Recent Charm results from CLEO-c

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On behalf of CLEO Collaboration

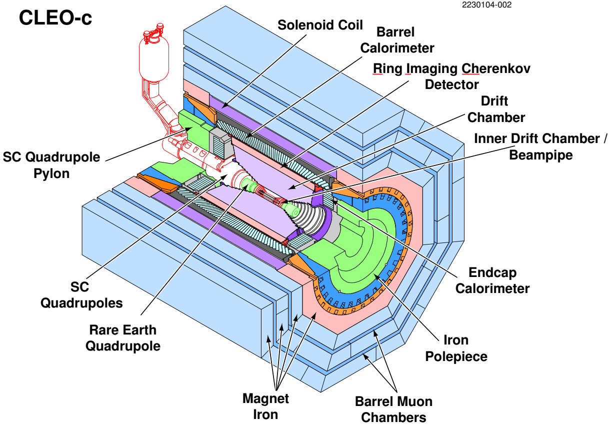
Outline

1. CLEO-c experiment
2. Measurement of D, D_s hadronic branching fractions
3. Leptonic branching fractions
    - $D^+ \rightarrow \mu^+ \nu_\mu$
    - $D_s^+ \rightarrow \mu^+ \nu_\mu$
    - $D_s^+ \rightarrow \tau^+ \nu_\tau (\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau, \tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau)$
4. CLEO-c results related to γ measurement

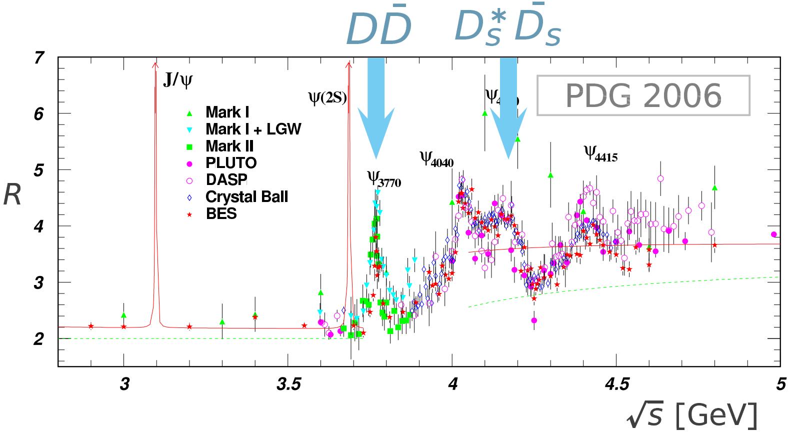
Cornell Electron Storage Ring(CESR)

CLEO-c experiment

- General-purpose symmetric detector
- Particle ID: dE/dx& Ring Imaging Cherenkov $\Rightarrow$ Great π/K separation.
- Tracking: $\delta p/p = 0.6\%$ at 1 GeV
- CsI calorimeter: $\delta E/E \sim 5\%$ at 100 MeV



Data Samples



- $D\bar{D}$ @ 3770 : 818 pb^{-1} (281 pb^{-1} $\sim 1.8 \times 10^6\, D\bar{D}$);
- $D_s^*\bar{D}_s$ @ 4170 : 602 pb^{-1} (298 pb^{-1} $\sim 0.29 \times 10^6\, D_s^*\bar{D}_s$)

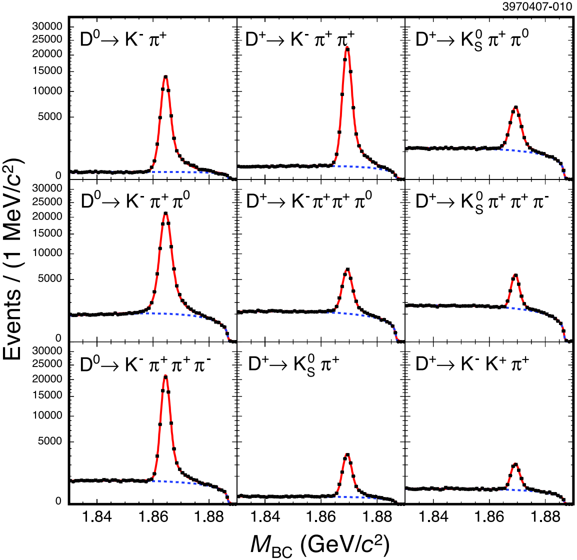
Hadronic Decays

D hadronic branching fractions

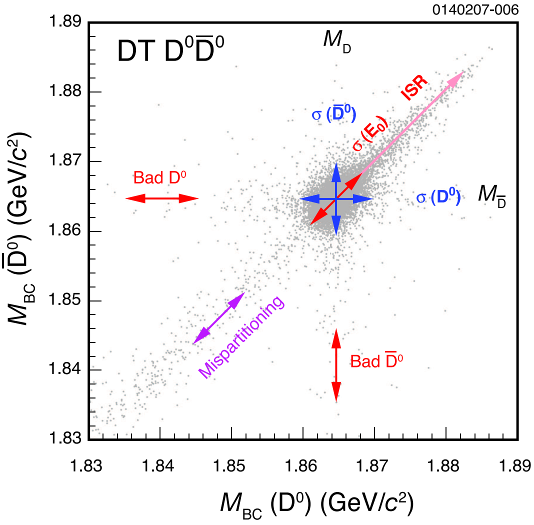
- Use a "double tag" technique, pioneered by MARK III
  $N_i = N_{D\bar{D}}\mathcal{B}_i\epsilon_i$, $\bar{N}_j = N_{D\bar{D}}\mathcal{B}_j\bar{\epsilon}_j$, $N_{ij} = N_{D\bar{D}}\mathcal{B}_i\mathcal{B}_j\epsilon_{ij}$
  $\Rightarrow N_{D\bar{D}} = \frac{N_i\bar{N}_j}{N_{ij}}\frac{\epsilon_{ij}}{\epsilon_i\bar{\epsilon}_j}$, $\mathcal{B}_i = \frac{N_{ij}}{\bar{N}_j}\frac{\bar{\epsilon}_j}{\epsilon_{ij}}$.
- The following final states are used:
  D^0: $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$
  D^+: $K^-\pi^+\pi^+$, $K^0_S\pi^+$, $K^-\pi^+\pi^+\pi^0$, $K^0_S\pi^+\pi^+\pi^-$, $K^0_S\pi^+\pi^0$, $K^-K^+\pi^+$.
- Identify D's from "beam-constrained mass" and ΔE:
  $M_{bc} = \sqrt{E^2_{beam} - |\vec{p}_D|^2}$, $\Delta E = E_D - E_{beam}$.
- Determine separately the D and $\bar{D}$ yields.
  18 single tag yields, $45(3^2+6^2)$ double tag yields.
- In a combined χ^2 fit we extract 9 branching fractions and $D^0\bar{D}^0$ and D^+D^- yields. The fit includes the systematic errors.

Single tag fits

- Use $281 \mathrm{pb}^{-1}$ data.
- Extract yields from M_{bc} fits.
- Plots are shown in square-root scale.
- Lineshape includes:
  - Detector resolution
  - ISR in $e^+e^- \to \psi(3770)$
  - $\psi(3770)$ lineshape
  - Beam energy spread



Double tag fits

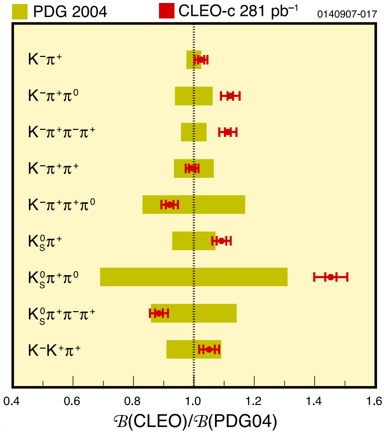


- Double tag yields are obtained from a 2-dimensional fit to $M_{bc}(D)$ vs. $M_{bc}(\bar{D})$
- Fit function includes:
  - Signal peak
  - One D correct, one D incorrect
  - Both D's incorrect
  - Mispartitioning

Branching fraction results

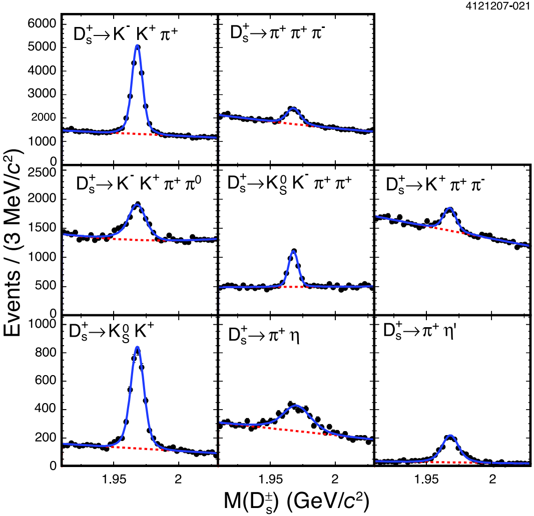
Mode	$\mathcal{B}(\%)$
$D^0 \rightarrow K^-\pi^+$	$3.89 \pm 0.04 \pm 0.06 \pm 0.04$
$D^0 \rightarrow K^-\pi^+\pi^0$	$14.57 \pm 0.12 \pm 0.38 \pm 0.05$
$D^0 \rightarrow K^-\pi^+\pi^+\pi^-$	$8.30 \pm 0.07 \pm 0.19 \pm 0.07$
$D^+ \rightarrow K^-\pi^+\pi^+$	$9.14 \pm 0.10 \pm 0.16 \pm 0.07$
$D^+ \rightarrow K^-\pi^+\pi^+\pi^0$	$5.98 \pm 0.08 \pm 0.16 \pm 0.02$
$D^+ \rightarrow K^0_S\pi^+$	$1.53 \pm 0.02 \pm 0.04 \pm 0.01$
$D^+ \rightarrow K^0_S\pi^+\pi^0$	$6.99 \pm 0.09 \pm 0.25 \pm 0.01$
$D^+ \rightarrow K^0_S\pi^+\pi^+\pi^-$	$3.12 \pm 0.05 \pm 0.09 \pm 0.02$
$D^+ \rightarrow K^+K^-\pi^+$	$0.94 \pm 0.02 \pm 0.02 \pm 0.003$
Cross Section	**Values(nb)**
$\sigma(e^+e^- \rightarrow D^0\bar{D}^0)$	$3.66 \pm 0.03 \pm 0.06$
$\sigma(e^+e^- \rightarrow D^+D^-)$	$2.91 \pm 0.03 \pm 0.05$

- The last error is the systematic error from FSR
- PRD 76, 112001(2007)



D_s hadronic branching fractions

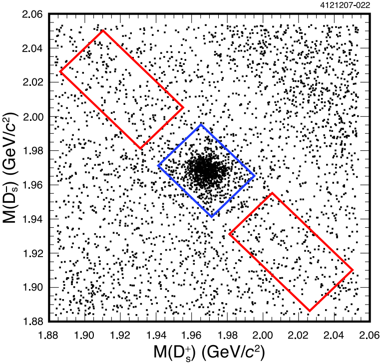
- $D_s^* D_s$, with $D_s^* \to D_s\gamma$(dominate)
- For hadronic branching fractions, don't look for the decay γ. Use invariant mass.
- Use $298\mathrm{pb}^{-1}$ of data collected at $E_{cm} = 4170$.
- The following final states are studied: $K_S^0 K^+$, $K^- K^+ \pi^+$, $K^- K^+ \pi^+ \pi^0$, $K_S^0 K^- \pi^+ \pi^+$, $\pi^+\pi^+\pi^-$, $\pi^+\eta$, $\pi^+\eta'$, and $K^+\pi^+\pi^-$.



D_s hadronic branching fractions

Mode	$\mathcal{B}(\%)$	PDG 2007
$K_S^0K^+$	$1.49 \pm 0.07 \pm 0.05$	2.2 ± 0.4
$K^-K^+\pi^+$	$5.50 \pm 0.23 \pm 0.16$	5.3 ± 0.8
$K^-K^+\pi^+\pi^0$	$5.65 \pm 0.29 \pm 0.40$	-
$K_S^0K^-\pi^+\pi^+$	$1.64 \pm 0.10 \pm 0.07$	2.7 ± 0.7
$\pi^+\pi^+\pi^-$	$1.11 \pm 0.07 \pm 0.04$	1.24 ± 0.20
$\pi^+\eta$	$1.58 \pm 0.11 \pm 0.18$	2.16 ± 0.30
$\pi^+\eta'$	$3.77 \pm 0.25 \pm 0.30$	4.8 ± 0.6
$K^+\pi^+\pi^-$	$0.69 \pm 0.05 \pm 0.03$	0.67 ± 0.13

- $\sigma(e^+e^- \to D_s^* D_s) = 0.98 \pm 0.05 \pm 0.02 \pm 0.01$ nb
- The last error is due to luminosity measurement.
- PRL 100, 161804 (2008)



Leptonic Decays

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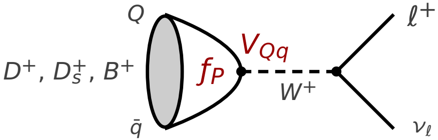


$$\Gamma(P_{Q\bar{q}} \to \ell^+ \nu_\ell) = \frac{G_F^2 |V_{Qq}|^2 {f_P}^2}{8\pi} m_{Q\bar{q}} m_\ell^2 \left(1 - \frac{m_\ell^2}{m_{Q\bar{q}}^2}\right)^2$$

- Measure rates to extract decay constant f_P (V_{Qq}).
- Check lattice calculations of decay constants.
  - f_D at CLEO-c and $(f_B/f_D)_{\mathrm{LQCD}} \Rightarrow f_B$ for precise $|V_{td}|$.
  - f_D/f_{D_s} checks $(f_B/f_{B_s})_{\mathrm{LQCD}}$ for $|V_{td}|/|V_{ts}|$.

$D^+ \to \mu^+ \nu_\mu$

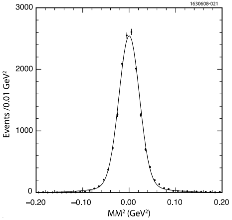
- Fully reconstruct D^--tag $K^+\pi^-\pi^-$, $K^+\pi^-\pi^-\pi^0$, $K_S^0\pi^-$, $K_S^0\pi^-\pi^0$, $K_S^0\pi^-\pi^-\pi^+$, and $K^+K^-\pi^-$.
- Look for oppositely charged single track event recoiling against the tag
  - consistent with μ^+, case (i) $E_{CC} < 300$ MeV, 99% $D^+ \to \mu^+\nu$, 55%$D^+ \to \tau^+\nu$ $(\tau^+ \to \pi^+\bar{\nu})$.
  - consistent with π^+, case (ii) $E_{CC} > 300$ MeV, 45% $D^+ \to \tau^+\nu$ $(\tau^+ \to \pi^+\bar{\nu})$
  - consistent with e^+, pass electron identification, for $D^+ \to e^+\nu$
- Veto events w/ any extra shower $E > 250$ MeV (to veto $D^+ \to \pi^+\pi^0$)
- Signal variable :

$$MM^2 = \left(E_{CM} - E_{D^-} - E_{\mu^+}\right)^2 - \left(-\vec{P}_{D^-} - \vec{P}_{\mu^+}\right)^2$$

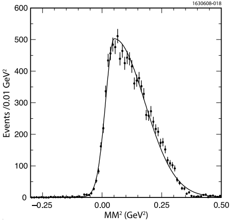
- Use $818\mathrm{pb}^{-1}$ data.

$D^+ \to \mu^+\nu_\mu$ signal shape

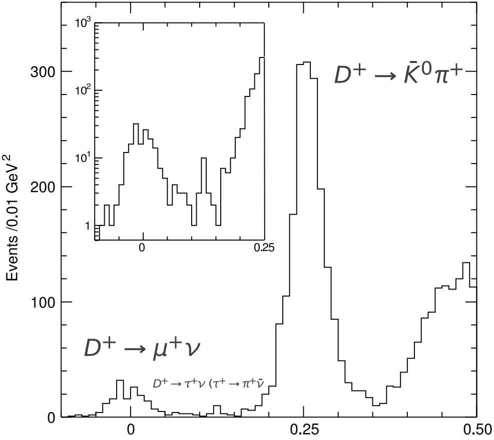
$D^+ \to \mu^+\nu_\mu$ signal MC



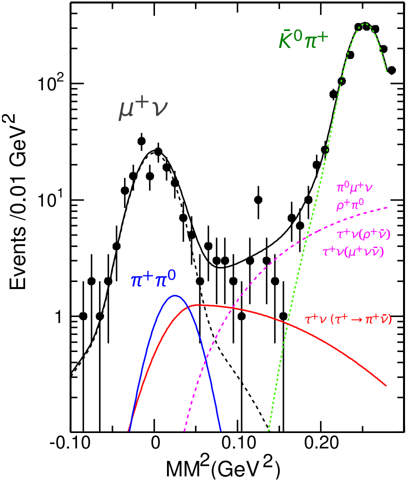
$D^+ \to \tau^+\nu_\tau$ signal MC

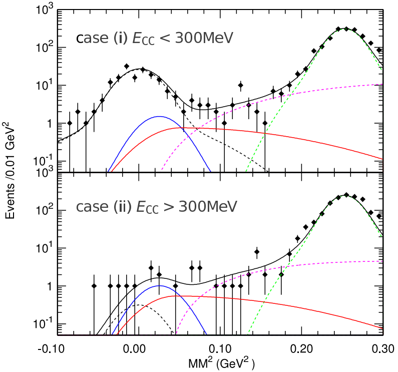


- MM^2, case (i) $E_{CC} < 300$ MeV



$D^+ \to \mu^+\nu_\mu$, $D^+ \to \tau^+\nu_\tau$ signal fit





- SM $\mu^+\nu/\tau^+\nu$ ratio 2.65 fixed.
  149.7 ± 12.0 $\mu^+\nu$, 25.8 $\tau^+\nu$ $(\tau^+ \to \pi^+\bar{\nu})$
- SM $\mu^+\nu/\tau^+\nu$ ratio float.
  153.9 ± 13.5 $\mu^+\nu$, 13.5 ± 15.3 $\tau^+\nu$

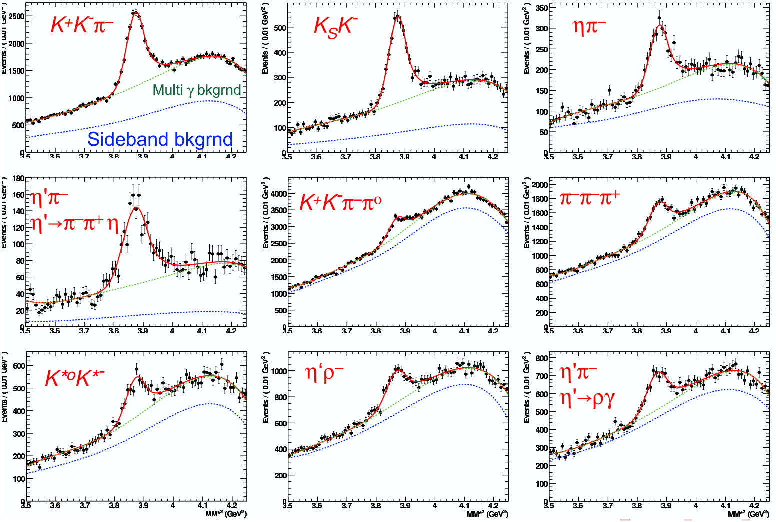
- Simultaneous fit to both case (i) and (ii). $\tau^+\nu$ signal yield : 27 ± 16.4

Branching fractions & f_D

- arXiv:0806.2112
- Fix $\tau\nu/\mu\nu$ at SM ratio of 2.65
  - $B(D^+ \to \mu^+\nu) = (3.82 \pm 0.32 \pm 0.09) \times 10^{-4}$
  - $f_{D^+} = (205.8 \pm 8.5 \pm 2.5)$ MeV
- Float $\tau\nu/\mu\nu$
  - $B(D^+ \to \mu^+\nu) = (3.93 \pm 0.35 \pm 0.09) \times 10^{-4}$
  - $f_{D^+} = (207.6 \pm 9.3 \pm 2.5)$ MeV
- Upper Limits (90% C.L.)
  - $B(D^+ \to \tau^+\nu) < 1.2 \times 10^{-3}$
  - $B(D^+ \to e^+\nu) < 8.8 \times 10^{-6}$
- CP asymmetry, $A_{CP} = \frac{\Gamma(D^+\to\mu^+\nu)-\Gamma(D^-\to\mu^-\bar{\nu})}{\Gamma(D^+\to\mu^+\nu)+\Gamma(D^-\to\mu^-\bar{\nu})} = 0.08 \pm 0.08$, consistent with no CP violation.
- Our result f_{D^+} is consistent with the latest LQCD calculation, $f_{D^+} = (207 \pm 4)$ MeV (PRL 100, 062002).

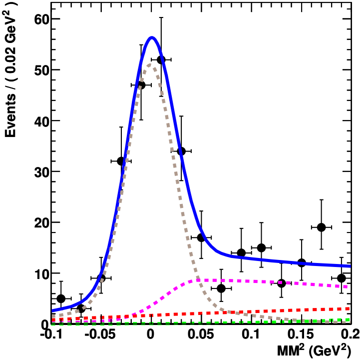
D_s^+ leptonic decays

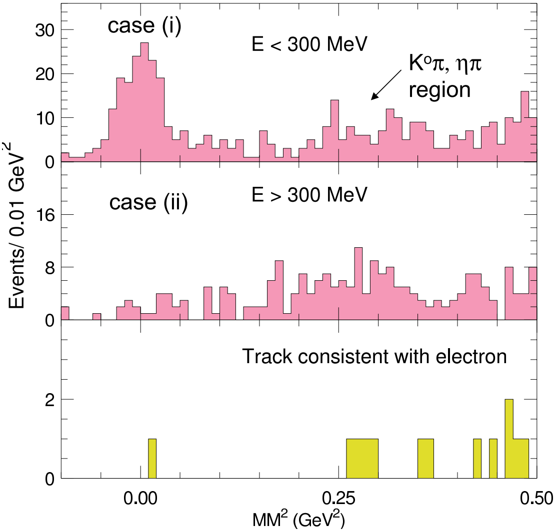
- Here we do require finding the $D_s^* \to D_s\gamma$ decay γ.
- Use mass recoiling against tag $D_s + \gamma$.
- $\sim 400\ \mathrm{pb}^{-1}$ data, total of 30848 ± 695 tags



$D_s^+ \to \mu^+\nu_\mu$, $D_s^+ \to \tau^+\nu_\tau$ $(\tau^+ \to \pi^+\bar{\nu}_\tau)$

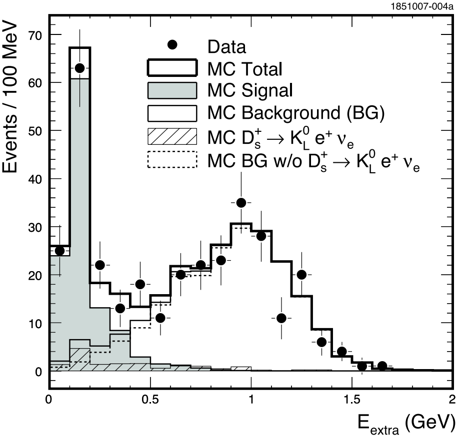
- 99% of $\mu^+\nu$ in $E_{cc} < 300$ MeV
- 55%/45% split of $\tau^+\nu(\tau^+ \to \pi^+\nu)$ in two cases
- Small e^- background
- Fit to both case i and case ii:





$D_s^+ \to \tau^+\nu_\tau \ (\tau^+ \to e^+\nu_e\bar{\nu}_\tau)$

- Here, we don't bother with decay γ.
- 298 pb^{-1} @ 4170 – $e^+e^- \to D_s D_s^*$
- Require only one track, satisfy electron ID
- Plot the energy in the calorimeter, not due to tag side or the electron.
- $E_{extra} < 400\mathrm{MeV}$ is the signal region.
- Extrapolate background from D_s semileptonic decays (mainly $D_s^+ \to \eta e^+\nu_e$) from region above 400 MeV
- $D_s^+ \to K_L^0 e^+\nu_e$ background from $D_s^+ \to K_S^0 e^+\nu_e$ measurement, $B(D_s^+ \to K_S^0 e^+\nu_e) = (0.14 \pm 0.06 \pm 0.01)\%$
- Background is $\sim$ 21% of yield in signal region
- $B(D_s^+ \to \tau^+\nu_\tau) = (6.17 \pm 0.71 \pm 0.34)\%$
- $f_{D_s} = (273 \pm 16 \pm 8)$ MeV ($|V_{cs}| = 0.9738$)
- PRL 100, 161801 (2008)



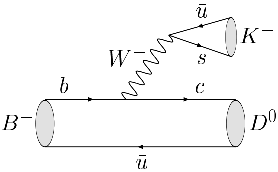
- $N_S = 101.6 \pm 11.5$
- $N_B = 21.4 \pm 1.0$

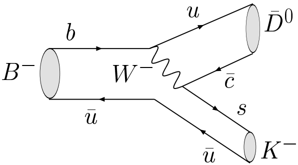
Branching fractions & f_{D_s}(preliminary)

1. Fix SM ratio: $\mathcal{B}_{D_s\to\mu\nu} = (0.613 \pm 0.044 \pm 0.020)\%$, $f_{D_s} = 268.2 \pm 9.6 \pm 4.4$ MeV.
2. Float the ratio:
    - $\mathcal{B}_{D_s\to\mu\nu} = (0.600 \pm 0.054 \pm 0.020)\%$, $f_{D_s} = 265.4 \pm 11.9 \pm 4.4$ MeV.
    - $D_s \to \tau\nu, \tau \to \pi\nu$: $\mathcal{B}_{D_s\to\tau\nu} = (6.1 \pm 0.9 \pm 0.2)\%$, $f_{D_s} = 271 \pm 20 \pm 4$ MeV.
3. $D_s \to \tau\nu, \tau \to e\nu_e\nu_\tau$: $\mathcal{B}_{D_s\to\tau\nu} = (6.17 \pm 0.71 \pm 0.36)\%$, $f_{D_s} = 273 \pm 16 \pm 8$ MeV.
4. Combine 1 and 3: $f_{D_s} = 269.4 \pm 8.2 \pm 3.9$ MeV.
5. Lattice QCD: $f_{D_s} = 241 \pm 3$ MeV.
6. CLEO f_{D_s} is $\sim 3\sigma$ above Lattice QCD calculation.

CLEO-c impact on γ measurement

γ measurement from $B^{\pm} \to DK^{\pm}$



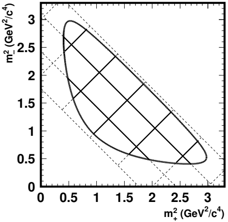


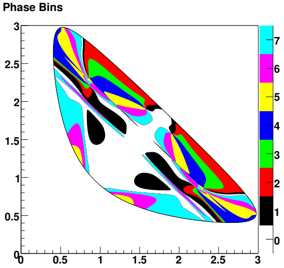
$$\frac{A_{B^- \to \bar{D}^0 K^-}}{A_{B^- \to D^0 K^-}} = r_B e^{i(\delta_B - \gamma)}$$

D^0, $\bar{D}^0$ decay to a common mode(eg, $K^0_S \pi^+ \pi^-$)

- Extraction through interference between $b \to c$ and $b \to u$ transitions.
- $D^0/\bar{D}^0 \to K^0_S \pi^+ \pi^-$ Dalitz analysis is used to extract γ. Interference depends on $D^0, \bar{D}^0$ phase difference($\delta_{x,y} - \delta_{y,x}$), as function of position in Dalitz plot. To date, this has been taken from results of Dalitz analysis, which suffer from a model dependence.
- A model independent way using binned Dalitz analysis has been proposed by Giri et al. (PRD 68, 054018(2003)) and further investigated by Bondar et al.(Eur. Phys. J. C 47, 347-353(2006)).
- CP eigenstate Data at CLEO plays an important role in the model indpendent approach.

Binned analysis





Square bins ⇒ $\Delta\delta_D$ bins

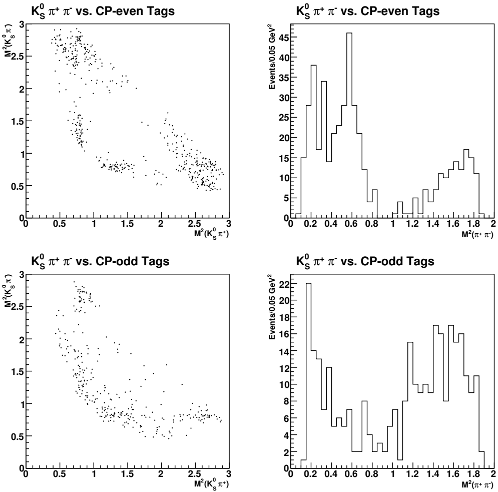
- It can be shown:

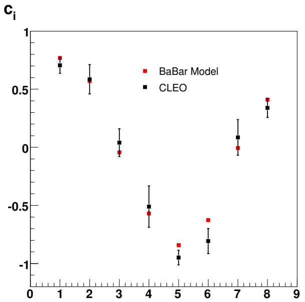
$$c_i = \frac{(M_i^+/S_+ - M_i^-/S_-)}{(M_i^+/S_+ + M_i^-/S_-)} \frac{(K_i + K_{\bar{\imath}})}{2\sqrt{K_i K_{\bar{\imath}}}}.$$

- $M_i^+(M_i^-)$, CP even(odd) tagged $K_S^0\pi^+\pi^-$ events in each bin
- $K_i(K_{\bar{\imath}})$, flavor tagged $K_S^0\pi^+\pi^-$ events in each bin

$$\begin{aligned} f_D(x,y) &= |f_D(x,y)|e^{i\delta_D(x,y)} && (1) \\ c_i &= \frac{1}{\sqrt{F_i F_{\bar{\imath}}}} \int_{D_i} |f_D(x,y)||f_D(y,x)|\cos(\delta_{x,y} - \delta_{y,x})dxdy && (2) \\ s_i &= \frac{1}{\sqrt{F_i F_{\bar{\imath}}}} \int_{D_i} |f_D(x,y)||f_D(y,x)|\sin(\delta_{x,y} - \delta_{y,x})dxdy && (3) \end{aligned}$$

CP tagged $K_S^0\pi^+\pi^-$ results(preliminary)





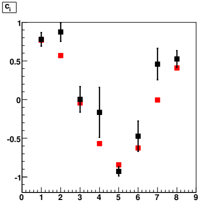
c_1	0.706±0.069±0.028
c_2	0.586±0.126±0.037
c_3	0.041±0.120±0.043
c_4	-0.510±0.178±0.074
c_5	-0.949±0.063±0.029
c_6	-0.807±0.108±0.039
c_7	0.085±0.154±0.046
c_8	0.339±0.082±0.024

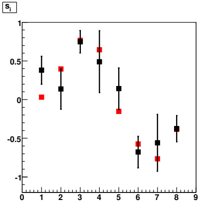
- ∼ 800 CP events

$K_S^0\pi^+\pi^-$ vs. $K_S^0\pi^+\pi^-$ results (preliminary)

- CP tagged sample can only get c_i
- Using $K_S^0\pi^+\pi^-$ vs. $K_S^0\pi^+\pi^-$ sample, one can extract c_i and s_i simultaneouly.

$$M_{i,j} = \frac{1}{2N_{D,\bar{D}}\mathcal{B}_f^2}\left(K_iK_{\bar{j}} + K_{\bar{i}}K_j - 2\sqrt{K_iK_{\bar{j}}K_{\bar{i}}K_j}(c_ic_j + s_is_j)\right).$$





	Value		Value
c_1	0.779±0.087±0.062	s_1	0.380±0.179±0.085
c_2	0.874±0.120±0.113	s_2	0.137±0.260±0.084
c_3	0.003±0.166±0.152	s_3	0.749±0.145±0.053
c_4	-0.165±0.323±0.152	s_4	0.490±0.400±0.093
c_5	-0.929±0.058±0.044	s_5	0.141±0.268±0.085
c_6	-0.472±0.196±0.099	s_6	-0.679±0.203±0.059
c_7	0.459±0.204±0.170	s_7	-0.558±0.367±0.106
c_8	0.526±0.109±0.114	s_8	-0.376±0.169±0.060

- $\sim$ 450 events

- Combine CP tagged $K_S^0\pi^+\pi^-$ and double $K_S^0\pi^+\pi^-$ results, uncertainty on γ is about 5° (Bondar et al. arXiv:0801.0840).

Summary

- D, D_s hadronic decays
  - The D^0 and D^+ branching fractions are systematics limited.
  - The D_s branching fractions not yet systematic limited.
- Leptonic decays
  - f_D measured to $\pm 4.5\%$, statistical error dominates.
  - f_{D_s} measured to $\pm 3.0\%$, statistical error dominates.
  - f_{D_s} is $\sim 3\sigma$ above Lattice QCD calculation. Using full $602 \mathrm{pb}^{-1}$ data, will further update f_{D_s}.
  - $B(D_s^+ \to \tau^+\nu_\tau)/B(D_s^+ \to \mu^+\nu_\mu)$ consistent with theory.
- CLEO-c impact on γ measurement
  - c_i, s_i values are extracted for model independent approch to measure γ.

Thank you!