Opportunities at FCC-ee
Focusing on Flavor Physics

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My views on the future program

- Building a $10\times$ better microscope than the LHC is a clear case
  We ought to explore Nature to the shortest distance scales that technologies allow
- When HL-LHC stops running, Higgs will have been studied for nearly 30 years
  LHC is a Higgs factory, will want better precision & probe unexplored Higgs couplings — like other areas
- We don't know where and how new physics will show up $\Rightarrow$ need broad program
  We must study the Higgs as much as possible, but it's no longer uncharted territory (except for 1st gen.)
  $\Rightarrow$ A high-p_T anomaly, a Higgs coupling anomaly, or a flavor anomaly, will be on similar footings
- If any deviation from SM is established, it would make a clear case for FCC-ee
- FCC-ee can be a discovery machine; very rich and challenging physics program
  FCC-ee measurements will be essential to fully exploit FCC-hh (α_s, m_t, etc.)

Outline

- Why flavor?
  Unique sensitivites
- Beyond LHCb and Belle II: FCC
  Huge increases in data, what can they teach us?

New physics scales probed

- Heavy new physics generates dimension > 4 operators in SMEFT

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

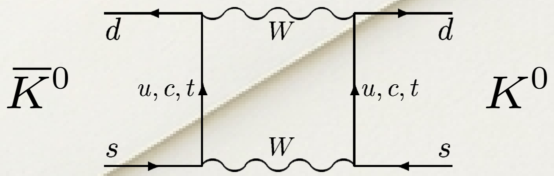
- Dim-5 $LL\phi\phi$ discovered, iff m_ν violates lepton # ($0\nu\beta\beta$?); No dim-6 term established yet
- Baryon number violation: $\dfrac{QQQL}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^{16}\,\text{GeV}$
- Higgs & precision electroweak: $\dfrac{(\phi D^\mu \phi)^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^{4}\,\text{GeV}$
- Flavor and CP violation (and EDMs): $\dfrac{QQQQ}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^{(3\dots8)}\,\text{GeV}$

  Flavor and CPV are the only experimental probes of the $10^2 - 10^5\,\text{TeV}$ scale
- New physics could show up any time the sensitivities improve (by a substantial amount)

Origin of high scale sensitivity

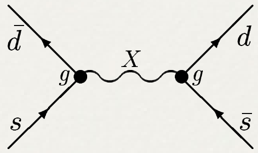
- Back of an envelope calculation of Δm_K: loop, CKM, GIM suppressions
- Why is $\Delta m_K / m_K \sim 7 \times 10^{-15}$?

  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:

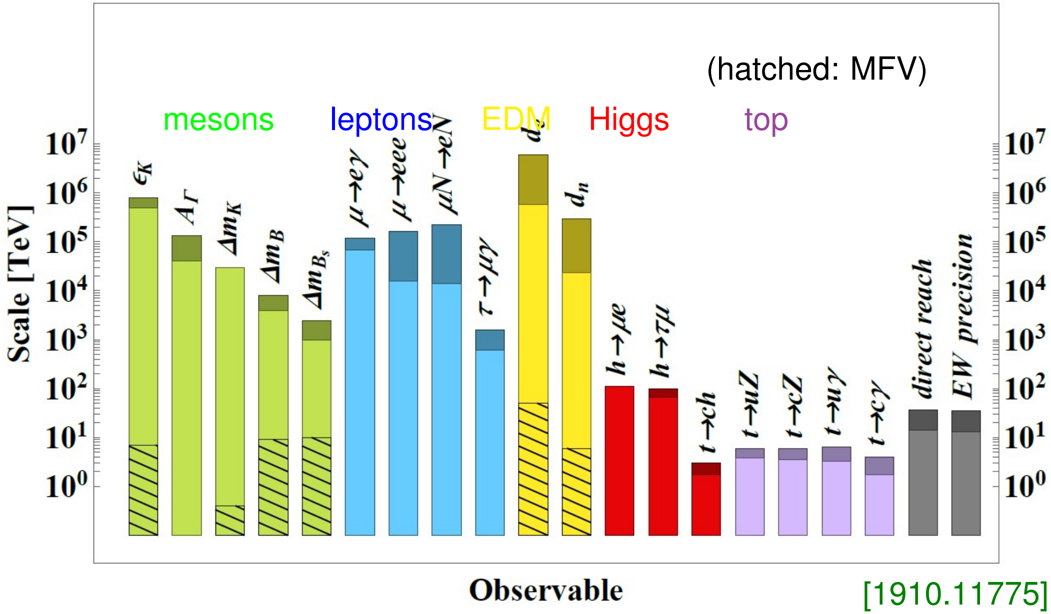


$$\frac{\Delta m_K^{(X)}}{\Delta m_K} \sim \frac{g^2\, \Lambda_{\mathrm{QCD}}^3}{M_X^2\, \Delta m_K} \Rightarrow M_X > g \times 10^3\,\mathrm{TeV}$$

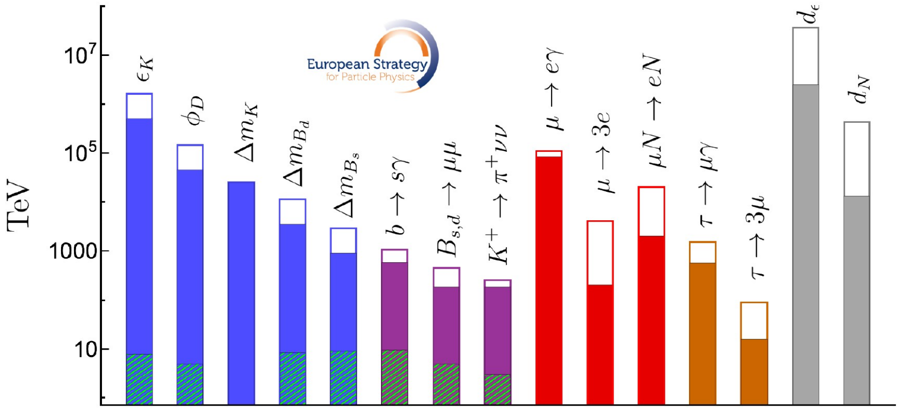
- Alternatively, sensitivity to TeV-scale particles with one-loop couplings $[g \sim \mathcal{O}(10^{-3})]$

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

Scales, as shown in European strategy



[1910.11775]



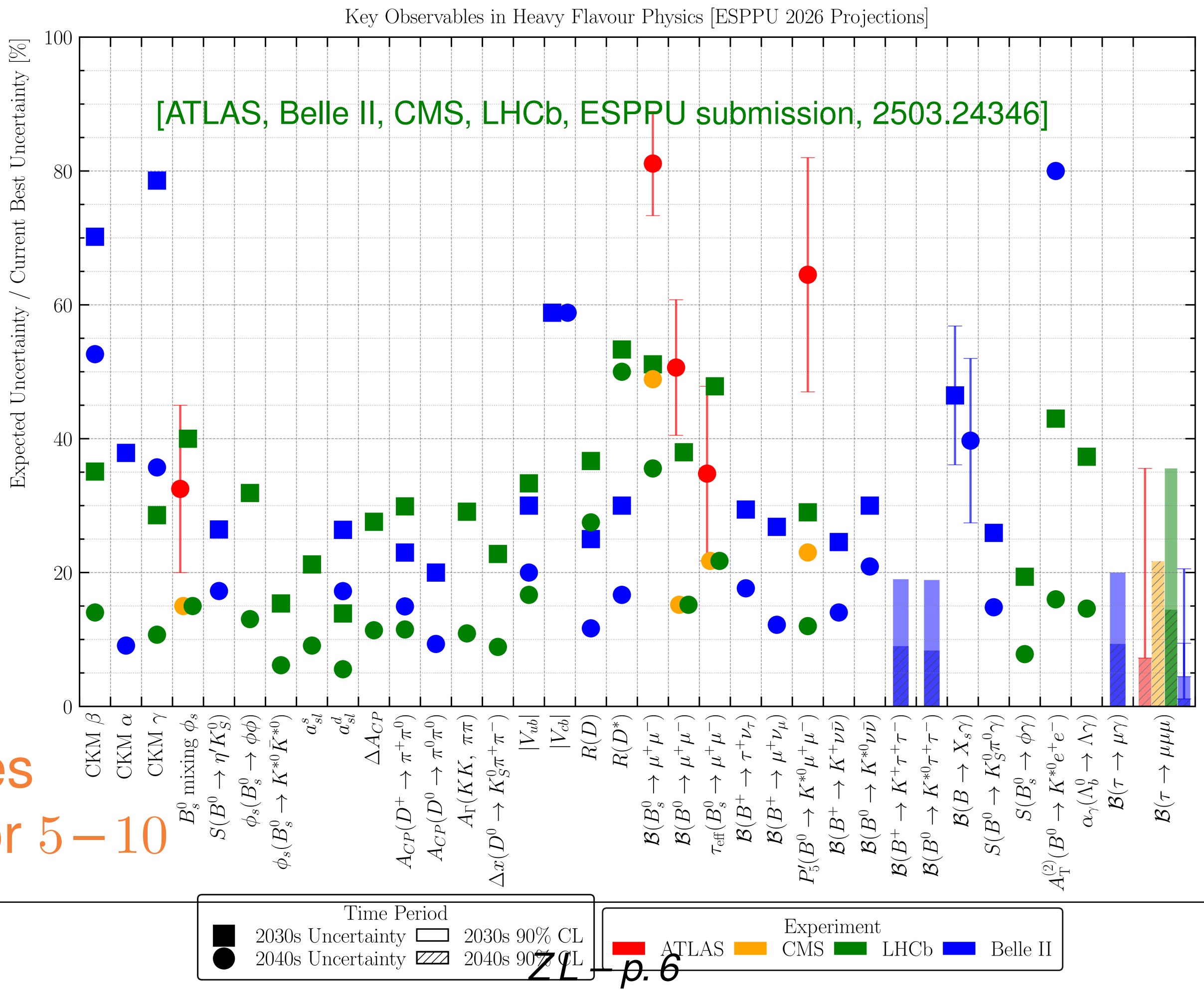
[2511.03883]

- All TeV-scale NP models must contain some mechanism to avoid violating constraints

  Models devised to make deviations from SM small, revisit model building when tensions with SM arise

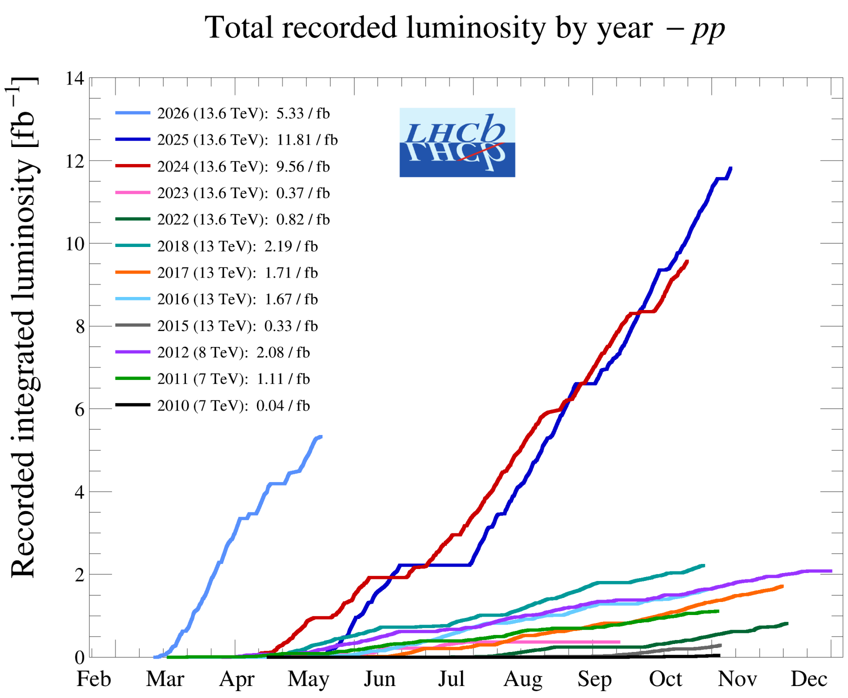
- Suppressions in SM are strongest for kaons, often Δm_K & ϵ_K are the most constraining

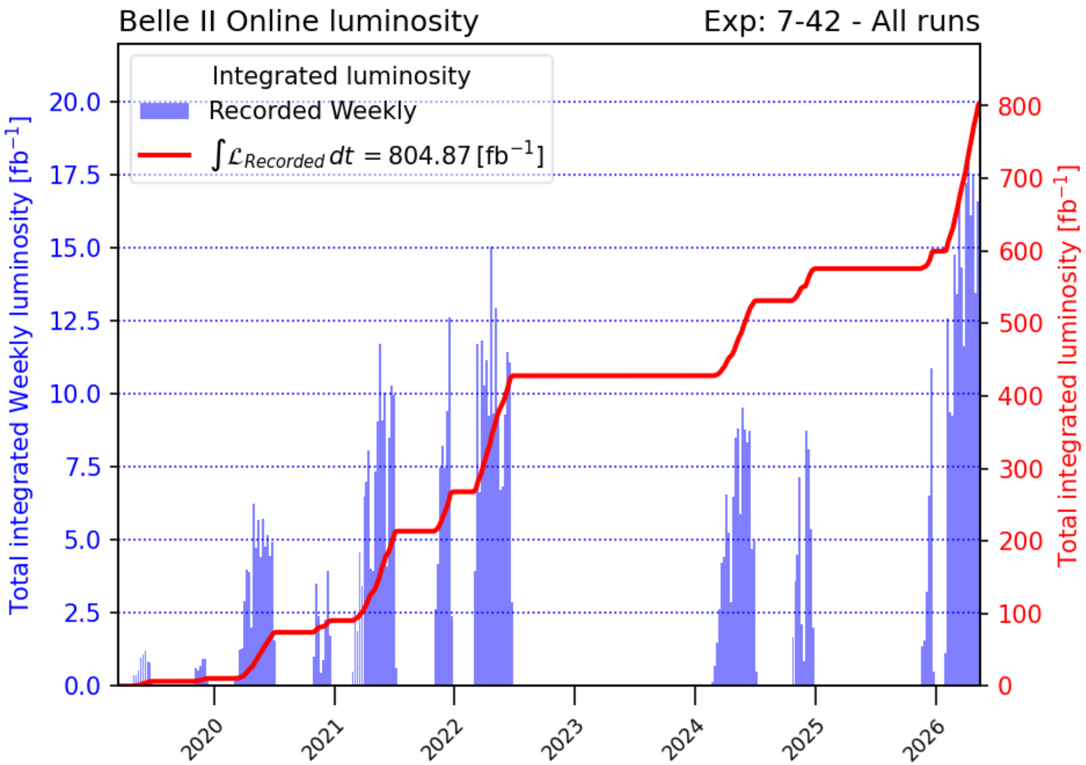
Large upcoming improvements



Many uncertiainties will shrink by factor $5-10$

Past LHCb and Belle II data taking





(Hardly any LHCb result is available yet from Run 3)

(As of Spring 2026, Belle II data > Belle data)

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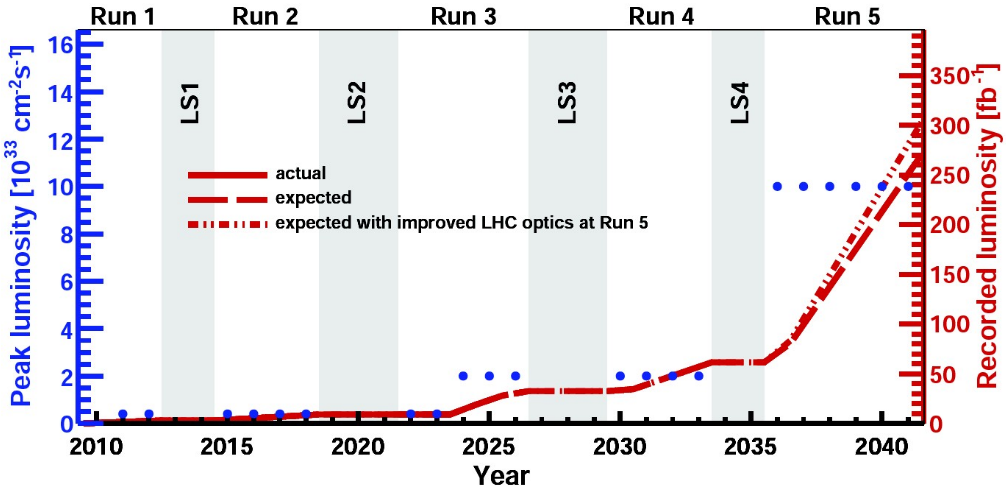
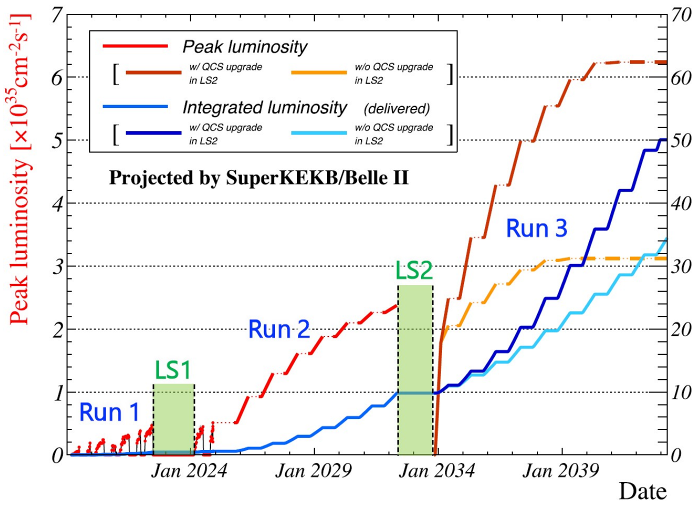
Future LHCb and Belle II plans



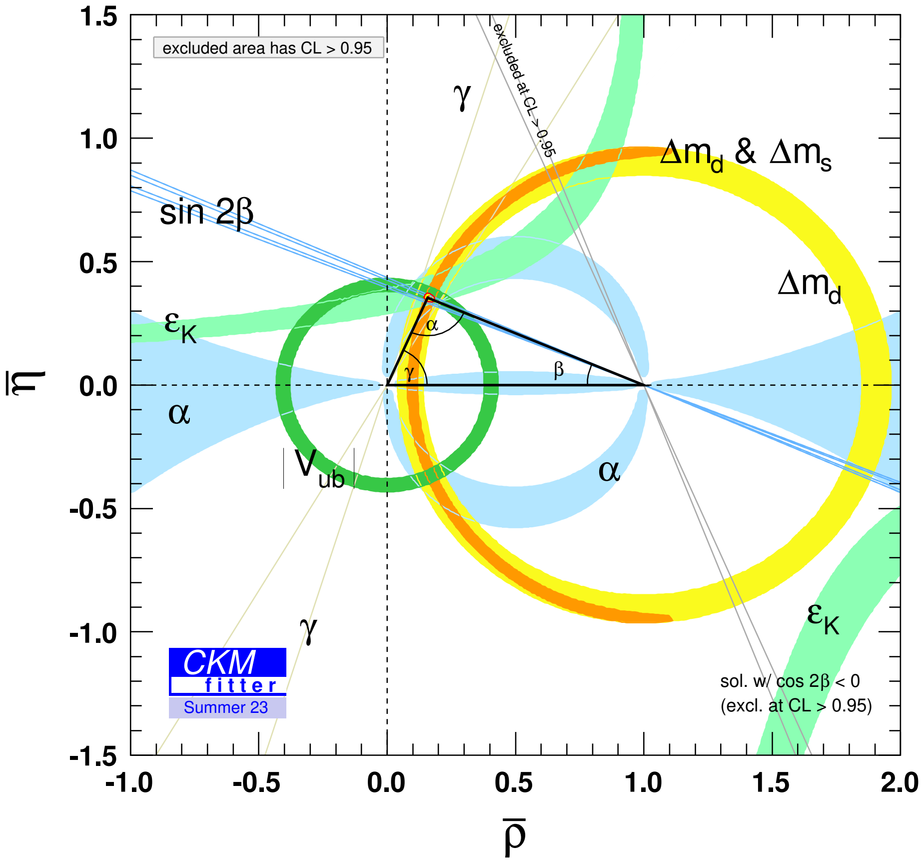


- LHCb upgrade in LS2 (inst. lumi.: 2×10^{33})
- LHCb Upgrade II in LS4 (inst. lumi.: 1.5×10^{34})
ATLAS & CMS competitive in some modes

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

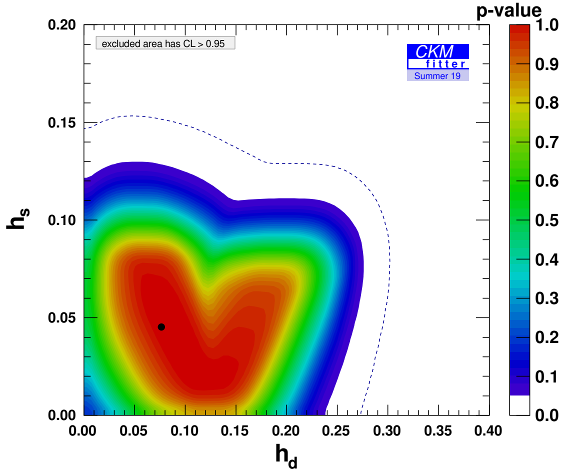
Snapshot: CKM fit in the SM

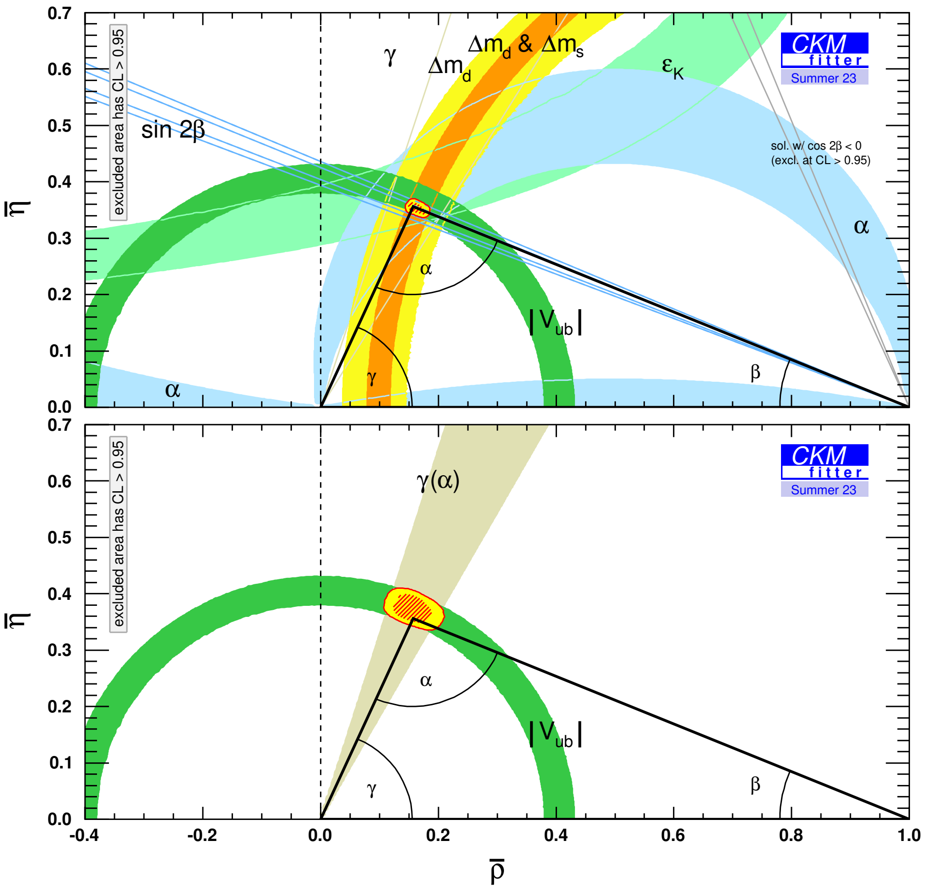
- Spectacular progress in the last 25 years
- The CKM mechanism describes consistently CP violation and flavor changing processes
- We did not know this, not even at $\mathcal{O}(1)$ level before BaBar and Belle



Snapshot: CKM fit in the SM

- Spectacular progress in the last 25 years
- Looser constraints if NP is allowed in the fit
  Full fit (upper) vs. tree-dominated (lower) plot
- Implies, e.g., that $10-20\%$ corrections to $B-\overline{B}$ mixing are still possible





Hints of deviations from the SM

- From a distance, everything looks fine... looking closer:

  Less than half of B decays measured; most are incalculable, we have theories for some (HQET, SCET)

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

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

  – Charged-current nonleptonic $b \to c$ decays (e.g., $B \to D^{(*)}h \quad [h = K, \pi]$)

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

  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?

Breadth and surprises

- Most cited physics paper of each B factory was not in the planned program (#s mid-April)

- BaBar:

  Evidence for an excess of $\bar{B} \to D^{(*)}\tau^- \bar{\nu}_\tau$ decays #2
  BaBar Collaboration • J.P. Lees (Annecy, LAPP) et al. (May, 2012)
  Published in: *Phys.Rev.Lett.* 109 (2012) 101802 • e-Print: 1205.5442 [hep-ex]
  pdf links DOI cite claim reference search 1,364 citations

- Belle:

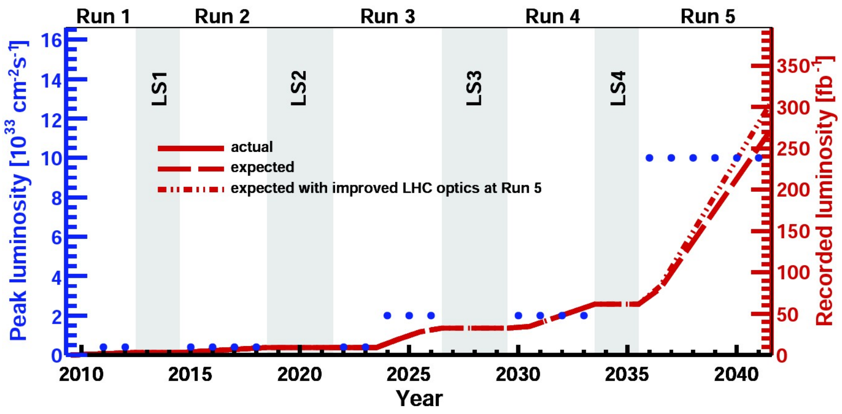
  Observation of a narrow charmonium-like state in exclusive $B^\pm \to K^\pm \pi^+ \pi^- J/\psi$ decays #1
  Belle Collaboration • S.K. Choi (Gyeongsang Natl. U.) et al. (Sep, 2003)
  Published in: *Phys.Rev.Lett.* 91 (2003) 262001 • e-Print: hep-ex/0309032 [hep-ex]
  pdf links DOI cite claim reference search 2,938 citations

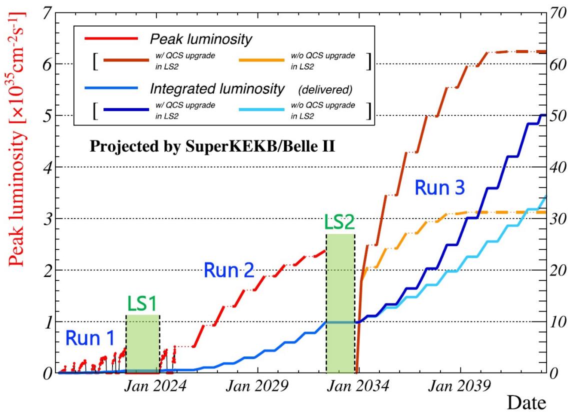
- LHCb:

  Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays #1
  LHCb Collaboration • Roel Aaij (CERN) et al. (Jul 13, 2015)
  Published in: *Phys.Rev.Lett.* 115 (2015) 072001 • e-Print: 1507.03414 [hep-ex]
  pdf links DOI cite claim reference search 2,129 citations

- Huge increases in data often yielded unexpected discoveries

Far future flavor





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

FCC-ee data sets for flavor

- Production yields, compared to Belle II goals: [Monteil & Wilkinson, 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 (5×10^{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]

- $t\bar{t}$ threshold: m_t is a flavor parameter... can FCNC sensitivity surpass that of HL-LHC?

Flavor physics at FCC-ee

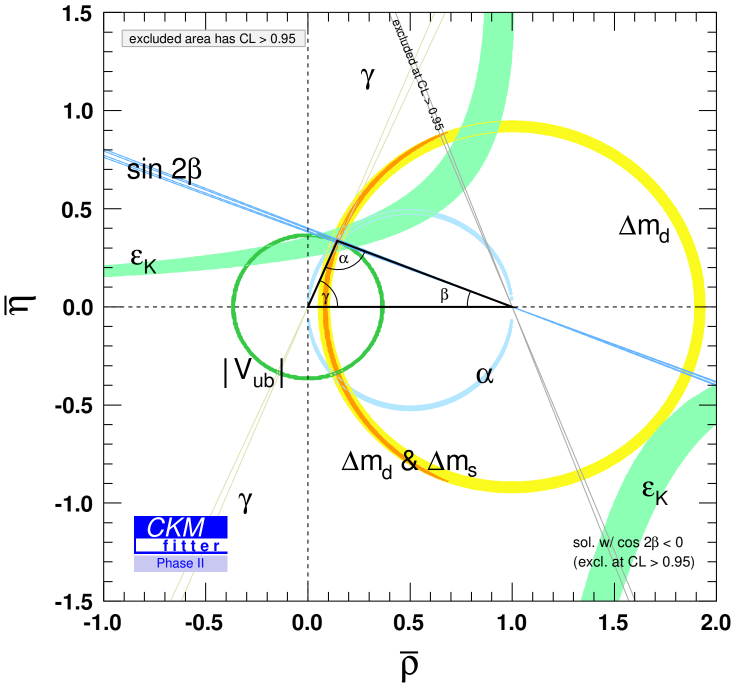
- $10^5 \times$LEP is the right target (mass scale) $\propto$ (uncertainty)$^{-1/2}$ $\propto$ (stat)$^{-1/4}$
- Can one appreciate / anticipate a 10^5 improvement? (Recall: Belle II goal / ARGUS $\sim 10^5$)
  Theory and experimental techniques both changed a lot! (e.g., full hadronic reconstruction)
  Asymmetric B factories on $\Upsilon(4S)$ were devised 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 sensitivities 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
  (R_b, R_ℓ for each lepton flavor, τ lifetime & mass, etc.)

Towards theory at the per mille level

- Theory uncertainty of γ is negligible (2nd order EW)
  World average $\gamma = (66.4 \pm 2.8)^\circ$

  Theory uncert. of everything else nontrivial at $\sim 1\%$ level
- Most precise so far: $\sin 2\beta = 0.710 \pm 0.011\ (22.62 \pm 0.45)^\circ$

  Precision of γ may overtake that of β
- Can the precision of β keep up with statistics?
  There are claims of possibly large V_{ub} ("penguin") contamination
- Which other measurements can reach such precision?
  (Both theory and experiment)



[2006.04824]

$B_q \to J/\psi\, h$ using $SU(3)$ flavor

- Expand amplitudes: $A(B_q \to J/\psi\, h) = (V_{cb}^* V_{cq})\big(A_c^{(0)} + \varepsilon A_c^{(1)}\big) + (V_{ub}^* V_{uq}) A_u^{(0)} + \dots$
- $SU(3)$ flavor symmetry $\Rightarrow$ 5 $A_c^{(0)}$, 4 $A_c^{(1)}$, 3 $A_u^{(0)}$ relations [ZL & Robinson, 1507.06671]
- 16 observables vs. 6 independent complex amplitudes: 1 $A_c^{(0)}$, 2 $A_c^{(1)}$, 3 $A_u^{(0)}$
- 4 relations when working to this order

- "New" relation: (might have been implicitly known)

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

[ZL, Y. Nir, R. Schein, 2506.21675]

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

- Uncertainty can be reduced by better measurement of $S^s_{\psi K_S}$ in $B_s \to \psi K_S$ (Run 1 only)

CP violation in $B^\pm \to \pi^\pm\pi^0$

- Direct CP asymmetry: $A_{CP}(B^\pm \to \pi^\pm\pi^0) = \dfrac{\Gamma(B^- \to \pi^-\pi^0) - \Gamma(B^+ \to \pi^+\pi^0)}{\Gamma(B^- \to \pi^-\pi^0) - \Gamma(B^+ \to \pi^+\pi^0)}$

  World average: $A_{CP}(B^\pm \to \pi^\pm\pi^0) = -0.01 \pm 0.04$ (past theory papers: $10^{-4} - 10^{-2}$)

- In the "isospin limit": $A_{CP}(B^\pm \to \pi^\pm\pi^0) = 0$, however: [Grossman, ZL, Nir, 2605.04137]

  electroweak penguins, $\pi - \eta$ mixing, isospin violation in QCD penguins, $\Delta I = 5/2$

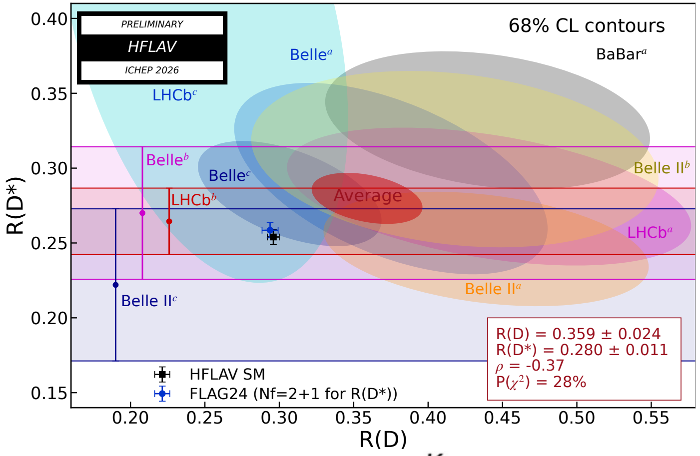
  Our SM prediction: $A_{CP}(B^\pm \to \pi^\pm\pi^0) \sim 3 \times 10^{-3}$ $\Rightarrow$ try to measure better!

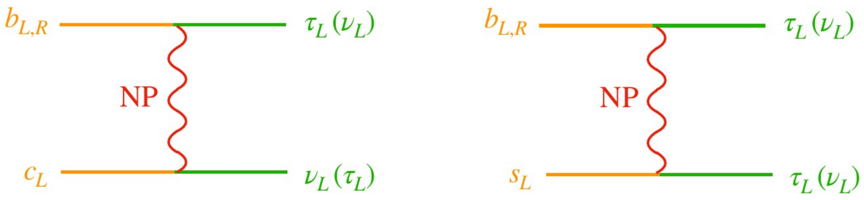
- Understanding the accuracy of isospin relations in charmless B decays is important:
  - $A_{CP}(B^\pm \to \pi^\pm\pi^0)$ has direct implications for the extraction of α from $B \to \pi\pi$
  - May help understand the $K\pi$ puzzle (Gronau's sum rule based on isospin)
  - $A_{CP}(D^\pm \to \pi^\pm\pi^0)$ may shed light on the puzzle regarding the large value of ΔA_{CP}

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

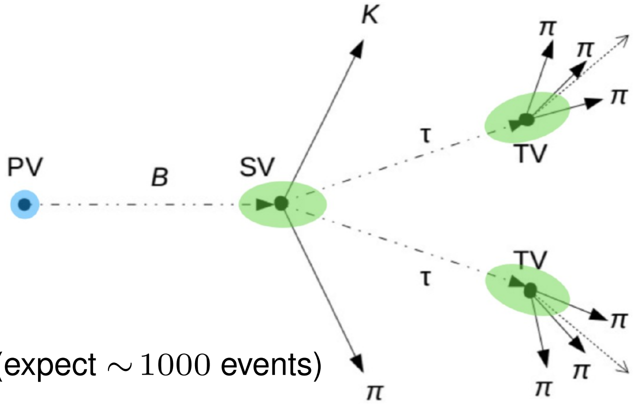




[Stefanek]

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

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



(expect ~ 1000 events)

- Boost of B in Z decay provides ideal environment

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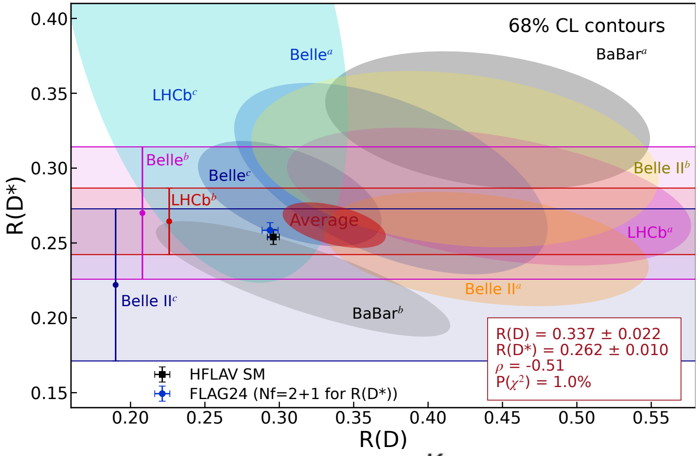

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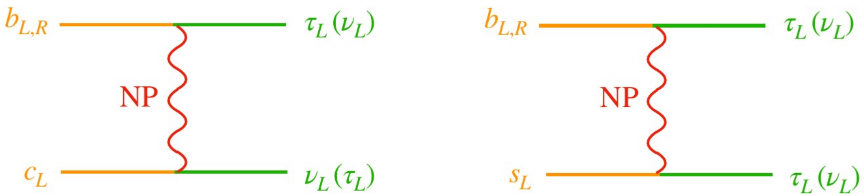

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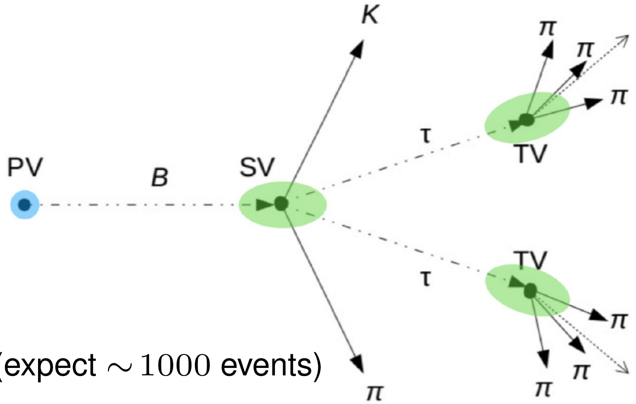


(expect ~ 1000 events)

- Boost of B in Z decay provides ideal environment

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

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

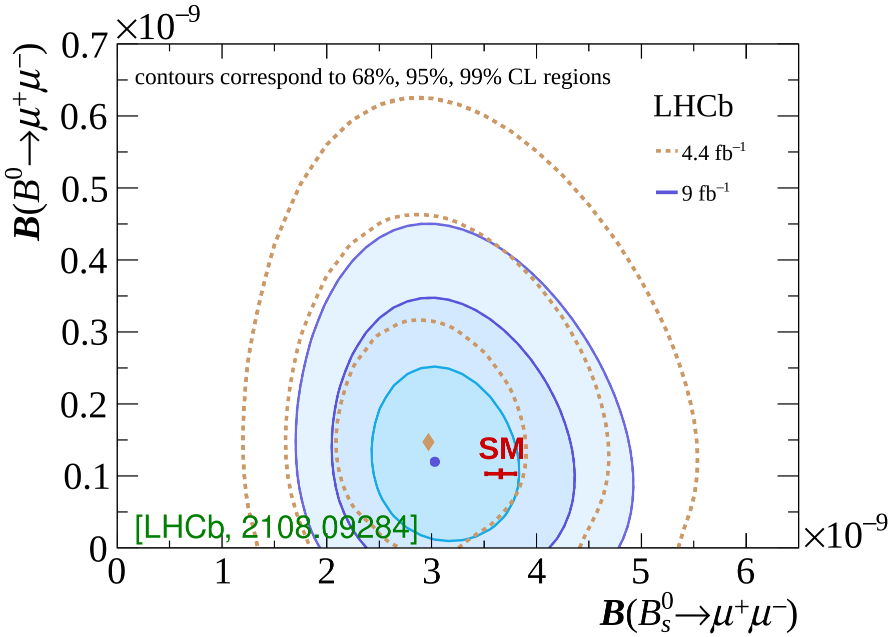
  SM uncertainty $\simeq (2\%) \oplus f^2_{B_q} \oplus \text{CKM}$, and may be further reduced

- 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 $K \to \pi\nu\bar\nu$



PDG average: [LHCb, CMS, ATLAS]

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

(Very) rare (semi)leptonic decays

- Unique capabilities for decays with large missing energy, i.e., ν or τ in final state
  (And better than LHCb for $e^{\pm}$)

- Tera-Z could be the first to measure:
  Many decays mediated by $b \to s\nu\bar{\nu}$ or $b \to s\tau^+\tau^-$, and their $b \to d$ counterparts
  $B \to K^{(*0)}\tau^+\tau^-$, $\Lambda_b \to \Lambda\tau^+\tau^-$, $B \to K^{(*)}\nu\bar{\nu}$, $B_s \to \phi\nu\bar{\nu}$, $\Lambda_b \to \Lambda\nu\bar{\nu}$, $B \to \pi(\rho)\nu\bar{\nu}$, etc.

- Two-body $B \to \ell^+\ell^-$ decays sensitive to very high scales (comparable to $K \to \pi\nu\bar{\nu}$)
  $B_{s,d} \to \mu^+\mu^-$: tera-Z expected to be comparable to HL-LHC
  $B_{s,d} \to \tau^+\tau^-$: tera-Z is much more sensitive: measure it, if $\geq$ SM level [$\sim 8 \times 10^{-7}$]

- Another important 2-body decay, to be measured by FCC-ee: $B_c \to \tau\bar{\nu}$

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

- Only seen in K so far; In the SM: m_c^2/m_b^2 and CKM suppressions, can be lifted by BSM

[hep-ph/0202010]

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

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

  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]

  Plenty of room between current sensitivity and the SM predictions

  (Hard to extrapolate whether LHCb becomes systematics limited)

- 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

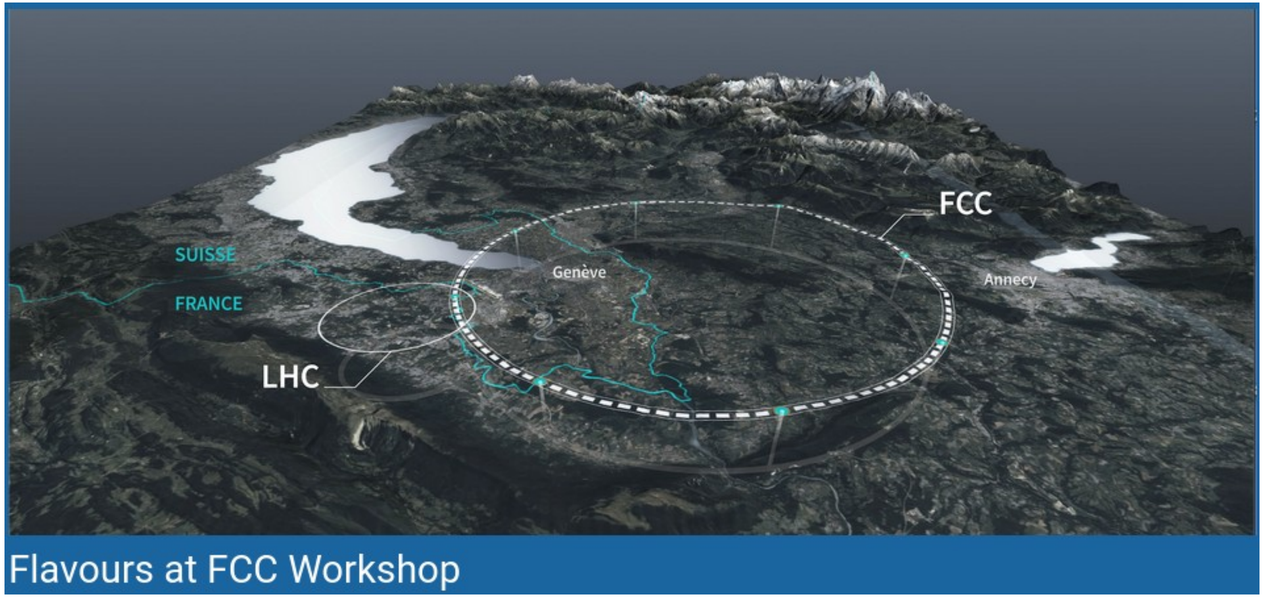
Final remarks

What are the largest useful data sets?

- No one has seriously explored it!
- Many measurements will remain far from being limited by theory uncertainties:
  - The CKM angle $\gamma(\equiv \phi_3)$
  - $B_{s,d} \to \mu\mu$, $B \to \mu\nu$ and other leptonic decays
  - $A_{\mathrm{SL}}^{d,s}$ — CPV in $B_{(s)}$ mixing
  - Lepton flavor violation & lepton universality violation searches
  - Dark sector searches, etc.
- In some decays, even in 2040s we'll have (exp. bound)$/$SM $\gtrsim 10^3$
- NP sensitivity would improve with data $\gg$ LHCb, Belle II, tera-Z

$\Rightarrow$ Case for an experiment focused on flavor at FCC-hh...

Workshop advertisement



Flavours at FCC Workshops, next one @ CERN: Jan 19 – 22, 2027 [Isidori, ZL, Monteil, Wilkinson]

Goal: deepen understanding of the potential of FCC for flavor physics — Get involved!

Conclusions

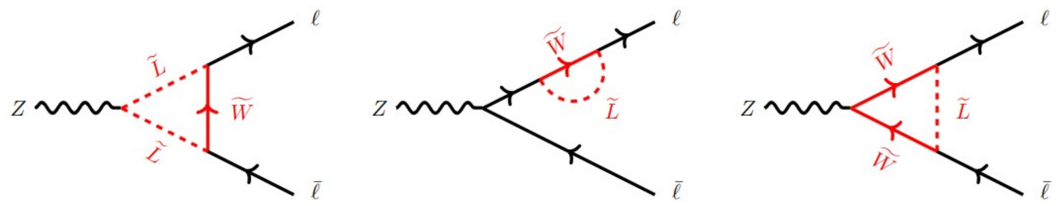
- Flavor physics probes scales $\gg 1\,\mathrm{TeV}$, sensitivity limited by statistics
  New physics could show up any time when measurements improve
- There is much to be learned from future measurements at LHCb, Belle II, ATLAS, CMS
- If any of the tensions with SM becomes decisive $\Rightarrow$ compelling case for largest statistics
- Interesting challenges both for experiment and theory to maximize sensitivity
  Explosion of data always triggered unforeseen developments
- FCC-ee has very rich physics program, can be a discovery machine
  In flavor physics, the only way to go well beyond Belle II and LHC(b)
- Clear motivations to aim for the largest data sets that technology may allow

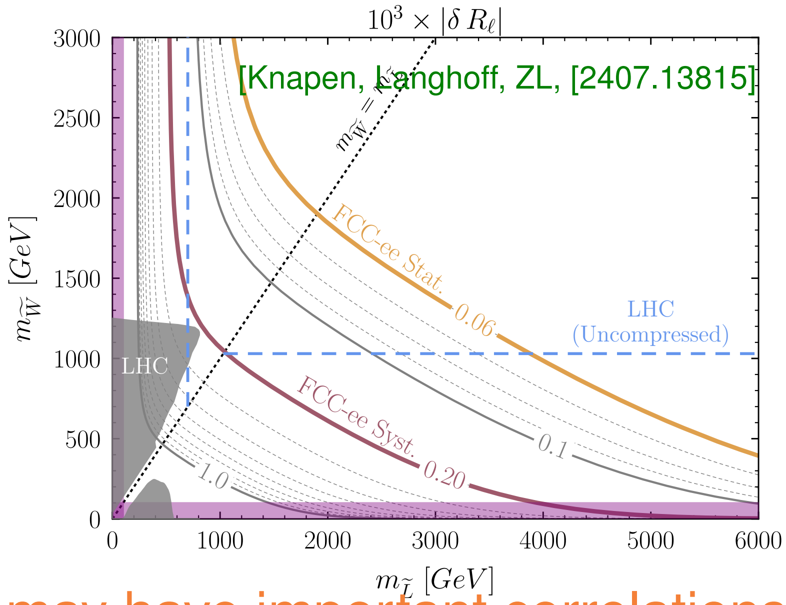
Extra slides

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	±	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

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

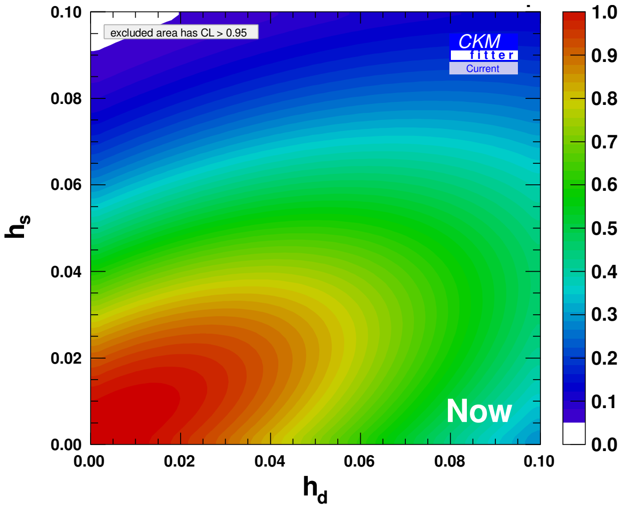
  General parametrization: $h\, e^{2i\sigma} = A_{\rm NP}(B^0 \to \overline{B}{}^0) / A_{\rm SM}(B^0 \to \overline{B}{}^0)$ ($h_{d,s}$, $\sigma_{d,s}$: NP param's)

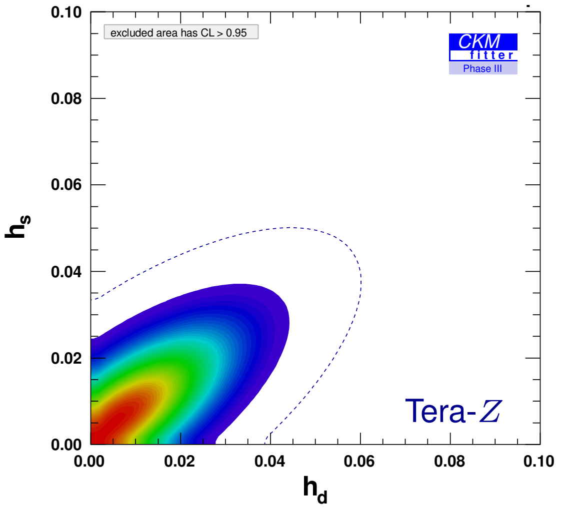
- CKM fit with 4 BSM param's added; combines many measurements and theory inputs [Charles *et al.*, 2006.04824]

  ($\Rightarrow$ conservative view of future progress)

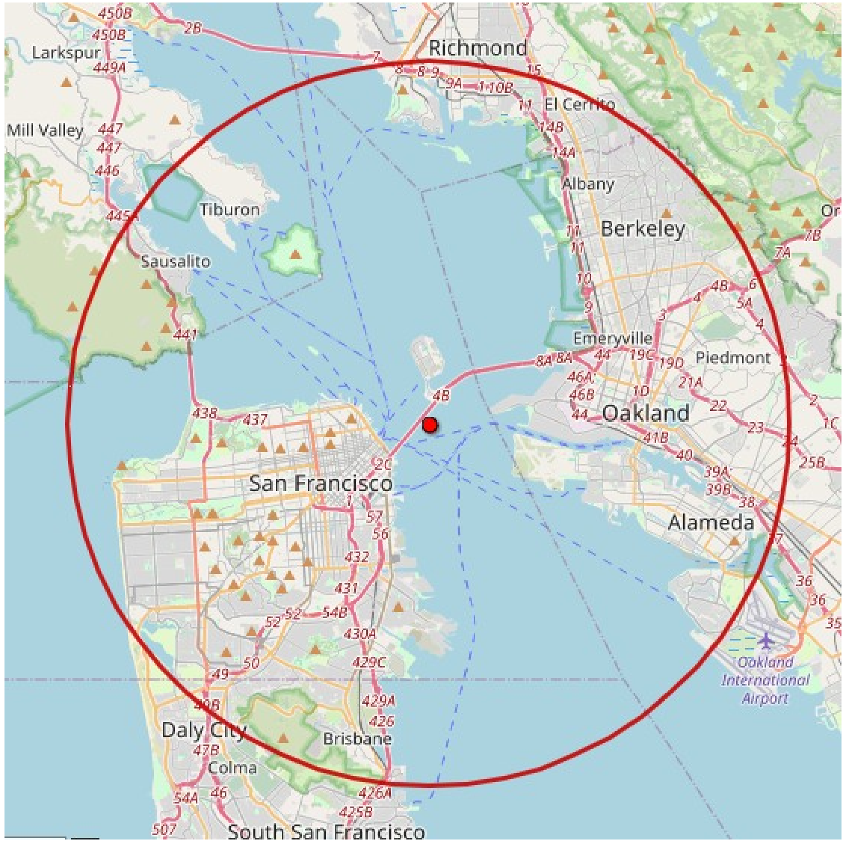
- Sensitive to TeV scale, even if NP is MFV-like

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





FCC doesn't look that big in the Bay Area



US units for FCC enthusiasts:

X mile radius $\Leftrightarrow 10X$ km circumference

(2π miles = 10 km)

Units for flavor: $m_B/\mathrm{MeV} =$ mile / foot

10^{-2} and 10^{-4} coincidences, respectively