Lattice perspective on leptonic and semileptonic decays

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1. Introduction

Goals in the study of leptonic and semileptonic D decays

* Precise determination of CKM matrix elements ($|V_{cd,cs}|$)

$$\text{Experiment} = (\text{known factors}) \times (V_{CKM}) \times (\underbrace{\text{hadronic matrix elements}}_{\text{lattice QCD}})$$

* Check Standard Model

** Consistency of different determinations of CKM matrix elements

** Test unitarity of CKM matrix.

** Comparison of shape of form factors with experimental data.

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** Comparison of shape of form factors with experimental data.

* Validate lattice QCD techniques to use in B physics

* Constraining possible NP models

Fajfer, Nisandzic and Rojec, 1502.07748, **Barranco et al.**, 1303.3896, 1404.0454

** Correlated signals of NP in leptonic and semileptonic decays.

1. Introduction: Lattice QCD

Lattice QCD: Numerical evaluation of QCD path integral (rely only on first principles).

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Goal: Precise calculations ($\leq 5\%$ error)

* Control over systematic errors:

** Unquenched calculations: $N_f = 2$, $\mathbf{N_f = 2+1}$ or $\mathbf{N_f = 2+1+1}$.

** Discretization: improved actions + simulations at several $a's$
$\rightarrow$ continuum limit.

** Chiral extrapolation: simulate at several m_π and extrapolate to $m_\pi^{\rm phys}$ using `ChPT`.

** Renormalization: non-perturbative, perturbative.

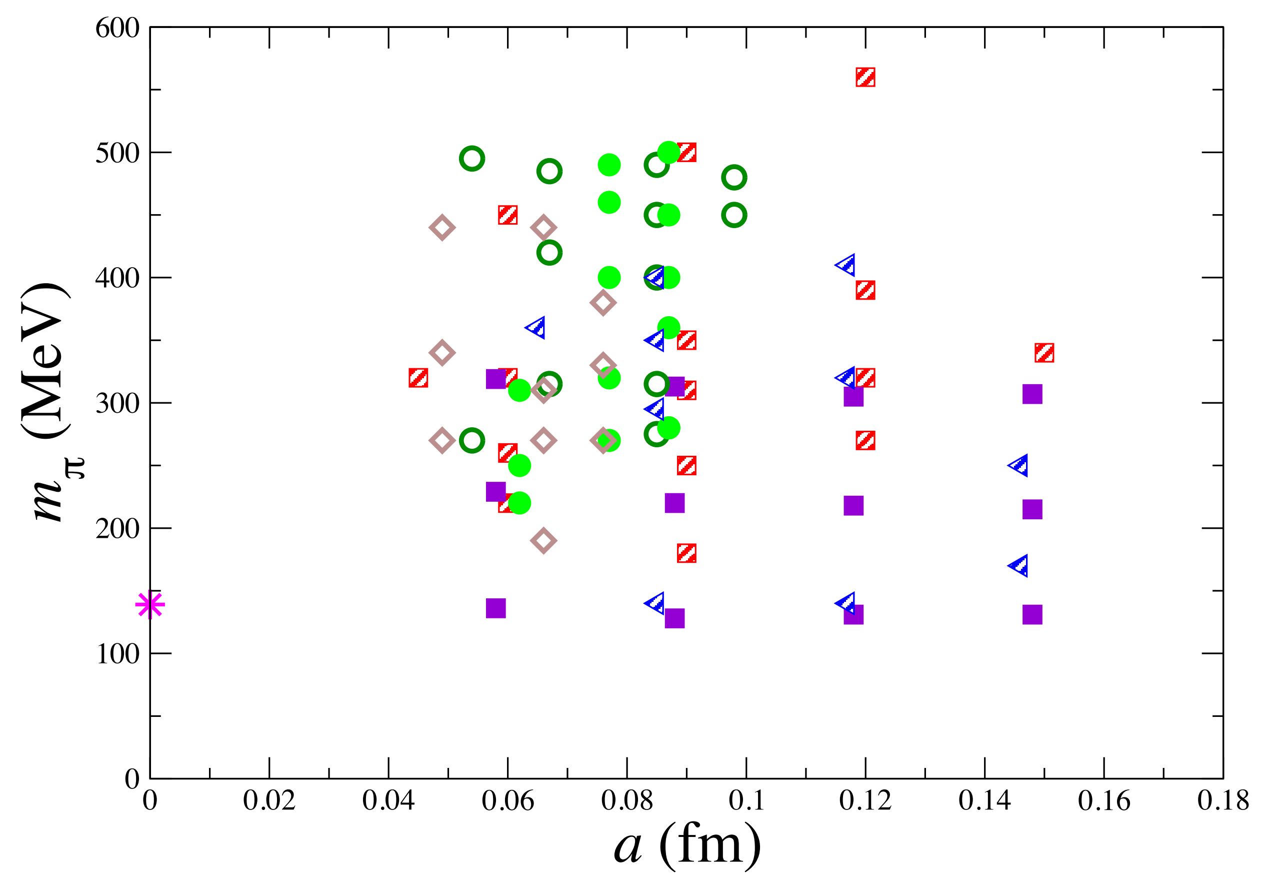
** Tuning lattice scale and masses

** Finite volume, **isospin effects, electromagnetic effects**, ...

Systematically improvable

1. Introduction: Overview of simulations parameters

Several $N_f = 2+1$ and even $N_f = 2+1+1$, and **physical quark masses**.



ETM: Circles (ETM,Orsay)

MILC: Squares

(FNAL/MILC,HPQCD,SWME)

RBC/UKQCD: Triangles (χQCD)

CLS: Diamonds (ALPHA)

$N_f = 2$: open
$N_f = 2+1$: shaded
$N_f = 2+1+1$: filled

plot by **A. El-Khadra**,

First results with simulations with physical light quark masses (BMW, PACS-CS, MILC, RBC/UKQCD, ETMC)

1. Introduction: Averaging lattice QCD results

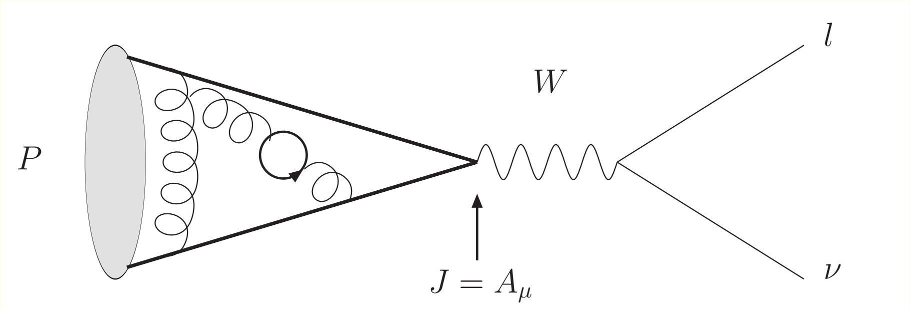
Flavor Lattice Averaging Group (FLAG-2): 28 people representing all big lattice collaborations.

- Advisory Board: S. Aoki, C. Bernard, C. Sachrajda
- Editorial Board: G. Colangelo, H. Leutwyler, T. Vladikas, U. Wenger
- Working Groups:
  - u, d and s quark masses: L. Lellouch, T. Blum, V. Lubicz
  - $|V_{us}|, |V_{ud}|$: A. Jüttner, T. Kaneko, S. Simula
  - `LEC's`: S. Dürr, H. Fukaya, S. Necco
  - B_K: H. Wittig, J. Laiho, S. Sharpe
  - α_s: R. Sommer, R. Horsley, T. Onogi
  - $f_{B_{(s)}}, f_{D_{(s)}}, \hat{B}_B$: **A. El Khadra, Y. Aoki, M. Della Morte**
  - B, D `semileptonic and radiative decays`: **R. Van de Water, E. Lunghi, C. Pena**

http://itpwiki.unibe.ch/flag/

arXiv:1310.8555 (last version: August 2014).

2. Leptonic D decays



$\mathcal{B}(D_q \to l\nu) \sim 4.5 - 3.5\%$

$\tau_{D_q} < 1.5\%$

$f^2_{D_q} \sim 1\%$

$others < 0.4\%$

$$\underbrace{\mathcal{B}(D_q \to l\nu)}_{\textbf{experiment}} = \frac{G_F^2 \tau_{D_q}}{8\pi} m_l^2 m_{D_q} \left(1 - \frac{m_l^2}{m_{D_q}^2}\right)^2 |V_{cq}|^2 \underbrace{f^2_{D_q}}_{\textbf{lattice}}$$

(with $q = d, s$ and $D_q = D^+, D_s$)

Simple matrix element $\langle 0|\bar{c}\gamma_\mu\gamma_5 q|D_q(p)\rangle = i f_{D_q} p_\mu$ → precise calculations

or, if using the same action for light and charm valence quarks,

$(m_c + m_q)\langle 0|\bar{c}\gamma_5 q|D_{(s)}(p=0)\rangle = f_{D_q} M^2_{D_q}$ (no need of renormalization)

Reduction of error: use relativistic (improved) formulations for c.

2. Leptonic D decays: New results (> 2013)

\# $N_f = 2$:

- * **TWQCD**, 1404.3648: $a \sim 0.06 fm$ and $m_\pi \leq 260$ MeV

$$f_D = 202.3(3.4)\,\text{MeV} \qquad f_{D_s} = 258.7(3.1)\,\text{MeV} \qquad f_{D_s}/f_D = 1.279(26)$$

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\# $N_f = 2 + 1$:

* χ**QCD**, 1410.3343: Different set of configurations (**RBC/UKQCD**) and valence quark formulation (overlap) than previous calculations: two lattice spacings.

$$f_{D_s} = 254(2)(4)\,\mathrm{MeV}$$

2. Leptonic D decays: New results (> 2013)

$N_f = 2 + 1 + 1$:

* **FNAL/MILC**, 1407.3772: highly improved action, **MILC** configurations with **phys. quark masses** and small lattice spacing (4 $a's$, smallest $a \approx 0.06$ fm)

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$$f_{D^+} = 212.6^{+1.1}_{-1.2}\,\mathrm{MeV} \qquad f_{D_s} = 249.0^{+1.3}_{-1.5}\,\mathrm{MeV} \qquad f_{D_s}/f_{D^+} = 1.1712^{+31}_{-34}$$

  - ** $\sim 0.5\%$ error dominated by continuum extrapolation error
  - ** They calculate the difference between f_{D^+} and the isospin limit value, f_D:

$$f_{D^+} - f_D = 0.47^{+11}_{-5}\,\mathrm{MeV}$$

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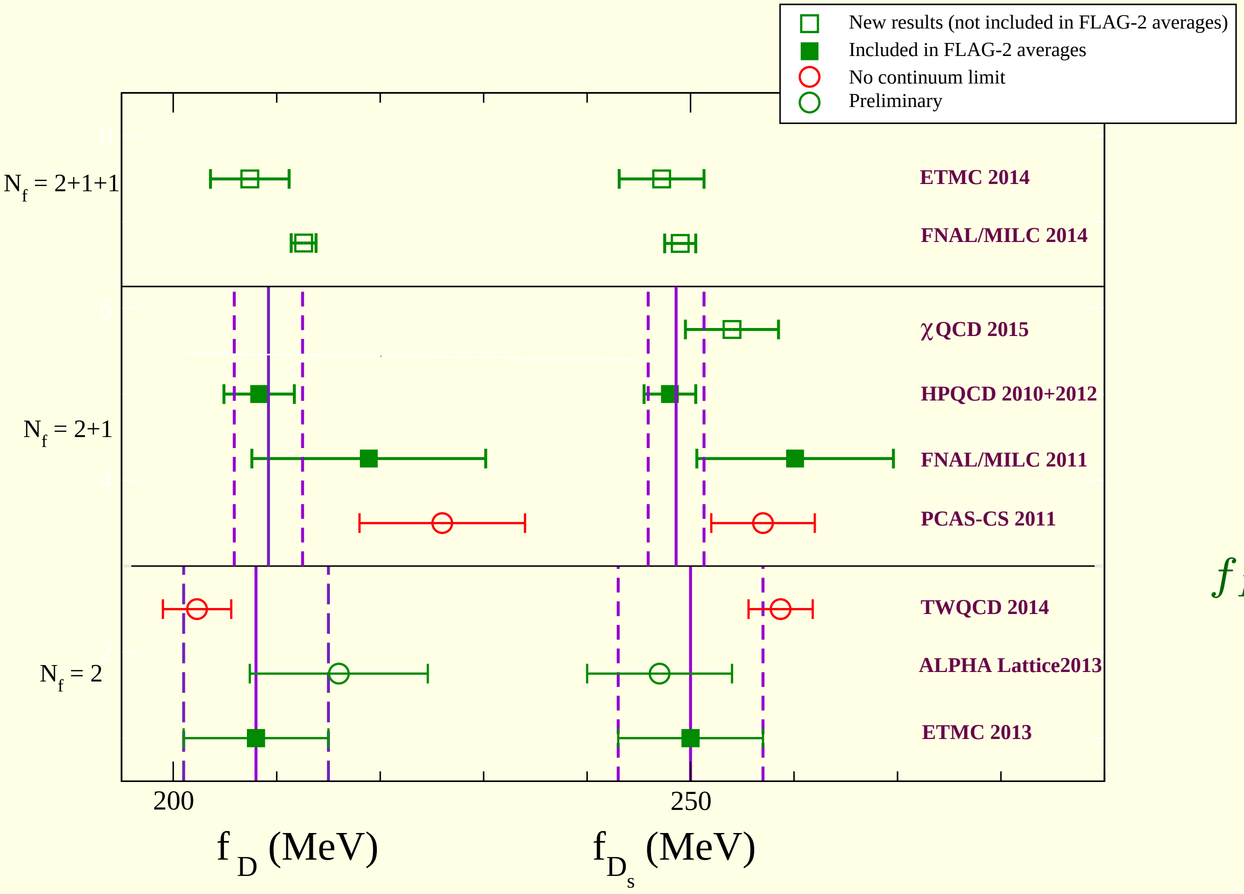
* **ETMC**, 1411.7908: **ETMC** configurations with 3 $a's$ (smallest $a \approx 0.06$ fm),

$m_\pi \geq 210$ MeV

$$f_D = 207.2(3.8)\,\mathrm{MeV} \qquad f_{D_s} = 247.2(4.1)\,\mathrm{MeV} \qquad f_{D_s}/f_D = 1.192(22)$$

** Error dominated by stat.+ chiral extrapolation error

2. Leptonic D decays



$$\mathbf{FLAG-2, N_f = 2}$$

$$f_D = (208 \pm 7)\ MeV$$

$$f_{D_s} = (250 \pm 7)\ MeV$$

$$\mathbf{FLAG-2, N_f = 2+1}$$

$$f_D = (209.2 \pm 3.3)\ MeV$$

$$f_{D_s} = (248.6 \pm 2.7)\ MeV$$

FNAL/MILC $N_f = 2+1+1$

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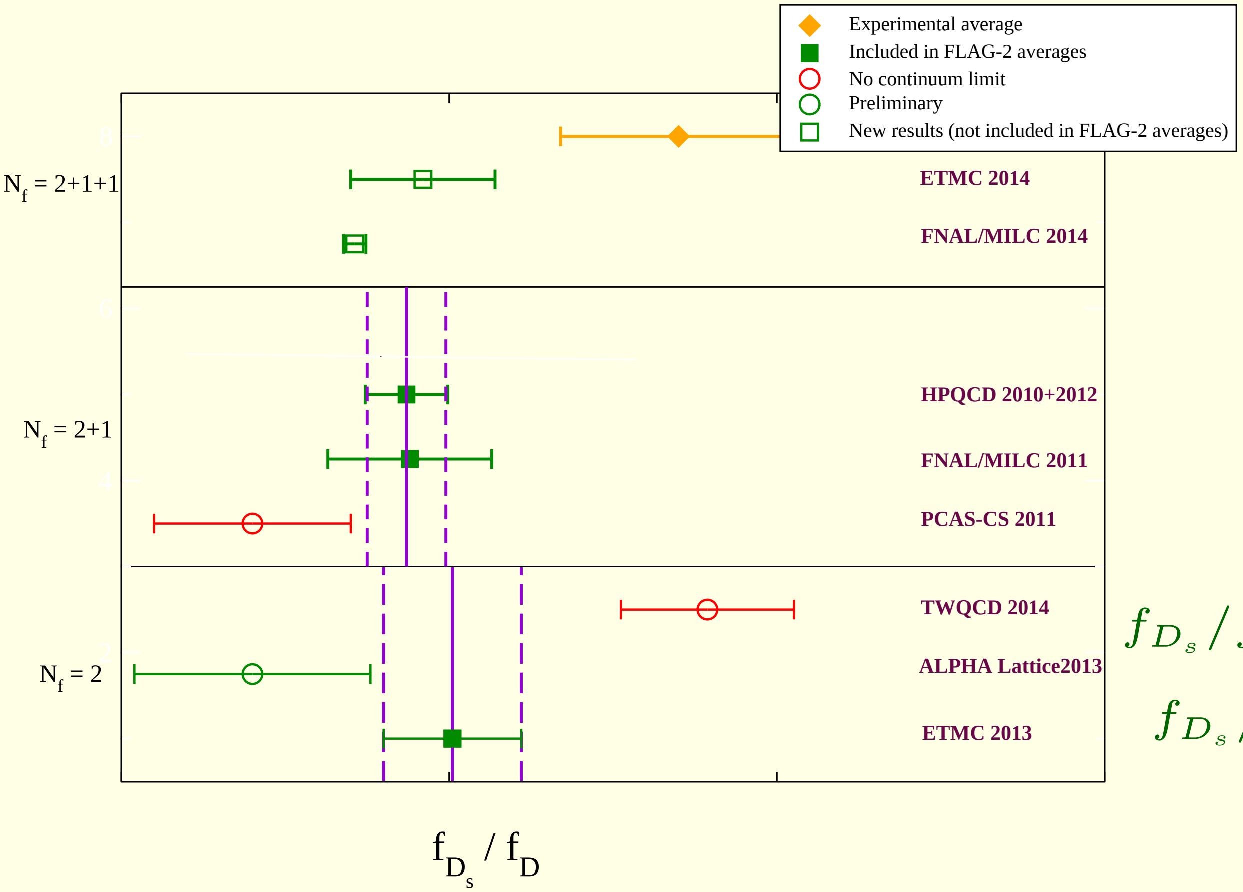

$$\mathbf{FLAG-2, N_f = 2}$$

$$f_{D_s}/f_D = 1.20 \pm 0.020$$

$$\mathbf{FLAG-2, N_f = 2+1}$$

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$$N_f = 2 + 1 + 1:$$

$$f_{D_s}/f_{D^+}\big|_{\mathrm{FNAL/MILC}} = 1.1712^{+31}_{-34}$$

$$f_{D_s}/f_D\big|_{\mathrm{ETMC}} = 1.192 \pm 0.022$$

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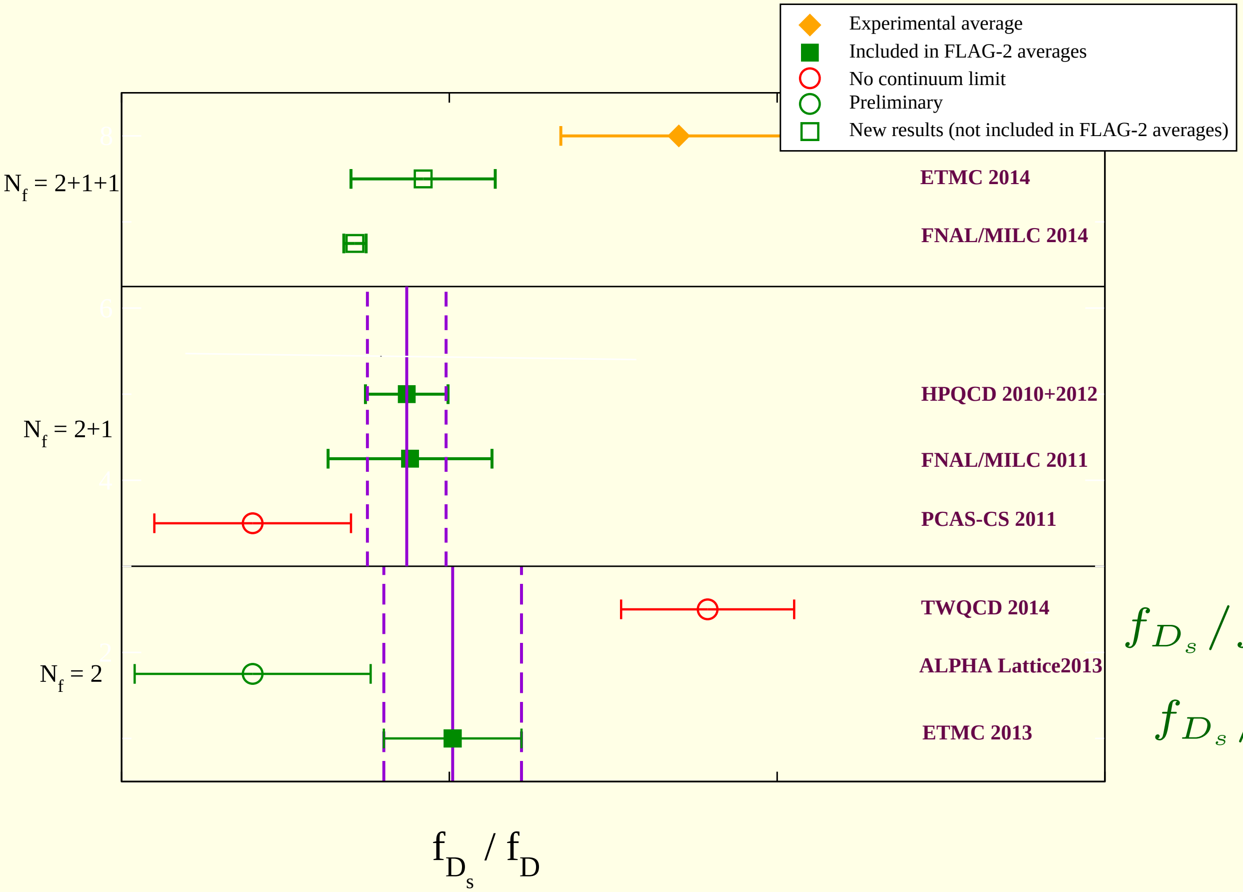

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Experiment: Average from **G. Rong**, CKM2014, 1411.3868 and unitarity values $|V_{cs}| = 0.97343 \pm 0.00015$, $|V_{cd}| = 0.22522 \pm 0.00061$ from **PDG2014**:

$$f_{D_s}/f_{D^+}\big|_{\mathrm{exp.}} = 1.270 \pm 0.036$$

2.7σ larger than $N_f = 2+1+1$ **FNAL/MILC** result
and 2.3σ larger than $N_f = 2+1$ **FLAG-2** average

2. Leptonic D decays: $N_f = 2+1$ calculations in progress

* **RBC/UKCD**, 1502.00845: plans to calculate several charm physics observables (and extrapolate to am_b).

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* **FNAL/MILC**, 1501.01991: Fermilab c + asqtad (relativistic) $s, u = d$ calculation with 5 $a's$ and high statistics

** Estimated total error: $f_D \sim 2.1\%$, $f_{D_s} \sim 1.8\%$, $f_{D_s}/f_D \sim 1\%$

(larger error is heavy-quark mass tunning for $f_{D_{(s)}}$)

** Errors reduced by a factor of ~ 2.5, now comparable to **HPQCD**

** Use same action for b and c → precise calculations of ratios f_B/f_D and f_{B_s}/f_{D_s} (many systematics cancel)

2. Leptonic decays: Charm-light and charm-charm vector mesons

$$\langle 0|V_i|M^*(\vec{0},\lambda)\rangle = f_{M*}m_{M^*}e_i^\lambda$$

where e_i^λ is the polarization vector of the meson M^*.

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Predictions for f_{D^*} and $f_{D_s^*}$ (using relativistic action for c)

- $N_f = 2$ on **ETM** configurations

$$f_{D_s^*}/f_{D_s} = 1.26(3) \qquad f_{D^*}/f_D = 1.208(27)$$

Becirevic et al, 1201.4039 **Becirevic et al**, 1407.1019

- $N_f = 2+1$ calculation by **HPQCD**, 1312.5264

$$f_{D_s^*}/f_{D_s} = 1.10(2) \quad \rightarrow \quad f_{D_s^*} = 274(6)\ \mathrm{MeV}$$

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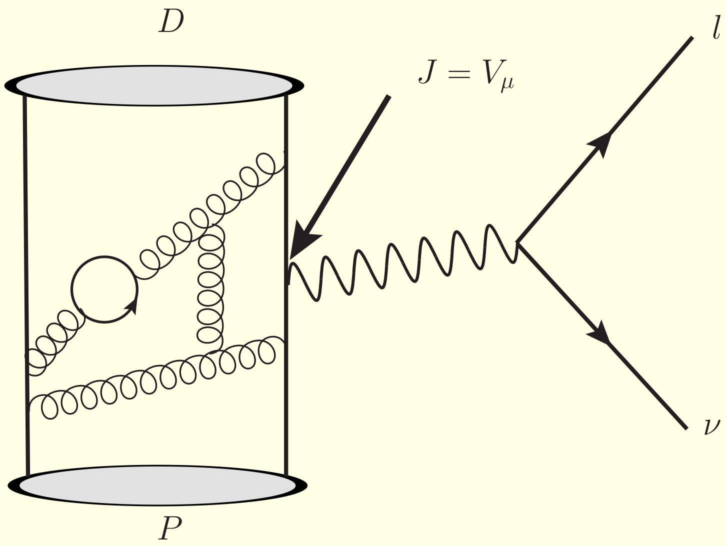
Calculations of $f_{J/\Psi}$ (experimental value $f_{J/\Psi}^{exp} = 407(5)\ \mathrm{MeV}$)

* Calculation on $N_f = 2$ **ETM** configurations by **Becirevic and Sanfilippo**, 1206.1445 :

$$f_{J/\Psi} = 414 \pm 8^{+9}_{-0}\ \mathrm{MeV}$$

* $N_f = 2+1$ calculation by **HPQCD**, 1208.2855: $f_{J/\Psi} = 405(6)(2)\ \mathrm{MeV}$

3. Semileptonic D decays



$P = \pi, K$

$x = d, s$ daughter light quark

$q = (p_D - p_P)$ (momentum of lepton pair)

$$\underbrace{\frac{d\Gamma(D \to Pl\nu)}{dq^2}}_{experimental} = \frac{G_F^2}{24\pi^3}\frac{(q^2 - m_l^2)^2\sqrt{E_P^2 - m_P^2}}{q^4 m_D^2}|V_{cx}|^2$$

$$\left[\left(1 + \frac{m_l^2}{2q^2}\right) m_D^2(E_P^2 - m_P^2)\underbrace{|f_+(q^2)|^2}_{lattice\, QCD} + \frac{3m_l^2}{8q^2}(m_D^2 - m_P^2)^2\underbrace{|f_0(q^2)|^2}_{lattice\, QCD}\right]$$

With vector and scalar form factors $f_+(q^2)$ and $f_0(q^2)$ defined by

$$\langle P(p_P)|V_\mu|D(p_D)\rangle = \left(p_{P\mu} + p_{D\mu} - \frac{m_D^2 - m_P^2}{q^2}q_\mu\right) f_+(q^2) + \frac{m_D^2 - m_P^2}{q^2}q_\mu\, f_0(q^2)$$

3. Semileptonic D decays

For $l = e, \mu$ the contribution from $f_0(q^2)$ can be neglected and

$$\underbrace{\frac{d\Gamma(D \to Pl\nu)}{dq^2}}_{experimental} = \frac{G_F^2}{24\pi^3} |\vec{p}_P|^3 \, |V_{cx}|^2 \, \underbrace{|f_+^{DP}(q^2)|^2}_{lattice\,QCD}$$

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The errors on those studies are still dominated by errors in the calculation of the relevant form factors.

$$\frac{d}{dq^2}\Gamma(D \to K(\pi)l\nu) \quad \propto \quad |V_{cs(cd)}|^2 \, |f_+^{D\to K(\pi)}(q^2)|^2$$

$$1.1(2.8)\%\,\mathrm{error} \qquad\qquad 5(8.7)\%\,\mathrm{error}$$

3. Semileptonic D decays: $q^2 = 0$

Two main strategies to eliminate the need of renormalize the lattice currents

- # Double ratios of 3-point correlators **Becirevic, Haas, Mescia** 0710.1741
  (get the form factors from linear combinations of the double ratios)

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Two main strategies to eliminate the need of renormalize the lattice currents

- # Double ratios of 3-point correlators **Becirevic, Haas, Mescia** 0710.1741
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- # Use the Ward identity ($S = \bar{x}c$) **HPQCD**, Phys.Rev.D82:114506(2010)

$$q^{\mu}\langle P|V_{\mu}^{cont.}|D\rangle = (m_c - m_x)\langle P|S^{cont}|D\rangle$$

that relates matrix elements of vector and scalar currents. In the lattice

$$q^{\mu}\langle P|V_{\mu}^{lat.}|D\rangle Z = (m_c - m_x)\langle P|S^{lat.}|D\rangle$$

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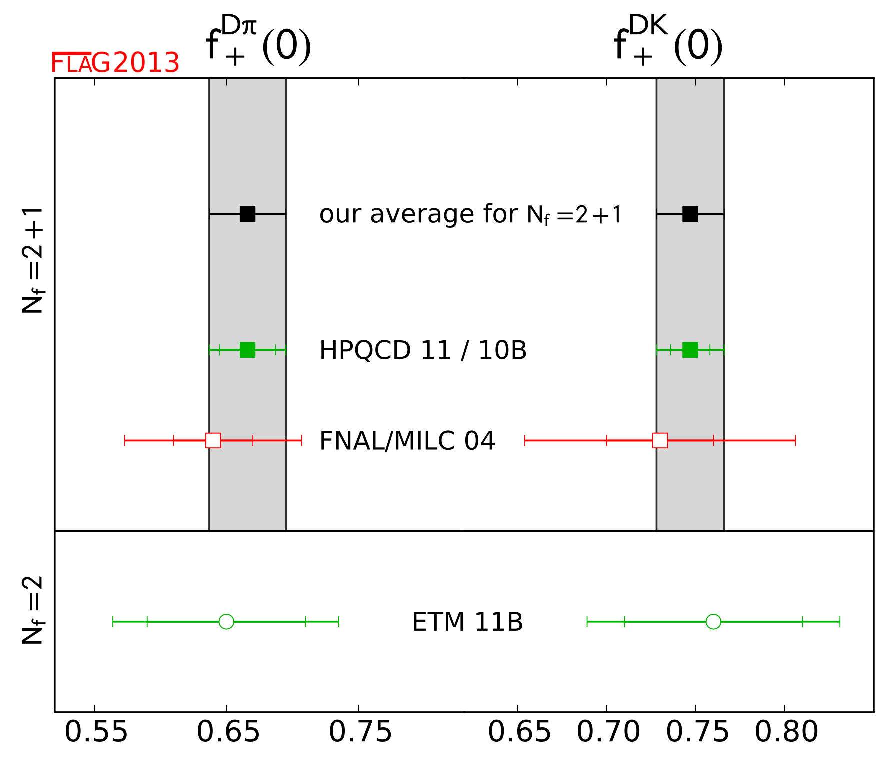
$$q^\mu \langle P|V_\mu^{lat.}|D\rangle Z = (m_c - m_x)\langle P|S^{lat.}|D\rangle$$

→ replace the V_μ with an S current in the 3-point function

$$f_0^{DP}(q^2) = \tfrac{m_c - m_x}{m_D^2 - m_P^2}\langle P|S|D\rangle_{q^2} \Longrightarrow \boxed{f_+^{PD}(0) = f_0^{PD}(0) = \tfrac{m_c - m_x}{m_D^2 - m_P^2}\langle S\rangle_{q^2=0}}$$

3. Semileptonic D decays: $q^2 = 0$

Important reduction of errors in the lattice determination of the form factors $f_+^{D\pi(K)}(0)$ by the **HPQCD Collaboration**, Phys.Rev.D82:114506(2010), due mainly to



* Use a relativistic action, HISQ, to describe light and charm quarks.

* Absolutely normalized current

HPQCD, 1008.4562, 1109.1501

$$f_+^{D\pi}(0) = 0.666(29)$$
$$f_+^{DK}(0) = 0.747(19)$$

\# Work in progress: $N_f = 2+1+1$ **FNAL/MILC**, 1411.1651 with physical quark masses.

3. Semileptonic D decays: $q^2 \neq 0$

Determination of $|V_{cs}|$ from $D \to Kl\nu$ at non-zero momentum transfer

HPQCD, 1305.1462

Calculation of $f_0^{DK}(q^2)$ (using Ward identity method) and $f_+^{DK}(q^2)$ (using its definition)

- Global fit to available experimental data (using $z-$expansion) → extraction of $|V_{cs}|$ using all experimental q^2 bins.

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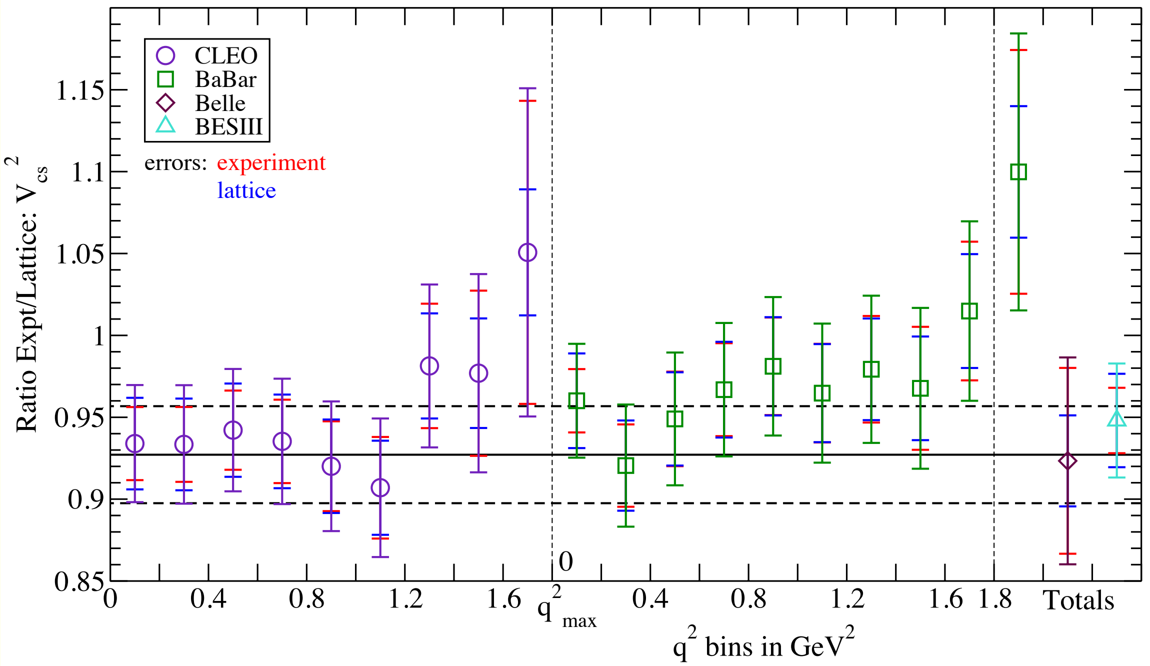

$$\boxed{|V_{cs}| = 0.963(5)_{exp}(14)_{lat}}$$

Unitarity value **PDG2014**: $|V_{cs}| = 0.97343 \pm 0.00015$

3. Semileptonic D decays: $q^2 \neq 0$

Work in progress ($N_f = 2$):

* **ETM**: Preliminary results in **PoSLattice 2013, 391 (2013)**

Work in progress ($N_f = 2+1$):

* **FNAL/MILC**: Preliminary results in 1211.4964. Fermilab charm and staggered light, four lattice spacings, $m_\pi \geq 180$ MeV.

** Same actions used for $B \to \pi l \nu$ form factors calculation → can calculate accurately $\left| \frac{f_+^{B\pi}}{f_+^{D\pi}} \right|$ → alternative calculation of $|V_{ub}|$ (see **A. Oyanguren** talk)

Work in progress ($N_f = 2+1+1$):

* **ETM**, Lattice2014: Twisted mass, three lattice spacings, $m_\pi \geq 210$ MeV

* **FNAL/MILC**: relativistic action for c, physical quark masses, four lattice spacings.

3. Semileptonic D decays: beyond gold-platted quantities

\# Alternative determination of $|V_{cs}|$: $\boxed{D_s \to \phi l \nu}$ **HPQCD**, 1311.6669

More challenging: five form factors (vector meson), unstable meson ...

* Treat ϕ as stable and estimate the error.

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* q^2 and angular distributions agree with **BaBar** data.

$$|V_{cs}| = 1.017(44)_{lat}(35)_{exp}(30)_{K\bar{K}}$$

* Expected reduction of exper. errors at **BESIII** → need improvement of theor. calculation (lattice error dominated by statistical error)

* Are the heavy meson form factors at a given q^2 insensitive to the spectator m_q? (compare $D_s \to \phi$ and $D \to K^*$).

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Exploratory $N_f = 2+1$ calculation of $D \to \eta^{(\prime)} l \nu$ **G. Bali et al**, 1406.5449

* Calculate $\eta - \eta'$ mixing angles and disconnected contributions

3. Semileptonic D decays: correlations with leptonic decays

Cancel CKM matrix elements building ratios of semileptonic and leptonic decay widths

* $N_f = 2+1$ **HPQCD** calculation

$$\left[\frac{f_+^{D\pi}(0)}{f_D}\right]_{lat} = (3.20 \pm 0.15)\,\mathrm{GeV}^{-1}$$

* Using **HPQCD** $f_+^{D\pi}(0)$ and $N_f = 2+1+1$ **FNAL/MILC** f_{D+}

$$\left[\frac{f_+^{D\pi}(0)}{f_{D+}}\right]_{lat} = (3.13 \pm 0.14)\,\mathrm{GeV}^{-1}$$

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$$\left[\frac{f_+^{D\pi}(0)}{f_{D+}}\right]_{exp} = (3.11 \pm 0.08)\,\mathrm{GeV}^{-1}$$ **G. Rong et al**, 1410.3232

Good agreement experiment-theory

3. Semileptonic D decays: correlations with leptonic decays

Cancel CKM matrix elements building ratios of semileptonic and leptonic decay widths

* $N_f = 2+1$ **HPQCD** calculation

$$\left[\frac{f_+^{D\pi}(0)}{f_D}\right]_{lat} = (3.20 \pm 0.15)\,\mathrm{GeV}^{-1}$$

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\# Several $N_f = 2+1$ and $N_f = 2+1+1$ calculations in progress.

4. $|V_{cd}|$, $|V_{cs}|$: CKM unitarity in the second row

Extracting CKM matrix elements $|V_{cd(cs)}|$ from leptonic decays

Experimental averages: **BaBar, Belle, CLEO-c, BESIII**

$$f_{D_s}|V_{cs}| = (252.0 \pm 3.7 \pm 1.8)\ \text{MeV} \qquad f_{D^+}|V_{cd}| = (45.92 \pm 1.04 \pm 0.15)\ \text{MeV}$$

Y. Fang et al, 1409.8049 **G. Rong et al**, 1410.3232

Decay constant errors $\sim 0.5\%$ → need EM effects when combining with experiment

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Following **FNAL/MILC**, 1407.3772

- * Universal long-distance EM: $\downarrow\sim 2.5\%$ **Kinoshita**, PRL2, 1959
- * Universal short-distance EM: $\uparrow\sim 1.8\%$ **Sirlin**, NPB196, 1982
- * Hadronic structure dependent EM effects: **rough estimate** $\sim 0.6\%$.

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$$|V_{cd}| = 0.220 \pm 0.004_{lat} \pm 0.005_{exp} \pm 0.001_{EM}$$

$$|V_{cs}| = 1.017 \pm 0.011_{lat} \pm 0.017_{exp} \pm 0.006_{EM}$$ **FLAG-2** $N_f = 2+1$

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$$|V_{cd}| = 0.217 \pm 0.001_{lat} \pm 0.005_{exp} \pm 0.001_{EM}$$

$$|V_{cs}| = 1.016 \pm 0.005_{lat} \pm 0.017_{exp} \pm 0.006_{EM}$$ **FNAL/MILC**, $N_f = 2+1+1$

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Extracting CKM matrix elements $|V_{cd(cs)}|$ from semileptonic decays

Experimental averages:

$f_+^{DK}(0)|V_{cs}| = 0.717 \pm 0.004$ $\qquad$ $f_+^{D\pi}(0)|V_{cd}| = 0.143 \pm 0.002$

Y. Fang et al, 1409.8049 $\qquad$ **G. Rong et al**, 1410.3232

(not included **Babar**, Phys.Rev.D 91 052022 (2015)
$|V_{cd}|f_+^{D\pi}(0) = 0.1374 \pm 0.0038 \pm 0.0022 \pm 0.0009$, **talk by A. Oyanguren**)

* Experimental averages for neutral and charged D do not remove corrections from Coulomb attraction between charged FS particles in neutral mode $\sim 1\%$

→ Needed when lattice errors are reduced (forthcoming calculations from **FNAL/MILC, ETM, RBC/UKQCD, ...**)

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$$|V_{cd}| = 0.215 \pm 0.009_{lat} \pm 0.003_{exp} \qquad |V_{cs}| = 0.960 \pm 0.024_{lat} \pm 0.005_{exp}$$

(with **HPQCD**, $N_f = 2+1$ $f_+^{D\pi}(0) = 0.666(29)$ and $f_+^{DK}(0) = 0.747(19)$)

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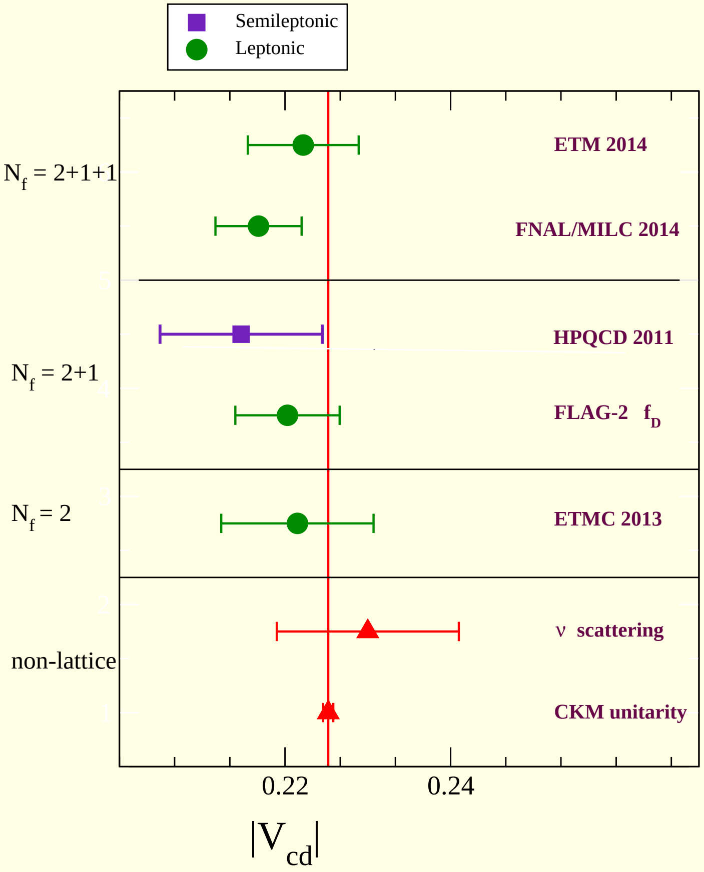

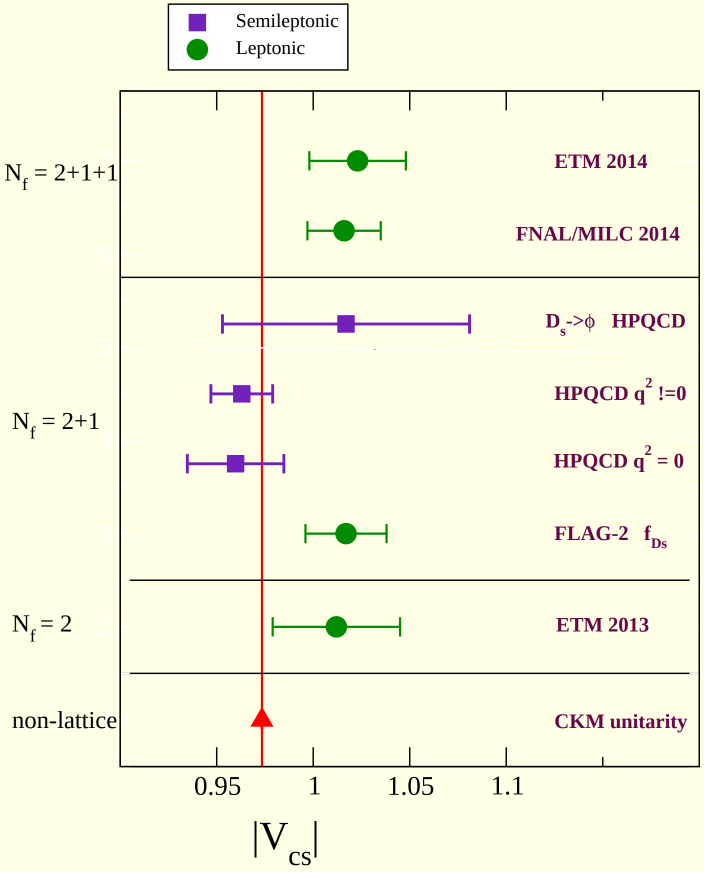

* $|V_{cd}|$: Pretty good agreement between different determinations, but some tension $N_f = 2+1+1$ FNAL/MILC leptonic-unitarity.

* $|V_{cs}|$: Slight tensions leptonic-semileptonic ($D \to K l \nu$) and leptonic-unitarity.

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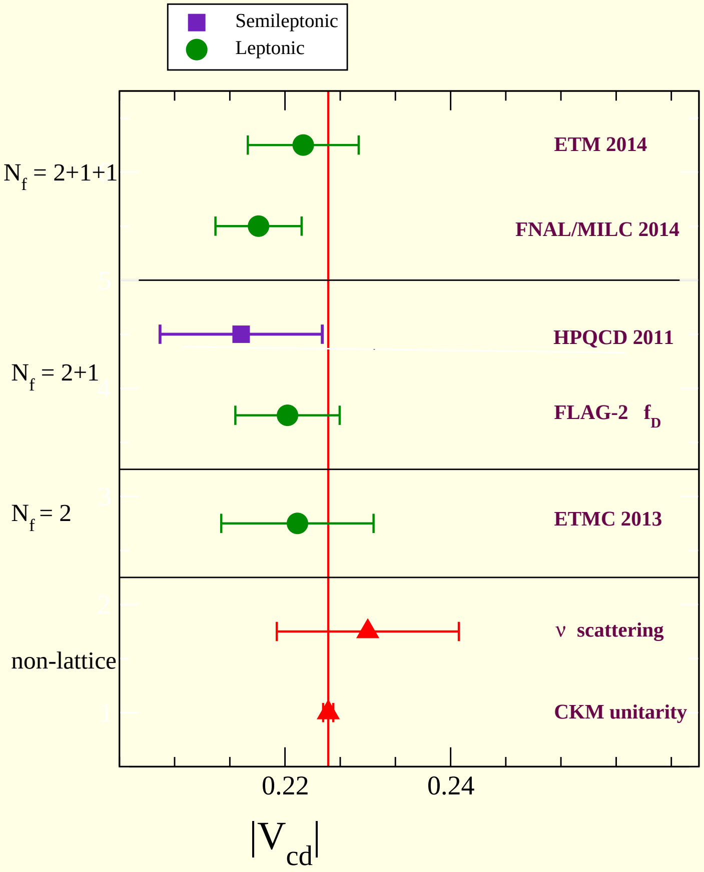

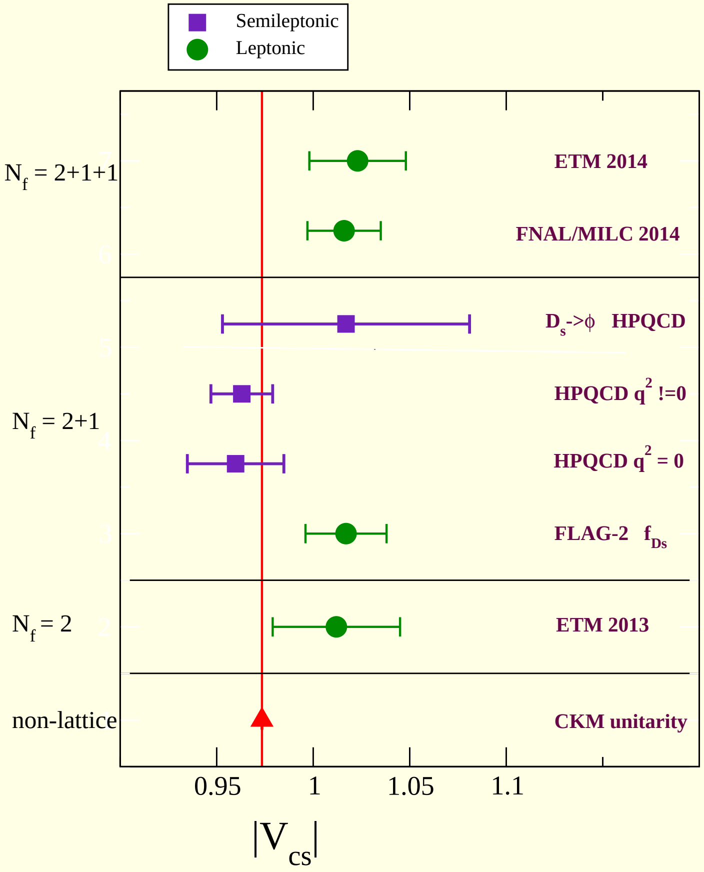

Using the most precise leptonic numbers ($N_f = 2+1+1$ FNAL/MILC)

$$1 - |V_{cd}|^2 - |V_{cs}|^2 - |V_{cb}|^2 = -0.07(4)$$

Using $N_f = 2+1$ FLAG-2 averages for decay constants

$$1 - |V_{cd}|^2 - |V_{cs}|^2 - |V_{cb}|^2 = -0.08(4)$$

4. Conclusions and outlook

\# Relativistic description of charm → important reduction of lattice QCD errors in decay constants and semileptonic form factors …

$$\texttt{Error}\ f_{D_{(s)}}\ \sim 0.5\% \qquad \texttt{Error}\ f_+^{DK(\pi)}\ \sim 2.5-4.3\%$$

… still theory errors are dominant in $|V_{cd(cs)}|$ extractions from semileptonic decays.

* Several on-going calculations of the shape of $f_{+(0)}(q^2)$ will further reduce errors **FNAL/MILC** (with two different decriptions of the c), **ETM**, **HPQCD** …

** Need experimental results reported in a model independent way, i.e., in q^2 bins (including full covariance matrix).

* Physical quark masses also important in the reduction of errors, especially for D^+ quantities.

4. Conclusions and outlook

At current level of precision we need to include subdominant effects:

* **EM effects** → Eventually will do QCD+QED simulations.

N. Tantalo, 1311.2797, **Divitiis et al**, 1303.4896, **A. Portelli**, plenary talk at Lattice 2014, **N. Carrasco et al**, 1502.00257

* Include `charm` in the sea

* Strong isospin breaking effects: leading order corrections included via tuning light valence quarks (effects of degenerate sea are NNLO in `CHPT`).

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\# Extend the same techniques to B physics

2. Leptonic D decays: New results (> 2013)

Reduction of errors in f_D and f_{D_s} mainly due to the use of relativistic actions, and using the same action for light and charm quarks.

\# $N_f = 2 + 1 + 1$:

* **FNAL/MILC**, 1407.3772: highly improved action, **MILC** configurations with **phys. quark masses** and small lattice spacing (smallest $a \approx 0.06$ fm)

$$\begin{aligned} f_{D_s} &= 249.0 \pm 0.3_{stat} \, {}^{+0.1}_{-1.4}\Big|_{a^2 \; extr.} \pm 0.2_{FV} \pm 0.1_{em} \pm 0.4_{f_\pi} \text{ MeV} \\ f_{D+} &= 212.6 \pm 0.4_{stat} \, {}^{+0.9}_{-1.1}\Big|_{a^2 \; extr.} \pm 0.3_{FV} \pm 0.1_{em} \pm 0.3_{f_\pi} \text{ MeV} \end{aligned}$$