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Electroweak Physics at CEPC

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Focusing on the Post-Higgs-Discovery era of High Energy Frontier, the CEPC is envisioned to be a future circular collider with multiple operation phases. The CEPC has a total circumference of at least 54 kilometer and at least two interaction points. In its 10 years operation at ∼240 GeV, it will collect a sample of ∼1M $e^+e^- \to ZH$ events. CEPC will also collide e^+e^- at $\sim m(Z)$ producing 10 billion Z bosons in one year. This data will boost the precision of electroweak measurements by orders of magnitude. This paper introduces the electroweak physics program and at the CEPC.

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1. Introduction to CEPC

The Chinese high energy physics community has been exploring options for the next accelerator based particle physics facility in China. The discovery of a Standard Model (SM) like Higgs boson at approximately 125 GeV at the LHC [1, 2] brought about the opportunity to investigate the feasibility of a circular e^+e^- collider (CEPC) [3] operating at $\sqrt{s}$~240GeV as a Higgs factory [4, 5]. The CEPC can also operate at the Z pole ($\sqrt{s}$~91GeV) and near the WW threshold($\sqrt{s}$~160GeV) [3]. Orders of magnitude of increase in luminosity at the Z pole compared to the LEP collider is expected.

2. Electroweak measurement at CEPC

The Z boson factories LEP 1 at CERN and SLC at SLAC observed about 2×10^7 Z-decays, and could determine Z boson properties with a precision reaching the 10^3 level. This allowed to test the SM at the electroweak loop level and constrained new particles from possible new physics beyond the SM provided these were not very much heavier than the electroweak symmetry breaking scale of 246 GeV. However, many theories addressing the naturalness of the SM or the hierarchy problem introduced by an elementary Higgs sector predict or are consistent with new physics mass scales of the order of one or several TeV. To observe quantum fluctuations associated with such scales one needs to improve the precision in at least some electroweak observables by about another order of magnitude, which in turn requires the production of 10^9 Z bosons or more.

This level of precision can be achieved by the CEPC with its large integrated luminosity and the production of the order of 10^{10} Z bosons already assuming a basic design. Beyond that various design options, including polarized beams, a dedicated WW threshold scan, or yet higher luminosities would increase the precision and therefore the reach in mass scale even further. Precise measurements of the W and Z boson masses, widths, and couplings at the CEPC could thus discover deviations from the SM and reveal indirectly the existence of new particles even before they may have been produced directly.

Very significant improvements are expected from the CEPC for most of the observables. Table 1 compares the expected precisions from a basic CEPC design to achieved precisions from the LEP experiments for various measurements. Some details regarding the estimation of these uncertainties are described in this section. These are conservative expectations.

2.1 Z pole measurements

The CEPC offers the possibility of dedicated low-energy runs at the Z pole with a large integrated luminosity ($>$ 100 fb^{-1}) and threshold scan runs around the Z pole (from 88 GeV to 94 GeV). These runs allow ultra-high precision electroweak measurements of the Z boson decay partial width, defined as $R_f = \Gamma_{Z\to f\bar{f}}/\Gamma_{\text{had}}$ and and $R_\ell = \Gamma_{Z\to\ell\bar{\ell}}/\Gamma_{\text{had}}$. (Notice that R_ℓ is defined as the ratio to any one charged lepton flavor, not the ratio to the sum of all lepton flavors.) It would also perform high precision measurements of the forward-backward charge asymmetry (A_{FB}), the effective weak mixing angle ($\sin^2\theta_W^{\text{eff}}$), and the mass of the Z boson (M_Z). The threshold scan runs are also crucial for the calibrations of leptons and jets. It is also possible to perform some measurements with the Z boson without these dedicated low-energy runs near or at the Z pole. For

PoS(ICHEP2016)692

Table 1: The expected precision in a selected set of EW precision measurements and the comparison with the precision from LEP experiments.

Observable	LEP precision	CEPC precision	CEPC runs	$\int \mathscr{L}$ needed in CEPC
m_Z	2 MeV	0.5 MeV	Z threshold scan runs	$> 100\text{fb}^{-1}$
m_W	33 MeV	0.5 MeV	ZH runs	$> 100\text{fb}^{-1}$
A^b_{FB}	1.7%	0.15%	Z threshold scan runs	$> 150\text{fb}^{-1}$
$\sin^2\theta^{\text{eff}}_W$	0.1%	0.01%	Z threshold scan runs	$> 100\text{fb}^{-1}$
R^b	0.3%	0.08%	Z pole	$> 100\text{fb}^{-1}$
N^ν	1.7%	0.2%	ZH runs	$> 100\text{fb}^{-1}$
R^μ	0.2%	0.05%	Z pole	$> 100\text{fb}^{-1}$
R^τ	0.2%	0.05%	Z pole	$> 100\text{fb}^{-1}$

example, the direct measurement of the number of light neutrino species can be performed in ZH runs intended for Higgs boson measurements.

2.1.1 R_b

The width of the Z boson to each of its decay channels is proportional to the fundamental Z-fermion couplings. The partial width R_b is sensitive to electroweak radiative corrections from new physics particles. For example, the existence of the scalar-tops or charginos in the supersymmetry model could lead to a visible change of R_b from the SM prediction.

Precise measurements of R_b have been made by LEP collaborations [6] and by the SLD collaboration [7] at SLAC using hadronic Z events.

Decays of b-hadrons were tagged using tracks with large impact parameters and/or reconstructed secondary vertices, complemented by event shape variables. The combination of LEP and SLD measurements yields a value of 0.21629 ± 0.00066 for R_b. The relative statistical uncertainty of R_b is 5×10^{-4}. The main systematics uncertainty includes the uncertainty due to hemisphere tag correlations for b events (0.2%), the uncertainty due to gluon splitting (0.15%), the uncertainty due to charm physics modelling (0.1%) and the uncertainty due to light quark modelling (0.1%).

A precision of 0.08% can be achieved for the measurement of R_b at CEPC, and it will improve the current precision in experimental measurement by a factor of 4. Assuming the CEPC will collect a total integrated luminosity of 100 fb^{-1} at the Z pole, the statistical uncertainty improves by at least a factor of 10 and the systematic uncertainties will reduce also. The uncertainty due to hemisphere tag correlations for b events will be reduced to a level of 0.05% due to the expected improvement in the b-tagging performance of the CEPC detector. The improvement of b-tagging efficiency is important to reduce the correction in C_b since the correlation becomes irrelevant in the limit of 100% b-tagging efficiency.

Due to that fact that a next-generation vertex detector will be used in the CEPC detector, the b-tag efficiency is expected to be around 80% with a b-jet purity of 90%, which is about 15% higher than the efficiency in the SLD experiment. The impact of C_b to R_b will reduce by at least a factor of four with respect to previous measurements.

The CEPC measurement is thus expected to have a 5-10% purer b-tagged sample at the 90% tagging efficiency compared to previous measurements. Therefore the uncertainty due to the modeling of the light quarks in the CEPC measurement can be reduced to a level of 0.05% using a tighter b-tagging working point.

More precise gluon splitting measurements is expected to perform in CEPC, therefore the uncertainty due to gluon splitting can be reduced to 0.08% level.

The uncertainty due to charm physics modelling can be reduced to 0.05% by reducing the mis b-tag efficiency for charm jets. Typical working points at LEP measurements have a b-tagging efficiency of 60% and a charm mistag rate of 1.3%. The b-tag efficiency of charm jets can be reduced to less than 0.5% compared to LEP measurement in 65% b jet purity working point.

2.1.2 The partial decay width of $Z \to \mu^+\mu^-$

The $\mu^+\mu^-$ channel provides the cleanest leptonic final state. Combining the measurements from all four LEP experiments [8, 9, 10, 11], the overall uncertainty of R_μ is 0.2%. The statistical uncertainty of R_μ is 0.15%. Main systematic uncertainties from the ALEPH measurement come from the uncertainty in muon momentum scale (0.009%) and in muon momentum resolution (0.005%), the uncertainty in the modeling of $Z \to \mu^+\mu^-\gamma$ events (0.05%), and the uncertainty of photon energy scale is 0.05% in $Z \to \mu^+\mu^-\gamma$ process.

A precision of 0.05% can be achieved at the CEPC. Benefitted from the excellent CEPC tracking detector, the uncertainties due to muon momentum scale and resolution will be negligible. The energy resolution in EM calorimeter of the CEPC detector is expected to be at least 10 times better than the resolutions at LEP experiments. Therefore, the uncertainty due to photon energy scale and resolution in $Z \to \mu^+\mu^-\gamma$ process can be reduced to 0.02%. The main challenge in this measurement is to reduce the systematics due to QED ISR events. More detailed studies of radiative events in Z threshold scan runs are expected. Benefitted from high statistics in Z threshold scan runs, the source of uncertainty can be reduced to a level of 0.03%.

2.1.3 The forward-backward asymmetry A^b_{FB} at Z pole

The measurement of the forward-backward asymmetry in $e^+e^- \to b\bar{b}$ events at the Z pole $A^{b,0}_{FB}$ gives an important test of Standard Model. $A^{b,0}_{FB}$ the forward-backward charge asymmetry in $Z \to b\bar{b}$ events at Z pole, and it offers the most precise determination of the weak mixing angle. The measurements have been made at LEP [8, 9, 10, 11] using about 10^6 hadronic Z events.

$Z \to b\bar{b}$ events were identified by tagging two b jets. Each event was divided into forward and backward categories by the plane perpendicular to the thrust axis and contains the interaction point. The combination of the LEP and at SLD measurements gives a measured value of $A^{b,0}_{FB} = 0.1000 \pm 0.0017$. The statistical uncertainty is 1.2% and the main systematic uncertainties come from hemisphere tag correlations for b events (1.2%), tracking resolution and vertex detector alignment (0.8%), charm physics modelling (0.5%), and QCD and thrust axis correction (0.7%).

A precision of 10^{-4} can be achieved for the measurement of $A^{b,0}_{FB}$ at the CEPC, improving the current precision by more than a factor of 10. The expected statistical uncertainty is at a level of 0.05%. The uncertainty due to hemisphere tag correlations for b events can be reduced to 0.1%

due to high b-tagging efficiency. The uncertainty due to charm physics modeling can be reduced to 0.05% by choosing a tighter b-tagging working point. The uncertainty due to tracking resolution and vertex detector alignment can be reduced to 0.05%. The expected tracking momentum resolution in the CEPC detector is $\sigma/p_T = 2\times10^{-4}\times p_T + 0.005$, which is 10 times better than the resolutions of the LEP detectors. The uncertainty due to QCD and thrust axis correction can be reduced to 0.1% due to at least 10 times better granularity in the CEPC calorimeters. Overall, the expected systematics at CEPC measurement can be reduced to a level of 0.15%.

2.1.4 The prospect of the effective weak mixing angle measurement

The weak mixing angle $\sin^2\theta_W^{\text{eff}}$ is a very important parameter in the electroweak theory of the SM. It is the only free parameter that fixes the relative couplings of all fermions to the or Z. It describes the rotation of the original W_0 and B_0 vector boson states into the observed γ or Z bosons as a result of spontaneous symmetry breaking. The weak mixing angle is very sensitive to electron radiative correction, and it can be used perform a precise test of the SM theory. Further more, if there is any new heavy gauge boson Z', the weak mixing angle is expected to deviate from the SM prediction due to the contribution from physics in loop corrections. Therefore $\sin^2\theta_W^{\text{eff}}$ is very sensitive to new physics as well.

The centre-of-mass energy dependence of the forward-backward asymmetry arises from the interference of the Z boson with the virtual photon and thus depends on $\sin^2\theta_W^{\text{eff}}$. In other words, the effective weak mixing angle can be extracted by studying the $\sqrt{s}$ dependence of the forward-backward asymmetry.

The effective weak mixing angle measurement has been performed in LEP [8, 9, 10, 11] using $Z\to bb$ events and $Z\to ll$ events. The forward-backward asymmetry A_{FB} in one Z-pole datasets and two off Z-pole datasets ($\sqrt{s}$ = 89.4 GeV , $\sqrt{s}$ = 93.0 GeV) are used to extract $\sin^2\theta_W^{\text{eff}}$. The current experimental result is $\sin^2\theta_W^{\text{eff}} = 0.23153\pm0.00016$. $Z\to b\bar{b}$ events were identified by tagging two b jets. The main uncertainty includes uncertainty on the A_{FB}^b measurement as described in Sec. 2.1.3. and the statistical uncertainty in off Z-pole datasets.

Both Z-pole and off Z-pole runs are needed to perform the effective weak mixing angle measurement at the CEPC. The Z off-peak runs are expensive, therefore we need to optimize the integrated luminosity for off-peak runs. In order to improve the precision of $\sin^2\theta_W^{\text{eff}}$ by a factor of 3 and The required CEPC integrated luminosity for Z-pole runs are between 100 fb^{-1} and 1000 fb^{-1}, at least 10 fb^{-1} integrated luminosity is needed for off Z-pole runs. The expected precision of effective weak mixing angle measurement in CEPC using $Z\to b\bar{b}$ events is expected to be 0.02%.

2.2 W mass measurement

In e^+e^- collisions, W bosons are produced mainly through $e^+e^-\to W^+W^-$ process. The cross section of this process at the WW production threshold is very sensitive to m_W. m_W can be measured from polarized threshold scan runs.

At centre-of-mass energies above W^+W^- production threshold, the mass of the W bosons can be determined by measuring the momentum of its decay products. This is called direct measurement approach in this section.

The measurements have been made at LEP using both polarized threshold scan method and direct measurement approach. Threshold scan method suffered from large statistical uncertainty (about 200 MeV). The direct measurement approach using $\ell\nu qq$ and $qqqq$ channels at LEP provides a better measurement. The uncertainty due to limited data statistics in the direct measurement was found to be about 30 MeV [15, 16, 17, 18] . The main systematics uncertainty from the measurement includes the modeling of hadronization (13 MeV) and radiative corrections (8 MeV), and energy scale of lepton and missing energy(10 MeV).

Using the threshold scan method, a precision of 2.5 MeV can be achieved for the measurement at the CEPC. Assuming the CEPC can provide a 6-points threshold scan runs with 500 fb^{-1} integrated luminosity. The $\sqrt{s}$ of threshold scan runs are assumed to be 160.6, 161.2, 161.4, 161.6, 162.2 and 170.0 GeV. $\ell\nu qq$ channels can be used to measure $e^+e^- \to W^+W^-$ cross section as a function of $\sqrt{s}$. Assuming the momentum scale uncertainty in the CEPC accelerator can at 10-ppm level, The list of systematics uncertainties are summarized in Table 2.

Table 2: Using threshold scan measurement method in dedicated WW threshold scan runs, the expected precision in m_W measurement in CEPC detectors and the comparison with LEP experiments.

ΔM_W(MeV)	LEP	CEPC
$\sqrt{s}$(GeV)	161	160-170
$\int\mathscr{L}$(fb^{-1})	3	1000
channel	$\ell\nu qq, qqqq$	$\ell\nu qq$
beam energy	13	1.0
background	13	0.5
efficiency	8	0.5
luminosity	10	1.0
polarization	3	0.5
jet energy scale	—	0.5
statistics	20	1.0
total	36	2.5

Using direct measurement method, a precision of 3 MeV can be achieved for the measurement at CEPC. The main advantage of direct measurement method is that no dedicated run is needed, all the measurements can be performed in ZH runs with $\sqrt{s} \sim 240$ GeV. Another advantage is that this method have lower requirement for accelerator performance. The main challenge of this method is to handle the uncertainty due to QED radiations. The energy spread from beamstrahlung is proportional to the square of the beam energy. To reduce the dependence of the m_W precision on the absolute beam polarization and momentum determination, a dedicated study using radiative return ($e^+e^- \to Z\gamma$) events is necessary [19]. The uncertainty due to beam beamstrahlung effect can be reduced to 1 MeV level using 1000 fb^{-1} data. Other systematic uncertainties include lepton momentum scale and the modeling of hadronization. The list of systematics uncertainties are summarized in Table 3.

Table 3: Using direct measurement method in *ZH* runs, the expected precision in m_W measurement in CEPC detectors and the comparison with the LEP experiments.

ΔM_W(MeV)	LEP	CEPC
$\sqrt{s}$(GeV)	161	250
$\int \mathscr{L}$(fb^{-1}	3	1000
channel	$l\nu qq, qqqq$	$l\nu qq$
beam energy	9	1.0
hadronization	13	1.5
radiative corrections	8	1.0
lepton and missing energy scale	10	1.5
bias in mass reconstuction	3	0.5
statistics	30	1.0
overall systematics	21	2.5
total	36	3.0

3. Summary

A preliminary study has shown that the CEPC collider has great physics potential. Based on the preliminary studies presented here, the experiments at the CEPC are expected to measure the key electroweak parameters to a precision significantly beyond what was achievable at the LEP.

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