New CLEO Results on Mixing and CP Violation Searches in $D^0$ Decay and $D^{*+}$ Intrinsic Width

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- Intrinsic width measurement of the $D^{*+}$
- New CLEO results on $D^0$-$D^0$ mixing and CP violation
  - First measurement of "wrong-sign" $D^0 \rightarrow K^+\pi^-\pi^0$ rate
  - Searches for CP violation in $D^0$ decays to pseudoscalar particles
  - Measurement of the mixing parameter $\gamma$ using CP even decays $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$
- Conclusions and future directions
The CLEO II.V Detector

CESR storage ring operating on/near Upsilon(4S)

9 fb-1 of integrated luminosity
First Measurement of the $D^{*+}$ Width

- Probe of non-perturbative strong physics of heavy-light quark systems
  - Framework of theory understood
  - Predictions range from 15 - 150 keV
- Previous best measurement is upper limit from ACCMOR
  - Significant improvement in statistics
  - CLEO II.V resolution ~150 keV
Measurement Technique

• Use well-measured decay channel

\[ D^{*+} \rightarrow D^0 \pi^+_{\text{slow}}; D^0 \rightarrow K^- \pi^+ \]

• Experimentally, we measure the energy released in the D^{*+} decay, Q:

\[ Q \equiv m(K^- \pi^+ \pi^+_{\text{slow}}) - m(K^- \pi^+) - m_{\pi^+} \]

• \( \Gamma(D^{*+}) \) can be expressed in terms of its partial width to \( D^0 \pi^+ \)

• We assume \( \Gamma(D^0) \ll \Gamma(D^{*+}) \)
  – Therefore, \( \Gamma(Q) \) comes entirely from \( D^{*+} \) width convoluted with tracking resolution

• Perform fit to determine \( \Gamma(Q) \)

• Must REALLY understand detector and Monte Carlo simulation of resolution
  – No zero-width calibration mode
  – CLEO detector and simulation well-studied
Extracting the Intrinsic Width

- Unbinned maximum likelihood fit to Q
- Fit to Breit-Wigner line shape
- Input measured Q and $\sigma_Q$ for each event
- Variables in fit:
  - $\Gamma(Q)$, $<Q>$
  - $N_s$: number of signal events
  - $f_{\text{mis}}$: fraction of mismeasured signal events
  - $\sigma_{\text{mis}}$: resolution of mismeasured events
  - $N_b$: number of background events
- Fixed background shape from fit to MC

$\Gamma(D^{*+}) = 96.2 \pm 4.0$ (stat) keV
Tests of the Detector Simulation

- Excellent agreement of resolution between Monte Carlo and data
  - No corrections necessary
- All known contributions to resolution carefully checked in simulation

\[ \sigma_Q \approx 150 \text{ keV} \]
Tests of the Detector Simulation

- Mis-modeling of the tracking resolution will effect kinematic variables of decay
- Test for mis-modeling of key variables of decay:

\[ \theta, P(\pi_{\text{slow}}), P(D^0) \]

\[ \frac{\partial Q}{\partial \theta}, \frac{\partial Q}{\partial P(\pi_{\text{slow}})}, \frac{\partial Q}{\partial P(D^0)} \]

- Good MC/data agreement of Q peak width distribution with ~90 keV D*+ width
  - Dependence well modeled
Tests of the Detector Simulation

- Not quite as good agreement of mean $Q$
  - Included as systematic error
  - We are not trying to measure the mean, however
Effect of Tracking Mistakes on $\Gamma(Q)$ Result

- Fit to sample with tight tracking selection
- Apply very tight cuts to tracks to remove tracking mistakes
  - SVX hits in both views on all layers
  - No hits within 2 mm of silicon wafer edge
  - Large fraction of possible drift chamber hits
  - Tight matching of tracks between tracking devices
- Results are consistent with nominal fit

$\Gamma(D^{*+}) = 104 \pm 20 \text{ (stat) keV}$
Test Sensitivity to Mismodeling of Decay Kinematics

- Fit to sample with tight kinematic selection
- Select sample with minimal dependence on kinematics of decay:
  - Small values of \( \frac{\partial Q}{\partial P_{D^0}} \) and \( \frac{\partial Q}{\partial P_{\pi_{slow}}} \)
- Result is consistent with nominal fit

\[
\Gamma(D^{*+}) = 103.8 \pm 5.9 \text{ (stat)} \text{ keV}
\]
# Summary of Systematic Errors

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta \Gamma(D^{*+})$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variation of $\langle Q \rangle$</td>
<td>16</td>
</tr>
<tr>
<td>Mismodeling of $\sigma_Q$</td>
<td>11</td>
</tr>
<tr>
<td>Fit variable correlations</td>
<td>8</td>
</tr>
<tr>
<td>$D^0$ production point</td>
<td>4</td>
</tr>
<tr>
<td>Background shapes</td>
<td>4</td>
</tr>
<tr>
<td>Offset Correction</td>
<td>2</td>
</tr>
<tr>
<td>Data format digitization</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>22</strong></td>
</tr>
</tbody>
</table>
Conclusions: D*+ Width Measurement

- We measure the D*+ width with best precision yet:

\[ \Gamma(D^{*+}) = 96 \pm 4 \text{ (stat)} \pm 22 \text{ (syst)} \text{ keV} \]

- Consistent with predictions based on HQET and relativistic quark models
- Higher than predictions based on QCD sum rules
- Input into phenomenology of other important heavy-light quark systems
Searches for Non-Standard Model Physics Through $D^0$-$\bar{D}^0$ Mixing

\[
x = \frac{\Delta M}{\Gamma} : \text{Window to new physics}
\]

\[
y = \frac{\Delta \Gamma}{2\Gamma}
\]

**Standard Model prediction:**

\[
|x| \approx \tan^2 \theta_C \times \text{GIM suppression} \approx 10^{-6} - 10^{-2}
\]

\[
\approx 0.05
\]

**Signatures of Non-Standard model physics:**

1) Large $|x|$, 2) $|x| >> |y|$, $CP$ viol. interference between 3) $x$ and $y$ or 4) $x$ and DCSD
Analysis Technique

Use tagged $D^0$'s from $D^{*+}$ decays:

- **Sign of slow $\pi$ tags initial $D^0$ flavor**
- **Sign of $K$ tags final $D^0$ flavor,** unless DCSD

### Analysis Technique

\[
\bar{r}_{WS}(t) = \left( \frac{\bar{R}_D}{\text{Pure DCSD}} + \sqrt{\frac{\bar{R}_D}{\text{Interference}} y^t} + \frac{1}{4} \left[ x'^2 + y'^2 \right] t^2 \right) e^{-t}
\]

This analysis: $R_{WS} = \int_0^\infty \bar{r}_{WS}(t) dt \equiv \frac{\Gamma(D^0 \rightarrow K^+\pi^0\pi^0)}{\Gamma(D^0 \rightarrow K^+\pi^-\pi^0)}$

Note: C conjugate versions are implied throughout this talk, but not shown for clarity.
Data Sample and Selection

- Good quality charged tracks
- Good $\pi^0$
  - $p(\pi^0) > 340$ MeV/c
  - $E(\gamma) > 30$ (60) MeV Central (Endcap)
  - $|m(\gamma\gamma)-m(\pi^0)| < 2\sigma$
- $D^0$ vertex: PROB > 0.0001
- $|m(\pi K\pi^0)-m(D^0)| > 4\sigma$
- $\pi_{\text{slow}}$ refit through intersection of $D^0$ and CESR beam spot: PROB > 0.0001
- $p(D^{*+}) > 2.5$ GeV/c
Complication of Multi-body Decays

CLEO finds rich RS Dalitz plot: \( \rho(770)^+, K^*(892)^-, \bar{K}^*(892)^0 \), \( \rho(1700)^+, K_0(1430)^-, \bar{K}_0(1430)^0, K^*(1680)^- \), non-resonant.

\[ \rho^+ \rightarrow \pi^+\pi^0 \]

\[ K^{*-0} \rightarrow K^-\pi^+ \]

\[ K^{*-0} \rightarrow K^-\pi^0 \]

Efficiency of All Cuts

\[ R_{WS} = \frac{N_{WS}}{N_{RS}} \cdot \frac{\bar{\epsilon}_{RS}}{\bar{\epsilon}_{WS}} \]

From WS Q-m\((K\pi\pi^0)\) fit

From WS Dalitz plot fit

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(Submitted to Phys. Rev. D)
Fit to Determine $N_{WS}/N_{RS}$

- Two-dimensional maximum likelihood fit to $Q - m(K\pi\pi^0)$ distribution
- Background shapes from Monte Carlo (8X data set)
  - RS $\bar{D}^0 \rightarrow K\pi\pi^0 +$ uncorrelated $\pi_{\text{slow}}$
  - Charm decays other than correctly reconstructed $D^0 \rightarrow K\pi\pi^0$
  - $e^+e^- \rightarrow u\bar{u}, d\bar{d},$ or $s\bar{s}$
- Signal shape from RS data

$$\frac{N_{WS}}{N_{RS}} = \left( 0.43^{+0.11}_{-0.10} \right) \%$$

Statistical significance of signal = 4.9σ
Determination of Efficiency Ratio

- **Maximum likelihood fit to wrong-sign Dalitz plot**
  - Fit $m^2(K^+\pi^-)$ vs $m^2(K^+\pi^0)$ distribution
  - Start with measured RS amplitudes and phases
  - Allow $A(K^{*0}\pi^0)$, $\phi(K^{*0}\pi^0)$, $A(K^{*+}\pi^-)$, and $\phi(K^{*+}\pi^-)$ to float relative to $K^+\rho^-$ mode
    - $A$ and $\phi$ of minor modes fixed relative to $K^+\rho^-$
  - Efficiency function from fit to non-resonant MC sample
  - Background function from fit to side band in $Q$
  - Signal fraction from WS $Q$-m($K\pi\pi^0$) fit
  - Large statistical and systematic errors on amplitudes and phases, but efficiency ratio relatively insensitive

\[ \frac{\bar{\varepsilon}_{RS}}{\bar{\varepsilon}_{WS}} = 1.00 \pm 0.02 \text{ (stat)} \]
Important Systematic Errors in $R_{WS}$ Measurement

- $Q - m(K\pi\pi^0)$ background shapes: fits to sub-regions: 14%

- Efficiency ratio: 9%
  - Uncertainty in amplitudes and phases of minor resonances: 8%
  - Dalitz plot of backgrounds: 3%
  - Uncertainty of Dalitz plot fit method: 3%

$K^{*+}\pi^-$
$\delta$(ratio) = 2%

$K^{*0}\pi^0$
$\delta$(ratio) = 28%

$K^{+}\rho^-$
$\delta$(ratio) = 1%

> $10\sigma$ inconsistent with data!

- Statistical error of Dalitz plot fit included as systematic: 2%
Result of $R_{WS}$ Measurement

\[
R_{WS} = \frac{N_{WS}}{N_{RS}} \cdot \frac{\overline{\epsilon}_{WS}}{\overline{\epsilon}_{RS}}
\]

From WS Q-m $K\pi\pi^0$ fit From WS Dalitz plot fit

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta(R_{WS})/R_{WS}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q-m bckg. shapes</td>
<td>14%</td>
</tr>
<tr>
<td>Efficiency ratio</td>
<td>9%</td>
</tr>
<tr>
<td>Mismodeling of selection variables</td>
<td>3%</td>
</tr>
<tr>
<td>Statistics of Q-m bckg. shapes</td>
<td>2.4%</td>
</tr>
<tr>
<td>Total</td>
<td>17%</td>
</tr>
</tbody>
</table>

\[
R_{WS} = \left(0.43^{+0.11}_{-0.10}\ (\text{stat.}) \pm 0.07\ (\text{syst.})\right)\%
\]

First non-zero rate measurement in this channel
Mixing and DCSD Limits

CLEO $D^0 \rightarrow K^+\pi\pi^0$ ($|x'|=0$)

CLEO $D^0 \rightarrow K^+\pi\pi^0$ ($|x'|=0.028$)
Mixing and DCSD Limits

Note: If $D^0 \rightarrow X \rightarrow K \pi \pi^0$ and $D^0 \rightarrow K \pi$ do not have the same strong phase, then $x'$, $y'$, and $R_{\text{DCSD}}$ are not necessarily the same variables for different decays.
Searches for Direct CP Violation in $D^0$ Decays

- Cabibbo-suppressed charm decays are a good place to look for non-Standard Model effects:
  - Expected to be small in Standard Model
  - Multiple paths to same final state with a weak phase difference
  - Large final state interactions likely
    - Enhance CP violation
- Search in the channels: $D^0 \rightarrow K^+K^-$, $\pi^+\pi^-$, $K^0_S\pi^0$, $\pi^0\pi^0$, and $K^0_SK^0_S$
- Experimentally, we measure the asymmetry for final state $f$:

\[ A = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(D^0 \rightarrow \bar{f})}{\Gamma(D^0 \rightarrow f) + \Gamma(D^0 \rightarrow \bar{f})} \]
Searches for CP Violation in $D^0 \rightarrow K^+K^-$, $\pi^+\pi^-$

- $D^0$ flavor tagged by pion charge in $D^{*+} \rightarrow D^0\pi^+_\text{slow}$
- Refit $\pi^+_\text{slow}$ through intersection of $D^0$ and run-averaged beam spot
- Fit Q spectrum to obtain yields
  - Monte Carlo simulation of backgrounds
  - Fit in bins of $D^0$ momentum
- Dominant systematic errors:
  - Fitting procedure (0.69%)
  - Reconstruction bias (0.48%)
Searches for Direct CP Violation in $D^0 \rightarrow K^+K^-$, $\pi^+\pi^-$

\[
A(K^+K^-) = 0.0005 \pm 0.0218 \text{ (stat)} \pm 0.0084 \text{ (syst)}
\]

\[
A(\pi^+\pi^-) = 0.0195 \pm 0.0322 \text{ (stat)} \pm 0.0084 \text{ (syst)}
\]
Searches for Direct CP Violation in $D^0 \rightarrow K^0_S\pi^0$, $\pi^0\pi^0$, and $K^0_SK^0_S$

- Do not have well-reconstructed $D^0$ direction to refit slow pion
- 13.7 fb$^{-1}$ from both CLEO II and CLEO II.V configurations
  - No benefit from silicon vertex detector in this mode

- Analysis method:
  - Reconstruct $K^0_S$ in $\pi^+\pi^-$ mode
  - Select candidate events near $D^0$ mass
  - Fit to Q side bands

- Background subtract to obtain yields
- Implicit assumption of no CP asymmetry in background

- $D^0 \rightarrow K^0_S\pi^0$: 9099$^{+/-}153$ Events
- $D^0 \rightarrow \pi^0\pi^0$: 810$^{+/-}89$ Events
- $D^0 \rightarrow K^0_SK^0_S$: 65$^{+/-}14$ Events
Searches for Direct CP Violation in $D^0 \rightarrow K^0_S\pi^0$, $\pi^0\pi^0$, and $K^0_SK^0_S$

- Systematic errors: Potential false asymmetries from
  - Fit method: 0.5%
  - Background: 0.35% in $K^0_S\pi^0$, 12% in $K^0_SK^0_S$, negl. in $\pi^0\pi^0$
  - Slow pion finding: 0.19%

- Asymmetry results:
  - Significant improvement over previous measurement in $K^0_S\pi^0$ channel
  - First measurements in $\pi^0\pi^0$, and $K^0_SK^0_S$ channels

\[
A(K^0_S\pi^0) = (+ 0.1 \pm 1.3 \text{ (stat + syst)})\% \\
A(\pi^0\pi^0) = (+ 0.1 \pm 4.8 \text{ (stat + syst)})\% \\
A(K^0_SK^0_S) = (− 23 \pm 19 \text{ (stat + syst)})\%
\]
Measurement of $y$ Using CP-even Decays of $D^0$ to $K^+K^-$ and $\pi^+\pi^-$

- Theorists trying to reconcile CLEO $D^0\rightarrow K^+\pi^-$ and FOCUS $D^0\rightarrow K^+K^-$ measurements

  A. Petrov, hep-ph/0009160

- Possible explanations:
  - $y$ of order few percent?!
    - Would be very surprising
  - Very large strong phase between Cabibbo-favored decay and DCSD (very large SU(3) symmetry breaking)

- Experimentally, we compare lifetime with well-measured $D^0\rightarrow K^-\pi^+$ mode:

  $$y = \frac{\tau_{CP}^-}{\tau_{CP}^+} - 1, \quad CP \equiv CP \text{ neutral state}$$
Analysis Technique

- Use $D^{*+} \rightarrow D^0\pi^+_{\text{slow}}$ tag to reduce background
  - Select signal region in $Q$
- Reconstruct $D^0$ proper time
- Fit the proper time distribution to determine the $D^0$ lifetime
Determination of $D^0$ Lifetime in $D^0 \rightarrow K^-\pi^+$, $K^+K^-, \pi^+\pi^-$

- **Unbinned maximum likelihood fit to proper time**
  - Resolution from measured proper time error and two Gaussians
  - Parameters of fit:
    - Number of signal events
    - $D^0$ lifetime
    - Background fraction
    - Fraction of background with lifetime
    - Lifetime of background
    - Fraction of mismeasured events
    - Error of mismeasured events
y Results

- Consistent with
  - CLEO $D^0 \rightarrow K^+\pi$ measurement
  - FOCUS $D^0 \rightarrow K^+K^-$ measurement
  - E791 measurement (not shown)

- Dominant systematic errors due to:
  - Stat. uncertainty of MC lifetime correction study (0.009 ps)
  - Background description (0.008 ps)
  - Proper time resolution model (0.005 ps)
  - Fit procedure (0.005 ps)

\[ y_{K^+K^-} = -0.019 \pm 0.029 \text{ (stat)} \pm 0.016 \text{ (syst)} \]
\[ y_{\pi^+\pi^-} = 0.005 \pm 0.043 \text{ (stat)} \pm 0.018 \text{ (syst)} \]
\[ y = -0.011 \pm 0.025 \text{ (stat)} \pm 0.014 \text{ (syst)} \]
Mixing and DCSD Limits

Assuming strong phase, $\delta_s$, between CFD and DCSD of zero.
Conclusions

• Best measurement of the $D^{*+}$ width:

$$\Gamma(D^{*+}) = 96 \pm 4 \text{ (stat) } \pm 22 \text{ (syst) keV}$$

• First measurement of “wrong sign” rate in $D^0 \to K^+\pi^-\pi^0$:

$$R_{WS} = \left(0.43^{+0.11}_{-0.10} \text{ (stat.) } \pm 0.07 \text{ (syst.)}\right)\%$$

  – Combined proper time/Dalitz fit under study -- stay tuned!

• New direct CP violation search results

$$A(K_S^0\pi^0) = (+0.1 \pm 1.3 \text{ (stat + syst)})\%$$

$$A(\pi^0\pi^0) = (+0.1 \pm 4.8 \text{ (stat + syst)})\%$$

$$A(K_S^0K_S^0) = (-23 \pm 19 \text{ (stat + syst)})\%$$

$$A(K^+K^-) = 0.0005 \pm 0.0218 \text{ (stat) } \pm 0.0084 \text{ (syst)}$$

$$A(\pi^+\pi^-) = 0.0195 \pm 0.0322 \text{ (stat) } \pm 0.0084 \text{ (syst)}$$

• New $y$ measurement:

$$y = -0.011 \pm 0.025 \text{ (stat) } \pm 0.014 \text{ (syst)}$$