Measurement of the Forward-Backward Asymmetry in $e^+e^- \to \mu^+\mu^-$ at CEPC Z Pole with the TDR Reference Detector

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Introduction

- The ee→μμ channel at Z pole is the simplest channel at CEPC, and can be utilized to verify the basic performance of CEPC software.
- θ_w (electroweak mixing angle) determines the value of A_{FB} (forward-backward asymmetry).
- The measurement A_{FB} of ee→Z/γ*→μμ provides a precise verification of the θ_w.
- The A_{FB} is defined by the angle θ_{CM} between the final-state μ^- and the initial-state e^- in the dilepton center-of-mass frame.

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$$\frac{1}{\sigma}\frac{d\sigma}{dcos\theta} = \frac{3}{8}(1 + \cos^2\theta) + A_{FB}cos\theta$$

Other experimental results

- **LEP Result**

  The combination of LEP measurements yields a value of $A_{FB} = 0.0169 \pm 0.0013$ in the $\mu^{+}\,\mu^{-}$ channel.

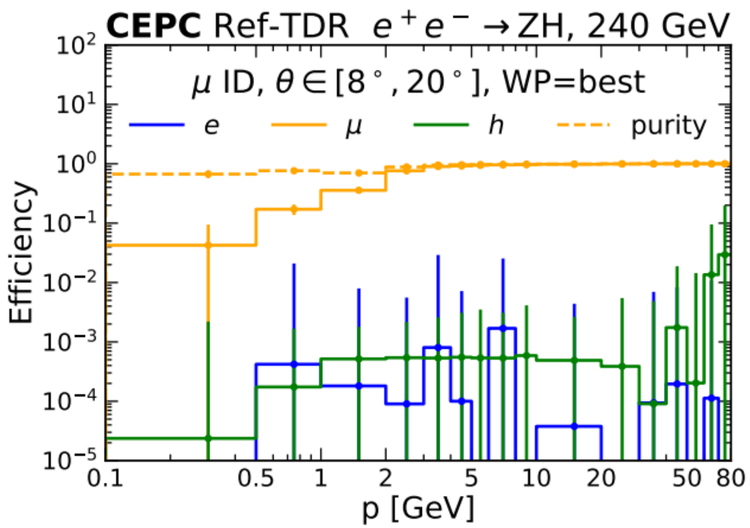
  (arXiv:0509008v3 figure2.13)

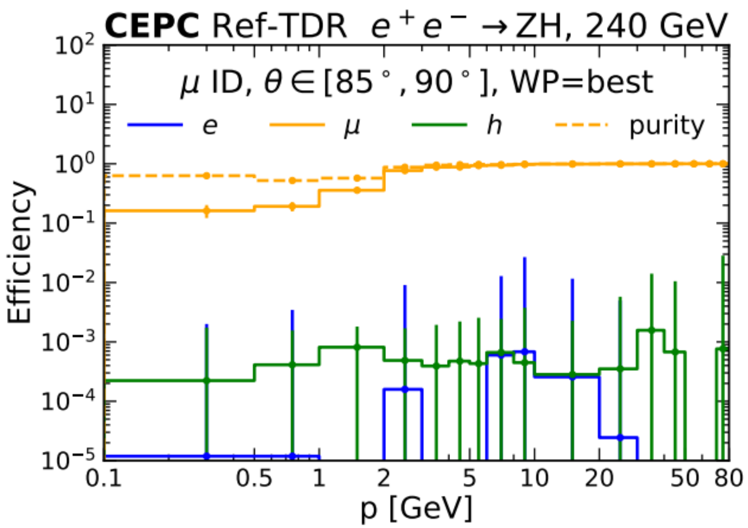
- **FCC-ee Prediction**
  - Statistical uncertainty : 3×10^{-6} (Base on 10^{11} muon pairs)
  - Energy spread uncertainty : 9.2×10^{-6} (Assume $\Delta E_{cm} = 0.1\text{MeV}$)
  - Total uncertainty : 1×10^{-5}

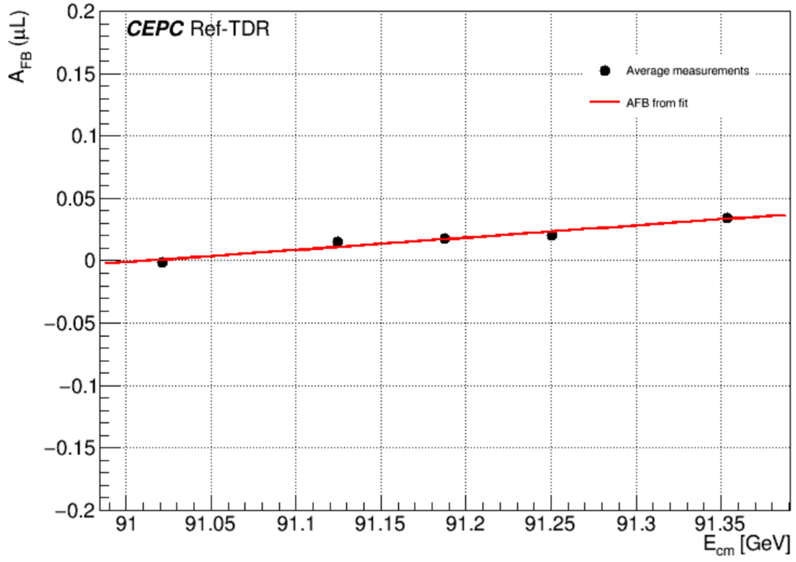
  (arXiv:2106.13885v2 table3)

Sample production

- ee→μμ events are simulated with Whizard + Phythia at LO and Z pole energy.
- The simulation includes the Z/γ* interference along with ISR and FSR effects, and incorporates the beam energy spread of 0.13% at the Z pole.
- Process the sample into with the detector ref-TDR version of the CEPC software.
- A XGBoost classifier was developed for muon ID, with excellent performance.

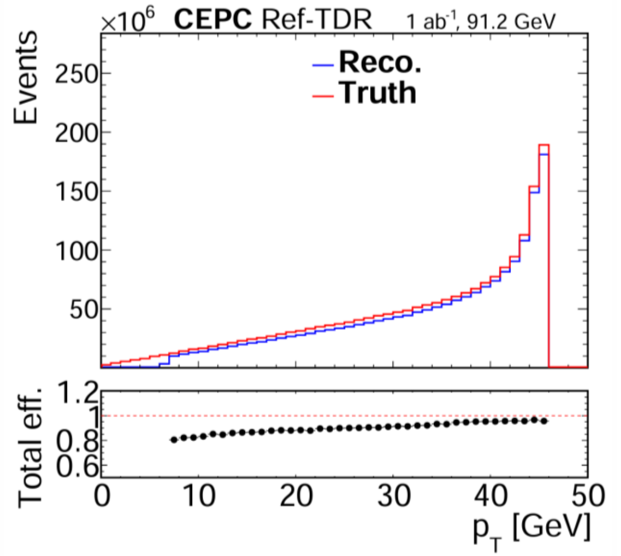


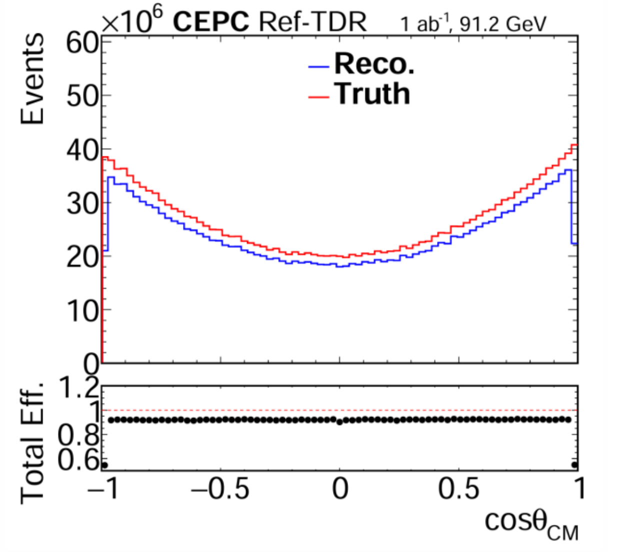




The event selection and cutflow

- P_T > 1GeV and |cosθ|<0.99
- Reco-level selection for a pair of opposite charge muons from Z with muon ID.
- Selection in a ±10 GeV Z mass window.
- A |cosθ|>0.05 cut to reduce muon misidentification.

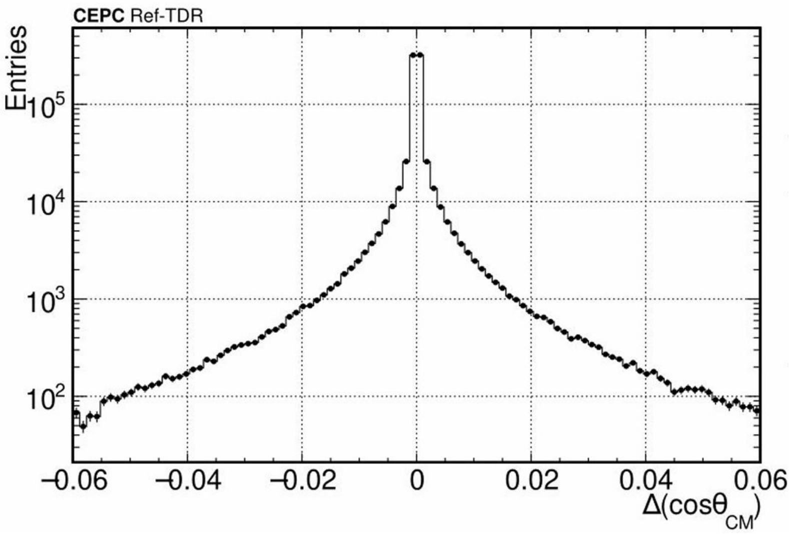




	$e^+e^- \to \mu^+\mu^-$	$e^+e^- \to \tau^+\tau^-$	$e^+e^- \to b\bar{b}$	$e^+e^- \to e^+e^-$
Cross section	1.5 nb	1.5 nb	6.7 nb	6.6 nb
Simulated events	982476	185855	44550	32397
A pair of muons	967262	5135	1035	0
Z mass window	903640	5	0	0
Muon $\lvert\cos(\theta)\rvert > 0.05$	869450 (88.5%)	5 (0.003%)	0 (<0.002%)	0 (<0.003%)

The Calculation of $A_{FB}(\mu)$ counting Method

- Forward and backward events are classified by the angle θ_{CM} of the μ⁻, which is reconstructed in the CM frame.
- $\Delta\theta_{CM}$ is a function of both the energy and angular resolution of the PFO.
- The observed $A_{FB}(\mu)$ measured using PFO is corrected back to the full phase space.



	No selection	After selections	Using PFO
Forward ($\cos(\theta_{CM}) > 0$)	499136	442727	442723
Backward ($\cos(\theta_{CM}) < 0$)	483340	426723	426727
A^{μ}_{FB} or A^{obs}_{FB}	0.016078	0.018407	0.018398
A^{μ}_{FB} after a phase space correction	N/A	0.016078	0.016070

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Discussion of uncertainties

- Statistical uncertainties
  One-month run: 1.34 billion muon pairs (4×10^{10} Z bosons), 3.1×10^{-5} statistical uncertainty.
- Systematic uncertainties
  - Muon mis-identification: Impact of selecting incorrect PFO pairs is negligible.
  - Background: Uncertainty measured as 1×10^{-6} from background contamination.
  - Detector acceptance & resolution: Uncertainty estimated to be 9×10^{-6} for $|cos\theta_{\mu^-}|$ and $p_T^{\mu^-}$.
  - Beam energy spread: Uncertainty of 1×10^{-6} from 0.13%-0.14% Gaussian spread.
  - Beam energy calibration: Dominant uncertainty of 2.7×10^{-5} from 300 keV calibration uncertainty.

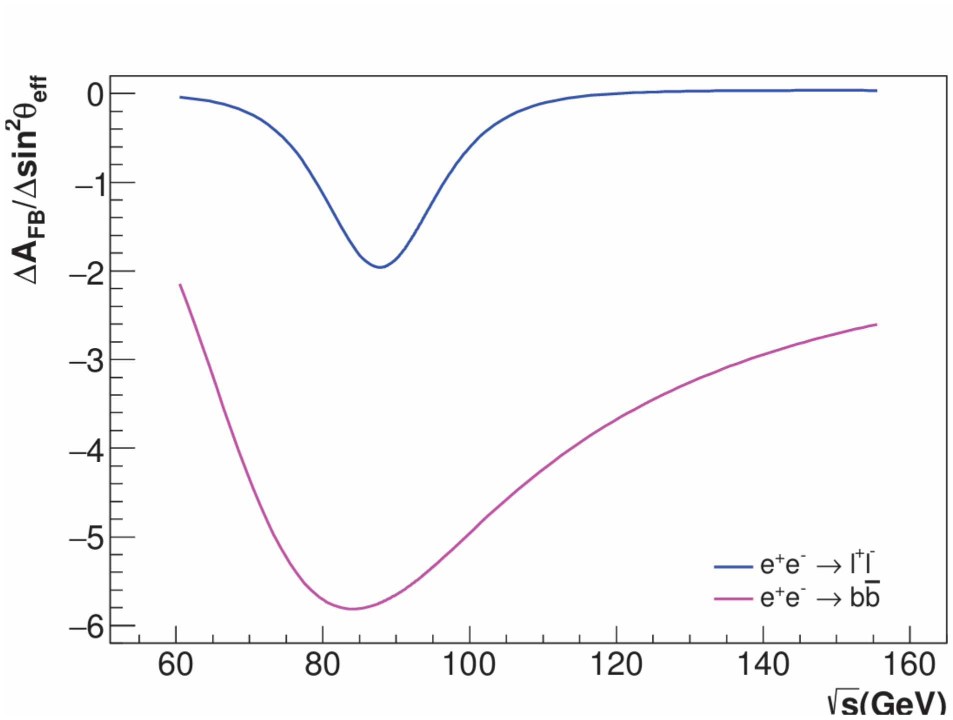
Summary

- $\Delta A_{FB}(\mu)$: ±0.000031 (stat.) ±0.000028 (syst.) @ 1 ab^{-1}
- Orders of magnitude improvement with respect to LEP (±0.0014)
- Comparable with FCC-ee (total uncertainty ±0.00001 @ 60 ab^{-1})

• A 300 keV assumption for the beam energy calibration, compared with 100 keV at FCC-ee.

- This is the first time that $A_{FB}(\mu)$ measurements have been conducted based on the TDR software and detailed systematic error analysis.
- We will conduct more measurements on the properties of Z boson and the final states of Z decays.

Backup



arXiv:2204.09921v2

FIG. 3: The sensitivity of $S = \partial A_{FB}/\partial \sin^2\theta^{\ell}_{\rm eff}$ as a function of $\sqrt{s}$ for $e^+e^- \to Z/\gamma^* \to \ell^+\ell^-$ and $e^+e^- \to Z/\gamma^* \to b\bar{b}$ productions.

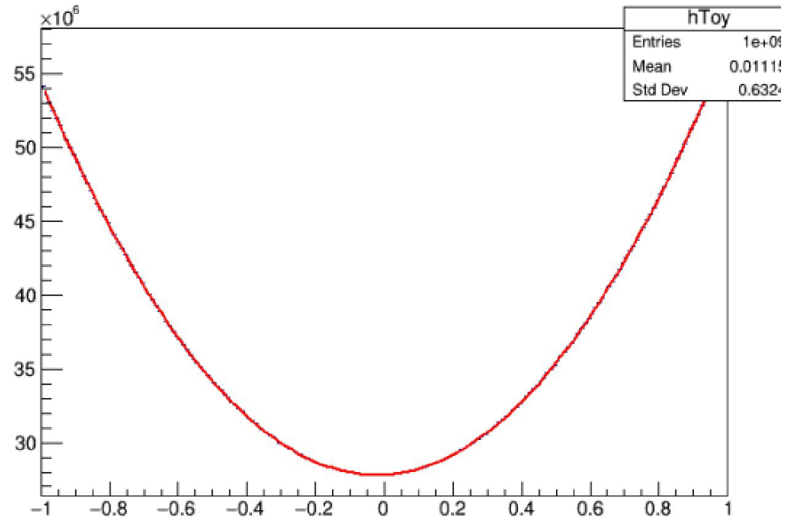
Backup

Fitting the costheta distribution

$$\sigma_F = \int_0^1 \frac{d\sigma}{dcos\theta} dcos\theta \quad \sigma_B = \int_{-1}^0 \frac{d\sigma}{dcos\theta} dcos\theta \quad (9)$$

and $cos\theta$ is the angle of the outgoing fermion measured relative to the incident electron direction. The experiments determine A_{FB} from fits to the angular distribution which can be written as

$$\frac{1}{\sigma} \frac{d\sigma}{dcos\theta} = \frac{3}{8}\left(1 + cos^2\theta\right) + A_{FB}\, cos\theta \qquad (10)$$



- Set costheta function = [0]*(1 + [1]*x + x*x), where [1] = 8/3 * A_FB
- Tested with a toy with 10^9 events, based on the 1M MC sample in analysis
  - Input AFB = 0.016736
  - Fitted AFB = 0.016732±0.0000296
  - Counting AFB = 0.016736 ± 0.0000316
- The results are consistent, however, the statistic error didn't' significantly reduced and it's hard to estimate systematics with fitting method, so it's only a verification

Backup

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

where

$$\sigma_F = \int_0^1 \frac{d\sigma}{dcos\theta} dcos\theta \quad \sigma_B = \int_{-1}^0 \frac{d\sigma}{dcos\theta} dcos\theta \quad (9)$$

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At the Z^0 pole, ignoring the γ and γZ interference terms, we can write

$$A_{FB}^{0,l} = \frac{3}{4} A_e A_l \qquad (11)$$

where the lepton asymmetries are defined by

$$A_l \equiv \frac{2 g_v^l\, g_a^l}{((g_v^l)^2 + (g_a^l)^2)} \qquad (12)$$

with g_v^l and g_a^l being the vector and axial-vector coupling constants.

$$sin^2\theta_w^{eff} = \frac{1}{4}\left(1 - \frac{g_v}{g_a}\right). \qquad (6)$$

$$A_{FB}^{0,l} = \frac{3}{4}(A_l)^2 \propto \left(\frac{1 - 4\sin^2\theta_w^{eff}}{(1 - 4\sin^2\theta_w^{eff})^2 + 1}\right)^2$$

https://doi.org/10.1016/S0920-5632(99)00392-8