V_{cs} determination from $D \to K\ell\nu$

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HPQCD

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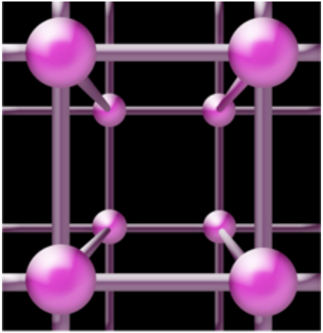
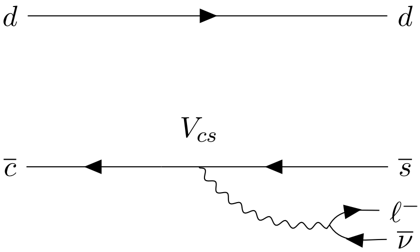
Overview

I will summarise the results
in arXiv:2104.09883 (in press)

- Motivation.
- Calculation of hadronic form factors.
- $D \to K$ form factor results.
- Sub 1% accurate determination of V_{cs} by three semi-independent methods.

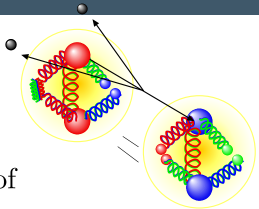


Motivation

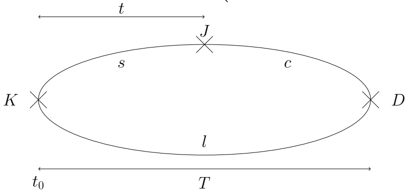


- Flavour changing weak decays of heavy mesons can test the SM.
- $D \to K\ell\nu$ depends on CKM element: V_{cs}. We calculate form factors for the hadronic part of the decay.
- CKM unitarity is a good place to look for new physics.
- We need very precise CKM element determinations to test SM.

$D \to K$ form factors



- Want meson form factors over the full range of $q^2 = (p_{\text{mother}} - p_{\text{daughter}})^2$ values.
- f_0 and f_+ form factors use matrix elements from 3-point correlation functions with scalar and vector current insertions.
- Typically use 3 or 4 T values on each ensemble, as well as averaging over 8 or 16 t_0 values (4 on finest lattice).

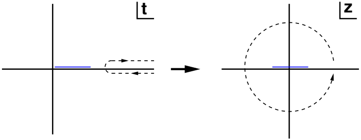


$D \to K$ form factors

- MILC HISQ 2+1+1 ensembles. All valence quarks HISQ.
- 5 lattice spacings in range 0.15-0.045fm. All with $m_s/m_l = 5$, and 3 with physical m_l too.
- Charm mass easy to reach on all ensembles and discretisation effects in the HISQ action very small.
- Cover whole physical q^2 range using twisted b.c.s to give momentum to daughter s quark.
- Vector current non-perturbatively renormalised using PCVC.
- Once we have data on each ensemble, need to extrapolate to the continuum.

$D \to K$ form factors

Convert to z space to perform standard continuum-chiral extrapolation:

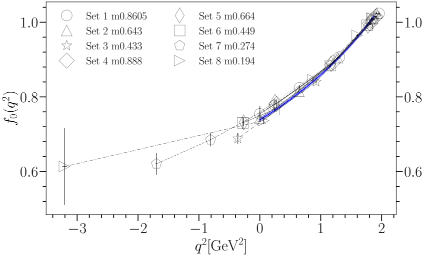


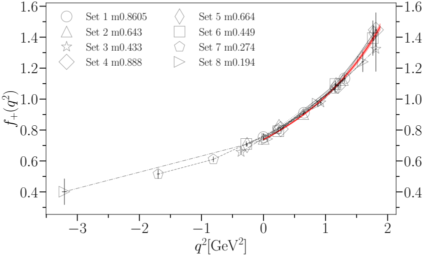
$$f_0(q^2) = \frac{1+L}{1-\frac{q^2}{M^2_{D_s^0}}} \sum_{n=0}^{N-1} a_n^0 z^n, \qquad N = 3$$

$$f_+(q^2) = \frac{1+L}{1-\frac{q^2}{M^2_{D_s^*}}} \sum_{n=0}^{N-1} a_n^+ \Big(z^n - \frac{n}{N}(-1)^{n-N} z^N \Big). \tag{1}$$

$$a_n^{0,+} = (1+\mathcal{N}_n^{0,+}) \sum_{j=0}^{2} d_{jn}^{0,+} \Big(\frac{am_c^{\mathrm{val}}}{\pi} \Big)^{2j}. \tag{2}$$

$D \to K$ form factor results





- We obtain the full q^2 range $\implies$ can compare bin by bin with exp. partial decay rate data to extract V_{cs}.

$D \to K$ form factor results

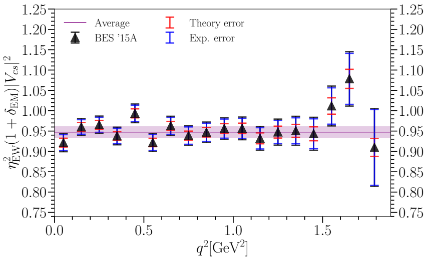
Full differential rate includes previously neglected electroweak and EM corrections, as well as terms in $\epsilon = \frac{m_\ell^2}{q^2}$,

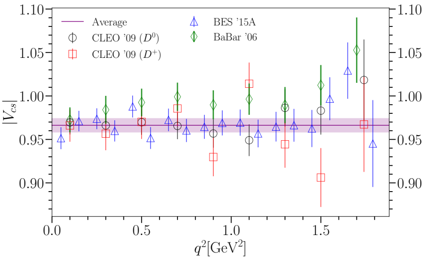
$$\frac{d\Gamma^{D\to K}}{dq^2} = \frac{G_F^2(\eta_{\mathrm{EW}}|V_{cs}|)^2}{24\pi^3}(1-\epsilon)^2(1+\delta_{\mathrm{EM}})\times \left[|\vec{p}_K|^3(1+\frac{\epsilon}{2})|f_+(q^2)|^2 + |\vec{p}_K|M_D^2\left(1-\frac{M_K^2}{M_D^2}\right)^2\frac{3\epsilon}{8}|f_0(q^2)|^2\right], \quad (3)$$

where $\eta_{\mathrm{EW}} = 1.009(2)$. We take δ_{EM} as a 0.5% (1%) error for K^0 ($K^\pm$). Final state interactions dominate δ_{EM} - hence K^0 smaller. We can use this to extract V_{cs} in three different ways:

V_{cs} results

Method 1: Using q^2 binned differential decay rates,

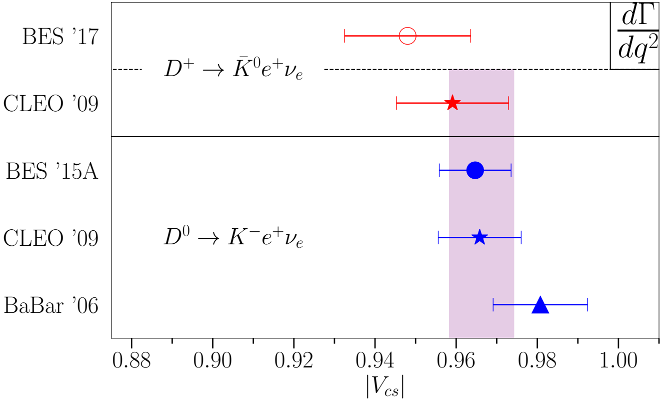




- Experimental error dominates each bin, theory dominates final result.

$$\Delta_i\Gamma = \int_{q_i^2}^{q_{i+1}^2} \frac{d\Gamma}{dq^2} dq^2 \tag{4}$$

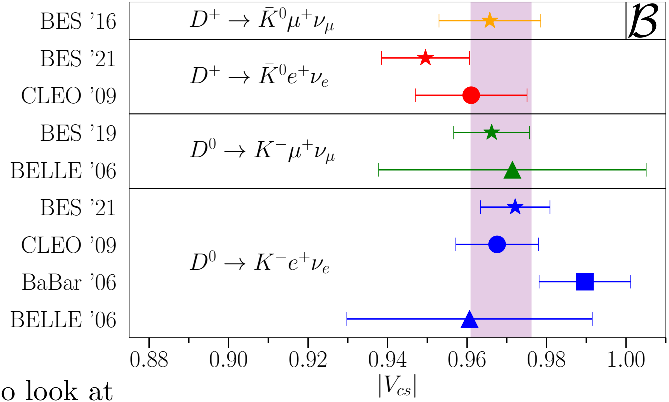
V_{cs} results



- Preferred method using whole q^2 range and multiple experiments.
- Theory still (just) dominates error, but can also be improved with future binned experimental data (with correlations).

V_{cs} results

Method 2: Using total branching fraction for all 4 decay modes,

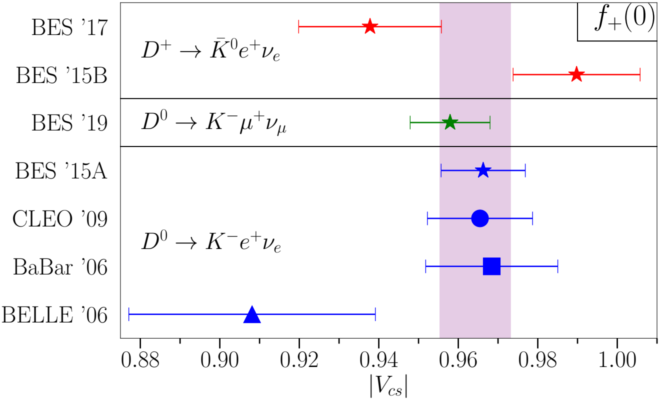


Can also look at
$R_{\mu/e} = \mathcal{B}_\mu/\mathcal{B}_e$

$$\mathcal{B} = \tau_D \int_0^{q^2_{\max}} \frac{d\Gamma}{dq^2} dq^2 \quad (5)$$

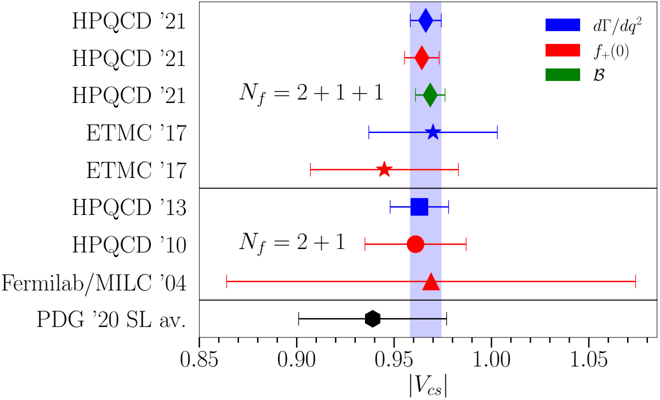
V_{cs} results

Method 3: Using $|V_{cs}|f_+(0)$



$$f_+(0)\eta_{\mathrm{EW}}\sqrt{(1+\delta_{\mathrm{EM}})}|V_{cs}| = 0.7180(33)$$ *(HFLAV, arXiv:1612.07233)*

V_{cs} results

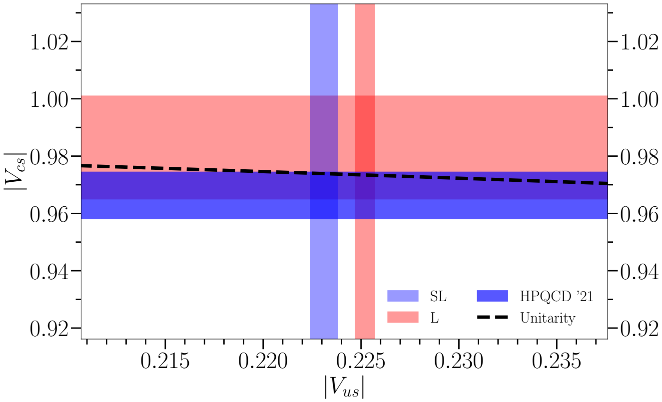


HPQCD '21 results:

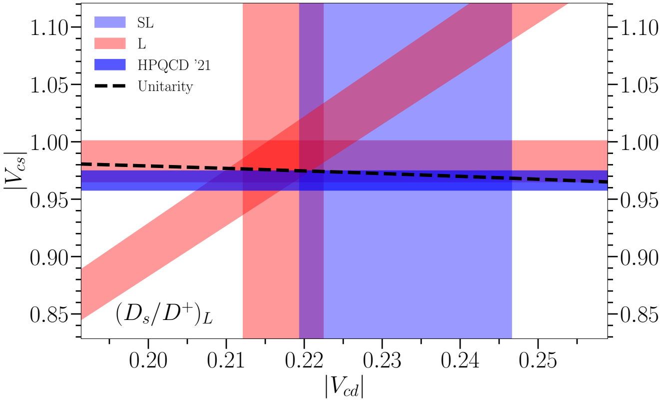
$$|V_{cs}|^{\Gamma} = 0.9663(53)_{\mathrm{latt}}(39)_{\mathrm{exp}}(19)_{\eta_{\mathrm{EW}}}(40)_{\delta_{\mathrm{EM}}}$$
$$|V_{cs}|^{\mathcal{B}} = 0.9686(54)_{\mathrm{latt}}(39)_{\mathrm{exp}}(19)_{\eta_{\mathrm{EW}}}(30)_{\delta_{\mathrm{EM}}}$$
$$|V_{cs}|^{f_+(0)} = 0.9643(57)_{\mathrm{latt}}(44)_{\mathrm{exp}}(19)_{\eta_{\mathrm{EW}}}(48)_{\delta_{\mathrm{EM}}}$$

V_{cs} results

$|V_{cs}| = 0.9663(80)$, big improvement on current PDG sl value of 0.939(38)



V_{cs} results



Additional constraint from leptonic D_s and D^+ decays, combined with lattice decay constants.

Conclusions

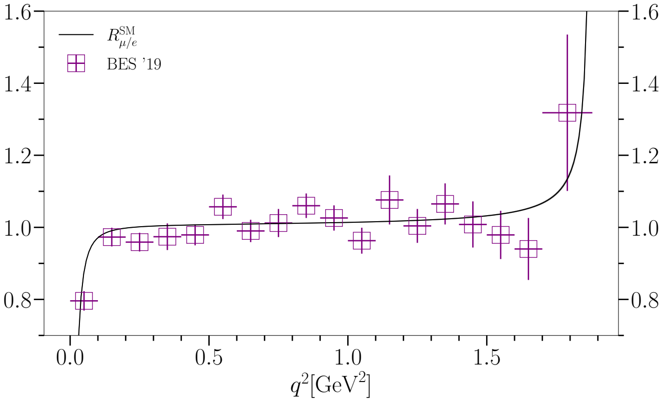
$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 0.9826(22)_{V_{cd}}(155)_{V_{cs}}(1)_{V_{cb}}$$
$$|V_{us}|^2 + |V_{cs}|^2 + |V_{ts}|^2 = 0.9859(2)_{V_{us}}(155)_{V_{cs}}(1)_{V_{ts}}$$

- $|V_{cs}| = 0.9663(80)$ determination from $D \to K\ell\nu$ using bin by bin comparisons with experimental differential decay rate.
- First determination showing V_{cs} to be significantly lower than 1 and first sub 1% uncertainty.
- Agrees well with determinations from 2 other methods.
- Theory and experimental error similar. EM error also a large contribution.
- New generation of lattice calculation, more stats, or EM work needed for theory improvement.
- Can also look for BSM physics in $R_{\mu/e}$.

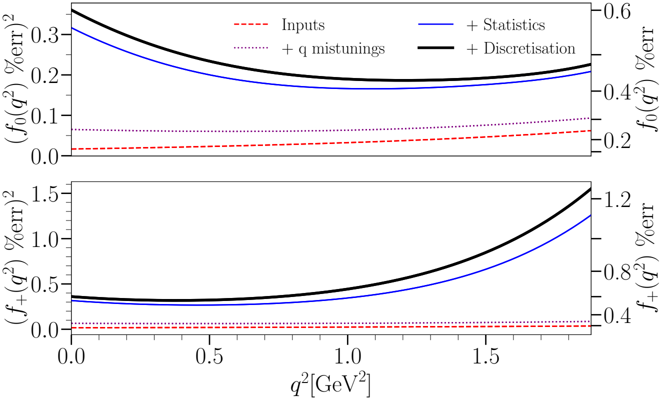
Thanks for listening. Any questions?

Extra Slides

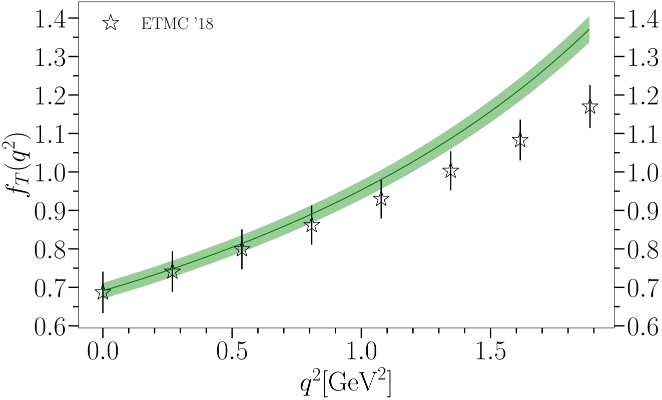
$$R_{\mu/e} = \frac{\mathcal{B}_\mu}{\mathcal{B}_e}.$$



Extra Slides



Extra Slides



Extra Slides

$$Z_V \langle K | V^0 | \hat{D} \rangle = \\ f_+(q^2)\Big(p_D^0 + p_K^0 - \frac{M_D^2 - M_K^2}{q^2} q^0\Big) \\ + f_0(q^2)\frac{M_D^2 - M_K^2}{q^2} q^0, \tag{6}$$

$$\langle K | S | D \rangle = \frac{M_D^2 - M_K^2}{m_c - m_s} f_0(q^2), \tag{7}$$

$$Z_T \langle \hat{K} | T^{i0} | \hat{D} \rangle = \frac{2iM_D p_K^i}{M_D + M_K} f_T(q^2), \tag{8}$$

Extra Slides

$$z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}} \tag{9}$$

$$\frac{m_l}{m_s} \approx \frac{M_\pi^2}{M_{\eta_s}^2} \tag{10}$$