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

CEPC work meeting report

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

2025.8.27

Motivation

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

▶ Key parameter in electroweak sector

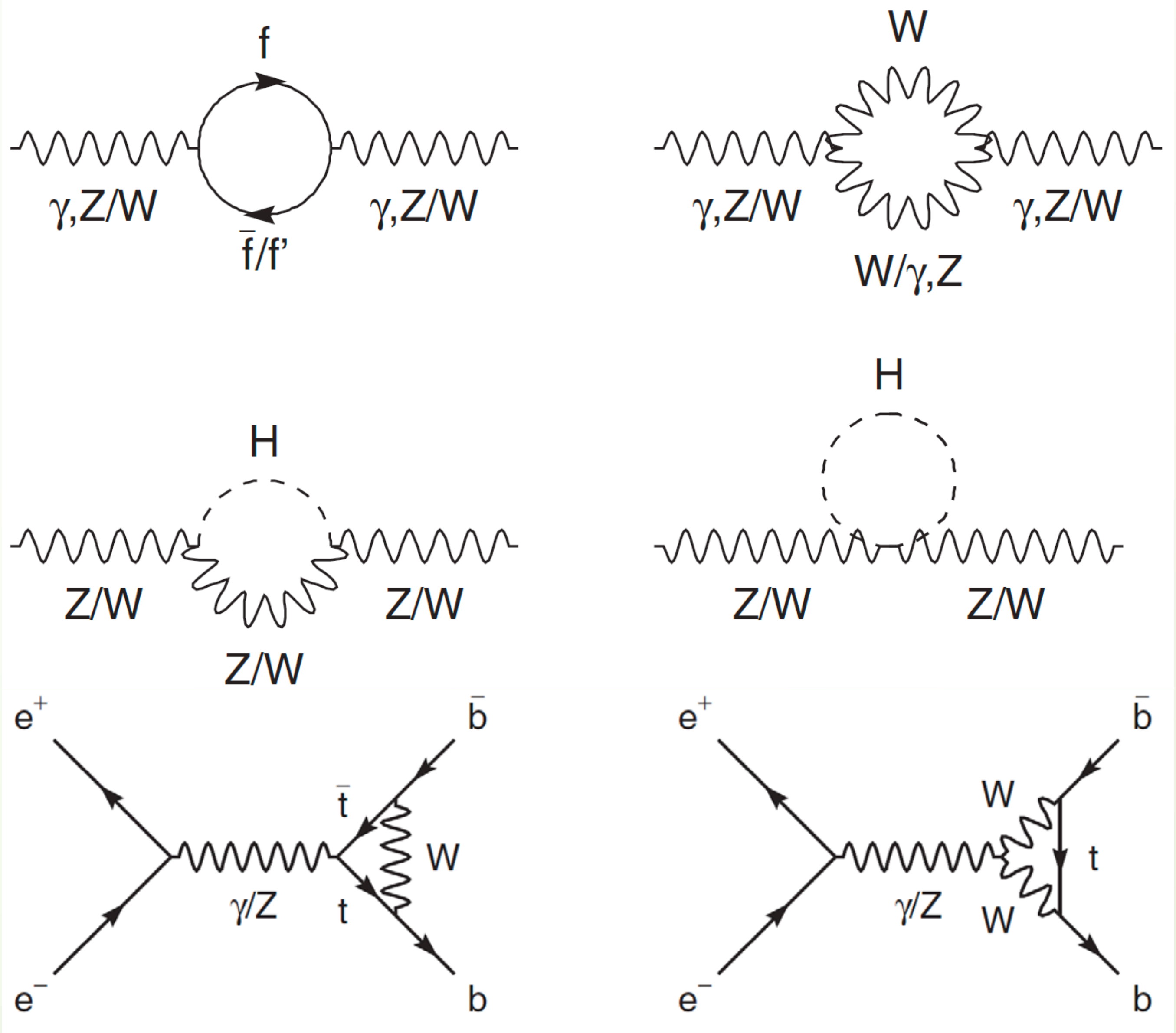
- $\alpha, G_\mu, m_Z, m_W, \boldsymbol{\sin^2\theta_W}, \ldots$

▶ Related to m_W, m_Z in tree level by

- $\sin^2\theta_W = 1 - \dfrac{m_W^2}{m_Z^2}$

▶ Effective weak mixing angle

- $\sin^2\theta_{\rm eff} = (1 - m_W^2/m_Z^2)\cdot(1+\Delta\kappa)$
- $\Delta\kappa$ absorb higher order corrections
- Measurement of $\sin^2\theta^{\ell}_{\rm eff}$ is important in both SM validation and new physics search



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

▸ LEP&SLAC (precision $\sim 0.1\,\%$)

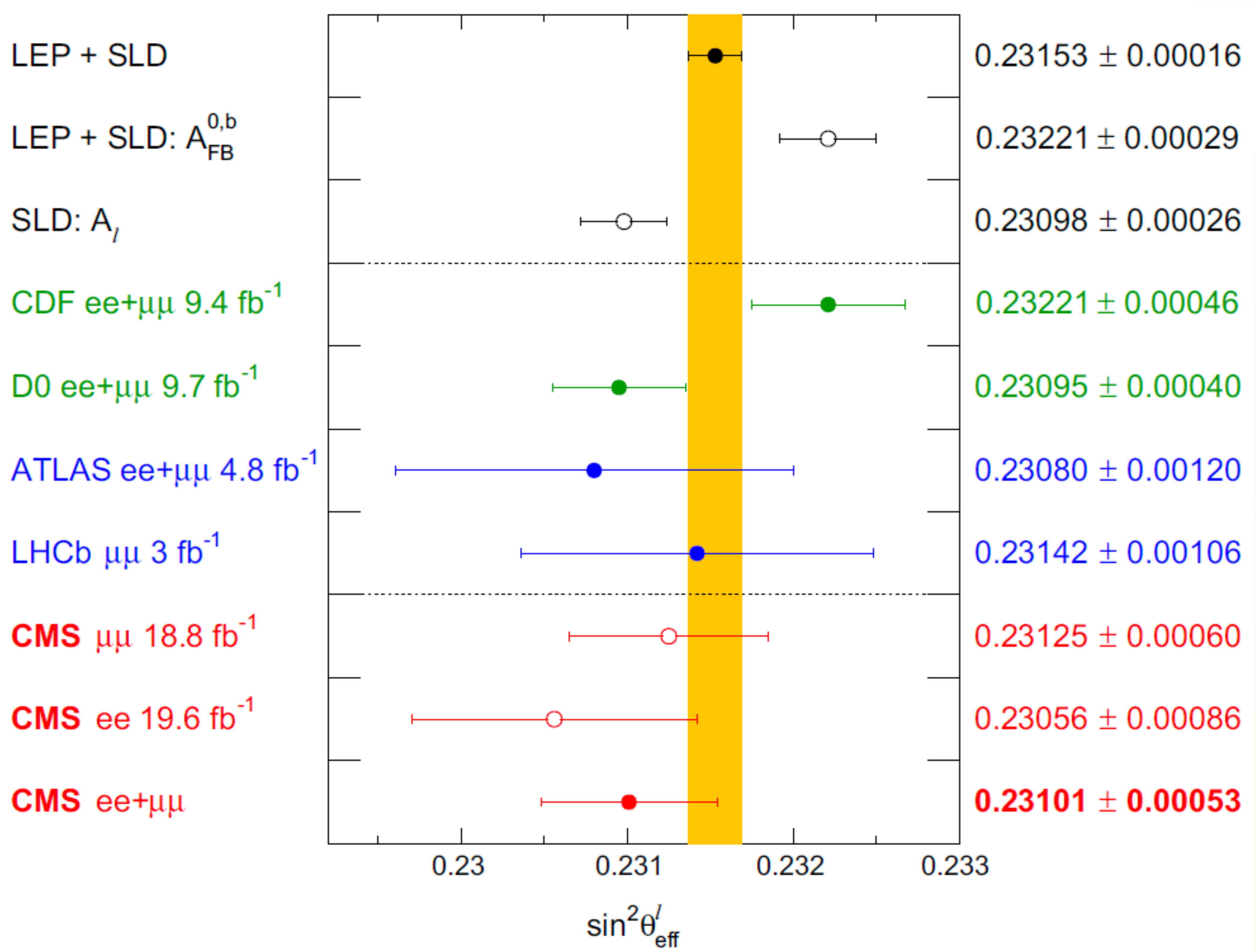
- LEP: 0.23188 ± 0.00021
- SLAC: 0.23098 ± 0.00026
- Statistical dominant

▸ Tevatron

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

▸ LHC

- PDF, QCD & systematic dominant
- Aiming for ~ 0.00010 in the future



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 8TeV: $\sin^2\theta^{\ell}_{\text{eff}} = 0.23101 \pm 0.00036(\text{stat.}) \pm \mathbf{0.00018(syst.)} \pm \mathbf{0.00016(theo.)} \pm \mathbf{0.00031(PDF)}$

Measurement of $\sin^2\theta_{\text{eff}}^{\ell}$ in the future

▸ Measurement before Higgs discovery

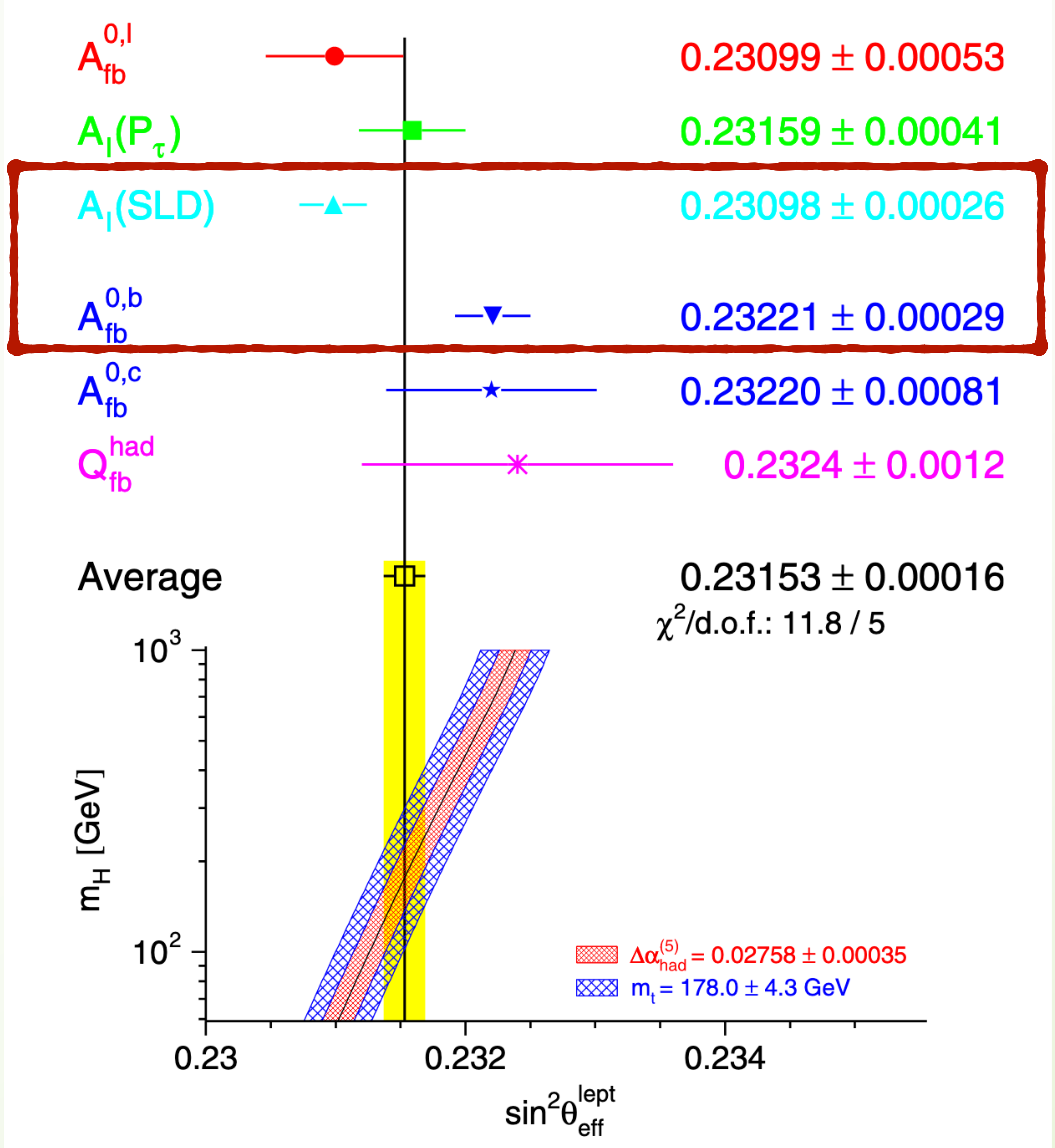
- World average under SM assumption
- $\sim 0.1\ \%$ precision good enough for Higgs mass prediction

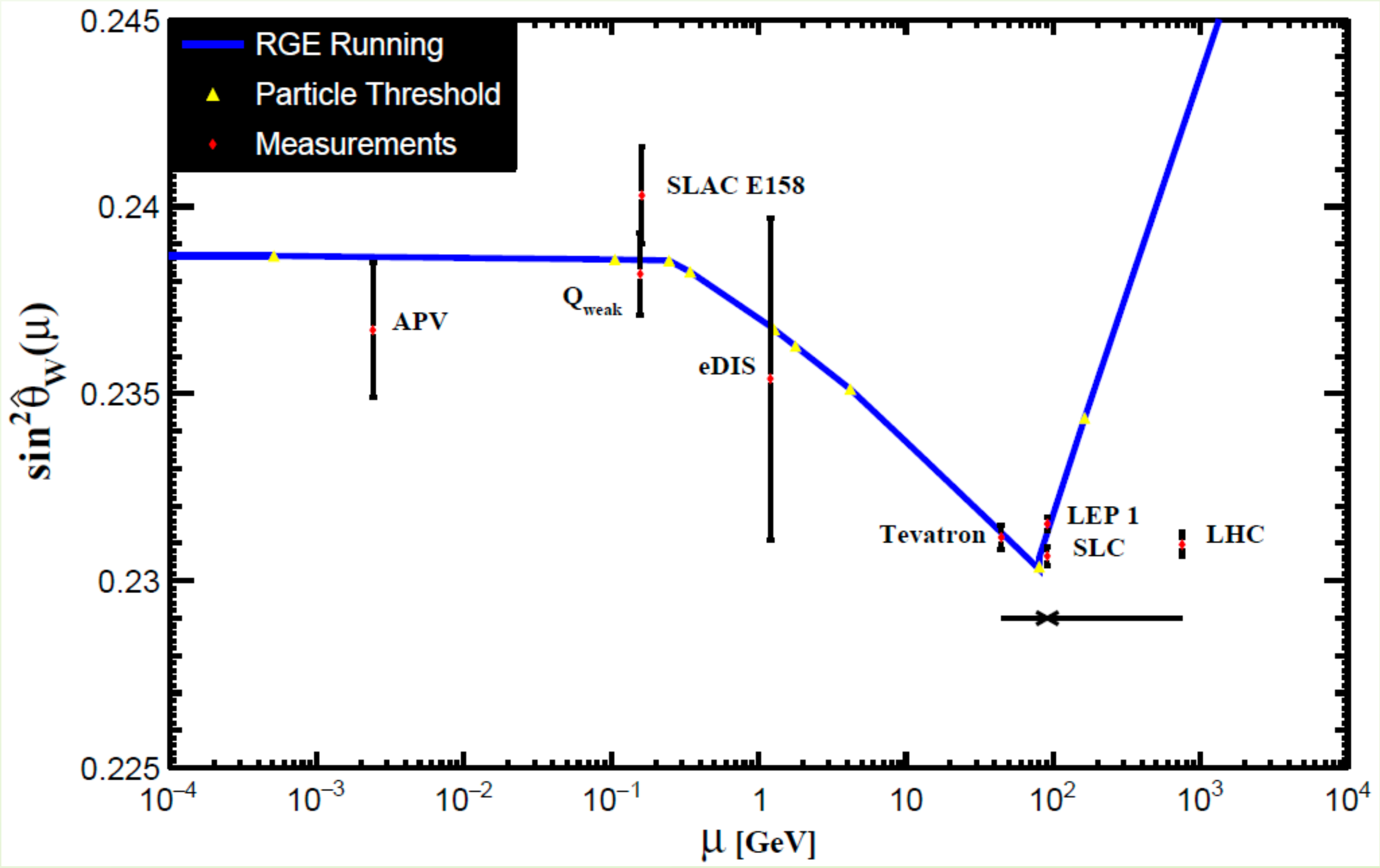
▸ Measurement in the future

- Higgs mass ~125GeV, we can make fully global test of SM & search for new physics
  - Flavor comparison (lepton, different quark flavors…)
  - Experimental uncertainty should be comparable to theoretical uncertainty ($\mathcal{O}(10^{-5})$)

Current experimental uncertainty	Theoretical calculation error
~0.00030	~0.00004

  - Energy running of $\sin^2\theta_{\text{eff}}^{\ell}$
- This kind of EW precision measurements rely on lepton collider like CEPC



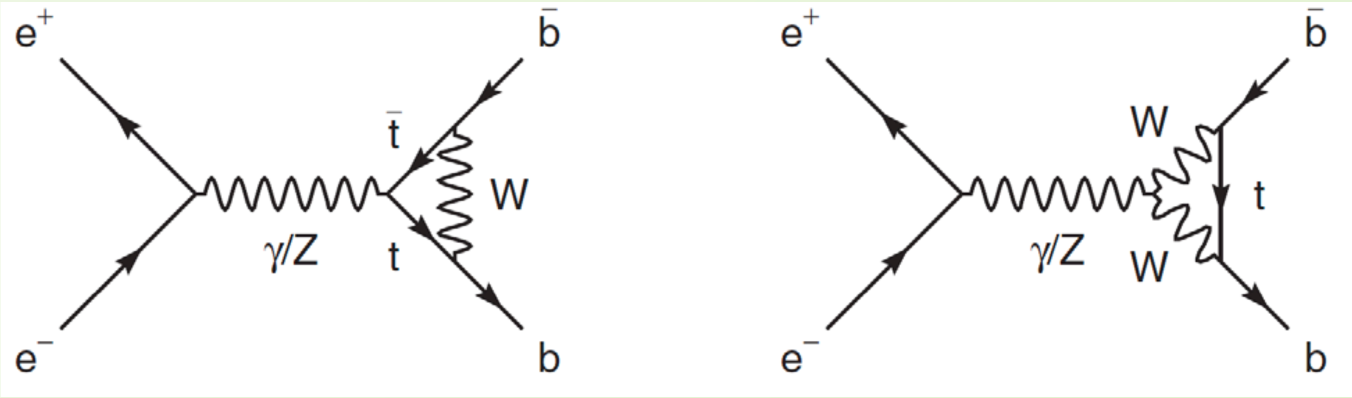


Note: this is $\bar{MS}$ scheme defined weak mixing angle

Measurement of $\sin^2\theta^{\ell}_{\text{eff}}$ in sense of new physics search

▸ For a $f\bar{f} \to f\bar{f}$ process, new physics possibly come from:

- **The propagator**
  - ZPrime or other any new particles, modification of Z self energy, …
  - In 1990s, Peskin introduces the oblique parameters S, T, U to parameterize propagator related new physics in a model-independent way
    - $\sin^2\theta^{\ell}_{\text{eff}}$ and m_W are most sensitive to this parameterization.
  - In 2010s, theorist make complete 2-loop and partial 3-loop EW correction calculation
    - $\delta m_W \sim 6\text{MeV}, \delta\sin^2\theta^{\ell}_{\text{eff}} \sim 0.00004$
- **The vertex**
  - Most interesting: Zbb vertex, as b mass is large enough to form t-W loop



$\sin^2\theta_{\text{eff}}^{\ell}$ measurement at the CEPC

▸ High precision measurement

- Final precision expected to be $\Delta\sin^2\theta_{\text{eff}}^{\ell} \sim \mathcal{O}(10^{-5})$

▸ Independent measurement via different final states

- Lepton channel, b, c, light ($\Delta\sin^2\theta_{\text{eff}}^{\ell} \sim \mathcal{O}(10^{-5})$)

▸ Running weak mixing angle with energy scale ($\sin^2\theta_W(\mu)$)

- Make measurement at energy scale high than Z pole for the first time

▸ CEPC advantage

- As a lepton collider, CEPC has very small systematics. (No PDF, cms energy comes from beam energy directly, …)
- Hugh statistics — 4 trillion Z in two years (Z period, 100ab^{-1})

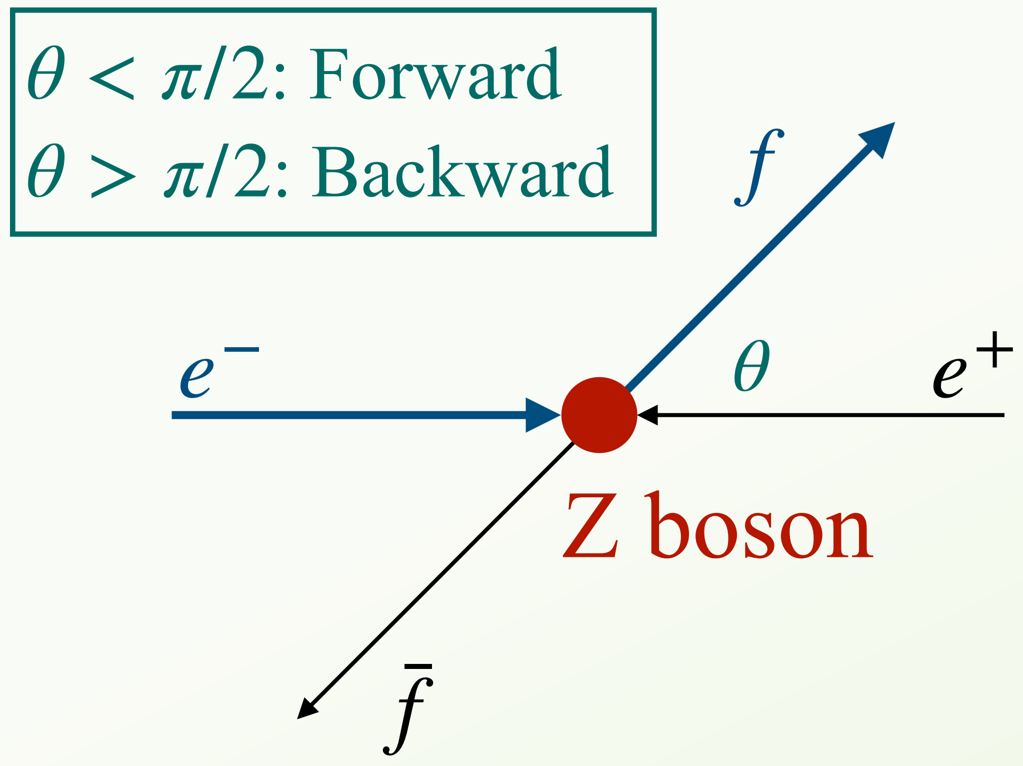
Measurement

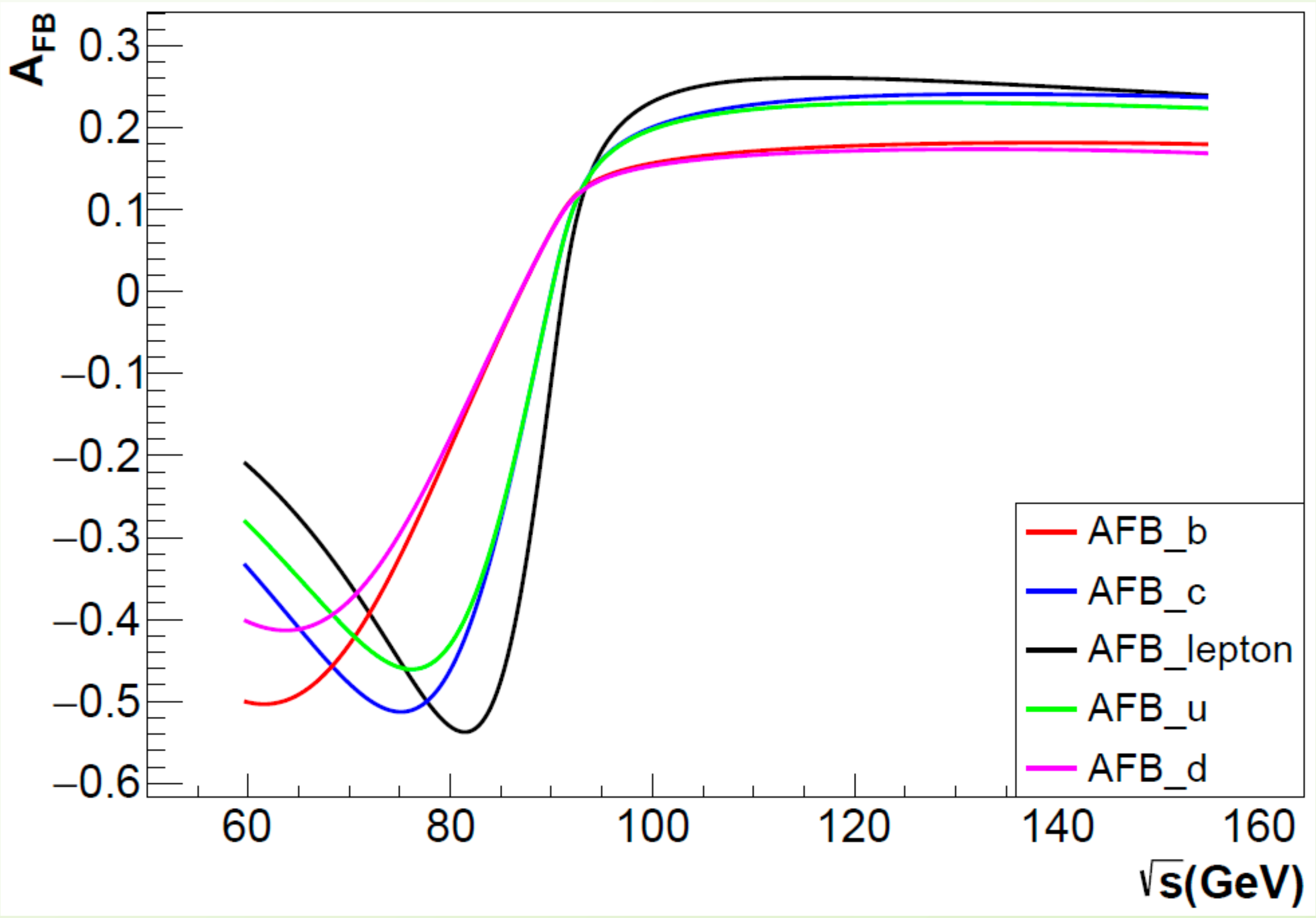
$\sin^2\theta^f_{\text{eff}}$ measurement using A_{FB}

▸ AFB (Forward-Backward Asymmetry)

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

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



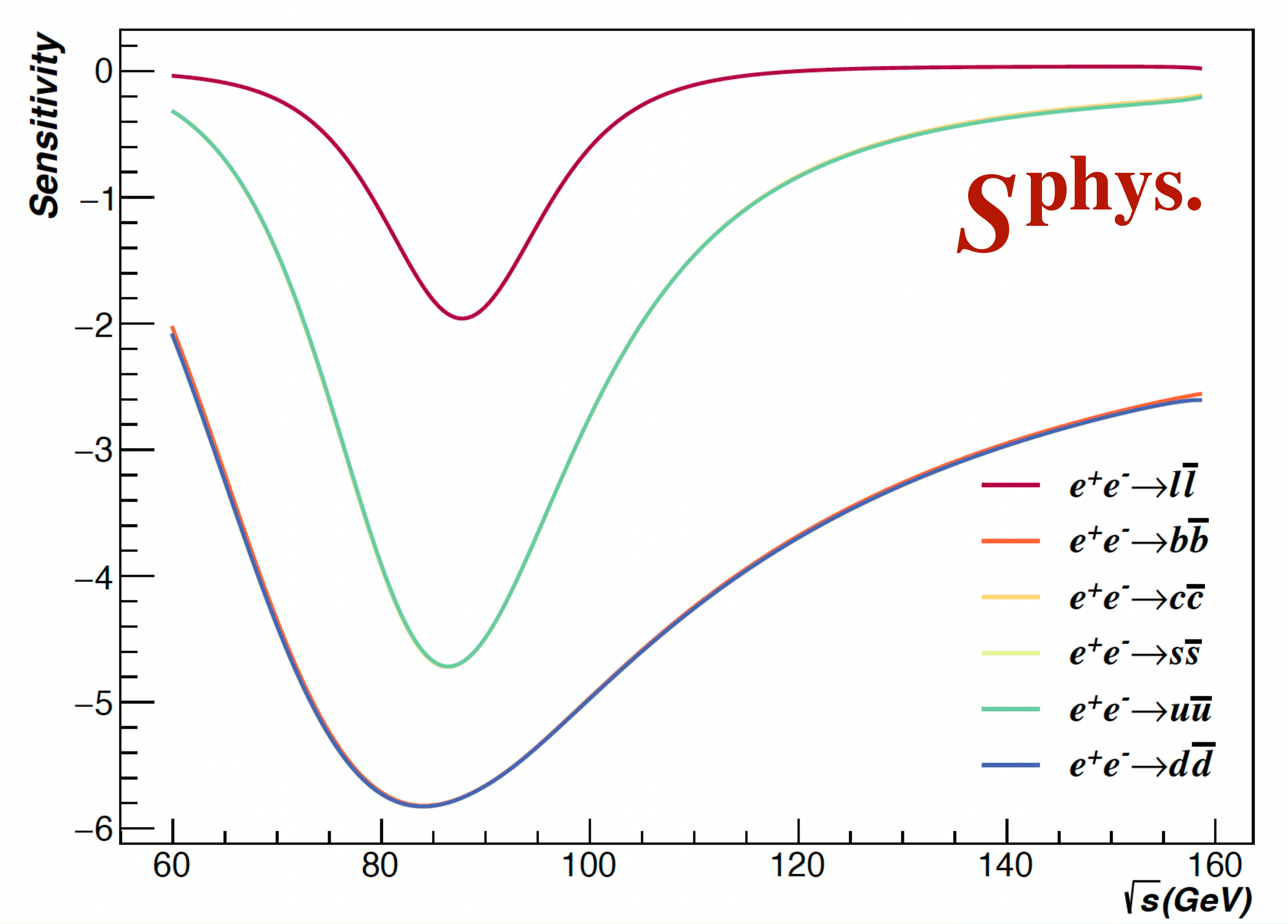


▸ Other observables (not including)

- In SLC, use some polarization-related observables
- In LEP, tau final state polarization was also measured

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

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



$$S^{\rm phys.} = \frac{\partial A^{\rm phys.}_{FB}}{\partial \sin^2\theta_{\rm eff}}$$

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

$\epsilon_{\rm tagging}$	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
- Different 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

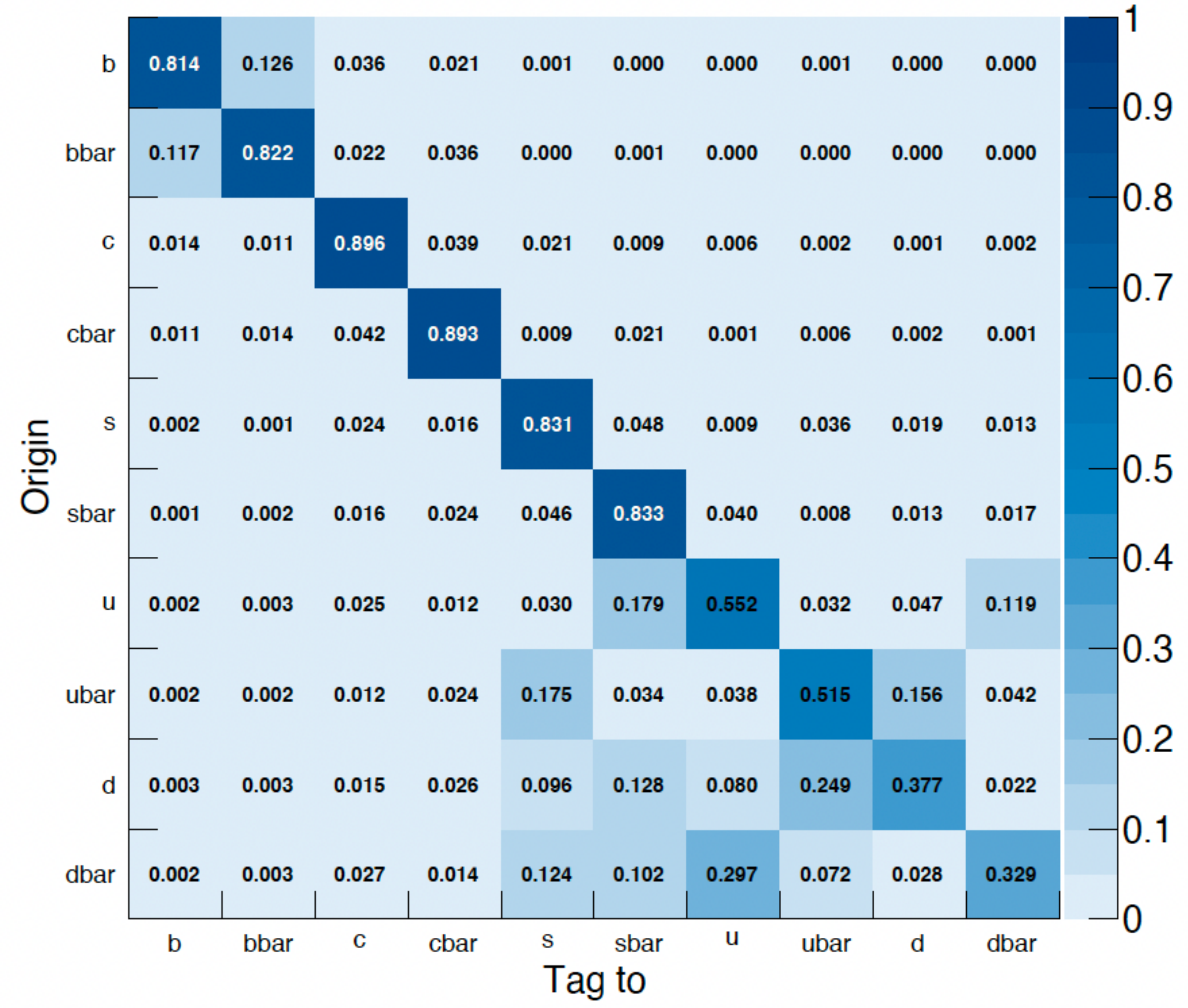


Fig. 3: The updated confusion matrix. Several cuts are added for increasing the sample purity. In this matrix, each row is normalized to 1. The thrown jets are not included in the matrix.

Particle-level jet tagging performance

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

Event-level jet tagging performance

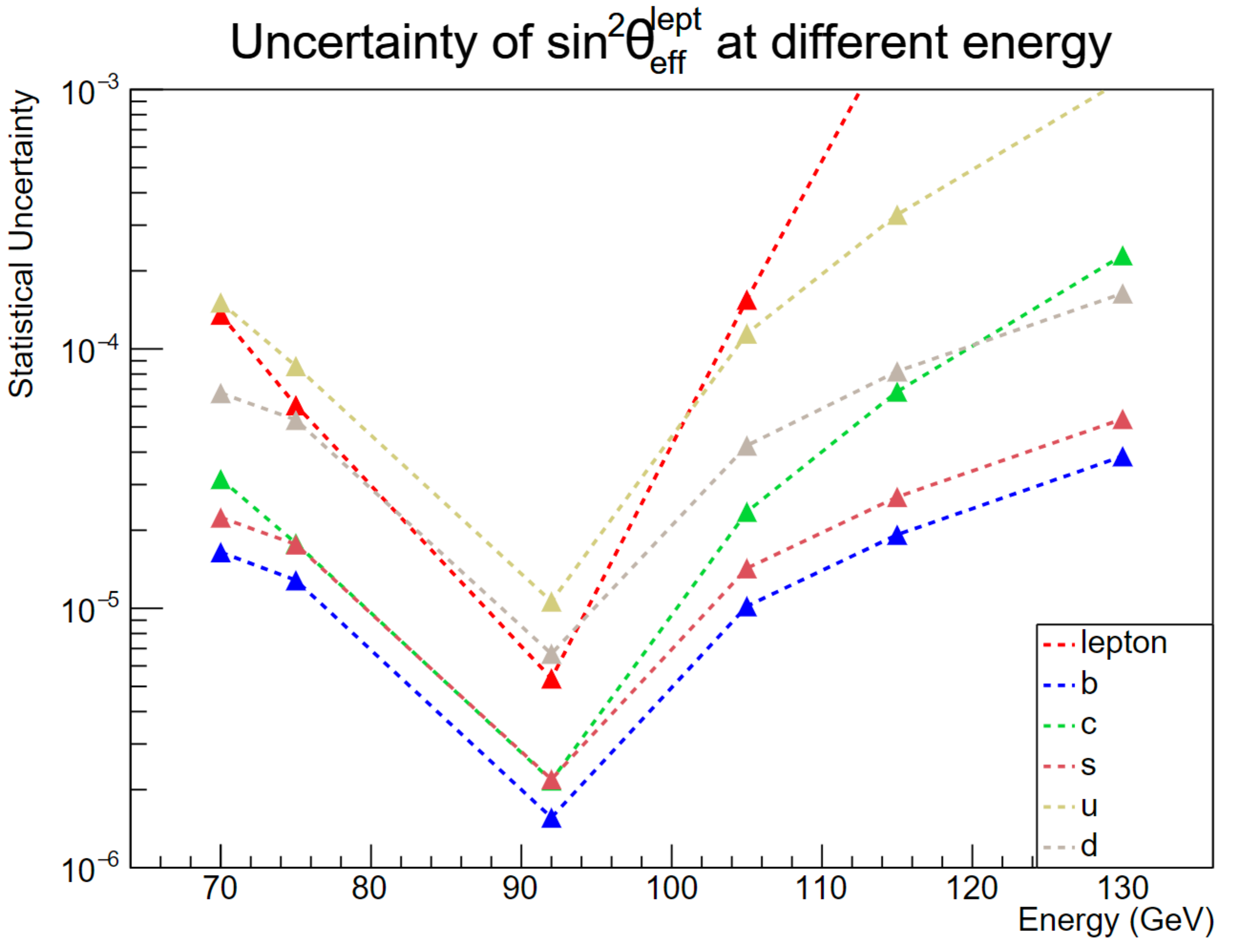
for the AFB measurement

Results

Results on the $\sin^2\theta_{\text{eff}}^{\ell}$ measurement

Expected statistical uncertainties on $\sin^2\theta_{\text{eff}}^{\ell}$ 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 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 negligilble

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

▸ 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_{FB}^{s} 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	$b(0.3\%)$
$s\bar{s}$	96.7%	0.148	0.030	0.130	$u(1.7\%)/d(1.4\%)$

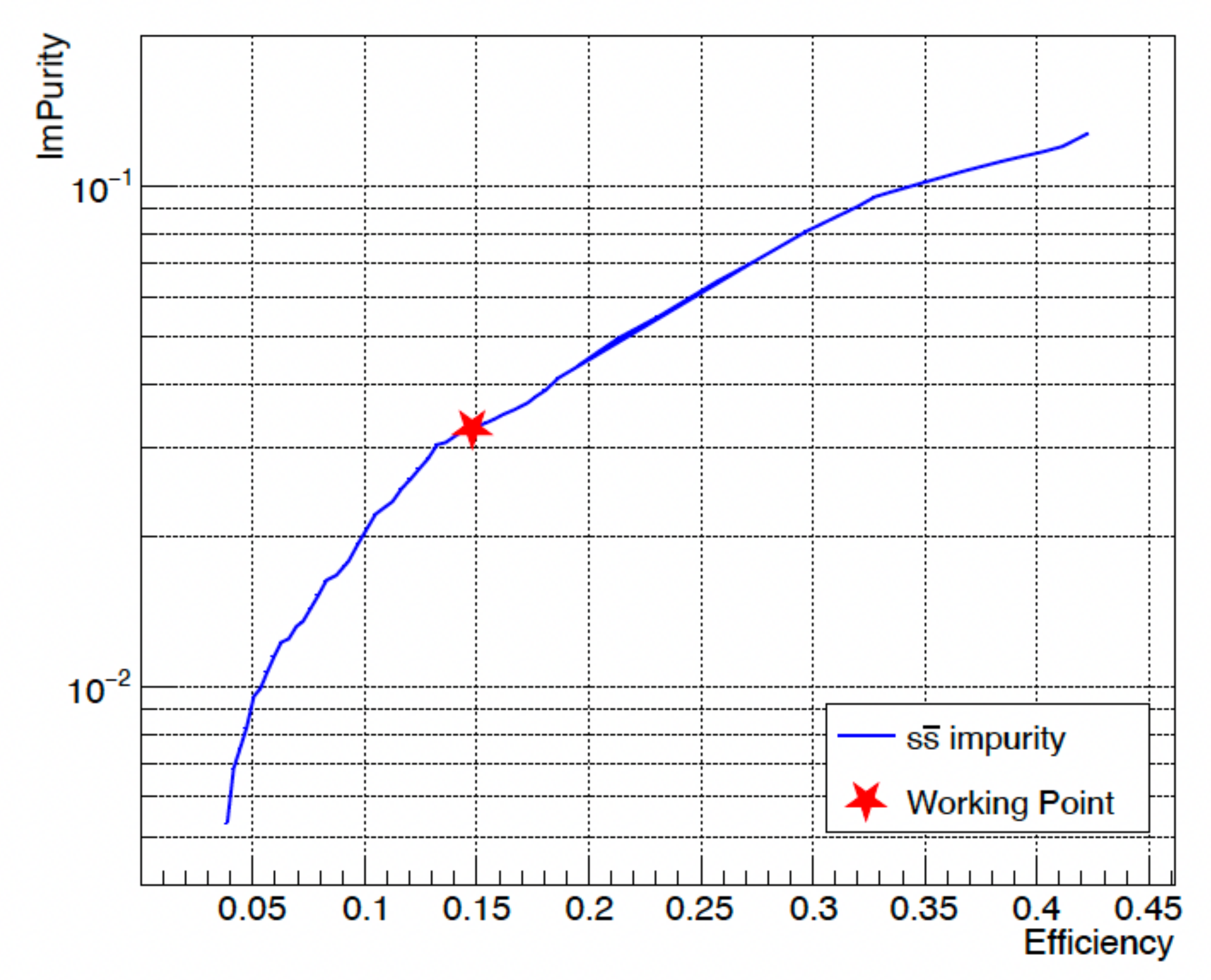
▸ Background contamination

- $A_{FB}^{\text{obs.}} = P \cdot A_{FB}^{\text{signal}} + \boldsymbol{P_{\text{bkg.}}} \cdot \boldsymbol{A_{FB}^{\text{bkg.}}}$
- 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

- 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

▸ Robustness and effectiveness of the Working Point



Conclusion on the $\sin^2\theta_{\text{eff}}^{\ell}$ measurement @CPEC

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

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

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

Previous work with lepton and b quark: https://iopscience.iop.org/article/10.1088/1674-1137/acf91f
Work with new jet tagging: under revision

Thanks