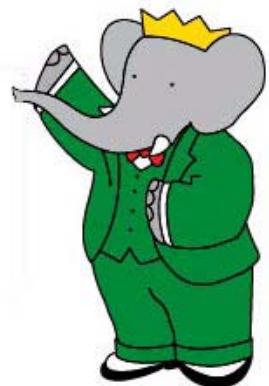


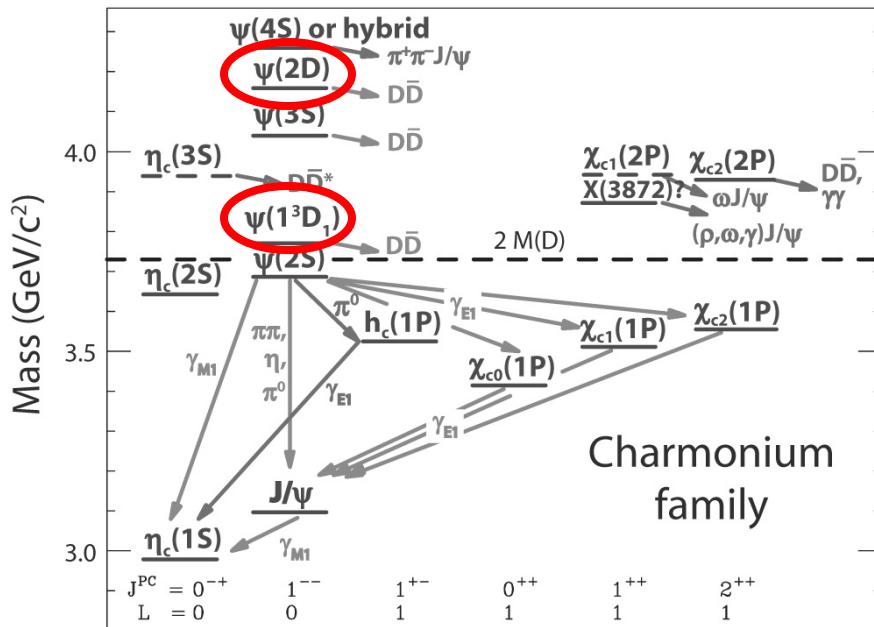
Observation of the $Y(1^3D_{J=2})$ bottomonium state through decays to $\pi^+\pi^-Y(1S)$

J. William Gary
University of California, Riverside
for the Babar Collaboration

All results are preliminary



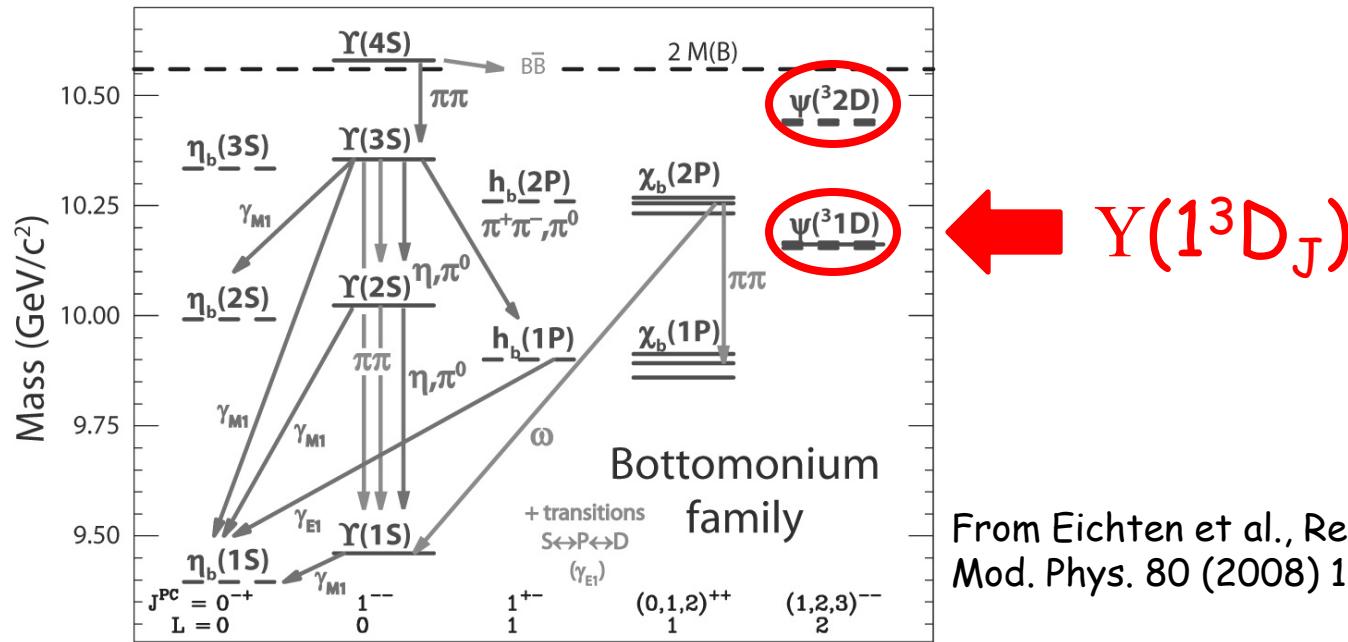
Charmonium



From Eichten et al., Rev. Mod. Phys. 80 (2008) 1161

- Two D-wave states observed: $\psi(3770)$ and $\psi(4153)$
- Above open-flavor threshold, decay to $D\bar{D}$, broad widths
 - QCD calculations above open threshold more difficult
 - Test of the calculations lacks precision

Bottomonium



From Eichten et al., Rev. Mod. Phys. 80 (2008) 1161

Expect two D-wave states below open-flavor threshold

→ Narrow states, well-defined masses

→ Opportunity for a precise test of theory based on higher L states

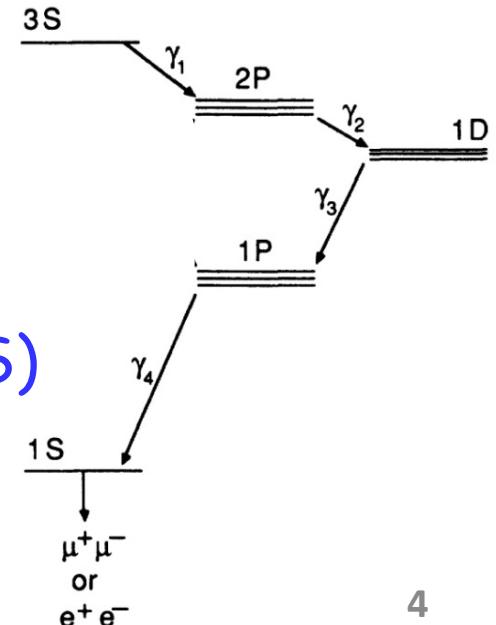
Can access $\Upsilon(1^3D_J)$ through γ transitions from the $\Upsilon(3S)$

$Y(1^3D_J)$ states

- $b\bar{b}$ bound state: $L=2, S=1 \rightarrow$ Triplet: $J=1,2,3$
- Predicted mass $\sim 10160 \pm 10$ MeV/c²
[Godfrey & Rosner, PR D64 (2001) 097501]
- Predicted separation between triplet states $\sim 5-12$ MeV
- Expected intrinsic widths ~ 30 KeV/c² \ll exptl. resolution

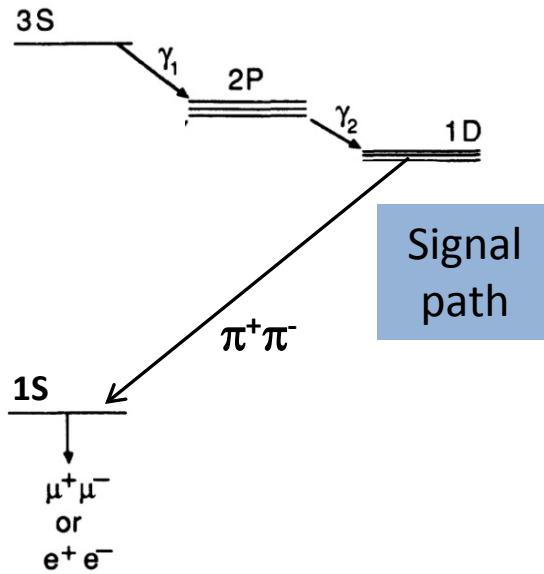
CLEO [PRD70 (2004) 032001]

- Observation of $Y(1^3D_J) \rightarrow \gamma\gamma Y(1S)$
(radiative decay channel)
- 4γ transition from the $Y(3S)$ to the $Y(1S)$
- Mass: $10161.1 \pm 0.6 \pm 1.6$ MeV/c²
- Single state seen, interpreted as $J=2$



Babar: $Y(1^3D_J) \rightarrow \pi^+\pi^-Y(1S)$

→ hadronic decay channel, with $Y(1S) \rightarrow e^+e^-$ or $\mu^+\mu^-$



- $\pi^+\pi^-l^+l^-$ invariant mass
 - provides best $Y(1^3D_J)$ mass resolution (~ 3 MeV/c 2)
 - Smallest systematic uncertainties
- The L, J & parity P can be tested from the $\pi^+\pi^-$ invariant mass, and angular distributions of the tracks
- L, J and P still need confirmation

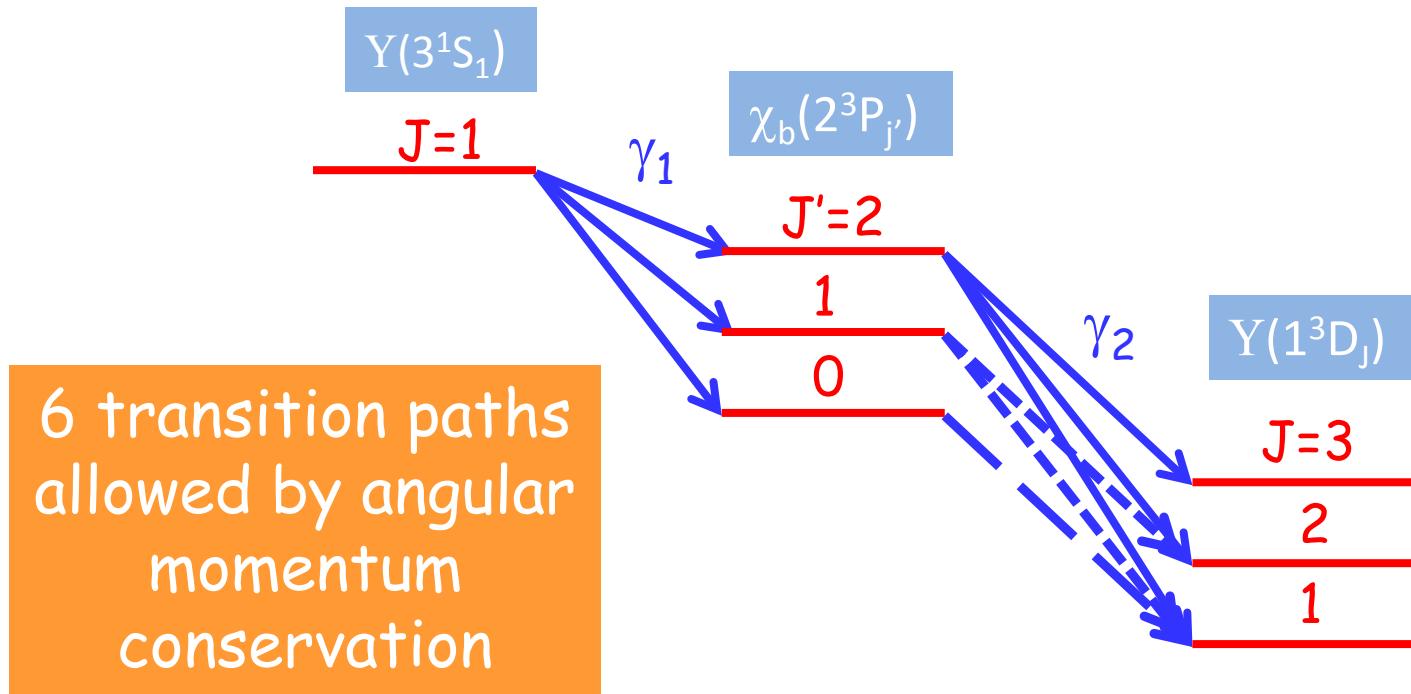
CLEO upper limit on branching fraction product:

$$Y(3S) \rightarrow 2\gamma Y(1D) \rightarrow 2\gamma \pi^+\pi^- Y(1S) \rightarrow 2\gamma \pi^+\pi^- l^+l^- < 6.6 \times 10^{-6}$$

or $Y(1D) \rightarrow \pi^+\pi^- Y(1S) < 4\% @ 90\% C.L.$

Babar: 122×10^6 $Y(3S)$ events (20x CLEO sample)

$$Y(3S) \rightarrow \gamma_1 \chi_{bJ'}(2P) \rightarrow \gamma_1 \gamma_2 Y(1^3D_J)$$



Branching fractions of $Y(3S) \rightarrow \gamma_1 \chi_{bJ'}(2P)$ are known

Branching fractions of $\chi_{bJ'}(2P) \rightarrow \gamma_2 Y(1^3D_J)$

→ predictions by Kwong & Rosner, PRD38 (1988) 279

→ partial verification from the CLEO measurement

Pure electric dipole transitions w. corresponding angular distributions

$Y(3S) \rightarrow \gamma\gamma Y(1D) \rightarrow \gamma\gamma\pi^+\pi^- Y(1S) \rightarrow \gamma\gamma\pi^+\pi^- |^{+/-}$

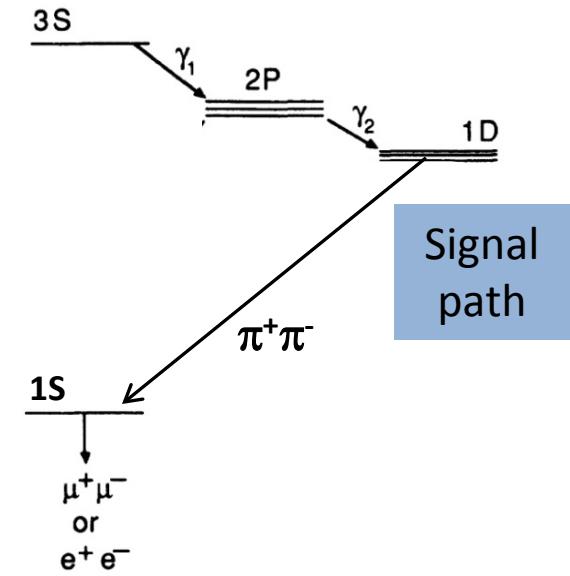
event selection

(1) Charged tracks:

- Require exactly 4 charged tracks
 - 2 identified as a $\pi^+\pi^-$ pair
 - 2 identified as an e^+e^- or $\mu^+\mu^-$ pair
- $Y(1S)$ candidate: require

$$|m_{Y(1S)} - m_{\mu^+\mu^-}| < 0.2 \text{ GeV} , \text{ or}$$

$$-0.35 < m_{Y(1S)} - m_{e^+e^-} < 0.2 \text{ GeV } (\sim 3\sigma)$$
 and then constrain $m_{|^{+/-}}$ to the $Y(1S)$ mass
- $Y(1D)$ candidate: combine $Y(1S)$ candidate with $\pi^+\pi^-$



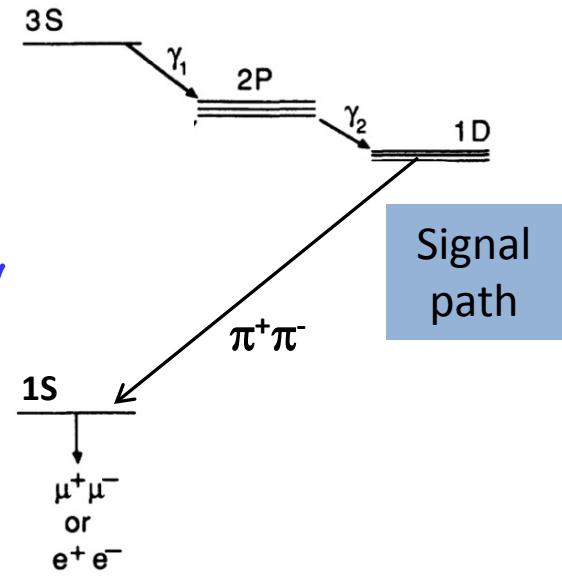
Then add 2 photons to the $Y(1D)$ candidate to form a $Y(3S)$ candidate ...

$\text{Y}(3S) \rightarrow \gamma\gamma \text{Y}(1D) \rightarrow \gamma\gamma\pi^+\pi^- \text{Y}(1S) \rightarrow \gamma\gamma\pi^+\pi^- |\text{+}|\text{-}$

event selection

(2) Photons:

- Require ≥ 1 photon consistent with $\text{Y}(3S) \rightarrow \gamma_1 \chi_b(2p)$
 - $\rightarrow E_{\gamma_1} > 70 \text{ MeV in CM ; Resolution } \sim 7 \text{ MeV}$
 - $\rightarrow \text{Expect } 86\text{-}122 \text{ MeV}$
- ≥ 1 photon consistent with $\chi_b(2p) \rightarrow \gamma_2 \text{Y}(1^3D_J)$
 - $\rightarrow E_{\gamma_2} > 60 \text{ MeV in CM}$
 - $\rightarrow \text{Expect } 80\text{-}117 \text{ MeV}$
- Choose combination that minimizes χ^2 :
- try all 6 possible paths
- No cut is made on this χ^2 !



$$\chi^2 = \sum_{i=1,2} (E_{\gamma_i} - E_{\text{expect},i})^2 / \sigma_{E_{\gamma_i}}^2$$

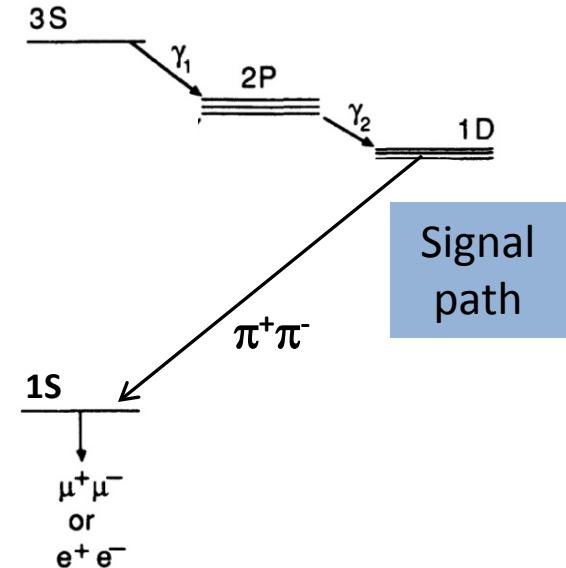
$Y(3S) \rightarrow \gamma\gamma Y(1D) \rightarrow \gamma\gamma\pi^+\pi^- Y(1S) \rightarrow \gamma\gamma\pi^+\pi^- l^+l^-$ event selection

(3) $Y(3S)$ candidate: sanity checks

- Require $Y(3S)$ CM momentum $< 0.3 \text{ GeV}/c$
- $Y(3S)$ energy (resolution 25 MeV) equals sum of beam energies within 100 MeV

→ very loose, ~100% efficient for signal;

→ $Y(3S)$ selection doesn't bias results
(verified through tests in which the
 $Y(1^3D_J)$ masses are varied)



$$m_{Y(1D)} \sim 10.16 \pm 0.01 \text{ GeV}/c^2$$

Define a wide fit interval $10.11 < m_{\pi^+\pi^-l^+l^-} < 10.28 \text{ GeV}/c^2$

263 candidate $Y(3S) \rightarrow 2\gamma Y(1D) \rightarrow 2\gamma\pi^+\pi^- Y(1S) \rightarrow 2\gamma\pi^+\pi^- l^+l^-$
events fall within the fit interval; relative number of e^+e^-
& $\mu^+\mu^-$ events consistent with expected efficiencies

Backgrounds

4 categories of background events within the fit interval
In roughly decreasing order of importance, these are:

1. $Y(3S) \rightarrow \gamma \chi_b(2P) \rightarrow \gamma \omega Y(1S)$
 - $\omega \rightarrow \pi^+ \pi^- \pi^0$
 - $\omega \rightarrow \pi^+ \pi^-$, combine with a random (noise) γ
2. $Y(3S) \rightarrow \pi^+ \pi^- Y(1S)$ with FSR γ 's
3. $Y(3S) \rightarrow \eta Y(1S)$ with $\eta \rightarrow \pi^+ \pi^- \pi^0 (\gamma)$
4. $Y(3S) \rightarrow \gamma \gamma Y(2S)$ or $\pi^0 \pi^0 Y(2S)$
with $Y(2S) \rightarrow \pi^+ \pi^- Y(1S)$

The backgrounds are small and non-peaking in the
 $Y(1^3D_J)$ signal region $10.14 < m_{\pi^+ \pi^- l^+ l^-} < 10.18 \text{ GeV}/c^2$

Maximum Likelihood fit

Probability Density Functions (PDFs):

- Define for each of the 3 $Y(1D_J)$ signal states
→ double-Gaussian + Gaussian w. exponential tail
- Each of the 4 background categories

11 free parameters:

- 3 $Y(1D_J)$ signal yields & 3 $Y(1D_J)$ masses
- Background 1 & 2 yields, $\chi_{b1}(2P)$ mass, $\chi_{b1,2}(2P) \rightarrow \omega (\rightarrow \pi^+ \pi^-)$ yields

Fix background 3 & 4 yields to expected values based on the measured branching fractions

Fit validation:

- Ensemble of (MC with full detector) simulated experiments
- Small biases (1-2 events) evaluated for signal yields
- No biases in mass values, outputs follow inputs, etc.

Data Control Sample

$Y(3S) \rightarrow \gamma \chi_b(2P) \rightarrow \gamma\gamma Y(2S) \rightarrow \gamma\gamma\pi^+\pi^- Y(1S)$
with $Y(2S) \rightarrow l^+l^-$

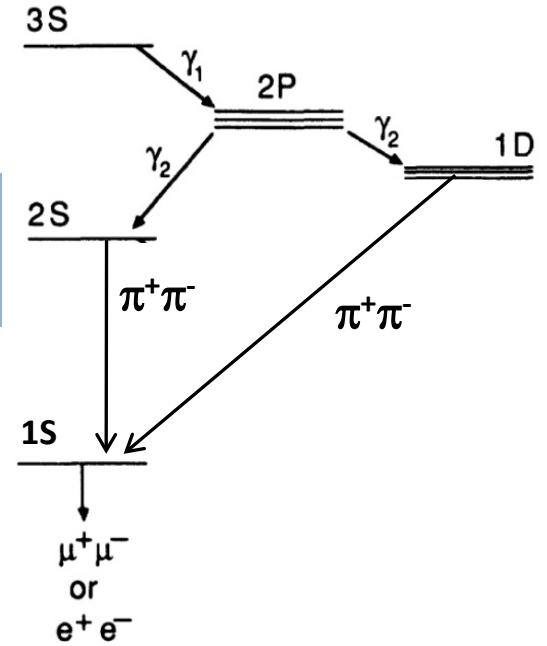
- Validate the signal PDFs
- Calibrate the mass value(s)

Compare the reconstructed $Y(2S)$ mass and resolution between data & simulation

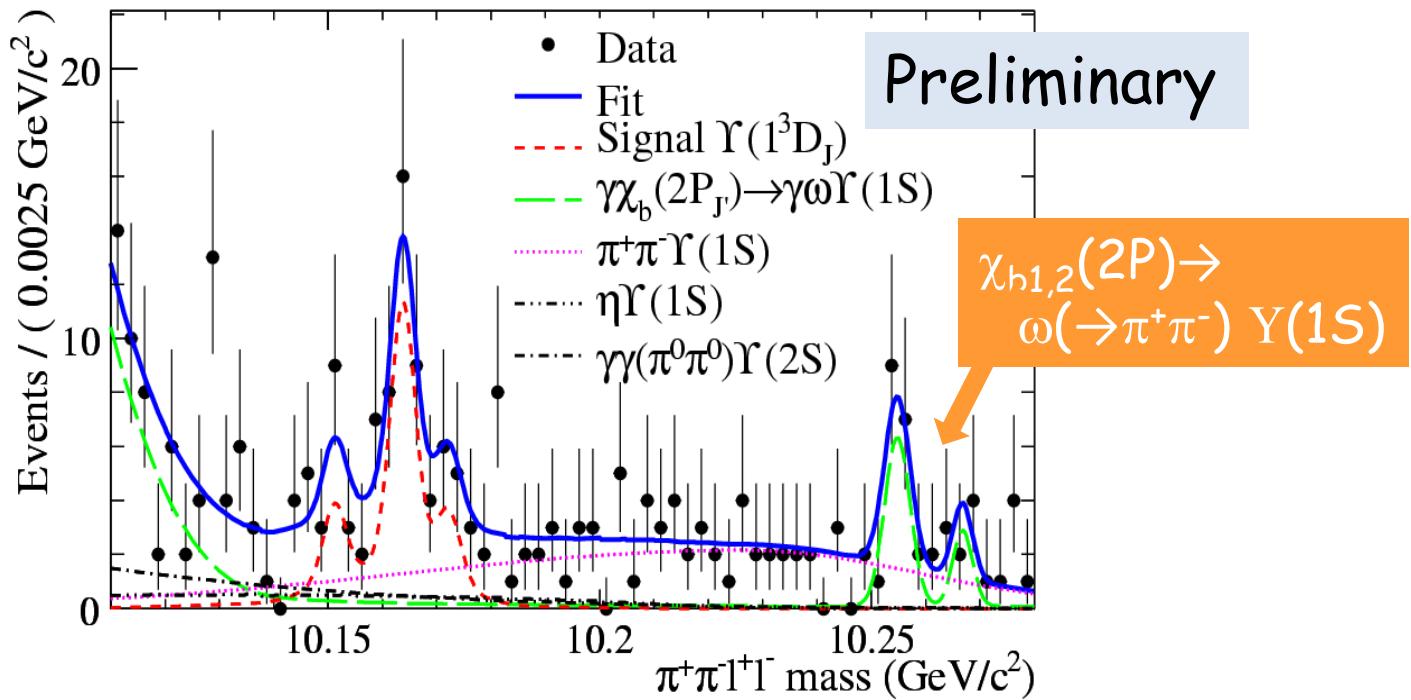
$Y(2S)$ mass low by 0.70 ± 0.15 MeV/c² compared to PDG

- apply this shift as a correction to the fitted $Y(1D_J)$ masses
- small difference in resolution results in small syst. error

Control sample



Fit results

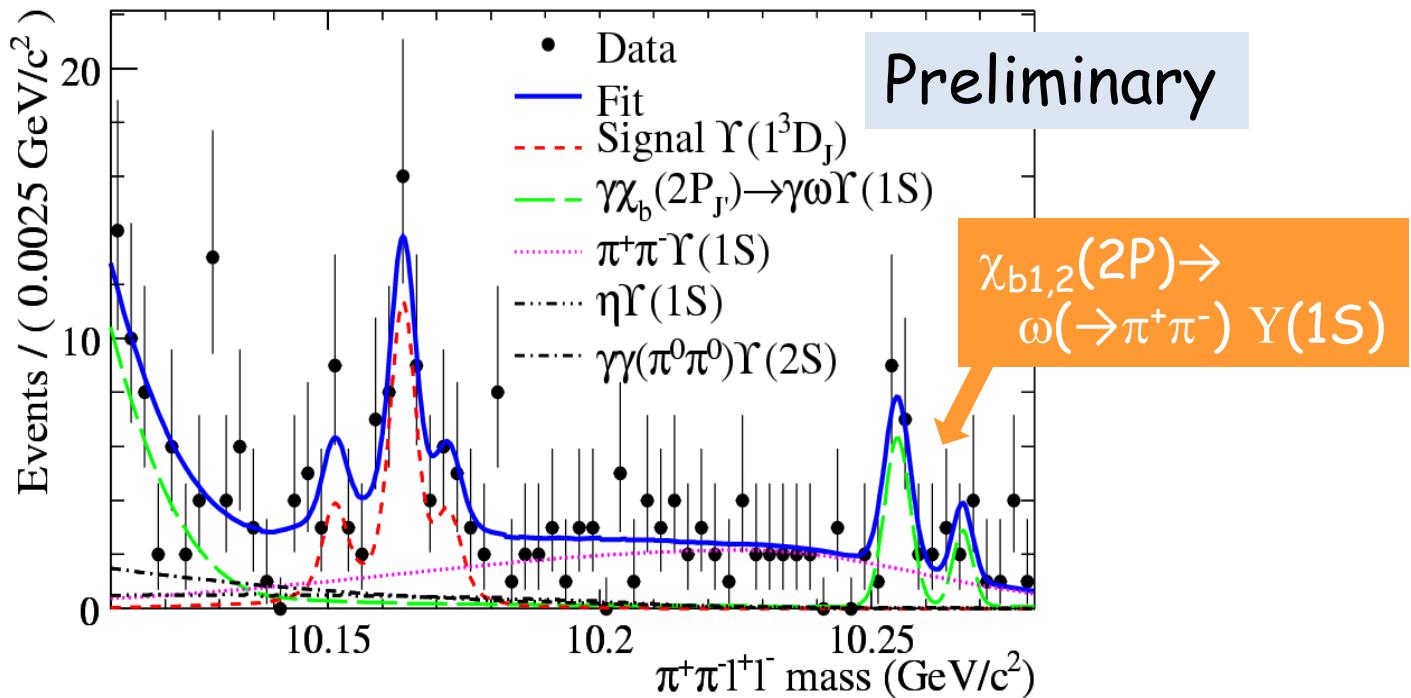


$J=1,2,3$ combined: $53.8^{+10.2}_{-9.5}$ events

7.6σ (stat. only)
 6.2σ (stat. + syst.)

→ First observation of hadronic $\Upsilon(1^3D_J)$ decays

Fit results

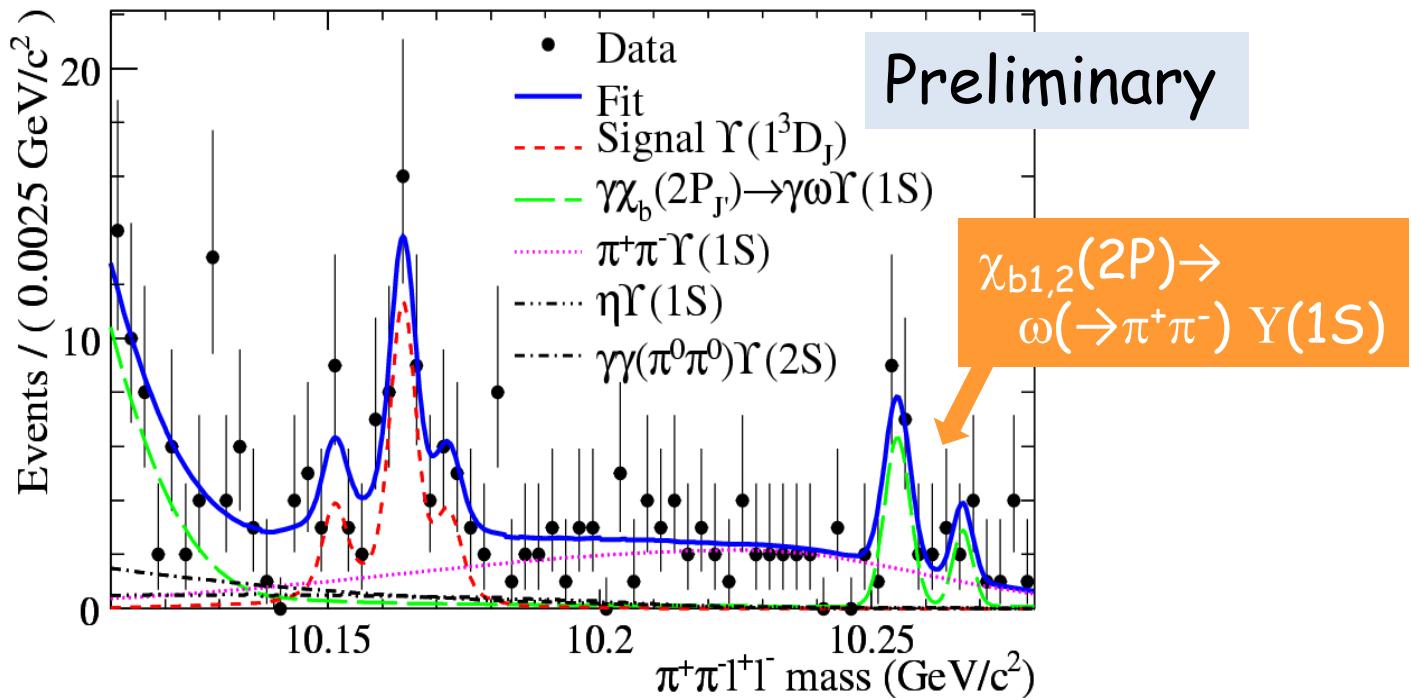


| J | Event yields | Significance (w.syst.) | Fitted mass value |
|---|----------------------|------------------------|---------------------------|
| 1 | $10.6_{-4.9}^{+5.7}$ | $2.0 \ (1.8) \sigma$ | |
| 2 | $33.9_{-7.5}^{+8.2}$ | $6.5 \ (5.8) \sigma$ | $10164.5 \pm 0.8 \pm 0.5$ |
| 3 | $9.4_{-5.2}^{+6.2}$ | $1.7 \ (1.6) \sigma$ | |

CLEO:
 $10161.1 \pm 0.6 \pm 1.6 \text{ MeV}$

Uncertainty of J=2 mass reduced by ~45%

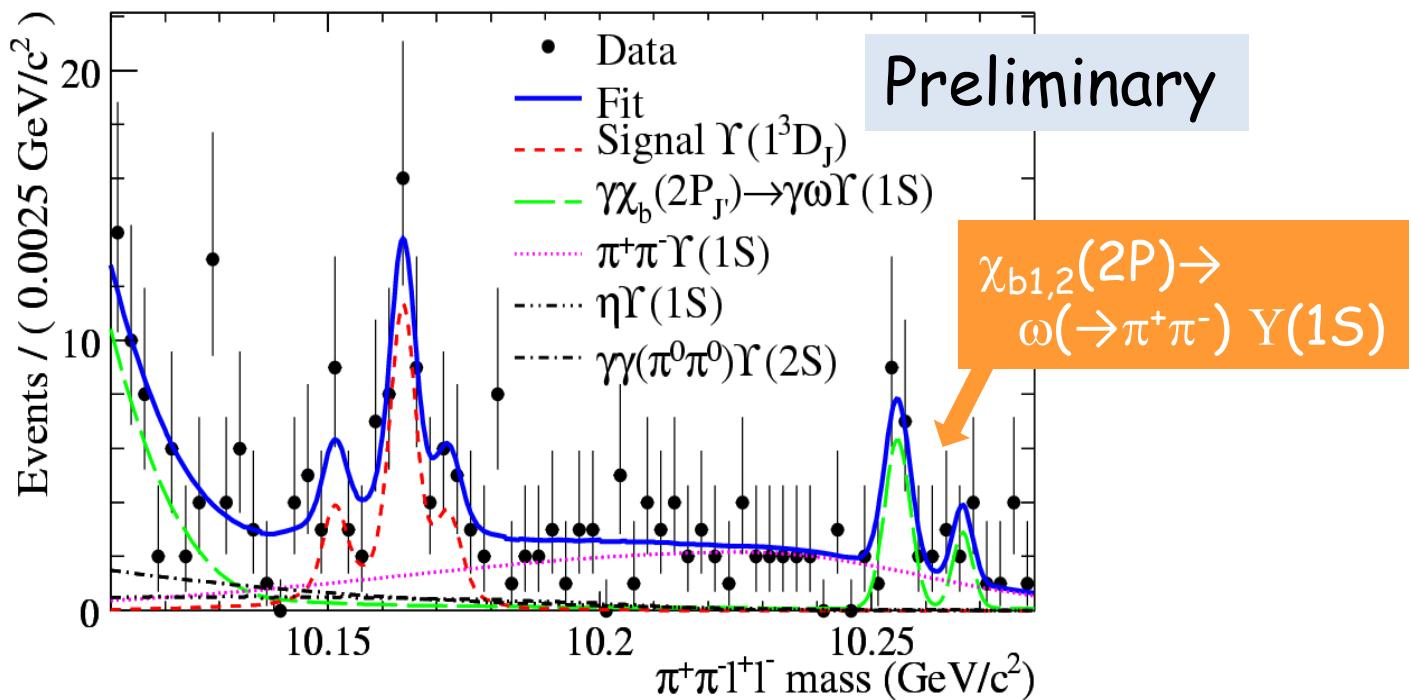
Fit results



| Fitted background yields (events) | expected | Fit |
|---|----------|-------------|
| $\Upsilon(3S) \rightarrow \gamma\chi_b(2P) \rightarrow \gamma\omega\Upsilon(1S) ; \omega \rightarrow \pi^+\pi^-\pi^0$ | 51 | 50 ± 9 |
| $\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ | 94 | 94 ± 13 |

→ No evidence for background from unaccounted sources

Fit results



| Fitted $\chi_{b1}(2P)$ mass | After correction from $Y(2S)$ | PDG |
|-----------------------------|-------------------------------|-------------------|
| 10255.0 ± 0.7 (stat.) | 10255.7 ± 0.7 | 10255.5 ± 0.5 |

→ Validation of mass calibration

Systematic Uncertainties

Dominant systematic terms ...

For the signal yields:

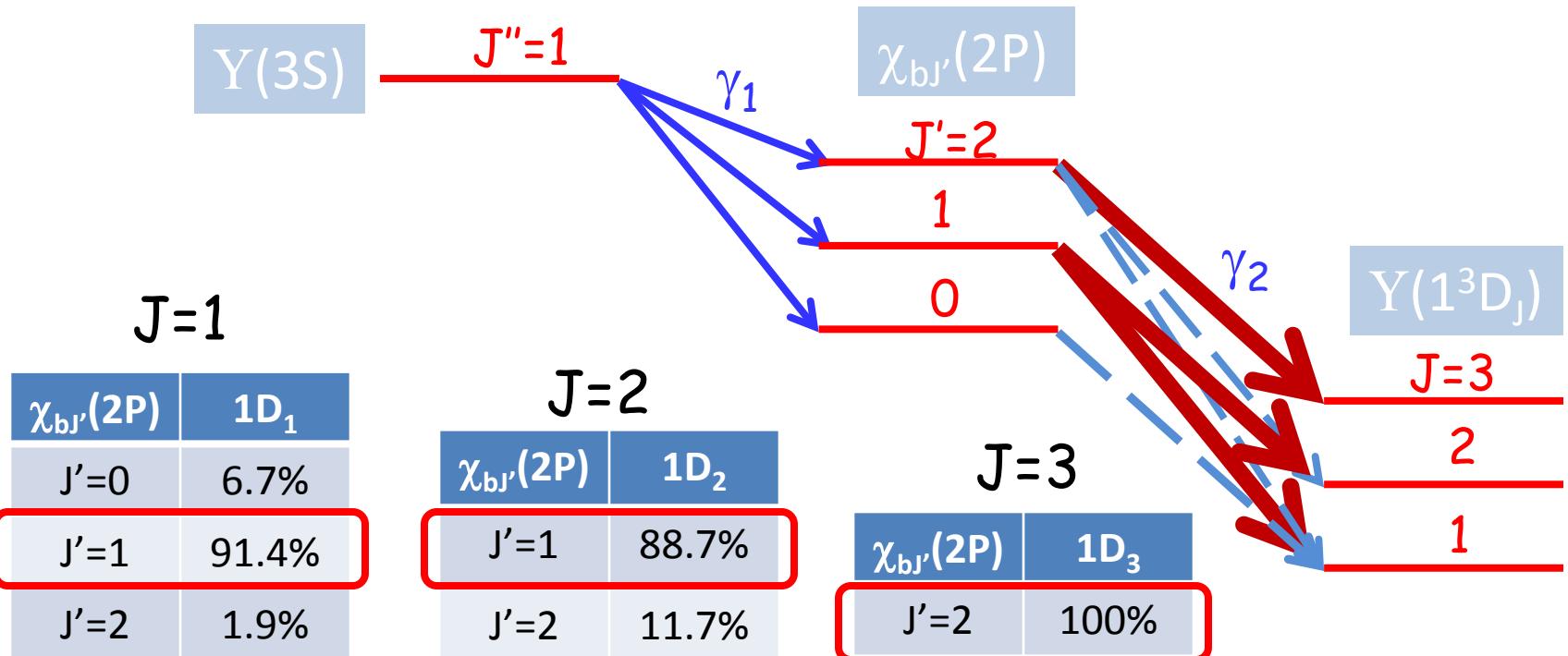
- Vary yields of the 2 non-dominant backgrounds (categories 3 & 4) by $\pm 100\%$ & uncertainties
- systematic uncertainties of $\sim \underline{2 \text{ events}}$

For the signal masses:

- The $Y(2S)$ mass calibration
- Add half the mass shift of $0.70 \text{ MeV}/c^2$ and the $Y(2S)$ mass uncertainty ($0.31 \text{ MeV}/c^2$) in quadrature
- Systematic uncertainty of $\sim \underline{0.5 \text{ MeV}/c^2}$

Plus systematics from the number of $Y(3S)$ events, reconstruction efficiencies, particle ID efficiencies, & signal PDF parametrizations [validate with $Y(2S)$ control sample]

Branching Fractions



- 6 unknown BFs with efficiencies that differ by up to ~7.5%
- Only 3 measured yields
- Determine the 3 dominant BFs only
- Ratios relative to the minor BFs fixed according to theory

[Kwong & Rosner, PRD38 (1988) 279]

Preliminary Branching Fractions

- $BF = (\text{yield} - \text{bias}) / [\text{efficiency} \times N_{Y(3S)}]$
- Efficiency $\approx 26\%$ averaged over $Y(1S) \rightarrow \mu^+\mu^-$ & e^+e^- , for $J=1,2,3$
- $N_{Y(3S)} = 122 \times 10^6$ events

Branching fraction product for entire decay chain,
 $Y(3S) \rightarrow \gamma \chi_{bJ'}(2P) \rightarrow 2\gamma Y(1^3D_J) \rightarrow 2\gamma \pi^+\pi^- Y(1S) \rightarrow 2\gamma \pi^+\pi^- l^+l^-$,
and for the dominant modes only:

| $\chi_{bJ'}(2P)$ | 1^3D_J | Product BF | 90% C.L. upper limit |
|------------------|----------|--|-------------------------|
| $J'=1$ | $J=1$ | $(1.27_{-0.69}^{+0.81} \pm 0.28) \times 10^{-7}$ | $< 2.50 \times 10^{-7}$ |
| $J'=1$ | $J=2$ | $(4.9_{-1.0}^{+1.1} \pm 0.3) \times 10^{-7}$ | |
| $J'=2$ | $J=3$ | $(1.34_{-0.83}^{+0.99} \pm 0.24) \times 10^{-7}$ | $< 2.80 \times 10^{-7}$ |

CLEO upper limit: $< 6.6 \times 10^{-6}$

Compare Branching Fractions to theory

Divide measured branching fraction products by

- the known $Y(3S) \rightarrow \gamma_1 \chi_b(2P)$ BF's
- the Kwong & Rosner predictions for the $\chi_b(2P) \rightarrow \gamma_2 Y(1^3D)$ BF's

| from J. Rosner, PRD67 (2003) 097504 | | | | | |
|-------------------------------------|--|-------------------------|-----------------------|--------------|------------------|
| 1^3D_J | BF [$Y(1^3D_J) \rightarrow \pi^+ \pi^- Y(1S)$] | 90% C.L. upper limit | Kwang & Yan (1981) | Ko (1993) | Moxhay (1988) |
| J=1 | $(0.42_{-0.23}^{+0.27} \pm 0.10)\%$ | < 0.82% | 40% | 1.6% | 0.20% |
| J=2 | $(0.66_{-0.14}^{+0.15} \pm 0.06)\%$ | | 46% | 2.0% | 0.25% |
| J=3 | $(0.29_{-0.18}^{+0.22} \pm 0.06)\%$ | < 0.62% | 49% | 2.2% | 0.27% |

Kwang & Yan don't account for centrifugal barrier [see Kwong & Rosner, PRD38 (1988) 279]

CLEO limit < ~4% @ 90% C.L. already excludes Kwang & Yan

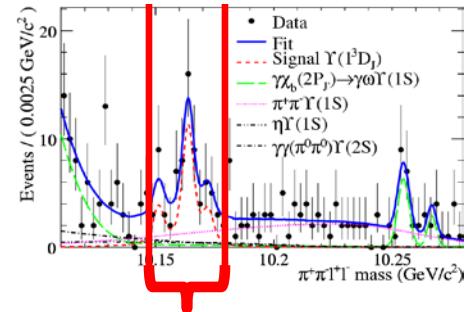
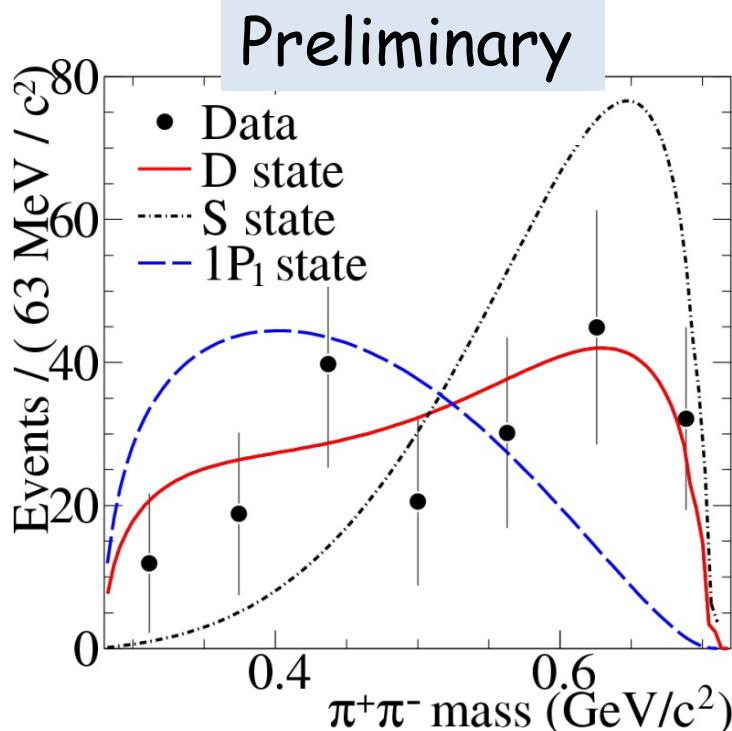
Multiply predictions by 2/3 to obtain $\pi^+ \pi^-$ contribution:
→ data halfway between Ko ~ 1.3% & Moxhay ~ 0.16%

The $\pi^+\pi^-$ invariant mass

[T.-M. Yan, PRD22 (1980) 1652; Y.-P. Kuang et al., PRD37 (1988) 1210]

Background subtracted using the estimates from the ML fit

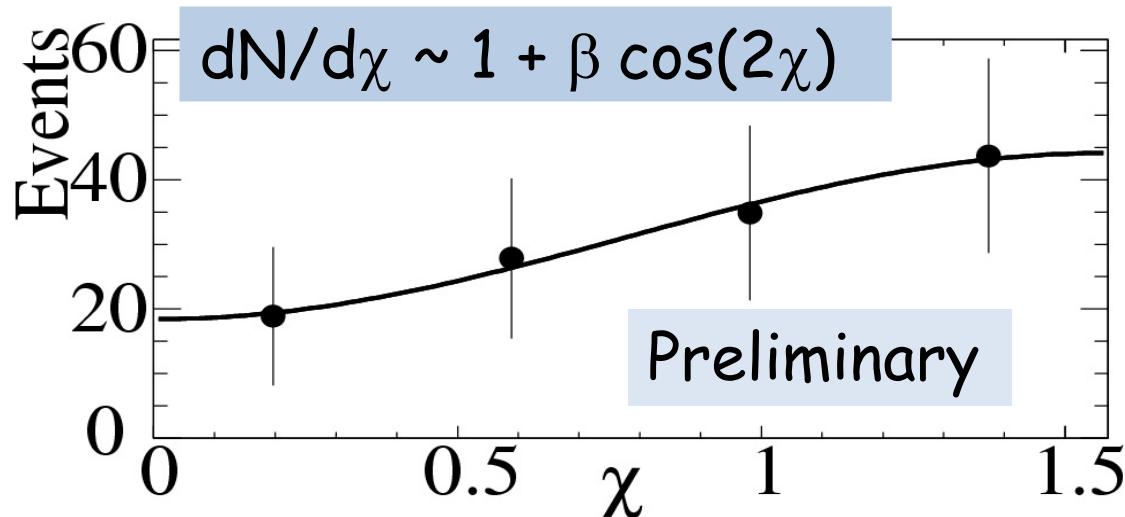
Corrected for mass-dependent variation in efficiency



Select events in $\Upsilon(1^3D_J)$ region:
10.14 to 10.18
 GeV/c^2

χ^2 probability for decay of a D, S, or 1P_1 bottomonium state to $\pi^+\pi^-\Upsilon(1S)$: 84.6, 3.1, or 0.3%

Angle χ between the $\pi^+\pi^-$ & l^+l^- planes



$|\beta|$: depends on unknown helicity amplitudes,
etc. → determine from data

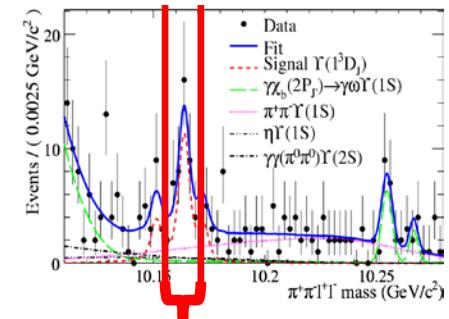
Sign of β : $\text{sign}(\beta) = (-1)^{JP}$ P=parity

[J.R. Dell'Aquila & C.A. Nelson, PRD33 (1986) 80]

Fit: $\beta = -0.41 \pm 0.29 \pm 0.10 \rightarrow$ consistent with J=2 & P=-1

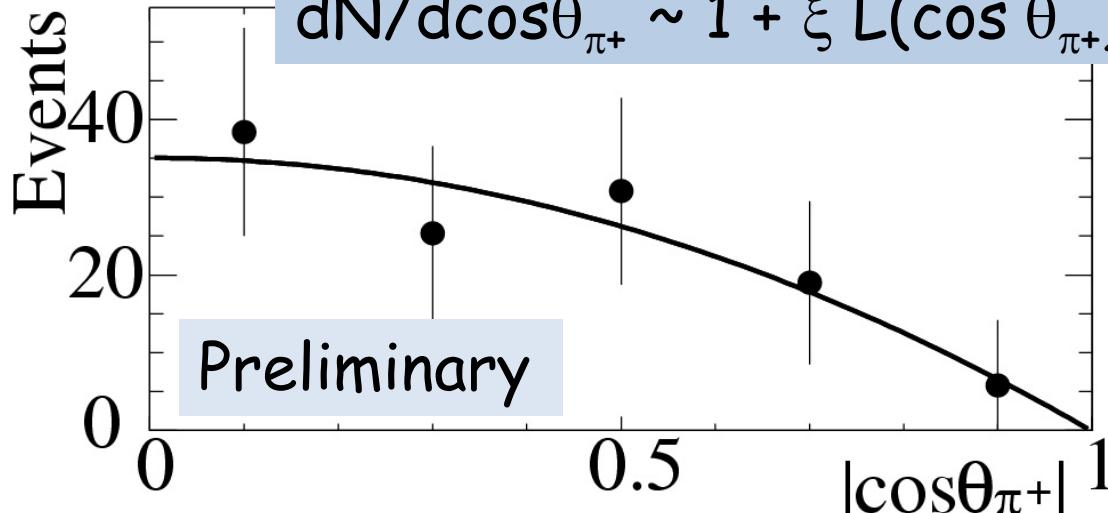
[were J odd, $dN/d\chi$ would decrease with increasing χ for P=-1]

Define χ in the
 $Y(1^3D_{J=2})$ rest
frame



Select events in $Y(1^3D_{J=2})$
region:
10.155 to 10.168 GeV/c^2

π^+ helicity angle θ_{π^+}



$\xi \rightarrow$ determine from data

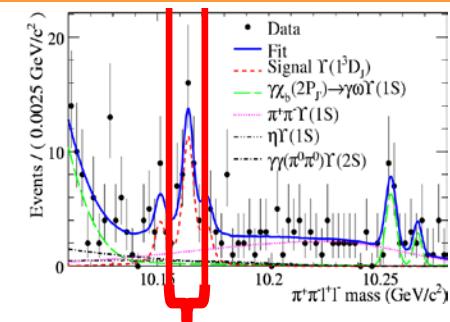
Were the observed "Y(1D)" an S state,
the $\pi^+\pi^-$ would be emitted in an S-wave
 $\rightarrow \xi = 0$

For a D state with $J=2$, need $L_{\pi\pi}=2$

$$dN/d\cos\theta_{\pi^+} \sim 1 + \xi (3\cos^2\theta_{\pi^+} - 1)/2$$

Fit: $\xi = -1.0 \pm 0.4 \pm 0.1 \rightarrow$ Disfavors S-wave hypothesis
Consistent with $J=2$

Angle of π^+ in
 $\pi^+\pi^-$ rest frame
wrt boost from
 $Y(1^3D_{J=2})$ frame



Select events in $Y(1^3D_{J=2})$
region:
10.155 to 10.168 GeV/c²

Summary

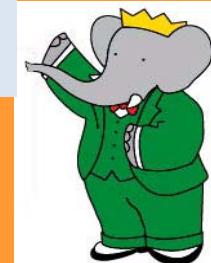
arXiv:1004.0175 [hep-ex]

- We have observed the $Y(1^3D_J)$ through hadronic decays

$$Y(3S) \rightarrow \gamma \chi_{bJ}(2P) \rightarrow 2\gamma Y(1^3D_J) \rightarrow 2\gamma \pi^+ \pi^- Y(1S)$$

- 54 events (6.2σ stat.+syst.), 34 in the $J=2$ peak (5.8σ)
- $m_{Y(1D,J=2)} = 10164.5 \pm 0.8 \pm 0.5 \text{ MeV}/c^2$
- $\text{BF}[Y(1^3D_{J=2}) \rightarrow \pi^+ \pi^- Y(1S)] = (0.66_{-0.14}^{+0.15} \pm 0.06)\%$
- $\pi^+ \pi^-$ mass distribution of the $Y(1^3D_J)$ consistent with $L=2$
- Charged particle angular distributions in decays of the dominant $Y(1^3D_{J=2})$ state
 - Disfavor $L=0$
 - Are consistent with $L=2, J=2, P=-1$

Preliminary



BACKUP

Branching Fraction Calculation

e.g., for transitions through the $\Upsilon(1^3D_{J=2})$ state

$$N_{1D_2} = N_{3S} \left[(\epsilon_{12}^e + \epsilon_{12}^\mu) \mathcal{B}_{3S \rightarrow 2P_1} \mathcal{B}_{2P_1 \rightarrow 1D_2} \mathcal{B}_{1D_2 \rightarrow \pi\pi\Upsilon(1S)} \mathcal{B}_{\Upsilon(1S) \rightarrow \ell\ell} \right. \\ \left. + (\epsilon_{22}^e + \epsilon_{22}^\mu) \mathcal{B}_{3S \rightarrow 2P_2} \mathcal{B}_{2P_2 \rightarrow 1D_2} \mathcal{B}_{1D_2 \rightarrow \pi\pi\Upsilon(1S)} \mathcal{B}_{\Upsilon(1S) \rightarrow \ell\ell} \right],$$

$\varepsilon_{J'J}$ = efficiency for the transition path through
the $\chi_b J'$ and $\Upsilon(1^3D_J)$

$$= N_{3S} \underbrace{\mathcal{B}_{3S \rightarrow 2P_1} \mathcal{B}_{2P_1 \rightarrow 1D_2} \mathcal{B}_{1D_2 \rightarrow \pi\pi\Upsilon(1S)} \mathcal{B}_{\Upsilon(1S) \rightarrow \ell\ell}}_{\text{Quoted branching fraction product}} \left[1 + \frac{(\epsilon_{22}^e + \epsilon_{22}^\mu) \mathcal{B}_{3S \rightarrow 2P_2} \mathcal{B}_{2P_2 \rightarrow 1D_2}}{(\epsilon_{12}^e + \epsilon_{12}^\mu) \mathcal{B}_{3S \rightarrow 2P_1} \mathcal{B}_{2P_1 \rightarrow 1D_2}} \right] \underbrace{\varepsilon_{J'J}}_{\text{Kwong & Rosner}}$$