Absolute measurements of Pure leptonic $D_s$ decays and $f_{D_s}$ decay constant from BaBar

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Overview

- The BaBar experiment
- Motivation
- Reconstruction
- Systematic uncertainties
- Results
- Summary and conclusion
The BaBar detector is at the SLAC National Accelerator Laboratory, home of the PEP-II asymmetric energy $e^+e^-$ collider.

The experiment was an excellent B, charm and $\tau$ factory, generating over 700 million $cc$ pairs, from December 1999 to April 2008.
In the standard model the leptonic decays of the $D_s$ meson provide a clean way to measure the decay constant $f_{D_s}$:

$$B(D_s \rightarrow l \nu) = \frac{\Gamma(D_s \rightarrow l \nu)}{\Gamma(D_s \rightarrow all)} = \frac{G_F^2 |V_{cs}|^2 f_{D_s}^2 M_{D_s}^3 (m_l/M_{D_s})^2 \left(1 - \frac{m_l^2}{M_{D_s}^2}\right)^2}{8\pi}$$
Motivation

- In October 2009 unquenched lattice quantumchromodynamical (UL-QCD) calculations of the decay constant $f_{D_s}$ disagree with experimental results by $2\sigma$:

- **Green band**: world average of experimental results.
- **Gray band**: World average of UL-QCD calculations
- **Pink band**: $D_s \rightarrow \mu \nu$ measurements
- **Blue band**: $D_s \rightarrow \tau \nu$ measurements

Status of $f_{D_s}$ October 2009.

$\chi^2$/dof = 0.40

<table>
<thead>
<tr>
<th>Collaboration</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDG 2006</td>
<td>0.273</td>
</tr>
<tr>
<td>BaBar/HFAG</td>
<td>0.314</td>
</tr>
<tr>
<td>Belle</td>
<td>0.314</td>
</tr>
<tr>
<td>CLEO $\pi\nu$</td>
<td>0.329</td>
</tr>
<tr>
<td>CLEO $e\nu$</td>
<td>0.329</td>
</tr>
<tr>
<td>ETMC</td>
<td>0.329</td>
</tr>
<tr>
<td>Fermilab/MILC</td>
<td>0.329</td>
</tr>
<tr>
<td>HPQCD</td>
<td>0.329</td>
</tr>
</tbody>
</table>

$a 2.0\sigma$ discrepancy, or $1.8\sigma \pm 1.6\sigma \pm -0.3\sigma$. 
This discrepancy could be the result of new physics:

- Charged Higgs boson

- Leptoquarks

- SUSY

More details in the backup slides.
The event reconstruction allows an absolute measurement of branching fractions.

The number of $D_s$ mesons produced at BaBar is measured (the denominator.)

The number of $D_s \rightarrow l \nu$ events is measured (the numerator.)

The branching fraction is obtained by calculating the efficiency corrected ratio of these numbers.

This analysis uses the entire dataset, including $\Upsilon(4S)$, $\Upsilon(3S)$, $\Upsilon(2S)$ and off-peak data.
The event topology is split into two halves:

- **Tag side**
  - Charm tag ($D$)
  - Flavor balancing kaon ($K$)
  - Baryon balancing proton ($p$)
  - Fragmentation system ($X$)

- **Signal side**
  - $D_s$ meson ($D_s$)
  - Photon ($\gamma$)
  - Lepton ($l$)
The charm tag is reconstructed in the following modes:

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>D⁰</strong></td>
<td><strong>D⁺</strong></td>
<td><strong>Λ⁺</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Mode</strong></td>
<td><strong>Branching fraction</strong></td>
<td><strong>Mode</strong></td>
<td><strong>Branching fraction</strong></td>
</tr>
<tr>
<td>D⁰ → K⁻π⁺</td>
<td>3.9%</td>
<td>D⁺ → K⁻π⁺π⁺</td>
<td>9.4%</td>
</tr>
<tr>
<td>D⁰ → K⁻π⁺π⁰</td>
<td>13.9%</td>
<td>D⁺ → K⁻π⁺π⁺π⁰</td>
<td>6.1%</td>
</tr>
<tr>
<td>D⁰ → K⁻π⁺π⁻π⁺</td>
<td>8.1%</td>
<td>D⁺ → K⁰ˢ⁻π⁺</td>
<td>1.5%</td>
</tr>
<tr>
<td>D⁰ → K⁰ˢ⁻π⁺π⁻</td>
<td>2.9%</td>
<td>D⁺ → K⁰ˢ⁻π⁺π⁰</td>
<td>6.9%</td>
</tr>
<tr>
<td>D⁰ → K⁻π⁺π⁺π⁺π⁰</td>
<td>4.2%</td>
<td>D⁺ → K⁰ˢ⁻π⁺π⁻</td>
<td>3.1%</td>
</tr>
<tr>
<td>D⁰ → K⁰ˢ⁻π⁺π⁻π⁰</td>
<td>5.4%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Λ⁺ → Σ⁻π⁺</td>
</tr>
</tbody>
</table>
Charm tag selection

- The charm tag modes selections were optimized with respect to significance using 8 fb$^{-1}$ of data.
- Selection variables are:
  - tag mass.
  - particle identification.
  - momentum in the center of mass frame.
  - $P(\chi^2|n)$ of a kinematic fit of the tag.
- Significance ranges from 9 ($\Lambda_c^+ \rightarrow \Sigma \pi^+$) to 350 ($D^0 \rightarrow K^-\pi^+$)
- Tags are 74% $D^0$, 23% $D^+$, 4% $\Lambda_c^+$. 
The energy at BaBar is far above $c\bar{c}$ production threshold.

Additional mesons are produced at the interaction point.

We reconstruct the fragmentation system in the following states:

<table>
<thead>
<tr>
<th>No pions</th>
<th>$\pi^\pm$</th>
<th>$\pi^\pm\pi^\pm$</th>
<th>$\pi^\pm\pi^\pm\pi^\pm$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0$</td>
<td>$\pi^\pm\pi^0$</td>
<td>$\pi^\pm\pi^\pm\pi^0$</td>
<td></td>
</tr>
</tbody>
</table>

$K\bar{K}$ contributions are negligible.
The reconstruction of the fragmentation system is often incomplete due to:

- Misreconstruction.
- Missing particles in the event.
- Particle identification efficiency effects.

Define:

- $n_X^T$ as the true number of pions from fragmentation.
- $n_X^R$ as the reconstructed number of pions from fragmentation.

Unfold the $n_X^T$ distribution from $n_X^R$. 
$D_s^{*+}$ reconstruction

- A $D_s^{*+}$ meson is reconstructed recoiling against the DKX system.
- A photon consistent with the decay $D_s^{*+} \rightarrow D_s^+ \gamma$ is identified.
- A kinematic fit is performed to the whole event.
- The mass of the $D_s^{*+}$ candidate is then constrained to the mass provided by the Particle Data Group.
Right sign and wrong sign

- We define right sign and wrong sign reconstructions:
  - Right sign: any reconstruction where the DKX system flavor and charge are consistent with recoiling against a $D_s^{*+}$.
  - Wrong sign: any reconstruction where the DKX system flavor and charge are not consistent with recoiling against a $D_s^{*+}$.
  - Other: any other reconstruction (e.g., where the charge of the system recoiling against the DKX system would be zero.)
The yield of $D_s$ mesons is determined using a 2-D fit to:

- Mass recoiling against the $DKX\gamma$ system
- $n_X^R$, the reconstructed number of pions in the fragmentation system.

We obtain $n(D_s) = 67,200 \pm 1500$. 
While the 2-D fit is being performed the $n_T$ distribution is unfolded.

A weights model for each value of $n_T = j$ is constructed:

$$w_{j}^{RS} = \frac{(j - \alpha)^\beta e^{-\gamma j}}{\sum_{k=0}^{6}(k - \alpha)^\beta e^{-\gamma k}}$$

The parameters are floated in the 2-D fit.

Efficiencies are calculated after $n_T$ unfolding.
To validate the $D_s$ reconstruction technique a $D_s \rightarrow KK\pi$ crosscheck is used.

Due to resonances, an efficiency weighted Dalitz plot is used.

We obtain $B(D_s \rightarrow KK\pi) = (5.78 \pm 0.20 \pm 0.30) \times 10^{-2}$

Consistent with the Particle Data Group.
Extra energy

- An important variable in the analysis is the extra energy, $E_{\text{Extra}}$.
- $E_{\text{Extra}}$ is the energy in the calorimeter where:
  - Each cluster of calorimeter crystals does not overlap with the candidates in the reconstruction.
  - Each cluster has a minimum energy of 30MeV.
- If the only remaining particles in the event are neutrinos, we expect $E_{\text{Extra}}$ to be very small.
D_s \rightarrow e \nu  \text{ reconstruction}

- An electron candidate is identified, using standard particle identification techniques.
- The mass of the D_s candidate is constrained to the mass provided by the Particle Data Group.
- We require $E_{\text{Extra}} < 1\,\text{GeV}$.
- A kinematic fit to the whole event is performed.
- A binned maximum likelihood fit to the mass squared recoiling against the DKX $\gamma e$ system, $m_m^2$, is performed.
We obtain a yield of 6.1 ± 2.2 ± 5.2 events.

A Bayesian limit is obtained, assuming a uniform prior distribution for $B(D_s \rightarrow e \nu)$.

Using Monte Carlo integration we obtain:

$$B(D_s \rightarrow e \nu) < 2.8 \times 10^{-4}$$
The same fit and selection criteria are used to measure the branching fraction $B(D_s \rightarrow \mu \nu)$.

This time we identify a muon candidate.

We obtain events $274 \pm 17$, which yields

$$B(D_s \rightarrow \mu \nu) = (6.02 \pm 0.37 \pm 0.33) \times 10^{-3}$$
**$D_s \rightarrow \tau \, \nu$ reconstruction**

- We measure the final states
  - $\tau \rightarrow e \, \nu \, \nu$
  - $\tau \rightarrow \mu \, \nu \, \nu$

- Particle identification procedure remains the same as for $D_s \rightarrow e \, \nu$ and $D_s \rightarrow \mu \, \nu$ as appropriate.

- For $D_s \rightarrow \tau \, \nu$; $\tau \rightarrow \mu \, \nu \, \nu$ we require $m_m^2 > 0.3$ GeV$^2c^{-4}$ to remove backgrounds from $D_s \rightarrow \mu \, \nu$ events.

- For $D_s \rightarrow \tau \, \nu$ decays we perform a binned maximum likelihood fit to $E_{\text{Extra}}$. 
We obtain the following yields of events:

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield</th>
<th>Branching fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_s \rightarrow \tau \nu$ ; $\tau \rightarrow e \nu \nu$</td>
<td>$408 \pm 42$</td>
<td>$(4.91 \pm 0.50 \pm 0.66) \times 10^{-2}$</td>
</tr>
<tr>
<td>$D_s \rightarrow \tau \nu$ ; $\tau \rightarrow \mu \nu \nu$</td>
<td>$340 \pm 32$</td>
<td>$(5.07 \pm 0.48 \pm 0.54) \times 10^{-2}$</td>
</tr>
<tr>
<td>Combined</td>
<td></td>
<td>$(5.00 \pm 0.35 \pm 0.49) \times 10^{-2}$</td>
</tr>
</tbody>
</table>
Systematic uncertainties

- Due to the nature of the reconstruction, most of the systematic uncertainties cancel out exactly.
- The remaining dominant systematic uncertainties arise from:

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Dominant uncertainty</th>
<th>Contribution to uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_s \rightarrow e \nu$</td>
<td>$n_\chi^T$ weights model</td>
<td>2.8%</td>
</tr>
<tr>
<td>$D_s \rightarrow \mu \nu$</td>
<td>Signal and background models</td>
<td>3.4%</td>
</tr>
<tr>
<td>$D_s \rightarrow \tau \nu$; $\tau \rightarrow e \nu \nu$</td>
<td>Background model</td>
<td>9.6%</td>
</tr>
<tr>
<td>$D_s \rightarrow \tau \nu$; $\tau \rightarrow \mu \nu \nu$</td>
<td>Background model</td>
<td>11.7%</td>
</tr>
</tbody>
</table>
Results

Values for $f_{D_s}$ are obtained using the formula:

$$f_{D_s^+} = \frac{1}{G_F m_\ell \left(1 - \frac{m_\ell^2}{M_{D_s^+}^2}\right) |V_{cs}|} \sqrt{\frac{8\pi B(D_s^+ \rightarrow \ell\nu)}{M_{D_s^+} \tau_{D_s^+}}},$$

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$B(D_s \rightarrow \ell\nu)$</th>
<th>$f_{D_s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_s \rightarrow \mu\nu$</td>
<td>$(6.02 \pm 0.37 \pm 0.33) \times 10^{-3}$</td>
<td>$(265.7 \pm 8.4 \pm 7.9) \text{ MeV}$</td>
</tr>
<tr>
<td>$D_s \rightarrow \tau\nu$; $\tau \rightarrow e\nu\nu$</td>
<td>$(4.91 \pm 0.50 \pm 0.66) \times 10^{-2}$</td>
<td>$(247 \pm 13 \pm 17) \text{ MeV}$</td>
</tr>
<tr>
<td>$D_s \rightarrow \tau\nu$; $\tau \rightarrow \mu\nu\nu$</td>
<td>$(5.07 \pm 0.48 \pm 0.54) \times 10^{-2}$</td>
<td>$(243 \pm 12 \pm 14) \text{ MeV}$</td>
</tr>
<tr>
<td>Combined</td>
<td></td>
<td>$(258.6 \pm 6.4 \pm 7.5) \text{ MeV}$</td>
</tr>
</tbody>
</table>
These results are very competitive:

HPQCD (2010) give $f_{D_s} = (248.0 \pm 2.5) \text{ MeV}$
Conclusion and summary

- BaBar used its entire dataset to provide precise absolute measurements of the branching fractions:
  - $B(D_s \rightarrow e \nu) < 2.8 \times 10^{-4}$
  - $B(D_s \rightarrow \mu \nu) = (6.02 \pm 0.37 \pm 0.33) \times 10^{-3}$
  - $B(D_s \rightarrow \tau \nu) = (5.00 \pm 0.35 \pm 0.49) \times 10^{-2}$
  - $B(D_s \rightarrow KKp) = (5.78 \pm 0.20 \pm 0.30) \times 10^{-2}$

- The resulting value for $f_{D_s}$ is competitive with the world average.

- These results give $f_{D_s} = (258.6 \pm 6.4 \pm 7.5) \text{ MeV}$
  - $1.0 \sigma$ from most recent UL-QCD expectation (HPQCD).

- Publication accepted by PRD-RC (DVR1031).
Backup

- New physics potential
- Excited charm tag reconstruction
- Flavor and baryon balancing
- $D_s \rightarrow K_SK$ crosscheck
Is UQ-LQCD \( f_{D_s} \) calculation wrong?

- The same method gives high accuracy calculation for \( f_D \).
- The disagreement increases as the lattice spacing decreases.
- We’d expect to see a similar disagreement for \( f_D \).
  - Another analyst is currently measuring \( f_D \) using \( B(D \rightarrow \mu \nu) \)

What about leptoquarks?

- Limits on proton lifetime constrain possible models.
- Measurements of \( \tau \rightarrow \eta \nu \) and \( D \rightarrow \mu \mu \) constrain couplings to the kinds of quarks. (eg leptoquarks would have to prefer the \( s \) quark to the \( d \) quark)

And a Higgs?

- A Higgs boson would tend to couple to the \( cs \) more than \( cd \). This could be the first sign of a Higgs boson!
Excited charm tags

- In order to “clean up” the event, we attempt to reconstruct excited charm tags in the decay modes:

  | $D^{*+} \rightarrow D^0 \pi^+$ | $D^{*0} \rightarrow D^0 \pi^0$ |
  | $D^{*+} \rightarrow D^+ \pi^+$ | $D^{*0} \rightarrow D^0 \gamma$ |

- Reconstructions are **not** rejected if they fail to meet these criteria.

- Reconstructing these tags reducing combinatorial backgrounds in later reconstruction.
Flavor and baryon balancing

- We require flavor to be balanced in the event:
  - The charm tag balances the charm of the $D_s$ meson.
  - An additional kaon is required to balance the strangeness of the $D_s$ meson.
    - Both $K^\pm$ and $K_S^0$ are considered
  - If a $\Lambda_c^+$ is present, a proton is required to balance the baryon number of the $\Lambda_c^+$. 
Another crosscheck ($D_s \rightarrow K_SK$) is used to perform studies in the data:

- This is not blind.
- It’s used mainly to check shapes of probability density functions.
- It showed that the kinematic fit $\chi^2$ distribution was not well modeled in MC.
- Used to inform smearing and shifting of signal probability density function.