Lattice Gauge Theory Contributions to New Physics Searches

Review of Heavy-Quark Flavour Physics

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Outline of the Talk

I will mostly focus on b decays:

- Lattice methods for simulating b quarks
- $b \to c\ell\bar{\nu} : B_q \to D_q^{(*)}\ell\nu, R\left(D_{(s)}^{(*)}\right), A_{FB}$
- $b \to s\ell^+\ell^-: B \to K^{(*)}, R\left(K^{(*)}\right), P_5', B_s \to \phi\ell^+\ell^-$
- $b \to u/d: B \to \pi, B_s \to K$

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Disclaimer: This talk will contain my own opinions!

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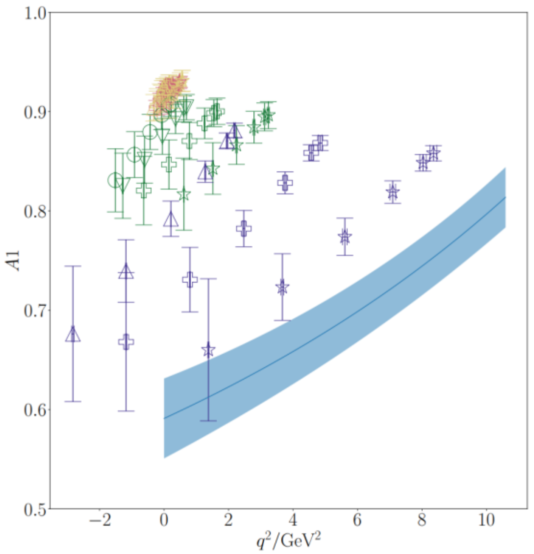
Relativistic b decays on the lattice

Several recent and currently ongoing lattice calculations of hadronic matrix elements using relativistic b quarks, e.g.

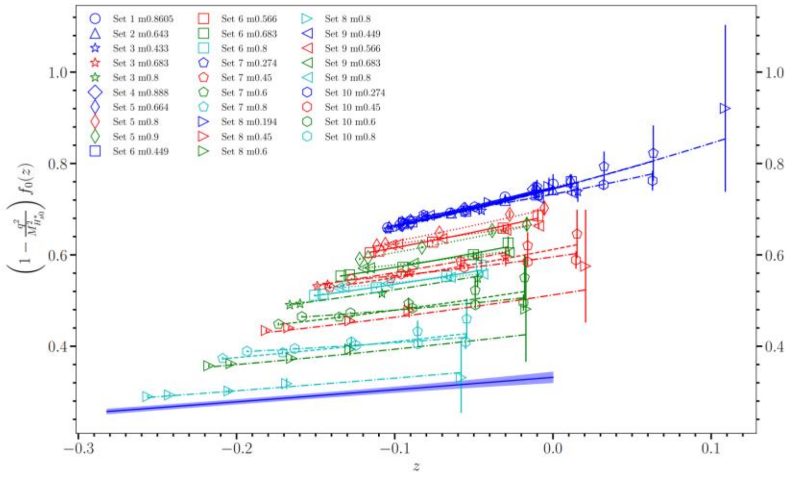
B_c-meson decays [2003.00914, 2007.06957, 2108.11242], B_s-meson decays [1906.00701, 2105.11433], B-meson decays [2203.04938, 2207.12468, 2301.09229, 2304.03137]

Common approach:

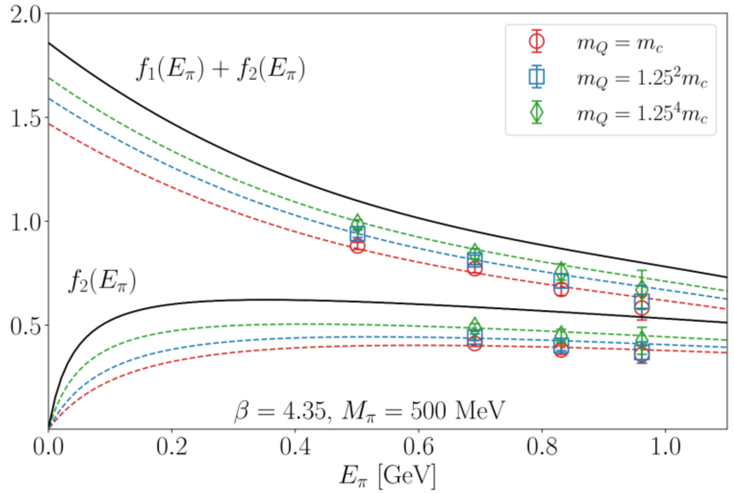
- Perform lattice calculation at multiple b quark masses at and below m_b, using the same action for all quarks
- fit results using HQET-like form to disentangle physical mass dependence and control discretisation effects



$B_s \to D_s^*$ [2105.11433]



$B \to K$ [2207.12468]



$B \to \pi$ [2203.04938]

Relativistic $\boldsymbol{b}$ decays on the lattice

Advantages:

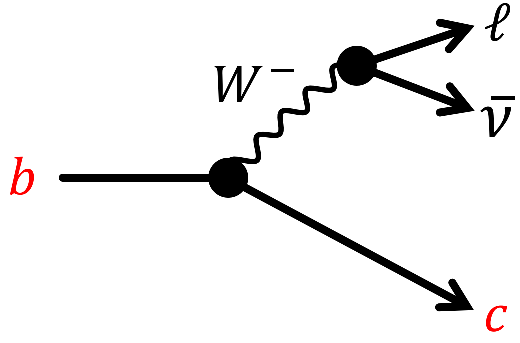
- Allows for nonperturbative renormalisation of currents using, e.g. RI-SMOM, partially conserved current relations.
- Connects b- and c-decays and gives heavy-mass dependence - test of HQET.
- Statistics limited

Challenges:

- Must compute and analyse many more correlation functions
- Fitting correlation functions simultaneously is difficult
- Some subtlety in choice of fit function, e.g. which basis to use for form factors

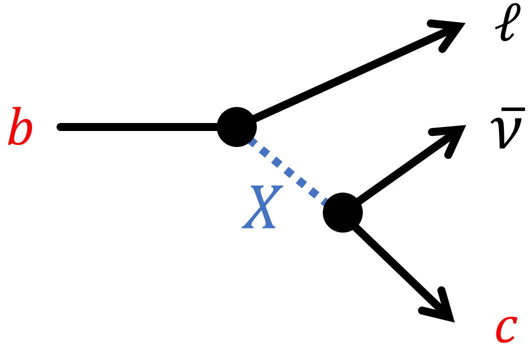
$b \to c\ell\bar{\nu}$

- In Standard Model (SM) mediated at tree level by the weak interaction



$$\to H_{\text{eff}} = \frac{4}{\sqrt{2}} G_F V_{cb} \bar{c}_L \gamma_\mu b_L \, \bar{\ell}_L \gamma^\mu \nu_L$$

- New Physics could modify this coupling, e.g. leptoquarks (LQ)

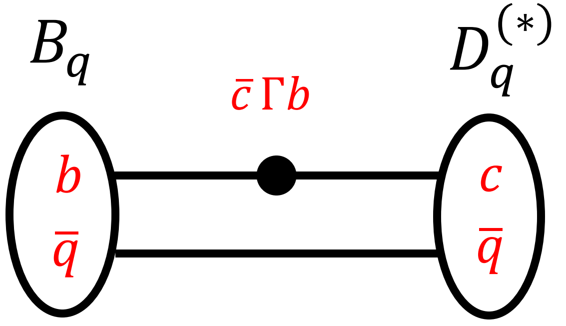


$$\to \delta H_{\text{eff}}^{\text{NP}} = \frac{4}{\sqrt{2}} G_F V_{cb} [\, C_{V_L} \, \bar{c}_L \gamma_\mu b_L \, \bar{\ell}_L \gamma^\mu \nu_L + C_{V_R} \bar{c}_R \gamma_\mu b_R \, \bar{\ell}_L \gamma^\mu \nu_L$$
$$+ C_{S_L} \bar{c}_R b_L \, \bar{\ell}_R \nu_L + C_{S_R} \bar{c}_L b_R \, \bar{\ell}_R \nu_L$$
$$+ C_T \bar{c}_R \sigma_{\mu\nu} b_L \, \bar{\ell}_R \sigma^{\mu\nu} \nu_L + \text{h.c.}]$$

Exclusive $b \to c\ell\bar{\nu}$ Decays

In nature, b and c quarks appear confined within hadrons

- Theory predictions require nonperturbative matrix elements of operators in H_{eff} between QCD bound states



$$\to \langle D_q^{(*)} | \bar{c}\Gamma b | B_q \rangle$$

These are typically parameterised in terms of **form factors (FFs)** according to the Lorentz and helicity structure of the decay

- 3 independent FFs for P to P, 7 for P to V

$$\left\langle D_q | \bar{c} b | B_q \right\rangle = \sqrt{M_{B_q} M_{D_q}} (w+1)\, h_S(w),$$

$$\left\langle D_q | \bar{c}\gamma^\mu b | B_q \right\rangle = \sqrt{M_{B_q} M_{D_q}} [\, h_+(w)(v+v')^\mu + h_-(w)(v-v')^\mu] \,,$$

$$\left\langle D_q | \bar{c}\sigma^{\mu\nu} b | B_q \right\rangle = i \sqrt{M_{B_q} M_{D_q}} [\, h_T(w)(v'^\mu v^\nu - v'^\nu v^\mu)] \,.$$

$$\left\langle D_q^* | \bar{c}\gamma^5 b | B_q \right\rangle = -\sqrt{M_{B_q} M_{D_q}} h_P(w)(\epsilon^* \cdot v),$$

$$\left\langle D_q^* | \bar{c}\gamma^\mu b | B_q \right\rangle = i \sqrt{M_{B_q} M_{D_q}} h_V(w) \varepsilon^{\mu\nu\alpha\beta} \epsilon^*_\nu v'_\alpha v_\beta \,,$$

$$\left\langle D_q^* | \bar{c}\gamma^\mu \gamma^5 b | B_q \right\rangle = \sqrt{M_{B_q} M_{D_q}} [h_{A_1}(w)(w+1)\epsilon^{*\mu} - h_{A_2}(w)(\epsilon^{*\mu} \cdot v) v^\mu - h_{A_3}(w)(\epsilon^{*\mu} \cdot v) v'^\mu],$$

$$\left\langle D_q^* | \bar{c}\sigma^{\mu\nu} b | B_q \right\rangle = -\sqrt{M_{B_q} M_{D_q}} \varepsilon^{\mu\nu\alpha\beta} [h_{T_1}(w)\epsilon^*_\alpha (v+v')_\beta + h_{T_2}(w)\epsilon^*_\alpha (v-v')_\beta + h_{T_3}(w)(\epsilon^* \cdot v) v_\alpha v'_\beta].$$

$$v = p_{B_q}/M_{B_q}, \quad v' = p_{D_q^{(*)}}/M_{D_q^{(*)}}, \quad w = v \cdot v'$$

Exclusive $b \to c\ell\bar{\nu}$ Decays

Lattice calculations of the FFs are progressing rapidly, with many new results in the last few years:

Fermilab-MILC: 2+1 asqtad, Wilson-clover b and c quarks

HPQCD: 2+1+1 HISQ, heavy-HISQ b

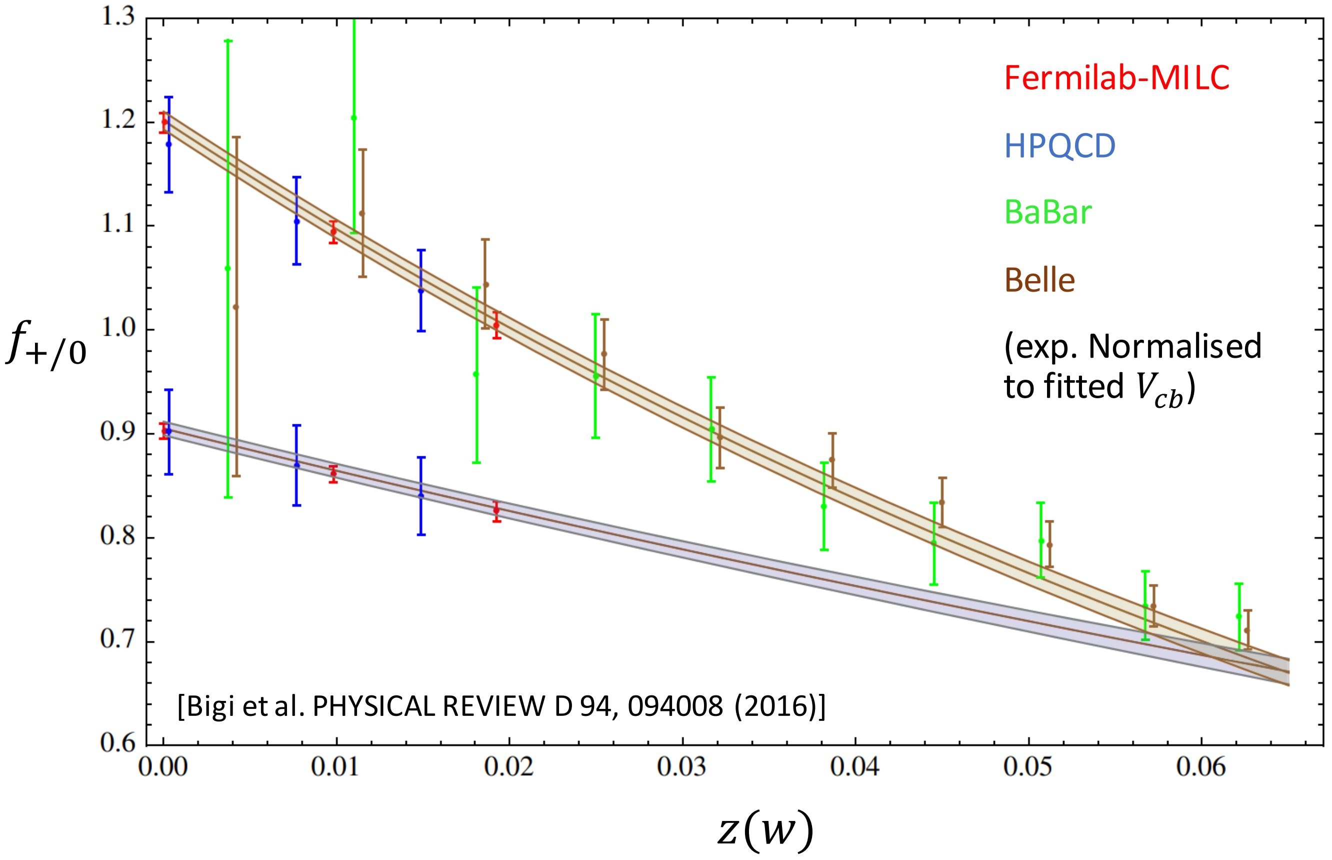
JLQCD: 2+1 Möbius domain-wall, Möbius domain-wall b

	$h_\pm(w)$	$h_T(w)$	$h_{A_{1,2,3},V}(w)$	$h_{T_{1,2,3}}(w)$
$B \to D^{(*)}$	✓ [1503.07237] ✓ [1505.03925*] (✓)	(✓)	✓[2105.14019] (✓) [2304.03137] (✓) [2306.05657]	(✓) [2304.03137]
$B_s \to D_s^{(*)}$	✓ [1906.00701]		✓ [2105.11433] (→[2304.03137])	(✓) [2304.03137]
$B_c \to J/\psi(\eta_c)$			✓ [2007.06957]	

* 2+1 asqtad, NRQCD b quarks, HISQ c quarks

$B \to D\ell\bar{\nu}$

Good agreement between lattice calculations for SM FFs and also with experiment!



$$\frac{d\Gamma}{dw} = |V_{cb}|^2 G(w)^2 \, R(w),$$

where for $\ell = \mu$ or e

$$G(w) = \frac{2\sqrt{M_B M_D}}{M_D + M_B} \times f_+(w).$$

This gives the most recent averages

$$V_{cb}^{\mathrm{HFLAV}} = 39.14 \pm 0.92_{\mathrm{exp}} \pm 0.36_{\mathrm{th}} \times 10^{-3}$$

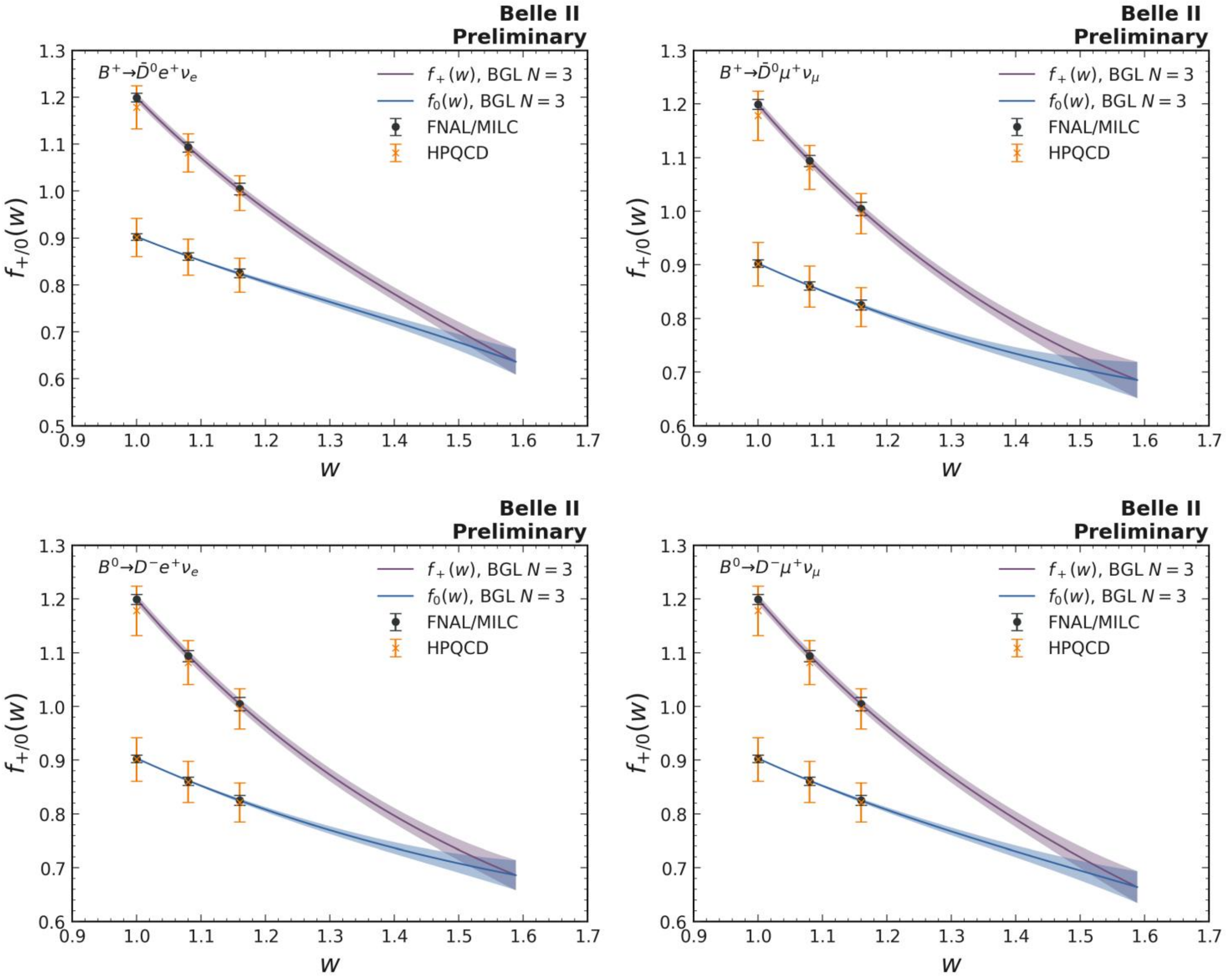
$$R_{\mathrm{th}}^{\mathrm{HFLAV}}(D) = \frac{\Gamma(B \to D\tau\bar{\nu}_\tau)}{\Gamma(B \to D\mu\bar{\nu}_\mu)} = 0.298 \pm 0.004$$

$$R_{\mathrm{exp}}^{\mathrm{HFLAV}}(D) = 0.339 \pm 0.030$$

$B \to D\ell\bar{\nu}$ Belle II [2210.13143]

New results from Belle II using 189fb^{-1} integrated luminosity also agree well with theory

- Note the limited w range of old lattice calculations
- Calculations underway at Fermilab-MILC collaboration to update with all-HISQ calculation



Clockwise from top left:

$$\frac{\chi^2}{\text{dof}} = \frac{18.2}{14}, \frac{12.3}{14}, \frac{11.0}{14}, \frac{15.1}{14}$$

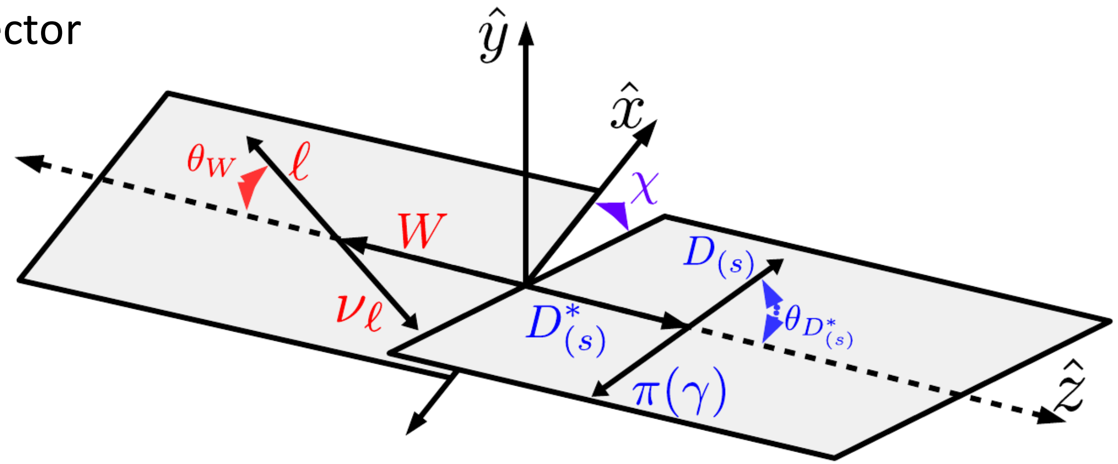
$B \to D^* \ell \bar{\nu}$

- Lattice calculation harder than for $B \to D$ due to noisier vector and larger number of FFs.
- Rich angular structure due to vector D^* final state
- Angular asymmetry observables, e.g.

$$A_{FB} = \frac{1}{\Gamma}\left[\int_0^1 - \int_{-1}^0\right] \frac{d\Gamma}{d\cos(\theta_W)} d\cos(\theta_W)$$

$$A_{\lambda_\ell} = \frac{\Gamma^{\lambda_\ell = -\frac{1}{2}} - \Gamma^{\lambda_\ell = +\frac{1}{2}}}{\Gamma}$$

$$F_L = \frac{\Gamma^{\lambda_{D^*}=0}}{\Gamma}$$



3 LQCD results for 4 SM FFs away from zero recoil

Published:

Fermilab-MILC: 2+1 asqtad, Wilson-clover b and c quarks

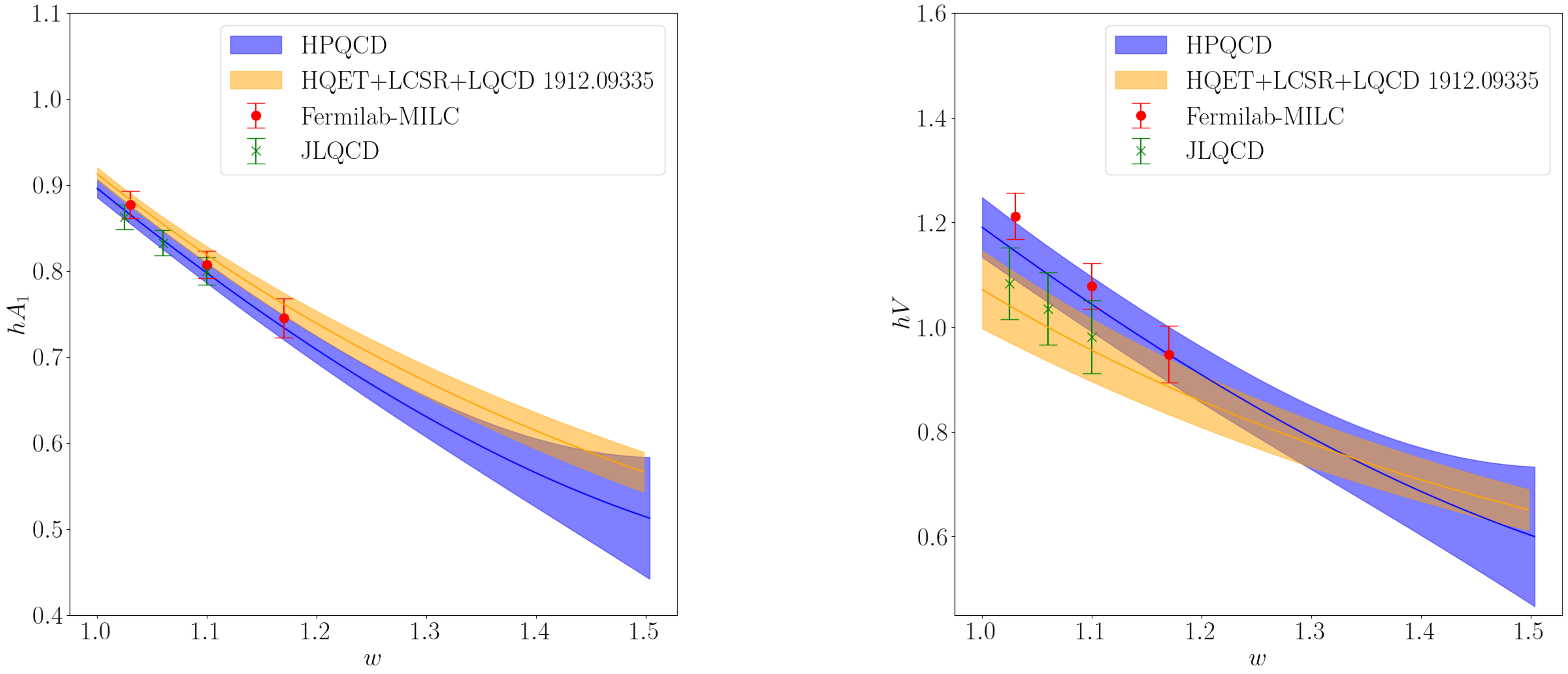
arxiv:

HPQCD: 2+1+1 HISQ, heavy-HISQ b (+ Tensor FFs)

JLQCD: 2+1 Möbius domain-wall

$B \to D^* \ell \bar{\nu}$

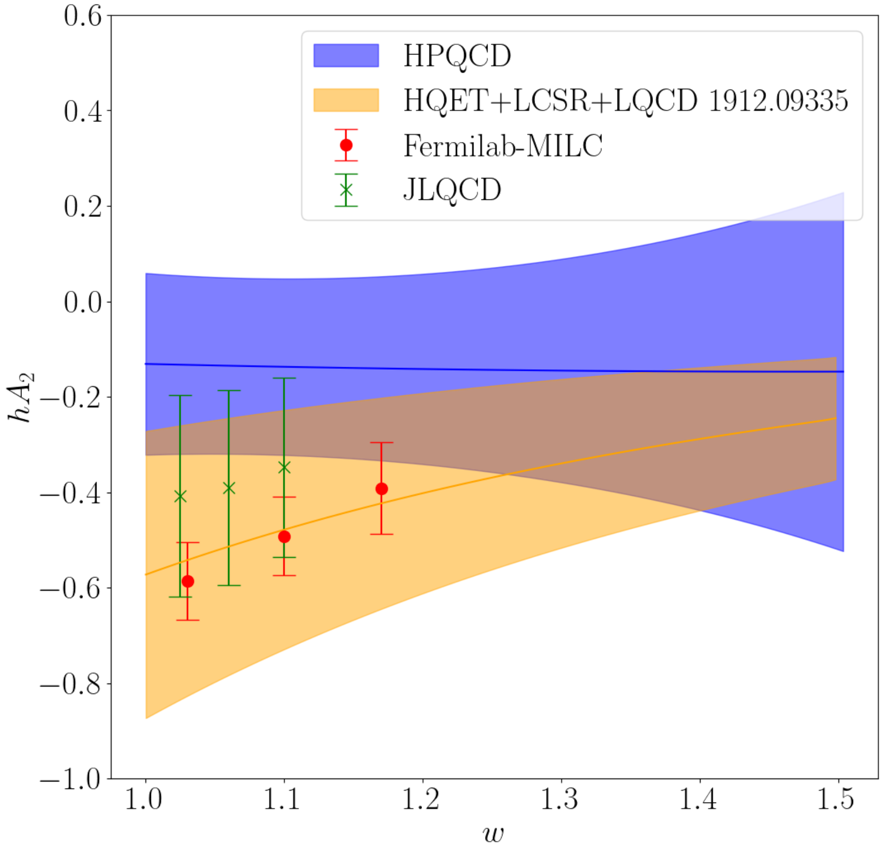
Good agreement between lattice calculations of the SM FFs h_{A_1} and h_V

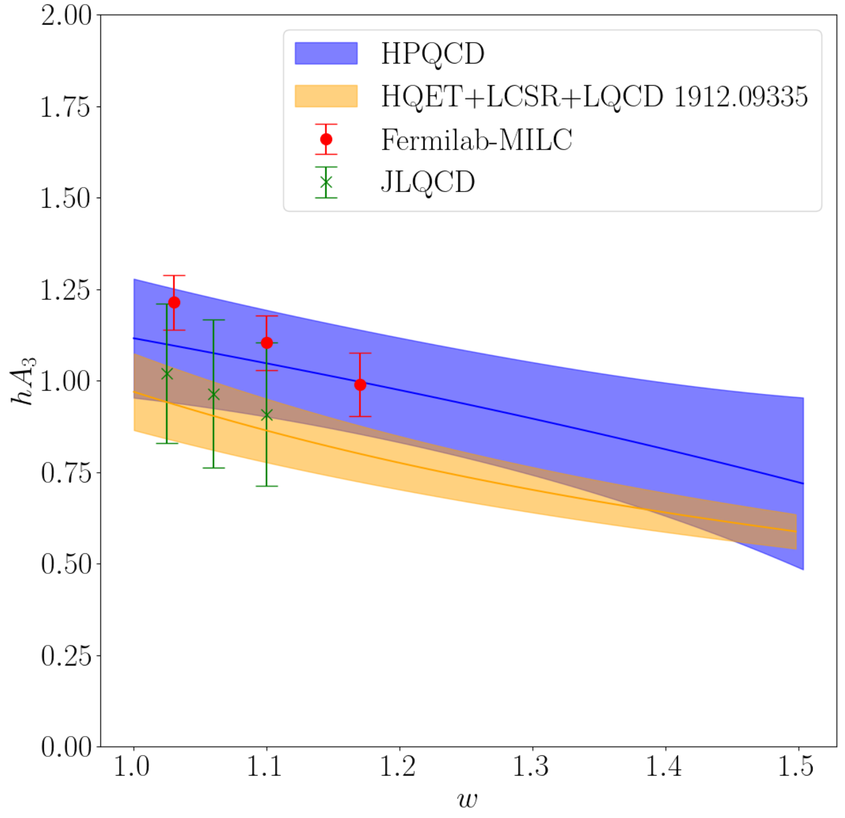


[2105.14019, 2304.03137,2306.05657]

$B \to D^* \ell \bar{\nu}$

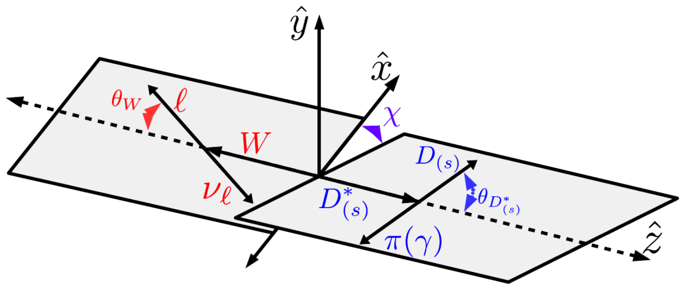
agreement between lattice calculations of SM FFs h_{A_2} and h_{A_3} less good





[2105.14019, 2304.03137,2306.05657]

$B \to D^*\ell\bar{\nu}$

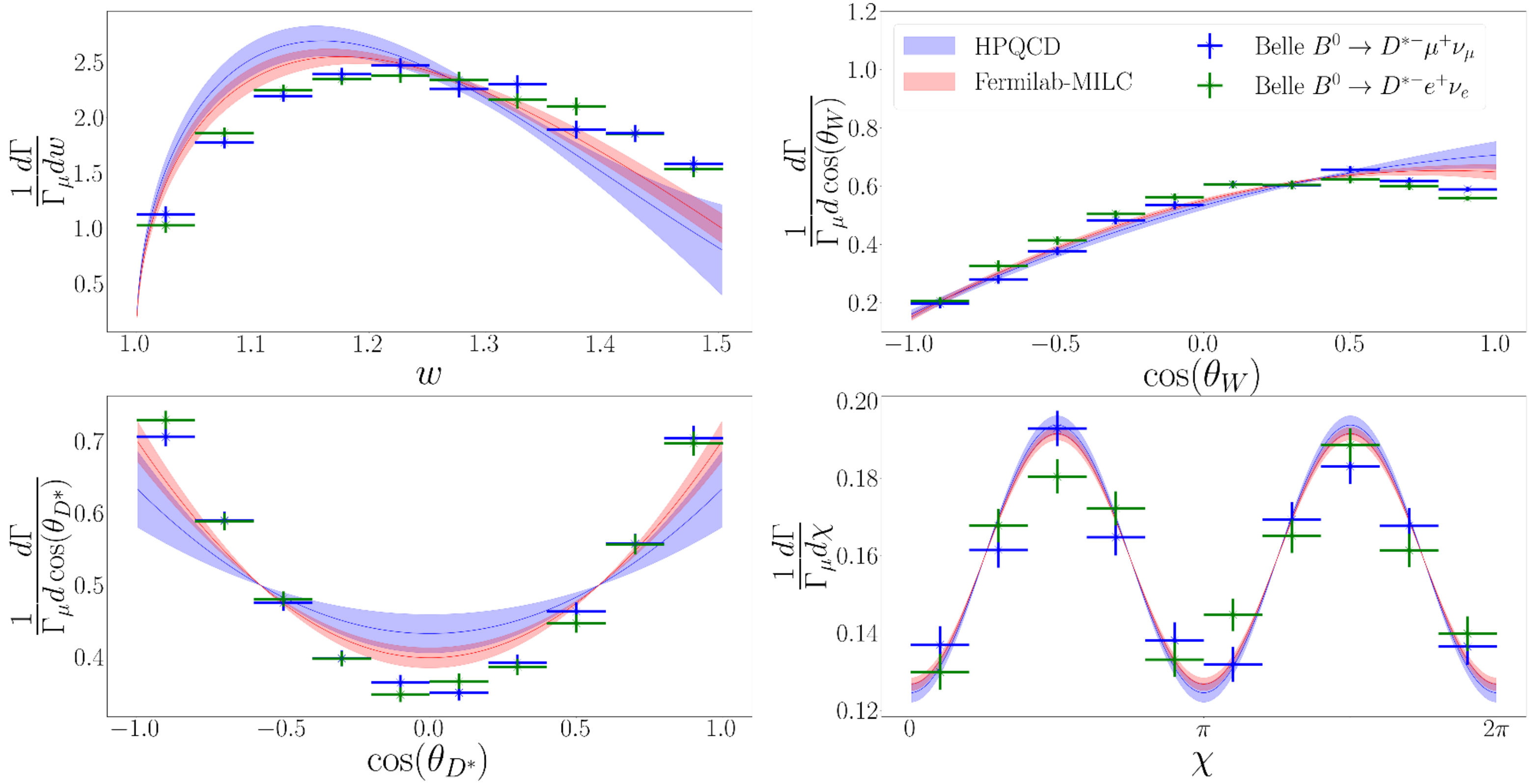


$$V_{cb}^{JLQCD} = 39.19(90) \times 10^{-3}$$

Some tension with experimental shape $\approx 2\sigma$.

Exclusive, model-independent V_{cb} using full range of Exp. data and lattice FFs

$$|V_{cb}^{\mathrm{FNAL}}| = 38.40 \pm 0.78 \times 10^{-3}$$
$$|V_{cb}^{\mathrm{HPQCD}}| = 39.31 \pm 0.74 \times 10^{-3}$$



Both in good agreement with 2021 HFLAV exclusive average, using $B \to D^{(*)}\ell\bar{\nu}$ and $B_s \to D_s^{(*)}\ell\bar{\nu}$:

$$|V_{cb}^{\mathrm{HFLAV}}| = 38.90 \pm 0.53 \times 10^{-3}$$

Compare the inclusive result:

$$|V_{cb}^{\mathrm{HFLAV}}| = 42.19 \pm 0.78 \times 10^{-3}$$

In tension at the level of $\approx 3.5\sigma$

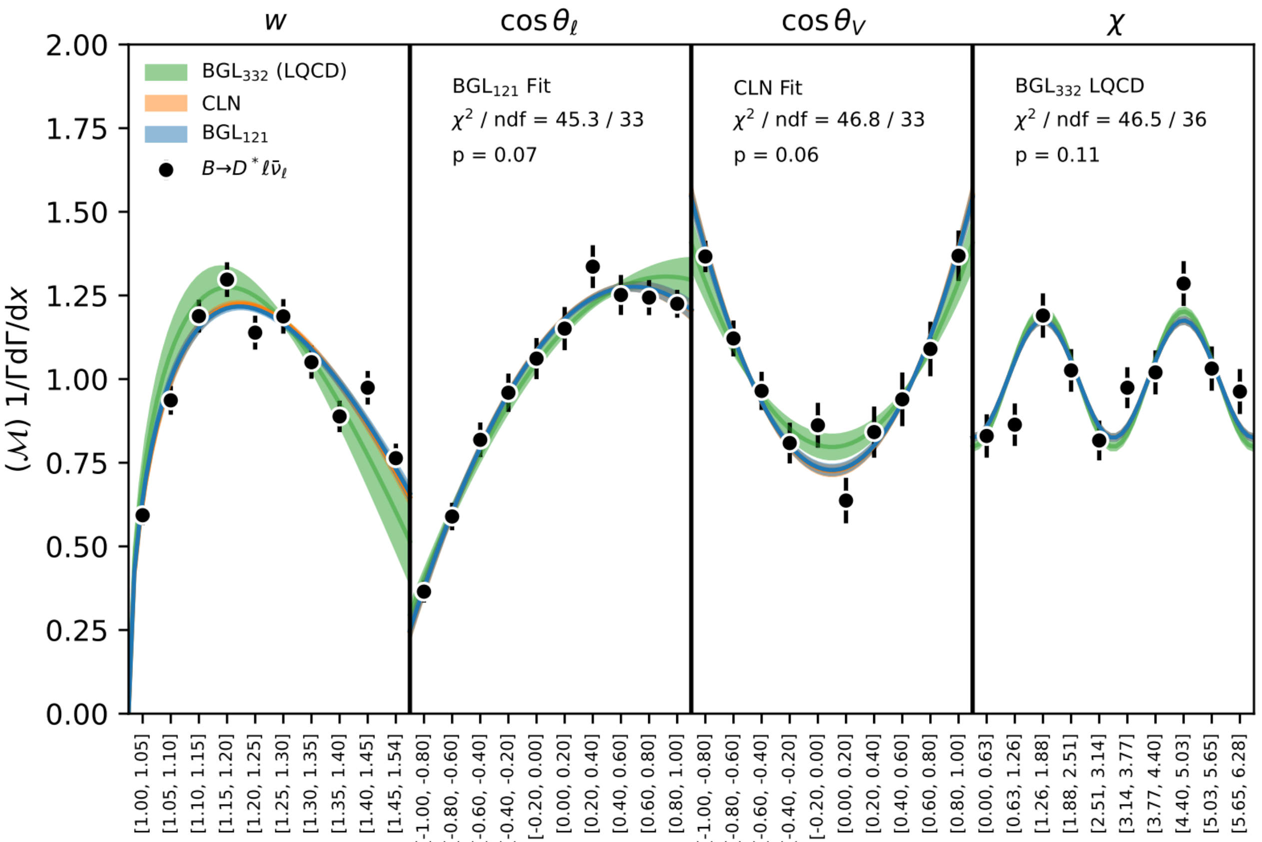
$B \to D^* \ell \bar{\nu}$ Belle [2301.07529]

New results from Belle for $\bar{B}^0$ and B^- mode shapes (Green BGL332 band is Fermilab-MILC 2105.14019) using full 711fb^{-1}. Using zero recoil lattice results together with HFLAV branching fractions they find:

$$|V_{cb}|_{\text{BGL}} = 40.6 \pm 0.9 \times 10^{-3}.$$

Also find angular asymmetry variables for light modes consistent with lattice-only SM results

	Belle 2301.07529	HPQCD 2304.03137
$A_{FB}^{\ell=e}$	0.230 ± 0.019	0.274 ± 0.023
$A_{FB}^{\ell=\mu}$	0.252 ± 0.020	0.270 ± 0.024
$A_{FB}^{\ell=\mu} - A_{FB}^{\ell=e}$	0022 ± 0.027	-0.0035 ± 0.0009
$\frac{F_L^{\ell=e} + F_L^{\ell=\mu}}{2}$	0.501 ± 0.012	0.430 ± 0.036



$R(D^*)$

$R^{JLQCD}(D^*) = 0.252(22)$

With lattice FFs across the full kinematic range, can determine a theory-only $R(D^*)$ without including experimental information on FFs. Find:

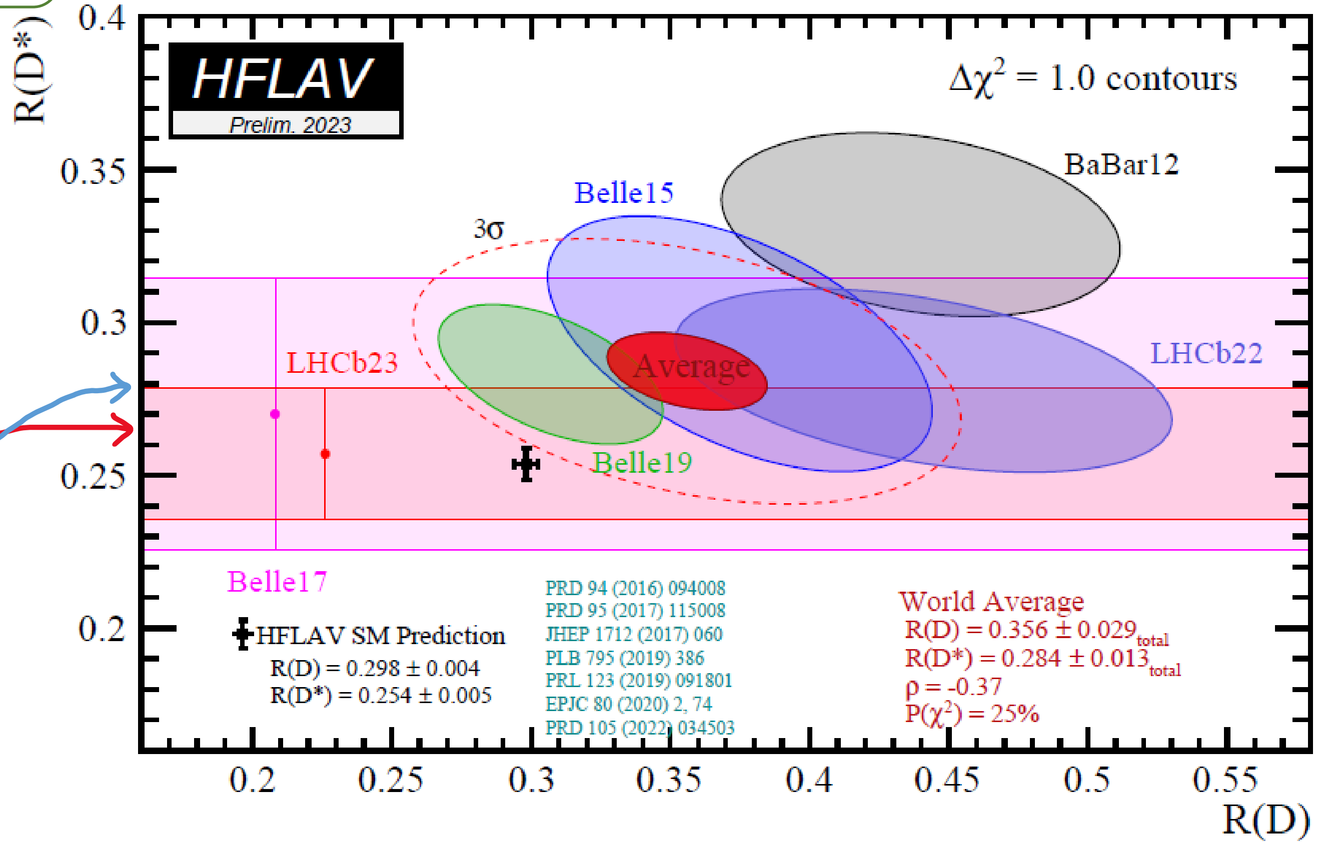
$$R(D^*) = \frac{\Gamma(B \to D^* \tau \bar{\nu}_\tau)}{\Gamma(B \to D^* \mu \bar{\nu}_\mu)}$$

Using lattice results only,

$$R^{\rm FNAL}(D^*) = 0.265 \pm 0.013,$$
$$R^{\rm HPQCD}(D^*) = 0.279 \pm 0.013.$$

However, fitting FFs to lattice+experiment gives

$$R^{\rm FNAL}_{\rm latt+exp}(D^*) = 0.2484 \pm 0.0013,$$
$$R^{\rm HPQCD}_{\rm latt+exp}(D^*) = 0.2471 \pm 0.0019.$$



Most recent measurements (including new 2023 LHCb measurement!) in good agreement with SM, but $\approx 3\sigma$ tension remains with average.

Need to improve understanding of the shape of the lattice FFs for $B \to D^* \ell \bar{\nu}$

- HQET fits to lattice $B \to D$ + zero recoil lattice $B \to D^*$ + QCDSR + LCSR agree with determinations using exp. data as input

Constraining NP in $b \to c\ell\bar{\nu}$ using $B \to D^{(*)}\ell\bar{\nu}$

These measurements can be used to constrain NP appearing in the light leptonic mode.

- The patterns of Wilson coefficients generated by different tree-level models are [1801.01112]:

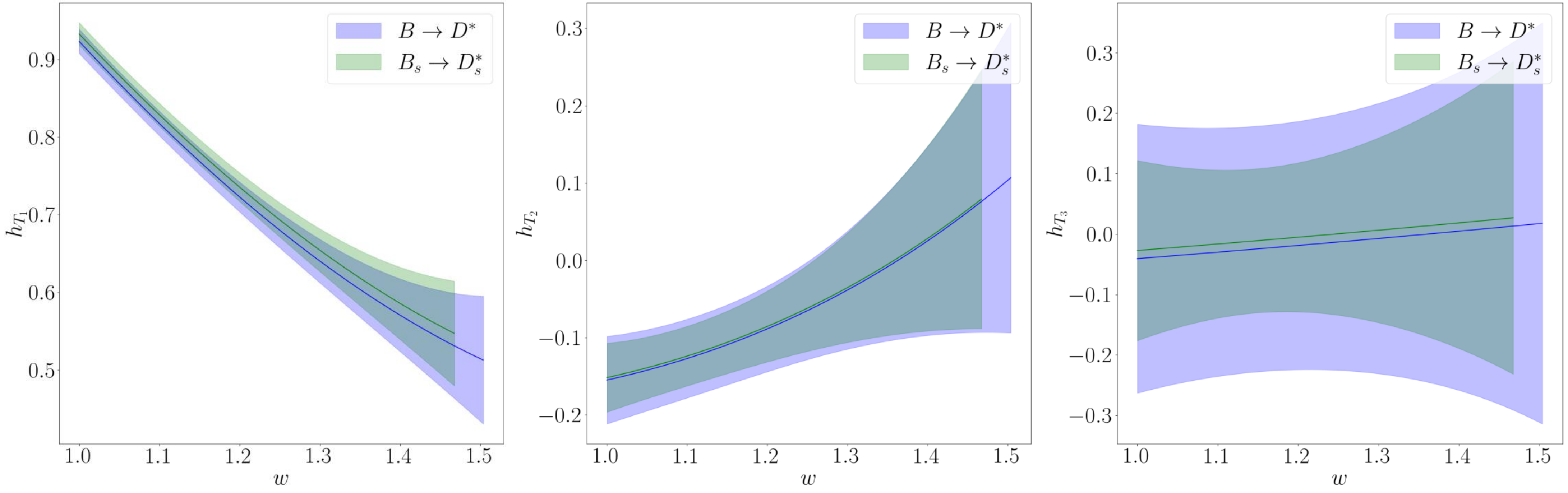
$$\delta H_{\text{eff}}^{\text{NP}} = \frac{4}{\sqrt{2}} G_F V_{cb} [$$
$$C_{V_L}\ \bar{c}_L \gamma_\mu b_L\ \bar{\ell}_L \gamma^\mu \nu_L$$
$$+C_{V_R}\ \bar{c}_R \gamma_\mu b_R\ \bar{\ell}_L \gamma^\mu \nu_L$$
$$+C_{S_L}\ \bar{c}_R b_L\ \bar{\ell}_R \nu_L$$
$$+C_{S_R}\ \bar{c}_L b_R\ \bar{\ell}_R \nu_L$$
$$+C_T\ \bar{c}_R \sigma_{\mu\nu} b_L\ \bar{\ell}_R \sigma^{\mu\nu} \nu_L + \text{h.c.}]$$

Note that C_{V_L} may be absorbed into V_{cb}

Tree-Level Models	C_{V_L}	C_{V_R}	C_{S_L}	C_{S_R}	$C_T = C_{S_L}/4$	$C_T = -C_{S_L}/4$
Vector-like singlet	✓					
Vector-like doublet		✓				
W'	✓					
$H^\pm$			✓	✓		
S_1	✓					✓
R_2					✓	
S_3	✓					
U_1	✓	✓				
V_2				✓		
U_3	✓					

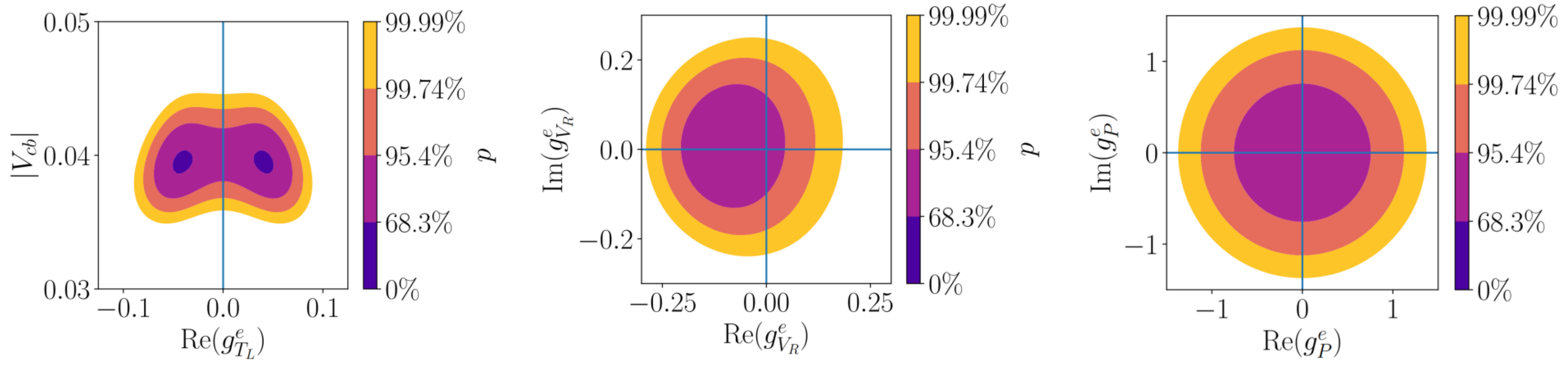
Constraining NP in $b \to c\ell\bar{\nu}$ using $B \to D^{(*)}\ell\bar{\nu}$

Lattice tensor FFs are now available for $B \to D^*\ell\bar{\nu}$ and $B_s \to D_s^*\ell\bar{\nu}$ from HPQCD [2304.03137]:

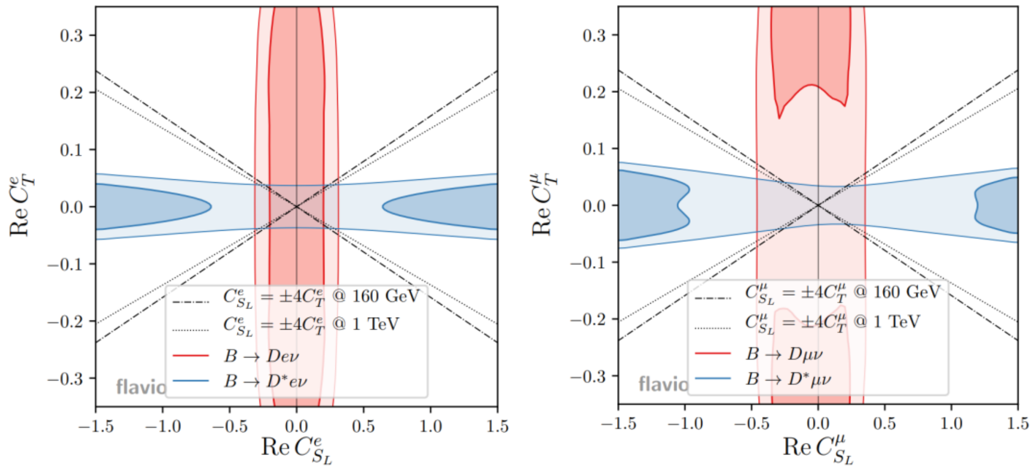


Constraining NP in $b \to c\ell\bar{\nu}$ using $B \to D^{(*)}\ell\bar{\nu}$

Constraints for Wilson coefficients using just $B \to D^{(*)}\ell\bar{\nu}$ with e.g. $\ell = e$ are all consistent with the SM [2304.03137]



Note that $B \to D^*\ell\bar{\nu}$ is much more sensitive to a tensor coupling than $B \to D\ell\bar{\nu}$, and vice-versa for the scalar coupling



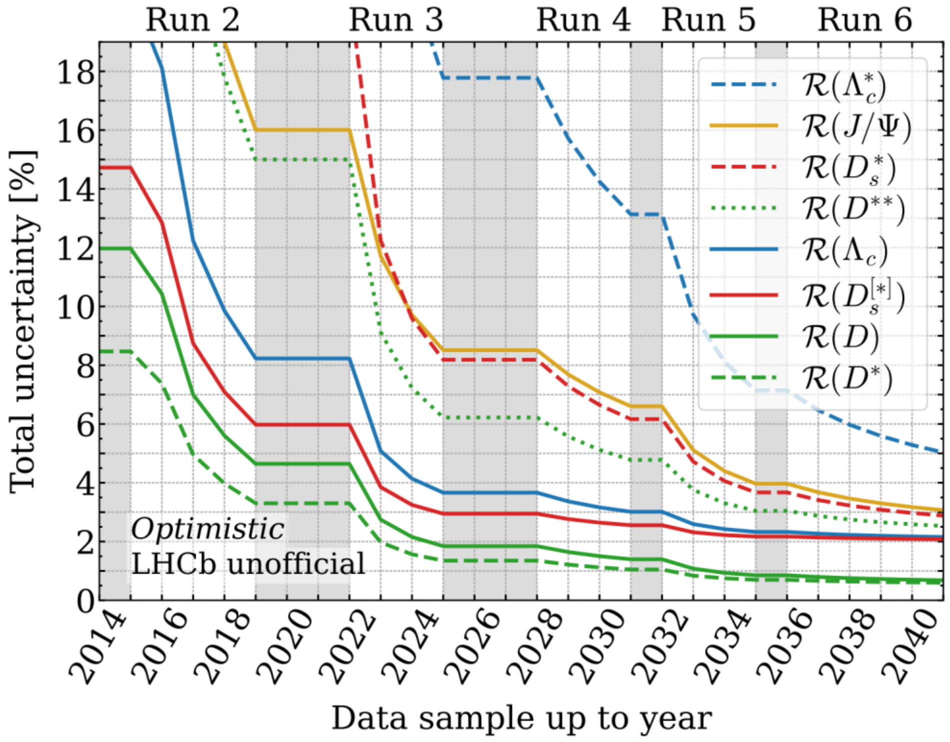
[Jung et al. JHEP01(2019)009]

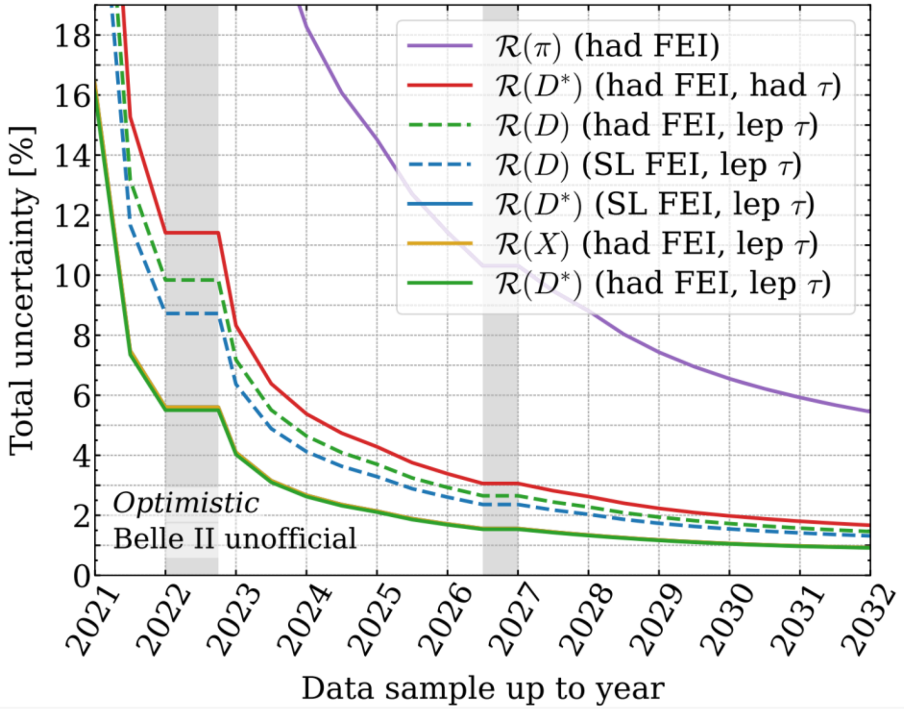
→ Ideally want fully correlated lattice calculation of all $B \to D^{(*)}\ell\bar{\nu}$ FFs

Experimental Outlook for $b \to c\ell\bar{\nu}$

Optimistically, uncertainties of R-ratio measurements may reach percent level

- Commensurate uncertainties on the theory side would require treatment of QED effects
- Most recent lattice only results give $R(J/\psi) = 0.2582(38)$, $R(D_s^*) = 0.265(9)$, much more precise than experiments are likely to obtain soon
- Differential decay rate data from Belle II will allow for further tests of angular asymmetries

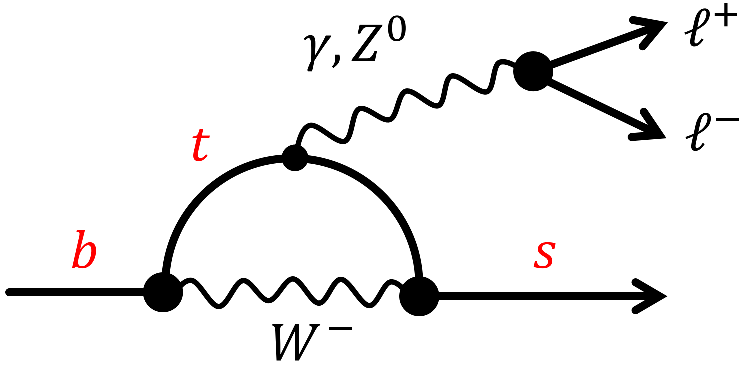




[Bernlochner et al. Rev. Mod. Phys. **94**, 015003]

$b \to s\ell^+\ell^-$

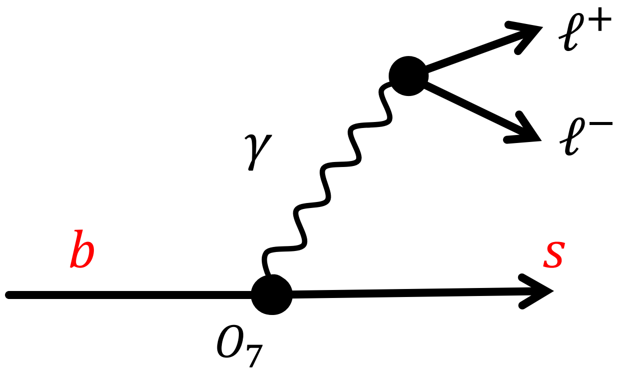
1-loop in the Standard Model

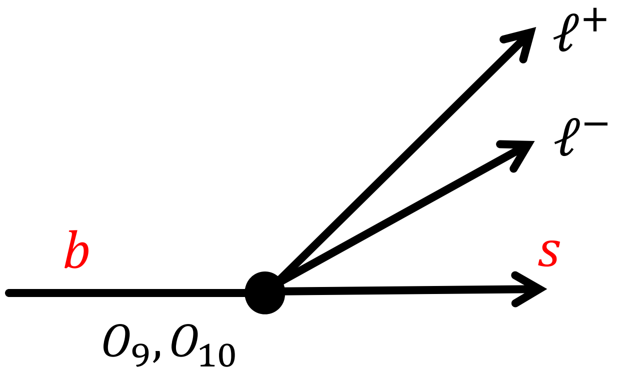


$$\to H_{\text{eff}} = -\frac{4}{\sqrt{2}} G_F \left[V_{tb}V_{ts}^* \sum_{i=1}^{10} C_i(\mu)O_i(\mu) + V_{ub}V_{us}^* \times \; \ldots \right]$$

$$\mu = m_b$$

Main contributions from H_{eff} are from local hadronic operators





$$O_7 = \frac{e}{16\pi^2} m_b \; \bar{s}_L \sigma^{\mu\nu} b_R \; F_{\mu\nu}$$

$$O_9 = \frac{e^2}{16\pi^2} m_b \; \bar{s}_L \gamma^\mu b_L \; \bar{\ell}\gamma_\mu \ell,$$

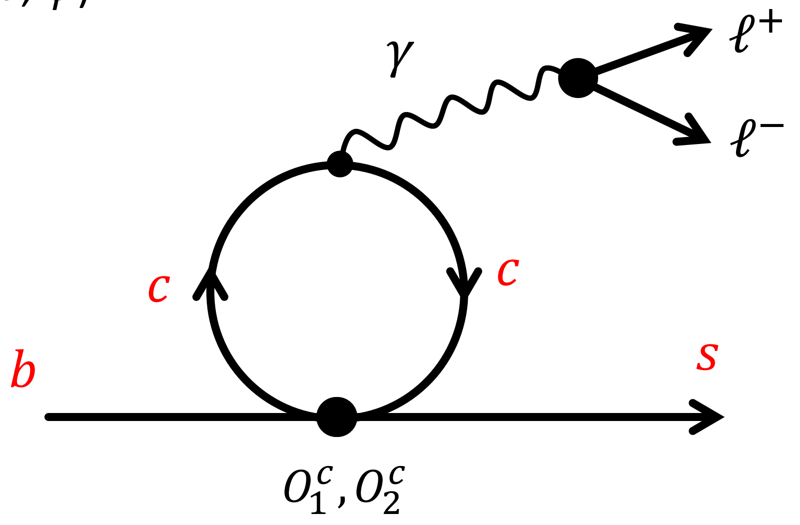
$$O_{10} = \frac{e^2}{16\pi^2} m_b \; \bar{s}_L \gamma^\mu b_L \; \bar{\ell}\gamma_\mu\gamma_5 \ell$$

$\to$ ‘local’ FFs:

$$\langle M(p') | O_i^{\text{had}} | B(p) \rangle \equiv F_\lambda^{B\to M}(q^2) S_\lambda(p', p)$$

$b \to s\ell^+\ell^-$

Non-local contributions from O_1^c, O_2^c coupling to J/ψ, $\psi(2S)$, as well as on-shell states coupling to γ from O_7 (e.g. ρ, ω, ϕ)



$$O_1^c = \bar{s}_L\gamma^\mu c_L\, \bar{c}_L\gamma_\mu b_L, \quad O_2^c = \bar{s}_L^j\gamma^\mu c_L^i\, \bar{c}_L^i\gamma_\mu b_L^j$$

→ 'non-local' FFs:

$$H_\lambda^{B\to M}(q^2)\mathrm{S}_\lambda(\mathrm{p}', \mathrm{p})$$
$$\equiv \langle M(p')\big|T\{j_\mu^{\mathrm{em}}, \textstyle\sum_{i=1}^2 C_i O_i^c + \sum_{i=3}^6 C_i O_i + C_8 O_8\}\big|B(p)\rangle$$

These non-local contributions are not well understood close to resonances

- Dispersive bound for non-local FFs give model independent constraints, control truncation error, include data for e.g. $\mathrm{B} \to K\, J/\psi\ell^+\ell^-$ [2011.09813, 2206.03797]
- Usual solution: exclude veto regions with q^2 around M_{res}^2
- Local FFs still dominate uncertainties

$b \to s\ell^+\ell^-$

Lattice calculations for $b \to s$ FFs are less advanced than for $b \to c$

Fermilab-MILC: 2+1 asqtad, Wilson-clover b

HPQCD: 2+1+1 HISQ, heavy-HISQ b

	$h_\pm(w)$	$h_T(w)$	$h_{A_{1,2,3},V}(w)$	$h_{T_{1,2,3}}(w)$
$B \to K^{(*)}$	✓ [2207.12468] ✓[1509.06235]	✓ [2207.12468] ✓[1509.06235]	✓ [1310.3722*]	✓ [1310.3722*]
$B_s \to \phi$			✓ [1310.3722*]	✓ [1310.3722*]
$B_c \to D_s^{(*)}$	✓ [2108.11242]	✓ [2108.11242]		

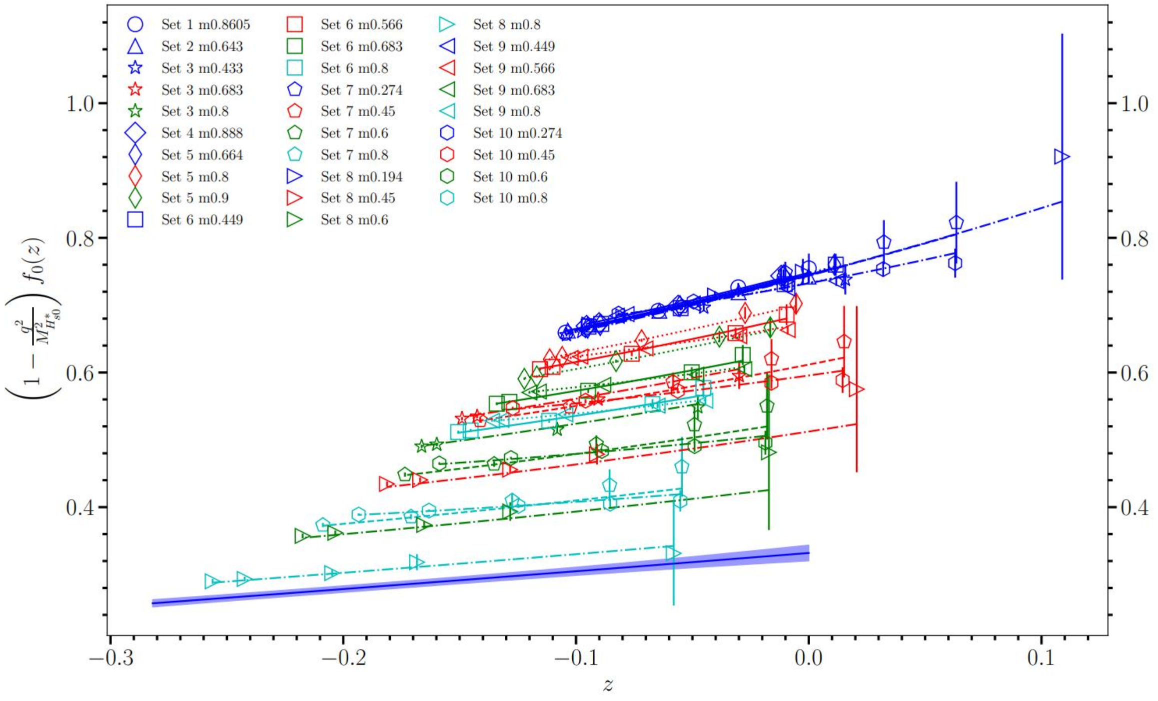
* 2+1 asqtad, NRQCD b quarks

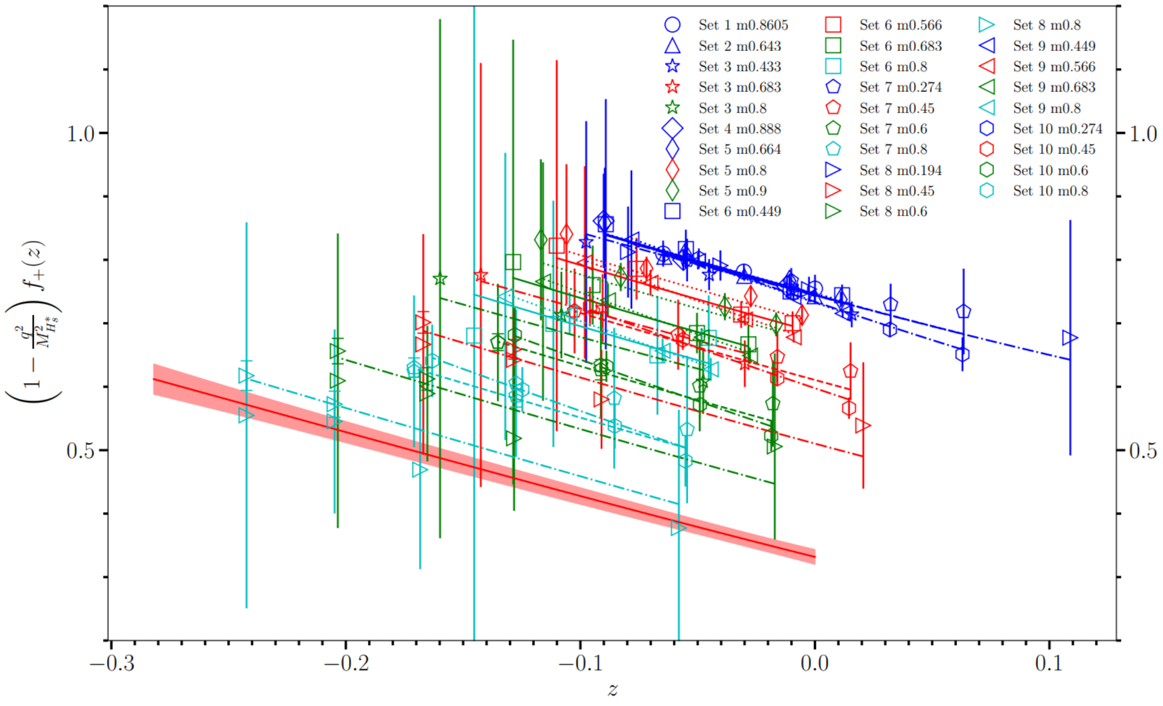
Note that the HPQCD calculation of the $B \to K$ SM+Tensor FFs [2207.12468] also included SM+Tensor $D \to K$ FFs. The Fermilab-MILC collaboration has also computed the $D \to \pi$, $D \to K$ and $D_s \to K$ SM FFs using 2+1+1 HISQ for all quarks [2212.12648], with work in progress to extend this calculation to the B.

$B \to K\ell^+\ell^-$ [2207.12468]

W. G. Parrott, C. Bouchard, and C. T. H. Davies: 2+1+1 HISQ, heavy-HISQ b

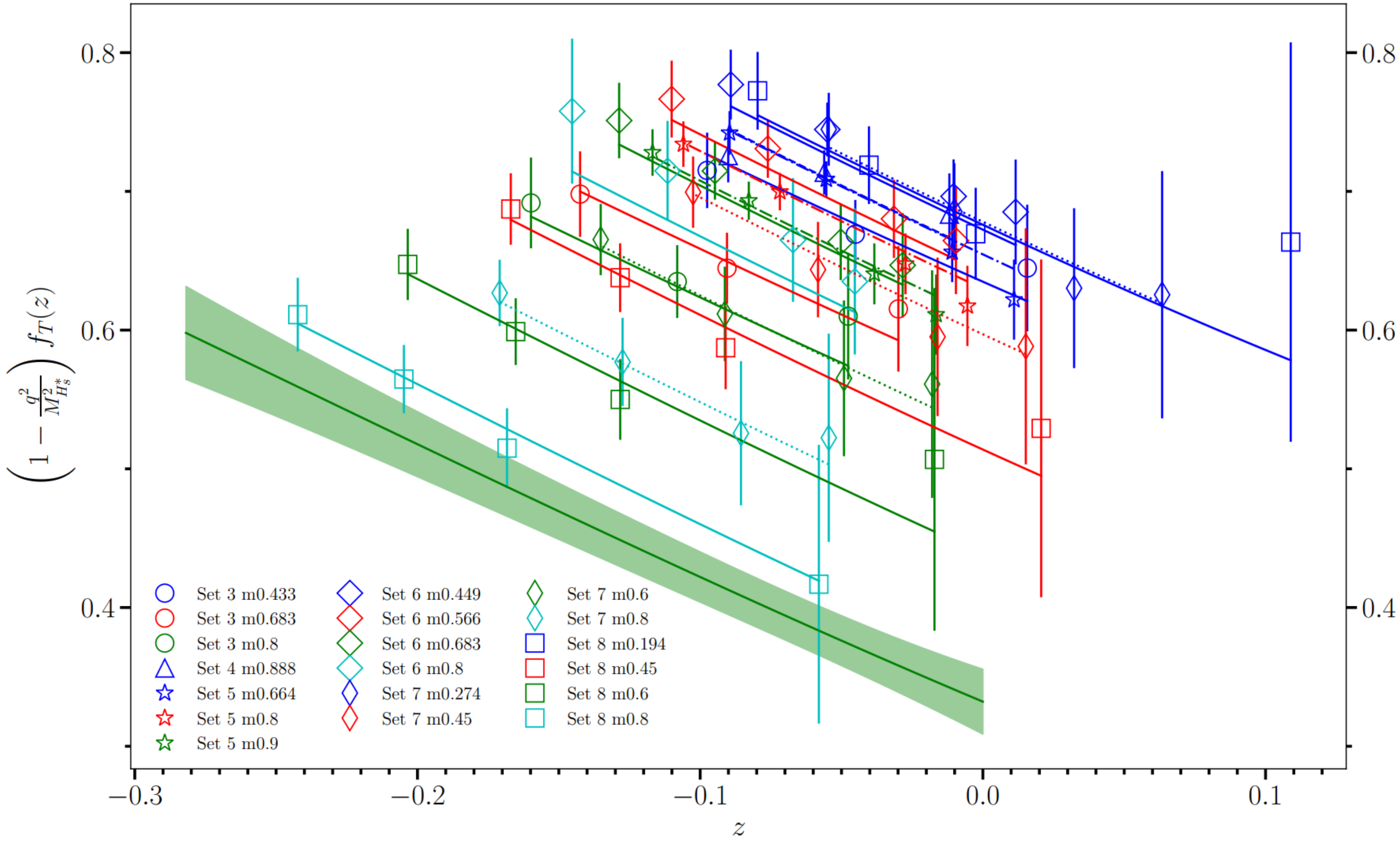
BCL parameterisation: $z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$, $\quad f^Y(\mathrm{q}^2) \sim L_\chi \times \; P\left(q^2, {M_{b\bar{s}}^{\mathrm{res}_Y}}^2\right) \times \sum a_n^Y\left(\frac{\Lambda_{\mathrm{QCD}}}{M_H}, am_h, a\Lambda_{\mathrm{QCD}}\right) z^n$





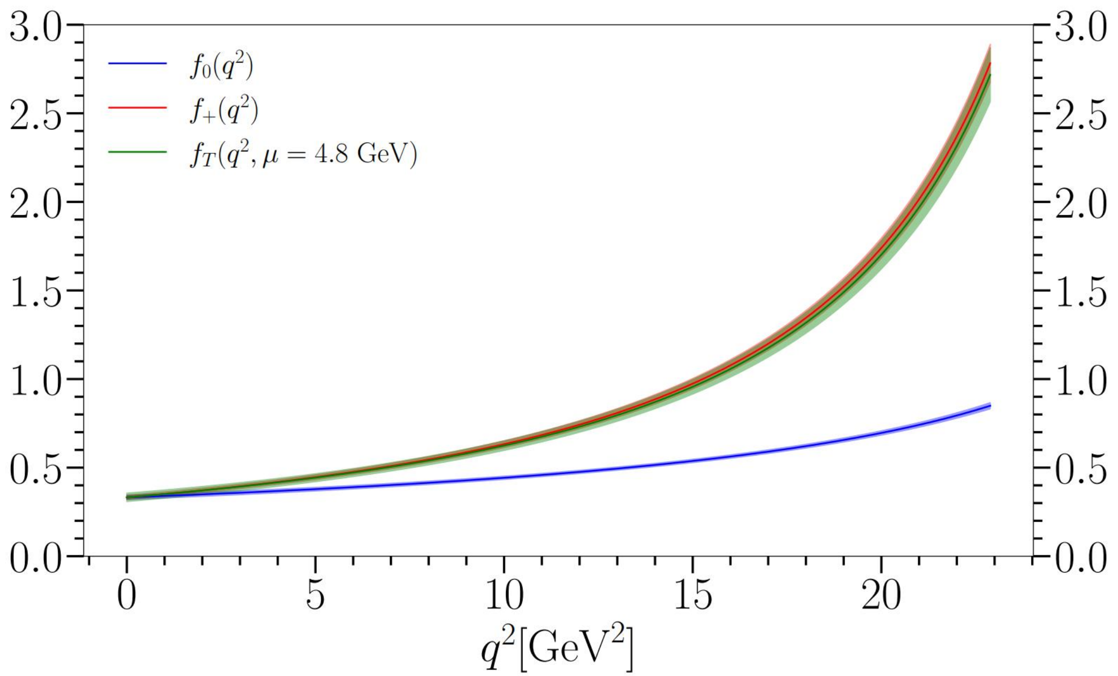
$B \to K\ell^+\ell^-$ [2207.12468]

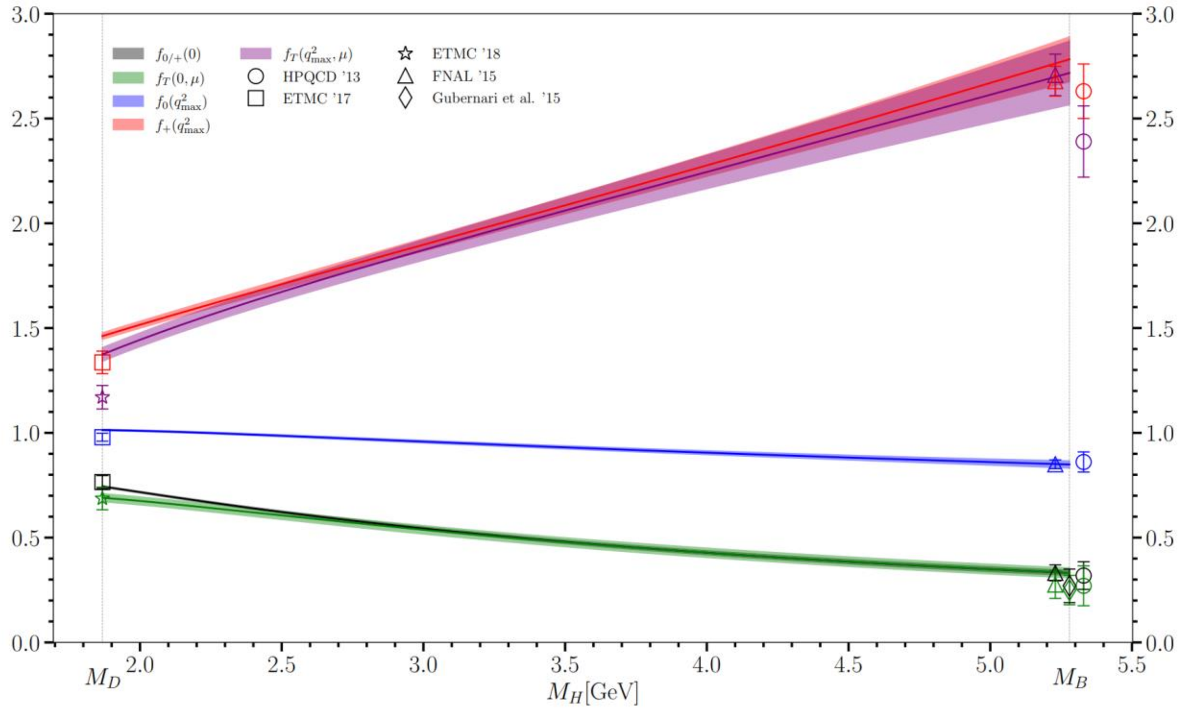
W. G. Parrott, C. Bouchard, and C. T. H. Davies: 2+1+1 HISQ, heavy-HISQ b



$\boldsymbol{B \to K\ell^+\ell^-}$ [2207.12468]

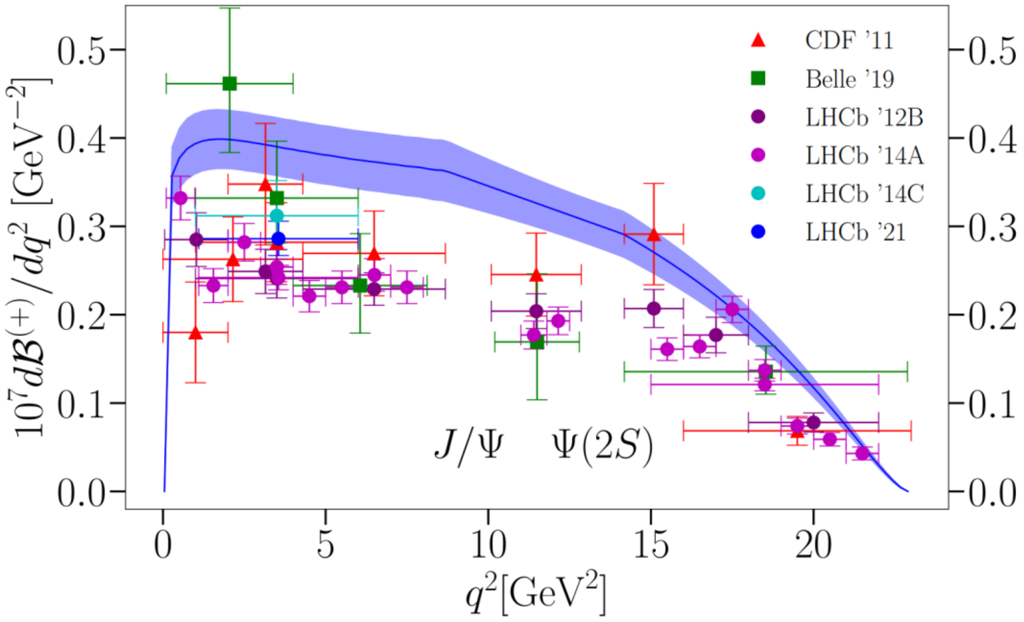
W. G. Parrott, C. Bouchard, and C. T. H. Davies: 2+1+1 HISQ, heavy-HISQ b



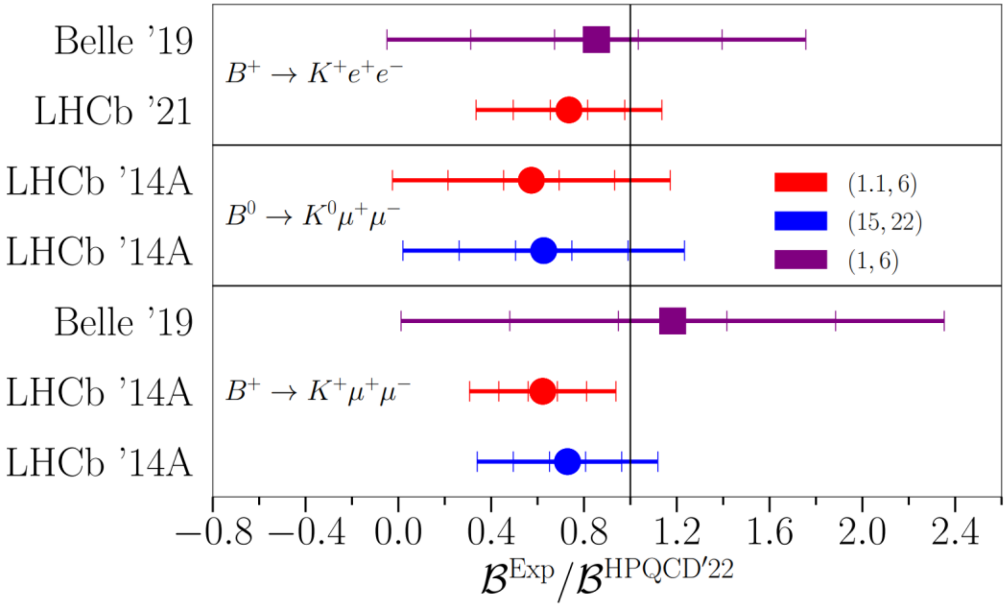


$B \to K\ell^+\ell^-$ [2207.13371]

W. G. Parrott, C. Bouchard, and C. T. H. Davies: 2+1+1 HISQ, heavy-HISQ b



- $B^+ \to K^+\ell^+\ell^-$ differential branching fraction shows clear discrepancy with experimental measurements [2207.13371]
- Similar situation for $B^0 \to K^0\ell^+\ell^-$ and $B^- \to K^-\ell^+\ell^-$ modes.

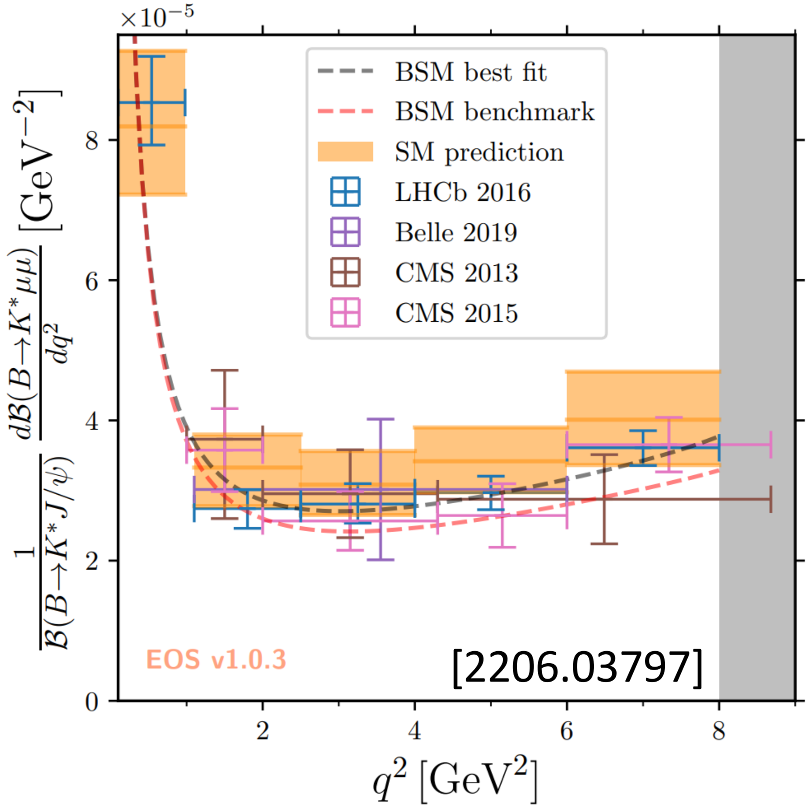


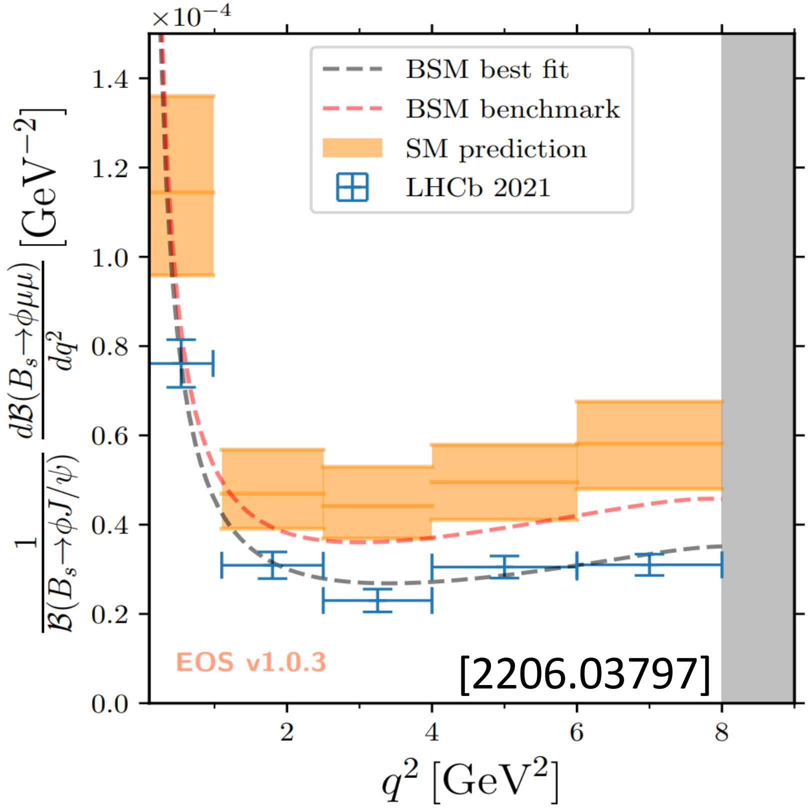
- Integrating over allowed regions gives tension at the level of $\approx 3-5\sigma$ with recent experimental measurements.

$B \to K^{*}\ell^{+}\ell^{-}, B_s \to \phi\ell^{+}\ell^{-}$

Dispersive bound for local and non-local FFs combined with older lattice results and LCSR [2206.03797]

- Similar discrepancy to $B \to K$ in both cases.





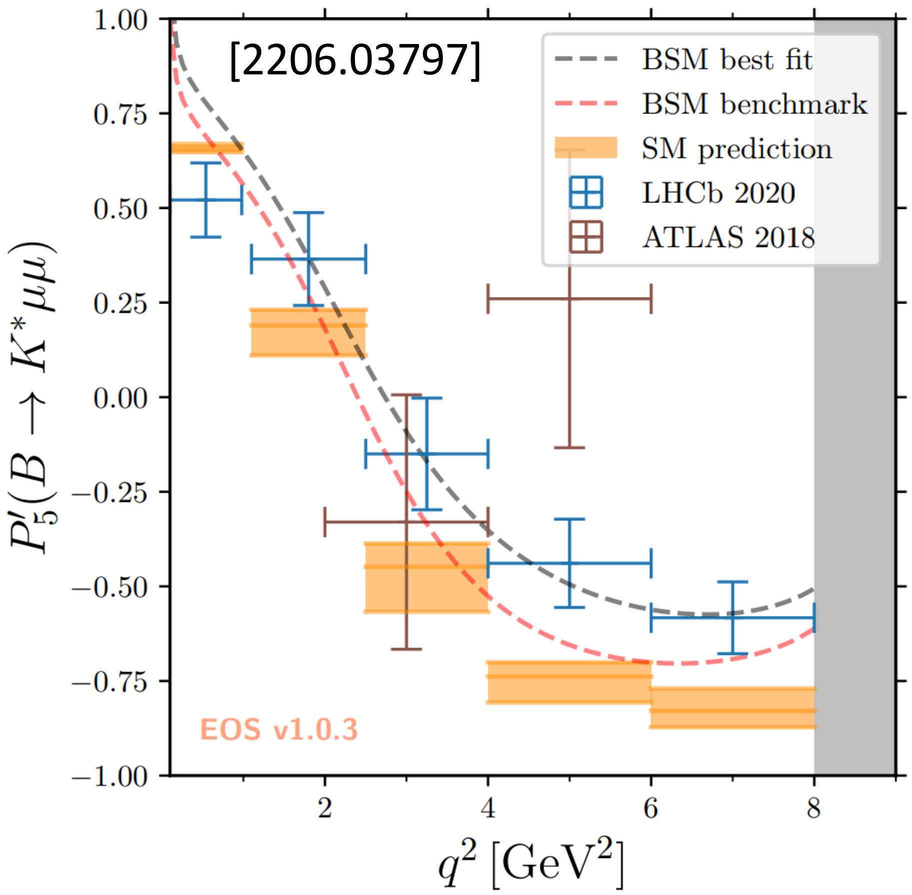
$B \to K^*\ell^+\ell^-, B_s \to \phi\ell^+\ell^-$

Similar level of discrepancy for P_5'

$$P_5'(q^2) = \frac{S_5(q^2)}{\sqrt{F_L(q^2)(1-F_L(q^2))}}$$

$$S_5(q^2) = -\frac{4}{3}\left[\int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} - \int_0^{\frac{\pi}{2}} - \int_{\frac{3\pi}{2}}^{2\pi}\right] d\phi \left[\int_0^1 - \int_{-1}^0\right] d\cos(\theta_K)$$
$$\times \frac{d^3(\Gamma - \bar{\Gamma})}{dq^2 d\cos(\theta_K) d\phi} \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}$$

$$F_L(q^2) = \frac{d\Gamma^{\lambda_{K^*}=0}}{dq^2} \Big/ \frac{d\Gamma}{dq^2}$$



$b \to s\ell^+\ell^-$: BSM analysis

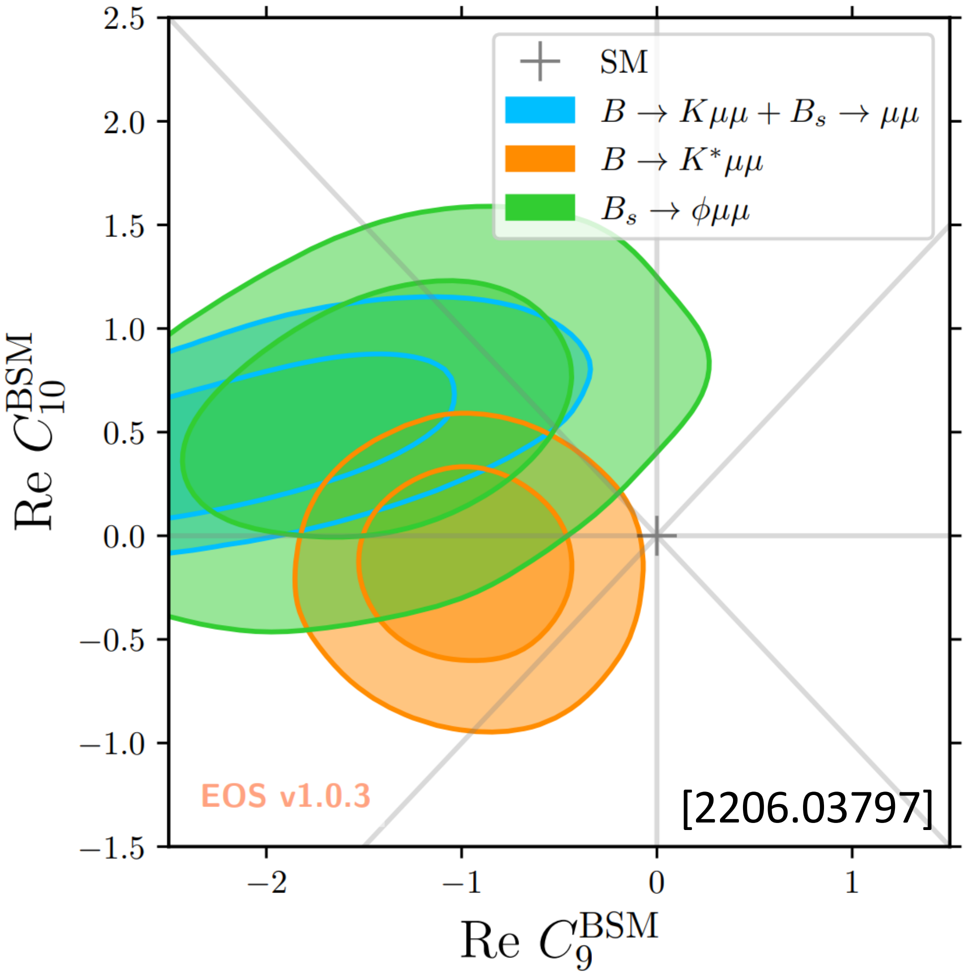
Combine experimental results with LQCD FFs with LCSR, improved dispersive bounds to constrain C_9 and C_{10} [2206.03797]

$B \to K\ \mu^+\mu^-$, $B_s \to \mu^+\mu^-$

$B \to K^*\mu^+\mu^-$

$B \to \phi\mu^+\mu^-$

→ Look forward to simultaneous BSM analysis using new LQCD (e.g. W. G. Parrott et al.) and new experimental results in these channels

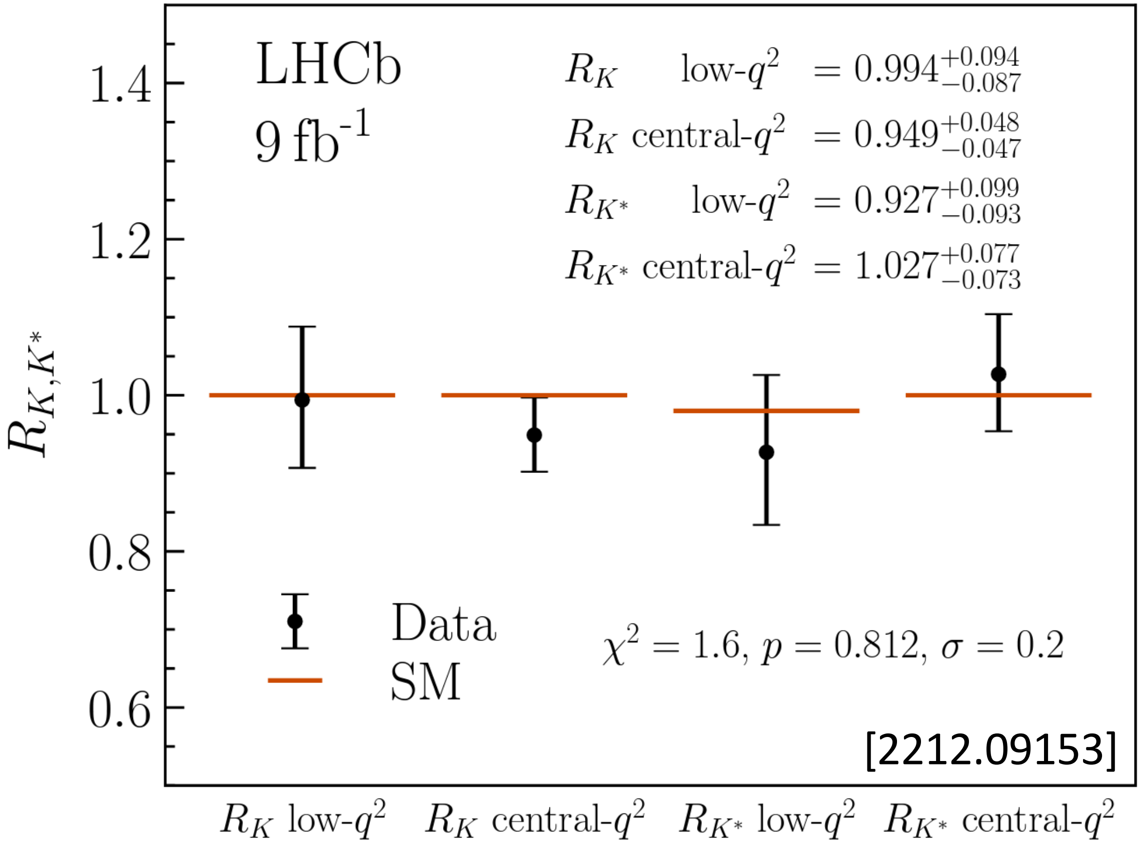


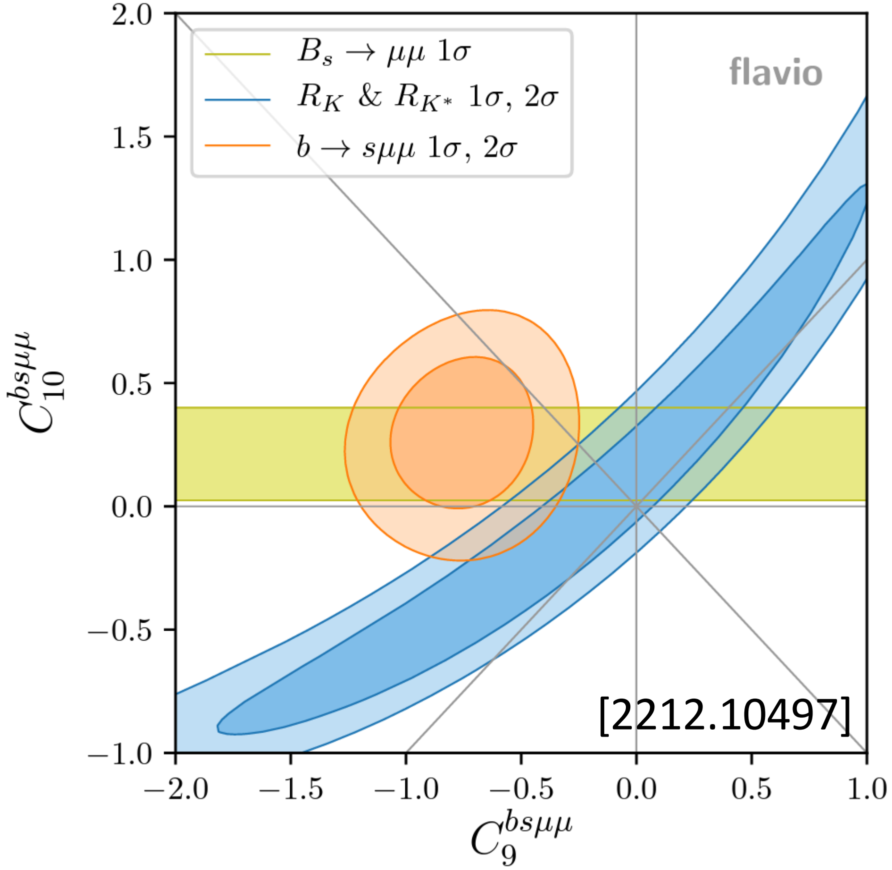
(this figure does not include HPQCD `22 $B \to K$ or CMS $B_s \to \mu^+\mu^-$ [2212.10311], bounds for each channel computed separately)

$b \to s\ell^+\ell^-$: BSM analysis - LFU

New measurement of $R_{K^{(*)}}$ by LHCb asks if deviations from SM seen in $b \to s\mu^+\mu^-$ can be explained consistently.

- Best performing 1D LFU NP case, C_9^{univ} [2212.10497]
- QCD effects could contribute → understanding non-local contributions very important





$b \to u\ell\bar{\nu}$

Form factors much more expensive computationally due to light quarks, especially for physical pions

Fermilab-MILC: 2+1 asqtad, Wilson-clover b and c quarks

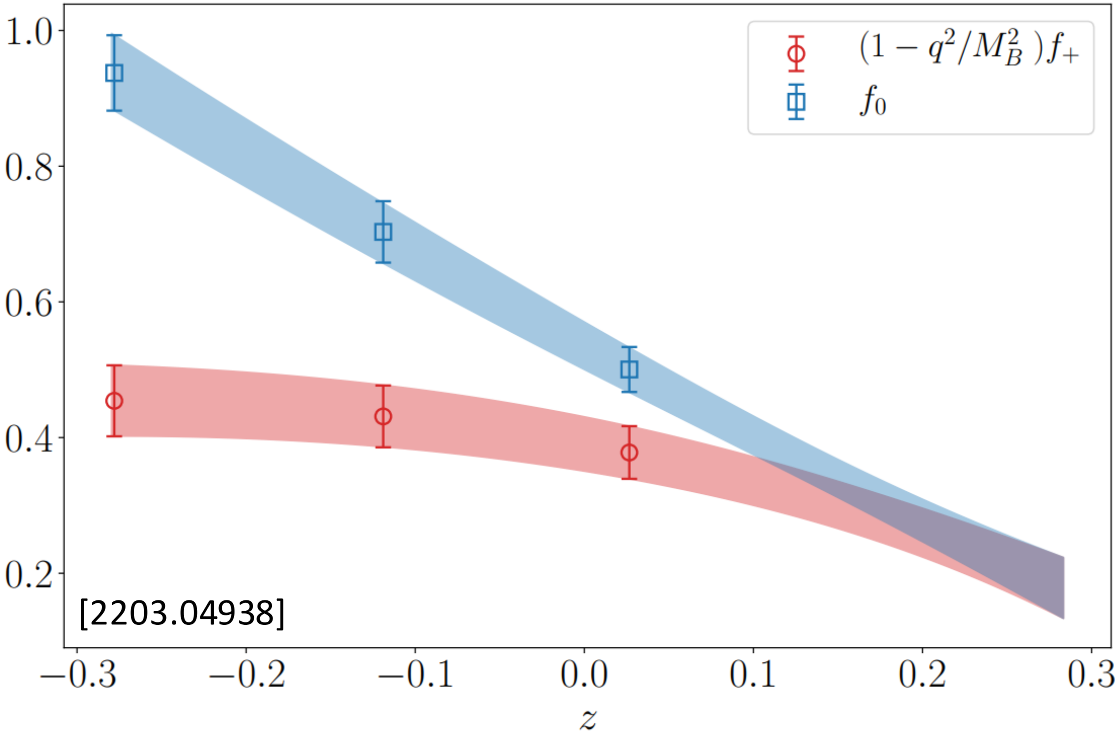
HPQCD: 2+1+1 HISQ, heavy-HISQ b

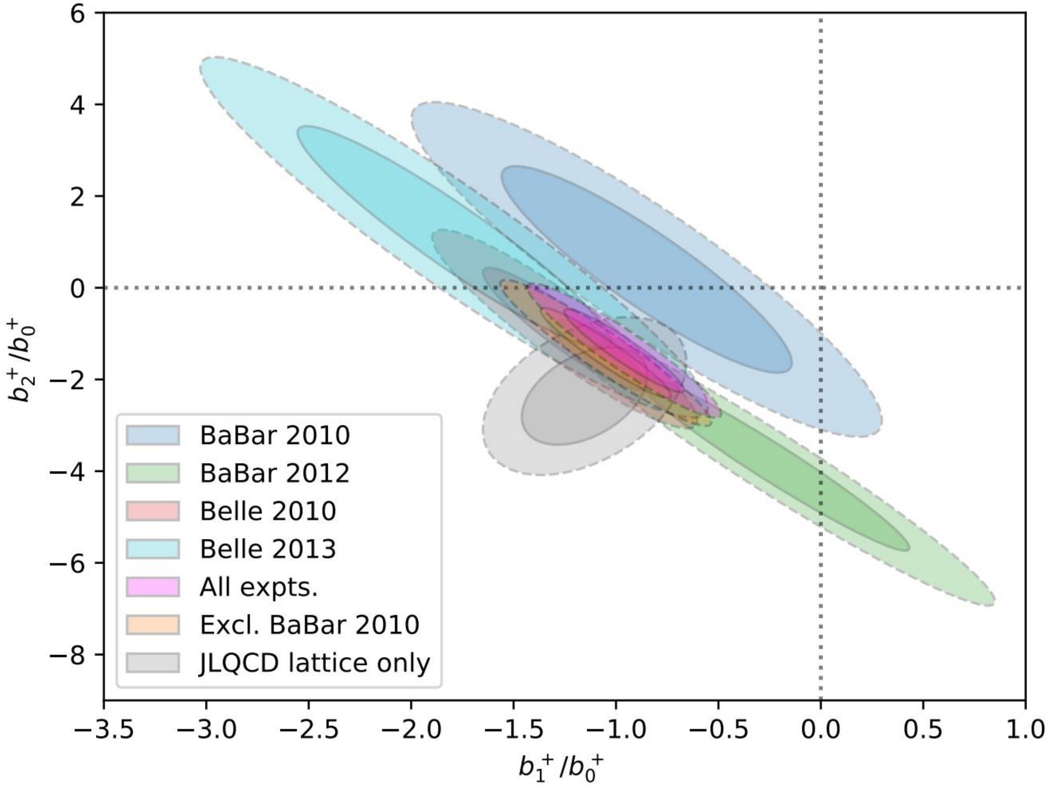
JLQCD: 2+1 Möbius domain-wall, Möbius domain-wall b

	$h_\pm(w)$	$h_T(w)$	$h_{A_{1,2,3},V}(w)$	$h_{T_{1,2,3}}(w)$
$B \to \pi / B \to \rho$	✓ [2203.04938] [1503.07839]			
$B_s \to K^{(*)}$	✓[1901.02561]			
$B_c \to D^{(*)}$	✓ [2108.11242]	✓ [2108.11242]		

$B \to \pi \ell \bar{\nu}$ [2203.04938]

Recent JLQCD calculation of $B \to \pi$ form factors



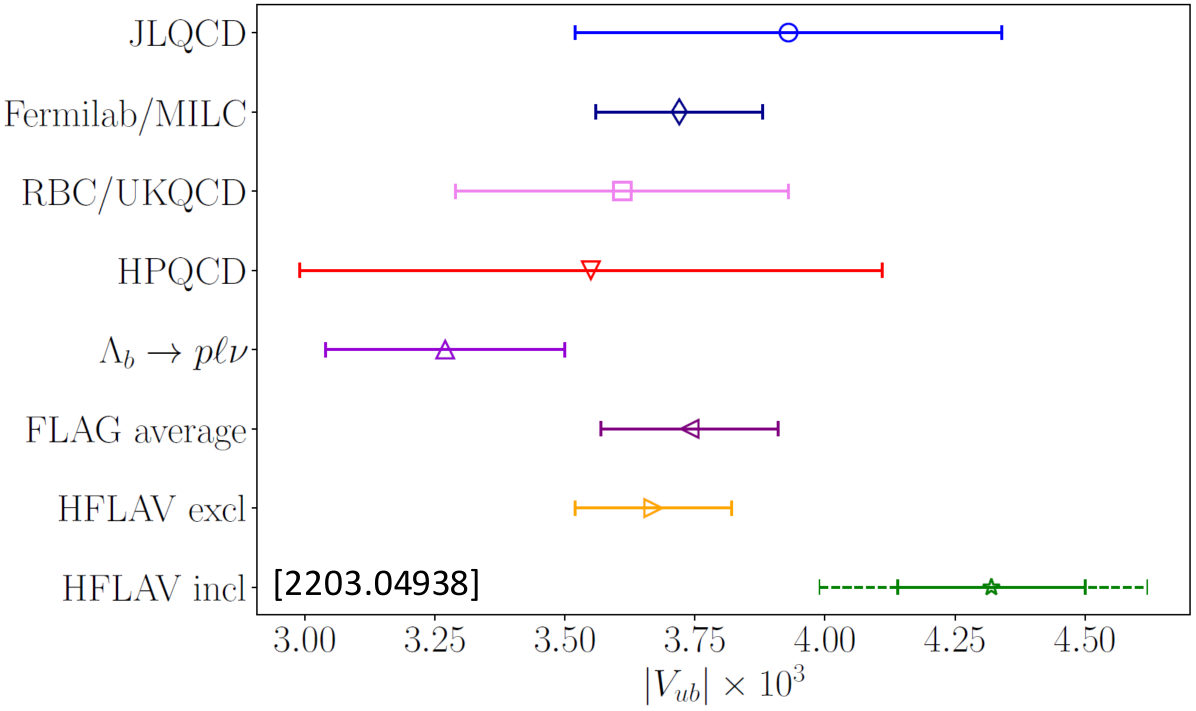


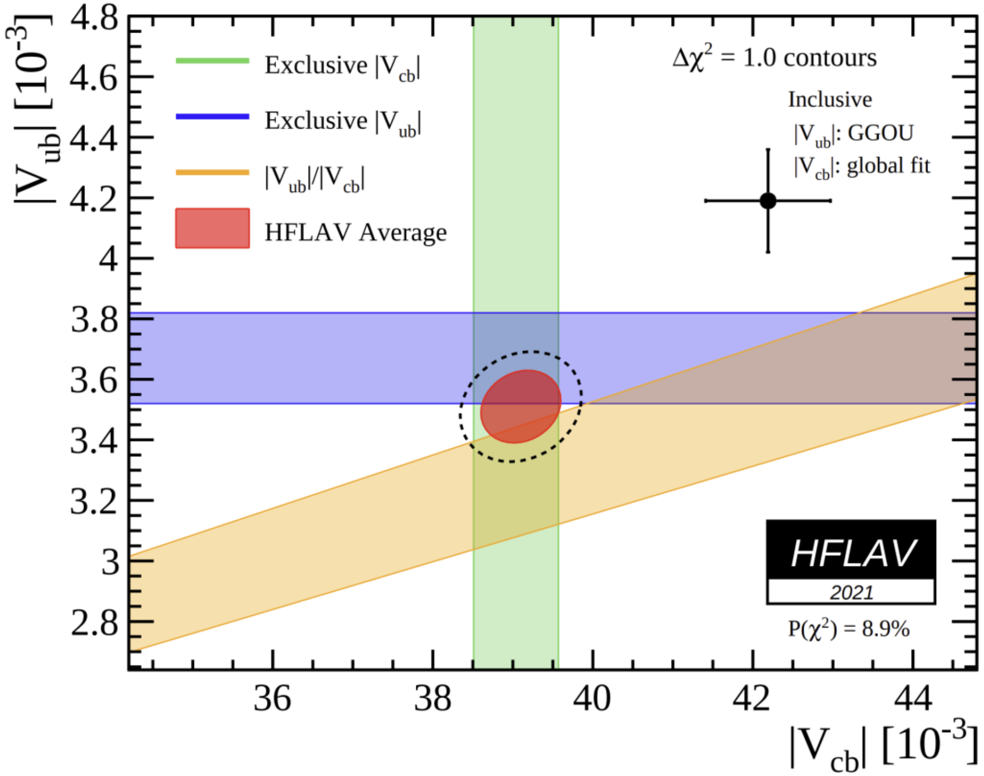
Good agreement between lattice shape parameters and experimental measurements

$B \to \pi\ell\bar{\nu}$ [2203.04938]

$B \to \pi\ell\bar{\nu}$ provides a means to compute the CKM matrix element $|V_{ub}|$

- JLQCD find $V_{cb} = 3.93 \pm 0.41 \times 10^{-3}$
- Work in progress by both HPQCD and Fermilab-MILC collaborations





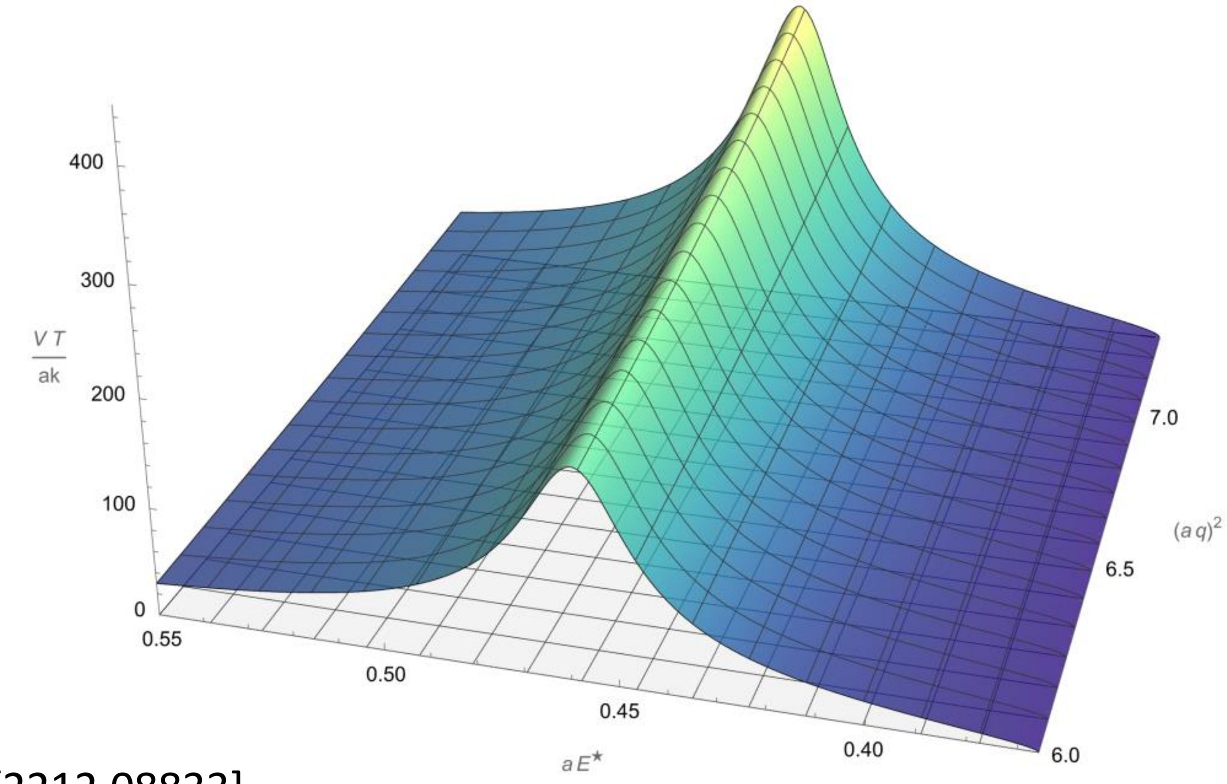
Also offers a test of LFU through the ratio $R(\pi) = \Gamma(B \to \pi\tau\bar{\nu}_\tau)$ / $\Gamma(B \to \pi\ell\bar{\nu}_\ell)$, expected to be measured by Belle II with precision of $\approx$ 14%

$B \to \rho(\to \pi\pi)\ell\bar{\nu}$ [2212.08833]

$B \to \rho(\to \pi\pi)\ell\bar{\nu}$ provides a complementary determination of the CKM matrix element $|V_{ub}|$

- Challenging on the lattice, due to ρ resonance.
- 2212.08833 follows the approach of Briceño, Hansen, and Walker-Loud (e.g. [1406.5965]) to compute the transition amplitude, $\frac{V\,T}{ak}$.

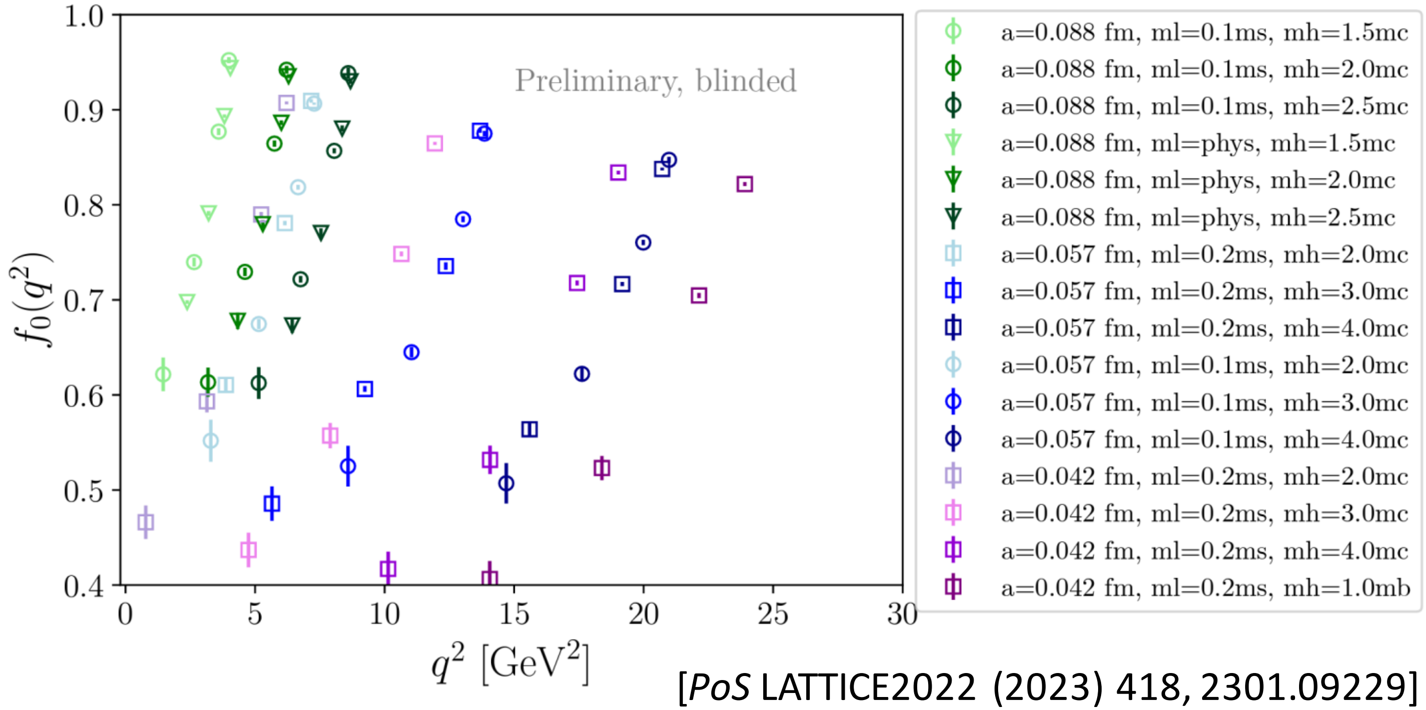
- Currently, only preliminary results for the vector current at a single lattice spacing.
- Nevertheless, demonstrates feasibility of such calculations
- Experimental data available from BaBar, Belle and recently Belle II [2211.15270] but hadronic matrix elements not yet well known.



[2212.08833]

$B_s \to K\ell\bar{\nu}$ [2203.04938]

Work in progress by Fermilab-MILC on $B_s \to K$ using 2+1+1 HISQ gauge configurations and HISQ heavy quarks, e.g



[*PoS* LATTICE2022 (2023) 418, 2301.09229]

Summary

$b \to c\ell\bar{\nu}$

- New $B_{(s)} \to D^*_{(s)}\ell\bar{\nu}$ SM+Tensor FFs from HPQCD, $B \to D^*\ell\bar{\nu}$ SM FFs from JLQCD, WIP by Fermilab-MILC on $B_{(s)} \to D^{(*)}_{(s)}\ell\bar{\nu}$
- Lattice $R(D^*)$ seems to disagree with HQET predictions, some discrepancy with semimuonic shape and asymmetry measurements from Belle and Belle II
- Need to look carefully at ingredients of lattice calculations
- New experimental results expected in $B \to D^*\ell\bar{\nu}$ and other channels soon

$b \to s\ell^+\ell^-$

- Recent SM+Tensor FFs from HPQCD confirm tension seen between theory and experiment in branching ratios in $\mathrm{B} \to K$ [2207.12468, 2207.13371], WIP also at Fermilab-MILC on $\mathrm{B} \to K$
- LHCb $R_{K^{(*)}}$ [2212.09153] highlights importance of understanding non-local contributions -> look to new dispersive bound calculations [2011.09813, 2206.03797]
- WIP on $B_s \to \phi$ and $\mathrm{B} \to K^*$ FFs at HPQCD will clarify situation in these channels where current discrepancy is based on older nonrelativistic calculations

$b \to u\ell\bar{\nu}$

- $B \to \pi\ell\bar{\nu}$ SM FFs from JLQCD in agreement with experimentally measured shape, give exclusive V_{cb} compatible with both inclusive and exclusive averages [2203.04938]
- WIP by Leskovec et al. on $B \to \rho(\to \pi\pi)\ell\bar{\nu}$ [2212.08833], treating the ρ resonance using the Lellouch-Lüscher method
- WIP by HPQCD on $B \to \pi\ell\bar{\nu}$
- WIP by Fermilab-MILC on $B_S \to K\ell\bar{\nu}$ and $B \to \pi\ell\bar{\nu}$

Thanks for listening!

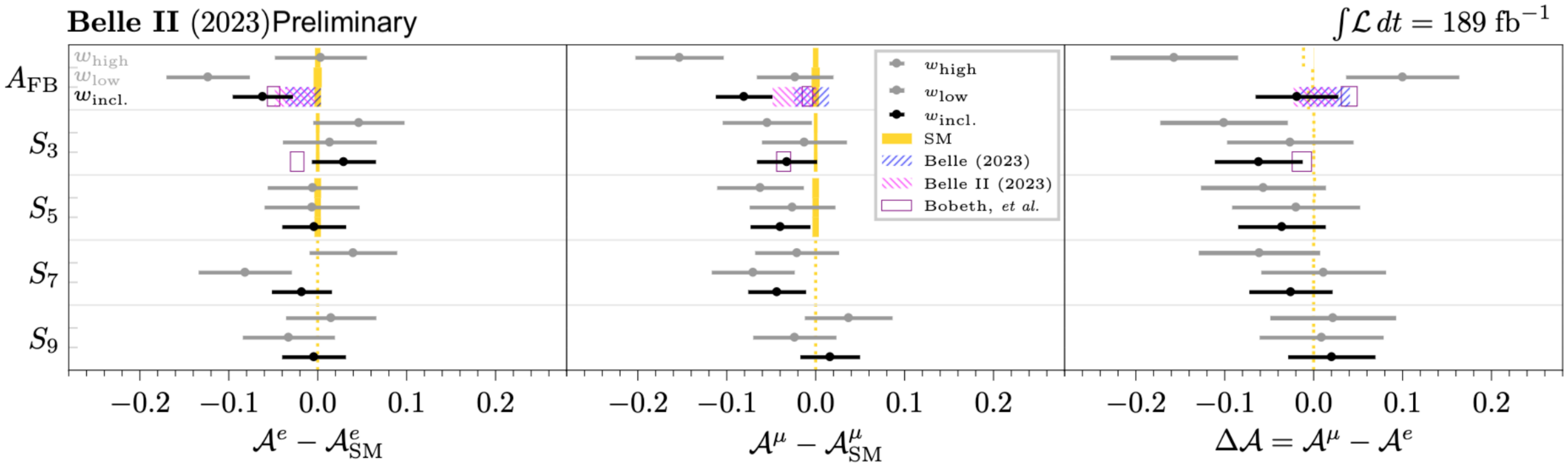
Backup Slides

$B^0 \to D^{*-}\ell^+\nu$ Belle II Preliminary [2305.10746]

Recently, Belle II reported preliminary results for a measurement of $|V_{cb}|$ using $189\mathrm{fb}^{-1}$ of e^+e^- collisions at the $\Upsilon(4S)$ resonance and $18\mathrm{fb}^{-1}$ of collisions $60\mathrm{MeV}$ below the $\Upsilon(4S)$ resonance.

Using LQCD for the normalisation at zero recoil:

$$|V_{cb}|_{\mathrm{BGL}} = 40.6 \pm 0.3^{stat} \pm 1.0^{syst} \pm 0.6^{theo} \times 10^{-3}.$$



$w \in [1.0, 1.275]$ (w_{low}), $\quad w \in [1.275, \approx 1.5]$ (w_{high})