Recent Experimental Results on (Semi-)Leptonic D Decays

& Extraction of $|V_{cd}|$ and $|V_{cs}|$

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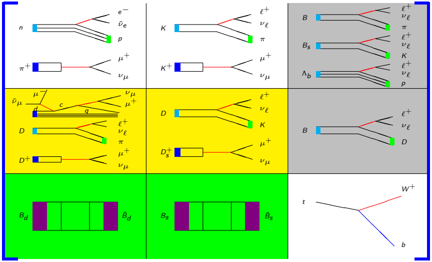
Outline

1. Introduction
2. Purely Leptonic D^+ and D_s^+ Decays
3. Semileptonic D Decays
4. Extraction of $|V_{cd}|$ and $|V_{cs}|$
5. Summary

Charm's Supporting Role in Test of SM

A Window for Week & Strong Physics

- D meson leptonic and semi-leptonic decays provide a window for us to investigate week and strong physics.
- CKM matrix elements can be determined with
  1. nuclear β decays
  2. meson (π, K, D, B) decays
  3. baryon decay
  4. $B\bar{B}$ mixing
  5. ν-$\bar{\nu}$ interaction, . . .



D, D_s | D, D_s+LQCD, B, B_s+LQCD | D, D_s+LQCD, B, B_s+DØ,CDF

Experiment **Theory**

Decay Rate = Know × (Form Factor)^2 × $|$CKM Element$|^2$

$\Uparrow$ (under Decay Rate) | $\Downarrow$ (under Form Factor) | $\Downarrow$ (under CKM Element)

$D^+_{(s)} \to \ell^+\nu$

$D \to K(\pi)\ell^+\nu$

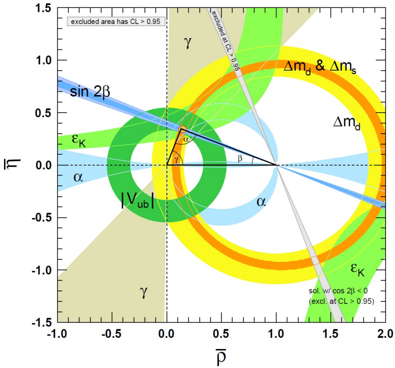
- Use unitarity for CKM elements to determine decay constant, form factors, and test QCD

- Use theory for form factors to extract $|V_{cd}|$ and $|V_{cs}|$

- Check unitarity of CKM matrix to search for New Physics
- Indirectly improve precision of the CKM elements of $|V_{td}|$, $|V_{ts}|$ and $|V_{ub}|$

Charm's Supporting Role in Test of SM

Constraints on Parameters of CKM unitarity triangle



Current Status

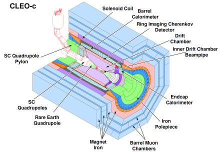
- The brown band is still dominated by errors of f_B and f_{B_s} calculated in LQCD;
- The dark green band is still dominated by error of B decay form factor $f_+^{B\to\pi}(0)$ calculated in LQCD;
- If LQCD calculations pass validation with experimental data, these bands can be reduced.

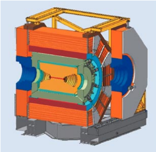
- Using $D_{(s)}$ leptonic & semi-leptonic decays validate decay constants f_D, f_{D_s} and form factors $f_+^{D\to\pi}(0)$, $f_+^{D\to K}(0)$ calculated in LQCD;
- If the LQCD pass the test with measured f_D, f_{D_s}, $f_+^{D\to\pi}(0)$ and $f_+^{D\to K}(0)$, error on f_B, f_{B_s} and $f_+^{B\to\pi}(0)$ calculated in LQCD would be reduced, then the error of apex of the unitarity triangle would be reduced.

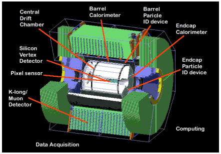
Status of e^+e^- Experiments

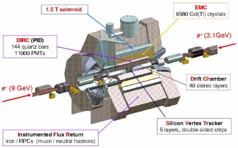
Charm Machines & B Factories

- Experiments near charm threshold
  1. CLEO-c/CESR: $D^+ \to \mu^+\nu_\mu$, $D_s^+ \to \ell^+\nu_\ell$; $D \to Ke^+\nu_e$, $\pi e^+\nu_e$
     (818 pb^{-1} data @ 3.773 GeV, 600 pb^{-1} data @ 4.170 GeV)
  2. BESIII/BEPCII: $D^+ \to \mu^+\nu_\mu$; $D^0 \to K^-e^+\nu_e$, $\pi^-e^+\nu_e$
     (2.92 fb^{-1} data @ 3.773 GeV)







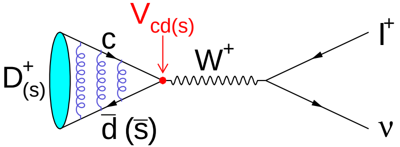


- Experiments at B factories
  1. Belle/KEK: $D_s^+ \to \ell^+\nu_\ell$; $D^0 \to K^-\ell^+\nu_\ell$, $\pi^-\ell^+\nu_\ell$
     (913 fb^{-1} data @ $\Upsilon(4S)$, $\Upsilon(5S)$)
  2. BaBar/PEP-II: $D_s^+ \to \ell^+\nu_\ell$; $D^0 \to K^-e^+\nu_e$, $\pi^-e^+\nu_e$
     (521 fb^{-1} data @ 10.58 GeV)

Purely Leptonic D^+ and D_s^+ Decays

In Standard Model

$$\Gamma(D_{(s)}^+ \to \ell^+\nu_\ell) = \frac{G_F^2 f_{D_{(s)}^+}^2}{8\pi}|V_{cd(s)}|^2 m_\ell^2 m_{D_{(s)}^+}\left(1-\frac{m_\ell^2}{m_{D_{(s)}^+}^2}\right)^2$$



- Decay rates measured experimentally
- $f_{D_{(s)}^+}$ can be determined with $V_{cd(s)}$ from global standard model fit
- f_{D^+} and $f_{D_s^+}$ affect calculated $f_{B_{(s)}}$ and then affect $|V_{td}|$ and $|V_{ts}|$
  - ☐ $|V_{td}|$ extracted from Δm_d in $B^0\bar{B}^0$ mixing
  - ☐ $|V_{ts}|$ extracted from Δm_s in $B_s^0\bar{B}_s^0$ mixing

  } ⇒ to constraint unitary triangle
- Search for New Physics

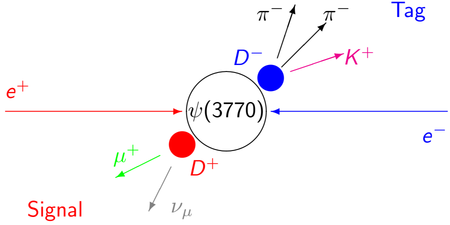
  Interference between W^+ and H^+ suppress $D_s^+ \to \ell^+\nu_\ell$ decays, but it does not suppress $D^+ \to \ell^+\nu_\ell$ decays

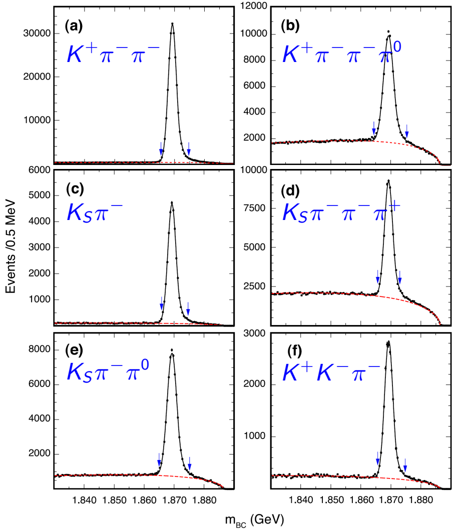
  J. L. Hewett, hep-ph/9505246; A.G. Akeroyd, hep-ph/0308260

CLEO-c: $D^+ \to \mu^+ \nu_\mu$

PRD 78, 052003 (2008) (818 pb^{-1} data taken at 3.773 GeV)

Method: $e^+e^- \to \psi(3770) \to D^+D^-$

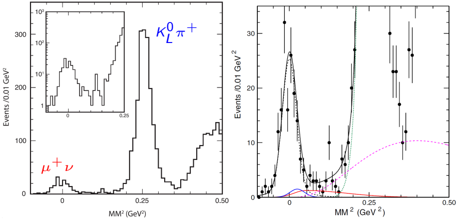




- BC mass $M_{BC} = \sqrt{E^2_{\rm beam} - p^2_{D_{\rm tag}}}$ was used to tag D^-
- $(0.46 \pm 0.00 \pm 0.03) \times 10^6$ D^- tags were reconstructed in 6 hadronic modes
- $MM^2 = (E_{\rm beam} - E_{\mu^+})^2 - (\vec{p}_{\bar{D}_{\rm tag}} - \vec{p}_{\mu^+})^2$ was used to select $D^+ \to \mu^+\nu_\mu$ decays

CLEO-c: $D^+ \to \mu^+\nu_\mu$

PRD 78, 052003 (2008) (818 pb^{-1} data taken at 3.773 GeV)



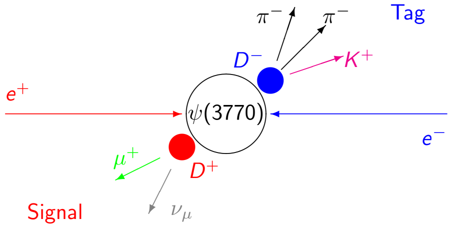
Results

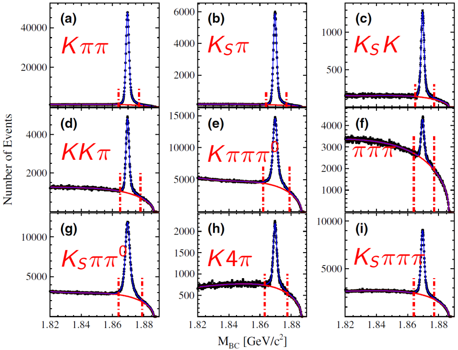
1. Fix the $\tau^+\nu$ contribution relative to the $\mu^+\nu$ in the fit to MM^2 distribution:
   - 149.7 ± 12.0 $\mu^+\nu$ events and 25.8 $\tau^+\nu$, $\tau^+ \to \pi^+\bar{\nu}$ events were obtained
   - $\mathcal{B}(D^+ \to \mu^+\nu_\mu) = (3.82 \pm 0.32 \pm 0.09) \times 10^{-4}$
   - $f_{D^+} = (205.8 \pm 8.5 \pm 2.5)$ MeV
2. Free the $\tau^+\nu$ contribution relative to the $\mu^+\nu$ in the fit to MM^2 distribution:
   - 153.9 ± 13.5 $\mu^+\nu$ events and 13.5 ± 15.3 $\tau^+\nu$, $\tau^+ \to \pi^+\bar{\nu}$ events were obtained
   - $\mathcal{B}(D^+ \to \mu^+\nu_\mu) = (3.93 \pm 0.35 \pm 0.09) \times 10^{-4}$
   - $f_{D^+} = (207.6 \pm 9.3 \pm 2.5)$ MeV

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

PRD 89, 051104(R) (2014) (2.92 fb^{-1} data taken at 3.773 GeV)

Method: $e^+e^- \to \psi(3770) \to D^+D^-$

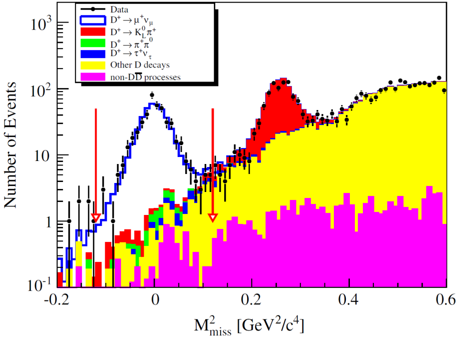




- $(1.703 \pm 0.003) \times 10^6$ D^- tags were reconstructed in 9 hadronic modes
- In signal side, required only one charged track which was positively identified as μ^+ with muon chamber measurements
- By examining $\mathrm{M}^2_{\mathrm{miss}} = (E_{\mathrm{beam}} - E_{\mu^+})^2 - (\vec{p}_{\bar{D}_{\mathrm{tag}}} - \vec{p}_{\mu^+})^2$ to select $D^+ \to \mu^+\nu_\mu$ decays

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

PRD 89, 051104(R) (2014) (2.92 fb^{-1} data taken at 3.773 GeV)



- There are 451 candidate $D^+ \to \mu^+\nu_\mu$ events in the $|M^2_{miss}| < 0.12$ GeV^2/c^4 signal region
- After subtracting 42.0 ± 2.3 background events, 409.0 ± 21.2 $D^+ \to \mu^+\nu_\mu$ events retained in signal region

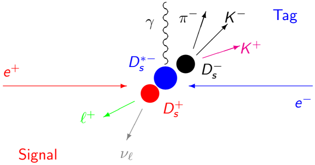
Results

- $\mathcal{B}(D^+ \to \mu^+\nu_\mu) = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$
- $f_{D^+} = (203.2 \pm 5.3 \pm 1.8)$ MeV
- $|V_{cd}| = 0.2210 \pm 0.0058 \pm 0.0047$

CLEO-c: $D_s^+ \to \ell^+ \nu_\ell$

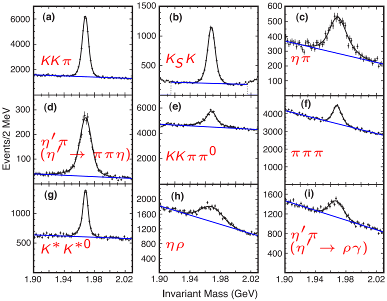
PRD 79, 052001 (2009) (600 pb^{-1} data recorded near 4.17 GeV)

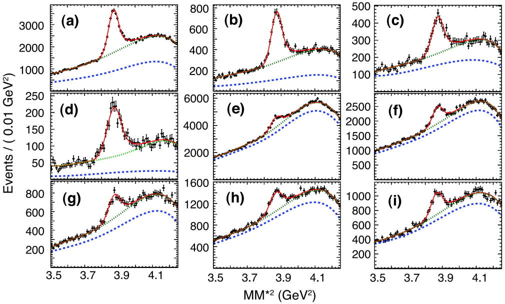
Method: $e^+e^- \to D_s^{*-} D_s^+$ + c.c



Reconstruct inclusive D_s^+ mesons in 2 steps:

1. Tag D_s^- mesons in 9 hadronic modes
2. Reconstruct γ from $D_s^{*-} \to D_s^- \gamma$ decay; tag D_s^+ with missing mass-squared (MM^{*2}) of the system recoiling against γ and D_s^- tag





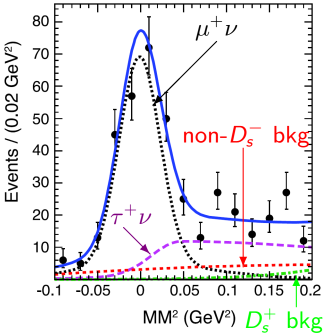
- $(43.9 \pm 0.9) \times 10^3$ D_s^{*-} tags were obtained by fitting to MM^{*2} spectra

CLEO-c: $D_s^+ \to \ell^+\nu_\ell$

PRD 79, 052001 (2009) (600 pb^{-1} data recorded near 4.17 GeV)

In the recoil side of D_s^{*-}:

- Examing distribution of MM^2 (Missing Mass-squared against the γ, tagged D_s^- and μ^+) select $D_s^+ \to \mu^+\nu_\mu$ decays
- $N^{\rm sig}(D_s^+ \to \mu^+\nu) = 222.4 \pm 17.1$
- $N^{\rm sig}(D_s^+ \to \tau^+\nu) = 125.6 \pm 15.7$



Results

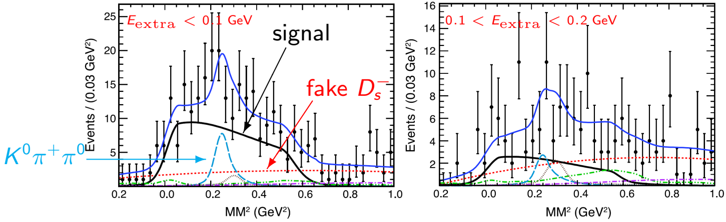
1. $\mathcal{B}^{\rm eff}(D_s^+ \to \mu^+\nu) = (0.565 \pm 0.045 \pm 0.017)\%$
   $f_{D_s^+} = (257.6 \pm 10.3 \pm 4.3)$ MeV
2. $\mathcal{B}(D_s^+ \to \tau^+\nu) = (6.42 \pm 0.81 \pm 0.18)\%$
   $f_{D_s^+} = (278.0 \pm 17.5 \pm 4.4)$ MeV

CLEO-c: $D_s^+ \to \tau^+\nu_\tau$, $\tau^+ \to \rho^+\bar{\nu}$

PRD 80, 112004 (2009) (600 pb^{-1} data recorded near 4.17 GeV)

From the same inclusive D_s^+ samples as the one in previous $D_s^+ \to \mu^+\nu_\mu$ analysis, select $D_s^+ \to \tau^+\nu_\tau, \tau^+ \to \rho^+\bar{\nu}$ decays:

- Reconstruct $\rho^+ \to \pi^+\pi^0$ ($|M_{\pi^+\pi^0} - M_{\rho^+}| < 250$ MeV)
- Examine MM^2 to select the decay



Results

Fitting MM^2 distributions in two $E_{\rm extra}$ bins $E_{\rm extra} < 0.1$ GeV and $0.1 < E_{\rm extra} < 0.2$ GeV yields 155.2 ± 16.5 and 43.7 ± 11.3 signal events, respectively

$\hookrightarrow \mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.52 \pm 0.57 \pm 0.21)\%$

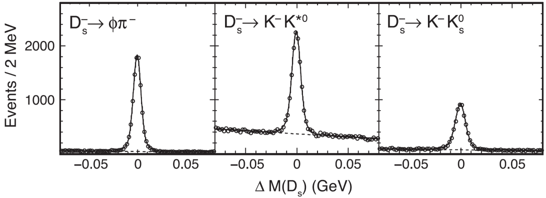
$\hookrightarrow f_{D_s^+} = (257.8 \pm 13.3 \pm 5.2)$ MeV

CLEO-c: $D_s^+ \to \tau^+\nu_\tau$, $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$

PRD 79, 052002 (2009) (600 pb^{-1} data recorded near 4.17 GeV)

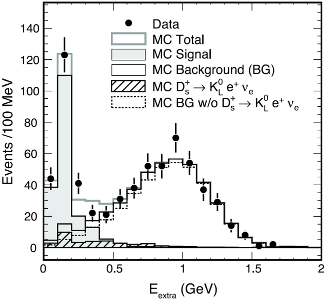
Single D_s^- tags:

- $(26.3 \pm 0.2) \times 10^3$ single D_s^- tags are reconstructed from 3 cleanest modes



Search for $D_s^+ \to \tau^+\nu_\tau$ decays:

- Only 1 single charged track identified as e^+, $p > 200$ MeV$/c$
- Examine $E_{\rm extra}$ (the total energy of rest of the event measured in calorimeter)



Results

After subtracting backgrounds, 180.6±15.9 events from the decay chain $D_s^+ \to \tau^+\nu_\tau \to e^+\nu_e\bar{\nu}_\tau\nu_\tau$ retained

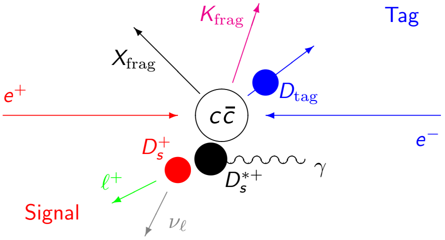
$\hookrightarrow \mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.30 \pm 0.47 \pm 0.22)\%$

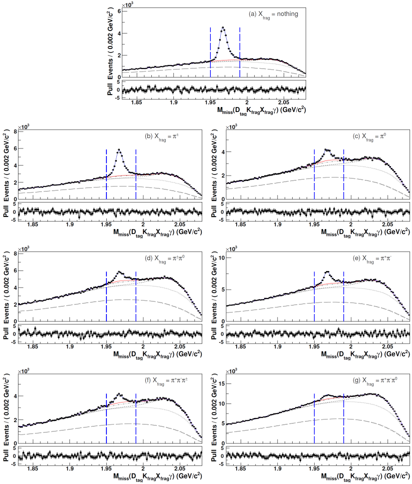
$\hookrightarrow f_{D_s^+} = (252.5 \pm 11.1 \pm 5.6)$ MeV

Belle: $D_s^+ \to \ell^+ \nu_\ell$

JHEP 1309 (2013) 139 (913 fb^{-1} data collected at or near $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances)

Method: $e^+e^- \to c\bar{c} \to D_{\rm tag} K_{\rm frag} X_{\rm frag} D_s^{*+}$, $D_s^{*+} \to D_s^+ \gamma$





Inclusive D_s^+ reconstruction:

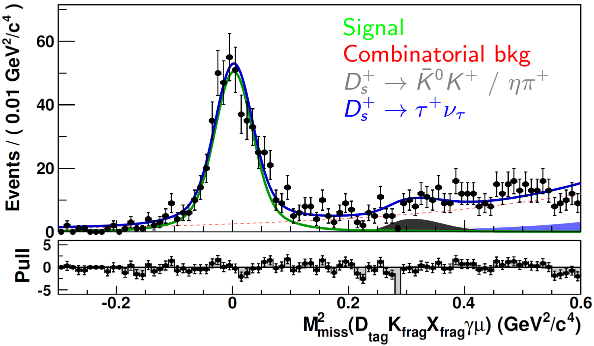
- First reconstruct charm tag $D_{\rm tag}$, $K_{\rm frag}$, $X_{\rm frag}$ and γ from $D_s^{*+} \to D_s^+\gamma$ decay, then identify D_s^+ by examining the recoil mass recoiling against $D_{\rm tag} K_{\rm frag} X_{\rm frag} \gamma$
- $N_{D_s^+}^{\rm inc} = (94.4 \pm 1.3_{\rm stat} \pm 1.5_{syst}) \times 10^3$

Belle: $D_s^+ \to \ell^+ \nu_\ell$

JHEP 1309 (2013) 139 (913 fb^{-1} data collected at or near $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances)

Reconstruction of $D_s^+ \to \mu^+ \nu_\mu$ decays:

- Single additional charged track identified as μ^+
- Examining missing mass-squared against $D_{\rm tag} K_{\rm frag} X_{\rm frag} \gamma \mu$ to select $D_s^+ \to \mu^+ \nu_\mu$ decays



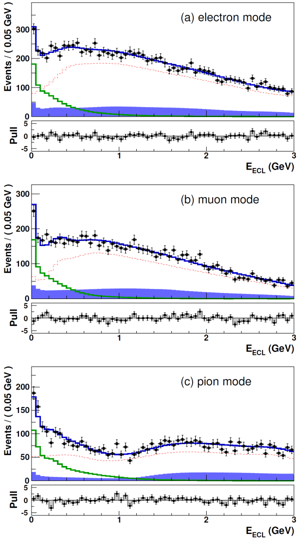
- $N(D_s^+ \to \mu^+ \nu_\mu) = 492 \pm 26$
  $\mathcal{B}(D_s^+ \to \mu^+ \nu_\mu) = (0.531 \pm 0.028 \pm 0.020)\%$

Belle: $D_s^+ \to \ell^+ \nu_\ell$

JHEP 1309 (2013) 139 (913 fb^{-1} data collected at or near $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances)

Reconstruction of $D_s^+ \to \tau^+ \nu_\tau$ decays:

- One additional charged track identified as e^+, μ^+ or π^+
- Examining the deposited energy $E_{\rm ECL}$ of the charged track in electromagnetic calorimeter, $E_{\rm ECL}$ peaks toward 0 for $D_s^+ \to \tau^+ \nu_\tau$ decays
- $N(D_s^+ \to \tau^+ \nu_\tau) = (2.22 \pm 0.08) \times 10^3$
  $\mathcal{B}(D_s^+ \to \tau^+ \nu_\tau) = (5.70 \pm 0.21^{+0.31}_{-0.30})\%$



Results of Decay Constant

$D_s^+ \to \ell^+ \nu_\ell$	$f_{D_s^+}$ (MeV)
$\mu^+ \nu_\mu$	$249.8 \pm 6.6(\rm stat.) \pm 4.7(\rm syst.) \pm 1.7(\tau_{D_s})$
$\tau^+ \nu_\tau$	$261.9 \pm 4.9(\rm stat.) \pm 7.0(\rm syst.) \pm 1.8(\tau_{D_s})$
Combination	$255.5 \pm 4.2(\rm stat.) \pm 4.8(\rm syst.) \pm 1.8(\tau_{D_s})$

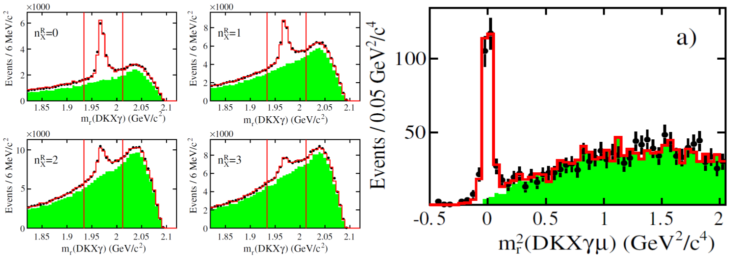
BaBar: $D_s^+ \to \ell^+ \nu_\ell$

PRD 82, 091103(R) (2010) (521 fb^{-1} data collected at 10.58 GeV)

Using similar method as Belle used: $e^+e^- \to c\bar{c} \to DKXD_s^{*+}$, $D_s^{*+} \to D_s^+\gamma$

Inclusive D_s^+ sample:

- $N_{D_s^+} = (67.2 \pm 1.5) \times 10^3$ D_s^+ selected by fitting to distribution of the missing mass $m_r(DKX\gamma)$



Search for $D_s^+ \to \mu^+\nu_\mu$ events:

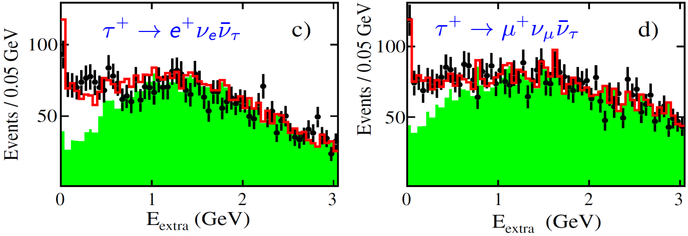
- Exactly one extra charged track identified as μ^+, $E_{\text{extra}} < 1.0$ GeV
- Signal yield $N_{\mu\nu} = 275 \pm 17$, extracted from fitting to $m_r^2(DKX\gamma\mu)$ distribution $\hookrightarrow \mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (6.02 \pm 0.38 \pm 0.34) \times 10^{-3}$

BaBar: $D_s^+ \to \ell^+ \nu_\ell$

PRD 82, 091103(R) (2010) (521 fb^{-1} data collected at 10.58 GeV)

Search for $D_s^+ \to \tau^+ \nu_\tau$ events:

- Exactly one extra charged track identified as an e^+ or μ^+
- $m_r^2(DKX\gamma\mu) > 0.5$ GeV$^2/c^4$ (Remove $\mu^+\nu_\mu$ events)



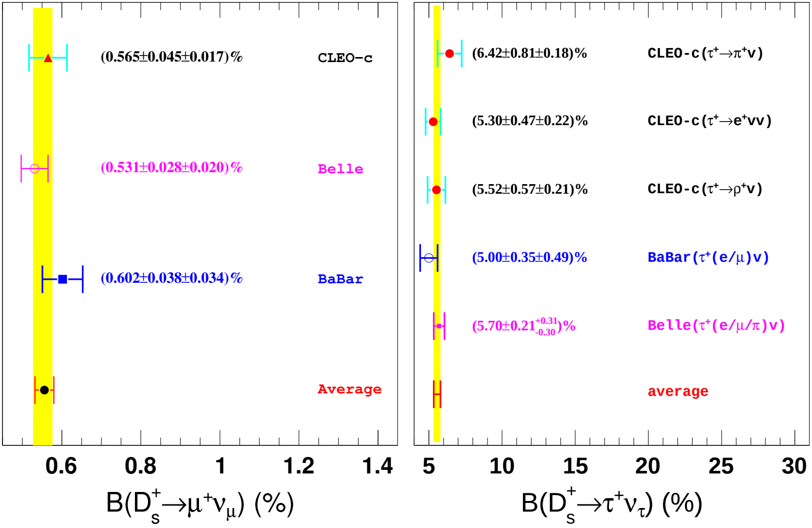
- Signal yields $N(D_s^+ \to \tau^+\nu_\tau, \tau^+ \to e^+\nu_e\bar{\nu}_\tau) = 408 \pm 42$,
  $N(D_s^+ \to \tau^+\nu_\tau, \tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau) = 340 \pm 32$
  $\hookrightarrow \mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.00 \pm 0.35(\text{stat}) \pm 0.49(\text{syst})) \times 10^{-2}$

Result of Decay Constant

- Error-weighted average of 3 $f_{D_s^+}$: $f_{D_s^+} = (258.6 \pm 6.4(\text{stat}) \pm 7.5(\text{syst}))$ MeV

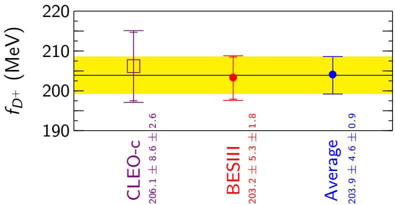
Leptonic D_s^+ Decays

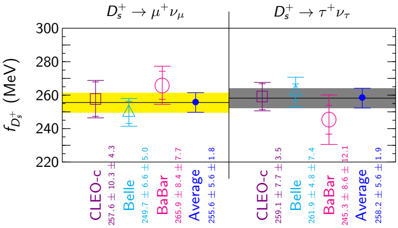
Comparison of Branching Fractions for $D_s^+ \to \mu^+\nu_\mu$ and $D_s^+ \to \tau^+\nu_\tau$



Comparisons of Decay Constants

To compare decay constants we re-determine these based on originally measured branching fractions in conjunction with $|V_{cd(s)}|$ determined from global SM fit.





- Average experimental result:

$$f_{D^+} = (203.9 \pm 4.7)\ \text{MeV}$$

- Experimental result for D_s^+ meson decay constant:

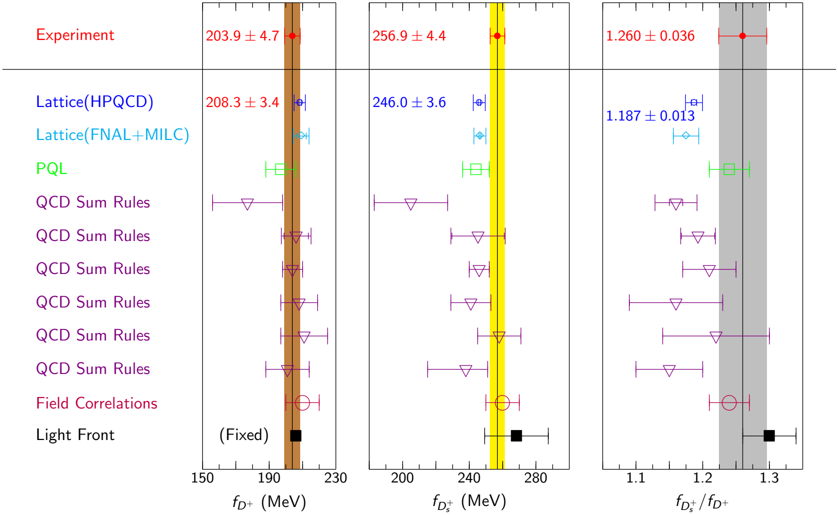
Channel	$f_{D_s^+}$ (MeV)
$\mu^+\nu$	255.6 ± 5.9
$\tau^+\nu$	258.2 ± 5.9
Average	256.9 ± 4.4[a]

- Experimental ratio of decay constants:

$$f_{D_s^+}/f_{D^+} = 1.260 \pm 0.036$$

[a] correcting common error in the μ^+ and τ^+ measurements would change $f_{D_s^+}$ by $\sim 0.18\%$ (J. Rosner, S. Stone; A. Zupanc)

Comparisons of Decay Constants



The experimental ratio of these decay constants $f_{D_s^+}/f_{D^+} = 1.260 \pm 0.036$ is larger than HPQCD calculated ratio $f_{D_s^+}/f_{D^+} = 1.187 \pm 0.004 \pm 0.012$ by 1.9 standard deviation.

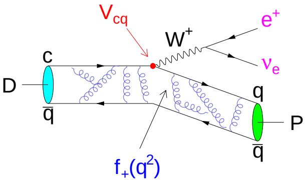
Semileptonic D Decays

- Differential Rates of $D \to Pe^+\nu_e$ ($P = \pi, K$) Decay:

$$\frac{d\Gamma}{dq^2} = X\frac{G_F^2|V_{cd(s)}|^2}{24\pi^3}p^3|f_+(q^2)|^2$$

Form Factor Parameterizations

Simple Pole Model	$f_+(q^2) = \frac{f_+(0)}{(1-q^2/M^2_{\rm pole})}$
Modified Pole Model	$f_+(q^2) = \frac{f_+(0)}{(1-q^2/M^2_{\rm pole})/(1-\alpha q^2/M^2_{\rm pole})}$
ISGW2 Model	$f_+(q^2) = f_+(q^2_{\rm max})(1+\frac{r^2}{12}(q^2_{\rm max}-q^2))^{-2}$
Series Expansion	$f_+(q^2) = \frac{1}{P(q^2)\Phi(q^2,t_0)}\sum_{k=0}^{\infty} a_k(t_0)[z(q^2,t_0)]^k$

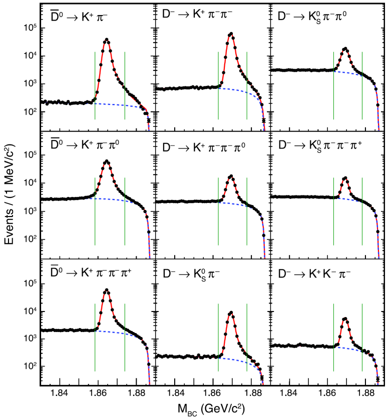


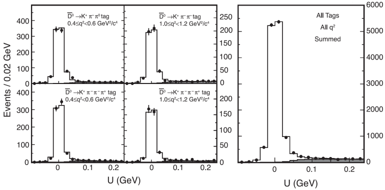
- Determine form factors $f_+^{\pi}(q^2)$ and $f_+^{K}(q^2)$ with inputs of $|V_{cd}|$ and $|V_{cs}|$
  - Validate $f_+^{\pi}(q^2)$ and $f_+^{K}(q^2)$ calculated in LQCD
  - Improve $f_+^{B\to\pi}(0)$ calculated in LQCD, then improve $|V_{ub}|$
  - Improve the precision of the unitarity triangle
- Determine $|V_{cd}|$ and $|V_{cs}|$

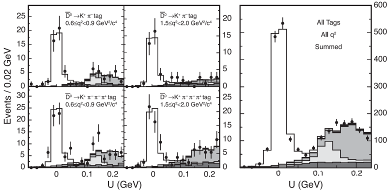
CLEO-c: $D^0 \to K^- e^+ \nu_e$, $\pi^- e^+ \nu_e$, $D^+ \to \bar{K}^0 e^+ \nu_e$, $\pi^0 e^+ \nu_e$

PRD 80, 032005 (2009) (818 pb^{-1} data collected at 3.773 GeV)

Method: $e^+e^- \to \psi(3770) \to D^0 \bar{D}^0, D^+ D^-$







$N_{\bar{D}^0_{tag}} = (0.662 \pm 0.001) \times 10^6$

$N_{D^-_{tag}} = (0.263 \pm 0.001) \times 10^6$

$N_{D^0 \to K^- e^+ \nu_e} = 11836 \pm 121$

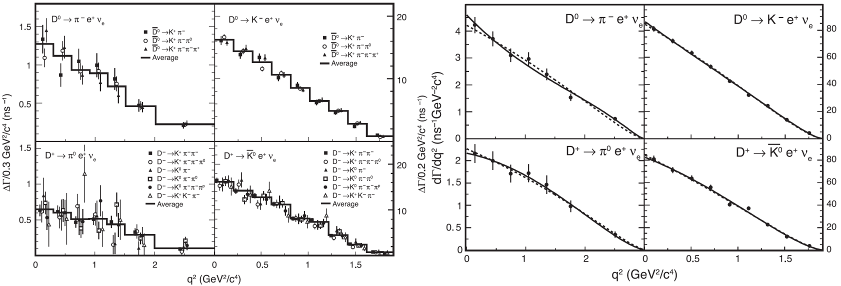
$N_{D^+ \to \bar{K}^0 e^+ \nu_e} = 8467 \pm 91$

$N_{D^0 \to \pi^- e^+ \nu_e} = 1374 \pm 39$

$N_{D^+ \to \pi^0 e^+ \nu_e} = 838 \pm 33$

CLEO-c: $D^0 \to K^- e^+ \nu_e$, $\pi^- e^+ \nu_e$, $D^+ \to \bar{K}^0 e^+ \nu_e$, $\pi^0 e^+ \nu_e$

PRD 80, 032005 (2009) (818 pb^{-1} data collected at 3.773 GeV)

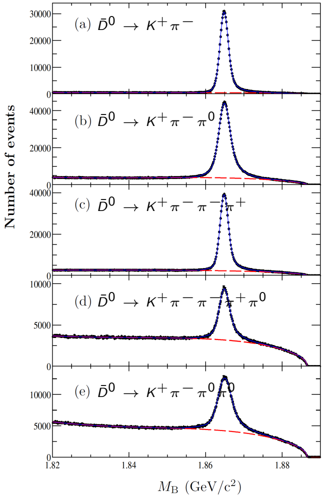


Branching fraction results

Mode	$\mathcal{B}$ (%)
$D^0 \to \pi^- e^+ \nu_e$	$0.288 \pm 0.008 \pm 0.003$
$D^0 \to K^- e^+ \nu_e$	$3.50 \pm 0.03 \pm 0.04$
$D^+ \to \pi^0 e^+ \nu_e$	$0.405 \pm 0.016 \pm 0.009$
$D^+ \to \bar{K}^0 e^+ \nu_e$	$8.83 \pm 0.10 \pm 0.20$

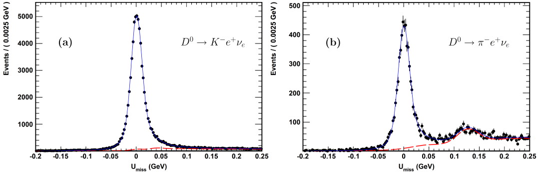
- Form factors
  - $f_+^K(0) = 0.739 \pm 0.007 \pm 0.005 \pm 0.000$
  - $f_+^\pi(0) = 0.666 \pm 0.019 \pm 0.004 \pm 0.003$
- CKM matrix element
  - $|V_{cd}| = 0.234 \pm 0.007 \pm 0.002 \pm 0.025$
  - $|V_{cs}| = 0.985 \pm 0.009 \pm 0.006 \pm 0.103$

New results based on 2.92 fb^{-1} data supersede those preliminary results presented at CHARM2012 which was based on $\sim 1/3$ data.



Method: $e^+e^- \to \psi(3770) \to D^0\bar{D}^0$

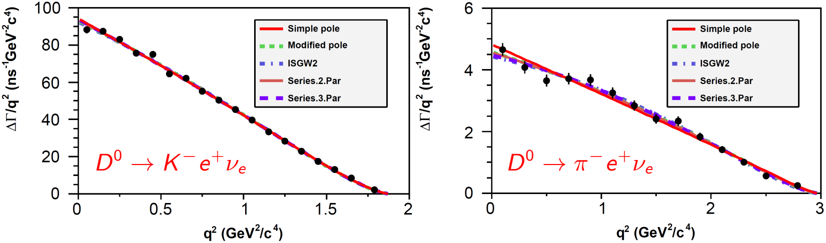
- $(2.793 \pm 0.004) \times 10^6$ $\bar{D}^0$ tags are reconstructed in 5 hadronic decay modes



- $N(D^0 \to K^- e^+ \nu_e) = (70.7 \pm 0.3) \times 10^3$
  $\hookrightarrow \mathcal{B}_{D^0 \to K^- e^+ \nu_e} = (3.505 \pm 0.014 \pm 0.033)\%$
- $N(D^0 \to \pi^- e^+ \nu_e) = (6.3 \pm 0.1) \times 10^3$
  $\hookrightarrow \mathcal{B}_{D^0 \to \pi^- e^+ \nu_e} = (0.2950 \pm 0.0041 \pm 0.0026)\%$

BESIII: $D^0 \to K^- e^+ \nu_e$, $\pi^- e^+ \nu_e$

Preliminary (2.92 fb^{-1} data collected at 3.773 GeV)



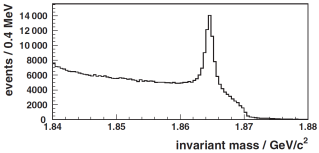
Model	$D^0 \to K^- e^+ \nu_e$		$D^0 \to \pi^- e^+ \nu_e$	
Simple pole	$f_+^K(0)\|V_{cs}\|$	$0.7209 \pm 0.0022 \pm 0.0033$	$f_+^\pi(0)\|V_{cd}\|$	$0.1475 \pm 0.0014 \pm 0.0005$
	$M_{\rm pole}$	$1.9207 \pm 0.0103 \pm 0.0069$	$M_{\rm pole}$	$1.9114 \pm 0.0118 \pm 0.0038$
Mod. pole	$f_+^K(0)\|V_{cs}\|$	$0.7163 \pm 0.0024 \pm 0.0034$	$f_+^\pi(0)\|V_{cd}\|$	$0.1437 \pm 0.0017 \pm 0.0008$
	α	$0.3088 \pm 0.0195 \pm 0.0129$	α	$0.2794 \pm 0.0345 \pm 0.0113$
ISGW2	$f_+^K(0)\|V_{cs}\|$	$0.7139 \pm 0.0023 \pm 0.0034$	$f_+^\pi(0)\|V_{cd}\|$	$0.1415 \pm 0.0016 \pm 0.0006$
	$r_{\rm ISGW2}$	$1.6000 \pm 0.0141 \pm 0.0091$	$r_{\rm ISGW2}$	$2.0688 \pm 0.0394 \pm 0.0124$
Series.2.Par	$f_+^K(0)\|V_{cs}\|$	$0.7172 \pm 0.0025 \pm 0.0035$	$f_+^\pi(0)\|V_{cd}\|$	$0.1435 \pm 0.0018 \pm 0.0009$
	r_1	$-2.2278 \pm 0.0864 \pm 0.0575$	r_1	$-2.0365 \pm 0.0807 \pm 0.0260$
Series.3.Par	$f_+^K(0)\|V_{cs}\|$	$0.7196 \pm 0.0035 \pm 0.0041$	$f_+^\pi(0)\|V_{cd}\|$	$0.1420 \pm 0.0024 \pm 0.0010$
	r_1	$-2.3331 \pm 0.1587 \pm 0.0804$	r_1	$-1.8434 \pm 0.2212 \pm 0.0690$
	r_2	$3.4223 \pm 3.9090 \pm 2.4092$	r_2	$-1.3871 \pm 1.4615 \pm 0.4677$

Belle: $D^0 \to K^-\ell^+\nu_\ell$, $\pi^-\ell^+\nu_\ell$

PRL 97, 061804 (2006) (282 fb^{-1} data collected at 10.58 GeV)

Method: $e^+e^- \to D^{(*)}_{\rm tag} D^{*-}_{\rm sig} X$, $D^{*-}_{\rm sig} \to \bar{D}^0_{\rm sig}\pi^-$, $X = \pi^\pm$, π^0, or $K^\pm$

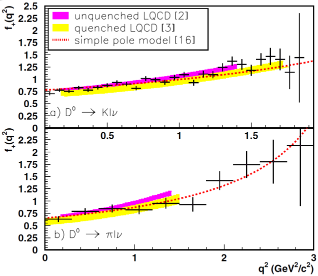
- $(56.5 \pm 0.3_{\rm stat} \pm 0.8_{\rm syst}) \times 10^3$ $\bar{D}^0_{\rm sig}$ tags were found
- Semileptonic decay is reconstructed with K^- and ℓ^+ candidates from the remaining tracks



Results

Channel	$K^-e^+\nu_e$	$K^-\mu^+\nu_\mu$	$\pi^-e^+\nu_e$	$\pi^-\mu^+\nu_\mu$
Yield	$1318 \pm 37 \pm 7$	$1249 \pm 37 \pm 25$	$126 \pm 12 \pm 3$	$106 \pm 12 \pm 6$

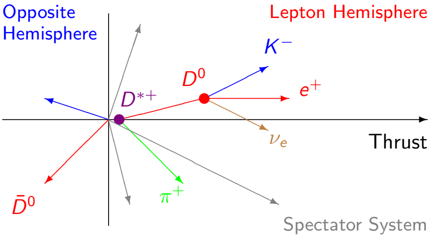
- Branching fractions
  - $\hookrightarrow \mathcal{B}(D^0 \to K^-\ell^+\nu_\ell) = (3.45 \pm 0.07 \pm 0.20)\%$
  - $\hookrightarrow \mathcal{B}(D^0 \to \pi^-\ell^+\nu_\ell) = (0.255 \pm 0.019 \pm 0.016)\%$
- Form factors
  - $\hookrightarrow f^K_+(0) = 0.695 \pm 0.007_{\rm stat} \pm 0.022_{\rm syst}$
  - $\hookrightarrow f^\pi_+(0) = 0.624 \pm 0.020_{\rm stat} \pm 0.030_{\rm syst}$

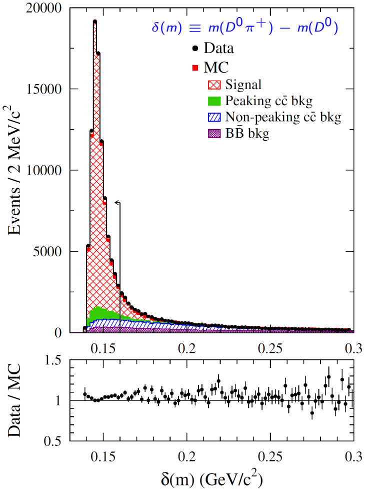


BaBar: $D^0 \to K^- e^+ \nu_e$

PRD 76, 052005 (2007) (75 fb^{-1} data collected at 10.58 GeV)

Method: $e^+e^- \to c\bar{c}$ fragmentation, $D^{*+} \to D^0\pi^+$, $D^0 \to K^- e^+ \nu_e$



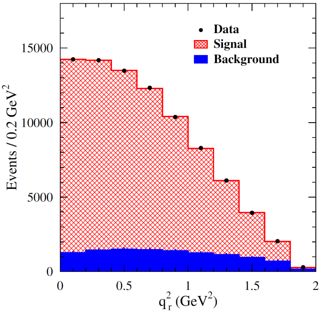


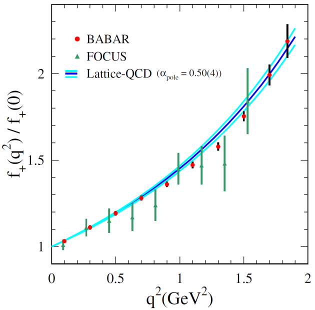
- Select K^-, e^+, π^+ in the same hemisphere
- Determine D^0 direction $(-\vec{p}_{\mathrm{all\ tracks} \neq K^-, e^+})$
- Estimate E_{ν_e} (missing energy in the lepton hemisphere)
- Constraint fit using D^0 and D^{*+} mass
- Fisher discriminant to reduce $B\bar{B}$, $c\bar{c}$ bkg

BaBar: $D^0 \to K^- e^+ \nu_e$

PRD 76, 052005 (2007) (75 fb^{-1} data collected at 10.58 GeV)

- 85.3×10^3 selected D^0 candidates containing 11.3×10^3 background events



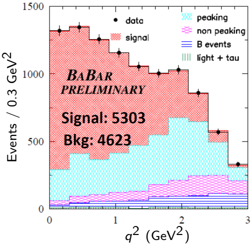


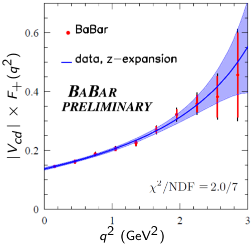
- $R_D = \frac{\mathcal{B}(D^0 \to K^- e^+ \nu_e)}{\mathcal{B}(D^0 \to K^- \pi^+)} = 0.927 \pm 0.007 \pm 0.012$
- Using $\mathcal{B}(D^0 \to K^- \pi^+)|_{\mathrm{PDG06}} = (3.80 \pm 0.07)\%$, BaBar determined $\mathcal{B}(D^0 \to K^- e^+ \nu_e) = (3.522 \pm 0.027 \pm 0.065)\%$
- $f_+(0) = 0.727 \pm 0.007 \pm 0.005 \pm 0.007$

BaBar: $D^0 \to \pi^- e^+ \nu_e$

Preliminary [A. Oyanguren's talk presented at ICHEP2014] (347.2 fb^{-1} data collected at $\Upsilon(4S)$)

Using similar BaBar analysis technique used in analysis of $D^0 \to K^- e^+ \nu_e$

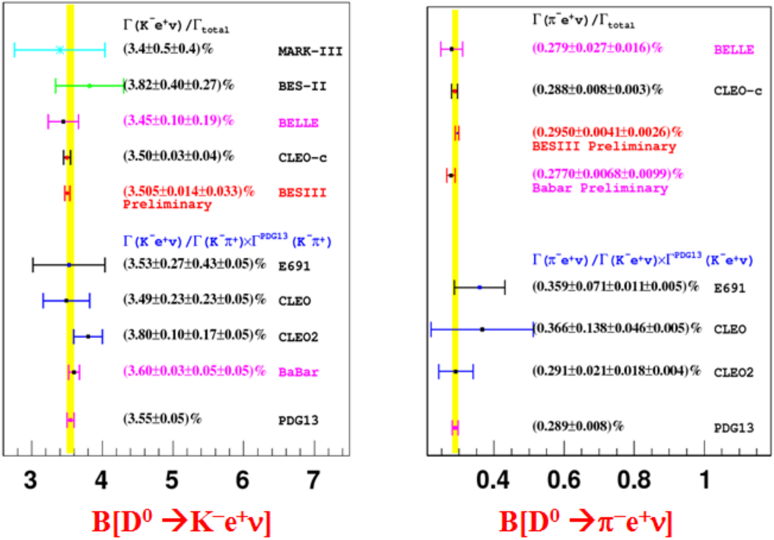




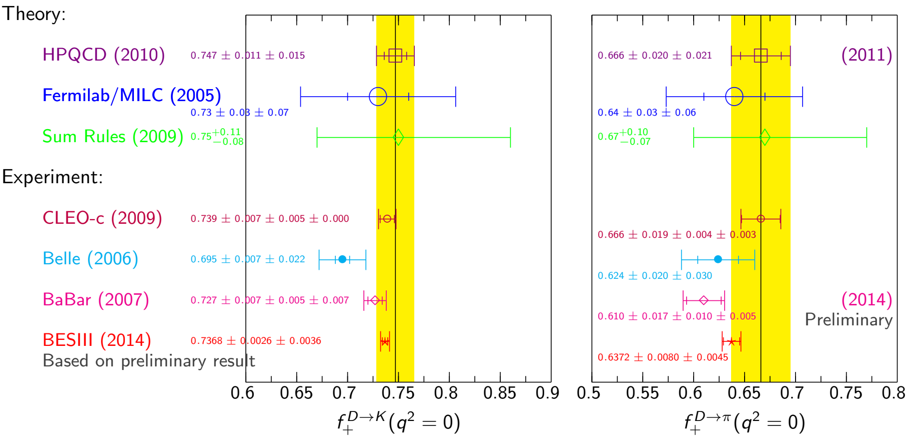
- 5.3×10^3 $D^0 \to \pi^- e^+ \nu_e$ events observed
- $R_D = \frac{\mathcal{B}(D^0 \to \pi^- e^+ \nu_e)}{\mathcal{B}(D^0 \to K^- \pi^+)} = 0.0702 \pm 0.0017 \pm 0.0023$
- Using $\mathcal{B}(D^0 \to K^- \pi^+)|_{\rm PDG} = (3.88 \pm 0.05)\%$, BaBar determined $B(D^0 \to \pi^- e^+ \nu_e) = (0.2770 \pm 0.0068 \pm 0.0092 \pm 0.0037)\%$
- $|V_{cd}| f_+^{D\to\pi}(0) = 0.1374 \pm 0.0038_{\rm stat.} \pm 0.0022_{\rm syst.} \pm 0.0009_{\rm ext.}$
- Using $|V_{cd}| = 0.2252 \pm 0.0009 \Rightarrow f_+^{D\to\pi}(0) = 0.610 \pm 0.017 \pm 0.010 \pm 0.005$
- Using $f_+^{D\to\pi}(0) = 0.666 \pm 0.020 \pm 0.021 \Rightarrow |V_{cd}| = 0.206 \pm 0.007 \pm 0.009$

Semi-leptonic D Decays

Comparison of $B(D \to Ke^+\nu_e)$ and $B(D \to \pi e^+\nu_e)$



Comparison of Form Factors



The averages of these four determined form factors are

$$f_+^{D\to K}(0) = 0.735 \pm 0.004 \text{ and } f_+^{D\to\pi}(0) = 0.637 \pm 0.008.$$

The BSIII made the best precise determinations of these two form factors.

Extraction of $|V_{cd}|$ and $|V_{cs}|$

- Leptonic D^+ and D_s^+ Decays

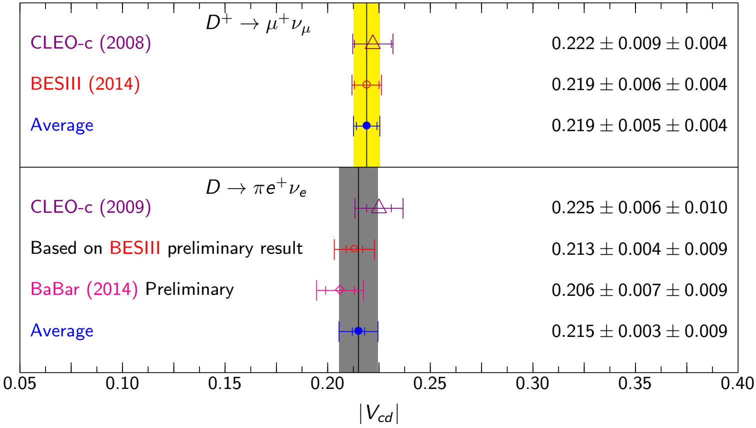
$$\Gamma(D^+_{(s)} \to \ell^+ \nu_\ell) = \frac{G_F^2 f^2_{D^+_{(s)}}}{8\pi} |V_{cd(s)}|^2 m_\ell^2 m_{D_{(s)}} \left(1 - \frac{m_\ell^2}{m^2_{D_{(s)}}}\right)^2$$

  - Input $f_{D^+} = (209.2 \pm 3.3)$ MeV and $f_{D_s^+} = (248.6 \pm 2.7)$ MeV from the Flavor Lattice Averaging Group
  - Directly determine $|V_{cd}|$ and $|V_{cs}|$
- Semileptoinc D^0 and D^+ Decays

$$\frac{d\Gamma(D \to \pi(K) e^+ \nu_e)}{dq^2} = X \frac{G_F^2}{24\pi^3} |V_{cd(s)}|^2 p^3 |f_+^{D\to\pi(K)}(q^2)|^2$$

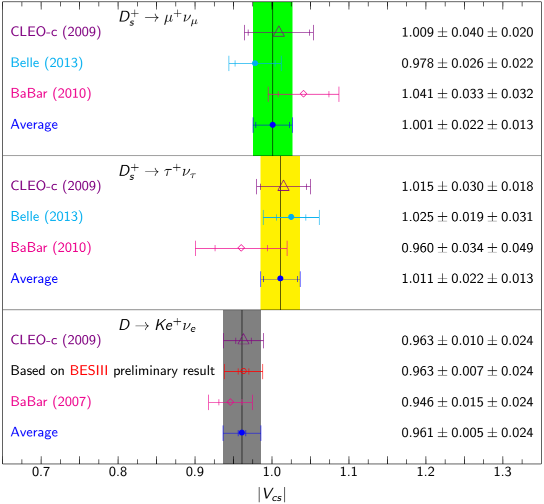
  - Input $f_+^{D\to\pi}(0) = 0.666 \pm 0.029$ and $f_+^{D\to K}(0) = 0.747 \pm 0.019$ from lattice QCD calculations
  - Directly determine $|V_{cd}|$ and $|V_{cs}|$
- Extract $|V_{\rm cd}|$ and $|V_{\rm cs}|$ with measured branching fraction or the product of $|V_{\rm cd(s)}|$ and f (f is decay constant or form factor) in conjunction with
  - Masses and leftimes of D mesons and leptons given in PDG2013
  - Newly updated decay constants and form factors calculated in LQCD

Extraction of $|V_{\rm cd}|$



- Average of these determined $|V_{\rm cd}|$ from leptonic and semileptonic decays $\hookrightarrow |V_{cd}| = 0.218 \pm 0.005$

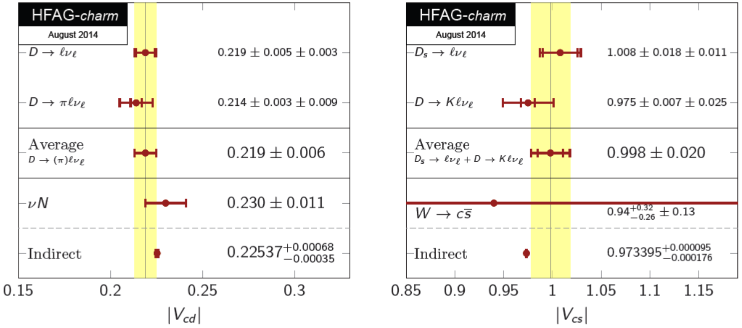
Extraction of $|V_{cs}|$



- Average of the determinations from leptonic and semileptonic decays
  $\hookrightarrow |V_{cs}| = 0.987 \pm 0.016$

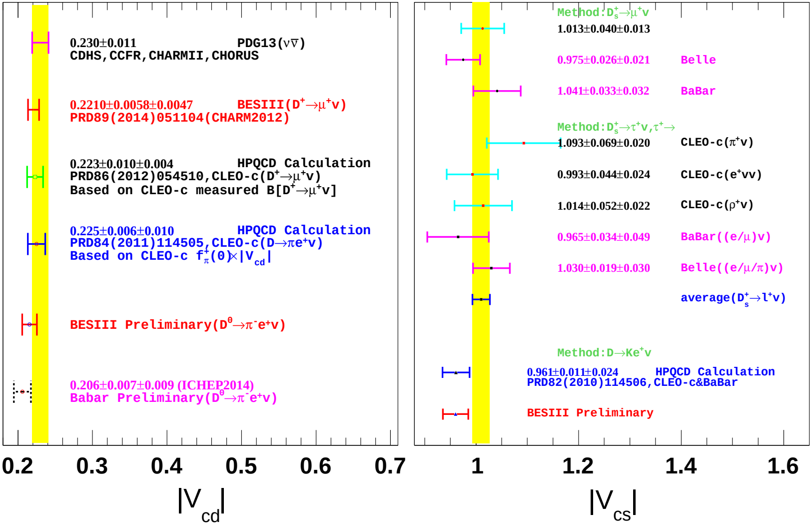
$|V_{cd}|$ and $|V_{cs}|$ determined by Dr. A. Zupanc in HFAG-charm Group

Dr. A. Zupanc determined $|V_{cd}|$ and $|V_{cd}|$ without using some preliminary results reported at International Conferences and the BESIII preliminary result of $|V_{cd(s)}|f_+^{\pi(K)}(0)$ reported at ICHEP2014 and Beauty2014 by H.L. Ma. (Thank Dr. A. Zupanc for letting me show these results at the CKM2014).



Comparison of $|V_{cd}|$ and $|V_{cs}|$

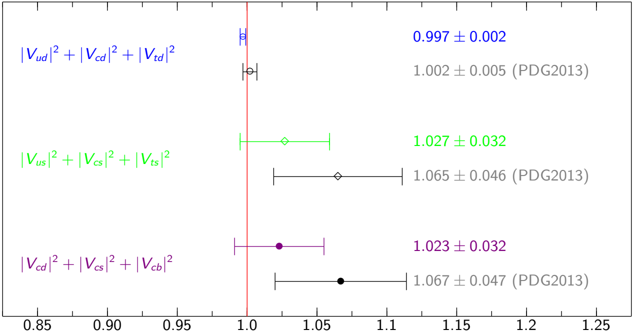
Leptonic and semi-leptonic D decays, Beauty2014, by H.L. Ma



Unitarity Checks

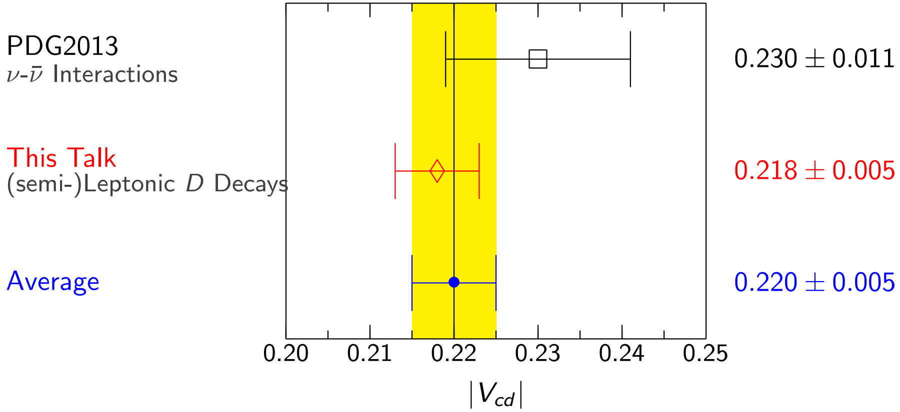
- Newly extracted values: $|V_{cd}| = 0.218 \pm 0.005$, $|V_{cs}| = 0.987 \pm 0.016$ from (semi-)leptonic D decays
- PDG2013 values: $|V_{ud}| = 0.97425 \pm 0.00022$, $|V_{td}| = (8.4 \pm 0.6) \times 10^{-3}$, $|V_{us}| = 0.2252 \pm 0.0009$, $|V_{ts}| = (42.9 \pm 2.6) \times 10^{-3}$ and $|V_{cb}| = (40.9 \pm 1.1) \times 10^{-3}$.

Using these $|V_{\rm cd}|$, $|V_{\rm cs}|$ and other CKM matrix elements given in PDG2013, we check the unitarity.



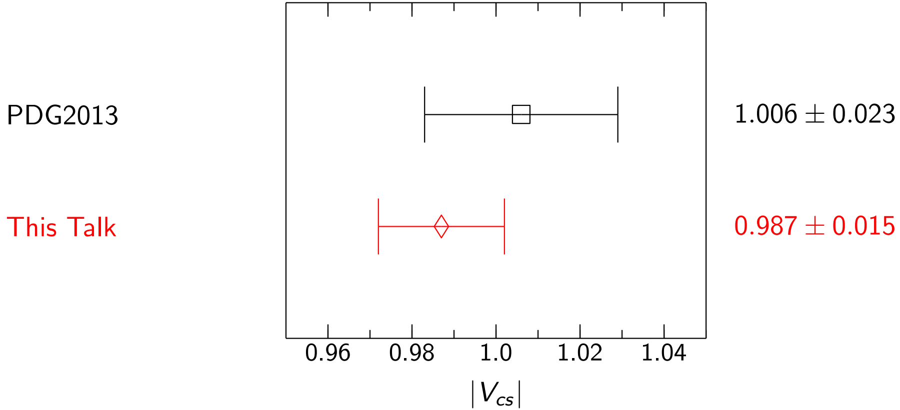
These newly determined $|V_{cd}|$ and $|V_{cs}|$ give more stringent checks of the CKM matrix unitarity compared to those given in PDG2013.

Comparisons of $|V_{cd}|$



The newly extracted $|V_{cd}|$ based on measurements of D leptonic and semi-leptonic decays are more precise than the one determined with $\nu\bar{\nu}$ interaction by 2 factor.

Comparisons of $|V_{cs}|$



The newly extracted $|V_{cs}|$ based on measurements of D_s^+ leptonic and D semi-leptonic decays including the BESIII preliminary results of D semi-leptonic decays in conjunction with newly updated $f_{D_s^+}$ and $f_+^K(0)$ calculated in LQCD are more precise than the one given in PDG2013 by 1.4 factor.

Summary

- Decay constants
  1. $f_{D^+} = 203.9 \pm 4.7$ MeV (CLEO-c, BESIII)
  2. $f_{D_s^+} = 256.9 \pm 4.4$ MeV (CLEO-c, BaBar, Belle)
  3. $f_{D_s^+}/f_{D^+} = 1.260 \pm 0.036$, which is larger than HPQCD prediction by 1.9σ.
- Form factors
  1. $f_+^{D\to K}(0) = 0.735 \pm 0.004$ (CLEO-c, BaBar, Belle, BESIII)
  2. $f_+^{D\to \pi}(0) = 0.637 \pm 0.008$ (CLEO-c, BaBar, Belle, BESIII)
  3. $\Delta f_+^K(0)/f_+^K(0) \sim 0.5\%$, $\Delta f_+^\pi(0)/f_+^\pi(0) \sim 1.3\%$ (Experiment)
  4. $\Delta f_+^K(0)/f_+^K(0) \sim 2.5\%$, $\Delta f_+^\pi(0)/f_+^\pi(0) \sim 4.4\%$ (LQCD —- FLAV Group)
- Extracted $|V_{\rm cd}|$
  1. The best determination of $|V_{cd}| = 0.2210 \pm 0.0058 \pm 0.0047$ was made by analyzing $D^+ \to \mu^+\nu_\mu$ decays at the BESIII experiment.
  2. Combining BESIII and CLEO-c measurements of $B(D^+ \to \mu^+\nu)$ in conjunction with f_{D+} calculated in LQCD, we find
  $$|V_{cd}| = 0.218 \pm 0.005.$$
  3. Combining $|V_{cd}| = 0.218 \pm 0.005$ from measurements of leptonic and semileptonic D decays together with PDG2013 $|V_{cd}| = 0.230 \pm 0.011$ determined from measurements of ν-$\bar{\nu}$ interaction, we find
  $$|V_{cd}| = 0.220 \pm 0.005.$$

Summary

- Extracted $|V_{\rm cs}|$
  1. Combining all measurements from leptonic and semileptonic D decays, we find
     $$|V_{cs}| = 0.987 \pm 0.016.$$
  2. Comparing PDG2013 values:
     $$|V_{cs}| = 1.006 \pm 0.023.$$
  3. If uncertainties of form factors calculated in LQCD could be negligible, the precisions of $|V_{cd}|$ and $|V_{cs}|$ from D semileptonic decays could reach to
     $$\Delta|V_{cd}|/|V_{cd}| \sim 1.2\%, \ \Delta|V_{cs}|/|V_{cs}| \sim 0.5\%$$
- The BESIII gave the best precise determinations of f_{D^+}, $|V_{\rm cd}|$, $f_+^K(0)$ and $f_+^\pi(0)$, while the Belle gave the best precise determination of $f_{D_s^+}$.
- These newly determined $|V_{cd}|$ and $|V_{cs}|$ give more stringent checks of the CKM matrix unitarity compared to those given in PDG2013.
- We have been waiting for further improved $f_+^{D\to\pi}(0)$ and $f_+^{D\to K}(0)$ calculated in LQCD to reduce uncertainties of experimentally determined $|V_{cd}|$ and $|V_{cs}|$.

Thank you very much for your attention!

Comparison of extracted $|V_{cd}|$ and $|V_{cs}|$ determined in different cases

Comparison of determined $|V_{cd}|$ and $|V_{cs}|$

CKM matrix element	Based on all recent experimental results	Dr A. Zupanc	PDG2014**
$\|V_{cd}\|$	0.218±0.005	0.219±0.006	0.225±0.008
$\|V_{cs}\|$	0.987±0.016	0.998±0.020	0.986±0.016

1. Based on all recent experimental results
   Determined with the measurements including some preliminary results mentioned in this talk, no correction to the originally measured branching fractions for some decays was made
2. Dr. A. Zupanc
   Not including some preliminary results reported at international conferences, corrections to tau lepton decay branching fraction was made, …
3. PDG2014
   Not including some preliminary results, some corrections for decay branching fractions were made

**Note: On 7 September 2014 I just found PDG2014 is available. So adding this comparison

Back Up

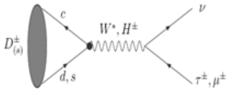
Leptonic $D_{(s)}^+$ Decays

Searching for New Physics

- **New Physics in $D_{(s)}^+$ leptonic decays**

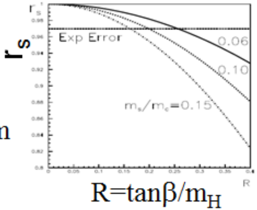
J.L. Hewett, hep-ph/9505246; A.G. Akeroyd, hep-ph/0308260

Interference between $W^\pm$ and $H^\pm$ suppresses $D_s^+ \to l^+\nu$, but it does not suppressed $D^+ \to l^+\nu$



$$\Gamma(D_{(s)}^+ \to l^+\nu) = \Gamma_{SM}(D_{(s)}^+ \to l^+\nu) r_s$$

$$r_s = \left[1 - m_{D_{(s)}^+}^2 R^2 \left(\frac{m_{d(s)}}{m_{d(s)} + m_c} \right) \right]^2$$



R=tanβ/m_H, where tanβ is the ratio of vacuum expectation values of the two Higgs doublets

- **If tanβ is large, it is possible to observe deviation from lepton universality in these decays**

Wei-Shu Hou, PRD48, 2342(1993)

$$\frac{\Gamma(D_{(s)}^+ \to \tau^+\nu)}{\Gamma(D_{(s)}^+ \to \mu^+\nu)} = \frac{m_{\tau^+}^2 (1 - m_{\tau^+}^2 / m_{D_{(s)}}^2)^2}{m_{\mu^+}^2 (1 - m_{\mu^+}^2 / m_{D_{(s)}}^2)^2}$$

Ratio expected to be 2.67 (9.76) from SM

Semi-leptonic *D* Decays

Comparison of measured Form Factors with those calculated in LQCD