Flavor physics: known and unknown

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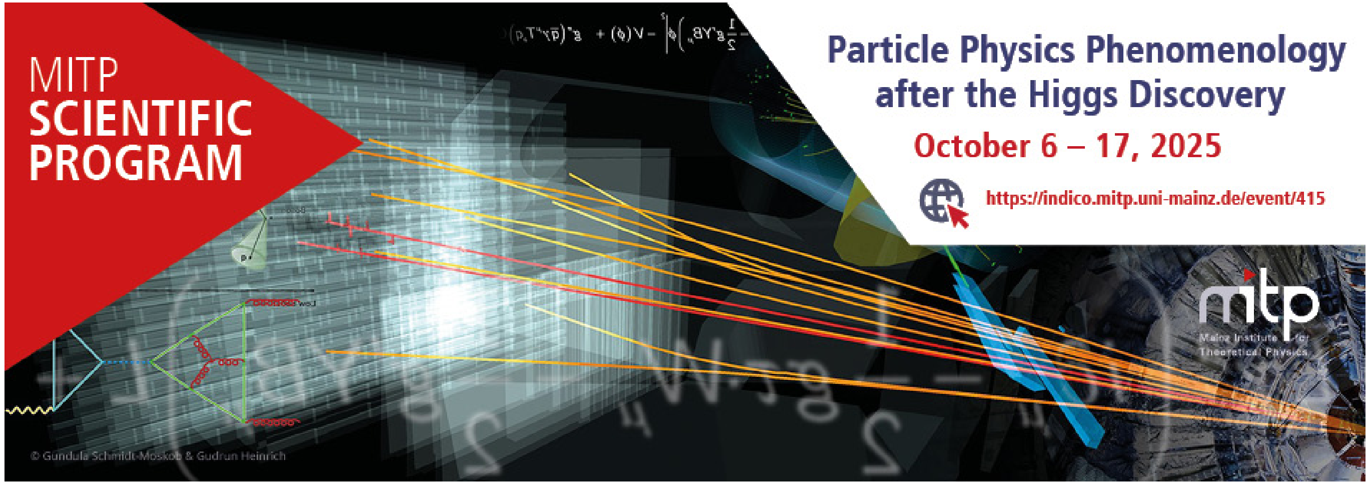

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Preliminaries

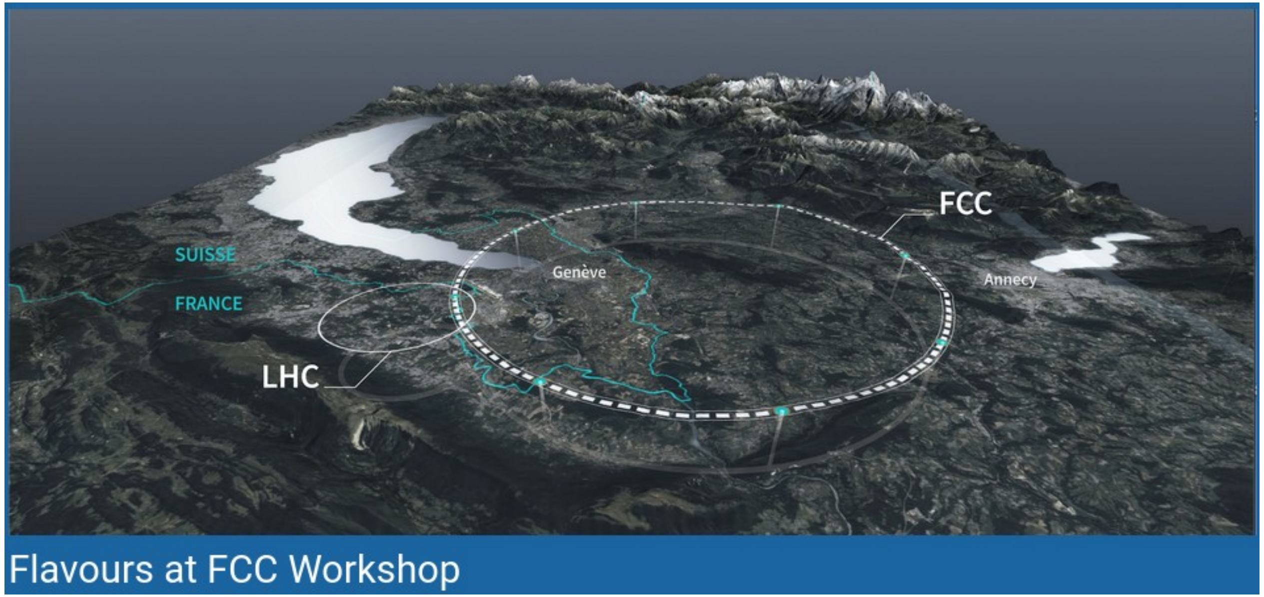
- Will try to merge two somewhat different stories:
  - I am most excited by the upcoming large increases in data: what can they teach us?
    BSM discovery potential + complementarity with high-p_T searches

    Luminosity ratio: (Full LHC) / (Run 1 + Run 2) is slightly greater for LHCb than at ATLAS & CMS
  - Or one could focus on current "anomalies" (i.e., tensions with SM predictions)
    Stimulated theoretical and experimental progress + might get first established
- Beyond LHC & Belle II: FCC

What I was asked to talk about...

- "Global view on precision Physics: How do high-energy LHC and flavor physics programs complement each other?" to trigger a discussion addressing questions like:
  - What has been achieved in the field after the Higgs discovery?
    (i) B_s constraints caught up with B_d; (ii) $R(D^{(*)})$ started in 2012; (iii) ΔA_{CP} late 2011
  - What are the perspectives of the field?
    If BSM scale $>$ few TeV, flavor may be the best chance to detect its first signals
  - What needs to be developed to create further advance
    ... regarding HL-LHC?
    Theory improvements could have big impact on BSM sensitivity... some examples
    ... regarding future collider projects?
    I think FCC-ee flavor program must be richer than what's known $\Rightarrow$ think about it...

Workshop advertisement



Physics at the Flavoured Circular Collider: Now – summer 2027, deepen understanding of the potential of the FCC for heavy flavour physics in the quark and lepton sector

Flavor physics — many puzzles

- Flavor $\equiv$ what distinguishes the three generations? (break $[U(3)]^5$ global sym.)

  Experimentally: rich and sensitive ways to probe the SM, and search for NP

- SM flavor: masses? mixing angles? 3 generations? — most of the SM parameters

  Flavor in SM is simple: only from Yukawa couplings to Higgs, many testable relations

- BSM flavor: TeV scale (hierarchy puzzle) $\ll$ “naive” scale of flavor & CP violation

  New particles that couple to quarks or leptons $\Rightarrow$ new flavor param’s, clues about BSM

- Baryon asymmetry requires CPV beyond the SM — how precisely can we test it?

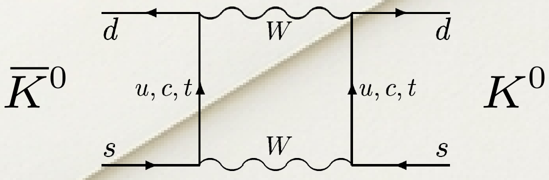
  (Not necessarily in flavor changing processes, nor necessarily in the quark sector)

- If NP is beyond HL-LHC reach, flavor is especially crucial (high scale sensitivity)

Origin of high scale sensitivity

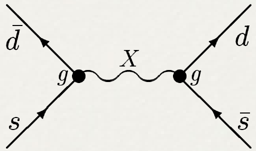
- Large suppressions in the SM — back of an envelope calculation of Δm_K:
- Why is $\Delta m_K / m_K \sim 7 \times 10^{-15}$?

In the SM: $\dfrac{\Delta m_K}{m_K} \sim \alpha_w^2\, |V_{cs}V_{cd}|^2\, \dfrac{m_c^2}{m_W^4}\, f_K^2$



Predicted $m_c \sim 1.5\,\mathrm{GeV}$ (Gaillard & Lee; Vainshtein & Khriplovich, 1974)

- If exchange of a heavy particle X contributes at the SM level:



$$\frac{\Delta m_K^{(X)}}{\Delta m_K} \sim \frac{g^2\, \Lambda_{\mathrm{QCD}}^3}{M_X^2\, \Delta m_K} \quad \Rightarrow \quad M_X > g \times 10^3\,\mathrm{TeV}$$

- Alternatively, sensitivity to TeV-scale particles with one-loop couplings $[g \sim \mathcal{O}(10^{-3})]$

Similar story for many other flavor-changing neutral current (FCNC) processes

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Some lessons — known since 1970s

- Flavor was critical in developing the SM, and mostly an input to model building
- All TeV-scale NP models must contain some mechanism to avoid violating constraints

  E.g., in SUSY, to suppress flavor and CP violation, impose: universality, heavy squarks, alignment

  Devised to make deviations small from the SM, revisit model building when tensions with SM arise
- The SM suppressions are strongest for kaons (1st – 2nd generation)

  For many models, Δm_K and ϵ_K are the most constraining — 3rd gen. "looks" different

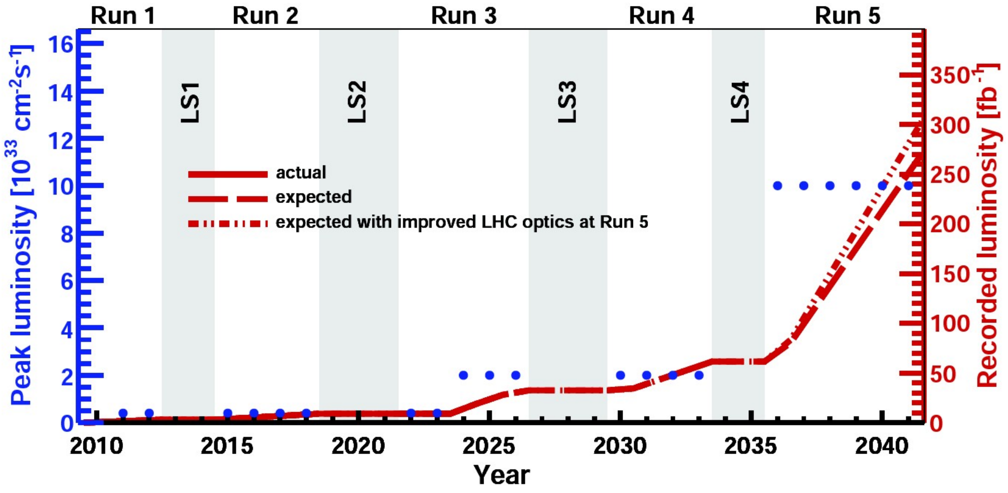
  The idea of (dominantly) 3rd generation NP goes back (at least) to the mid-90s [hep-ph/9512388, hep-ph/9607394]
- What can future data tell us?

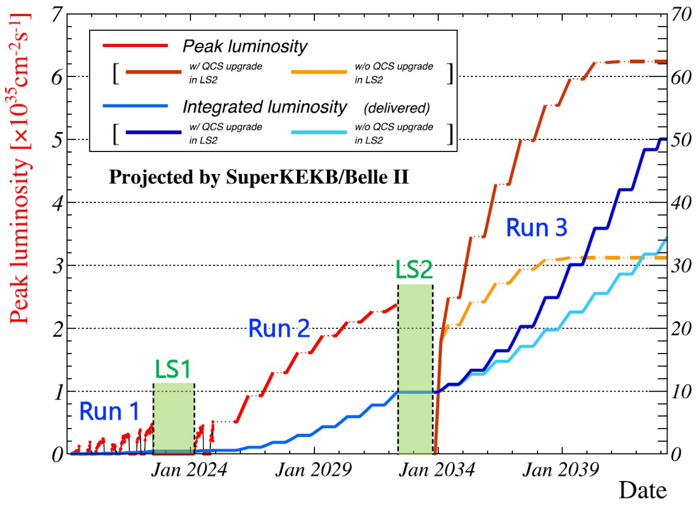
  If deviations from SM, upper bound on BSM scale, help understand its structure

Outline

- Testing quark flavor (CKM)
- B decays & recent tensions with SM
- Far future: FCC

Dedicated B physics experiments

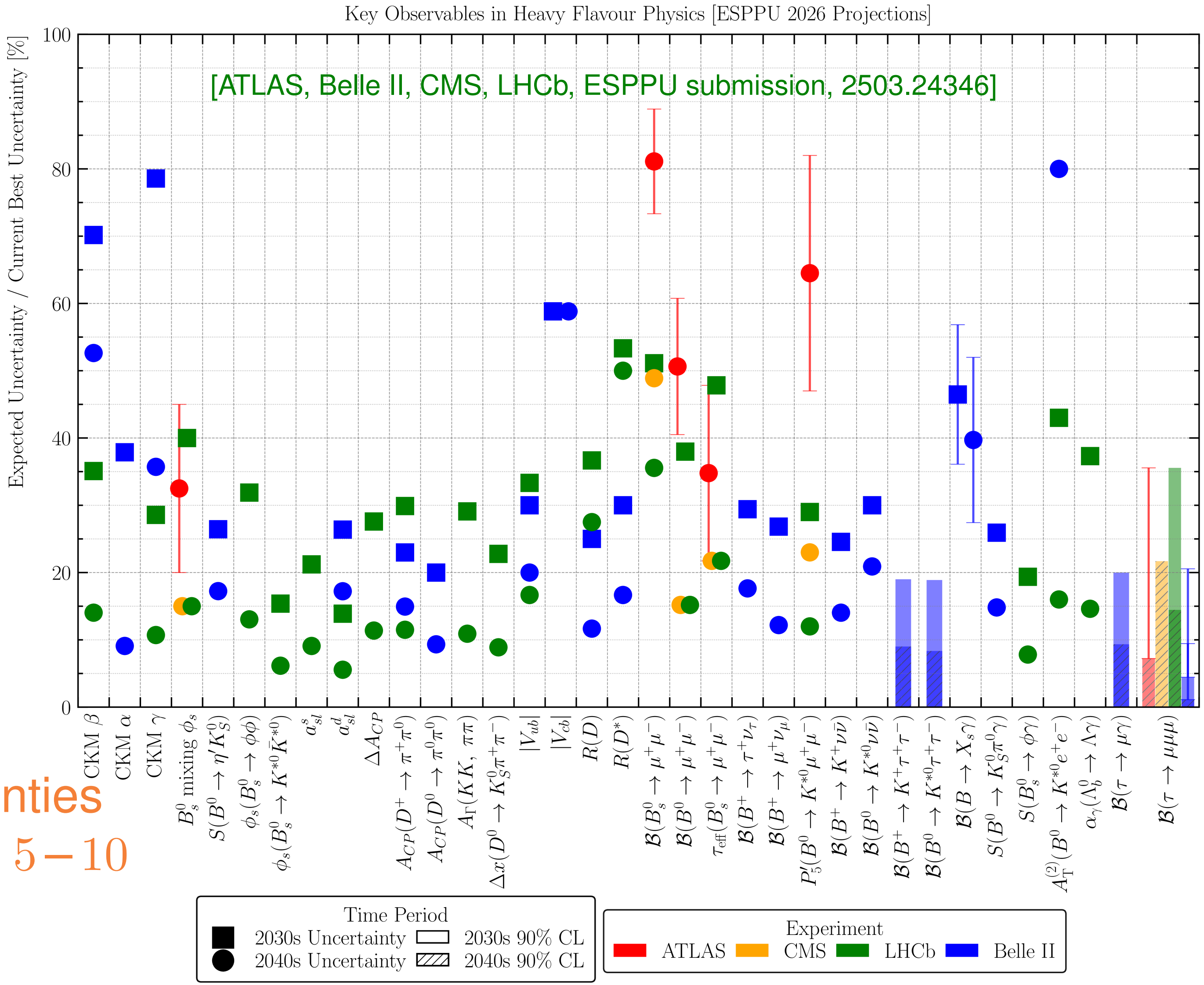




- LHCb upgrade in LS2 (inst. lumi.: 2×10^{33})
- LHCb Upgrade II in LS4 (inst. lumi.: 1.5×10^{34})
  ATLAS & CMS competitive in some modes

- Belle II goal: over $50 \times$ Belle data set
- Discussions about physics & feasibility of an upgrade (polarization? 250/ab?)

Extensive sensitivity projections: LHCb Upgrade II [1808.08865]; Belle II [1808.10567]; and including ATLAS & CMS @ HL-LHC [2503.24346]



Many uncertiainties will improve by $5-10$

Testing quark flavor

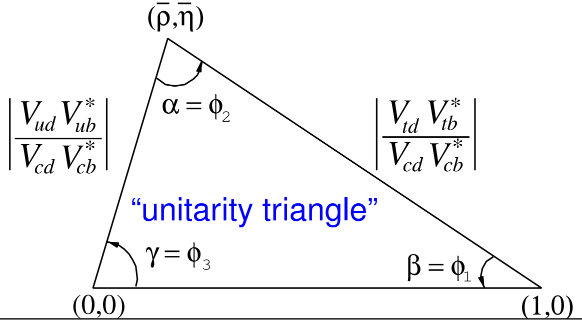
- $(u,\, c,\, t)\; W^{\pm}\; (d,\, s,\, b)$: 9 complex couplings $\Rightarrow$ many relations   Are they consistent?

$$V_{\rm CKM} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{\text{CKM matrix}} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \ldots$$

Only 4 parameters: λ (“Cabibbo angle”, from $K \to \pi\ell\nu$), A (from $b \to c\ell\nu$)
used to be less precise: $\bar\rho$ and $\bar\eta$ (only source of CP violation)

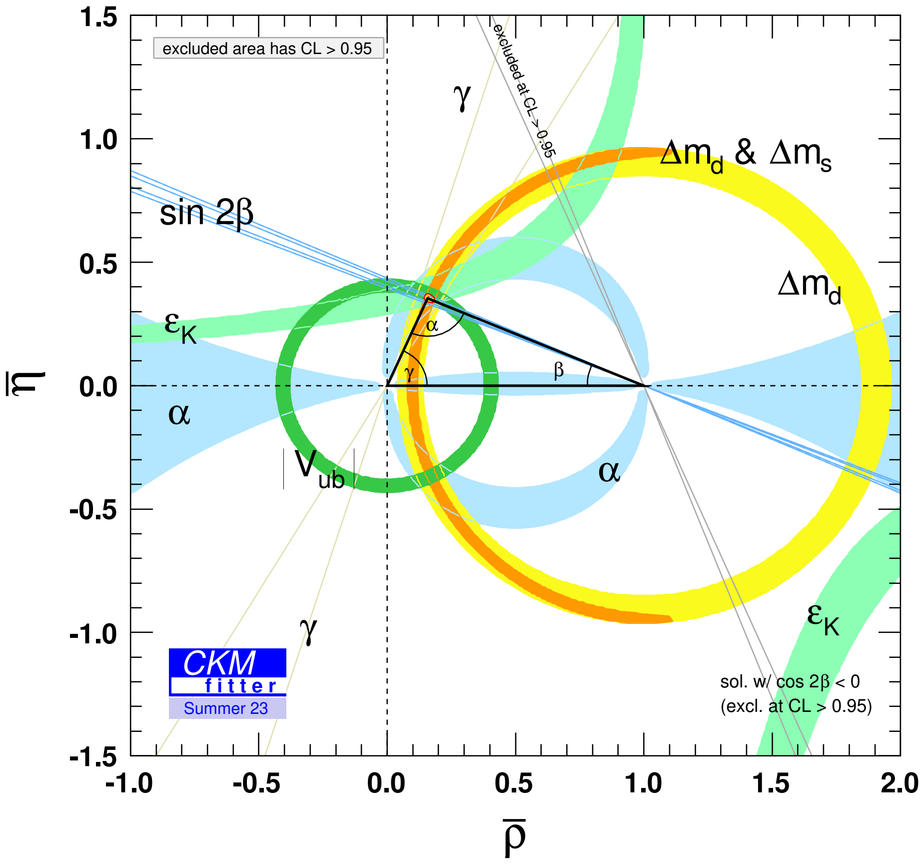
Measurements: magnitudes $\sim$ decay rates; phases $\sim CP$ violation

- Many observables are $f(\rho, \eta)$ — want to compare:
  - $b \to u\ell\bar\nu \;\Rightarrow\; |V_{ub}/V_{cb}|^2 \propto \rho^2 + \eta^2$
  - $\Delta m_{B_d}/\Delta m_{B_s} \;\Rightarrow\; |V_{td}/V_{ts}|^2 \propto (1-\rho)^2 + \eta^2$
  - CP violation in K, B, B_s decays



The CKM fit in the SM

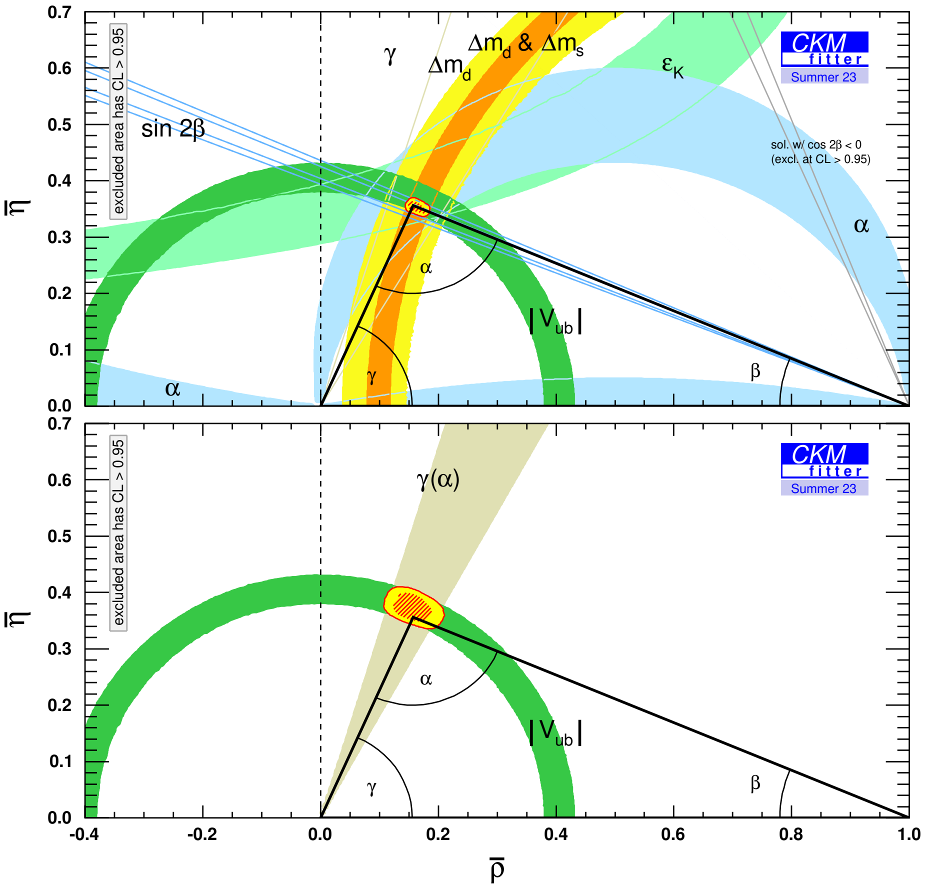
- Spectacular progress in last 25 years
- The CKM mechanism describes consistently CP violation and flavor changing processes



The CKM fit in the SM

- Spectacular progress in last 25 years
- The CKM mechanism describes consistently CP violation and flavor changing processes
- Looser constraints if NP is allowed in fits

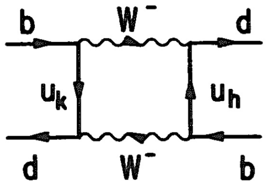
  Full fit (upper plot) vs. tree-level (lower plot)
- LHCb: B_s constraints caught up with B_d
- $\mathcal{O}(20\%)$ NP contributions to most loop-level processes (FCNC) are still allowed



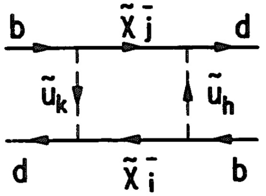
Fits with NP parameters added to the SM

- What if BSM parameters are added to these fits?
- Consider: tree-level decays dominated by SM, BSM only significant in FCNCs (loops)
- General parametrization of many scenarios by two real BSM parameters; redo CKM fit:

$$h\, e^{2i\sigma} = A_{\rm NP}(B^0 \to \overline{B}^0)/A_{\rm SM}(B^0 \to \overline{B}^0)$$



SM: $\dfrac{C_{\rm SM}}{m_W^2}$



NP: $\dfrac{C_{\rm NP}}{\Lambda^2}$

- Is $\eta = 0$ allowed? If not, then CKM mechanism plays a role in CP violation
  (If $\eta = 0$, CKM matrix conserves CP)
- Is $h \gtrsim 1$ allowed? If not, then CKM mechanism is dominant

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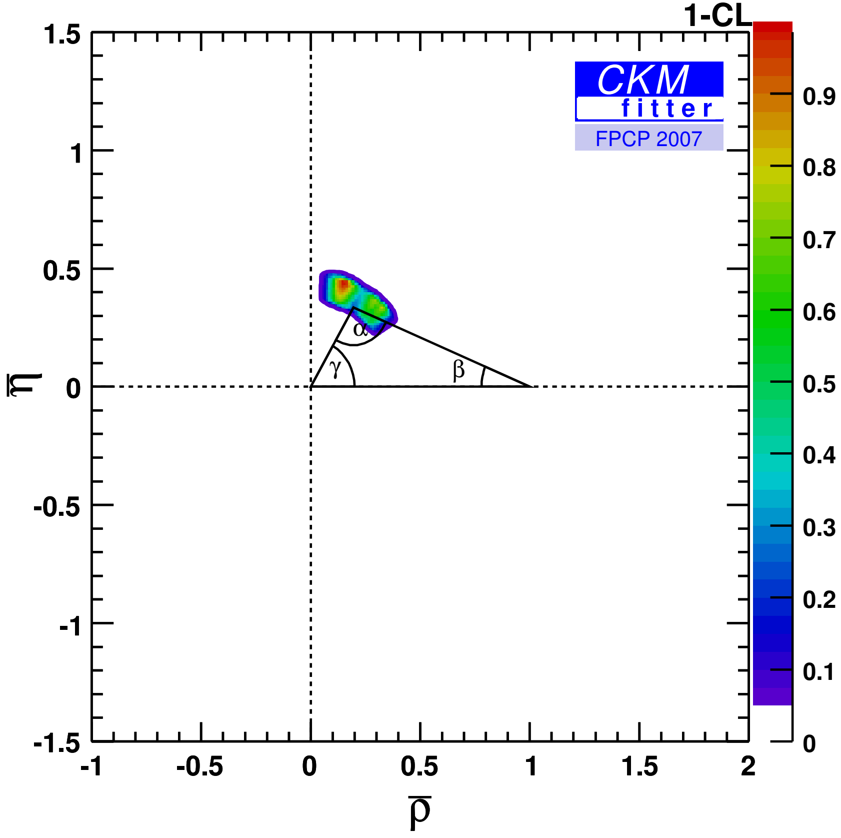
Is $\eta = 0$ allowed?

- CKM fit with h and σ parameters added:

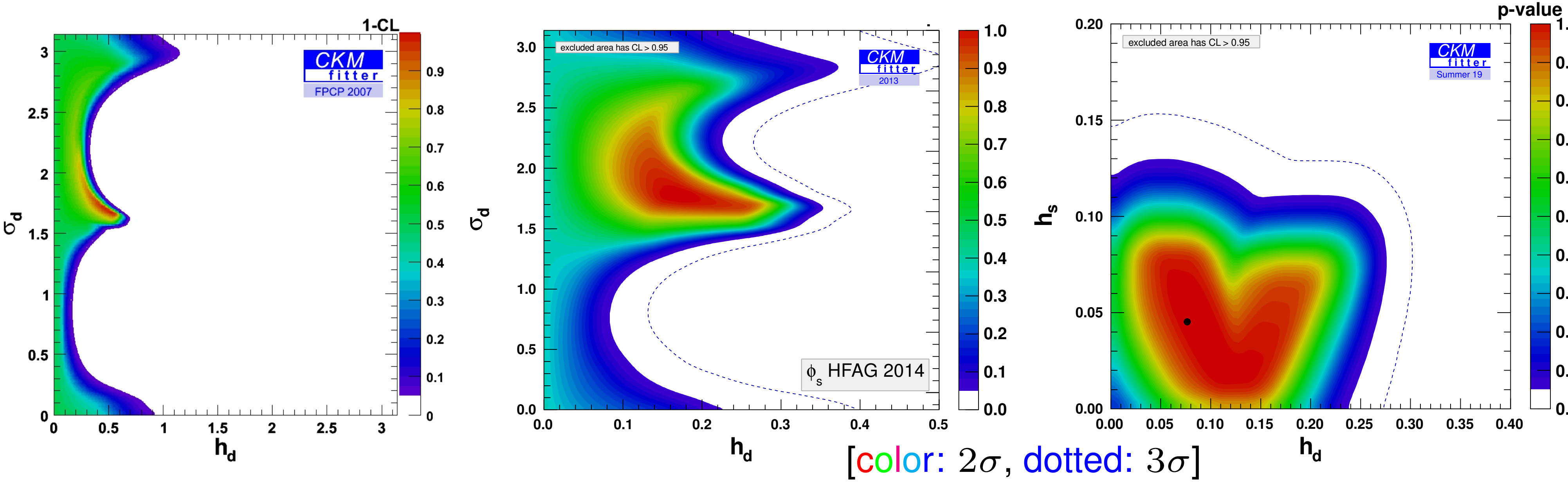
$$h\,e^{2i\sigma} = A(B^0 \to \overline{B}^0)/A_{\rm SM}(B^0 \to \overline{B}^0) - 1$$

- Weak interaction plays a role in CP violation, even if NP is present (only known since 2004!)



Is $h \sim \mathcal{O}(1)$ allowed?

- CKM fit with $h_{d,s}$ and $\sigma_{d,s}$ parameters added: $h\, e^{2i\sigma} = A_{\rm NP}(B^0 \to \overline{B}^0)/A_{\rm SM}(B^0 \to \overline{B}^0)$



- LHCb: BSM contributions to B_s mixing are even more constrained than those to B_d
- Weak interaction dominates observed CP violation: BSM / SM $\lesssim 20\%$

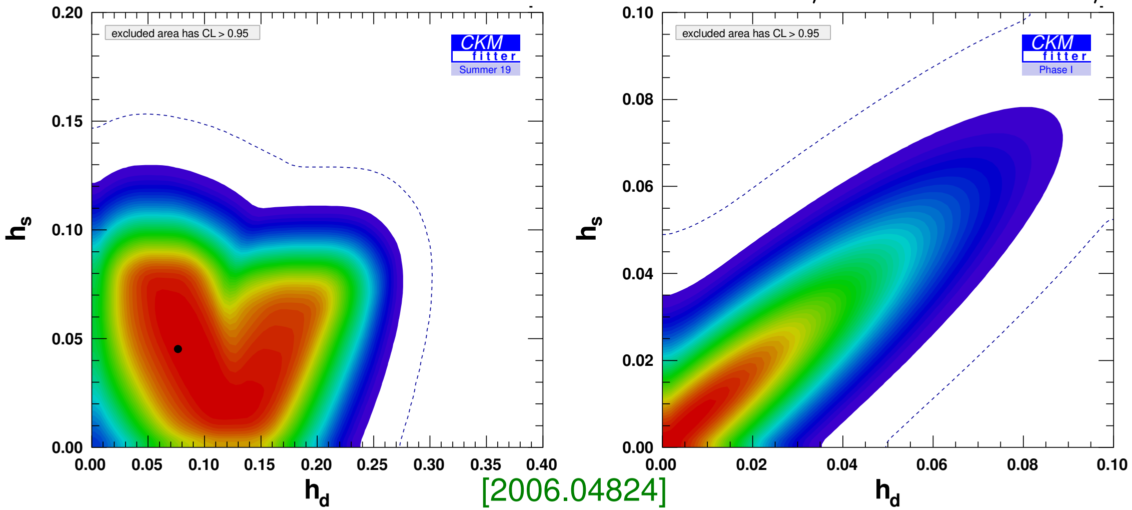
Improvements in next ~ 10 years

- At 95% CL: NP $\lesssim (0.25 \times$ SM$)$ $\Rightarrow$ NP $\lesssim (0.08 \times$ SM$)$

- Scale: $h \simeq \dfrac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2} \left(\dfrac{4.5\ \text{TeV}}{\Lambda}\right)^2$

$$\Rightarrow \Lambda \sim \begin{cases} 2.3 \times 10^3\ \text{TeV} \\ 20\ \text{TeV}\ \text{(tree + CKM)} \\ 2\ \text{TeV}\ \text{(loop + CKM)} \end{cases}$$

Now | LHCb $50/\text{fb}$ + Belle II $50/\text{ab}$



[2006.04824]

[color: 2σ, dotted: 3σ]

- Complementary to high-p_T searches (E.g., similar to HL-LHC $m_{\tilde g}$ reach)

- BSM sensitivity will continue to improve

Recent “anomalies”

NB: I dislike this phrase... Recent examples of “who ordered that?”

(Puzzles in the data / theory / Nature?)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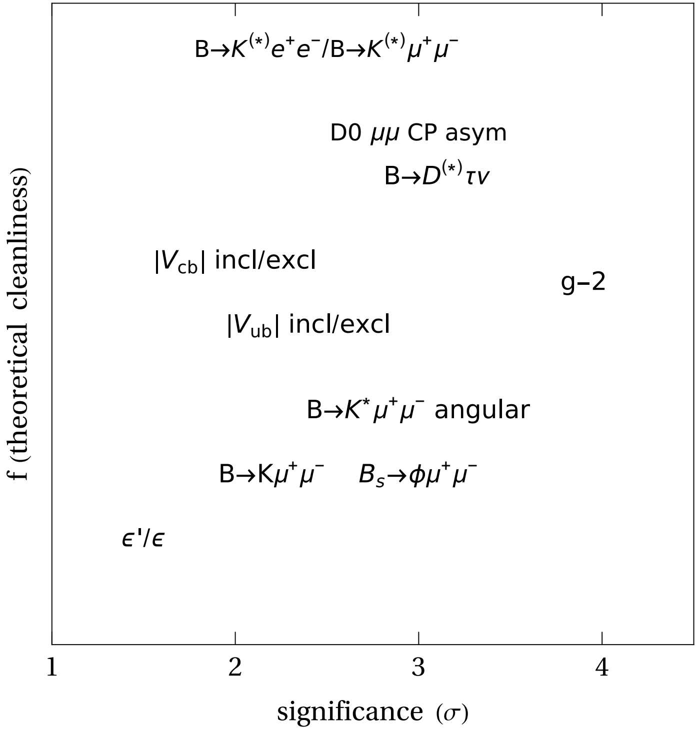
Hints of deviations from the SM — few years ago

- Intriguing tensions with the SM $\Rightarrow$ experimental scrutiny, new theory ideas
- Some could be unambiguous NP signals

  (vertical axis is an unspecified function)

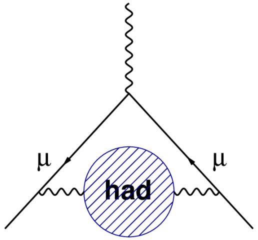
  Except for theoretically cleanest cases, cross-checks needed to build robust case
  - measurements of related observables
  - independent theory / lattice QCD calc.



- $g-2$ used to be most significant:

  HVP contributions scrutinized

  Big lattice QCD effort

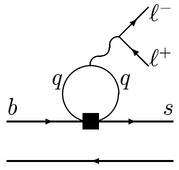


Won't cover many; e.g., 1st-row unitarity tension on the mend? [Gorchtein, Katyal, Ohayon, Sahoo, Seng, 2502.17070]

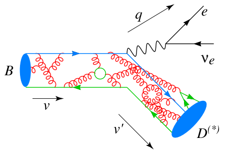
Hints of LFU violation — major recent focus

- Lepton non-universality would be clear evidence for NP

  1) $\cancel{R_K}$ ~~and~~ $\cancel{R_{K^*}}$ $\quad (B \to X\mu^+\mu^-)/(B \to Xe^+e^-) \sim 20\%$ correction to SM loop



  2) $R(D)$ and $R(D^*)$ $\quad (B \to X\tau\bar\nu)/(B \to X(e,\mu)\bar\nu) \sim 20\%$ correction to SM tree



  Accessible scales: $R_{K^{(*)}} \lesssim$ few $\times\, 10^1\,\mathrm{TeV}$, $\quad R(D^{(*)}) \lesssim$ few $\times\, 10^0\,\mathrm{TeV}$

- Theor. less clean: 3) P_5' angular distribution $(B \to K^*\mu^+\mu^-)$
  4) $B_s \to \phi\mu^+\mu^-$ and similar $b \to s\mu^+\mu^-$ rates

  Could fit 1), 3), 4) with one operator: $C_{9,\mu}^{(\mathrm{NP})}/C_{9,\mu}^{(\mathrm{SM})} \sim -0.2\,,\;\; O_{9,\mu} = (\bar s\gamma_\alpha P_L b)(\bar\mu\gamma^\alpha\mu)$

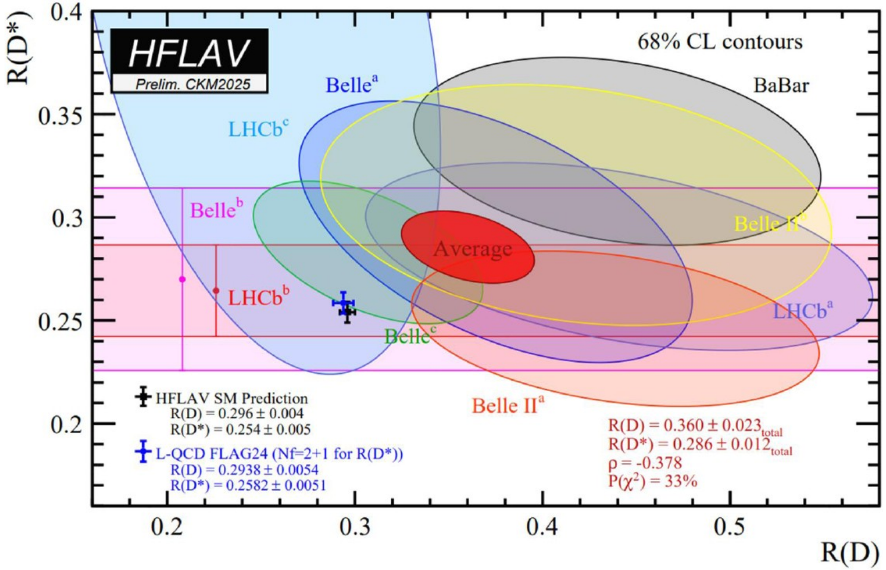
- Viable BSM models... leptoquarks? No clear connection to DM & hierarchy puzzle

- What are smallest deviations from SM, which can be unambiguously established?

The $B \to D^{(*)}\tau\bar\nu$ decay rates

- BaBar, Belle, LHCb: $R(X) = \dfrac{\Gamma(B \to X\tau\bar\nu)}{\Gamma(B \to X(e/\mu)\bar\nu)}$

  $\sim 3.5\sigma$ from SM expectations: theory robust due to heavy quark symmetry $+$ lattice QCD



- Imply NP scale $\lesssim$ few TeV

  Mediators within / near ATLAS & CMS reach

- Tree level: three ways to insert mediator: $(b\nu)(c\tau)$, $(b\tau)(c\nu)$, $(bc)(\tau\nu)$
  overlap with ATLAS & CMS searches for $\tilde b$, leptoquark, $H^\pm$

- Models built to fit these impacted ATLAS & CMS searches, motivated LFV searches

Aside: why not do this in SMEFT?

- Operator analysis (Lorentz invariance, not adding ν_R):

$$(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu),\ \ (\bar{c}\gamma_\mu P_R b)(\bar{\tau}\gamma^\mu P_L \nu),\ \ (\bar{c}P_R b)(\bar{\tau}P_L \nu),\ \ (\bar{c}P_L b)(\bar{\tau}P_L \nu),\ \ (\bar{c}\sigma^{\mu\nu}P_L b)(\bar{\tau}\sigma_{\mu\nu}P_L \nu)$$

Whether b, τ, c in L- or R-handed fields, connection to $b \to s\tau^+\tau^-$, $b \to s\nu\bar{\nu}$, $t \to c\tau^+\tau^-$

2nd and 5th terms can only arise from dim-8 $\Rightarrow$ often neglected

Connection to different generation transitions, only if some flavor structure is imposed

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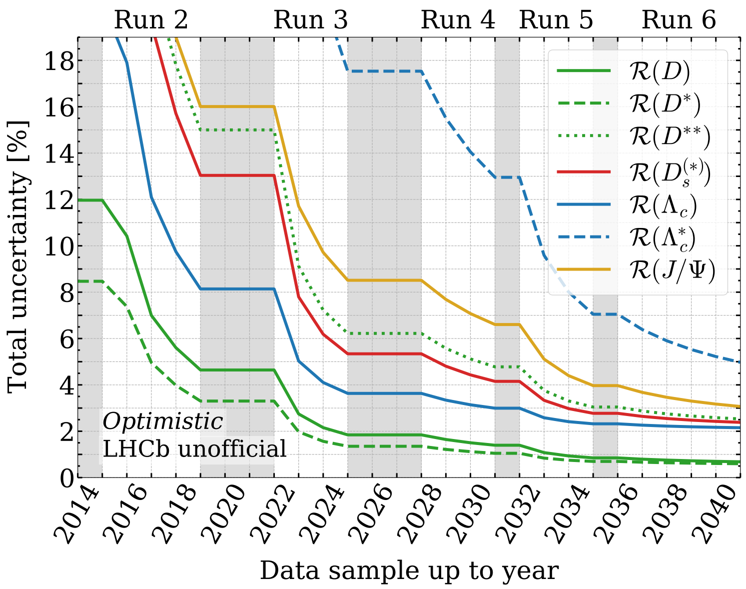
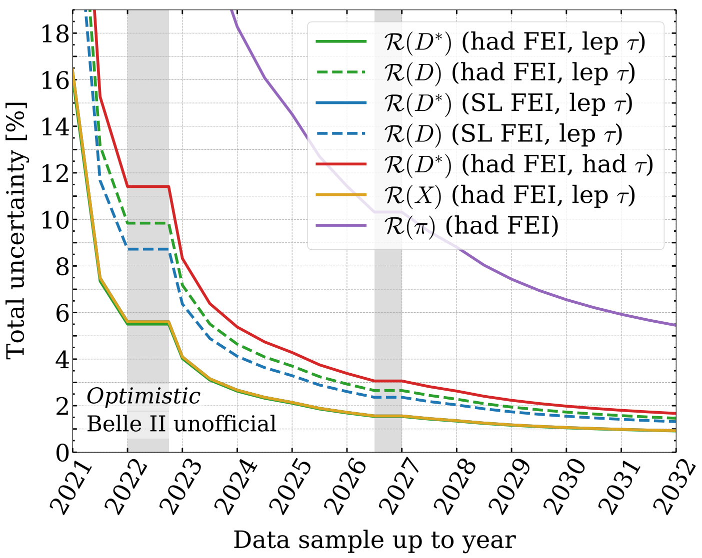
- Semileptonic operators ($l\bar{l}q\bar{q}$) are a large fraction of the operator basis:

SMEFT: 1053 semileptonic operators, 42% of the 2499 parameters of the dim-6 B & L conserving terms in the 3-generation SMEFT (558 CP-even, 495 CP-odd) [2402.09535]

LEET: 1944 semileptonic param's, 54% of the 3631 terms (1017 CP-even, 927 CP-odd)

Large future improvements





[2101.08326]

- Measurements will improve a lot, and reach few $\%$ in several decay modes
- May establish NP, even if deviations from SM decrease
- Will at least lead to much more robust $|V_{cb}|$ — critical for precision in many observables

Motivated many groups to push HQET further

- Determine all 6 $B \to D^{(*)} l\bar\nu$ form factors from 4 distributions in e, μ modes $(m_l = 0)$

  One Isgur-Wise function $+\ 3$ at $\mathcal{O}(\Lambda_{\rm QCD}/m_{c,b}) + \mathcal{O}(\Lambda^2_{\rm QCD}/m^2_{c,b}\,,\ \alpha_s^2)$ [1703.05330, 2206.11281]

- $\mathcal{O}(1/m^2_{c,b})$: number of unknown functions proliferate

  Studied truncations of $\mathcal{O}(1/m^2)$ terms: vanishing chromomagnetic (VC) limit or residual chiral (RC) expansion

  (Other approach is to include $1/m_c^2$ using light-cone sum rules) [1908.09398]

HQET order	All	Isgur-Wise functions RC Expansion	VC Limit
1	1	1	1
$1/m_{c,b}$	3	3	2
$1/m_c^2$	20	1	2
$1/m_{c,b}^2$	32	3	3

- Many open questions — focus for continuum methods and lattice QCD

  Justify truncations from first principles?

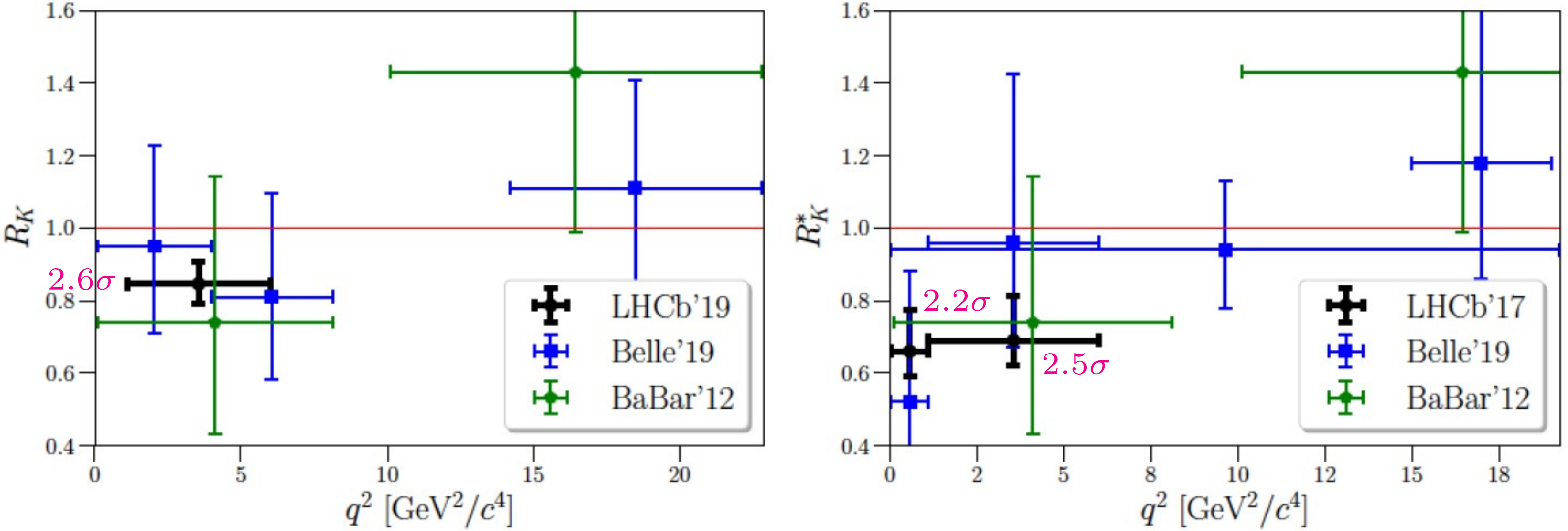
  Best way to fit data; truncation of a model independent (BGL) parametrization?

  Optimal combination with constraints from unitarity and lattice QCD?

  Some tension of FNAL/MILC vs. data?

R_K and R_{K^*} until 2022

- LHCb: $R_{K^{(*)}} = \dfrac{B \to K^{(*)}\mu^+\mu^-}{B \to K^{(*)}e^+e^-} < 1$ three bins $\sim 2.5\sigma$ from lepton universality



- Theorists' fits quoted $3-5\sigma$ (sometimes including P_5' and/or $B_s \to \phi\mu^+\mu^-$)
- Modifying one Wilson coefficient in $\mathcal{H}_{\rm eff}$ gave good fit: $\delta\, C_{9,\mu} \sim -1$

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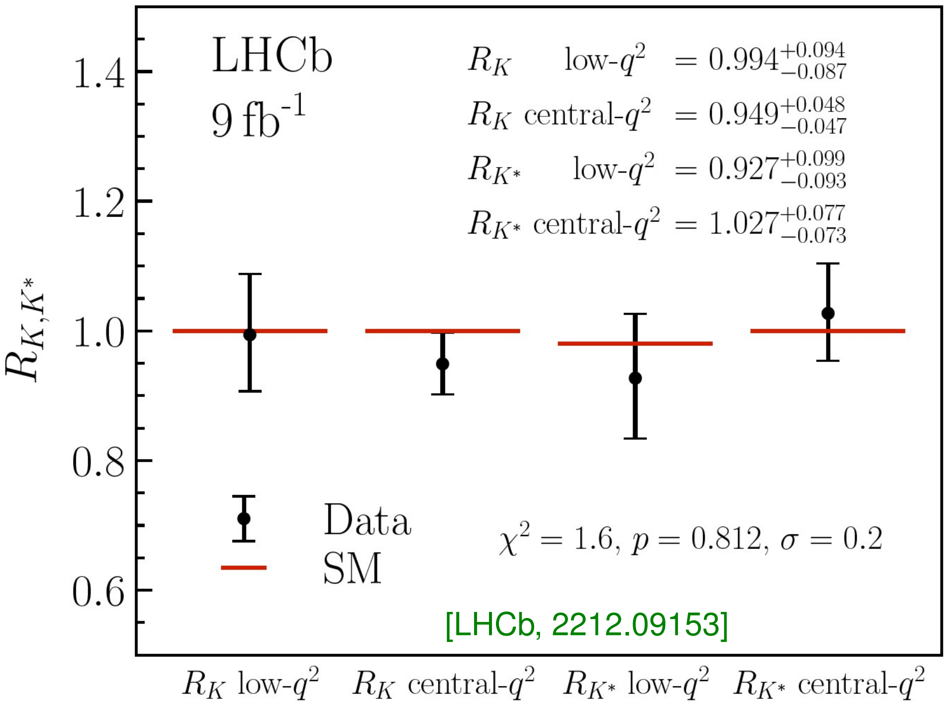
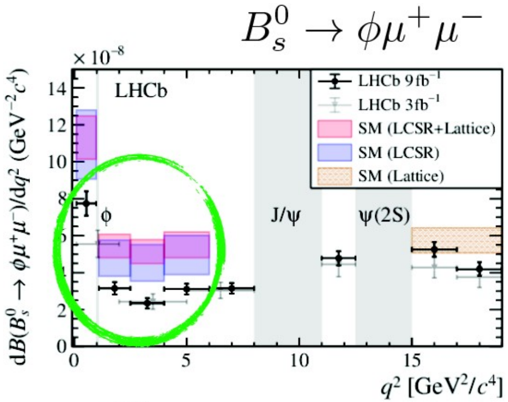
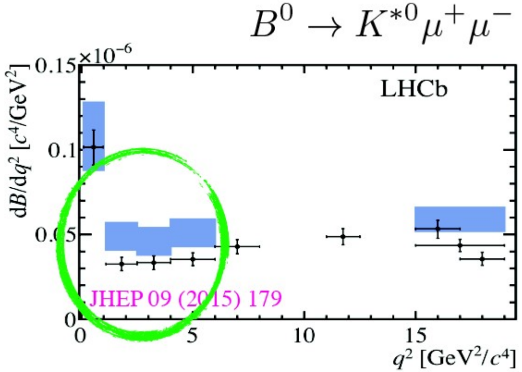
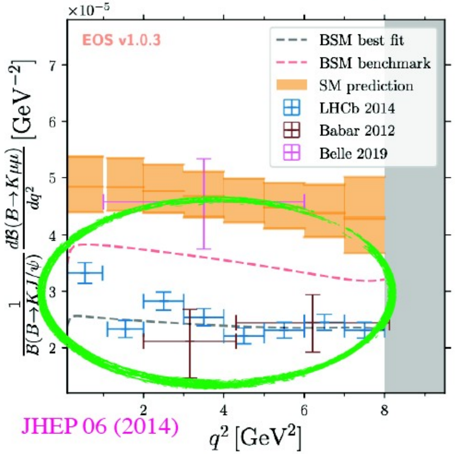
R_K and R_{K^*} now: SM-like, but rates too small?

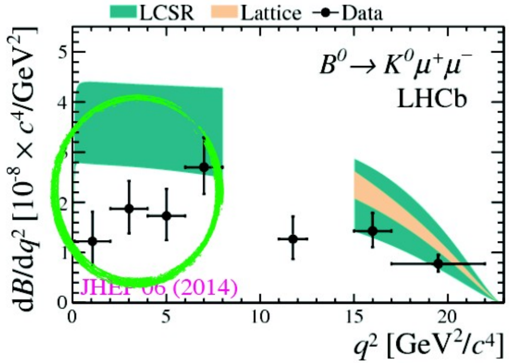


$0.1 < q^2 < 1.1\,\mathrm{GeV}^2$ (low-q^2), $1.1 < q^2 < 6.0\,\mathrm{GeV}^2$ (central)









[Smith, LHCP 2024]

The P_5' angular distribution in $B \to K^*\mu^+\mu^-$

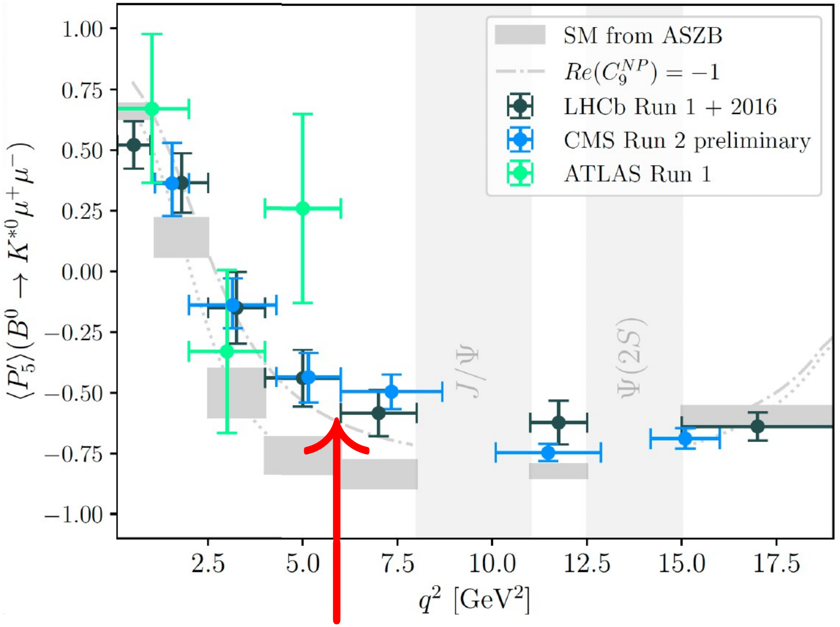
- "Optimized observables" [1202.4266 + long history]
  (assumptions about factorizable / nonfactorizable)

  Global fits: best fit, still: NP reduces C_9

  [Altmannshofer, Straub; Descotes-Genon, Matias, Virto; Jager, Martin Camalich; Bobet, Hiller, van Dyk; many more]

- Difficult for lattice QCD, large recoil

  What calculation determines how far below $m_{J/\psi}$ this comparison is reliable? (Different than $e^+e^- \to$ hadrons)



BSM, fluctuation, SM theory?

- Tests: other observables, q^2 dep., B_s and Λ_b decays

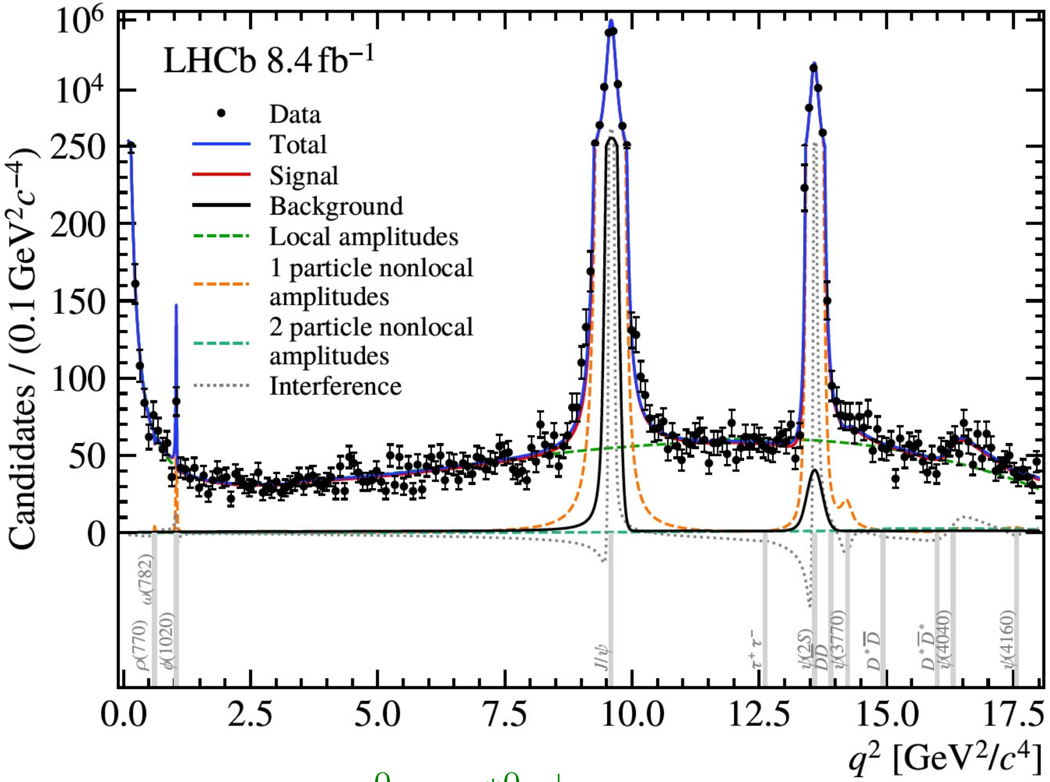
- Is the $c\bar{c}$ loop tractable? Impacts many interesting decay rates & CP viol. observables

Intense discussions of theory uncertainties

- My hope: data will help to make progress

  Large data sets often inspired progress in theory, and developing new approaches

- Only robust deviations based on model-independent theory will be seen as signs of new physics



[LHCb, $B^0 \to K^{*0}\mu^+\mu^-$ 2405.17347]

(Still) not understood: the $B \to K\pi$ puzzle

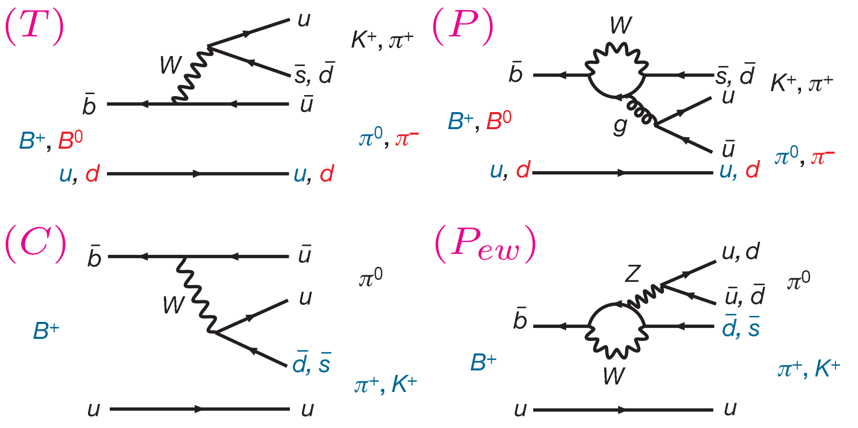
- Have we seen new physics in CPV?

$$A_{K^+\pi^-} = -0.0831 \pm 0.0031 \quad (P+T)$$

$$A_{K^+\pi^0} = 0.027 \pm 0.012 \quad (P+T+C+A+P_{ew})$$

- Large difference — small SM sources?

$$A_{K^+\pi^0} - A_{K^+\pi^-} = 0.111 \pm 0.012$$



(Annihilation not shown)

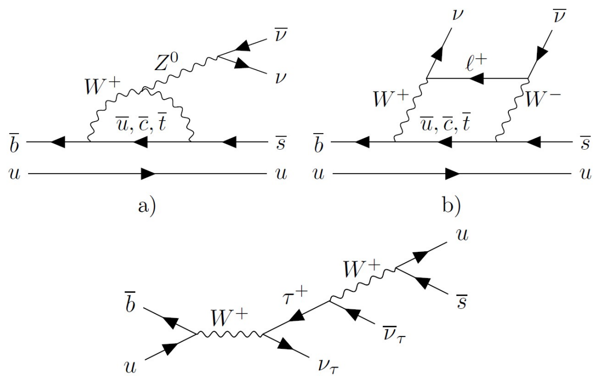
[Belle, Nature 452, 332 (2008)]

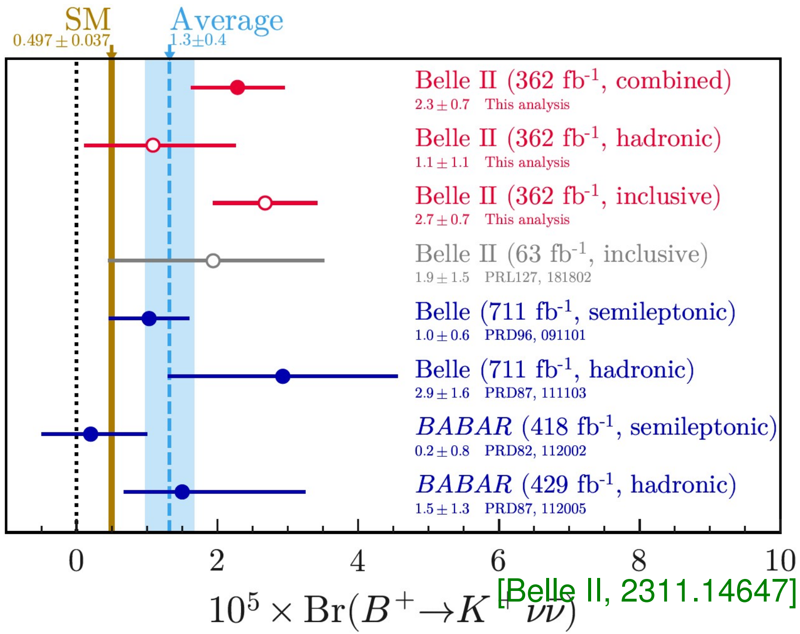
SCET / factorization predicts: $\arg(C/T) = \mathcal{O}(\Lambda_{\rm QCD}/m_b)$ and $A + P_{ew}$ small

- Large fluctuations? Breakdown of $1/m$ expansion? Missing something subtle? BSM?
- Can we unambiguously understand theory, so that such data could disprove the SM?

$B \to K\nu\bar{\nu}$ — unique to e^+e^- colliders

- Similar short-distance contributions, and much simpler long-distance ones





[Belle II, 2311.14647]

- Also relevant for dark sector searches ($B \to K+$invis.)
  (Is the excess in one bin of q^2?) [2309.00075, 2311.14629, etc.]

Belle II: 2.7σ from SM

- Input: precise form factor calculation [HPQCD, 2207.12468]

- If this tension becomes more significant, stopping NA62 after LHC Run 3 will look even more mistaken

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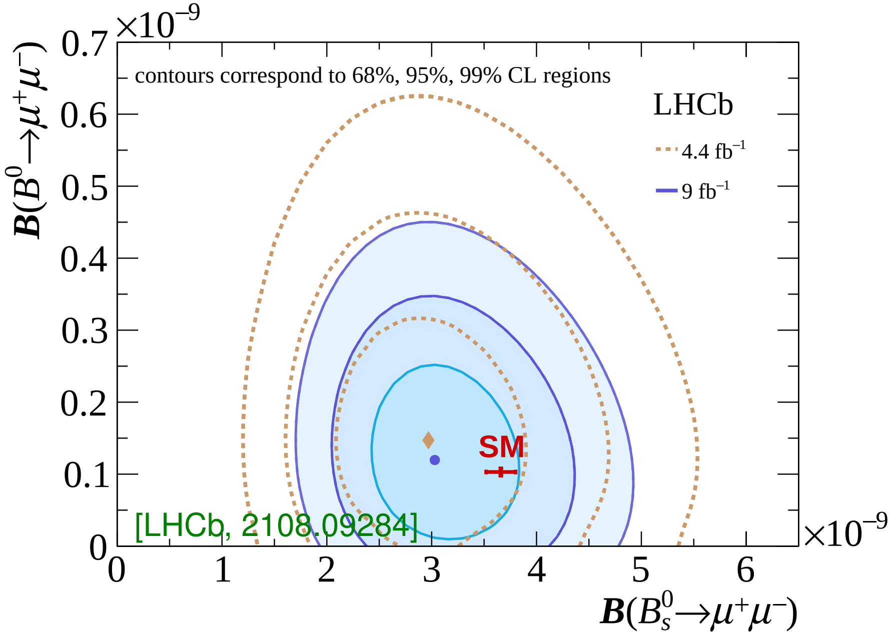
$B_{d,s} \to \mu^+\mu^-$: interesting well beyond HL-LHC

- $\mathcal{B}_{\rm SM}(B_s \to \mu^+\mu^-) \sim 3 \times 10^{-9}$, BSM predictions extended orders of magnitudes higher
- $\mathcal{B}_{\rm SM}(B_d \to \mu^+\mu^-) \sim 10^{-10}$, LHCb expects 10% (300/fb), CMS expects 15% (3/ab)

  SM uncertainty $\simeq (2\%) \oplus f_{B_q}^2 \oplus \mathrm{CKM}$, and may be further reduced
- Measure $|V_{ub}|$, using only isospin, from:

$$\mathcal{B}(B_u \to \ell\bar\nu)/\mathcal{B}(B_d \to \mu^+\mu^-)$$

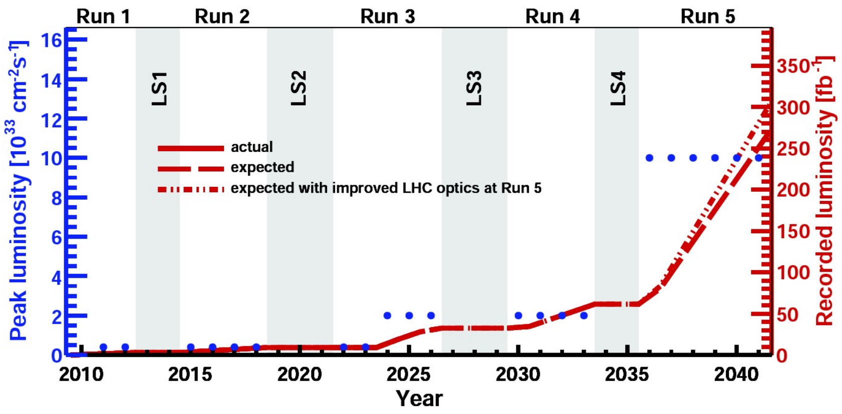
  (Most precise $|V_{ub}|$ at FCC-hh?)
- A decay with mass-scale sensitivity (dim.-6 operator) that competes with $K \to \pi\nu\bar\nu$

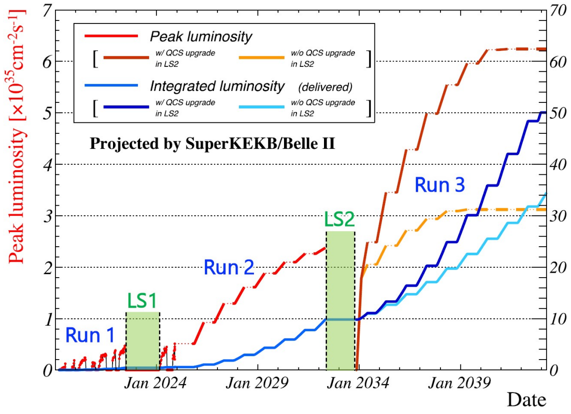


PDG average: [LHCb, CMS, ATLAS]

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.34 \pm 0.27) \times 10^{-9}$$

Far future





- Only FCC-ee would go well beyond LHCb + Belle II goals — clear case if BSM is seen

FCC-ee data sets for flavor

- $10^5\times$LEP is the right target (mass scale) $\propto$ (uncertainty)$^{-1/2}$ $\propto$ (stat)$^{-1/4}$

  Production yields compared to Belle II: [2106.01259]

Particle production (10^9)	$B^0+\overline{B}^0$	$B^\pm$	$B_s^0+\overline{B}_s^0$	$\Lambda_b+\bar\Lambda_b$	$B_c^\pm$	$c\bar c$	$\tau^+\tau^-$
Belle II (50 ab^{-1})	27	27	tbd	—	—	65	45
tera-Z (6×10^{12} Z)	600	600	150	130	3	600	170

  Comparison with LHCb more complex: roles of trigger, LHCb has advantage if final state is fully reconstructed, if there are neutrals, tera-Z may win

- WW threshold (10^8 WW): $W\to b\bar c$ can give a qualitatively new determination of $|V_{cb}|$

  Estimate 0.2% uncertainty, independent of B decays [Monteil @ 7th FCC Workshop, Jan 2024]; [2405.08880]

- Some electroweak precision measurements also concern flavor (R_ℓ for each flavor, τ_τ, m_τ)

Towards theory at the per mille level

- Theory uncertainty of γ is negligible (2nd order EW)

  Theory uncertainty of "everything else" being discussed

- Maybe β is most likely to be second best?

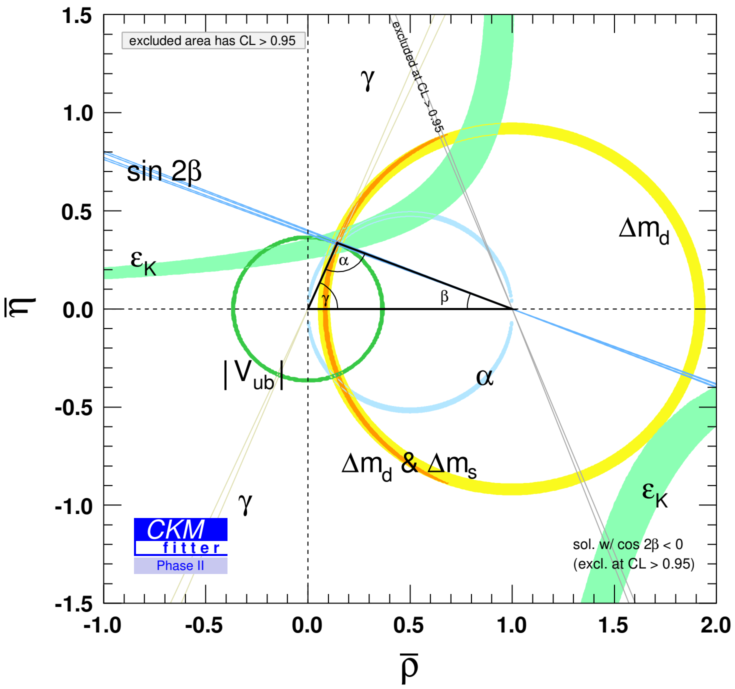
  There are claims of possibly large $|V_{ub}|$ ("penguin") contamination

  Recently noticed $SU(3)$ relation ($+\ B_s \to \psi K_S$ data):

  [ZL, Nir, Schein, 2506.21675]

$$S^d_{\psi K_S} - s_{2\beta} = -\left|\frac{V_{cd}}{V_{cs}}\right|^2 \frac{c_{2\beta}}{c_{2\beta_s}} \times (S^s_{\psi K_S} + s_{2\beta_s})$$

$$S^d_{\psi K_S} - s_{2\beta} = -0.037 \times (-0.04 \pm 0.41) = +0.001 \pm 0.015$$



- Uncertainty dominated now by experimental measurement of $S^s_{\psi K_S}$ in $B_s \to \psi K_S$

Sensitivity to new physics in B mixing

- In many BSM scenarios, dominant deviations from SM may be in neutral meson mixing

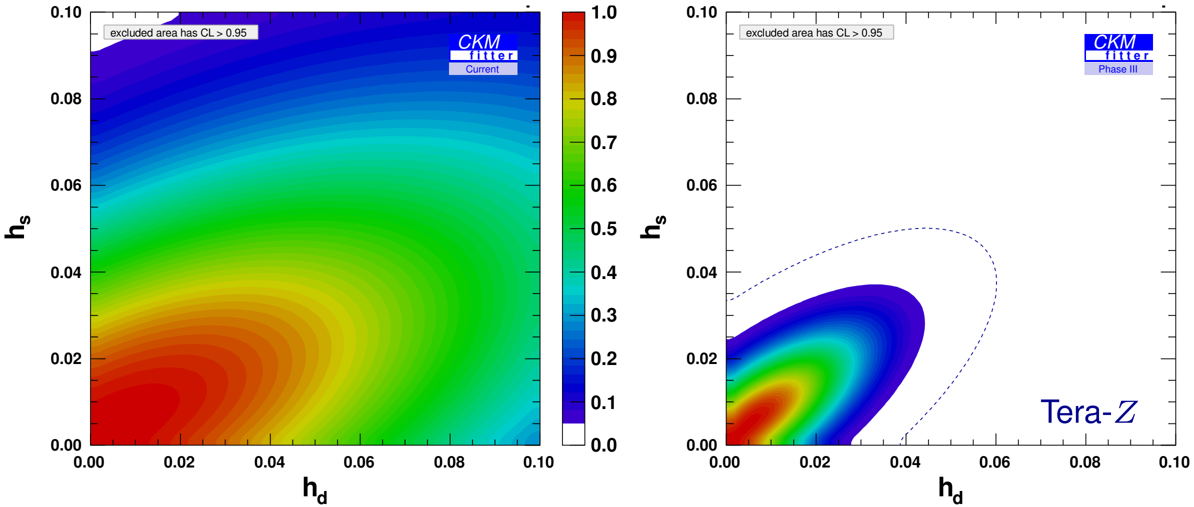
  Assume: (i) 3×3 CKM matrix is unitary; (ii) tree-level decays dominated by SM

  General parametrization: $h\,e^{2i\sigma} = A_{\rm NP}(B^0\to\overline{B}^0)/A_{\rm SM}(B^0\to\overline{B}^0)$ ($h_{d,s}$, $\sigma_{d,s}$: NP param's)

- CKM fit with 4 BSM param's added; combines many measurements and theory inputs [Charles *et al.*, 2006.04824]

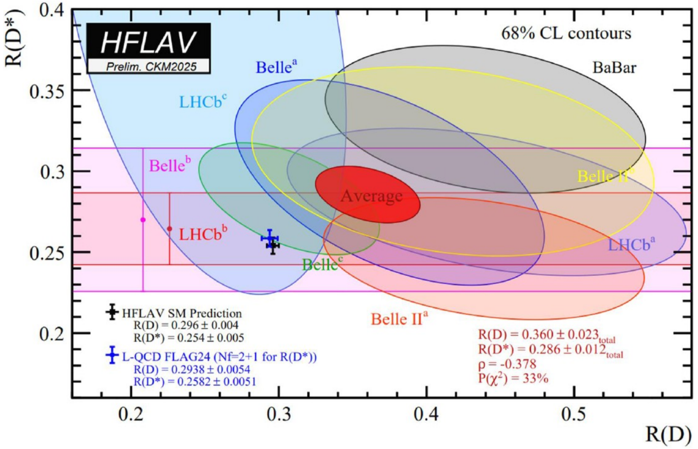
  ($\Rightarrow$ conservative view of future progress)

- $|V_{cb}|$ becomes a bottleneck; Tera-Z sensitivity will be better (no LQCD extrapolations)

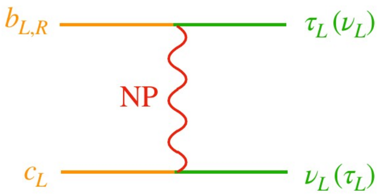


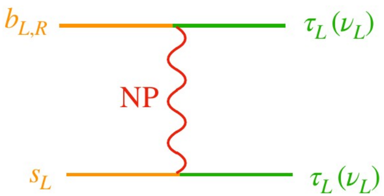
If BSM in $b \to c\tau\bar{\nu}$, must study $\nu\bar{\nu}$ & $\tau\tau$ modes

- SM and data in 3σ tension in $R(D^{(*)})$, if established, requires $\mathcal{O}(10\%)$ correction to a tree-level SM process



- If NP is charged under $SU(2)$, unavoidable connection to $b \to s\tau^+\tau^-$ or $b \to s\nu\bar{\nu}$ — correlations distinguish models

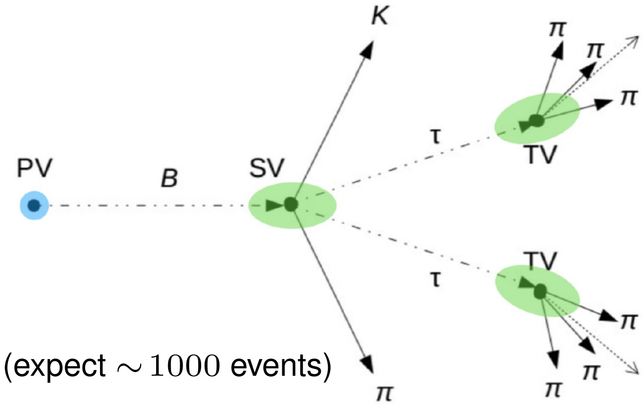




[Stefanek]

Only tera-Z can measure $B \to K^*\tau^+\tau^-$, $K^*\nu\bar{\nu}$ at SM level

Belle II: $\mathcal{B}(B \to K^*\tau^+\tau^-) < 1.8 \times 10^{-3}$ (SM $\sim 10^{-6}$) [2504.10042]



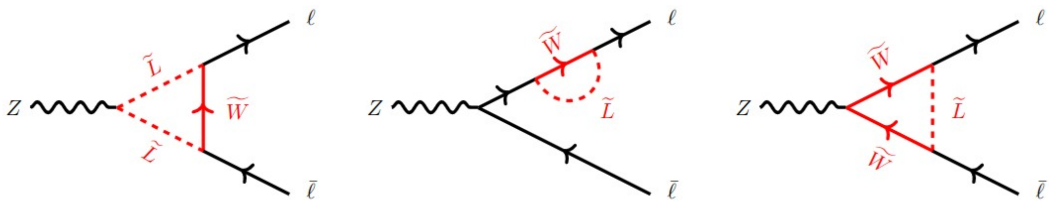
(expect ~ 1000 events)

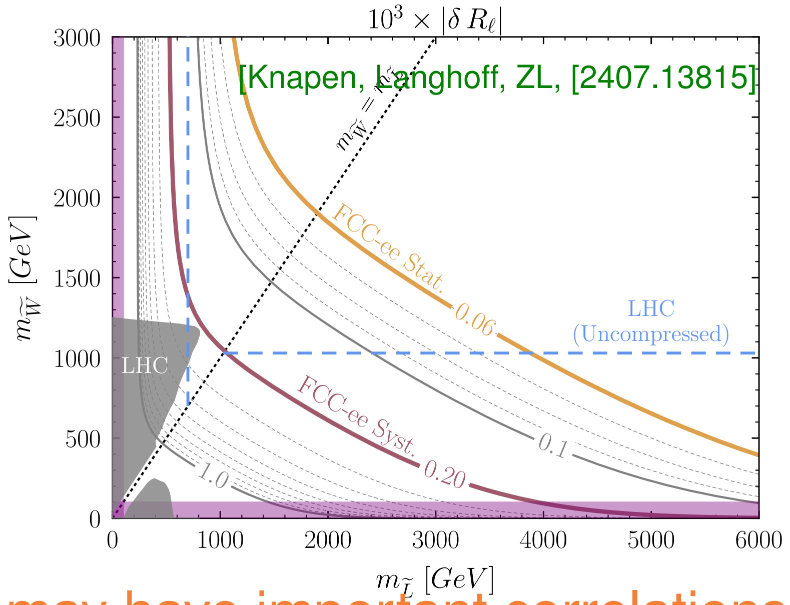
- Boost of B in Z decay provides ideal environment

Actual discovery potential? E.g., SUSY in $Z \to \ell^+\ell^-$

- Consider a SUSY simplified model: $\tilde{q}, \tilde{g}$ heavy, only electroweakinos & sleptons light
- Measurement: $R_\ell = \dfrac{\Gamma_{\ell^+\ell^-}}{\Gamma_{\text{hadrons}}}$

R_ℓ^Z $(\times 10^3)$	20 767	$\pm$	25	**0.05**	0.05	Ratio of hadrons to leptons
Systematic limitation in Midterm Report resolved by Feasibility Study						Acceptance for leptons





- Ultimate sensitivity depends on α_s, $\sin^2\theta_w$, etc.

  Several measurements combined for best physics reach

  Even better sensitivity to flavor violating effects $(e/\mu/\tau)$
- Can probe beyond (or between) HL-LHC exclusions
- Complementary to SMEFT studies, a specific model may have important correlations

Final remarks

What are the largest useful data sets?

- No one has seriously explored it!
- Many measurements will remain far from being limited by theory uncertainties:
  - For $\gamma \equiv \phi_3$, theory uncertainty only from higher order EW
  - $B_{s,d} \to \mu\mu$, $B \to \mu\nu$ and other leptonic decays (lattice QCD, [double] ratios)
  - $A_{\rm SL}^{d,s}$ — will experimental systematics become limiting?
  - Lepton flavor violation & lepton universality violation searches
  - Probably many more...
- Very broad program, dark sector searches, etc.
- In some decays, even in 2040s we'll have (exp. bound)$/$SM $\gtrsim 10^3$ (E.g., $B_{d,s} \to e^+e^-$, $\tau^+\tau^-$)
- NP sensitivity would improve with data $\gg$ LHCb, Belle II, tera-Z (flavor exp. for FCC-hh!?)

Theory challenges / opportunities

- New methods & ideas: recall that the best α and γ measurements are in modes proposed in light of Belle & BaBar data (i.e., not in the BaBar Physics Book)
  - Better SM upper bounds on $S_{\eta' K_S} - S_{\psi K_S}$, $S_{\phi K_S} - S_{\psi K_S}$, and $S_{\pi^0 K_S} - S_{\psi K_S}$
    And similarly in B_s decays, and for $\sin 2\beta_{(s)}$ itself
  - How big can CP violation be in $D^0 - \overline{D}^0$ mixing (and in D decays) in the SM?
  - Many lattice QCD calculations (operators within and beyond SM)
  - Better understanding of inclusive & exclusive semileptonic decays
  - Factorization at subleading order (different approaches), charm loops
  - Can direct CP asymmetries in nonleptonic modes be understood enough to make them "discovery modes"? [$SU(3)$, the heavy quark limit, etc.]
- We know how to make progress on some $+$ discover new frameworks / methods?

Summary

- Flavor physics probes scales $\gg 1\,\text{TeV}$, sensitivity limited by statistics
  New physics could show up any time measurements improve
- In most FCNC processes NP/SM $\sim 20\%$ still allowed (discovery $\Rightarrow$ upper bound on NP scale)
- Few tensions with SM — some of these (or others) could soon become decisive
- Interesting challenges both for experiment and theory to maximize sensitivity
  Explosion of data always triggered unforeseen developments
- Complementarity between high-p_T and precision probes of new physics will continue
- FCC-ee can be a discovery machine; tera-Z is a leap from LEP, rich physics program
  In flavor physics, the only way to go well beyond Belle II & LHC(b)

Extra slides

What is the scale of new physics?

- Flavor, K, B, D: $\dfrac{(\bar{b}\,\Gamma d)^2}{\Lambda^2} \;\Rightarrow\; \Lambda \gtrsim 10^2 - 10^5\ \text{TeV}$

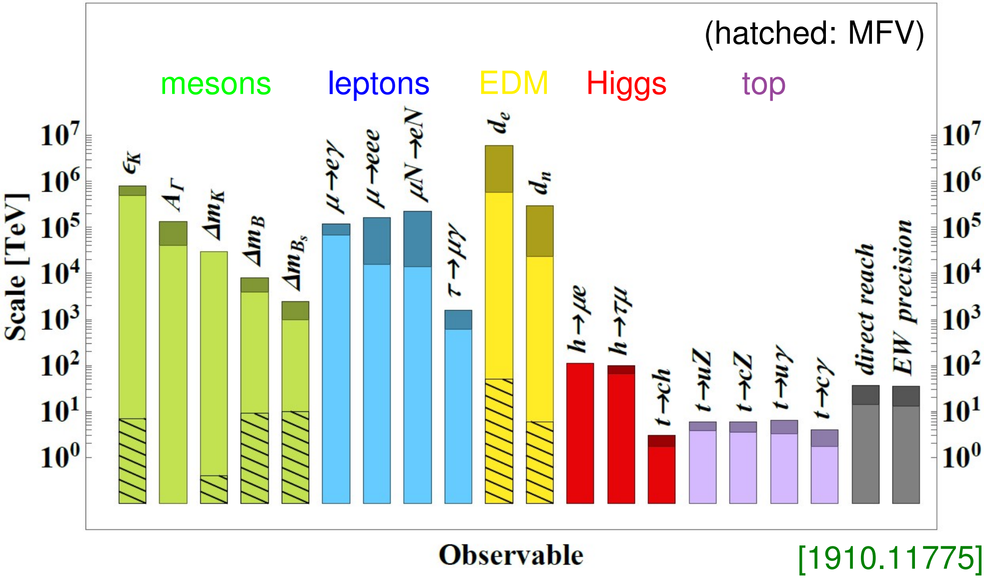
  Various mechanisms devised so that NP obeys bounds

  Note special sensitivity of meson mixings

- Electroweak: $\dfrac{(H^\dagger D_\mu H)^2}{\Lambda^2} \;\Rightarrow\; \Lambda \gtrsim 10\ \text{TeV}$

- Actual scales may be much less; e.g., in SM:

$$\frac{\Delta m_K}{m_K} \sim \frac{g_2^4}{16\pi^2}\, |V_{cs}V_{cd}|^2\, \frac{m_c^2}{m_W^4}\, f_K^2 \sim 7\times 10^{-15}$$



[1910.11775]

- Lack of NP in flavor tells us something; motivates tera-Z part of comprehensive search

- If NP is within any collider's reach, it must possess nontrivial structures (e.g., MFV-like)

Another FCNC, $B \to X_s\gamma$

- Maybe the most complex SM calculation; develop EFTs and RGEs, multi-loop techniques, SCET

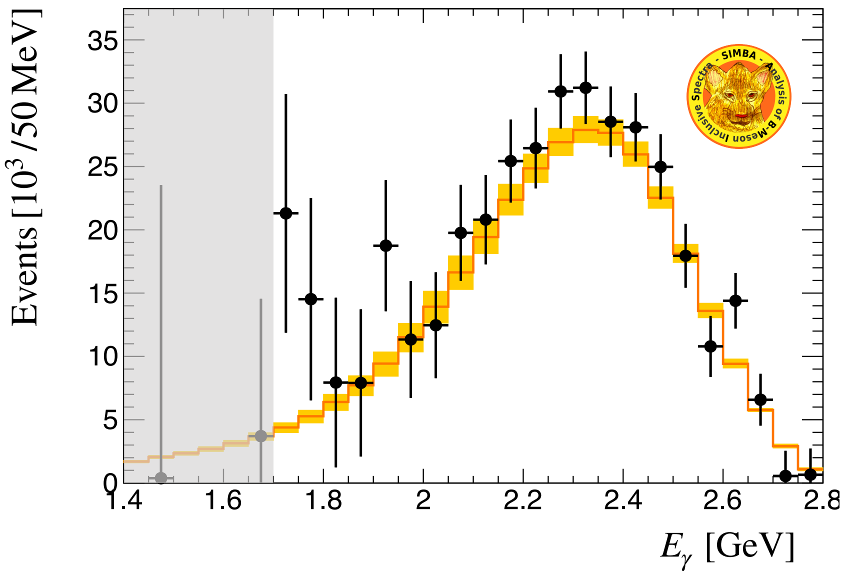
  Exp. & theor. uncertainty small in different regions

- Extract from global fit short-distance and hadronic parameters (shape functions) fully consistently

  [Bernlochner, Lacker, ZL, Stewart, Tackmann, Tackmann, 2007.04320]

- SIMBA: Consistent theory across E_γ spectrum
  Model-independent treatment of shape fn.

Belle inclusive Phys. Rev. Lett. 103, 241801 (2009)



$$|C_7^{\rm incl} V_{tb} V_{ts}| = (14.77 \pm 0.51_{\rm fit} \pm 0.59_{\rm theory} \pm 0.08_{\rm param}) \times 10^{-3}$$
$$m_b^{1S} = (4.750 \pm 0.027_{\rm fit} \pm 0.033_{\rm theory} \pm 0.003_{\rm param})\ {\rm GeV}$$

We find underestimated uncertainty by HFLAV
$\Rightarrow$ more room for NP

CP violation in D decays and mixing

- CP violation in D decays:

  LHCb, Nov. 2011: $\Delta A_{CP} \equiv A_{K^+K^-} - A_{\pi^+\pi^-} = -(8.2 \pm 2.4) \times 10^{-3}$ (I think a stretch in the SM)

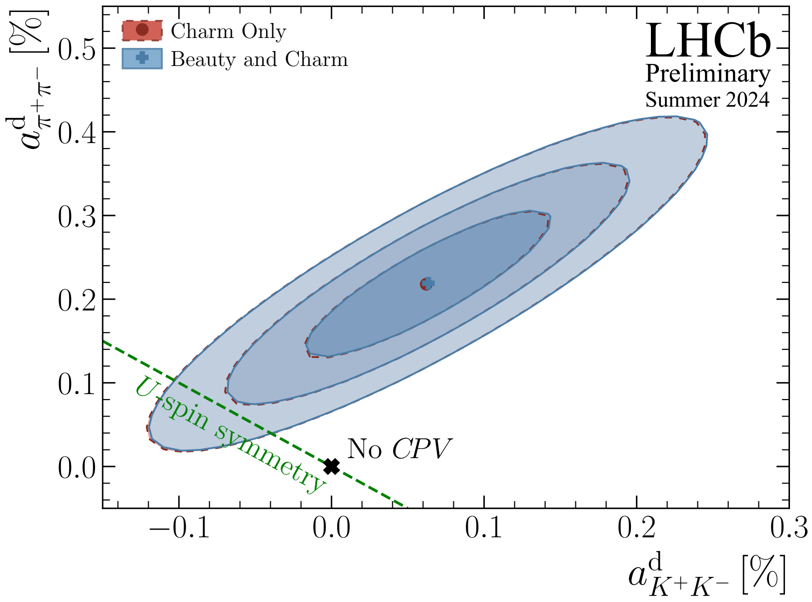
  LHCb, Mar. 2019: $\Delta A_{CP} = -(1.82 \pm 0.33) \times 10^{-3}$ [1903.08726]

- What is the maximal CPV that could be due to SM?

  CKM factors: $|V_{cb}V_{ub}/(V_{cd}V_{ud})| \simeq 7 \times 10^{-4}$

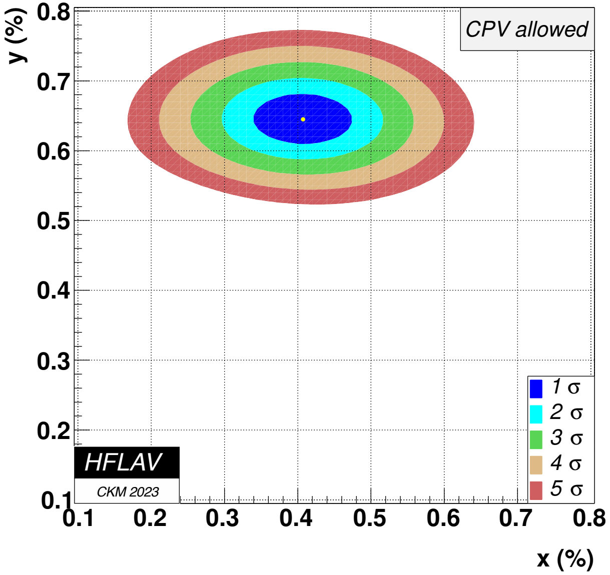
  Before measurements, most theory papers stated (assumed) that strong interaction suppresses CPV further

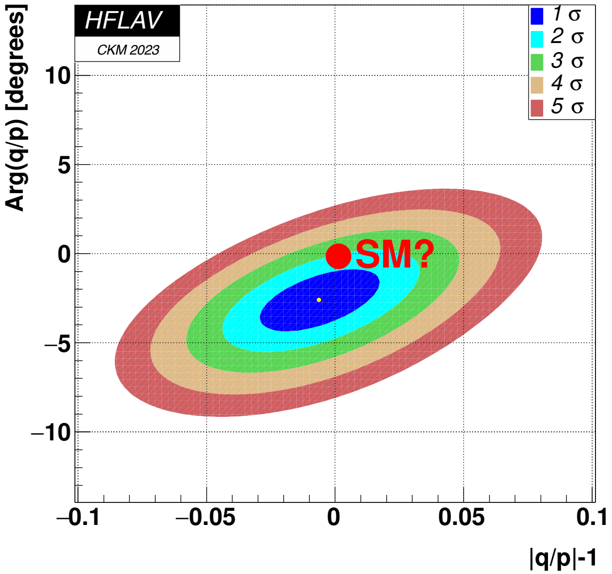
- Can we establish if CP violation in decay or mixing (more "inclusive") could still probe BSM?



CP violation in $D - \overline{D}$ mixing

- Mixing generated by down quarks
- SUSY: up-type squarks in box diagrams, interplay of D & K bounds
  $\Rightarrow$ alignment, universality, heavy squarks?
- Connections to FCNC top decays
- Only learned recently: $x/y = \mathcal{O}(1)$
  (Only in 2021 was $\Delta m \neq 0$ established at $> 3\sigma$)





- Very high scales probed, further improvements expected

CP violation in $B_{d,s}$ mixing: $A_{\rm SL}^{d,s}$

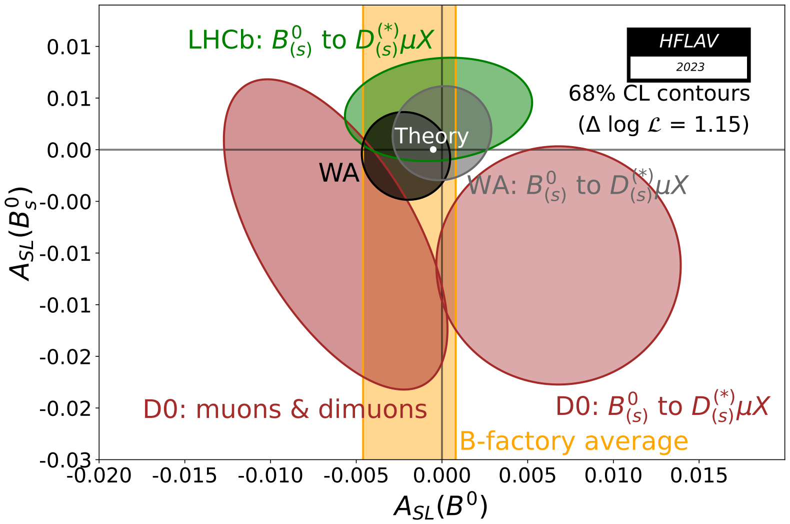
- Only observed in Kaons

  $B_{(s)}$: SM suppressed by m_c^2/m_b^2, may be lifted by BSM

  [hep-ph/0202010]

$$A_{\rm SL} = \frac{\Gamma[\overline{B}^0(t) \to \ell^+ X] - \Gamma[B^0(t) \to \ell^- X]}{\Gamma[\overline{B}^0(t) \to \ell^+ X] + \Gamma[B^0(t) \to \ell^- X]}$$

  Plenty of room between current sensitivity and SM predictions (not yet known if LHCb becomes syst. limited)

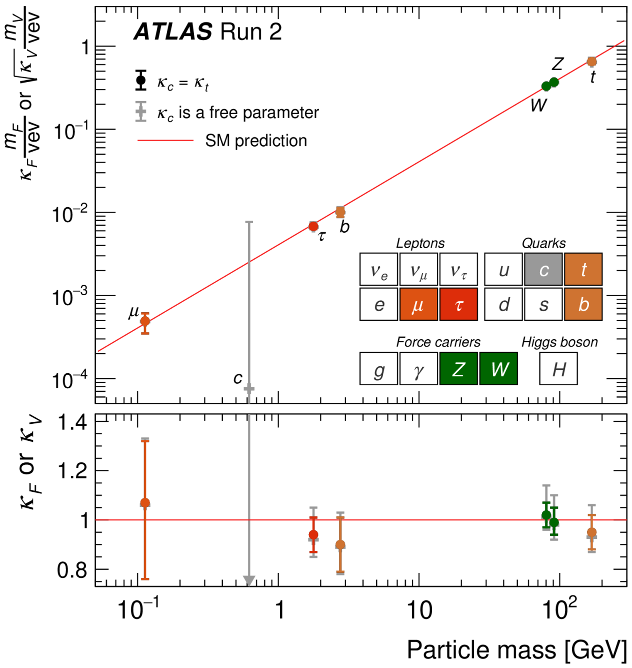


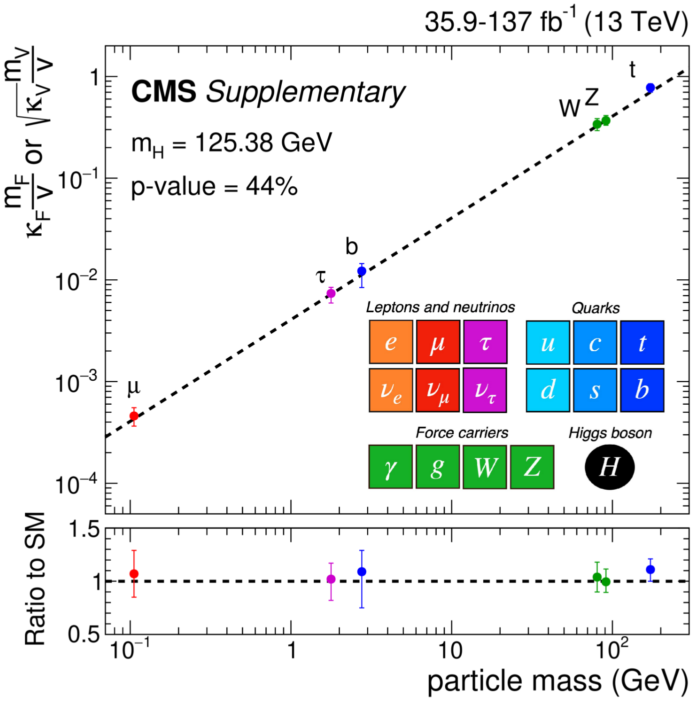
- Current status: Exp: $A_{\rm SL}^d = -(2.1 \pm 1.7) \times 10^{-3}$ $\quad A_{\rm SL}^s = -(0.6 \pm 2.8) \times 10^{-3}$

  SM: $A_{\rm SL}^d = -(4.7 \pm 0.6) \times 10^{-4}$ $\quad A_{\rm SL}^s = (2.22 \pm 0.27) \times 10^{-5}$ [1603.07770]

- Unique to Tera-Z: uncertainty $\sim 2.5 \times 10^{-5}$ for both $A_{\rm SL}^d$ and $A_{\rm SL}^s$, reach SM level

Higgs to fermion couplings is what flavor is...





- No constraint yet on origin of 1st generation fermion masses
- FCC-ee can establish role of Higgs in y_c, get close to y_s and y_e

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Similar decay of kaons: $K \to \pi\nu\bar{\nu}$

- Kaon CPV is at the right level (can fit ϵ_K with KM phase, but ϵ'_K notoriously hard)
- $K^+ \to \pi^+\nu\bar{\nu}$ searched for since 1960s (longer than Higgs), sensitive to $100\,\mathrm{TeV}$ scale

  Irreducible theory uncertainty few % (& $|V_{cb}|^4$)

- Recently: first $> 5\sigma$ observation [NA62, 2412.12015]

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$$

  Consistent with SM ($\approx 8 \times 10^{-11}$), at 1.7σ

- KOTO: $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) < 2 \times 10^{-9}$