Effective Weak Mixing Angle ($\sin^2\theta^{\ell}_{\text{eff}}$) Measurement @CEPC

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Zhenyu Zhao, Siqi Yang, Manqi Ruan, Yongfeng Zhu, Minghui Liu, Liang Han

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Motivation

Electroweak Precision measurements and $\sin^2\theta^{\ell}_{\text{eff}}$

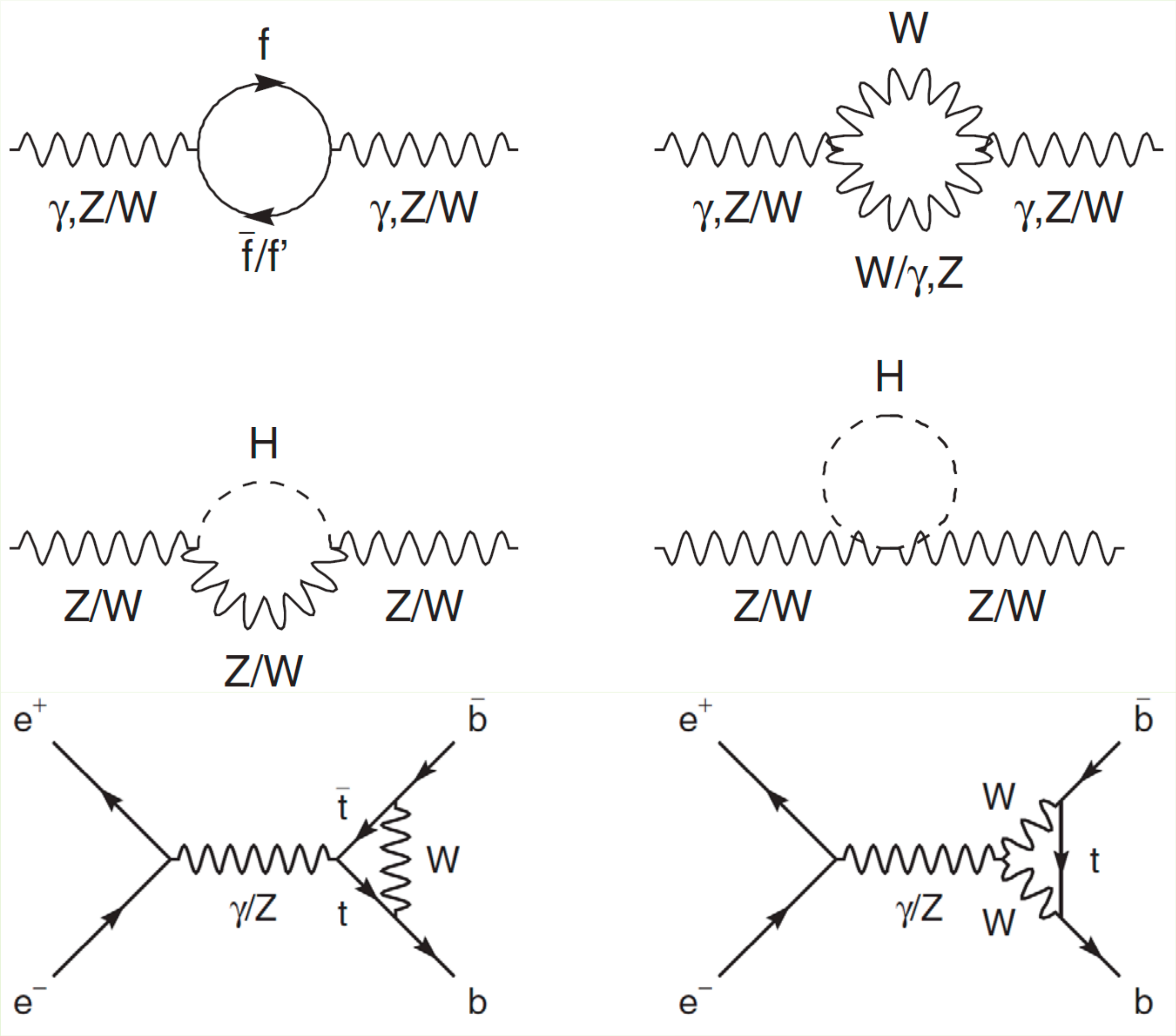
▸ Key parameter in electroweak sector

- α, G_μ, m_Z, m_W, $\mathbf{\sin^2\theta_W}$

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 ($\sin^2\theta^{\ell}_{\text{eff}}$)	10^{-3}

▸ Effective weak mixing angle

- $\sin^2\theta_{\text{eff}} = (1 - m_W^2/m_Z^2)\cdot(1+\Delta\kappa)$
- $\Delta\kappa$ absorb higher order corrections



$\sin^2\theta^{\ell}_{\text{eff}}$ measurement at lepton/hadron collider

▸ LEP&SLAC (precision $\sim 0.1\,\%$)

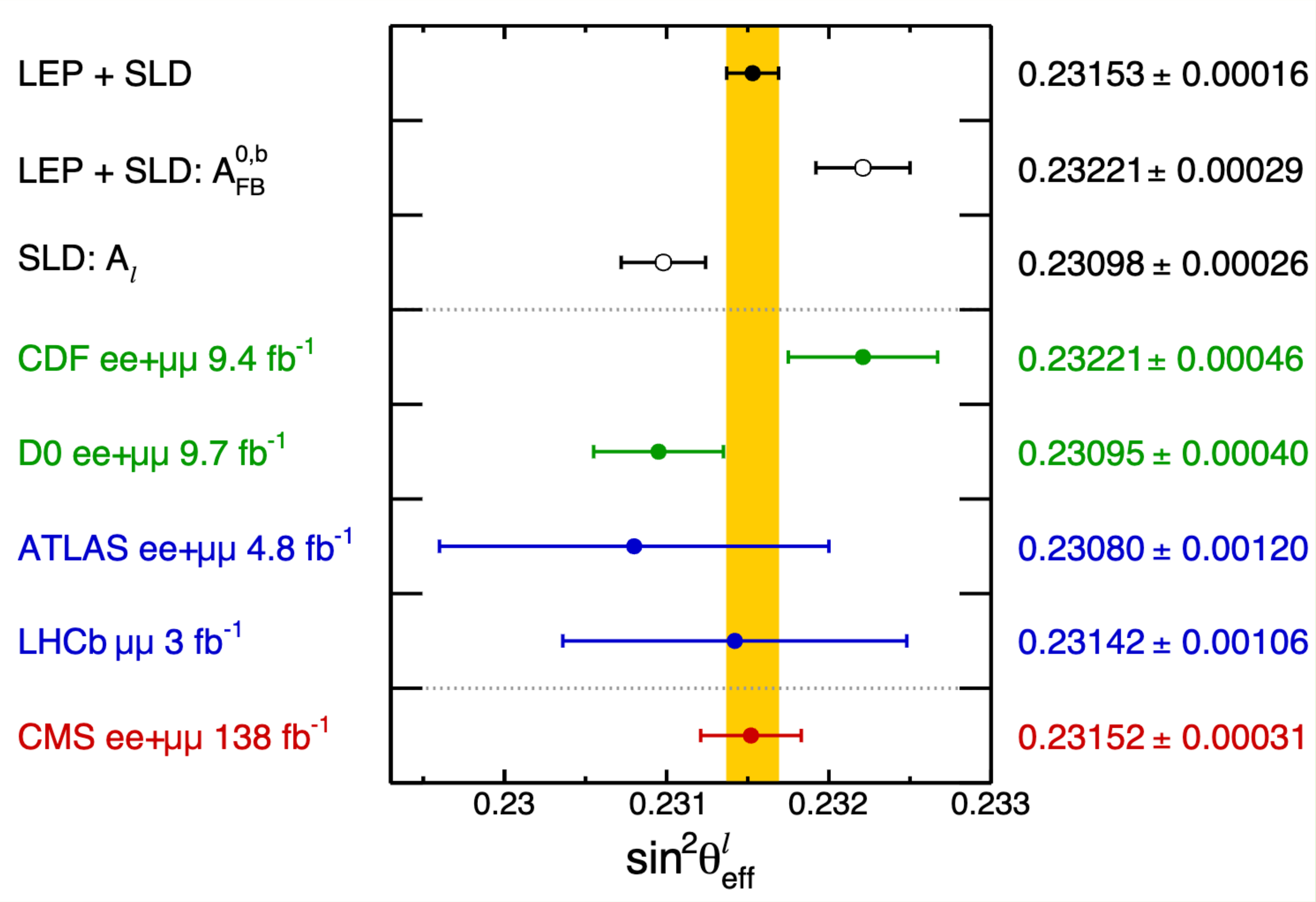
- LEP: 0.23188 ± 0.00021
- SLAC: 0.23098 ± 0.00026
- Statistical dominant

▸ Tevatron

- 0.23148 ± 0.00033 (D0+CDF)
- Statistic & PDF dominant

▸ LHC

- Not limited by the statistics
- PDF, QCD & systematic dominant

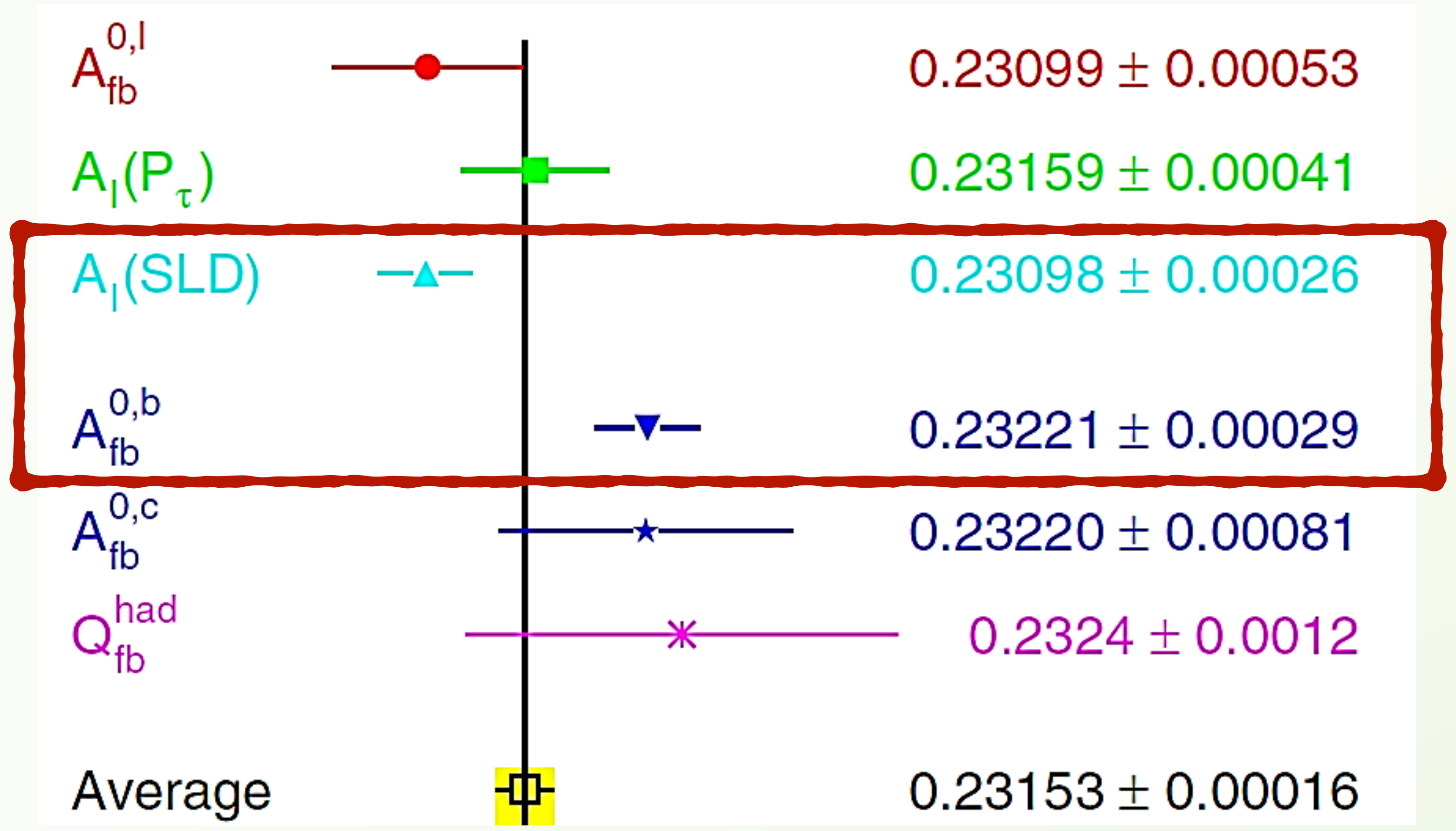


Tevatron: $\sin^2\theta^{\ell}_{\text{eff}} = 0.23148 \pm 0.00027(\text{stat.}) \pm 0.00005(\text{syst.}) \pm \mathbf{0.00018(PDF)}$
CMS 13TeV: $\sin^2\theta^{\ell}_{\text{eff}} = 0.23152 \pm 0.00010(\text{stat.}) \pm \mathbf{0.00015(syst.)} \pm \mathbf{0.00008(theo.)} \pm \mathbf{0.00027(PDF)}$

Measurement of $\sin^2\theta^f_{\text{eff}}$ in the future

▸ Measurement before Higgs discovery

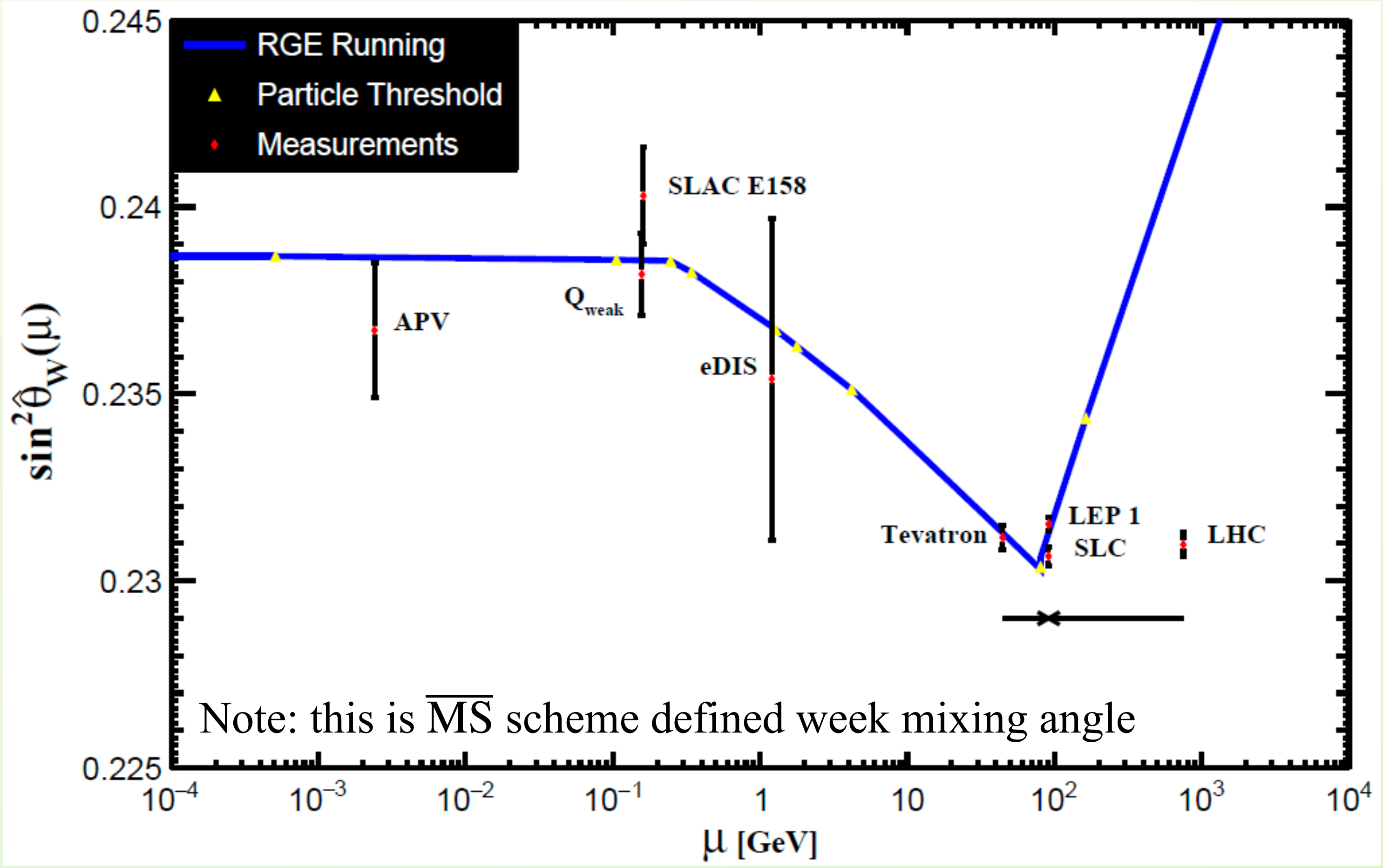
- World average under SM assumption
- $\sim 0.1\,\%$ precision is good enough for Higgs mass prediction



▸ Measurement at the CEPC

- Global test of SM & search for new physics
- From $\mathcal{O}(10^{-4})$ to $\mathcal{O}(10^{-5})$, comparable to current theoretical calculation
- Direct comparison between different progress (leptons, different quark final states)
- Running weak mixing angle with energy scale

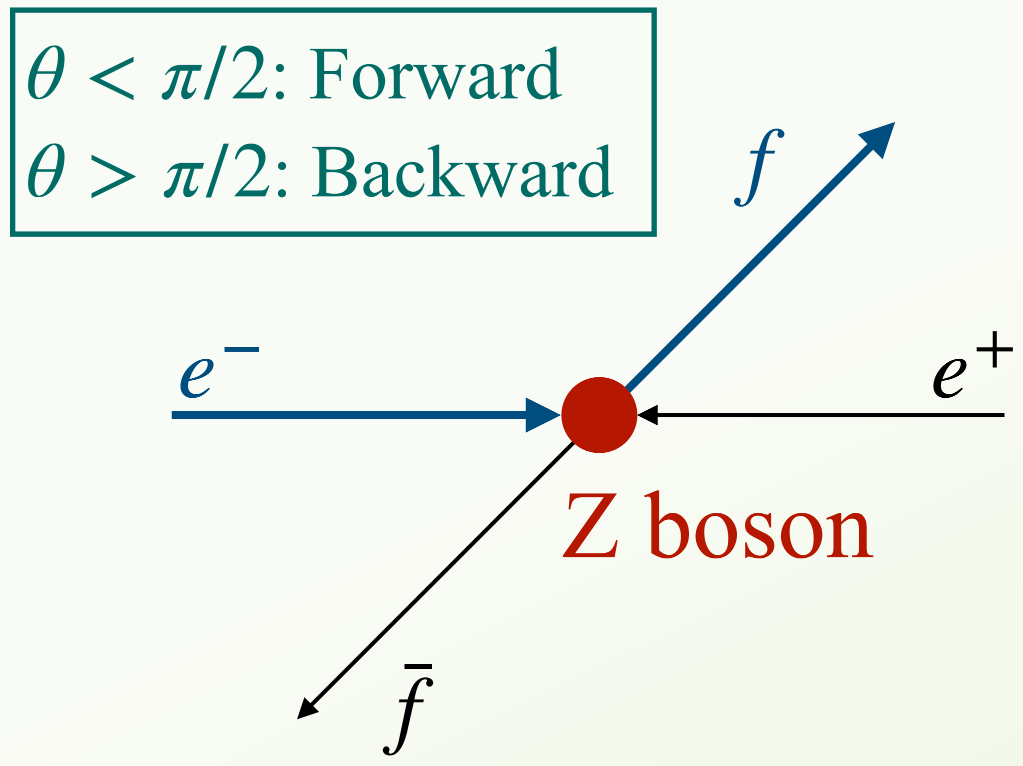
Current experimental uncertainty	Theoretical calculation error
~0.00030	~0.00004



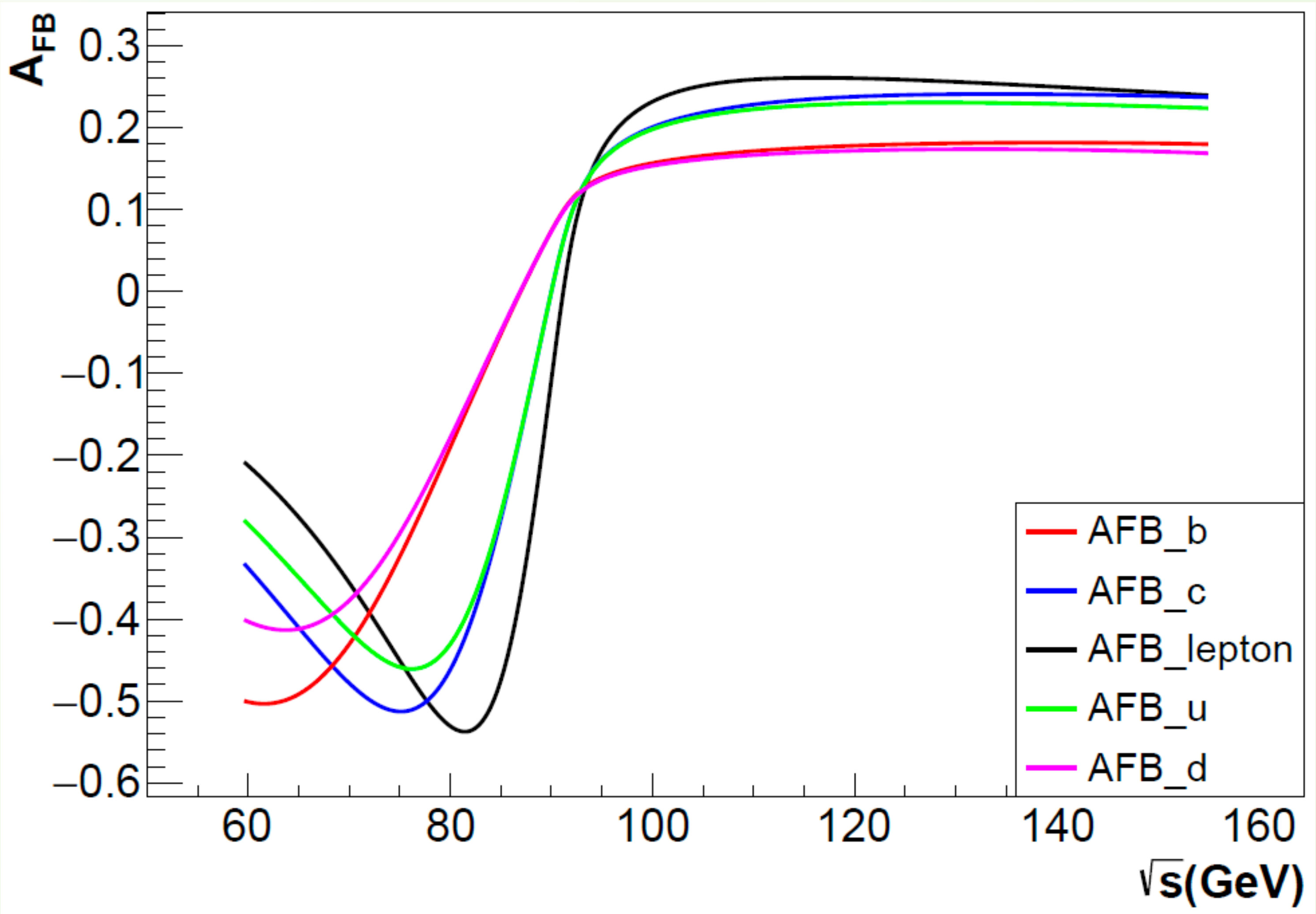
Measurement

$\sin^2\theta^f_{\text{eff}}$ measurement using A_{FB}

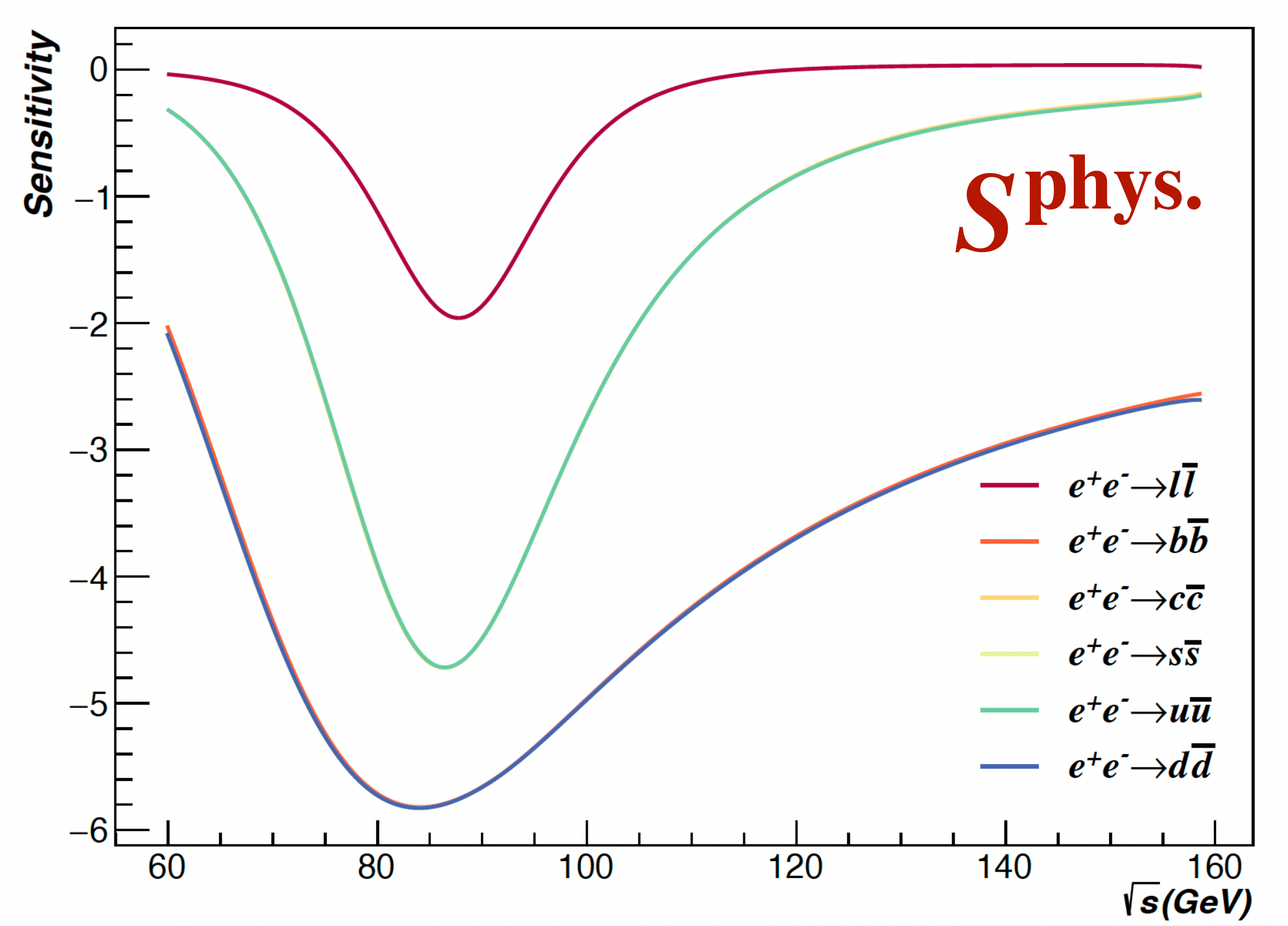
$$A_{FB} = \frac{N_F - N_B}{N_F + N_B} = A_{FB}(\sqrt{s}, \sin^2\theta^f_{\text{eff}})$$



- **Precisely governed by $\sin^2\theta^f_{\text{eff}}$**
- **Flavor dependent**



Sensitivity of A_{FB} to $\sin^2\theta^f_{\text{eff}}$



Sensitivity: $S = S^{\text{phys.}} \cdot Det$

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

$$Det = \frac{1}{1-2f} \cdot \sqrt{\frac{1}{\epsilon_{\text{tagging}}}} = \sqrt{\frac{1}{T_p}}$$

$\epsilon_{\text{tagging}}$	Overall efficiency of events observation
f	Charge mis-identification probability (event-level)

- **Lepton final state: ideal ($\epsilon \sim 100\,\%$, $f \sim 0$), sensitivity loss is negligible**
- **Quark (hadronic) final states:**
  - Flavor tagging and charge determination of a jet are not perfect
  - Tighter selection → low charge mis-identification and small efficiency → but this is beneficial

Jet tagging of different flavors

▸ Heavy quark jets (b/c)

- Easier to tag
- Difference in lifetime and their characteristic decays
- At the LEP, they use b and c final states to measure AFB

▸ For s jet

- Form Kaon, not as efficient as b and c jet
- At the CEPC, a GNN-based machine learning method is developed for jet tagging
- Better kaon identification+more advanced algorithm: CEPC can tag the s jet

▸ For u/d jets

- No characterized hadronization pattern, almost unable to perform effective tagging

Performance of the new jet algorithm

Particle-level jet tagging performance

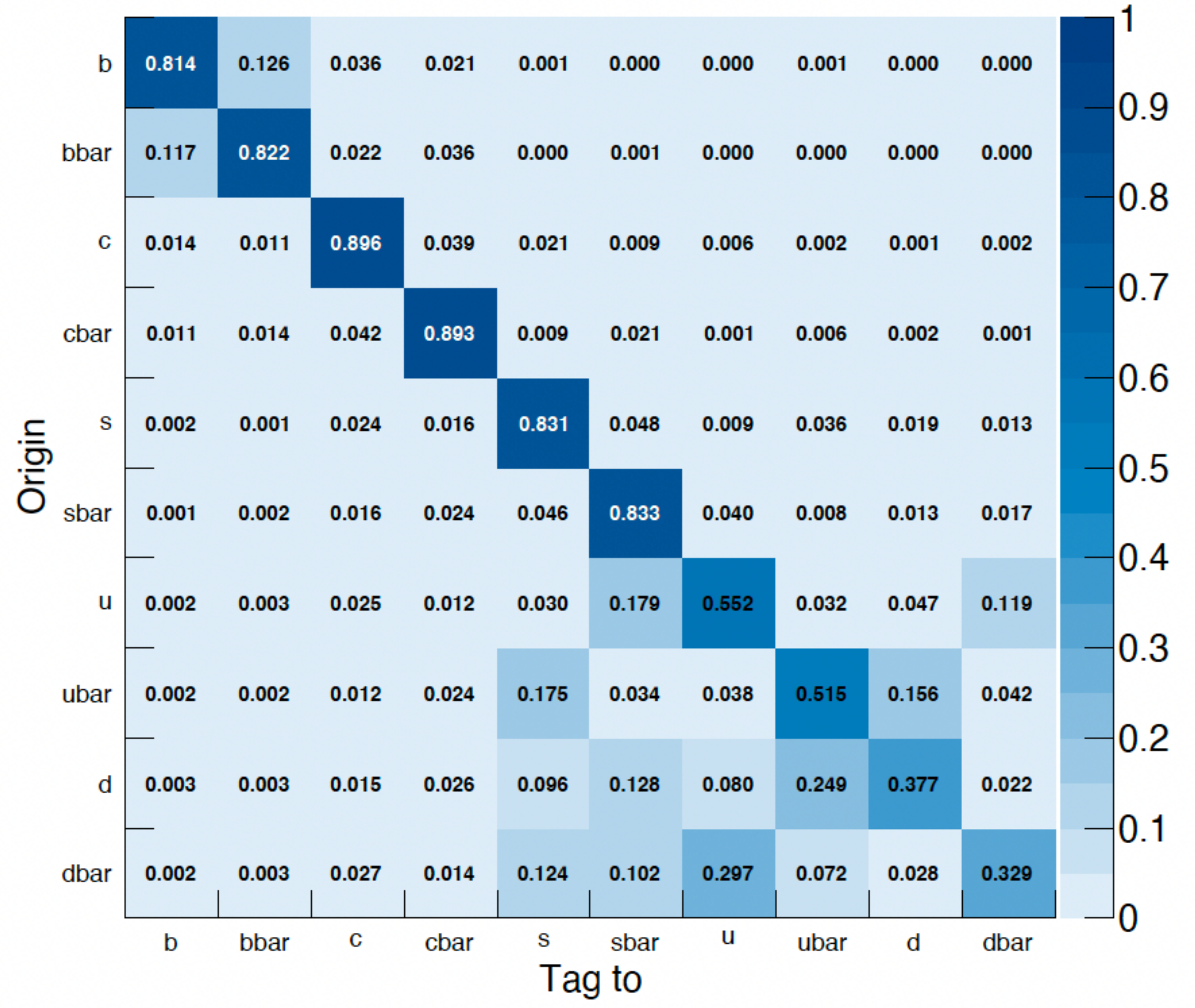


Fig. 3: The updated confusion matrix. Several cuts are added for increasing the sample purity. In this matrix, each row is normalized to 1. The thrown jets are not included in the matrix.

Event-level jet tagging performance

for the AFB measurement

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	$u(1.7\%)/d(1.4\%)$

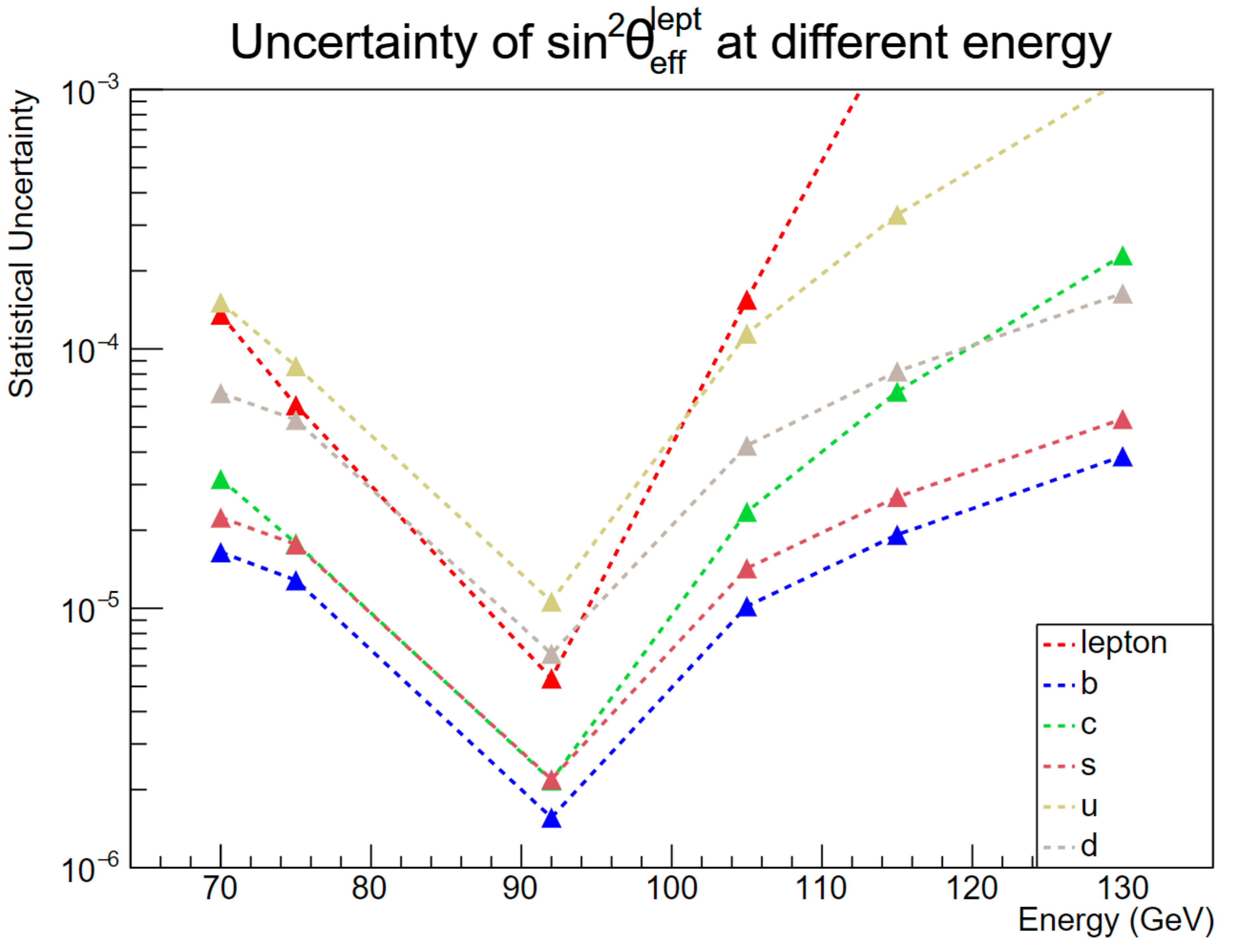
Jet Origin Identification: Phys. Rev. Lett. 132, 221802

Results

Results on the $\sin^2\theta^{\ell}_{\mathrm{eff}}$ measurement

Expected statistical uncertainties on $\sin^2\theta^{\ell}_{\mathrm{eff}}$ measurement
(Using one-month data collection, ~ 4e12/24 Z event at Z pole)

cms energy	lepton	b	c	s
70	1.5×10^{-4}	1.9×10^{-5}	3.4×10^{-5}	3.0×10^{-5}
75	6.8×10^{-5}	1.4×10^{-5}	1.9×10^{-5}	2.4×10^{-5}
92	4.9×10^{-6}	1.8×10^{-6}	2.4×10^{-6}	2.9×10^{-6}
105	1.7×10^{-4}	1.2×10^{-5}	2.6×10^{-5}	1.9×10^{-5}
115	2.0×10^{-3}	2.2×10^{-5}	7.4×10^{-5}	3.6×10^{-5}
130	4.0×10^{-3}	4.4×10^{-5}	2.5×10^{-4}	7.2×10^{-5}



1. High precision measurement at Z pole
2. High precision measurement for different final states
3. Energy running measurement (with b/c/s quark final state)

Systematics

▸ Determination of cms energy

- A great advantage at lepton collider is that, cms energy can be directly determined by beam energy
- At the CEPC, uncertainty of the electron and positron beam energy ~ 100keV
- Negligible in effective weak mixing angle measurement

▸ Uncertainty on efficiency and charge mis-identification

- AFB defined as a ratio — efficiency can be canceled, not contribute to the systematics
- Charge mis-identification — determined with data-driven method, uncertainty is negligible

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

▸ Other systematics (from LEP)

- Electron channel: t-channel & s-t interference (0.00085)
- Lepton channel: QED calculation (0.00006)
- B/c quark channel: QCD calculation (0.00007)

▸ A^s_{FB} measurement — slightly different…

Systematics in the s final state measurement

	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	$b(0.3\%)$
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▸ Background contamination

- $A_{FB}^{\text{obs.}} = P \cdot A_{FB}^{\text{signal}} + \boldsymbol{P}_{\textbf{bkg.}} \cdot \boldsymbol{A}_{\boldsymbol{FB}}^{\textbf{bkg.}}$
- For b/c final states: backgrounds are $c\bar{c}$, $b\bar{b}$, and very small proportion of $s\bar{s}$ — efficiency can be determined by data-driven method
- For s final state: backgrounds are $u\bar{u}$ and $d\bar{d}$, data-driven is not available.

▸ Estimation on the systematics of A_{FB}^{s} measurement

- Change the contamination rate to estimate the systematics
- Equivalence to $\Delta \sin^2 \theta_{\text{eff}}^{\ell} \sim 5 \times 10^{-4}$, comparable to the previous leptonic channel of the LEP's AFB measurement
- Serve as a first high precision s measurement

Conclusion on the $\sin^2\theta^{\ell}_{\text{eff}}$ measurement @CEPC

- **Estimation on $\sin^2\theta^{\ell}_{\text{eff}}$ measurement according to 1 month data collection**

Overall precision at Z pole	Flavor comparison	Precision at off Z pole
$\Delta\sin^2\theta^{\ell}_{\text{eff}} \sim \mathcal{O}(10^{-5})$	$\Delta\sin^2\theta^{\ell}_{\text{eff}} \sim \mathcal{O}(10^{-5})$ Able to make comparison First $s\bar{s}$ final state measurement ($\mathcal{O}(10^{-4})$)	$\Delta\sin^2\theta^{\ell}_{\text{eff}} \sim \mathcal{O}(10^{-5} \sim 10^{-4})$ Energy running test

- **Important in SM global test & new physics search**

Previous work with lepton and b quark:
[Chinese Physics C 47, 123002(2023). doi: 10.1088/1674-1137/acf91f]

Work with new jet tagging:
[European Physical Journal C 85, 993(2025). doi: 10.1140/epjc/s10052-025-14689-7]

Thanks