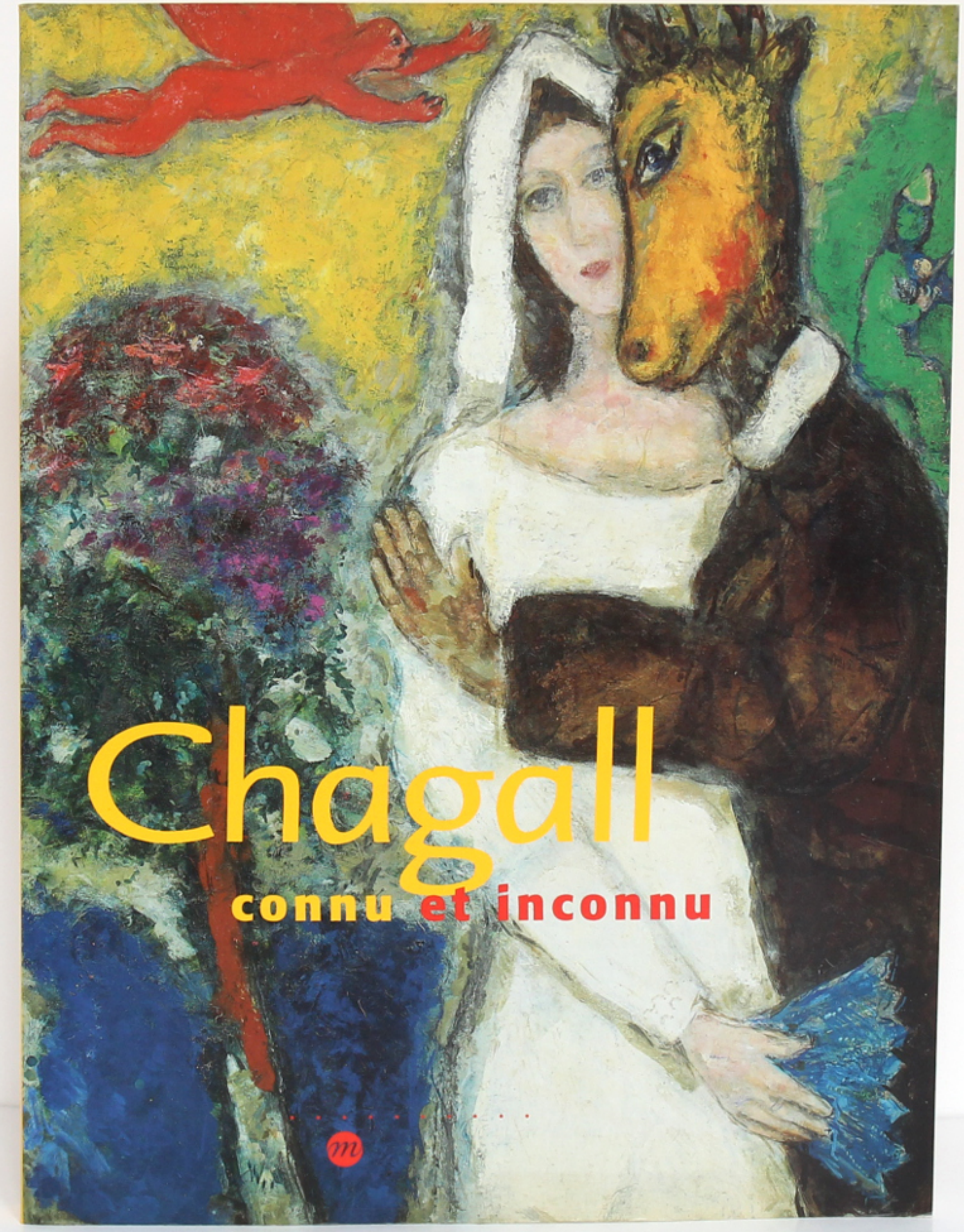
B physics: known and unknown

Zoltan Ligeti

Rencontres de Moriond
Electroweak Interactions and Unified Theories
March 15 – 22, 2026


Chagall
connu et inconnu

Outline

- Why flavor?
  Unique sensitivites
- Recent examples of what we know and don't know
  Lot to do, both for theorists and experimenters
- Far future: FCC
  Huge increases in data, what can they teach us?

New physics scales probed

- Heavy new physics generates dimension > 4 operators in SMEFT

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

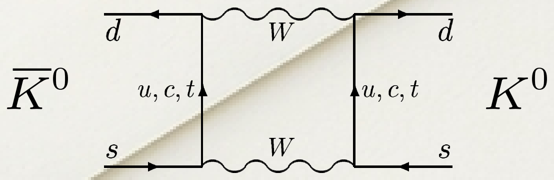
- Dim-5 $LL\phi\phi$ discovered, iff m_ν violates lepton # ($0\nu\beta\beta$?); No dim-6 term established yet
- Baryon number violation: $\dfrac{QQQL}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^{16}\,\text{GeV}$
- Higgs & precision electroweak: $\dfrac{(\phi D^\mu \phi)^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^4\,\text{GeV}$
- Flavor and CP violation (and EDMs): $\dfrac{QQQQ}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^{(3\ldots8)}\,\text{GeV}$
- These are the only experimental probes of the $10^2 - 10^5\,\text{TeV}$ scale

Origin of high scale sensitivity

- Back of an envelope calculation of Δm_K: loop, CKM, GIM suppressions

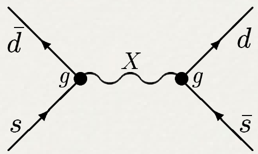
- Why is $\Delta m_K / m_K \sim 7 \times 10^{-15}$?

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

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

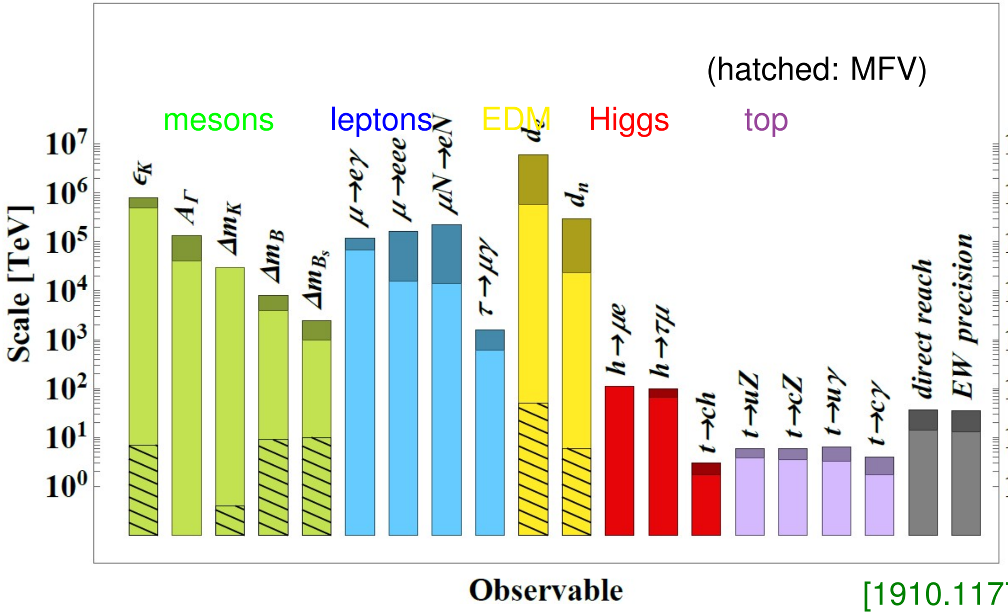


$$\frac{\Delta m_K^{(X)}}{\Delta m_K} \sim \frac{g^2\, \Lambda_{\rm QCD}^3}{M_X^2\, \Delta m_K} \quad \Rightarrow \quad M_X > g \times 10^3\,\text{TeV}$$

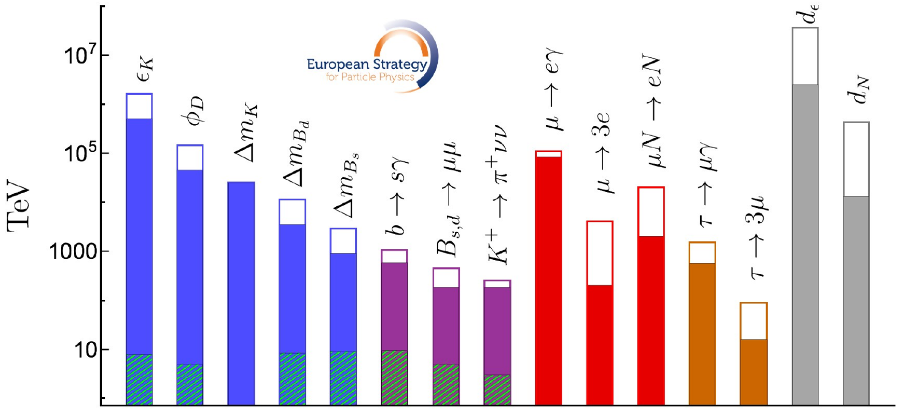
- Alternatively, sensitivity to TeV-scale particles with one-loop couplings $[g \sim \mathcal{O}(10^{-3})]$

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

Scales, as shown in European strategy



[1910.11775]



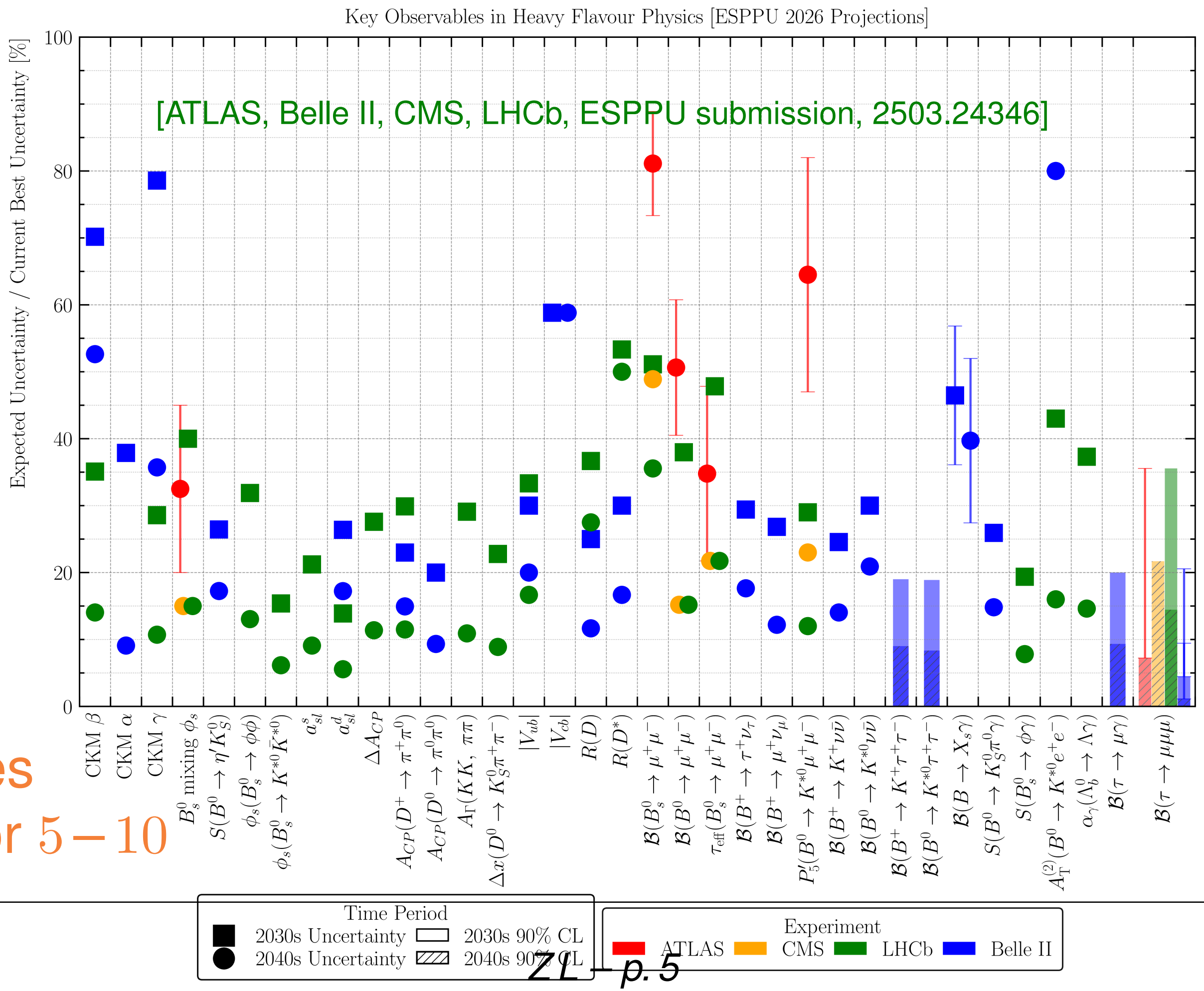
[2511.03883]

- 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

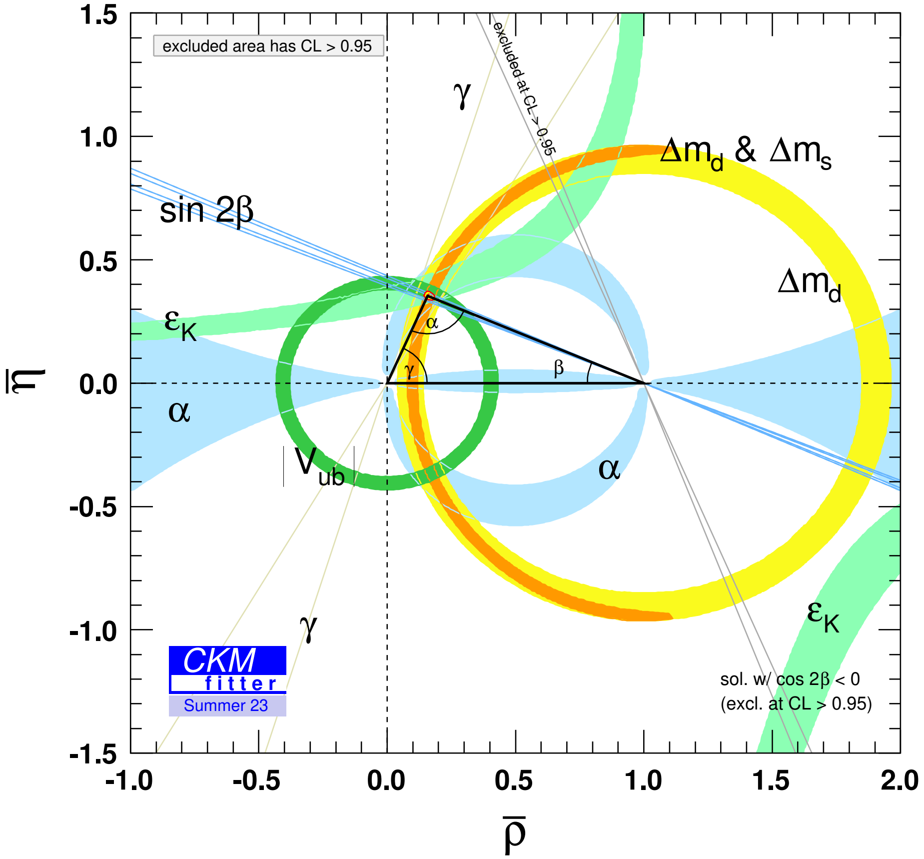
Large upcoming improvements



Many uncertiainties will shrink by factor $5-10$

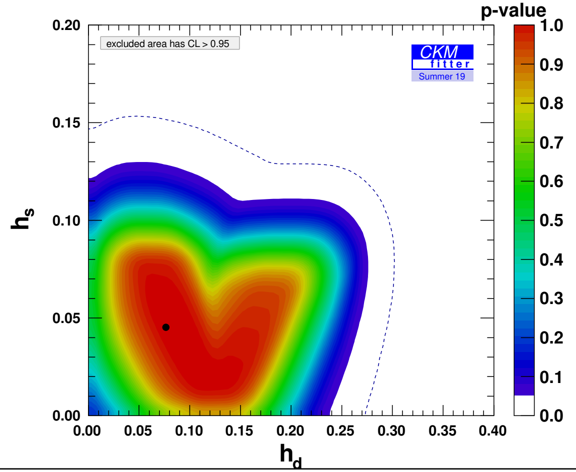
Snapshot: CKM fit in the SM

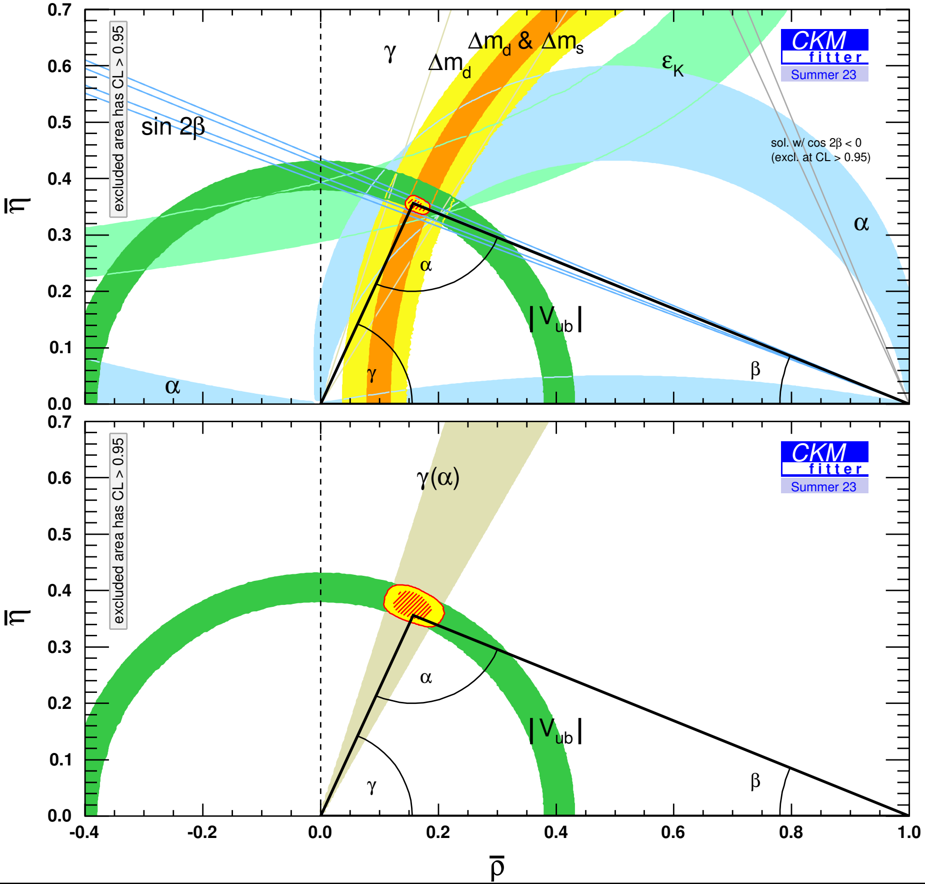
- Spectacular progress in last 25 years
- The CKM mechanism describes consistently CP violation and flavor changing processes



Snapshot: CKM fit in the SM

- Spectacular progress in 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





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Recent tensions between SM and data

Hints of deviations from the SM

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

  Less than half of B decays measured; most incalculable, but 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., $B \to D^{(*)}h$)

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

  There are more...

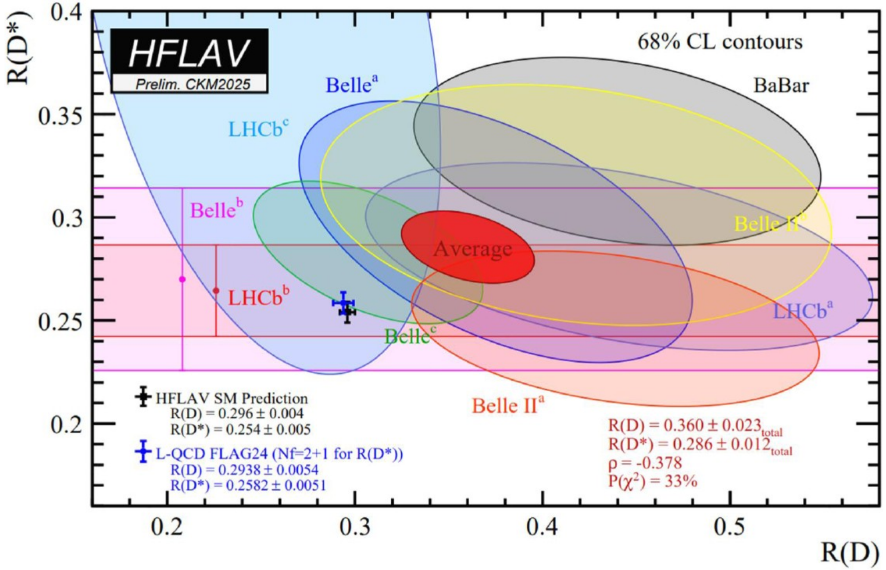
- Intriguing tensions with the SM $\Rightarrow$ experimental scrutiny, new theory ideas

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

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



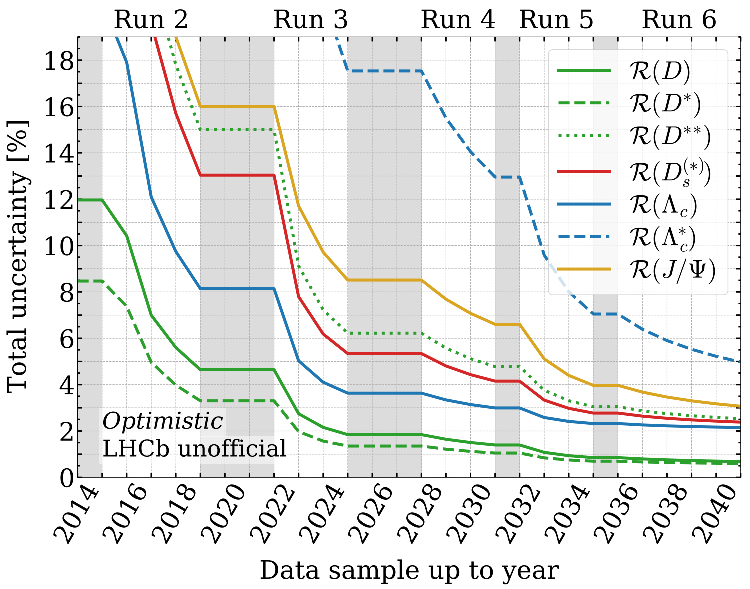
- Imply NP scale $\lesssim$ few TeV

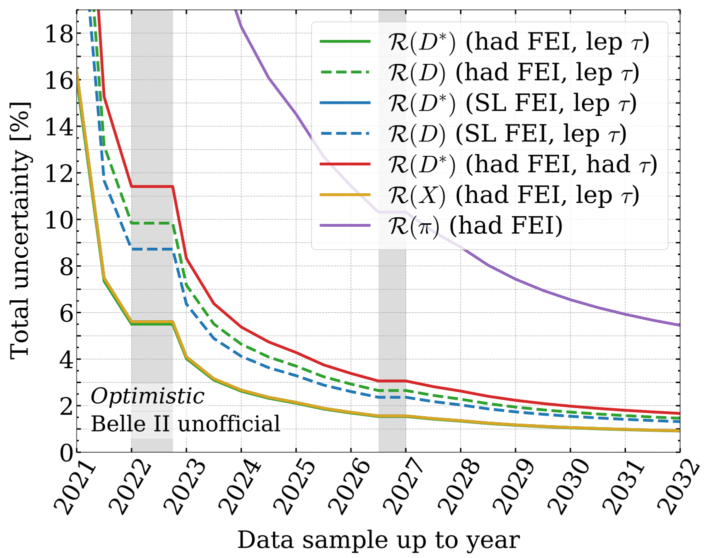
  Mediators within / near ATLAS & CMS reach

- 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

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

$|V_{cb}|$ 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

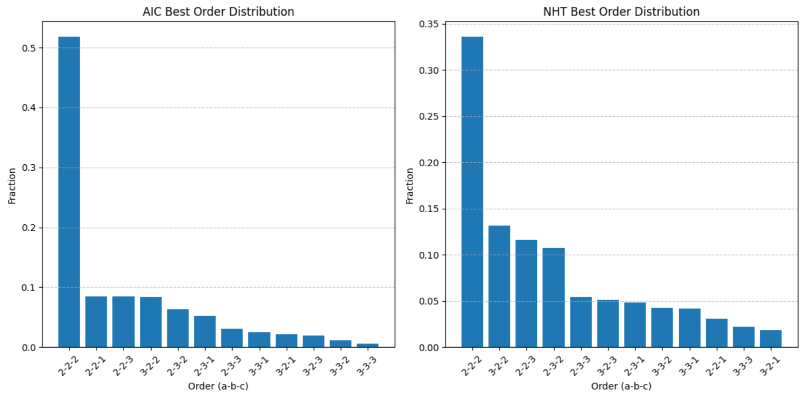
  $|V_{cb}|$ impacts many rare decay rate predictions, since $V_{ts}, V_{td} \propto A$

- Many open questions — need a lot more data:

  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

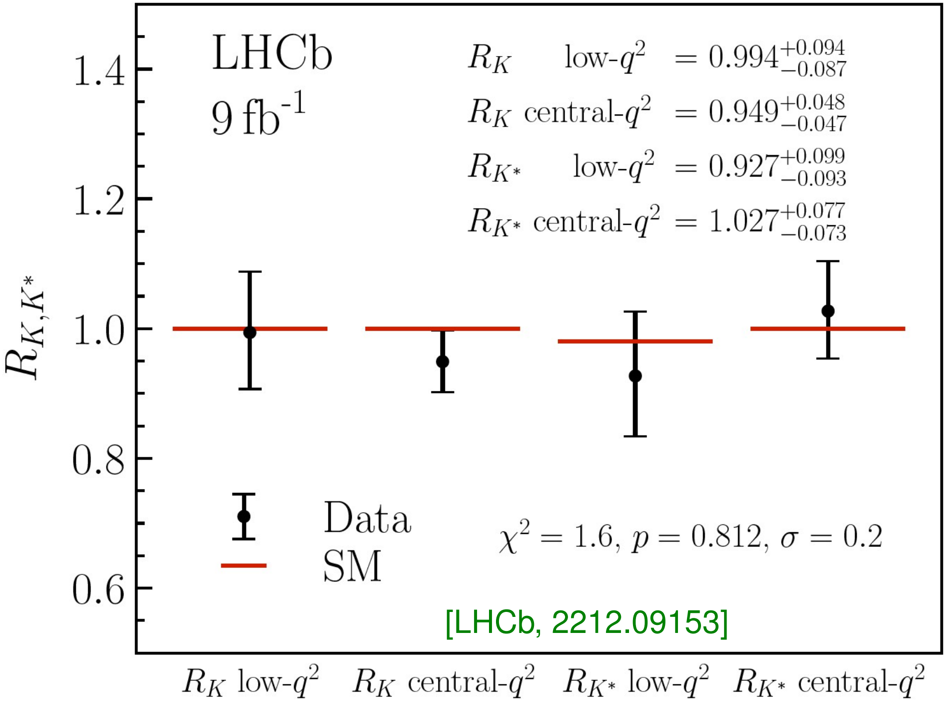


[Bernlochner, ZL, Persson, Robinson, to appear]

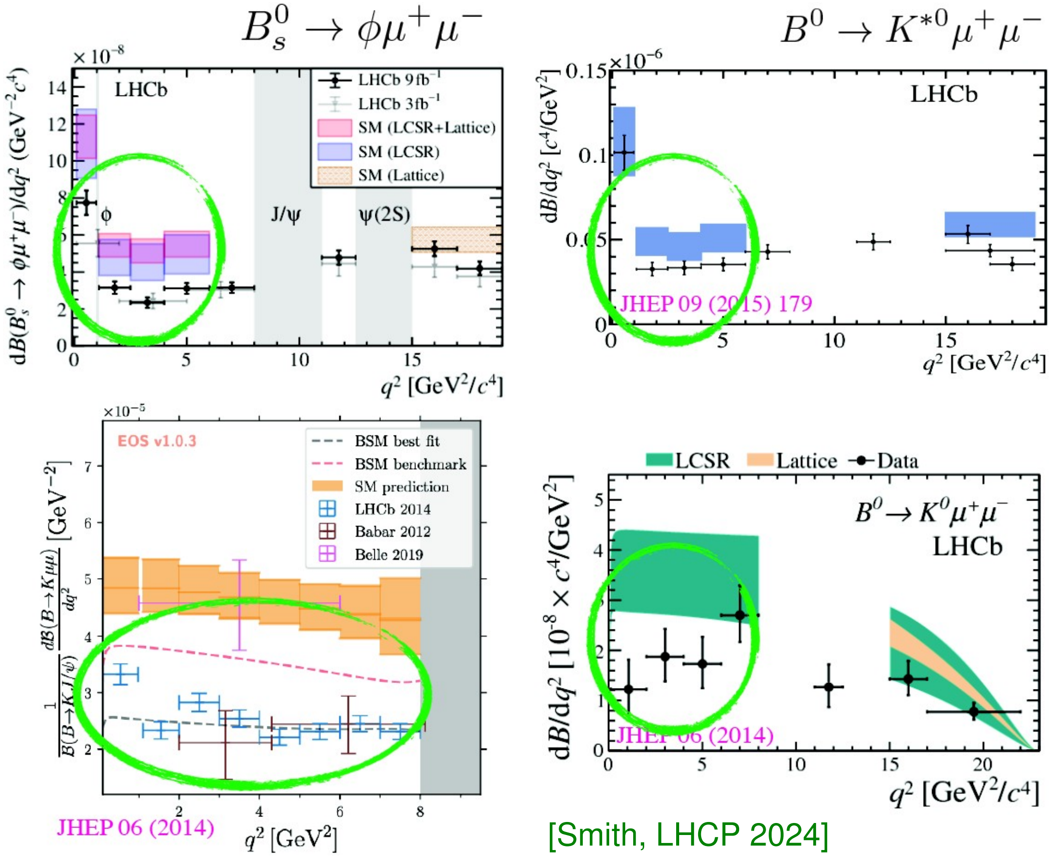
- Not to mention tension between exclusive and inclusive determination

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

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$



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



[Smith, LHCP 2024]

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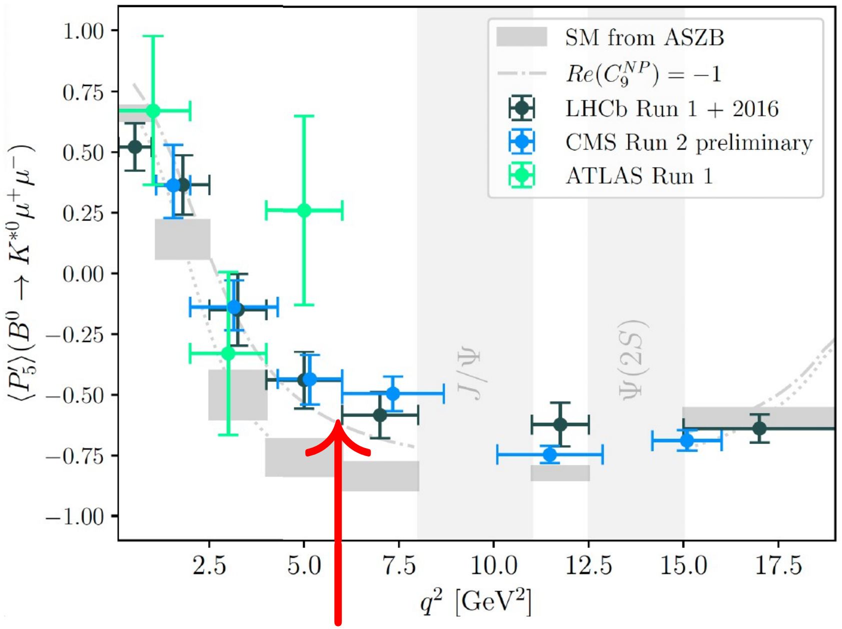
The P_5' angular distribution in $B \to K^* \mu^+ \mu^-$

- "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]



BSM, fluctuation, SM theory?

- 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

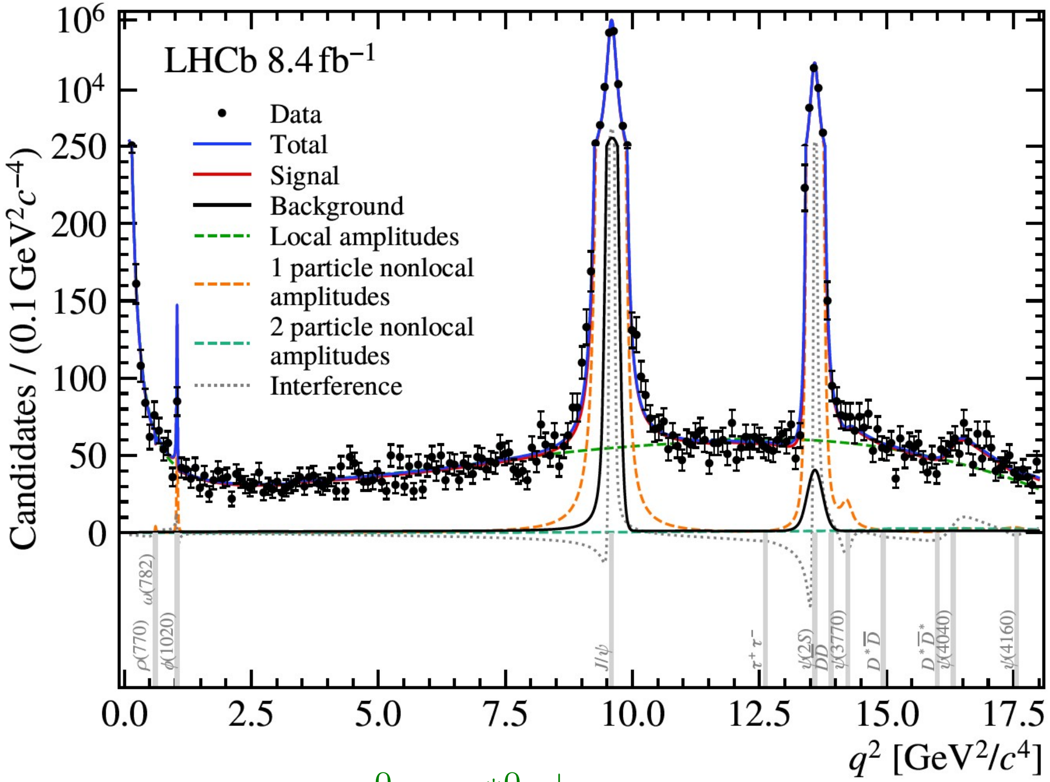
- Is the $c\bar{c}$ loop tractable? Impacts many interesting decay rates & CP viol. observables

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

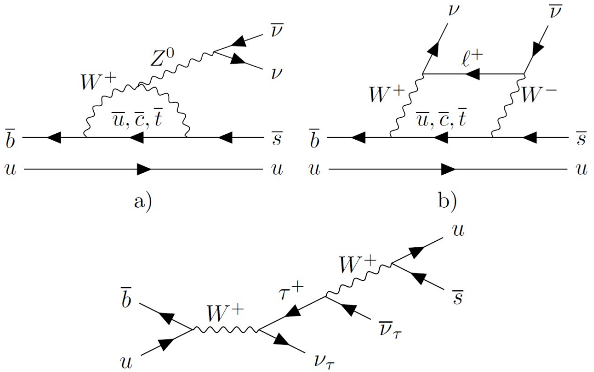
- Only robust deviations based on model-independent theory will be seen as signs of new physics

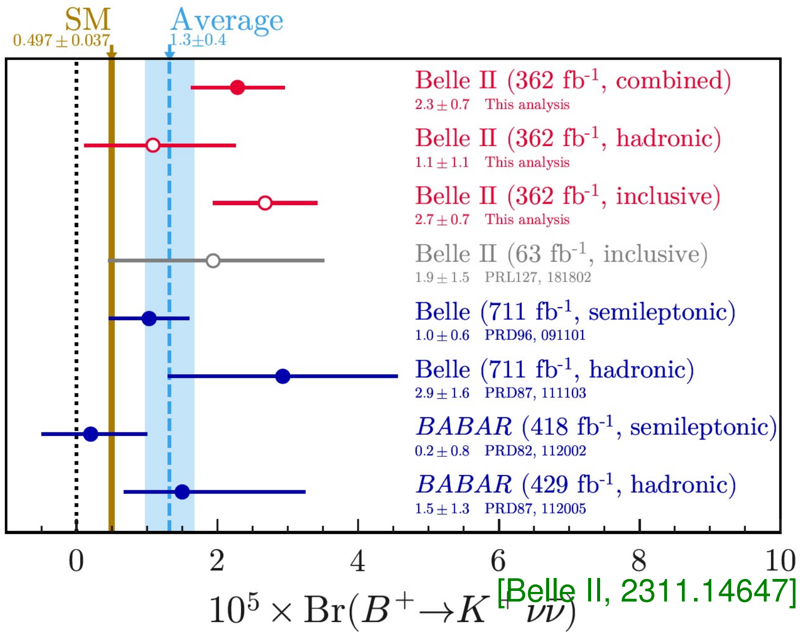


[LHCb, $B^0 \to K^{*0}\mu^+\mu^-$ 2405.17347]

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

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





[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, 2602.09666]

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

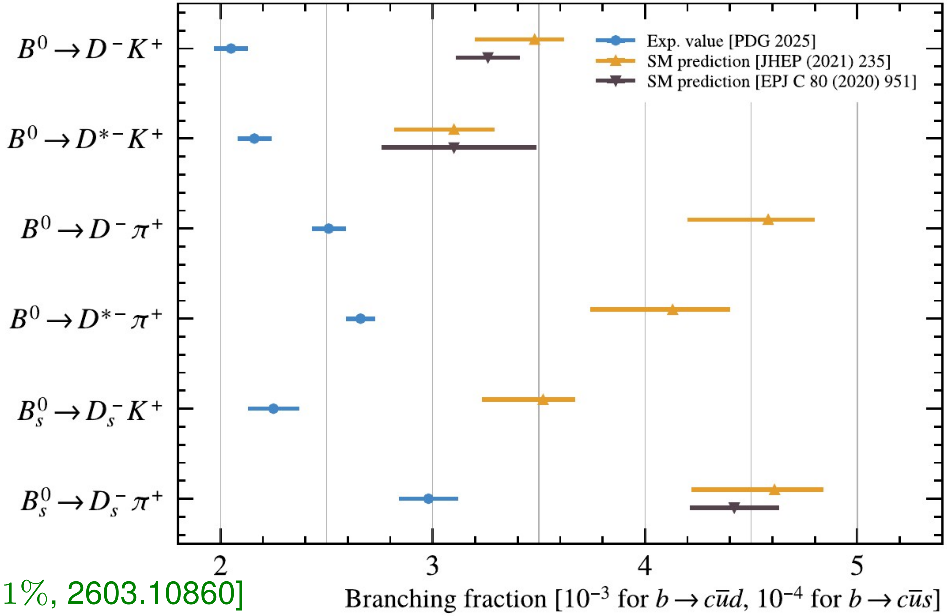
- If this tension becomes more significant, stopping NA62 after LHC Run 3 will look even more mistaken

Belle II: 2.7σ from SM

Nonleptonic $b \to c$ decays

- Some $B \to Dh$ decays factorize in heavy quark limit (plus power suppressed corrections)

  (Physical picture by Bjorken around 1990)



[LHCb: direct CPV in $B_s^0 \to D_s^- \pi^+ \lesssim 1\%$, 2603.10860]

- Need: semileptonic form factor near $q^2 = 0$, plus estimate of corrections

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

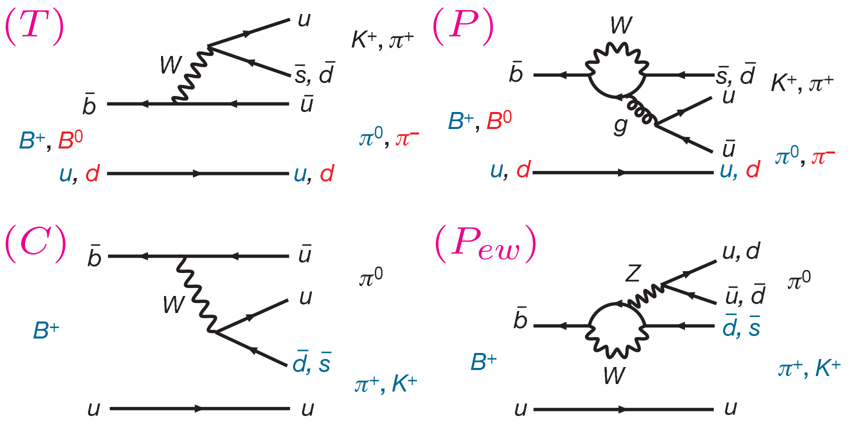
- Have we seen new physics in CPV?

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

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

- 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: $\arg(C/T) = \mathcal{O}(\Lambda_{\text{QCD}}/m_b)$ and $A + P_{ew}$ small

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

Belle II can make unique contribution

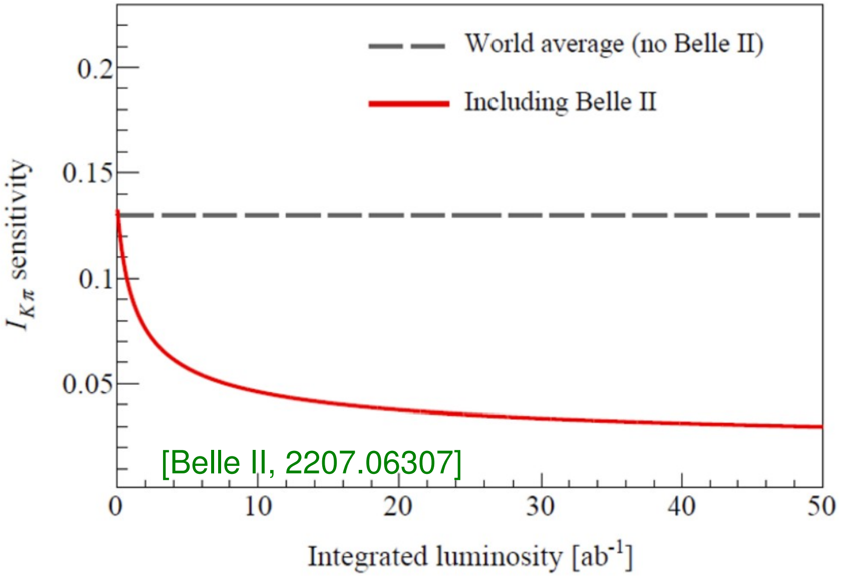
- Sum rule based on isospin for dominant amplitudes, and $SU(3)$ for subleading terms:

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

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

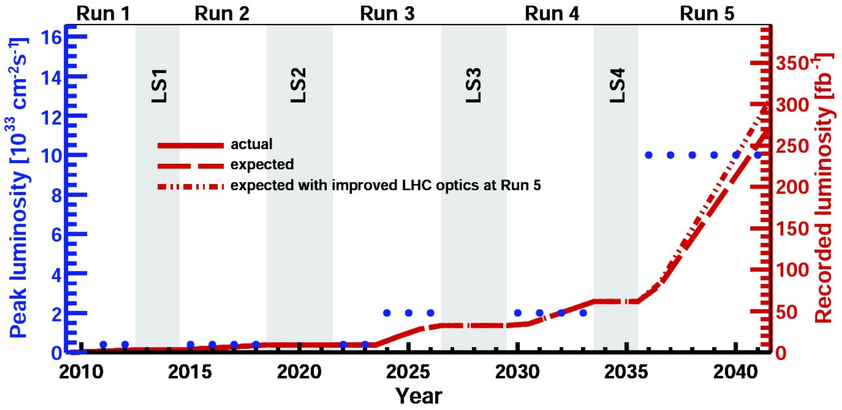
Limiting uncertainty: $\Delta(K^0\pi^0)$

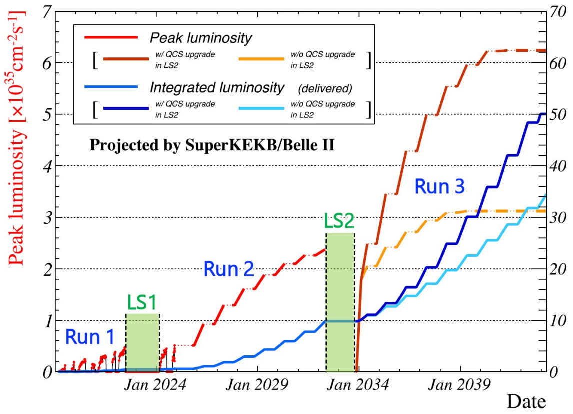
$$I_{K\pi} = \frac{\delta_{K\pi}}{2\Gamma(B \to K^+\pi^-)}$$



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

(Far) future





- 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: [2106.01259]

Particle production (10^9)	$B^0 + \overline{B}^0$	$B^\pm$	$B^0_s + \overline{B}^0_s$	$\Lambda_b + \bar{\Lambda}_b$	$B^\pm_c$	$c\bar{c}$	$\tau^+\tau^-$
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 / ARGUS $\sim 10^5$)

  Theory and experimental techniques both changed a lot! (e.g., full hadronic reconstruction)

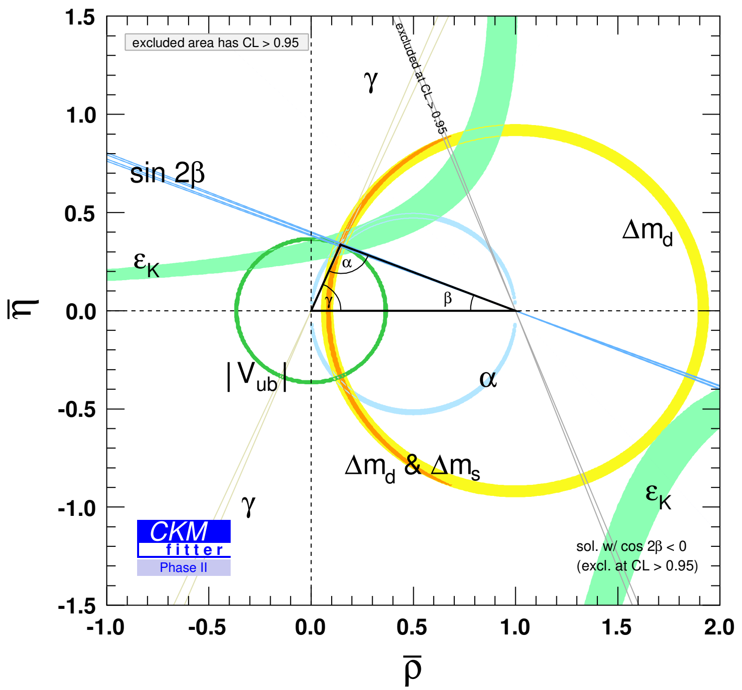
  Asymmetric B factories at $\Upsilon(4S)$ great for CP violation, less ideal for (semi)leptonic decays
- What was not even tried at LEP? (due to lack of statistics or lack of physics interest)
- Some rare decay sensitivity may improve linearly with statistics; e.g., $Z \to \mu\tau, \mu e$, etc.
- A lot of what's usually called precision electroweak, also concern flavor

  (τ lifetime & mass, R_b, R_ℓ for each ℓ flavor, etc.)

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: $A = (V_{cb}^* V_{cq})\big(A_c^{(0)} + \varepsilon A_c^{(1)}\big) + (V_{ub}^* V_{uq}) A_u^{(0)} + \dots$
- $SU(3)$ 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)

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

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

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

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

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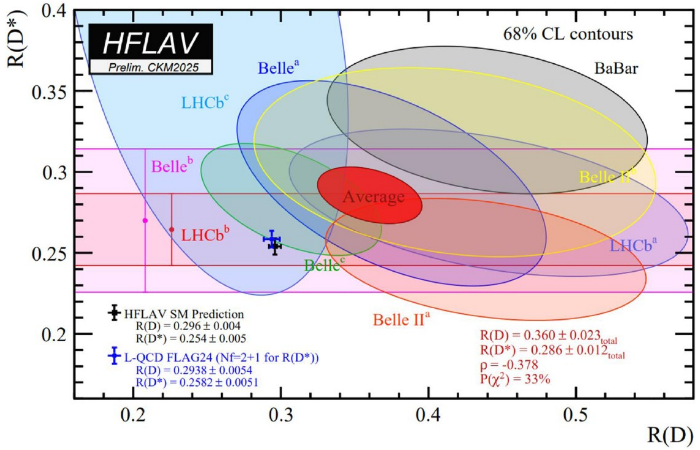
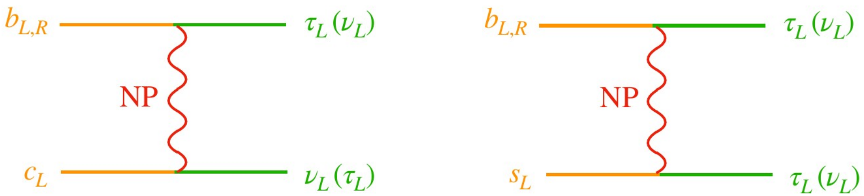
If BSM in $b \to c\tau\bar{\nu}$, must study $\nu\bar{\nu}$ & $\tau\tau$ modes

- 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

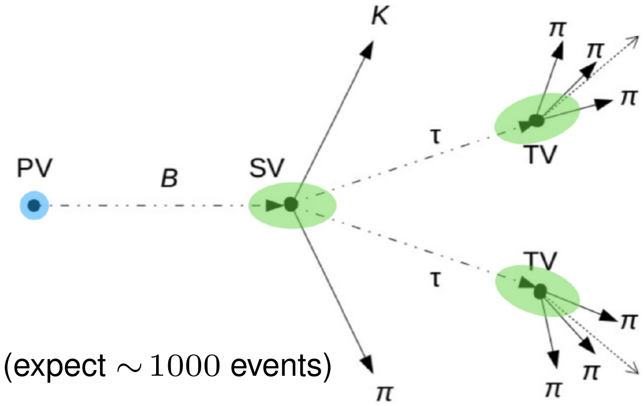


[Stefanek]

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

- $\mathcal{B}_{\rm SM}(B_s \to \mu^+\mu^-) \sim 3 \times 10^{-9}$, 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)

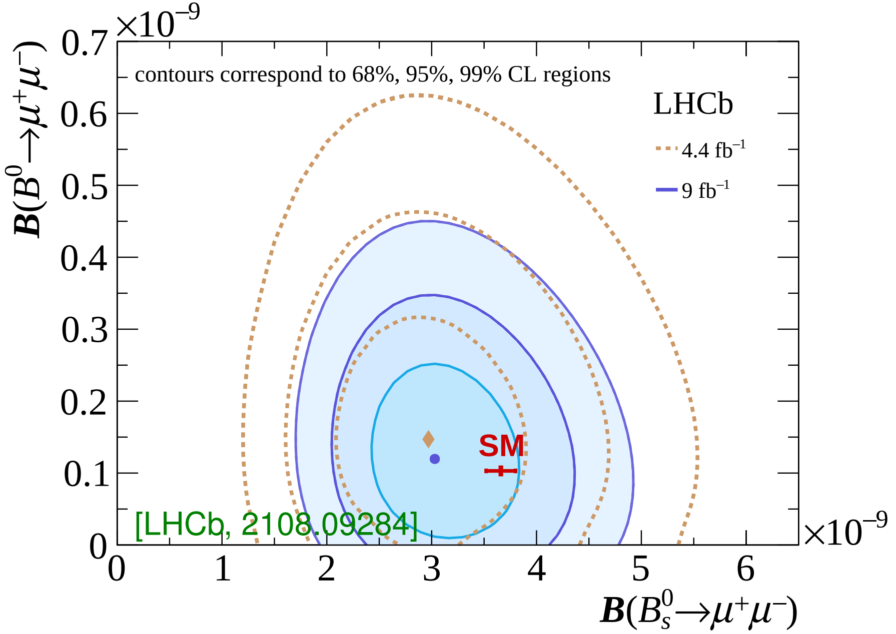
  SM uncertainty $\simeq (2\%) \oplus f_{B_q}^2 \oplus \mathrm{CKM}$, and may be further reduced

- 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 statistics...?)

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



PDG average: [LHCb, CMS, ATLAS]

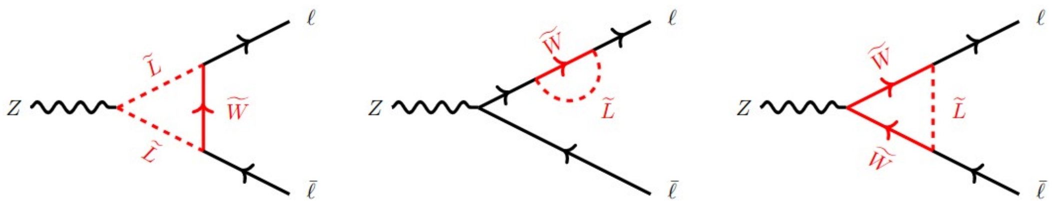
$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.34 \pm 0.27) \times 10^{-9}$$

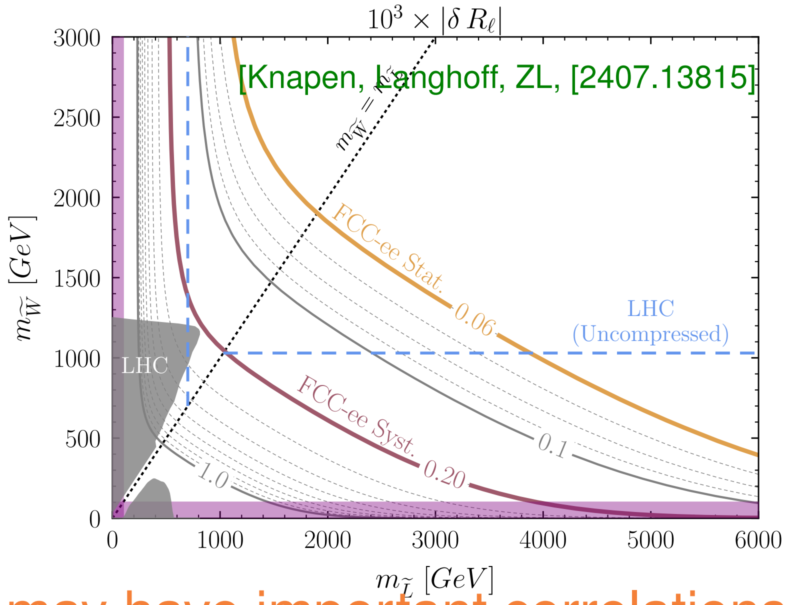
Actual discovery potential? E.g., SUSY in $Z \to \ell^+\ell^-$

- 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
						Acceptance for leptons

Systematic limitation in Midterm Report resolved by Feasibility Study





- 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

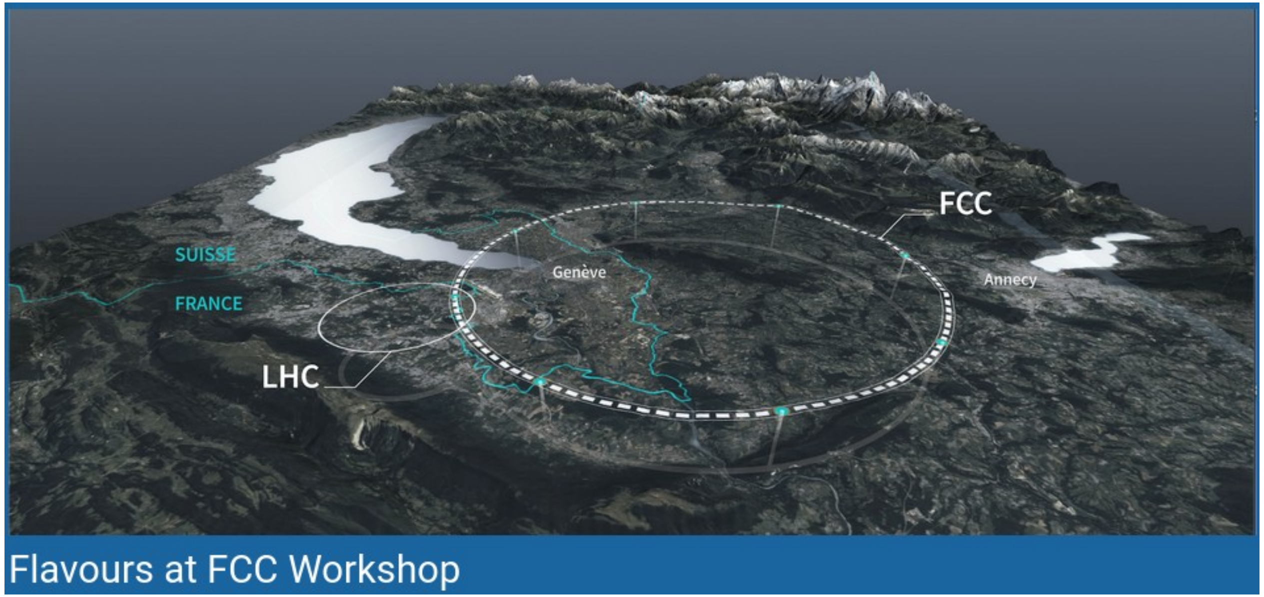
Final remarks

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
  - 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

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

Workshop advertisement



Physics at the Flavoured Circular Collider — Next workshop @ CERN: June 16 – 19

Goal: deepen understanding of the potential of the FCC for flavor physics

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
- Some tensions with the SM — one of these (or others) may become decisive
- 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)
- Compelling reasons to aim for the largest data sets that technology may allow

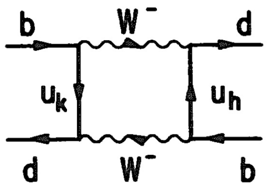
Extra slides

Constraints on NP parameters added to the SM

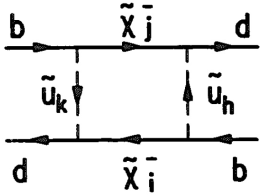
- In a large class of NP models, dominant contributions are to neutral meson mixing

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

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



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



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

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

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

- E.g., for $\dfrac{C_{ij}}{\Lambda^2}\,(\bar{q}_{i,L}\gamma^\mu q_{j,L})^2$ operator: $h \simeq \dfrac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2}\left(\dfrac{4.5\,\mathrm{TeV}}{\Lambda}\right)^2$, so $h < 0.08$ implies $\Lambda > \dfrac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2} \times 16\,\mathrm{TeV}$

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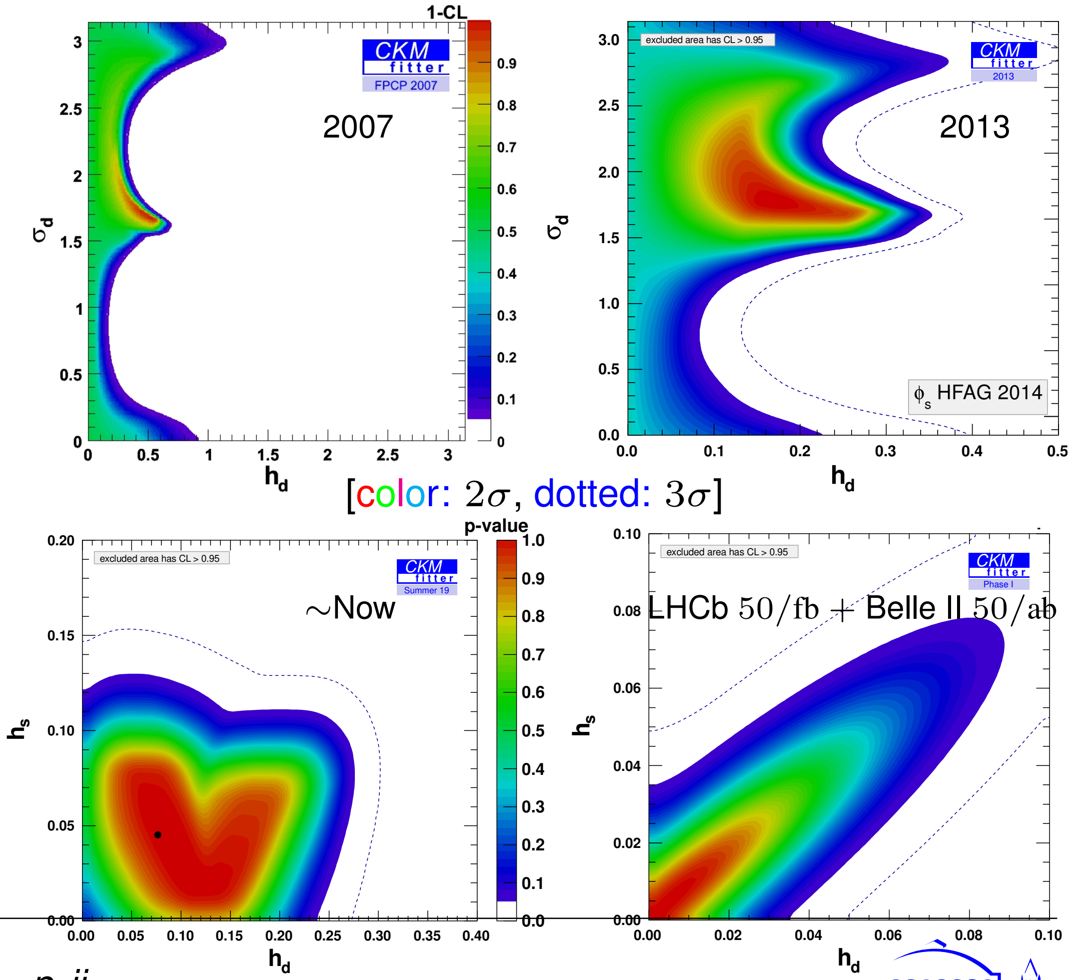
Evolving bounds on $h_{d,s}$

- CKM fit including $h_{d,s}$ and $\sigma_{d,s}$ param's:

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

- LHCb: BSM contributions to B_s mixing are constrained similar to those to B_d
- Weak interaction dominates observed CP violation: BSM / SM $\lesssim 20\%$
- Complementary to high-p_T searches (E.g., similar to HL-LHC $m_{\tilde g}$ reach)
- BSM sensitivity will continue to improve



Sensitivity to new physics in B mixing

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

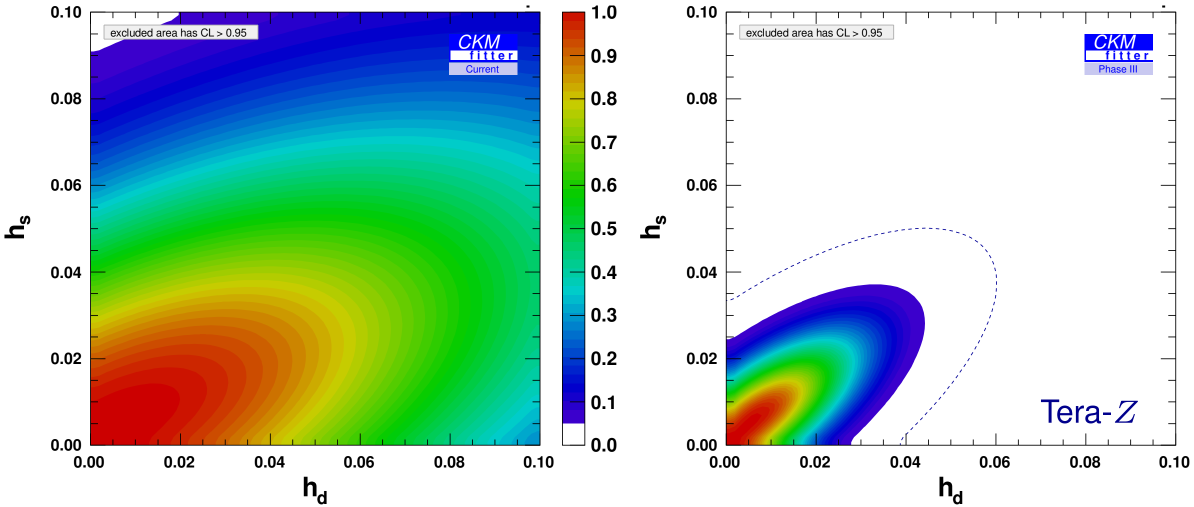
  Assume: (i) 3×3 CKM matrix is unitary; (ii) tree-level decays dominated by SM

  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)



4 relations for $B_q \to J/\psi\, h$ at this order

- $A_{\psi K^+}/A_{\psi\pi^+} = -|V_{cd}/V_{cs}|^2$
- $C^d_{\psi K^0}/C^s_{\psi \overline{K}^0} = -|V_{cd}/V_{cs}|^2$
- $(1+\bar\lambda^2)s_{2\beta} = S^d_{\psi K_S} - \bar\lambda^2 S^d_{\psi\pi} - 2\big(\Delta_K + \bar\lambda^2\Delta_\pi\big)c_{2\beta}\tan\gamma + \mathcal{O}(\varepsilon R_u\bar\lambda^2, R_u^2\bar\lambda^2, \delta)$ [1507.06671]

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

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

- "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!)

Theory challenges / opportunities

- New methods & ideas: recall that the most precise α and γ measurements are in modes proposed in light of Belle & BaBar data
  - 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

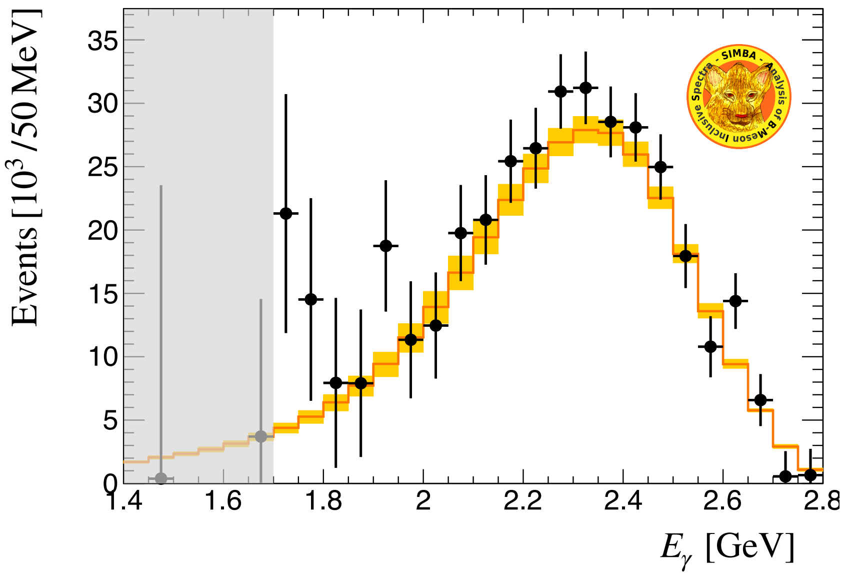
  Exp. & theor. uncertainty small in different regions

- 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)



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

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)

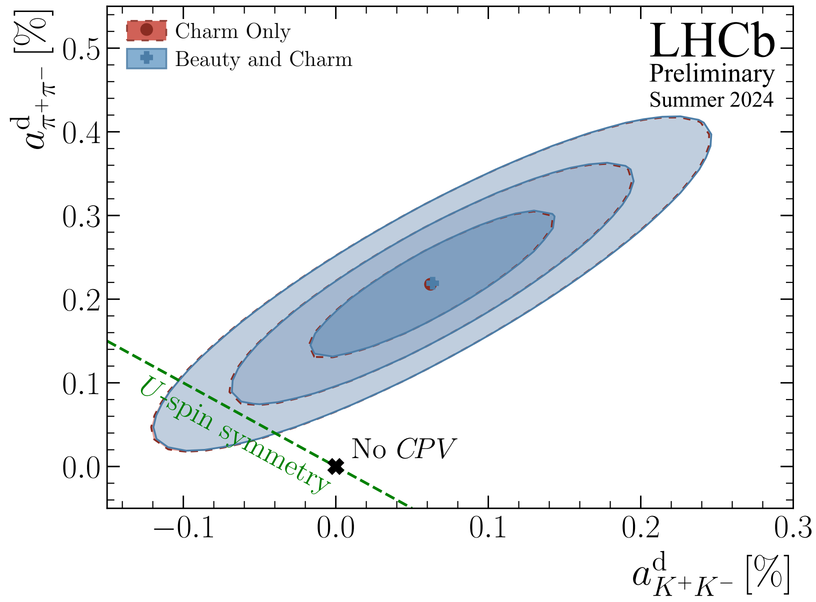
  LHCb, Mar. 2019: $\Delta A_{CP} = -(1.82 \pm 0.33) \times 10^{-3}$ [1903.08726]

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

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

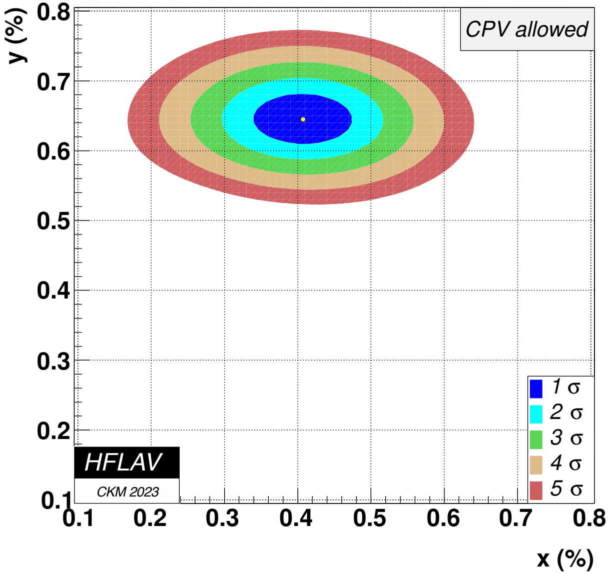
  Before measurements, most theory papers stated (assumed) that strong interaction suppresses CPV further

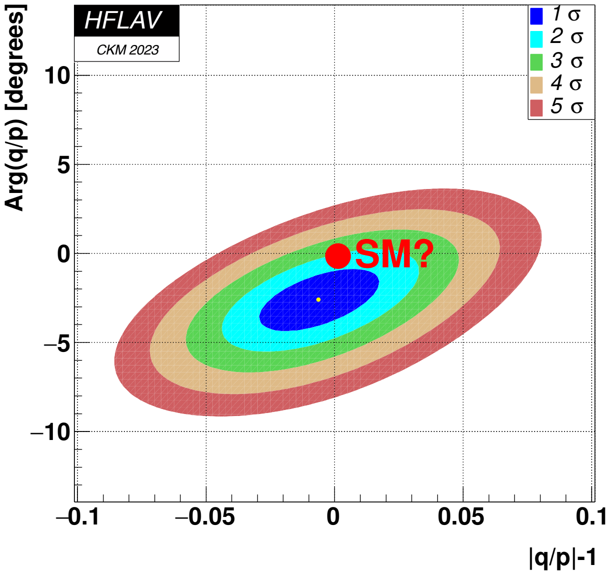
- Can we establish if CP violation in decay or mixing (more "inclusive") could still probe BSM?



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

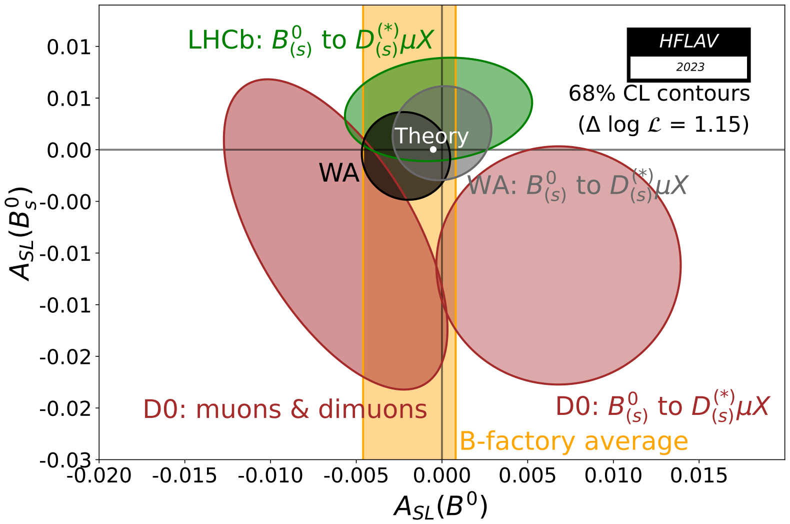
CP violation in $B_{d,s}$ mixing: $A_{\rm SL}^{d,s}$

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

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

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)

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

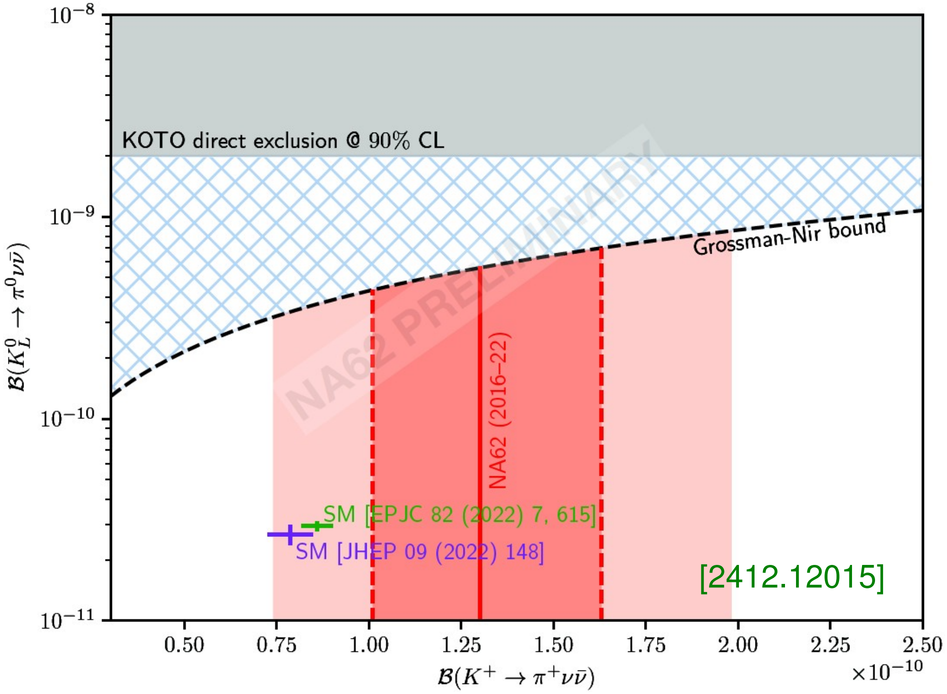
  Irreducible theory uncertainty few $\%$ (& $|V_{cb}|^4$)

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



Compare flavor and precision electroweak

- Flavor-changing neutral currents

  No tree level

  Loop $+$ CKM $+$ GIM $+$ CPV suppression

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

  Probe up to $\Lambda \sim 10^5\,\mathrm{TeV}$

  EW precision measurements

  Tree level

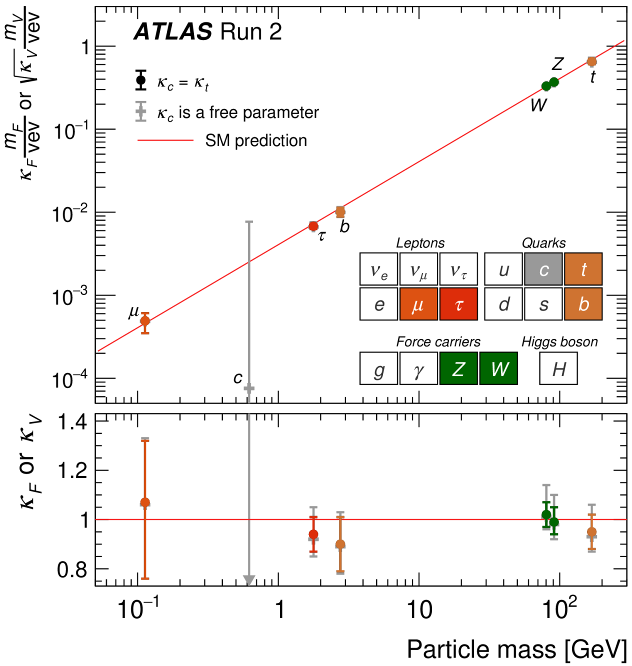
  Loop suppression

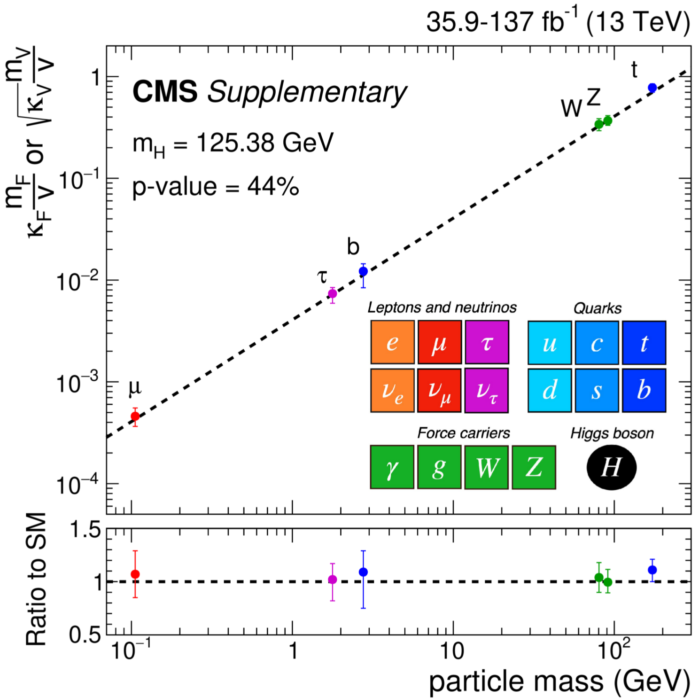
  $$\frac{1}{\Lambda^2} \sim \frac{\alpha_W}{m_W^2}$$

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

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

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