ESPPU – Flavour Parallel Session – 23 June 2025

Rare b decays and test of Lepton Flavour Universality

Marta Calvi - University of Milano-Bicocca and INFN

Andreas Juttner (CERN), Jernej Kamenik (Ljubljana), Patrick Koppenburg (Nikhef)

23–27 Jun 2025
Venice Lido

Introduction

Rare decays of beauty and charm hadrons are powerful tools in the quest for New Physics.
Many decay modes and wide range of observables

- Extremely precise measurements allow stringent test of SM predictions.
- Strongly suppressed decays provide null tests of SM.
- (Semi)-leptonic decays to leptons of different flavours can challenge LFU of SM.

Current precision on measurements is dominated by the limited size of available data samples.

The yields collected in the next years by existing or proposed flavour projects will bring improved sensitivity to key-observables and allow meaningful measurements of new ones.

- They will expand the range of complementary decay modes studied and give access to new strategies for data analysis.

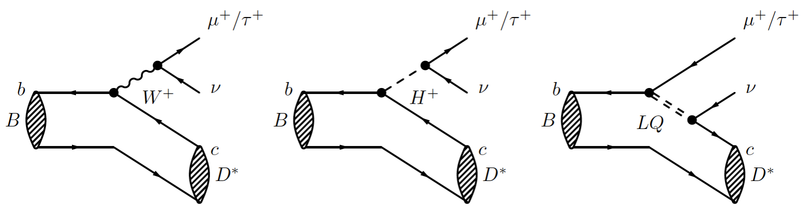
- *The following slides contain a partial and unavoidably incomplete overview of the wide landscape of measurements that are currently under study.*
  - *Projections are made using the inputs from submissions, when available, or references cited there.*

LFU in charged currents b decays: b→clν

LFU: electroweak couplings to all charged leptons are universal in the SM

differences between e, μ, τ are driven only by masses.

Any deviation from LFU is a key signature of physics processes beyond the SM.

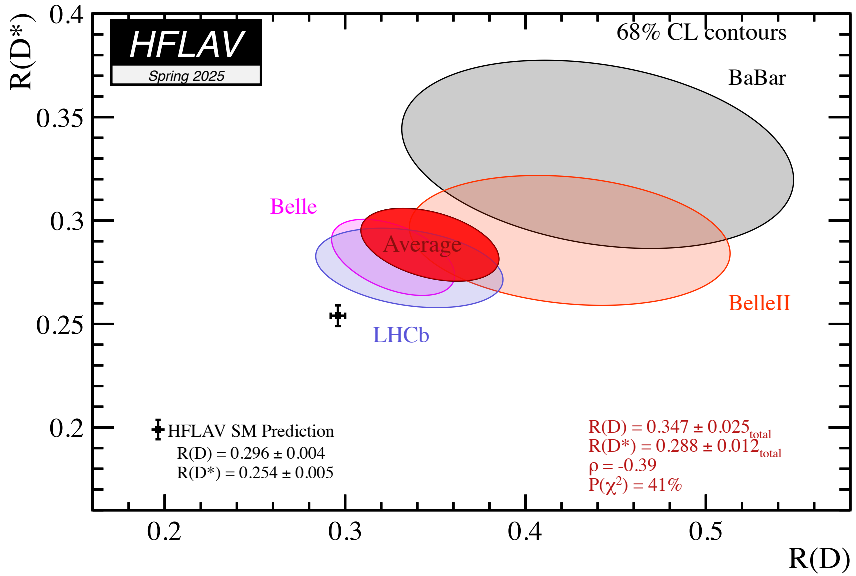


Decay modes with taus can probe several SM extensions and are particularly interesting where new mediators couple mostly to the third generation.

Main uncertainty cancel in the ratio

$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau^+ \bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \mu^+ \bar{\nu}_\mu)} \qquad \begin{array}{l} H_b = B^0, B_s^0, B_{(c)}^+, \Lambda_b^0 \\ H_c = D^*, D^0, D^+, D_s^+, J/\psi, \Lambda \end{array}$$

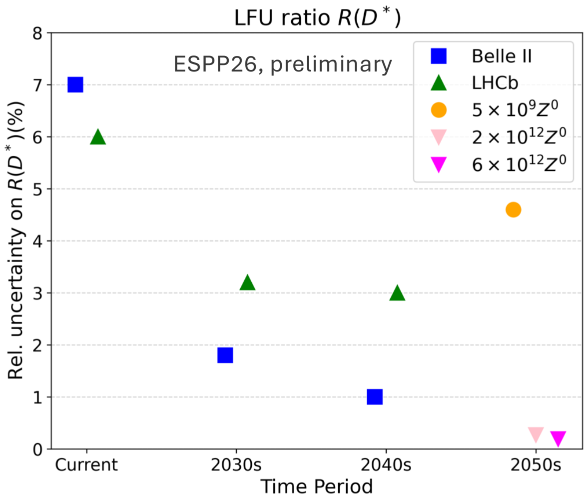
measured from muonic or hadronic tau decays

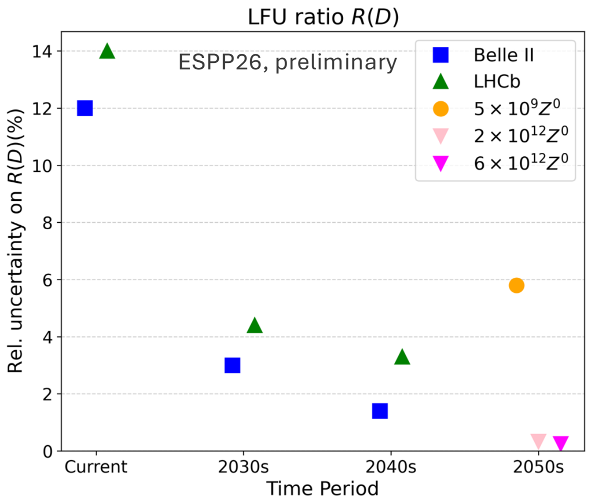


R(D) and R(D*) from different B and D decays modes globally exceed the SM predictions by about 3.8 σ

R(D) and R(D*) Prospects

- Current measurements have precision ~6-14 %.
- In the next 15 years we foresee an improvement by a factor ~10 from LHCb Upgrade II and Belle II.
  - The uncertainty related to background modelling (mainly higher charm states) is a limiting factor, but it should be possible to control it with specific measurements of these decays.



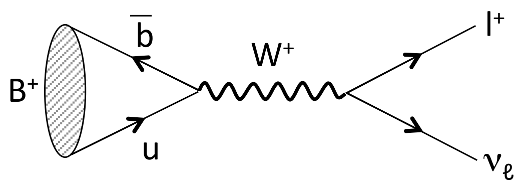


- Studies at FCC-ee, performed on $R(D_s)$ using hadronic tau decay and $D_s \rightarrow \phi(KK)\pi$ predict the uncertainty at permil level.
  Similar projections for $R(J/\psi)$ and $R(\Lambda)$.
- The SM uncertainty can reach the same level of precision in 2050's.

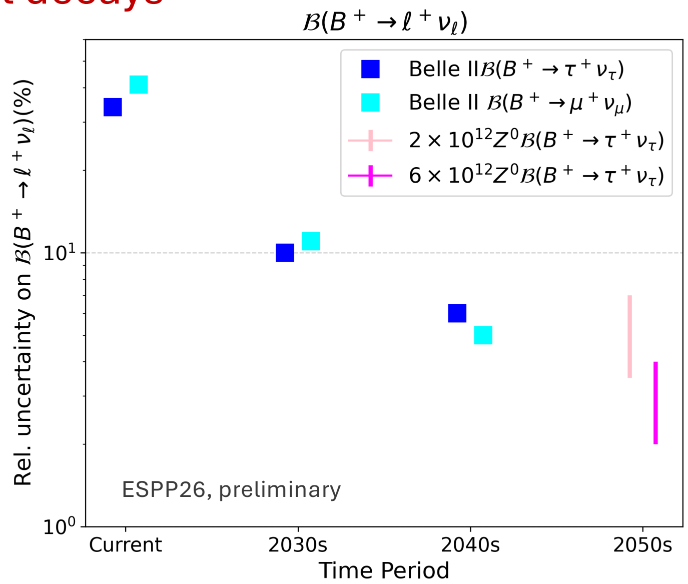
- In addition to B^0 and B^+ decays, LFU ratios can be measured with B_s and Λ_b and B_c at HL-LHC and at the Z^0, providing complementary tests and sensitivity on physics processes beyond the SM.
- Full angular analysis of $b \rightarrow cl\nu$ will also be possible with high precision.

LFU in b→u from fully leptonic decays

- New possibility will be opened for LFU tests also in b→u charged current decays by high statistics samples of leptonic decays to be collected at Belle II.
  - Will complement b→c tests with sensitivity to different coupling.



The ratio $\mathcal{B}(B^+\to\tau^+\nu)/\mathcal{B}(B^+\to\mu^+\nu)$ will be determined with a precision below ~10%.



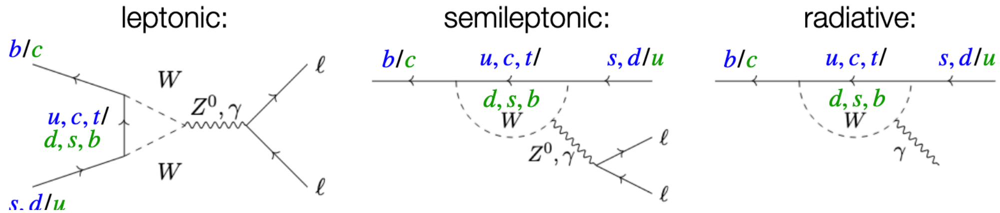
- Future e^+e^- colliders can improve further in tau modes (with hadronic decays), and probably also in muon modes.

- Leptonic decay of charged B_c meson $B_c^+\to\tau^+\nu_\tau$ can be observed for the first time at e^+e^- colliders .
  - Since f(b→B_c) is unknown, $\mathcal{B}(B_c^+\to\tau^+\nu_\tau)$ with ~3% precision can be derived from the ratio to $B_c^+\to J/\psi\mu^+\nu_\mu$ (that will be known at ~2%, using LQCD).
- $\mathcal{B}(B^+\to\tau^+\nu_\tau)$ and $\mathcal{B}(B_c^+\to\tau^+\nu_\tau)$ will play a prominent role in constraining the allowed parameter space in models with Higgs doublets and in specific leptoquark scenarios.
  - will also provide a new avenue for V_{ub} and V_{cb} determination (→ CKM talk).

FCNC in b→sl⁺l⁻

- Observation of suppression of FCNC has been pivotal in the construction of the SM.
- FCNC transitions, allowed only at loop level in the SM, are sensitive to virtual contributions of new mediators up to energy scales much higher than those reached by direct production.

- Leptonic, semileptonic and radiative B and D meson decays offer a broad range of observables, and can probe different operators in the EFT approach.



- b→sl⁺l⁻ can be described by an Effective Hamiltonian with left (SM) and right (NP) chirality operators

$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_i O_i + C_i' O_i')$$

Wilson coefficients $C_i^{(')}$: contain short-distance effects

Local operators $O_i^{(')}$: describe long-distance effects

New Physics enters through Wilson coefficient shifts:

$$C_i^{(')} = C_i^{('),\text{SM}} + C_i^{('),\text{NP}}$$

Operators in b→sl⁺l⁻

$$O_7^{(')} \propto (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$

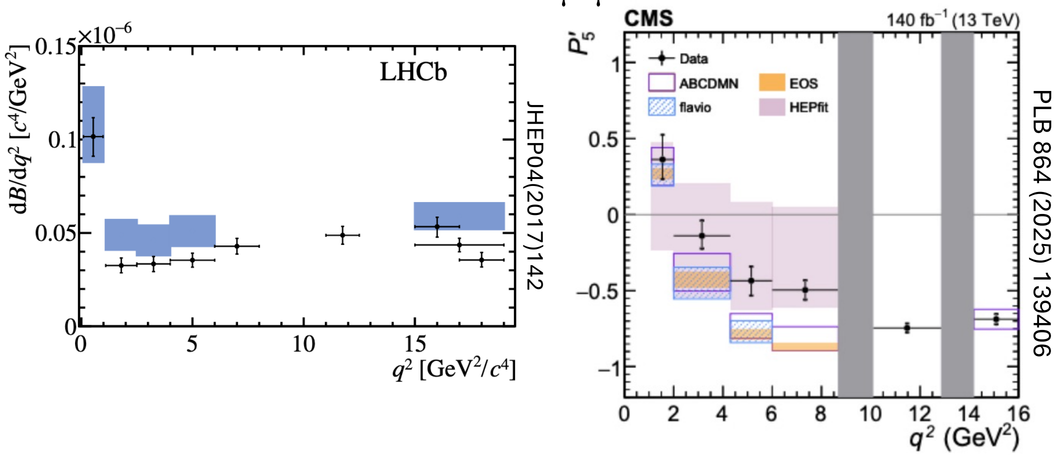
$$O_9^{(')} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma_\mu l)$$

$$O_{10}^{(')} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma_\mu \gamma_5 l)$$

FCNC in $b \to s l^+ l^-$

- Several type of measurements are possible: branching fraction as a function of q^2, CPV and angular analysis, lepton flavour universality tests.
- Current results for rates and angular observables in various $b \to s l^+ l^-$ channels are in tension with SM predictions, making improved understanding of high importance.
  - Comparison with theory predictions is hindered by the evaluation of QCD contributions (charm loops).

$B^0 \to K^{*0} \mu^+ \mu^-$



- With high statistics new strategies will be put in place and cleaner measurements will be possible to sort out the tensions:
  - Full angular analysis of $b \to s l^+ l^-$ decays, also in narrow bins of q^2, with the determination of all angular parameters, or directly of the Wilson Coefficients.
  - Comparisons between many different channels available at HL-LHC, including B_s^0 and Λ_b decays.
  - At future e^+e^- facilities running at the Z^0 time-dependent CP studies will also be performed, for example in $B_s^0 \to \phi \mu^+ \mu^-$ decays.

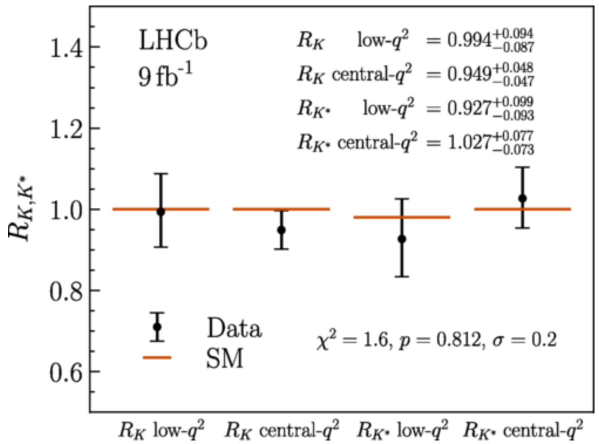
LFU in FCNC (R_K)

- Ratios of branching ratios are clean observables where most uncertainty drop out.
- R_K probes LFU in $b \rightarrow s l^+ l^-$ between first and second generation.
- Current measurements are in agreement with SM but expected precision improvements will allow much more stringent tests.

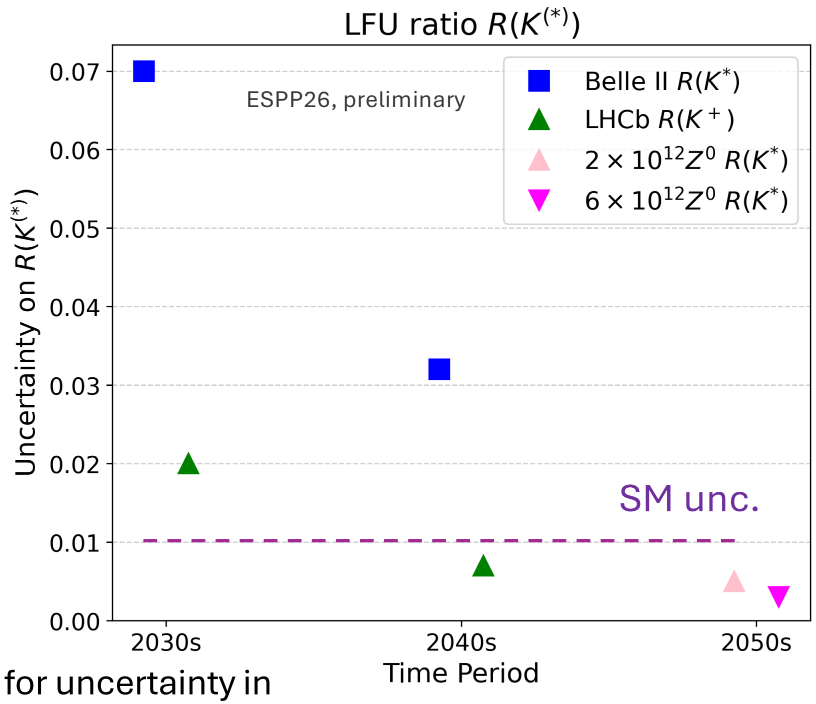
$$R_H \equiv \frac{\int \frac{d\Gamma(B\to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int \frac{d\Gamma(B\to He^+e^-)}{dq^2}\, dq^2}$$

$$H = K^+, K^{*,+/0}, K_S^0, pK, \phi, K\pi\pi, \ldots$$

$$q^2 = m^2(\ell^+\ell^-)$$



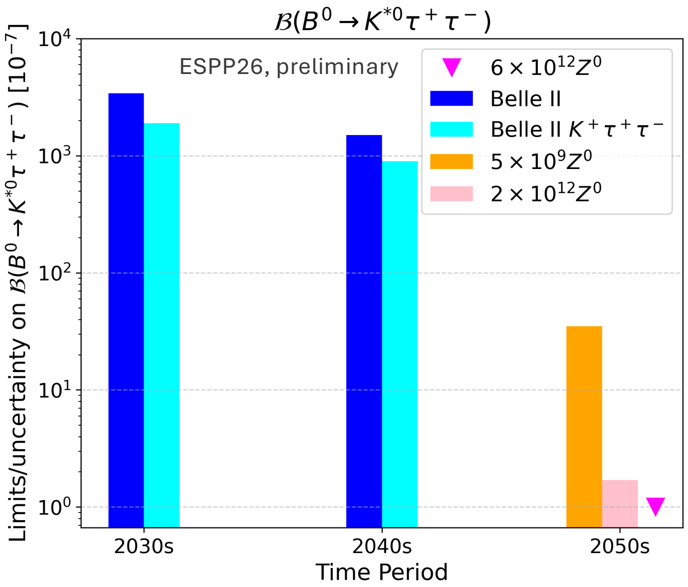
SM prediction on R_K is now at 1%. It is expected to improve for 2040's to match the experimental precision.

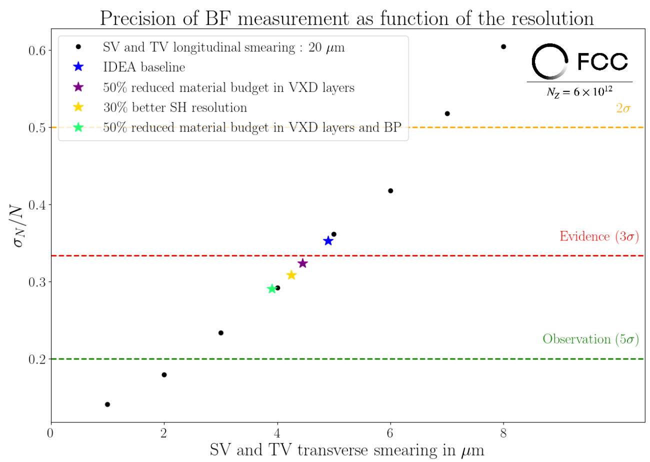


Projections for uncertainty in central-q^2 bin ($1.1<q^2<6$ GeV^2)

FCNC in b→sτ$^+$τ$^-$

- Decays to tau pairs $B^0 \to K^{+,*0}\,\tau^+\tau^-$ have not been observed yet.
  - They would allow to test a FCNC process involving third-generation leptons, complementing the present measurements of $b \to s l^+ l^-$ with light leptons.
- Current limit is from Belle $\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 3.1 \times 10^{-3}$ at 90% CL [PRD108 (2023) L011102]
- A factor >10 improvement in sensitivity is expected from Belle II at 50 ab^{-1}.
- Other two orders of magnitude improvement is expected at future e^+e^- colliders. Depending on detector resolutions they could arrive at the SM prediction of $\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-)^{SM} \sim 10^{-7}$.



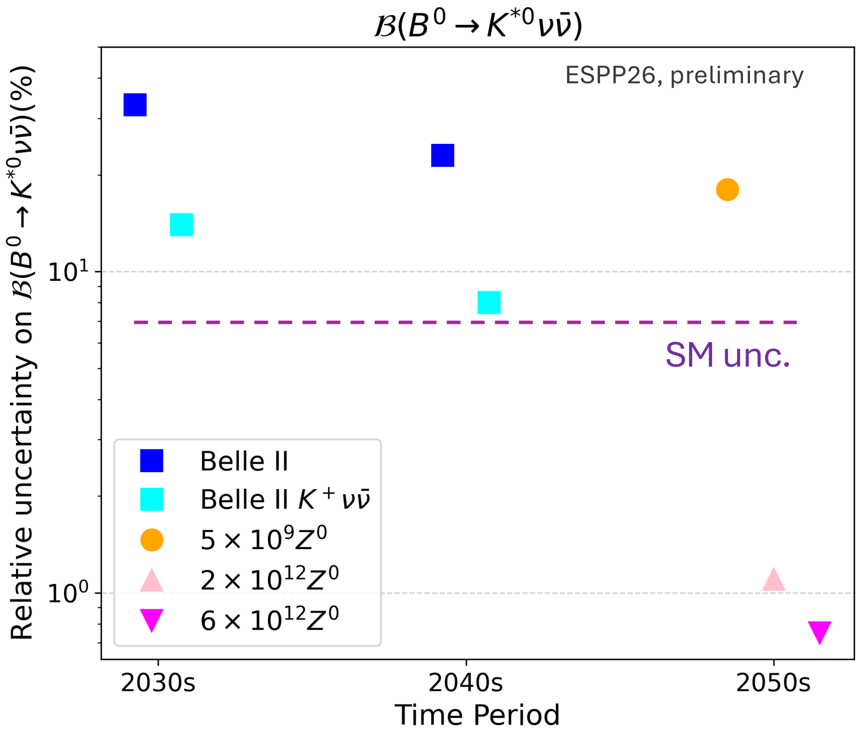


Sensitivity for $\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-)$ for various detector resolutions. From ID196

FCNC in b→s$\nu\bar{\nu}$

- New opportunities for test of NP in neutrino modes are opened by future measurements. Particularly interesting since b→s$\nu\bar{\nu}$ is a clean observable, not affected by long-distance charm-loops effects, and precisely predicted in the SM.

First evidence recently given by Belle II
$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) = (2.3 \pm 0.5^{+0.5}_{-0.4}) \times 10^{-5}$ (2.7σ above SM prediction)



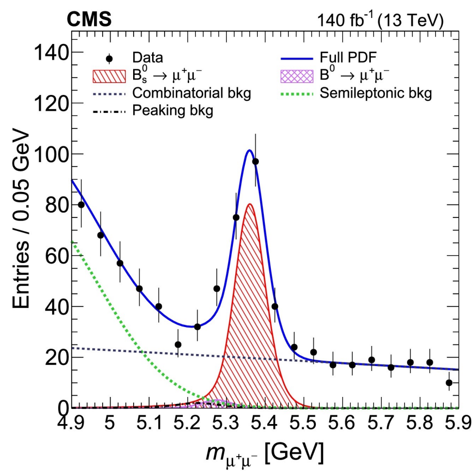
- Best precision at e^+e^- colliders is expected for $\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})$
  - B→K* form factors to be determined from LQCD at ~1%
- Many more neutrino modes can be considered, providing other new observables: $B_s^0 \to \phi\nu\bar{\nu}$, $B^0 \to K_S\nu\bar{\nu}$, $\Lambda_b^0 \to \Lambda^0 \nu\bar{\nu}$.
- With high statistics detailed kinematic studies (eg. $d\Gamma/dq^2$) possible, and searches for contributions of hidden sectors.

FCNC at leptonic B decays: $B_{(s)}^0 \rightarrow \mu^+\mu^-$

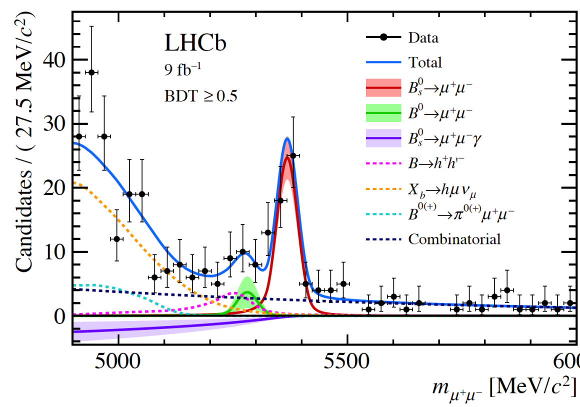
- $B_{(s)}^0 \rightarrow \mu^+\mu^-$ decay is one of the most theoretically clean and sensitive probes to reveal effects of NP beyond the SM unreachable by direct searches.
  - Being both loop- and helicity-suppressed it is very rare with $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)^{SM} = (3.66 \pm 0.14) \times 10^{-9}$

- The first observation of $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$ provided strong constraints on MSSM models.
  - Increased precision will be able to cover larger part of the unconstrained parameter space of MSSM models.

- The $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)$ is not measured yet, future precise determinations of this decay will allow new tests on extensions of the SM.
  - The ratio of branching ratios B^0/B_s^0 can probe several flavour models.



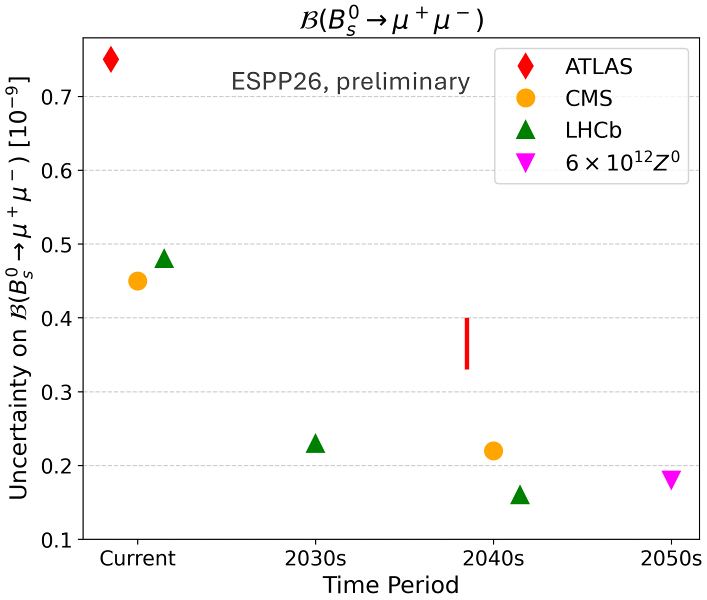
Phys.Lett.B 842,137955

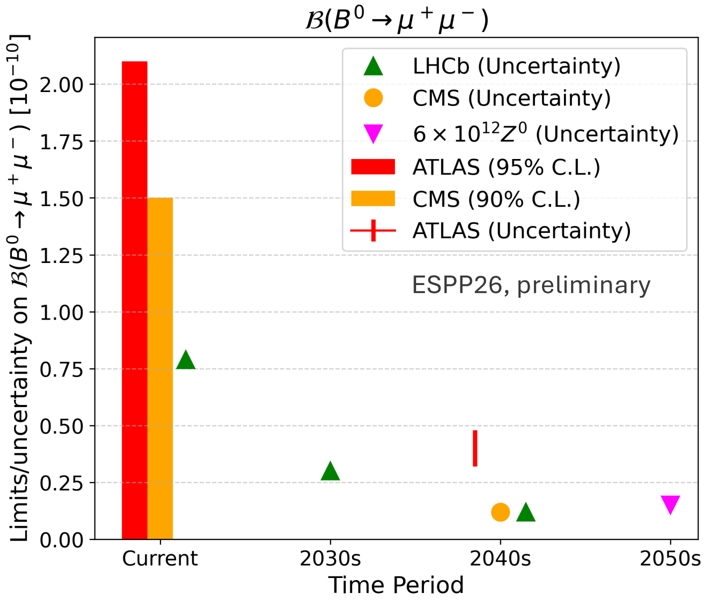


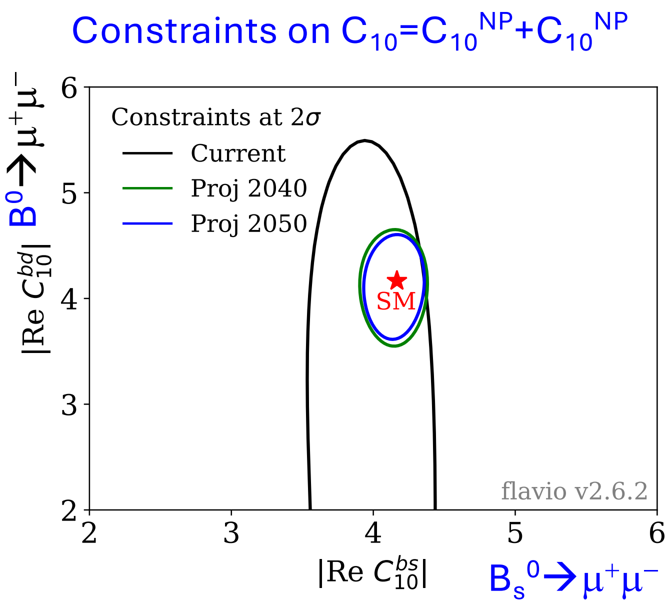
PRD 105, 012010

Leptonic B decays: $B_{(s)}^0 \rightarrow \mu^+\mu^-$

- At HL-LHC ATLAS and CMS also contribute in addition to LHCb.
- The uncertainty at the end of HL-LHC is expected to be 4% and 12% for B_s^0 and B^0, respectively.





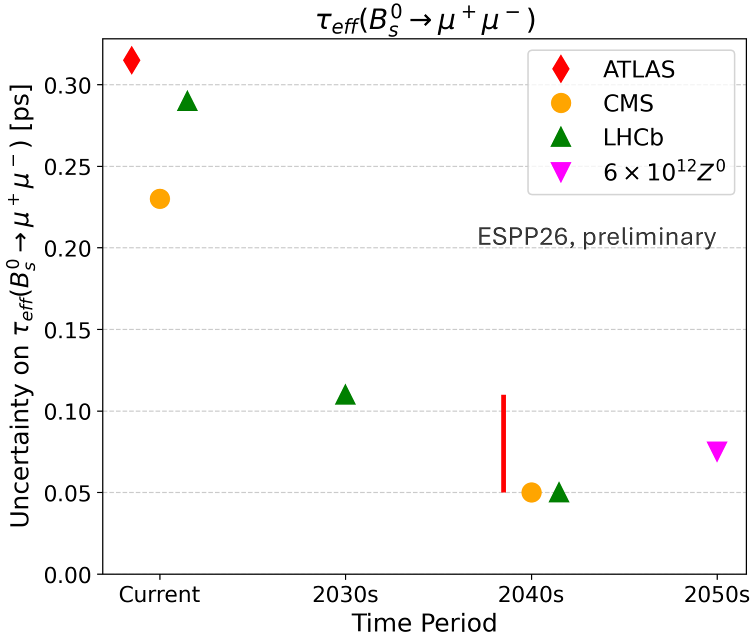


- Future colliders will not surpass the HL-LHC precision on branching ratios, due to lower statistics.

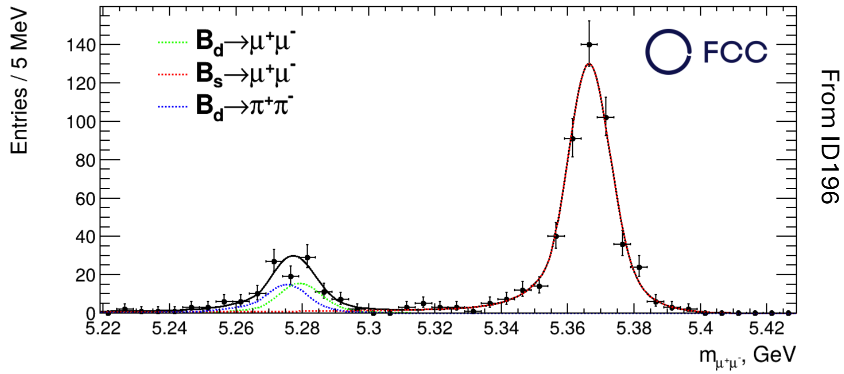
- Additional variables from these decays will also become precisely measured and provide more comprehensive tests.

- The effective lifetime $\tau_{eff}(B_s^0 \rightarrow \mu^+\mu^-)$ allows the degeneracy between any possible contribution from new scalar and pseudoscalar mediators to be broken.

- At future e^+e^- colliders, high tagging efficiency (~25%), together with excellent mass resolution, will help in time-dependent CPV measurement, as mixing-induced CP violation $S(B_s^0 \rightarrow \mu^+\mu^-)$.

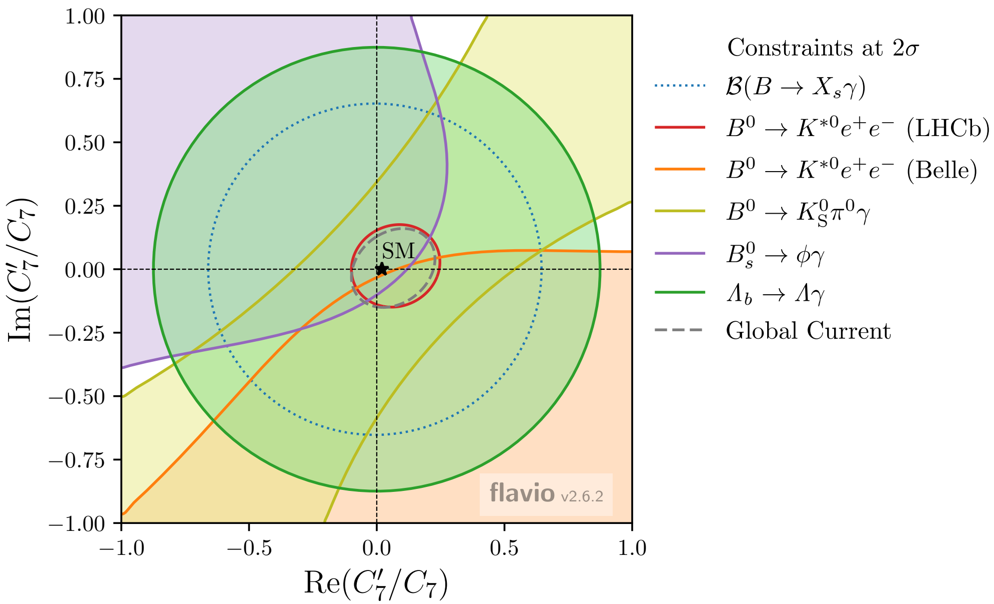


	2040's	2050's	
	LHCb 300 fb^{-1}	2×10^{12} Z^0	6×10^{12} Z^0
Uncertainty on $S(B_s^0 \rightarrow \mu^+\mu^-)$	0.20	0.29	0.17



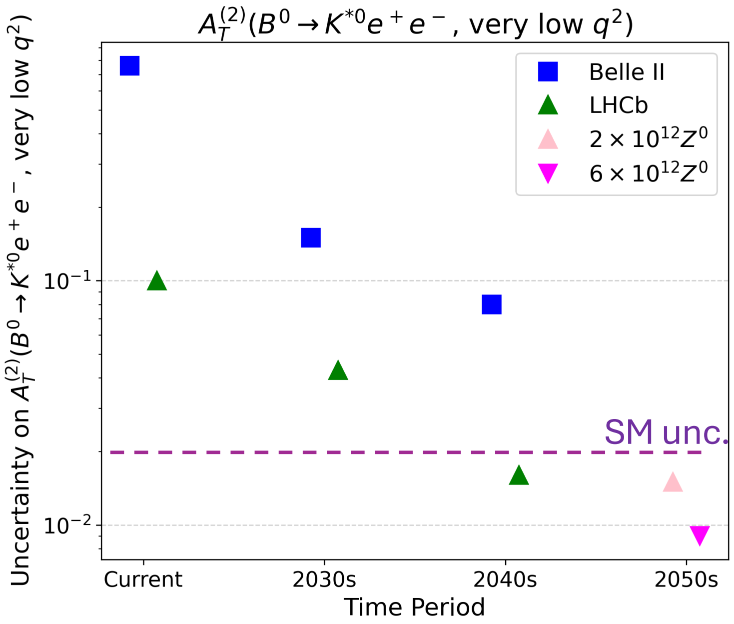
FCNC in b→sγ decays

- Radiative FCNC processes offer further complementary SM tests.
- A specific feature of b →sγ decays is that the emitted photon is highly polarised in the SM, due to the V−A nature of weak interactions.
- The polarisation of the photon can be probed in several complementary ways, with different observables. In particular
  - Angular distributions of $B^0 \to K^{*0}e^+e^-$ at very low q^2 ($0.0008 < q^2 < 0.257$ GeV^2)
  - Mixing-induced CP violation in $B^0 \to K_S\pi^0\gamma$ or $B_s^0 \to \phi\gamma$ decays
  - Polarisation in $\Lambda_b^0 \to \Lambda^0\gamma$ decays

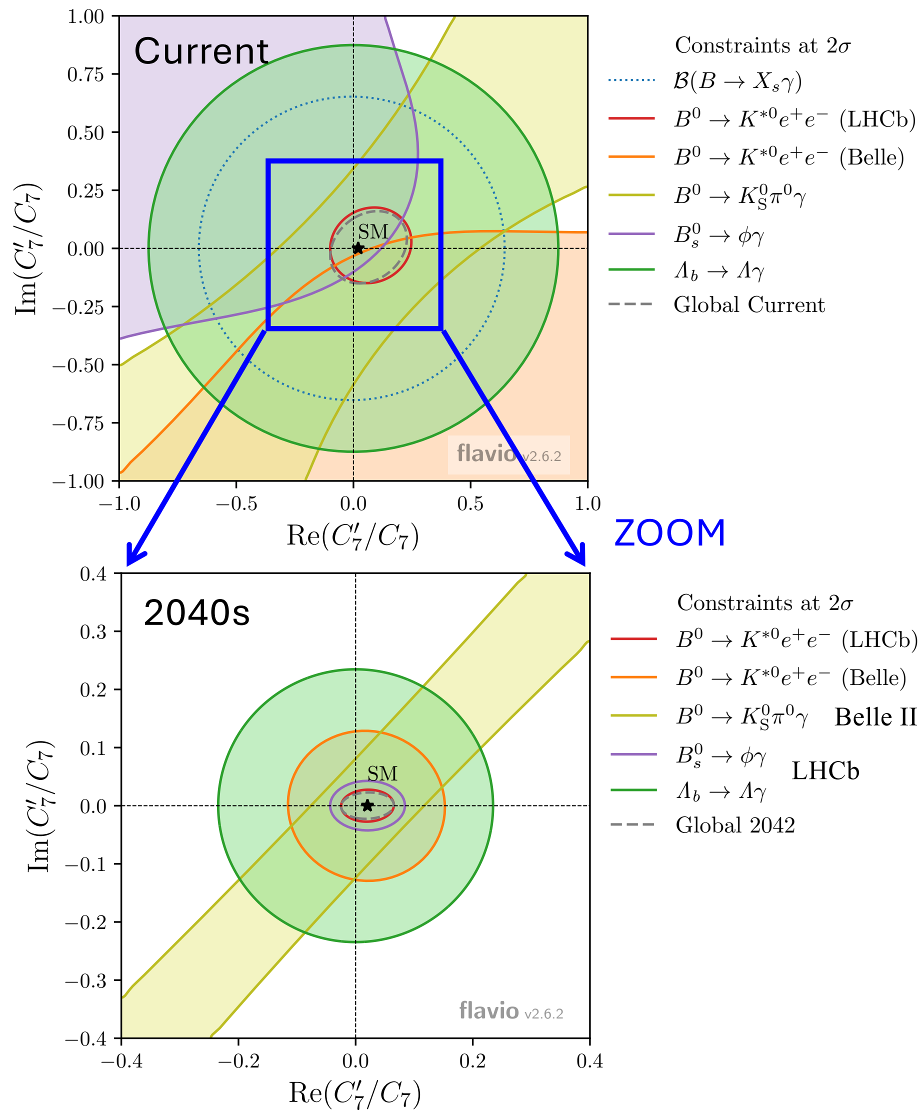


Current constraints on the real and imaginary parts of the ratio of right- and left-handed Wilson coefficients, C_7‘ and C_7.
The C_7 coefficient is fixed to its SM value.

- Precision improvements will come from LHCb and Belle II on complementary observables.



- A further leap will be possible from measurements at future e^+e^- colliders the Z^0 .
- Theoretical uncertainty might become the real limit on some observables.



FCNC in D decays

- Rare charm decays provide a unique probe of flavour in the up sector.
  - Complementary to beauty and kaon studies.
  - GIM cancellation make SM very suppressed while leptoquarks or sterile neutrino could significantly enhance the branching ratios.
- Rare decays are studied in leptonic, semi-leptonic and radiative modes. Interpretation in terms of NP is made difficult by the presence large long-distance contributions.
- New avenues opened by rare FCNC decays of D^0 mesons with neutrinos final states , free of LD contributions.
  - Current best limit by BES III $\mathcal{B}(D^0 \rightarrow \pi^0 \nu\bar{\nu})$ <2.1x10^{-4} @90% CL, with 2.93 fb^{-1}.

- Belle has searched for invisible final states setting $\mathcal{B}(D^0 \rightarrow$ invisible) <9.4x10^{-5} @90% CL, with 924 fb^{-1}.
  - Belle II will search for several neutrino mode.
- Searches will be done at STCF. Extrapolating from BESIII, $\mathcal{B}(D^0 \rightarrow \pi^0 \nu\bar{\nu})$<5 x$10^{-6}$ should be possible with 5 ab^{-1} .
- An FCC-ee (preliminary) study predicts to observe $D^0 \rightarrow \pi^+\pi^-\nu\bar{\nu}$ at 5σ down to 1.6x10^{-6}, using ~10^{12} D^0 mesons.

Conclusions

- The full exploitation, up to 2040's, of huge heavy flavour production at HL-LHC with LHCb upgrade II, and of the Belle II potentiality, will provide strong improvement in precision on key-observables.
  - Nice complementarity between pp and Υ(4S) experiments on fully-charged decays and decays with neutrals (eg. $B_{(s)}^0 \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow K_S\pi^0\gamma$ or $B^+ \rightarrow \tau^+\nu$).
- Large data samples will give access to a wider range of observables and to new analysis strategies.
  - We will have the possibility to resolve current tensions and discriminate between potential NP models.
- Future e^+e^- facilities running at the Z^0 will allow new and clean measurement notably in final states with multiple neutrinos such as $B^0 \rightarrow K^{*0}\tau^+\tau^-$ and $B^0 \rightarrow K^{*0}\nu\bar{\nu}$.
- Foreseen improvements in theoretical predictions will be necessary to match the experimental precisions.

Studies of rare decays and LFU tests will continue to provide invaluable inputs for the quest of NP in the coming years.

References

ESPPU submissions

- ID.223 - Projections for Key Measurements i in Heavy Flavour Physics
- ID.81 - Discovery Potential LHCb Upgrade II
- ID.205 - The Belle II Experiment at SuperKEKB
- ID.196 - Prospects in flavour physics at the FCC
- ID.233 – FCC Integrated Programme Stage 1: The FCC-ee Back-up Document
- ID.241 - The FCC integrated programme: a physics manifesto
- ID.141 – ECFA Higgs/Electroweak/Top Factory Study + Full Report - Submitted as Backup Document
- ID.165 – A Possible Future Use of the LHC Tunnel
- ID.188 – LEP3: A High-Luminosity e+e− Higgs & Electroweak Factory in the LHC Tunnel
- ID.231 – Super Tau Charm Facility

Other documents

- The Belle II Physics Book Prog. Theor. Exp. Phys. 2019, 123C01
- LHCb Collaboration, Physics Case for Upgrade II arXiv:1808.08865v4.
- Flavor Physics at CEPC: a General Perspective arXiv:2412.19743
- Tin Seng Manfred Ho et al, "Testing lepton flavor universality at future *Z* factories ", Phys. Rev. D 109 (2024), 093004, doi:10.1103/PhysRevD.109.093004
- X. Zuo et al., "Prospects for B_c and $B^+\to\tau^+\nu_\tau$ at FCC-ee", Eur. Phys. J. C 84 (2024) 87, doi:10.1140/epjc/s10052-024-12418-0, arXiv:2305.02998.
- Y. Amhis et al., "Prospects for $B_c^+\to\tau^+\nu_\tau$ at FCC-ee", JHEP 12 (2021) 133, doi:10.1007/JHEP12(2021)133, arXiv:2105.13330.
- Y. Amhis, M. Kenzie, M. Reboud, and A. R. Wiederhold, "Prospects for searches of $b\to s\nu\nu$ decays at FCC-ee", JHEP 01 (2024) 144, doi:10.1007/JHEP01(2024)144, arXiv:2309.11353.
- L. Li and T. Liu, "$b\to s\tau^+\tau^-$ physics at future Z factories", JHEP 06 (2021) 064, doi:10.1007/JHEP06(2021)064, arXiv:2012.00665.
- Tsz Hong Kwok et al, " Time-Dependent Precision Measurement of $B0s\to\varphi\mu+\mu-$ Decay at FCC-*ee* ", arXiv:2506.08089

Backup

	Current		2030's		2040's		2050's		
	LHCb	Belle	LHCb 50 fb^{-1}	Belle II 10 ab^{-1}	LHCb 300 fb^{-1}	BelleII 50 ab^{-1}	5x 10^9 Z	2x 10^{12} Z	6x 10^{12} Z
R(D) [$R(D_s)$] R(D*) [$R(D_s*)$]	14% 6%	12% 7%	4.4% 3.2%	3.0% 1.8%	3.3% 3.0%	1.4% 1.0%	~5.8% ~4.6%	~0.33% ~0.27%	~0.24% ~0.19%

	Current	2030's	2040's	2050's		
	Belle 0.711 ab^{-1}	Belle II 10 ab^{-1}	BelleII 50 ab^{-1}	5x 10^9 Z	2x10^{12} Z	6x 10^{12} Z
$\mathcal{B}(B^+ \to \tau^+\nu_\tau)$ $\mathcal{B}(B^+ \to \mu^+\nu_\mu)$	34% 41%	10% 11%	6% 5%	>70% -	3.5%-7% -	2-4% -
$\mathcal{B}(B_c^+ \to \tau^+\nu_\tau)$				>55%	3.4%-4.5%	2.6%-3.0%

	Current	2030's	2040's	2050's	
	LHCb 9 fb^{-1}	LHCb 50 fb^{-1}	LHCb 300 fb^{-1}	2x 10^{12} Z	6x 10^{12} Z
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ [10^{-9}] $\mathcal{B}(B^0 \to \mu^+\mu^-)$ [10^{-10}] $\tau_{eff}(B_s^0 \to \mu^+\mu^-)$ [ps] $S(B_s^0 \to \mu^+\mu^-)$	0.48 0.79 0.29 -	0.23 0.30 0.11 -	0.16 0.12 0.05 0.20	0.31 0.26 0.13 0.29	0.18 0.15 0.075 0.17

Projections have different level of robustness.
When not available they are derived by simple scaling.

Projected % uncertainties are referred to the SM value.

	2030's		2040's		2050's		
	LHCb 50 fb^{-1}	Belle II 10 ab^{-1}	LHCb 300 fb^{-1}	Belle II 50 ab^{-1}	5x 10^9 Z	2x 10^{12} Z	6x 10^{12} Z
R_K ($1.1<q^2<6$ GeV^2) R_{K^*}($1.1<q^2<6$ GeV^2)	0.020	0.080 0.070	0.007 0.008	0.036 0.032	0.10	0.005	0.003

Projections have different level of robustness.
When not available they are derived by simple scaling.

	current	2030's	2040's	2050's		
	Belle/BelleII	Belle II 10 ab^{-1}	Belle II 50 ab^{-1}	5x 10^9 Z	2x 10^{12} Z	6x 10^{12} Z
$\mathcal{B}(B^+ \to K^+\tau^+\tau^-)$ $\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-)$	$<10^{-3}$ $<1.8\ 10^{-3}$	$<1.9\ 10^{-4}$ $<3.4\ 10^{-4}$	$<0.9\ 10^{-4}$ $<1.5\ 10^{-4}$	$\sim 3.5\text{x}10^{-6}$	$\sim 1.7\text{x}10^{-7}$	$\sim 10^{-7}$
$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})$ $\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})$	30% 110%	14% 33%	8% 23%	- 18%	- 1.1%	- 0.75%

Belle projections on $K\tau\tau$ assume no signal.

Projected % uncertainties are referred to the SM values.

	2030's		2040's		2050's	
	LHCb 50 fb^{-1}	Belle II 10 ab^{-1}	LHCb 300 fb^{-1}	BelleII 50 ab^{-1}	2x 10^{12} Z	6x 10^{12} Z
$\mathcal{B}(B \to X_s\gamma;\ E_\gamma > 1.6$ GeV)	-	(6.2-9.6)%	-	(4.7-8.8)%	3.1%	1.8%
$S(B^0 \to K_S\pi^0\gamma)$	-	0.07	-	0.04	0.021	0.014
$S(B_s^0 \to \phi\gamma)$	0.062	-	0.025	-	0.010	0.006
$A_T^{(2)}$ ($B^0 \to K^{*0}e^+e^-$, very low q^2)	0.043	0.15	0.016	0.08	0.015	0.009
$\alpha_\gamma(\Lambda_b^0 \to \Lambda^0\gamma)$	0.097	-	0.038	-	0.012	0.007