Study of Bottomonium Decays

July 14, 2021

Zachary S. Stottler, Virginia Tech
Belle II Summer School

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Overview

• Introduction
  ▪ Modes of Interest
  ▪ Previous Measurement
  ▪ Datasets & \( \Upsilon(3S) \) Population

• Search for \( \chi_{bj}(nP) \rightarrow \omega \Upsilon(1S) \)
  ▪ Analysis Strategy
  ▪ Event Selection and Background Suppression
  ▪ Fitter & improved J=0 signal shape
  ▪ Branching Fraction Measurement
    ✓ Cross check of tail shapes
  ▪ Search for \( \chi_{bj}(3P) \rightarrow \omega \Upsilon(1S) \)

• Summary
Previous Measurement & Analysis Strategy

- $\chi_{b1,2}(2P)$ and $\chi_{b(0),1,2}(3P)$ states are kinematically accessible
- $\chi_{bj}(2P) \rightarrow \omega Y(1S)$ Discovered by CLEO
  - Analyzed $(5.81 \pm 0.12) \times 10^6 Y(3S)$ decays

We reconstruct the exclusive final state:

$\chi_{bj} \rightarrow \omega [Y(1S)] \rightarrow \pi^+ \pi^- \pi^0 [\ell^+ \ell^-]$

- High backgrounds for low energy photons make reconstruction of $Y(3S) \rightarrow \gamma \chi_{bj}(nP)$ suboptimal

Channel | Branching Fraction
--- | ---
$J=1$ | $(1.63^{+0.35+0.12}_{-0.31-0.11})\%$
$J=2$ | $(1.10^{+0.32+0.08}_{-0.28-0.07})\%$
## Data Samples

<table>
<thead>
<tr>
<th>Dataset</th>
<th>√s (MeV)</th>
<th>Exp.</th>
<th>Runs</th>
<th>L (fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y(4S) on-resonance</td>
<td>~ 10572</td>
<td>31-65</td>
<td>-</td>
<td>496.0</td>
</tr>
<tr>
<td>Y(4S) off-resonance</td>
<td>~ 10520</td>
<td>31-65</td>
<td>-</td>
<td>56.0</td>
</tr>
<tr>
<td>Y(3S) on-resonance</td>
<td>10354.7</td>
<td>49</td>
<td>1001–1185</td>
<td>2.999</td>
</tr>
<tr>
<td>Y(3S) off-resonance</td>
<td>10324.7</td>
<td>49</td>
<td>1193–1227</td>
<td>0.246</td>
</tr>
<tr>
<td>Y(2S) on-resonance</td>
<td>10023.3</td>
<td>67</td>
<td>1016–1123</td>
<td>6.5</td>
</tr>
<tr>
<td>Y(2S) on-resonance</td>
<td>10023.3</td>
<td>71</td>
<td>313–497, 537–696</td>
<td>18.2</td>
</tr>
<tr>
<td>Y(2S) off-resonance</td>
<td>9993.3</td>
<td>71</td>
<td>498–536</td>
<td>1.7</td>
</tr>
</tbody>
</table>

### Utilize:
- Y(3S) data available as all_mdsts
- Stiff Pair skim of Y(4S) data
- Stiff Pair skim of Y(2S) data — for studies of track and π⁰ finding efficiency

### Analysis
- Analysis is now unblinded on the χ_bj(nP) signal regions
- Together with Nishida-san & Nakazawa-san, we’ve recovered an additional 17 fb⁻¹
Count $\Upsilon(3S)$ via Decays to $\pi^+\pi^-\Upsilon(1S)$

Calculate $\Upsilon(3S)$ Population as:

$$N_{3S} = \frac{N_{\pi\pi\Upsilon}}{eB(\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S))B(\Upsilon(1S) \to \ell^+\ell^-)}$$

where $\ell = e, \mu$.

- $\Upsilon(3S)$ Population
  
  $$(27.94 \pm 0.26^{+0.48}_{-0.49} \pm 0.09) \cdot 10^6$$

$B(\chi_{bJ}(2P) \to \omega\Upsilon)$ are calculated by normalizing to $\pi\pi$

- Affords cancelation of several systematics including track-finding, lepton PID, and $B(\Upsilon(1S) \to \ell^+\ell^-)$.

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Event Selection & Background Suppression

FSP Selections

- At least 4 tracks with $|dr| < 0.5$ cm, $|dz| < 2.0$ cm, and track fit CL > 0
- At least 2 ECL clusters with:
  - No matched track
  - $\frac{E_0}{E_{25}} > 0.9$
  - Shower Width > 6 cm

Hard Tracks (Leptons)

- $p^C_M > 4.0$ GeV
- $M_{\ell\ell} \in (9.0, 9.8) \frac{\text{GeV}}{c^2}$
- Require exactly 1 di-lepton

Soft Tracks (Pions)

- $p^C_M < 0.45$ GeV/c
- $\cos(\psi_{\pi\pi}) < 0.95$
- Require exactly 1 di-pion

$\pi^0$ Candidates

- $p^C_{\pi^0} \in [80,430] \frac{\text{MeV}}{c}$
- $M_{\pi^0} \in [0.11, 0.15] \frac{\text{GeV}}{c^2}$
- Retain $\pi^0$ with smallest mass fit $\chi^2$
Event Selection & Background Suppression

FSP Selections
- At least 4 tracks with |d_r| < 0.5 cm, |d_z| < 2.0 cm, and track fit CL > 0
- At least 2 ECL clusters with:
  - No matched track
  - $\frac{E_0}{E_{25}} > 0.9$
  - Shower Width > 6 cm

Hard Tracks (Leptons)
- $p_T^{CM} > 4.0$ GeV
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- Retain $\pi^0$ with smallest mass fit $\chi^2$

Resonant $b\bar{b} \to \pi^+ \pi^- b\bar{b}'$ Veto
- $\Delta M_{\pi\pi} \in [9.83, 10.12]$ GeV
- $\Delta M_{\pi\pi} \notin (10.017, 10.029)$ GeV

Rejects 92.4% of resonant background at cost of 7.3% of signal

Resonant $b\bar{b}$ are sharply peaked in $\Delta M_{\pi\pi}$ offers better separation than $M_{reco}(\pi\pi)$

\[ FOM = \frac{N_S}{\sqrt{N_S + N_B}} \]
Signal Extraction: $\Delta M_\chi$

$J = 0$ SIGNAL

$J = 1$ SIGNAL

$J = 2$ SIGNAL

**Shapes:** Double-Sided Crystal Ball (DSCB) functions
- Reparameterize Signal Functions to account for Data-MC difference:
  $F(\mu, \sigma, \alpha_1, \alpha_2, n_1, n_2) \rightarrow F(\mu, \rho \times \sigma, \alpha_1, \alpha_2, n_1, n_2)$,
  where Red parameters are fixed, Blue are floated, and $\rho$ is a (common) “fudge factor”
$M_\omega$ signal shape of $\chi_{b0}$

J=0 signal shape differs from that of J=1,2.

- Mean is shifted low
- Strange threshold in tail

→ Define signal shape as product of sigmoid $(f(b, \delta M_{0L}^\omega))$ and DSCB

$\chi_{b0}^{(2P)} \to \chi(1S)$ in Signal MC

\[\begin{align*}
\mu_1 &= 0.372 \pm 0.021 \\
\mu_2 &= 2.56 \pm 0.10 \\
\delta M_{0L}^\omega &= 0.05126 \pm 0.000073 \\
\delta M_1^\omega &= 0.01430 \pm 0.000111 \\
\sigma_{\chi_{b0}^{(2P)}} &= 0.004668 \pm 0.000075 \\
N_{\text{sig}} &= 17146 \pm 131 \\
b &= -256.8 \pm 17 \\
N_0^\chi &= 3.05 \pm 0.97 \\
N_2^\chi &= 1.66 \pm 0.28
\end{align*}\]
Fit Strategy: Simultaneous Fit to $\Delta M_{\chi}$ & $M_\omega$

- All signal shapes are DSCB, except J=0 signal in $M_\omega$
- $\rho, \kappa$ are introduce to account for Data/MC difference in resolution.
Search for $\chi_{bJ}(2P) \rightarrow \omega Y(1S)$

Simultaneously Fit $M_\omega$ and $\Delta M_\chi$ in $Y(3S) \& Y(4S)$ Data

\( \chi_{bJ}(2P) \rightarrow \omega Y(1S) \)

\( \Delta M_\chi = M_{\chi(2S)} - M_{\chi(1S)} \)

Data

\( J = 0 \)
\( J = 1 \)
\( J = 2 \)

Combined $Y(3S)$ and $Y(4S)$ Data

Events/3.0 MeV/c\(^2\)

$\Delta M_\chi = (28.17 \pm 0.27 \pm 1.74) \cdot 10^6$

Results

<table>
<thead>
<tr>
<th>Channel</th>
<th>$B(\chi_{bJ}(2P) \rightarrow \omega Y(1S))$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J = 0$</td>
<td>$0.56^{+0.18}_{-0.19} \pm 0.05 \pm 0.06%$</td>
</tr>
<tr>
<td>$J = 1$</td>
<td>$(2.38 \pm 0.19)^{+0.06}_{-0.09} \pm 0.22%$</td>
</tr>
<tr>
<td>$J = 2$</td>
<td>$(0.46 \pm 0.12)^{+0.02}_{-0.04} \pm 0.06%$</td>
</tr>
</tbody>
</table>

Significance

<table>
<thead>
<tr>
<th>$J$</th>
<th>$\text{Significance}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$3.2\sigma$</td>
</tr>
<tr>
<td>1</td>
<td>$14.5\sigma$</td>
</tr>
<tr>
<td>2</td>
<td>$3.9\sigma$</td>
</tr>
</tbody>
</table>

Consistency

<table>
<thead>
<tr>
<th>$\text{Consistency}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.8\sigma$</td>
</tr>
</tbody>
</table>

Compare with PDG

<table>
<thead>
<tr>
<th>Channel</th>
<th>Branching Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J=1$</td>
<td>$(1.63^{+0.35}<em>{-0.31})^{+0.12}</em>{-0.11}%$</td>
</tr>
<tr>
<td>$J=2$</td>
<td>$(1.10^{+0.32}<em>{-0.28})^{+0.08}</em>{-0.07}%$</td>
</tr>
</tbody>
</table>
Signal Significance: Profile Likelihood Scan

Signal Significance is determined from a profile likelihood scan.

\[ \lambda(\nu) = \frac{\mathcal{L}(\nu | \hat{\theta})}{\mathcal{L}(\hat{\nu} | \hat{\theta})} \]

-2 log \( \lambda(\nu) \)

-2 log \( \lambda(\nu) \)

-2 log \( \lambda(\nu) \)

\[ Z = \sqrt{-2 \log \lambda(\nu = 0)} \]

Systematic uncertainties affecting the yield are convoluted with distribution of likelihood and Z is recalculated.

The reported significance has been verified using 100k toy MC samples, cf. BN1505.

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April 20, 2021
Cross Check: Refit with Tight $M_\omega$ Cut

Combined $\Upsilon(3S)$ and $\Upsilon(4S)$ Data

- Nominal Fit

Naïvely, $\exists$ Insufficient phase space for transition:
\[
\Delta_0 = M_{\chi_{b0}(2P)} - M_{Y(1S)} - M_\omega = -10.5 \text{ MeV}
\]

- The $\chi_{b0}(2P)$ is a wide state, $\Gamma_{\chi_{b0}} \gg \Gamma_{\chi_{b1,2}}$
  \[
  \Gamma_{\chi_{b0}} = 2.6 \text{ MeV} \quad \text{[Godfrey & Moats 2015]}
  \]
  \[
  \Gamma_\omega = 8.68 \text{ MeV} \quad \text{[PDG]}
  \]

Precedent in $c\bar{c}$ Sector

- $\chi_{c1}(3872)$ lies $\sim$8 MeV below threshold
- $\Gamma(X(3872)) < 1.2 \text{ MeV}$ (Belle 1107.0163)
- BaBar & Belle have see with $< 5\sigma$
- BES III recently observed transition ($5.7\sigma$)
  - 2019 – 1903.04695
  - Employ PHSP to model $X \to \omega f/\psi$
Cross Check: Refit with Tight $M_\omega$ Cut

Combined $\Upsilon(3S)$ and $\Upsilon(4S)$ Data $M_\omega \in [720,775]$ MeV

Data
- Total fit
- $J = 0$
- $J = 1$
- $J = 2$
- Background

$\Upsilon(3S,4S)$

$R_L$ Events/3.0 MeV/c²

Data
- Total fit
- $J = 1$
- $J = 2$
- Background

$\Upsilon(3S,4S)$

$R_R$ Events/3.0 MeV/c²

Pull

$\Delta M_\pi = M_{2\pi2\pi} - M_\Upsilon + M_\pi^{PDG}$ (GeV/c²)

Background: 3rd order polynomial

→ Studied in $M_{\pi^0}$ Sidebands

Background: RooDstD0BG

→ Studied in $M_{\pi^0}$ Sidebands

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Pull

$\Delta M_\pi = M_{2\pi2\pi} - M_\Upsilon + M_\pi^{PDG}$ (GeV/c²)

Background: 3rd order polynomial

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Background: RooDstD0BG

→ Studied in $M_{\pi^0}$ Sidebands

July 14, 2021
## Systematic Uncertainty

<table>
<thead>
<tr>
<th>Decay</th>
<th>( \chi_{b0}(2P) \rightarrow \omega \Upsilon(1S) )</th>
<th>( \chi_{b1}(2P) \rightarrow \omega \Upsilon(1S) )</th>
<th>( \chi_{b2}(2P) \rightarrow \omega \Upsilon(1S) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track-Finding</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>( \pi^0 ) Reconstruction</td>
<td>1.7%</td>
<td>1.7%</td>
<td>1.7%</td>
</tr>
<tr>
<td>Fit Procedure</td>
<td>+8.9%</td>
<td>+0.7%</td>
<td>+3.8%</td>
</tr>
<tr>
<td>Population of ( \Upsilon(3S) )</td>
<td>-9.1%</td>
<td>-3.0%</td>
<td>-7.7%</td>
</tr>
<tr>
<td>Input Branching Fractions</td>
<td>10.4%</td>
<td>9.4%</td>
<td>12.4%</td>
</tr>
<tr>
<td>Reconstruction Efficiency</td>
<td>0.8%</td>
<td>0.8%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Total</td>
<td>(+3.0% \pm 10.4%)</td>
<td>(+2.4% \pm 9.4%)</td>
<td>(+4.4% \pm 12.4%)</td>
</tr>
</tbody>
</table>

**TABLE IX:** Systematic uncertainties on the \( \chi_{b1,2}(2P) \rightarrow \omega \Upsilon(1S) \) branching fractions, by decay channel. The individual systematic uncertainties are summed in quadrature to obtain the total systematic error. Note that the large uncertainty from the input branching fractions is reported separately.
**Search for \( \chi_{bf}(3P) \rightarrow \omega \gamma(1S) \)**

**Event Selection Revisited**

**FSP Selections**
- At least 4 tracks with \(|dr| < 0.5 \text{ cm}, \ |dz| < 2.0 \text{ cm}, \) and track fit \( \text{CL} > 0 \)
- At least 2 ECL clusters with:
  - No matched track
  - \( \frac{E_y}{E_z} > 0.9 \)
  - width > 6 cm,

**Hard Tracks (Leptons)**
- \( p_T^{CM} > 4.0 \text{ GeV} \)
- \( M_{\ell\ell} \in (9.0, 9.8) \text{ GeV/}c^2 \)
- Require exactly 1 di-lepton

**Soft Tracks (Pions)**
- \( p_T^{CM} < 0.75 \text{ GeV/c} \)
- \( \cos(\psi_{\pi\pi}) < 0.95 \)
- Require exactly 1 di-pion

**\( \pi^0 \) Candidates**
- \( p_T^{CM} \pi^0 \in [80, 750] \text{ MeV/c} \)
- \( M_{\pi^0} \in [0.11, 0.15] \text{ GeV/}c^2 \)
- Retain \( \pi^0 \) with smallest mass fit \( \chi^2 \)

**Resonant \( b\bar{b} \rightarrow \pi^+\pi^- b\bar{b}' \) Veto**
- \( \Delta M_{\pi\pi} \notin (10.014, 10.030) \text{ GeV} \)
- \( \Delta M_{\pi\pi} < 10.32 \text{ GeV} \)

**\( \chi_{bf}(3P) \) Continuum Veto**
- MuID > 0.2 for leptons
- \( M_{\ell\ell} \in [9.2, 9.6] \text{ GeV} \)

**Reject \( Y(1S) \rightarrow e^+e^- \) to suppress large backgrounds**

**Peaking Background:**
- \( q\bar{q} \rightarrow \omega + h \)
- Removed by continuum veto

**Official Belle MC:** \( e^+e^- \rightarrow q\bar{q} \ (q = u, d, s, c) \)
Can estimate conservative upper limit on expected BF

- Assume $\mathcal{B}(\chi_{b1}(3P) \to \omega Y(1S)) \approx \mathcal{B}(\chi_{b1}(2P) \to \omega Y(1S))$

- Estimate: $\mathcal{B} \sim 8.4 \times 10^{-7}$

From the fit, a 90% CL upper limit is determined:

$$\mathcal{B}(\Upsilon(4S) \to \gamma \chi_{b1}(3P) \to \gamma \omega \Upsilon(1S)) < 1.4 \times 10^{-5}$$

513 fb$^{-1}$ of on-resonance $\Upsilon(4S)$ data analyzed
Summary

• We present Results:
  - First measurement of $\chi_{bJ}(2P) \to \omega \Upsilon(1S)$ since discovery in 2004
    \[
    \mathcal{B}(\chi_{b0}(2P) \to \omega \Upsilon(1S)) = (0.56^{+0.18}_{-0.19} \pm 0.05 \pm 0.06)\%
    \]
    \[
    \mathcal{B}(\chi_{b1}(2P) \to \omega \Upsilon(1S)) = (2.38 \pm 0.19^{+0.06}_{-0.09} \pm 0.22)\%
    \]
    \[
    \mathcal{B}(\chi_{b2}(2P) \to \omega \Upsilon(1S)) = (0.46 \pm 0.12^{+0.02}_{-0.04} \pm 0.06)\% \quad 3.2\sigma
    \]
  - New limit set:
    \[
    \mathcal{B}(\Upsilon(4S) \to \gamma \chi_{b1}(3P) \to \gamma \omega \Upsilon(1S)) < 1.4 \times 10^{-5} \quad (90\% \text{ CL})
    \]

*Paper Draft in progress – Pending Referee Approval we will proceed to CWR*
Thank you
We Interpret this as the $\chi_{b0}(2P) \to \omega Y(1S)$

This is surprising:

- $\exists$ Insufficient phase space for transition:
  $$\Delta_0 = M_{\chi_{b0}(2P)} - M_{Y(1S)} - M_\omega = -10.5 \text{ MeV}$$

- The $\chi_{b0}(2P)$ is a wide state, $\Gamma_{\chi_{b0}} \gg \Gamma_{\chi_{b1,2}}$
  $$\Rightarrow \Gamma_{\chi_{b0}} = 2.6 \text{ MeV} \quad \text{(Godfrey & Moats 2015)}$$
  $$\Rightarrow \Gamma_\omega = 8.68 \text{ MeV} \quad \text{[PDG]}$$
Similar Enhancement Seen in $c\bar{c}$ Region:

$\chi_{c1}(3872) \rightarrow \omega J/\psi$

- $X$ lies $\sim 8$ MeV below threshold
- $\Gamma(X(3872)) < 1.2$ MeV (Belle 1107.0163)
- BaBar & Belle have see with $< 5\sigma$

- BES III recently observed transition $(5.7\sigma)$
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  - Employ PHSP to model $X \rightarrow \omega J/\psi$

**FIG. 1:** The $M(\ell^{+}\ell^{-})$ and $M(\pi^{+}\pi^{-}\pi^{0})$ distributions from the full data sets.

**FIG. 2:** The $M(\omega J/\psi)$ distribution with results of an unbinned maximum-likelihood fit to data including three BW resonances (upper) and including two BW resonances (bottom) as signal. Dots with error bars are data, the red solid curves show the total fit results, the blue dotted curves are the MC simulated $\omega X_{c0}$ background component, the blue dashed curves are the linear background component, the pink dotted-dashed curves are the $X(3915)$ resonance, the pink double-dotted dashed curve is the $X(3960)$ resonance, and the green shaded histograms are the normalized contribution from the $J/\psi$- and $\omega$-mass sidebands.
**Cross Check: Signal Shape Asymmetry**

- **Question from Kirill Chilikin and Alex Bondar:** Verify on control channel that \( \pi^0 \) in final state does not induce data/MC difference in asymmetry of signal shapes?
- **Control Channel:** \( \Upsilon(2S) \rightarrow \pi^0 \pi^0 \Upsilon(1S) \rightarrow 4\gamma [\ell^+ \ell^-] \)
  - Reconstruct \( \Upsilon(1S) \) and \( \pi^0 \)'s with \( \omega \)-analysis cuts
  - Signal Shape: DSCB w/ \( \alpha_i, n_i \) fixed from MC
    \[ \mu, \sigma \] are floated

**Result:** \( B(2S \rightarrow \pi^0 \pi^0 1S) \)

\[ (8.75 \pm 0.10\%) \]

**Compare with PDG:**

\[ (8.6 \pm 0.4\%) \]

No significant data/MC difference in tail shapes.

Small artifacts in MC pull are result of large statistics of fit.
π⁰ Reconstruction Syst. Uncert.

\[ Y(2S) \rightarrow \pi^0 \pi^0 (Y(1S) \rightarrow \mu\mu) \]

Assessing a systematic uncertainty for soft π⁰'s, with \( p < 300 \text{ MeV/c} \)
Denominator: Tag events with hardest π⁰+Y(1S) candidate

Numerator: Count how many times the π⁰-pair is reconstructed

\[ \text{Single Pion Sample: } \pi^0 2\mu \]

\[ \text{Standard Sample: } 2\pi^0 2\mu \]

\[ \rho = \frac{\epsilon_{\text{Data}}}{\epsilon_{\text{MC}}} \], where \( \epsilon_i = \frac{N_i(\pi^0 2\mu)}{N_i(2\pi^0 2\mu)} \)

\( \rho = 0.975 \pm 0.017 \)
### Systematic Uncertainty from Measured BF\(s\)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Relative Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mathcal{B}(\Upsilon(3S) \to \gamma \chi_{b2}(2P)))</td>
<td>((13.1\pm1.6)%)</td>
<td>12.2%</td>
</tr>
<tr>
<td>(\mathcal{B}(\Upsilon(3S) \to \gamma \chi_{b1}(2P)))</td>
<td>((12.6\pm1.2)%)</td>
<td>9.5%</td>
</tr>
<tr>
<td>(\mathcal{B}(\Upsilon(3S) \to \gamma \chi_{b0}(2P)))</td>
<td>((5.9\pm0.6)%)</td>
<td>10.2%</td>
</tr>
<tr>
<td>(\mathcal{B}(\Upsilon(3S) \to \pi^+\pi^- \Upsilon(1S)))</td>
<td>((4.37\pm0.08)%)</td>
<td>1.8%</td>
</tr>
<tr>
<td>(\mathcal{B}(\omega \to \pi^+\pi^-\pi^0))</td>
<td>((89.2\pm0.7)%)</td>
<td>0.8%</td>
</tr>
<tr>
<td>(\mathcal{B}(\pi^0 \to \gamma\gamma))</td>
<td>((98.823\pm0.034)%)</td>
<td>0.03%</td>
</tr>
</tbody>
</table>