Z pole ee→μμ forward-backward asymmetry at CEPC

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Introduction

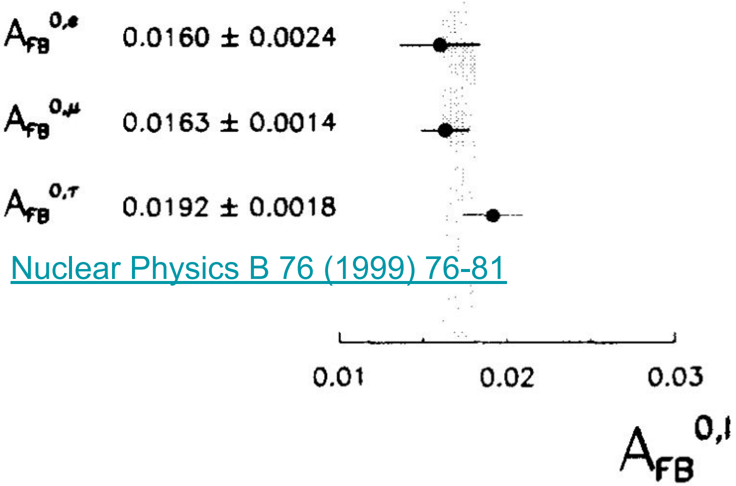
- The ee→μμ channel at Z pole is the simplest channel at CEPC, and can be utilized to verify the basic performance of CEPC software
- The measurement forward-backward asymmetry of ee→Z/γ*→μμ provides a precise verification of the weak mixing angle
- LEP measured $A_{FB}(\mu)$ = 0.0163±0.0014

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

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

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

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



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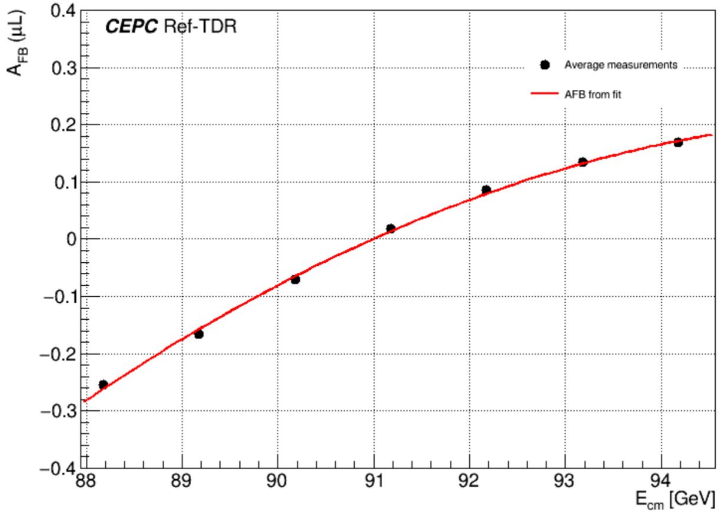
The simulated events

- ee→μμ events are simulated with Whizard+Phythia at LO and Z pole energy.
  - The interference between Z and γ∗has been included
  - The ISR and FSR have been included
- The $A_{FB}(\mu)$ is 0.0161 ± 0.0010 by simulating 1M events
  - Compatible with LEP result at Z pole

The nominal results are with five 0.2M samples
91.0216（Z mass - 1.4 σ)
91.1248 (Z mass - 0.53 σ)
91.1876（Z mass)
91.2504 (Z mass + 0.53 σ)
91.3536 (Z mass + 1.4 σ)

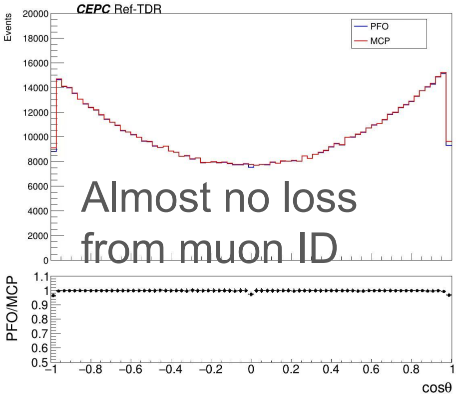
Where σ = 0.13% of Z mass, representing the beam energy spread in accelerator TDR



The event selection and cutflow

- Selections
  - PFOs are required to pass pT > 1 GeV, cos(θ) < 0.99
  - A pair of PFOs passing muon ID (Geliang's XGBoost "Best" WP), and with opposite charge
  - The di-muon mass should be within Z mass ± 10 GeV
  - The |cos(θ)| > 0.05 for μ-, to reduce the confusion of forward / backward events
    - This is cut is only for counting method
- Performance
  - Signal efficiency ~ 88.5% , no mis-identified muons and no charge flipping with 1M events
  - Background contamination: negligible, impact on $A_{FB}(\mu)$ is at the level of 10^{-6}

	$Z \to \mu\mu$	$Z \to \tau\tau$	$Z \to b\bar{b}$	$Z \to ee$
Cross-section	1.2 nb	1.2 nb	6.6 nb	1.2 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%)

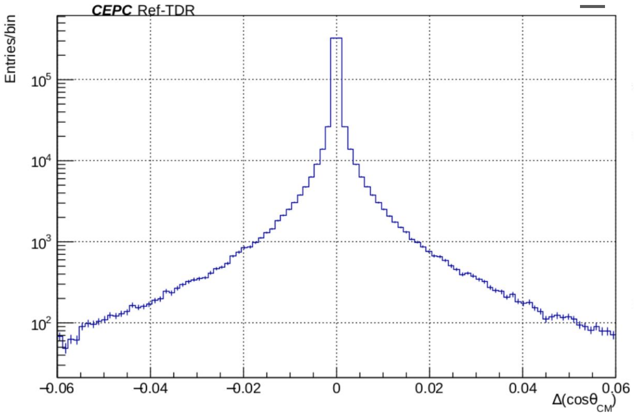


Almost no loss from muon ID

The calculation of $A_{FB}(\mu)$ - counting method

- The forward / backward events are judged by the θ_{CM} of μ-, where θ_{CM} is the θ recomputed at the center-of-mass frame
- $\Delta\theta_{CM}$ is a function of both energy and angular resolution of PFO
- The observed $A_{FB}(\mu)$ with PFO is corrected back to full phase-space

MCP-PFO costheta_CM

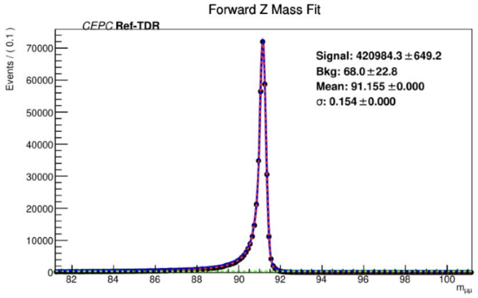


	MC particles wo selections	after selections	Using PFO
Forward events	499136	442727	442723
Backward events	483340	426723	426727
A^{μ}_{FB} or A^{obs}_{FB}	0.0160777	0.0184070	0.0183978
Corrected A^{μ}_{FB}			0.0160697

Discussion of uncertainties

- The statistical uncertainty
  - Nominal: assuming 1.35×10^{9} muon pairs (4×10^{10} Z bosons) expected during the one-month low-luminosity Z running in the first year of ZH operation, the stat un. of $A_{FB}(\mu)$ is 3.1×10^{-5}
  - Assuming 1.38×10^{11} muon pairs (4.1×10^{12} Z bosons) expected during 2 years of Z pole data taking, the statistical uncertainty of $A_{FB}(\mu)$ is 3×10^{-6}
- The systematic uncertainties
  - Energy spread: result assuming gaussian distribution of Ecm with a 0.13% energy spread, compared with the result of no energy spread, this uncertainty is 2×10^{-5}

  - The impact of $\gamma^* \to \mu\mu$: result from counting forward/backward events, compared with fitting $m(\mu\mu)$ (uniform background + DSCB signal), this uncertainty is 1×10^{-5}
  - The acceptance of $|\cos(\theta)| > 0.05$ and other kinematic cuts, and the forward/backward mis-classification: result by perform event selections and counting with MC particles instead of PFO, this uncertainty is 9×10^{-6}
    - Previously double-counted, now only check MCP/PFO diff. once
  - The uncertainty from mis-identification and backgrounds are $< 1 \times 10^{-6}$



Result of counting method

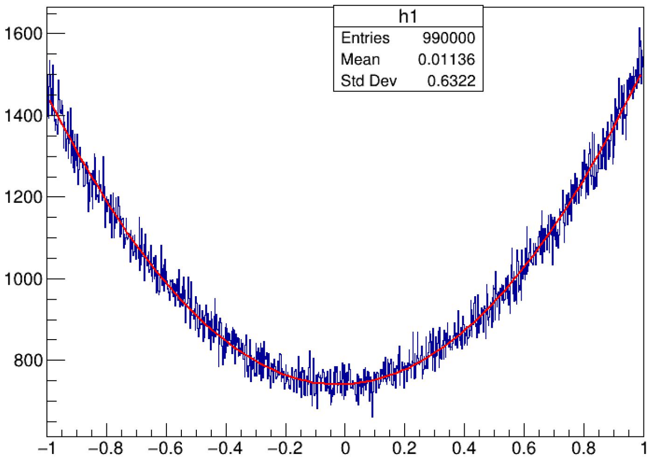
- This analysis measures the forward-backward asymmetry with $Z \rightarrow \mu^+\mu^-$ events at Z pole, $A_{FB}(\mu)$.
- The result of measurement is 0.016078±0.000031 (stat.) ±0.000024 (syst.) based on the dataset corresponding to the one-month low-luminosity Z running in the first year of ZH operation
- The CEPC result improves the precision of LEP result ($A_{FB}(\mu)$ = 0.0163 ±0.0014) by two magnitudes.

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
- Testing a 1M Z pile sample at 91.1876 GeV
  - With MCP, fitted [1] = 0.04463 ± 0.00251, so AFB = 0.01674 ± 0.00094
  - Counting AFB = (503202-486798)/(503202+486798) = 0.01657 ± 0.00100 (consistent)
  - The uncertainty here are the statistical fluctuations of the input 1M sample
  - If we perform bin-by-bin re-weighting on the PFO costheta distribution to MCP, the result is identical

Pros/Cons of fitting costheta on syst. uncertainties

	Cut-based Method	Fitting to CosTheta
Statistical uncertainty (3e-5)	Norm to 1350M muon pairs during 1st year ZH	Same but though fitting CosTheta
Energy Spread (2e-5)	Obtained from AFB vs energy function	Same but though fitting CosTheta
Impact of y* (1e-5)	Obtained from S+B fit on mass	N/A
The acceptance of $\|\cos(\theta)\| > 0.05$ and other kinematic cuts , and the resolution of θ_{CM} (9e-6)	Difference between MCP / PFO with same kinematic cuts	$\|\cos(\theta)\| > 0.05$ is removed now, however, both the MCP and PFO distributions have fluctuations because of the limitation of input sample
Mis-ID & backgrounds (<1e-6)	with / wo mis-ID muons, or with / wo background events	Same but though fitting CosTheta
The reweighting uncertainty	N/A	The non-closure of using re-weighting function from other 50% of sample, however, each half of the sample have fluctuations

Problem: the MCP/PFO difference and the difference from non-closure check are very large, because of the fluctuations of the costheta distribution

The fitting method

- Fitting costheta is a more beautiful method of measuring AFB
    - The interference of y*/Z is automatically considered
    - No |cos(θ)| > 0.05 cut is needed
- However, it needs large sample (same size as 10^9 expected Z->mumu events) to test the non-closure of re-weighting and the MCP/PFO difference
    - Solution: generating toy sample / toy distributions
    - For statistical uncertainty:
        - Generate a **parameterized costheta distribution** with 10^9 events, and fit for the stat-only uncertainty
    - For systematic uncertainty
        - No quick solution yet
        - We can do a very-fast-simulation from generative machine learning (we have one example in ATLAS H-yy), but it needs some development
- Strategy: consider counting as nominal method, and fitting costheta as backup