Recent Results on Hadron Spectroscopy from BESIII

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Williamsburg, Virginia, USA
Outline

- Confirmation of $p\bar{p}$ mass threshold enhancement at BESIII
- Confirmation of $X(1835)$ at BESIII
- Observation of $h_c$
- Summary
What can we do @BESIII

- **Light hadron spectroscopy**
  - Full spectra: normal & exotic hadrons  QCD
  - How quarks form a hadron?  Non-pQCD

- **Charm physics**
  - CKM matrix elements  SM & beyond
  - $D\bar{D}$ mixing & CPV  SM & beyond

- **Charmonium physics**
  - Spectroscopy & transition  pQCD & non-pQCD
  - New states above open charm thresholds  exotic hadrons ?
  - pQCD: rhopi puzzle  a probe to non-pQCD or ?

- **Tau physics & QCD**
  - Precision measurement of the tau mass & $R$ value

- **Search for rare & forbidden decays**
Why can we do @BESIII

- Gluon rich
- Kinematics favorable
- Clean environment, no combinatoric background
- Important $J^{PC}$ filter, and isospin filter

- High statistics: high luminosity machine
- Small systematic error: high quality detector.

  a good platform to study precision charm physics & search for new physics.
Confirmation of $p\bar{p}$ mass threshold enhancement at BESIII
Observation of $p\bar{p}$ threshold enhancement in $J/\psi \rightarrow \gamma p\bar{p}$ @ BESII

M = 1859 $\pm 3$ $\pm 5$ MeV/c$^2$
\Gamma < 30 MeV/c$^2$ (90% CL)

theoretical speculation:

- $pp$ bound state (baryonium)
- FSI effects
- ....
Non-observation of X(1860) at p̅p mass threshold@ BESII

PRL 99 (2007) 011802
\( \psi(2S) \rightarrow \gamma p\bar{p} \) (BES-II)

PRD 73 (2006) 032001
\( \Upsilon(1S) \rightarrow \gamma p\bar{p} \) (CLEO)

EPJ C53 (2008) 15
\( J/\psi \rightarrow \omega p\bar{p} \) (BES-II)

No significant signal of X(1860) found (only 2\( \sigma \) statistic significance)
pp mass threshold enhancement
in \( \psi' \rightarrow \pi^+ \pi^- J/\psi, J/\psi \rightarrow \gamma pp \) @BESIII

Event selection

- **Initial Selection Criteria:**
  - \( N_{\text{charged}} = 4, N_{\gamma} \geq 1 \)
  - Particle ID: \( n_p = 1, n_{\bar{p}} = 1 \)
  - \( \chi^2_{4C} (\gamma \pi^+ \pi^- p\bar{p}) < 100 \)

- **Final Selection Criteria:**
  - Reconstruction of J/\( \Psi \):
    \[ |M_{\pi\pi \_recoiling} - M_{J/\psi}| < 6 \text{ MeV} \]
  - \( |U_{\text{miss}}| < 0.04 \)
  - \( P_{t\gamma}^2 < 0.0005 \)
  - \( M_{\pi^+ \pi^- p\bar{p}} < M_{\psi'} - 15 \text{ MeV} \)
The mass threshold enhancement is evident in the $pp$ mass spectrum.

BESIII
Background study

• J/ψ sideband estimation
  □ ~2%

• Inclusive MC sample
  □ ψ(2S) → ππJ / ψ(J / ψ → π^0 p̅p)

• Main background
  from ψ(2S) → ππJ / ψ(J / ψ → π^0 p̅p)

No mass threshold enhancement observed from background
Mass spectrum fitting method

Fit function:

- **signal**: acceptance weighted S-wave BW function:
  \[ BW(M) \propto \frac{q^{(2l-1)}k^3}{(M^2 - M_0^2)^2 + M^2\Gamma^2} \]
  - \( q \): the proton momentum in cms of ppb
  - \( k \): the photon momentum
  - \( l \): the ppb orbital angular momentum

- **background shape**: \( f_{bkg}(\delta) = \delta^{\frac{1}{2}} + a_1\delta^{\frac{3}{2}} + a_2\delta^{\frac{5}{2}} \)
  - \( a_1 \) and \( a_2 \) are obtain from uniform phase space MC sample

\[ \psi' \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow \gamma pp \]
confirmation of \( pp \) mass threshold enhancement

\[
\psi' \rightarrow \pi^+ \pi^- J/\psi, J/\psi \rightarrow \gamma pp
\]

Published in Chinese Physics C 34(2010)421

\[
M = 1865 \pm 5 \text{ MeV}/c^2
\]

\[
\Gamma < 33 \text{ MeV}/c^2 \text{ (90\% CL)}
\]

Confirmed at BESIII, the mass and width are consistent with those from BESII.

\[
J/\psi \rightarrow \gamma pp
\]

\[
M = 1859^{+3}_{-10}^{+5}_{-25} \text{ MeV}/c^2
\]

\[
\Gamma < 30 \text{ MeV}/c^2 \text{ (90\% CL)}
\]
pp mass threshold enhancement
in \( J/\psi \rightarrow \gamma pp \) \( @ \) BESIII

The mass threshold enhancement is evident in pp mass spectrum
Fitting $p\bar{p}$ mass threshold enhancement

$J/\psi \rightarrow \gamma p\bar{p}$

BESIII preliminary

$M=1861.6 \pm 0.8$ MeV/c$^2$

$\Gamma < 8$ MeV/c$^2$ (90% CL)

$M=1859^{+3+5}_{-10-25}$ MeV/c$^2$

$\Gamma < 30$ MeV/c$^2$ (90% CL)

Consistent results at BESIII
Non-observation of mass enhancement in $\psi(2S) \rightarrow \gamma pp$ @BESIII

Confirmation of non-observation of enhancement in $\psi(2S)$ channel!

$\Rightarrow$ pure FSI effect unlikely
Confirmation of X(1835) at BESIII
Observation of $X(1835)$ @BESII

$J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'$

It’s necessary to confirm $X(1835)$ at BESIII with high statistic $J/\psi$ data sample
X(1835) in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$ ($\eta' \rightarrow \gamma \rho$) at BESIII

Event selection

- **Initial selection criteria:**
  - $N_{charged} = 4$, $N_{\gamma} \geq 2$
  - $N_{\pi} > 2$
  - Kinematic fit(4C):
    \[ \chi^2_{4C}(\gamma\pi^+\pi^-\pi^+\pi^-) < 40 \]
    \[ \chi^2_{4C}(\gamma\pi^+\pi^-\pi^+\pi^-) < \chi^2_{4C}(\gamma\pi^+\pi^-\pi^+\pi^-) \]

- **Final selection criteria:**
  - Reduce background from $\pi^0 \pi^+ \pi^- \pi^+ \pi^-$:
    \[ |m_{\gamma\gamma} - m_{\pi}| < 0.04 GeV \]
    \[ |m_{\gamma\gamma} - m_{\eta}| < 0.03 GeV \]
    \[ 0.72 GeV < m_{\gamma\gamma} < 0.82 GeV \]
$X(1835)$ in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^- (\eta' \rightarrow \gamma \rho)$

@BESIII

$|M(\pi^+ \pi^-) - m_\rho| < 0.2 \text{GeV}$

$|M(\gamma \pi^+ \pi^-) - m_\eta'| < 0.018 \text{GeV}$
Observation X(1835) in the mass spectrum of $\eta'\pi^+\pi^-$ ($\eta'\rightarrow\gamma\rho$)

- Significant peak at $M\sim 1835$ MeV
- Statistical significance of X(1835) is about $18\sigma$ @BESIII
- Statistical significance of X(1835) is about $6\sigma$ @BESII
X(1835) in J/ψ→γη′π⁺π⁻ (η′→ηπ⁺π⁻) @BESIII

Event selection

- \( N_{\text{charged}} = 4, \ N_\gamma \geq 3 \)
- \( N_\pi > 2 \)
- Kinematic fit(4C,5C):
  \[ \chi^2_{4C}(\gamma\gamma\pi^+\pi^-\pi^+\pi^-) < 40 \]
  \[ \chi^2_{5C}(\gamma\eta\pi^+\pi^-\pi^+\pi^-) < 40 \]
- Selection for η and η′ signal:
  \[ |M_{\gamma\gamma} - m_\eta| < 0.03 \text{GeV} \]
  \[ |M_{\pi\pi\eta} - m_{\eta'}| < 0.01 \text{GeV} \]
Observation of X(1835) in the mass spectrum of \( \eta'\pi^+\pi^- (\eta' \rightarrow \eta\pi^+\pi^-) \)

- Significant peak at M\(\sim\)1835MeV
- Statistic significance of X(1835) is about 9 \(\sigma\) @BESIII
- 5.1 \(\sigma\) @BESII
Background study for $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$
($\eta' \rightarrow \gamma \rho$ & $\eta' \rightarrow \eta \pi^+ \pi^-$)

- $\eta'$ sideband:
  - No clear peak at $M \sim 1835 \text{MeV}$

- Inclusive sample
  - Main background channel:
    $J/\psi \rightarrow \rho \pi \eta'$

- Analysis of $J/\psi \rightarrow \pi^0 \pi^+ \pi^- \eta'$ in data
  - No peak at $M \sim 1835 \text{MeV}$
X(1835) is confirmed in BESIII and the significance increases as statistics increases.

The possibility that there are two new resonances is under further study.

Statistic significance \(\sim 21\sigma\)@BESIII
- \(M = 1842.4 \pm 2.8\, (stat)\, MeV\)
- \(\Gamma = 99.2 \pm 9.2\, (stat)\, MeV\)

Statistic significance \(7.7\, \sigma\)@BESII
- \(M = 1833.7 \pm 6.1\, (stat) \pm 2.7\, (syst)\, MeV\)
- \(\Gamma = 67.7 \pm 20.3\,(stat) \pm 7.7\,(syst)\, MeV\)
Observation of $h_c$
Although the charmonium family has been studied for many years, knowledge is limited on the \( \bar{c}c \) P wave spin-singlet state \( h_c^{(1P_1)} \).

In 2008, \( h_c \) was observed by CLEOc.

In the charmonium decays, \( h_c \) can only be observed in the process of \( \psi(2S) \rightarrow \pi^0 h_c \).

The main decay mode of \( h_c \) is the E1 transition \( h_c \rightarrow \gamma \eta_c \).

\( M(h_c) \) is very close to \( M(1^{3P}) \approx 3525 \text{MeV} \)

\( \Delta M_{\text{hf}} = M<1^{1P_1}> - M(1^{3P}) \sim 0.08 \pm 0.18 \pm 0.12 \text{MeV} \)

consistent to \( 1^P \) hyperfine splitting of 0.
In previous experiments, the absolute branching ratios of \( \psi' \rightarrow \pi^0 h_c \) and \( h_c \rightarrow \gamma \eta_c \) have not been measured.

### CLEOc’s Result

- \( \psi' \rightarrow \pi^0 h_c \), \( h_c \rightarrow \gamma \eta_c \), E1-tagged

<table>
<thead>
<tr>
<th>Mode</th>
<th>Efficiency (%)</th>
<th>Yield</th>
<th>( B_1 \times B_2 \times 10^5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi^+ \pi^- \pi^0 )</td>
<td>27.0</td>
<td>1.6^{+5.4}_{-3.0}</td>
<td>&lt; 0.19</td>
</tr>
<tr>
<td>( 2(\pi^+ \pi^-) \pi^0 )</td>
<td>18.8</td>
<td>9.2^{+3.9}_{-2.9}</td>
<td>(1.88^{+0.48}_{-0.40})</td>
</tr>
<tr>
<td>( 3(\pi^+ \pi^-) \pi^0 )</td>
<td>11.5</td>
<td>35 \pm 26</td>
<td>(1.2 \pm 0.9 \pm 0.3) (&lt;2.5)</td>
</tr>
</tbody>
</table>

\[ B_1 \times B_2 \times 10^4 = 4.22 \pm 0.44 \pm 0.52 \quad 4.15 \pm 0.48 \pm 0.77 \]

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**PRL101,182003(2008)**
h_c in E1-tagged ψ(2S)→π^0 h_c, h_c→γ η_c

@BESIII

Event selection

- Select inclusive π^0 (ψ'→π^0 h_c)
  - Photon polar angle: |cosθ|<0.8
  - Photon energy: E_γ>40MeV
  - Each photon belongs to only one π^0
  - M_{γγ}∈[0.12,0.145]GeV/c^2
  - Do 1C fit for each π^0 candidate (no cut on χ^2)

- Select E1-photon γ to tag h_c→γ η_c
  - 450MeV<E_γ<540MeV
  - Not belonging to π^0 (0.10-0.145GeV/c^2) and η(0.53-0.56GeV/c^2)

- Background veto
  - π^+π^−J/ψ: |M_{rec}(π^+π^-)-3.097|>0.007GeV/c^2
  - π^0π^0J/ψ: |M_{rec}(π^0π^0)-3.097|>0.03GeV/c^2
E1-tagged $\psi' \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \eta_c$

- A fit of double-Gaussian $\otimes$ BW signal + E1-photon sideband background yield

Significance = 18.6$\sigma$

$N(h_c) = 3679 \pm 319$

$M(h_c) = 3525.40 \pm 0.13$ MeV

$\Gamma(h_c) = 0.73 \pm 0.45$ MeV

$\chi^2/d.o.f = 33.5/36$

$\text{Br}(\psi' \rightarrow \pi^0 h_c) \times \text{Br}(h_c \rightarrow \gamma \eta_c) = (4.58 \pm 0.40 \pm 0.50) \times 10^{-4}$
Select inclusive $\pi^0$ ($\psi' \rightarrow \pi^0 h_c$)

- Untagged E1-photon
- A fit of D-Gaussian $\otimes$ BW signal + 4th Poly. BG yield.

Mass and width is fixed as tagged measurement.

Combined with tagged results, we measured for the first time:

- \( \text{Br}(\psi' \rightarrow \pi^0 h_c) = (8.4 \pm 1.3 \pm 1.0) \times 10^{-4} \)
- \( \text{Br}(h_c \rightarrow \gamma \eta_c) = (54.3 \pm 6.7 \pm 5.2)\% \)

BES Collaboration, PRL 104, 132002 (2010)
## Summary for $h_c$ analysis

<table>
<thead>
<tr>
<th></th>
<th>BESIII</th>
<th>CLEOc</th>
<th>theoretical prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Br}(\psi' \to \pi^0 h_c)$</td>
<td>$4.58 \pm 0.40 \pm 0.50$</td>
<td>$4.19 \pm 0.32 \pm 0.45$</td>
<td>-</td>
</tr>
<tr>
<td>$\times \text{Br}(h_c \to \gamma \eta_c)$</td>
<td>[$10^{-4}$]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M$ [MeV/c$^2$]</td>
<td>$3525.40 \pm 0.13 \pm 0.18$</td>
<td>$3525.80 \pm 0.19 \pm 0.12$</td>
<td>-</td>
</tr>
<tr>
<td>$\Gamma$ [MeV]</td>
<td>$0.73 \pm 0.45 \pm 0.28$</td>
<td>-</td>
<td>$1.1$ (NRQCD) Kuang</td>
</tr>
<tr>
<td></td>
<td>$&lt;1.44$ @ 90% CL</td>
<td></td>
<td>$0.51$ (PQCD) Kuang</td>
</tr>
<tr>
<td>$\Delta M_{hf}(1P)$</td>
<td>$0.10 \pm 0.13 \pm 0.18$</td>
<td>$0.08 \pm 0.18 \pm 0.12$</td>
<td></td>
</tr>
<tr>
<td>$[\text{MeV/c}^2]$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{Br}(\psi' \to \pi^0 h_c)$</td>
<td>$8.4 \pm 1.3 \pm 1.0$</td>
<td>-</td>
<td>4 - 13</td>
</tr>
<tr>
<td>[10$^{-4}$]</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$\text{Br}(h_c \to \gamma \eta_c)$</td>
<td>$54.3 \pm 6.7 \pm 5.2$</td>
<td>-</td>
<td>41 (NRQCD) Kuang</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>88 (PQCD) Kuang</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>38 Godfrey, Rosner</td>
</tr>
</tbody>
</table>


BES Collaboration, PRL 104, 132002 (2010)

Summary

- p̅p mass threshold enhancement has been confirmed in \( \psi' \rightarrow \pi^+\pi^- J/\psi(\gamma \rho) \) and \( J/\psi \rightarrow \gamma \rho \) and no significance mass enhancement is observed in \( \psi' \rightarrow \gamma p\bar{p} \) at BESIII.

- X(1835) is confirmed in the two decay modes (\( \eta' \rightarrow \gamma \rho \) and \( \eta' \rightarrow \eta \pi^+\pi^- \)) for \( J/\psi \rightarrow \gamma \eta' \pi^+\pi^- \).

- From inclusive and E1-tagged analysis, we observed \( h_c \) and measured

  \[ \Gamma(h_c) = 0.89 \pm 0.57 \pm 0.23 \text{ MeV} \]

  \[ B_1(\psi' \rightarrow \pi^0 h_c) = (8.42 \pm 1.29 \text{ (stat.)}) \times 10^{-4} \text{ and} \]

  \[ B_2(h_c \rightarrow \gamma \eta_c) = (55.7 \pm 6.3 \text{ (stat.)})\% \text{ for the first time.} \]

- More Exciting results are expected in the coming years.
Back up
Back up

Observation of X(1835) in $J/\psi \rightarrow \gamma \pi^+\pi^-\eta'$ at BESII

Statistical Significance $\sim 6 \sigma$

Statistical Significance $\sim 5.1 \sigma$

PRL 95.262001(2005)
speculation for $X(18^{**})$

- The strong and narrow $p\bar{p}$ mass threshold enhancement has only been observed in $J/\psi$ radiative decay, not in any other place so far.

- Any model trying to interpret the mass threshold enhancement should also answer why it is not observed in other places, especially in $\psi(2S)$ and $Y(1S)$ radiative decays as well as in $J/\psi \to \omega \ p\bar{p}$ process.

- Whether $X(1860)$ and $X(1835)$ are the same resonance, still needs further study.
**$h_c$: spin-spin interaction**

The $cc$ singlet state $h_c$ was predicted by theory long time ago. In 2008, $h_c$ was observed by CLEO\_c in charmonium decays. $h_c$ can only be observed in the process of $\gamma(2S) \rightarrow p0h_c$. The main decay mode of $h_c$: the E1 transition $h_c \rightarrow \gamma h_c$.

- Test of QCD and potential model spin-spin-interaction tells us:

$$\Delta M_{h_f}(1P) = m(h_c) - \frac{1}{9} \left( m(x_{c0}) + 3m(x_{c1}) + 5m(x_{c2}) \right)$$
$h_c$ in CLEOc and E853

data were done. In the \textit{inclusive analysis} $h_c$ decays were identified by loose constraints on either the energy of the electric dipole (E1) photon from $h_c$ decay, or the mass of $\eta_c$. In the \textit{exclusive analysis} no constraint was placed on $E(\gamma)$. Instead, $\eta_c$ events were reconstructed in seven different hadronic decay channels of $\eta_c$. The combined significance level of the $h_c$ observation was $>6\sigma$, and the quoted mass was $M(h_c) = 3524.4 \pm 0.6 \pm 0.4$ MeV.

The Fermilab E835 measurement [3] made scans of antiproton energy for the reaction, $\bar{p}p \rightarrow h_c \rightarrow \gamma\eta_c$, $\eta_c \rightarrow \gamma\gamma$. The results from the year 1997 scan and the year 2000 scan were combined to obtain $M(h_c) = 3525.8 \pm 0.2 \pm 0.2$ MeV. The significance level of $h_c$ observation was $\sim 3\sigma$. No evidence was found for $h_c$ in the previously reported reaction $\bar{p}p \rightarrow h_c \rightarrow \pi^0 J/\psi$ [5].
Event selection for the inclusive $\pi^0$ and E1-tagged analysis

- **Inclusive analysis of $\psi(2S) \rightarrow \pi^0 h_c$**
  - Identify the $h_c$ signal by searching for an enhancement in the inclusive recoiling mass spectrum of $\pi^0$.

- **E1-tagged analysis of $\psi(2S) \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \eta_c$**
  - Tag the E1 photon (~503 MeV) emitted in $h_c \rightarrow \gamma_{E1} \eta_c$. No further constraints on the final states of the $\eta_c$ are imposed. The $h_c$ signal in $\pi^0$ recoil mass spectrum will be improved significantly.

- **Exclusive analysis of $\psi(2S) \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \eta_c$**
  - Fully reconstruct the exclusive final states of $\eta_c$. 

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2010-5-31  Fang Liu(IHEP)
Event selection for the inclusive $\pi^0$ and E1-tagged analysis

**Good charged track**
- IP region: $|R_{xy}| \leq 1\text{cm}$, $|Rz| \leq 10\text{cm}$
- Momentum: $p < 2.0\text{GeV}$
- Polar angle: $|\cos\theta| < 0.93$
- $N_{\text{charge}} \geq 2$, $N_{\text{good}} \geq 1$

**Good photon**
- $|\cos\theta| < 0.8; E_{\gamma} > 25\text{MeV}$
- $0.84 <|\cos\theta| < 0.92; E_{\gamma} > 50\text{MeV}$
- Angle between charged track and neutral track: $\Delta\theta < 20^\circ$
- EMC time: $0 \leq t \leq 14$ ($\times 50\text{ns}$)
Event selection for the inclusive $\pi^0$ and E1-tagged analysis

**signal $\pi^0$ candidate selection**
- Photon polar angle: $|\cos\theta|<0.8$
- Photon energy: $E_\gamma>40\text{MeV}$
- Each photon belongs to only one $\pi^0$
- $M_{\gamma\gamma}\in[0.12,0.145]\text{GeV/c}^2$
- Do 1C fit for each $\pi^0$ candidate (no cut on $\chi^2$)

**Tag E1 photon in $h_c \rightarrow \gamma_{E1} \eta_c$**
- $450\text{MeV}<E_\gamma<540\text{MeV}$
- Not belonging to $\pi^0$ ($0.10-0.145\text{GeV/c}^2$) and $\eta(0.53-0.56\text{GeV/c}^2)$

**Background Veto**
- $\pi^+\pi^-J/\psi$: $|M_{\text{rec}}(\pi^+\pi^-)-3.097|>0.007\text{GeV/c}^2$
- $\pi^0\pi^0J/\psi$: $|M_{\text{rec}}(\pi^0\pi^0)-3.097|>0.03\text{GeV/c}^2$
### Systematic error for $h_c$ analysis

<table>
<thead>
<tr>
<th>Source</th>
<th>$M(h_c)$ (MeV/c²)</th>
<th>$\Gamma(h_c)$ (MeV)</th>
<th>$B_1 (10^{-4})$</th>
<th>$B_1 \times B_2 (10^{-4})$</th>
<th>$B_2 (%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background shape and fit range</td>
<td>0.11</td>
<td>0.23</td>
<td>0.4</td>
<td>0.22</td>
<td>4.4</td>
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<tr>
<td>Energy scale, position</td>
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<td>0.06</td>
<td>0.5</td>
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<td>reconstruction and 1-C fit</td>
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<td>Energy resolution</td>
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<td>1.0</td>
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<tr>
<td>Background veto</td>
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<td>0.03</td>
<td>0.0</td>
<td>0.03</td>
<td>0.3</td>
</tr>
<tr>
<td>$\pi^0$ efficiency</td>
<td>0.00</td>
<td>0.00</td>
<td>0.3</td>
<td>0.14</td>
<td>0.0</td>
</tr>
<tr>
<td>$E1$ photon efficiency</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0</td>
<td>0.10</td>
<td>1.2</td>
</tr>
<tr>
<td>Number of $\pi^0$</td>
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<td>0.00</td>
<td>0.6</td>
<td>0.35</td>
<td>0.6</td>
</tr>
<tr>
<td>Number of charged tracks</td>
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<td>0.00</td>
<td>0.1</td>
<td>0.06</td>
<td>0.1</td>
</tr>
<tr>
<td>$N(\psi')$</td>
<td>0.00</td>
<td>0.00</td>
<td>0.4</td>
<td>0.19</td>
<td>0.0</td>
</tr>
<tr>
<td>$M(\psi')$</td>
<td>0.03</td>
<td>0.02</td>
<td>0.0</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>$M(\eta_c)$ and $\Gamma(\eta_c)$</td>
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<td>0.00</td>
<td>0.0</td>
<td>0.01</td>
<td>0.3</td>
</tr>
<tr>
<td>Total systematic error</td>
<td>0.18</td>
<td>0.28</td>
<td>1.0</td>
<td>0.50</td>
<td>5.2</td>
</tr>
</tbody>
</table>
The CLEO average mass in Eq. (6) leads to

\[ \Delta M_{hf}(1P) = +0.08 \pm 0.18 \text{(stat.)} \pm 0.12 \text{(syst.) MeV}. \]

These results are consistent with the lowest order expectation of 1P hyperfine splitting being zero. We notice that the triplet mass used above was obtained as \( \langle M(3P_J) \rangle = [M(3P_0) + 3M(3P_1) + 5M(3P_2)]/9 \), which is the evaluation of \( M(3P) \) in the lowest order, when the spin-orbit splitting is perturbatively small. It has been pointed out [4] that with \[ [M(3P_2) - M(3P_0)] \approx 140 \text{ MeV, the validity of the } \]
[perturbative determination of \( M(3P) \) is questionable. Indeed, the perturbative prediction that \( M(3P_1) - M(3P_0) = \frac{2}{5}[M(3P_2) - M(3P_1)] = 113.9 \pm 0.3 \text{ MeV } \]
[disagrees with the experimental result, 95.9 \pm 0.4 \text{ MeV, by } \]
[18 \text{ MeV. This necessarily implies that the true } M(3P) \text{ is } \]
different from the centroid value \( \langle M(3P_J) \rangle \). Since \[ \Delta M_{hf}(1P) \text{ is expected to be small (few MeV), if not } \]
[identically zero, it is important that higher order effects should be taken into account in deducing \( M(3P) \) from the known masses of \( 3P_J \) states [4], so that a true measure of \( \Delta M_{hf}(1P) \) can be obtained. Only then can the present measurement of \( M(h_c) \) be used to distinguish between the different potential model calculations, whose predictions for \( \Delta M_{hf}(1P) \) vary over a large range because of the different assumptions they make about relativistic effects, the Lorentz nature of the confinement potential, and smearing of the spin-spin contact potential [12]. Although the presently available lattice calculations do not have the required precision [13], it may be expected that future unquenched lattice calculations will resolve these problems.