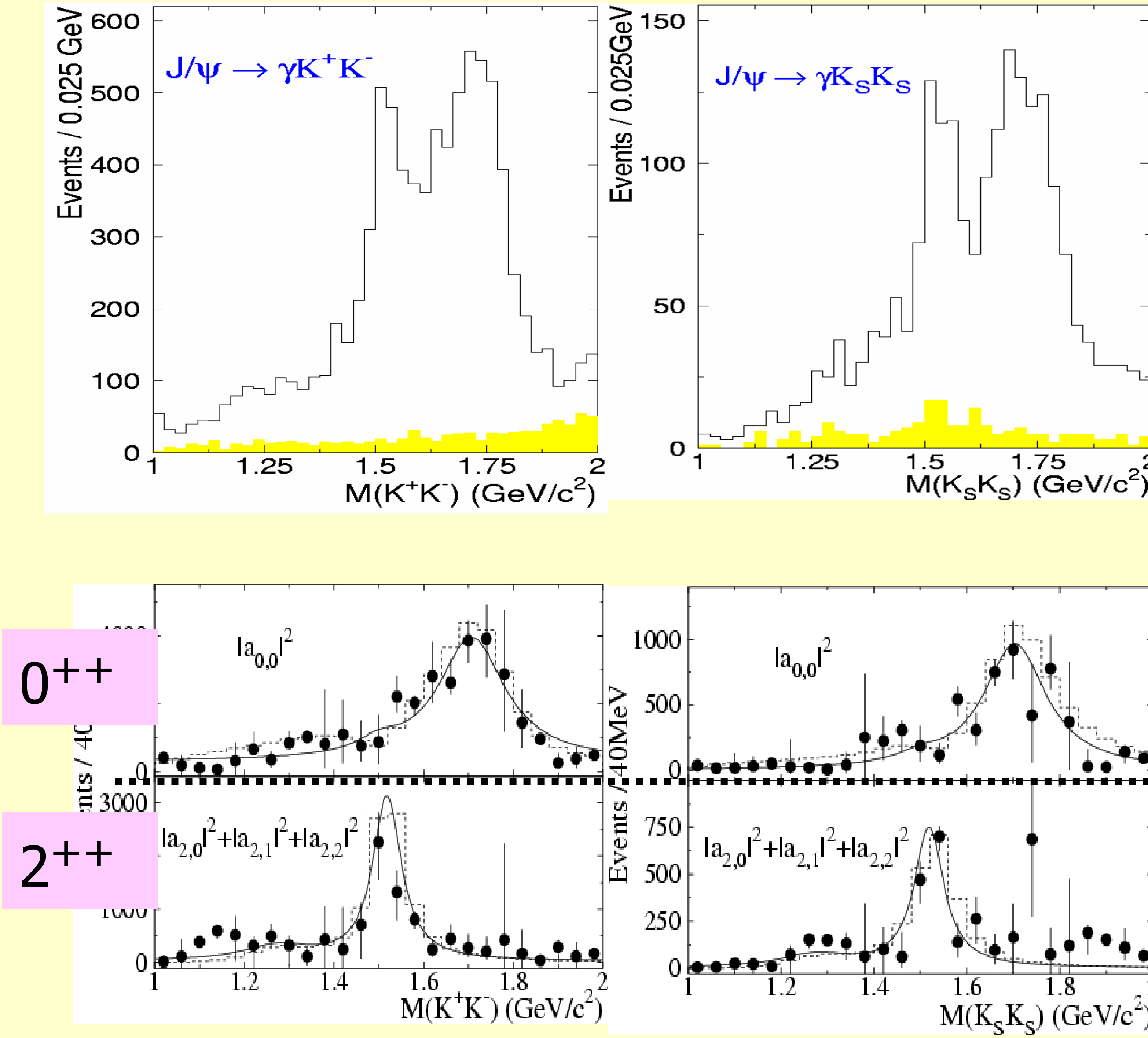
Search for E1 transitition between h_b and η_b



$B(\Upsilon'' \to h_b + (\pi^0 \text{ or } \pi^+\pi^-) \times B(h_b \to \gamma\eta_b))$ in units of 10^{-3}:



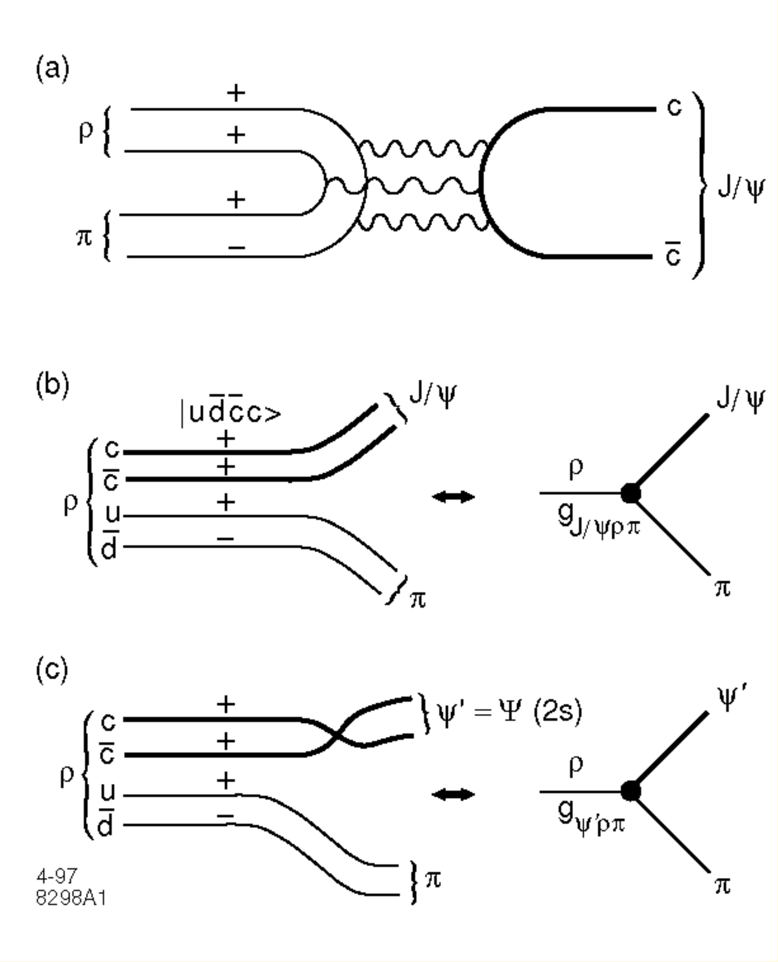
BES PWA findings in $J/\psi \to \gamma KK$



BES prelim, expect publication soon

$m=1518\pm6$MeV
$\Gamma=84^{+28}_{-24}$MeV

$m=1703^{+8}_{-10}$MeV
$\Gamma=84^{+27}_{-22}$MeV



Intrinsic Charm a la Brodsky and Lepage

DONE