The $D_{sJ}$ States at CLEO

- The $\textit{BaBar}$ discovery
- Introduction to $c\bar{s}$ meson spectroscopy
- Study of the $D_s\pi^0$ and $D_s^*\pi^0$ final states at CLEO
- Other decay modes of the new states
- Properties of $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$
- Interpretations

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June 23, 2004
Surprising discovery of $D_{sJ}^*(2317) \rightarrow D_s \pi^0$ in April 2003:
- Mass: $2317.3 \pm 0.4$ (stat.) $\pm 0.8$ (sys.) MeV
- Width: $8.6 \pm 0.4$ MeV
- Reconstructed $1267 \pm 53$ events
- Tentatively suggested to be a $^3P_0$ state with $J^P = 0^+$

Why surprising?
- Narrow ($< 10$ MeV)
- Observed in the isospin-violating $D_s \pi^0$ channel
- Less massive than most theoretical predictions for a $0^+$ $c\bar{s}$ state that could decay via this channel

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The New $D_{sJ}$ States at CLEO

PRL 90, 242001 (2003)
The $c\bar{s}$ Meson Spectroscopy

- **S-wave states:**

<table>
<thead>
<tr>
<th>$c\bar{s}$ meson</th>
<th>$J^P$</th>
<th>Mass</th>
<th>Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_s$</td>
<td>0$^-$</td>
<td>1969 MeV</td>
<td>decays weakly</td>
</tr>
<tr>
<td>$D_s^*$</td>
<td>1$^-$</td>
<td>2112 MeV</td>
<td>$B(D_s^* \rightarrow D_s \gamma) = 94%$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B(D_s^* \rightarrow D_s \pi^0) = 6%$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(suppressed by isospin and phase space)</td>
</tr>
</tbody>
</table>

- **P-wave states:**

$2S+1_L \ J : 1P_1$ and $3P_{0,1,2}$

Seen: $1^+ \ D_{s1}(2536) \rightarrow D^* K (\Gamma < 2.3$ MeV) [ARGUS 1989]

$2^+ \ D_{sJ}(2573) \rightarrow D K (\Gamma \sim 15$ MeV) [CLEO 1994]

- The remaining two states $0^+$ and $1^+$ were generally expected to be above $D K$ threshold and had large widths: $\sim 200$ MeV
The $c\bar{s}$ Meson Spectroscopy before 2003

Figure from Barnes, Close, Lipkin [PRD 68, 054006 (2003)]
The CLEO Experiment

- The CLEO detector is located at the south IR of Cornell Electron Storage Ring (CESR).

- Four “recent” running periods:
  1) **CLEOII (1989-1995)**
     ~4.5/fb, most on/near Υ(4S)
  2) **CLEOII.V (1995-1998)**
     ~9.5/fb, most on/near Υ(4S); Inner tracker replaced with silicon
  3) **CLEOIII (2000-2003)** ~10/fb, most on/near Υ(4S), also on Υ(1S), Υ(2S), Υ(3S); New silicon detector, drift chamber, and RICH
  4) **CLEO-c (2003-present)**
     running near charm threshold; Silicon detector replaced with ZD.
Event Selection and Basic Cuts

Reconstructing the decay chain: $D_s^{(*)} \rightarrow D_s^+ \pi^0$
with $D_s^+ \rightarrow \phi \pi^+$, $\phi \rightarrow K^+ K^-$ and $\pi^0 \rightarrow \gamma \gamma$

Some important requirements:

- $P(D_s \pi^0) > 3.5$ GeV
- $M(K^+K^-)$ within 10 MeV of the $\phi$ mass
- $|\cos(\theta_h)| > 0.3$ for the helicity of the $\phi$ decay
- $E_\gamma > 100$ MeV for each of the $\pi^0$ daughters and barrel photons only
- $-3.0 \sigma < M(\gamma \gamma) - M(\pi^0) < 2.5 \sigma$
The $D_s \pi^0$ Final State at CLEO

- **1995**: $D_s \pi^0 (3.75 \text{ fb}^{-1})$

- **2003**: $D_s \pi^0 (13.5 \text{ fb}^{-1})$

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The New $D_{sj}$ States at CLEO
Fit Results for $D_{sJ}^*(2317)$

- Single Gaussian fit:
  - Yield: $165 \pm 20$ events
  - Mean: $\Delta M = 349.4 \pm 1.0$ MeV
  - Width: $8.0 \pm 1.2$ MeV
- Inferred Mass: $2317.9 \pm 1.2$ MeV
- Expected mass resolution from MC: $6.0 \pm 0.3$ MeV

Note: generic MC is normalized to luminosity of data; excellent agreement except at the new resonance.
The $D_s \pi^0 \gamma$ final state at BaBar

Figure 3 from the BaBar paper

- No peak at 2.32 GeV
- But a new peak appears at 2.46 GeV
- Enhanced peak if required

$D_s \gamma$ forms a $D_s^*$

Regarding the nature of this peak being due to a second state or a kinematic reflection:

“…However, the complexity of the overlapping kinematics of the $D_s^*(2112)^+ \rightarrow D_s^+ \gamma$ and $D_s J^*(2317)^+ \rightarrow D_s^+ \pi^0$ requires more detailed study… to arrive at a definitive conclusion.”

PRL 90, 242001 (2003)
**Discovery of $D_{SJ}(2460)$ at CLEO**

$D_{SJ}(2460) \rightarrow D_{s}^{*+}\pi^{0}$ final state with $D_{s}^{*+} \rightarrow D_{s}^{+}\gamma$

- A peak at the mass difference $\Delta M = D_{s}^{*+}\pi^{0} - D_{s}^{*+}$ leads to the possibility of a second narrow resonance with a mass near 2.46 GeV.

- But the mass differences are both $\sim 350$ MeV, so they can reflect into each other!

- How and why is there cross feed?
Feed Down from $D_{sJ}(2460)$

$D_{sJ}(2460) \rightarrow D_s^*\pi^0$ with missing $\gamma$

$\Rightarrow$ reconstructed as $D_{sJ}^*(2317) \rightarrow D_s^+\pi^0$
Feed Up from $D_{sJ}^*(2317)$

$D_{sJ}^*(2317) \rightarrow D_s \pi^0 + \text{random } \gamma$

$\Rightarrow$ reconstructed as $D_{sJ}(2460) \rightarrow D_s^{*+} \pi^0$
Approaches to Study the Cross Feed

Untangle the cross feed between $D_s\pi^0$ and $D_s^{*}\pi^0$:

- Use Monte Carlo simulations as basis for “unfolding”
- Use sidebands from the data to estimate background
- Study lineshapes of peaks
Feed Down from $D_{sJ}(2460)$

$D_{sJ}^*(2317) \rightarrow D_s\pi^0$

Signal

$\sigma = 6.5 \pm 0.3 \text{ MeV}$

$D_{sJ}(2460) \rightarrow D_s^*\pi^0$ signal

reconstructed as $D_s\pi^0$

$\sigma = 14.9 \pm 0.4 \text{ MeV}$

The probability of $D_{sJ}(2460)$ feeding down to $D_{sJ}^*(2317)$ is $(84 \pm 4 \pm 10)\%$.  

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The New $D_{sJ}$ States at CLEO
Feed Up from $D_{sJ}^*(2317)$

$D_{sJ}(2460) \rightarrow D_s^* \pi^0$ Signal MC

$D_{sJ}(2317) \rightarrow D_s \pi^0$ signal + Random $\gamma$

$\sigma = 6.5 \pm 0.2$ MeV

$\sigma = 14.9 \pm 0.6$ MeV

The probability of $D_{sJ}^*(2317)$ feeding up to $D_{sJ}(2460)$ is $(9.1 \pm 0.7 \pm 1.5)\%$. 

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The New $D_{sJ}$ States at CLEO
Calculation of Real Signal from Unfolding

R0 ≡ number of reconstructed $D_{sJ}^*(2317) \rightarrow D_s \pi^0$ events, excluding feed-down
R1 ≡ number of reconstructed $D_{sJ} (2460) \rightarrow D_s^* \pi^0$ events, excluding feed-up

N0 ≡ number of events extracted from fit to the $D_s \pi^0$ mass spectrum in data
N1 ≡ number of events extracted from fit to the $D_s^* \pi^0$ mass spectrum in data

\[
\begin{align*}
N_0 &= R_0 + \text{feed-down} = R_0 + R_1 \times f_1 \\
N_1 &= R_1 + \text{feed-up} = R_1 + R_0 \times f_0
\end{align*}
\]

f0 ≡ probability that a $D_{sJ}^*(2317)$ feeds up and is reconstructed as $D_s^* \pi^0$
f1 ≡ probability that a $D_{sJ} (2460)$ feeds down and is reconstructed as $D_s \pi^0$

N0 = 190 ± 19  \hspace{1cm} f0 = 0.091 ± 0.017  \hspace{1cm} R0 = 155 ± 23
N1 = 55 ± 10  \hspace{1cm} f1 = 0.84 ± 0.11  \hspace{1cm} R1 = 41 ± 12
Estimate the $D_{sJ}(2460)$ Signal

<table>
<thead>
<tr>
<th></th>
<th>Sideband Subtraction</th>
<th>Unfolding Method</th>
</tr>
</thead>
<tbody>
<tr>
<td># of events</td>
<td>46 ± 12</td>
<td>41 ± 12</td>
</tr>
<tr>
<td>$M(D_{sJ} \pi^0) - M(D_{sJ}^*)$ (in MeV)</td>
<td>351.2 ± 1.6</td>
<td>350.6 ± 1.2</td>
</tr>
<tr>
<td>Signal width ($\sigma$) (in MeV)</td>
<td>5.5 ± 1.2</td>
<td>6.6 ± 0.5 MC</td>
</tr>
</tbody>
</table>
The sideband subtracted signal is significant at the 5.7 $\sigma$ level.
Study the $D_{sJ}^*(2317)$ Width

Fit with two Gaussians:

<table>
<thead>
<tr>
<th>Function</th>
<th>Narrow Width</th>
<th>Broad Width</th>
<th>Single Gaussian</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Gaussian (sigma)</td>
<td>5.9±1.2</td>
<td>16.5±6.3</td>
<td>8.3±1.2</td>
</tr>
<tr>
<td>2. Gaussian (sigma)</td>
<td>6.4±0.4</td>
<td>14.9±0.6</td>
<td></td>
</tr>
</tbody>
</table>

- Results are consistent with the existence of a narrow signal and a broader feed-down contribution.
- The amount of reflection in the fits is consistent with calculation.
- The reflection broadens the peak and also shifts the center of the peak. We can extract a more precise mass from this fit.
Searching for EM Decays of $D_{SJ}$

- $D_{SJ}(xxxx) \rightarrow D_s^+ \gamma$
  - $0^+ \rightarrow 0^- \gamma$ forbidden by angular momentum and parity
  - $1^+ \rightarrow 0^- \gamma$ allowed

- $D_{SJ}(xxxx) \rightarrow D_{s}^{*+} \gamma$
  - $0^+ \rightarrow 1^- \gamma$ allowed via $S$-wave decay
  - $1^+ \rightarrow 1^- \gamma$ allowed
Searching for Strong Decays of $D_{sj}$

- $D_{sj}(xxxx)^+ \rightarrow D_s^+ \pi^+ \pi^-$
  - conserved isospin but suppressed by OZI rule
  - $0^+ \rightarrow 0^- 0^- 0^-$ forbidden by angular momentum & parity
  - $1^+ \rightarrow 0^- 0^- 0^-$ allowed

- $D_{sj}(xxxx)^+ \rightarrow D_s^{*+} \pi^0$
  - $0^+ \rightarrow 0^- 1^- 0^-$ forbidden by angular momentum & parity
  - $1^+ \rightarrow 0^- 1^- 0^-$ allowed
## Upper Limits for the New States

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Yield</th>
<th>Efficiency (%)</th>
<th>Ratio (90% C.L.)</th>
<th>Theory Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{sJ}^*(2317)$</td>
<td>$D_s \pi^0$</td>
<td>$135 \pm 23$</td>
<td>$9.7 \pm 0.6$</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$D_s \gamma$</td>
<td>$-19 \pm 13$</td>
<td>$18.5 \pm 0.1$</td>
<td>$&lt; 0.052$</td>
</tr>
<tr>
<td></td>
<td>$D_s^* \gamma$</td>
<td>$-6.5 \pm 5.2$</td>
<td>$7.0 \pm 0.5$</td>
<td>$&lt; 0.059$</td>
</tr>
<tr>
<td></td>
<td>$D_s \pi^+ \pi^-$</td>
<td>$2.0 \pm 2.3$</td>
<td>$19.8 \pm 0.8$</td>
<td>$&lt; 0.019$</td>
</tr>
<tr>
<td></td>
<td>$D_s^* \pi^0$</td>
<td>$-1.7 \pm 3.9$</td>
<td>$3.6 \pm 0.3$</td>
<td>$&lt; 0.11$</td>
</tr>
<tr>
<td>$D_{sJ}(2460)$</td>
<td>$D_s^* \pi^0$</td>
<td>$41 \pm 12$</td>
<td>$6.0 \pm 0.2$</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$D_s \gamma$</td>
<td>$40 \pm 17$</td>
<td>$19.8 \pm 0.4$</td>
<td>$&lt; 0.49$</td>
</tr>
<tr>
<td></td>
<td>$D_s^* \gamma$</td>
<td>$-5.1 \pm 7.7$</td>
<td>$9.1 \pm 0.3$</td>
<td>$&lt; 0.16$</td>
</tr>
<tr>
<td></td>
<td>$D_s \pi^+ \pi^-$</td>
<td>$2.5 \pm 5.4$</td>
<td>$19.5 \pm 1.5$</td>
<td>$&lt; 0.08$</td>
</tr>
<tr>
<td></td>
<td>$D_s^*(2317) \gamma$</td>
<td>$3.6 \pm 3.0$</td>
<td>$2.0 \pm 0.1$</td>
<td>$&lt; 0.58$</td>
</tr>
</tbody>
</table>

Theoretical expectations from Bardeen, Eichten & Hill
The $D_{sJ}(2460)$ Signal from Belle

- Reconstructed 131 events in the $D_{sJ}^{*} \pi^0$ final state
- $93 \pm 22$ events after background subtracted (4.3$\sigma$)

Mass = $2456.5 \pm 1.3$(stat) $\pm 1.1$(syst) MeV

PRL 92, 012002 (2004)
The $D_{sJ}(2460)$ Signal from BaBar

Mass = $2458 \pm 1.0\text{(stat)} \pm 1.0\text{(syst)}$ MeV

PRD 69, 031101 (2004)
Theoretical Explanations

- Ordinary excited $\bar{c}s$ states:
  - $D_{SJ}$ are narrow because isospin is violated in the decay (only way for hadronic decay to occur since they are below $DK$ threshold) [Cho & Wise, PRD 1994]
  - HQET + chiral symmetry explain the mass difference [Nowak, Rho, Zahed, PRD 48, 4370 (1993) and Bardeen, Eichten & Hill, PRD 68, 054024 (2003)]
- $DK$ molecule [Barnes, Close & Lipkin, PRD 68, 054006 (2003)]
- Unitarized meson model used to explain the low mass as a threshold effect [Beveren & Rupp, PRL 91, 012003 (2003)]
- Mass obtained using QCD sum rules [Dai, Huang & Zhu, PRD 68, 114011 (2003)]
- Mass obtained using non-relativistic vector and scalar exchanges forces and recalculate within potential model [Cahn and Jackson, PRD 68, 037502 (2003)]
Contradictory Lattice QCD Results

- **Bali:** [PRD68, 071501 (2003)]
  - Lattice has trouble accommodating the properties of the two new states.

  - Gets the mass splitting $(1^+ - 0^+) - (1^- - 0^-) \approx 0$
  - Predicts masses that are generally smaller than the potential models

Figure from Dougall et al. (UKQCD)
Results in B decays from Belle

B → D̅D_{SJ}^+ decays

The angular distribution for D_{SJ}(2460) is consistent with J^P = 1^+

Mass = 2459.2 ± 1.6(stat) ± 2.0(syst) MeV

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The New D_{SJ} States at CLEO
Search for $D_s\pi^\pm$ from CDF & CLEO

Lack of evidence for $D_s\pi^\pm \Rightarrow$ isovector and four-quark interpretations of the new states are disfavored.

No evidence for $D_s\pi^\pm$ argues against a molecular interpretation.

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The New $D_{sj}$ States at CLEO
Results from BaBar, Belle, and CLEO

$D_{sJ}^*(2317): M(D_s\pi^0) - M(D_s)$

$\delta m = \Delta M(1^+ - 1^-) - \Delta M(0^+ - 0^-) = -2.1 \pm 1.4 \text{ MeV}$
Experimental Interpretations

Consistent interpretations as $0^+$ and $1^+$ $c\bar{s}$ mesons:

- The lack of $D_{sJ}^*(2317) \rightarrow D_s^* \pi^0$ supports the interpretation as being $0^+$, but doesn’t rule out other possibilities.
- The lack of $D_{sJ}(2460) \rightarrow D_s \pi^0$ and DK supports interpretation as $1^+$.
- Radiative decay seen in $D_{sJ}(2460) \rightarrow D_s \gamma$ by Belle \(\Rightarrow\) strong signature for its interpretation as $1^+$.
- $D_{sJ}(2460) \rightarrow D_s \pi^+ \pi^-$ decay expected (OZI) but not seen yet.
- The upper limits of other decay modes are consistent with theory for $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$ being $0^+$ and $1^+$, respectively.
- The mass difference between the $1^+ - 1^-$ and $0^+ - 0^-$ mass splittings is zero, consistent with predictions from HQET + chiral symmetry.
The $c\bar{s}$ Meson Spectroscopy after 2003

\begin{center}
\begin{tabular}{lccc}
\hline
\textbf{State} & \textbf{Mass} & \textbf{Width} & \textbf{Discovery} \\
\hline
$D_{sJ}^+$ & 2.573 GeV & 15\pm5 MeV & 1994 - CLEO \\
$D_{s1}^+$ & 2.536 GeV & 0.23 MeV & 1989 - ARGUS \\
$D_{sJ}^+$ & 2.460 GeV & <7 MeV & 2003 - CLEO \\
$D_{sJ}^{**}$ & 2.317 GeV & <7 MeV & 2003 - BaBar \\
$D_s^+$ & 2.112 GeV & <1.9 MeV & 1984 - ARGUS \\
$D_s^+$ & 1.969 GeV & 1.3\times10^{-10} & 1983 - CLEO \\
\hline
\end{tabular}
\end{center}
Summary for the CLEO analysis

- Confirmed $D_{sJ}^*(2317)$ observed by BaBar
  - Decaying to $D_s \pi^0$, as expected for $J^P = 0^+$.  
  - $M(D_s \pi^0) - M(D_s) = 350.0 \pm 1.2 \pm 1.0$ MeV

- Observed a new state $D_{sJ}(2460)$
  - Decaying to $D_s^* \pi^0$, as expected for $J^P = 1^+$. 
  - $M(D_s^* \pi^0) - M(D_s^*) = 351.2 \pm 1.7 \pm 1.0$ MeV

- Width $\Gamma < 7$ MeV (at 90% C.L.) for both states

- Searched for other decay modes to shed lights on the nature of $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$.

- Compatible results w/ models based on HQET and chiral symmetry: $1^+ \& 0^+$ are the chiral partners of the $1^- \& 0^-$ states, with the same mass splitting.
A Timeline for the New $D_{sJ}$ States

- **April 12, 2003**: BaBar reports observation of $D_{sJ}^*(2317)$
- **May 12, 2003**: CLEO reports existence of a second narrow state $D_{sJ} (2460)$, confirms existence of $D_{sJ}^*(2317)$
- **May 20, 2003**: Belle reports seeing both states at CIPANP
- **May 28, 2003**: CLEO submits final results to Phys. Rev. D.
- **June 3, 2003**: at FPCP, Belle reports seeing states in $B$ decay, also observes radiative decay $D_{sJ} (2460) \rightarrow D_s \gamma$.
  
  Papers submitted to EPS on July 16.
Another new narrow resonance at 2.632 GeV is observed by the SELEX experiment.

- News released on June 17, 2004
- SELEX observed $D_{sJ}(2632) \rightarrow D_s \, \eta$ and $D^0 \, K$

Is this new particle also seen in the $e^+e^-$ collider experiments (BaBar, Belle, and CLEO)?

If yes, what are its properties?
The $D_{sJ}(2632)$ from SELEX in 2004

$D^0 K^+$
- events: $25 \pm 9$
- Mass: $2569.9 \pm 4.3$
- $(S-B)/\sqrt{B}$: $5.4\sigma$
- $\Gamma$: $14^{+9}_{-6}$
- $<17$ (90% CL)

$D_s^+ \eta^0$
- events: $45 \pm 9.3$
- Mass: $2635.9 \pm 2.9$
- $(S-B)/\sqrt{B}$: $7.2\sigma$

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The New $D_{sJ}$ States at CLEO

hep-ex/0406045
The $D_{sJ}(2573)$ from CLEO in 1994

with 2 fb$^{-1}$ of data

- It was never re-analyzed with more data.

$D_{sJ}(2573) \rightarrow D^0 K$

PRL 72, 1972 (1994)
Conclusions

- Two new narrow resonances at 2.32 GeV and 2.46 GeV are observed by three e+e- collider experiments.
  - Consistent results from BaBar, Belle, and CLEO
  - Belle observed $D_{sJ}(2460) \rightarrow D_s \gamma$ in B decays and helped establish $J^P=1^+$ for $D_{sJ}(2460)$
- The nature of these two new states is not yet fully understood.
  - But some models predict the low mass for both states
  - Mixed states are possible
- The new discoveries would complete the $c\bar{s}$ meson spectroscopy if they are not proven otherwise.
- Another lesson that one should look for the unexpected!
- It has been an exciting period for both experimentalists and theorists!
Photon Energy Cuts for $M(D_s \pi^0)$
Photon Energy Cuts for $\Delta M(D_s^*\pi^0)$

- a) $E_\gamma > 30 \text{MeV}$
- b) $E_\gamma > 50 \text{ MeV}$
- c) $E_\gamma > 75 \text{ MeV}$
- d) $E_\gamma > 100 \text{ MeV}$
Mass Spectrum with clean cuts

More restrictive photon selection reduces combinatorial background!