PROCEEDINGS OF SCIENCE

Physics at FCC-ee

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The potential of physics studies at the Future Circular Collider with e^+e^- beams (FCC-ee) is briefly discussed. Special attention is paid to the measurements in the sector of quantum chromodynamics

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1. Introduction

The Future Circular Collider (FCC) design study [1] assumes the construction and exploitation of a $\sim$100 km circular tunnel infrastructure in the Geneva area. The Future Circular Collider with e^+e^- beams (FCC-ee) is proposed as the first phase of the project in the perspective of the successful physics program undertaken at LEP accelerator [2] and in view of the Higgs boson discovery [3] in 2012. In turn, the FCC-ee is envisioned to be replaced by the 100 TeV proton-proton collider FCC-hh. At the same time, the collisions of 60 GeV electrons from an energy recovery linac with 50 TeV protons, can be realized (FCC-eh). The efforts of the FCC design study have been collected in the Conceptual Design Report [4], issued in March 2019, and submitted as input to the European Particle Physics Strategy Update 2018-2020 [5]. The relevant, general information about the FCC-ee project can be found in [6, 7, 8].

The FCC-ee collider will profit from recent innovations, implemented at b-factories, like the nanobeam scheme, continuous injection and crab-crossing optics. The collider would collect data at four center-of-mass (CM) energies ($\sqrt{s}$), corresponding to the Z pole and the WW, HZ and $t\bar{t}$ thresholds. Its most relevant parameters [4] are presented in Table 1 and compared with LEP phase-2 (LEP2) collider [2]. At least two general-purpose spectrometers will be operating at the interaction points. Such detectors should be hermetic, lightweight in terms of the material content and provide very accurate tracking and fine-granularity calorimetry.

In the following chapters, the Higgs, Z and W bosons and top quark studies at the FCC-ee will be briefly reviewed. Finally the potential of QCD measurements will be discussed.

Parameter	LEP2	FCC-ee			
E_b [GeV]	104	45.6	80	120	175-182.5
I [mA]	4	1390	147	29	5.4
# of bunches/beam	4	16640	2000	393	48
β_x^* [m]	1.5	0.15	0.2	0.3	1.0
β_y^* [mm]	50	0.8	1	1	1.6
ε_x [nm]	30-50	0.27	0.28	0.63	1.46
ε_y [pm]	250	1	1.7	1.3	2.9
P_{SR} [MW]	22	100	100	100	100
L [10^{34} cm $^{-2}$s^{-1}/IP]	0.012	230	28	8.5	1.55
L_{tot} [ab^{-1}]	8×10^{-4}	150	10	5	1.7
Statistics (2 expts)		$\sim 5\times10^{12}$ Z (4 years)	$\sim 10^8$ WW (2 years)	$\sim 10^6$ ZH (3 years)	$\sim 10^6$ $t\bar{t}$ (5 years)

Table 1: Selected parameters of the FCC-ee accelerator. The characteristics of LEP2 collider have been supplemented for comparison. The following parameters are presented: beam energy (E_b), beam current (I), number of bunches, horizontal (vertical) beta function at the interaction point (IP) $\beta_x^*(\beta_y^*)$, horizontal (vertical) emittance ($\varepsilon_x(\varepsilon_y)$), synchrotron radiation power (P_{SR}), luminosity (L) and expected statistics of relevant events (from [4]).

2. Higgs boson physics at the FCC-ee

FCC-ee will measure Higgs boson production inclusively from its presence as a recoil to the Z in the process $e^+e^- \to ZH$ (cf. Fig. 1 from [4]). The resulting expected precision of the Higgs mass amounts to 10 MeV. The HZ cross-section (σ_{HZ}) is proportional to the square of the Higgs boson coupling to the Z, g_{HZZ}. The recoil method allows as well for the determination of the Higgs boson width (Γ_H) by counting the number of HZ events in which the Higgs decays into a pair of Z bosons ($\sigma_{HZ} \times \Gamma(H \to ZZ)/\Gamma_H \propto g^4_{HZZ}/\Gamma_H$). In turn, the numbers of events with Higgs boson exclusive decays into $XX = b\bar{b}$, $c\bar{c}$, $\tau^+\tau^-$, $\mu^+\mu^-$, $\gamma\gamma$, gg, W^+W^-, and invisible Higgs boson decays, allow to measure the respective Higgs couplings, g_{HXX}, with the accuracy below 1% [4].

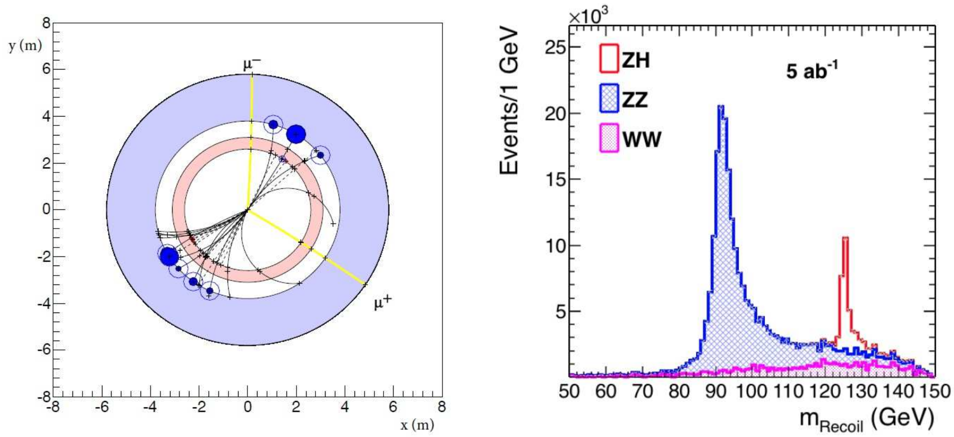

Figure 1: Left: A schematic view, transverse to the detector axis, of an $e^+e^- \to HZ$ event with $Z \to \mu^+\mu^-$ and with the Higgs boson decaying hadronically. The two muons from the Z decay are indicated. Right: Distribution of the mass recoiling against the muon pair, determined from the total energy-momentum conservation, with an integrated luminosity of 5 ab^{-1}. The peak around 125 GeV (in red) consists of HZ events. The rest od the distribution (in blue and pink) originate from ZZ and WW production.

3. Electroweak precision measurements at the Z pole

Precision electroweak measurements are at the center of the FCC-ee physics program, as they can play a key role in establishing the existence of new physics together with elucidating its theoretical interpretation. The expected FCC-ee data statistics of 5×10^{12} Z events corresponds to the increase by five orders of magnitude to compare with data sample collected at LEP1. This implies, that the overall precision of electroweak observables at the FCC-ee will be generally limited by systematic uncertainties. Thus, updated, more accurate theoretical calculations of electroweak observables are to be undertaken. Special attention should be as well paid to the accurate CM energy calibration, realized via resonant depolarisation. The corresponding systematic uncertainty of ≤ 100 keV is expected on both the mass and width of the Z boson (to compare with $\Delta M_Z = 2.1$ MeV and $\Delta\Gamma_Z = 2.3$ MeV at LEP1). The experimental precision of the selected electroweak observables, expected at FCC-ee, is presented in Table 2. In particular, an improved determination of the electromagnetic coupling constant at the Z mass ($\alpha_{\mathrm{QED}}(m_Z)$) [9] can be obtained using direct method based on the forward-backward muon asymmetry measurement at two optimal working points ($\sqrt{s_-} = 87.9$ GeV and $\sqrt{s_+} = 94.3$ GeV).

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Improvement factor
m_Z [keV/c^2]	91186700 ± 2200	5	100	22
Γ_Z [keV]	2495200 ± 2300	8	100	23
R_l^Z [$\times 10^3$]	20767 ± 25	0.06	0.2-1	125-25
$\alpha_S(m_Z)$ [$\times 10^4$]	1196 ± 30	0.1	0.4-1.6	75-19
R_b [$\times 10^6$]	216290 ± 660	0.3	<60	11
N_ν [$\times 10^3$]	2991 ± 7	0.005	1	7
$\sin^2\theta_W^{\mathrm{eff}}$ [$\times 10^6$]	231480 ± 160	3	2-5	44-28
$1/\alpha_{\mathrm{QED}}(m_Z)$ [$\times 10^3$]	128952 ± 14	4	small	3.5
$A^b_{\mathrm{FB},0}$ [$\times 10^4$]	992 ± 16	0.02	1-3	16-5
$A^{\mathrm{pol},\tau}_{\mathrm{FB}}$ [$\times 10^4$]	1498 ± 49	0.15	<2	25

Table 2: Measurements of selected electroweak observables, compared with the present accuracy.

4. Top quark and W boson properties at the FCC-ee

FCC-ee aims at the collection of enormous samples at the thresholds for the production of WW pairs ($\sim 10^8$ WW events) and $t\bar{t}$ pairs ($\sim 10^6$ $t\bar{t}$ events). Assmuning two, equally shared, working points at $\sqrt{s} = 157.5$ GeV and $\sqrt{s} = 162.5$ GeV, a simultaneous fit of the W mass and width to the $e^+e^- \to W^+W^-$ cross-sections measurements, is expected to yield an accuracy of 0.5 MeV on m_W and 1.2 MeV on Γ_W [4]. For the top quark, the optimal strategy is a multipoint scan in the CM energy range (340-345) GeV, leading to statistical precisions of ± 17 MeV (± 45 MeV) for the top-quark mass (width), respectively [4].

5. QCD studies at the FCC-ee

Studies of strong interactions in an extremely clean environment of high-luminosity e^+e^- collisions offer several significant advantages, as proved by a very successful QCD program, undertaken at LEP [10]. First of all, one deals with a fully-controlled QED initial state with known kinematics. Moreover, QCD phenomena manifest itself only in the final state and the resulting difficulties due to beam remnants and initial state parton distribution functions are absent. For FCC-ee at the Z peak, one expects data samples of hadronic events 10^5 larger than at LEP, The respective gain in statistics at the W^+W^- threshold amounts to 10^3. Moreover, the hadronic samples from Higgs boson (10^5 events) and top-quark will be available for the first time in e^+e^- collisions. In view of these assets, the three main objectives of QCD program at FCC-ee are:

1. determination of the strong interaction coupling constant α_s with the permille accuracy, to compare with the current precision of 1%,

2. high-precision studies of perturbative parton radiation encompassing high-order leading corrections and logarithmic resummations for event angularities (shapes), jet multiplicities, jet substructure, quark/gluon/heavy-quark discrimination, and q,g,c,b parton-to-hadron fragmentation functions,

3. high-precision non-perturbative QCD studies including color reconnection, parton hadronisation, final-state multiparticle correlations, very rare hadron production and decays, to name but a few.

The extraction of α_s will be based on huge samples of hadronic τ, W and Z events studied with N^{3}LO theoretical precision. For τ and W the relevant quantities are the ratios of hadronic to leptonic widths. The expected accuracies are $< 1\%$ from τ, and $\sim 0.3\%$ from W decays. At the Z peak, the α_s coupling constant can be determined from studies of event angularities (shapes), N-jet cross sections and jet rates, and from three hadronic observables: Γ_Z, $\sigma_0^{\rm had} = 12\pi/m_Z \cdot \Gamma_e \Gamma_{\rm had}/\Gamma_Z^2$ and $R_l^0 = \Gamma_{\rm had}/\Gamma_l$. The expected accuracy of the α_s extraction from Z decays amounts to $\sim 0.2\%$.

It is estimated [4], that jet rates will be determined by FCC-ee at the Z pole with 10^{-6} precision for: 4-jet events up to the scale $k_T \sim 30$ GeV (corresponding to $|\ln(y)| \sim 2$, for jet resolution parameter $y = k_T^2/s$), 5-jet events at $k_T \sim 20$ GeV ($|\ln(y)| \sim 3$), 6-jet events at $k_T \sim 12$ GeV ($|\ln(y)| \sim 4$) and 7-jet events at $k_T \sim 7.5$ GeV ($|\ln(y)| \sim 5$).

Event angularities (shapes) are affected by logarithmic enhancements, which are resummed nowadays up to N^{3}LO, and by hadronisation corrections, estimated with Monte Carlo generators. Consequently, studies of these observables yields insight into resummation and hadronisation effects. In case of the FCC-ee, analyses of data collected at different CM energies are expected to diminish non-perturbative uncertainties at the Z peak from 9% to 2%.

The FCC-ee studies of event angularities, based on $Z \to q\bar{q}$ and $H \to gg$ samples, can also provide an important insight into the patterns of quark/gluon radiation and, correspondingly, into the discrimination between quark and gluon jets. In particular, there is currently a relatively good agreement between different Monte Carlo generators in the description of event angularities for quark jets. At the same time, however, the predictions of Monte Carlo generators for the gluon jets, vary significantly. Thus, FCC-ee can bring here crucial improvement in the quality of quark-qluon jet discriminators and in the description of gluon jets. Special attention will be also paid to ameliorations in the performance of taggers for b and c quark jets.

Studies of color reconnection (CR) effects, corresponding to the color flow between color singlets parton systems of different origin, are among the most important issues of non-perturbative QCD. The CR effects are best studied in e^+e^- annihilation in the process $e^+e^- \to q_1\bar{q}_2q_3\bar{q}_4$ with the formation of color singlets $(q_1\bar{q}_2)$ and $(q_3\bar{q}_4)$ or, alternatively, $(q_1\bar{q}_4)$ and $(q_3\bar{q}_2)$. The LEP results excluded the no-CR null hypothesis at 99.5% CL [12], but data were too scarce to provide any quantitative studies. The 10^3 gain in statistics at FCC-ee with the associated precision of the W mass determination at the level of 1 MeV, will allow to evaluate the presumable shift in the m_W measured in hadronic events to compare with the semileptonic WW pairs which are unaffected by CR effects. Moreover, such comparison can be performed in three different CM energies. As shown in Table 3, the mass shifts expected in different CR models differ significantly between the models together with exhibiting variations as a function of $\sqrt{s}$.

$\sqrt{s}$	$< \delta \bar{m}_W >$ [MeV]						
[GeV]	I	II	II'	GM-I	GM-II	GM-III	CS
170	+18	-14	-6	-41	+49	+2	+7
240	+95	+29	+25	-74	+400	+104	+9
350	+72	+18	+16	-50	+369	+60	+4

Table 3: Reconstructed average W mass shift predicted by different CR models in PYTHIA 8, relative to the no-CR baseline, in $e^+e^- \to W^+W^- \to q_1\bar{q}_2q_3\bar{q}_4$ at three FCC-ee CM energies [13].

6. Summary and acknowledgements

The FCC-ee collider aims at ambitious physicis program which would qualitatively improve the experimental precision of practically all Standard Model observables. In particular a substantial progress is expected in the QCD studies.

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