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

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HPQCD

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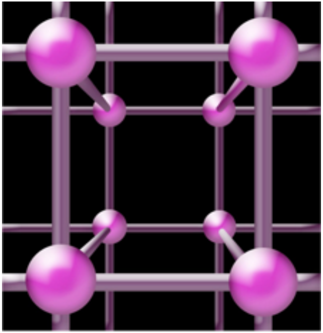
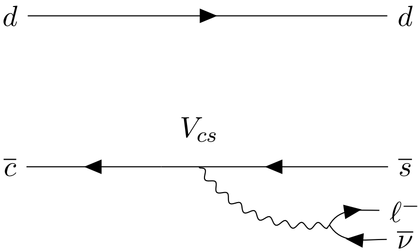
Overview

I will summarise the results
in arXiv:2104.09883

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



Motivation

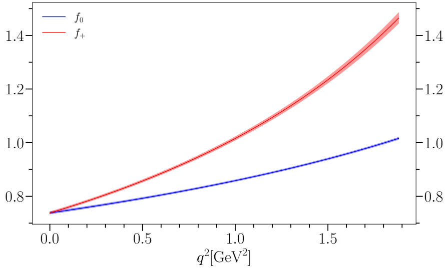


- Flavour changing weak decays of heavy mesons can test the SM.
- $D \to K\ell\nu$ depends on CKM element: V_{cs}. We calculate hadronic part of decay.
- CKM unitarity is a good place to look for new physics.
- We need very precise CKM element determinations to test SM.

Form factors

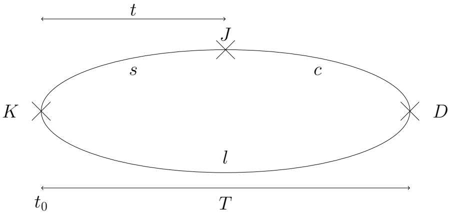
$$\frac{d\Gamma^{D\to K}}{dq^2} = \frac{G_F^2|V_{cs}|^2}{24\pi^3}|\vec{p}_K|^3\ |f_+(q^2)|^2$$

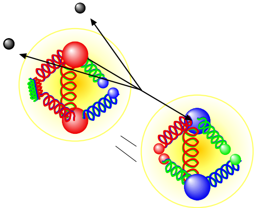
- Parameterise the ‘QCD bit’ in the differential decay rate.
- Interested in $f_+(q^2)$ and $f_0(q^2)$ form factors for $D \to K$.
- Encode meson structure.
- Describe the shape in $q^2 = (p_{\text{mother}} - p_{\text{daughter}})^2$ space.



$D \to K$ form factors

- Want meson form factors over the full range of q^2 values.
- Require three-point correlators with scalar and vector current insertions for f_0 and f_+.
- Calculate these using lattice QCD - averaging over gluon fields.

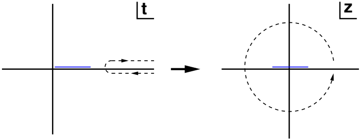




$D \to K$ form factors

- MILC HISQ 2+1+1 ensembles. All valence quarks HISQ.
- 5 lattice spacings in range 0.15-0.045fm. Three with physical light quark masses - others with heavier light quarks as they are very expensive.
- Charm mass easy to reach on all ensembles.
- Cover whole physical q^2 range.

$D \to K$ form factors

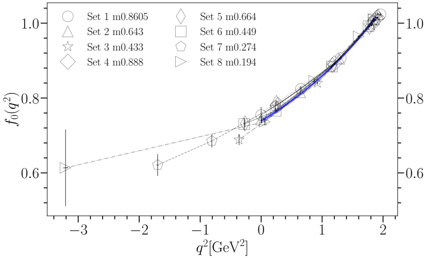


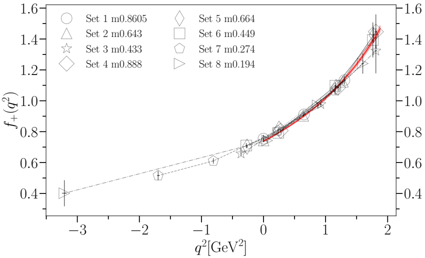
Convert to z space to perform standard continuum-chiral extrapolation, guided by effective theories:

$N = 3$

$$f_0(q^2) = \frac{logs}{1 - \frac{q^2}{M^2_{D_s^0}}} \sum_{n=0}^{N-1} a_n^0 z^n,$$
$$f_+(q^2) = \frac{logs}{1 - \frac{q^2}{M^2_{D_s^*}}} \sum_{n=0}^{N-1} a_n^+ \left(z^n - \frac{n}{N} (-1)^{n-N} z^N \right). \tag{1}$$

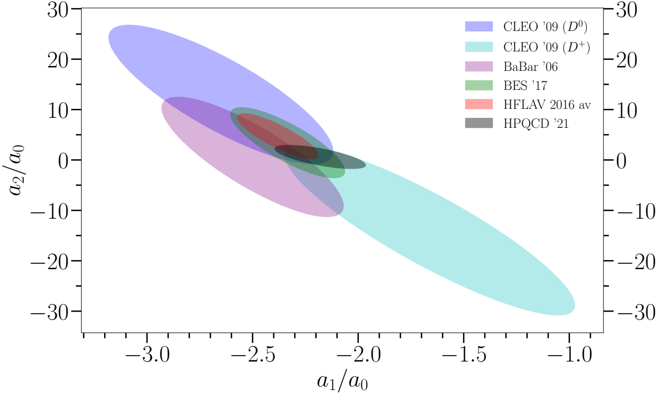
$D \to K$ form factor results





- We obtain the full q^2 range $\implies$ can compare bin by bin with exp. partial decay rate data to extract V_{cs}.
- Experiments also use z expansion, so we can compare coefficients to test SM using shape in z.

$D \to K$ form factor results



Ratios of f_+ z expansion coefficients a_n, directly compare form factor shape with experiment. 68% confidence ellipses show good agreement.

$D \to K$ form factor results

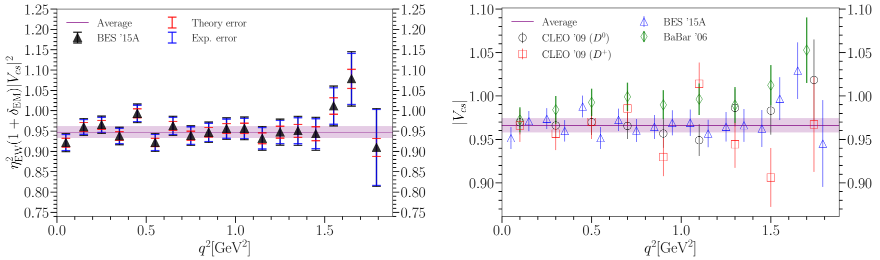
Full expression includes previously neglected electroweak and EM corrections, as well as terms in $\epsilon = \frac{m_\ell^2}{q^2}$,

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

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

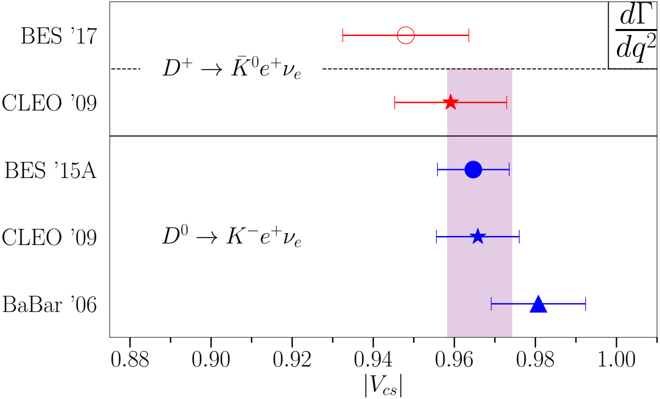
Method 1: Using q^2 binned differential decay rates,



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

$$\Delta_i\Gamma = \int_{q_i^2}^{q_{i+1}^2} \frac{d\Gamma}{dq^2} dq^2 \quad (3)$$

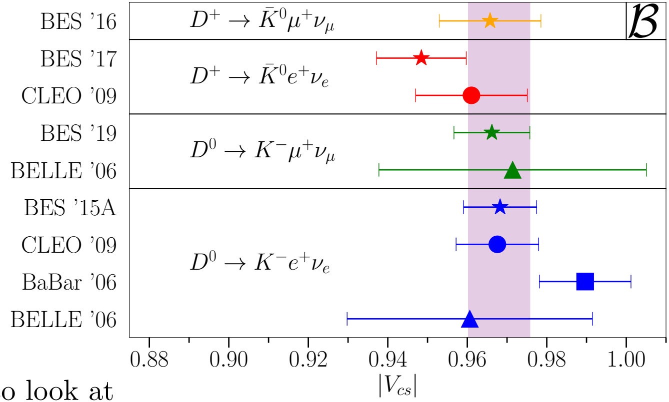
V_{cs} results



- 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,

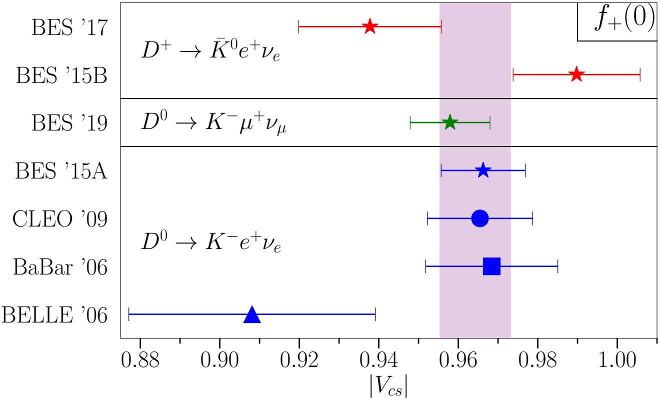


Can also look at
$R_{\mu/e} = \mathcal{B}_\mu/\mathcal{B}_e$

$$\mathcal{B} = \tau_D \int_0^{q^2_{\max}} \frac{d\Gamma}{dq^2} dq^2 \tag{4}$$

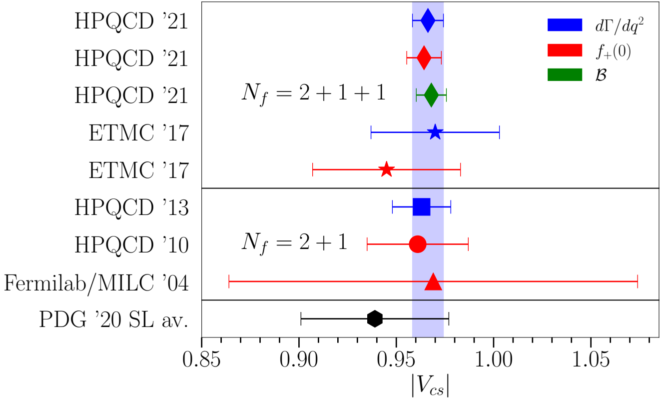
V_{cs} results

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



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

V_{cs} results

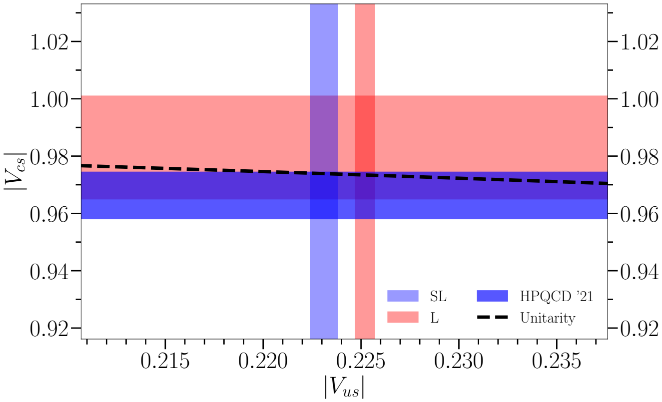


HPQCD '21 results:

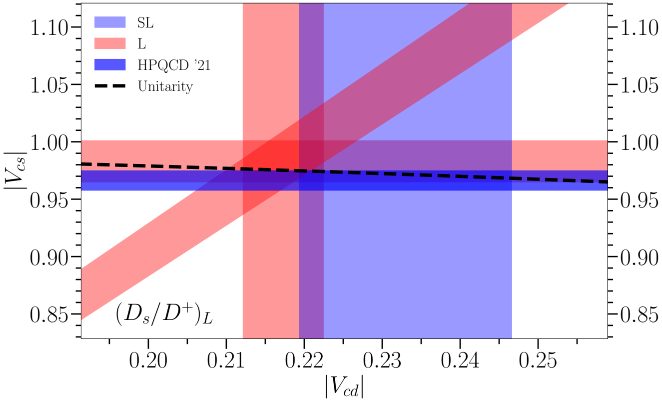
$$|V_{cs}|^{\Gamma} = 0.9663(53)_{\text{latt}}(39)_{\text{exp}}(19)_{\eta_{\text{EW}}}(40)_{\delta_{\text{EM}}}$$
$$|V_{cs}|^{\mathcal{B}} = 0.9680(54)_{\text{latt}}(42)_{\text{exp}}(19)_{\eta_{\text{EW}}}(30)_{\delta_{\text{EM}}}$$
$$|V_{cs}|^{f_+(0)} = 0.9643(57)_{\text{latt}}(44)_{\text{exp}}(19)_{\eta_{\text{EW}}}(48)_{\delta_{\text{EM}}}$$

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.

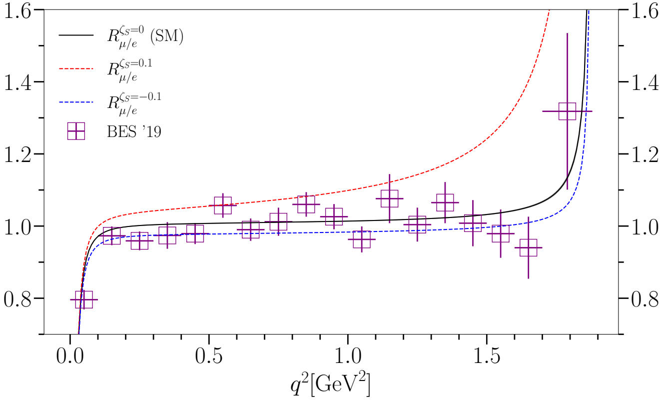
Conclusions

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

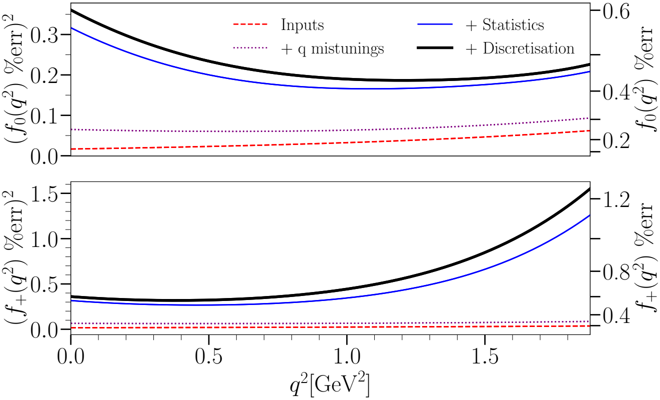
- $|V_{cs}| = 0.9663(80)$ determination from $D \to K\ell\nu$ using bin by bin comparisons with experimental differential decay rate.
- First determination showing V_{cs} to be significantly lower than 1 and first sub 1% uncertainty.
- Agrees well with determinations from 2 other methods.
- Theory and 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?

$R_{\mu/e} = \frac{\mathcal{B}_\mu}{\mathcal{B}_e}$. ζ allows for NP scalar coupling in μ which modifies the f_0 coefficient (see arXiv:1502.07488).



Extra Slides



Extra Slides

$$Z_V \langle K| V^0 |\hat{H}\rangle =$$
$$f_+(q^2)\left(p_H^0 + p_K^0 - \frac{M_H^2 - M_K^2}{q^2} q^0\right) \tag{5}$$
$$+ f_0(q^2)\frac{M_H^2 - M_K^2}{q^2} q^0,$$

$$\langle K| S |H\rangle = \frac{M_H^2 - M_K^2}{m_h - m_s} f_0(q^2), \tag{6}$$

$$Z_T \langle \hat{K}| T^{i0} |\hat{H}\rangle = \frac{2iM_H p_K^i}{M_H + M_K} f_T(q^2), \tag{7}$$

Extra Slides

$$z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}} \tag{8}$$

$$\frac{m_l}{m_s} \approx \frac{M_\pi^2}{M_{\eta_s}^2} \tag{9}$$