Precision measurements of the Z properties

Dimuons are the simplest events at the FCC-ee, with a μ⁺ and a μ⁻ almost back-to-back, both easily identifiable with a track in the tracker and the muon chambers, and almost no interaction within the calorimeter. Their momenta and directions can be measured with high accuracy, typically 50 MeV and 100 μrad, respectively, for 45 GeV muons. Dimuon events are therefore used routinely used for measurements that require extreme precision. The measurement of the Z mass and the Z width can be performed “just” by counting the numbers of such events at the Z pole (vs ~ 91.2 GeV) and around it (vs ~ 88 and 94 GeV). The FCC-ee not only offers a statistical precision of a few keV on mZ and ΓZ, but even more importantly a way – unique to circular colliders – to calibrate the beam energy in situ with a 50 keV accuracy, with “continuum” resonant depolarization of monitoring bunches, turning to a target precision better than 100 keV on mZ and ΓZ. The ratio of the number of dimuons to that of hadronic Z decays enables a measurement of the strong coupling constant αs(mZ) with a precision of 0.0002 or better. Because of the parity-violating couplings of the Z to the muons, μ²/μ² (vs) tend to be forward (backward). The forward-backward asymmetry at the Z pole depends solely on the weak mixing angle, sin²θW. Around the Z pole, a dependence on the electromagnetic coupling constant αe/mZ arises from the interference with the photon exchange. With over 10¹⁰ dimuons, an experimental precision of 5×10⁻⁶ (dominated by the beam energy accuracy) is obtained on sin²θW, and a statistics-dominated relative precision of 3×10⁻⁴ on αe/mZ can be contemplated if the beam energy spread is known to a few per mil. In the standard model, these precision measurements allow mH, Mµµ, and mW,W to be predicted with great accuracy and be compared to their direct measurements at the FCC-ee for new physics discovery.

Beam energy spread and asymmetry; Beam energy and number of neutrinos

At the FCC-ee, beamstrahlung is pushed at its limits to maximize the luminosity, which causes a large beam energy spread, from 60 MeV at the Z pole to 350 MeV at the top energies. Because the pertaining biases to the measurements of ΓZ and mZ are two to three orders of magnitude larger than their target precisions, the beam energy spread needs to be measured to a few per mil. Dimuon events are instrumental for this purpose, too. The effect of energy spread is to slightly boost the two events by roughly three orders of magnitude larger than their target precisions, the beam energy spread must be measured to a few per mil.

At centre-of-mass energies above the WW threshold, the resonant depolarization method is not available to measure the beam energy. The distribution of y(1-2x), however, presents a pronounced peak around mW/2, from the radiative return to the Z resonance. The precise measurement of y(1-2x) at the Z pole allows in turn the determination of sin²θW at higher energies. This method can be calibrated at the WW threshold, where resonant depolarization can be concurrently used. Radiative returns to the Z selected with an energetic photon in the detector acceptance are also instrumental for the measurement of the number of light neutrino species with a precision of 0.0008.

Sensitivity to heavy new physics

The precision measurements from dimuons at the Z pole may be found not to fit either with the standard model or with the direct measurements of mH, Mµµ, and mW,W or with both. Such an observation would mean that new weakly-coupled physics (or particles) exist. This new physics is often generically parameterized in terms of effective dimension six operators, whose effects become predominant above a certain energy scale λ. Provided that the precision of theory predictions improves up to matching the FCC-ee-experimental accuracy, a sensitivity to new physics scales of 10 to 100 TeV is at hand. A correlated pattern of deviations between sets of measurements at all FCC-ee-centre-of-mass energies may also provide direct hints of the specific underlying new physics. In composite Higgs models, for example, the interference with an extra neutral gauge boson of mass mZ’ ~ 3 TeV and width ~ 600 GeV, which would have been unnoticed at LEP and about which HL-LHC cannot say much, would modify the dimuon cross section in such a way that FCC-ee would be able to determine all gauge sector parameters of the model (including the Z’ mass) to 5%.

Due to lack of space, only sixteen recipes are given above. The 984 others are on the back.