Flavor Physics & CP violation

[*Material for the Discussion*]

- **Why ?**
- **How ?**
  - Short/mid-term
  - Long-term

Keywords:
- ✓ Diversity
- ✓ Synergy with the HE frontier

Why ?

- *Why 3 fermion generations ?*
- *Are fermion masses calculable from new basic principles?*
- *Is there a connection between quarks, charged-leptons, and neutrino masses?*

- *Beside the Higgs, are there other interactions distinguishing the 3 families?*
- *If so, which is their energy scale?*

- *Is there CP violation in flavour-blind processes?*
- *What is the explanation of the strong CP problem?*

We need to address these fundamental questions !

(*which are not less crucial or fundamental than Higgs hierarchy problem*)

Many theoretical ideas [→ Nir, Dine], but no clear answers yet...

To make progress we need experimental clues, which can only come from dedicated experiments

Why ?

Flavor and CP violating processes are also particularly interesting since they allow us to (indirectly) *probe very high energy scales*

$$A(\psi_i \to \psi_j + X) = A_0 \left(\frac{c_{\mathrm{SM}}}{v^2} + \frac{c_{\mathrm{NP}}}{\Lambda^2_{\mathrm{NP}}} \right)$$

This is particularly important, in view of the present lack of clear indications about NP scale [**synergy with HE**]

- SM success in flavour physics @ B factories + EWPO @ LEP → strong indication of light Higgs + energy gap @ LHC (*that is what we se now...*)

- All "recent" discoveries at the HE frontier in particle physics [c, b, t, H] were anticipated by indirect indications from flavor, CPV, and EWPO

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- All "recent" discoveries at the HE frontier in particle physics [c, b, t, H] were anticipated by indirect indications from flavor, CPV, and EWPO
- Hard to expect a discovery at HE without indirect clues at low energies...

Indirect NP searches must be a key ingredient of our future strategy!

How ?

I. The light sector [u, d, s + e, μ]

Three "clear" cases calling for **diversity** in the **short/mid-term**:

	addresses:	*requires*:	
• EDMs [d_e, d_n, d_N,...]	Strong CP light Y's	**Rings/Magnetic traps** [*Long list...*]	→ Paul
• μ→e processes	$1^{st} \leftrightarrow 2^{nd}$ lepton mix.	**Intense μ beams** [MEG, Mu3e,Mu2e, COMET]	→ Kuno (*Tue*)
• Rare K decays	$1^{st} \leftrightarrow 2^{nd}$ quark mix.	**Intense K beams** [NA62, KEVLER, KOTO]	→ Sozzi

- ✓ Outstanding physics goals (fundamental & unique)
- ✓ Difficult experiments, but on a smaller scale

Two or more experiments for each of these dedicated "low-energy" research lines would be extremely welcome !

How ?

II. The heavy sector [b, c + τ]

Bright near-term future [~ 10 yrs] with **LHCb (I+II)** & **Belle-II**

This is likely to be the most exciting frontier of particle physics in the next ~ 10 years:

→ Schune

- Large discovery potential (*wide parameter range still to be explored*)
- Further "enriched" by
  - present anomalies... → Fajfer (*Tue*)
  - expected progress from lattice QCD → Pena

I have strong expectations !

▸ How ?

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Clear mid-term future [~ 10-20 yrs] with an outstanding case:

- **LHCb-II** [@ HL-LHC]: ultimate precision on "all-visible" B and D decay modes [$B_{s,d} \to \mu\mu$, R_{K,K^*}, CKM, charm CPV, ...]

possibly complemented by specific initiatives, such as

- **TauFV** [@ SHIP beam line]: $\tau \to 3\mu$ @ 10^{-10} unique, outstanding goal !
- **STC** @ Novosibirsk [*competitiveness after Belle-II less clear...*]

→ Luisiani (*Tue*)

▸ How ?

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A strong case for the long-term future [> 20 yrs]:

- **Flavor physics @ FCC-ee** [running at the Z-pole , with 5×10^{12} Z's !]

  Unique potential on b and τ decays with missing energy, from $Z \to bb$, $\tau\tau$
  Just one example: $B \to K^*\tau\tau$ [*holy grail of present anomalies...*]:
  ~1000 SM events @ FCC-ee vs. ~10 @ Belle-II

  And of course FCC-ee would allow major improvements on EWPO & Higgs
  → **ideal set-up to optimize indirect NP searches**

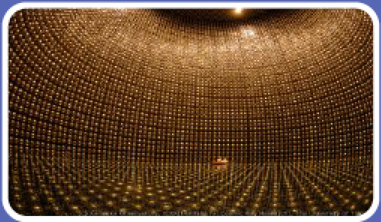
Summary slides from today's speakers

Quarks: smallness, hierarchy

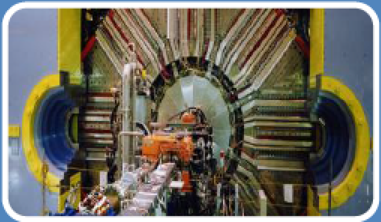
⟹ Approximate symmetry?

Squarks: degeneracy, alignment

⟹ Flavor paradise, but where are they?

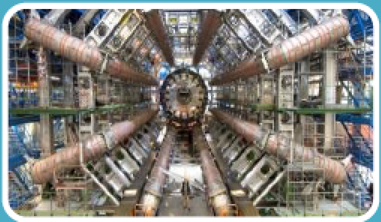


Neutrinos: anarchy ⟹ Knowing more does not necessarily mean understanding better



Flavor Factories: top, bottom, charm, tau, strange, mu

⟹Rich and exciting program for LFU, LFV, CPV, FCNC



Higgs: diagonality? proportionality? CPV?

⟹ a new opportunity for flavor

Which future facility or experiment is scientifically better for challenging SM and identifying NP through K decays?

- Kaon decays have great potential to contribute in unique, complementary, self-contained ways to the understanding of flavour

BUT

- "Facility" is not a single general-purpose experiments

THEREFORE

- Forbidden/LFV decay searches can probe unreachable mass scales, will mostly come as byproducts

WHILE

- Ultra-rare K decays are the most-promising driving goal in the field: experiments are hard and different shots must be taken at them

HENCE

- After fully exploiting the **existing p machines** (CERN SPS, J-PARC) with suitable sharing to fixed-target intensity frontier experiments
- A **very intense (MW) slowly-extracted proton machine** (the driver for an energy-frontier machine?) would be a highly versatile, multi-purpose, discovery tool, allowing ultimate NP searches though K decays, suited to whatever NP turns out to be

Summary

LHC:
- main results from LHCb
- ATLAS and CMS also contributing and are working to enlarge their flavour physics scope

A charged hadron PID is mandatory for a full physics program.

Important to have experiments in very different environments (pp and e^+e^-).

LHCb Upgrade II (x2 in Λ_{NP} wrt Upgrade I) $\Rightarrow$ LHCC framework TDR for beg. of 2021.

Complementarity/synergy with τ-charm factories results (BES III), and lower energy experiments

In order to benefit from the experimental precision, parallel effort on the reduction of theoretical uncertainties is required

In the longer term: « Z^0-factory » a fantastic tool for Flavour Physics

Critical for medium term:
preparation of LHCb Upgrade II, full exploitation of LHCb & Belle II data samples

conclusions & outlook

- lattice flavour phenomenology has long reached its age of maturity, keeping apace with/abreast of experiment.

- upcoming era will require sub-percent precision in staple observables. tools are in place.
  - finer lattice spacings for precision B-physics
  - quantitative control of e.m. and strong isospin breaking corrections

- new avenues being open for lattice studies.
  - baryon decay
  - long-distance contributions to OPE
  - multihadron/resonances in final state
  - inclusive rates

- lattice collaborations have become large and resource-intensive, in both human and computational terms; sustained support is needed to keep synergy with experimental efforts.

Takeaways

1. Dimension $5/6$ operators: sensitive to very high energy scales, if the new physics doesn't have elaborate flavor structure, correlated with what we see at low energies. Could well be first probe of extremely high energy physics (10^3 TeV)?). Improved measurements of d_n, d_e, etc., always welcome.
2. Dimension four: θ.

Directions for simulations and experiments:

Each of the possible solutions suggests research directions.

1. $m_u = 0$: probably ruled out, but continued improvements in lattice simulations, especially tests of θ-dependence of interest.*
2. Nelson-Barr: challenging to build models which are not severely fine-tuned, but the flip side is that such models almost inevitably make predictions close to current limits. If a discovery, new physics nearby, or far away?
3. Peccei-Quinn symmetry: in many ways the most promising solution of strong CP. Here the big puzzle is the *quality* of the symmetry. Simplest explanations as in string theory, point to large values of f_a. So important to pursue current generation of experiments (ADMX) but to be constantly looking for improvements.

Conclusions + Recommendations

EDM measurements achieve a fantastic absolute measurement sensitivity

- EDM are sensitive to new physics complementary to LHC and flavor factories
- Fastest progress with atomic-molecular EDM experiments

- neutron EDMs profit from new sources and innovations in shielding and magnetometry ("medium size" measurements at large scale facilities) - big leap around the corner (a must to be continued)
- proton EDM could become a new player ("medium size" measurements at large scale facilities)
  - High risk - high gain - high costs - high patience (a must to be continued)
- heavy lepton EDM require large scale facilities - absolute sensitivity not competitive

  justifications through anomaly observed in lepton sector (still exploratory but small costs)
- heavy baryon EDM discussed at LHCb using channeling - interesting and encourage to study elimination of systematics (false effects)
- atomic EDM have highest absolute sensitivities ("small scale experiments") (a must to be continued)
- Different atomic systems show complementarity (FRIB related molecules very promising)
- Combined fits are now setting stringent limits on couplings with EFT