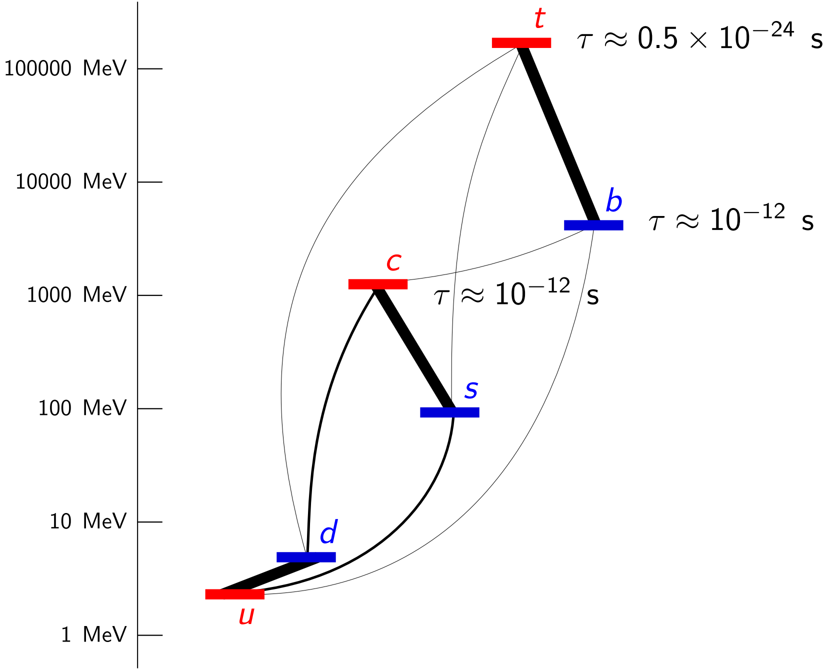
Weak decays of b and c quarks

https://snowmass21.org/rare/weakbc

Angelo Di Canto (BNL) and Stefan Meinel* (U. of Arizona)

Frontier for Rare Processes and Precision Measurements
Kickoff Meeting, July 27, 2020

*Speaker.


100000 MeV
10000 MeV
1000 MeV
100 MeV
10 MeV
1 MeV
t
$\tau \approx 0.5 \times 10^{-24}$ s
b
$\tau \approx 10^{-12}$ s
c
$\tau \approx 10^{-12}$ s
s
d
u

Bottom

- FCNC processes are easily observed and are usually short-distance-dominated.
- CP-violating effects can be very large.

Charm

- FCNC processes are more strongly GIM-suppressed and are usually long-distance-dominated.
- CP-violating effects in the SM tend to be very small.

Our group explores experimental and theoretical aspects of

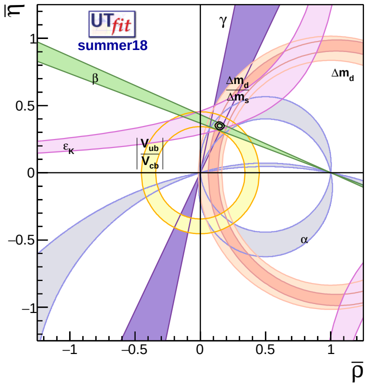
- Mixing and CP violation in b decays
- Mixing and CP violation in c decays
- CKM constraints
- Rare b decays
- Rare c decays
- Tests of lepton flavor universality in charged-current decays
- Tests of lepton flavor universality in neutral-current decays
- Searches for processes that are forbidden in the Standard Model
- Determinations of relevant hadronic properties (lifetimes, branching fractions, hadronic matrix elements, scattering phase shifts, ...)

CKM constraints

1st and 3rd generation triangle:

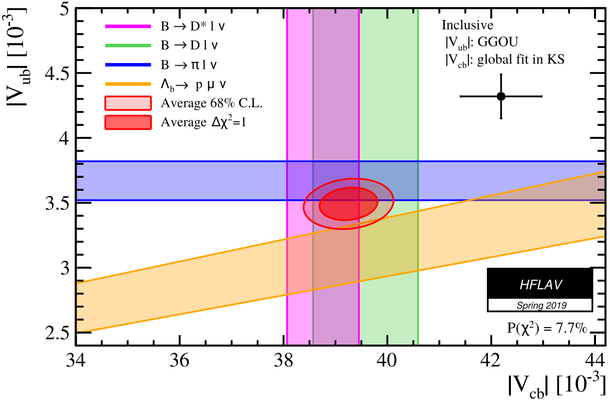
$$\begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} + 1 + \frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}} = 0$$



See talk by M. Bona at ICHEP 2020 for updates!

$|V_{ub}|$ and $|V_{cb}|$: exclusive vs. inclusive



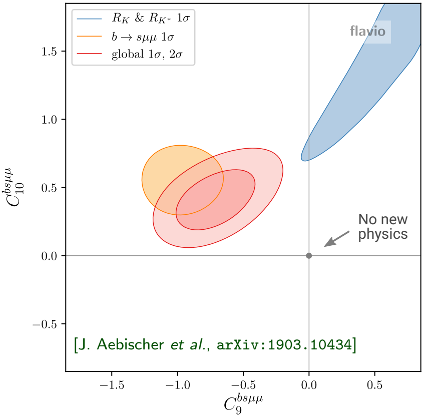
$|V_{cb}|$ and ε_K

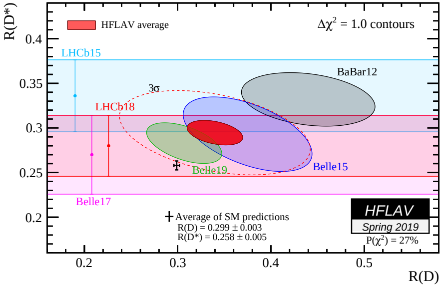
$\|V_{cb}\|$	method	reference	$\|\varepsilon_K\|^{\mathrm{SM}}$	$\Delta\varepsilon_K$
exclusive	CLN	BELLE-19	1.456 ± 0.172	4.47σ
exclusive	BGL	BELLE-19	1.443 ± 0.181	4.32σ
exclusive	CLN	BABAR-19	1.456 ± 0.169	4.55σ
exclusive	BGL	BABAR-19	1.451 ± 0.175	4.44σ
exclusive	combined	HFLAV-19	1.576 ± 0.154	4.23σ
inclusive	kinetic	HFLAV-17	2.060 ± 0.212	0.79σ
inclusive	1S	HFLAV-17	2.020 ± 0.176	1.18σ

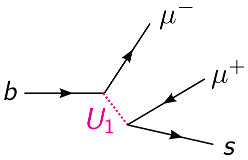
$$|\varepsilon_K|^{\mathrm{expt}} = 2.228(11) \times 10^{-3}$$

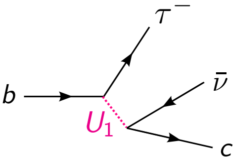
[J. Kim *et al.*, `arXiv:1912.03024`]

$b \to s\mu^+\mu^-$ and $b \to c\tau\bar{\nu}$









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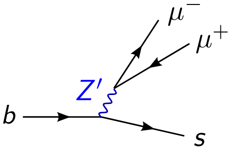
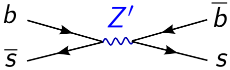
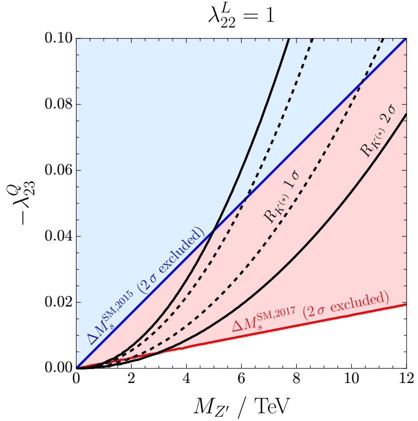
$b \to s\mu^+\mu^-$ and B_s-$\bar{B}_s$ mixing







[L. Di Luzio, M. Kirk, A. Lenz, arXiv:1811.12884]

Charm CP violation

PHYSICAL REVIEW LETTERS **122,** 211803 (2019)

Editors' Suggestion | Featured in Physics

Observation of *CP* Violation in Charm Decays

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 21 March 2019; revised manuscript received 2 May 2019; published 29 May 2019)

$$A_{CP}(f;t) = \frac{\Gamma(D^0(t)\to f) - \Gamma(\overline{D}^0(t)\to f)}{\Gamma(D^0(t)\to f) + \Gamma(\overline{D}^0(t)\to f)}$$

Time-averaged measurement:

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-15.4 \pm 2.9)\times 10^{-4}$$

Mostly sensitive to direct CP violation.

Experiments

LHCb

- Huge advantage in production rate, but also large backgrounds
- Superior decay-time resolution for time-dependent measurements
- Access to all b-hadron species

Belle II

- Cleaner environment allows for more generous selections — milder efficiency effects
- Unique access to fully neutral final states and decays with invisible particles

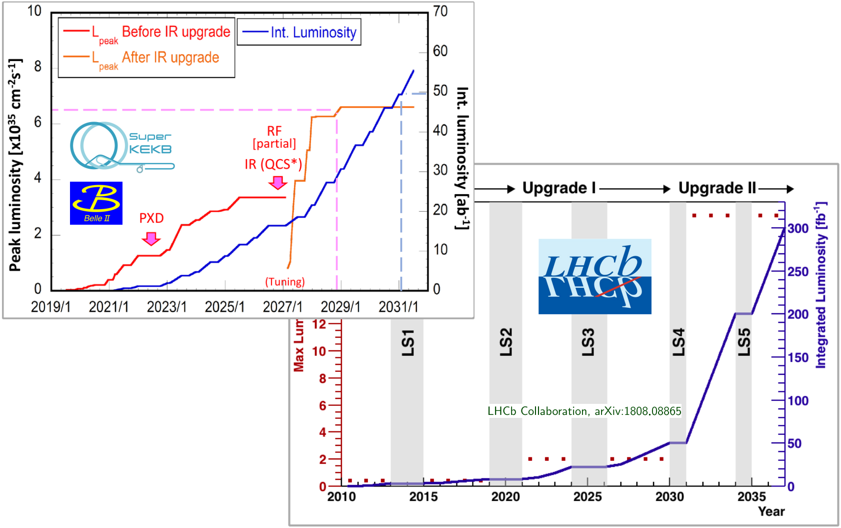
ATLAS/CMS

- Larger inst. lumi. than LHCb, access to final states with dimuons

BESIII/charm-τ factory (SCT/STCF)

- Unique access to quantum-correlated $D^0\bar{D}^0$ pairs

Belle II and LHCb integrated luminosity prospects



Maybe also a Belle III running at $5\times$(Belle II inst. lumi.) to collect 250 ab^{-1}?

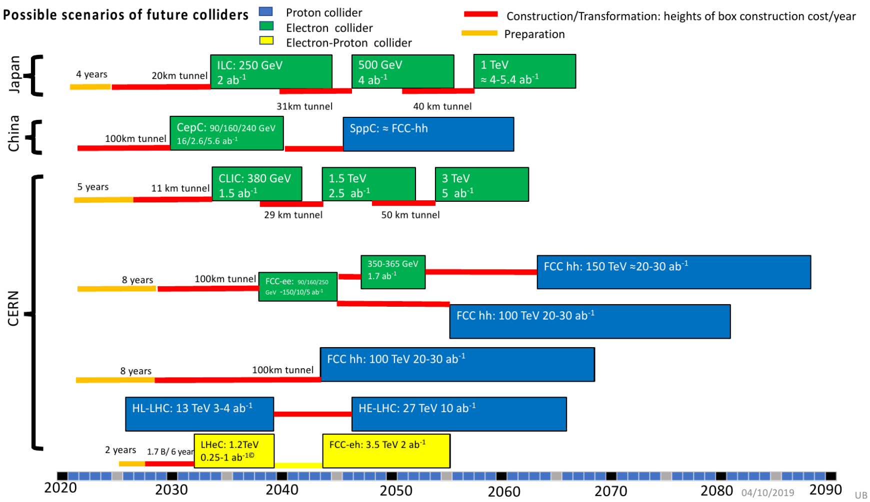
Observable	LHCb 2018	LHCb 2025	Belle II 2029	End of HL-LHC (2039) LHCb	End of HL-LHC (2039) ATLAS/CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

… and many other observables. [LHCb Collaboration, arXiv:1808.08865]

Some projections depend on improved measurements of input quantities by other experiments, or improved lattice QCD calculations.

Example: γ from $B \to D(\to K_S\pi\pi)K$ requires strong phases in D-meson decay from BESIII, super-tau-charm factories

Possible Future Energy-Frontier Colliders



[U. Bassler, CERN-ESU-005]

Heavy-hadron yields

Table 7.1: Expected production yields of heavy-flavoured particles at Belle II (50 ab^{-1}) and FCC-ee.

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\overline{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	1000	1000	250	250	550	170

[Abada *et al.*, EPJC **79** 6, 474]

Particle	Tera-Z	Belle II	LHCb
***b* hadrons**			
B^+	6×10^{10}	3×10^{10} ($50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$)	3×10^{13}
B^0	6×10^{10}	3×10^{10} ($50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$)	3×10^{13}
B_s	2×10^{10}	3×10^{8} ($5\,\mathrm{ab}^{-1}$ on $\Upsilon(5S)$)	8×10^{12}
b baryons	1×10^{10}		1×10^{13}
Λ_b	1×10^{10}		1×10^{13}
***c* hadrons**			
D^0	2×10^{11}		
D^+	6×10^{10}		
D_s^+	3×10^{10}		
Λ_c^+	2×10^{10}		
τ^+	3×10^{10}	5×10^{10} ($50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$)	

Table 2.4: Collection of expected number of particles produced at a tera-Z factory from 10^{12} Z-boson

[CEPC Study Group, `arXiv:1811.10545`]

Λ_b's produced through Z-boson decays are strongly longitudinally polarized, which gives access to new observables. [G. Hiller and A. Kagan, `arXiv:hep-ph/0108074`]

Theory

- BSM simplified models and UV-complete theories
- Effective weak Hamiltonians
- SMEFT
- Lattice QCD
- QCD factorization
- Light-cone sum rules
- Heavy-quark effective theory
- Soft-collinear effective theory
- Heavy-hadron and hard-pion chiral perturbation theory
- Dispersive methods
- Flavor-symmetry relations and quark models

Many of these methods are also explored by the Snowmass Theory Frontier. Our RF1 topical group focuses on applications to weak interactions of b and c quarks.

A puzzle in $\bar{B}^0_{(s)} \to D^+_{(s)}\{\pi^-, K^-\}$ decays and extraction of the f_s/f_d fragmentation fraction

Marzia Bordone* and Tobias Huber†
Theoretische Physik 1, Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Straße 3, D-57068 Siegen, Germany

Nico Gubernari‡ and Danny van Dyk§
Technische Universität München, James-Franck-Straße 1, 85748 Garching, Germany

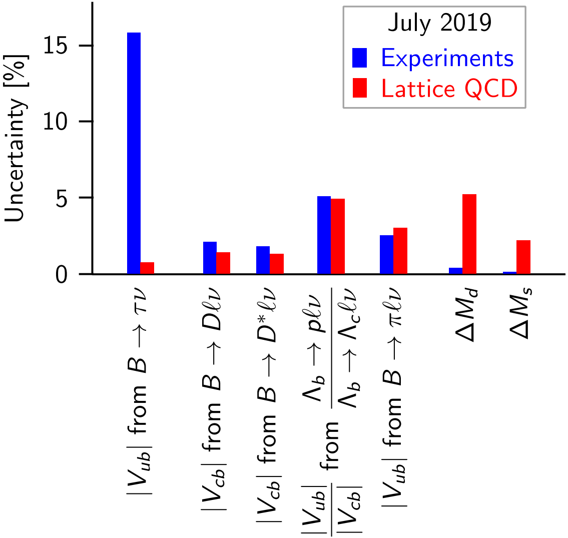
Martin Jung¶
Dipartimento di Fisica, Università di Torino & INFN, Sezione di Torino, I-10125 Torino, Italy

Our comparison of the various experimental measurements of these modes and our theoretical predictions shows a clear and very significant discrepancy at the level of 4.4σ. This high level is due to drastically reduced parametric uncertainties. We identify the following possible four causes of the discrepancy, none of which is fully satisfactory on its own:

[M. Bordone *et al.*, arXiv:2007.10338]

Lattice QCD

Example: b leptonic and semileptonic decays and mixing



Lattice QCD

New directions

- Matrix elements with multi-hadron states
- Matrix elements with nonlocal insertions of multiple currents
- QED corrections
- Inclusive observables

Some of these are discussed in the USQCD whitepaper "Opportunities for lattice QCD in quark and lepton flavor physics"

[C. Lehner, S. Meinel, *et. al.*, arXiv:1904.09479]

but there are already many new developments since the whitepaper was written

Examples of questions

- What causes the exclusive-inclusive discrepancies in $|V_{ub}|$ and $|V_{cb}|$?
- What causes the anomalies in $b \to s\ell^+\ell^-$ and $b \to c\tau\nu$?
- Is lepton-flavor-number conservation also violated?
- What are the options for UV-complete theories that explain the b anomalies?
- What is the Standard-Model prediction for ΔA_{CP} in charm?

Examples of questions

- Which of the physics projections for the LHCb upgrade and for Belle II need to be updated? What other measurements can be done?
- What are the prospects for an upgrade / a successor of SuperKEKB and Belle II?
- Which auxiliary measurements (normalization branching fractions, strong phases, ...) need to be improved?
- What can be done with longitudinally polarized Λ_b and Λ_c baryons produced in Z decays at future e^+e^- colliders?
- What unique opportunities does a muon collider offer for b and c physics? (Directly produce new mediators coupling to $\mu^+\mu^-$?)
- How can experimental data be presented to provide the best information to theorists? What SM assumptions are already baked into the data analysis, and can that be avoided or undone?

How to get involved

- Subscribe to our mailing list, join our Slack channel, and complete our community survey. Instructions are at
  https://snowmass21.org/rare/weakbc
- Attend our workshops and participate in the discussions
- Submit LOIs or contributed papers:
  https://snowmass21.org/loi,
  https://snowmass21.org/submissions/start
- Send us emails with your ideas or questions:
  dicanto@bnl.gov, smeinel@arizona.edu

Planned workshops

First workshop, joint with RF5:

- "Lepton flavor (universality) violation in meson and baryon decays"
  ~~August 13~~ September 28-29, 2020
  https://indico.fnal.gov/event/44442/

Further workshops will be announced through our mailing list and on the Wiki.

We welcome suggestions of topics and speakers.