Onia Hadronic Transitions at CLEO
D. Kreinick – Cornell University

ψ(3770) → π π J/ψ
ϒ(mS) → π π ϒ(nS)  m=2,3; n=1,2
New approach for analyzing ϒ(mS) → π π ϒ(nS)
ψ(2S) → π⁺ π⁻ π⁰ η_c

Will not have time to present
ψ(3770) → π⁰/η J/ψ (PRL 96, 082004 (2006))
χ_b' → π π χ_b (hep-ex/0511019, accepted PRD)
χ_b → ω ϒ(1S) (PRL 92, 222002 (2004))
ψ(3770) to light hadrons
\[ \psi(3770) \rightarrow \pi \pi J/\psi \]

Observe \( \ell^+\ell^- \) from the \( J/\psi \) and \( \pi^+\pi^- \) or \( \pi^0\pi^0 \) in 281/pb of \( \psi(3770) \) data

Major backgrounds
- Radiative return to \( \psi(2S) \) with ~87 MeV ISR photon
- Direct production of \( \psi(2S) \) on tail of Breit-Wigner
- Small linear background

\[ \vec{k} = \vec{0} - \vec{p}_{\ell^+} - \vec{p}_{\ell^-} - \vec{p}_\pi - \vec{p}_\pi \] poor resolution

Better if you calculate \( k \) more carefully:

\[ |\vec{k}| = k = \frac{s - M_J^2 + m_X^2 - 2\sqrt{s(p_X^2 + m_X^2)}}{2(\sqrt{p_J^2 + M_J^2} - p_J \cos \phi)} \]

\( M_J \) = PDG mass of \( J/\psi \)
\( m_X, p_X \) = measured \( \pi\pi \) mass and momentum
\( p_J \) = momentum of \( \ell^+\ell^- \)
\( \phi \) = angle between \( J/\psi \) momentum and \( \vec{k} \)

Expected yield from \( \psi(2S) \)
(2 MeV \( \gamma \) cutoff)
k Distribution $\psi(3770) \rightarrow \pi \pi J/\psi$

Branching ratios

$\psi(3770) \rightarrow \pi^+\pi^- J/\psi$

$(189\pm20\pm20)\times10^{-5}$

$\psi(3770) \rightarrow \pi^0\pi^0 J/\psi$

$(80\pm25\pm16)\times10^{-5}$

PRL 96, 082004 (2006)
ππ mass distribution looks like the others (except the strange ϒ(3S) → ππϒ(1S))

ϒ data from 1994
\( \Upsilon(mS) \rightarrow \pi \pi \Upsilon(nS) \)

**Exclusive: Observe**

- \( \pi^+ \pi^- \) or \( \pi^0 \pi^0 \) and \( \ell^+ \ell^- \) from \( \Upsilon(nS) \)

- \( \Upsilon(3S) \rightarrow \pi^0 \pi^0 \text{trk}^+ \text{trk}^- \)
  - \( 3S \rightarrow 1S \)
  - \( 3S \rightarrow 2S \)

- \( \Upsilon(2S) \rightarrow \pi^+ \pi \Upsilon(1S) \)

**Inclusive: Observe only the \( \pi^+ \pi^- \)**

- \( \Upsilon(3S) \rightarrow \pi^+ \pi \Upsilon(1S) \)

510 < \( m_{\pi \pi} \) < 530 MeV

**Mass recoiling against \( \pi \pi, \text{GeV} \rightarrow \)**
M_{\pi\pi} distributions

\[ \Upsilon(2S) \rightarrow \pi^+ \pi^- \Upsilon(1S) \]
\[ \Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(2S) \]
\[ \Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(1S) \]

Charged pions range out

\( \pi^0 \pi^0 \)

Not done yet

\[ \text{BR}(\Upsilon(2S) \rightarrow \pi^+ \pi^- \Upsilon(1S)) \sim 18\% \]
\[ 2 \times \text{BR}(\Upsilon(3S) \rightarrow \pi^0 \pi^0 \Upsilon(2S)) \sim 4\% \]
\[ \text{BR}(\Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(1S)) \sim 4\% \]
Matrix Element Analysis for $\Upsilon(mS) \rightarrow \pi \pi \Upsilon(nS)$

3 body final state $\Rightarrow$ 2 Dalitz variables, traditionally $M_{\pi\pi}^2$ and $M_{\Upsilon\pi}^2$

Here, we prefer $M_{\pi\pi}^2$ and $\cos\theta_x$

($\cos\theta_x$ is linear in $M_{\Upsilon\pi}^2$)

PCAC + Lorentz invariance (Brown and Cahn, PRL 35, 1 (1975))

$$M = A \times (\varepsilon' \cdot \varepsilon) \times (q^2 - 2m_{\pi}^2) +$$

(Yan form; Moxhay adds constant for $B^*B^*$)

$$B \times (\varepsilon' \cdot \varepsilon) \times (E_1 \ast E_2) +$$

(Traditionally neglected)

$$C \times [(\varepsilon' \cdot q_1)(\varepsilon \cdot q_2) + (\varepsilon' \cdot q_4)(\varepsilon \cdot q_1)]$$

(spín flip, neglect)

where $q_i$ are the pion momenta, $E_i$ their energies

$q^2 = (q_1 + q_2)^2 = M_{\pi\pi}^2$ $\varepsilon'$, $\varepsilon$ polarization vectors of $\Upsilon'$, $\Upsilon$

A $\cos\theta_x$ dependence indicates the presence of a $B$ term
2-D distributions (all MC)

Matrix Elements

$A^2(q^2-2m_{\pi}^2)^2$

$2AB(q^2-2m_{\pi}^2)E_1E_2$

$B^2E_1^2E_2^2$

Tricky business, but we hope to have results soon
$\psi(2S) \to \pi\pi\pi\eta_c$ and the $\rho\pi$ puzzle

Annihilation into 3g:

\[ Q = \begin{array}{c}
\text{expect transition probability}
\end{array} \]

\[ Q_h = \frac{B(\psi(2S) \to h)}{B(J/\psi \to h)} \approx \frac{B(\psi(2S) \to \ell^+\ell^-)}{B(J/\psi \to \ell^+\ell^-)} \approx 12\% \quad \text{"12\% rule"} \]

Naively anticipate this to hold for individual hadronic channels, but it doesn’t:

- \( (\psi(2S) \to \pi\rho)/(J/\psi \to \pi\rho) = 1.4 \times 10^{-3}, \) off a factor \( \sim 100 \)
  PRL 94, 012005 (2005)
- Many individual hadronic modes deviate above or below the predicted 12\%
Survival before Annihilation


“... The cc pair in the ψ' does not annihilate directly into three gluons, but rather survives before annihilating. An interesting prediction is that a large fraction of all ψ' decays could originate from the ψ'→η_c(3π) channel which we urge experimentalists to identify. Our model solves the problem of the apparent hadronic excess in ψ' decays as well as the ρπ puzzle...”

This decay mechanism is postulated to dominate ψ(2S) decays.
Predict ψ(2S)→ππη_c as much as 1% or more
\( \eta_c \) Decay Channels used

5.6 pb\(^{-1}\) of data, 3.1M \( \psi(2S) \) events

<table>
<thead>
<tr>
<th>Mode</th>
<th>Br Rate, (%)</th>
<th>%error in BR</th>
<th>effic, %</th>
<th>Syst Error (%)</th>
<th>Signal evts</th>
<th>Side Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta_c \to K^+K^0\pi^0 )</td>
<td>0.95</td>
<td>28</td>
<td>3.1</td>
<td>30</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>( \eta_c \to \eta \pi^+\pi^- ), ( \eta \to \gamma\gamma )</td>
<td>1.3</td>
<td>37</td>
<td>2.8</td>
<td>38</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>( \eta_c \to \eta \pi^+\pi^- ), ( \eta \to \pi^+\pi^-\pi^0 )</td>
<td>0.7</td>
<td>37</td>
<td>0.8</td>
<td>39</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( \eta_c \to K^+K^-\pi^+\pi^- )</td>
<td>1.5</td>
<td>40</td>
<td>3.1</td>
<td>41</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>( \eta_c \to \pi^+\pi^-\pi^+\pi^- )</td>
<td>1.2</td>
<td>25</td>
<td>4.1</td>
<td>26</td>
<td>6</td>
<td>19</td>
</tr>
<tr>
<td>( \eta_c \to K^+\pi^+K^0 )</td>
<td>3.8</td>
<td>28</td>
<td>1.6</td>
<td>30</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>all six modes</td>
<td>9.5</td>
<td></td>
<td>15</td>
<td>18</td>
<td>33</td>
<td></td>
</tr>
</tbody>
</table>

June 28, 2006  
Onia Hadronic Transitions at CLEO - Kreinick  
11 of 13
Spectrum of $\eta_c$ Candidates

CLEO-c data

1% branching ratio

Upper Limit
0.11% @ 90% C.L.
Predicted $\sim$ 1%

Expect 10$\times$ the data by summer’s end
Summary

ππ transitions:
CLEO sees $\psi(3770) \rightarrow \pi\pi J/\psi$ at the $\sim 10^{-3}$ level

ππ mass plots for $\Upsilon(nS) \rightarrow \pi\pi \Upsilon(mS)$

All the dipion mass distributions look like the Yan form, except $\Upsilon(3S) \rightarrow \pi\pi \Upsilon(1S)$

Described technique for extracting matrix element by fitting in $q^2$-cos$\theta_x$ space

A possible explanation for the $\rho\pi$ puzzle predicts a large $\psi(2S) \rightarrow \pi\pi\pi\eta_c$. We don’t see it.
Backup Slides
$k$ Distribution $\psi(3770) \to \pi^0/\eta \ J/\psi$

Branching ratio

$\psi(3770) \to \eta \ J/\psi$

$(87\pm33\pm22) \times 10^{-5}$

$\psi(3770) \to \pi^0 \ J/\psi$

$<28 \times 10^{-5}$ (90% CL)
k-distribution: $J/\psi \pi^+ \pi^-$

Direct

$\psi(3770)$

RR \rightarrow $\psi(2S)$

Bkg
error bar: data, histogram: MC (normalized to prediction)

Scaled energy

ψ(2S) → ηc 3π, ηc → K^+ K^- π^0

ψ(2S) → ηc 3π, ηc → ρπ^+ π^−

ψ(2S) → ηc 3π, ηc → (γγ)π^+ π^−

ψ(2S) → ηc 3π, ηc → K^+ K^- π^+ π^−

ψ(2S) → ηc 3π, ηc → ρ^+ ρ^− π^− π^+

ψ(2S) → ηc 3π, ηc → K^- π^+ K^0
Search for $\eta_c$ production

Invariant Mass

$\text{m}(K^+K^-\pi^0)$

$\text{m}(\eta \rightarrow \gamma \gamma \pi^+\pi^-)$

$\text{m}(\eta \rightarrow 3\pi \pi^+\pi^-)$

$\text{m}(K^+K^-\pi^+\pi^-)$

$\text{m}(\pi^+\pi^-\pi^+\pi^-)$

$\text{m}(K^-\pi^+K_S^0)$

Error bar: data, histogram: MC (normalized to prediction)
FIG. 4: The data events falling into our three defined regions for the charged one-pion analysis, shaded according to their $\chi^2$ value. The darkest boxes are for events with $\chi^2$ values between 0 and 1 and the lightest for those with $\chi^2$ values between 3 and 4. Most of the events in the small signal region (the smaller rectangle) show low values for $\chi^2$, indicating excellent fits of the photon energy sum to that expected for signal events.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$N_{obs}$</th>
<th>$N_{ck}$</th>
<th>$\epsilon_{1-1}$ (%)</th>
<th>$\epsilon_{2-2}$ (%)</th>
<th>$\Gamma_{\pi\pi}$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged one-pion</td>
<td>17</td>
<td>2.4 ± 0.7</td>
<td>$(1 \pm 0.07)(10.6 \pm 0.8)$</td>
<td>$(1 \pm 0.07)(9.6 \pm 0.3)$</td>
<td>$1.24 \pm 0.35 \pm 0.12$</td>
</tr>
<tr>
<td>Neutral one-pion</td>
<td>35</td>
<td>26.7 ± 5.8</td>
<td>$(1 \pm 0.10)(13.4 \pm 1.7)$</td>
<td>$(1 \pm 0.10)(12.3 \pm 1.0)$</td>
<td>$1.12 \pm 0.80 \pm 0.72$</td>
</tr>
<tr>
<td>Charged two-pion</td>
<td>–</td>
<td>–</td>
<td>$(1 \pm 0.10) \cdot 5.1$</td>
<td>$(1 \pm 0.10) \cdot 4.3$</td>
<td>–</td>
</tr>
<tr>
<td>Neutral two-pion</td>
<td>–</td>
<td>–</td>
<td>$(1 \pm 0.11) \cdot 7.2$</td>
<td>$(1 \pm 0.11) \cdot 6.4$</td>
<td>–</td>
</tr>
<tr>
<td>Combined two-pion</td>
<td>8</td>
<td>3.1 ± 0.6</td>
<td>–</td>
<td>–</td>
<td>$0.52 \pm 0.30 \pm 0.08$</td>
</tr>
</tbody>
</table>

TABLE IV: The various contributions to the calculation of the partial width from sources in this experiment. The two two-pion analyses have been combined for the width determination. Of the two quoted uncertainties, the first is statistical and the second is from the uncertainties in $N_{ck}$ and the efficiencies. An additional systematic uncertainty of $\sim 22\%$ comes from branching fractions, estimates of the total widths, and the number of $\Upsilon(3S)$.
\[ \Upsilon(3S) \rightarrow \Upsilon(1S) \omega X \]

ASSUME \( \pi^+ \pi^- \pi^0 \) form an \( \omega \)

\[
M_{\text{recoil}}^2 = \left( M_{\Upsilon(3S)} - (p_{\pi^+} + p_{\pi^-} + p_{\pi^0}) \right)^2
\]