中国科学技术大学
University of Science and Technology of China

$\sin^2\theta^l_{eff}$ measurement at the CEPC

Final report of PPEStat2023

Zhenyu Zhao (赵振宇)
SA2004068
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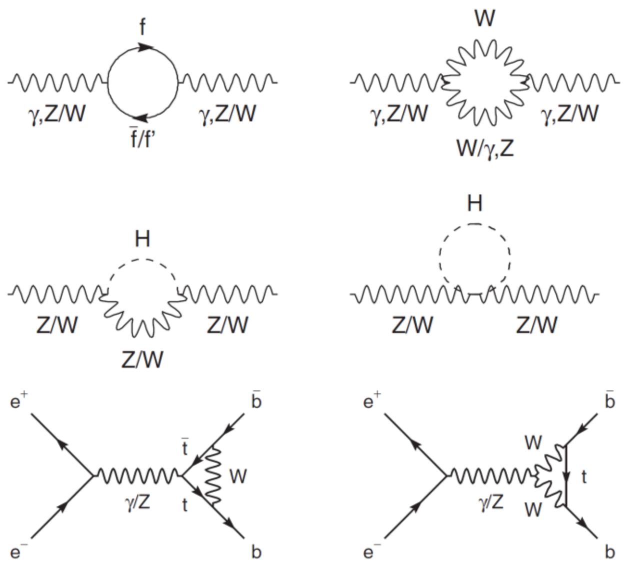
Electroweak Precision measurements and $\sin^2\theta^l_{eff}$

- Key parameter in electroweak sector:
  - $\alpha, G_\mu, M_Z, M_W,$ **$\sin^2\theta_W$**
- Effective weak mixing angle:
  - $\sin^2\theta^l_{eff} = (1 - m_W^2/m_Z^2) * (1 + \Delta\kappa)$
  - $\Delta\kappa$ absorb higher order corrections

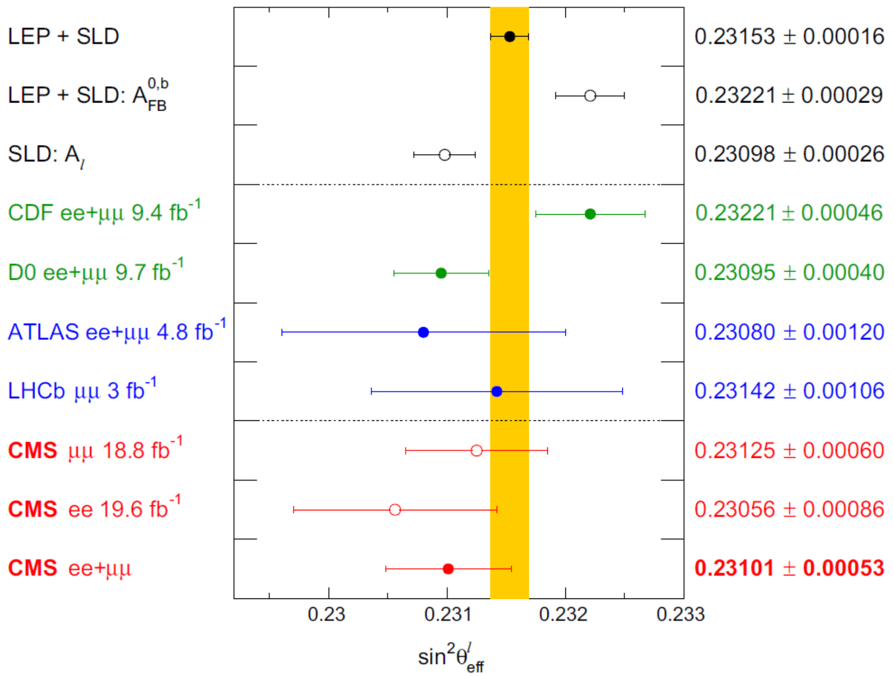
Physical constants	Experimental uncertainty (relative)
Fermi Constant (G_F)	10^{-7}
Mass of Z (m_Z)	10^{-5}
Mass of W (m_W)	10^{-4}
Effective Weak mixing angle ($\sin^2\theta_{eff}$)	10^{-3}



Important in global test and physics search, but has a bad precision.

$sin^2\,\theta_{eff}^{l}$ measurement at lepton/hadron collider

- LEP&SLAC (precision~0.1%)
  - LEP: 0.23188 ± 0.00021
  - SLAC: 0.23098 ± 0.00026
  - Statistical dominant error
- Tevatron
  - 0.23148 ± 0.00033 (DØ+CDF)
  - Statistic & PDF dominant error
- LHC
  - 0.23101 ± 0.00053 (CMS 8TeV)
  - Aiming for ~0.1% in the future
  - PDF, QCD & systematic dominant error



The sensitivity of A_{FB}/A_{LR} to $\sin^2\theta^l_{eff}$

Asymmetry parameter A_f

- For the e^+e^- experiment, we define an asymmetry parameter for convenience:

- $A_f = \frac{2 \cdot g_V^f / g_A^f}{1 + \left(g_V^f / g_A^f\right)^2}$

- Where $g_V^f / g_A^f = 1 - 4 \cdot |Q_f| \cdot \sin^2 \theta_{eff}^f$

- Thus, $A_f = A_f(\sin^2 \theta_{eff}^f)$

	A_f	$\partial A_f / \partial \sin^2 \theta_{eff}^f$
lepton	0.1513	1.80
b quark	0.923	5.59

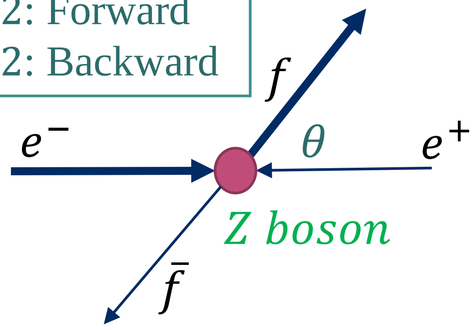
$\sin^2\theta^l_{eff}$ measurement using A_{FB} & A_{LR}

- Fermion pair production $e^+e^- \to f\bar{f}$ at Z pole

$$\frac{d\sigma}{d\cos\theta} \sim (1+\cos^2\theta) + 2A_eA_f\cos\theta$$

- Define: $A_{FB} = \frac{N_F - N_B}{N_F + N_B} = A_{FB}(\sin^2\theta^l_{eff})$
- We have $A^{0,f}_{FB} = \frac{3}{4}A_eA_f$

$\theta < \pi/2$: Forward
$\theta > \pi/2$: Backward



$\sin^2\theta_{eff}^{l}$ measurement using A_{FB} & A_{LR}

- For the collision with a polarized electron beam (polarization=$\mathcal{P}_e$)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} \sim (1 - A_e\mathcal{P}_e)(1+\cos^2\theta) + 2(A_e - \mathcal{P}_e)A_f\cos\theta$$

Define $A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}\frac{1}{|\mathcal{P}_e|}$, where L, R is (event produced by) left hand ($\mathcal{P}_e < 0$) and right hand

Thus, $A_{\mathrm{LR}}^{0} = A_e$

$\sin^2\theta^l_{eff}$ measurement using A_{FB} & A_{LR}

- To estimate the error on $\sin^2\theta^l_{eff}$ measurement, we can define the Sensitivity,

  $$S = \frac{\partial(Obs)}{\partial \sin^2\theta^l_{eff}}$$

- For A^e_{FB} case, $S_{FB} \sim \frac{\partial\left(\frac{3}{4}A_e^2\right)}{\partial \sin^2\theta^l_{eff}} \sim \frac{3}{2}A_e \cdot \frac{\partial A_e}{\partial \sin^2\theta^l_{eff}}$

- For A^e_{LR} case, $S_{LR} \sim \frac{\partial A_e}{\partial \sin^2\theta^l_{eff}} = \frac{2}{3A_e} \cdot S_{FB} \sim 4.4 \cdot S_{FB}$

A_{LR} is more sensitive to the effective weak mixing angle than A_{FB}
(but need polarized electron beam)

Error estimation of A_{FB} measurement

Statistical error of A_{FB}

According to the definition, $\Delta A_{FB} = \sqrt{\frac{1-A_{FB}{}^{2}}{N}}$

1.Tagging efficiency ϵ_{tag}:

$$N \rightarrow N \cdot \epsilon_{tag}$$

2.Charge mis-identification (event level) f:

$$A_{FB}^{obs.} = \frac{\big((1-f)N_F + fN_B\big) - \big((1-f)N_B + fN_F\big)}{N_F + N_B} = (1-2f)A_{FB}^{phy.}$$

$$\Delta A_{FB}^{phy.} = \sqrt{\frac{1-\left(A_{FB}^{obs.}\right)^2}{\epsilon(1-2f)^2 \cdot N}}$$

$$tagging\ power = \epsilon(1-2f)^2$$

Final result of error estimation on $\sin^2\theta_{eff}^{l}$

- CEPC proposed a 2-year running period around the Z pole ($50\mathrm{ab}^{-1}$)
- 1 month data~1.7×10^{11}Z events

collision energy (GeV)	$\delta \sin^2 \theta_{\text{eff}}^{\ell}$ in lepton final state	$\delta \sin^2 \theta_{\text{eff}}^{\ell}$ in b quark final state
70	1.5×10^{-4}	4.1×10^{-5}
75	6.8×10^{-5}	3.3×10^{-5}
92	4.9×10^{-6}	3.5×10^{-6}
105	1.7×10^{-4}	2.7×10^{-5}
115	2.0×10^{-3}	4.8×10^{-5}
130	4.0×10^{-3}	9.8×10^{-5}

TABLE I: The expected statistical uncertainties on $\sin^2 \theta_{\text{eff}}^{\ell}$. Results are estimated according to 1 month data collection.

Error estimation of P_τ measurement

Measurement using P_τ

- Tau is the only final state we've known whose polarization can be measured at CEPC.
- The definition of P_τ is:

$$P_\tau(\cos\theta) = \frac{\mathrm{d}(\sigma_r - \sigma_l)}{\mathrm{d}\cos\theta} \Big/ \frac{\mathrm{d}(\sigma_r + \sigma_l)}{\mathrm{d}\cos\theta}$$

- And P_τ is connected to $\sin^2\theta_{eff}^{f}$ by:

$$P_\tau(\cos\theta) = \frac{A_\tau \cdot (1+\cos^2\theta) + A_e \cdot (2\cos\theta)}{(1+\cos^2\theta) + A_\tau A_\mathrm{e} \cdot (2\cos\theta)}$$

Kinematic parameter

1) $\tau \to \pi\nu$

2) $\tau \to \rho\nu$

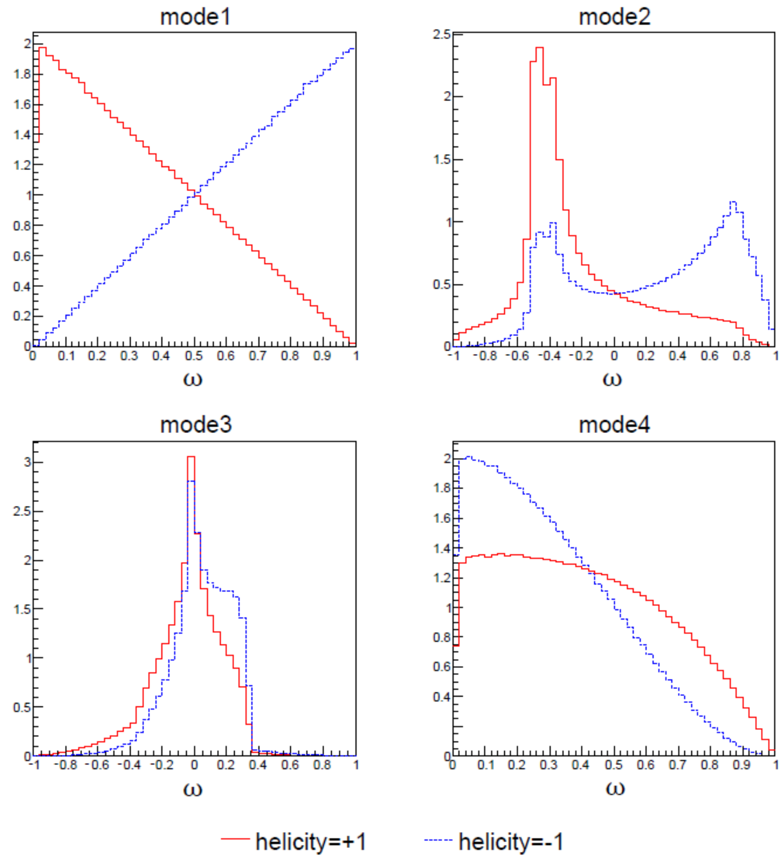
$\rho \to \pi\pi^0$

3) $\tau \to a_1\nu$

$a_1 \to \pi\pi\pi$ or $\pi\pi^0\pi^0$

4) $\tau \to \mu\nu\overline{\nu}$

5) $\tau \to e\nu\overline{\nu}$



- The final fitting result is: $\Delta\sin^2\theta_{eff}^{l} \sim 2.15 \times 10^{-6}$ (using 1 month data).

Conclusion

$sin^2\theta^l_{eff}$ measurement at the CEPC

- A work for prediction. Not many data, just basic statistics estimation.
- A_{FB} and A_{LR} measurement
  - Different sensitivity to $\sin^2\theta^l_{eff}$ (can be estimated roughly by simple calc.)
  - Efficiency and charge mis-identification problems
- P_τ measurement
  - Kinematic spectrum

- Both can provide $\mathcal{O}(10^{-5})$ precision measurement of $\sin^2\theta^f_{eff}$ (except A_{LR})
- Provide energy-running test using A_{FB}.

Thanks

Zhenyu Zhao (赵振宇)
SA2004068