RF1: Weak decays of b and c quarks

Summary of our draft report

Angelo Di Canto (BNL) and Stefan Meinel (University of Arizona)

The draft of our report is available at

https://www.overleaf.com/read/dymwtdkzgbtr

This report describes the physics case for precision studies of weak decays of b and c quarks, and it discusses the experimental and theory programs needed to exploit these physics opportunities in the next decades. This report is not a review of heavy-quark physics, and no attempt has been made to provide complete references to prior work.

We welcome your suggestions for improvements! Thanks to everyone who already sent us comments. This session is an opportunity for more feedback.

In the following, we will give an overview of the content of the report.

Contributed whitepapers

Title (some shortened to fit)	Authors	Reference
New physics in B meson mixing: future sensitivity and limitations	J. Charles *et al.*	2006.04824
$b \to s\tau^+\tau^-$ physics at future Z factories	L. Li, T. Liu	2012.00665
Charm Physics in the High-Luminosity Super τ-Charm Factory	H.-Y. Cheng, X.-R. Lyu, Z.-Z. Xing	2203.03211
The Future Circular Collider	G. Bernardi *et al.*	2203.06520
A New Tool for Detecting BSM Physics in $B \to K^*\ell\ell$ Decays	A. Sibidanov *et al.*	2203.06827
A new tool to search for physics beyond the SM in $\bar{B} \to D^{*+}\ell^-\bar{\nu}$	B. Bhattacharya *et al.*	2203.07189
Flavor Model Building	W. Altmannshofer, J. Zupan	2203.07726
Belle II Executive Summary	D. M. Asner *et al.*	2203.10203
The Belle II Detector Upgrade Program	F. Forti *et al.*	2203.11349
Japan's Strategy for Future Projects in High Energy Physics	M. Endo *et al.*	2203.13979
Physics in the τ-charm Region at BESIII	R. E. Mitchell *et al.*	2204.08943
The Physics potential of the CEPC	H. Cheng *et al.*	2205.08553
Upgrading SuperKEKB with a Polarized Electron Beam	S. Banerjee, J. M. Roney *et al.*	2205.12847
A lattice QCD perspective on weak decays of b and c quarks	O. Witzel *et al.*	2205.15373
Belle II physics reach and plans for the next decade and beyond	D. Tonelli *et al.*	2207.06307
Lattice QCD and Particle Physics	A. S. Kronfeld *et al.*	2207.07641
Future physics potential of LHCb	LHCb	[link]
Physics with the Phase-2 ATLAS and CMS Detectors	ATLAS and CMS	[link]

+ a few others also cited in our report.

Solicited overview whitepapers

We had solicited four whitepapers to give an overview of the physics discovery potential and questions that can be addressed from both theory and experiments point of views.

Title	Authors	Reference
Rare decays of b and c hadrons	W. Altmannshofer, F. Archilli	2206.11331
LFV and LFUV in b and c decays	D. Guadagnoli, P. Koppenburg	2207.01851
High precision in CKM unitarity tests in b and c decays	A. Lenz, S. Monteil	in preparation
Searches for CP violation in b and c decays	A. Dery, Y. Grossman, S. Schacht, D. Tonelli	in preparation

Also see https://snowmass21.org/rare/weakbc for links to the **workshops** we held.

Executive summary of the report

Precision measurements in weak decays of heavy flavored hadrons can test in unique ways our understanding of the fundamental interactions and of the observed baryon asymmetry in the Universe.

The observation of several anomalies by the BaBar, Belle and LHCb experiments in such decays, including evidence for violation of lepton universality, contrasts with the lack of major discoveries in direct production of new particles and motivates continuation of a strong heavy-flavor program in the next decades.

While the mass scales probed by direct searches for non-Standard-Model phenomena at the energy frontier will only marginally increase in the near future, a substantial advancement is expected in the study of weak decays of b and c quarks.

The next 10 to 20 years will see the unprecedented development of a highly synergistic program of experiments, at both pp and e^+e^- colliders, which will be complemented by advancement in theory, including lattice QCD.

Experimental measurements and theory predictions of several key observables will reach unprecedented precision and will allow to test the SM in ways that have not been possible thus far. With a strong participation in this program, the US high-energy-physics community will remain at the forefront of indirect searches for new physics and keep a leading role in expanding humankind's understanding of fundamental interactions.

Report sections

1. The path to discovery in heavy-quark physics
2. Experimental efforts in the next two decades
3. Farther into the future
4. Expected theory progress
5. Current and future U.S. involvement

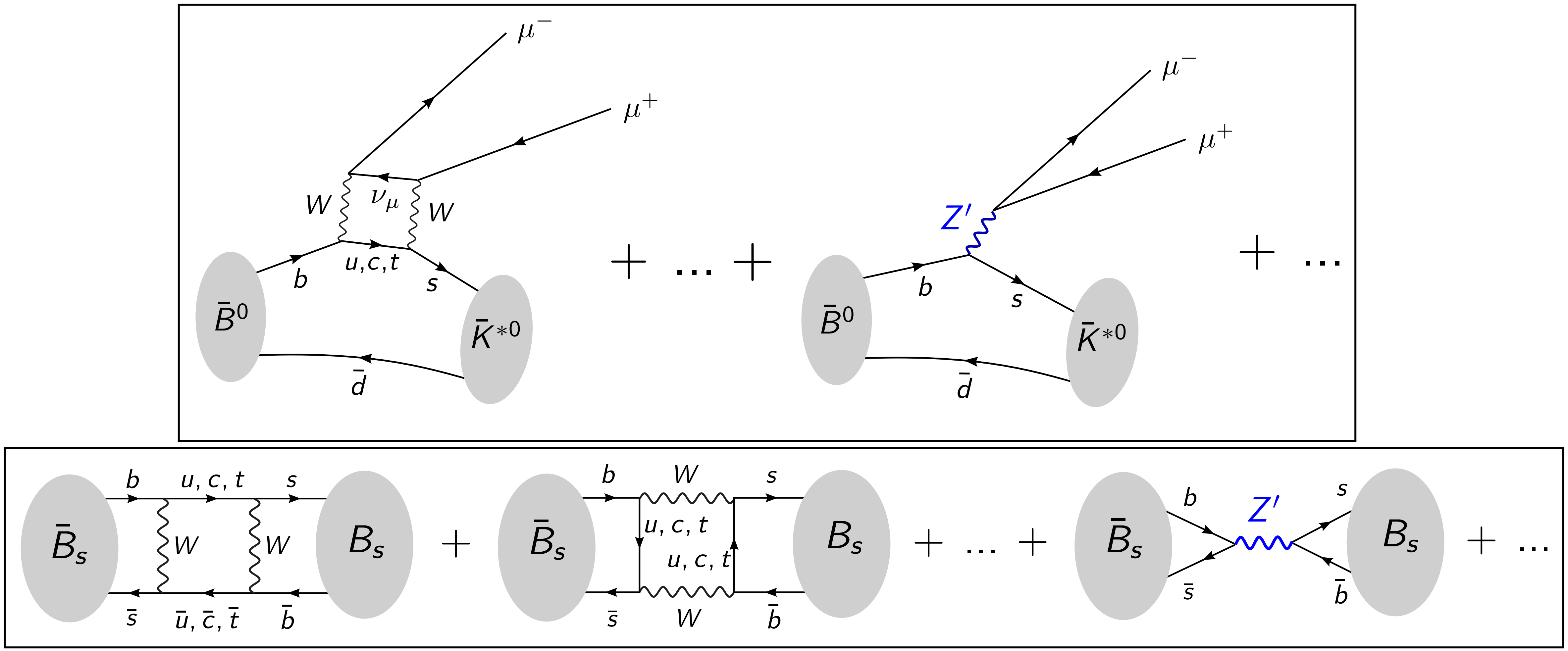
Report sections

1. The path to discovery in heavy-quark physics
2. Experimental efforts in the next two decades
3. Farther into the future
4. Expected theory progress
5. Current and future U.S. involvement

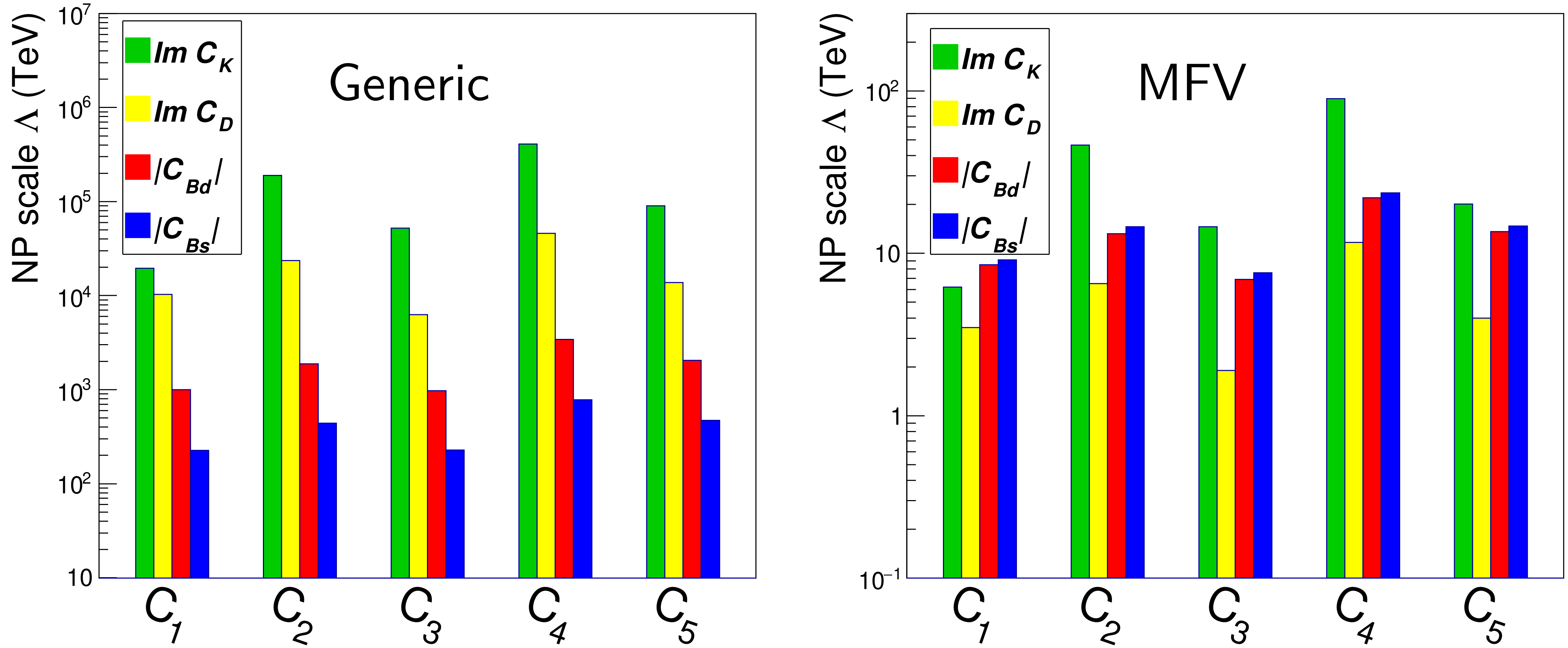
The path to discovery in heavy-quark physics

This is an introductory section, explaining why weak decays of b and c quarks are powerful probes of physics beyond the Standard Model. Some of the things we highlight are

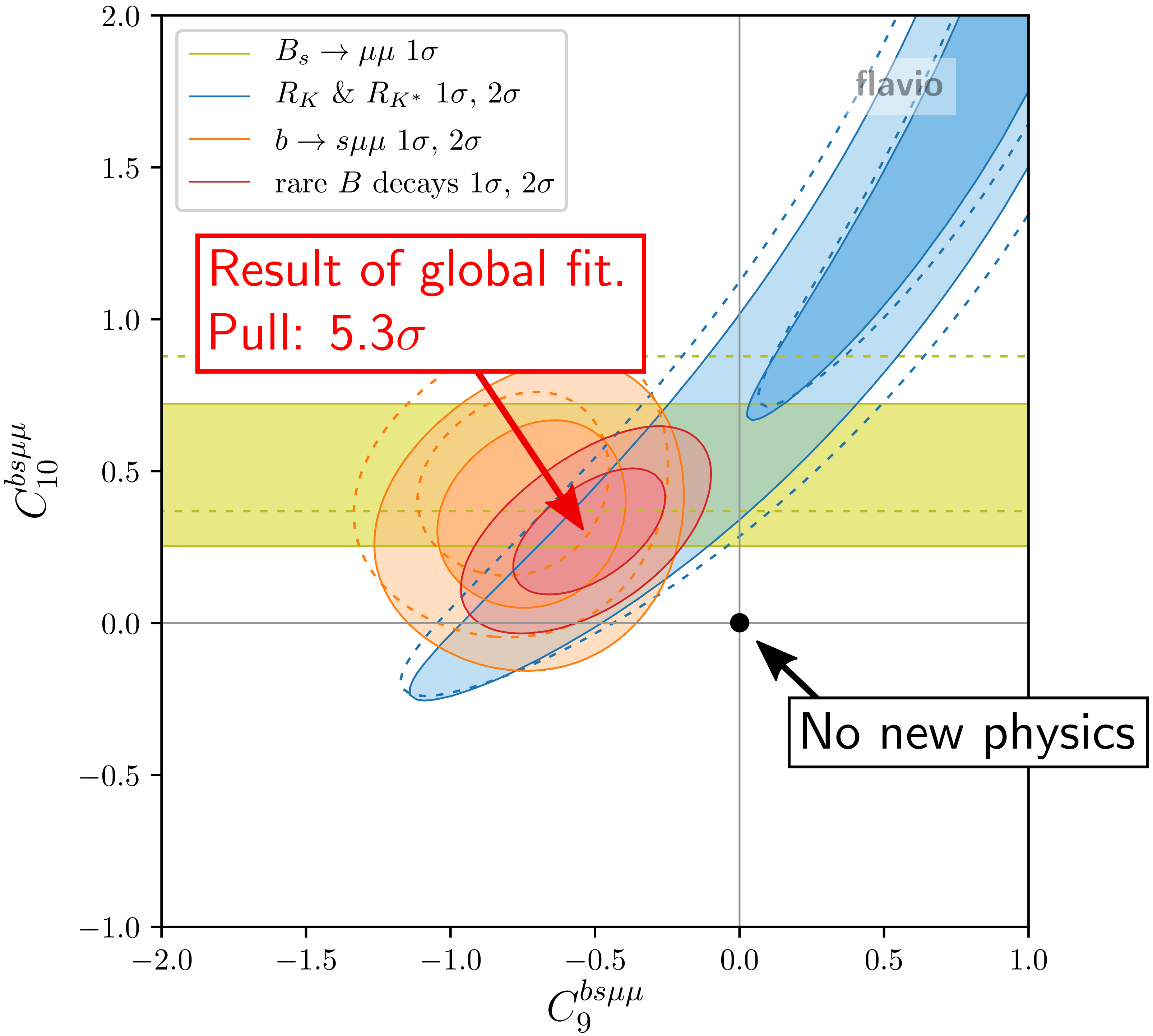
- Arbitrarily heavy elementary particles can, as virtual particles, affect low-energy processes
- Many extensions of the Standard Model predict new sources of flavor-changing interactions and CP violation. Flavor physics measurements provide tight constraints
- b and c hadrons give access to precision measurements for many different possible final states
- New-physics effects in different observables are often correlated, and a broad program of measurements and theory is helpful to discover and characterize BSM physics
- Intriguing deviations from SM predictions have been observed in $b \to s\ell\ell$ and $b \to c\tau\bar{\nu}$ transitions, indicating violation of lepton-flavor universality



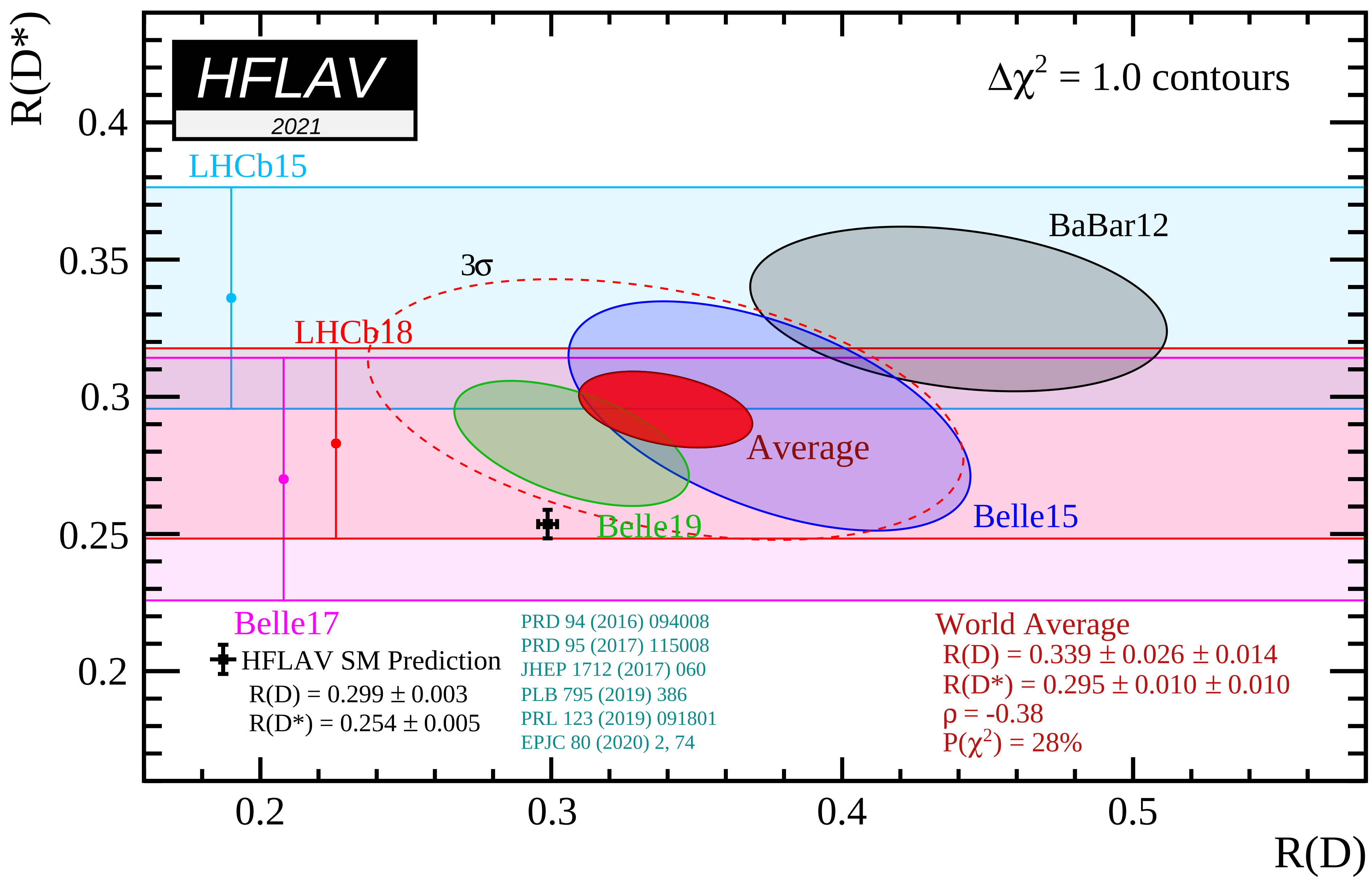
Schematic representation of (top) the $\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$ decay amplitude and (bottom) of the B_s^0-$\bar{B}_s^0$ mixing amplitude as a sum over all possible Feynman diagrams. The diagrams on the left are examples of SM contributions, while the diagram on the right would contribute in theories with a flavor-changing neutral gauge boson Z'.



Lower bounds at 95% C.L. on the new-physics (NP) scale Λ from $\Delta F = 2$ transitions for strongly-coupled NP with (left) arbitrary flavor structure and (right) minimal flavor violation [Silvestrini:2019sey,UTfit:2007eik]. The parameter C_F $(F = K, D, B_d, B_s)$ is the ratio between the full (SM+NP) amplitude and the SM amplitude for F^0-$\bar{F}^0$ mixing; the parameter C_i $(i = 1, \ldots, 5)$ is the coupling of the NP dimension-six operator $\mathcal{Q}_i$ (defined in Ref. [UTfit:2007eik]) governing the corresponding $\Delta F = 2$ transition.



The deviations observed in rare b-hadron decays can be explained model-independently by allowing the Wilson coefficients of the operators $O_9 = \bar{s}\gamma_\mu P_L b\, \bar{\ell}\gamma^\mu \ell$ and $O_{10} = \bar{s}\gamma_\mu P_L b\, \bar{\ell}\gamma^\mu \gamma_5 \ell$ in the weak effective Hamiltonian to differ, for $\ell = \mu$ only, from the Standard-Model values. Shown here are fit results for these differences $C_9^{bs\mu\mu}$ and $C_{10}^{bs\mu\mu}$ to experimental data, using theoretical calculations including lattice QCD. The global fit to all observables (red) has a $> 5\sigma$ pull (from Ref. [Altmannshofer:2021qrr], with annotations added)



The ratios of branching fractions $R(D) = \mathcal{B}(B \to D\tau^+\nu)/\mathcal{B}(B \to D\ell^+\nu)$ and $R(D^*) = \mathcal{B}(B \to D^*\tau^+\nu)/\mathcal{B}(B \to D^*\ell^-\nu)$, where ℓ denotes muons or electrons, are predicted precisely in the SM to be $R(D) = 0.299 \pm 0.003$, $R(D^*) = 0.254 \pm 0.005$ (the black point in this figure). The averages of experimental measurements of these ratios correspond to the red ellipse, which exceed the SM predictions with a combined significance of about 3.3σ [HFLAV].

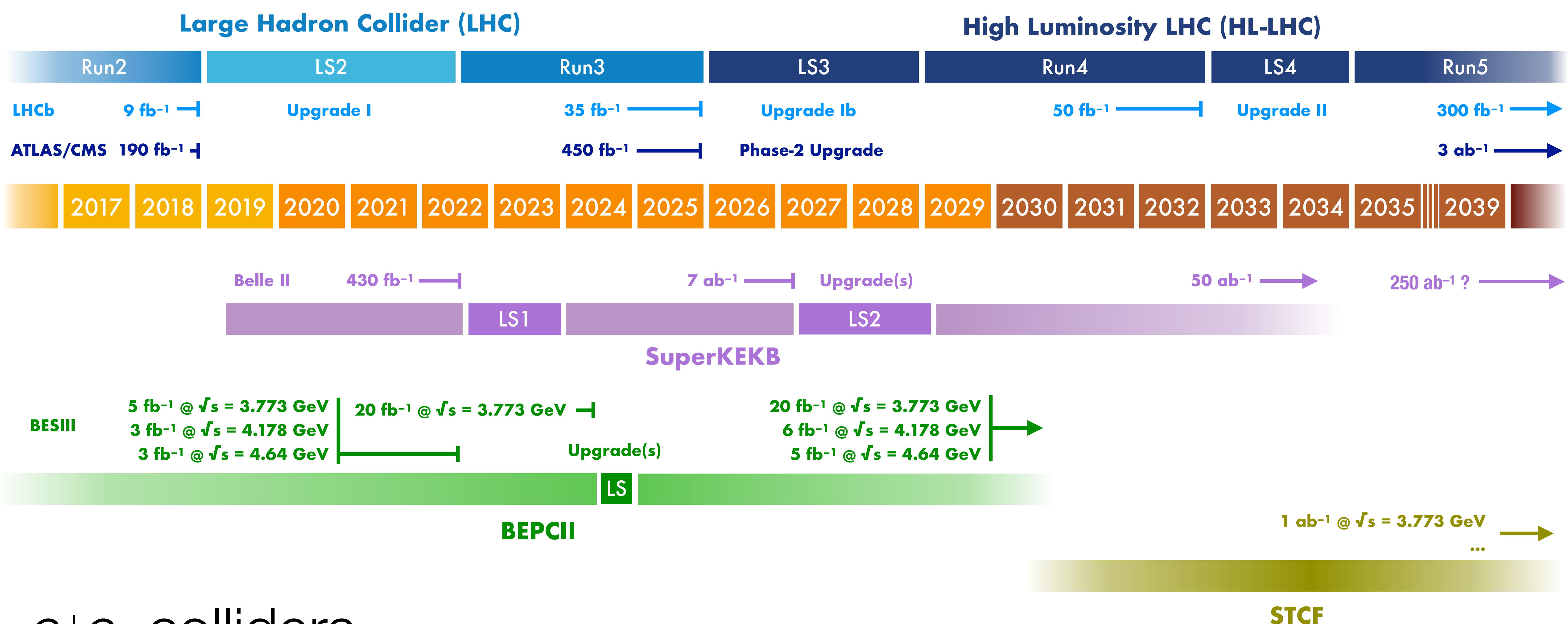
Cross-frontier session on the flavor anomalies

Thursday, July 21			
8:00 AM → 10:00 AM	**Cross Frontier Sessions: RF-EF-TF RF1 Flavor anomalies and exotics at colliders** A panel during the 22j session discussing the intersecctions of the three frontiers		241 (MGH)
	8:00 AM	**current status (and prospects) of flavor anomalies (20'+10')** **Speaker**: Rafael Silva Coutinho (Syracuse University)	30m
	8:30 AM	**BSM models (20'+10')** **Speaker**: Wolfgang Altmannshofer (UC Santa Cruz)	30m
	9:00 AM	**high-energy searches at present and future colliders (20'+10')** **Speaker**: Cari Cesarotti (Harvard University)	30m
	9:30 AM	**Discussion on flavor anomalies in Snowmass reports and main message**	30m

Report sections

Timeline of heavy-flavor experiments

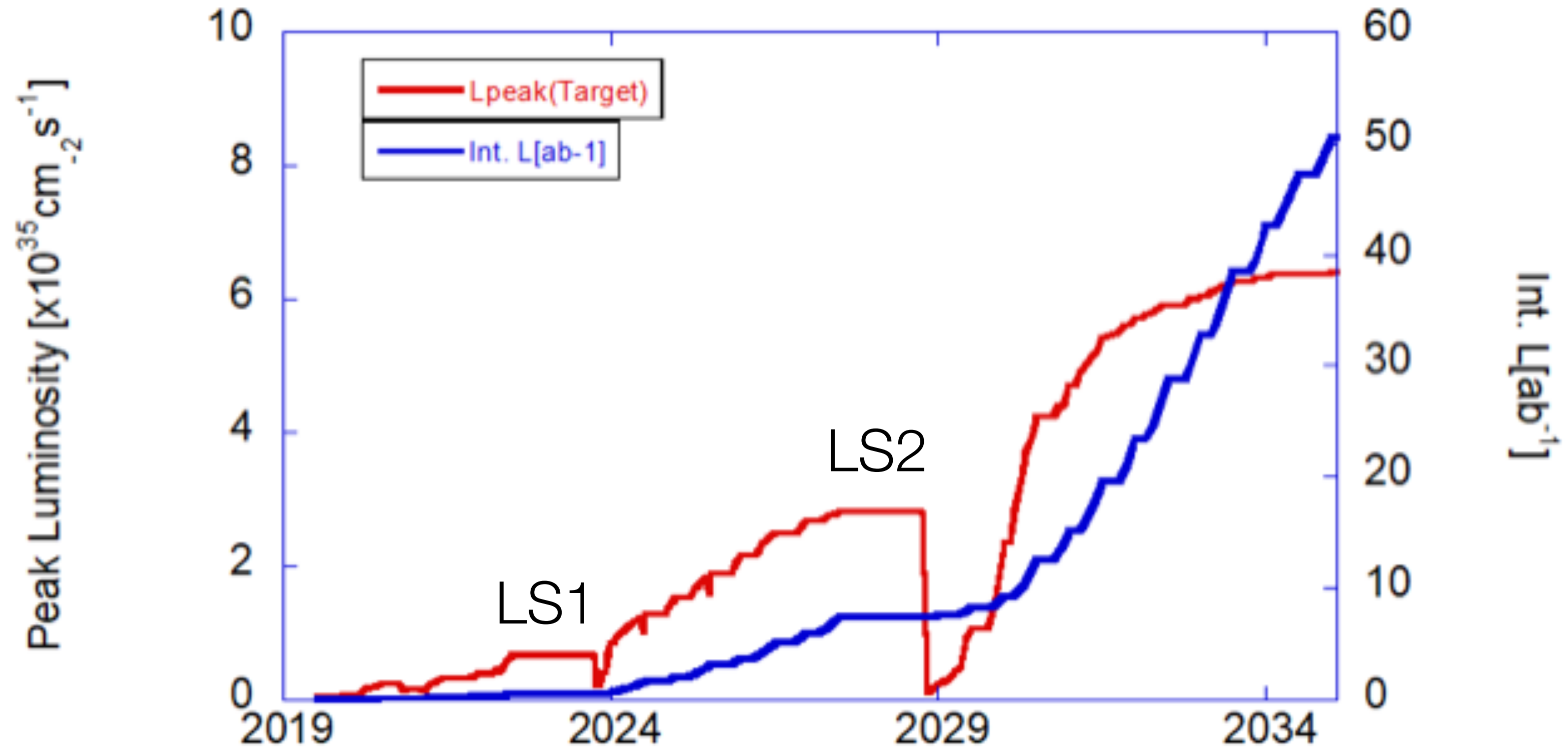
hadron colliders



e^+e^- colliders

Belle II status and plans

- Running since 2019. Achieved peak $L = 4.7 \times 10^{34} cm^{-2} s^{-1}$ int. $L = 430\ fb^{-1}$
- Now in LS1 (till ~end of 2023), mainly to replace an incomplete vertex detector



- International task force of accelerator experts formed in 2021 to help define the path towards target $L = 6.5 \times 10^{35}\ cm^{-2} s^{-1}$ and target int. $L = 50\ ab^{-1}$ by mid-2030s
  - Upgrade SuperKEKB in LS2 (~2027-2029) to reach target peak L (QCS, lattice?)
  - Upgrade vertex detector to accommodate the new interaction-region design, and other sub-detectors to improve robustness against increasing machine background

Proposals beyond current Belle II program

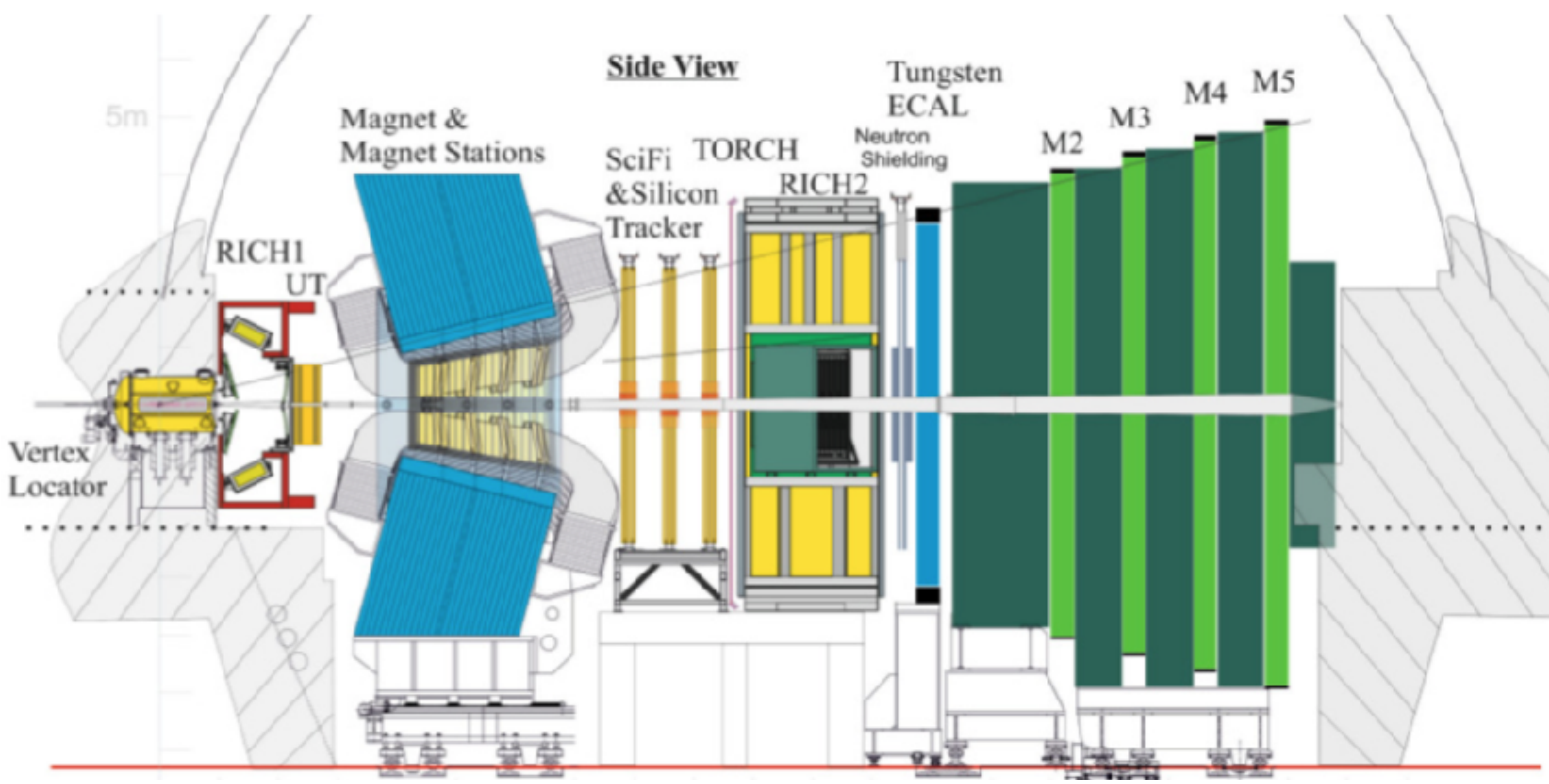
- Beam polarization to perform precision electroweak (and τ-physics) measurements
  - Could begin while SuperKEKB completes its program of delivering $50\mathrm{ab}^{-1}$ to Belle II and continue afterwards
- Running at ultra-high luminosities ($L > 10^{36}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$) and integrate $\sim 250\mathrm{ab}^{-1}$
  - Such an upgrade may effectively complement the heavy-flavor program of the LHC experiments. However, the feasibility from the accelerator perspective is still unclear, and so is the upgrade timeline

LHCb status and plans

- Collected about 9fb^{-1} during Run 1 and 2
- Upgrade I detector just started taking data and plans to get 50fb^{-1} by 2032
    - Considering the enhanced online-selection efficiency, the yield of beauty and charm hadrons available for analyses will increase by factors up to 10 (depending on the final states) compared to Run 2
- Upgrade II during LS4 (2033-2034) to run at $L = 2{\times}10^{34}\text{cm}^{-2}\text{s}^{-1}$ (10× Upgrade I) and collect 300fb^{-1} by end of Run 6 (early 2040s)
    - Now part of the baseline HL-LHC plan
    - Some preparatory work (Upgrade Ib) can be performed already during LS3 (2026-2028) to also benefit the physics performance during Run 4, beyond what has been projected for Upgrade I

LHCb Upgrade II

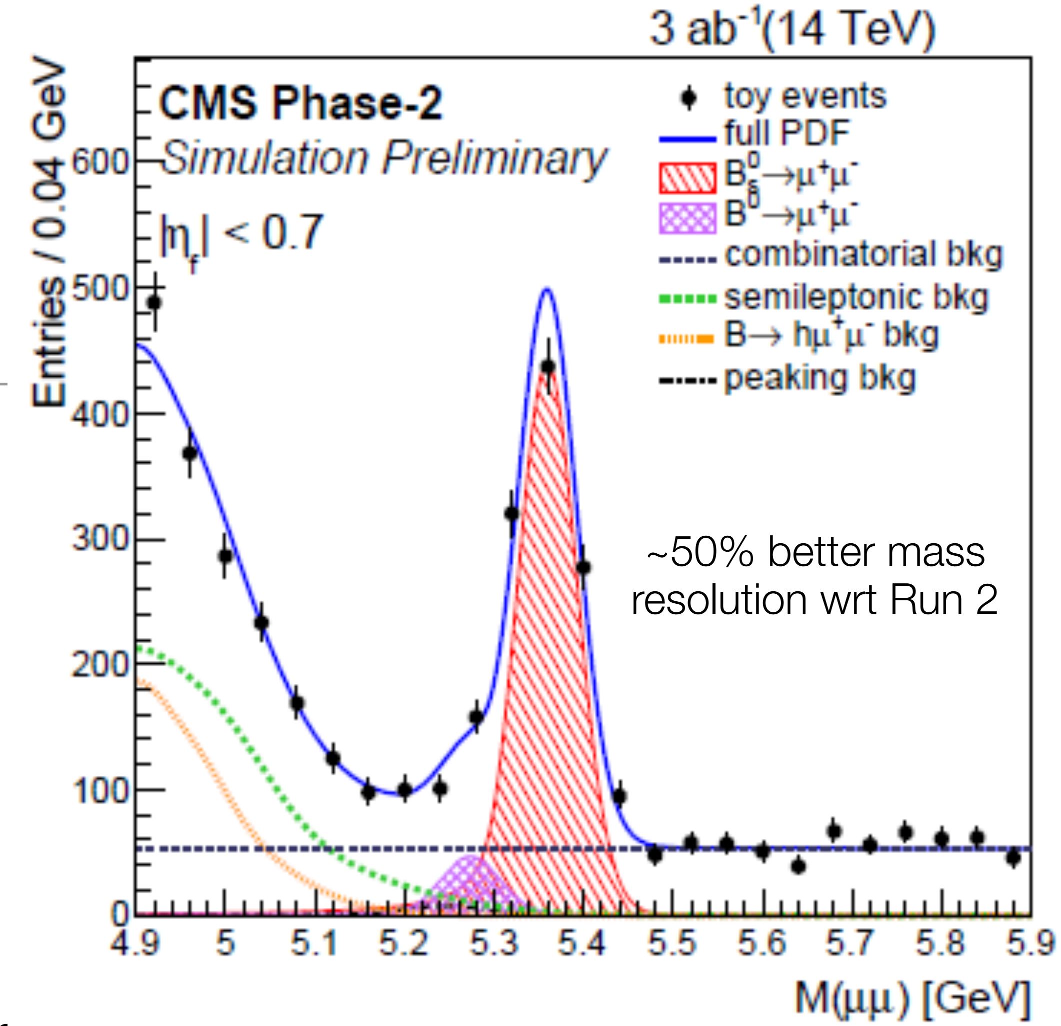
- LHCb physics program limited by the detector (and not by the LHC)
- Baseline target: keep same performance as in Run 2, but run at $L = 2\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with 40x larger pile-up
- Extremely challenging upgrade, currently in early planning [LHCb-TDR-023]: options available, dedicated R&D needed, estimated cost of ~175MCHF for baseline option

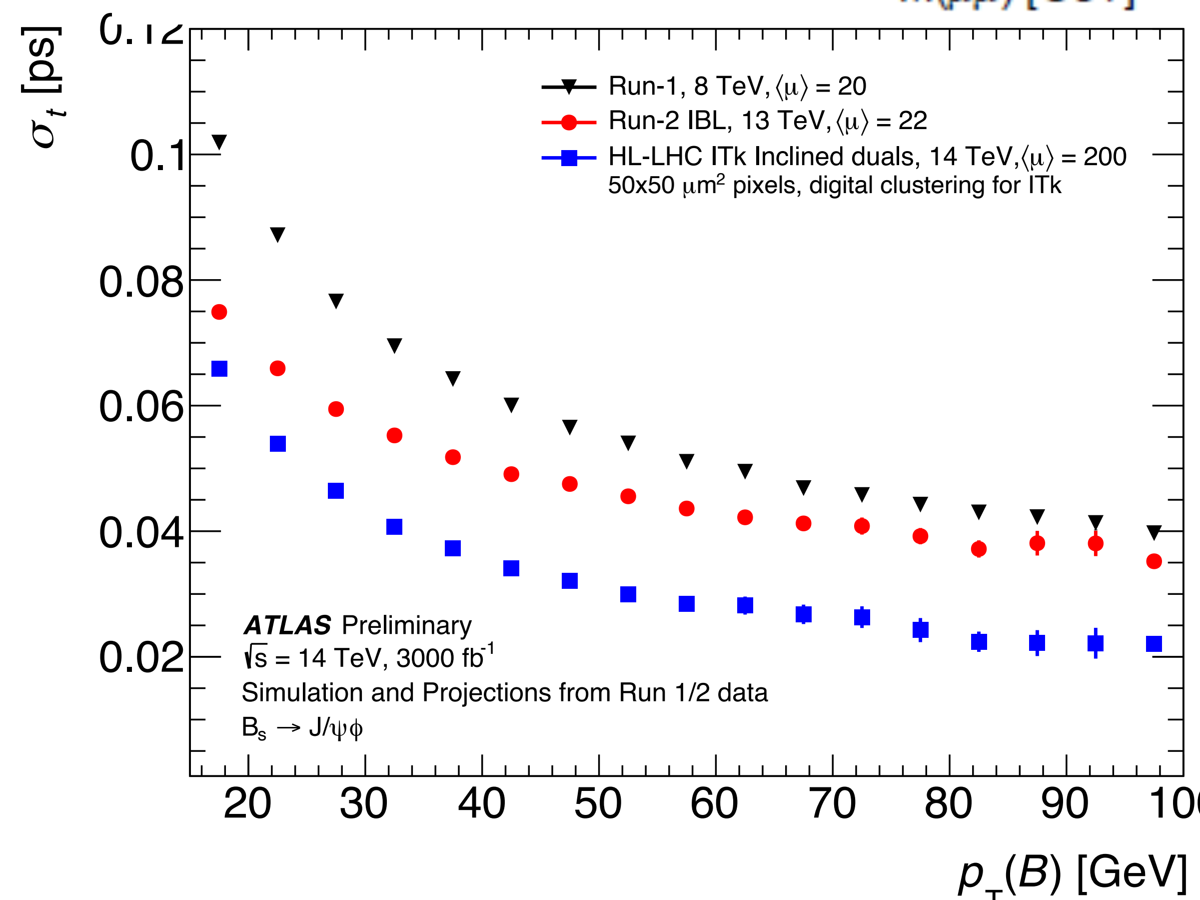


- Key ingredients:
  - High granularity
  - Fast timing (tens of ps)
  - Radiation hardness (up to few $10^{16}\, n_{eq}/\mathrm{cm}^2$)
- DAQ and trigger:
  - Full detector readout at 30 MHz
  - Offline-quality reconstruction at trigger level for real-time analysis

ATLAS/CMS upgrades

- For the HL-LHC both experiments are planning significant modification of the detectors (Phase-2 upgrades scheduled during Long Shutdown 3 in 2026-2028) to maintain effective data taking and event reconstruction at increased luminosity and pileup
- Particularly relevant for heavy-flavor physics are upgrades to
  - the tracking systems, which would result in improved mass and decay-time resolutions, and to
  - the trigger systems, to maintain the online selection efficient at the relatively low transverse momenta typical of the final state muons from beauty decays





BESIII and STCF

- BESIII at BEPCII uses e^+e^- collisions to study the broad spectrum of physics accessible in the τ-charm region
  - Since the start of operations in 2009, BESIII has collected more than 35 fb^{-1} of data, comprising several samples that are relevant for weak decays of charm hadrons
    - 5 fb^{-1} at $\sqrt{s}$=3.773 GeV (unique sample of correlated $D^0\bar{D}^0$ pairs)
    - 3 fb^{-1} at $\sqrt{s}$=4.178 GeV (near the $D_s D_s^*$ threshold)
    - >3 fb^{-1} at $\sqrt{s}$=4.64 GeV (above the $\Lambda_c\bar{\Lambda}_c$ threshold)
  - The experiment will run at least for the next 5-10 years and expects to integrate 20 fb^{-1} at $\sqrt{s}$=3.773 GeV (by June 2024), 6 fb^{-1} at $\sqrt{s}$=4.178 and 5 fb^{-1} at $\sqrt{s}$=4.64 GeV
- A Super τ-Charm factory (STCF) has been proposed in China to continue and extend the BESIII physics program at collision energies between 2 and 7 GeV and with peak luminosity of at least 5×10^{34}cm^{-2}s^{-1}
  - The current schedule foresees the construction to happen between 2024 and 2030, and at least 10 years of operations (including implementation of a polarized e^- beam)

Complementarity

LHCb

- Huge advantage in production rate, but large backgrounds results in lower efficiencies (advantage remains mostly for charged final states)
- Larger boost and 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
- Quantum-correlated $B\bar{B}$ production allows efficient determination of production flavor for time-dependent *CP*-violation measurements

ATLAS/CMS

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

charm-τ factories (BESIII/STCF)

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

Expected progress on (some) key observables

Observable	Current best	Belle II $50\,\mathrm{ab}^{-1}$	Belle II $250\,\mathrm{ab}^{-1}$	LHCb $50\,\mathrm{fb}^{-1}$	LHCb $300\,\mathrm{fb}^{-1}$	ATLAS $3\,\mathrm{ab}^{-1}$	CMS $3\,\mathrm{ab}^{-1}$	BESIII $20\,\mathrm{fb}^{-1}$ $(*)$	STCF $1\,\mathrm{ab}^{-1}$ $(*)$
Lepton-flavor-universality tests									
$R_K(1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.044 [31]	0.036	0.016	0.017	0.007				
$R_{K^*}(1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.12 [32]	0.032	0.014	0.022	0.009				
R_D	0.037 [33]	0.008	< 0.003	na	na				
R_{D^*}	0.018 [33]	0.0045	< 0.003	0.005	0.002				
Rare decays									
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ $[10^{-9}]$	0.46 [34, 35]			na	0.16	0.46–0.55	0.39		
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	0.69 [34, 35]			0.27	0.11	na	0.21		
$\mathcal{B}(B^0 \to \overline{K}^{*0}\tau^+\tau^-)$ UL $[10^{-3}]$	2.0 [36, 37]	0.5	na						
$\mathcal{B}/\mathcal{B}_{\mathrm{SM}}(B^+ \to K^+\nu\overline{\nu})$	1.4 [38, 39]	0.08–0.11	na						
$\mathcal{B}(B \to X_s\gamma)$	10% [40, 41]	2–4%	na						
CKM tests and CP violation									
α	5° [42]	0.6°	0.3°						
$\sin 2\beta(B^0 \to J/\psi\, K_\mathrm{S}^0)$	0.029 [43]	0.005	0.002	0.006	0.003				
γ	4° [44]	1.5°	0.8°	1°	0.35°			0.4° (†)	$< 0.1°$ (†)
$\phi_s(B_s^0 \to J/\psi\,\phi)$	32 mrad [45]			10 mrad	4 mrad	4–9 mrad	5–6 mrad		
$\lvert V_{ub}\rvert(B^0 \to \pi^-\ell^+\nu)$	5% [46, 47]	2%	$< 1\%$	na	na				
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert(\Lambda_b^0 \to p\mu^-\overline{\nu})$	6% [48]			2%	1%				
$f_{D^+}\lvert V_{cd}\rvert(D^+ \to \mu^+\nu)$	2.6% [49]	1.4%	na					1.0%	0.15%
$S_{CP}(B^0 \to \eta' K_\mathrm{S}^0)$	0.08 [50, 51]	0.015	0.007	na	na				
$A_{CP}(B^0 \to K_\mathrm{S}^0\pi^0)$	0.15 [50, 52]	0.025	0.018	na	na				
$A_{CP}(D^+ \to \pi^+\pi^0)$	11×10^{-3} [53]	1.7×10^{-3}	na	na	na			na	na
$\Delta x(D^0 \to K_\mathrm{S}^0\pi^+\pi^-)$	18×10^{-5} [54]	na	na	4.1×10^{-5}	1.6×10^{-5}			na	na
$A_\Gamma(D^0 \to K^+K^-, \pi^+\pi^-)$	11×10^{-5} [55]	na	na	3.2×10^{-5}	1.2×10^{-5}			na	na

Table 1-1. *Projected uncertainties (or 90% CL upper limits) in several key heavy-flavor observables over the next two decades. A missing entry means that the observable cannot be measured, the abbreviation* na *means that, although the observable can be measured, the projected uncertainty is not available. Projections are taken from Refs. [17, 19, 56] (Belle II), Refs. [57, 28] (LHCb), Ref. [23] (ATLAS and CMS), Refs. [25, 30] (BESIII and STCF). $(*)$ Integrated luminosity at $\sqrt{s} = 3.773$. (†) Projected uncertainties on γ resulting from BESIII/STCF measurements of the D strong-phase differences, which will contribute as external inputs to the Belle II and LHCb measurements.*

Disclaimer

- It is impossible to make a complete and exhaustive list of interesting observables in *b* and *c* physics in a short report

- Selecting only a few “golden” channels would be too reductive as the strength of the field relies on combining several complementary inputs — often from different experiments, and theory — to reduce the interpretation unknowns

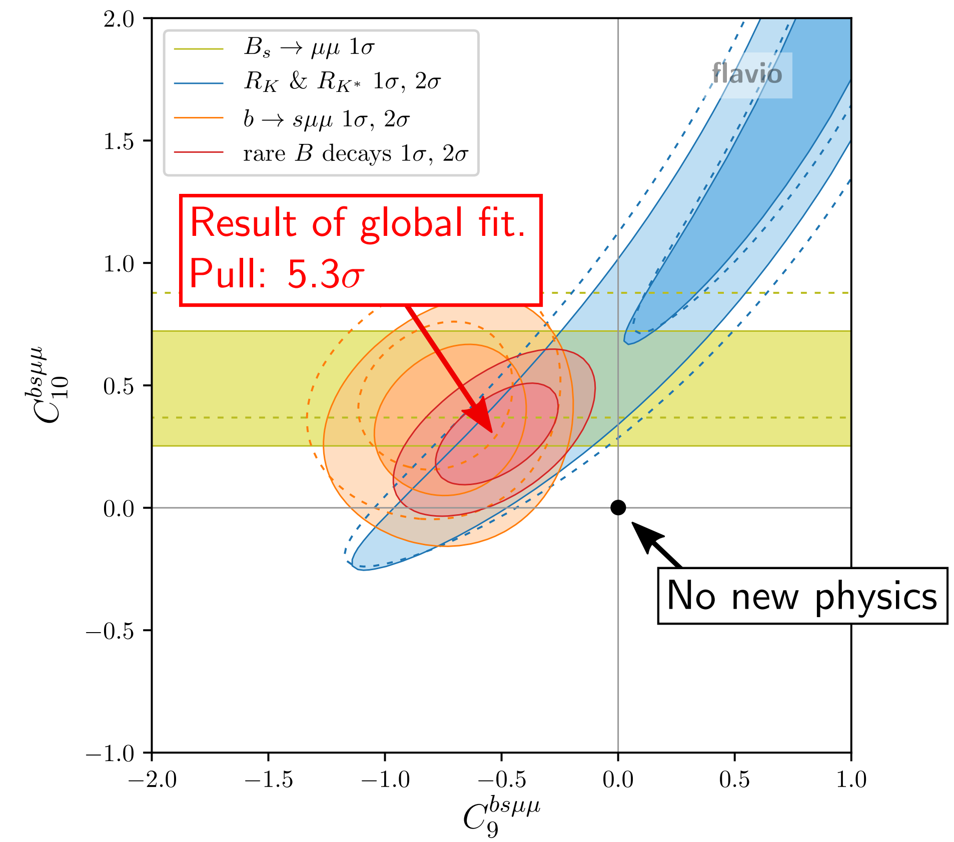
- The aim of the report is therefore to provide an overview of the observables that are currently most interesting, either because their measurements already show hints of deviations from the SM or because they are severely limited by the experimental uncertainties

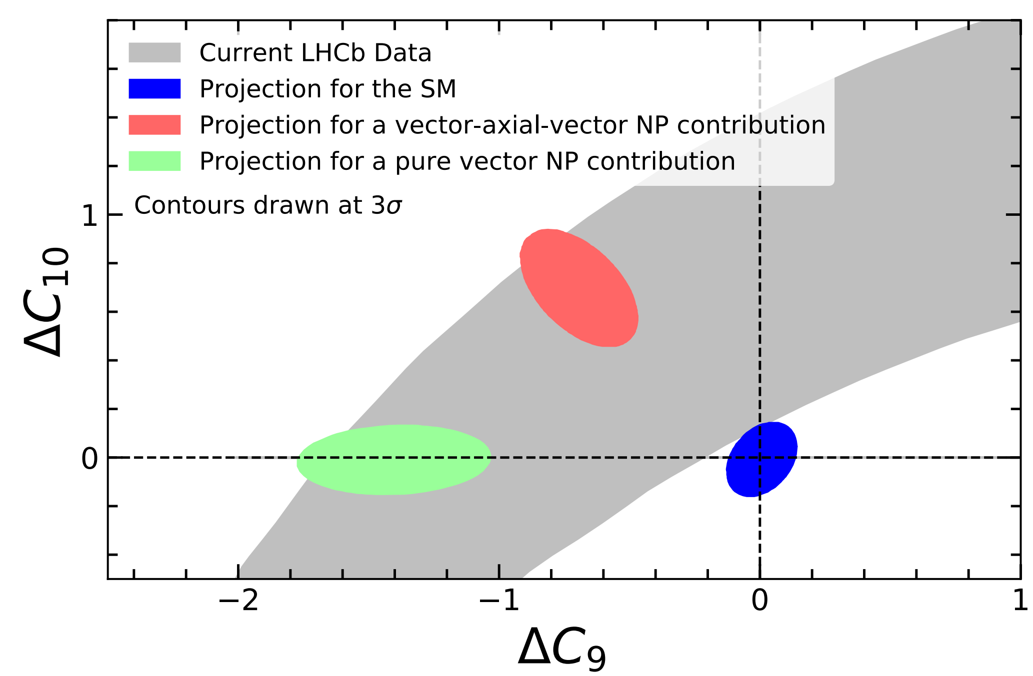
Lepton-flavor-universality tests

- Measurements of LFU observables in $b \to s\ell^+\ell^-$ decays will reach 1%-level uncertainties in the next decade, a precision sufficient to establish or reject the level of LFU violation seen in the current measurements

- LHCb Upgrade II will then open new avenues with sensitivity to even cleaner theoretically observables crucial to distinguish between different NP models (*e.g.*, such as the difference between the values of C_9 and C_{10} for $b \to se^+e^-$ and $b \to s\mu^+\mu^-$ using angular observables)

- Additionally, further suppressed $b \to d\ell^+\ell^-$ transitions will become accessible. For example, the statistical precision on the ratio $B(B^+ \to \pi^+\mu^+\mu^-)/B(B^+ \to \pi^+e^+e^-)$ is expected to reach a few percent at LHCb





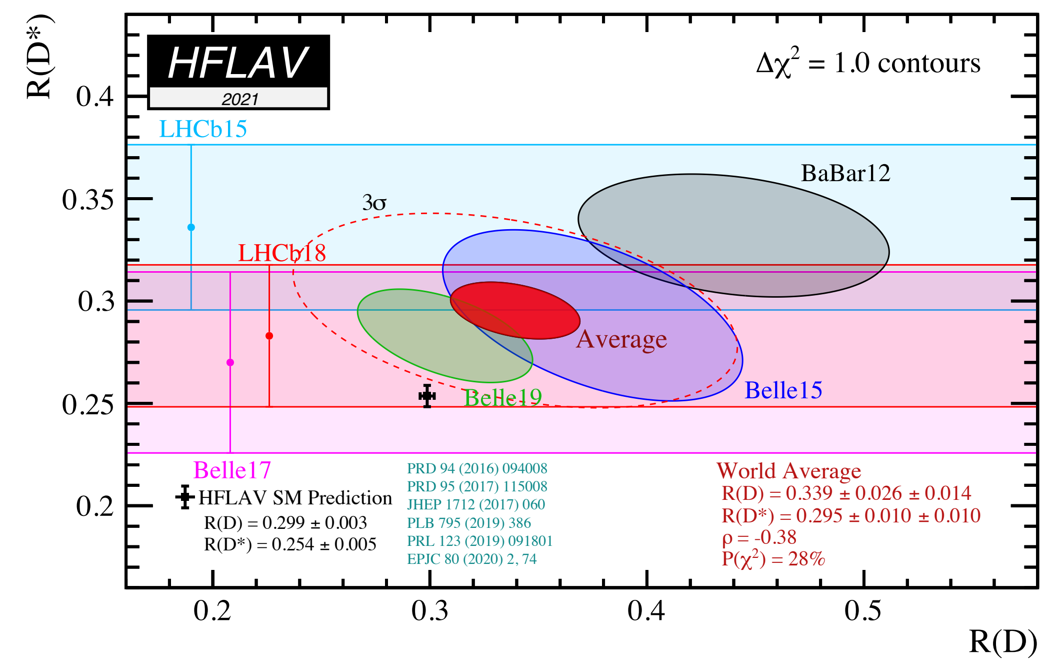
Lepton-flavor-universality tests

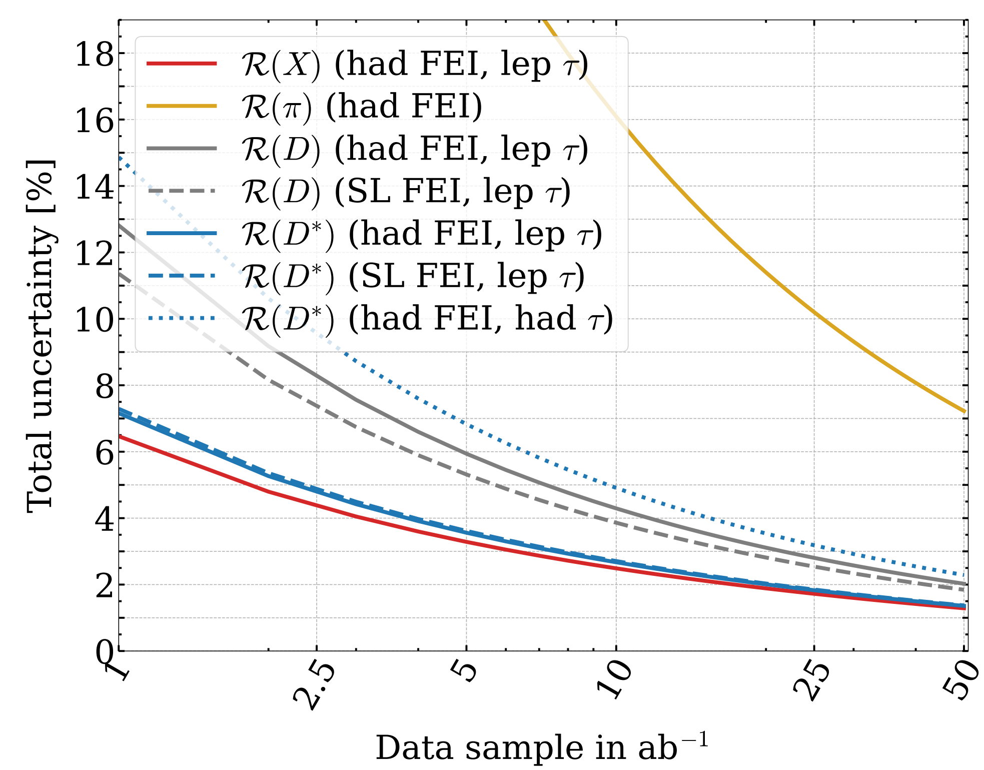
- Tests of LFU in $b \to c\tau^-\bar{\nu}$ decays are expected to be dominated by Belle II, thanks to the ability to constrain the kinematics of the undetected neutrinos by leveraging on the precise knowledge of the production mechanism

- LHCb will uniquely contribute with measurements based on other b hadrons (B_s, Λ_b, B_c)

- Observables related to angular distributions will provide supplementary sensitivity to non-SM physics and key information to decipher the dynamics

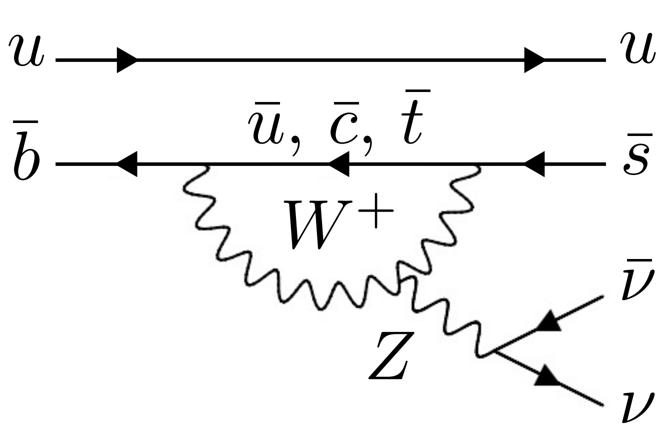
- Other possibilities to test electron vs. muon universality in semileptonic charm and beauty decays (*e.g.*, through Δ variables) have also been recently proposed, showing good prospects at BESIII, STCF and Belle II

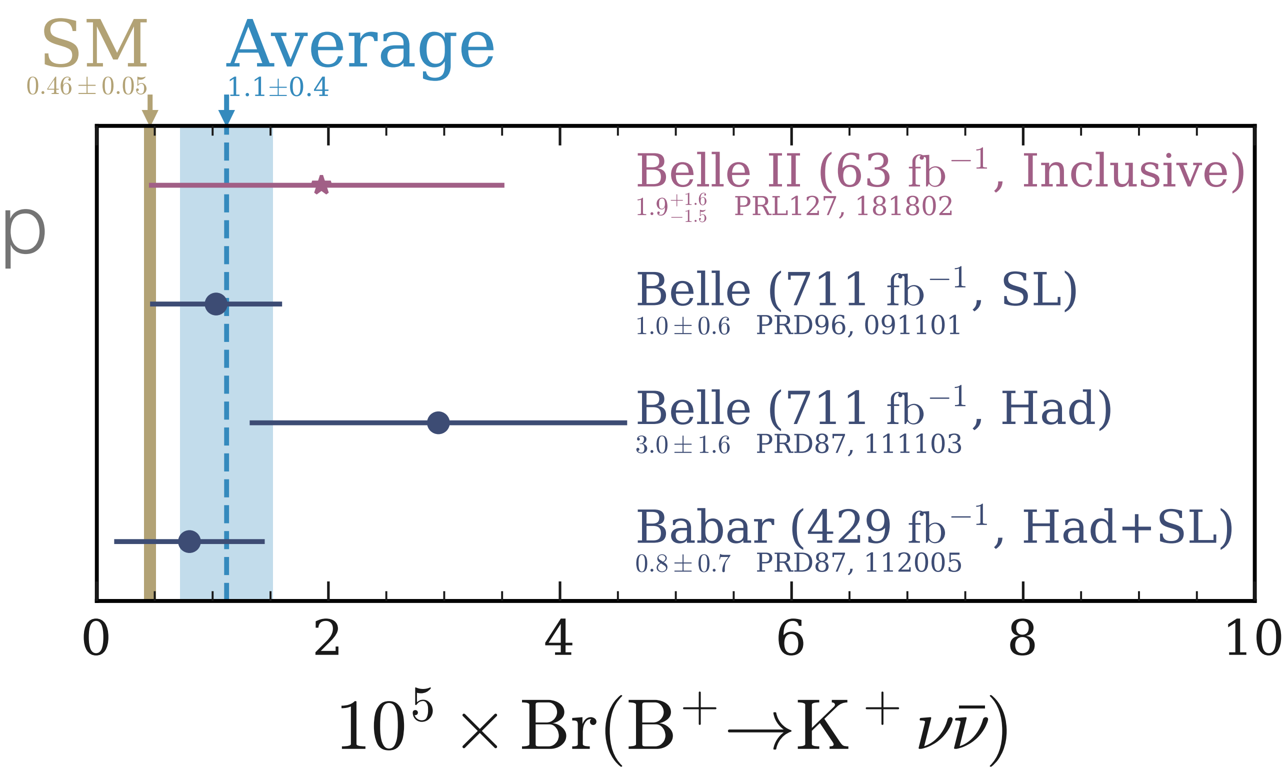




Rare decays: $B \to K^{(*)}\nu\bar{\nu}$

- Complementary to $b \to s\ell^+\ell^-$ transitions, but with no charm-loop contamination (theoretically clean)



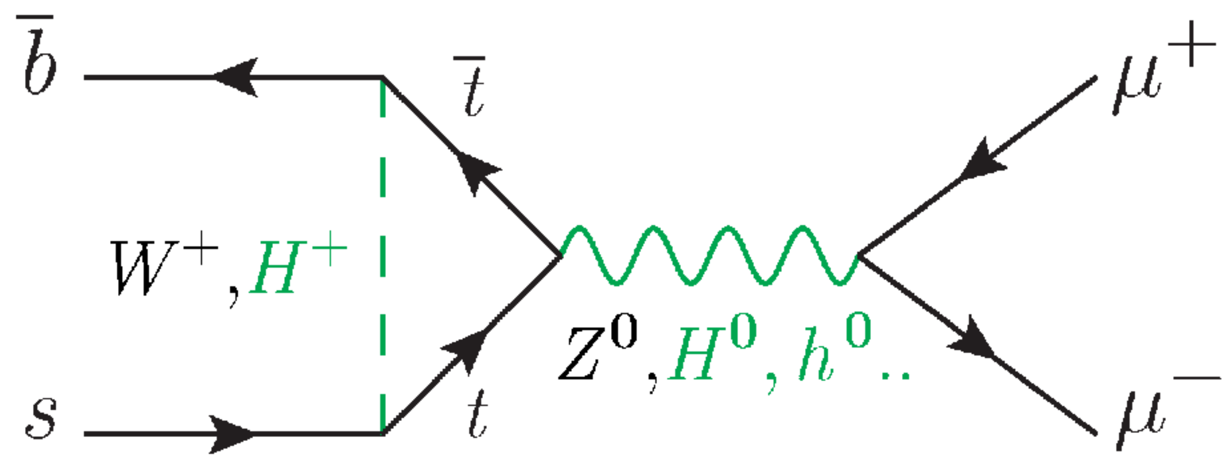


- Accessible only at Belle II
  - SM rate of $B^+ \to K^+\nu\bar{\nu}$ can be measured at >3σ with 5/ab

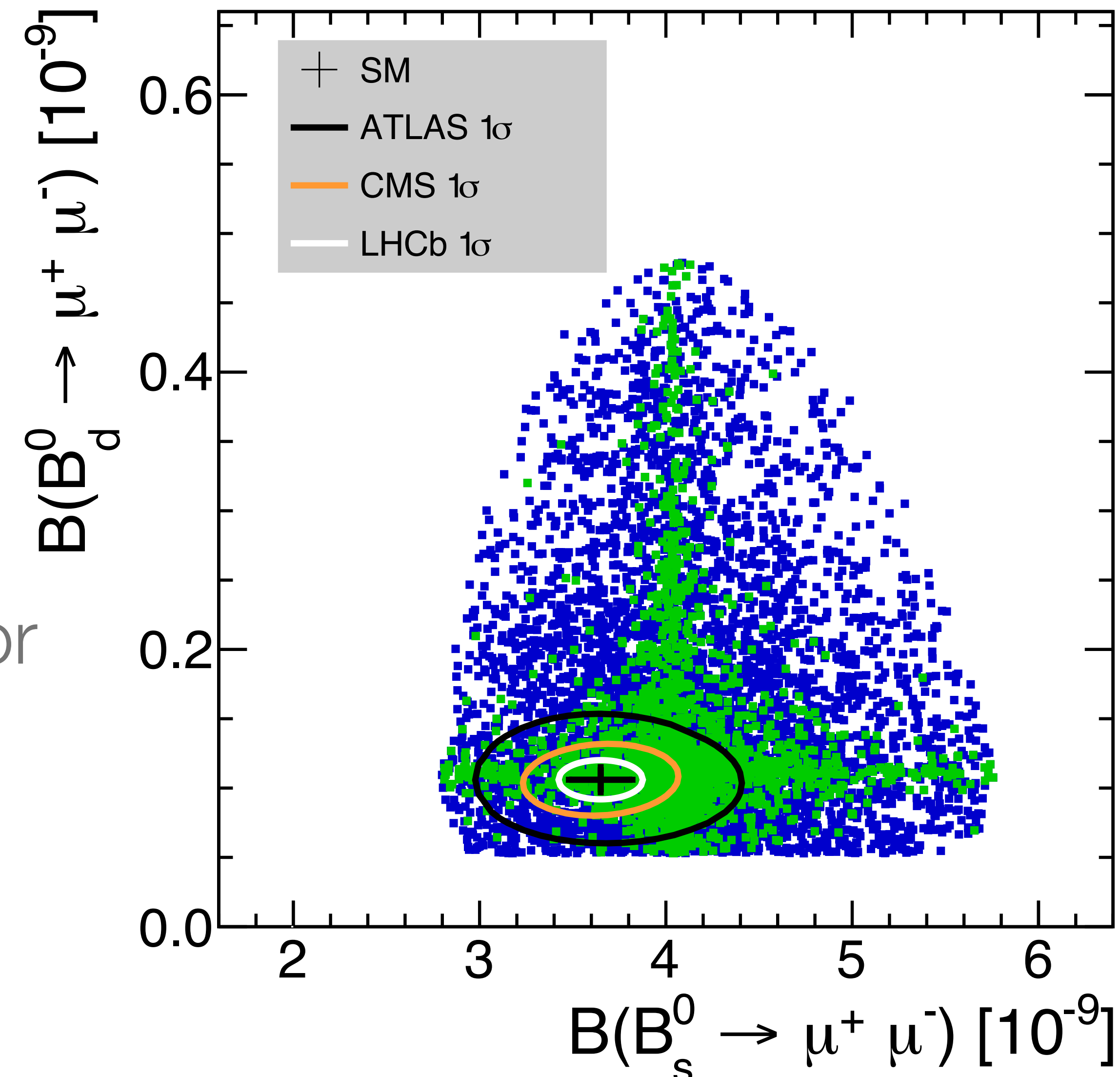
Baseline (improved) uncertainties on rate relative to SM

Decay	$1\,\mathrm{ab}^{-1}$	$5\,\mathrm{ab}^{-1}$	$10\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$
$B^+ \to K^+\nu\bar{\nu}$	0.55 (0.37)	0.28 (0.19)	0.21 (0.14)	0.11 (0.08)
$B^0 \to K^0_S\nu\bar{\nu}$	2.06 (1.37)	1.31 (0.87)	1.05 (0.70)	0.59 (0.40)
$B^+ \to K^{*+}\nu\bar{\nu}$	2.04 (1.45)	1.06 (0.75)	0.83 (0.59)	0.53 (0.38)
$B^0 \to K^{*0}\nu\bar{\nu}$	1.08 (0.72)	0.60 (0.40)	0.49 (0.33)	0.34 (0.23)

Rare decays: $B_{(s)} \to \mu^+\mu^-$ decay



- Powerful probe of the SM gauge sector
- LHCb Upgrade II will approach SM uncertainty (currently limited by CKM matrix elements, B_s decay constant)
- Effective lifetime and time-dependent *CP* asymmetry are additional NP probes that will become accessible during HL-LHC



SUSY allowed
+ other exp. constraints

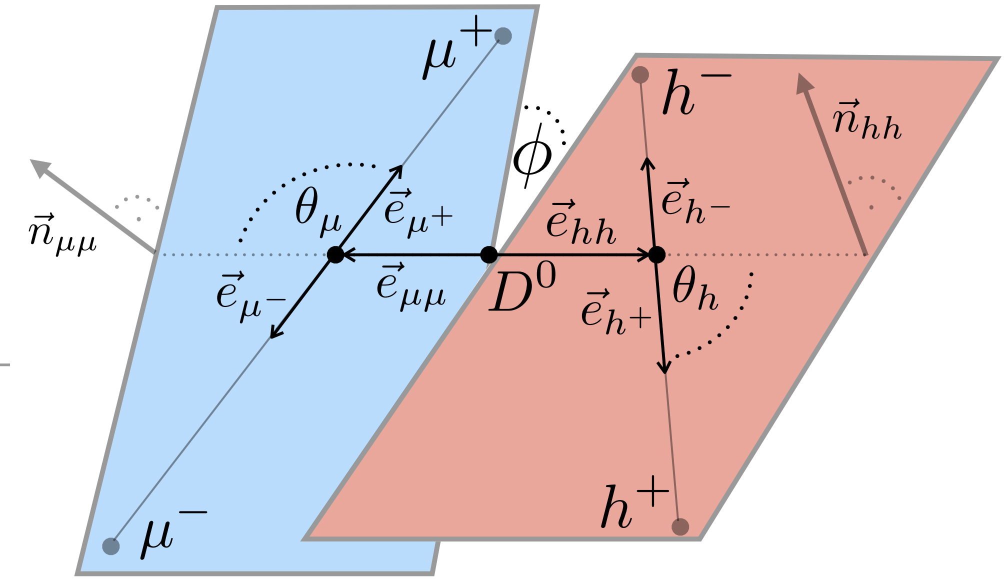
Rare charm decays

- Rare and forbidden decays of charm hadrons probe beyond-SM contributions in $c \to u$ transitions and are therefore complementary to searches done in the *b* sector

- Despite the SM rate being dominated by long-distance dynamics, null-test observables related to angular distributions and *CP* violation provide NP discovery potential in the near future

- At LHCb, tests with $D^0 \to h^+ h^- \mu^+ \mu^-$ decays (now at 0.1-0.01) are expected to reach sub-percent precision and will be complemented by studies of other modes and by tests of lepton-flavor universality

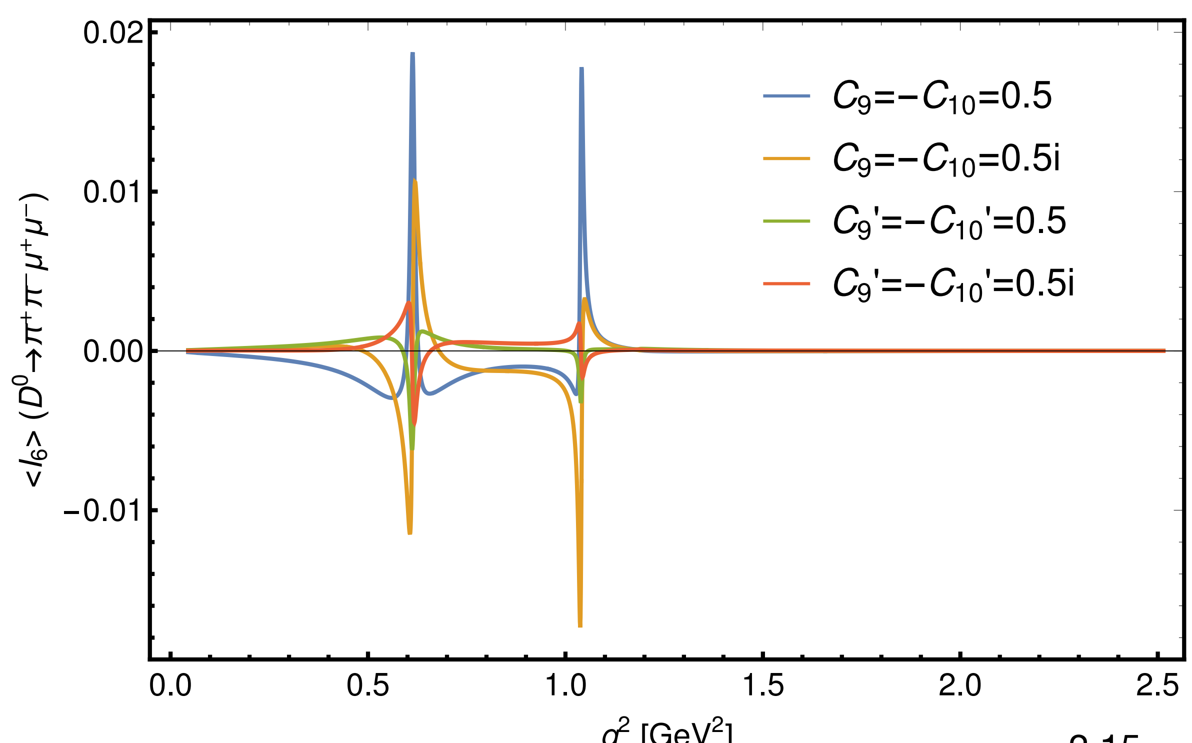
- Lepton-flavor universality tests and unique studies of $c \to u \nu \bar{\nu}$ decays are expected to be possible also at e^+e^- colliders



$$\frac{d\Gamma}{d\cos\theta_\mu d\cos\theta_h d\phi} = \begin{aligned} & I_1 + \\ & I_2 \cdot \cos 2\theta_\mu + \\ & I_3 \cdot \sin^2 2\theta_\mu \cos 2\phi + \\ & I_4 \cdot \sin 2\theta_\mu \cos\phi + \\ & I_5 \cdot \sin\theta_\mu \cos\phi + \\ & I_6 \cdot \cos\theta_\mu + \\ & I_7 \cdot \sin\theta_\mu \sin\phi + \\ & I_8 \cdot \sin 2\theta_\mu \sin\phi + \\ & I_9 \cdot \sin^2\theta_\mu \sin 2\phi \end{aligned}$$

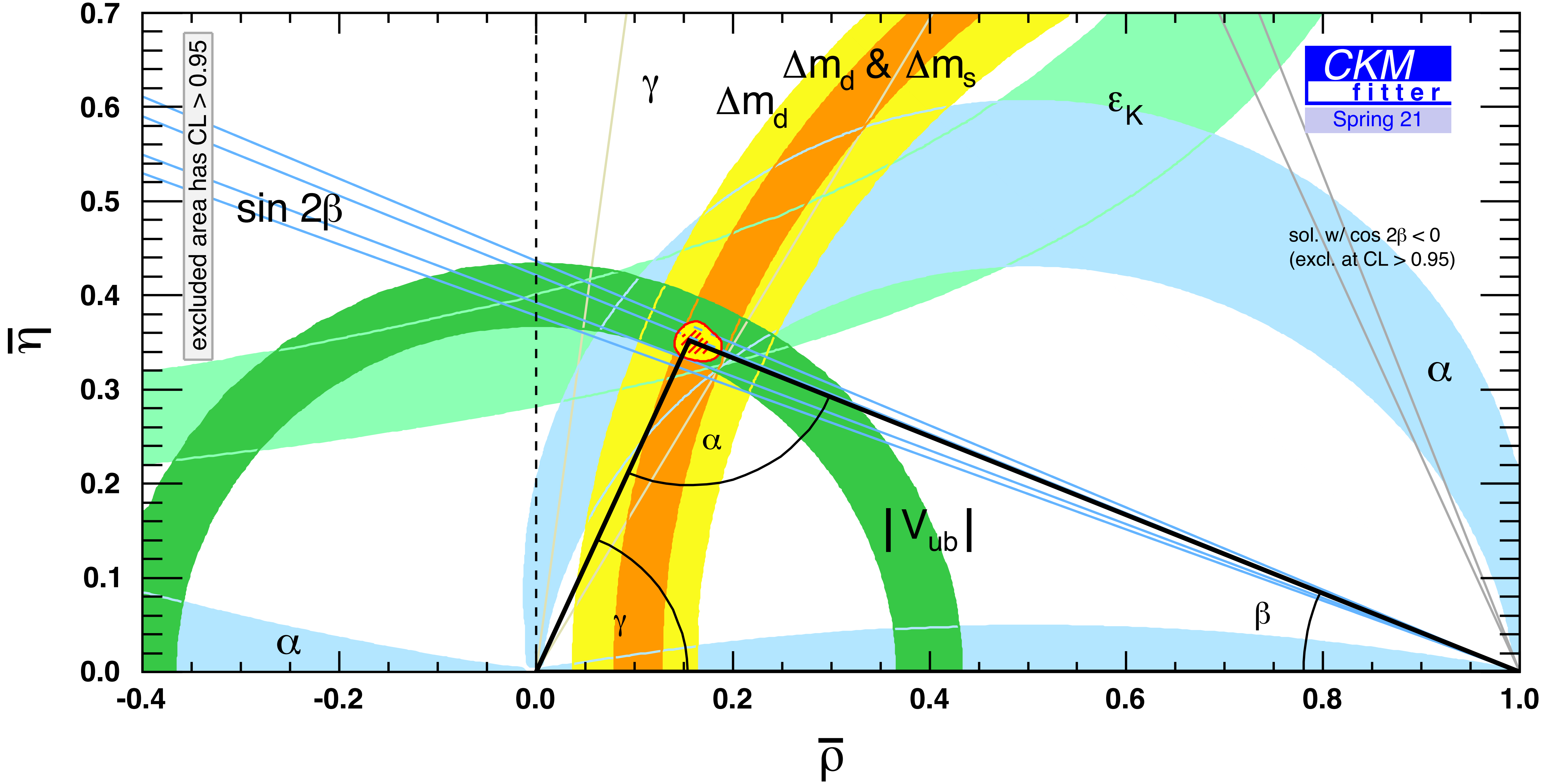
I_5, I_6, I_7 clean null tests!

$[I_6 = A_{FB}]$

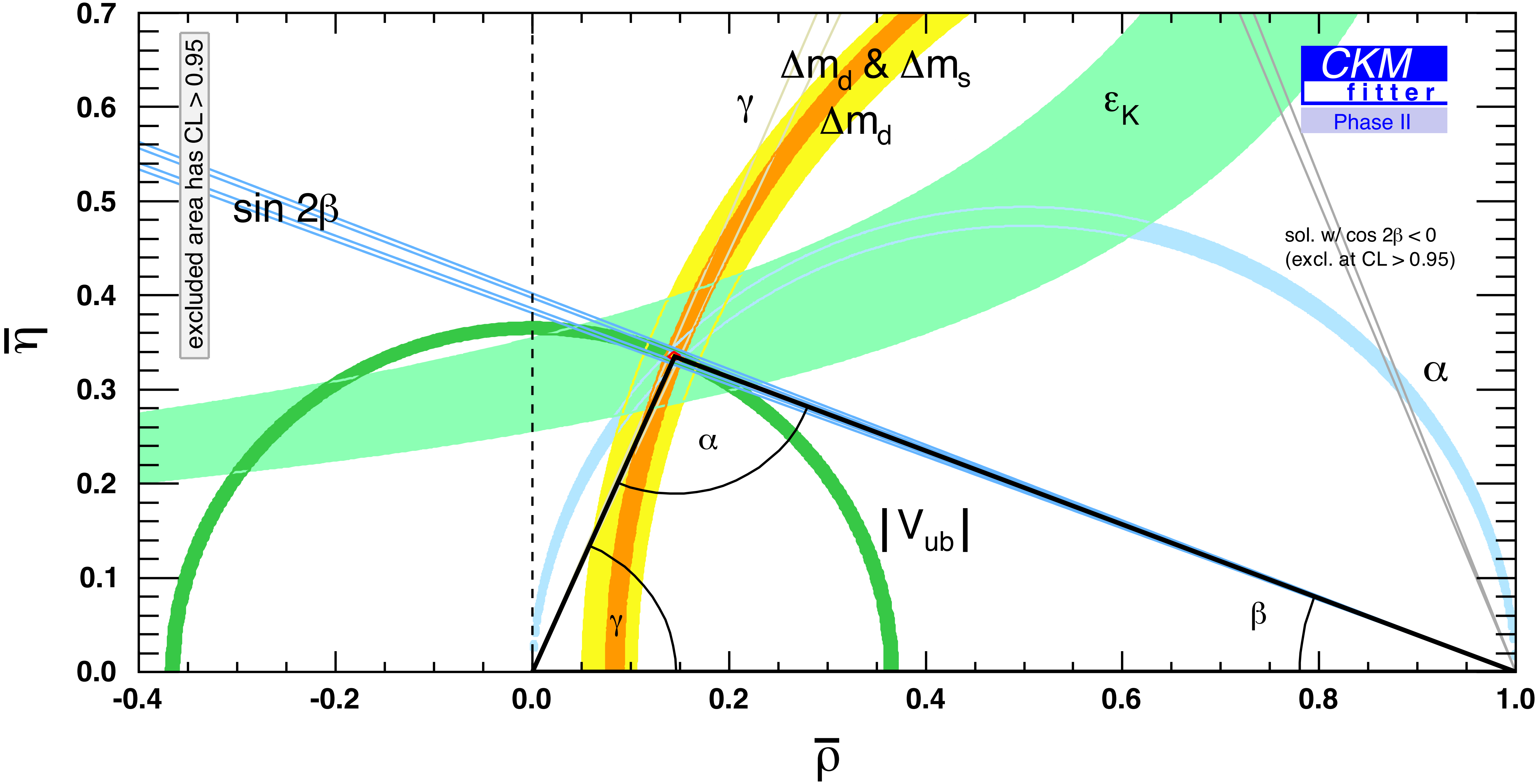


2.15

CKM unitarity tests

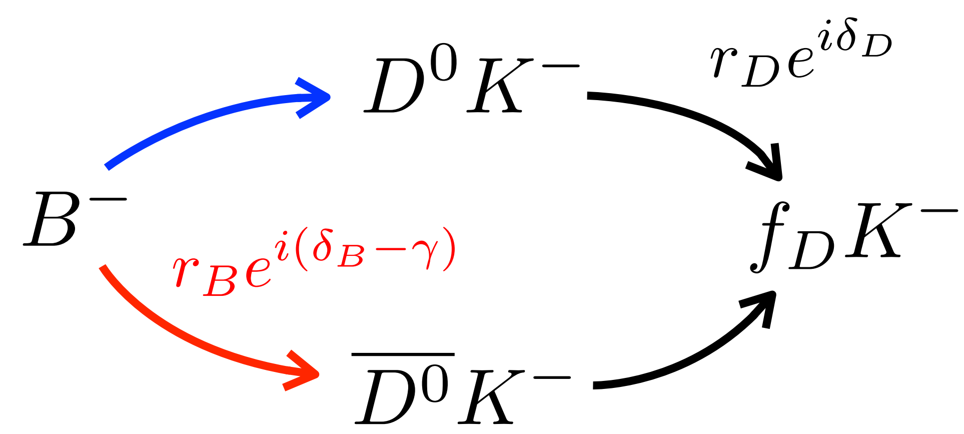


CKM unitarity tests



CKM tests: γ

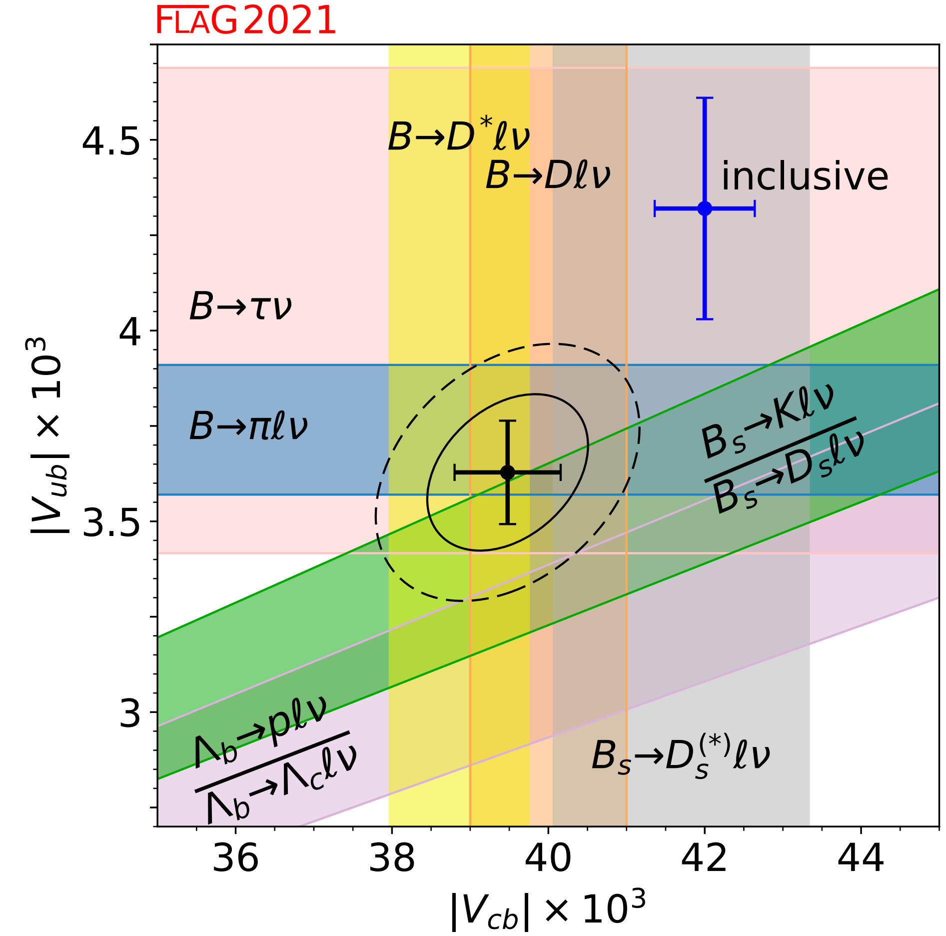
- The only *CP*-violation parameter that can be measured from tree-level decays (negligible theory prediction)
- New *CP* violating effects in non-leptonic tree-level decay can modify the SM relation between γ and the CKM elements by several degrees
- LHCb dominates the current 4° precision, and is expected to keep the lead in the next decades
- Complementarity is trilateral: inputs from coherent $D^0\bar{D}^0$ data instrumental to reach the asymptotic precision
  - Current ~1.5° contribution (CLEO+BESIII) expected to shrink to ~0.4° (BES III after 2024) and to ~0.1° (STCF)

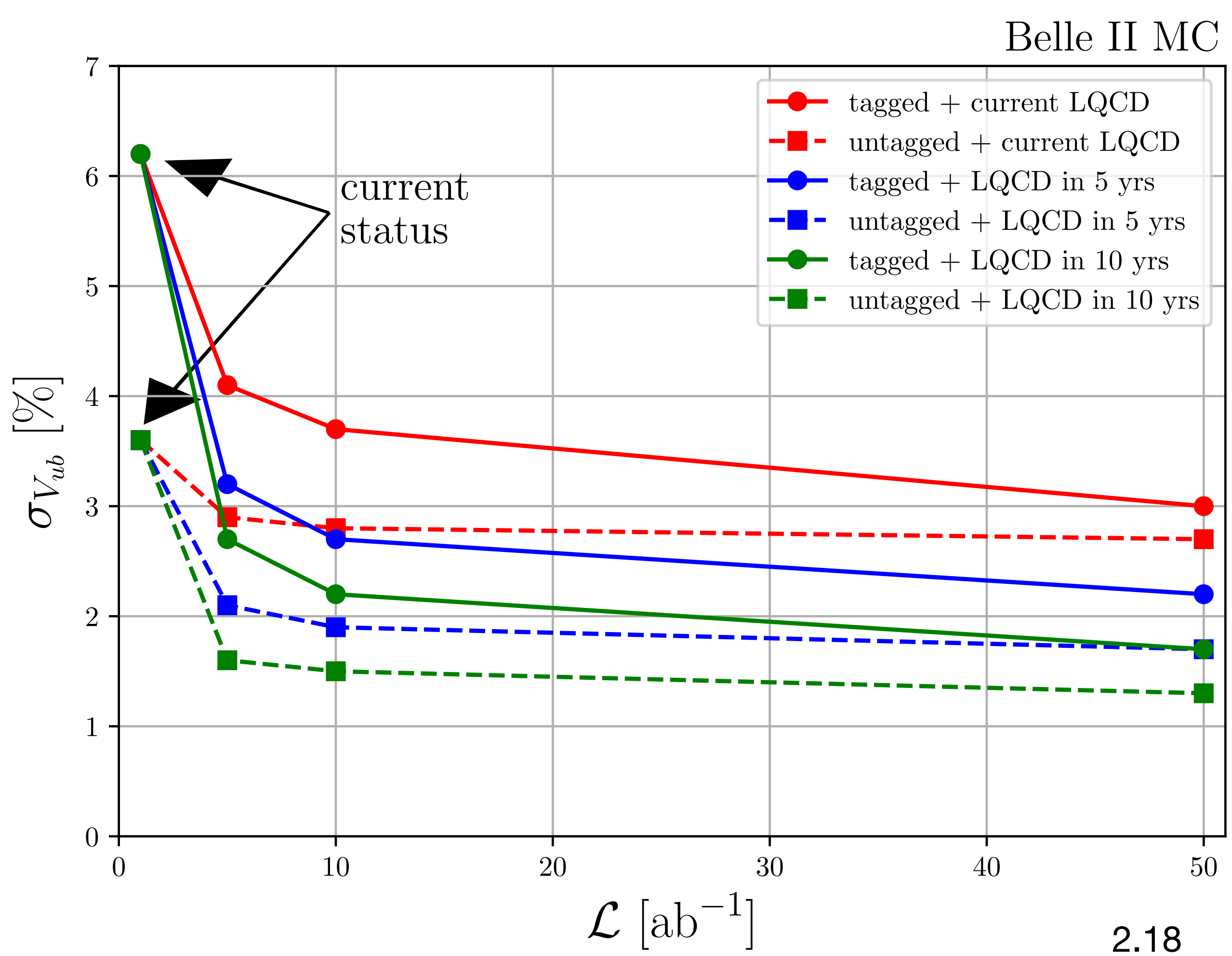


	Precision
Now	4°
Belle II (50/ab)	1.5°
LHCb (50/fb)	1°
Belle II (250/ab)	0.8°
LHCb (300/fb)	0.35°

CKM tests: V_{ub}, V_{cb}

- Long-standing discrepancy between exclusive and inclusive determinations. Resolving the tension is a high priority that will require a combined experiment-theory effort
- Belle II will drive the global experimental progress throughout the next decade
- LHCb can achieve competitive sensitivity on the ratio $|V_{ub}|/|V_{cb}|$ using Λ_b and B_s decays
- Not obvious that data and theory improvements will solve discrepancy — if keep doing the same, why would we get different results? Opportunity to innovate



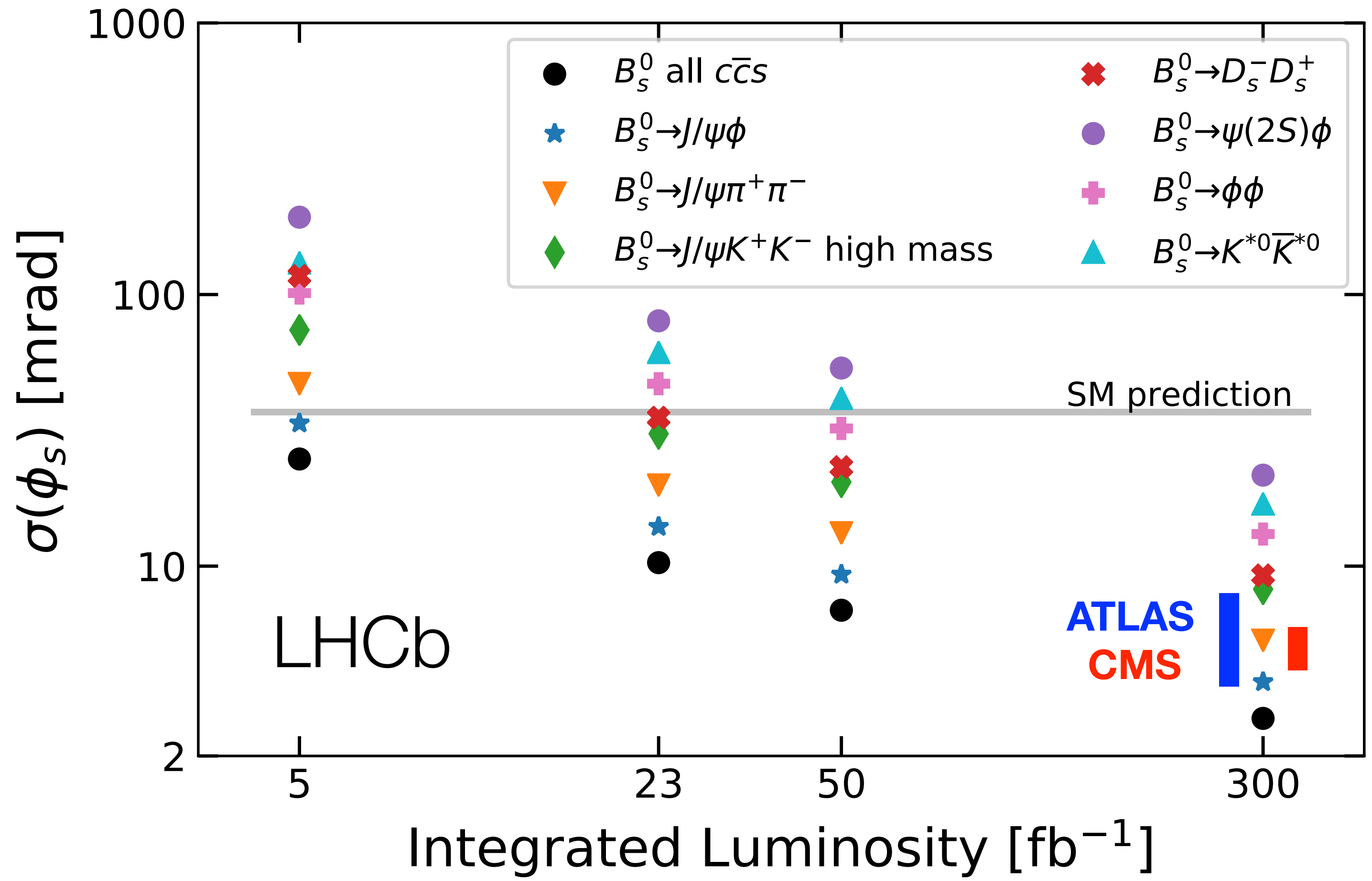


CKM tests: V_{cd}, V_{cs}

- $|V_{cs}|$ and $|V_{cd}|$ determinations offer additional constraining information
- Currently known with ~1% uncertainties from leptonic and semileptonic $D_{(s)}$ decays. No much room for improvements in the next decade
  - The precision with semileptonic decays is limited by the lattice-QCD computation of the decay form-factors. Measurements with leptonic decays are, instead, limited by experimental uncertainties
  - The relative uncertainties in $|V_{cs}|$ and $|V_{cd}|$ from leptonic decays are expected to be reduced at BESIII from 2.6% and 1.2% to approximately 1.1% and 0.9%, respectively
- Further improvement may be possible at STCF, provided that systematic uncertainties can be reduced well below the 1% level

CP violation in $B_{(s)}$ mixing

- Mixing strengths limited by theory uncertainties
- Mixing phases limited by experimental (statistical) uncertainties. Large room for improvement, especially for B_s
- During HL-LHC precision with $B_s \to J/\psi\phi$ will be ~4 mrad, well below the tree-level SM value



- Will either expose NP or provide precise reference for non-SM searches in gluonic-penguin channels
  - Important to assess sub-leading penguin pollution to tree-level decays using SU(3)-related channels

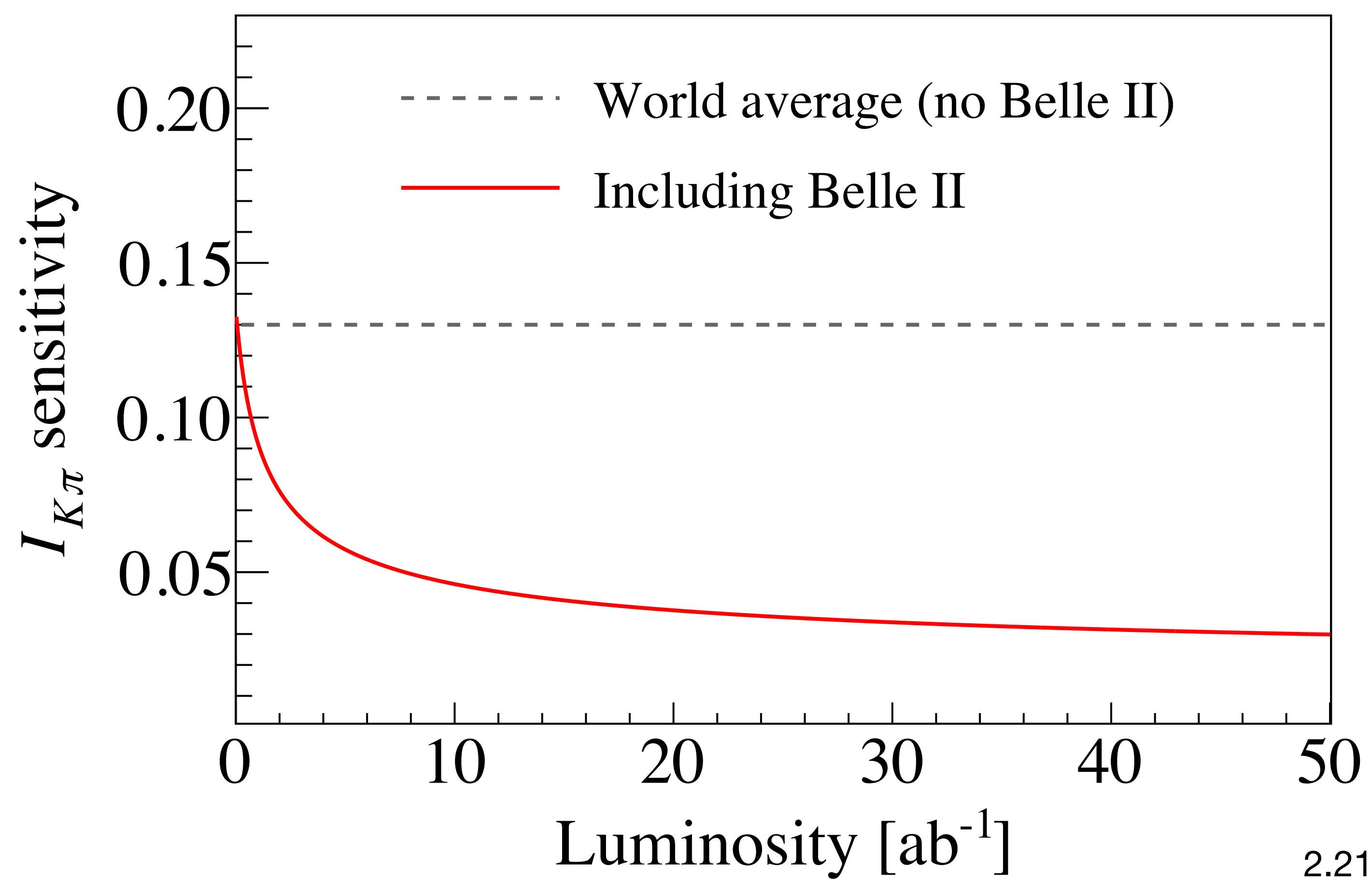
Charmless B decays

- Hadronic unknowns from soft gluons: hard to extract reliably CKM phases from single processes. Appropriate combinations of channels suppress unknowns offering stringent beyond-SM tests

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

- Current precision of 13% will reduce to ~2% thanks to precise LHCb determinations in charged final states and unique Belle II access to $K^0\pi^0$

- Similar tests accessible in $K^*\pi$ and $K^*\rho$ systems



CKM angle α

- Charmless B decays give also access to α, the least known angle of the CKM unitarity triangle, which also suffer from much larger theory uncertainties than other CKM angles

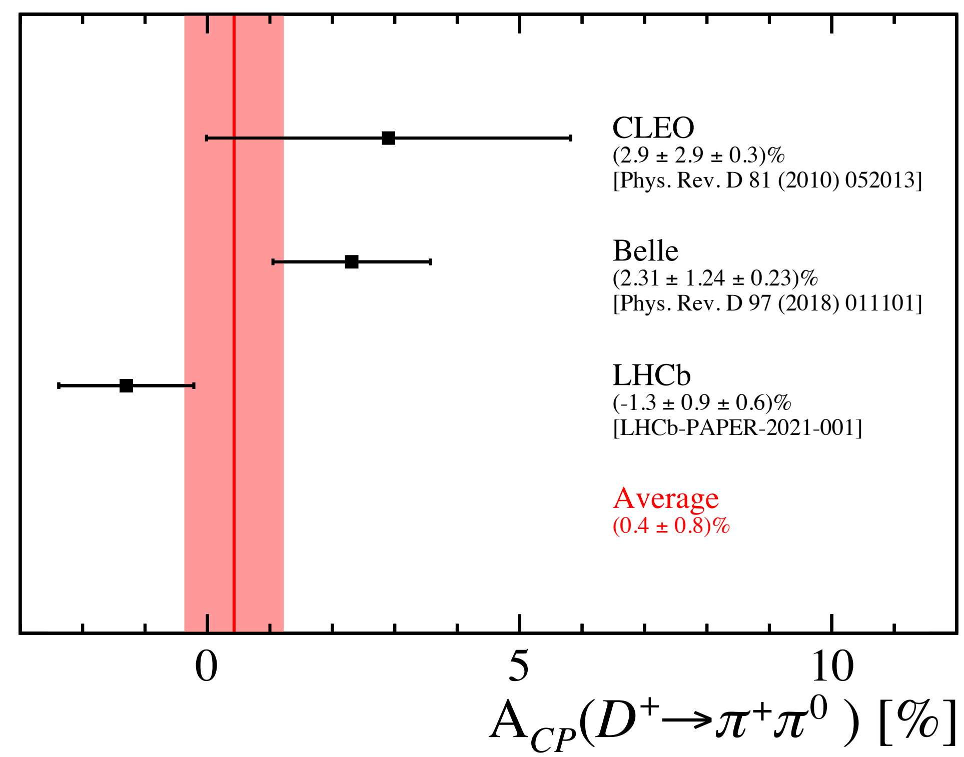
- Appropriate combinations of measurements from decays related by isospin symmetries, such as $B^0 \rightarrow (\pi\pi)^0, (\rho\pi)^0, (\rho\rho)0$ and $a_1^{\pm}\pi^{\mp}$, reduce the impact of hadronic uncertainties and yield a robust direct determinations of α with a 4° uncertainty

- Belle II accesses all inputs and expects to reach sub-1° precision

- Need to be accompanied by an improved understanding of the size of isospin breaking (*e.g.*, using $B \rightarrow \pi\eta^{(\prime)}$)

Direct CP violation in charm

- Unique opportunities to search for new sources of CP violation coupling preferentially to up-type quarks
- $D^+ \to \pi^+\pi^0$: one of the few golden channels left! Isospin forbids CP violation in the SM offering powerful null test for NP
  - Precision expected to improve by almost an order of magnitude in the next decade

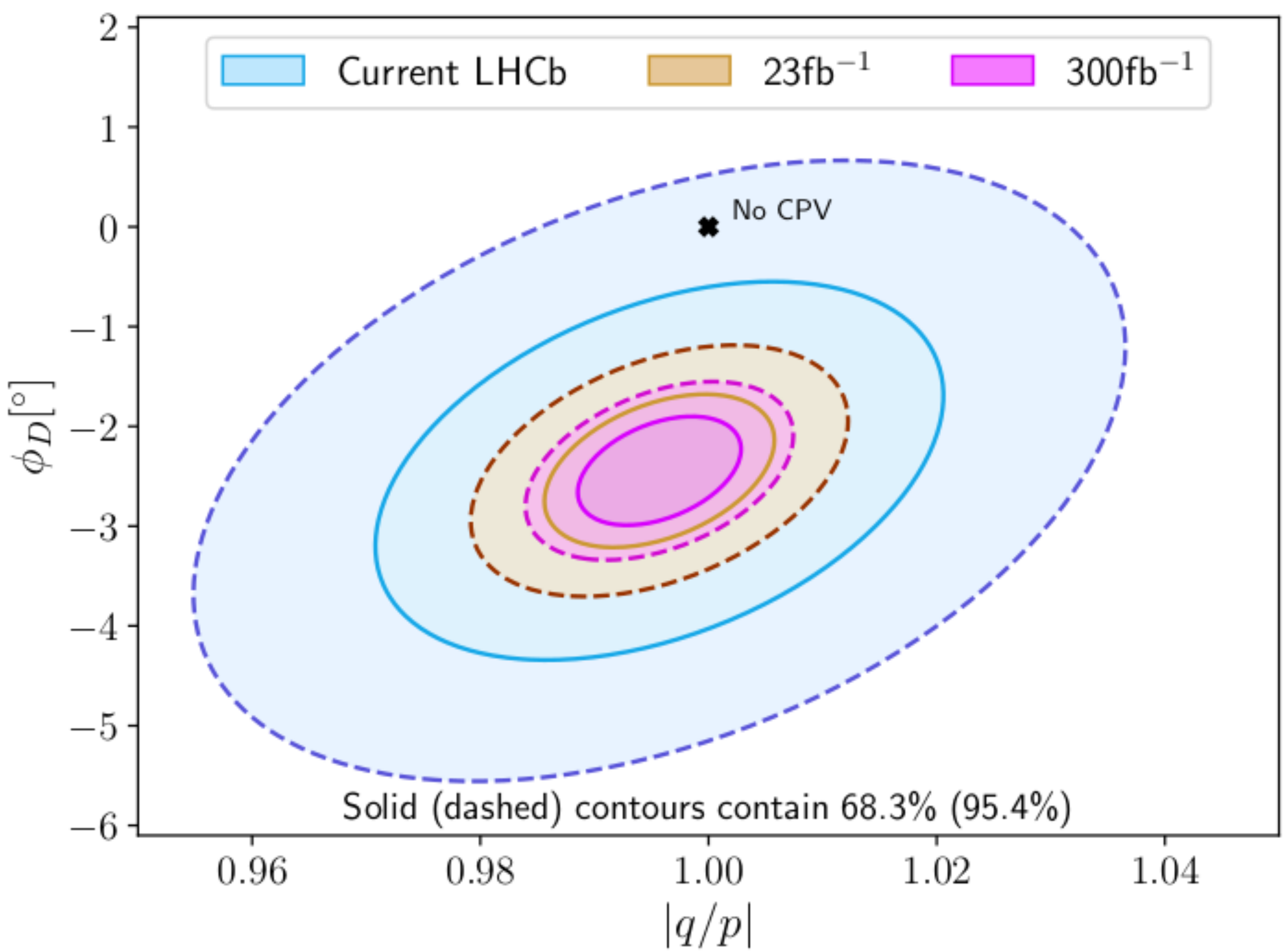


- Complemented by isospin sum-rule of $D \to \pi\pi$ decays

$$R = \frac{\mathcal{A}_{CP}(D^0 \to \pi^+\pi^-)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{+-}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} + \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{\mathcal{A}_{CP}(D^0 \to \pi^0\pi^0)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{00}}\left(\frac{\mathcal{B}_{+-}}{\tau_{D^0}} + \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} - \frac{\mathcal{A}_{CP}(D^+ \to \pi^+\pi^0)}{1 + \frac{3}{2}\frac{\tau_{D^+}}{\mathcal{B}_{+0}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} + \frac{\mathcal{B}_{+-}}{\tau_{D^0}}\right)}$$

  - A nonzero value of R would indicate NP
  - Currently R consistent with zero within 0.24%, limited by $\pi^0\pi^0$. Belle II will improve test power by an order of magnitude in the next decade

Mixing-induced *CP* violation in charm



- Compelling access to beyond-SM physics. Precise predictions are hard, but LHCb's sensitivity to ~x10 enhancements with respect to naive SM predictions offers unique discovery potential

Report sections

1 The path to discovery in heavy-quark physics

2 Experimental efforts in the next two decades

3 Farther into the future

4 Expected theory progress

5 Current and future U.S. involvement

Farther into the future

EF report:

Thus, the energy frontier believes that it is essential to complete the HL-LHC program, to support construction of a Higgs factory and to ensure the long-term viability of the field by developing a multi-TeV energy frontier facility such as a muon collider or a hadron collider.

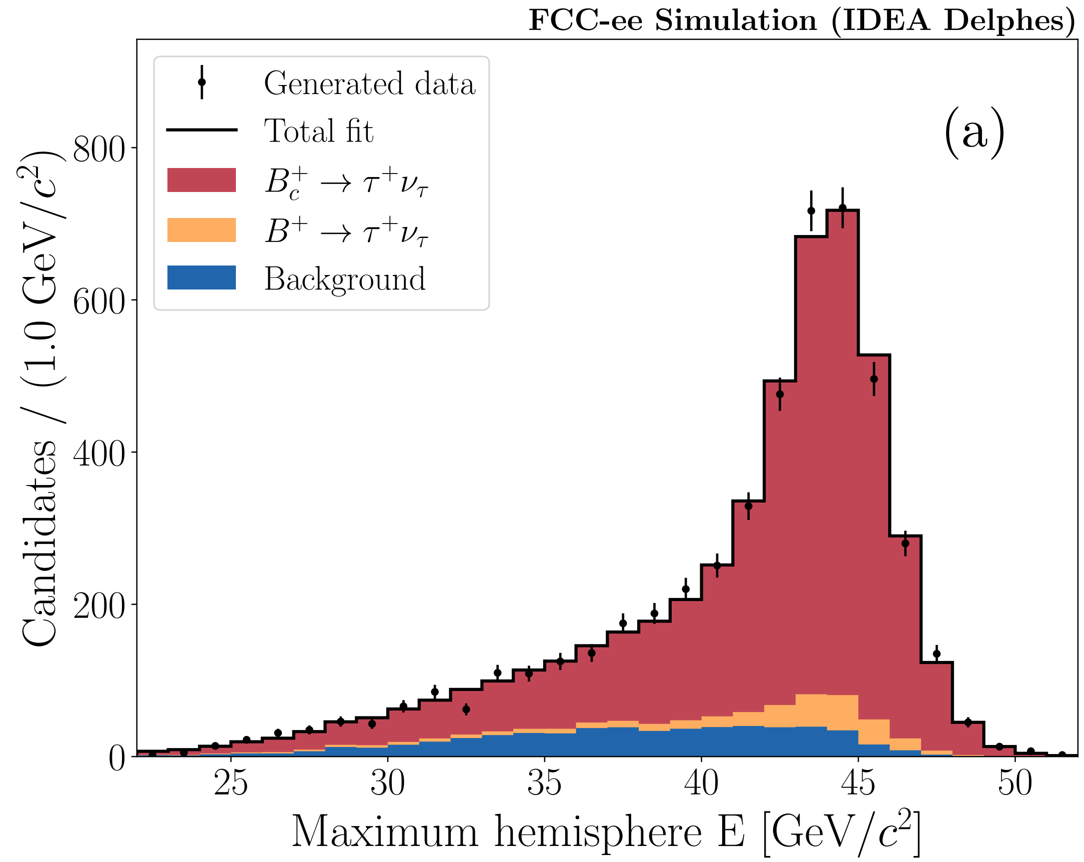
- While the next collider is mostly motivated by the need to understand the mechanism behind the electroweak-symmetry breaking, the important role of heavy-quark physics should still be considered as key for a broad and rich HEP program

- On the other hand, the great potential to disclose indications of NP (or severely constrain its nature) in the next decades means that quark-flavor physics is likely to provide crucial inputs about what should be the next multi-TeV energy-frontier facility

Heavy-flavor physics at a Higgs factory

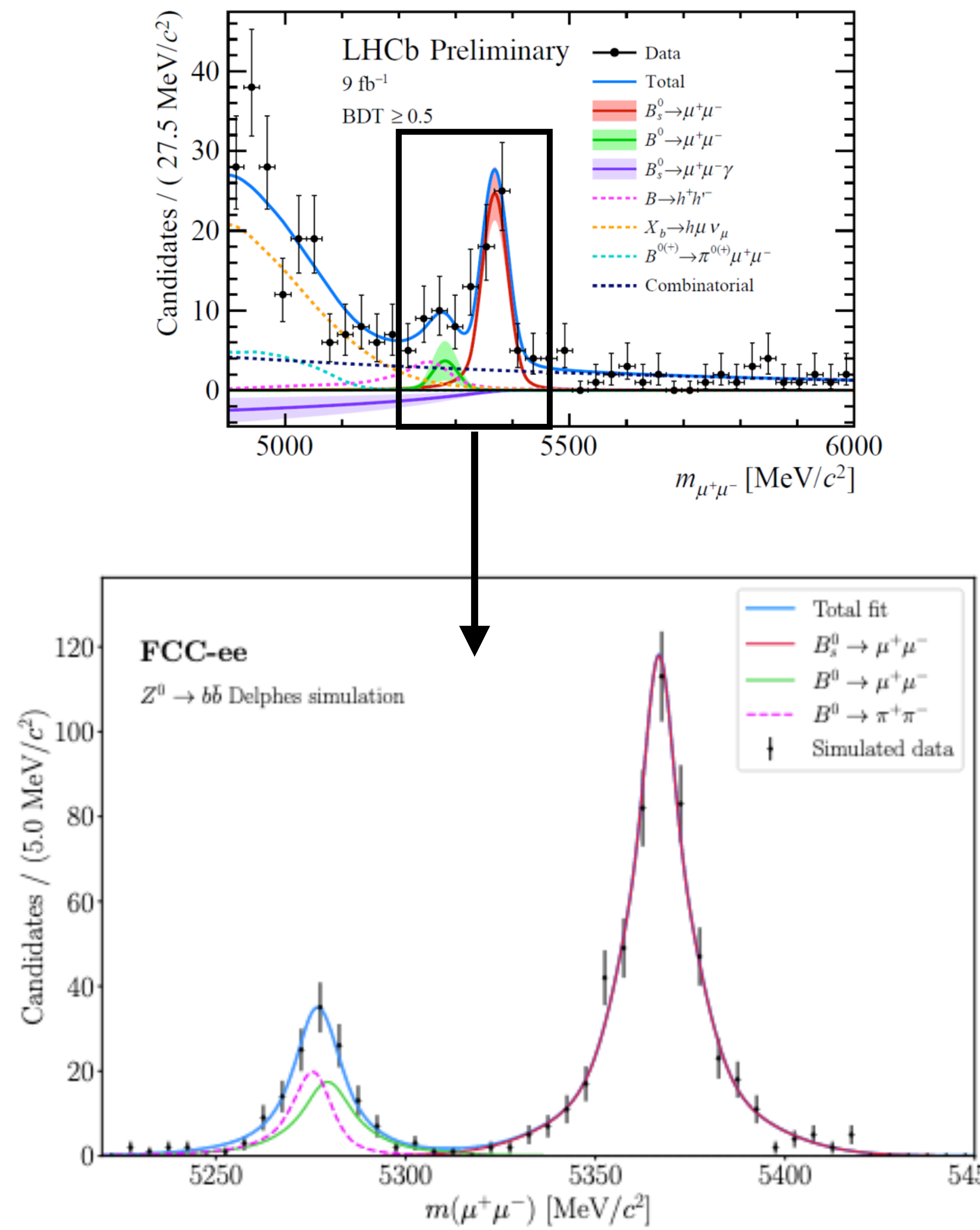
- The proposed Higgs factories will operate at all the relevant electroweak thresholds (Z^0, H^0, W^+W^-, $t\bar{t}$) and will give access to abundant samples of b and c hadrons
    - Moreover, all b-flavored particles will be produced and with a significant boost to allow measurements of decay-time-dependent observables
- At the Z^0, a particular strength will be the ability to make very sensitive studies of hadronic modes with neutrals; of suppressed FCNC processes (*e.g.*, $b \to s(d)\tau^+\tau^-$, $b \to s(d)\nu\bar{\nu}$); and of favored, but experimentally challenging, modes such as $B_c \to \mu^+\nu$ and $B_c \to \tau^+\nu$
- At higher energies, unique opportunity to directly measure CKM elements from hadronic decays of W^+ bosons: *i.e.*, with no systematic limitations due to the knowledge of hadronic inputs
    - *e.g.*, measurements of $|V_{cb}|$ with up to an order of magnitude improved precision with respect to present results

Channel	BelleII	LHCb-U1a	Z-factory
B^0, $\overline{B}^0$	$\sim 5 \times 10^{10}$	$\sim 6 \times 10^{13}$	$\sim 1.2 \times 10^{11}$
$B^\pm$	$\sim 5 \times 10^{10}$	$\sim 6 \times 10^{13}$	$\sim 1.2 \times 10^{11}$
B_s^0, $\overline{B}_s^0$	$\sim 6 \times 10^{8}$	$\sim 2 \times 10^{13}$	$\sim 3.2 \times 10^{10}$
$B_c^\pm$	–	$\sim 2 \times 10^{11}$	$\sim 2.2 \times 10^{8}$
Λ_b^0, $\overline{\Lambda}_b^0$	–	$\sim 2 \times 10^{13}$	$\sim 1.0 \times 10^{10}$



Heavy-flavor physics at a Higgs factory

- Performance requirements for precise measurements of weak decays of *b* and *c* quarks are not necessarily the same as those for electroweak and Higgs physics
  - *e.g.*, excellent tracking is at reach; good particle identification, and ultra-high resolution calorimetry and vertexing are highly desirable
- This motivates a machine with four interaction points with at least one experiment devoted to heavy-flavor physics



Report sections

Expected theory progress: subsections

- Decay constants and local form factors
- QED corrections to leptonic and semileptonic decays
- Exclusive rare b and c hadron decays
- Inclusive semileptonic and radiative decays
- Neutral-meson mixing
- Heavy-hadron lifetimes
- Nonleptonic bottom-hadron decays
- Nonleptonic charm-hadron decays
- Model building

Decay constants and local form factors

Decay constants: $\langle 0|\bar{q}'\Gamma q|H\rangle$

Local form factors: $\langle H'|\bar{q}'\Gamma q|H\rangle$

These are key inputs in

- the determination of $|V_{ub}|$, $|V_{cb}|$, $|V_{cd}|$, $|V_{cs}|$
- the theory predictions for lepton-flavor universality ratios
- the theory of rare b and c decays

Lattice QCD typically provides the most precise, first principles results (but HQET and LCSR are also useful). The uncertainties of the D, D_s, B, B_s decay constants from lattice QCD have already reached 0.3%, 0.2%, 0.7%, 0.6%, respectively. In the coming years, similar precision should be reached for semileptonic form factors involving stable mesons.

For semileptonic form factors with two-hadron/resonance final states, such as for $B \to K^*(\to K\pi)\ell^+\ell^-$ and $B \to \rho(\to \pi\pi)\ell\nu$, finite-volume methods for rigorous lattice calculations have been developed and should be implemented.

QED corrections to leptonic and semileptonic decays

With QCD uncertainties reduced to the sub-percent level, further theoretical improvements are needed in the treatment of QED corrections.

Significant progress in the treatment of QED corrections has been made recently in soft-collinear effective-field theory and factorization. Several novel sources of dangerous logarithms have been identified, including *hard* collinear logs. Light-cone distribution amplitudes need to be generalized to include QED.

First lattice-QCD calculations of structure-dependent QED corrections to leptonic decays have been performed for pion and kaon leptonic decays, and the approach is also applicable to $B_{(s)}$ and $D_{(s)}$ leptonic decays. This includes real-photon emission, which (for large E_γ) lifts the helicity suppression and provides sensitivity to a larger set of operators in the weak effective Hamiltonian.

Exclusive rare b and c hadron decays

$\frac{\mu\mu}{ee}$ ratios: R_K & friends

branching fractions: $B_{(s)} \to \ell^+\ell^-$

angular observables $<$ branching fractions:

$H_b \to H_{s,d}\,\nu\bar{\nu}$
$H_c \to H_u\,\nu\bar{\nu}$

$H_b \to H_{s,d}\,\ell^+\ell^-$
$H_b \to H_{s,d}\,\gamma$

$H_c \to H_u\,\ell^+\ell^-$
$H_c \to H_u\,\gamma$

$\longrightarrow$ Increasing theory uncertainty

Dominant sources of uncertainties (in the SM):

- $\frac{\mu\mu}{ee}$ ratios: QED corrections
- $B_{(s)} \to \ell^+\ell^-$: the value of $|V_{cb}|$
- $H_b \to H_{s,d}\,\nu\bar{\nu}$ and $H_c \to H_u\,\nu\bar{\nu}$: local form factors
- $H_b \to H_{s,d}\,\ell^+\ell^-$ and $H_b \to H_{s,d}\,\gamma$: local form factors and nonlocal matrix elements (relative importance depends on q^2).
- $H_c \to H_u\,\ell^+\ell^-$ and $H_c \to H_u\,\gamma$: nonlocal matrix elements

For $B \to K^{(*)}\,\ell^+\ell^-$ and $B_s \to \phi\,\ell^+\ell^-$, there has been significant recent progress with the nonlocal charm matrix elements at low q^2 using the light-cone OPE + dispersive bounds.

Inclusive semileptonic and radiative decays

$\bar{B} \to X_c \ell^- \bar{\nu}$:

- Theory uncertainty has reached 1% level thanks to calculations of higher-order radiative and relativistic corrections
- Number of HQE parameters can be reduced using reparametrization-invariant observables such as q^2 moments
- Concerns at sub-percent precision level: duality violations, HQE convergence, QED corrections, $b \to u\ell^- \bar{\nu}$ and $b \to c\tau^-(\to \ell^- \nu\bar{\nu})\bar{\nu}$ backgrounds

$\bar{B} \to X_u \ell^- \bar{\nu}$:

- Large charm background requires kinematic cuts. HQE breaks down in endpoint region $\to$ light-cone OPE $\to$ shape functions. Data-driven approaches can reduce model-dependence.

Inclusive semileptonic decays using lattice QCD:

- Lattice methods have been developed, and exploratory computations, along with a comparison to OPE predictions, have been performed.

$\bar{B} \to X_s \gamma$ and $\bar{B} \to X_s \ell^+ \ell^-$:

- $\bar{B} \to X_s \gamma$ and $\bar{B} \to X_s \ell^+ \ell^-$ (low q^2) theory uncertainties are currently $\sim 5\%$, can be reduced by completing the NNLO QCD corrections without interpolation in the charm mass and by controlling nonperturbative effects.

Neutral-meson mixing

B^0-$\bar{B}^0$ and B_s-$\bar{B}_s$ mixing:

- Uncertainties of Δm_d, Δm_s, and $\Delta\Gamma_s$: experiment 0.4%, 0.03%, 5%; theory $\mathcal{O}(10\%)$. Main nonperturbative input: hadronic matrix elements of dimension-6 and dimension-7 operators (lattice QCD or sum rules). Improved calculations will lead to tighter constraints on new physics.

D^0-$\bar{D}^0$ mixing:

- The CP-violating contributions are reasonably well described by local hadronic matrix elements of $\Delta C = 2$ operators. Known from lattice QCD with $\mathcal{O}(10\%)$ uncertainties.
- The long-distance contributions from nonlocal matrix elements of two $\Delta C = 1$ operators are poorly known. It may be possible to calculate them on the lattice using similar methods as those developed for inclusive decays.

Heavy-hadron lifetimes

Comparing experiment and theory for heavy-hadron lifetimes (or lifetime ratios) can also provide useful constraints on physics beyond the SM.

Similar to inclusive semileptonic decays, the standard theoretical tool is the HQE (and some of the Wilson coefficients and hadronic matrix elements are shared between these applications). Significant sources of theoretical uncertainty for b-hadron lifetimes are spectator effects described by four-quark operators, and the Darwin term. There have been exploratory lattice calculations of spectator effects more than 20 years ago. New state-of-the-art lattice calculations would be desirable to complement sum-rule calculations.

Nonleptonic bottom-hadron decays

In determinations of CKM angles from nonleptonic $B_{(s)}$ decays, the dominant hadronic matrix elements can be fitted to experimental data by combining multiple observables. However, except for γ, subleading effects (for example, the "penguin" contamination in $B^0 \to J/\psi K_S^0$ and $B_s^0 \to J/\psi\phi$), have become, or will become important.

Theoretical tools include flavor symmetries, perturbative QCD, QCD factorization/soft-collinear effective theory, and light-cone sum rules, often combined with an expansion in $1/m_b$.

An interesting puzzle has emerged concerning the branching fractions of $B_{(s)}^0 \to D_{(s)}^{(*)-}\{\pi^+, K^+\}$ decays, where improved QCD-factorization predictions are several sigma higher than experimental measurements.

Direct lattice calculations of exlusive nonleptonic B decays are not expected to become feasible. However, lattice calculations can contribute in other ways to the theory of nonleptonic b decays, for example by predicting the B-meson light-cone distribution amplitude.

Nonleptonic charm-hadron decays

LHCb has observed direct CP violation in charm decays,

$$\Delta a_{CP}^{\text{dir}} \equiv a_{CP}^{\text{dir}}(D^0 \to K^+K^-) - a_{CP}^{\text{dir}}(D^0 \to \pi^+\pi^-) = (-0.161 \pm 0.028)\%.$$

The SM prediction is of order

$$\Delta a_{CP}^{\text{dir}}\big|_{\text{SM}} \sim 10^{-3} \times r_{\text{QCD}},$$

with r_{QCD} being a ratio of pure low-energy QCD amplitudes.

Calculating the QCD amplitudes from first principles is even more challenging than in the case of nonleptonic b decays, due to the stronger QCD coupling at the lower energy and the lower heavy-quark mass, meaning that many of the theoretical tools are less suitable, and predictions of r_{QCD} cover a wide range.

The theoretical understanding can also be improved by combining measurements of the CP asymmetries in all singly-Cabibbo-suppressed charm-meson decays, taking advantage of flavor-$SU(3)$ sum rules. In addition, the long-term prospects for direct lattice-QCD calculations of the relevant QCD amplitudes using the Lellouch-Lüscher approach are better than for nonleptonic B decays, due to the smaller number of open multi-hadron channels at $\sqrt{s} \sim m_D$.

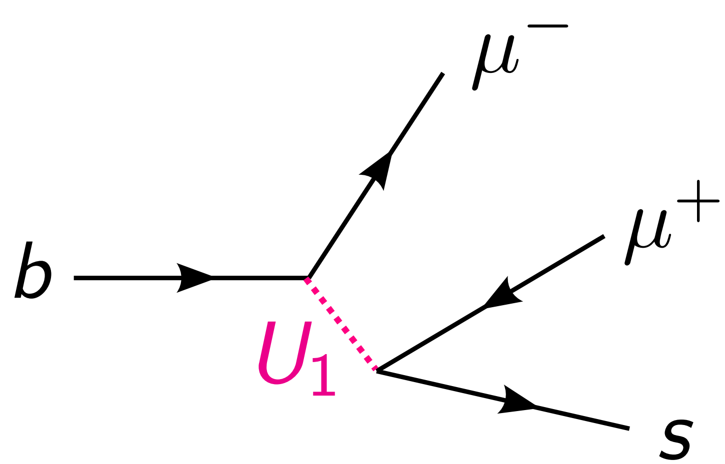
Model building

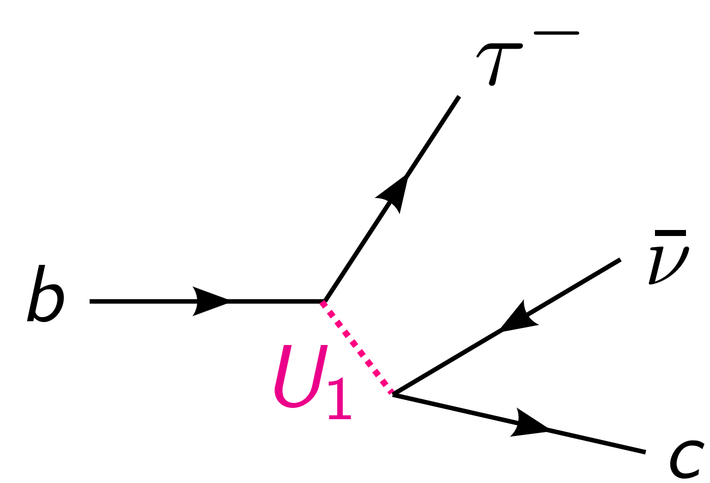
BSM model building may be approached from different directions. Many models are primarily designed to address questions relating to naturalness problems, dark matter, or baryogenesis. Nevertheless, such models often lead to new sources of flavor-changing interactions that may be observed in weak decays of b or c quarks.

On the other hand, the observation of deviations from the SM in weak decays of b or c quarks motivates a directed effort to build models that can explain these deviations while remaining consistent with other measurements. There are several levels:

- Model-independent analyses in a low-energy effective theory
- Additional constraints on effective operators from invariance under SM gauge group for heavy NP
- Simplified models
- UV-complete models

We discuss BSM models that can explain the anomalies in $b \to s\ell^+\ell^-$ and/or $b \to c\tau^-\bar{\nu}$, for example the U_1 leptoquark that may be one of the gauge bosons in a generalized version of the Pati-Salam grand unified theory.





Report sections

Remarks about US involvement — experiments

- The U.S. has been a leader in heavy-quark physics, involving a vigorous community and a series of extremely successful domestic experiments (CLEO, BaBar, Tevatron). Such a strong domestic program did not limit participation in offshore experiments, such as Belle at KEK in Japan
- Since the shutdown of PEP-II and of the Tevatron, the US has ceded leadership in heavy-flavor physics to offshore experiments. As a consequence, the experimental heavy-flavor community and funding have shrunk over the years
- International recognition of the importance of a continued heavy-flavor-physics program in the next decades is evident from the commitments in Europe and Asia. Need to ensure a significant level of US participation in future heavy-flavor experiments
    - In particular, U.S. contributions to LHCb Upgrade II and future upgrades of Belle II must be encouraged.
- While the identification of the next energy-frontier facility will be mostly motivated by the need to understand the mechanism behind the electroweak-symmetry breaking and/or by the need to increase the reach of direct searches, the important role of heavy-quark physics should still be considered as key for a broad and rich HEP program. Strong U.S. participation in these efforts should also be encouraged

Remarks about US involvement — theory

- The experimental progress in heavy-flavor physics has often benefited from a close collaboration with the theory community. The U.S. has strong theory groups working on quark-flavor physics, which are internationally recognized and influential

- Scientists in the U.S. have pioneered heavy-quark effective theory, nonrelativistic QCD, heavy-hadron chiral perturbation theory, and lattice formulations for heavy quarks.

- In order for the strong theory and lattice efforts in the U.S. to continue, stable support for researchers and for computing resources is essential