And now, a word or two on the other heavy onia ...

Recent Results in Bottomonium
Ties to Charmonium

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Bottom compared to Charm

Heavy quark symmetry

\[
\begin{aligned}
Q &= b \text{ or } c \\
\frac{m_b}{m_c} &= \frac{5 \text{ GeV}}{1.7 \text{ GeV}} \approx 3 \\
\frac{|q_b/q_c|}{|e/3 / 2e/3|} &= 1/2 \\
\frac{r_b}{r_c} &\approx \frac{0.3 \text{ fm}}{0.5 \text{ fm}} = 0.6 \\
\frac{\beta_b^2}{\beta_c^2} &\approx \frac{m_c}{m_b} \approx 1/3 \\
\frac{\alpha_{S,b}}{\alpha_{S,c}} &\approx \frac{0.2}{0.3} = 2/3
\end{aligned}
\]

Cornell potential \( \sim (a/r) + br \)

Some implications ... b-bbar will differ in a calculable way ...

More Coulomb-like, less able to probe confinement region, more asymptotically free, more states below threshold, more non-relativistic, smaller M1 rates, higher decay multiplicities, less copiously produced in e\(^+\)e\(^-\)

Bottomonium a different laboratory to study the same physics

Aug. 6, 2007  D.Kreinick - Bottomonia
Charmonium and Bottomonium

**Charmonium**

- $\eta_c(1S)$
- $\psi(1S)$
- $\psi(2S)$

**Bottomonium**

- $\eta_b(1S)$
- $\psi_b(1P)$
- $\chi_b(1P)$
- $h_b(1P)$
- $h_b(2P)$
- $T(1S)$
- $T(2S)$
- $T(3S)$

Rich spectroscopy, various production schemes, interesting decay scenarios, many important states not yet observed.
• **Direct production in** $e^+e^-$:
  - CLEO: 6M $\Upsilon(3S)$, 9M $\Upsilon(2S)$, 21M $\Upsilon(1S)$
  - Belle: 11M $\Upsilon(3S)$ (in a *few* days’ run!)
  - Belle and BaBar: 100’s of M $\Upsilon(4S)$

• **ISR Production:**
  - Belle and BaBar: 10’s of M $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$
  - Harder to know how to use effectively

• **Hadro-production:**
  - CDF
  - D0

  Production Ratios

  Polarizations
**Polarization in Production**

**p¯p** production of onia can be modeled with NRQCD

Uses “universal” matrix elements with color-octet pieces, which describe production cross sections adequately

Polarization parametrized by $\alpha = (\sigma_T - 2 \sigma_L)/(\sigma_T + 2 \sigma_L)$

Measured by angular distribution in di-lepton (dimuon) decays:

$$dN/d\cos\theta^* \sim (1 + \alpha \cos^2\theta^*)$$

**NRQCD predicts a large transverse polarization at high $p_T$**

- gluon fragmentation becomes dominant mechanism
- $\alpha$ should approach unity at high $p_T$

**$k_T$-factorization (“semi-hard”) makes opposite prediction**

- large longitudinal polarizations at high $p_T$
- $\alpha$ becomes negative at large $p_T$

**Neither formulation works well in charmonium**

**New results in bottomonium from D0 with 1.3/\text{fb}, \sim 420K $\Upsilon$s**
D0 observes significant polarization in $\Upsilon(1S)$ production, inconsistent with NRQCD
$\Upsilon(2S)$ is "not inconsistent" with NRQCD
Bottomonium only deepens the puzzle for polarization in onium production

Neither phenomenology describes $\bar{c}c$ well
Dipion Transition Matrix Element

Older studies

ψ' to ψ
- BES 2000
- Novikov-Shiftman ('81)
- Yan ('80)

2S to 1S
- Exclusive
- Inclusive
- Yan ('80)

3S to 2S
- Exclusive
- Inclusive
- Moxhay ('89)
- Yan ('80)

3S to 1S ??!
- Exclusive
- Inclusive
- Moxhay ('89)
- Yan ('80)

New inputs to old puzzle

PRD 75, 071103 (2007)

Belle
4S → 1S

BaBar
4S → 2S

PRD 96, 232001 (2006)
Brown and Cahn [PRL 35, 1 (1975)] use PCAC and current algebra:

\[ M = A (\varepsilon' \cdot \varepsilon)(q^2 - 2m_\pi^2) + B (\varepsilon' \cdot \varepsilon)E_1 E_2 + C [(\varepsilon' \cdot q_1)(\varepsilon \cdot q_2) + (\varepsilon' \cdot q_2)(\varepsilon \cdot q_1)] \]

- CLEO fits 2-D “Dalitz” plot \( q^2 = M_{\pi\pi}^2 \) & \( M_{\Upsilon\pi}^2 \), for the three di-pion transitions among the \( \Upsilon(nS) \) states [hep-ex/0706.2317]

- Only the two terms, with complex, constant form factor coefficients A and B, are needed to give good fits to the data

<table>
<thead>
<tr>
<th>Initial ( \Upsilon )</th>
<th>Final ( \Upsilon )</th>
<th>( \text{Re} \left( \frac{B}{A} \right) )</th>
<th>( \text{Im} \left( \frac{B}{A} \right) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3S</td>
<td>1S</td>
<td>-2.52 ± 0.04</td>
<td>±1.19 ± 0.06</td>
</tr>
<tr>
<td>2S</td>
<td>1S</td>
<td>-0.75 ± 0.15</td>
<td>0.00 ± 0.11</td>
</tr>
<tr>
<td>3S</td>
<td>2S</td>
<td>-0.40 ± 0.32</td>
<td>0.00 ± 1.10</td>
</tr>
</tbody>
</table>

Includes system. uncert’s \( |C/A|_{3\to1} < 1.09 @ 90\% \text{ CL} \)

Dubynskiy/Voloshin [hep-ph/0707.1272] argue that CLEO parametrization is too naïve, B cannot be constant over the Dalitz plot

Good to revisit with Belle \( (Q = b) \) and CLEOc/BES \( (Q = c) \) data!
In charmonium $\psi(2S) \to \eta J/\psi$ is (surprisingly) large $\sim 3\%$

Kuang [hep-ph10601044 v2] scales $\Gamma \sim (p^*)^3/m_Q^4$ to predict

$$B(\Upsilon(2S) \to \eta \Upsilon(1S)) = (8.1 \pm 0.8) \times 10^{-4}$$
$$B(\Upsilon(3S) \to \eta \Upsilon(1S)) = (6.7 \pm 0.7) \times 10^{-4}$$

CLEO seeks $\Upsilon(2S) \to \eta \Upsilon(1S)$ with $\Upsilon(1S) \to \mu\mu$ or $e^+e^-$, and $\eta \to \gamma\gamma$ or $\pi^+\pi^-\pi^0$

Sees preliminary $\sim 5\sigma$ evidence

$$B(\Upsilon(2S) \to \eta \Upsilon(1S)) = (2.5 \pm 0.7 \pm 0.5) \times 10^{-4}$$

Also seek $\pi^0$, find no excess over background

$$B(\Upsilon(2S) \to \pi^0\Upsilon(1S)) < 2.1 \times 10^{-4}$$

consistent with expected ratio to $\eta$ (.16)
Onia decays to undetectable particles are a window on physics beyond the Standard Model (BSM):

- **Dark matter candidate,** $\chi$?
  $\mathcal{B}(\Upsilon(1S) \rightarrow \chi \chi) = 0.41\%$ McElrath [PRD 72, 103508 (2005)]

- **New gauge bosons? Light gravitino?** Fayet [PRD 74, 054034 (2006)]

- $\nu\nu$ via $Z^0$ a very small potential background

But how does one “see” such invisible decays?

Tag presence of $\Upsilon$ via $\pi\pi$ transition from higher state!

Require recoil against $\pi\pi$ be $\Upsilon$

Require detector otherwise empty
$\Upsilon(1S) \rightarrow \mu\mu$

**11M $\Upsilon(3S)$ events**
Poor trig/acceptance efficiency

**9M $\Upsilon(2S)$ events**
2 track trigger prescaled by 20

Inclusive $\gamma$ decays to invisible particles

No tracks, no $>250$ MeV $\gamma$s

Expected background

PRL 98, 132001 (2007)
PRD 75, 031104 (2007)
90%CL limits:

\[ B(\Upsilon \rightarrow \text{"invisible"})_{\text{Belle}} < 0.25\% \]
\[ B(\Upsilon \rightarrow \text{"invisible"})_{\text{CLEO}} < 0.39\% \]

Each limit is an order of magnitude better than previous best

Combined limit about half \( \chi \chi \) prediction of 0.41\%

Betters gravitino mass limit by \( \times 4 \) to \( m_{3/2} > 1.2 \times 10^{-7} \) eV

Such BSM decays also accessible in charmonium!

- More limited mass range
- Smaller predicted branching fraction

See R. McElrath’s talk next in this session!
Dermisek, Gunion, McElrath propose adding to the MSSM a non-SM-like pseudoscalar higgs $a_0$ with $m_{a_0} < 2m_b$ ([hep-ph/0612031] “NMSSM”)

“natural,” avoids fine tuning

evades the LEP limit $M_h>100$ GeV since $h\to a_0 a_0$, but $a_0\not\to b\bar{b}$ and LEP sought $b$ jets

$a_0 \to \tau^+\tau^-$ should predominate if $m_{a_0} > 2m_\tau$

Should be visible in $\gamma \to \gamma a_0$

Experimentally, CLEO seeks monochromatic $\gamma$

Use $\Upsilon(2S) \to \pi\pi\Upsilon(1S)$ tag to eliminate $e^+e^- \to \tau\tau\gamma$ background

Flag presence of $\tau$ pair with two 1-prong $\tau$ decays (one lepton), missing energy

Preliminary

 photon spectrum

ULs improved an order of magnitude or more

Rules out many, but not all NMSSM models
Among the most common radiative decays in J/ψ is γf₂(1270).

Unlike in the J/ψ system, few exclusive radiative decays of the ϒ are known, but CLEO has now found this decay for ϒ in two modes.
Radiative Decays to f’s

For $\Upsilon \to \gamma f_2(1270)$ simple scaling from charmonium works:

Expect $B(\psi \to \gamma f_2) / B(\Upsilon \to \gamma f_2) = (q_c / q_b)^2 (m_b / m_c)^2 (\Gamma_{bb} / \Gamma_{cc}) \approx 20$

Observe

\[
B(\Upsilon \to \gamma f_2(1270)) = (10.2 \pm 0.8 \pm 0.7) \times 10^{-5} \ (\pi^+ \pi^-) \quad \text{PRD73, 032001 (2006)}
\]

\[
B(\Upsilon \to \gamma f_2(1270)) = (10.5 \pm 1.6 \pm 1.9) \times 10^{-5} \ (\pi^0 \pi^0) \quad \text{PRD75, 072001 (2007)}
\]

\[
B(\Upsilon \to \gamma f_2(1270)) = (10.23 \pm 0.97) \times 10^{-5} \ \text{(combined)}
\]

\[
B(\psi \to \gamma f_2) / B(\Upsilon \to \gamma f_2) = 14.0 \pm 1.7
\]

Dominant helicity = 0, as expected from theory
Another prominent radiative decay is $J/\psi \rightarrow \gamma \eta'$:
\[
B(J/\psi \rightarrow \gamma \eta') = (4.7 \pm 0.3) \times 10^{-3}
\]
\[
B(J/\psi \rightarrow \gamma \eta') / B(J/\psi \rightarrow \gamma f_2) = 3.4 \pm 0.4
\]
\[
B(J/\psi \rightarrow \gamma \eta') \left[ B(\Upsilon \rightarrow \gamma f_2)/B(J/\psi \rightarrow \gamma f_2) \right] = (3.5 \pm 0.5) \times 10^{-4}
\]
\[
B(J/\psi \rightarrow \gamma \eta) \left[ B(\Upsilon \rightarrow \gamma f_2)/B(J/\psi \rightarrow \gamma f_2) \right] = (0.7 \pm 0.1) \times 10^{-4}
\]

But we know the $\eta'$ to be rather unconventional
- Anomalous 5x larger branching ratio compared to $\eta$
- 14% gluonic content? - KLOE [PLB648 267 (2007)]
- Possible charmonium content?

Theoretical approaches include:
- VDM - Intemann [PRD 27 2755 (1983)]
- Mixing with $\eta_b$ - Chao [Nucl Phys B335 101 (1990)]
- Higher twist contribution - Ma [PRD65 097506 (2002)]
Radiative Decays to $\eta, \eta'$

New 90% CL limits from CLEO

Use 21 M $\Upsilon$ decays to get:

- $B(\Upsilon \to \gamma \eta') < 1.9 \times 10^{-6}$
- $B(\Upsilon \to \gamma \eta) < 1.0 \times 10^{-6}$

Naïve scaling fails by 2 orders of magnitude

Chao’s mixing approach not supported for $\eta'$ (factor of 30)

Intemann’s VDM predictions $\sim 10^{-7}$

Ma’s predictions a bit below these limits
Summary

Bottomonium is a useful complement to charmonium in studying QCD in production, spectroscopy and decay

New results in polarization of $\Upsilon$ in $pp$ production are not well described by NRQCD or $k_T$-factorization
A 2D fitting technique for $\Upsilon(nS) \rightarrow \pi\pi(mS)$ transitions may help clarify a longstanding puzzle
The pseudoscalar hadronic transition $\Upsilon(2S) \rightarrow \eta\Upsilon(1S)$ has finally been seen, about $1/3$ as large as scaling from charm predicts
Searches for decays of $\Upsilon(1S)$ to invisibles have upper limits smaller than the predictions of $\chi\chi$ or gravitino
A search for low mass pseudoscalar higgs $a_0$ sees none
The radiative decay $\Upsilon(1S) \rightarrow \gamma f_2(1270)$ has been seen at about the strength predicted from charmonium, but $\Upsilon(1S) \rightarrow \gamma\eta'$ upper limit is two orders of magnitude smaller than naïve scaling from $J/\psi$ decay
Backup Slides
We have improved ULs by about an order of magnitude or more.

We are constraining NMSSM models.

Many models with $2m_\tau < m_a < 7.5$ GeV (represented by red points) ruled out by our results.