PROCEEDINGS OF SCIENCE

Flavour Physics beyond the current foreseen programs. A closer look at Future Circular Colliders.

Stéphane Monteil*
Laboratoire de Physique Corpusculaire, Université Clermont Auvergne, Université Blaise Pascal, CNRS/IN2P3, Clermont-Ferrand, France
E-mail: monteil@in2p3.fr

A new type of flavour factory emerges from Future Circular Colliders projects, beyond the current and foreseen experimental programs. Commensurate (or even larger) statistics and clean experimental environment as for the Belle II experiment, production of all species of Heavy Flavours and large boost as in the LHCb experiment, the operation of a future e^+e^- circular collider at the Z-boson mass pole is likely providing unique opportunities for Flavour Physics at large. Nearly half-way towards the completion of the Design Study, some initial ideas aimed at supporting the Physics case of the FCC-*ee* are examined.

16th International Conference on B-Physics at Frontier Machines
2-6 May 2016
Marseille, France

*Speaker.

PoS(BEAUTY2016)058

1. Introduction: a long term vision for particle Physics

A possible long-term strategy for high-energy physics at colliders, after the exploitation of the Large Hadron Collider (LHC) and its High Luminosity upgrade, considers a tunnel of about 100 km circumference, which takes advantage of the present CERN accelerator complex. The Future Circular Colliders (FCC) concept follows on the successful experience and outcomes of the LEP-LHC machines. A possible first step of the project is to fit in the tunnel a high-luminosity e^+e^- collider aimed at studying comprehensively the electroweak scale with centre-of-mass energies ranging from the Z pole up to beyond the $t\bar{t}$ production threshold. A 100 TeV proton-proton collider is considered as the ultimate goal of the project and defines the infrastuctures.

Future Circular Collider study groups have been formed in a 5 years design study hosted by CERN, aiming at a Conceptual Design Report and a review cost in time for next European Strategy milestone at the horizon of 2020, when the full statistics of the LHC Run I and Run 2 will have been analyzed.

The unprecedented statistics at the Z pole ($\mathcal{O}(10^{13})$ Z decays) potentially delivered by the high-luminosity e^+e^- collider can be studied in particular to explore further the flavour Physics case at large. We will discuss the Physics potential of the measurements of rare decays of b-hadrons, which can complement the knowledge and anticipated results from the current and foreseen b-Physics programs (LHCb upgrade and Belle II experiment). The large statistics at the Z pole can be used as well to scrutinize Lepton Flavour Violating (LFV) Z decays.

2. The Physics case of FCC-*ee* at large

The study of high luminosity circular e^+e^- colliders operating at the ZH production threshold followed from the first evidence of a relatively low-mass Higgs boson candidate [1]. Initial investigations at the physics case are gathered in [2] and form the starting basis of the present design study. The versatility of the machine centre-of-mass energy definition allows to study all relevant electroweak thresholds and addresses electroweak precision physics in an unrivaled way. This is complemented by an excellent measurement of the beam energy at the Z and WW thresholds by means of a continuous monitoring of the resonant depolarization of dedicated bunches [3]. The beam energy at the Z pole can hence be known at a precision of 100 keV. The following ensemble of precision measurements should allow to detect anomalies in the electroweak symmetry breaking mechanism (if they exist) and/or the existence of new weakly interacting particle(s):

- At the Z pole, $\mathcal{O}(10^{13})$ Z-boson decays are aimed at being registered. Among the precision measurements, one can determine the Z-boson mass and width with the intrinsic limitation of the beam energy measurement resolution. Conversely, the Z pole fermion asymmetries and partial widths can be known at or better than 10^{-5} precision level. Additionally, the study of the muon forward-backward asymmetries below and above the Z pole, provides a unique way to measure directly the electromagnetic coupling constant $\alpha(m_Z^2)$ [4], complementing the standard approach using the low-energy $e^+e^- \to q\bar{q}$ data.

- Provided that the monochromaticity performance of the beams reaches the natural width of the Higgs-boson, the Yukawa coupling of the electron can be uniquely constrained from direct H production at $\sqrt{s} = m_H$ [5].

- $\mathcal{O}(10^8)$ of $Z, \gamma \to W^+W^-$ decays are targeted to provide a W mass measurement at ~ 500 keV precision.

- Operating at $\sqrt{s} \sim 240$ GeV, a million of Higgs-boson decays allow measurements of most partial widths of the Higgs boson with the exquisite permil precision.

- Eventually, at the highest energy threshold, $\mathcal{O}(10^6)$ top-quark pairs provide the measurement of the top-quark mass at the typical precision level of 10 MeV and their decays allow to study with *finesse* the top-quark electroweak couplings [6].

The figure 1 gathers the luminosity profiles of several e^+e^- collider projects and supports the above-mentioned event yields at each relevant electroweak threshold. The design study must also go beyond this natural electroweak scoping and address as well the ability to explore the invisible decay modes of the H and Z bosons, the possibility to discover rare exotic decay modes involving the right-handed partners of the active neutrinos or light supersymmetric partners of the top quark for instance. Moreover, the immense statistics of Z-boson decays opens a new territory and opportunities for flavour physics studies, which will be described in the next section.

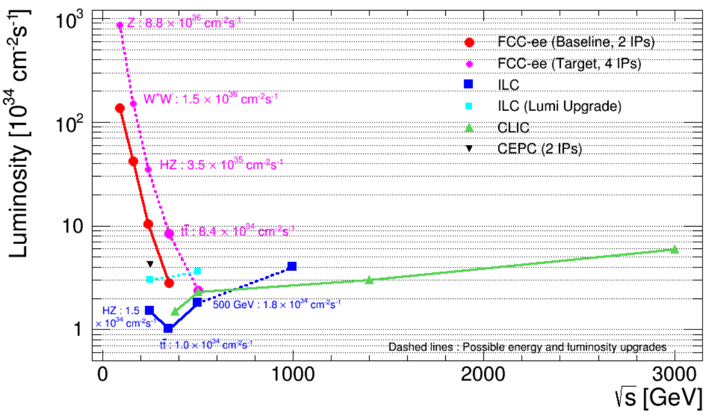

Figure 1: Comparison of e^+e^- colliders luminosities.

3. Foreseeable Flavour Physics landscape and the FCC-*ee* program

As far as CP violation and rare b-flavoured hadrons or τ decays are concerned, the two main players at the horizon of 2025 are the upgraded LHCb experiment at CERN (Europe) and the Belle II experiment at KEK (Japan). Beyond these confirmed experimental programs, several large or medium scale projects related to Flavour Physics are envisaged to probe Beyond Standard Model Physics. Among them, there are prospective studies to educate the possibility to run the LHCb spectrometer in the High Luminosity phase of the LHC or to make use of high intensity beam lines (*e.g.* SPS and FCC injectors) with fixed target experiments. The 100 TeV proton proton collider explored in the FCC design study must also provide itself a Flavour Physics program. It is currently being devised.

The very large statistics at the Z-boson mass pole, the clean experimental environment as for the Belle II experiment, the production of all species of Heavy Flavours and large boost as in the LHCb experiment are making the FCC-*ee* a natural perspective for Flavour Physics.

The design study is ongoing and actual analyses with sensible detector designs and simulations are currently being developed. Though it is premature to discuss their results here, I will attempt to provide a hierarchised view of the FCC-*ee* flavour Physics reach, examined in the light of the foreseeable legacy of the LHCb experiment upgrade and the Belle II project. This takes the form of the following quadriptych:

- Leptonic or semileptonic decay modes involving B_s, B_c or $b-$baryons: the loop-induced leptonic decays $B_{d,s} \to ee, \mu\mu, \tau\tau$ provide SM candles and are sensitive to several realisations of BSM Physics. The observation of $B_s \to \tau\tau$, as involving third generation leptons, is invaluable to complement our understanding and likely uniquely reachable at FCC-*ee*. The charged-current mediated leptonic decays $B_{u,c} \to \mu\nu_\mu, \tau\nu_\tau$ offer a possibility to determine $|V_{cb}|$ with mild theoretical uncertainties. Contrarily to the tauonic decay of $B_{d,s}$ which only receives contributions from $\Delta B = 1$ FCNCs with axial and pseudoscalar leptonic currents, the electroweak penguin transitions $B_{d,s} \to X\tau^+\tau^-$ are sensitive to a larger variety of possible NP effects [7]. As it will be discussed in the next section, the FCC-*ee* is the likely unique place for its observation. Eventually, the CP violation in mixing can be measured through semileptonic asymmetries. It is unobserved to date and the current limits could be pushed towards the SM predictions.

- Decay modes involving B_s, B_c or $b-$baryon with neutral final state particles (π_0, K_S, η, η',ν): this type of final states benefits from the cleanliness of the e^+e^- experimental environment. CP eigenstates are often involving neutral particles and a canonical example of the Physics reach is the measurement of the B_s weak mixing phase which can be attained through the decay $B_s \to K^0_S K^0_S$. The measurements of the very rare FCNC processes $B_s \to X\nu\nu$ could complement the measurements of the B_d modes expected at Belle II.

- The many-body fully hadronic b-hadron decays: typical decays useful for CP violation studies such as $B_s \to \psi\eta', \eta_c\phi$, $B_s \to D_s K$ are falling in this category. The latter allows a measurement of the weak phase $\gamma + \phi_s$ and could be measured with an improved precision w.r.t. LHCb. It is particularly demanding in terms of particle identification (PID) and will be used in the Design Study as a benchmark for PID detector studies.

- Lepton Flavour Violating processes: an illustration of this Physics case will be developed in the next Section of this document. Let's set the scene. The detection of a rare decay $Z \to \ell_i \ell_j (i \neq j)$ would serve as an indisputable evidence of new physics. These searches are complementary to other LFV observables measurements at lower energy such as $\ell \to \ell'\gamma$, μ to e conversion .... The significant $\tau^+\tau^-$ production at the Z pole also allows to search for the rare decays $\tau \to e\gamma, \mu\gamma, eee, \mu\mu\mu$ and would more generally benefit to the τ-lepton Physics.

Decay mode	$B^0 \to K^*(892)e^+e^-$	$B^0 \to K^*(892)\tau^+\tau^-$	$B_s(B^0) \to \mu^+\mu^-$	$B_s \to D_s K$
Belle II	$\sim$ 2 000	$\sim$ 10	n/a (5)	n/a
LHCb Run I	150	-	$\sim$ 15 (-)	$\sim$ 6000
LHCb Upgrade	$\sim$ 5000	-	$\sim$ 500 (50)	$\sim$ 200000
FCC-*ee*	$\sim$ 200000	$\sim$ 1000	$\sim$1000 (100)	few 10^6

Table 1: Comparison of order of magnitudes for expected reconstructed yields of a selection of decay modes in Belle II, LHCb upgrade and FCC-*ee* experiments. The Standard model branching fractions are assumed. The yields for the electroweak penguin decay $B^0 \to K^*(892)e^+e^-$ are given in the low q^2 region.

The table 1 gathers a comparison of the (anticipated) reconstructed yields of some of the above-mentioned decay modes for the Belle II, LHCb upgrade and FCC-*ee* experiments.

4. Illustration by examples: flavour changing neutral currents

4.1 Electroweak penguins in b-quark transitions

The processes involving a quark transition $b \to s\ell^+\ell^-$ (here ℓ denotes an electron or a muon) are receiving increasing phenomenological [8–11] and experimental [12–14] interests. The departures from Standard Model predictions observed in the latter studies are questioning the lepton universality in quark-based transitions and suggest BSM gauge-mediated processes. If these deviations are confirmed, it is of utmost importance to complete our understanding with observables involving the third generation charged lepton τ. In that respect, the decays $B_s \to \tau^+\tau^-$ and $\bar{B}^0 \to K^{*0}(892)\tau^+\tau^-$ are obvious candidates to study. The presence of neutrinos in the final states of these decays makes the experimental search very challenging. However, an excellent knowledge of the decay vertices, which can be obtained thanks to the multibody hadronic τ decays, may help to fully solve the kinematics of these decays. The decay $\bar{B}^0 \to K^{*0}(892)\tau^+\tau^-$ has been studied in the context of the FCC-*ee* machine with Monte Carlo events generated with a fast simulation featuring a parametric detector. It has been shown that thousand of events can be expected, opening the way to measurements of the angular properties of the decay. The figure 2 displays the reconstructed invariant mass distribution of simulated SM signal and background events corresponding to 10^{13} Z-boson decays. To our knowledge, these FCC-*ee* performances are unequalled at any current or foreseeable experiment.

4.2 Lepton Flavour violating Z-boson decays

These decays are forbidden in the SM by the GIM mechanism [15], and their rates are predicted extremely small (below 10^{-50}) when the SM is minimally extended to incorporate flavour violation in the neutral lepton sector induced by the leptonic mass mixing matrix [16]. Sizeable rates for these LFV $Z \to \ell_1^{\mp}\ell_2^{\pm}$ processes would hence reflect the existence of new particles such as sterile neutral fermions. This scenario is particularly attractive since it addresses (by parts in most cases) all the outstanding experimental or observational arguments for BSM physics: the neutrino masses and mass mixings, the dark matter candidate and the origin of baryonic asymmetry in the Universe through leptogenesis [17, 18].

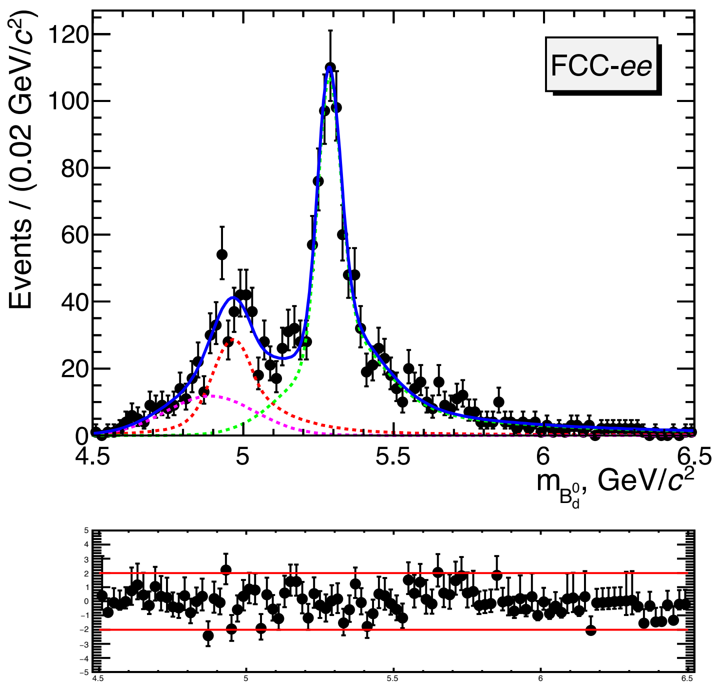

Figure 2: Invariant mass reconstruction of $\bar{B}^0 \to K^{*0}(892)\tau^+\tau^-$ candidates. The *tau* particles are decaying into three prongs $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ allowing the τ decay vertex to be reconstructed. The primary vertex (Z vertex) is reconstructed from primary tracks and the secondary vertex ($\bar{B}^0$ vertex) is reconstructed thanks to the $K^*(892)$ daughter particles ($K^*(892) \to K^+\pi^-$). Two dominant sources of backgrounds are included in the analysed sample, namely $\bar{B}_s \to D_s^+ D_s^- K^{*0}(892)$ and $\bar{B}^0 \to D_s^+ \bar{K}^{*0}(892)\tau^-\bar{\nu}_\tau$. They are modelled by the red and pink probability density functions (p.d.f.), respectively. The signal p.d.f. is displayed in green.

A phenomenological study [19] has been undertaken to study the potential of the FCC-*ee* machine to probe the existence of sterile neutral fermions in the light of the improved determination of neutrino oscillations parameters, the new bounds on low-energy LFV observables as well as cosmological bounds. This work addressed as well the complementarity of these searches with the current and foreseeable precision of similar searches at lower energy experiments. The best sensitivity to observe or constrain LFV in the $e\mu$ sector is then obtained by the experiments based on the muon-electron conversion in nuclei [20]. In contrast, the study of the decays $Z \to e\tau$ and $Z \to \mu\tau$ would provide invaluable and unique insight in the connection to the third generation.

The current limits on the branching ratios of charged lepton flavour violating Z-boson decays were established by the LEP experiments [21–23]. More recently, the ATLAS experiment improved the bound for $e\mu$ final states [24]. The typical limits sit in the ballpark $\mathcal{O}(10^{-5} - 10^{-6})$. The production at FCC-*ee* of 10^{13} Z-boson decays will provide improved limits by several orders of magnitude and could probe new physics scenarii up to $\mathcal{O}(10^{-9})$ branching fractions according to a first experimental study of the backgrounds including the irreducible SM $Z \to \tau^+\tau^-$ decay [25].

5. Summary

Flavour Physics studies embodied in a possible long-term strategy for high-energy physics at colliders have been discussed in this document. The FCC-*ee* project, and its interplay with the proton collider counterpart, will provide exquisite precision electroweak Physics.

References

[1] A. Blondel and F. Zimmermann, "A High Luminosity e^+e^- Collider in the LHC tunnel to study the Higgs Boson," 2011.

[2] M. Bicer and et al, "First look at the physics case of TLEP," *JHEP*, vol. 2014, jan 2014.

[3] L. Arnaudon *et al.*, "Accurate determination of the LEP beam energy by resonant depolarization," *Z. Phys.*, vol. C66, pp. 45–62, 1995.

[4] P. Janot, "Direct measurement of $\alpha_{QED}(m_Z^2)$ at the FCC-ee," *JHEP*, vol. 02, p. 053, 2016.

[5] D. d'Enterria, "Physics at the FCC-ee," in *17th Lomonosov Conference, 2015*, 2016.

[6] P. Janot, "Top-quark electroweak couplings at the FCC-ee," *JHEP*, vol. 04, p. 182, 2015.

[7] W. Altmannshofer, S. Gori, M. Pospelov, and I. Yavin, "Quark flavor transitions in $L_\mu - L_\tau$ models," *Phys. Rev.*, vol. D89, p. 095033, 2014.

[8] W. Altmannshofer and D. M. Straub, "New physics in $B \to K^* \mu\mu$?," *EPJ*, vol. C73, p. 2646, 2013.

[9] A. Buras, F. De Fazio, J. Girrbach, and M. V. Carlucci, "The Anatomy of Quark Flavour Observables in 331 Models in the Flavour Precision Era," *JHEP*, vol. 02, p. 023, 2013.

[10] R. Gauld, F. Goertz, and U. Haisch, "An explicit Z'-boson explanation of the $B \to K^* \mu^+\mu^-$ anomaly," *JHEP*, vol. 01, p. 069, 2014.

[11] S. Descotes-Genon, L. Hofer, J. Matias, and J. Virto, "Global analysis of $b \to s\ell\ell$ anomalies," *JHEP*, vol. 06, p. 092, 2016.

[12] R. Aaij *et al.*, "Test of lepton universality using $B^+ \to K^+\ell^+\ell^-$ decays," *Phys. Rev. Lett.*, vol. 113, p. 151601, 2014.

[13] R. Aaij *et al.*, "Angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay using 3 fb^{-1} of integrated luminosity," *JHEP*, vol. 02, p. 104, 2016.

[14] A. Abdesselam *et al.*, "Angular analysis of $B^0 \to K^*(892)^0\ell^+\ell^-$," in *LHC Ski 2016*, 2016.

[15] S. L. Glashow, J. Iliopoulos, and L. Maiani, "Weak Interactions with Lepton-Hadron Symmetry," *Phys. Rev.*, vol. D2, pp. 1285–1292, 1970.

[16] G. Mann and T. Riemann, "Effective Flavor Changing Neutral Curretn in the standard theory and Z-boson decay ," *Annalen Phys.*, vol. 40, p. 334, 1984.

[17] T. Asaka, S. Blanchet, and M. Shaposhnikov, "The nuMSM, dark matter and neutrino masses," *Phys. Lett.*, vol. B631, pp. 151–156, 2005.

[18] R. N. Mohapatra and J. W. F. Valle, "Neutrino Mass and Baryon Number Nonconservation in Superstring Models," *Phys. Rev.*, vol. D34, p. 1642, 1986.

[19] A. Abada, V. De Romeri, S. Monteil, J. Orloff, and A. M. Teixeira, "Indirect searches for sterile neutrinos at a high-luminosity Z-factory," *JHEP*, vol. 04, p. 051, 2015.

PoS(BEAUTY2016)058

[20] Y. Kuno, "A search for muon-to-electron conversion at J-PARC: The COMET experiment," *PTEP*, vol. 2013, p. 022C01, 2013.

[21] O. Adriani *et al.*, "Search for LFV in Z decays," *Phys. Lett.*, vol. B316, pp. 427–434, 1993.

[22] R. Akers *et al.*, "A Search for LFV Z^0 decays," *Z. Phys.*, vol. C67, pp. 555–564, 1995.

[23] P. Abreu *et al.*, "Search for LF number violating Z^0 decays," *Z. Phys.*, vol. C73, pp. 243–251, 1997.

[24] G. Aad *et al.*, "Search for the LFV decay $Z \to e\mu$ in pp collisions at $\sqrt{s}$= 7 TeV with the ATLAS detector," *Phys. Rev.*, vol. D90, no. 7, p. 072010, 2014.

[25] M. Dam. private communication, 2016.