Flavour Physics possibilities at FCC-ee

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On behalf of the FCC-ee design study
Outline of the talk

• Introduction to the FCC project

• Few words on the $e^+e^-$ machine

• The Physics case at large.

• The Flavour Physics case:
  • Leptons
  • Quarks
1. Introduction to FCC:

- Starting from the former European HEP strategy 2013

Summary: European Strategy Update 2013
Design studies and R&D at the energy frontier

...“to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update”:

d) CERN should undertake design studies for accelerator projects in a global context,

- with emphasis on proton-proton and electron-positron high-energy frontier machines.
- These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures,
- in collaboration with national institutes, laboratories and universities worldwide.


- At the time the LHC Run II will have delivered its results, have an educated vision of the reach of future machines for the next round of the European Strategy in 2018/19.
1. Introduction to FCC: the scope of the project

• Forming an international collaboration to study:
  
• 100 TeV $pp$-collider (FCC-$hh$) as long term goal, defining infrastructure requirements.
  
• $e^+e^-$ collider (FCC-$ee$) as potential first step.
  
• $p$-$e$ (FCC-$he$) as an option.
  
• 80-100 km infrastructure in Geneva area.
  
• Conceptual design report and cost review for the next european strategy → 2018/19.
1. Introduction to FCC: the design study timeline

- Applies to all machine and experiment designs:

### Proposal for FCC Study Time Line

<table>
<thead>
<tr>
<th></th>
<th>2014</th>
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<th>2016</th>
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- **Prepare**
  - Kick-off, collaboration forming, study plan and organisation

- **Ph 1: Explore options “weak interaction”**

- **Ph 2: Conceptual study of baseline “strong interact.”**
  - Workshop & Review → identification of baseline

- **Workshop & Review, cost model, LHC results → study re-scoping?**

- **Ph 3: Study consolidation**

- **Workshop & Review → contents of CDR**

- **Release CDR & Workshop on next steps**

We are here

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Flavours @ FCC-ee
2. The $e^+e^-$ machine. Baseline design

- Physics from the $Z$ pole to top pair production (90 - 400 GeV), crossing $WW$ and $ZH$ thresholds with unprecedented statistics everywhere.

- Two rings (top-up injection) to cope with high current and large number of bunches at operating points up to $ZH$.

- Description of the machine in M. Koratzinos’s poster.

- To some extent, SuperKEKB shall already meet some of the challenges of FCC-ee:

<table>
<thead>
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<th>Some SuperKEKB parameters:</th>
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<tr>
<td>$\beta_y': 300 \mu m$</td>
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<td>FCC-ee (H): 1 mm</td>
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<td>$\sigma_y: 50 \text{ nm}$</td>
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<td>FCC-ee (H): 50 nm</td>
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<tr>
<td>$\varepsilon / \varepsilon_y: 0.25%$</td>
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<td>FCC-ee (H): 0.2% to 0.1%</td>
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<td>$e^+e^-$ production rate: $2.5 \times 10^{13} / s$</td>
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<td>FCC-ee (H): $&lt; 3 \times 10^{13} / s$</td>
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<td>Off-momentum acceptance at IP: $\pm 1.5%$</td>
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<tr>
<td>FCC-ee (H): $\pm 2.0%$ to $\pm 2.5%$</td>
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<tr>
<td>Beam Lifetime: 5 minutes</td>
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<td>FCC-ee (H): 20 minutes</td>
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<tr>
<td>Centre-of-mass energy: ~10 GeV</td>
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<tr>
<td>FCC-ee (H): 240 GeV</td>
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</table>
2. The $e^+e^-$ machine: luminosity figure.

- The energy allocation of the machine is to be worked out; still ...
- ... we’re speaking here of $10^{12}/10^{13} Z$, $10^8 WW$, $10^6 H$ and $10^6$ top pairs.
3. The $e^+e^-$ Physics case at large.

First look at the physics case of TLEP

The TLEP Design Study Working Group


ABSTRACT: The discovery by the ATLAS and CMS experiments of a new boson with mass around 125 GeV and with measured properties compatible with those of a Standard-Model Higgs boson, coupled with the absence of discoveries of phenomena beyond the Standard Model at the TeV scale, has triggered interest in ideas for future Higgs factories. A new circular $e^+e^-$ collider hosted in a 80 to 100 km tunnel, TLEP, is among the most attractive solutions proposed so far. It has a clean experimental environment, produces high luminosity for top-quark, Higgs boson, W and Z studies, accommodates multiple detectors, and can reach energy up to the tt threshold and beyond. It will enable measurements of the Higgs boson properties and of Electroweak Symmetry-Breaking (EWSB) parameters with unprecedented precision, offering exploration of physics beyond the Standard Model in the multi-TeV range. Moreover, being the natural precursor of the VHE-LHC, a 100 TeV hadron machine in the same tunnel, it builds up a long-term vision for particle physics. Altogether, the combination of TLEP and the VHE-LHC offers, for a great cost-effectiveness, the best precision and the best search reach of all options presently on the market. This paper presents a first appraisal of the salient features of the TLEP physics potential, to serve as a baseline for a more extensive design study.

- This initial study focused primarily on the Higgs Physics (w/ full simulation but CMS detector).
- EWK precision tests examined from LEP ($Z,W$) or LC (top) extrapolations so far.
- The Design Study aims at reaching a fully educated view of the Physics Case from realistic detector simulation studies.
- Explore all the Physics possibilities including Flavours. The latter is not at the heart of the project but can be a supplément d’âme.
3. The $e^+e^-$ Physics case at large: examples

Physics reach related to the luminosity figure:

✓ ElectroWeak Precision tests:

Z pole, $WW$ and top pairs thresholds.

See M. Dam’s and P.Janot’s talks here.

✓ Higgs.

See M. Klute’s talk here.

✓ Summary.

See A. Blondel’s poster here.
4. The Flavours in the big picture.

- Is there a Flavour case in this big picture?

- At least, there are obvious flavour-related questions to be examined, in the light of the anticipated precision that Flavour Physics experiments can reach (Belle II, LHCb upgrade and LFV experiments).

- I’d like to convince you that the answer is definitely yes.

- Illustrations starting with leptons.
• With the advent of the discovery of a SM-like BEH boson, there is a strong case for the existence of right-handed neutrinos possibly below or at the electroweak scale.

• A high-luminosity $Z$ factory with $10^{12} / 10^{13} Z$ offers the opportunity to scan their parameter space below the electroweak scale.

• The sterile neutrinos can be searched for directly through their decays or indirectly through the charged lepton flavour-violating $Z$ decays. Will give examples of both.

• Yukawa for charged fermions

$$\mathcal{L}_Y = Y^d_{ij} \bar{Q}_L i \phi d_R j + Y^u_{ij} \bar{Q}_L i \widetilde{\phi} u_R j + Y^\ell_{ij} \bar{L}_L i \phi \ell_R j + \text{h.c.}$$

• Most general Lag. form for neutrals

$$\mathcal{L}_N = \frac{M_{ij}}{2} \bar{N}_i \phi N_j + Y^{\nu}_{ij} \bar{L}_Li \phi N_j$$
4.1 Flavours at the $Z$: the lepton Physics Case

- Most general form for neutrals $L$
  \[ \mathcal{L}_N = \frac{M_{ij}}{2} \bar{N}^c_i N_j + Y_{ij} \bar{L}_i \phi N_j \]

- Somehow, the only (provocative) question is how many?
4.1 Flavours at the Z: the lepton Physics Case

- Lepton Flavour-Violating $Z$ decays in the SM with lepton mixing are typically
  \[ \mathcal{B}(Z \rightarrow e^\pm \mu^\mp) \sim \mathcal{B}(Z \rightarrow e^\pm \tau^\mp) \sim 10^{-54} \text{ and } \mathcal{B}(Z \rightarrow \mu^\pm \tau^\mp) \sim 4 \times 10^{-60} \]

- Any observation of such a decay would be an indisputable evidence for New Physics.


- The FCC-ee high luminosity $Z$ factory would allow to gain up to six orders of magnitude ...

- Complementary to the direct search for steriles.

- The following plots are based on a work from V. De Romeri et al.
4.1 LFV in rare Z-decays

Studies for the Giga-Z (Wilson, DESY-EFCA LC workshop (1998-1999), J. I. Illana and T. Riemann, Phys. Rev. D63 (2001) ... are revisited taking into account:

- $\theta_{13}$ and other neutrino data
- new contributions of sterile states are already severely constrained:
  - radiative decays (MEG)
  - 3-body decays
  - cosmology
  - neutrinoless double $\beta$ decays
  - invisible Z-width
  ....
4.1 LFV in rare Z-decays: “3+1” toy model

3+1 model is a convenient ad-hoc extension; 4th state encodes contributions of arbitrary number of sterile neutrinos.

- Steriles with mass $> 80$ GeV and mixings $O(10^{-5}-10^{-4})$ within FCC-ee reach.
- Low-energy experiments (COMET ...) at work to probe the electron-muon sector.
- FCC-ee provides the stringent constraint in tau-mu sectors.

V. De Romeri et al. JHEP 1504 (2015) 051 and a talk here.
4.1 Flavours at the Z: the lepton Physics Case


- The sterile neutrinos are produced from mixing with active neutrinos out of the Z decay.

- The $N$ decay lifetime depends on the mass of the sterile and the mixings.

- Branching fraction almost saturated with the final states:
  
  $\nu N \rightarrow \ell^+ \ell^- \nu$, $N \rightarrow q \bar{q} \ell$, $N \rightarrow q \bar{q} \nu$

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4.2 Flavours at the Z: the quarks Physics Case

• The $CP$ violation and rare $b$-decays landscape has to be examined from the anticipated results of both the LHCb upgrade and the Belle II experiments.

• LHCb sees all species of $b$-particles (and charm in abundance) and is especially good at rare decays with muons and fully charged decay modes. Less efficient for electrons, neutrals, missing energy, hadronic multibody decays.

• Belle II should explore deeply/widely the $B_d$ and $B_u$ meson systems. Might also run above the $\Upsilon(5S)$ threshold but can’t resolve the oscillation of $B_s$ meson.

• The latter highs and lows define a path to complete the picture in the event nothing new is observed meanwhile.
• A possible/appealing realm for FCC-ee in the classic flavours is therefore provided by the following triptych most likely unique to FCC-ee:

1) Any leptonic or semileptonic decay mode involving $B_s$, $B_c$ or $b$-baryon (those are coming polarized), including electrons.

2) Any decay mode involving $B_s$, $B_c$ or $b$-baryon with neutrals.

3) Multibody (means 4 and more) hadronic $b$-hadron decays.

• We highlighted flagship modes for each category in order to build the Physics Work Packages.
1) Any leptonic or semileptonic decay mode involving $B_s$, $B_c$ or $b$-baryon, including electrons, in no particular order:

- $B_{d,s} \to e\mu, \mu\mu, \tau\tau$: if the second will be mostly covered by LHCb and CMS, the first can be searched for with a similar precision. The latter $B_s \to \tau\tau$ is most likely unique to FCC-ee and subjected to third family specific couplings.

- Leptonic decays in direct annihilation $B_{u,c} \to \mu\nu_\mu, \tau\nu_\tau$. The latter is a chance to get $|V_{cb}|$ with mild theoretical uncertainties.

- If the baseline machine is to be confirmed with the crab-waist option, the flavours scope with $10^{13}$ Z is likely to change dramatically. For instance, it would be possible to get $|V_{ub}|$ theory-free (well, strong isospin symmetry only ...) out of ratios of rare decays (B. Grinstein @ CKM06). Not mentioning that the large boost at the Z can be beneficial for classical methods.
4.2 Flavours at the $Z$: the quarks Physics Case

2) Any decay mode involving $B_s$, $B_c$ or $b$-baryon with neutrals.

- $B_{d,s} \rightarrow \gamma\gamma$: theoretically difficult.
- $B_s \rightarrow K_SK_S$: CP violation studies. Also interesting for downstream tracking of $V^0$ in general.
- $B \rightarrow X\ell\ell$ (*stτ at first*): rare FCNC complementing LHCb and Belle II.

3) Multibody (4 and more) hadronic $b$-hadron decays.

- $B_s \rightarrow \psi\eta'$ or $\eta_c\Phi$: flavour tagging required for weak mixing phase.
- $B_s \rightarrow D_sK$: PID definitely required to isolate the signal.
- Modes to be used to define the Particle Identification needs.
4.2 The radiative decays as a first exploration.

- The rare decays $b \to s \ell^+\ell^-$ are receiving increasing experimental and phenomenological interests:
  - good laboratory for new quark/lepton transitions operators.
  - possibly clean theoretical (QCD) uncertainties.
  - some signs of departures of the data w.r.t. the SM/QCD predictions.

![Graph showing the observable $P_5$ in bins of $q^2$.](image)

Figure 17: The observable $P_5$ in bins of $q^2$. The shaded boxes show the SM prediction taken from Ref. [13]. The blue open markers show the result of the 1 fb$^{-1}$ analysis from Ref. [7].
4.2 The radiative decays as a first exploration.

- The rare decays $b \rightarrow s \ell^+\ell^-$ are receiving increasing experimental and phenomenological interests:
  - good laboratory for new quark/lepton transitions operators.
  - possibly clean theoretical (QCD) uncertainties.
  - clear experimental signatures.
  - some signs of departures of the data w.r.t. the SM/QCD predictions in the muon final states.

- The electron final states allows a dedicated study at low $q^2$. $O(10^5)$ events! Exploration started at LHCb: $O(10^2)$ events (RunI).
- The tau lepton final states is unexplored so far but is necessary to complete the landscape, whatever the NP scenario is there or ruled out.

- Experimentally, aim at:
  - measuring the **branching fraction**, 
  - studying the **angular distributions**.

In both cases, FCC-ee provides a unique access to these territories.
4.2 The radiative decays as a first exploration.

- The transition $B^0 \to K^{*0} \tau^+\tau^-$ can be fully solved.
- Two neutrinos missing $\to$ six momentum coordinates to find.
- The secondary vertex is determined from the resonant $K^{*0} \to K^-\pi^+$
- Limit ourselves to the $\tau$ decays in three prongs: $\tau^+ \to a_1^- \nu_\tau$

**Constraints:**
- $B$ flight distance $\to$ 2 d.o.f.
- $\tau$ flight distances $\to$ 4 d.o.f.
- $\tau$ masses $\to$ 2 d.o.f.
- saturate the d.o.f. of the problem.

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**Performance** of the partial reconstruction.
Introduce typical detector resolutions on Momentum, PV, SV and TV.

**Efficiency** $\sim 40\%$ and typical core resolution is at the level of $\sim 80$ MeV.
5. Summary

• An effort for a design study of a large $pp$ and $ee$ collider is structured in order to provide an educated view of the Physics reach of such a facility for the next update of the HEP European strategy (2018/19).

• The $ee$ collider should provide experiments with an unprecedented luminosity from the $Z$ pole to the top pair threshold.

• The Flavour Physics, as an indissociable part of the electroweak symmetry breaking understanding, is a natural and obvious contributor.

• We are just starting to explore the possibilities, in particular with $10^{12} / 10^{13} Z$. 
5. References and links as a Summary

• The project is getting mature. The FCC software is getting up. A good moment to contribute.

• Aim at gathering small teams of experimentalists and theoreticians on benchmark subjects. At work for LFV $Z$ decays and $B^0 \rightarrow K^{*0} \tau^+\tau^-$, planned for $B^0_s \rightarrow \tau^+\tau^-$ and $B^0 \rightarrow K^{*0} e^+e^-$. More are welcome.

• Information on FCC and FCC-ee can be found there:
  http://tlep.web.cern.ch/

• A dedicated e-list for the Flavours WG is set-up here with self-subscription for CERN users:
  https://e-groups.cern.ch/e-groups/Egroup.do?egroupId=10116182&tab=3

• Otherwise get in touch with us:
  jernej.kamenik@ijs.si or monteil@in2p3.fr.
Back-up slides.
1. Introduction to FCC

- 80-100 km infrastructure in Geneva area: A flavour of the location:
1. Introduction to FCC

- In Geneva area.
- Infrastructure studies ongoing. A 93 km planar racetrack:
2. The $e^+e^-$ machine. Baseline design

- Physics from the $Z$ pole to top pair production (90 - 400 GeV), crossing $WW$ and $ZH$ thresholds with unprecedented statistics everywhere.

- Two rings (top-up injection) to cope with high current and large number of bunches at operating points up to $ZH$.

- Not a straightforward extrapolation of LEP. Many Challenges:
  - Brehmsstrahlung@IP limits the beam lifetime at top energy.
  - Polarization of the beams (at least natural one for beam energy measurement - EWK precision measurements)
  - RF system must deal w/ contradictory requirements (high gradients (top) / high currents ($Z$)).

- Baseline design is a target. Not an actual working machine.
2. The $e^+e^-$ machine. Challenges

- To some extent, SuperKEKB is a testbench for FCC-ee:

**Some SuperKEKB parameters**: ©P. Janot

- $\beta^*_y : 300 \mu m$
  - FCC-ee (H) : 1 mm
- $\sigma_y : 50 \text{ nm}$
  - FCC-ee (H) : 50 nm
- $\varepsilon_y/\varepsilon_x : 0.25\%$
  - FCC-ee (H) : 0.2\% to 0.1\%
- $e^+$ production rate : $2.5 \times 10^{12} / s$
  - FCC-ee (H) : $< 1 \times 10^{11} / s$
- Off-momentum acceptance at IP : ±1.5\%
  - FCC-ee (H) : ±2.0\% to ±2.5\%
- Beam Lifetime : 5 minutes
  - FCC-ee (H) : 20 minutes
- Centre-of-mass energy: ~10 GeV
  - FCC-ee (H) : 240 GeV
4. Scope of the FCC-ee Flavour Physics working

- Understand the experimental precision with which rare decays of $c$- and $b$-hadrons and CP violation in the heavy-quark sector could be measured with $10^{12}$ $Z$, as well as the potential sensitivity to new physics, and compare to the ultimate potential of the (soon to be) running LHCb upgrade and Belle II experiments. Examine the relevance of a dedicated PID ($\pi / K / p$ separation) detector,

- The very same objective stands for the rare lepton decays.

- Examine the physics reach of lepton flavour violating processes and neutrino-related Physics unique to the FCC-ee.

- Have a platform to think of beyond standard observables.

- “What would like to do/see with/in $10^{12} / 10^{13}$ $Z$?” makes a nice playground to start with.
2. The $e^+e^-$ machine: luminosity figure.