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Measurement of the effective weak mixing angle using $b\bar{b}$, $c\bar{c}$ and $s\bar{s}$ final states at the CEPC

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Abstract The proposed Circular Electron Positron Collider (CEPC) is expected to provide adequate events around the Z boson mass pole, allowing high precision determination on the effective weak mixing angle. Specifically, one can acquire large data samples of the $Z \to b\bar{b}$, $Z \to c\bar{c}$ and $Z \to s\bar{s}$ events with high purity, even though the efficiencies of the jet tagging are limited to ensure a good separation between different flavors. According to recent studies of the detector and reconstruction algorithms, with the new jet tagging method at the CEPC detector which gives a purity of 99.9% for the $b\bar{b}$ and $c\bar{c}$ samples and 97% for the $s\bar{s}$ sample, the corresponding uncertainties on the effective weak mixing angle determined from those samples are better than 10^{-4} using data collected within 1 month. It allows high precision determinations of the effective weak mixing angle from different quark flavors especially for c and s quarks, which is essential to the standard model global test and potential new physics searches.

1 Introduction

The weak mixing angle, θ_W, is a fundamental parameter in the SU(2) $\times$ U(1) electroweak (EW) interaction of the standard model (SM). At high energy colliders, θ_W can be determined from the Drell-Yan process $f_i\bar{f_i} \to Z/\gamma^* \to f_j\bar{f_j}$ in a less model-dependent way: it has been proved that higher order loop corrections (including potential new physics beyond SM) can be effectively absorbed by replacing the weak mixing angle in the born-level calculations with the effective weak mixing angle [1]:

$$\sin^2\theta_{\text{eff}}^f = \kappa_f \sin^2\theta_W \qquad (1)$$

where κ_f is the flavor-dependent scale factor. In custom, the leptonic effective weak mixing angle ($\sin^2\theta_{\text{eff}}^\ell$) is chosen as the experimental determined parameter, while the quark effective weak mixing angles are converted to the leptonic one accordingly. Since the higher order loop corrections are flavor-dependent, measuring the weak mixing angle from the Drell-Yan processes with different f is essential to both the SM global test and the beyond SM new physics search.

In the past two decades, $\sin^2\theta_{\text{eff}}^\ell$ has been measured at the energy scale of the Z boson mass pole. The SLC $e^+e^- \to f\bar{f}$ measurement exploited the polarization of the electron beam, providing a pure leptonic determination, giving $\sin^2\theta_{\text{eff}}^\ell[\text{SLC}] = 0.23098 \pm 0.00026$ [1]; The LEP $e^+e^- \to b\bar{b}$ measurement contains both Z-to-lepton and Z-to-heavy quark couplings, giving $\sin^2\theta_{\text{eff}}^\ell[\text{LEP-b}] = 0.23221 \pm 0.00029$ [1]. These two measurements achieve the best precision of the $\sin^2\theta_{\text{eff}}^\ell$ determination, while their central value differ by 3.2 standard deviation. At the proton-antiproton collider Tevatron, $\sin^2\theta_{\text{eff}}^\ell$ is measured in $p\bar{p}(q\bar{q}) \to \ell^+\ell^-$ events, where the initial state is dominated by the light quarks u and d. The combined result of D0 and CDF gives $\sin^2\theta_{\text{eff}}^\ell[\text{Tevatron}] = 0.23148 \pm 0.00033$ [2] with a precision comparable to the best LEP and SLC ones. At the proton-proton collider LHC, $\sin^2\theta_{\text{eff}}^\ell$ is also measured. Although light quark contributions are still dominating in the pp collisions, massive quarks become much more significant, making the LHC measurements a mixture of all kinds of quarks. The latest measurement of $\sin^2\theta_{\text{eff}}^\ell$ from LHC is provided by the CMS collaboration, giving $\sin^2\theta_{\text{eff}}^\ell[\text{CMS}] = 0.23102 \pm 0.00053$ [3]. Besides, $\sin^2\theta_{\text{eff}}^\ell$ has been measured at LEP using $e^+e^- \to c\bar{c}$ events [1]. However, the precision is much worse.

In the previous study of the weak mixing angle measurement at CEPC [4], we demonstrated that the uncertainty on $\sin^2\theta_{\text{eff}}^\ell$ can be reduced to 0.00001 in measurements using

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lepton and b quark final states, at M_Z. In this article, we report a new study of measuring $\sin^2\theta^\ell_{\text{eff}}$ using b, c and s quark final states at the CEPC. Such measurements are not available at hadron colliders, not only because of the challenges in flavor identification, but also due to the difficulties in reconstruction of the Z boson mass using the final state jets. The large uncertainty from the parton distribution functions is also a limitation at hadron colliders. At the CEPC, the invariant mass of the $e^+e^- \to f\bar{f}$ event is determined directly from the beam energy, which can be precisely controlled with uncertainty lower than an MeV [5]. To acquire a $b\bar{b}$, $c\bar{c}$ or $s\bar{s}$ sample, a tight selection criteria should be applied to the final state jets to identify the flavor. It would cause considerable loss in efficiency. However with more than 4 trillion Z candidates expected during the 2-year Z pole run at the CEPC, the statistical fluctuation in such measurements still can be negligible. Therefore, CEPC can provide high precision determination on $\sin^2\theta^\ell_{\text{eff}}$ using different quark flavors, especially for c and s quark final states. These results, together with measurements dominated by leptons and light quarks, would be important inputs to the global analysis of the electroweak sector.

2 Method

$\sin^2\theta^\ell_{\text{eff}}$ is extracted from the forward-backward asymmetry A_{FB} of the $e^+e^-_i \to Z/\gamma^* \to f_i\bar{f}_i$ events. A_{FB} is defined as:

$$A_{FB}(\sin^2\theta^\ell_{\text{eff}}) = \frac{N_F - N_B}{N_F + N_B} = A_{FB}$$

where N_F and N_B are the number of forward and backward events. At electron-positron collider, the initial state naturally selects the spatial direction by the charge of the leptons. Therefore, forward(backward) events can simply be defined according to $\cos\theta > 0 (< 0)$, where θ is the scattering angle formed by the directions of the incoming electron beam and the outgoing fermion. The statistical uncertainty in the $\sin^2\theta^\ell_{\text{eff}}$ measurement can be expressed as:

$$\delta\sin^2\theta^\ell_{\text{eff}}[\text{stat.}] = \sqrt{\frac{1}{N}} \cdot \sqrt{\frac{1-(A_{FB})^2}{\epsilon\cdot(1-2p)^2}} \cdot \frac{1}{|S|} \tag{2}$$

where $N = N_F + N_B$ is the total number of events in the selected data sample, p is the probability of mis-identifying the final state fermion and anti-fermion charges, and ϵ is the selection efficiency. S is the sensitivity factor describes the relationship between A_{FB} and $\sin^2\theta^\ell_{\text{eff}}$:

$$S = \frac{\partial A_{FB}}{\partial \sin^2\theta^\ell_{\text{eff}}}.$$

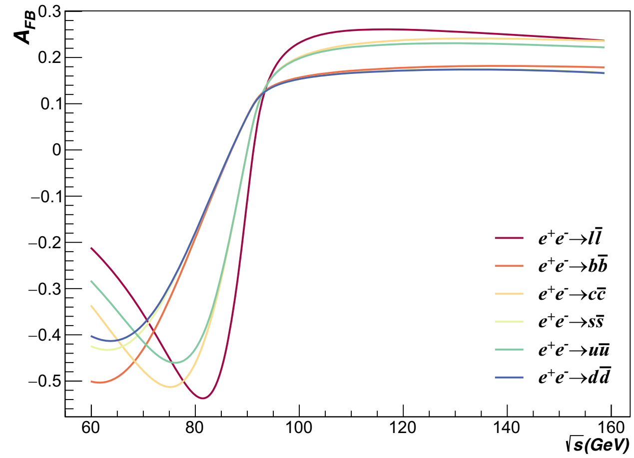

Fig. 1 A_{FB} spectrum as a function of $\sqrt{s}$ for different flavors in the $e^+e^- \to Z/\gamma^* \to f\bar{f}$ process

Since $\sin^2\theta^\ell_{\text{eff}}$ is an effective parameter absorbing potential SM and beyond SM loop corrections, S can be precisely and model-independently predicted.

In previous study [4], we have concluded that for a given $f_i\bar{f}_i$ data sample with negligible background events, the experimental systematic in the $\sin^2\theta^\ell_{\text{eff}}$ measurement is negligible, because (i) forward/backward judgement depends only on the sign of $\cos\theta$ rather than its value; (ii) the rate of mis-identifying fermion and anti-fermion charge in the data can be precisely measured; (iii) the efficiency of online triggers and offline event selection criteria cancelled in the relative asymmetry. This is true for the lepton final states, as the probabilities of mis-identifying other particles into electrons or muons are negligibly small. However, it is always challenging to tell the flavor of a final state quark reconstructed as a jet in the detector. In general, the observed asymmetry A^{obs}_{FB} in an $f_i\bar{f}_i$ sample is written as:

$$\begin{aligned} A^{\text{obs}}_{FB} &= \frac{N^f_F + N^{\text{mis}}_F - N^f_B - N^{\text{mis}}_B}{N^f_F + N^{\text{mis}}_F + N^f_B + N^{\text{mis}}_B} \\ &= A^f_{FB} + (1-R)\cdot\left(A^{\text{mis}}_{FB} - A^f_{FB}\right) \end{aligned} \tag{3}$$

where terms with superscript f correspond to the $f_i\bar{f}_i$ events, while terms with superscript *mis* correspond to other flavors mis-identified. R is the purity of the sample, i.e., $1-R$ is the faction of the mis-identified events in the sample. Even in the SM leading order calculations, A_{FB} in the up-type quark events (u and c) is different from that in the down-type quark events (d, s, b), as shown in Fig. 1. Therefore, additional systematics may arise when R is not small.

In principle, the flavor of jets can be identified according to the secondary vertex and the shape of the shower formed in the detector. A jet-tagging algorithm finds a balance between the efficiency of selection criteria and the purity of a sample with specific flavor requirement. Usually, the purity of a sample is limited in order to enlarge the efficiency. However, for the CEPC, a 4 trillion Z candidates sample is proposed around M_Z. It allows a high purity of jet-tagging algorithm, with a tolerable reduction on the efficiency.

Recently, a jet tagging algorithm, Jet Origin Identification (JOI) is proposed [6] at the CEPC. It is a GNN-based deep learning algorithm [7]. It uses the impact parameters of the charged particles, which are the transverse and longitudinal distances of the reconstructed particle trajectory to the designed collision point, and the momentum of the particles reconstructed in the jet cone, to tag the flavor and charge of a jet.

In the baseline scenario of the JOI algorithm, leptons (including only e and μ) and charged hadrons ($\pi^{\pm}$, $K^{\pm}$, protons, and anti-protons) are assumed to be perfectly identified. We note that hadronically decaying τ leptons are currently treated as ordinary charged hadrons within jets. And since the behavior of hadronic τ is significantly different from other hadrons, we do not consider τ-related backgrounds, such as contamination from $Z \to \tau^+\tau^-$ events, in our analysis.

In [6], two other scenarios are also considered: 1) only assume perfect identification of leptons, and 2) assume perfect identification of leptons, charged hadrons, together with K^0_S/K^0_L. We choose a moderate scenario in this work, to avoid over-optimistic assumptions on K^0 identification, and to fully utilize the excellent charged hadron identification capability of the CEPC detector. With the capability of $K^{\pm}$ identification, s-jet tagging performance will be significantly improved, as kaons are the most distinctive hadrons in the s-jet final state. This assumption is based on the CEPC detector design. At the CEPC, considerable emphasis has been placed on particle identification (PID) capabilities in recent detector R&D. These include the use of gaseous trackers and time-of-flight (ToF) systems, and ongoing studies of RICH-like technologies.

The algorithm is trained, validated, and tested with the $e^+e^- \to \nu\bar{\nu}H,\ H \to q\bar{q}/gg$ sample [6]. In this paper, for each quark final state, 100k $e^+e^- \to Z/\gamma^* \to q\bar{q}$ events are simulated to determine the tagging performance. The events are generated with PYTHIA6 [8], followed by a Geant4-based [9] simulation of the CEPC detector [5].

For a jet, the JOI algorithm provides a confidence score l_q for each quark flavor of d, $\bar{d}$, u, $\bar{u}$, s, $\bar{s}$, c, $\bar{c}$, b, and $\bar{b}$. A jet candidate can then be classified with a flavor according to the highest score of l_q. When evaluating the tagging performance in A_{FB} measurements, we use the exclusive Durham algorithm (eekt) to cluster each event into exactly two jets, suitable for the hemisphere-based A_{FB} definition. The truth label of each jet is marked by the flavor of the initial quark parton, as motivated by the need to directly correlate the final-state jet with the production-level quark for the definition of the A_{FB} observable.

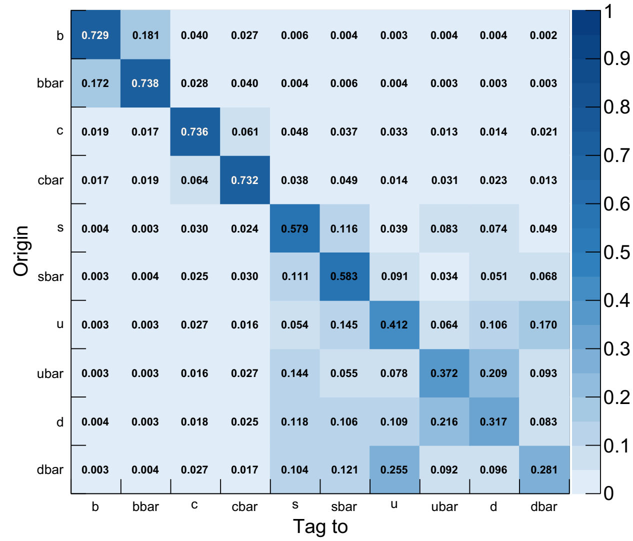

Fig. 2 The tagging-matrix with perfect identification of leptons and charged hadrons. The matrix is normalized to unity for each true label (row)

The normalized tagging-matrix is shown in Fig. 2. The vertical axis represents the flavor of the final state quark in truth level, while the horizontal axis corresponds to the flavor of a jet identified according to the highest score of l_q given by the JOI algorithm in the simulation. Each bin in the matrix corresponds to the probability of a flavor q_i in truth level to be identified as flavor q_j after simulation. For b and c quarks, the highest probability of mis-identification happens with their own anti-quarks due to a wrong charge. For s quarks, mis-identifications from u and d quarks are dominant. For u and d, mis-identification between these two light quarks is significant, making them almost un-distinguishable.

The numbers in Fig. 2 correspond to the identification of a single quark. In practice, the Z candidates are selected by requiring the final states to have a $q\bar{q}$ pair. This would improve the purity at the event level. This would cause inefficiency by excluding those $q\bar{q}$ events at truth level but identified as other flavors in the simulation. Table 1 summarizes the event level purity, efficiency, the p factor in Eq. 2 which describes the probability of mis-identifying q between $\bar{q}$, and the tagging-power parameter defined as $T = \epsilon \times (1-2p)^2$.

To further improve the purity, we apply the following requirement: a jet candidate is flavor identified first according to the highest value of flavor score $l_{\mathrm{flv}}(q) = l_q + l_{\bar{q}}$, and we further require that this value should be greatter than 0.5, so that the JOI algorithm gives a clear judgement on the flavor; charge seperation score $|l_q - l_{\bar{q}}|$ is required to be greater than 0.3, to further suppress the p parameter of charge mis-identification.

By doing this, the efficiency is further reduced. However, as discussed, the large data sample proposed at CEPC allows to pursue a higher purity by sacrificing the efficiency.

Table 1 (Event-level) purity R, efficiency ϵ, p factor, and tagging power T determined in the $Z \to q\bar{q}$ process using the JOI tagging algorithm. No additional selection is applied to the jet tagging scores; all reconstructed jets are categorized, reflecting the baseline performance without analysis-specific optimizations. The statistical uncertainties on these numbers are negligible with the 500k simulated events

	Purity R	Efficiency ϵ	Mis-id p	Tagging power T
$b\bar{b}$	99.7%	0.581	0.060	0.451
$c\bar{c}$	98.4%	0.567	0.015	0.534
$s\bar{s}$	87.9%	0.407	0.106	0.253

Figure 3 gives the tagging-matrix for single jet, derived from the samples with the additional selection criteria applied. Table 2 shows the updated event-level information accordingly. The purities of $b\bar{b}$, $c\bar{c}$ and $s\bar{s}$ candidates are further improved. The reductions in efficiency are tolerable. As will be discussed later, both the systematics due to the residual mis-identification and the statistical uncertainty are small. Such performance allows the determinations of $\sin^2\theta^{\ell}_{\text{eff}}$ using charm quark final state with a precision much higher than the previous one from LEP [1]. It also allows a determination of $\sin^2\theta^{\ell}_{\text{eff}}$ using strange quark final state which has never been achieved before. For the $b\bar{b}$ case, we already demonstrated a high purity and a good precision of $\sin^2\theta^{\ell}_{\text{eff}}$ determination at Z pole in the previous study [4]. However, uncertainties on the off-pole measurement of $\sin^2\theta^{\ell}_{\text{eff}}$ can be large, since the sensitivity factor S significantly reduces when the collision energy increases. According to Eq. 2, the statistical uncertainty on the extracted $\sin^2\theta^{\ell}_{\text{eff}}$ depends on the tagging-power T. In this work, the tagging-power of the $b\bar{b}$ events is improved from 0.088 to 0.365, due to the new JOI algorithm. As will be discussed later, this will improve the precision of the $\sin^2\theta^{\ell}_{\text{eff}}$ measurement as a function of collision energy.

We do not use $u\bar{u}$ and $d\bar{d}$ events to measure $\sin^2\theta^{\ell}_{\text{eff}}$ in this work. As discussed, there are no criteria sufficient enough to distinguish the jets from one another. A study shows that when $l_{\text{flv}}(u)$ or $l_{\text{flv}}(d)$ is required with higher value, the corresponding efficiency can be reduced to almost zero. It reflects the fact that jets from u and d quarks are naturally similar in the shape, momentum and impact parameters, which are used as the main variables in the JOI algorithm.

3 Uncertainties and results

The uncertainties on the extracted $\sin^2\theta^{\ell}_{\text{eff}}$ in $b\bar{b}$, $c\bar{c}$ and $s\bar{s}$ final states due to the statistical fluctuation are summarized in Table 3. They are estimated according to Eq. 2, where the tagging-power is acquired from the JOI simulations in the previous section, the sensitivity factor S and the asymmetry A_{FB} itself are calculated using the ZFITTER package [10]. The total number of events N corresponds to 1.7×10^{11} Z candidates in one month data taken of the proposed CEPC running plan [5].

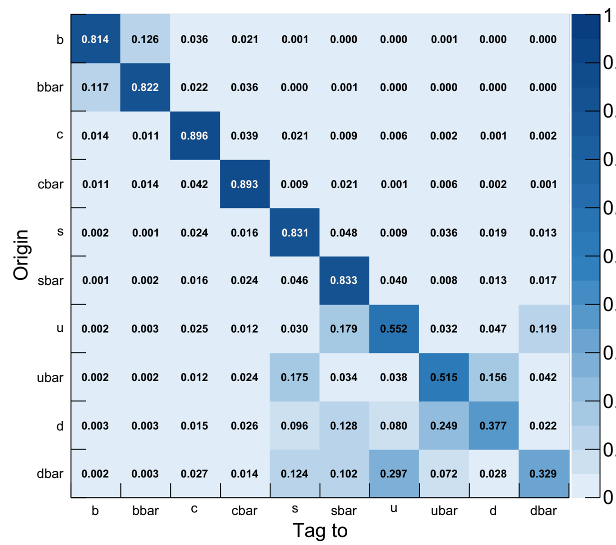

Fig. 3 The updated confusion matrix. Several cuts are added for increasing the sample purity. In this matrix, each row is normalized to 1. The thrown jets are not included in the matrix

Several sources of systematic uncertainties in the A_{FB} measurement have been previously discussed in [4]. Among them, the uncertainty from the center-of-mass energy is negligible at CEPC due to precise beam energy calibration (beam energy determined to 100keV precision, corresponding to a relative uncertainty of much lower than 0.01% on $\sin^2\theta^{\ell}_{\text{eff}}$.) The overall tagging efficiency does not contribute to a bias in A_{FB} since it is a ratio-type observable. Charge misidentification effects, which can dilute the A_{FB} signal, can be determined by data-driven measurements (e.g., tag-and-probe method [11]). Additionally, the impact of QCD corrections for b/c measurements, mainly hard gluon emission effect, is on the order of $\mathcal{O}(10^{-5})$ with LEP's experience.

The most critical source of systematic uncertainty arises from sample purity, i.e., the contamination from mis-tagged jets of other flavors. In the $s\bar{s}$ measurement, where background from u and d jets dominates, this uncertainty requires careful treatment. In practice, the purity and efficiency can be measured using the tag-and-probe method [11]. However, due to the lack of distinctive decay features in u/d jets, their mis-tag rates cannot be accurately measured in a data-driven way. This differs from the case in $b\bar{b}$ and $c\bar{c}$ measurements,

Table 2 (Event level) purity R, efficiency ϵ, p factor, and tagging power T in the $Z \to q\bar{q}$ events with additional selection criteria applied

	R	ϵ	p	T	Major contribution of mis-identification
$b\bar{b}$	$\sim 99.9\%$	0.401	0.023	0.365	$c(0.03\%)$
$c\bar{c}$	99.6%	0.453	0.003	0.447	$b(0.3\%)$
$s\bar{s}$	96.7%	0.148	0.030	0.130	$u(1.7\%)/d(1.4\%)$

Table 3 The estimated statistical uncertainties on $\sin^2\theta^{\ell}_{\text{eff}}$ measurements with b, c, and s final states. Results are estimated according to one month data collection

$\sqrt{s}$/GeV	$\delta\sin^2\theta^{\ell}_{\text{eff}}$ in b final state	$\delta\sin^2\theta^{\ell}_{\text{eff}}$ in c final state	$\delta\sin^2\theta^{\ell}_{\text{eff}}$ in s final state
70	1.9×10^{-5}	3.4×10^{-5}	3.0×10^{-5}
75	1.4×10^{-5}	1.9×10^{-5}	2.4×10^{-5}
92	1.8×10^{-6}	2.4×10^{-6}	2.9×10^{-6}
105	1.2×10^{-5}	2.6×10^{-5}	1.9×10^{-5}
115	2.2×10^{-5}	7.4×10^{-5}	3.6×10^{-5}
130	4.4×10^{-5}	2.5×10^{-4}	7.2×10^{-5}

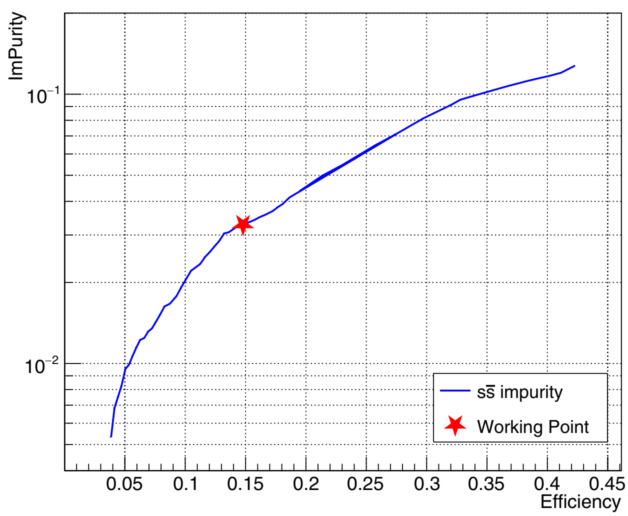

Fig. 4 Efficiency scan for $s\bar{s}$ events, we use different Working Points (i.e., $l_{\text{flv}}(q)$ and $|l_q - l_{\bar{q}}|$ cuts) to evaluate the impurity changes v.s. efficiency. The red star point is the Working Point we use in this paper

where the dominant contamination are b, c and small proportion of s jets, and can be measured using the tag-and-probe method very effectively.

As a rough and safe estimation of the systematic uncertainty in $s\bar{s}$ measurement, the possibilities of mis-identifying u and d quark into s quark (which are the dominant contribution in s quark mis-identification according to Table 2) are varied by a factor of 2. For the observed A_{FB}, we have $A^{s,\text{obs.}}_{FB} \approx P_s \cdot A^{s}_{FB} + P_u \cdot A^{u}_{FB} + P_d \cdot A^{d}_{FB}$, where $P_s = 96.7\%$, $P_u = 1.7\%$, $P_d = 1.4\%$ are the (im)purity in the $s\bar{s}$ sample. We double/half the P_u and P_d to calculate the bias of the observed $A^{s,\text{obs.}}_{FB}$. Due to high similarity between u and d jets in terms of their observable signatures, their mis-tag rates are strongly correlated. Therefore, we tried different combinations (double/double, half/half, double/half, and half/double) and take the biggest difference as the uncertainty. By doing this, the systematic in $s\bar{s}$ events extrapolated to $\sin^2\theta^{\ell}_{\text{eff}}$ is 5×10^{-4}, indicating that the mis-identification would be the major source of uncertainty in the $s\bar{s}$ final state measurements. Although it is not as precise as the b and c channels, it provides a determination on strange quark with quite a good accuracy. We also perform a scan over the selection cuts applied to the tagging scores as a supplementary study. Figure 4 illustrates the stability of the selection in the $s\bar{s}$ sample. When the selection criteria are tightened to achieve higher purity, up to 99%, the efficiency decreases but remains at a non-negligible level of approximately 5%. This demonstrates that the measurement remains feasible even under such extreme working points, providing further evidence for the robustness of the analysis.

4 Conclusion

We report a study of measurements of $\sin^2\theta^{\ell}_{\text{eff}}$ using $b\bar{b}$, $c\bar{c}$ and $s\bar{s}$ final states at the CEPC. According to the JOI algorithm recently developed at the CEPC, Z candidates with $b\bar{b}$, $c\bar{c}$ and $s\bar{s}$ final states can be separately selected with high purity and good efficiency. For the $b\bar{b}$ and $c\bar{c}$ final states, both statistical uncertainty and systematic due to the mis-identification can be small, providing a precision of $\delta\sin^2\theta^{\ell}_{\text{eff}} \sim 10^{-5}$ not only in the Z pole region, but also for high mass region up to 130 GeV, with which we can make an adequate test of the energy-running effect of $\sin^2\theta^{\ell}_{\text{eff}}$. For the $s\bar{s}$ final state, the mis-identification from the u and d light quarks cannot be ignored. However, determination using the strange quark has never been achieved before, and the systematics extrapolated on $\sin^2\theta^{\ell}_{\rm eff}$ can be controlled to $\mathcal{O}(10^{-4})$, which is comparable to the current precision of $\sin^2\theta^{\ell}_{\rm eff}$ determination from LEP, SLC and hadron colliders. These measurements in the future would provide important experimental inputs to the global analysis of the SM electroweak sector, which is essential not only to the global test of the SM with a high precision, but also to the indirect searches of beyond SM new physics.

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Data Availability Statement Data will be made available on reasonable request. [Authors' comment: The code/software generated during and/or analysed during the current study is available from the corresponding author on reasonable request.]

Code Availability Statement Code/software will be made available on reasonable request. [Authors' comment: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.]

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