

B semileptonic form factors in lattice QCD

Elvira Gámiz



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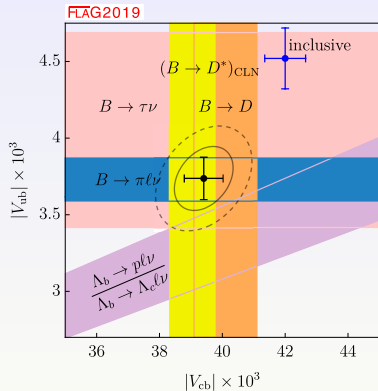


*Centro Andaluz de Física de Partículas
Elementales*

- Conference on Flavour Physics and CP Violation (FPCP) 2020 ·
- 9 June 2020 ·

Introduction: V_{ib} exclusive vs inclusive tension

Long-standing tension between exclusive and inclusive determinations of the **CKM** matrix elements $|V_{cb}|$ and $|V_{ub}|$ at the $\sim 3\sigma$ level.

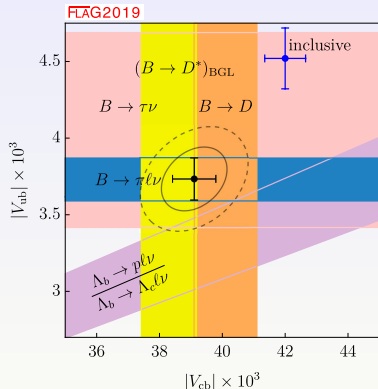


LQCD inputs

- * $B \rightarrow \pi \ell \nu$: $f_+(q^2)$ ($f_0(q^2)$)
- * $\Lambda_b \rightarrow p \mu \nu / \Lambda_b \rightarrow \Lambda_c \mu \nu$:
Six form factors for each channel
- * $B \rightarrow D^* \ell \nu$: $\mathcal{F}(\omega = 1)$
- * $B \rightarrow D \ell \nu$: $\mathcal{G}(\omega)$ (related to $f_+(q^2)$)

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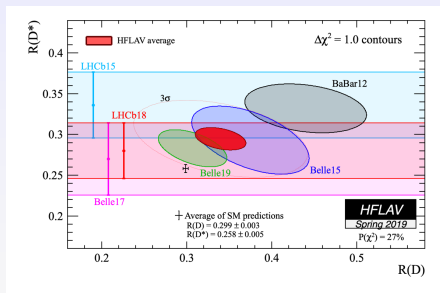
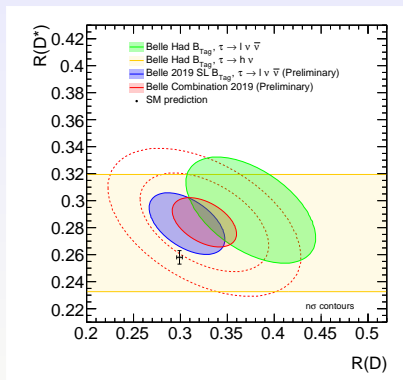
($\omega = v_B \cdot v_D$ velocity transfer to the leptonic pair)

- With latest experimental results for $B \rightarrow D^*$, the origin of the tension for $|V_{cb}|$ is still an open issue.
- New data with increased precision from **Belle II** and **LHCb**.

Introduction: Lepton Flavor Universality tests

Belle 1904.08794

$$R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)})_{\tau\nu\tau}}{\mathcal{B}(B \rightarrow D^{(*)})_{\ell\nu}}$$



Exper. average **HFLAV 19**: $R(D) = 0.340 \pm 0.027 \pm 0.013$, $R(D^*) = 0.295 \pm 0.011 \pm 0.008$

SM average **HFLAV 19**: $R(D) = 0.299 \pm 0.003$, $R(D^*) = 0.258 \pm 0.005$

- **Belle 2019** consistent with SM, but world average at $\sim 3\sigma$ from SM

Neutral-current b decays

Flavor-changing neutral currents $b \rightarrow q$ transitions are potentially sensitive to NP effects $B \rightarrow K^* \gamma$, $B \rightarrow K^{(*)} \ell^+ \ell^-$, $B \rightarrow \pi \ell^+ \ell^-$

Tensions at the $2 - 3\sigma$ level between SM predictions (with lattice inputs for the relevant form factors) and experimentally measured $b \rightarrow s \ell^+ \ell^-$ observables

Branching fractions: $B^0 \rightarrow K^{*0} \mu^+ \mu^-$, $B^+ \rightarrow K^{(*)+} \mu^+ \mu^-$,
 $B_s \rightarrow \phi \mu^+ \mu^-$

Angular observables: $B^+ \rightarrow K^{(*)+} \mu^+ \mu^-$, $B_s \rightarrow \phi \mu^+ \mu^-$

Lepton Flavour Universality ratios (μ/e):

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$, $B^+ \rightarrow K^{(*)+} \mu^+ \mu^-$

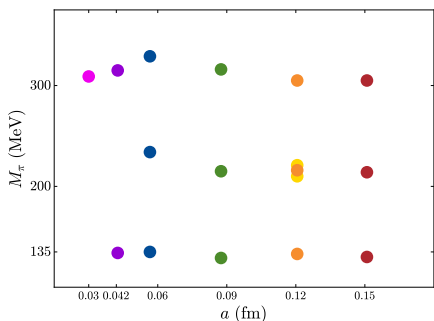
Very small sensitivity to hadronic form factors $\sim 10^{-4}$

$$R_{K^{(*)}}(q_{min}^2, q_{max}^2) \equiv \frac{\int_{q_{min}^2}^{q_{max}^2} dq^2 d\mathcal{B}(B \rightarrow K^{(*)} \mu^+ \mu^-)}{\int_{q_{min}^2}^{q_{max}^2} dq^2 d\mathcal{B}(B \rightarrow K^{(*)} e^+ e^-)}$$

Introduction: Lattice QCD

Combined chiral-continuum extrapolation

Example: MILC $N_f = 2 + 1 + 1$



Many lattice collaborations doing now simulations with **physical light-quark masses**; PACS-CS, BMW, MILC, RBC/UKQCD, ETM...

ChPT techniques still necessary to reduce errors and/or correct/estimate systematic effects: *light and heavy quark discretization, finite volume, isospin-breaking, mass mistunings, ...*

Introduction: Heavy quarks on the lattice

Challenging description of b quarks on the lattice: $(am_h)^n$ errors.

- **Effective theory description:** *Fermilab interpretation, RHQ, OK, NRQCD...*
 - Cheaper simulations but requires matching and can still have ap artifacts.
 - Simulate at $am_h \simeq am_b$.
- **Improved relativistic description:** **ETM, HPQCD, FNAL/MILC, RBC/UKQCD**
 - Reduce errors (potentially results as accurate as for light quarks) and simplified renormalization or not renormalization at all.
 - Numerically more expensive.
 - Need lattice spacing small enough to safely simulate b ($am_b \leq 0.9$)
 - With current ensembles $m_c \leq m_h < m_b$: Need HQ inspired parametrization to extrapolate (or interpolate) to the physical b .

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LQCD results limited to high q^2 to avoid large statistical errors and discretization corrections that grow with momentum.

B semileptonic decays: charged currents

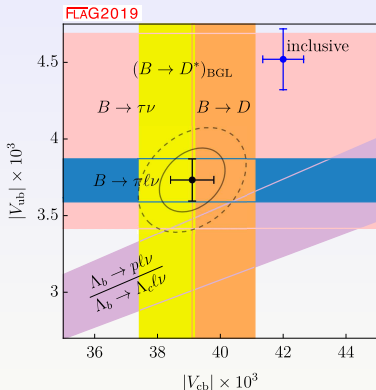
Some lattice results and plots in this talk taken from

Flavour Lattice Averaging Group (FLAG2019): EPJC 80 (2020) 113

(flag.unibe.ch/2019/ for updates)

Exclusive vs inclusive $|V_{ub}|$ and $|V_{cb}|$

Long-standing tension between exclusive and inclusive determinations of the **CKM** matrix elements $|V_{cb}|$ and $|V_{ub}|$ at the $\sim 3\sigma$ level.



LQCD inputs

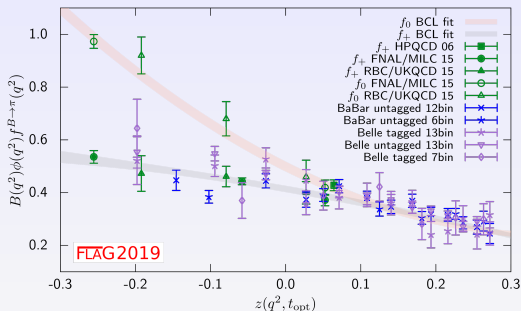
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($w = v_B \cdot v_D$ velocity transfer to the leptonic pair)

$$\frac{d\Gamma(B \rightarrow D^* l \nu)}{dw} = (\text{known}) \times |V_{cb}|^2 \times (w^2 - 1)^{1/2} |\mathcal{F}(w)|^2$$

$$\frac{d\Gamma(B \rightarrow D l \nu)}{dw} = (\text{known}) \times |V_{cb}|^2 \times (w^2 - 1)^{3/2} |\mathcal{G}(w)|^2$$

Status exclusive $|V_{ub}|$ extraction



$|V_{ub}|$ from $B \rightarrow \pi l \nu$

Combined **BCL** fit to experim. and $N_f = 2 + 1$ lattice data on different q^2 regions

RBC/UKQCD, 1501.05373

FNAL/MILC, 1503.07839

HPQCD, hep-lat/0601021

$$|V_{ub}|^{FLAG2019} = 3.73(14) \cdot 10^{-3}$$

Good consistency between lattice and experimental shapes and similar errors

$$|V_{ub}|^{\text{inclusive, HFLAV2019, GGOU}} = (4.32 \pm 12_{-0.13}^{+0.12}) \cdot 10^{-3} \quad \sim 3\sigma \text{ disagreement.}$$

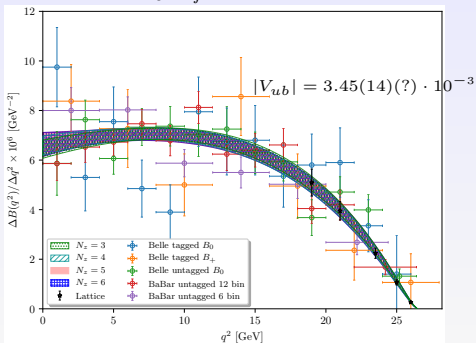
- **Leptonic determinations:** Less precise (dominated by exp. errors on $\mathcal{B}(B \rightarrow \tau \nu)$) and **BaBar** and **Belle** results don't agree very well.

Important role for **Belle II** for both leptonic and semileptonic



Status exclusive $|V_{ub}|$ extraction: On-going calculations

Preliminary $N_f = 2 + 1$ JLQCD:



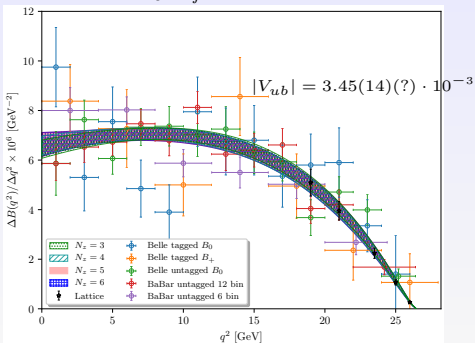
J. Koponen talk at Lattice 2019

Möbius Domain Wall (relativistic): use multiple $m_h > m_c$ and extrapolate to m_b

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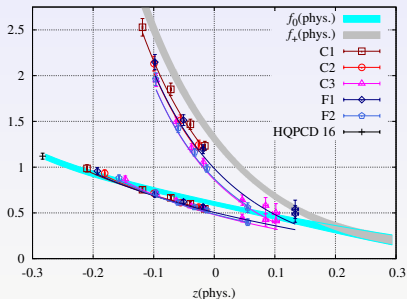
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Challenge: Extend lattice calculations to larger momenta (smaller q^2).

Preliminary $N_f = 2 + 1 + 1$ HPQCD:



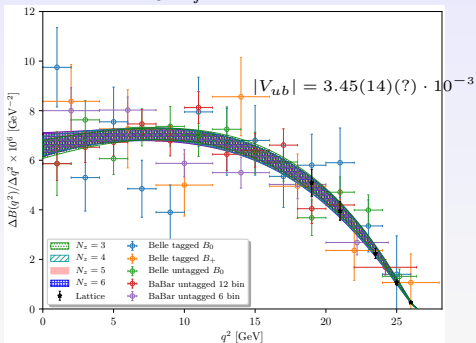
C. Bouchard talk at Lattice 2019

NRQCD heavy quarks, also f_T

Several points with $q^2 \sim 6\text{GeV}^2$

Status exclusive $|V_{ub}|$ extraction: On-going calculations

Preliminary $N_f = 2 + 1$ JLQCD:



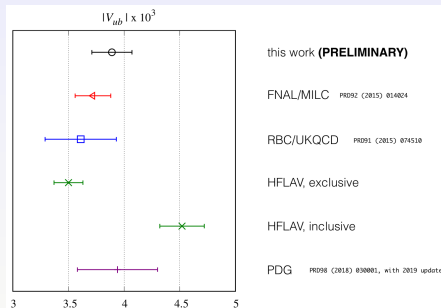
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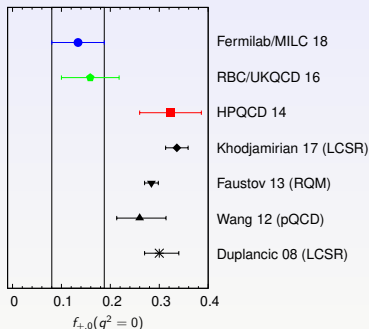
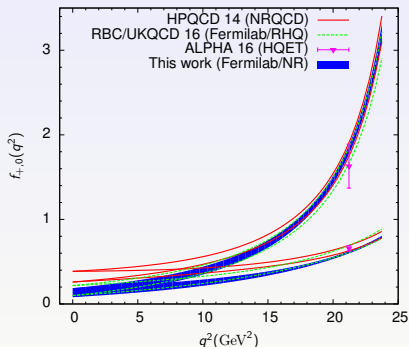
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NRQCD heavy quarks, also f_T

Several points with $q^2 \sim 6\text{GeV}^2$

Status exclusive $|V_{ub}|$ extraction: $B_s \rightarrow K\ell\nu$

Three LQCD calculations of the relevant form factors: **HPQCD 1406.2279**, **RBC/UKQCD 1501.05373**, **FNAL/MILC 1901.02561** (plots below from **FNAL/MILC19**)

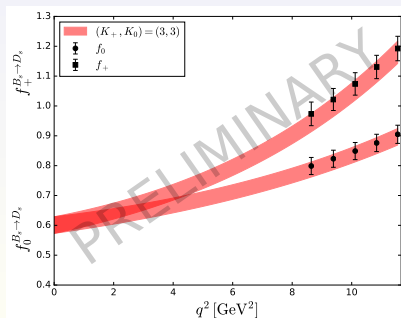
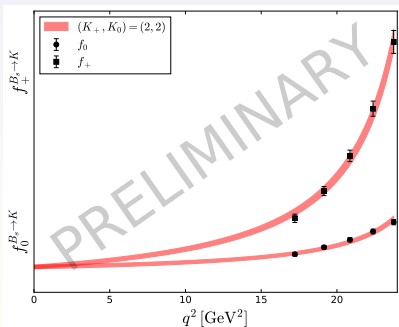


- Also, $f_{0,+}(B_s \rightarrow K\ell\nu)/f_{0,+}(B_s \rightarrow D_s\ell\nu)$ to get $|V_{ub}/V_{cb}|$
- **Experimentally:** Under investigation by **LHCb**, expected to be measured at the $\Upsilon(5S)$ run at **Belle-II**

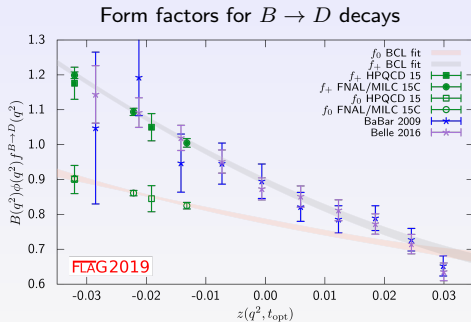
(maybe 5-10% precision for the decay rate at Belle-II)

Status exclusive $|V_{ub}|$ extraction: On-going calculations

- $N_f = 2 + 1 + 1$ FNAL/MILC (also f_T): $B \rightarrow \pi(K)$ and $B_s \rightarrow K$ (close to finalized) **Fermilab b**
Z. Gelzer, talk at Lattice 2019, 1912.13358
- $N_f = 2 + 1$ RBC/UKQCD (also f_T): $B \rightarrow \pi(K)$ and $B_s \rightarrow K$ **RHQ b**
RBC/UKQCD, talks at Lattice 2019, 1912.09946



Status exclusive $|V_{cb}|$ extraction: $B \rightarrow D\ell\nu$

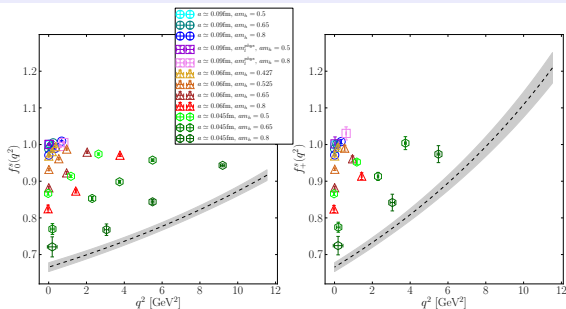


$|V_{cb}| = 40.1(1.0) \cdot 10^{-3}$ in acceptable agreement with either $|V_{cb}^{B \rightarrow D^*}|$ and inclusive determinations

At least five collaborations working on $b \rightarrow c$ decays: **HPQCD**,
FNAL/MILC, **JLQCD**, **RBC/UKQCD**, **LANL-SWME**

Status exclusive $|V_{cb}|$ extraction: $B_s \rightarrow D_s^{(*)} \ell \nu$

$B_s \rightarrow D_s$ form factors with relativistic b HPQCD 1906.0701

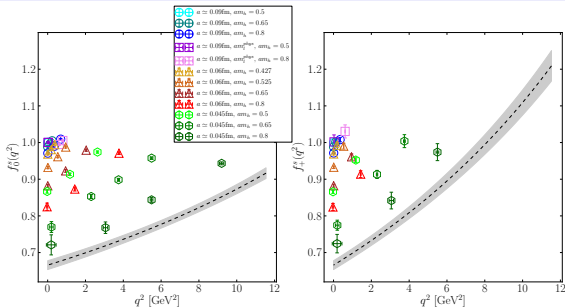


At finest lattice spacing almost the entire physical q^2 range is covered.

- HPQCD 1904.02046 also calculated $h_{A_1}^{B_s \rightarrow D_s^*}(1) = 0.9020(96)(90)$ with relativistic b

Status exclusive $|V_{cb}|$ extraction: $B_s \rightarrow D_s^{(*)} \ell \nu$

$B_s \rightarrow D_s$ form factors with relativistic b **HPQCD 1906.0701**



At finest lattice spacing almost the entire physical q^2 range is covered.

- **HPQCD 1904.02046** also calculated $h_{A_1}^{B_s \rightarrow D_s^*}(1) = 0.9020(96)(90)$ with relativistic b
- This lattice input together with recent measurement **LHCb 2001.03225**

$$|V_{cb}|_{CLN} = 41.4(0.6)(0.9)(1.2) \cdot 10^{-3} \quad |V_{cb}|_{BGL} = 42.3(0.8)(0.9)(1.2) \cdot 10^{-3}$$

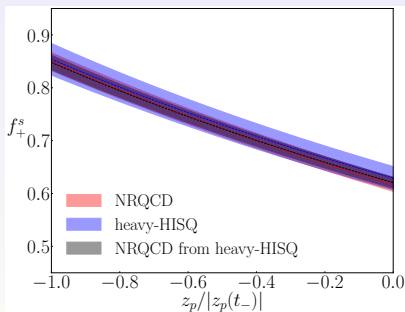
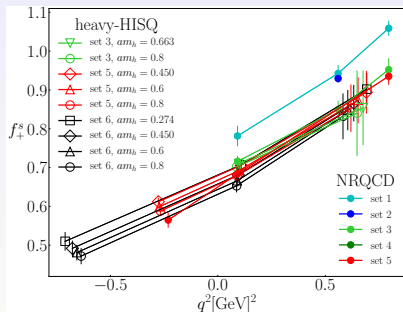
Errors too large to say anything about CLN vs BGL

$B_c \rightarrow B_{(s)}^0 \bar{\ell} \nu$: (Potential) extraction of $|V_{cs,cd}|$

New HPQCD 2003.0091: $N_f = 2 + 1 + 1$ using **two different descriptions for b**

- NRQCD: $am_h = am_b$ and Relativistic heavy-HISQ: $am_c \leq am_h \leq 0.8am_b$ (both using HISQ for $u = d$ and c)

Measurable at LHCb



- Cover complete physical q^2 range
- Good agreement across entire physical z range (for B^0 and B_s^0). Also for f_0

$$\Gamma(B_c^+ \rightarrow B_s^0 \bar{\ell} \nu_\ell) = 52.4(1.8)(1.8) \cdot 10^9 \text{s}^{-1}, \quad \Gamma(B_c^+ \rightarrow B_s^0 \bar{\ell} \nu_\ell) = 3.10(11)(18) \cdot 10^9 \text{s}^{-1}$$

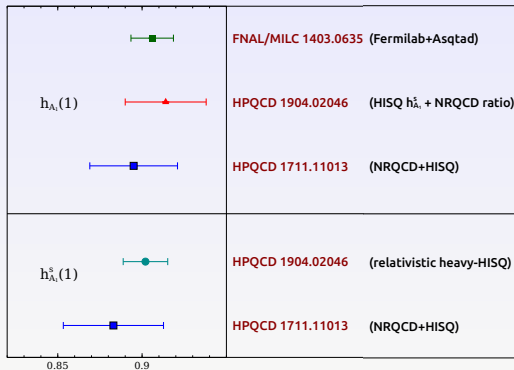
Status exclusive $|V_{cb}|$ extraction: $B \rightarrow D^* \ell \nu$

$|V_{cb}|^{B \rightarrow D^*}$ relies on parametrizations to extrapolate experimental data to zero recoil (lattice data).

$$\frac{d\Gamma(B \rightarrow D^* \ell \nu)}{dw} = |V_{cb}|^2 (w^2 - 1)^{1/2} [\text{factors} |\mathcal{F}(w)|^2 + \text{factors} |H_s(w)|^2]$$

- At zero recoil: $\mathcal{F}(1) = h_{A_1}(1)$
- At non-zero recoil: $h_{A_1}(\omega), h_{A_2}(\omega), h_{A_3}(\omega), h_{A_V}(\omega)$.
 - In the limit $m_\ell = 0$: $h_{A_1}, R_1 = \frac{h_V}{h_{A_1}}$ and $R_2 = \frac{r h_{A_2} + h_{A_3}}{h_{A_1}}$, with $r = M_{D^*}/M_B$

Status exclusive $|V_{cb}|$ extraction: $B_{(s)} \rightarrow D_{(s)}^* \ell \nu$ at zero recoil



$$h_{A_1}(1)_{\text{FNAL/MILC14}} = 0.906(4)(12)$$

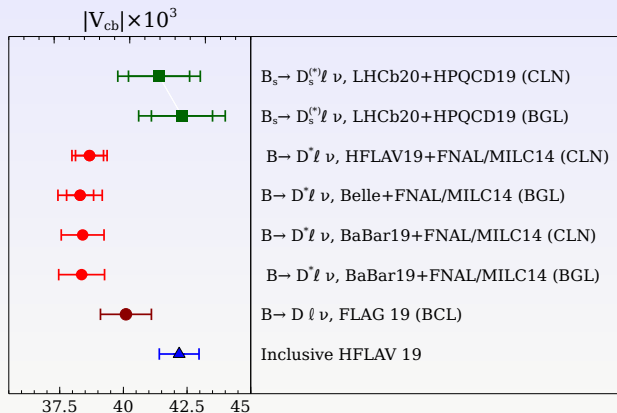
$$h_{A_1}(1)_{\text{HPQCD17}} = 0.895(10)(24)$$

HPQCD 17: small dependence on spectator quark (h_{A_1} vs $h_{A_1}^s$)

(similar insensitivity to spectator quark in $R(D)$ vs $R(D_s)$)

HPQCD 1904.02046 uses $\mathcal{F}^{B_s \rightarrow D_s^*}(1) = h_{A_1}^s(1) = 0.9020(96)_{\text{stat}}(90)_{\text{sys}}$ (relativistic b) and $h_{A_1}^s(1)/h_{A_1}(1)$ from **HPQCD 1711.11013** (NRQCD b) to get $h_{A_1}(1)$

Status exclusive $|V_{cb}|$ extraction: Summary

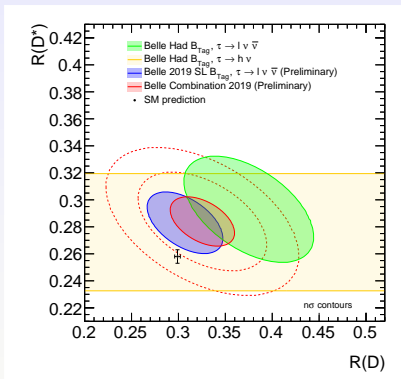


Important to have more precise experimental and lattice inputs to

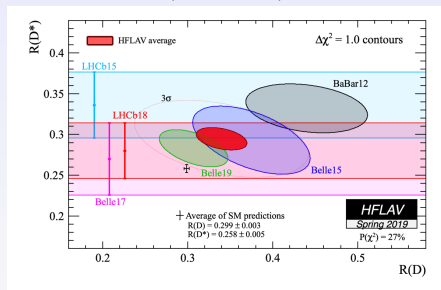
- Shed light over the persistent exclusive-inclusive tension.
- Check whether the parametrization (BGL/CLN) have any impact.

$B \rightarrow D^{(*)} \ell \nu$: Lepton Flavor Universality tests

Plot from Belle 1904.08794



$$R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \nu_\tau)}{\mathcal{B}(B \rightarrow D^{(*)} \ell \nu)}$$



$$R(D)^{\text{HFLAV19}} = 0.340 \pm 0.027 \pm 0.013$$

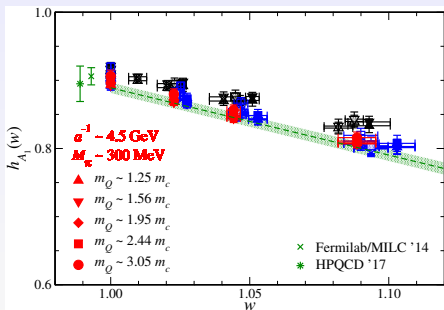
$$R(D^*)^{\text{HFLAV19}} = 0.295 \pm 0.011 \pm 0.008$$

- $R(D)^{\text{FLAG19}} = 0.300(8)$ [only lattice data]
- Need LQCD form factors for $B \rightarrow D^*$ at $\omega \neq 1$: $R(D^*)^{\text{latt}}$ (reduction of error in $P_1(1)$ in the scalar form factor), differential and angular observables ($F_L^{D^*}, P_\tau^{D^*}, \dots$), information about the shape (stabilize fits, CLN vs BGL, ...)

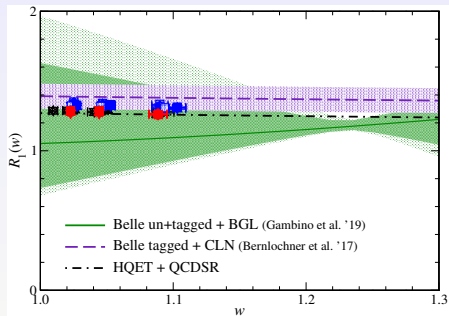
$B \rightarrow D^* \ell \nu$ beyond zero recoil

Preliminary: JLQCD, 1912.11770. Relativistic- b domain wall $N_f = 2 + 1$

$$R_1 = h_V/h_{A_1}$$



- Only statistical errors included so far
- Different colors are different a (Red=smallest a)
- Controlled chiral and continuum extrapol.

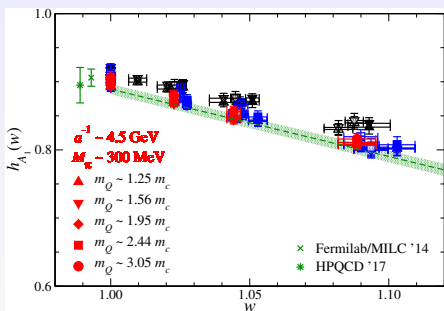


Consistency (also for R_2) among LQCD, BGL, CLN, and NLO HQET

$B \rightarrow D^* l \nu$ beyond zero recoil

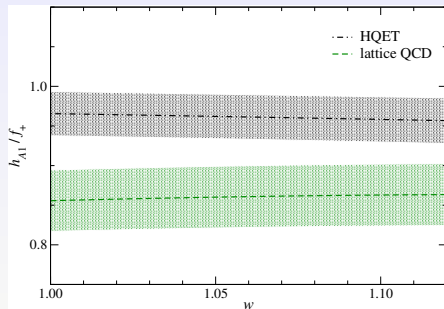
Preliminary: **JLQCD, 1912.11770**. Relativistic- b domain wall $N_f = 2 + 1$

f_+ the vector form factor for $B \rightarrow D$



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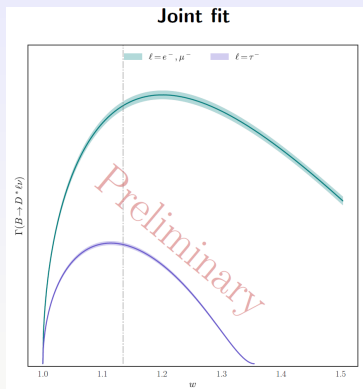
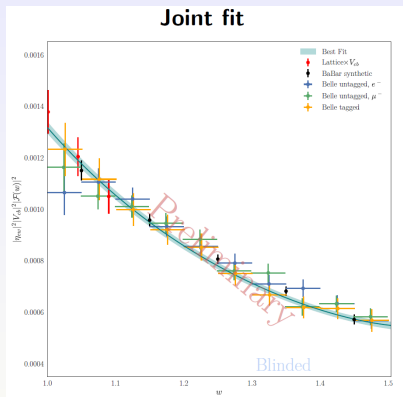
On-going: BSM form factors.



Reasonable agreement in shape, $\sim 10\%$ difference in normalization between NLO HQET prediction and JLQCD results.

$B \rightarrow D^* \ell \nu$ beyond zero recoil

Preliminary: $N_f = 2 + 1$ **FNAL/MILC** (Plots from **A. Vaquero, Lattice 2019**)



z-expansion: Currently subject to intensive cross-checks.

More $b \rightarrow c\ell\nu$ LFU tests

Can help to shed light on existing tensions $R(X \rightarrow Y) = \frac{\mathcal{B}(X \rightarrow Y \tau \nu)}{\mathcal{B}(X \rightarrow Y \mu \nu)}$

Quantity	Theoretical (Lattice) Prediction	Experiment
$R(B_c \rightarrow J/\psi)$	in progress: C. Davies Reconnect20 Preliminary 0.2636(37) close to $R(D^*)$	0.71 ± 0.25 LHCb 1711.05623 aim to 2% exp. error
$R(D_s)$	0.2987(46), HPQCD 1906.00701 [HPQCD 1703.09728 FNAL/MILC 1202.6346, ETMC 1310.5238]	LHCb
$f_+^{B_s \rightarrow K}(0)/f_+^{B_s \rightarrow D_s}(0)$ for $ V_{ub} / V_{cb} $	HPQCD 1808.09285, FNAL/MILC 1901.02561 in progress: RBC/UKQCD 1903.02100, 1912.09946	LHCb
$R(D_s^*)$	in progress (longer term): similar (easier) to $R(D^*)$	LHCb
$R(\Lambda_b \rightarrow \Lambda_c)$	0.333 ± 0.010 **	LHCb
$R(\Lambda_b \rightarrow \Lambda_c^*)$	in progress: S. Meinel, G. Rendón	LHCb

** W. Detmold, C. Lehner, S. Meinel 1503.01421, A. Datta, S. Kamali, S. Meinel, A. Rashed 1702.02243

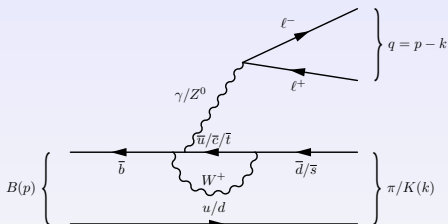
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(flag.unibe.ch/2019/ for updates)

Neutral-current b decays: Lattice inputs



For $B \rightarrow P\ell\ell$, (local) hadronic contributions are parametrized in terms of matrix elements of current (vector, axial and tensor) operators through three form factors

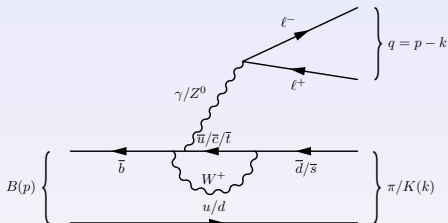
$$f_+, f_0 \text{ (for } m_\ell \neq 0) \text{ and } f_T$$

+ non-factorizable contributions

Allow the calculation of branching fractions, angular observables and LFUV quantities

(Tests against experiment, extract CKM matrix elements $|V_{td,ts}|$, constrain Wilson coefficients C_9 and C_{10})

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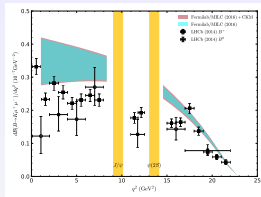
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- $B_{(s)} \rightarrow V\ell^+\ell^-$ provide richer set of observables but additional challenges for LQCD: $V = K^*, \phi$ unstable, more (7) form factors ...
- Non-factorizable contributions under control? New physics or charm-loops? See **K. Nakayama (JLQCD)**, talk at [Lattice 2019, 2001.10911](#)

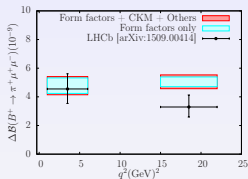
Neutral-current b decays: Lattice inputs

SM predictions systematically higher than experiment.

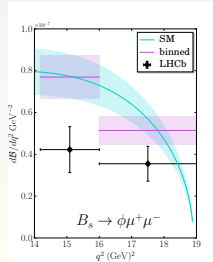
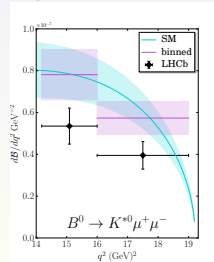
FNAL/MILC, 1509.06235



FNAL/MILC, 1507.01618



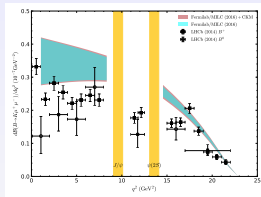
Horgan, Liu, Meinel and Wingate, 1310.3722, 1310.3887



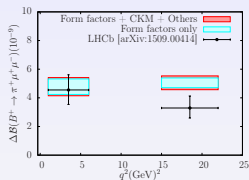
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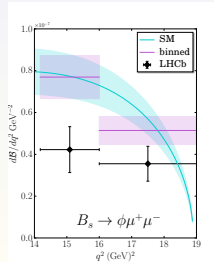
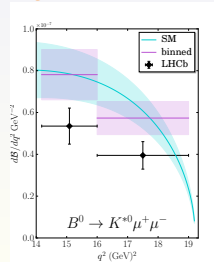
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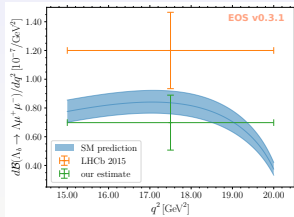


$\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$ LHCb 1503.07138 vs SM

(LQCD) Detmold & Meinel 1602.01399 vs

updated experimental inputs from Blake,

Meinel & van Dyk 1912.05811

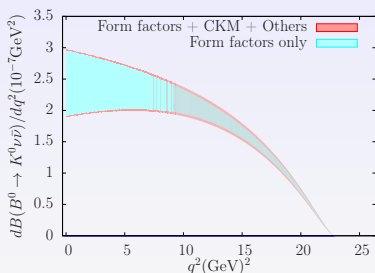
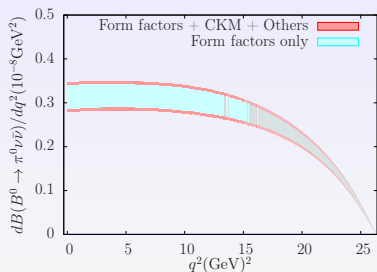


- * New LHCb angular observables 1808.00264
- * New BESIII parity-violating parameter α 1903.09421
- * Updated value of the fragmentation fraction $f(b \rightarrow \Lambda_b)$.

Compatible with SM

Rare semileptonic B decays to $\nu\bar{\nu}$ states

D. Du et al. 1510.02349 with FNAL/MILC form factors



Predictions for both neutral and charged channels: **complementary information** (also $|V_{td,ts}|$)

- Theoretically clean (no problem with charm LD contributions)
- Difficult to measure experiment., Belle-II expected precision $\sim 10\%$ for $B \rightarrow K$

$$\mathcal{B}(B^0 \rightarrow \pi^0 \nu\bar{\nu}) \cdot 10^7 = 0.668(41)(49)(16);$$

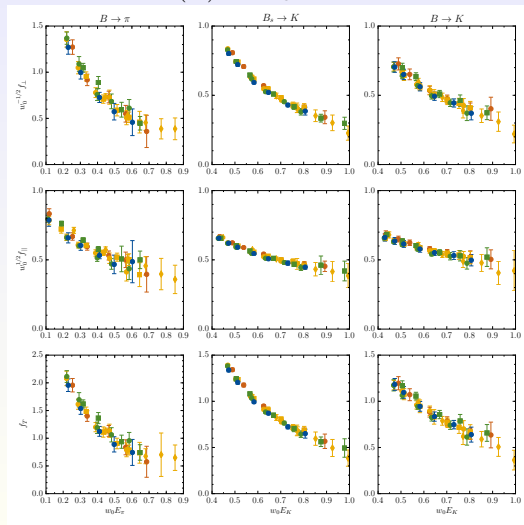
$$\mathcal{B}(B^0 \rightarrow K^0 \nu\bar{\nu}) \cdot 10^7 = 40.1(2.2)(4.3)(0.9)$$

$$\mathcal{B}(B^+ \rightarrow \pi^+ \nu\bar{\nu}) \cdot 10^6 = 9.62(1)(92);$$

$$\mathcal{B}(B^+ \rightarrow K^+ \nu\bar{\nu}) \cdot 10^6 = 4.94(52)(6)$$

Form factors for $B_{(s)} \rightarrow \pi(K)\ell^+\ell^-$: in progress

FNAL/MILC on $N_f = 2 + 1 + 1$ HISQ ensembles, HISQ light quarks, Fermilab b, c . Form factors for $B \rightarrow \pi(K)$ and $B_s \rightarrow K$



Preliminary and blinded

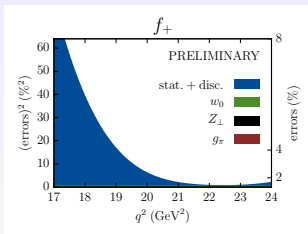
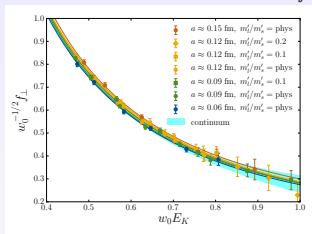
- $a \approx 0.15$ fm, $m'_l/m'_s = \text{phys}$
- $a \approx 0.12$ fm, $m'_l/m'_s = 0.2$
- $a \approx 0.12$ fm, $m'_l/m'_s = 0.1$
- $a \approx 0.12$ fm, $m'_l/m'_s = \text{phys}$
- $a \approx 0.09$ fm, $m'_l/m'_s = 0.1$
- $a \approx 0.09$ fm, $m'_l/m'_s = \text{phys}$
- $a \approx 0.06$ fm, $m'_l/m'_s = \text{phys}$

Plots courtesy of Zech Gelzer

Form factors for $B_{(s)} \rightarrow \pi(K) \ell^+ \ell^-$: in progress

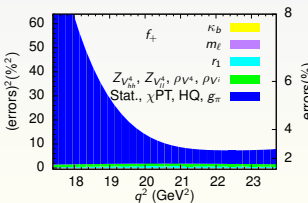
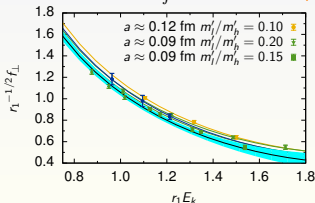
Example: comparison to previous $B_s \rightarrow K$ FNAL/MILC calculation

Preliminary and blinded $N_f = 2 + 1 + 1$ FNAL/MILC, Z. Gelzer



Similar $a \rightarrow$ similar statistics, smaller discretization (HISQ)

Published $N_f = 2 + 1$ FNAL/MILC 1901.02561




Physical m_l' ensembles \rightarrow remove chiral extrapolation error

Future prospects

- **LQCD on-going (and planned) calculations should reduce current non-pert. errors, provide new inputs for CKM studies, and help to clarify current tensions/anomalies.**
- General lines of improvement
 - Simulating all flavors with the same (relativistic description) and b near its physical mass.
 - Include isospin breaking and structure-dependent QED corrections.
 - Extend q^2 range.

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- First Lattice calculations of radiative corrections: $\Gamma(\pi(K) \rightarrow \mu^+ \bar{\nu}[\gamma])$ **Di Carlo et al**, 1904.08731, **Martinelli at Lat2019** 1910.07342
 - Extend to heavy mesons and semileptonic decays.
- Methodology and pilot computation of inclusive semileptonic decays from lattice QCD, **P. Gambino, S. Hashimoto**, 2005.13730
- Theoretical framework for semileptonic B decays to unstable vector meson final states exists **Briceño et al** 1406.5965, **Agadjanov et al** 1605.03386, **Hansen, Meyer, Robaina** 1704.08993
 - Pilot studies of form factors for $B_s \rightarrow K^*(\rightarrow K\pi)\ell\nu$, $B \rightarrow K^*(\rightarrow K\pi)\ell\ell, \dots$ underway **Leskovec, Meinel, Rendón**; See **Rendón talk at Lattice 2019**
- New ideas to study charmonium contribution to $B \rightarrow K\ell^+\ell^-$ on the lattice **K. Nakayama talk at Lattice19** (Ishikawa, Hashimoto) 2001.10911

(similar formulation to LD effects in $K \rightarrow \pi\ell\ell$) 

Summary of lattice inputs

Quantity	current error	2025 Projections
$B \rightarrow \pi$ for $ V_{ub} _{\text{theor}}$	2.9%	1%(1.4%)
$B \rightarrow D$ for $ V_{cb} _{\text{theor}}$	1.4%	0.3%(1%)
(first param. BCL z -exp.)	1.5%	0.5%(1.1%)
$B \rightarrow D^*$ for $ V_{cb} _{\text{theor}}$	1.4%	0.4%(0.7%)
$h_{A_1}^{B \rightarrow D^*}(\omega = 1)$		1-1.5%
$P_1^{B \rightarrow D^*}(\omega = 1)$		
$\Lambda_b \rightarrow p(\Lambda_c)$	4.9%	1.2%(1.6%)
for $ V_{ub}/V_{cb} _{\text{theor}}$		
$B \rightarrow K$ (first param. BCL z -exp.)	2%	0.7%(1.2%)
$B_s \rightarrow K$ (first param. BCL z -exp.)	4%	1.3%(1.7%)

M. Della Morte, E. Lunghi, E. G. for *Opportunities in Flavour Physics at the HL-LHC and HE-LHC*, 1812.07638 (with a few updates)

Backup slides