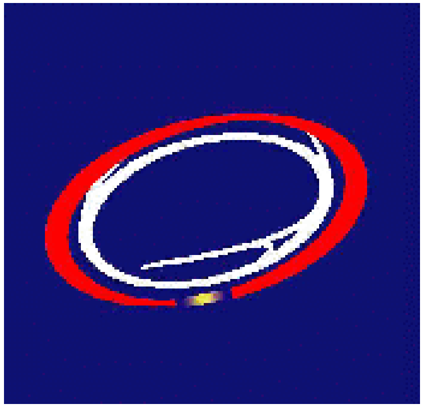
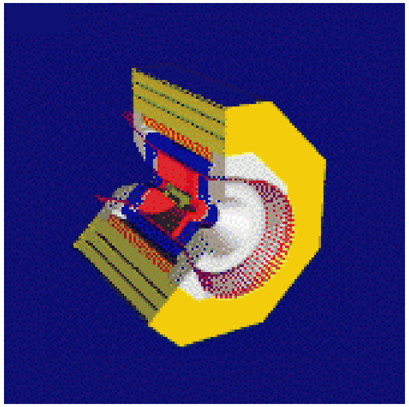
Hall D at Jefferson Lab

Glue χ / CESR-c
Mapping the Meson Spectrum



CESR-c/CLEO-c



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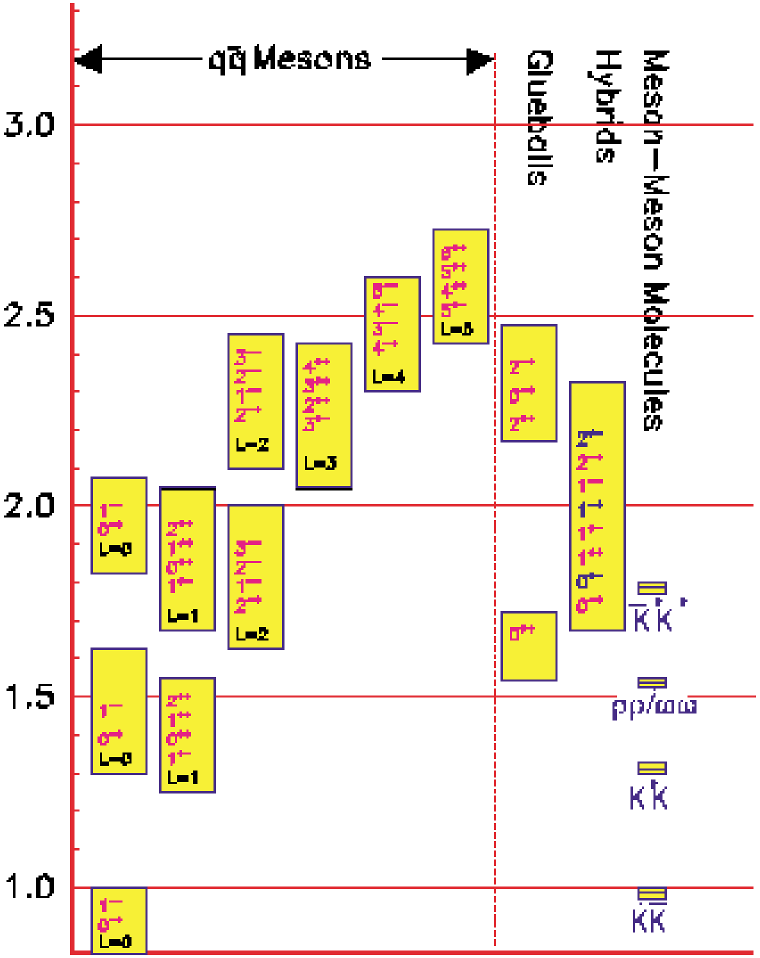
The New York Times
ON THE WEB

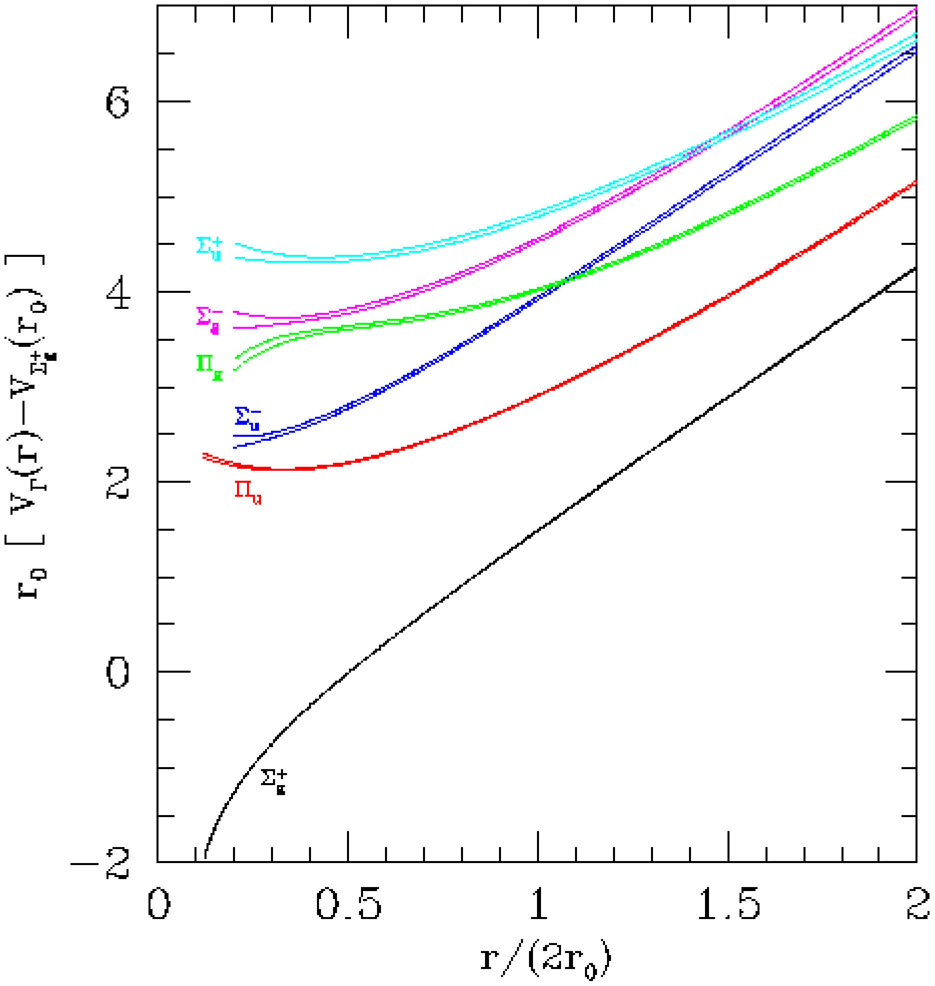
August 15, 2000

10 Physics Questions to Ponder for a Millenium or Two

One of those questions:

How can we understand quark and gluon confinement in Quantum Chromodynamics ?

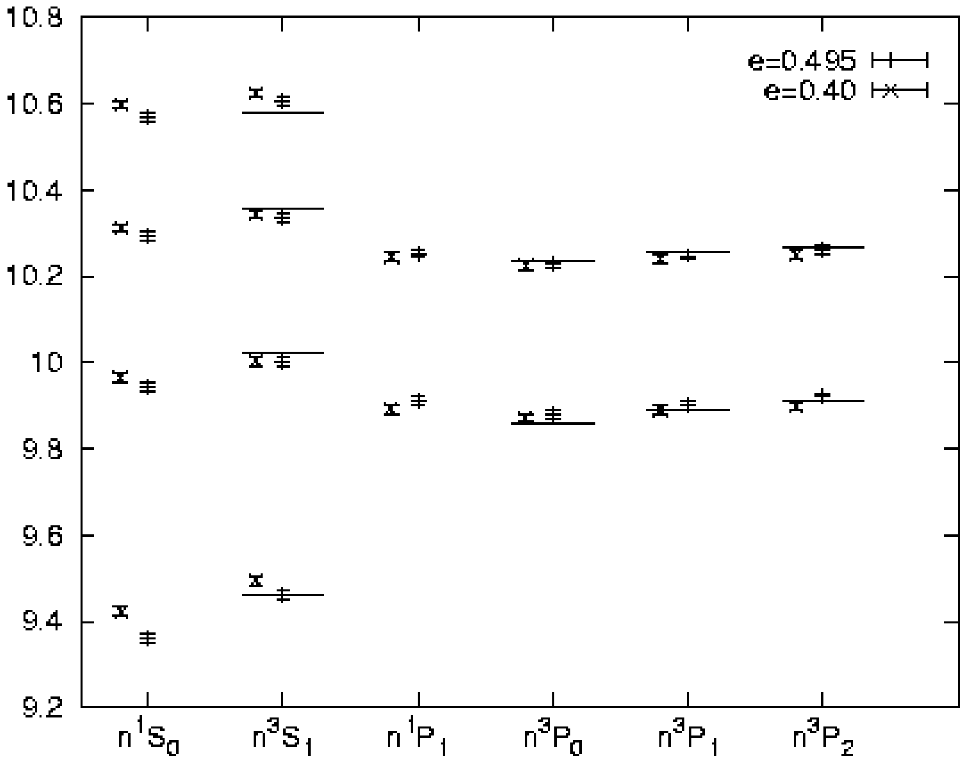

qq̄ Mesons
Glueballs
Hybrids
Meson–Meson Molecules
3.0
2.5
2.0
1.5
1.0
1^{--} 0^{-+} L=0
1^{--} 0^{-+} L=0
2^{++} 1^{++} 0^{++} 1^{+-} L=1
1^{--} 0^{-+} L=0
2^{++} 1^{++} 0^{++} 1^{+-} L=1
3^{--} 2^{--} 1^{--} 2^{-+} L=2
3^{--} 2^{--} 1^{--} 2^{-+} L=2
4^{++} 3^{++} 2^{++} 3^{+-} L=3
5^{--} 4^{--} 3^{--} 4^{-+} L=4
6^{++} 5^{++} 4^{++} 5^{+-} L=5
0^{++}
2^{-+} 0^{-+} 2^{++}
2^{+-} 2^{-+} 1^{--} 1^{-+} 1^{+-} 1^{++} 0^{+-} 0^{-+}
$\bar{K}K^*$
ρρ/ωω
$K\bar{K}^*$
$K\bar{K}$


$r_0\,[\,V_\Gamma(r) - V_{\Sigma_g^+}(r_0)\,]$
$r/(2r_0)$
Σ_u^+
Σ_g^-
Π_g
Σ_u^-
Π_u
Σ_g^+
−2
0
2
4
6
0
0.5
1
1.5
2

$b\bar{b}$ *Spectroscopy at CLEO/CESR*

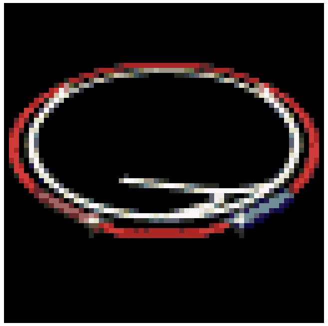
- Lattice QCD calculations are starting to make quantitative predictions for the hadron mass spectrum
- Hadron properties needed to extract weak parameters from experiment
- Need to test Lattice calculations against experiment

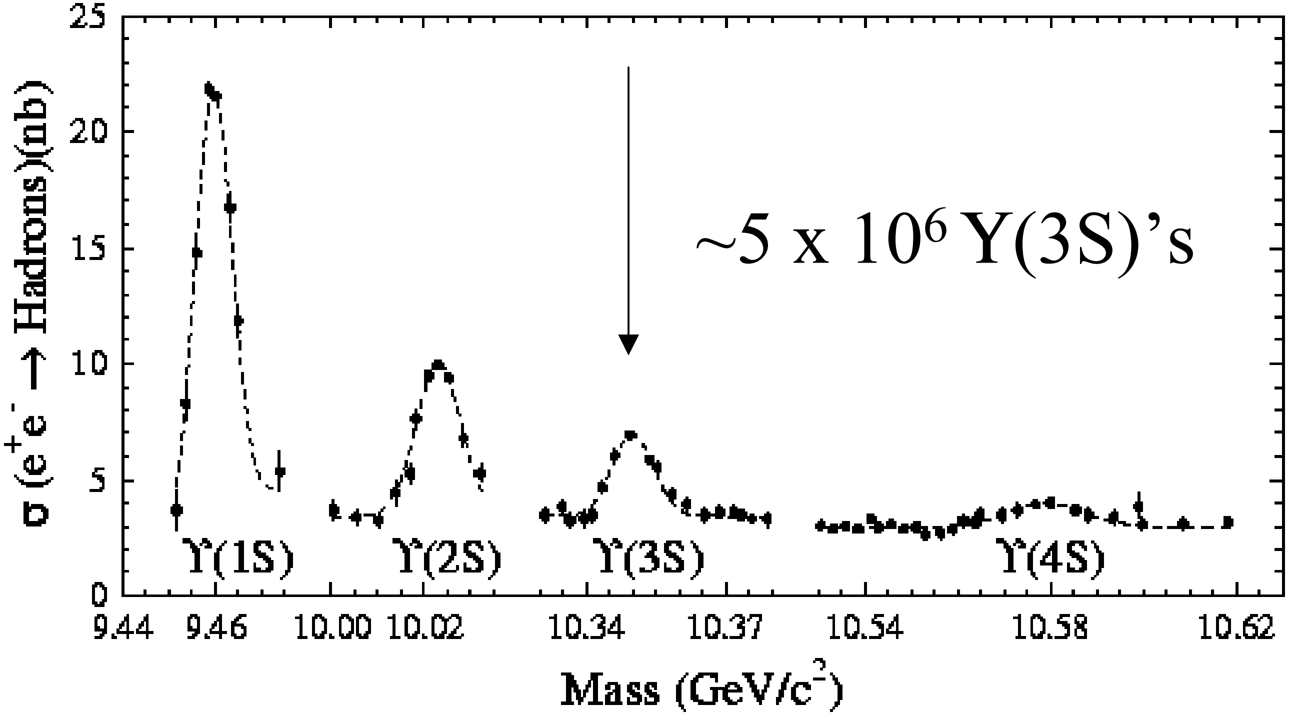
$b\bar{b}$ Mass



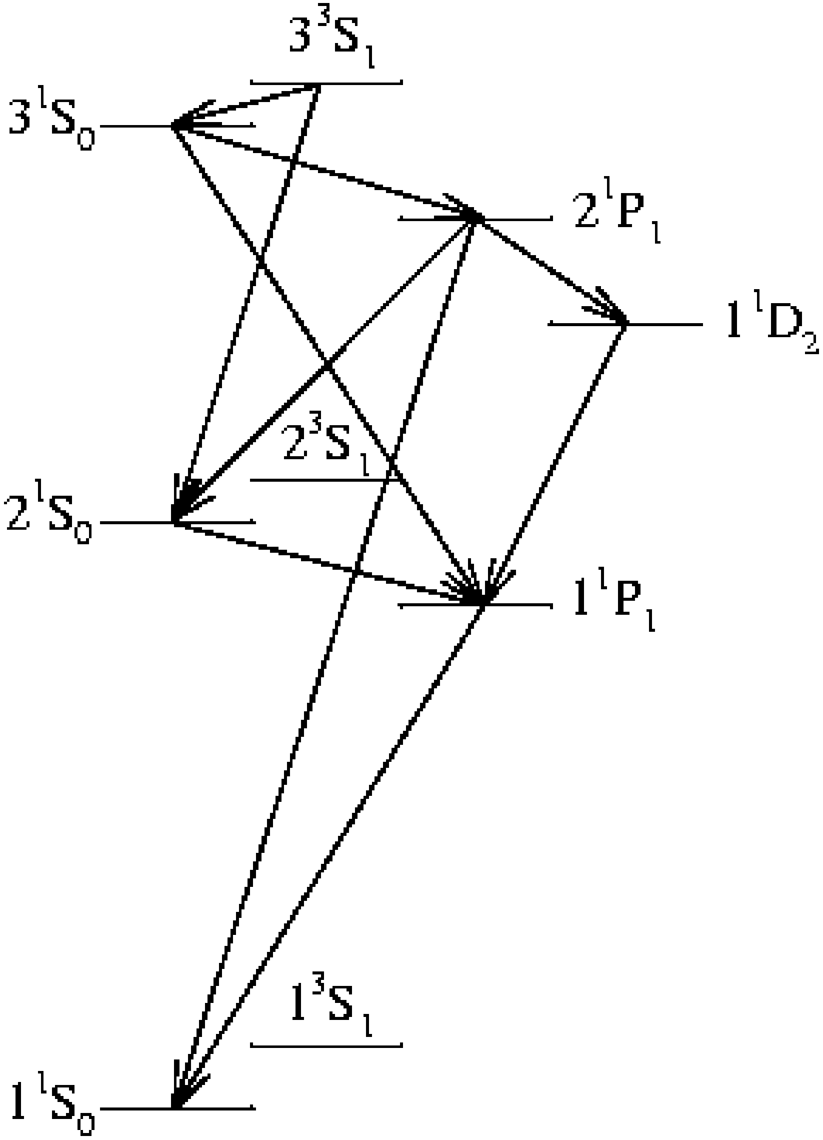
Bali, Schilling and Wachter
Hep-ph/9611226

- The spin triplet states have been observed
- But no spin singlet states have been seen




σ (e⁺e⁻ → Hadrons)(nb)
25
20
15
10
5
0
Υ(1S)
Υ(2S)
Υ(3S)
Υ(4S)
9.44
9.46
10.00
10.02
10.34
10.37
10.54
10.58
10.62
Mass (GeV/c²)

~5 x 10^6 Υ(3S)'s



Estimate radiative widths and BR using quark model:

Production of the $\eta_b(nS)$ states: $\Upsilon(nS) \rightarrow \eta(n'S) + \gamma$

$$\Gamma({}^3S_1 \rightarrow {}^1S_0 + \gamma) = \frac{4}{3}\alpha \frac{e_Q^2}{m_Q^2} \left| \langle f | j_0(kr/2) | i \rangle \right|^2 \omega^3$$

	Transition	BR (10^{-4})
Υ(3S)		
(Γ_{tot}=52.5 keV)	$\rightarrow 3^1S_0$	0.10
	$\rightarrow 2^1S_0$	4.7
	$\rightarrow 1^1S_0$	25
Υ(2S)	$\rightarrow 2^1S_0$	0.21
(Γ_{tot}=44 keV)	$\rightarrow 1^1S_0$	13
Υ(1S)	$\rightarrow 1^1S_0$	2.2
(Γ_{tot}=26.3 keV)		

S.G + J. Rosner, Phys Rev D64, 074011 (2001)

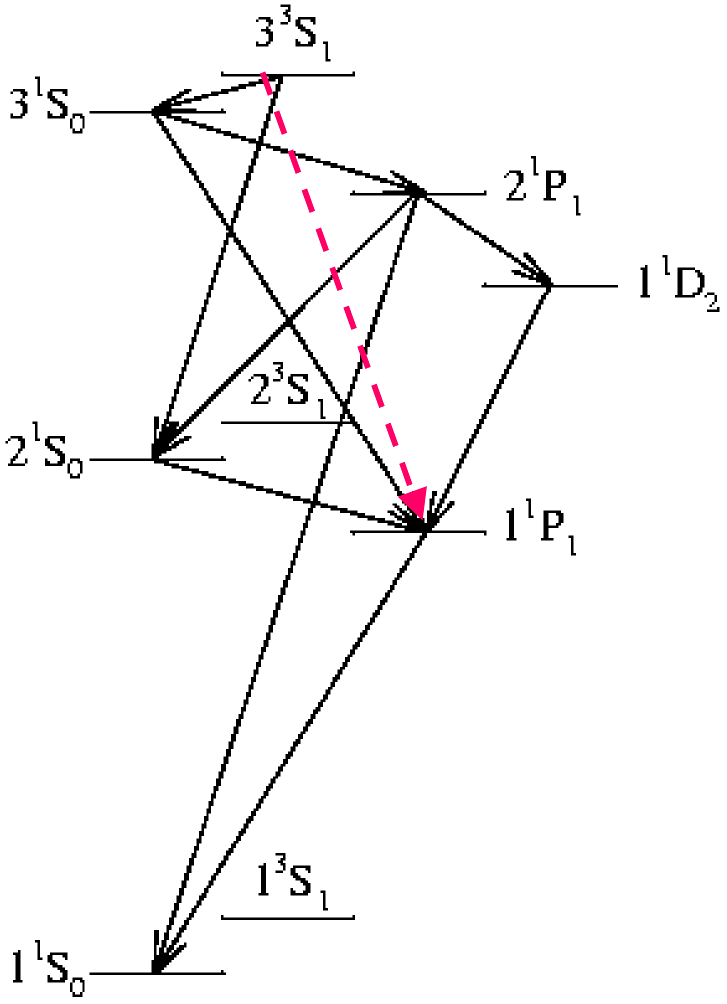
Production of the singlet P-wave states

S.G + J. Rosner, in progress

Two interesting cascades:

- $\Upsilon(3S) \to 2^1S_0\,\gamma \to 1^1P_1\,\gamma$
- $\Upsilon(3S) \to \pi\ 1^1P_1 \to 1^1S_0\,\gamma$

Need branching ratios and hence partial widths



(preliminary results)

$$\Gamma(2^1S_0 \rightarrow 1^1P_1 + \gamma) = \frac{4}{3}\alpha e_Q^2 \left|\langle {}^1P_1 | r | {}^1S_0 \rangle\right|^2 \omega^3 = 3.7\,\mathrm{keV}$$

$$\Gamma(2^1S_0 \rightarrow ggg) = \frac{2\alpha_S^2}{3M_Q} |R_P'(0)|^2 = 3\,\mathrm{MeV}$$

$\mathrm{BR}(2^1S_0\ \gamma \rightarrow 1^1P_1\ \gamma) = 0.12\%$

And

$\mathrm{BR}(3^3S_1\ \gamma \rightarrow 2^1S_0\ \gamma) = 4.7 \times 10^{-4}$

$\mathrm{BR}(\ \Upsilon(3S) \rightarrow 2^1S_0\ \gamma \rightarrow 1^1P_1\ \gamma) = 5.6 \times 10^{-7}$

therefore only ~ 3 events

(A challenge for the experimentalists!)

BR(Υ(3S) → π 1^1P_1) = 0.1%

$$\Gamma(1^1P_1 \to 1^1S_0 + \gamma) = \frac{4}{9}\alpha e_Q^2 \left|\langle {}^1P_1 | r | {}^1S_0 \rangle\right|^2 \omega^3 = 36.7\,\mathrm{keV}$$

$$\Gamma(1^1P_1 \to ggg) = \frac{20\alpha_S^3}{9\pi M_Q^4}\left|R_P'(0)\right|^2 \ln(4m_b\langle r\rangle) = 61.3\,\mathrm{keV}$$

BR(1^1P_1 γ → 1^1S_0 γ)=36.7%

(preliminary results)

Expect ~1800 events!

Production of the D-wave states

- By direct scans in e^+e^- to produce $^3D_1$
- In e.m. cascades: $\Upsilon(3S) \to \gamma\, \chi'_b \to \gamma\gamma\, ^3D_J$
- Some 4γ cascades with observable # of events:

Cascade	Events
$3^3S_1 \to 2^3P_2 \to 1^3D_3 \to 1^3P_2 \to 1^3S_1$	39
$3^3S_1 \to 2^3P_2 \to 1^3D_2 \to 1^3P_1 \to 1^3S_1$	14
$3^3S_1 \to 2^3P_1 \to 1^3D_2 \to 1^3P_1 \to 1^3S_1$	100
$3^3S_1 \to 2^3P_1 \to 1^3D_1 \to 1^3P_1 \to 1^3S_1$	17

S.G + J. Rosner, Phys Rev D64, 097501 (2001)

- The e^+e^- final states leads to less background
- $\mu^+\mu^-$ final states also contribute if μ's are identified

In the CESR run just completed expect to see evidence for the

2^1S_0 , 1^1S_0 , 1^1P_1 , 1^3D_2

And maybe the

3^1S_0 , 1^3D_1 and 1^3D_3

Would represent a significant increase in our knowledge of quarkonium and provide an important benchmark against which to measure the results of lattice QCD

${}^3S_1 - {}^3D_1$ *Mixing and E1 Radiative Transitions in Charmonium*

SG, G. Karl, P.O'Donnell, Z. Phys. C31, 77 (1986)

- Desire to test internal structure of hadrons
- Radiative transitions are sensitive probe of internal structure
- Study electromagnetic transitions

$$\psi' \rightarrow \gamma + \chi_J \text{ and } \chi_J \rightarrow \gamma + \psi$$

As a sensitive test of the ${}^3D_1$ admixture in the ψ'

- Use widths and angular distributions
- By orthogonality also obtain ${}^3S_1$ content of the ψ''

Parametrize the $^3D_1$ contribution with the parameter ζ:

$$\varsigma = \frac{1}{\sqrt{2}} \tan\theta \, \frac{\left\langle {}^3D_1 \middle| r \middle| {}^3P_J \right\rangle}{\left\langle {}^3S_1 \middle| r \middle| {}^3P_J \right\rangle}$$

- Where θ is the $^3S_1 - {}^3D_1$ mixing angle
- The widths are then given by:

$$\Gamma({}^3S_1 \leftrightarrow {}^3P_0) \propto (1 - 2\zeta)^2$$

$$\Gamma({}^3S_1 \leftrightarrow {}^3P_1) \propto (1 + \zeta)^2$$

$$\Gamma({}^3S_1 \leftrightarrow {}^3P_2) \propto (1 - \frac{1}{5}\zeta)^2$$

- Unfortunately the models aren't precise enough to constrain D-wave admixtures from experimental measurements
- A more sensitive test of ${}^3S_1 - {}^3D_1$ mixing is the effect on photon angular distributions
- For θ and θ' the angles between the photon and either lepton in the ψ or ψ' rest frame the angular distributions are of the form:

$$W(\theta,\theta') \approx 1 + \beta_J \cos^2(\theta,\theta')$$

$$\beta_0 = 1$$

$$\beta_1 = -\frac{1}{3} + \frac{16}{9}\varepsilon\left[\frac{1+\frac{1}{5}\zeta - \frac{4}{5}\zeta^2}{1+2\zeta+\zeta^2}\right]$$

$$\beta_2 = \frac{1}{13} - \frac{240}{169}\varepsilon\left[\frac{1+\frac{1}{5}\zeta - \frac{2}{25}\zeta^2}{1-\frac{2}{5}\zeta+\frac{1}{25}\zeta^2}\right]$$

To first order in

$$\varepsilon = \xi k_\gamma / 4m_c$$

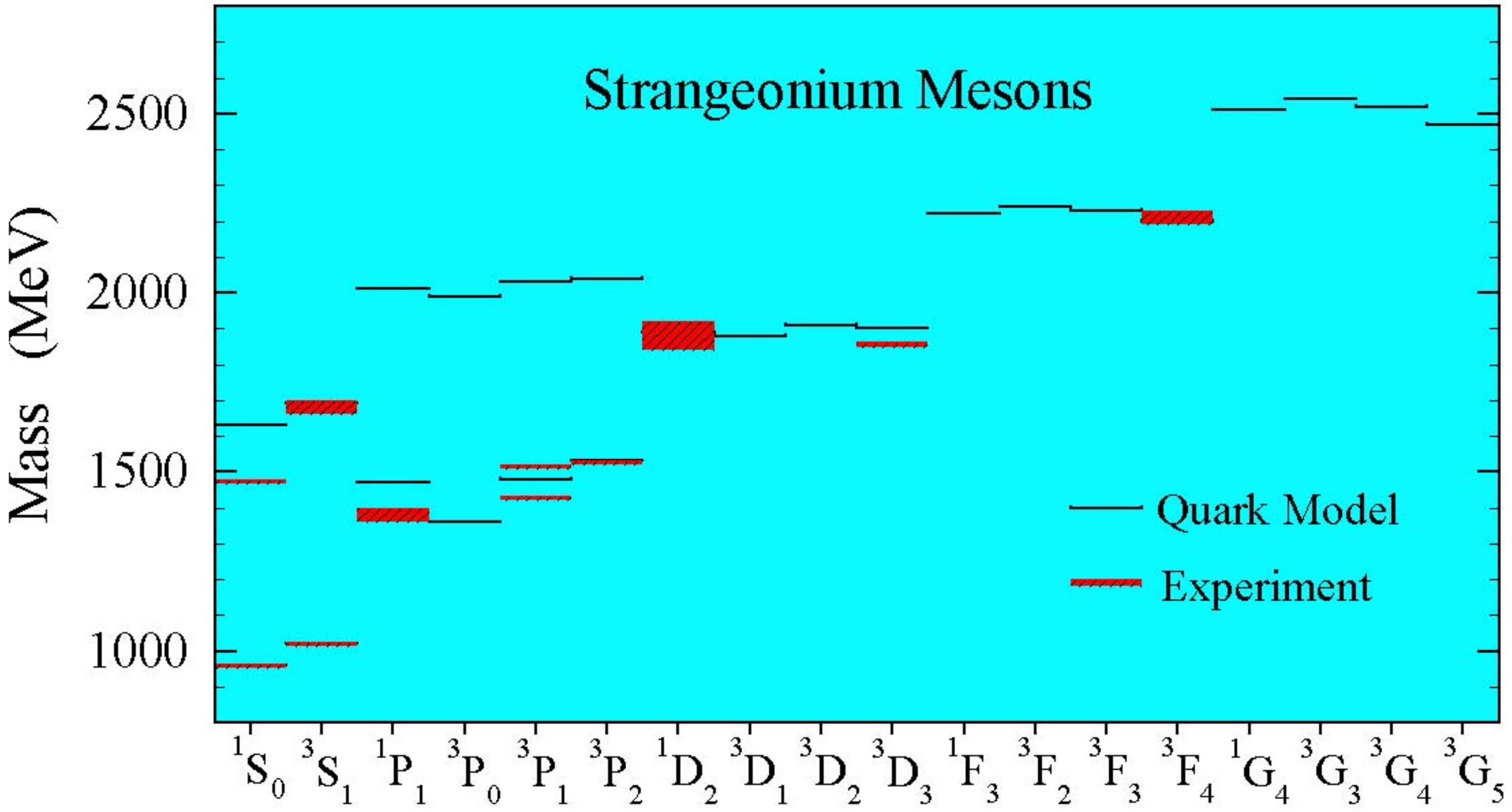
$\xi = +1$ for $\chi \rightarrow \gamma\psi$

$\xi = -1$ for $\psi' \rightarrow \gamma\chi$

One could make a quantitative determination of the Mixing angle with new, more precise, measurements.

$s\bar{s}$ *Spectroscopy at Hall D*

- Eventually need to test lattice calculations in light quark sector
- $s\bar{s}$ mesons form intermediate regime between light and heavy



- Good agreement for few confirmed states
- But many unconfirmed states
    - $f_1(1530)$
    - $h_1(1380)$
- But many puzzles:
    - $f_0(980)$
      $\eta(1440)$
    - $f_1(1420)$
    - $f_J(1710)$
    - $f_J(2200)$
    - $f_0(1500)$

- The photon has significant $s\bar{s}$ content
- Therefore can finally study strangeonium in detail
    - Fill in missing states
    - Resolve these puzzles

Summary

In the last decade we have seen much theoretical progress – especially in LGT

Need comparible experimental progress to compare to LGT results

Need theory and experiment to go hand in hand to fully understand *Soft QCD*

CLEO-c and Hall D are complementary

- **CLEO-c will study charmonium spectrum**
- **Hall D will study strangeonium spectrum**