Recent results on bottomonium spectroscopy from Babar

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Babar experiment

• PEP-II rings: Asymmetric e+e- collider @ SLAC
• Collected data 1999-2008; data analysis still very active

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y(4S)</td>
<td>430 fb⁻¹</td>
</tr>
<tr>
<td>Y(3S)</td>
<td>30 fb⁻¹</td>
</tr>
<tr>
<td>Y(2S)</td>
<td>14 fb⁻¹</td>
</tr>
<tr>
<td>Other</td>
<td>~60 fb⁻¹</td>
</tr>
</tbody>
</table>

- CPV in B decays, CKM physics \( \sim 465 \times 10^6 \ Y(4S) \rightarrow B\bar{B} \) events
- \( \sim 650 \times 10^6 \ e^+e^- \rightarrow c\bar{c} \) events: 1ˢᵗ observation of \( D^0-\bar{D}^0 \) mixing [2007]
- \( \sim 430 \times 10^6 \ e^+e^- \rightarrow \tau^+\tau^- \) events (360 x combined LEP sample): LFV
- ISR events: unique access to low energy \( e^+e^- \) cross sections

Bill Gary, ISMD 2010, Sept. 21, 2010
**Topics**

**Bottomonium: Y(3S) sample**

(I) Search for $\eta_b$ using $\gamma \rightarrow e^+e^-$ conversions (singlet L=0) [also uses the $\Upsilon(2S)$ sample]

(II) Search for $h_b(1P)$ state (singlet L=1)

(III) Observation of $1D_{J=2}$ state (triplet L=2) [arXiv:1004.0175]

All results are preliminary
Bottomonium

- Spectrum below open-flavor threshold richer than charmonium
- Masses & BFs important to test potential models & lattice QCD
- Hadronic transitions probe non-perturbative QCD

- Bottomonium states with \( L = 0,1 \) & \( S = 1 \) → known since 1970s & 1980s
- \( \Upsilon(1D_{J=2}) \) observed by CLEO (2004)
- \( \eta_b \) by Babar (2008)
- \( h_b(1P) \) state not yet observed

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

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From Eichten et al., Rev. Mod. Phys. 80 (2008) 1161 — seen
--- --- = unseen
= the states discussed here

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$\eta_b$ and $h_b$: hyperfine mass splittings → spin dependence of the $q\bar{q}$ potential

From Eichten et al., Rev. Mod. Phys. 80 (2008) 1161
(I) $\eta_b$ search using $\gamma \rightarrow e^+e^-$ conversions

L=0, S=0 singlet

Bottomonium family
$\eta_b$ search using $\gamma \rightarrow e^+e^-$ conversions

- $\eta_b$ discovered in the recoil $\gamma$ spectrum in $\Upsilon(3S) \rightarrow \gamma \eta_b$
- Confirmed by Babar in $\Upsilon(2S)$ [2009] and by CLEO in $\Upsilon(3S)$ [2010]

World average mass: $9390.9 \pm 2.8$ MeV
**η_b search using γ→e⁺e⁻ conversions**

New study: Y(3S) & Y(2S) → γ η_b using γ → e⁺e⁻
Converted photons: 5x better energy resolution (25→5 MeV)

Reconstructed E_γ in Y(3S) → γη_b MC events (CM frame)

5 monochromatic γs in η_b region:
1-3) χ_bJ(2p)→γ2p Y(1S); J=0,1,2
4) ISR e⁺e⁻→γ_isr Y(1S)
5) Signal γ

Detection efficiency lower but still expect ~ 3σ significance → independent measurement of η_b mass
Identify $\gamma \rightarrow e^+e^-$ conversions ($\chi^2$ test; require $m_\gamma < 30$ MeV)

Veto $\gamma \rightarrow e^+e^-$'s that form a $\pi^0$ candidate with any other $\gamma$

Other cuts: thrust, multiplicity

$\chi^2$ fit to $\gamma$ recoil energy spectrum
  $\rightarrow$ Combinatoric background
  $\rightarrow$ 5 "peaking" components
  $\rightarrow$ Simultaneous fit to the $\Upsilon(3S) & \Upsilon(2S)$ samples with the $\eta_b$ mass a fitted parameter
η_b search using γ→e^+e^- conversions

Y(3S) sample

Signal efficiency=1.4%

773±220 η_b events (expect 770)
**η_b search using γ→e^+e^- conversions**

**Y(2S) sample**

**Signal efficiency**

= 1.1%

χ_bJ(1P), J=0,1,2

289±281 η_b events (expect 390)

**PRL 103(2009)161801**
**η_b** search using γ→e+e- conversions

- Simultaneous fit to Y(2S) & Y(3S) sample
  - $\eta_b$: 3.3σ (stat.) ; 2.6σ (stat.+syst.),

- Fitted $\eta_b$ mass shifted +12 MeV from world average: significance of shift (~2.5σ) under investigation

- Side-benefit of analysis: the separated $Y(nS) \rightarrow \gamma\chi_{bJ}(n-1P) \rightarrow \gamma\gamma Y(1S)$ BFs
  - $\rightarrow$ uncertainties reduced by ~3-4 compared to current world averages

<table>
<thead>
<tr>
<th>nS</th>
<th>mP</th>
<th>J</th>
<th>BF (x10^-3)</th>
<th>PDG</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2</td>
<td>1</td>
<td>13.0±0.3±0.7</td>
<td>10.7±1.9</td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>2</td>
<td>9.6±0.3±0.5</td>
<td>9.3±1.7</td>
<td>2.9</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>25.2±0.6±1.2</td>
<td>24.2±5.7</td>
<td>4.2</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
<td>14.4±0.5±0.8</td>
<td>15.7±3.0</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Fitted $\eta_b$ mass: 9403.3±2.4^{+0.9}_{-1.5}$ MeV
(II) Search for $h_b(1P)$ state

Expect $m_{h_b(1P)} = \left[ m_{\chi b_0(1P)} + 3m_{\chi b_1(1P)} + 5m_{\chi b_2(1P)} \right] / 9 \approx 9900$ MeV

$L=1, S=0$ singlet

Bottomonium family

Intrinsic width $\sim 0.1$ MeV
Search for $h_b(1P)$

- $\Upsilon(3S) \rightarrow \gamma h_b$ forbidden (C-parity)

- Favored production mechanisms
  
  $B[\Upsilon(3S) \rightarrow \pi^0 h_b] \sim 4 \times 10^{-4}$ [Voloshin]
  $B[\Upsilon(3S) \rightarrow \pi^+ \pi^- h_b] \sim 10^{-5}$ [Voloshin]
  $\sim 10^{-3}-10^{-4}$ [KTY]

  Kuang, Tuan & Yan, PR D37 (1988) 1210

- Expected decays: $h_b \rightarrow \gamma \eta_b$ ($\sim 41\%$), $ggg$ ($57\%$), $\gamma gg$ ($2\%$)
Search for $h_b(1P)$

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- Expected decays: $h_b \to \gamma \eta_b$ (~41%), $ggg$ (57%), $\gamma gg$ (2%)

- $S/B$ enhanced by requiring monochromatic $\gamma_m$: $h_b \to \gamma_m \eta_b$

- Expect $E_{\gamma_m} = 490$ MeV (resolution 25 MeV)

- $h_c(1P)$ observed in analogous decay chain: $\psi(2S) \to \pi^0 h_c$; $h_c \to \gamma_m \eta_c$
  - [CLEO 2005; BES 2010]
\[ \Upsilon(3S) \rightarrow \pi^0 h_b \text{ channel} \]

- Reconstruct \( \pi^0 \rightarrow \gamma \gamma \) candidate \([50 < m_{\gamma\gamma} < 200 \text{ MeV}]\)
- Reject if a signal \( \pi^0 \rightarrow \gamma \gamma \) photon forms a \( \pi^0 \) with any other photon \((<15 \text{ MeV of } m_{\pi^0})\)
- \( \gamma \) helicity \(|\cos \Theta_h| < 0.7\) in \( \pi^0 \) CM
- Recoil mass against the \( \pi^0 \)

\[
M_{\text{recoil}} \equiv \sqrt{(E_{\Upsilon(3S)}^* - E_{\pi^0}^*)^2 - (p_{\pi^0}^*)^2}
\]

(peaks at \( h_b \) mass for signal)

- Require a photon consistent with \( h_b \rightarrow \gamma_m \eta_b \): \( 420 < E_{\gamma_m}^* < 540 \text{ MeV} \)
- Reject event if \( \gamma_m \) forms a \( \pi^0 \) candidate with any other photon
- Overall reconstruction efficiency \( \sim 22\% \)
Recoil mass: $\Upsilon(3S) \rightarrow \pi^0 h_b$

- $\chi^2$ fit: smooth combinatoric background + signal peak
- $h_b$ mass and yield free
- $8682 \pm 2981$ signal events
  - $\sim 3\sigma$ (stat.), $2.7\sigma$ (stat.+syst.)

- Fitted mass: $9903 \pm 4$ MeV
  - agrees with expectation (9900)

- Product BF
  - $B[\Upsilon(3S) \rightarrow \pi^0 h_b ] \times B[h_b \rightarrow \gamma \eta_b ]$
  - $= (3.3\pm1.1\pm0.4) \times 10^{-4}$
  - agrees with Voloshin (1986)
  - $[=4 \times 10^{-4}]$

[CLEO (1994): $<2.7 \times 10^{-3}$ for $m_{h_b}=9.9$ GeV]
$Y(3S) \rightarrow \pi^+\pi^- h_b$ channel

- Select identified $\pi^+\pi^-$ pair that originates at IP
- Remove obvious $K_S$ candidates
- Recoil mass against the $\pi^+\pi^-$

$$M_{recoil} \equiv \sqrt{(E^*_{Y(3S)} - E^*_{\pi^+\pi^-})^2 - (\vec{p}^*_{\pi^+\pi^-})^2}$$

* = CM [=$Y(3S)$] frame

- Fully inclusive search (no $h_b \rightarrow \gamma m \eta_b$ requirement to increase efficiency)
- Reconstruction efficiency $\sim 42\%$
Recoil mass: \( Y(3S) \rightarrow \pi^+\pi^-h_b \)

\[ [Y(3S) \rightarrow Y(2S)+X] \]

\[ Y(2S) \rightarrow \pi^+\pi^-Y(1S) \]

\[ Y(3S) \rightarrow \pi^+\pi^-Y(2S) \]

\( \chi^2 \) fit \( \rightarrow \) Fitted signal yield (\( m_{hb}=9900 \) MeV): \(-1106\pm2432\) events

\[ [Y(3S) \rightarrow \gamma \chi_{bJ}(2P)] \]

\( \chi_{bJ}(2P) \rightarrow \pi^+\pi^-\chi_{bJ}(1P); J=J'=1,2 \)
→ No indication of a signal in the $\Upsilon(3S) \rightarrow \pi^{+}\pi^{-}h_{b}$ channel

$B[\Upsilon(3S) \rightarrow \pi^{+}\pi^{-}h_{b}] < 1.0 \times 10^{-4}$ at 90% CL for $m_{h_{b}} = 9.9$ GeV

[CLEO 1994: $< 1.8 \times 10^{-3}$ for $m_{h_{b}} = 9.9$ GeV]

→ Predictions for ratio $B[\Upsilon(3S) \rightarrow \pi^{0}h_{b}] / B[\Upsilon(3S) \rightarrow \pi^{+}\pi^{-}h_{b}]$:

$\sim 20$ [Voloshin] ; $\sim 1/20$ [Kuang et al.]

→ data more consistent with Voloshin
Observation of $1^3D_J$ state

- Predicted mass $\sim 10160 \pm 10$ MeV [Godfrey & Rosner, PRD64 (2001) 097501]

- Predicted separation between triplet states $\sim 5-12$ MeV
- Expected intrinsic widths $\sim 30$ KeV $\ll$ exptl. resolution
• Observation of $\Upsilon(1^{3}D_{J=2}) \rightarrow \gamma\gamma\Upsilon(1S)$ (radiative decay channel)

• 4\(\gamma\) transition from the $\Upsilon(3S)$ to the $\Upsilon(1S)$

• Mass: $10161.1 \pm 0.6 \pm 1.6$ MeV

• Single state seen, interpreted as $J=2$ based on comparison of the measured & expected BFs and the observed $\gamma$ energies

• Awaits confirmation of $L, J, P$
Babar: $Y(1^{3}D_{J}) \rightarrow \pi^{+}\pi^{-}Y(1S)$

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

- $\pi^{+}\pi^{-}l^{+}l^{-}$ invariant mass
  $\rightarrow$ provides best $Y(1^{3}D_{J})$ mass resolution ($\sim 3$ MeV)
  $\rightarrow$ Smallest systematic uncertainties

- The L, J & parity P can be tested from the $\pi^{+}\pi^{-}$ invariant mass, and angular distributions of the tracks

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.
(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
- $\Upsilon(1S)$ candidate: require
  \[ |m_{\Upsilon(1S)} - m_{\mu^+\mu^-}| < 0.2 \text{ GeV} \], or\[ -0.35 < m_{\Upsilon(1S)} - m_{e^+e^-} < 0.2 \text{ GeV} \] (~3$\sigma$)
  and then constrain $m_{l^+l^-}$ to the $\Upsilon(1S)$ mass
- $\Upsilon(1D)$ candidate: combine $\Upsilon(1S)$ candidate with $\pi^+\pi^-$

(2) **Photons:**

Add 2 photons consistent with the decay chain to form a $\Upsilon(3S)$ candidate ...
(3) **Y(3S) candidate**: sanity checks

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

→ very loose, ~100% efficient for signal;

(4) **Maximum Likelihood fit**

- 3 signal peaks ($J=1,2,3$), mass and yield of each peak is floated
- All known backgrounds, which are small and non-peaking in the $Y(1^3D_J)$ signal region
**Fit results**

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

$\rightarrow$ First observation of hadronic $\Upsilon(1^{3}D_{J})$ decays

- **Fit results**
  - 7.6 $\sigma$ (stat. only)
  - 6.2 $\sigma$ (stat. + syst.)

**Preliminary**

- $\chi_{b1,2}(2P)\rightarrow\omega(\rightarrow\pi^{+}\pi^{-})\Upsilon(1S)$
### Preliminary Fit results

<table>
<thead>
<tr>
<th>J</th>
<th>Event yields</th>
<th>Significance (w.syst.)</th>
<th>Fitted mass value</th>
<th>CLEO: 10161.1±0.6 ±1.6 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.6_{-4.9}^{+5.7}</td>
<td>2.0 (1.8) σ</td>
<td>10164.5 ± 0.8 ± 0.5</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>33.9_{-7.5}^{+8.2}</td>
<td>6.5 (5.8) σ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>9.4_{-5.2}^{+6.2}</td>
<td>1.7 (1.6) σ</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Uncertainty of J=2 mass reduced by ~45%
Branching Fractions

\[ J'^{=1} \]

\[ Y(3S) \]

\[ \chi_{bJ'}(2P) \]

\[ J'=2 \]

\[ \gamma_1 \]

\[ \gamma_2 \]

\[ \gamma_3 \]

\[ 1 \]

\[ 0 \]

\[ \gamma_4 \]

\[ \gamma_5 \]

\[ \gamma_6 \]

\[ 1 \]

\[ 2 \]

\[ 3 \]

\[ 1^3D_j \]

\[ \text{J} = 1 \]

\[ \chi_{bJ'}(2P) \]

\[ 1D_1 \]

\[ J' = 0 \]

6.7%  

J' = 1 91.4%  

J' = 2 1.9%  

\[ \text{J} = 2 \]

\[ \chi_{bJ'}(2P) \]

\[ 1D_2 \]

\[ J' = 0 \]

\[ J' = 1 \] 88.7%  

\[ J' = 2 \] 11.7%  

\[ \text{J} = 3 \]

\[ \chi_{bJ'}(2P) \]

\[ 1D_3 \]

\[ J' = 0 \]

\[ J' = 1 \] 100%  

\[ J' = 2 \]

\[ \rightarrow 6 \text{ unknown BF}s with efficiencies that differ by up to } \sim 7.5\% \]

\[ \rightarrow \text{Only 3 measured yields} \]

\[ \rightarrow \text{Determine the 3 dominant BF}s only} \]

\[ \rightarrow \text{Ratios relative to the minor BF}s fixed according to theory} \]

• BF = (yield - bias) / [efficiency x N_{Y(3S)}]
• Efficiency ≈ 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:

<table>
<thead>
<tr>
<th>\chi_{bJ'}(2P)</th>
<th>1^3D_J</th>
<th>Product BF</th>
<th>90% C.L. upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>J'=1</td>
<td>J=1</td>
<td>(1.27_{-0.69}^{+0.81}\pm 0.28) \times 10^{-7}</td>
<td>&lt; 2.50 \times 10^{-7}</td>
</tr>
<tr>
<td>J'=1</td>
<td>J=2</td>
<td>(4.9_{-1.0}^{+1.1}\pm 0.3) \times 10^{-7}</td>
<td></td>
</tr>
<tr>
<td>J'=2</td>
<td>J=3</td>
<td>(1.34_{-0.83}^{+0.99}\pm 0.24) \times 10^{-7}</td>
<td>&lt; 2.80 \times 10^{-7}</td>
</tr>
</tbody>
</table>

**CLEO upper limit:** < 6.6x10^{-6}
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

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>J=1</td>
<td>$(0.42_{-0.23}^{+0.27} \pm 0.10)%$</td>
<td>&lt; 0.82%</td>
<td>40%</td>
<td>1.6%</td>
<td>0.20%</td>
</tr>
<tr>
<td>J=2</td>
<td>$(0.66_{-0.14}^{+0.15} \pm 0.06)%$</td>
<td>46%</td>
<td>2.0%</td>
<td>0.25%</td>
<td></td>
</tr>
<tr>
<td>J=3</td>
<td>$(0.29_{-0.18}^{+0.22} \pm 0.06)%$</td>
<td>&lt; 0.62%</td>
<td>49%</td>
<td>2.2%</td>
<td>0.27%</td>
</tr>
</tbody>
</table>

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:

$\rightarrow$ data halfway between Ko ~ 1.3% & Moxhay ~ 0.16%
The $\pi^+\pi^-$ invariant mass


Background subtracted using the estimates from the ML fit

Corrected for mass-dependent variation in efficiency

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

Select events in $\Upsilon(1^3D_J)$ region: 10.14 to 10.18 GeV
Angle $\chi$ between the $\pi^+\pi^-$ & $l^+l^-$ planes

$$dN/d\chi \sim 1 + \beta \cos(2\chi)$$

Define $\chi$ in the $\Upsilon(1^{3}D_{J=2})$ rest frame

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

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


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 $\chi$ for $P=-1$]
Summary

- Collected world’s largest sample of \( \Upsilon(3S) \) in 2008

- Converted photons in \( \Upsilon(3S) \) & \( \Upsilon(2S) \rightarrow \gamma \eta_b \):
  - \( \eta_b \) observed @ 2.6\( \sigma \) significance (3.3\( \sigma \) stat.)
  - Improvements in the \( \eta_b \) mass determination (under study)
  - Improvement in \( \chi_{bJ}(2P) \rightarrow \gamma \Upsilon(1S) \) and \( \chi_{bJ}(1P) \rightarrow \gamma \Upsilon(1S) \) BFs (\( J=1,2 \)) by factors of \( \sim 3-4 \)

- Search for the \( h_b(1P) \) state
  - No evidence for \( \Upsilon(3S) \rightarrow \pi^+\pi^- h_b(1P) \)
  - Evidence @ 2.7\( \sigma \) (~3\( \sigma \) stat.) for \( \Upsilon(3S) \rightarrow \pi^0 h_b(1P) \)

- First observation of the \( \Upsilon(1^3D_J) \) through hadronic decays (6.2\( \sigma \))
  - Factor of 2 improvement in \( J=2 \) mass measurement
  - First tests of \( L, J, P \) assignments
BACKUP
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
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) \( \gamma \)

2. \( Y(3S) \rightarrow \pi^+\pi^- Y(1S) \) with FSR \( \gamma \)'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 \( 10.14 < m_{\pi^+\pi^-|+|-} < 10.18 \text{ GeV/c}^2 \)
Branching Fraction Calculation

e.g., for transitions through the $Y(1^3D_J=2)$ state

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

$\epsilon_{J'J} = \text{efficiency for the transition path through the } \chi_{bJ'} \text{ and } Y(1^3D_J)$

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

Quoted branching fraction product

Kwong & Rosner
\[ \pi^+ \text{ helicity angle } \theta_{\pi^+} \]

\[ \frac{dN}{d\cos \theta_{\pi^+}} \approx 1 + \xi L(\cos \theta_{\pi^+}) \]

\( \xi \rightarrow \) 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 \( L_{\pi\pi} = 2 \)

\[ \frac{dN}{d\cos \theta_{\pi^+}} \approx 1 + \xi (3\cos^2 \theta_{\pi^+} - 1)/2 \]

Fit: \( \xi = -1.0 \pm 0.4 \pm 0.1 \rightarrow \) Disfavors S-wave hypothesis

Consistent with \( J=2 \)

Angle of \( \pi^+ \) 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/c^2