FCC Flavor Physics Workshops

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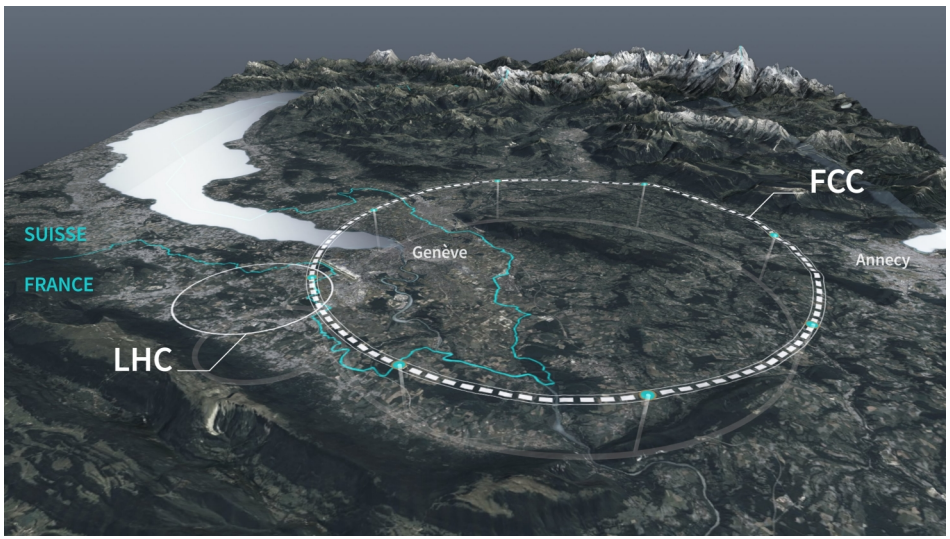


Physics at the Flavoured Circular Collider, Nov 19 – 21, 2025

How this came about

- I was contacted in the Summer to help organize workshops on flavor physics at the FCC

  Goals: grow the community;

  consolidate what has been done already;

  bring our understanding of what is possible at FCC-ee in flavor to a similar level of maturity as that which already exists for Higgs and electroweak physics

- Capabilities for flavor can be important for detector planning and R&D that is underway
- First workshop Nov. 19–21: `https://indico.cern.ch/event/1588013`
- 194 registrants; lower bound, as even some speakers didn't register... focus on physics

My views on the 2040s landscape

- When HL-LHC stops running, Higgs will have been studied for 30 years

  LHC is a Higgs factory, will want better precision & probe unexplored Higgs couplings — as in B decays

- 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, are now on similar footings

- The HL-LHC is a luminosity frontier experiment; greatest increase in discovery reach for precision measurements, weakly produced states — not particles near kinematic limit

- Ultimately, 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

Why flavor physics?

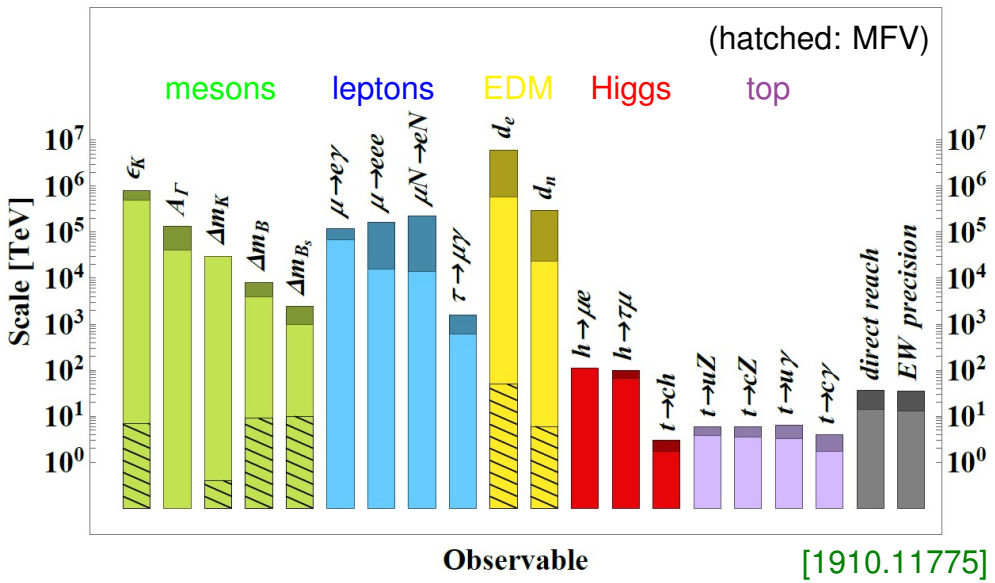
- Flavor, K, B, D: $\dfrac{(\bar{b}\,\Gamma d)^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^2 - 10^5\ \text{TeV}$

  The only probe of such scales (& EDMs)

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

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

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



[1910.11775]

- Lack of NP motivates tera-Z as part of a comprehensive search
- If NP is within any collider's reach, non-generic flavor structure ($\Rightarrow$ flavor is a powerful probe)
- Of the future colliders discussed, only FCC would go well beyond LHCb + Belle II goals

Five Working Groups

- WG1 – Rare decays and FCNCs: Wolfgang Altmannshofer, Marzia Bordone, Thibaud Humair, Renato Qualigliani, Eluned Smith, Niharika Rout
- WG2 – CP violation in nonleptonic b-hadron decays: Alberto Bragagnolo, Laurent Dufour, Matt Kenzie, Stefan Schacht, Michele Veronesi, Jure Zupan
- WG3 – Charged current processes: Cristina Agapopoulou, Andreas Juttner, Markus Prim, Dean Robinson, Raynette van Tonder, Xunwu Zuo
- WG4 – Charm: mixing, CPV, and rare decays: Michel Bertemes, Gudrun Hiller, Nathan Jurik, Jernej Kamenik, Dominik Mitzel
- WG5 – Tau physics and selected electroweak properties: Maria Cepeda, Romain Madar, Aurelien Martens, Emilie Passemar, Olcyr Sumensari

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.)

Objectives and Questions

– Obtain realistic estimates for precision on key flavor benchmarks

– Identify and develop strategies for potentially limiting systematics (both exp & theor.)

– Investigate requirements on and impact of various detector designs

– Formulate new measurement strategies and identify new processes of interest

– Understand the complementarities with the HL-LHC

– Explore the interplay with the Higgs, electroweak, and possible hidden sectors

– Assess if there exists a physics case to go beyond 6×10^{12} Z decays

– Address cross-cutting questions: normalizing BF measurements, hadronization fraction measurements, modeling parton shower and fragmentation, etc.

How to get involved?

- Many ways to contribute, both for experimentalists and theorists:
  - Sign up for mailing lists (next page)
  - Contact conveners
  - Engage with some experimental and/or theoretical studies
  - Come to next workshop: June 16 – 19 at CERN (4 days)

Don’t forget to sign up to the WG e-groups

FCC-PED-PhysicsGroup-Flavours-Rare@cern.ch
To subscribe: https://e-groups.cern.ch/e-groups/EgroupsSubscription.do?egroupName=FCC-PED-PhysicsGroup-Flavours-Rare

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which will be used for general announcements. (Can subscribe directly: https://e-groups.cern.ch/e-groups/EgroupsSubscription.do?egroupName=FCC-PED-PhysicsGroup-Flavours)

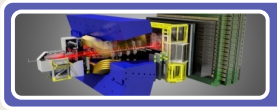
Please use institutional email addresses, as you have to be approved.

There are also Mattermost channels (see info on workshop webpage).

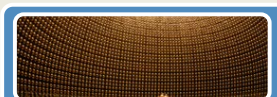
Conclusions — from Yossi Nir


Flavor violation and CPV probe otherwise uncharted territory: $10 - 10^4$ TeV


FV and CPV probe otherwise uncharted territory of d=6 SMEFT operators


FCC-ee will provide unprecedented huge statistics


FCC-ee will provide unprecedented low background

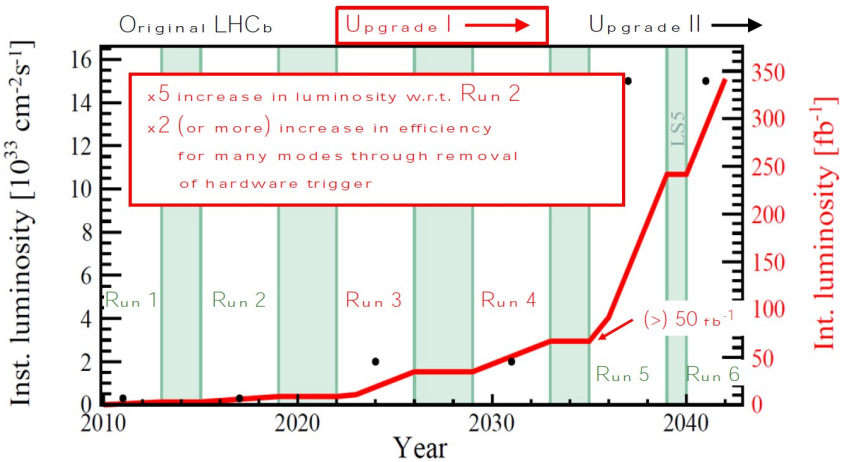

FCC-ee will provide unique tagging capabilities

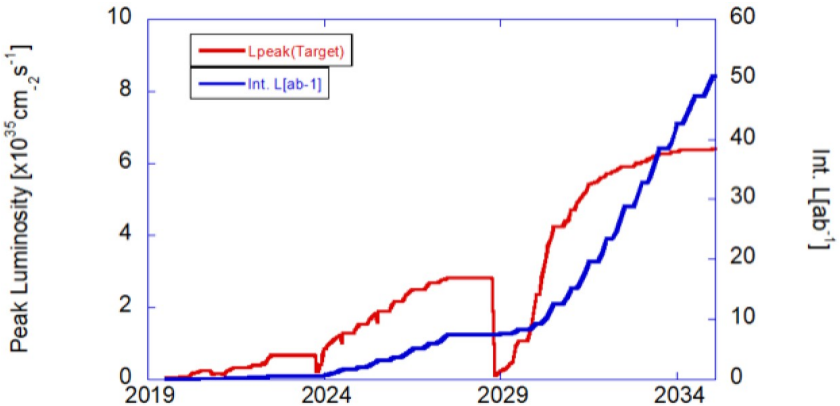

FCC-ee has a guaranteed, rich, unique, exciting flavor program

- The whole FCC-ee program is greater than the sum of the parts — even just in flavor
- Interesting challenges to maximize sensitivity — both for experiment and theory

Extra slides

Flavor and future colliders





- 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

Extensive sensitivity projections: 1808.08865, 1812.07638

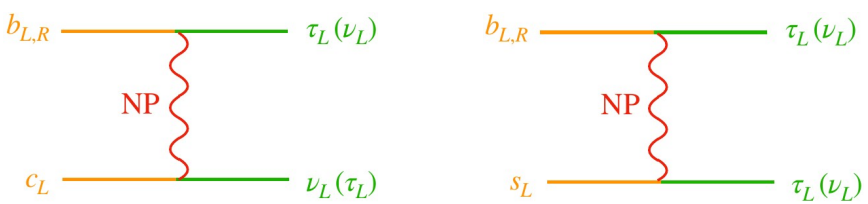
- Goal: over $50\times$ the Belle data set
- Discussions about physics case and feasibility of an upgrade, aiming 50/ab $\rightarrow$ 250/ab (parallel LHCb Upgrade II)

Extensive sensitivity projections: 1808.10567

- Only Tera-Z would go well beyond current program — clear case if BSM seen in flavor

The $b \to c\tau\bar{\nu}$ anomalies could make compelling case

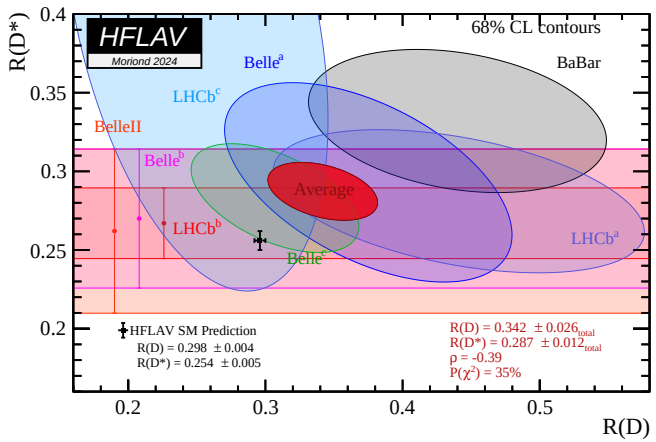
- Over 3σ tension for $R(D^{(*)})$, if it prevails, requires $\mathcal{O}(10\%)$ correction to a tree-level SM process
- If NP is charged under $SU(2)$, unavoidable connection to $b \to s\tau^+\tau^-$ or $b \to s\nu\bar{\nu}$ — correlations distinguish models

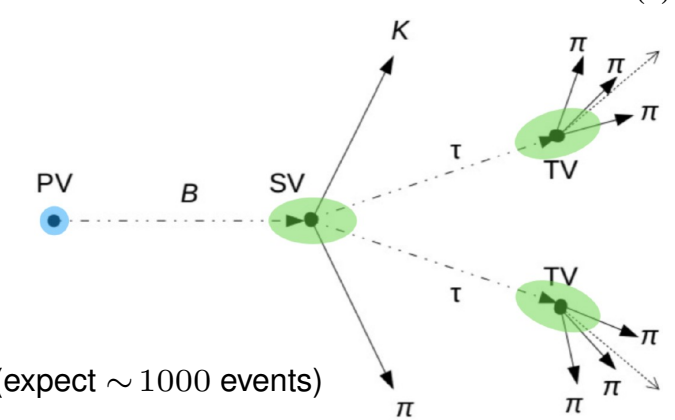


[image credit]

Tera-Z: measure $B \to K^*\tau^+\tau^-$, $K^*\nu\bar{\nu}$ even at SM level

- Boost of B from Z decay provides ideal environment





(expect ~ 1000 events)

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

- Only seen in K so far; for $B_{(s)}$, the m_c^2/m_b^2 suppression in the SM may be lifted by BSM

[hep-ph/0202010]

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

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

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

(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 for
  $B_{s,d} \to \tau^+\tau^-$: 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: $B_c \to \tau\bar{\nu}$
- $b \to c\tau\bar{\nu}$ and $s\ell^+\ell^-$ anomalies: in many models, correlated effects in many processes

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 evaluation of $S_{\eta' K_S} - S_{\psi K_S}$, $S_{\phi K_S} - S_{\psi K_S}$, 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?

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)
  - $A_{\rm SL}^{d,s}$ — when would experimental systematics become limiting?
  - Lepton flavor violation & lepton universality violation searches
  - Probably many more...
- Very broad program, dark sector searches, etc.
- In some decays, even in 2040s we'll have (exp. bound)/SM $\gtrsim 10^3$ (E.g., $B_{d,s} \to e^+e^-,\ \tau^+\tau^-$)
- NP sensitivity would improve with data $\gg$ LHCb, Belle II, tera-Z ($\Rightarrow$ flavor exp. @ FCC-hh?)