Flavour Physics opportunities and detector challenges at FCC-ee

Stéphane Monteil,
Clermont University, LPC-IN2P3-CNRS.

w/ A. Lusiani (Flavour perf.), J. Kamenik and G. Isidori (Flavour prog.)
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Outline

• Flavours@FCC-ee: setting the scene.

• Overview of selected studies performed so far
  • Rare decays.
  • CKM profile.
  • Tau Physics.
  • Connecting dots.

• Outlook.
1) FCC-ee specifics for Flavour Physics.

A- Particle production at the $Z$ pole:

- About 15 times the Belle II anticipated statistics for $B^0$ and $B^+$.
- All species of $b$-hadrons are produced.
- Expect $\sim 4 \cdot 10^9$ $B_c$-mesons assuming $f_{B_c}/(f_{B_u} + f_{B_d}) \sim 3.7 \cdot 10^{-3}$

<table>
<thead>
<tr>
<th>Working point</th>
<th>Lumi. / IP [$10^{34}$ cm$^{-2}$s$^{-1}$]</th>
<th>Total lumi. (2 IPs)</th>
<th>Run time</th>
<th>Physics goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z$ first phase</td>
<td>100</td>
<td>26 ab$^{-1}$/year</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>$Z$ second phase</td>
<td>200</td>
<td>52 ab$^{-1}$/year</td>
<td>2</td>
<td>150 ab$^{-1}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Particle production ($10^9$)</th>
<th>$B^0 / \bar{B}^0$</th>
<th>$B^+ / B^-$</th>
<th>$B^0_s / \bar{B}^0_s$</th>
<th>$\Lambda_b / \bar{\Lambda}_b$</th>
<th>$c\bar{c}$</th>
<th>$\tau^- / \tau^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle II</td>
<td>27.5</td>
<td>27.5</td>
<td>n/a</td>
<td>n/a</td>
<td>65</td>
<td>45</td>
</tr>
<tr>
<td>FCC-ee</td>
<td>300</td>
<td>300</td>
<td>80</td>
<td>80</td>
<td>600</td>
<td>150</td>
</tr>
</tbody>
</table>

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Flavours @ FCC
1) FCC-ee specifics for Flavour Physics.

B- The Boost at the $Z$:

\[ \langle E_{X_b} \rangle = 75\% \times E_{\text{beam}}; \langle \beta \gamma \rangle \sim 6. \]

- Fragmentation of the $b$-quark:
- Makes possible a topological rec. of the decays w/ miss. energy.

C- Comparison w/ LHCb and Belle II. Advantageous attributes:

<table>
<thead>
<tr>
<th>Attribute</th>
<th>$\Upsilon(4S)$</th>
<th>$pp$</th>
<th>$Z^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All hadron species</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>High boost</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Enormous production cross-section</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Negligible trigger losses</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Low backgrounds</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Initial energy constraint</td>
<td>✓</td>
<td>✓</td>
<td>(✓)</td>
</tr>
</tbody>
</table>

D- Versatility: the $Z$ pole does not saturate all Flavour possibilities. Beyond the obvious flavour-violating Higgs and top decays, the $WW$ operation will enable to collect several $10^8$ $W$ decays on-shell AND boosted.
1) FCC-ee specifics for Flavour Physics.

![Graph showing FCC-ee results](image)

**FCC-ee**

$Z^0 \rightarrow b\bar{b}$ Delphes simulation

- Total fit
- $B_s^0 \rightarrow \mu^+\mu^-$
- $B^0 \rightarrow \mu^+\mu^-$
- $B^0 \rightarrow \pi^+\pi^-$
- Simulated data

**LHCb Preliminary**

$9 \text{ fb}^{-1}$

BDT ≥ 0.5

![Graph showing LHCb results](image)
1) **FCC-ee specifics for Flavour Physics.**

E- Detector performance: exquisite tracking is necessary and at reach. Invariant-mass resolution as it is in the current state of IDEA fast simulation:

Ultra-high resolution calorimetry and vertexing are in addition highly desirable. Performance to be determined in the Feasibility Study Phase.
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Flavours @ FCC
2) Overview of the studies: Rare decays & Friends


- How to go further with indirect measurements? Belle II and LHCb will refine these measurements. But final states with tau lepton is a promising way forward. FCC-ee unique. Two flashed here $B^0 \to K^{*0} \, \tau^+\tau^-$ and $B_c \to \tau^+\nu$. Other modes (relevant as well) are under study, e.g. $b \to s\nu\nu$.

- These transitions with third generation particles are a must to study.
2) Overview of the studies: Rare decays & Friends

- $B^0 \rightarrow K^{*0} \tau^+ \tau^-$. 

- **Six** momentum components to be searched for:
  - $B^0$ momentum direction from $K\pi$ fixes 2 d.o.f.
  - $\tau$ momenta direction fixes 4 d.o.f.
  - Mass of the $\tau$ provides 2 additional constraints
  - The system is in principle over-constrained.
2) Overview of the studies: Rare decays & Friends

- $B^0 \rightarrow K^{*0} \tau^+\tau^-$: a couple of backgrounds that an adequate vertexing can discriminate.

![Graph showing invariant mass distribution with selected events and natural number of events](image-url)

- PV (3.0µm) & SV & TV (20.0µm, 3.0µm) SMEARED
- Core $\sigma = 14.5$ MeV/c$^2$
- Core gaussian fraction = 0.96
- Probability to recognize a $\pi^0 = 0.50$

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2) Overview of the studies: Rare decays & Friends

- \( B^0 \to K^{*0} \tau^+ \tau^- \): executive summary

- IDEA Delphes card for \( p \) resolution. Vertexing performance from smearing: allows to assess the required performance.

- Study w/ background has started. Initial look promising [\( O(200) \) events at SM value]. Some overwhelming backgrounds (with several \( \pi^0 \) discovered).

- A selection is in order.

- Outlook: attempt at a “comprehensive" bkg estimate (getting to it). Actual vertex detector geometries to be assessed as a function of the precision.
2) Overview of the studies: Rare decays & Friends

• $B_c \rightarrow \tau^+ \nu$: another fundamental test of lepton universality. Counterpart of $R_{D,D^*}$. A promising study lies here [2105.13330, see also 2007.08234]

Bottomline: few percent precision mostly limited yet by the knowledge of the normalisation BF ($J/\psi \mu \nu$).
2) Overview of the studies: CKM profile & Friends

- CKM profile is at the heart of the Flavour programme. Possible status of the CKM profile in the late 2030s assuming SM is valid (Lattice-QCD expected improvements in; LHCb-biased view).

- Belle II will add up to this. The question is: can we do better?
2) Overview of the studies: CKM profile & Friends

- $B^+ \rightarrow \tau^+\nu$: access $|V_{ub}|$ with the only knowledge of the decay constant. Work in progress building on [hep-ex:2105.13330].

Bottomline: similar yields / purities as for $B_c \rightarrow \tau^+\nu$. 

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2) Overview of the studies: CKM profile & Friends

- Another projection is the model-independent search for BSM CPV phases in mixing processes

hep-ph 2006.04824

![Diagrams showing p-values for different parameters](image)

FIG. 2. Current (top left), Phase I (top right), Phase II (bottom left), and Phase III (bottom right) sensitivities to $h_d - h_s$ in $R_d$ and $R_s$ mixings, resulting from the data shown in Table I (where central values for the different inputs have been adjusted). The dotted curves show the 99.7% CL (3σ) contours.

- Bottleneck in precision: $V_{cb}$ and Lattice-QCD mixing parameters
2) Overview of the studies: CKM profile & Friends

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rescaled to SM

— Now,

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— Now, after LHCb-U1 and Belle II — 2030

**FIG. 2.** Current (top left), Phase I (top right), Phase II (bottom left), and Phase III (bottom right) sensitivities to $h_d - h_s$ in $R_{cb}$ and $R_{s}$ mixings, resulting from the data shown in Table I (where central values for the different inputs have been adjusted). The dotted curves show the 99.7% CL (3σ) contours.

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after LHCb U2 and Belle III
— 2040

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rescaled to SM — Now,

after LHCb-U1 and Belle II — 2030

after LHCb U2 and Belle III — 2040

FCC-ee.
Vcb in.
LQCD not

• Bottleneck in precision: $V_{cb}$ and Lattice-QCD mixing parameters
2) Overview of the studies: CKM profile & Friends

- $|V_{cb}|$ measurement: the WW threshold. First look here.

<table>
<thead>
<tr>
<th>Eff. \ q-jet</th>
<th>b-jet</th>
<th>c-jet</th>
<th>uds-jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>b-tag</td>
<td>25 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c-tag</td>
<td>10 %</td>
<td>50 %</td>
<td>2 %</td>
</tr>
</tbody>
</table>

- Numbers picked from *Tracking and Vertexing at Future Linear Colliders: Applications in Flavour Tagging* — Tomohiko Tanabe. ILD@ILC. IAS Program on High Energy Physics 2017, HKUST

- With these state-of-the-art inputs, precision on $|V_{cb}|$ improves from 1.9% (current) to 0.4%. Ultimate statistical precision is $O(10^{-4})$.

- Actual study in order. *A driver for the b- and c- tagging performance.*
2) Overview of the studies: CKM profile & Friends

- Sub-degree gamma angle measurement at reach:

\[
\int L dt = 150 \text{ ab}^{-1}
\]

PDG: \( \gamma = (71.1^{+4.6}_{-5.3})^\circ \)

Measurement of CP violation with \( B_s \rightarrow D_s K \)

\[ \delta(\rho) \approx 3.2 \times 10^{-3} \text{(stat.)} \]

\[ \delta(\sin^2 \phi_{\text{CKM}}) \approx \delta(\sin^2 \gamma) \approx 5 \times 10^{-3} \text{(stat.)} \approx \delta(\gamma) \approx 0.4^\circ \text{(stat.)} \]

Result 3:

Potential statistical gain of factor 4-5 with \( D_s^\pm \rightarrow K^0 K^\pm, \phi \rho^\pm, \ldots \) but background needs to be studied (see later)+

Additionnal potential gain (another factor \( \sim 2 \)) with \( B_s \rightarrow D_s^\pm K^\mp, D_s^\pm K^{*+}, D_s^{*\pm} K^{*+}, \) most modes including \( \gamma(s) \)

- A lot more to do with neutrals!

- Several null tests of the SM accessible w/ unprecedented precision, e.g. semileptonic asymmetries, \( \phi_s \) in penguin-dominated diagrams …
2) Overview of the studies: CKM profile & Friends

- Degree alpha measurement: a study to get started.

- The alpha angle can be measured through an isospin analysis from $B^0 \rightarrow (\pi \pi)^{+/-00}$. The knowledge of parameter $S^{00}$, that can be accessed from time-dependent studies, allows to lift degeneracies among solutions.

![Figure 4: Constraint on the reduced amplitude $a^{+-} = A^{+-}/A^{+0}$ in the complex plane for the $B \rightarrow \pi \pi$ (left) and $B \rightarrow \pi \pi$ systems (right). The individual constraint from the $B^0(B^0) \rightarrow \pi^+ \pi^-$ observables and from the $B^0(B^0) \rightarrow \pi^0 \pi^0$ observables are indicated by the yellow and green circular areas, respectively. The corresponding isospin triangular relations $a^{00} + a^{+-}/\sqrt{2} = 1$ (and CP conjugate) are represented by the black triangles.]

- Accessible through Dalitz decays of the $\pi^0$ in $B^0 \rightarrow (\pi^0 \pi^0)$. Vertex is there. Statistics too [O(10k)]. A possible case study for EM calo. design.
2) Overview of the studies: others

• Many other categories to explore. To cite two of them that shall be addressed in the feasibility study.

  —) Mass and lifetime properties, spectroscopy, exotics.

  —) Charm physics.

  Both categories are not touched yet to my knowledge on the experimental side but are a must-do.

• The invariant-mass resolutions, charged and hopefully neutrals as well, at FCC-ee for narrow states shall make marvels in spectroscopy.

2) Overview of the studies: connecting some dots

- Embrace top quark, $Z$ pole and Flavour observables to operate a SMEFT analysis. Exercised first with top quark:

Very first look at simulated $t\bar{t}$bar events

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Motivation Part I

- Goal: Global fit with current and future measurements in top + flavor physics
- Intermediate steps I and II completed

I. sensitive observables
   - event simulation for different values of $C_i$

II. model finding
   - parameterisations as function of $C_i$ (model)

... global fit
   - Bayesian analysis with appropriate choice of priors

constraints on model parameters $C_i$

L. Röhrig | May 25, 2022

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2) Overview of the studies: Tau lepton physics

- Touched so far through the lepton universality studies and Lepton Flavour violating decays (LFV Z and tau directly).

### Lepton Universality - Universality of Fermi constant

The Fermi constant is measured in \( \mu \) decays and defined by

\[
\frac{G_F}{\sqrt{2}} = \frac{G_F}{\sqrt{2}} \cdot \frac{1}{\text{MeV}^2} 
\]

Similarly, we can define the Fermi constant measured in \( \tau \) decays by

\[
\frac{G_F}{\sqrt{2}} = \frac{G_F}{\sqrt{2}} \cdot \frac{1}{\text{MeV}^2} 
\]

- **Universality supported by current data -**
  - \( \sigma \) error ellipse (blue) consistent with mass (red)
  - Shown in yellow: "guestimates" on FCC - ee precisions

**Today:**
- FCC - ee: Will see \( 3 \times 10^{-11} \) \( \tau \) decays
- Statistical uncertainties at the 10 ppm level
- How well can we control systematics?

**Use** J/\( \psi \) mass as reference (known to 2 ppm)

Laboratory flight distance of 2.2 mm \( \Rightarrow \) 10 ppm corresponds to 22 nm (!)

No improvement since LEP (statistics limited)

Depends primarily on \( e^-/\pi^- (\& e^-/\rho^-) \) separation

**Tracking** vertex detector ECAL \( \frac{dE}{dx} \)

### Necessary ingredients:

- **Mass**
- **Lifetime**
- **Leptonic branching fractions**

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2) Overview of the studies: Tau lepton physics

- A non-exhaustiveTau Physics advantages and prospects:
  - About 200 billions of tau pairs at the Z pole.
  - About 3 times the Belle II anticipated statistics but with a 25 boost!
  - Beyond EWPO (polarisation), stringent lepton universality tests. Global improvement can be two orders of magnitude w.r.t. state of the art.
  - 2-3 orders of magnitude w.r.t. state of the art in sensitivity for LFV Z decays. 1-2 orders of magnitude for actual LFV tau decays.
  - Hadronic branching fractions, spectral functions, strong coupling constant: the QCD program with tau is rich.
3) Outlook

- Flavour Physics defines shared (vertexing, tracking, calorimetry) and specific (hadronic PID) detector requirements. The feasibility study entangles the Physics performance and detector concepts. **Flavour physics places most demanding requirements for vertexing and calorimetry.**

- The feasibility study will be used to systematically address the physics case while placing requirements on the detectors. Hadron particle identification deserves a special treatment and Flavour physics is at the heart of it.

- All studies at the Z pole shown above are made for $5 \times 10^{12}$ $Z$ decays. Most of flavour observables will remain statistically limited. More would be desirable! The machine study from two IPs to four IPs is positive and would bring about a factor 2 (1.7) in integrated luminosity.

- Four experiments can as well allow for different experiment designs, including a flavour-oriented concept.
3) Outlook

• A flavour physics working group has been set up and will get up and running before this Summer. Here to subscribe:
  • https://e-groups.cern.ch/e-groups/EgroupsSubscription.do?egroupName=FCC-PED-PhysicsGroup-Flavours
  • First meeting of the Flavour performance WG is soon to be announced.
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4) Back-ups
3) Outlook — Feasibility Study

The FCC integrated program
inspired by successful LEP – LHC programs at CERN

comprehensive long-term program maximizing physics opportunities

- stage 1: FCC-ee (Z, W, H, t\bar{t}) as Higgs factory, electroweak & top factory at highest luminosities
- stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options
- complementary physics
- common civil engineering and technical infrastructures, building on and reusing CERN’s existing infrastructure
- FCC integrated project allows seamless continuation of HEP after completion of the HL-LHC program
3) Outlook — Feasibility Study — Backups.

Timeline of the FCC integrated programme

- Feasibility Study: 2021-2025
- If project approved before end of decade → construction can start beginning 2030s
- FCC-ee operation ~2045-2060
- FCC-hh operation 2070-2090++

F. Gianotti

FCC Feasibility Study Overview
Michael Benedikt
Paris, 30 May 2022

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3) Outlook — Feasibility Study

- Civil engineering and infrastructures
3) Outlook — Feasibility Study

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