Form Factors For Bottom and Charm → Strange Semileptonic Decays

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HPQCD

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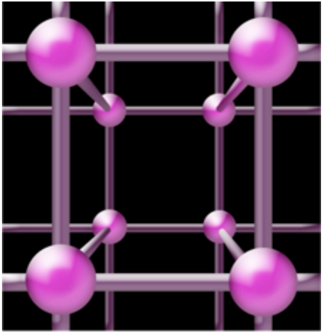
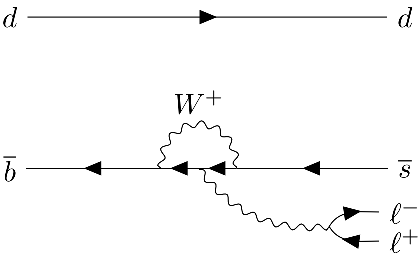
Overview



- Motivation
- Hadronic form factors for meson decays
- A brief introduction to Lattice QCD and heavy-HISQ
- $B \to K\ell^+\ell^-$ form factor calculation
- Preliminary $B \to K\ell^+\ell^-$ and $D \to K\ell\nu$ results

Motivation

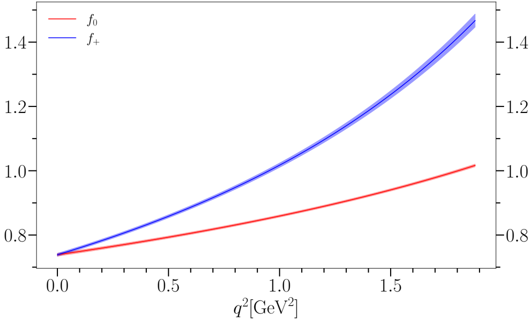


- Flavour changing weak decays of heavy mesons can test the SM
- $D \to K\ell\nu$ depends on CKM element: V_{cs}
- $B \to K\ell^+\ell^-$ is a FCNC, proceeds via loop diagrams
- Both good places to look for new physics

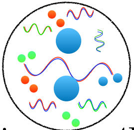
Form factors

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

- Parameterise the 'QCD bit' in decays rates etc.
- Describe the shape in $q^2 = (p_{\text{parent}} - p_{\text{daughter}})^2$ space



Intro to LQCD



- Problem: QCD non-perturbative at low energies.
- Need to solve path integral. Discretise Euclidean action on a 4D lattice of space-time points with spacing a.
- Many discretisations of the action exist. We use a highly improved (HISQ) action which removes effects associated with the naive discretisation process through order a^2.
- For QCD we must integrate over quark and gluon fields.
- Calculate correlation functions by inserting operators and performing Monte Carlo integration. Repeat for many a values and extrapolate to continuum ($a = 0$).

$$\int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}A e^{-S[\bar{\psi},\psi,A]}$$

Intro to LQCD

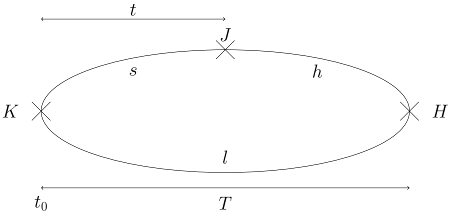
We can calculate two and three point functions to study meson masses and decays from first principles, but with some limitations:

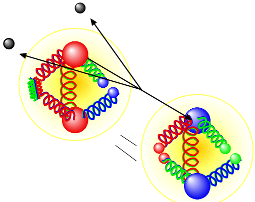
- The computational cost of calculations is very large. This grows quickly with lighter masses and finer lattices.
- Errors grow large with masses where $am \gtrsim 0.8$. This means to reach the b mass we must use very fine lattices where a is very small.

The solution is to study heavy mass behaviour. Work with several heavy masses $m_c \leq m_h \leq m_b$ and then evaluate the result at the b mass: heavy-HISQ.

Form Factors in heavy-HISQ

- Calculate meson form factors over the full range of q^2 values.
- Interested in $f_+(q^2)$, $f_0(q^2)$ and $f_T(q^2)$ form factors for pseudoscalar to pseudoscalar decays.
- Require three-point correlators with scalar, vector and tensor current insertions.



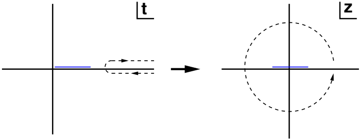


Example: $B \to K$

- MILC HISQ 2+1+1 ensembles. All valence quarks HISQ
- 5 lattice spacings in range 0.15-0.045fm. Some with physical light quarks.
- Physical b is $am_b \approx 0.9$ on finest lattice
- Choose several heavy masses and daughter momenta for each ensemble
- Combine heavy mass fit with continuum extrapolation
- $D \to K$ comes 'for free'
- Cover whole physical q^2 range

Example: $B \to K$

Perform standard z space fit:

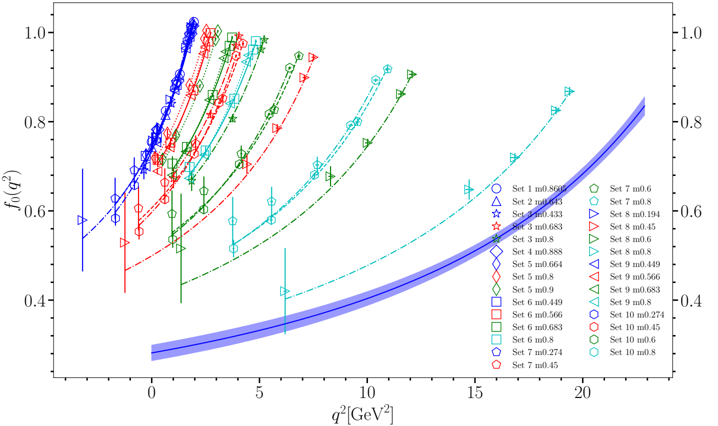


$$\begin{aligned} f_0(q^2) &= \frac{logs}{1-\frac{q^2}{M^2_{H^0_s}}}\sum_{n=0}^{N-1} a_n^0 z^n, \\ f_{+,T}(q^2) &= \frac{logs}{1-\frac{q^2}{M^2_{H^*_s}}}\sum_{n=0}^{N-1} a_n^{+,T}\Big(z^n - \frac{n}{N}(-1)^{n-N}z^N\Big), \end{aligned} \quad (1)$$

$$\begin{aligned} a_n^{0,+} = &\Big(1+\rho_n^{0,+}\log\Big(\frac{M_H}{M_D}\Big)\Big)\times \\ &\sum_{i,j,k=0}^{N_{ijk}-1} d_{ijkn}^{0,+}\Big(\frac{\Lambda_{\text{QCD}}}{M_H}\Big)^i\Big(\frac{am_h^{\text{val}}}{\pi}\Big)^{2j}\Big(\frac{a\Lambda_{\text{QCD}}}{\pi}\Big)^{2k} \\ &\times(1+\mathcal{N}_n^{0,+}). \end{aligned} \quad (2)$$

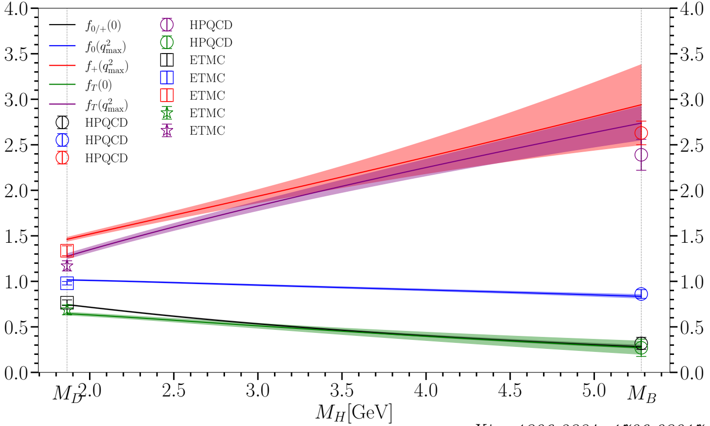
$\Lambda_{\text{QCD}} = 0.5\text{GeV}$

$B \to K$ preliminary results



Continuum result at the b mass in blue. Heavy-HISQ allows us to evaluate at any mass from c to b.

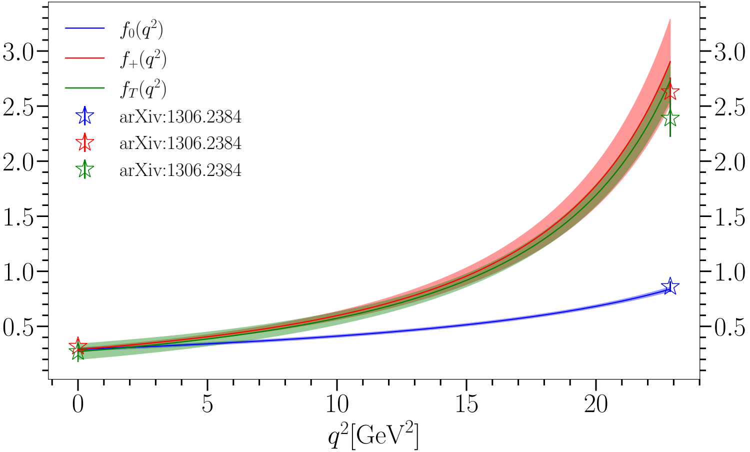
$B \to K$ preliminary results



arXiv: 1306.2384, 1706.03017, 1803.04807

We can study behaviour with heavy mass.

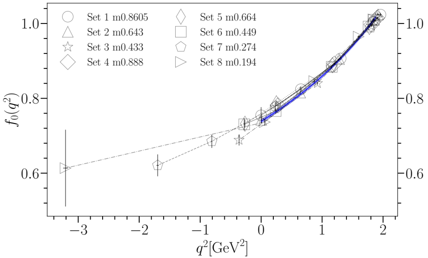
$B \to K$ preliminary results

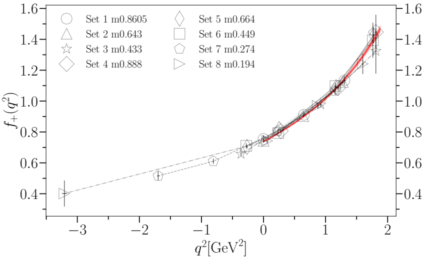


Tensor important for SM $B \to K$ due to $b \to s$ transition

Normalisation with $\mu = 2$GeV, matched to $\bar{\text{M}}\text{S}$ at 3 loop at b mass

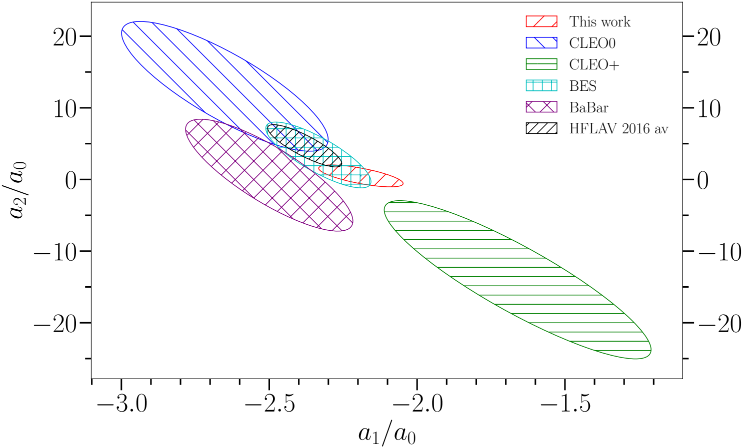
$D \to K$ preliminary results (*B. Chakraborty, C. T. H. Davies*)





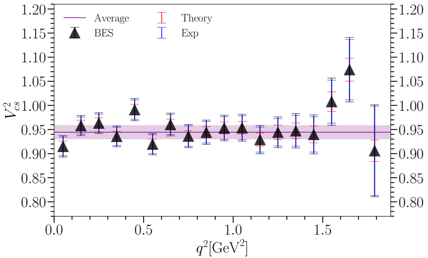
- Charm mass easy to reach on ensembles
- Full q^2 range $\implies$ can compare bin by bin with exp. partial decay rate data
- Lots of good exp. data available, can compare shape

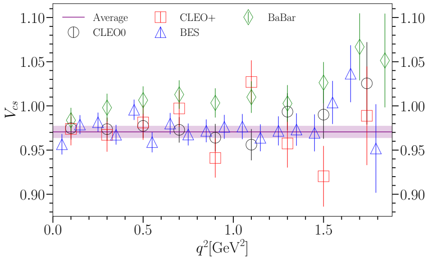
$D \to K$ preliminary results (*B. Chakraborty, C. T. H. Davies*)



One σ error ellipses. Ratios of f_+ z expansion coefficients a_n, directly comparable with experiment.

$D \to K$ preliminary results (*B. Chakraborty, C. T. H. Davies*)



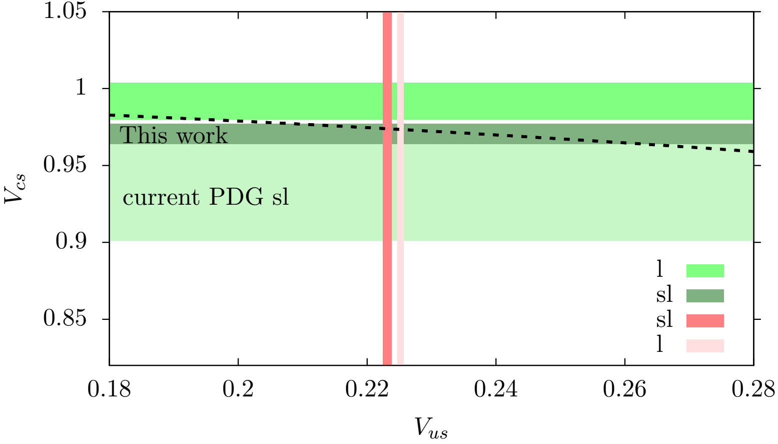


- Experimental error dominates each bin.

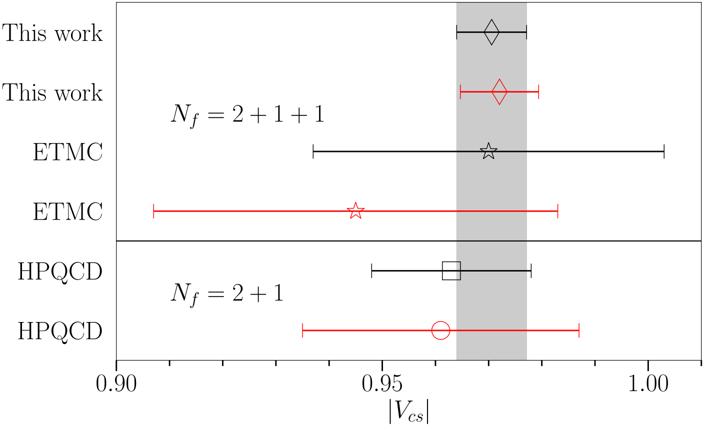
$$\Delta_i \Gamma = \int_{q_i^2}^{q_{i+1}^2} \frac{d\Gamma}{dq^2} dq^2 = \frac{G_F^2 |V_{cs}|^2}{24\pi^3} \int_{q_i^2}^{q_{i+1}^2} |\vec{p}_K|^3 |f_+(q^2)|^2 dq^2 \qquad (3)$$

$D \to K$ preliminary results (*B. Chakraborty, C. T. H. Davies*)

Preliminary $V_{cs} = 0.9706(66)[(54)_{\text{th}}(37)_{\text{ex}}]$, big improvement on current PDG sl value of 0.939(38)



$D \to K$ preliminary results (*B. Chakraborty, C. T. H. Davies*)



$f_+(0)|V_{cs}| = 0.7180(33)$
(HFLAV, arXiv:1612.07233)

arXiv: 1706.03657, 1305.1462, 1008.4562

Conclusions

- Heavy HISQ an effective method for studying heavy to strange decays and form factors
- Can improve upon $B \to K\ell^+\ell^-$ and $D \to K\ell\nu$ results
- Improvement on V_{cs} determination from $D \to K\ell\nu$ using bin by bin comparisons with experiment

Thanks for listening. Any questions?

Extra Slides

$$Z_V \langle K | V^0 | \hat{H} \rangle =$$
$$f_+(q^2)\Big(p_H^0 + p_K^0 - \frac{M_H^2 - M_K^2}{q^2} q^0\Big)$$
$$+ f_0(q^2) \frac{M_H^2 - M_K^2}{q^2} q^0, \quad (4)$$

$$\langle K | S | H \rangle = \frac{M_H^2 - M_K^2}{m_h - m_s} f_0(q^2), \quad (5)$$

$$Z_T \langle \hat{K} | T^{i0} | \hat{H} \rangle = \frac{2iM_H p_K^i}{M_H + M_K} f_T(q^2), \quad (6)$$

Extra Slides

$$z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}} \quad (7)$$

$$\frac{m_l}{m_s} \approx \frac{M_\pi^2}{M_{\eta_s}^2} \quad (8)$$