Leptonic Decays of Charm

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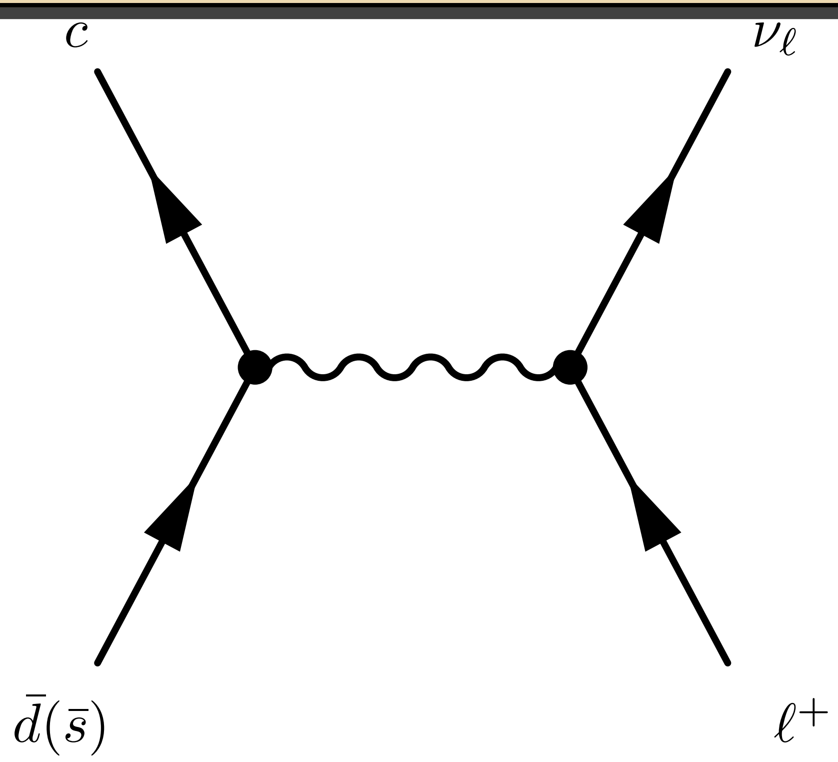
Outline

1. $D_s^+ \to \ell^+ \nu_\ell$ Decays at Belle
2. Review of D Leptonic Decays
3. Conclusions

Leptonic Decays of D and D_s Mesons

- Leptonic decays of charm mesons are suppressed in SM $\Rightarrow$ are a convenient place to search for New Physics
- At $\Upsilon(4S)$ the cross section of $c\bar{c}$ production ~ 1.1 nb $\Rightarrow$ each fb^{-1} brings 10^6 events, so the B factory is also a charm factory
- $c\bar{c}$ pairs are produced inclusively at B factories
- At lower energy $\psi(3770)$ is a factory of $D^+D^-,\ D^0\bar{D}^0$
- At $\sqrt{s} \sim 4.17$ GeV $D_s^+D_s^-$ are copiously produced
- The main players are BaBar, Belle and LHCB for inclusive studies as well as CLEOc and BESIII for exclusive production

Leptonic Decays $D^+_{(s)} \to \ell^+ \nu_\ell$ – I



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

A way to measure $f_{D^+_{(s)}}|V_{\rm cd}|(|V_{\rm cs}|)$, then $f_{D^+_{(s)}}$ and $|V_{\rm cd}|(|V_{\rm cs}|)$

Search for New Physics (H^+ interfering with W^+)

Leptonic Decays $D^+_{(s)} \to \ell^+\nu_\ell$ – II

The decay is helicity suppressed with $\Gamma(\ell^+\nu_\ell) \propto m_\ell^2 \Rightarrow$
$\Gamma(e^+\nu_e) \ll \Gamma(\mu^+\nu_\mu) \ll \Gamma(\tau^+\nu_\tau)$

$$R^{D_s}_{\tau/\mu} \equiv \mathcal{B}(D_s^+ \to \tau^+\nu_\tau)/\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) =$$
$$m_\tau^2/m_\mu^2 \cdot (1 - m_\tau^2/m_{D_s}^2)^2/(1 - m_\mu^2/m_{D_s}^2)^2 = 9.762 \pm 0.031,$$

$$R^{D^+}_{\tau/\mu} \equiv \mathcal{B}(D^+ \to \tau^+\nu_\tau)/\mathcal{B}(D^+ \to \mu^+\nu_\mu) = 2.67 \pm 0.01$$

A test of lepton flavor universality in decays with μ/τ,
decays to $e^+\nu_e$ hardly observable

Study of $D_s^+ \to \ell^+\nu_\ell$ at Belle. Method – I

Belle studied $D_s^+ \to \ell^+\nu_\ell$ with 913 fb^{-1} at $\Upsilon(4S)$ and $\Upsilon(5S)$,
A. Zupanc et al., JHEP 1309, 139 (2013)

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

One of the two charm quarks hadronizes into a D_s^{*-} meson,
the other – into a tagging charm hadron, $D_{\rm tag}$ (D^0, D^+, Λ_c^+, D^{*+}, D^{*0}).

Belle ran at energies well above the $D_{\rm tag}K_{\rm frag}X_{\rm frag}D_s^{*-}$ threshold,
additional particles $X_{\rm frag}$ can be produced in hadronization:
an even number of kaons plus any number of pions or photons.

Study of $D_s^+ \to \ell^+\nu_\ell$ at Belle. Method – II

The number of inclusively reconstructed D_s^- mesons is extracted from the distribution of events in the missing mass,

$M_{\rm miss}(D_{\rm tag}K_{\rm frag}X_{\rm frag}\gamma)$, recoiling against the $D_{\rm tag}K_{\rm frag}X_{\rm frag}\gamma$ system

$$M_{\rm miss}(D_{\rm tag}K_{\rm frag}X_{\rm frag}\gamma) = \sqrt{p_{\rm miss}(D_{\rm tag}K_{\rm frag}X_{\rm frag}\gamma)^2},$$

where $p_{\rm miss}$ is the missing four-momentum in the event

$$p_{\rm miss}(D_{\rm tag}K_{\rm frag}X_{\rm frag}\gamma) = p_{e^+} + p_{e^-} - p_{D_{\rm tag}} - p_{K_{\rm frag}} - p_{X_{\rm frag}} - p_\gamma.$$

Here, $p_{D_{\rm tag}}$, $p_{K_{\rm frag}}$, $p_{X_{\rm frag}}$, and p_γ are the measured four-momenta of the reconstructed $D_{\rm tag}$, strangeness-conserving kaon, fragmentation system and the photon from $D_s^{*-} \to D_s^-\gamma$. Correctly reconstructed events produce a peak in the $M_{\rm miss}(D_{\rm tag}K_{\rm frag}X_{\rm frag})$ at the nominal D_s^- meson mass.

Study of $D_s^+ \to \ell^+ \nu_\ell$ at Belle. Method – III

18 modes of $D_{\rm tag}$ in total

6 modes of D^0 (38.4%):

$K^-\pi^+,\ K^-\pi^+\pi^0,\ K^-\pi^+\pi^+\pi^-,\ K^-\pi^+\pi^+\pi^-\pi^0,\ K^0_S\pi^+\pi^-,\ K^0_S\pi^+\pi^-\pi^0$

6 modes of D^+ (28.0%):

$K^-\pi^+\pi^+,\ K^-\pi^+\pi^+\pi^0,\ K^0_S\pi^+,\ K^0_S\pi^+\pi^0,\ K^0_S\pi^+\pi^+\pi^-,\ K^+K^-\pi^+$

6 modes of Λ_c^+ (16.8%):

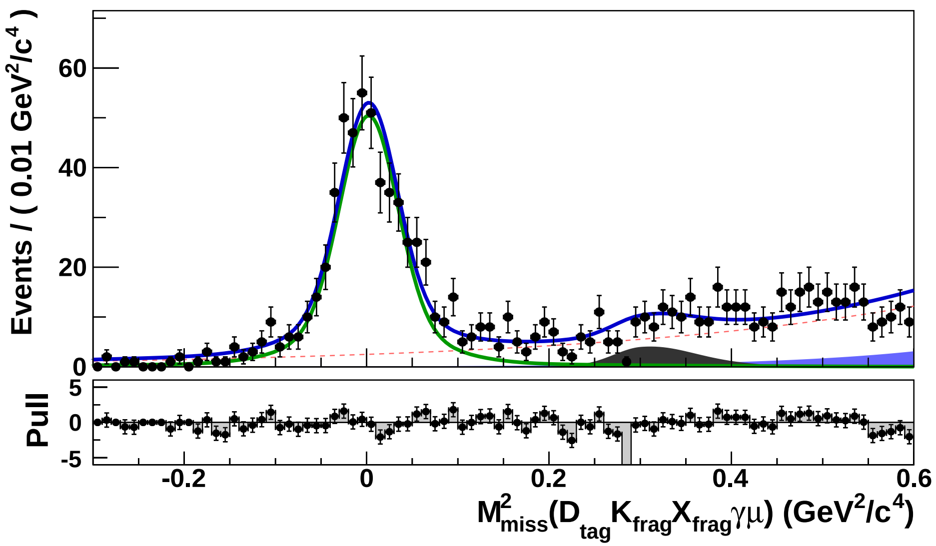
$pK^-\pi^+,\ pK^-\pi^+\pi^0,\ pK^0_S,\ \Lambda\pi^+,\ \Lambda\pi^+\pi^0,\ \Lambda\pi^+\pi^+\pi^-$

7 $X_{\rm frag}$ modes of pions only:

nothing, $\pi^\pm,\ \pi^0,\ \pi^\pm\pi^0,\ \pi^\pm\pi^\mp,\ \pi^\pm\pi^\mp\pi^\pm,\ \pi^\pm\pi^\mp\pi^0$

94360 ± 1310 events

Study of $D_s^+ \to \mu^+\nu_\mu$ at Belle



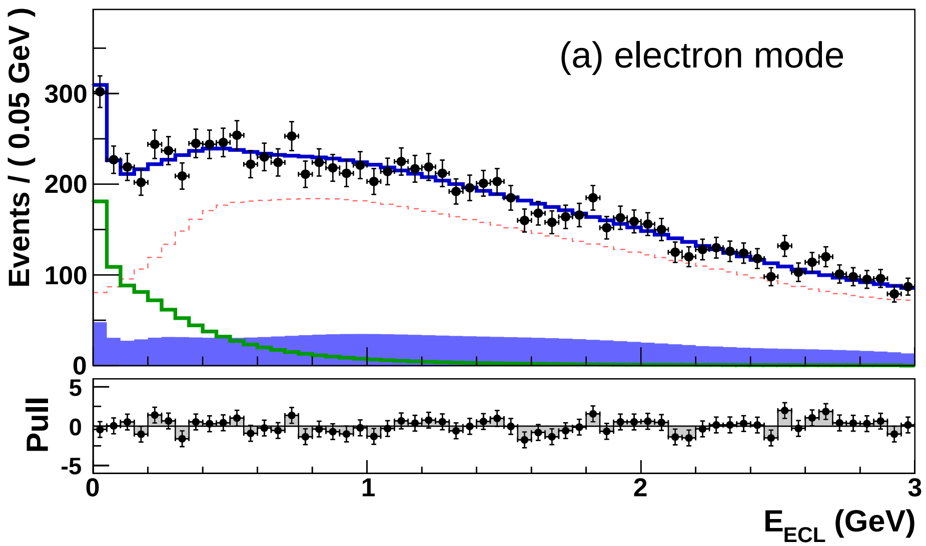
$$M^2_{\rm miss}(D_{\rm tag}K_{\rm frag}X_{\rm frag}\gamma\mu) = p^2_{\rm miss}(D_{\rm tag}K_{\rm frag}X_{\rm frag}\gamma\mu),$$

where the missing four-momentum is given by

$$p_{\rm miss}(D_{\rm tag}K_{\rm frag}X_{\rm frag}\gamma\mu) = p_{e^+} + p_{e^-} - p_{D_{\rm tag}} - p_{K_{\rm frag}} - p_{X_{\rm frag}} - p_\gamma - p_\mu.$$

$$N = 492 \pm 26$$

Study of $D_s^+ \to \tau^+\nu_\tau$ at Belle

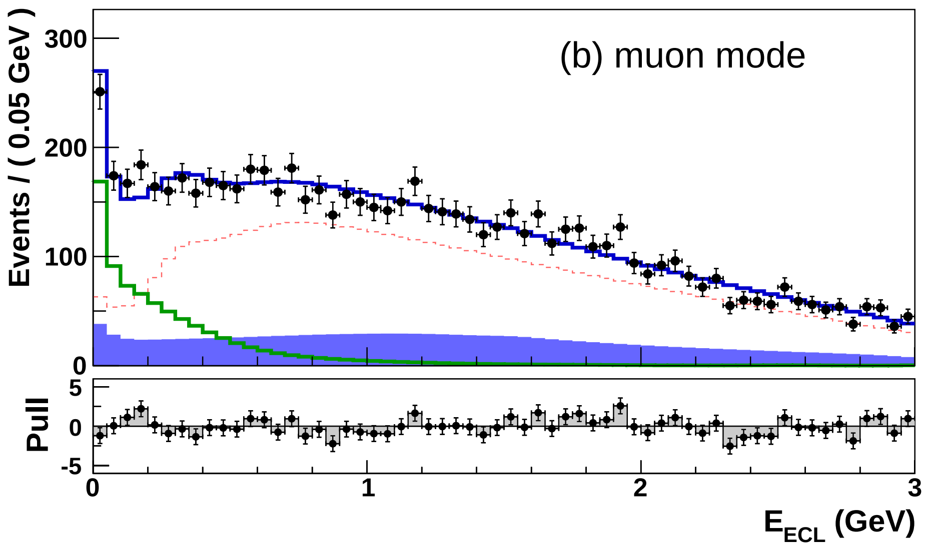


$\tau^+ \to e^+\nu_e\bar{\nu}_\tau$

Because of extra ν's no peak in $M_{\rm miss}$, small $E_{\rm ECL}$ instead

$N = 952 \pm 59$

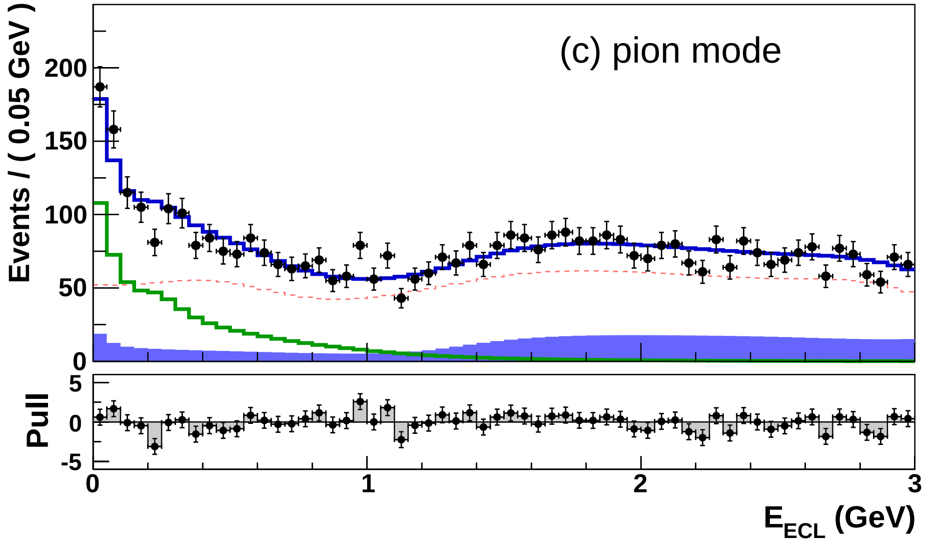
Study of $D_s^+ \to \tau^+\nu_\tau$ at Belle – II



$$\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$$

$$N = 758 \pm 48$$

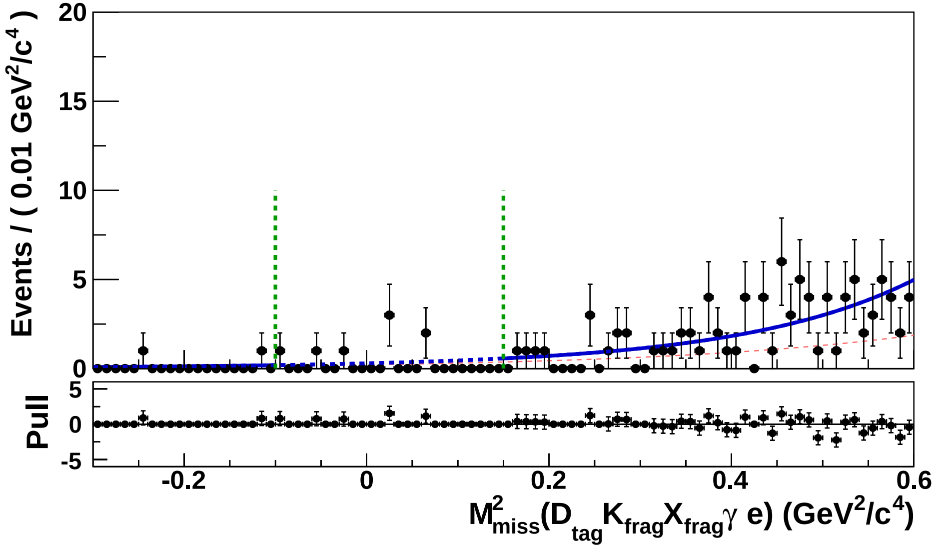
Study of $D_s^+ \to \tau^+\nu_\tau$ at Belle – III



$$\tau^+ \to \pi^+\bar{\nu}_\tau$$

$$N = 496 \pm 35$$

Study of $D_s^+ \to e^+\nu_e$ at Belle



8 events observed in the signal region consistent with the expected background of $8.7 \pm 0.9 \pm 0.8$ events

Study of $D_s^+ \to \ell^+ \nu_\ell$ at Belle

D_s^+ decay mode	Signal yield	$f_{\rm bias} \cdot \varepsilon$ [%]	$\mathcal{B}$ [%]
$\mu^+ \nu_\mu$	492 ± 26	98.2	$0.531 \pm 0.028 \pm 0.020$
$\tau^+ \nu_\tau$ (e mode)	952 ± 59	18.8	$5.37 \pm 0.33^{+0.35}_{-0.31}$
$\tau^+ \nu_\tau$ (μ mode)	758 ± 48	13.7	$5.86 \pm 0.37^{+0.34}_{-0.59}$
$\tau^+ \nu_\tau$ (π mode)	496 ± 35	8.7	$6.04 \pm 0.43^{+0.46}_{-0.40}$
$\tau^+ \nu_\tau$ (combined)	2217 ± 83	41.2	$5.70 \pm 0.21^{+0.31}_{-0.30}$

Results with different τ decays are consistent and are combined

Study of $D_s^+ \to \ell^+\nu_\ell$ at Belle

$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (5.31 \pm 0.28(\text{stat.}) \pm 0.20(\text{syst.})) \times 10^{-3}$

is consistent with and much more precise than the previous Belle one:

$(6.44 \pm 0.76(\text{stat.}) \pm 0.57(\text{syst.})) \times 10^{-3}$

$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.70 \pm 0.21(\text{stat.})^{+0.31}_{-0.30}(\text{syst.})) \times 10^{-2}$,

doubling the total statistics of the previous experiments

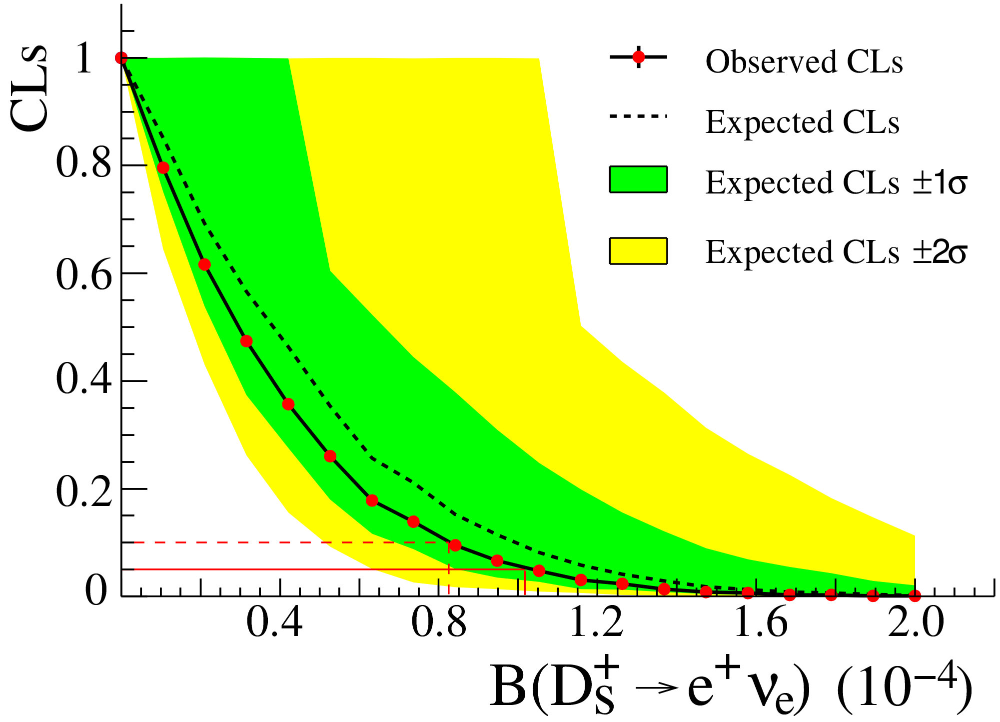
and consistent with the PDG2012 $(5.43 \pm 0.31) \times 10^{-2}$

As a test of lepton flavor universality,

$R^{D_s}_{\tau/\mu} = 10.73 \pm 0.69(\text{stat.})^{+0.56}_{-0.53}(\text{syst.})$,

in agreement with the SM value of 9.762 ± 0.031

Study of $D_s^+ \to e^+\nu_e$ at Belle



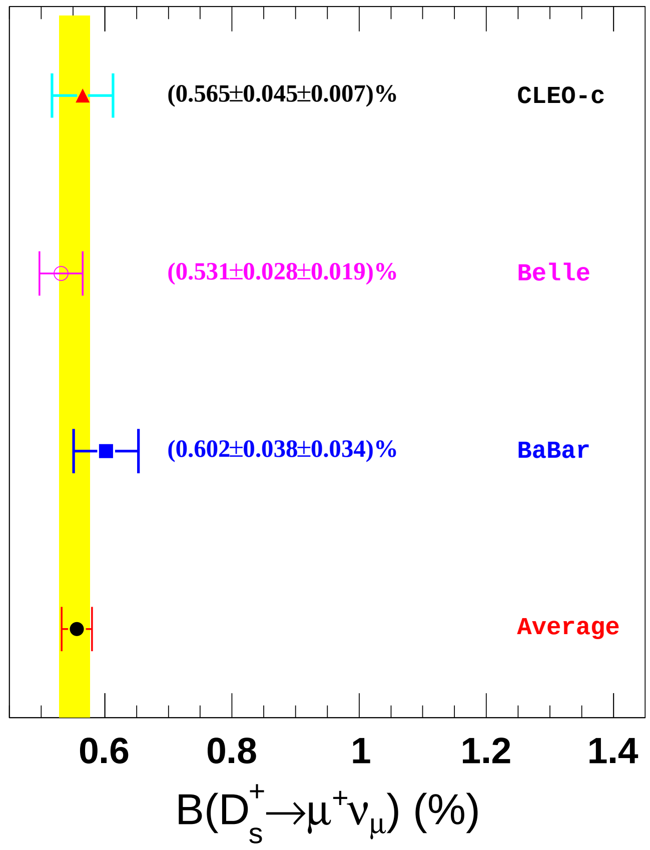
$\mathcal{B}(D_s^+ \to e^+\nu_e) < 0.83 \times 10^{-4}$ at 90% CL

compared to $< 1.2 \times 10^{-4}$ from CLEO with 600 pb^{-1} at 4.17 GeV

Summary on $D_s^+ \to \mu^+\nu_\mu$ – I

$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu),\ 10^{-3}$	$N_{\rm ev}$	Group	Reference
$5.31 \pm 0.28 \pm 0.20$	492 ± 26	Belle	JHEP 1309, 139 (2013)
$6.02 \pm 0.38 \pm 0.34$	275 ± 17	BaBar	PRD 82, 091103 (2010)
$5.65 \pm 0.45 \pm 0.17$	235 ± 14	CLEO	PRD 79, 052001 (2009)
5.56 ± 0.25	–	Average	

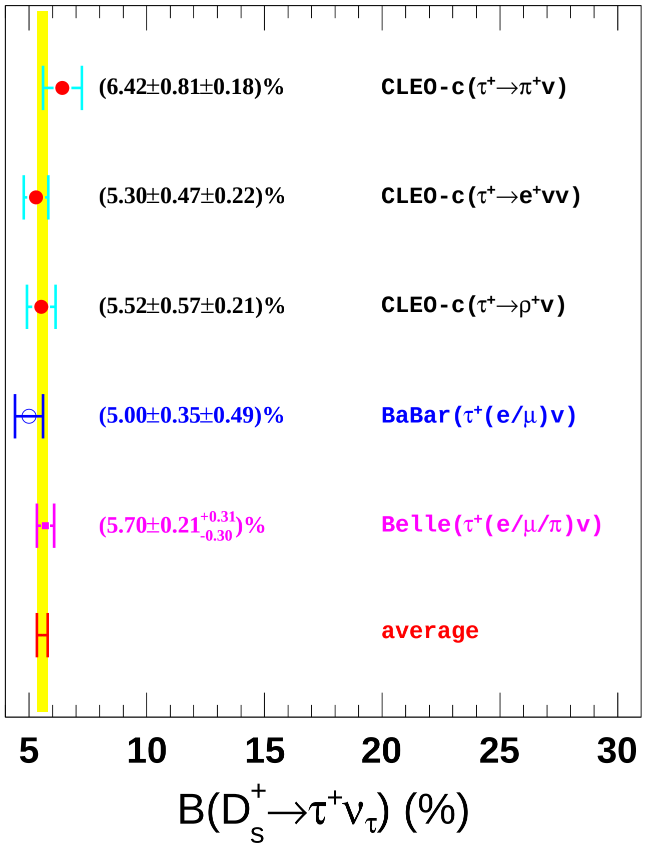
Summary on $D_s^+ \to \mu^+ \nu_\mu$ – II



Summary on $D_s^+ \to \tau^+\nu_\tau$ – I

$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)$, 10^{-2}	$N_{\rm ev}$	Group	Reference
$5.70 \pm 0.21^{+0.31}_{-0.30}$	2.2k	Belle	JHEP 1309, 139 (2013)
$5.00 \pm 0.35 \pm 0.49$	748 ± 53	BaBar	PRD 82, 091103 (2010)
$6.42 \pm 0.81 \pm 0.18$	126 ± 16	CLEO	PRD 79, 052001 (2009)
$5.52 \pm 0.57 \pm 0.21$	155 ± 17	CLEO	PRD 80, 112004 (2009)
$5.30 \pm 0.47 \pm 0.22$	181 ± 16	CLEO	PRD 79, 052002 (2009)
5.54 ± 0.24	–	Average	

Summary on $D_s^+ \to \tau^+\nu_\tau$ – II



Determination of f_{D_s} at Belle

$$f_{D_s} = \frac{1}{G_F m_\ell \left(1 - \frac{m_\ell^2}{m_{D_s}^2}\right) |V_{cs}|} \sqrt{\frac{8\pi \mathcal{B}(D_s^+ \to \ell^+ \nu_\ell)}{m_{D_s} \tau_{D_s}}}.$$

From $|V_{ud}| = 0.97425 \pm 0.00022$ and $|V_{cb}| = (40.9 \pm 1.1) \times 10^{-3}$ and using the relation $|V_{cs}| = |V_{ud}| - |V_{cb}|^2/2$,

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

consistent with the most precise LQCD 248.0 ± 2.5 MeV,
C.T.H. Davies et al., Phys. Rev. D 82, 114504 (2010)

Determination of f_{D^+} at BESIII

BESIII used 2.92 fb^{-1} at 3.773 GeV to study $e^+e^- \to D^+D^-$,
M. Ablikim et al., Phys. Rev. D 89, 051104 (2014)

$$B(D^+ \to \mu^+\nu_\mu) = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4} \text{ and}$$

$$f_{D^+}|V_{\rm cd}| = (45.75 \pm 1.20 \pm 0.39) \;\; \text{MeV}.$$

With $|V_{\rm cd}| = 0.22520 \pm 0.00065$ from the global CKM fit

$$f_{D^+} = (203.2 \pm 5.3 \pm 1.8) \quad \text{MeV}$$

or taking $f_{D^+} = 207 \pm 4$ MeV from LQCD

$$|V_{\rm cd}| = 0.2210 \pm 0.0058 \pm 0.0047.$$

A talk by H. Ma

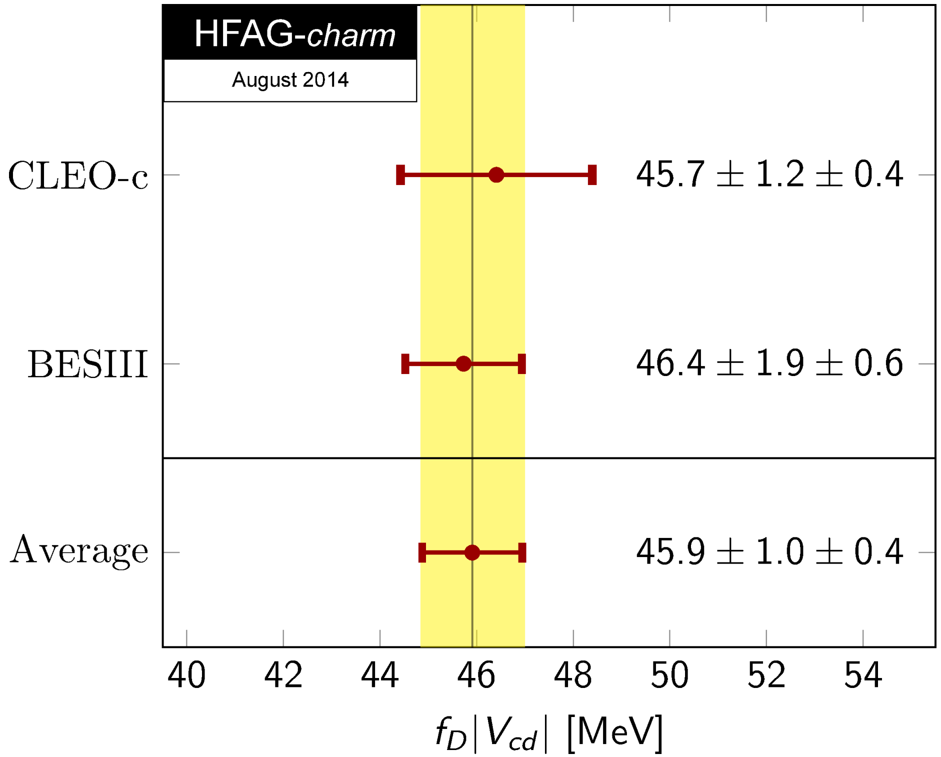
$D^+ \to \ell^+ \nu_\ell$ Decays

Mode	Group	$\int L dt$, fb^{-1}	$N_{\rm ev}$	$\mathcal{B}$
$e^+\nu_e$	CLEO	0.818	–	$< 8.8 \cdot 10^{-6}$
$\mu^+\nu_\mu$	CLEO	0.818	150 ± 13	$(3.82 \pm 0.32 \pm 0.09) \cdot 10^{-4}$
	BESIII	2.9	409 ± 21	$(3.71 \pm 0.19 \pm 0.06) \cdot 10^{-4}$
	Average	–	–	$(3.74 \pm 0.17) \cdot 10^{-4}$
$\tau^+\nu_\tau$	CLEO	0.818	–	$< 1.2 \cdot 10^{-3}$

CLEO, B.I. Eisenstein et al., Phys. Rev. D 78, 052003 (2008)

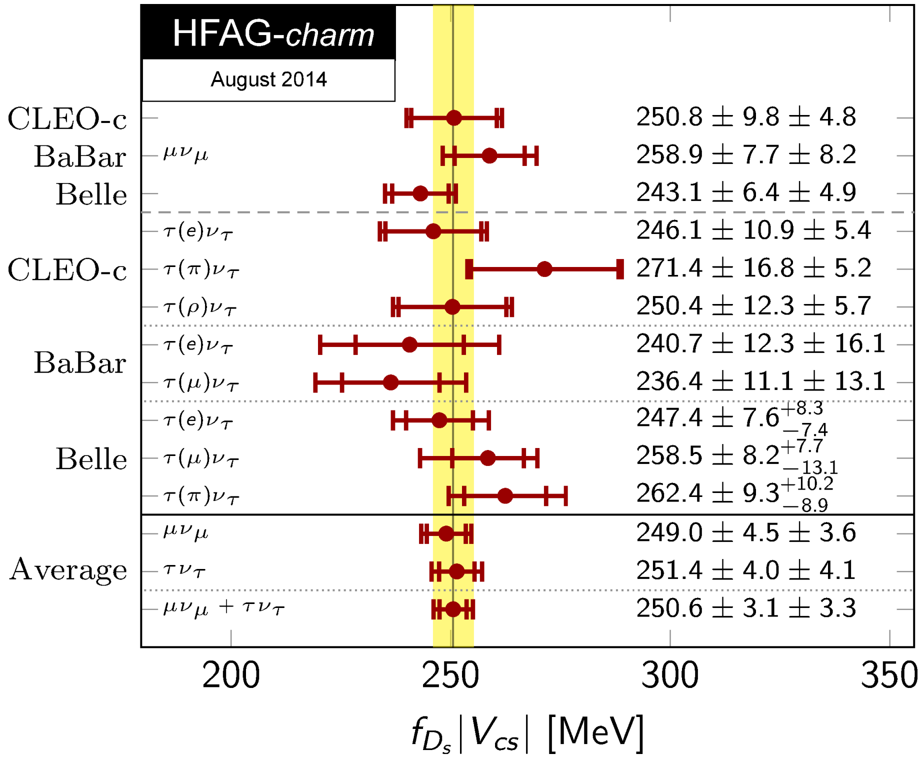
BESIII, M. Ablikim et al., Phys. Rev. D 89, 051104 (2014)

HFAG on $f_D|V_{cd}|$



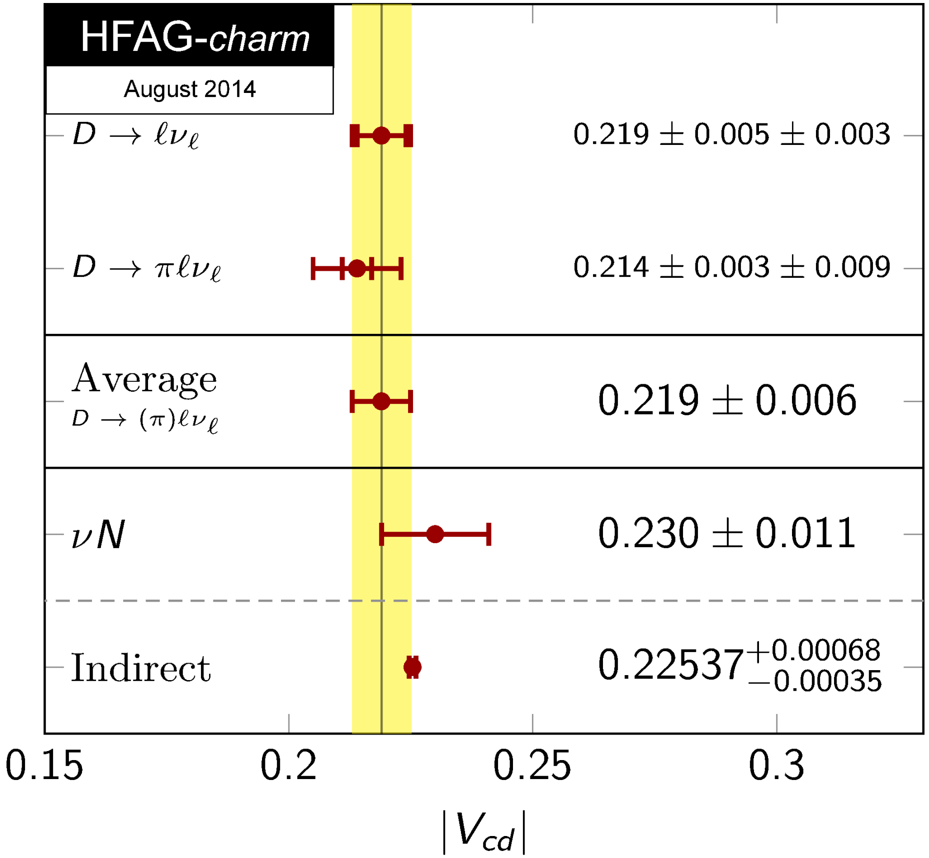
HFAG, Y. Amhis et al., arXiv:1412.7515

HFAG on $f_{D_s}|V_{cs}|$



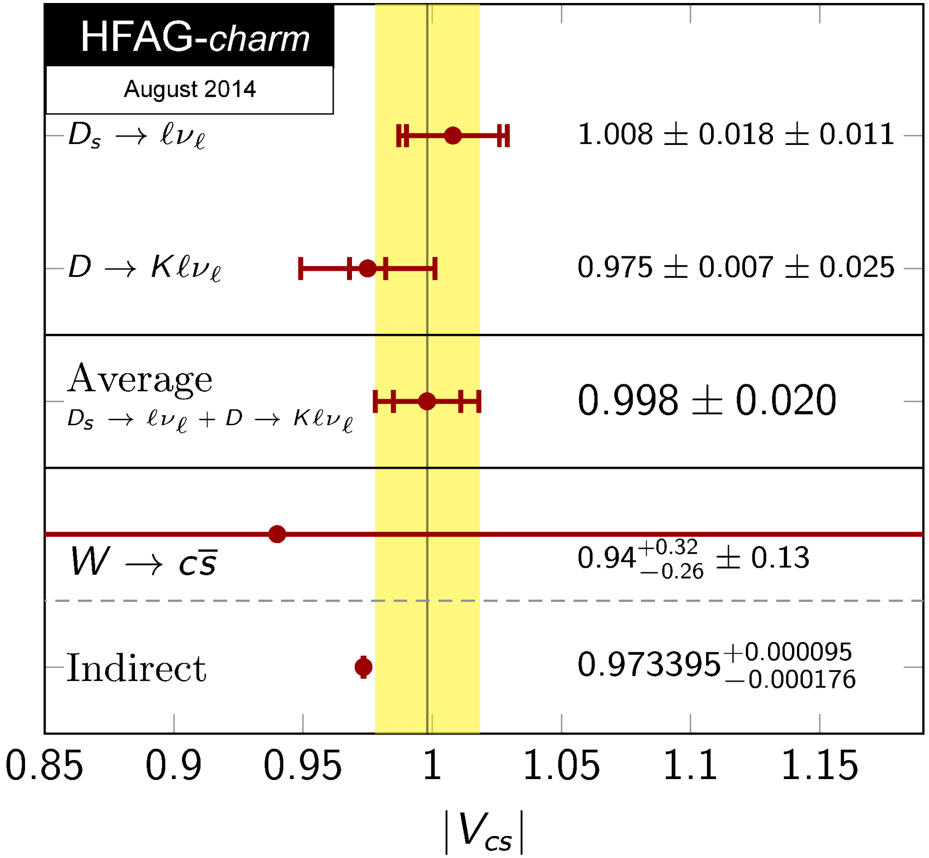
HFAG, Y. Amhis et al., arXiv:1412.7515

HFAG on $|V_{cd}|$



HFAG, Y. Amhis et al., arXiv:1412.7515

HFAG on $|V_{cs}|$



HFAG, Y. Amhis et al., arXiv:1412.7515

HFAG on $f_{D_{(s)}}$

Quantity	LQCD	Experiment
f_D, MeV	209.2 ± 3.3	203.7 ± 4.9
f_{D_s}, MeV	248.6 ± 2.7	257.4 ± 4.6
f_{D_s}/f_D	1.187 ± 0.012	1.264 ± 0.038

There is fair agreement of the constants,
the experimental ratio is 1.9σ higher

$D^0 \to \gamma\gamma$ Decays

In SM, FCNC decays are suppressed by GIM ($\mathcal{B} \sim (1-3)\cdot 10^{-8}$)

In MSSM, gluino exchange enhances $\mathcal{B}$ to $6 \cdot 10^{-6}$

Group	$\int Ldt$, fb^{-1}	$\mathcal{B}$, 10^{-6}	Reference
CLEO	13.8	< 29	PRL 90, 101801 (2003)
BaBar	470.5	< 2.2	PRD 85, 091107 (2012)
BESIII	2.92	< 3.8	arXiv:1505.03087
Belle	832	???	In progress

$D^0 \to \ell^+\ell^-$ Decays

In SM, FCNC decays are strongly suppressed (GIM, loop level, helicity),
($\mathcal{B} \sim 2.7 \cdot 10^{-5}\mathcal{B}(D^0 \to \gamma\gamma)$ or $\sim 10^{-13}$)

R-parity violating SUSY, LED, leptoquarks enhance $\mathcal{B}$ to $\sim 10^{-8}$

LFV decays very small in SM

Mode	Group	$\int Ldt$, fb^{-1}	$\mathcal{B}$
$D^0 \to e^+e^-$	Belle	660	$< 7.9 \cdot 10^{-8}$
$D^0 \to \mu^+\mu^-$	LHCb	0.9	$< 6.2 \cdot 10^{-9}$
$D^0 \to e^\pm\mu^\mp$	Belle	660	$< 2.6 \cdot 10^{-7}$

Belle, M. Petric et al., Phys. Rev. D 81, 091102 (2010)

LHCb, R. Aaij et al., Phys. Lett. B 725, 15 (2013)

Conclusions

- Leptonic decays of D^0, D^+, D_s^+ are very convenient to search for effects of New Physics
- There has been significant experimental progress due to CLEO, BESIII, BaBar, Belle and LHCb
- LHCb has strong advantage for decays accessible to it because of large data samples at high energy
- Experience of CLEOc and BESIII shows advantages of exclusive measurements with $e^+e^- \to D^+D^-,\ D^0\bar{D}^0,\ D_s^+D_s^-$
- Future progress is related to LHCb, BelleII and hopefully Super-c-τ