The search for new physics in $B \to K\ell^+\ell^-$ and $B \to K\nu\bar{\nu}$ using precise lattice QCD form factors

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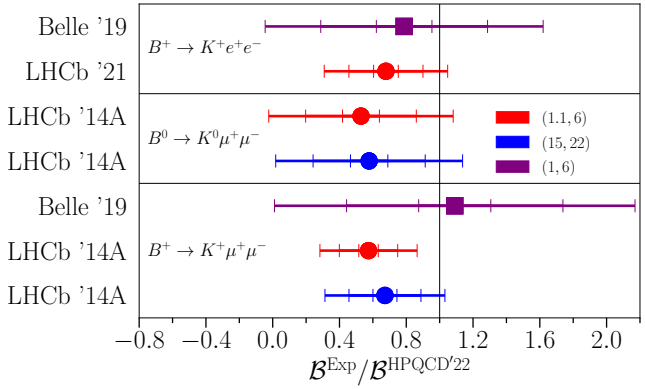
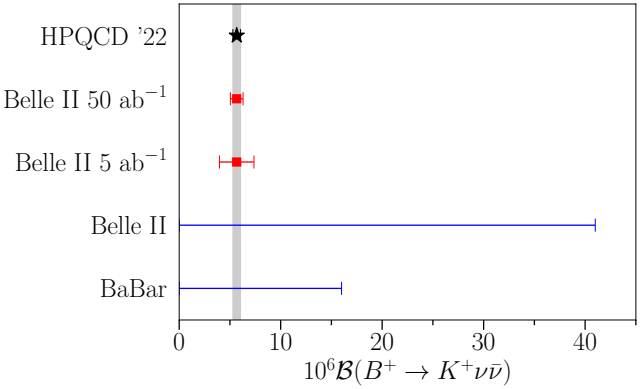
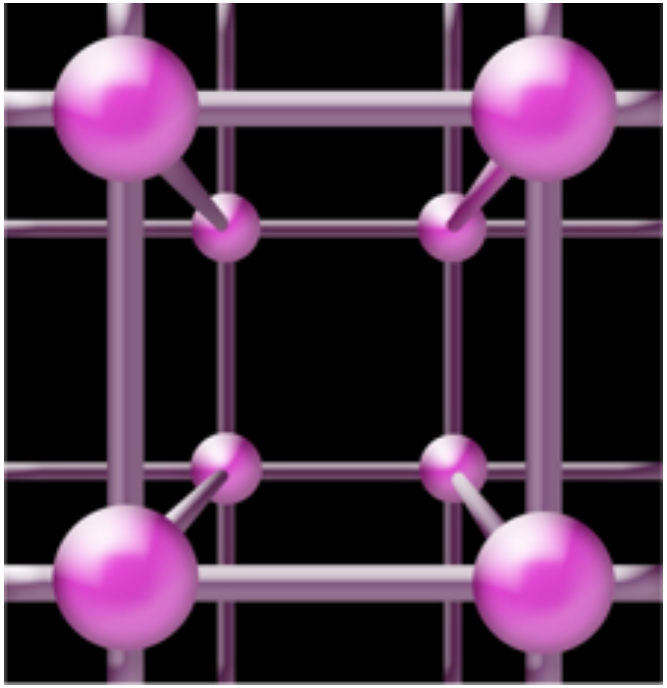




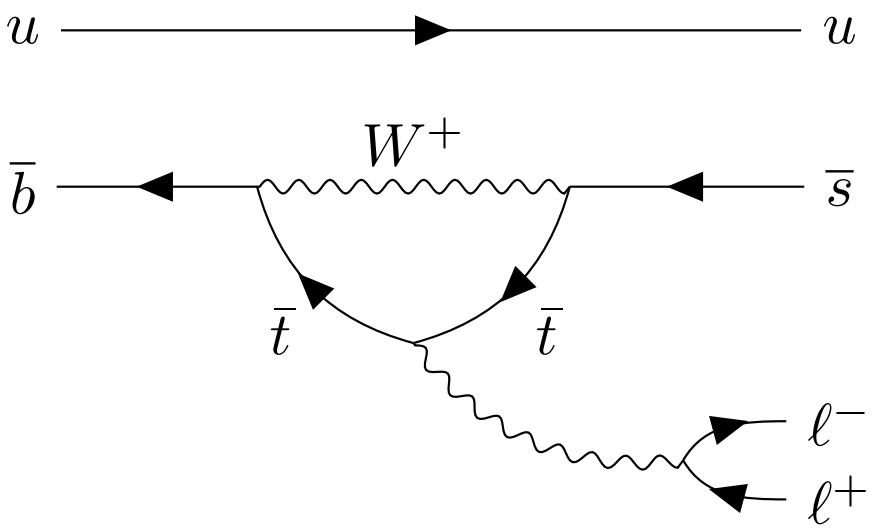
C. Bouchard, C.T.H. Davies

Overview

- Results of arXiv 2207.12468 and 2207.13371
- $B \to K$ motivation
- Calculation of hadronic form factors on the lattice
- Studying $B \to K$ using heavy-HISQ
- Results:
  $B \to K$ form factors and phenomenology
  Tensions with LHCb



$B \to K$ motivation

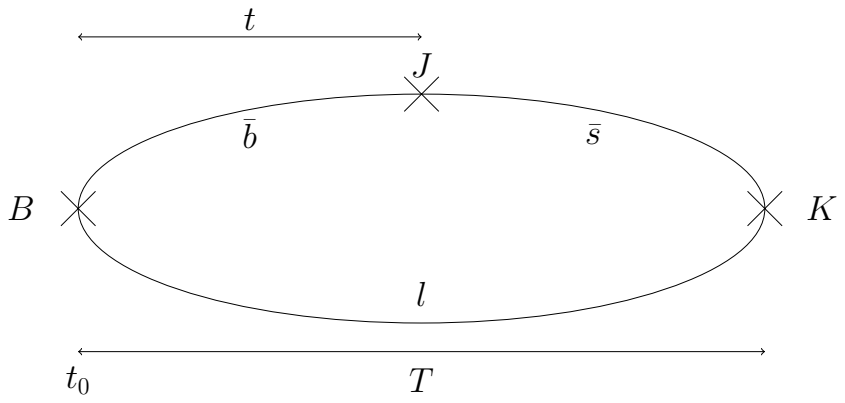


- Rare flavour changing neutral currents require loops
- Highly suppressed in the SM
- A good place to look for new physics
- We need very precise theoretical and experimental determinations to test SM
- Theory requires precise form factors for the hadronic part of the decay, which we calculate on the lattice

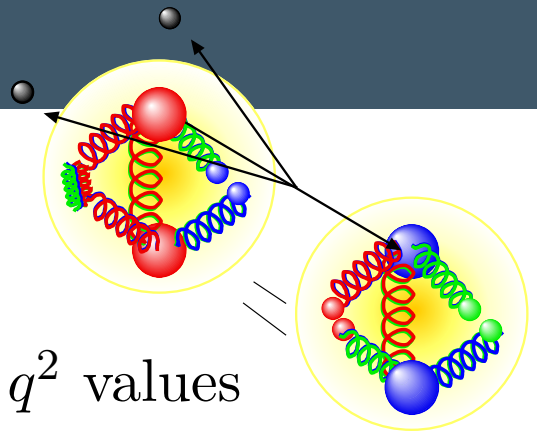
Form factors on the lattice

$$\frac{d\Gamma}{dq^2} = \mathcal{F}_1|F_P(f_0, f_+, W_i)|^2 + \mathcal{F}_2 f_+^2 + \mathcal{F}_3|F_V(f_+, f_T, W_i)|^2 + \mathcal{F}_4|f_+ F_P^*(f_0, f_+, W_i)|$$

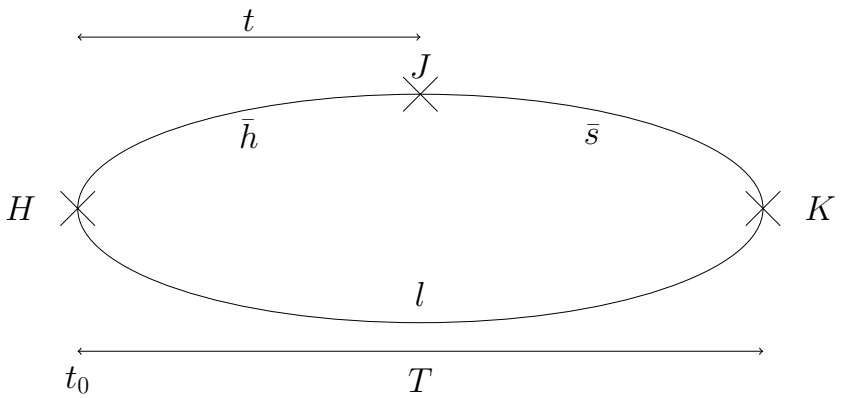
- Parameterise the 'QCD bit' in a differential decay rate
- Need $f_0(q^2)$, $f_+(q^2)$ and $f_T(q^2)$ form factors for $B \to K\ell^+\ell^-$
- Encode meson structure and describe the shape in $q^2 = (p_{\text{mother}} - p_{\text{daughter}})^2$ space
- Form factors are constructed from matrix elements calculated via 3pt functions on the lattice



$H \to K$ form factors

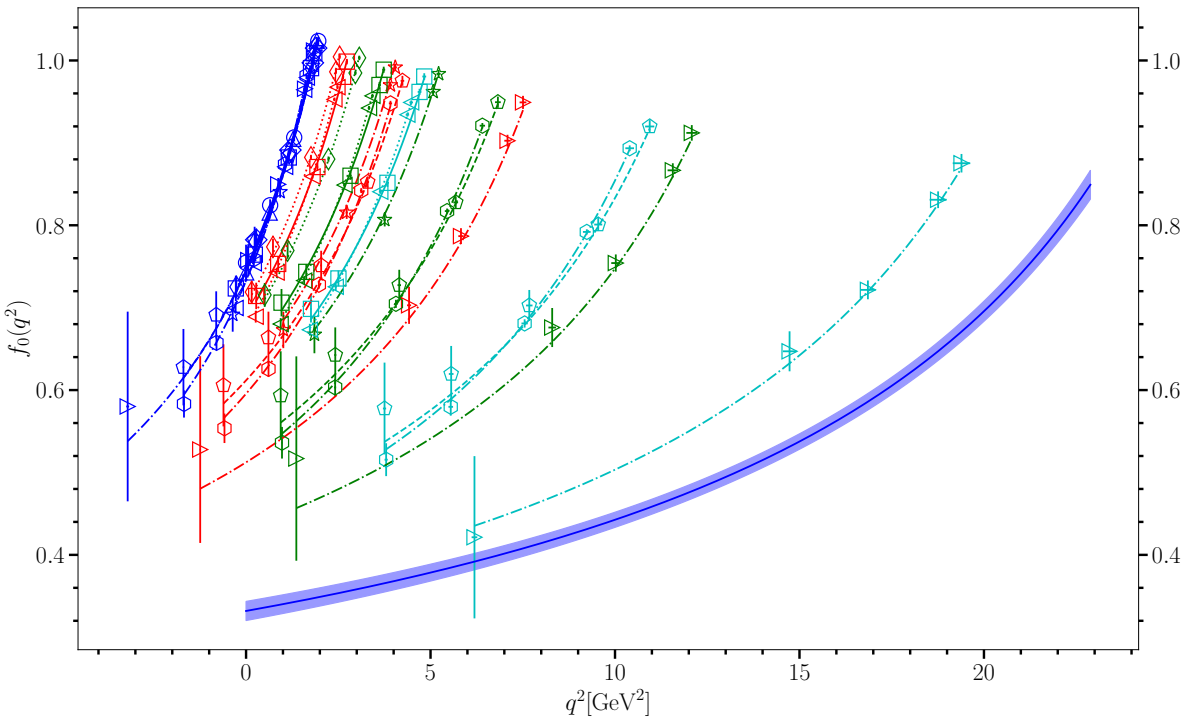


- Want meson form factors over the full range of q^2 values
- f_0, f_+ and f_T form factors use matrix elements from 3-point correlation functions with scalar, vector and tensor current insertions
- Typically use 3 or 4 T values on each ensemble, as well as averaging over 8 or 16 t_0 values (4 on finest lattice)
- We fit the time dependence to extract matrix elements from correlators



$H \to K$ form factors

Heavy-HISQ:



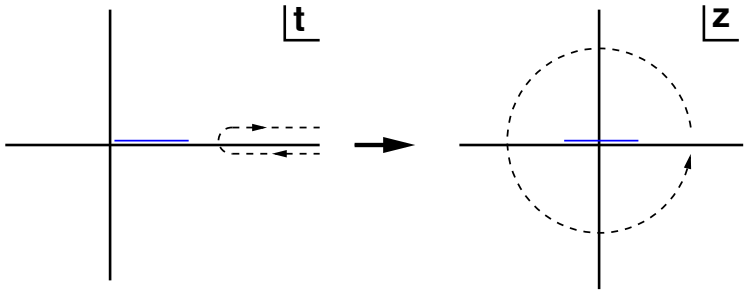
- Can't reach physical b mass
- Proceed for $H \to K$ using 'heavy' mass m_h
- $am_c \leq am_h \leq 0.8$ on each ensemble
- $am_b \approx 0.9$ on finest
- f_0 & f_+ non-pert. normalised (PCVC)
  For f_T, use normalisation from arXiv 2008.02024
- First fully relativistic calculation

Lattice details

- 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. $0.038 \leq (am_c)^2 \leq 0.789$
- Heavier masses on finer ensembles
- Cover whole physical q^2 range using twisted b.c.s to give momentum to daughter s quark
- Once we have data on each ensemble, need to extrapolate to the continuum and B mass

Moving to $B \to K$

Convert to z space and extrapolate in heavy mass too:



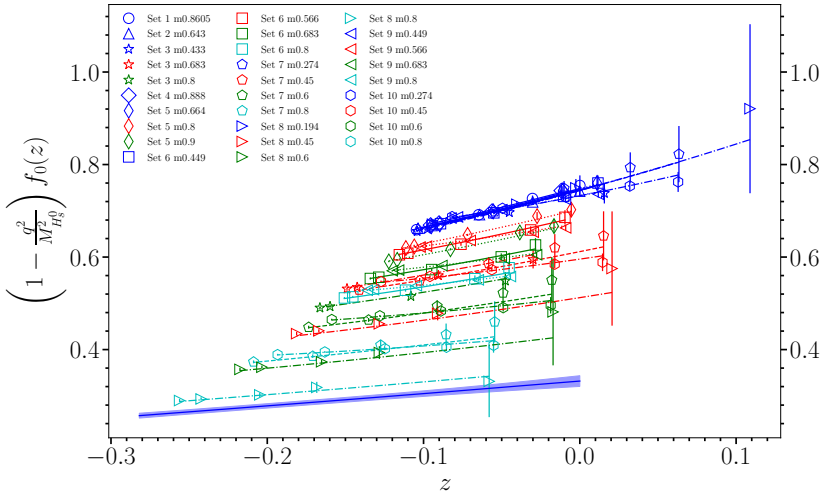
$$f_0(q^2) = \frac{1+L}{1-\frac{q^2}{M^2_{H^*_{s0}}}} \sum_{n=0}^{N-1} a_n^0 z^n,$$

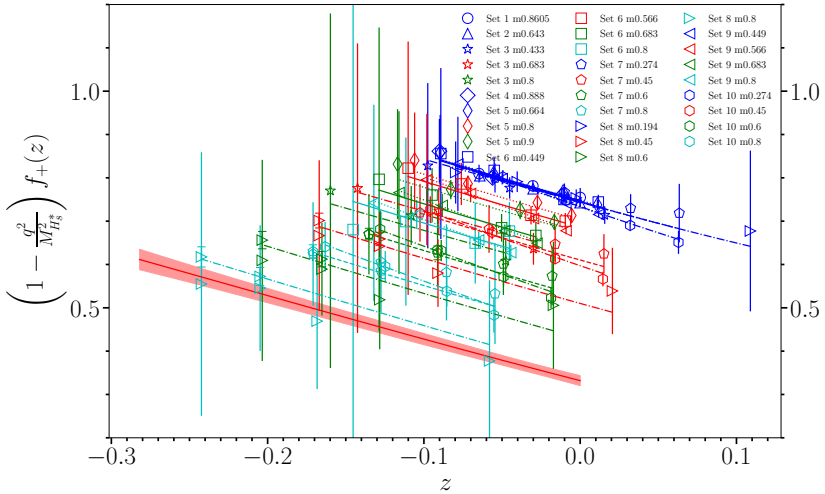
$$N = 3$$
$$x_\pi = \frac{M_\pi^2}{(4\pi f_\pi)^2}$$

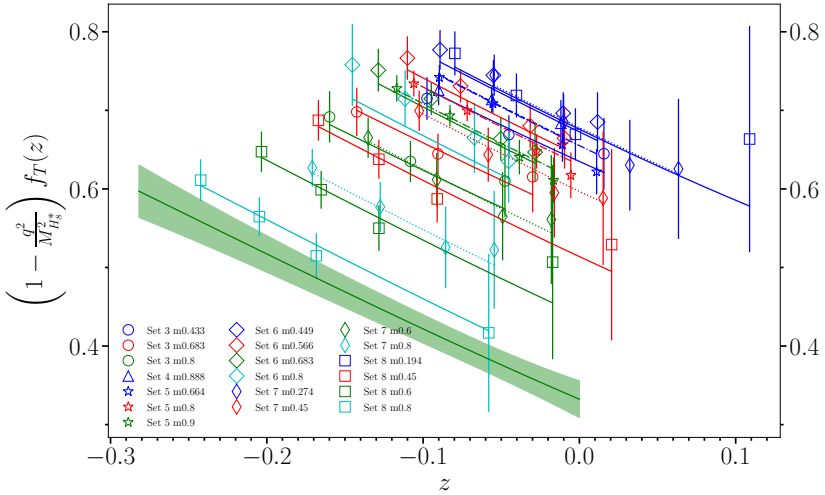
$$f_{+,T}(q^2) = \frac{1+L}{1-\frac{q^2}{M^2_{H^*_s}}} \sum_{n=0}^{N-1} a_n^{+,T}\left(z^n - \frac{n}{N}(-1)^{n-N} z^N\right).$$

$$a_n^{0,+,T} = \left(\frac{M_D}{M_H}\right)^{\zeta_n}\left(1+\rho_n^{0,+,T}\log\left(\frac{M_H}{M_D}\right)\right)(1+\mathcal{N}_n^{0,+,T})\times$$
$$\sum_{i,j,k,l=0}^{N_{ijkl}-1} d_{ijkln}^{0,+T}\left(\frac{\Lambda_{\rm QCD}}{M_H}\right)^i\left(\frac{am_h^{\rm val}}{\pi}\right)^{2j}\left(\frac{a\Lambda_{\rm QCD}}{\pi}\right)^{2k}(x_\pi - x_\pi^{\rm phys})^l.$$

$B \to K$ form factors

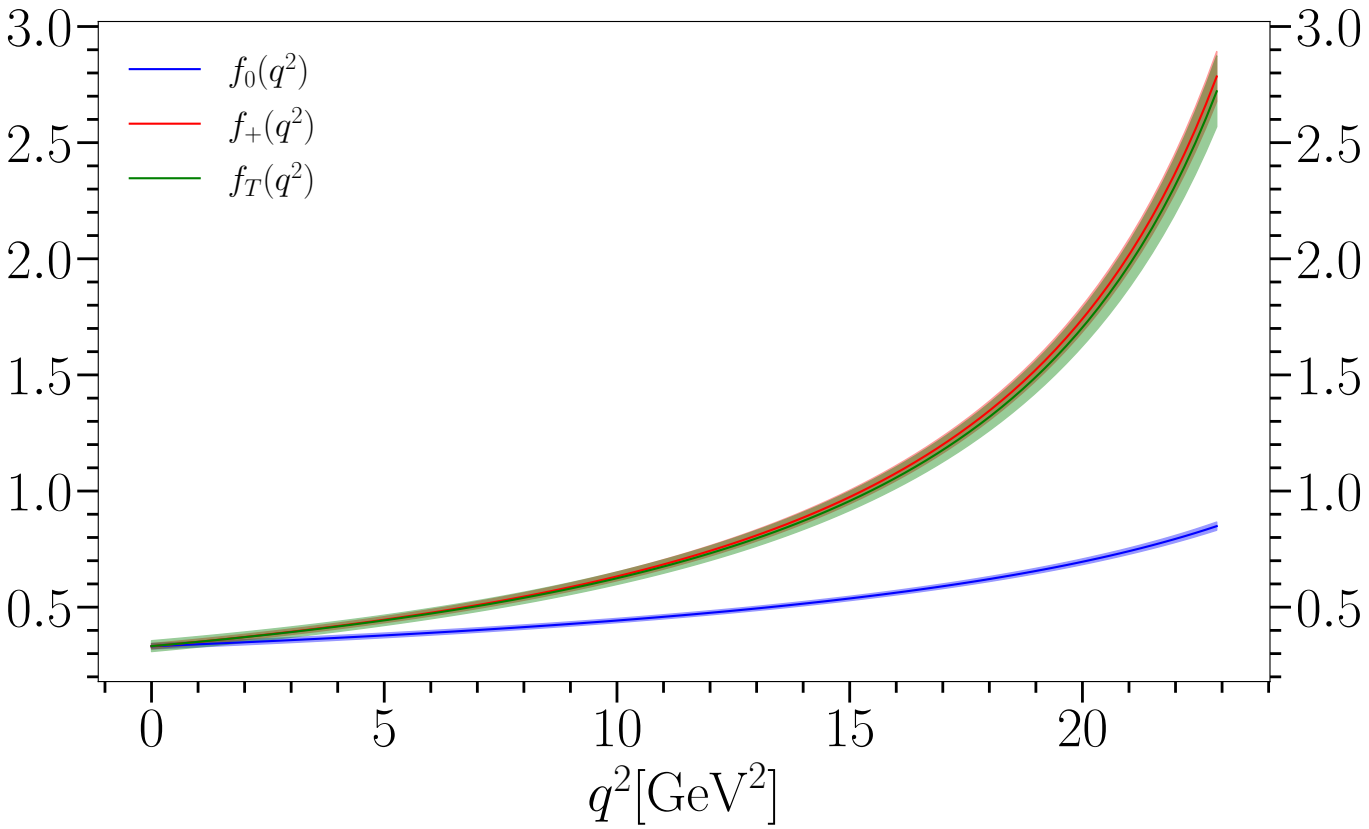






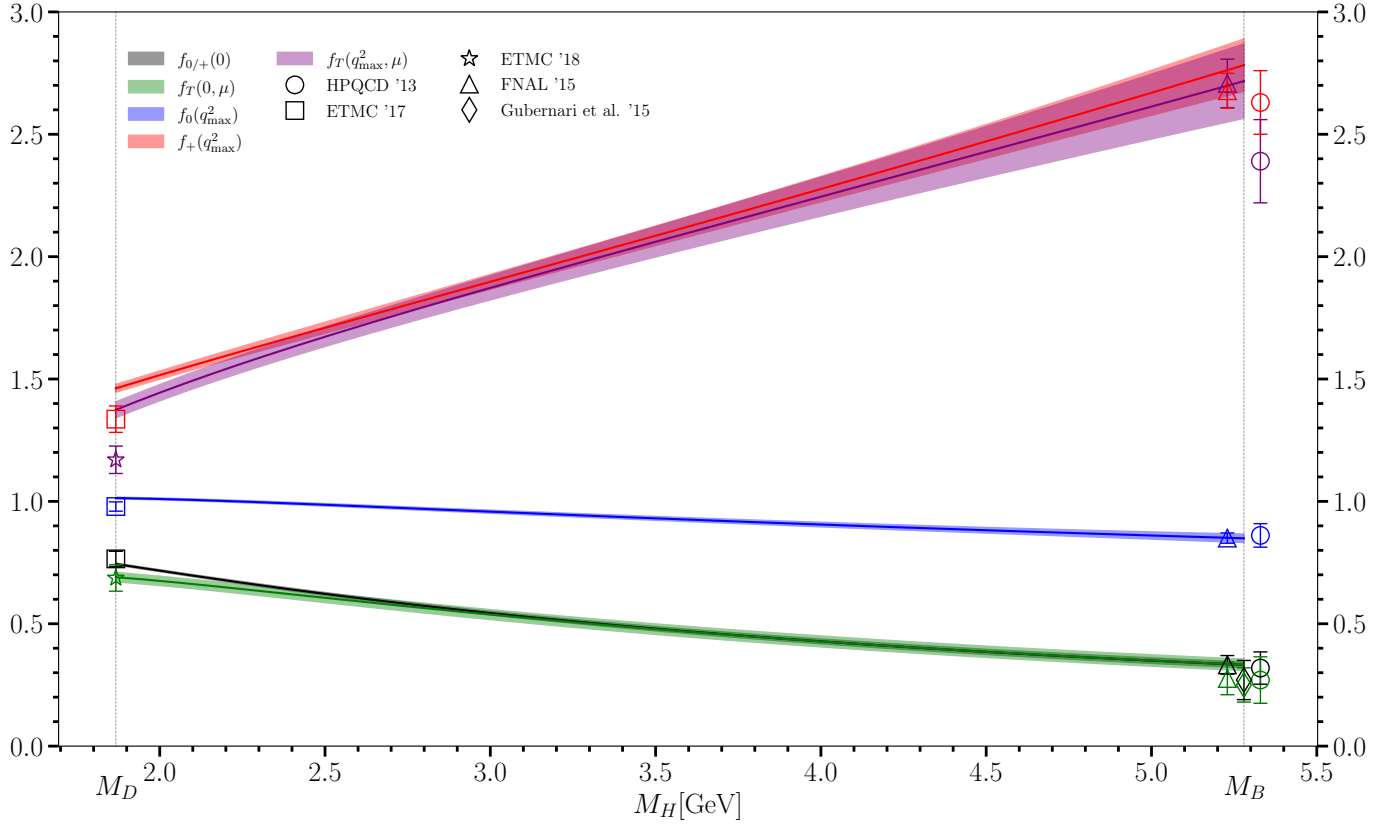
The z expansion is well behaved in all cases.

$B \to K$ form factors



Evaluate at the continuum, physical point and B mass to give precise form factors across whole q^2 range.

$B \to K$ form factors



Heavy-HISQ fits behaviour in M_H at fixed q^2. Improvements in precision, particularly at low q^2. Agree at $D \to K$ end too.

$B \to K\ell^+\ell^-$ phenomenology

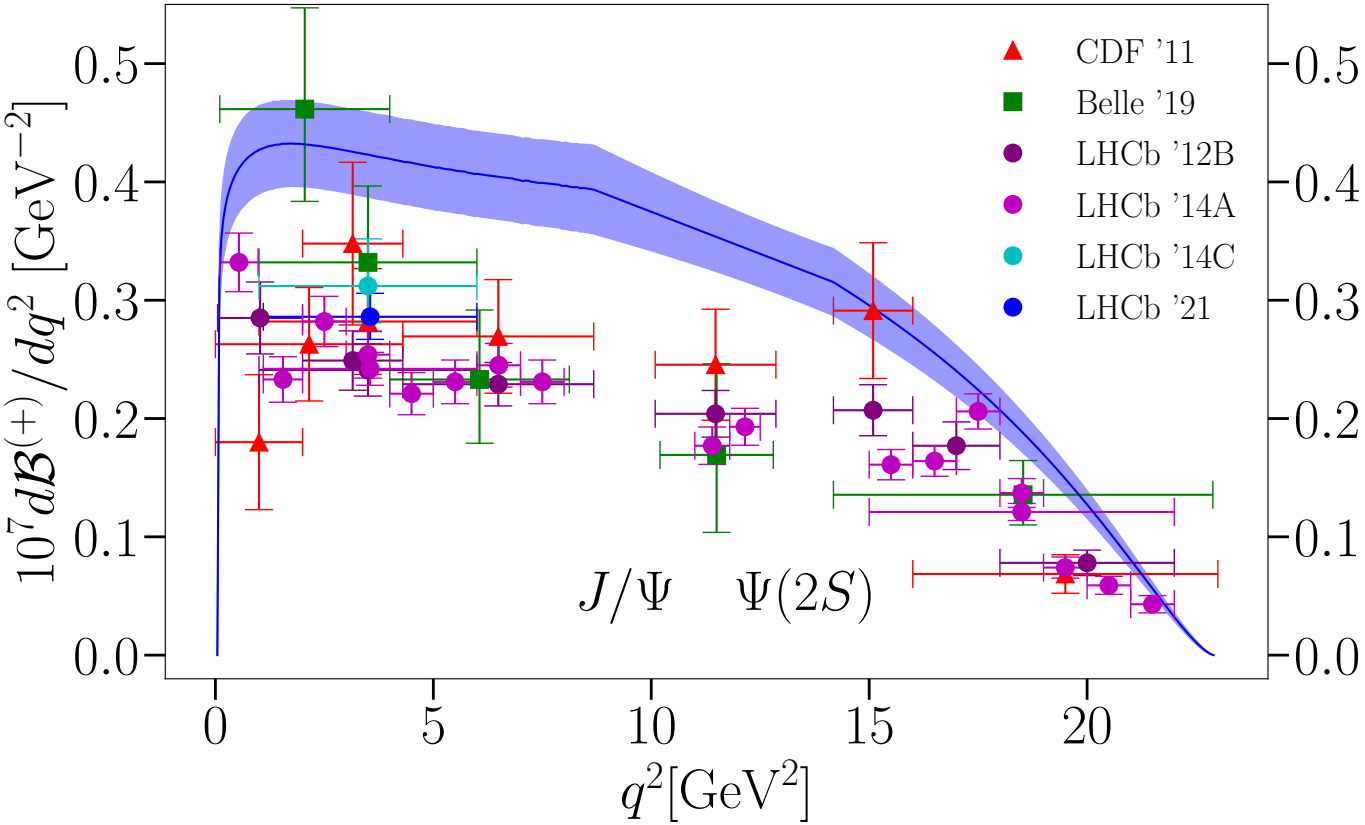
We can use the form factors to get at the differential decay rate for $B \to K\ell^+\ell^-$:

$$\frac{d\Gamma^{B\to K\ell^+\ell^-}}{dq^2} = \mathcal{F}_1|F_P(f_0, f_+, W_i)|^2 + \mathcal{F}_2 f_+^2$$
$$+\mathcal{F}_3|F_V(f_+, f_T, W_i)|^2 + \mathcal{F}_4|f_+F_P^*(f_0, f_+, W_i)|$$

where W_i are Wilson coefficients and $\mathcal{F}_i$ are known functions of kinematic factors and W_i (see 2207.13371). Does not account for $c\bar{c}$ resonances.

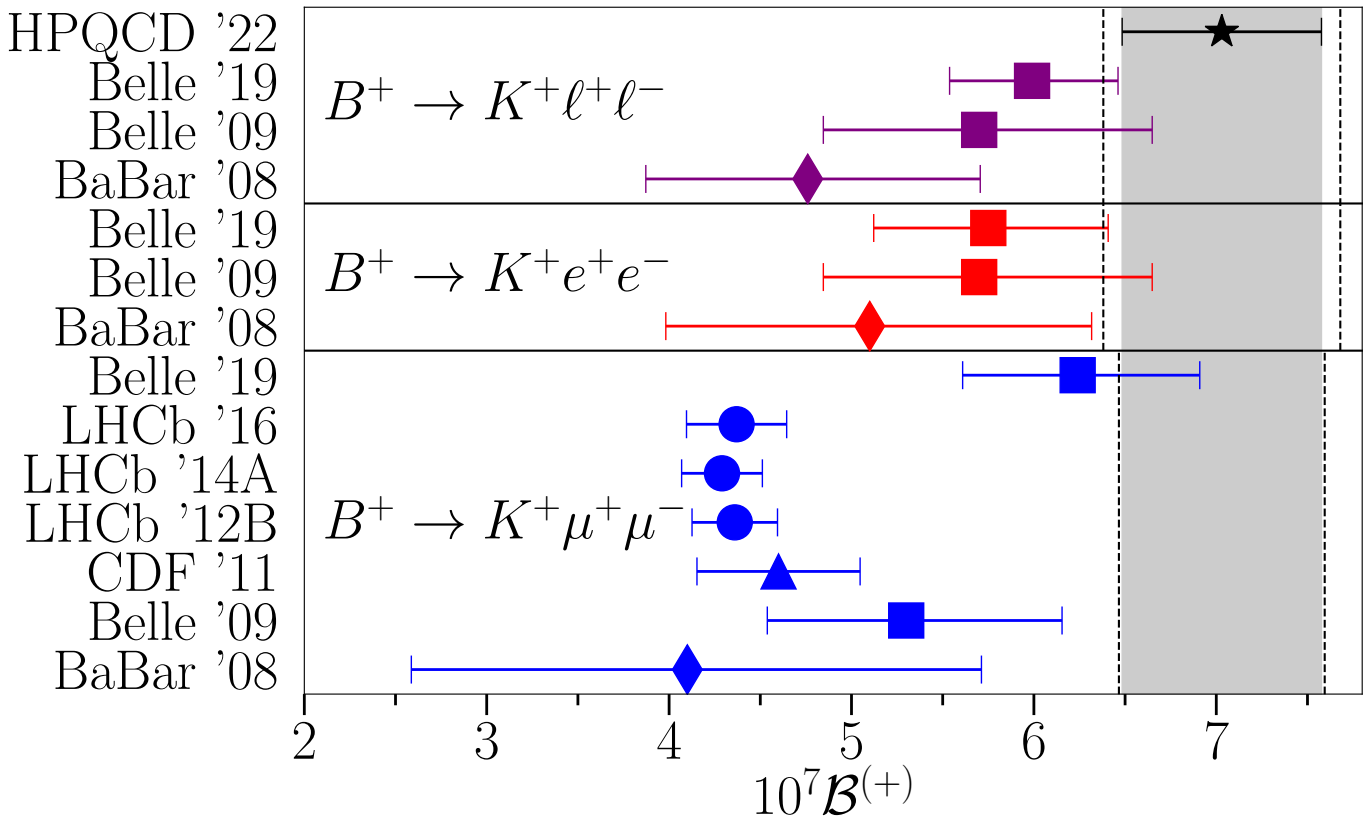
We can compare this with experiment, in differential form and integrate to get $\mathcal{B} = \Gamma\tau_B$.

$B \to K\ell^+\ell^-$ phenomenology



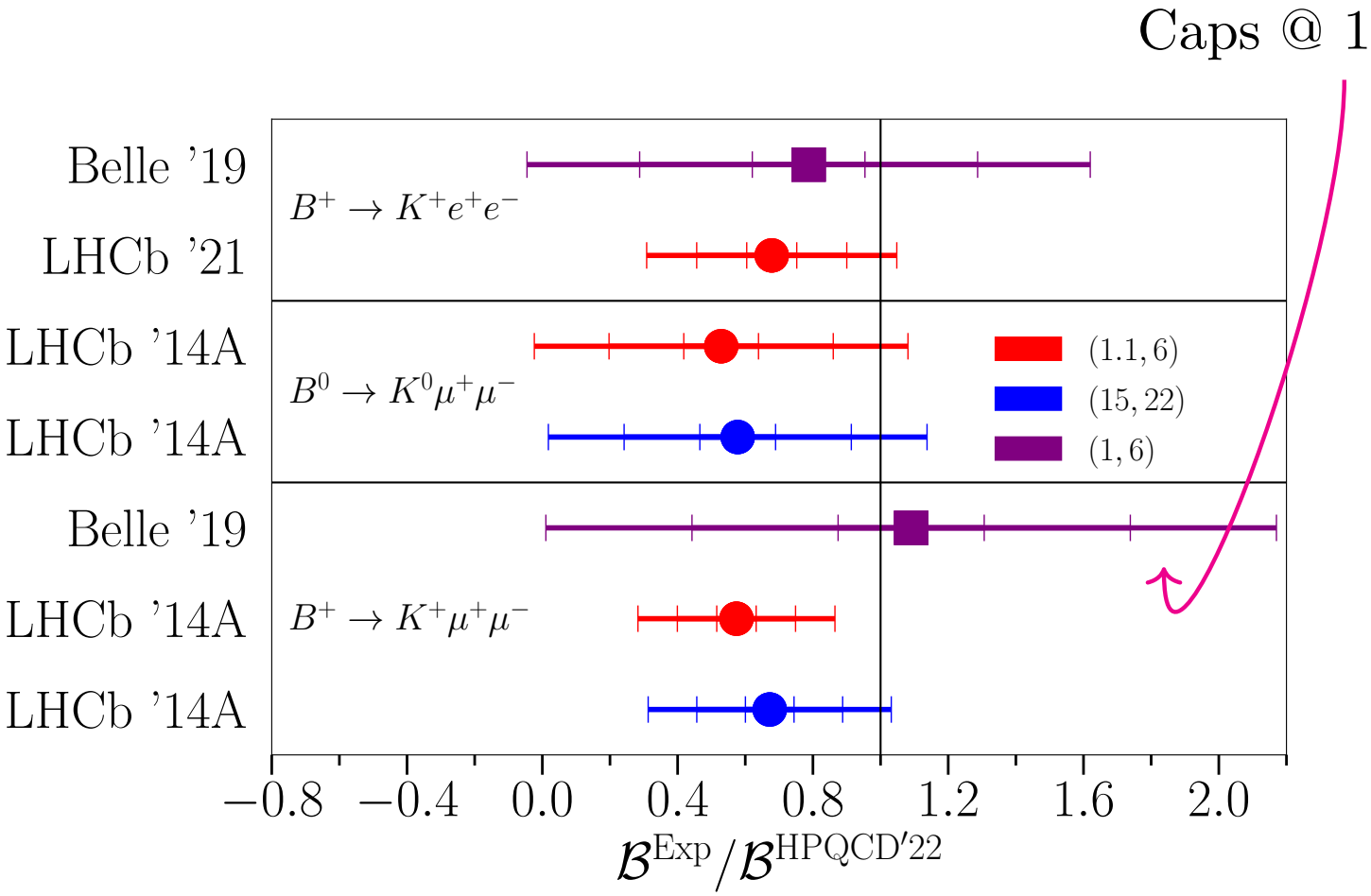
We can compare $\frac{d\mathcal{B}(B^+ \to K^+\mu(e)^+\mu(e)^-)}{dq^2}$ with binned experimental data.

$B \to K\ell^+\ell^-$ phenomenology



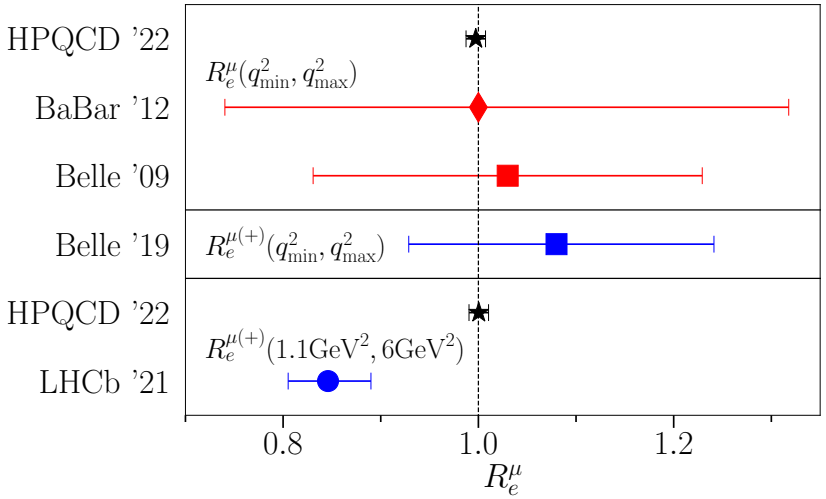
Can also integrate across the whole q^2 range to get the branching fraction. Vetoed region treated the same as experiment.

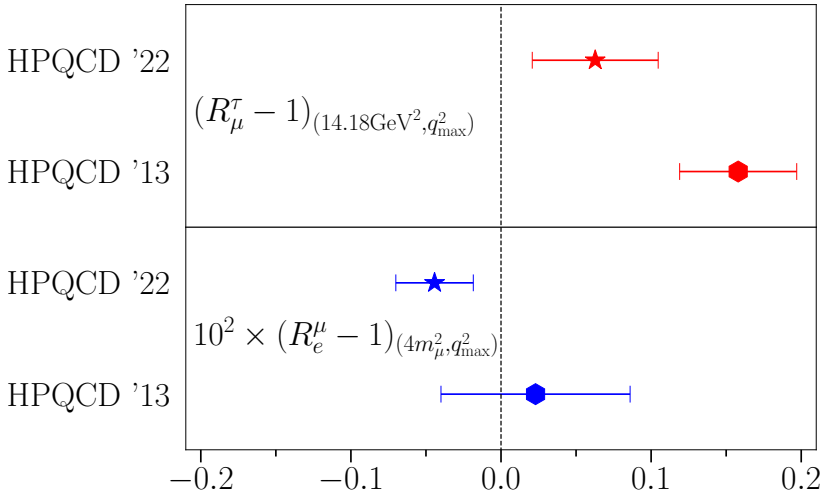
$B \to K\ell^+\ell^-$ phenomenology



We find large tensions in the theoretically clean regions of q^2: 1.1-6 GeV^2 and 15-22 GeV^2.

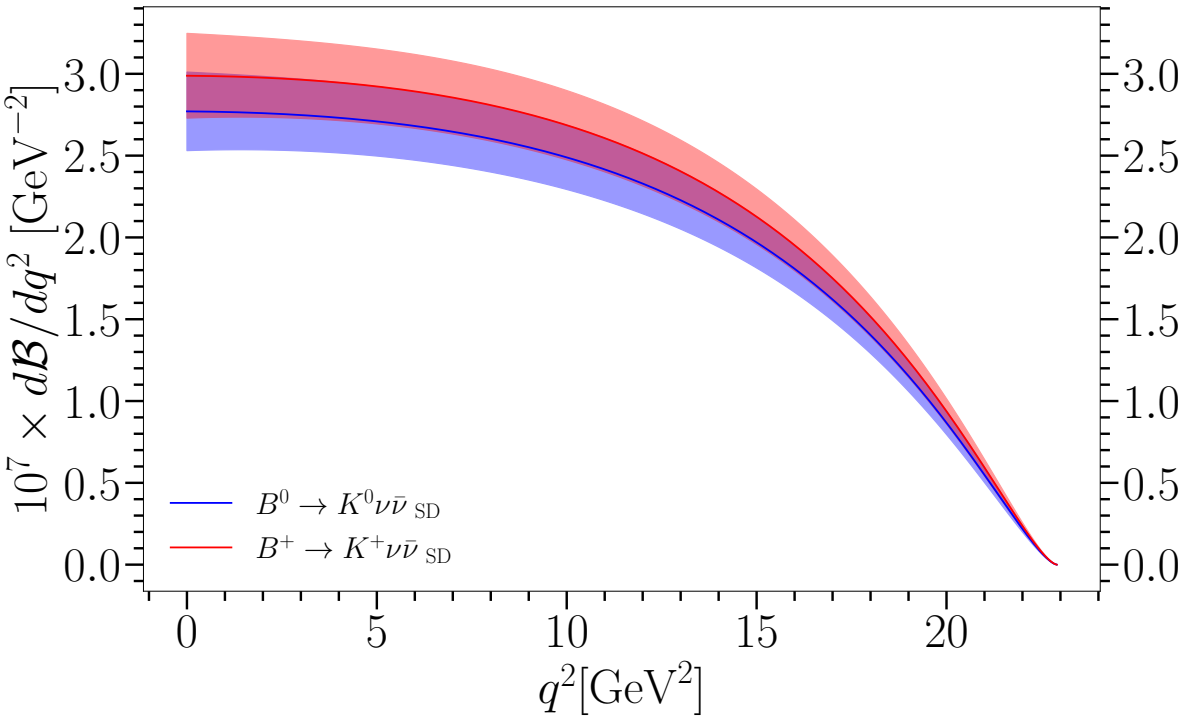
$B \to K\ell^+\ell^-$ phenomenology





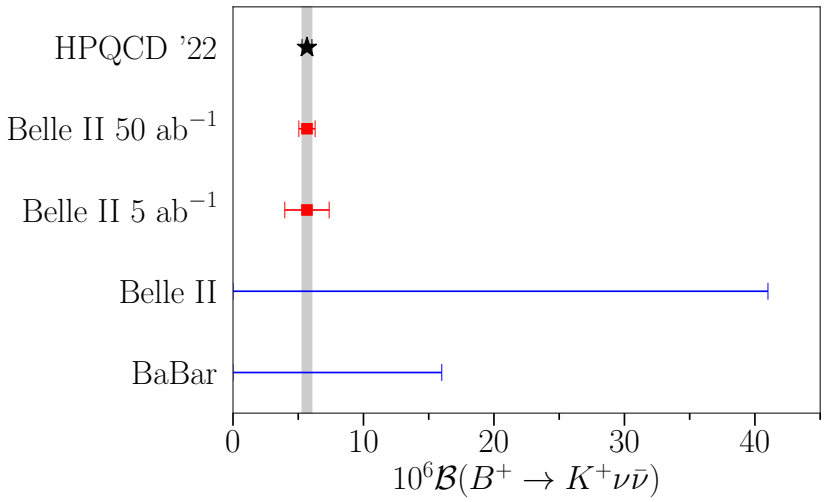
Our $R_e^\mu = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)}$ (including 1% uncertainty for QED on the left) is much more precise than experiment - does not contribute to tension.

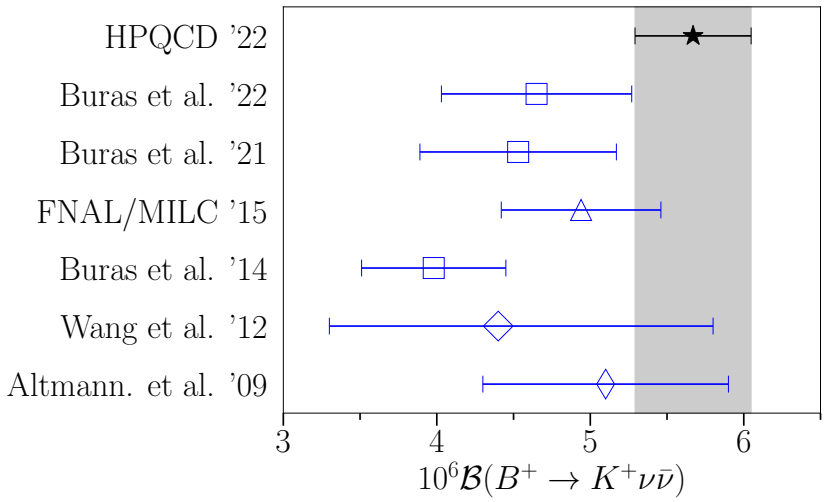
$B \to K\nu\bar{\nu}$ phenomenology



$$\frac{d\mathcal{B}(B \to K\nu\bar{\nu})_{\rm SD}}{dq^2} = \frac{(\eta_{\rm EW} G_F)^2 \alpha_{\rm EW}^2 X_t^2}{32\pi^5 \sin^4\theta_W} \tau_B |V_{tb}V_{ts}^*|^2 |\vec{p}_K|^3 f_+^2(q^2)$$

$B \to K\nu\bar{\nu}$ phenomenology





Experimental bounds on theoretically clean $\mathcal{B}(B \to K\nu\bar{\nu})$ are expected to improve as Belle II takes more data.

Conclusions

- First fully relativistic calculation of $B \to K$ form factors
- Reduced uncertainty, particularly at low q^2
- $B \to K$ branching fractions show $3 - 5\sigma$ tension with LHCb in clean regions
- Reduced below 2σ with BSM adjustments to C_9 and C_{10}
- Uncertainty on R_e^μ dominated by experiment and QED
- Branching fractions for $B \to K\nu\bar{\nu}$ now with $< 10\%$ error
- Belle II promised similar uncertainty at 50 ab^{-1} (arXiv: 2101.11573)

Thanks for listening. Any questions?