B physics: known and unknown

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KEK Theory Meeting on Particle Physics Phenomenology

February 16 – 19, 2026

Outline

- Why flavor?
  (Unique sensitivites)

- Recent examples of what we know and don't know
  (Lot to do, both for theorists and experimentalists)

- Future: HL-LHC & Belle II sensitivity $\Rightarrow$ then FCC
  (Huge increases in data, what can they teach us?)

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What is flavor physics?

- 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)

- Neutrino mass: What is the Lagrangian? (is lepton # violated?)
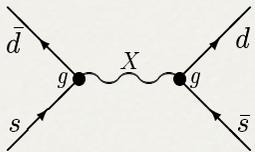
Origin of high scale sensitivity

- 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 $m_c \sim 1.5 \, \text{GeV}$ (Gaillard & Lee; Vainshtein & Khriplovich, 1974)
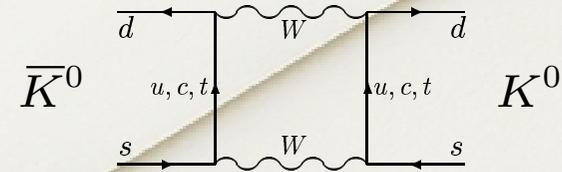
- If exchange of a heavy particle X contributes at the SM level:

$$\dfrac{\Delta m_K^{(X)}}{\Delta m_K} \sim \dfrac{g^2 \, \Lambda_{\text{QCD}}^3}{M_X^2 \, \Delta m_K} \;\Rightarrow\; M_X > g \times 10^3 \, \text{TeV}$$

- 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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New physics scales probed

- Heavy new physics generates dimension > 4 operators in SMEFT

$$\mathcal{L} = \text{SM} + \sum_i \frac{C_{5i}}{\Lambda} \mathcal{O}_{5i} + \sum_i \frac{C_{6i}}{\Lambda^2} \mathcal{O}_{6i} + \ldots$$

- Dim-5 $LL\phi\phi$ discovered, iff m_ν violates lepton # ($0\nu\beta\beta$?); No dim-6 term established yet

- Baryon number violation: $\dfrac{QQQL}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^{16}\,\text{GeV}$

- Higgs & precision electroweak: $\dfrac{(\phi D^\mu \phi)^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^4\,\text{GeV}$

- Flavor and CP violation (and EDMs): $\dfrac{QQQQ}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^{(3\ldots8)}\,\text{GeV}$

The only experimental probe of the $10^2 - 10^5\,\text{TeV}$ scale

Compare flavor and precision electroweak

- **Flavor-changing neutral currents**

  No tree level

  Loop + CKM + GIM + CPV suppression

  $$\frac{1}{\Lambda^2} \sim \frac{\alpha_W}{m_W^2} \left(V_{ik} V_{jk}^* \right) \frac{m_q^2}{m_W^2} \frac{J_{\mathrm{CKM}}}{|V_{ik} V_{jk}|}$$

  Probe $\Lambda \sim 10^5 \, \mathrm{TeV}$
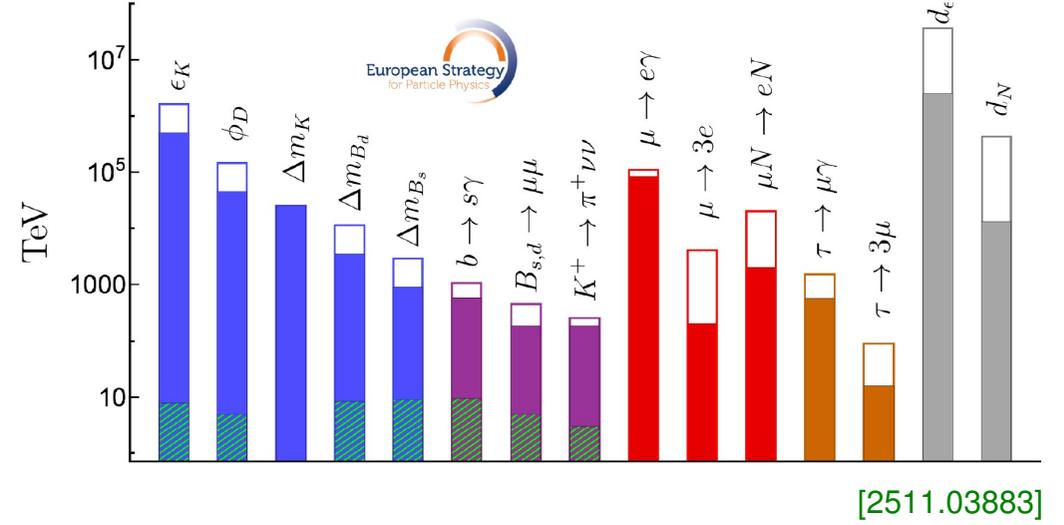
  EW precision measurements
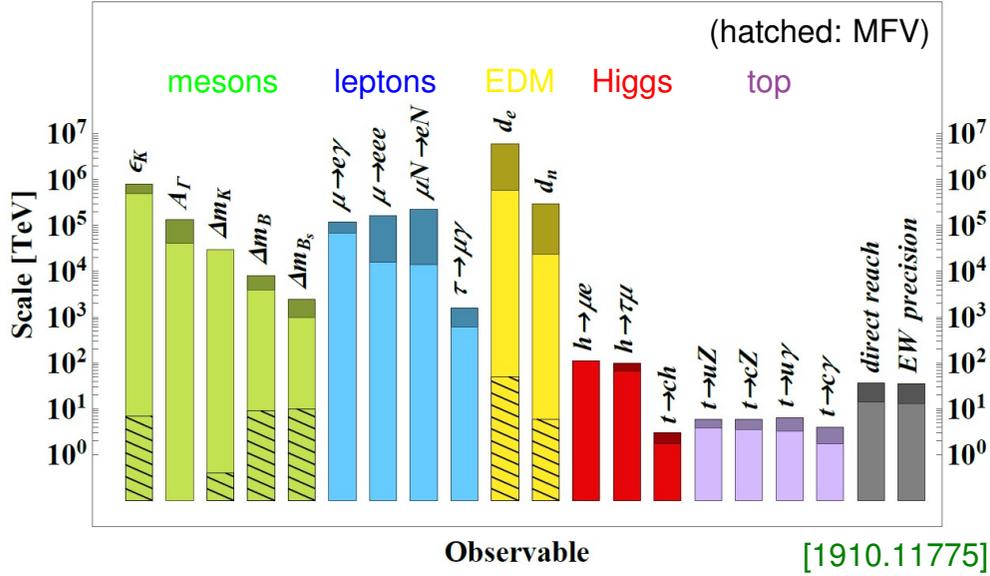
  Tree level

  Loop suppression

  $$\frac{1}{\Lambda^2} \sim \frac{\alpha_W}{m_W^2}$$

  Probe $\Lambda \sim 10 \, \mathrm{TeV}$

- Both are important: new physics probably has additional small parameters / structures

Plots from European strategy

[1910.11775]

[2511.03883]

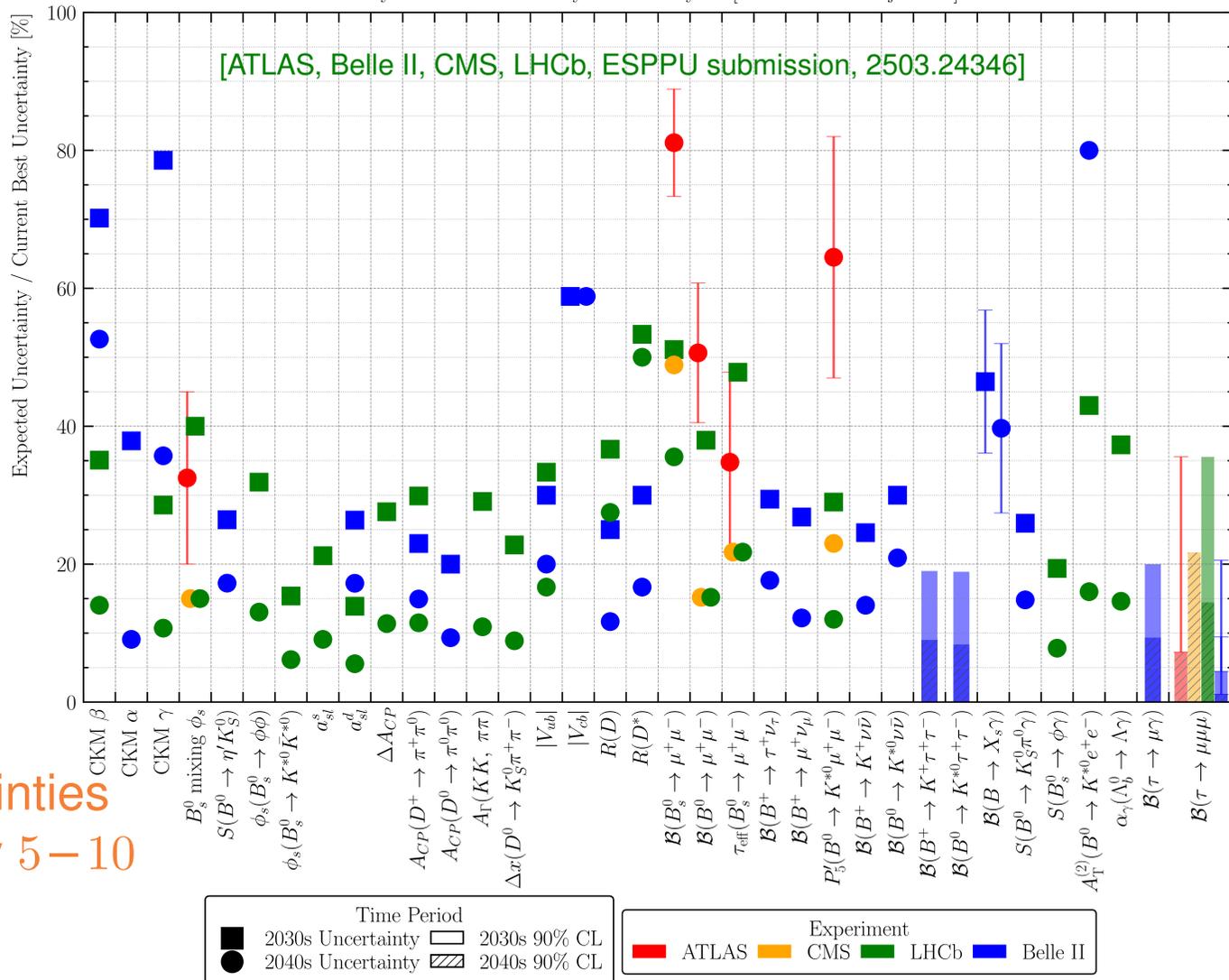ZL – p. 6

Some lessons: not new, but got lot sharper

- 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

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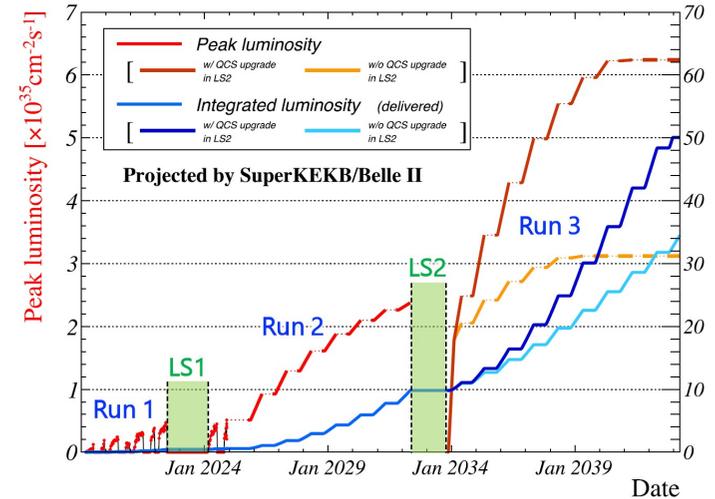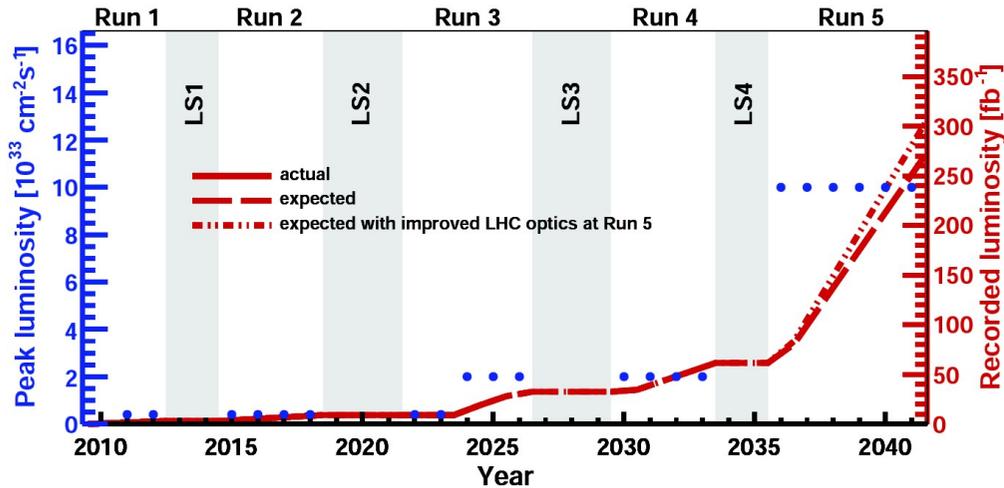
- LHCb upgrade in LS2 (inst. lumi.: 2×10^{33})
- LHCb Upgrade II in LS4 (inst. lumi.: 1.5×10^{34}) ATLAS & CMS competitive in some modes

- 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]

Key Observables in Heavy Flavour Physics [ESPPU 2026 Projections]

[ATLAS, Belle II, CMS, LHCb, ESPPU submission, 2503.24346]

Many uncertiainties will improve by $5-10$

# Where are we now? Testing quark flavor

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

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

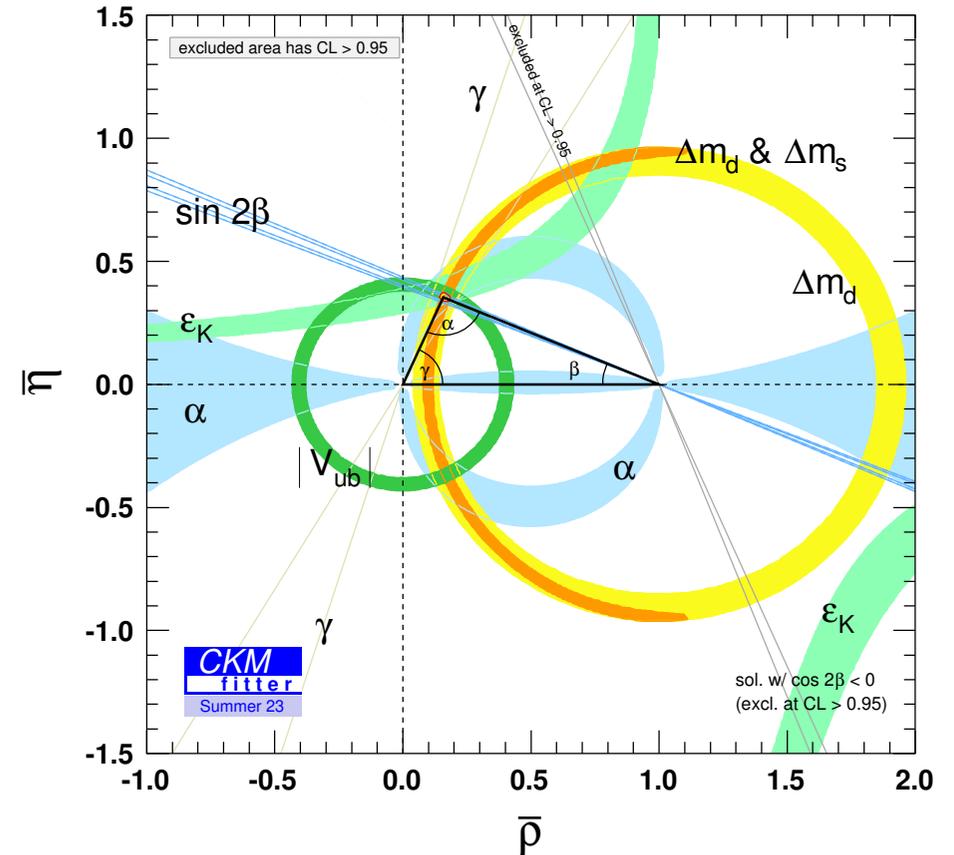Measurements: magnitudes $\sim$ decay rates; phases $\sim CP$ violation

● 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
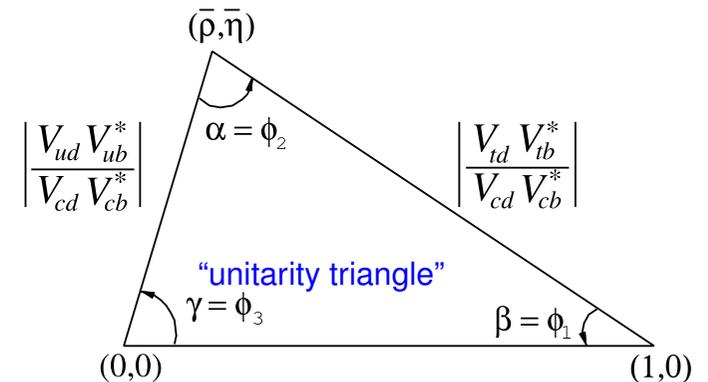
The CKM fit in the SM

- Spectacular progress in last 25 years

- The CKM mechanism describes consistently CP violation and flavor changing processes

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- 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
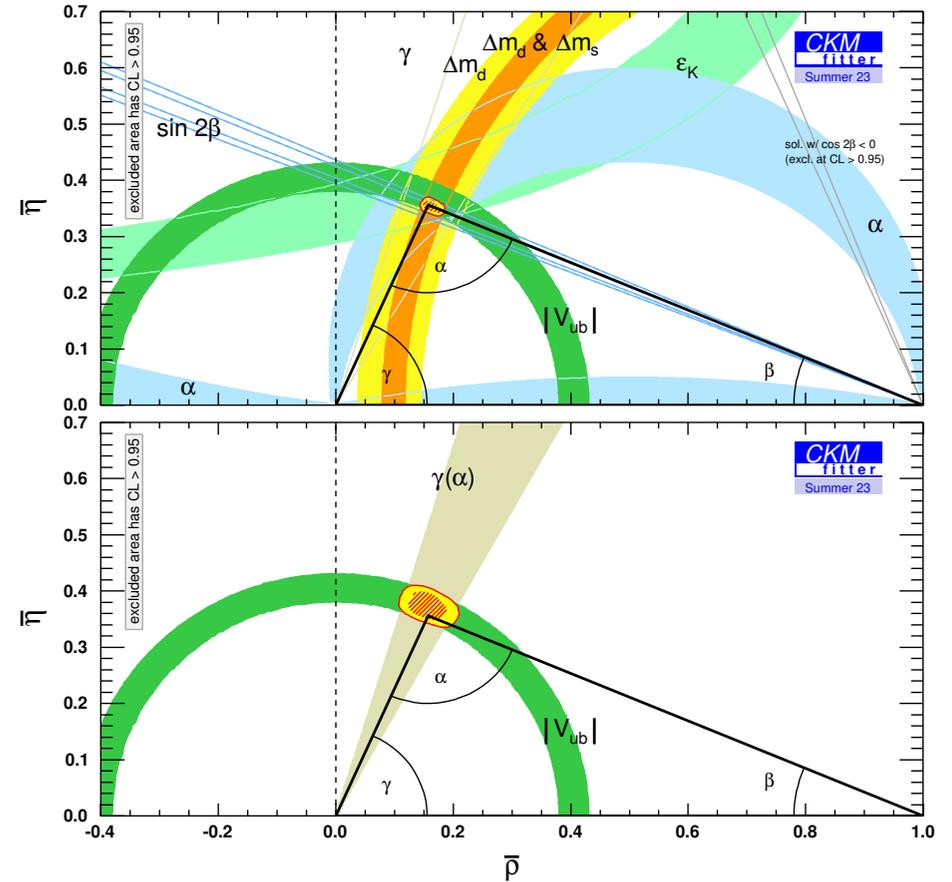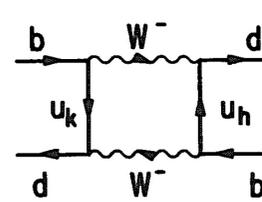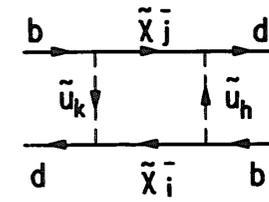
Constraints on NP parameters added to the SM

- In a large class of NP models, dominant contributions are to neutral meson mixing

- General parametrization of many scenarios by two real BSM parameters; redo CKM fit:

$$h\,e^{2i\sigma} = A_{\mathrm{NP}}(B^0 \to \overline{B}^0)/A_{\mathrm{SM}}(B^0 \to \overline{B}^0)$$
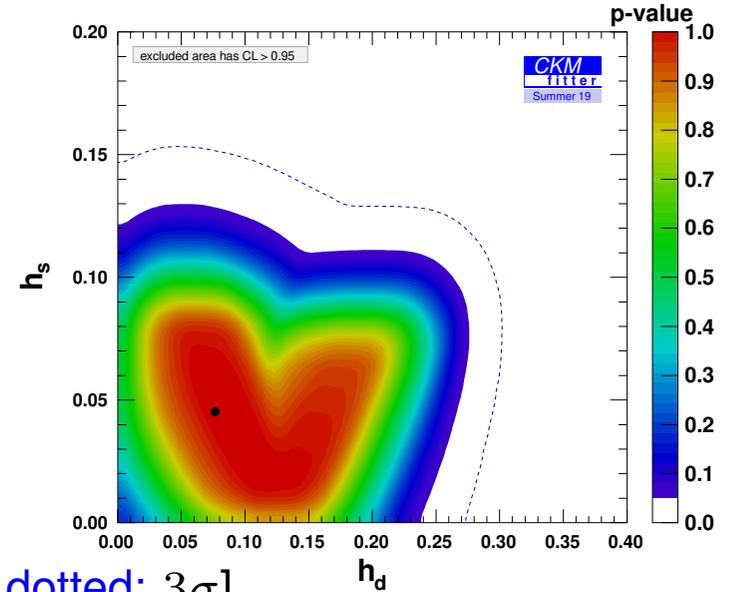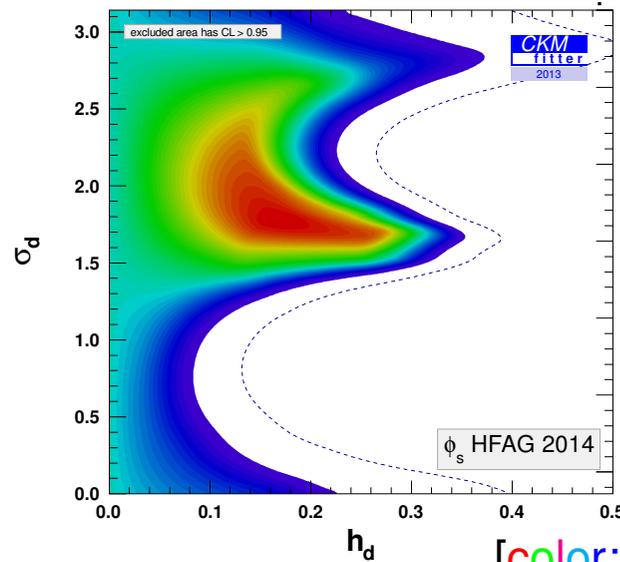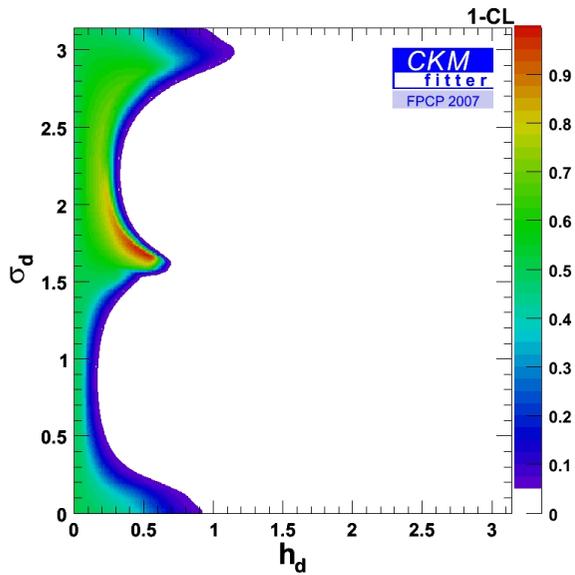
SM: $\dfrac{C_{\mathrm{SM}}}{m_W^2}$ NP: $\dfrac{C_{\mathrm{NP}}}{\Lambda^2}$

Tree-level decays dominated by SM, BSM only significant in FCNCs (loops)

- Is $h \gtrsim 1$ allowed? If not, then CKM mechanism is dominant

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Evolving bounds on $h_{d,s}$

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

[color: 2σ, dotted: 3σ]

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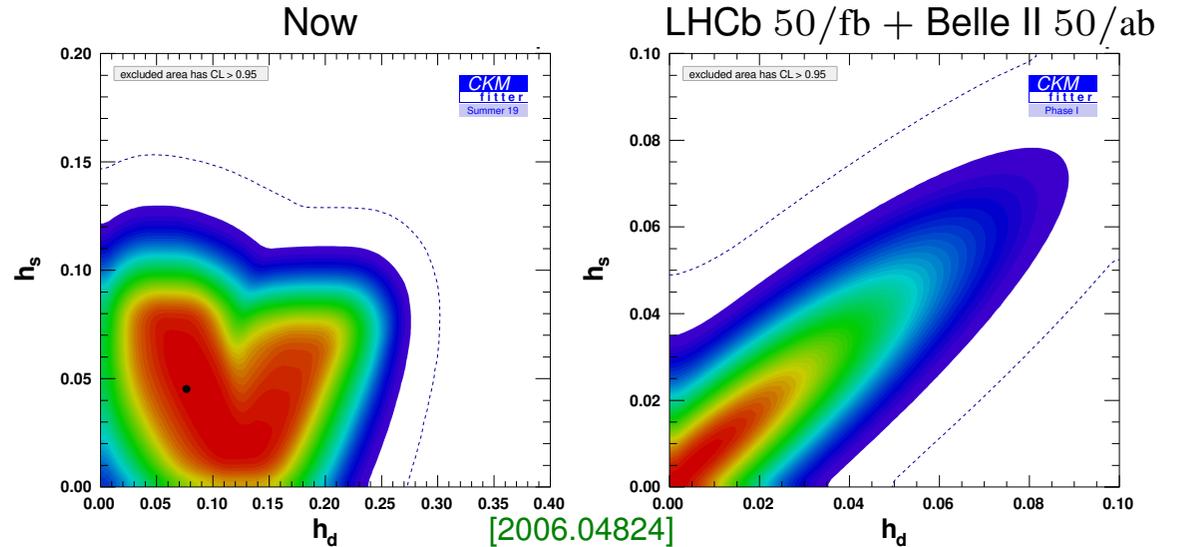- Weak interaction dominates observed CP violation: BSM/SM $\lesssim 20\%$

Improvements in next ~ 10 years

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

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

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

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

- BSM sensitivity will continue to improve

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

[2006.04824]

[color: 2σ, dotted: 3σ]

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

Recent tensions between SM and data

Hints of deviations from the SM

● From a distance, everything seems to work... looking closer:

  – Charged current semileptonic decays (e.g., $B \to D^{(*)} \ell \bar{\nu}$)

  – Neutral current (FCNC) semileptonic decays (e.g., $B \to K^{(*)} \ell \bar{\ell}$)

  – Dominantly charged current nonleptonic decays (e.g., $B \to D^{(*)} h$)

  – Dominantly FCNC nonleptonic decays (e.g., $B \to K h$)

  There are more...

● Intriguing tensions with the SM $\Rightarrow$ experimental scrutiny, new theory ideas

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

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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

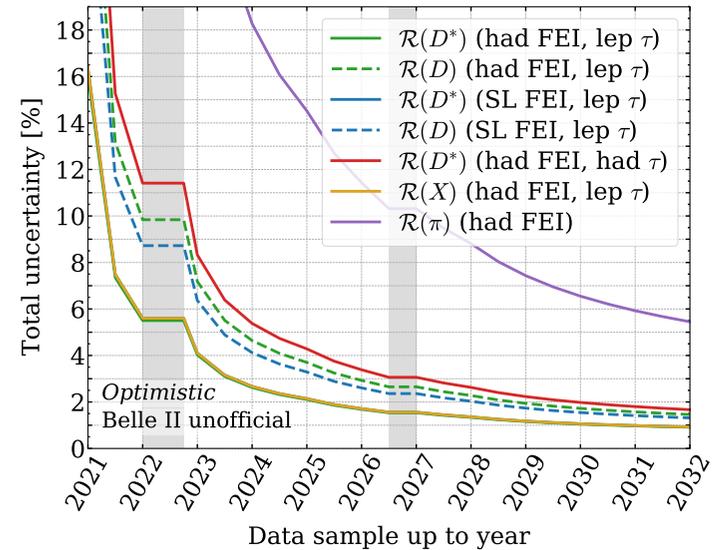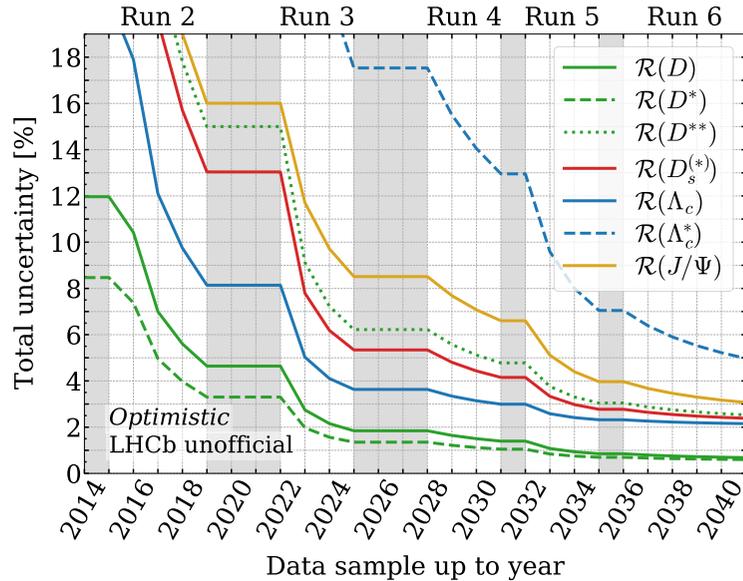- Imply NP scale $\lesssim$ few TeV

  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

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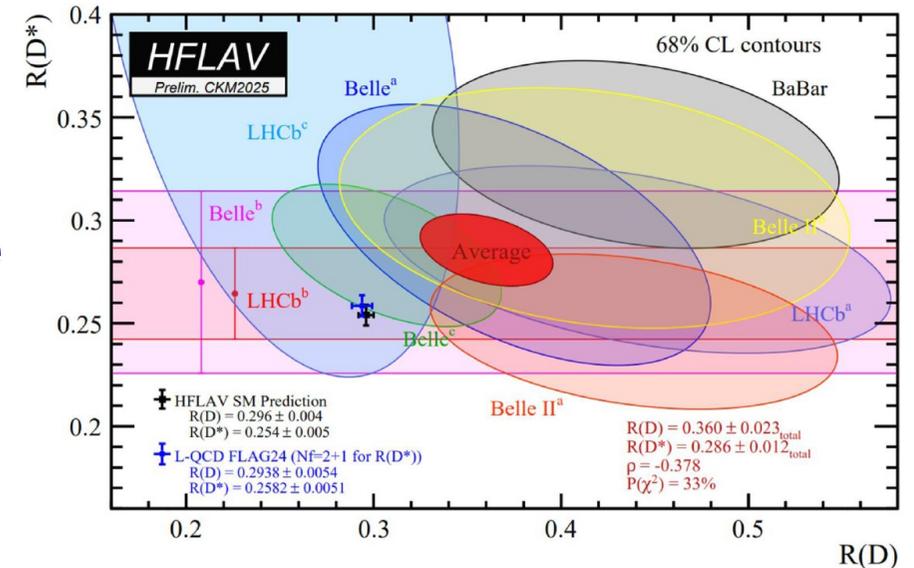
Large future improvements

[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

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$|V_{cb}|$ and pushing HQET further

- $|V_{cb}|$ is measured from "zero recoil" limit of $\mathrm{d}\Gamma(B \to D^{(*)}\ell\bar\nu)/\mathrm{d}q^2$

  HQET most constraining + LQCD most precise
  In practice, measuring all distributions helps — additional information

  Impacts many rare decay rate predictions, since $V_{ts}, V_{td} \propto A$

- Many open questions:

  How to fit data: truncate model independent (BGL)
  param.? (Many proposals, Akaike information criterion, etc.)
  Optimal combination with constraints from unitarity
  and lattice QCD?

  Some tension between LQCD and data

AIC Best Order Distribution

NHT Best Order Distribution

[Bernlochner, ZL, Persson, Robinson, to appear]

- Not to mention tension between exclusive and inclusive determination

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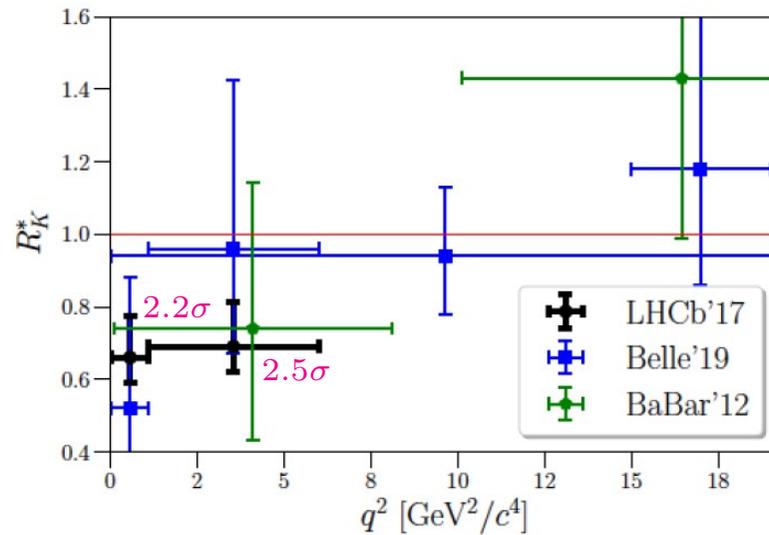● **LHCb:** $R_{K^{(*)}} = \dfrac{B \to K^{(*)}\mu^+\mu^-}{B \to K^{(*)}e^+e^-} < 1$ three bins $\sim 2.5\sigma$ from lepton universality
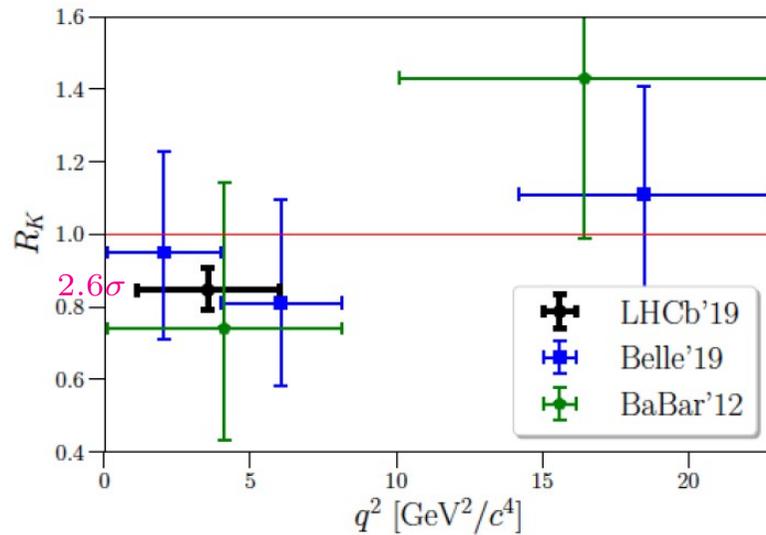
● Theorists' fits quoted $3-5\sigma$ (sometimes including P_5' and/or $B_s \to \phi\mu^+\mu^-$)

● Modifying one Wilson coefficient in $\mathcal{H}_{\text{eff}}$ 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?

LHCb
9 fb^{-1}

R_K low-q^2 $= 0.994^{+0.094}_{-0.087}$

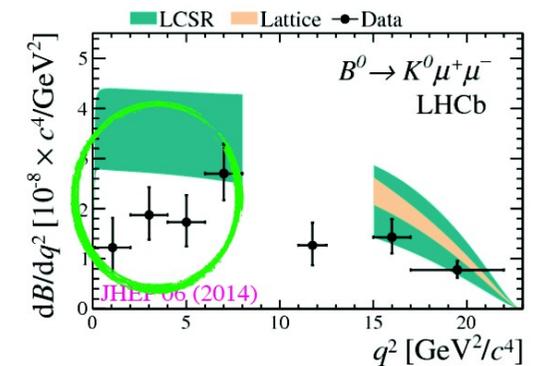R_K central-q^2 $= 0.949^{+0.048}_{-0.047}$

R_{K*} low-q^2 $= 0.927^{+0.099}_{-0.093}$

R_{K*} central-q^2 $= 1.027^{+0.077}_{-0.073}$

Data
SM

$\chi^2 = 1.6, \; p = 0.812, \; \sigma = 0.2$

[LHCb, 2212.09153]

R_K low-q^2 R_K central-q^2 R_{K*} low-q^2 R_{K*} central-q^2
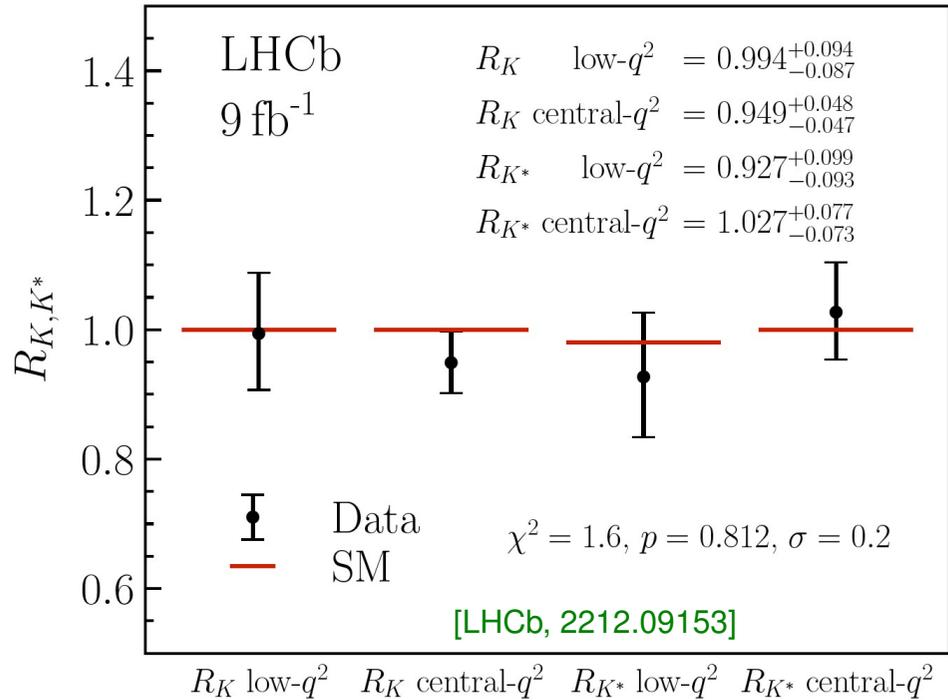
$0.1 < q^2 < 1.1\,\mathrm{GeV}^2$ (low-q^2), $\;1.1 < q^2 < 6.0\,\mathrm{GeV}^2$ (central)

$B_s^0 \to \phi \mu^+ \mu^-$

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

JHEP 09 (2015) 179

JHEP 06 (2014)

[Smith, LHCP 2024]

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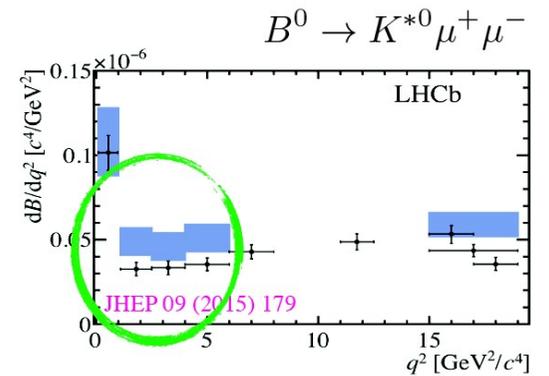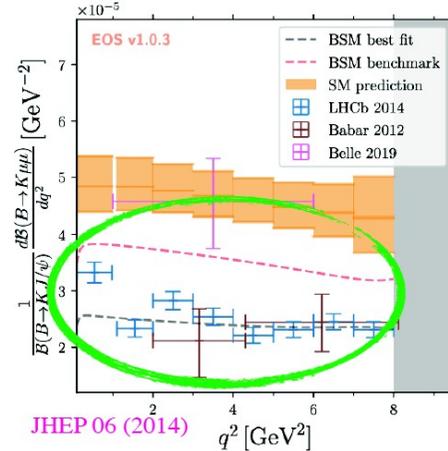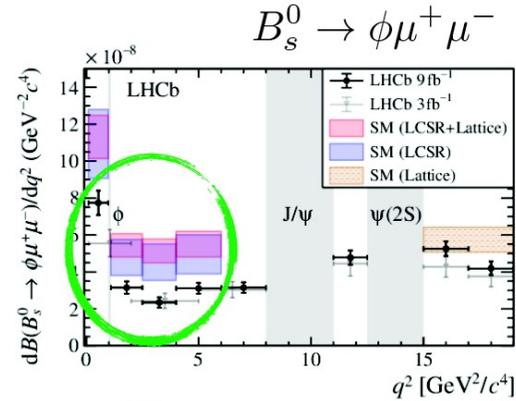
The P_5' angular distribution in $B \to K^* \mu^+ \mu^-$

- **"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)

- 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
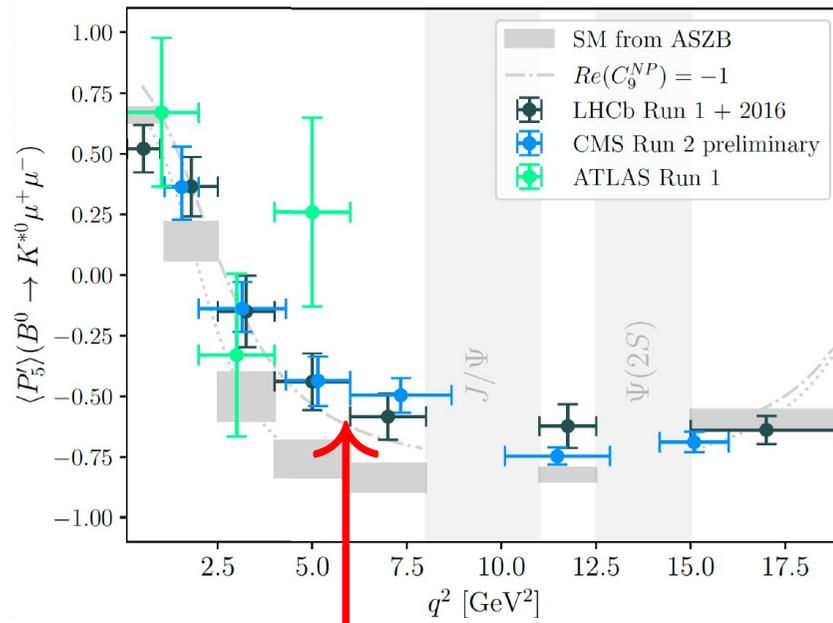
BSM, fluctuation, SM theory?

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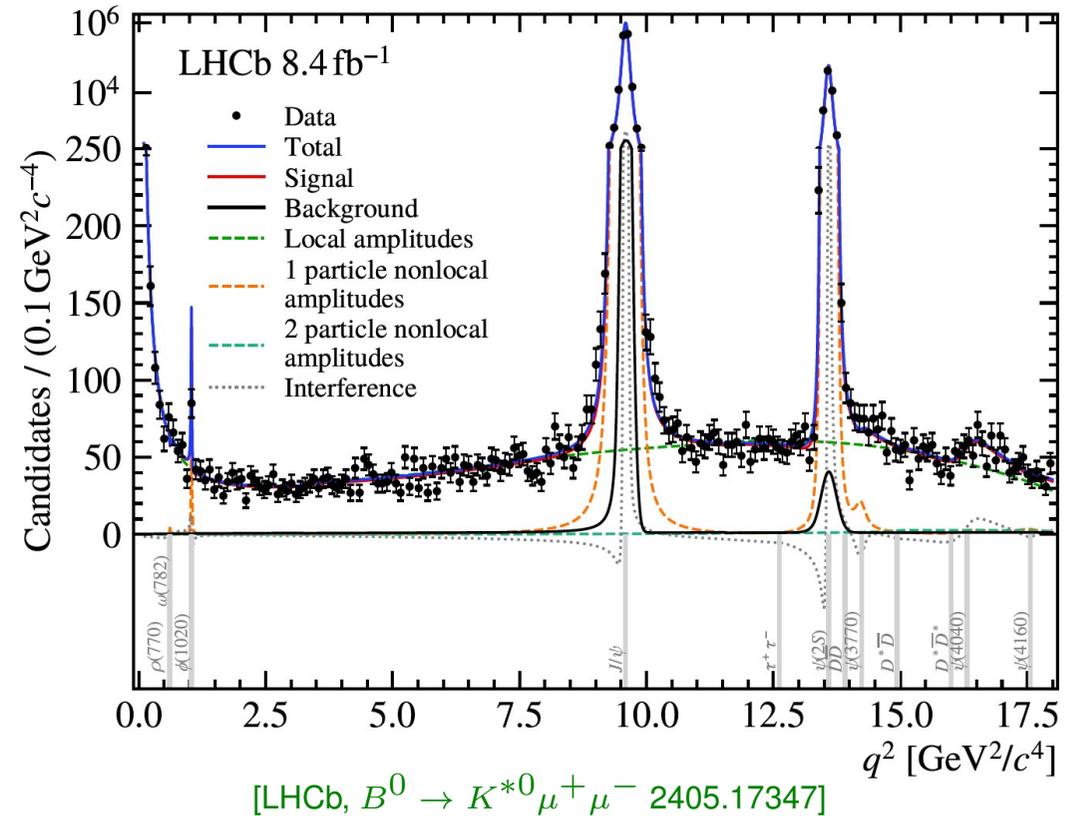
$B \to K\nu\bar{\nu}$ — unique to e^+e^- colliders

- Similar short-distance contributions, and much simpler long-distance ones
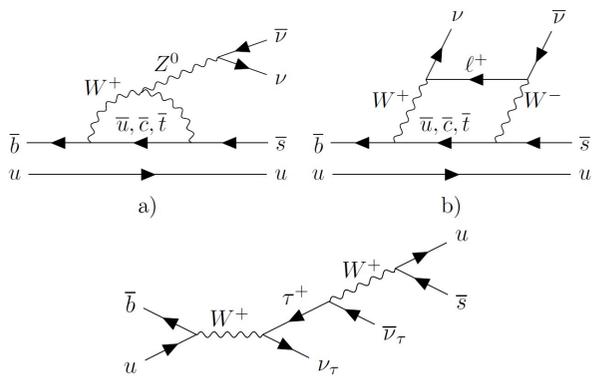
- Also relevant for dark sector searches ($B \to K+$invis.)
  (Is the excess in one bin of q^2?) [2309.00075, 2311.14629, 2602.09666]

- 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

$$10^5 \times \text{Br}(B^+ \to K^+ \nu\bar{\nu})$$

[Belle II, 2311.14647]
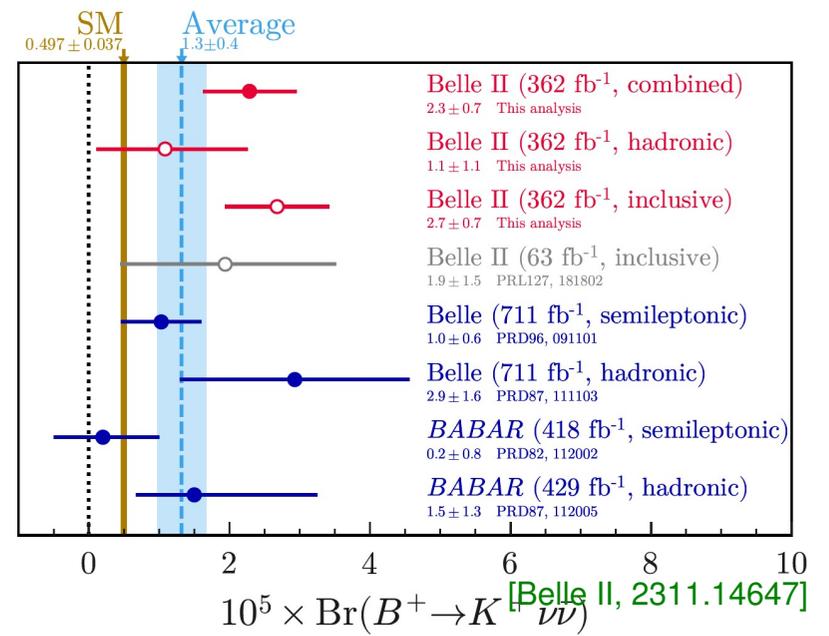
Belle II: 2.7σ from SM

• Some $B \to Dh$ decays factorize in heavy quark limit + power suppressed corrections

Branching fraction [10^{-3} for $b \to c\bar{u}d$, 10^{-4} for $b \to c\bar{u}s$]

Exp. value [PDG 2025]
SM prediction [JHEP (2021) 235]
SM prediction [EPJ C 80 (2020) 951]
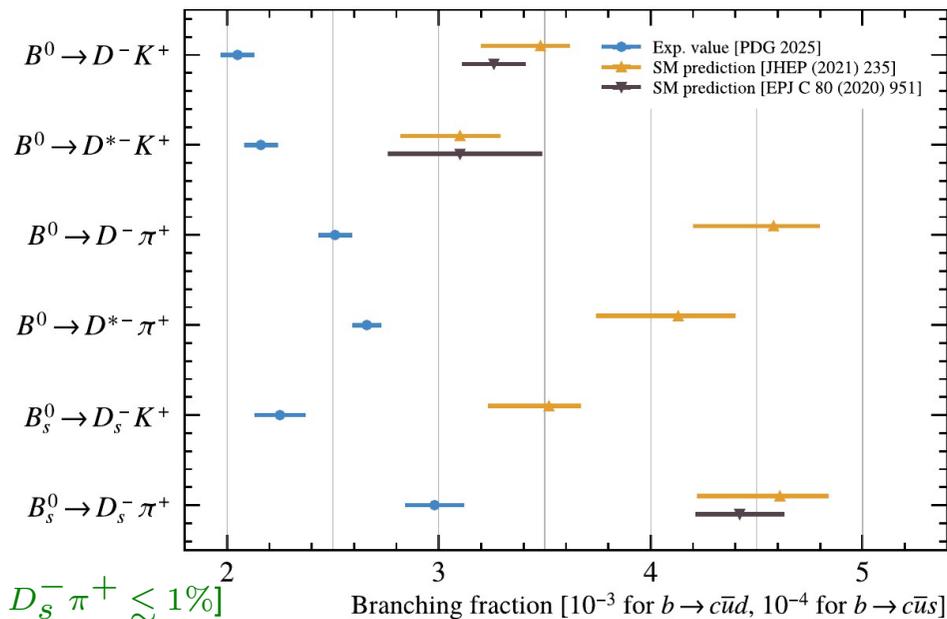
[LHCb, 2/10/2026: direct CPV in $B_s^0 \to D_s^- \pi^+ \lesssim 1\%$]

• Need: semileptonic form factor near $q^2 = 0$, estimate power suppressed corrections

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(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: $\arg(C/T) = \mathcal{O}(\Lambda_{\mathrm{QCD}}/m_b)$ **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?**

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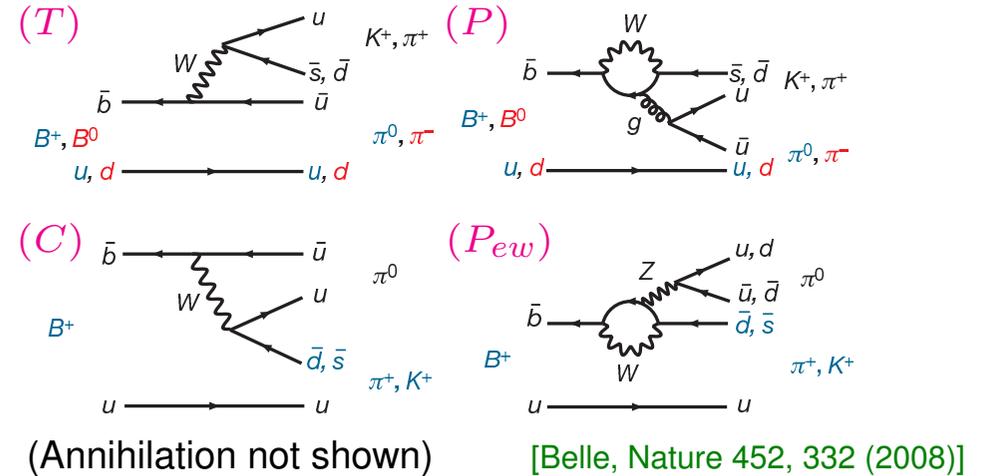
Belle II can make unique contribution

● Sum rule based on isospin for dominant amplitudes, and $SU(3)$ for subleading terms:

$$\delta_{K\pi} = \Delta(K^+\pi^-) + \Delta(K^0\pi^-) - 2\Delta(K^+\pi^0) - 2\Delta(K^0\pi^0) \qquad \Delta(f) = \Gamma(\overline{B} \to \bar{f}) - \Gamma(B \to f)$$

Expect: $|\delta_{K\pi}/\Delta(K^+\pi^-)| \lesssim$ few %   [Gronau, hep-ph/0508047]

$$I_{K\pi} = \frac{\delta_{K\pi}}{2\Gamma(B \to K^+\pi^-)}$$

Interesting to measure well beyond
Belle II sensitivity $\Rightarrow$ FCC-ee

[Belle II, 2207.06307]

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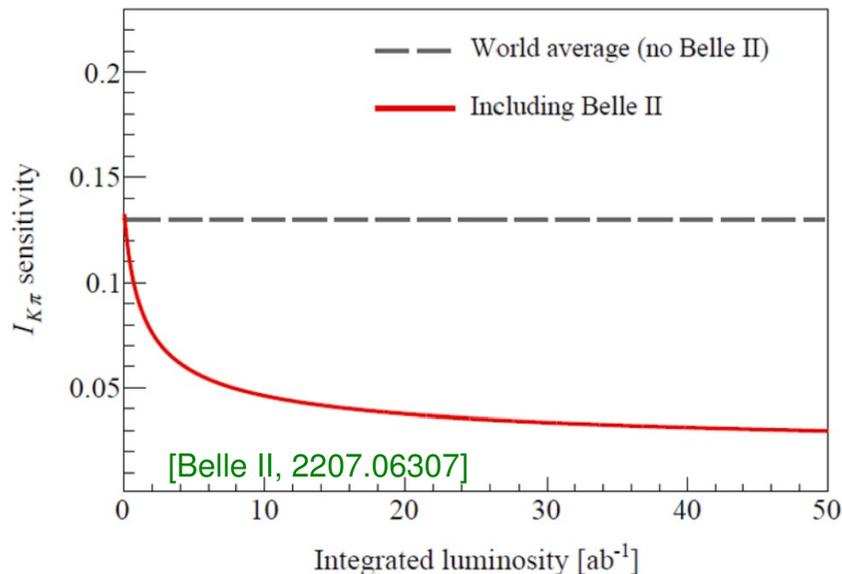
(Far) future

$\sin 2\beta$ and $B_q \to J/\psi\, h$

$$\left(q = u, d, s; \quad h = \pi, K\right)$$

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

  World average $\gamma = (66.4 \pm 2.8)^\circ$

  Theory uncertainty of "everything else" being discussed

- Most likely, β will be second best

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

- World average: $\sin 2\beta = 0.710 \pm 0.011 \quad (22.62 \pm 0.45)^\circ$

[2006.04824]

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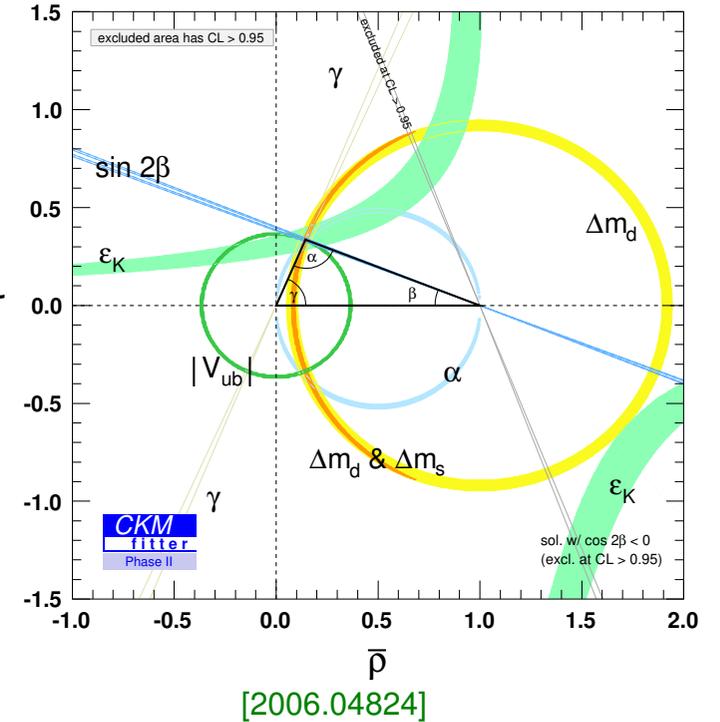
16 **observables in** $B_q \to J/\psi\,h$

Process	$\mathcal{B}$	A or C	S
$B^+ \to J/\psi\pi^+$	$(3.92 \pm 0.09) \times 10^{-5}$	$(+1.23 \pm 0.47) \times 10^{-2}$	—
$B^+ \to J/\psi K^+$	$(1.020 \pm 0.019) \times 10^{-3}$	$(+1.8 \pm 3.0) \times 10^{-3}$	—
$B_d \to J/\psi\pi^0$	$(1.74 \pm 0.07) \times 10^{-5}$	$(+8.5 \pm 8.5) \times 10^{-2}$	-0.87 ± 0.11
$B_d \to J/\psi K^0$	$(8.91 \pm 0.21) \times 10^{-4}$	$(+0.9 \pm 1.0) \times 10^{-2}$	$+0.708 \pm 0.012$
$B_s \to J/\psi\pi^0$	$< 1.21 \times 10^{-5}$	NA	NA
$B_s \to J/\psi K_S$	$(1.92 \pm 0.14) \times 10^{-5}$	$-0.28 \pm 0.41 \pm 0.08$	$-0.08 \pm 0.40 \pm 0.08$

Recent experimental results: LHCb, 2411.12178, 2402.05528; Belle II 2410.08622; Belle 2311.12724

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- Expand amplitudes: $A = (V_{cb}^* V_{cq})\big(A_c^{(0)} + \varepsilon A_c^{(1)}\big) + (V_{ub}^* V_{uq}) A_u^{(0)} + \dots$

- $SU(3)$ flavor symmetry $\Rightarrow 5\ A_c^{(0)},\ 4\ A_c^{(1)},\ 3\ A_u^{(0)}$ relations   [ZL & Robinson, 1507.06671]

- 6 independent complex amplitudes: $1\ A_c^{(0)},\ 2\ A_c^{(1)},\ 3\ A_u^{(0)}$

  So there must be 4 relations when working to this order

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- $A_{\psi K^+}/A_{\psi \pi^+} = -|V_{cd}/V_{cs}|^2$

  $\Rightarrow$ LHCb's ΔA_{CP} implies: $A_{\psi\pi^+} \simeq (1.23 \pm 0.47) \times 10^{-2}$ and $\mathcal{A}_{\psi K^+} \simeq (-6.5 \pm 2.5) \times 10^{-4}$

- $C^d_{\psi K^0}/C^s_{\psi \overline{K}^0} = -|V_{cd}/V_{cs}|^2$

  $\Rightarrow$ Narrow allowed range of $C^s_{\psi \overline{K}^0} = -0.17 \pm 0.19$ compared to direct measurement

- $(1 + \bar{\lambda}^2)s_{2\beta} = S^d_{\psi K_S} - \bar{\lambda}^2 S^d_{\psi\pi} - 2(\Delta_K + \bar{\lambda}^2 \Delta_\pi)c_{2\beta}\tan\gamma + \mathcal{O}(\varepsilon R_u \bar{\lambda}^2, R_u^2 \bar{\lambda}^2, \delta)$ [1507.06671]

  where: $\Delta_K = \dfrac{\Gamma(B_d \to \psi K^0) - \Gamma(B^+ \to \psi K^+)}{\Gamma(B_d \to \psi K^0) + \Gamma(B^+ \to \psi K^+)}$, $\Delta_\pi = \dfrac{2\Gamma(B_d \to \psi \pi^0) - \Gamma(B^+ \to \psi \pi^+)}{2\Gamma(B_d \to \psi \pi^0) + \Gamma(B^+ \to \psi \pi^+)}$

  $\Rightarrow \sin 2\beta - S^d_{\psi K_S} = 0.05 \pm 0.03$ (+ issues of production asym vs. isospin violation [2306.04686])

- $S^d_{\psi K_S} - s_{2\beta} = -|V_{cd}/V_{cs}|^2 \, (c_{2\beta}/c_{2\beta_s}) \, (S^s_{\psi K_S} + s_{2\beta_s})$ [2506.21675]

  $\Rightarrow S^d_{\psi K_S} - \sin 2\beta = 0.001 \pm 0.015$

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Extracting $\sin 2\beta$

- Substantial range of predictions in literature for $S^d_{\psi K_S} - \sin 2\beta$

- Neglecting $|(V_{ub}V_{us})/(V_{tb}V_{ts})(P/T)|$ uncertainty should be $\mathcal{O}(0.01)$

$$\sin 2\beta = S^d_{\psi K_S}$$

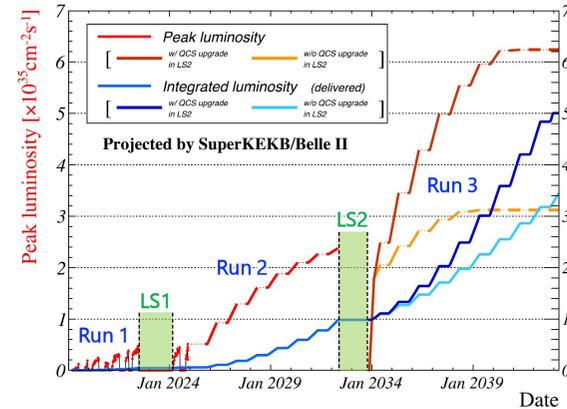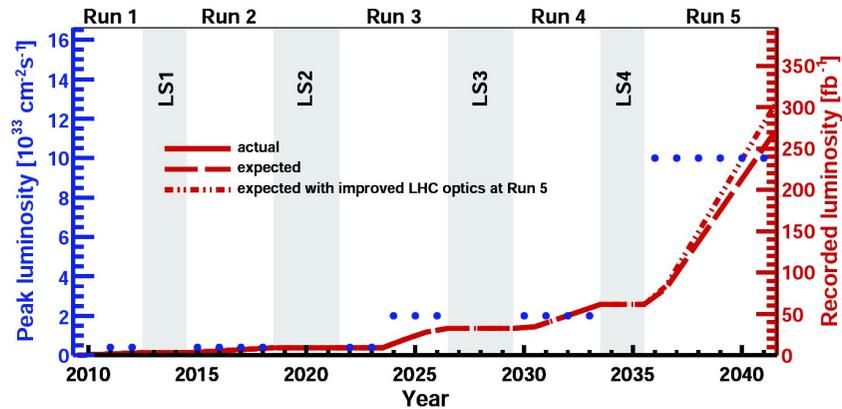- Using flavor $SU(3)$, uncertainty should be $\mathcal{O}(0.003)$

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

- At next order: hadronic uncertainty suppressed if $C^s_{\psi K_S}$ is small

$$\sin 2\beta = S^d_{\psi K_S} + \left|\frac{V_{cd}}{V_{cs}}\right|^2 \frac{c_{2\beta}}{c_{2\beta_s}} (S^s_{\psi K_S} + s_{2\beta_s}) \left[1 + \frac{R^{sd}_{\overline{K}^0 K^0} - 1}{2} + \frac{C^s_{\psi K_S} c_{2\beta_s}}{S^s_{\psi K_S}} \left(\varepsilon \operatorname{Im} \frac{A^{(1)}_c}{A^{(0)}_c} - \rho(1+\bar{\lambda}^2)\frac{C^s_{\psi K_S}}{2\eta}\right)\right]$$

- Wishlist: More precise $S^s_{\psi K_S}$ and $C^s_{\psi K_S}$ (LHCb result only used $3/\text{fb}$ in Run 1 [1503.07055])

Flavor @ FCC

● Of the future colliders discussed, only FCC would go well beyond LHCb + Belle II goals

Flavor physics at FCC-ee

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

- Can one appreciate / anticipate a 10^5 improvement? (Recall : Belle II / ARGUS $\sim 10^5$)
  Theory and experimental techniques both changed a lot! (e.g., full hadronic reconstruction)
  Asymmetric B factories at $\Upsilon(4S)$ great for CP violation, less ideal for (semi)leptonic decays

- What was not even tried at LEP? (due to lack of statistics or lack of physics interest)

- Some rare decay sensitivity may improve linearly with statistics; e.g., $Z \to \mu\tau, \mu e$, etc.

- A lot of what's usually called precision electroweak, also concern flavor
  (τ lifetime & mass, R_b, R_ℓ for each ℓ flavor, etc.)

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FCC-ee data sets for flavor

● 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 ($50\,\text{ab}^{-1}$)	27	27	tbd	—	—	65	45
tera-Z ($5 \times 10^{12}\ Z$)	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)

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

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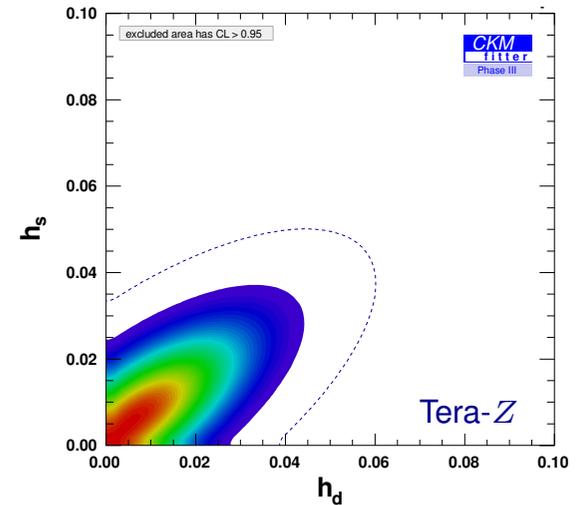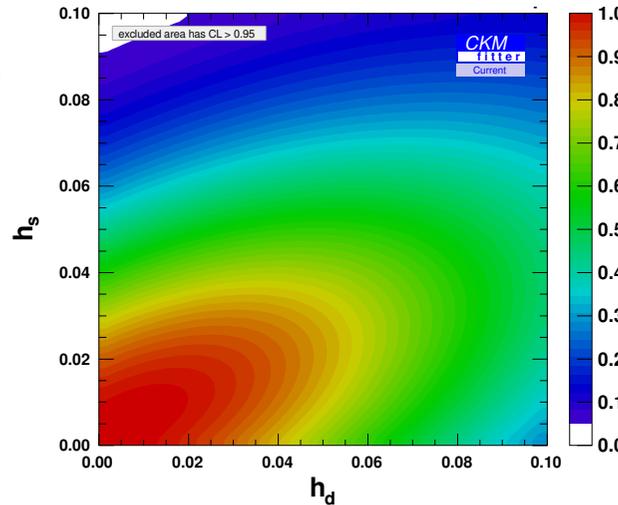
If BSM in $b \to c\tau\bar{\nu}$, must study $\nu\bar{\nu}$ & $\tau\tau$ modes
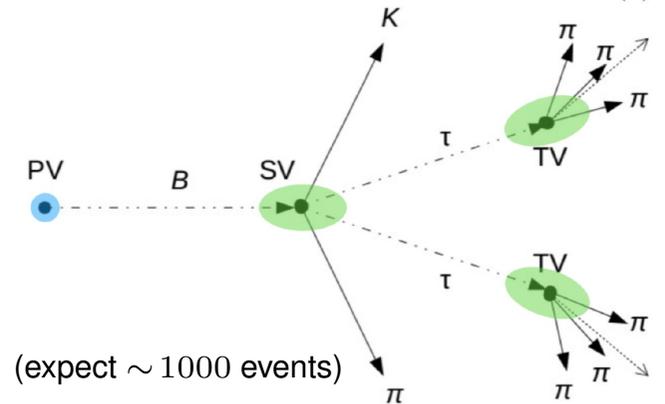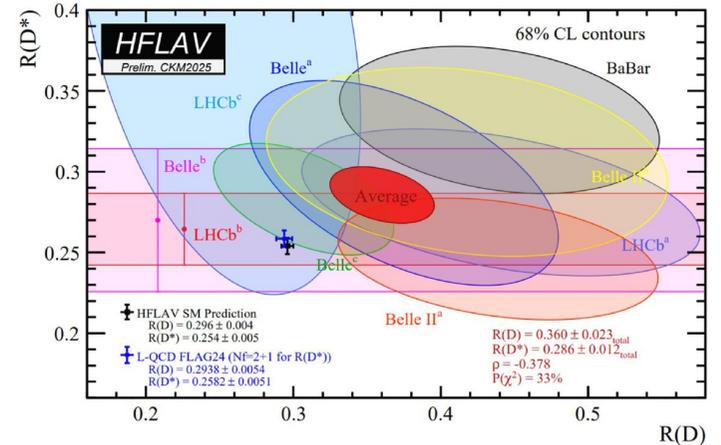
- SM and data in 3σ tension in $R(D^{(*)})$, if established, requires $\mathcal{O}(10\%)$ correction to a tree-level SM process

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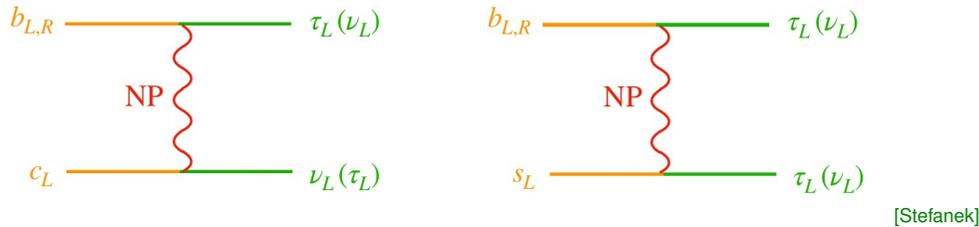
Only tera-Z can measure $B \to K^*\tau^+\tau^-$, $K^*\nu\bar{\nu}$ at SM level

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

- Boost of B in Z decay provides ideal environment

(expect ~ 1000 events)

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$B_{d,s} \to \mu^+\mu^-$: interesting at all imaginable statistics

- $\mathcal{B}_{\mathrm{SM}}(B_s \to \mu^+\mu^-) \sim 3 \times 10^{-9}$, BSM predictions extended orders of magnitudes higher

- $\mathcal{B}_{\mathrm{SM}}(B_d \to \mu^+\mu^-) \sim 10^{-10}$, LHCb expects 10% (300/fb), CMS expects 15% (3/ab)
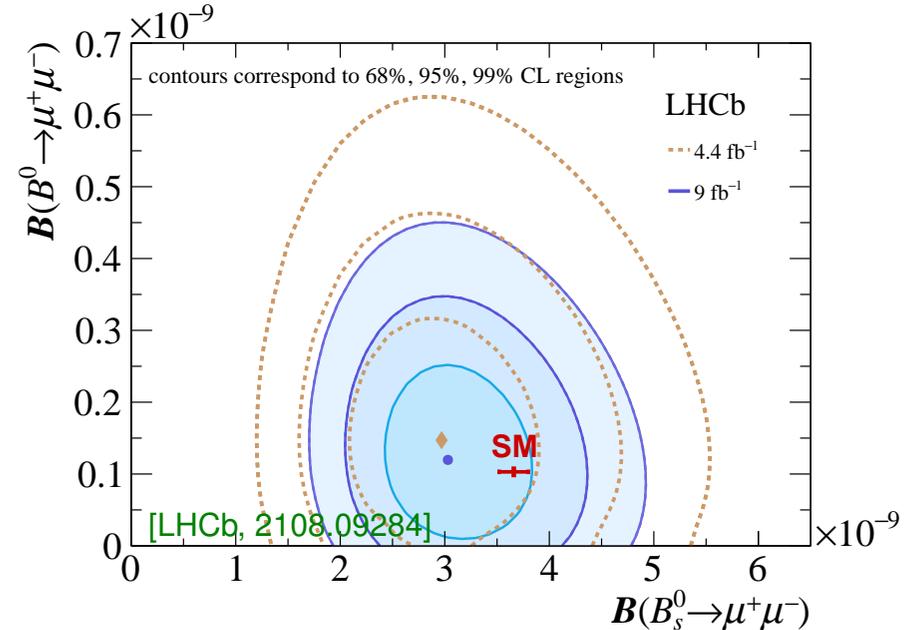
  SM uncertainty $\simeq (2\%) \oplus f_{B_q}^2 \oplus \mathrm{CKM}$, and may be further reduced

- 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 statistics...?)

- A decay with mass-scale sensitivity (dim.-6 operator) that competes with $K \to \pi\nu\bar{\nu}$

contours correspond to 68%, 95%, 99% CL regions

LHCb

4.4 fb^{-1}

9 fb^{-1}

SM

[LHCb, 2108.09284]

$\boldsymbol{B}(B_s^0 \to \mu^+\mu^-)$

PDG average: [LHCb, CMS, ATLAS]
$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.34 \pm 0.27) \times 10^{-9}$$

# 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 ($\times 10^3$) | 20767 | $\pm$ | 25 | **0.05** | 0.05 | Ratio of hadrons to leptons |

Systematic limitation in Midterm Report resolved by Feasibility Study — Acceptance for leptons

[Knapen, Langhoff, ZL, [2407.13815]]
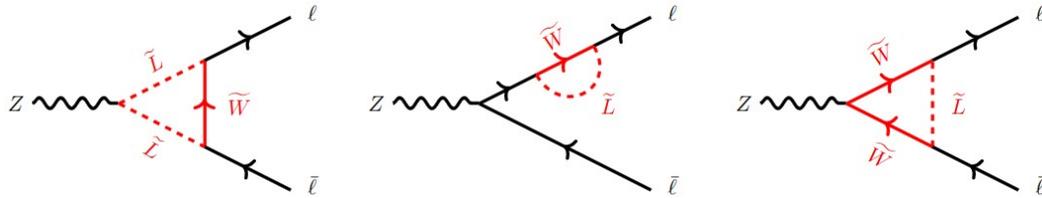
- Ultimate sensitivity depends on α_s, $\sin^2\theta_w$, etc.

  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
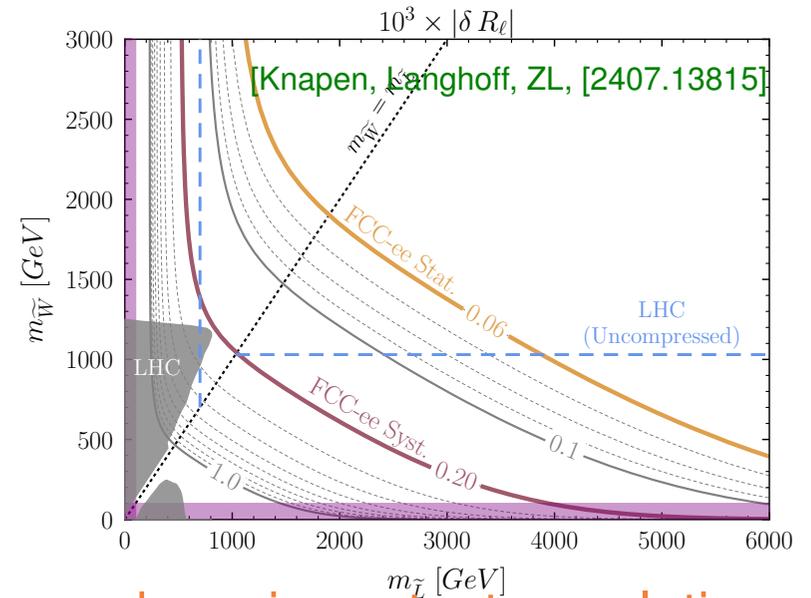
Final remarks

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 $(\text{exp. bound})/\text{SM} \gtrsim 10^3$ (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!?)

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Workshop advertisement

Flavours at FCC Workshop

Physics at the Flavoured Circular Collider — Next workshop @ CERN: June 16−19
Goal: deepen understanding of the potential of the FCC for flavor physics (2025−2027)

Conclusions

- Flavor physics probes scales $\gg 1\,\mathrm{TeV}$, sensitivity limited by statistics
  New physics could show up any time measurements improve

- There is much to be learned from future measurements at LHCb, Belle II, ATLAS, CMS

- 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 is a leap from LEP, rich physics program, can be a discovery machine
  In flavor physics, the only way to go well beyond Belle II & LHC(b)

- Compelling reasons to aim for the largest data sets that technologies may allow

Extra slides

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?

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)

$$|C_7^{\mathrm{incl}} V_{tb} V_{ts}| = (14.77 \pm 0.51_{\mathrm{fit}} \pm 0.59_{\mathrm{theory}} \pm 0.08_{\mathrm{param}}) \times 10^{-3}$$

$$m_b^{1S} = (4.750 \pm 0.027_{\mathrm{fit}} \pm 0.033_{\mathrm{theory}} \pm 0.003_{\mathrm{param}}) \, \mathrm{GeV}$$
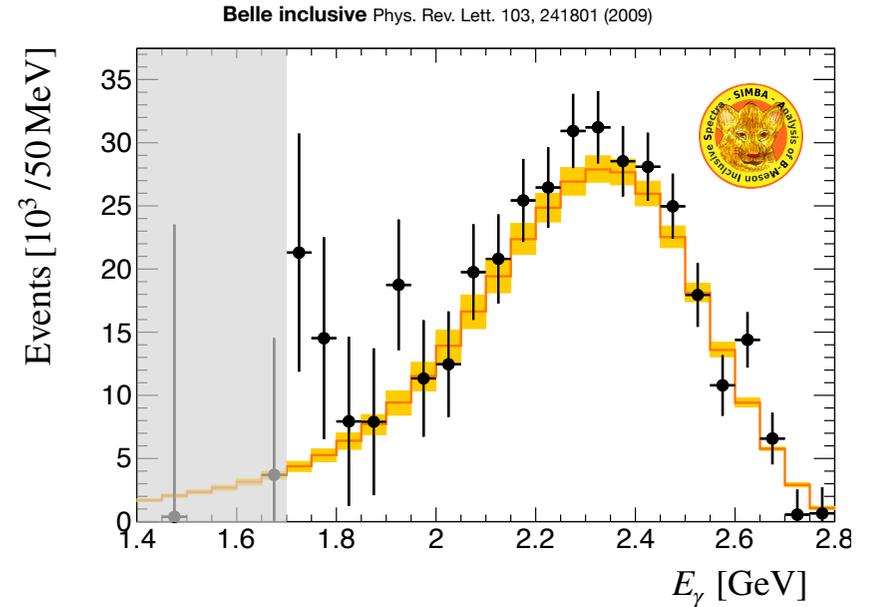
We find underestimated uncertainty by HFLAV
$\Rightarrow$ more room for NP

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?

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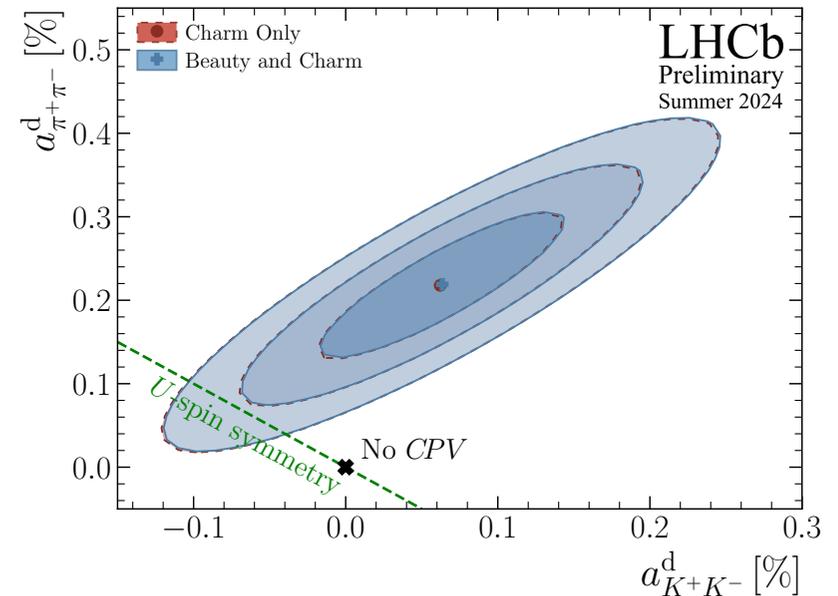
CP violation in $D - \bar{D}$ mixing

- **Mixing generated by down quarks**

- **SUSY:** up-type squarks in box diagrams, interplay of D & K bounds
  ⇒ 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**
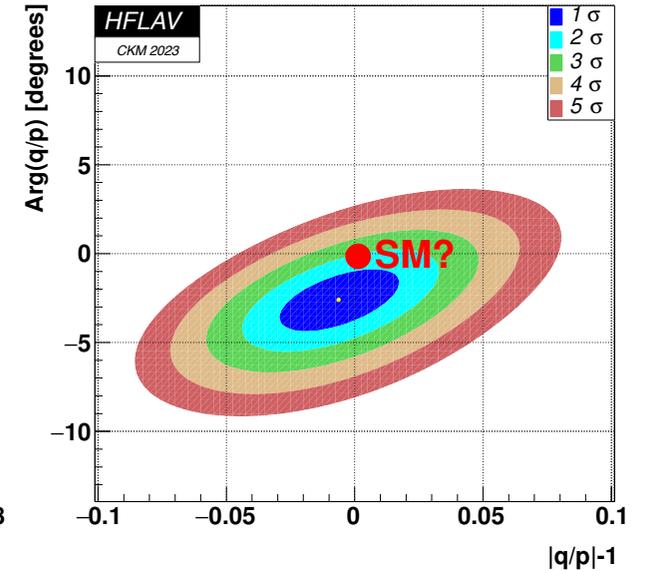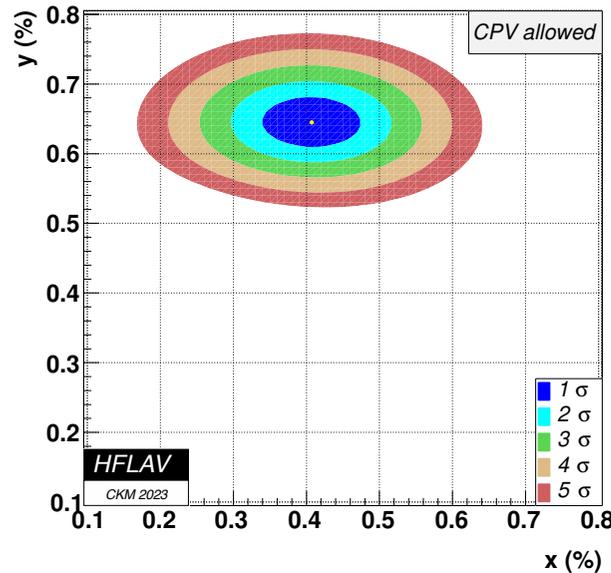
CP violation in $B_{d,s}$ mixing: $A_{\mathrm{SL}}^{d,s}$
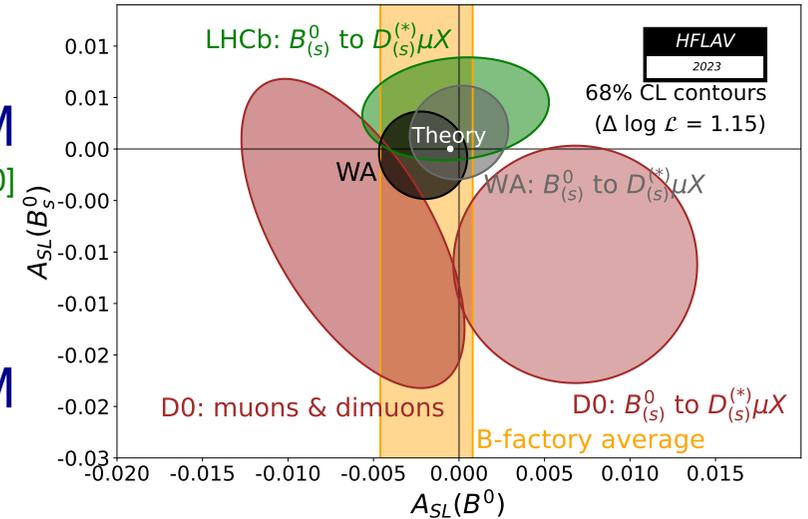
- **Only observed in Kaons**

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

  [hep-ph/0202010]

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

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

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

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

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

ZL – p. v

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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

- 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)

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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)

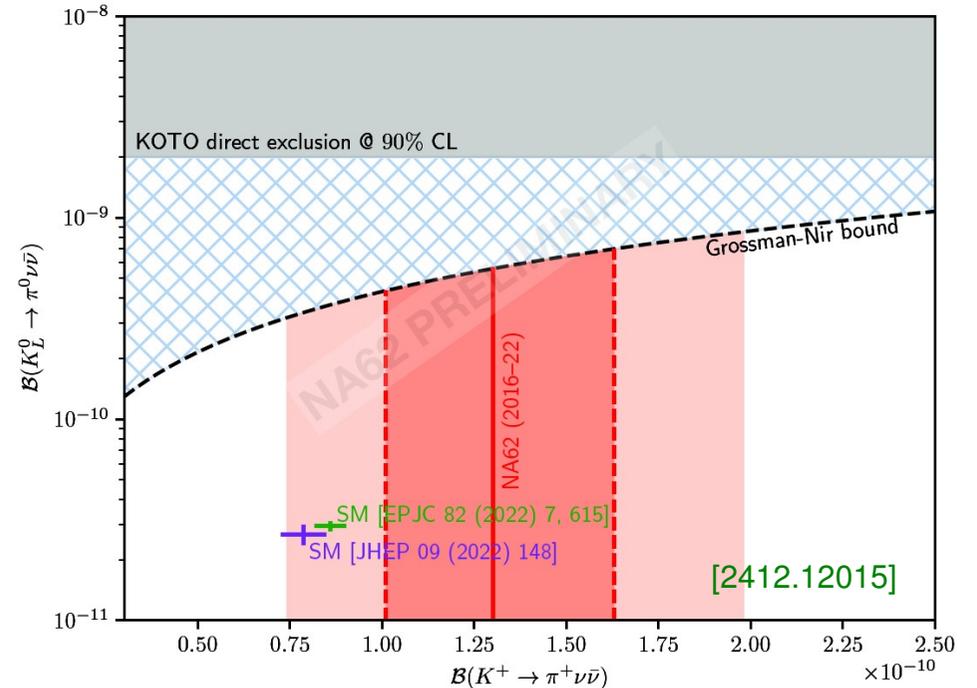- $K^+ \to \pi^+ \nu \bar{\nu}$ searched for since 1960s (longer than Higgs), sensitive to $100\,\mathrm{TeV}$ scale

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

- Recently: first $> 5\sigma$ observation [NA62, 2412.12015]
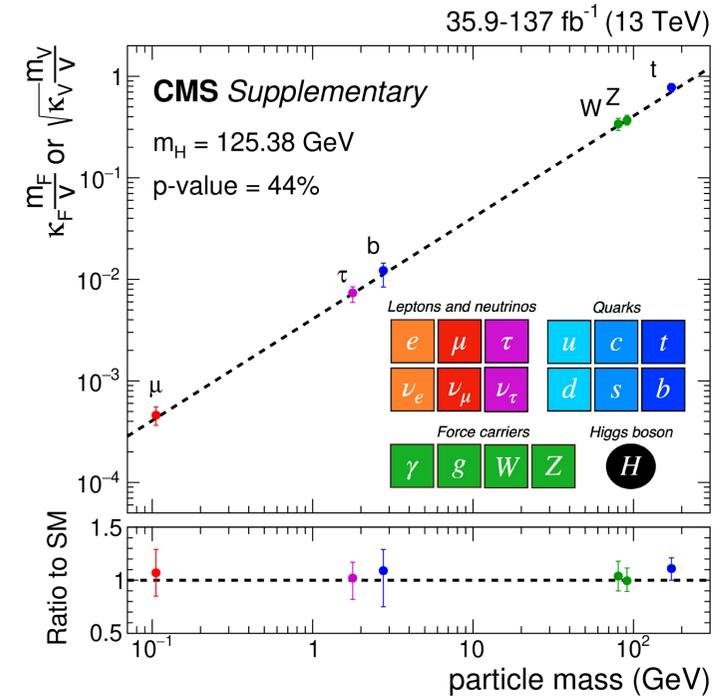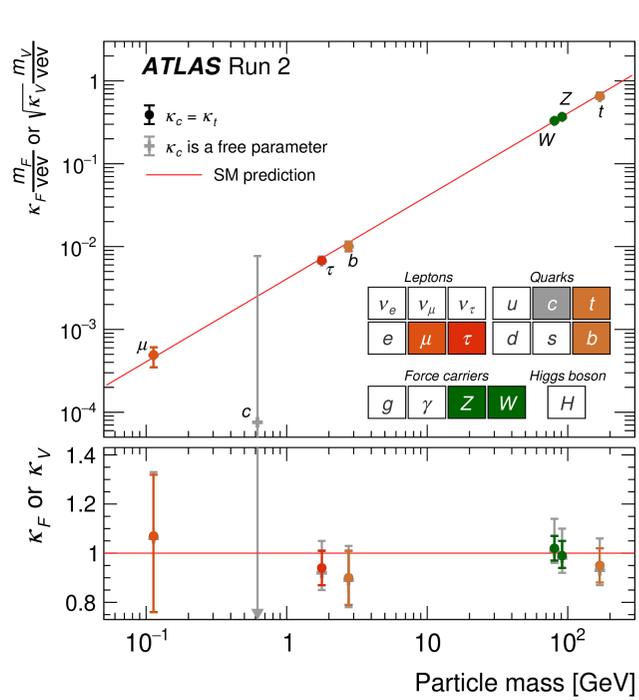
  $$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$$

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

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

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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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