Snowmass2021 - Letter of Interest

Measurement of the leptonic effective weak mixing angle at CEPC

Thematic Areas: (check all that apply □/■)

□ (EF01) EW Physics: Higgs Boson properties and couplings
□ (EF02) EW Physics: Higgs Boson as a portal to new physics
□ (EF03) EW Physics: Heavy flavor and top quark physics
■ (EF04) EW Precision Physics and constraining new physics
□ (EF05) QCD and strong interactions: Precision QCD
□ (EF06) QCD and strong interactions: Hadronic structure and forward QCD
□ (EF07) QCD and strong interactions: Heavy Ions
□ (EF08) BSM: Model specific explorations
□ (EF09) BSM: More general explorations
□ (EF10) BSM: Dark Matter at colliders
□ (Other) *[Please specify frontier/topical group]*

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Abstract:
We present a study of the measurement of the leptonic effective weak mixing angle, $\theta^{\ell}_{\text{eff}}$, at CEPC. Taking the advantage of the CEPC's high luminosity, the relative precision of $\sin^2\theta^{\ell}_{\text{eff}}$ can be at least one order of magnitude better than $\mathcal{O}(0.1\%)$ which has been achieved at LEP, SLC and Tevatron. It will be the first time that experimental observation and the standard model theoretical calculation on the Z pole electroweak symmetry breaking can be directly compared at two-loop level. CEPC can also provide a $\mathcal{O}(0.1\%)$ precision on the comparison between $\sin^2\theta^{\ell}_{\text{eff}}$ from different decay channels, including muon and electron, τ, heavy quarks (b and c), and light quarks (u and d). Besides, $\sin^2\theta^{\ell}_{\text{eff}}$ can be measured at off-pole energy points, providing direct observations on the running effect of $\sin^2\theta^{\ell}_{\text{eff}}$.

I. Motivation and introduction

The leptonic effective weak mixing angle is the key parameter in the electroweak global fitting. It is important not only to the standard model global fitting, but also predictions in potential new physics. It is defined as an effective parameter which could absorb standard model or beyond standard model higher order effects. The experimental precisions of the $\sin^2\theta^{\ell}_{\text{eff}}$ measurements at the Z mass pole region are at $\mathcal{O}(0.1\%)$ level, including 0.23221 ± 0.00029 from the LEP combined $e^+e^- \to b\bar{b}$ results, 0.23098 ± 0.00026 from the SLC $e^+e^- \to e^+e^-$ polarization asymmetry observation, and 0.23179 ± 0.00033 from the combined D0 and CDF measurements, dominated by the light quark $q\bar{q} \to \ell^+\ell^-$ processes [1;2]. The theoretical uncertainty on $\sin^2\theta^{\ell}_{\text{eff}}$ can be reduced to 0.00005 around Z pole by performing complete two-loop level calculations [3]. As a conclusion, the $\sin^2\theta^{\ell}_{\text{eff}}$ related global fittings are now limited by the experimental precision in the past two decades. By the discovery of the Higgs boson in 2012, all parameters in the standard model predictions are experimentally fixed. As direct new physics searches have been going on for almost 10 years at the Large Hadron Collider but no obvious clue found, precise comparison between experiment and theoretical results in the global fitting becomes important. This requires significant improvements on the experimental measurements on $\sin^2\theta^{\ell}_{\text{eff}}$.

CEPC is an ideal collider to provide high precision measurements on $\sin^2\theta^{\ell}_{\text{eff}}$. It is planning a two-year run period around the Z pole, which can generate $3{\sim}6\times10^{11}$ single Z boson events. With such a large data sample, the statistical uncertainty, which is the dominant uncertainty in the LEP and SLC measurement, we can easily reduce the statistical uncertainty around 0.00001 on $\sin^2\theta^{\ell}_{\text{eff}}$. High precisions can be achieved independently in different decay channels, including muon and electron, τ, light quarks (u and d), and heavy quarks (b and c). The comparison channels is part of the standard model global test. The running effect on the translated $\sin^2\theta_W$ as a function of the energy scale is another physics interest. By now, there is no direct weak mixing angle measurement at an energy scale higher than the Z pole region. It would be very important to experimentally test the theoretical prediction that $\sin^2\theta_W$ would run to a higher value as the energy scale goes up.

LHC also has possibility to achieve a high precision on $\sin^2\theta^{\ell}_{\text{eff}}$, but would be very difficult. Uncertainties from parton distribution functions which models the initial state quark momentum are at $\mathcal{O}(0.1\%)$ level with respect to the $\sin^2\theta^{\ell}_{\text{eff}}$ value. Systematic uncertainties under high instantaneous luminosity collisions are expected to be same large with that from PDFs. In general, trying to measure $\sin^2\theta^{\ell}_{\text{eff}}$ at hadron colliders requires a series of long term studies. Besides, hadron colliders could not provide direct observations on τ and heavy quark couplings.

As a conclusion, CEPC could bring a relative precision of $\sin^2\theta^{\ell}_{\text{eff}}$ at $\mathcal{O}(0.01\%)$ level, and at $\mathcal{O}(0.1\%)$ level for comparison between different channels and for observation on the energy running effect.

II. Measurements and Expected precisions

The effective weak mixing angle can be observed from the forward-backward asymmetry (A_{FB}) via the $e^+e^- \to Z/\gamma^* \to f\bar{f}$ process. A_{FB} is defined as:

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B} \tag{1}$$

where N_F and N_B represent the number of forward events, defined as those events having final state fermions along the direction of the e^- beam, and the number of backward events, defined as those having final state fermions along the direction of the e^+ beam. Around Z pole, $\sin^2\theta^{\ell}_{\text{eff}}$ and A_{FB} has approximately a linear relationship. The statistical uncertainty of the $\sin^2\theta^{\ell}_{\text{eff}}$ extracted from A_{FB} can be expressed as:

$$\Delta\sin^2\theta^{\ell}_{\text{eff}}(\text{stat.}) = \sqrt{\frac{1-A^2_{FB}}{N\times\epsilon}} \times \frac{\sqrt{1-2f+f^2}}{1-2f} \times S \tag{2}$$

where S is the slope of the $\sin^2\theta^{\ell}_{\text{eff}}$-$A_{FB}$ linear relationship representing the sensitivity, N is the total number of forward and backward events, ϵ is the overall efficiency of observing an event, and f is the probability of wrongly identifying the charge of the final state fermions. Systematics comes from the determination on ϵ and f, which could be very precision at lepton colliders. Even for those LEP measurements including both lepton and b quark channels, such uncertainties are negligible compared to the statistical uncertainty. Theoretical uncertainties comes from the calculation of S.

By the above discussions, we provide a preliminary estimation on the Z pole region in Table. 1. Note that the uncertainty corresponds to a one month data sample at CEPC.

channels	low mass measurement at 75 GeV	Z pole measurement at 91.19 GeV	high mass measurement at 130 GeV
lepton decay channel uncertainty	0.00017	0.00001	0.006
b quark channel uncertainty	0.00009	<0.00001	0.00016

Table 1: Expected uncertainty on $\sin^2\theta^{\ell}_{\text{eff}}$ with 1 month data collection in different channels and at different energy points.

References

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[2] T. Aaltonen *et al.* (CDF and D0 Collaborations), Phys. Rev. D **97**, 112007 (2018).

[3] M. Awramik, M. Czakon, A. Freitas, and G. Weiglein, Phys. Rev. Lett. **93** 201805.