Interesting processes and puzzles involving heavy flavors

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Detecting new physics

Direct searches

- "Bump" in the spectrum
  - → Theory can e.g. guide experiment by developing models/predicting signals
  - → Deduce scalar Higgs boson, electro-weak symmetry breaking

Indirect searches

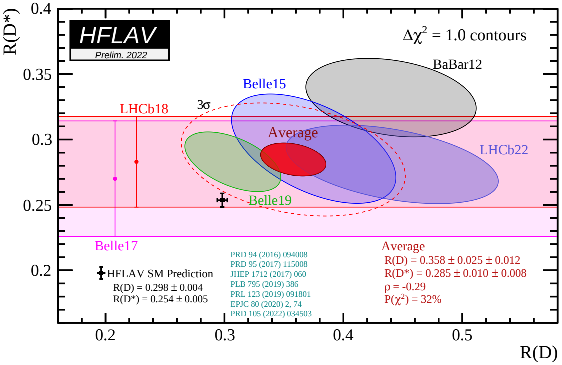
- New physics contributes to SM processes e.g. via loops
- Precision test of the Standard Model
  - → Calculate SM process precisely and compare with experiment
  - → Discrepancy could be *new physics* e.g. $R_D^{(*)}$

Detecting new physics: $R_D^{(*)}$

[HFLAV]

- Testing universality of lepton flavors

$$R^{\tau/\mu}_{D^{(*)}} \equiv \frac{BF(B \to D^{(*)}\tau\nu_\tau)}{BF(B \to D^{(*)}\mu\nu_\mu)}$$



Detecting new physics

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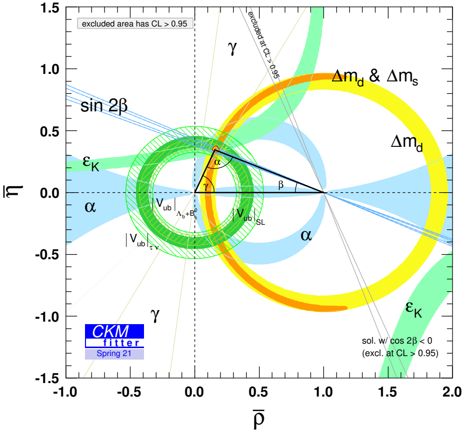
Indirect searches

- New physics contributes to SM processes e.g. via loops
- Precision test of the Standard Model
  - → Calculate SM process precisely and compare with experiment
  - → Discrepancy could be *new physics* e.g. $R_D^{(*)}$
- Combine several determinations to perform an over-constrained fit: CKM unitarity triangle

Detecting new physics: CKM triangle

- Use tree-level determinations of $|V_{ub}|$ and $|V_{cb}|$
  - → Commonly used $B \to \pi\ell\nu$ and $B \to D^{(*)}\ell\nu$
  - → Long standing $2-3\sigma$ discrepancy between exclusive ($B \to \pi\ell\nu$) and inclusive ($B \to X_u\ell\nu$)
  - → $B \to \tau\nu$ has larger error



[http://ckmfitter.in2p3.fr]

Cabibbo-Kobayashi-Maskawa (CKM) matrix

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} = \begin{bmatrix} 0.97370(14) & 0.2245(8) & 0.00382(24) \\ 0.221(4) & 0.987(11) & 0.041(14) \\ 0.0080(3) & 0.0388(11) & 1.013(30) \end{bmatrix}$$

[PDG, Workman et al. PTEP (2022) 083C01]

$$\frac{|\delta V_{CKM}|}{|V_{CKM}|} = \begin{bmatrix} 0.014 & 0.35 & 6.3 \\ 1.8 & 1.1 & 3.4 \\ 3.8 & 2.8 & 3.0 \end{bmatrix} \%$$

- Heavy sector less well explored compared to light sector
- Large experimental efforts: LHCb, Belle II, BESIII, ...

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \leftrightsquigarrow \begin{bmatrix} \pi \to \ell\nu & K \to \ell\nu \quad K \to \pi\ell\nu & B \to \pi\ell\nu \\ D \to \ell\nu \quad D \to \pi\ell\nu & D_s \to \ell\nu \quad D \to K\ell\nu & B \to D\ell\nu \quad B \to D^*\ell\nu \\ B_d \leftrightarrow \overline{B}_d & B_s \leftrightarrow \overline{B}_s & \end{bmatrix}$$

- Typical nonperturbative LQCD calculations to extract CKM matrix elements
- Why is the uncertainty for $|V_{ub}|$ so large?

Heavy flavors on the lattice

- Quark masses

up $\sim$ 0.002 GeV

charm $\sim$ 1.25 GeV

top $\sim$ 175 GeV

down $\sim$ 0.005 GeV

strange $\sim$ 0.095 GeV

bottom $\sim$ 4.2 GeV

- Lattice simulations have a cutoff a^{-1}
  - → Fully relativistic quarks require $am \ll 1$ i.e. $m \ll a^{-1}$
  - → Typically $a^{-1} \gtrsim 2$ GeV $\Rightarrow m_{\text{charm}} \lesssim a^{-1} \lesssim m_{\text{bottom}}$
  - → Charm but in particular bottom quarks require special considerations

Simulating heavy flavors

- Traditionally: simulate charm and bottom using effective actions
  - → Heavy quark effective Theory (HQET), Non-Relativistic QCD, Relativistic Heavy Quark (RHQ, Fermilab, Tsukuba)
  - → Allows to simulate charm and bottom quarks on coarser lattices
  - → Additional systematic uncertainties, partly perturbative renormalization, ...
  - → Few percent total errors

- State-of-the-art: fully relativistic simulations at $a^{-1} > 2$ GeV
  - → Heavy Highly Improved Staggered Quarks (HISQ), Heavy Domain-Wall Fermions (DWF), ...
  - → Same action for light (up/down/strange) as for heavy (charm/bottom) quarks
    - ⇝ Simulate heavier than charm and extrapolate
  - → Fully nonperturbative renormalization straight-forward, reduced systematic uncertainties
  - → Sub-percent precision feasible ⇝ QED effects become relevant

Overview

- Semileptonic decays to extract $|V_{ub}|$ and $|V_{cb}|$

- Neutral $B_{(s)}$ meson mixing to extract $|V_{td}|$ and $|V_{ts}|$

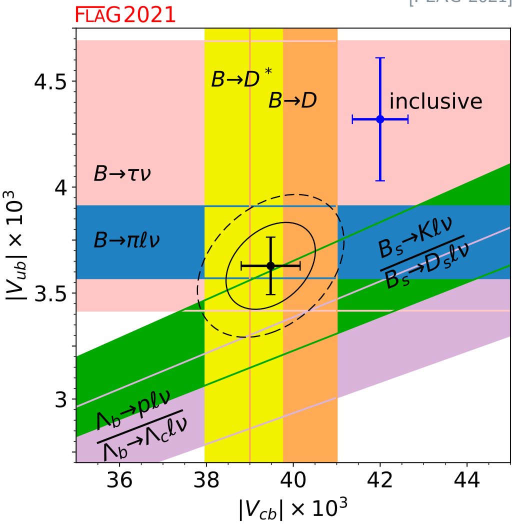
- Summary

$|V_{ub}|$ and $|V_{cb}|$

$|V_{ub}|$ and $|V_{cb}|$

- Leptonic decays $B^+_{(c)} \to \ell^+ \nu_\ell$ experimentally difficult
  - → Only $B^+ \to \tau^+ \nu_\tau$ measured (large error)
- Semileptonic decays preferred
  - → Exclusive e.g. $B \to \pi\ell\nu$
  - → Inclusive e.g. $B \to X_u \ell\nu$
  - → B, B_s, Λ_b initial state
- Longstanding tension between exclusive and inclusive determinations

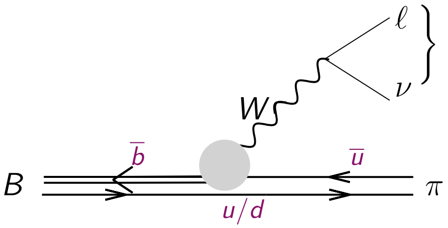
[FLAG 2021]



Inclusive decays

- B factories run at the $\Upsilon(4s)$ threshold which decays dominantly to a $B\bar{B}$ pair
- Tag one B meson and look at the decay products of the other B meson
- Account for all decays where a u or c quark has been identified
  - → c quarks are heavy
    - ⇒ Fewer possible decay channels
      $B \to D$ ($\sim 22\%$), $B \to D^*$ ($\sim 45\%$), $B \to D^{**}$ ($\sim 25\%$), ...
    - ⇒ Relatively clean measurement
  - → u quarks are light
    - ⇒ Very many decay channels
    - ⇒ Less clean measurement
- Sum of all exclusive channels should add up to the inclusive measurement
- Theoretical prediction needs to similarly account for all possible decays ⇝ QCD sum rules
  - → Novel ideas for LQCD: [Hashimoto PTEP(2017)053B03] [Hansen, Meyer, Robaina PRD96(2017)094513] [Bailas et al. PTEP(2020)043B07] [Gambino, Hashimoto PRL 125(2020)032001] ...

Exclusive semi-leptonic decays: $B \to \pi\ell\nu$



$$q^2 = M_B^2 + M_\pi^2 - 2M_B E_\pi$$

- Conventionally parametrized placing the B meson at rest

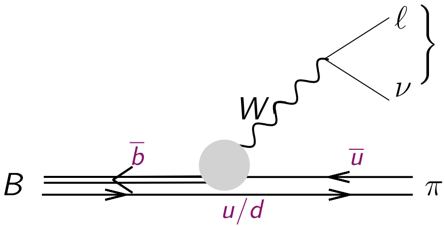
$$\frac{d\Gamma(B\to\pi\ell\nu)}{dq^2} = \frac{G_F^2|V_{ub}|^2}{24\pi^3}\frac{(q^2-m_\ell^2)^2\sqrt{E_\pi^2-M_\pi^2}}{q^4 M_B^2}$$

experiment CKM known

$$\times\left[\left(1+\frac{m_\ell^2}{2q^2}\right)M_B^2(E_\pi^2-M_\pi^2)|f_+(q^2)|^2 + \frac{3m_\ell^2}{8q^2}(M_B^2-M_\pi^2)^2|f_0(q^2)|^2\right]$$

nonperturbative input

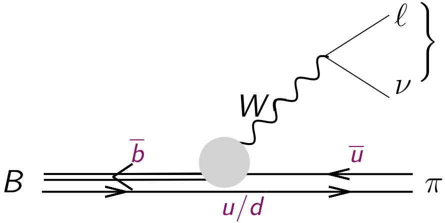
Exclusive semi-leptonic decays: $B \to \pi\ell\nu$



$$q^2 = M_B^2 + M_\pi^2 - 2M_B E_\pi$$

- Nonperturbative input
  - → Parametrizes interactions due to the (nonperturbative) strong force
  - → Use operator product expansion (OPE) to identify short distance contributions
  - → Calculate the flavor changing currents as point-like operators using lattice QCD

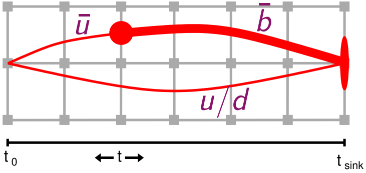
Exclusive semi-leptonic decays: $B \to \pi \ell \nu$



$$q^2 = M_B^2 + M_\pi^2 - 2M_B E_\pi$$

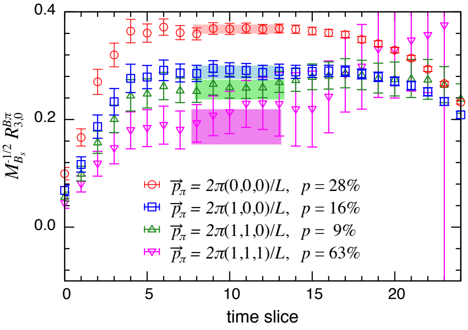
- Calculate hadronic matrix element for the flavor changing vector current V^μ in terms of the form factors $f_+(q^2)$ and $f_0(q^2)$

$$\langle \pi | V^\mu | B \rangle = f_+(q^2)\left(p_B^\mu + p_\pi^\mu - \frac{M_B^2 - M_\pi^2}{q^2} q^\mu \right) + f_0(q^2) \frac{M_B^2 - M_\pi^2}{q^2} q^\mu$$

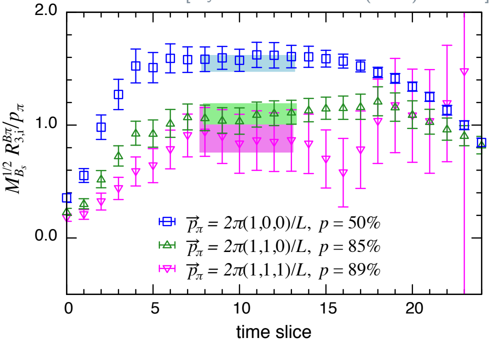


Steps of the $B \to \pi\ell\nu$ calculation

1. Extract form factors on each ensemble



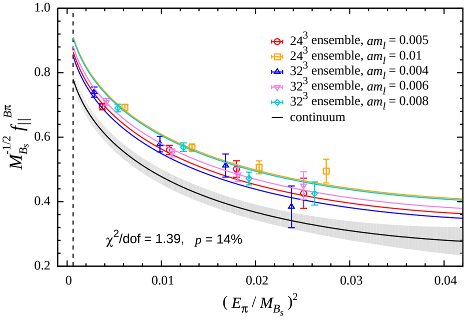
[Flynn et al. PRD 91 (2015) 074510]

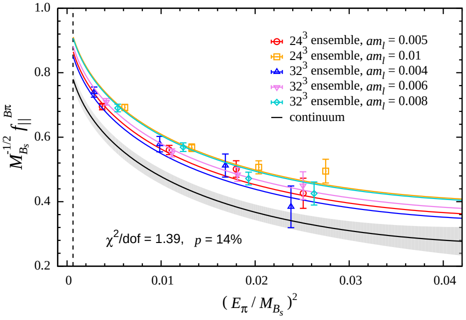


Steps of the $B \to \pi\ell\nu$ calculation

1. Extract form factors on each ensemble
2. Perform chiral-continuum extrapolation

[Flynn et al. PRD 91 (2015) 074510]

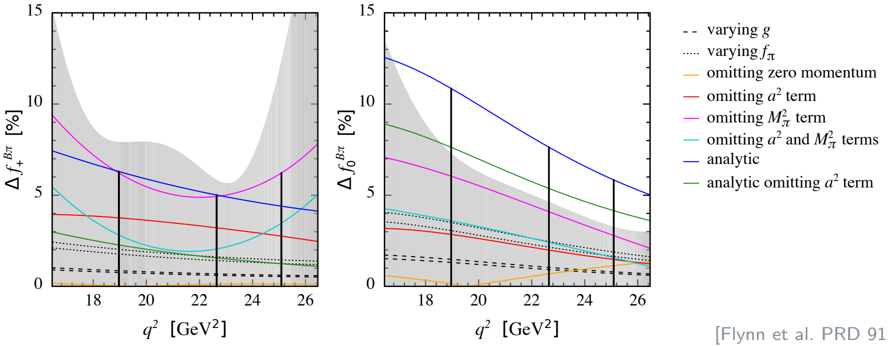




Steps of the $B \to \pi \ell \nu$ calculation

1. Extract form factors on each ensemble
2. Perform chiral-continuum extrapolation

   $\to$ Explore other extrapolations, vary inputs, ...

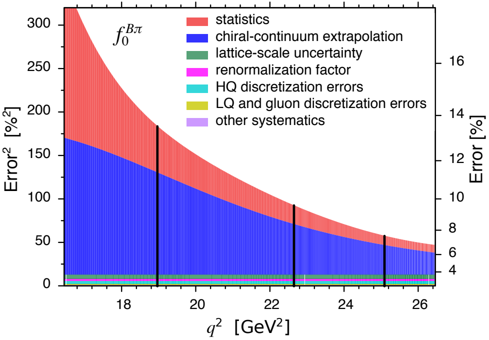


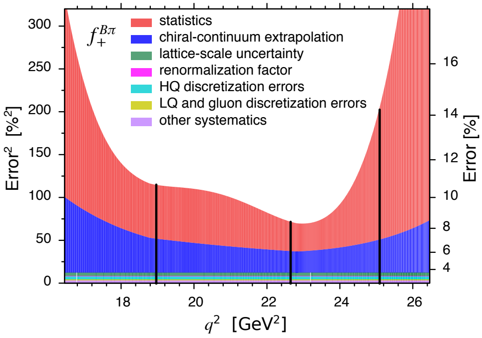
[Flynn et al. PRD 91 (2015) 074510]

Steps of the $B \to \pi\ell\nu$ calculation

1. Extract form factors on each ensemble
2. Perform chiral-continuum extrapolation
   $\to$ Explore other extrapolations, vary inputs, . . .
3. Estimate further systematic uncertainties

[Flynn et al. PRD 91 (2015) 074510]

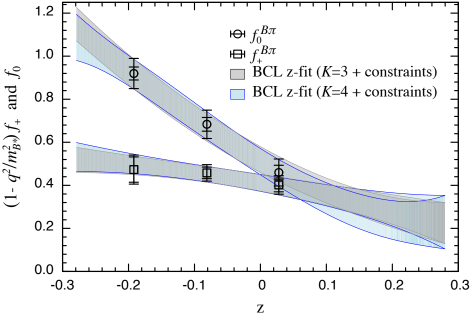


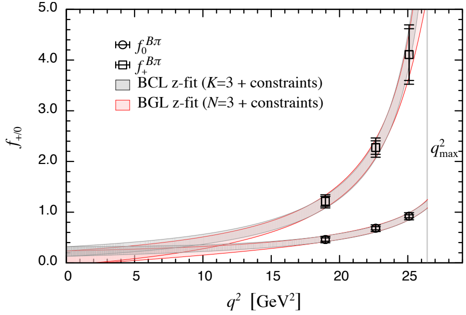


Steps of the $B \to \pi \ell \nu$ calculation

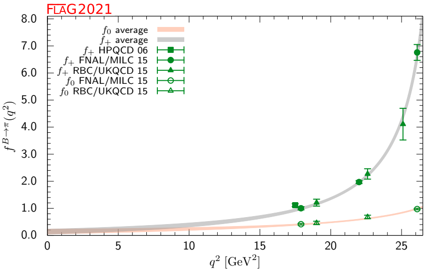
1. Extract form factors on each ensemble
2. Perform chiral-continuum extrapolation
   → Explore other extrapolations, vary inputs, ...
3. Estimate further systematic uncertainties
4. Kinematical extrapolation
   → z-expansion (BGL, BCL, CLN (if applicable))
   → Compare to other calculations, QCD sum rules
   → Combine with experimental data, extract $|V_{ub}|$

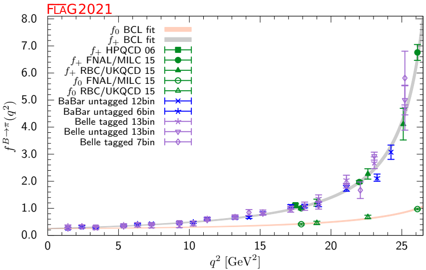
[Flynn et al. PRD 91 (2015) 074510]





FLAG average [FLAG 2021]





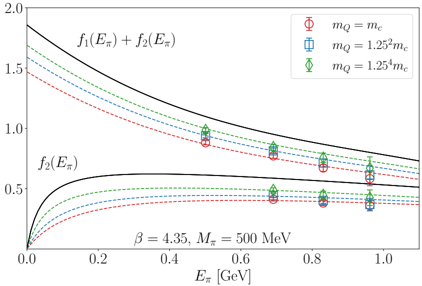
- FLAG average: Fermilab/MILC [Bailey et al. PRD92(2015)014024], RBC/UKQCD [Flynn et al. PRD 91 (2015) 074510]
  → Shown in addition HPQCD [Dalgic et al. PRD73(2006)074502][PRD75(2007)119906]
- Used effective actions only allowed determinations of form factors at large q^2
- Combined fit with experimental data gives $|V_{ub}^{excl}|$
  [BaBar PRD 83 (2011) 032007][PRD 86 (2012) 092004] [Belle PRD 83 (2011) 071101][PRD 88 (2013) 032005]
- Shape of lattice data consistent with experimental data

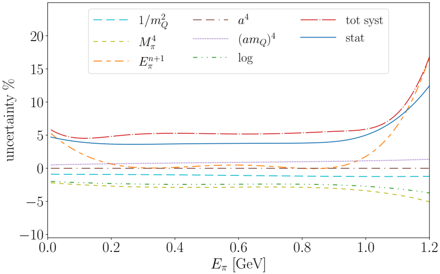
New in 2022: JLQCD [Colquhoun et al. PRD 106 (2022) 054502]

- Unitary setup
  - → MDWF light/strange and heavy quarks with $am_c \leq am_Q \leq 2.44 \cdot am_c$
  - → Additional extrapolation in the heavy quark mass to reach m_b
  - → Fully nonperturbative renormalization

- $a \approx 0.044$ fm, 0.055 fm, 0.080 fm
- $M_\pi \gtrsim 230$ MeV

- Comparable stat. and sys. errors
  - → Total errors: $f_+ \sim 10\%$, $f_0 \sim 6\%$





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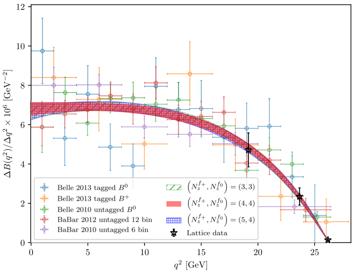
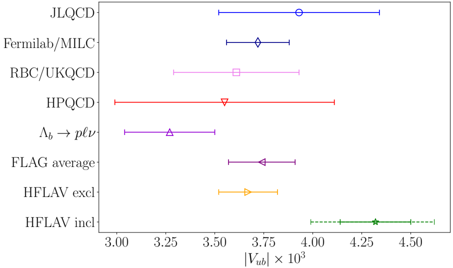
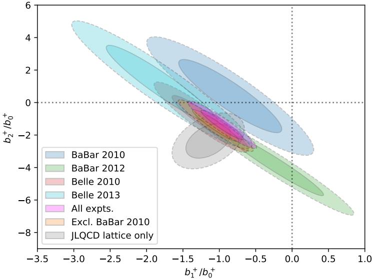






- Joint fit to determine $|V_{ub}|$
  $\Rightarrow |V_{ub}| = (3.93 \pm 0.41) \cdot 10^{-3}$
- Updates from other collaborations expected relatively soon
- Shape parameters of BCL z-fit
  $\to$ Tension with BaBar 2010
  $\to$ Looking forward to new data from Belle II

What are the challenges calculating $B \to \pi\ell\nu$?

- Ratio of $m_{\text{bottom}}/m_{\text{up}}$ is worst
  $\Rightarrow$ Signal-to-noise issue

- B meson are heavy (5279 MeV), pions are light (138 MeV)
  $\rightarrow$ Decay releases lots of energy $\rightsquigarrow$ large range in q^2 to be covered
  $\rightarrow$ Requires simulations of pions with very high momenta (noisy)

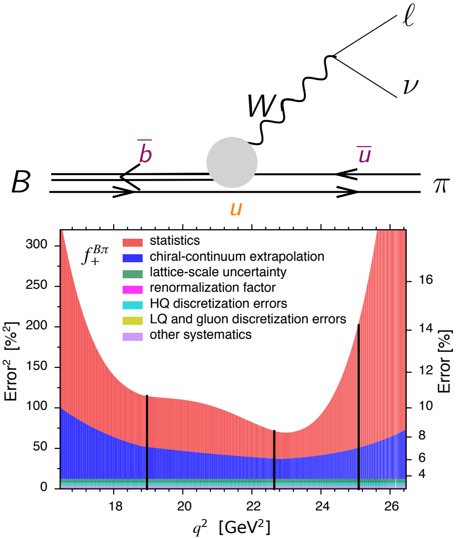
- Experimentally clean environment of B factories (strongly) preferred

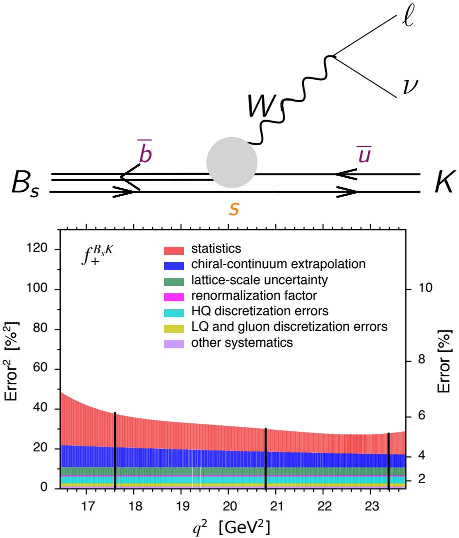
- Alternative B decay modes have their own theoretical/experimental challenges e.g. $B \to \rho(\to \pi\pi)\ell\nu$ on the lattice

Alternative: $B_s \to K\ell\nu$ or $\Lambda_b \to p\ell\nu$

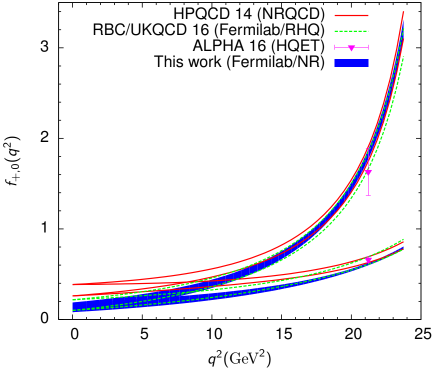
- Experimentally not ideal for B factories
  - → Running at $\Upsilon(5s)$ is less efficient in creating $B_s\bar{B}_s$ pairs
- Abundantly created in pp collisions at the LHC ⇝ LHCb
  - → Normalization not straight forward at LHCb, better to consider (double-)ratios
  - → Determine $|V_{cb}|/|V_{ub}|$ from $B_s \to D_s\ell\nu / B_s \to K\ell\nu$ or $\Lambda_b \to \Lambda_c\ell\nu/\Lambda \to p\ell\nu$ [Detmold, Lehner, Meinel, PRD92 (2015) 034503]
- Compare:
  $M_B = 5279$ MeV : $M_\pi = 138$ MeV ~ 38, q^2 range $\sim [m_\ell^2, 27]$ GeV^2
  $M_{B_s} = 5367 MeV$: $M_K = 494$ MeV ~ 11, q^2 range $\sim [m_\ell^2, 24]$ GeV^2
  ⇝ cheaper and more precise to compute with LQCD

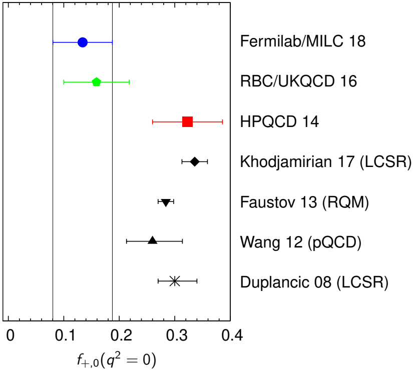
Comparison $B \to \pi\ell\nu$ vs. $B_s \to K\ell\nu$ [Flynn et al. PRD 91 (2015) 074510]





$B_s \to K\ell\nu$





- HPQCD, RBC-UKQCD, ALPHA, Fermilab/MILC
  [Bouchard et al. PRD90(2014)054506] [Flynn et al. PRD91(2015)074510] [Bahr et al. PLB757(2016)473] [Bazavov et al. PRD100(2019)034501]
- Lattice form factors differ at $q^2 = 0$

$B_s \to K\ell\nu$

- First measurement of ratio $B_s \to D_s\ell\nu / B_s \to K\ell\nu$ by LHCb [LHCb PRL 126 (2021) 081804]
  → Only two q^2 bin "high" > 7 GeV^2 and "low" < 7 GeV^2
- FLAG 2021 average [FLAG 2021]
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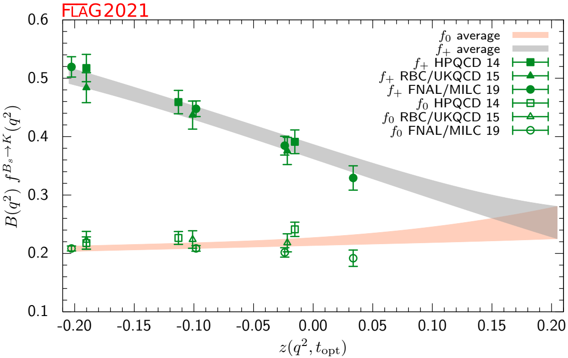

$$\frac{1}{|V_{ub}|^2}\int_{q^2=m_\mu^2}^{7\ \mathrm{GeV}^2} \frac{d\Gamma(B_s \to K^-\mu^+\nu_\mu)}{dq^2} = (2.26 \pm 0.38)\mathrm{ps}^{-1}$$

$$\frac{1}{|V_{ub}|^2}\int_{7\ \mathrm{GeV}^2}^{q^2_{\rm max}=(M_{Bs}-M_K)^2} \frac{d\Gamma(B_s \to K^-\mu^+\nu_\mu)}{dq^2} = (4.02 \pm 0.31)\mathrm{ps}^{-1}$$

$B_s \to K\ell\nu$

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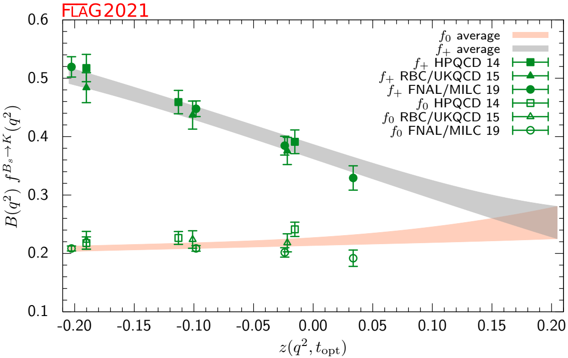

$$\left(\frac{|V_{ub}|}{|V_{cb}|}\right)^{\text{low}} = 0.0819 \pm 0.0072_{\text{lat}} \pm 0.0029_{\text{exp}}$$

$$\left(\frac{|V_{ub}|}{|V_{cb}|}\right)^{\text{high}} = 0.0860 \pm 0.0037_{\text{lat}} \pm 0.0038_{\text{exp}}$$

- Reasonably consistent, but ...

$B_s \to K\ell\nu$

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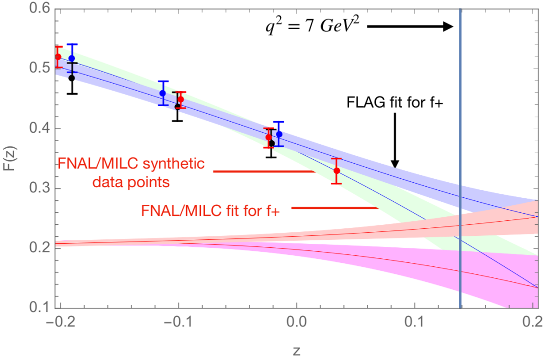


- Using only Fermilab/MILC LHCb got

$$\frac{1}{|V_{ub}|^2}\int_{7\ \text{GeV}^2}^{q^2_{\max}} \frac{d\Gamma(B_s \to K^-\mu^+\nu_\mu)}{dq^2} = (3.32 \pm 0.49)\text{ps}^{-1}$$

$$\left(\frac{|V_{ub}|}{|V_{cb}|}\right)^{\text{high}} = 0.0946 \pm 0.0068_{\text{lat}} \pm 0.0041_{\text{exp}}$$

[Lunghi Barolo 2022]

Determining $|V_{cb}|^{\text{excl}}$

- Heavy-to-heavy transition ⇝ HQET relations

- Available channels
  - → $B \to D\ell\nu$
  - → $B_s \to D_s\ell\nu$
  - → $B \to D^*\ell\nu$
  - → $B_s \to D_s^*\ell\nu$

pseudoscalar final states

vector final states

- D^* and D_s^* suitable for using the narrow width approximation
  - → Treat as QCD-stable particle

Exclusive semi-leptonic decays: $B_{(s)} \to D^*_{(s)}\ell\nu$

$$\langle D^*_{(s)}(k,\varepsilon_\nu)|\mathcal{V}^\mu|B_{(s)}(p)\rangle = V(q^2)\frac{2i\varepsilon^{\mu\nu\rho\sigma}\varepsilon^*_\nu k_\rho p_\sigma}{M_{B_{(s)}} + M_{D^*_{(s)}}}$$

$$\begin{aligned}\langle D^*_{(s)}(k,\varepsilon_\nu)|\mathcal{A}^\mu|B_{(s)}(p)\rangle =& A_0(q^2)\frac{2M_{D^*_{(s)}}\varepsilon^*\cdot q}{q^2}q^\mu \\ &+ A_1(q^2)(M_{B_{(s)}} + M_{D^*_{(s)}})\left[\varepsilon^{*\mu} - \frac{\varepsilon^*\cdot q}{q^2}q^\mu\right] \\ &- A_2(q^2)\frac{\varepsilon^*\cdot q}{M_{B_{(s)}} + M_{D^*_{(s)}}}\left[k^\mu + p^\mu - \frac{M^2_{B_{(s)}} - M^2_{D^*_{(s)}}}{q^2}q^\mu\right]\end{aligned}$$

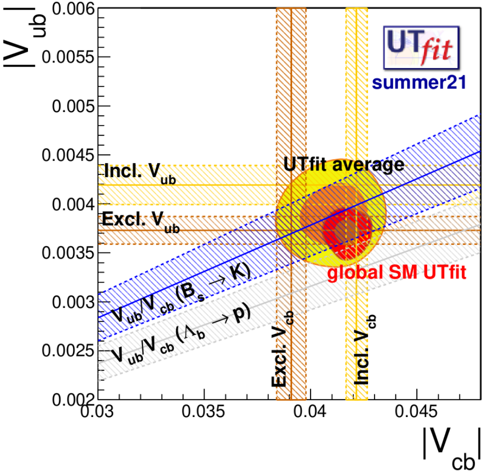
- Determine the four form factors $V(q^2)$, $A_0(q^2)$, $A_1(q^2)$, $A_2(q^2)$ or in HQE convention $h_V(w)$, $h_{A_0}(w)$, $h_{A_1}(w)$, $h_{A_2}(w)$
- Narrow-width approximation i.e. $D^*_{(s)}$ is treated as a QCD-stable particle

First lattice calculations over the full q^2 range

- $B_s \to D_s^* \ell\nu$
  - $\to$ HPQCD [Judd, Davies PRD105(2022).094506]
- $B \to D^* \ell\nu$
  - $\to$ Fermilab/MILC [Bazavov et al. EPJC 82(2022)1141]
  - $\to$ JLQCD [Kaneko et al. PoS Lattice2021 (2022) 561]
  - $\to$ LANL/SWME [Jang et al. PoS Lattice2019 (2020) 056]
  - $\to$ HPQCD [Harrison Talk Barolo 2022]
- Some tension in the shape of the form factors
  - $\to$ Further scrutiny required

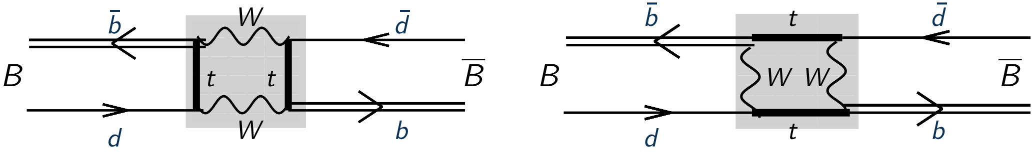
Using unitarity to constrain $|V_{ub}|$ and $|V_{cb}|$

[UTfit PoS EPS-HEP2021(2022)500]



$|V_{td}|$ and $|V_{ts}|$

Neutral meson mixing



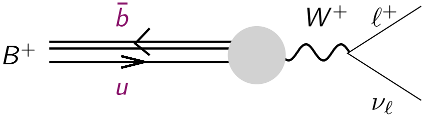
- B-meson mixing dominated by top-loops ⇒ short distance

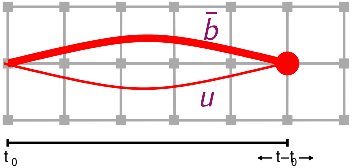
$$\Delta m_q = \frac{G_F^2 m_W^2}{6\pi^2} \eta_B S_0 M_{B_q} f_{B_q}^2 B_{B_q} \left| V_{tq}^* V_{tb} \right|^2, \qquad q = d, s$$

- Constants and lattice uncertainties cancel in ratio [Bernard, Blum, Soni PRD58(1998)014501]

$$\frac{\Delta m_s}{\Delta m_d} = \frac{M_{B_s}}{M_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}, \qquad \xi^2 = \frac{f_{B_s}^2 B_{B_s}}{f_{B_d}^2 B_{B_d}}$$

Decay constants (leptonic decays)





- Conventional parametrization

$$\Gamma(B \to \ell\nu_\ell) = \frac{m_B}{8\pi} G_F^2 \quad f_B^2 \quad |V_{ub}|^2 \quad m_\ell^2 \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2$$

experiment nonperturbative input CKM known

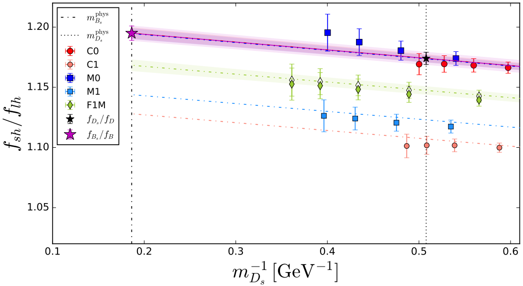
⇝ Determine $|V_{ub}|$ by combining f_B with $B \to \tau\nu$ experimental measurement

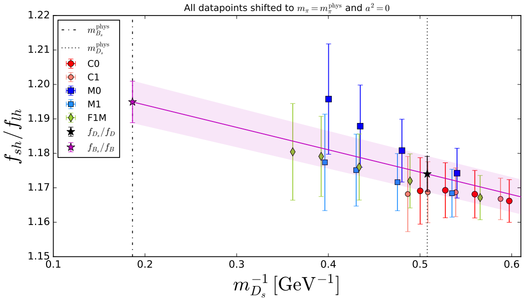
- Measure matrix element with axial current

$$\langle 0|A_\mu|B(p)\rangle = i f_B p_\mu$$

SU(3) breaking ratios: f_{D_s}/f_D and extrapolating to f_{B_s}/f_B

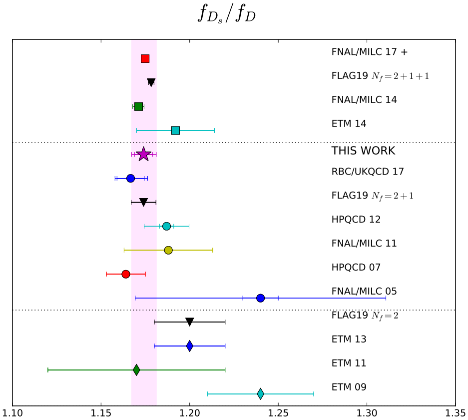
- SU(3)-breaking ratios for $D_{(s)}$ and $B_{(s)}$ mesons [arXiv:1812.08791]
- Stout-smeared MDWF action to simulate charm and heavier than charm quarks

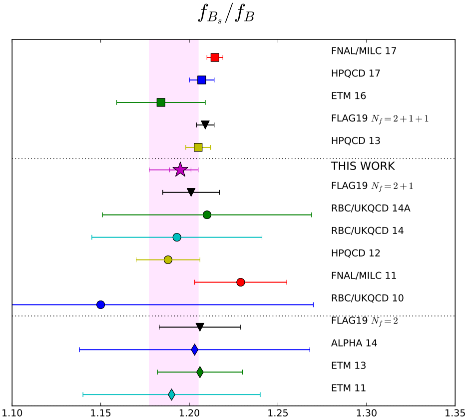




- Ratios obtained at unitary light quark masses
- Ratios shifted to M_π^{phys} and $a^2 = 0$

Comparison SU(3) breaking ratios: f_{D_s}/f_D and f_{B_s}/f_B



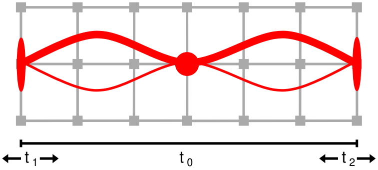


$$f_{D_s}/f_D = 1.1740(51)_{\text{stat}}\begin{pmatrix}+68\\-68\end{pmatrix}_{\text{sys}}$$

$$f_{B_s}/f_B = 1.1949(60)_{\text{stat}}\begin{pmatrix}+95\\-125\end{pmatrix}_{\text{sys}}$$

$$|V_{cd}/V_{cs}| = 0.2164(57)_{\text{exp}}\begin{pmatrix}+12\\-12\end{pmatrix}_{\text{lat}}$$

Bag parameters



- Determine full five operator basis

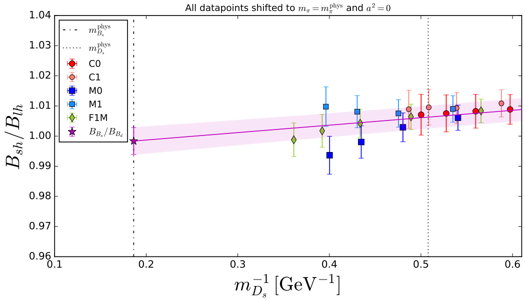
  $\rightarrow$ SM Δm_q

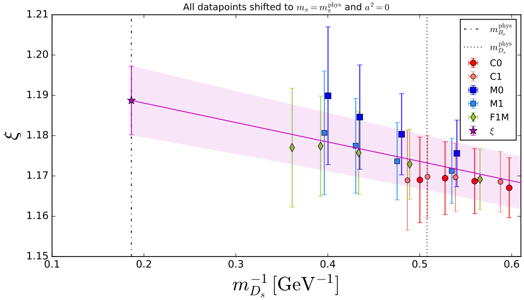
$$\langle \bar{B}_q^0 | [\bar{b}\gamma^\mu(1-\gamma_5)q][\bar{b}\gamma_\mu(1-\gamma_5)q] | B_q^0 \rangle = \frac{3}{8} f_{B_q}^2 M_{B_q}^2 B_{B_q}$$

- Additional dim-7 operators [Davies et al. PRL124(2020)082001]

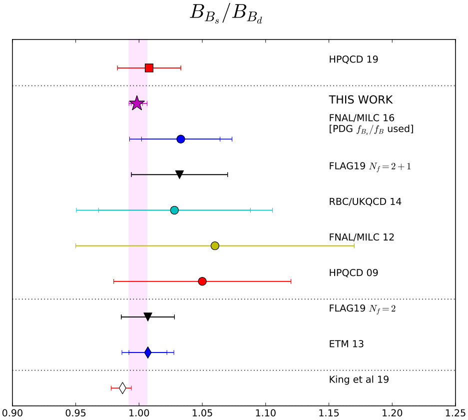
SU(3) breaking ratios: B_{B_s}/B_B and ξ

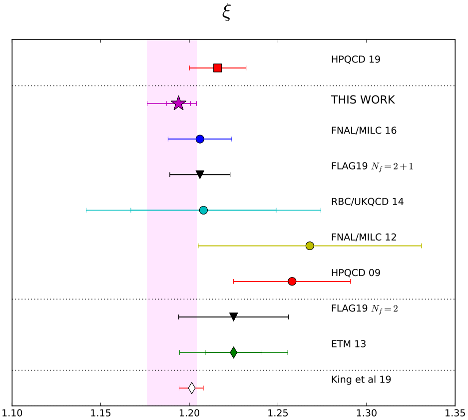
- Ratios shifted to M_π^{phys} and $a^2 = 0$





Comparison SU(3) breaking ratios: B_{B_s}/B_B and ξ





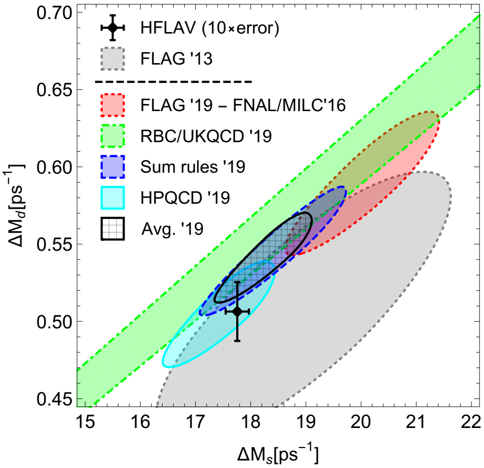
$$B_{B_s}/B_B = 0.9984(45)_{\text{stat}}\begin{pmatrix}+80\\-63\end{pmatrix}_{\text{sys}}$$

$$\xi = 1.1939(67)_{\text{stat}}\begin{pmatrix}+95\\-177\end{pmatrix}_{\text{sys}}$$

$$|V_{td}/V_{ts}| = 0.2039(41)_{\text{exp}}\begin{pmatrix}+162\\-301\end{pmatrix}_{\text{lat}}$$

Comparison to experiment

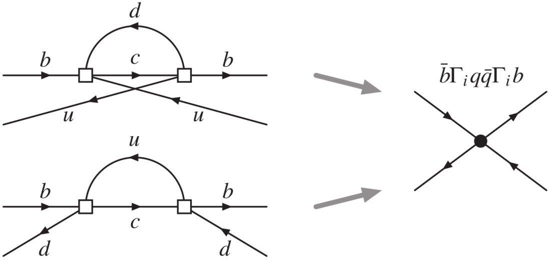
[Di Luzio et al. JHEP12(2019)009]



Lifetimes and decay width

- $\Delta B = 0$ operators
  [Flynn and Lin J.Phys.G 27 (2001) 1245]

$$O_1^q = \bar{b}_L \gamma_\mu q_L \bar{q}_L \gamma^\mu b_L$$
$$O_2^q = \bar{b}_R q_L \bar{q}_L b_R$$
$$T_1^q = \bar{b}_L \gamma_\mu T^a q_L \bar{q}_L \gamma^\mu T^a b_L$$
$$T_2^q = \bar{b}_R T^a q_L \bar{q}_L T^a b_R$$



⇝ determine matrix elements for $q = u, d, s$ to estimate effects from different spectators

$$\frac{1}{2M_{B_q}}\langle B|O_i^q|B_q\rangle = \frac{f_{B_q}^2 M_{B_q}}{8}\mathcal{B}_i \qquad \frac{1}{2M_{B_q}}\langle B_q|T_i^q|B_q\rangle = \frac{f_{B_q}^2 M_{B_q}}{8}\epsilon_i$$

- Obtain ratios for different mesons (baryons) e.g. $\frac{\tau(B^-)}{\tau(B_d^0)} = 1 + a_1\epsilon_+ a_2\epsilon_2 + a_3\mathcal{B}_1 + a_4\mathcal{B}_2$
- Calculation of lifetimes much harder than bag parameters
  → Operators mix under renormalization ⇝ working on gradient flow renormalization scheme
  → Contributions from disconnected diagrams

Summary

- Heavy flavors are challenging
  - → Require to accommodate another scale on the lattice
  - → Simulations with physical light quarks are even more challenging
  - → Semi-leptonic decay processes cover a large range q^2
  - → Leptonic decays experimentally difficult

- Puzzles in heavy flavor physics
  - → Tension between $|V_{ub}|^{\text{excl}}$ vs. $|V_{ub}|^{\text{incl}}$ and $|V_{cb}|^{\text{excl}}$ vs. $|V_{cb}|^{\text{incl}}$
  - → Shape comparisons of form factors
  - → Is new physics hiding in R-ratios?
  - → Or in mixing?

RBC-UKQCD's 2+1 flavor DWF and Iwasaki gauge field ensembles

	L	a^{-1}(GeV)	am_l	am_s	M_π(MeV)	# configs.	
C1	24	1.784	0.005	0.040	338	1636	[PRD 78 (2008) 114509]
C2	24	1.784	0.010	0.040	434	1419	[PRD 78 (2008) 114509]
M1	32	2.383	0.004	0.030	301	628	[PRD 83 (2011) 074508]
M2	32	2.383	0.006	0.030	362	889	[PRD 83 (2011) 074508]
M3	32	2.383	0.008	0.030	411	544	[PRD 83 (2011) 074508]
C0	*48*	*1.730*	*0.00078*	*0.0362*	*139*	*40*	[PRD 93 (2016) 074505]
M0	64	2.359	0.000678	0.02661	139	—	[PRD 93 (2016) 074505]
F1	48	2.774	0.002144	0.02144	234	98	[JHEP 1712 (2017) 008]

- Lattice spacing determined from combined analysis [Blum et al. PRD 93 (2016) 074505]
- a: ~ 0.11 fm, ~ 0.08 fm, ~ 0.07 fm