Brief intro to Flavor Physics @ FCC-ee

Gino Isidori
[ University of Zürich ]

- General considerations
- The special role of the 3\textsuperscript{rd} family
- Highlights of FCC-ee in \textit{tau} \& \textit{b} physics
- Conclusions
General considerations [On the importance of indirect NP searches]

- We have good reasons to expect new degrees of freedom in the TeV-scale domain. However, no direct signals of New Physics has been observed so far at the high-energy frontier (whose exploration is far from being complete...)

No clear indications on the precise location of the New Physics threshold

- We should not forget that in the last ~ 40 years all the discoveries at the high-energy frontier [c, b, t, H] were anticipated by indirect indications from indirect searches (flavor/CP and EWPO).

Hard to expect a discovery at High Energies without **indirect clues** at Low Energies...
General considerations [On the importance of indirect NP searches]

Hard to expect a discovery at HE without indirect clues at low energies (general field-theory argument):

\[
A(\psi_i \rightarrow \psi_j + X ) = A_0 \left[ 1 + \frac{c_{NP} m_W^2}{c_{SM} \Lambda^2} \right]
\]

\[
\mathcal{L}_{NP-EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_{NP}}{\Lambda^{d-4}} O_i^{d \geq 5}
\]
General considerations [On the importance of indirect NP searches]

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\textbf{General considerations} [On the importance of indirect NP searches]

The FCC-ee offers a \textbf{unique opportunity} in this respect with the huge statistics @ the Z pole:

\[ A(\psi_i \rightarrow \psi_j + X) = A_0 \left[ \frac{c_{\text{SM}}}{M_W^2} + \frac{c_{\text{NP}}}{\Lambda^2} \right] \]

For the clean observables (pure stat. error) determined by Z decays:

\[ \Lambda_{\text{NP}} \mid_{N_Z \ [\text{LEP}]} \sim 10 \times \Lambda_{\text{NP}} \]

\[ c_{\text{NP}} \mid_{N_Z \ [\text{FCC-ee}]} = 0.003 \times c_{\text{NP}} \times 10^5 \times N_Z \ [\text{FCC-ee}] \]

\textbf{Unprecedented jump in precision!}
General considerations [On the importance of indirect NP searches]

The FCC-ee offers a unique opportunity in this respect with the huge statistics @ the Z pole:

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\[ \Lambda_{NP} \]

\[ c_{NP} \]

\[ N_Z \text{ [LEP]} \]

\[ \sim 10 \times \Lambda_{NP} \]

\[ 0.003 \times c_{NP} \]

\[ 10^5 \times N_Z \text{ [FCC-ee]} \]

\[ \Lambda_{NP} \]

\[ c_{NP} \]

\[ \tau \tau \text{ [Belle]} \]

\[ \sim 6 \times \Lambda_{NP} \]

\[ 0.03 \times c_{NP} \]

\[ 10^3 \times \tau \tau \text{ [FCC-ee]} \]

For th. clean observables (pure stat. error) determined by Z decays

Unprecedented jump in precision!

For \( b \bar{b} \) & \( \tau \tau \) pairs we have to take into account also Belle-II (~ 50 \times Belle), & LHCb

But... → LHCb is poor on missing-energy modes (virtually all tau decays..)

→ At Belle-II there are no \( B_s \), and \( b \) & \( \tau \) have a very small boost
The special role of the 3\textsuperscript{rd} family
**The special role of the 3rd family**

For a long time, the vast majority of model-building attempts to extend the SM was based on the *implicit* hypotheses of *flavor-universal* New Physics

- Concentrate on the 
  Higgs hierarchy problem
- Postpone the flavor problem to higher scales

3 gen. = “identical copies” up to high energies

Less compelling after the LHC results:

*No clear sign of NP from direct searches*
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Less compelling after the LHC results:

\textit{No clear sign of NP from direct searches}

\textit{strong bounds on NP \textit{coupled universally} to all families}

\textit{worsening of the Higgs hierarchy problem}
The special role of the 3rd family

CMS preliminary

Overview

3rd family NP

Universal NP

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).
The special role of the 3rd family

Shift of paradigm to address both the Higgs hierarchy problem and the flavor puzzle: multi-scale UV completion with flavor non-universal interactions

Main idea:

- Flavor non-universal interactions already at the TeV scale:
  - 1st & 2nd gen. have small masses because they are coupled to NP at heavier scales

3 gen. = “identical copies” up to high energies

Energy

$\Lambda_1$ → $\psi_1$ mass
$\psi_{1,2} & \psi_3$

$\Lambda_2$ → $\psi_2$ mass
$\psi_2 & \psi_3$

$\Lambda_{3,H}$ → $\psi_3$ mass
$\psi_3$

$\Lambda_{EW}$ → SM EFT

Dvali & Shifman '00
Panico & Pomarol '16
Bordone et al. '17
Allwicher, GI, Thomsen '20
Barbieri '21
Davighi & G.I. '23
The special role of the 3rd family

Shift of paradigm to address both the Higgs hierarchy problem and the flavor puzzle: multi-scale UV completion with flavor non-universal interactions

Effective organizing principle for the flavor structure of the SMEFT
**The special role of the 3rd family**

Shift of paradigm to address both the Higgs hierarchy problem and the flavor puzzle: *multi-scale* UV completion with *flavor non-universal* interactions

A renewed phenomenological interest in this type of approach has been triggered by the B-physics anomalies (*hinting to violations of lepton flavor universality, mainly in 3rd gen.*)

But the construction has an intrinsic, more general, interest:

- Explain the origin of the flavor hierarchies
- Allow TeV-scale NP coupled (mainly) to 3rd gen. → Higgs sector stabilization

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FCC pheno Workshop – CERN, 5-7 July 2023

Allwicher, GI, Thomsen '20
Davighi & G.I. '23

→ talk by Joe Davighi
The special role of the 3\textsuperscript{rd} family

Renewed phenomenological triggered by the B-physics anomalies:

N.B.:
1) The drop in significance of the neutral-current anomalies does not imply a major shift in the preferred parameter space
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Renewed phenomenological triggered by the B-physics anomalies:

N.B.:

1) The drop in significance of the neutral-current anomalies does not imply a major shift in the preferred parameter space.

2) Beside the (low) significance in present data, this set-up has an interesting “UV motivation” → useful benchmark for FCC-ee studies.

SU(4)[3]×SU(3)[12] × G\textsubscript{EW}

TeV-scale U\textsubscript{1} coupled mainly to 3\textsuperscript{rd} gen.

SU(3) × SU(2)\textsubscript{L}×U(1)\textsubscript{Y}
Highlights of FCC-ee in tau & b physics
E.g.: (I) LFU tests in tau decays

| $|g_\mu/g_e|$ | $\Gamma_{\tau\rightarrow\mu}/\Gamma_{\tau\rightarrow e}$ | $\Gamma_{\pi\rightarrow\mu}/\Gamma_{\pi\rightarrow e}$ | $\Gamma_{K\rightarrow\mu}/\Gamma_{K\rightarrow e}$ | $\Gamma_{K\rightarrow\pi\mu}/\Gamma_{K\rightarrow\pi e}$ | $\Gamma_{W\rightarrow\mu}/\Gamma_{W\rightarrow e}$ |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1.0018 (14)     | 1.0021 (16)     | 0.9978 (20)     | 1.0010 (25)     | 0.996 (10)      |

<table>
<thead>
<tr>
<th>$g_{\tau}/g_{\mu}$</th>
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<td>1.0011 (15)</td>
<td>0.9962 (27)</td>
<td>0.9858 (70)</td>
<td>1.034 (13)</td>
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| $|g_{\tau}/g_e|$ | $\Gamma_{\tau\rightarrow\mu}/\Gamma_{\mu\rightarrow e}$ | $\Gamma_{W\rightarrow\tau}/\Gamma_{W\rightarrow e}$ |
|-----------------|-----------------|-----------------|
| 1.0030 (15)     | 1.031 (13)      |

- NP expectation from motivated NP (→ flavor deconstruction) up to current bounds (i.e. $\sim 2 \times 10^{-3}$)
- SM theory precision $\sim 10^{-5}$
- Belle-II can (at most) reach an error $\sim 0.3 \times 10^{-3}$
- FCC-ee could go below $10^{-4}$ !

**Unique opportunity!**
**Highlights of FCC-ee in tau & b physics**

E.g.: (1) LFU tests in tau decays

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Highlights of FCC-ee in tau & b physics

E.g.: (I) LFU tests in tau decays

LFU violations in tau decays expected in motivated LQ models addressing the B anomalies

Allwicher, GI, Selimovic, ’21
Allwicher, GI, Lizana, Selimovic, Stefanek, ’23
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bit.ly/3kkuuyg

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4321 model [vector LQ]

hypothetical 3σ bands with $\Gamma(\tau \to \mu \nu \nu)$ & $\Gamma(\tau \to e \nu \nu)$ @ $2 \times 10^{-4}$
**Highlights of FCC-ee in tau & b physics**

E.g.: (II) LFV in tau & B decays

Lepton Flavor Violation of the type $\tau \rightarrow \mu$ naturally large ($\sim |V_{cb}|$) in several NP models

...including the vector LQ [*]

[*] upper bound on $\tau \rightarrow \mu$ mixing reduced by $\sim \frac{1}{2}$ due to new $R_K$
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**Highlights of FCC-ee in tau & b physics**

E.g.: (III) Rare B decays

The kinematical configuration with boosted b's and tau's (from Z decays) + “clean” environment, gives to the FCC-ee b-physics program a special advantage (compared to B-factories & LHC-b) to a series of very interesting rare B decays

### III.a All decays into tau leptons:

\[ B \rightarrow K^* (K) \tau^+\tau^- : \quad BR_{\text{SM}} \sim 10^{-7} \]

*Golden modes related to present anomalies → potential huge NP effects*

- \( BR_{\text{exp}} (B \rightarrow K\tau^+\tau^-) : < 2 \times 10^{-3} [\text{Babar}] \)
- Belle-II (\( B \rightarrow K^*\tau^+\tau^- \)): \~\sim 1 \text{ event @ SM rate (with small S/B)}
**Highlights of FCC-ee in tau & b physics**

Detailed study of $B \rightarrow K^{*}\tau^{+}\tau^{-}$ [highly non-trivial channel also @ FCC-ee]:

[Graphical representation of the study of $B \rightarrow K^{*}\tau^{+}\tau^{-}$]

- Precision of BF measurement as a function of the resolution
- Invariant B0 mass with sel solutions and natural number of event
**Highlights of FCC-ee in tau & b physics**

Detailed study of $B \rightarrow K^{*+}\tau^{+}\tau^{-}$ [highly non-trivial channel also @ FCC-ee]:

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Precision of BF measurement as a function of the resolution

- SV and TV longitudinal smearing: 20 $\mu$m

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Belle II (50 ab$^{-1}$)

$C_{LR}^c = 0$

$C_{LR}^c = -C_{LL}^c$

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T. Miralles
[Cracow meeting]
**Highlights of FCC-ee in tau & b physics**

Detailed study of $B \rightarrow K^*\tau^+\tau^-$ [highly non-trivial channel also @ FCC-ee]:

![Graph showing precision of BF measurement as a function of the resolution](image1)

![Graph showing the SM prediction of $B(B^+ \rightarrow K^{+}\tau^{+}\tau^{-})$](image2)

- **Aebischer, GI, Pesut, Stefanek, Wilsch, 23**

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III.a All decays into tau leptons:

\[ B \to K^* (K) \tau^+ \tau^- : \quad \text{BR}_{\text{SM}} \sim 10^{-7} \]

III.b Charged-currents (w & w/o taus)

\[ B_{c,u} \to \tau \nu \]

\[ \frac{B(B_{u(c)} \to \tau \nu)}{B(B_{u(c)} \to \mu \nu)} \quad \text{Very interesting LFU tests below 1 \%}, \quad \text{provided th. control on QED corrections...} \]

III.c FCNC inclusive modes:

\[ B \to X \ell \ell \quad \& \quad B \to X \nu \bar{\nu} \quad \text{Decay modes sensitive to a variety of NP models, with good th. control compared to exclusive modes} \]

→ talk by Claudia Cornella
**Highlights of FCC-ee in tau & b physics**

Detailed study of $B_c \rightarrow \tau \nu$

Amhis, Hartmann, Helsens, Hill, Sumensari, ’23

\[
R_c = \frac{\mathcal{B}(B_c^+ \rightarrow \tau^+ \nu_{\tau})}{\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_{\mu})}
\]
**Highlights of FCC-ee in tau & b physics**

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Amhis, Hartmann, Helsens, Hill, Sumensari, '23
Concluding remarks

- In the absence of a clear indication for the next energy threshold, a new generation of indirect NP searches with EWPO + Flavor is a must → unique opportunity with FCC-ee

- In the Flavor sector there will be two other important players before FCC-ee (LHCb-II + Belle-II), but FCC-ee has key advantages in specific $b$ & $\tau$ modes due its peculiar environment ($boosted b$ & $\tau + clean$)

- From a model-building perspective, these $b$ and $\tau$ modes are very interesting probes of a wide class of motivated models ($\rightarrow$ flavor deconstruction)

- More work is needed to fully exploit the discovery potential of FCCee in this area. Three main directions:
  - feasibility studies;
  - $SM$ precision calculations;
  - identification of NP benchmarks $\leftrightarrow$ correlation studies