Effective weak mixing angle($\sin^2\theta_{eff}^{f}$) measurement at the CEPC

And update using ***Jet Origin Identification***

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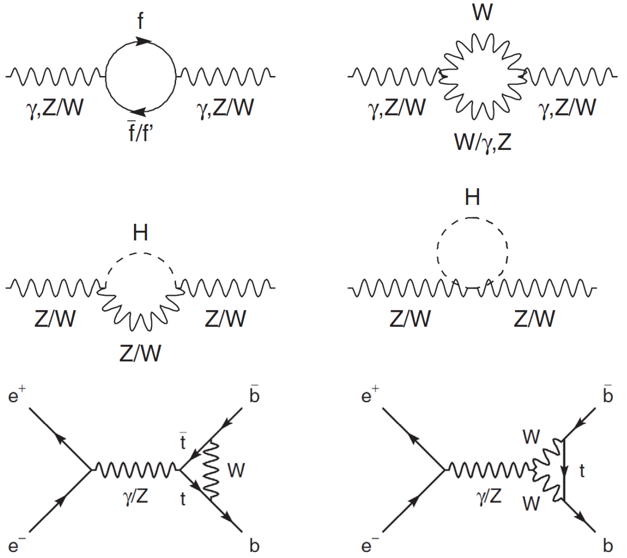
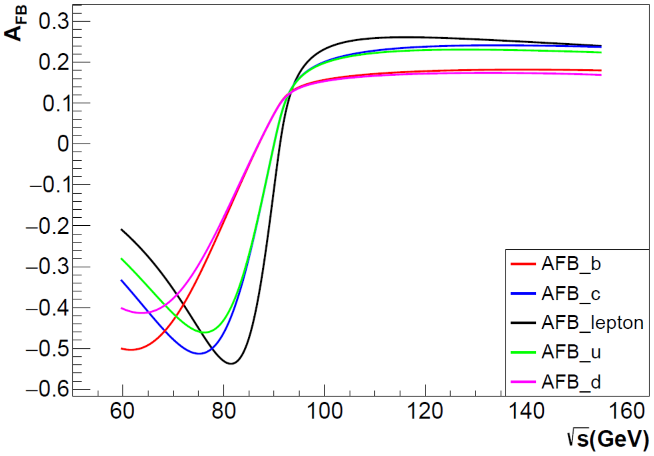
Electroweak Precision measurements and $\sin^2\theta_{eff}^{f}$

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

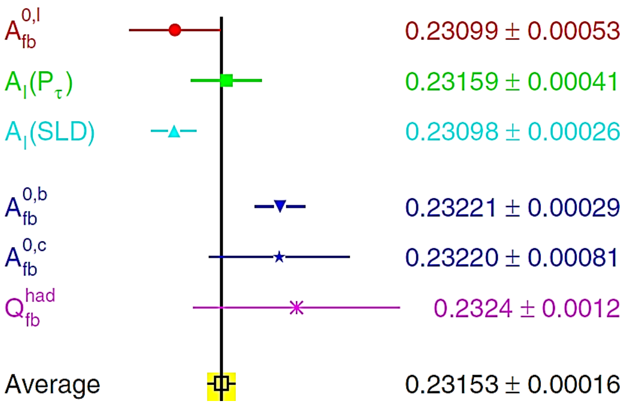


- A_{FB}: Forward-Backward Asymmetry
  - $e^+e^- \to f\bar{f}$
  - $A_{FB}^f = A_{FB}^f(\sqrt{s}, \sin^2\theta_{eff}^f)$
  - Flavor dependent



$\sin^2\theta_{eff}^{l}$ measurement at previous and CEPC

- LEP&SLAC (precision~0.1%)
  - LEP: 0.23188 ± 0.00021
  - SLAC: 0.23098 ± 0.00026
  - Statistical dominant.



- High luminosity at the CEPC
  - CEPC: 4 trillion Z in 2 years (Z period, 100ab^{-1})
- Low systematics

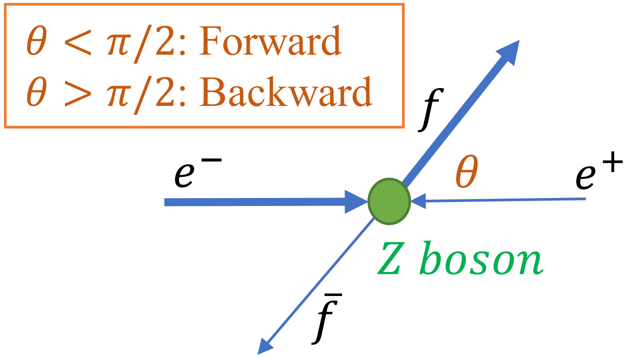
- $\sin^2\theta_{eff}^{l}$ measurement @ CEPC
  - 1. From $\mathcal{O}(0.1\%)$ to $\mathcal{O}(0.01\%)$
  - 2. Direct comparison of different channel
  - 3. Test of $\sin^2\theta_W$ running effect.

Experimental uncertainty	Theoretical calc. error
~0.00030	~0.00004

https://iopscience.iop.org/article/10.1088/1674-1137/acf91f

$\sin^2\theta_{eff}^f$ measurement using A_{FB}

- $A_{FB} = \frac{N_F - N_B}{N_F + N_B} = A_{FB}^f(\sqrt{s}, \sin^2\theta_{eff}^f)$
- Flavor dependent
- Uncertainty:
  - $\delta A_{FB} = \sqrt{\frac{1 - A_{FB}^2}{N}}$
  - N is the data size.



Sensitivity and Tagging power

$$\boldsymbol{sensitivity: S = S^{phy} * Det}$$

$$S^{phy} = \frac{\partial A_{FB}^{phy}}{\partial \sin^2 \theta_{eff}}$$

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

$\epsilon_{tagging}$	overall efficiency of events observation
f	charge mis-identification probability (event-level)

tagging power: $\boldsymbol{\epsilon * (1 - 2f)^2}$

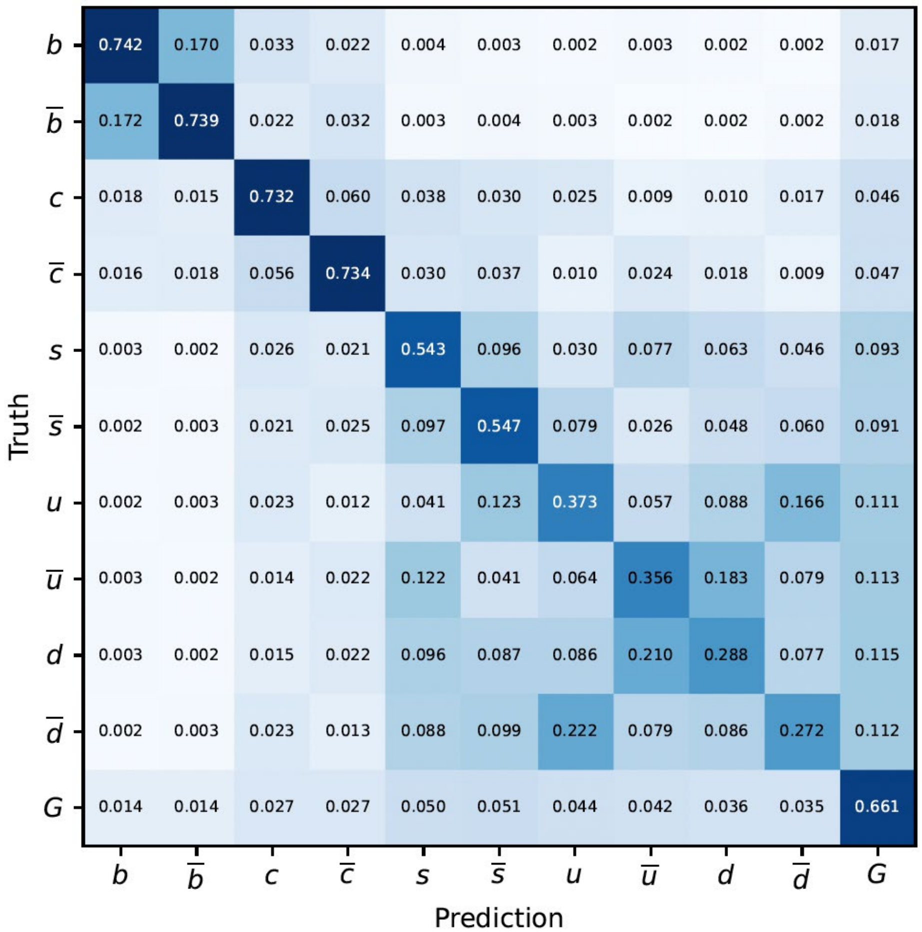
Lepton	Quarks
$\epsilon \sim 100\%$ $f \sim 0$	tagging power: $\epsilon * (1 - 2f)^2$ $= 0.088$ (for b quarks)

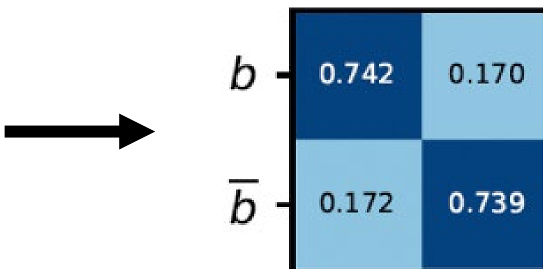
Previous work by Hanhua Cui *et al.*, perform jet tagging and charge measurement.

This selection is **event-level**

Hanhua Cui, Manqi Ruan, Jet Charge at CEPC, in Joint Workshop of the CEPC Physics, Software and New Detector Concept, April 16, 2021. Online resource can be found at: https://indico.ihep.ac.cn/event/13888/session/12/contribution/71/material/slides/0.pdf.

Jet Origin Identification (from Manqi)





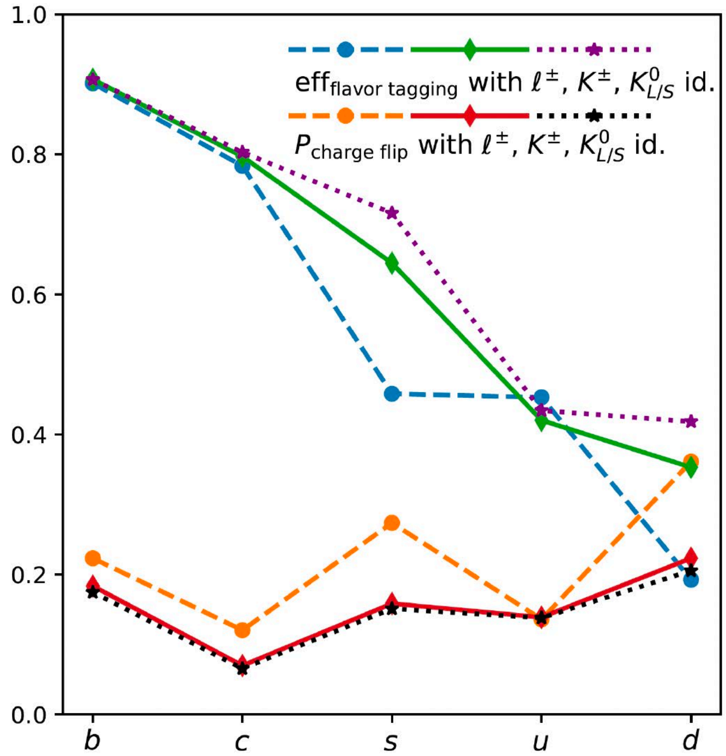
Single quark identification

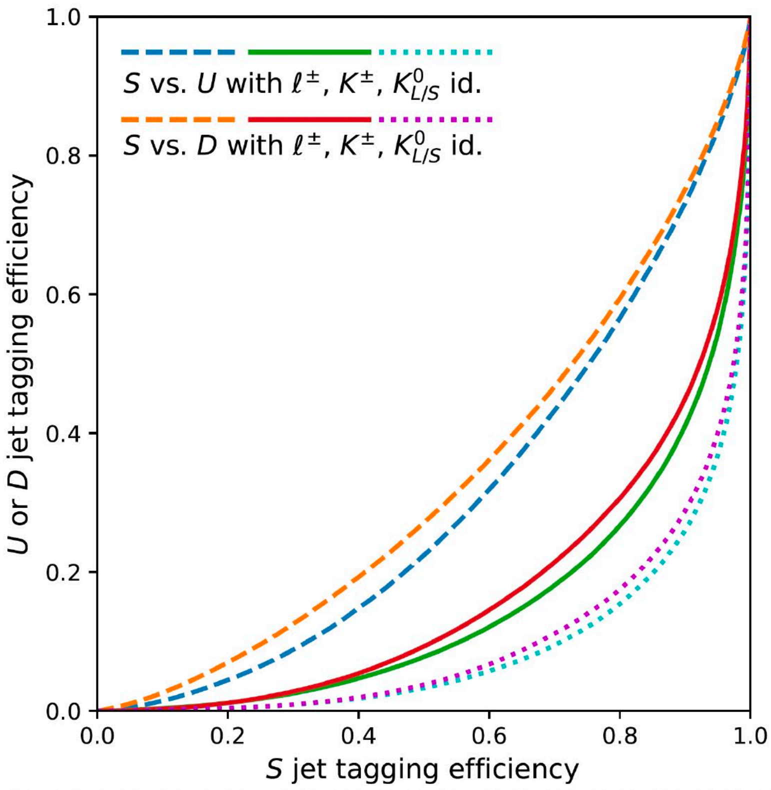
Eff = (0.74 + 0.17 + 0.74 + 0.17)/2 = 0.91

Charge flip rate = 0.17/0.91 = 0.19

https://arxiv.org/abs/2310.03440
https://arxiv.org/abs/2309.13231

Performance with different PID scenarios

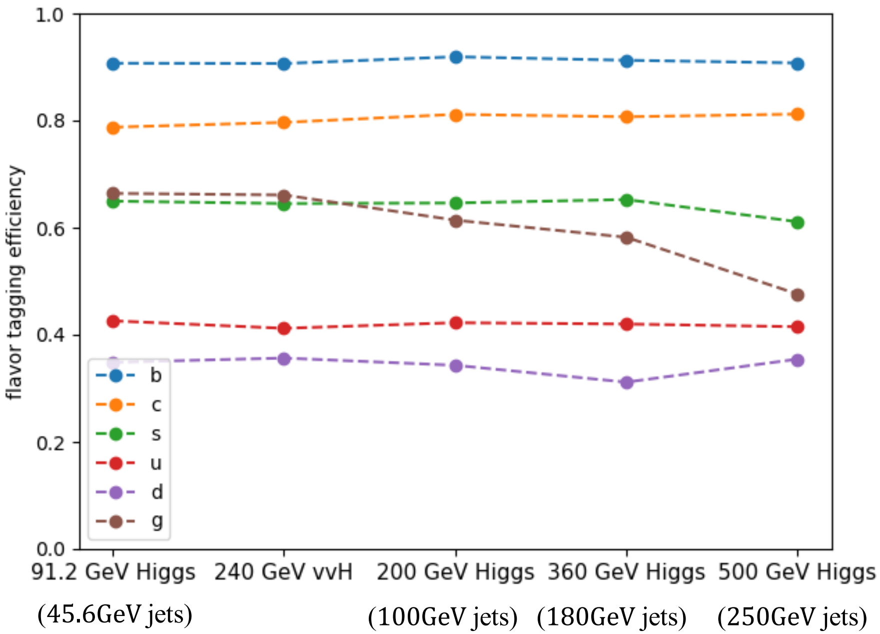




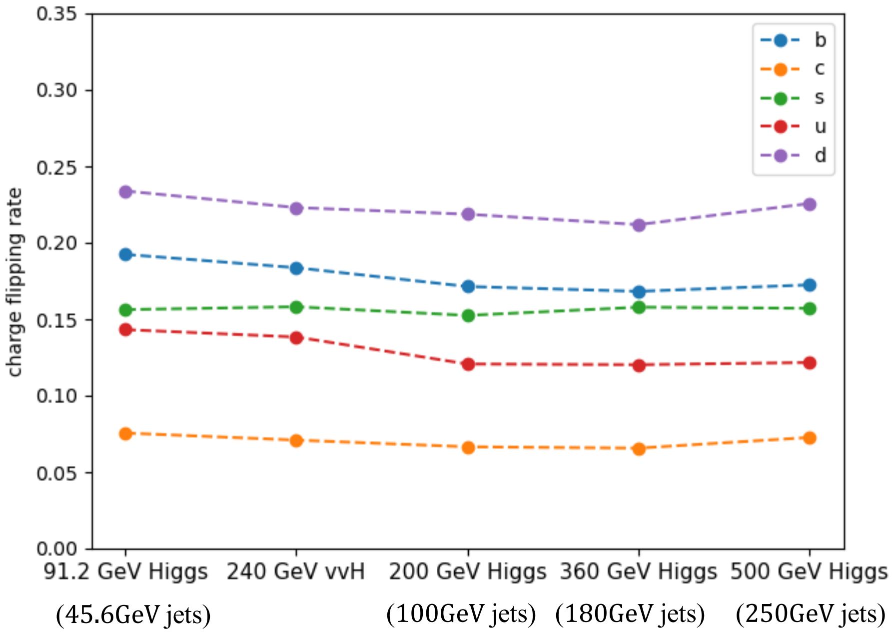
23/10/2023 CEPC WS@NJU 6

Stability of Jet Origin Identification (from Manqi)

Efficiency



Charge flipping rate



Update using *Jet Origin Identification*

Truth \ Prediction	b	$\bar{b}$	c	$\bar{c}$	s	$\bar{s}$	u	$\bar{u}$	d	$\bar{d}$	G
b	0.742	0.170	0.033	0.022	0.004	0.003	0.002	0.003	0.002	0.002	0.017
$\bar{b}$	0.172	0.739	0.022	0.032	0.003	0.004	0.003	0.002	0.002	0.002	0.018
c	0.018	0.015	0.732	0.060	0.038	0.030	0.025	0.009	0.010	0.017	0.046
$\bar{c}$	0.016	0.018	0.056	0.734	0.030	0.037	0.010	0.024	0.018	0.009	0.047
s	0.003	0.002	0.026	0.021	0.543	0.096	0.030	0.077	0.063	0.046	0.093
$\bar{s}$	0.002	0.003	0.021	0.025	0.097	0.547	0.079	0.026	0.048	0.060	0.091
u	0.002	0.003	0.023	0.012	0.041	0.123	0.373	0.057	0.088	0.166	0.111
$\bar{u}$	0.003	0.002	0.014	0.022	0.122	0.041	0.064	0.356	0.183	0.079	0.113
d	0.003	0.002	0.015	0.022	0.096	0.087	0.086	0.210	0.288	0.077	0.115
$\bar{d}$	0.002	0.003	0.023	0.013	0.088	0.099	0.222	0.079	0.086	0.272	0.112
G	0.014	0.014	0.027	0.027	0.050	0.051	0.044	0.042	0.036	0.035	0.661

Jet Origin Identification: particle-level

Take b-quark as an example:

Truth \ Prediction	b	$\bar{b}$	other
b	ω_{11}	ω_{12}	ω_{13}
$\bar{b}$	ω_{21}	ω_{22}	ω_{23}
other	ω_{31}	ω_{32}	ω_{33}

True: $p(b\bar{b}) = \omega_{11} \cdot \omega_{22} = 0.5483$

Fake: $p(\bar{b}b) = \omega_{12} \cdot \omega_{21} = 0.0292$

~~Same Sign~~: $p(bb + \bar{b}\bar{b}) = 0.253$

~~Single b~~: $p(b/\bar{b} + other) = 0.161$

} 0.992

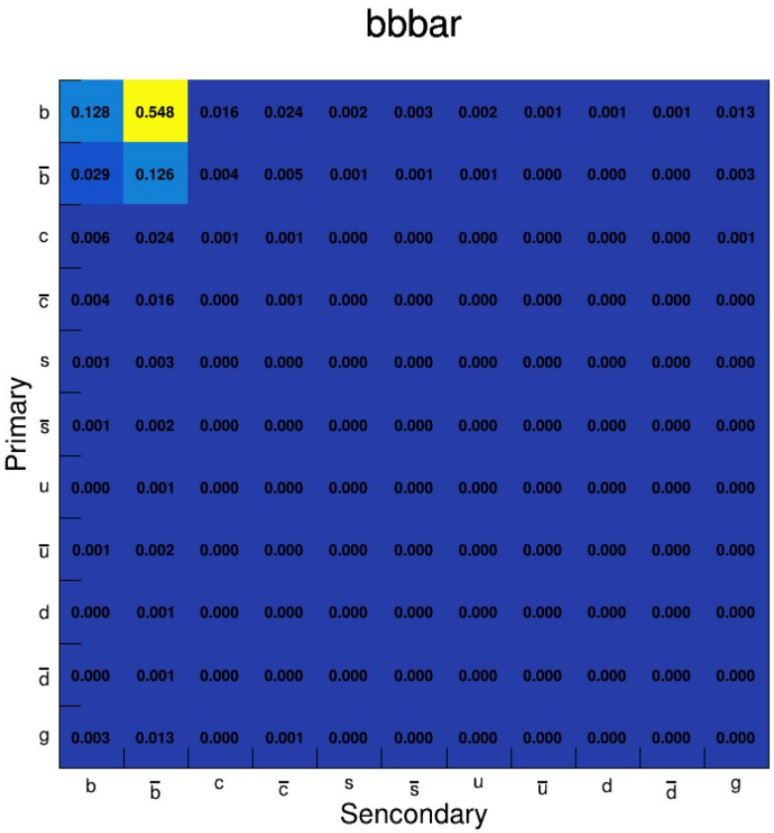
$\boldsymbol{\epsilon \sim p(b\bar{b} + \bar{b}b) = 0.578}$

$\boldsymbol{f \sim \frac{p(\bar{b}b)}{p(b\bar{b}+\bar{b}b)} = 0.051}$

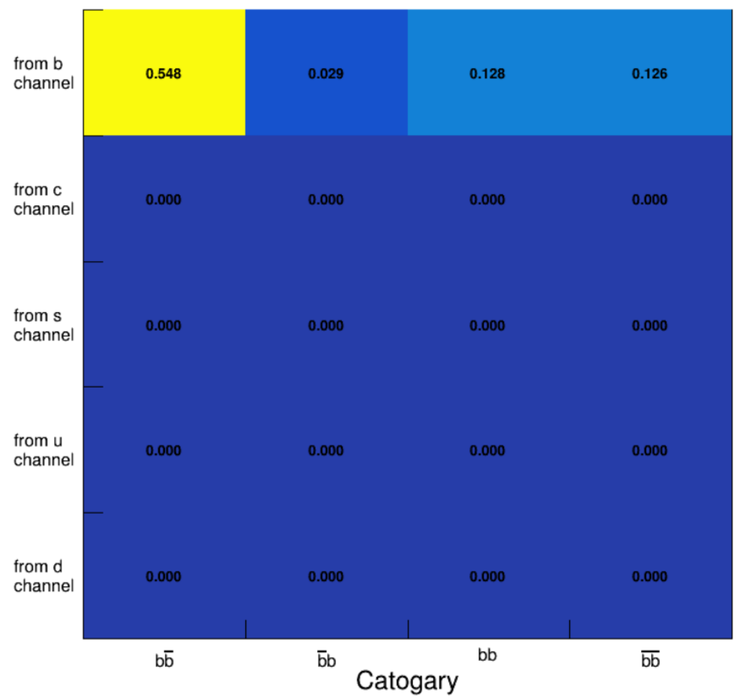
tagging power~0.467 **(Previous: 0.088)**

Considering contamination from other channels

1. A $b\bar{b}$ event can be tagged as:



2. Using table 1, consider $e^+e^- \to Z \to h\bar{h}$
Considering branch ratio of each channel.
A Tagged $b\bar{b}/\bar{b}b/\cdots$ event can come from:



$$\epsilon = 0.548 + 0.029 = 0.577$$

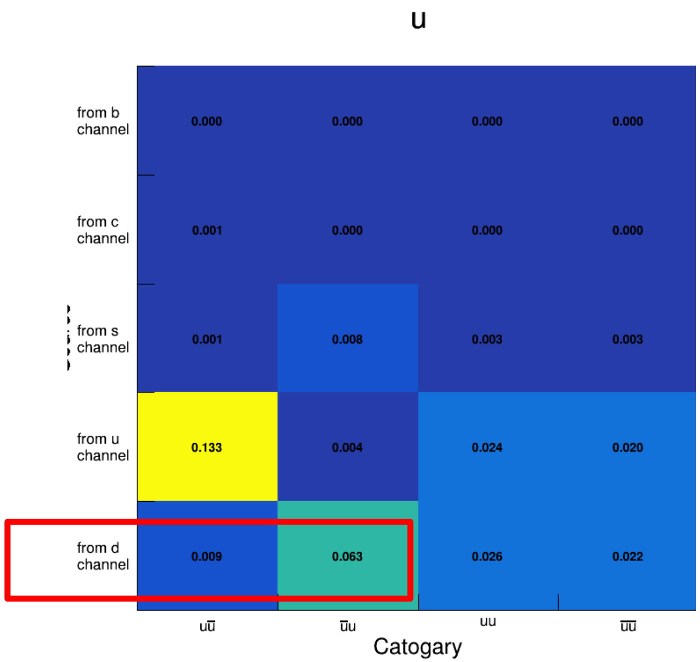
$$f = \frac{0.029}{0.548 + 0.029} = 0.050$$

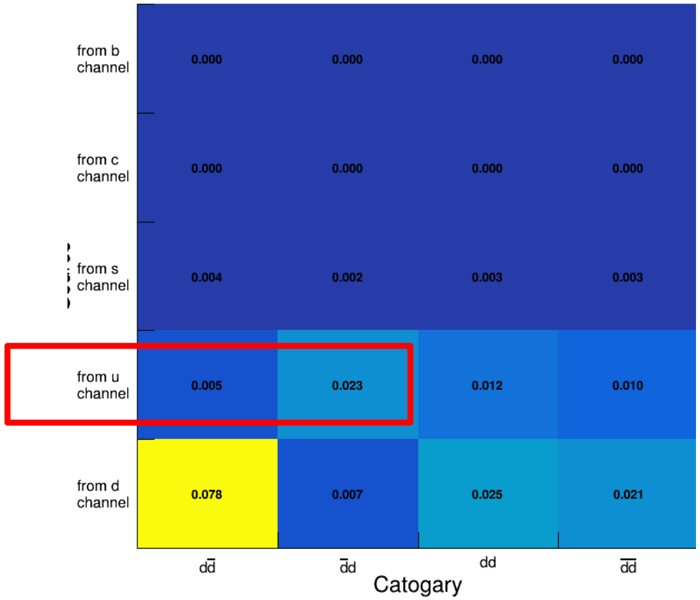
$$\text{tagging power} = \epsilon \cdot (1 - 2f)^2 = 0.467$$

Estimation of tagging power

	Purity P	Efficiency ϵ	Mis-id f	Tagging power
b	**~100%**	**0.577**	**0.05**	**0.467**
c	**99%**	**0.546**	**0.00056**	**0.528**
s	**90.5%**	**0.338**	**0.086**	**0.232**
u	62.6%	0.219	0.342	0.022
d	71.4%	0.119	0.269	0.025

- With a high-purity sample, b/c channel can be used to measure $\sin^2\theta^l_{eff}$.
- (Maybe) after adjusting the working point, s, even u/d channel can also be utilized.
- (Maybe) a joint measurement of u/d.





Updated result on $\sin^2 \theta^l_{eff}$ measurement

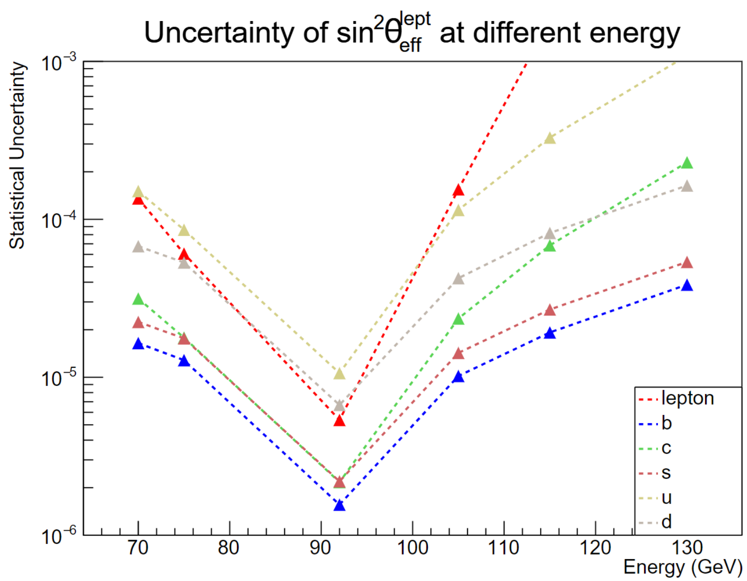
Table 2. Sensitivity S of different final state particles.

$\sqrt{s}$/GeV	S of $A^{e/\mu}_{FB}$	S of A^{d}_{FB}	S of A^{u}_{FB}	S of A^{s}_{FB}	S of A^{c}_{FB}	S of A^{b}_{FB}
70	0.224	4.396	1.435	4.403	1.445	4.352
75	0.530	5.264	2.598	5.269	2.616	5.237
92	1.644	5.553	4.200	5.553	4.201	5.549
105	0.269	4.597	1.993	4.598	1.994	4.586
115	0.035	3.956	1.091	3.958	1.087	3.942
130	0.027	3.279	0.531	3.280	0.520	3.261

Table 3. Cross section of process $e^+e^- \to f\bar{f}$ calculated using the ZFITTER package. Values of the fundamental parameters are set as $m_Z = 91.1875$ GeV, $m_t = 173.2$ GeV, $m_H = 125$ GeV, $\alpha_s = 0.118$ and $m_W = 80.38$ GeV.

$\sqrt{s}$/GeV	σ_μ/mb	σ_d/mb	σ_u/mb	σ_s/mb	σ_c/mb	σ_b/mb
70	0.039	0.032	0.066	0.031	0.058	0.028
75	0.039	0.047	0.073	0.046	0.065	0.043
92	1.196	5.366	4.228	5.366	4.222	5.268
105	0.075	0.271	0.231	0.271	0.227	0.265
115	0.042	0.135	0.122	0.135	0.118	0.132
130	0.026	0.071	0.068	0.071	0.066	0.069

Expected statistical uncertainties on $\sin^2 \theta^l_{eff}$ measurement.
(Using one-month data collection, ~ *4e12/24 Z events* at Z pole)



$\sqrt{s}$	b	c	s	u	d
70	1.6×10^{-5}	3.2×10^{-5}	2.2×10^{-5}	1.5×10^{-4}	6.8×10^{-5}
75	1.3×10^{-5}	1.8×10^{-5}	1.8×10^{-5}	8.6×10^{-5}	5.3×10^{-5}
92	1.6×10^{-6}	2.2×10^{-6}	2.2×10^{-6}	1.1×10^{-5}	6.7×10^{-6}
105	1.0×10^{-5}	2.4×10^{-5}	1.4×10^{-5}	1.1×10^{-4}	4.2×10^{-5}
115	1.9×10^{-5}	6.8×10^{-5}	2.7×10^{-5}	3.3×10^{-4}	8.2×10^{-5}
130	3.9×10^{-5}	2.3×10^{-4}	5.4×10^{-5}	1.1×10^{-3}	1.6×10^{-4}

Summary

- Previous work: make estimation on effective weak mixing angle according to 1 month data collection

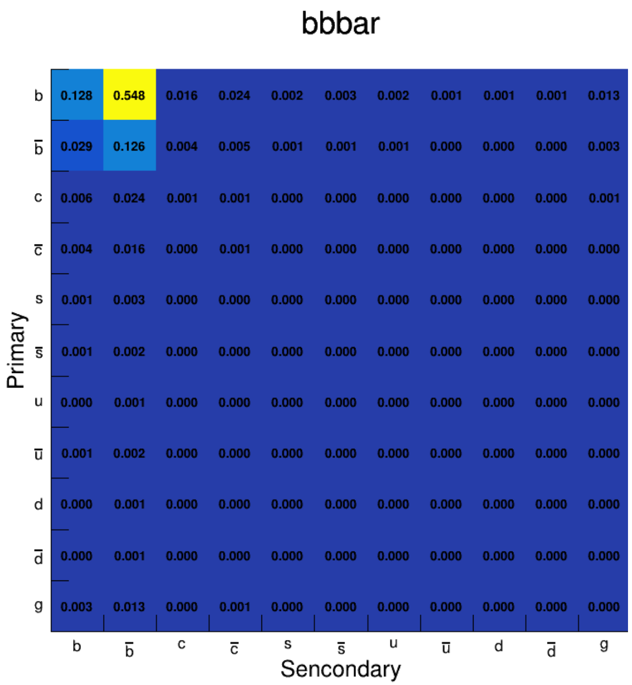
Overall precision at Z pole	Lepton/quark comparison	Precision at off Z pole
$\Delta\sin^2\theta_{eff} \sim \mathcal{O}(10^{-5})$	$\Delta\sin^2\theta_{eff} \sim \mathcal{O}(10^{-5})$ Able to make comparison	$\Delta\sin^2\theta_{eff} \sim \mathcal{O}(10^{-5} \sim 10^{-4})$

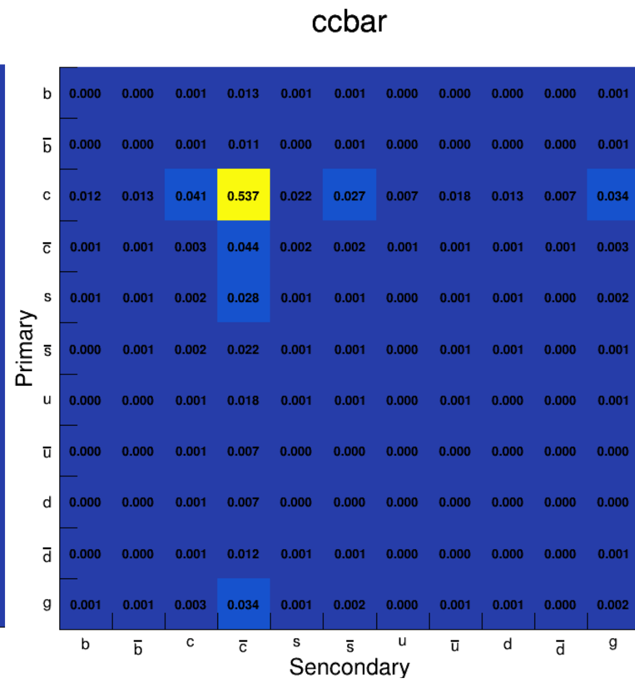
- With Jet Origin Identification:
  - b/c has a very high-performance update
  - Some ways may help to utilize s channel, even u/d
    - Adjust working point of the jet origin classification
    - Joint measurement of u and d

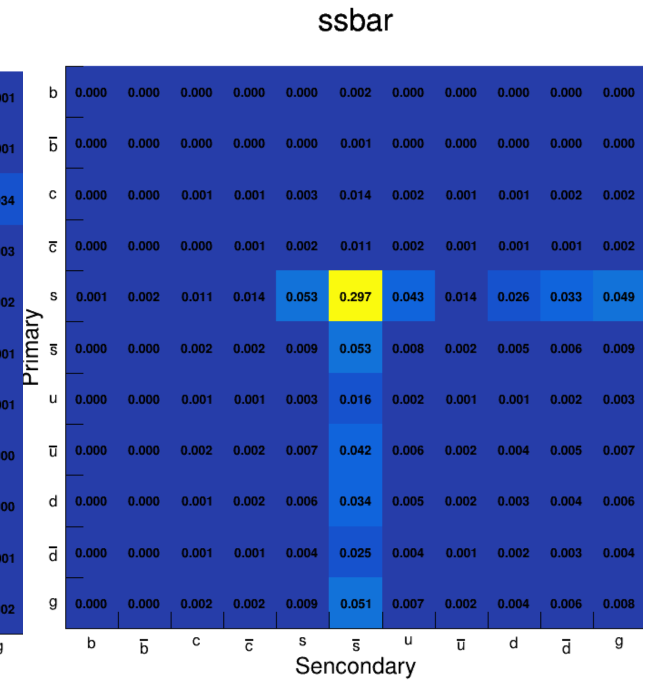
This Work (Previous, without Jet Origin Identification):
https://iopscience.iop.org/article/10.1088/1674-1137/acf91f
(**DOI**: 10.1088/1674-1137/acf91f)

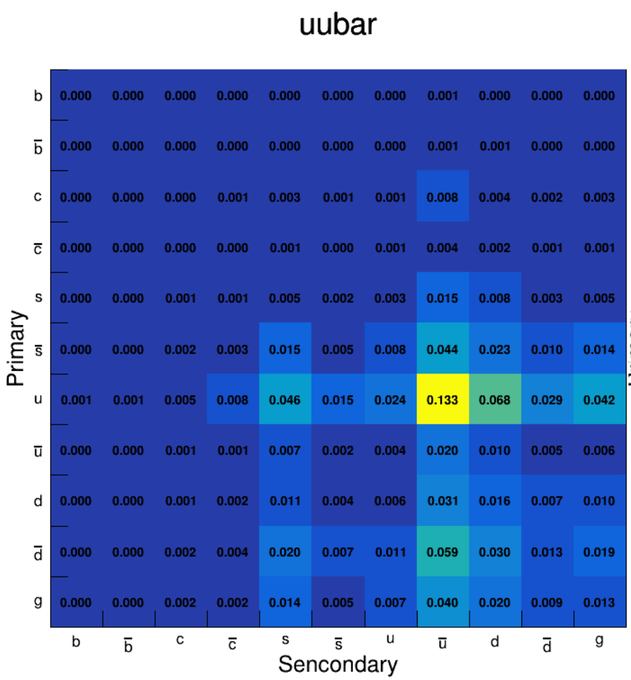
Thanks

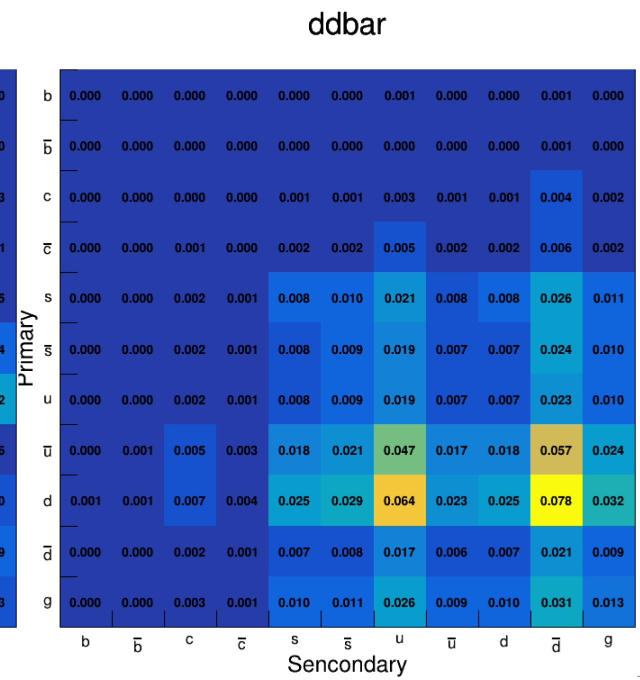
Backups





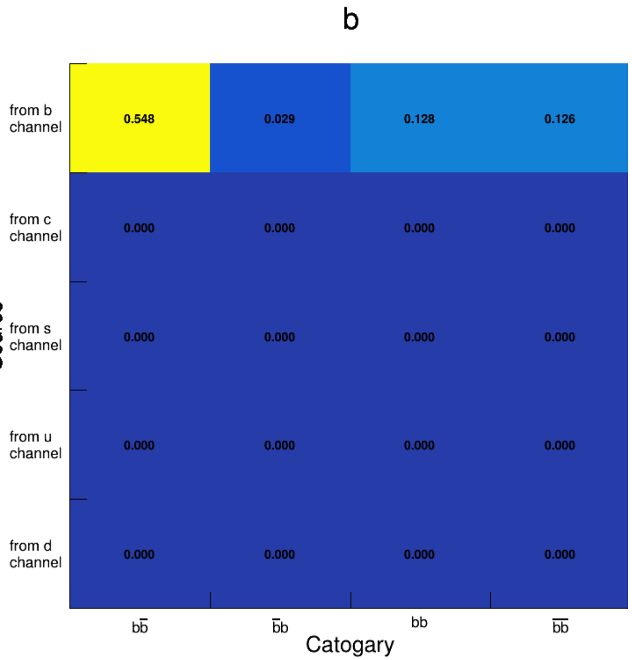


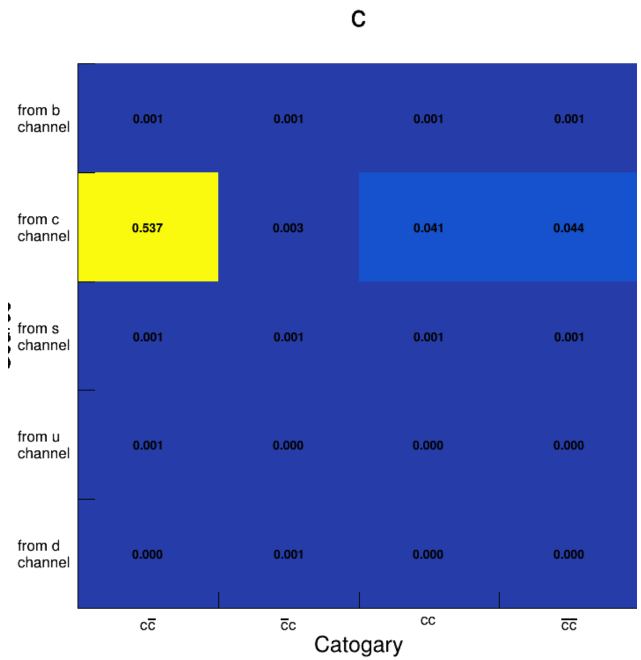


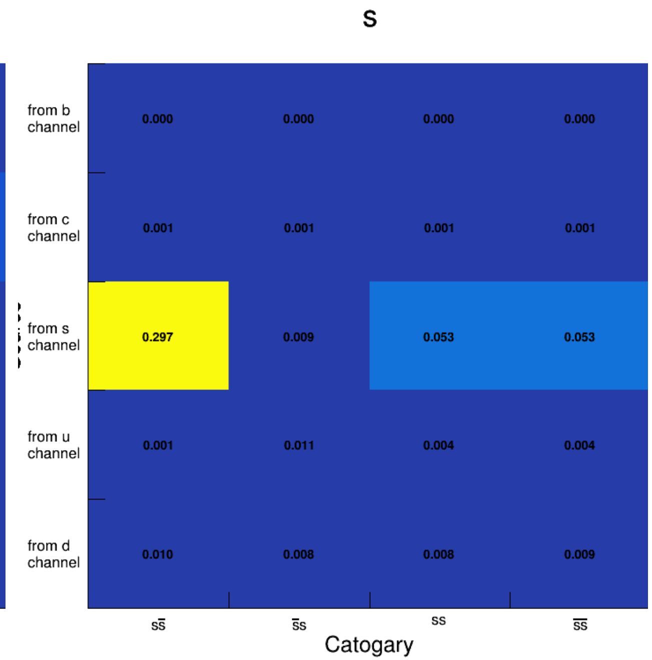


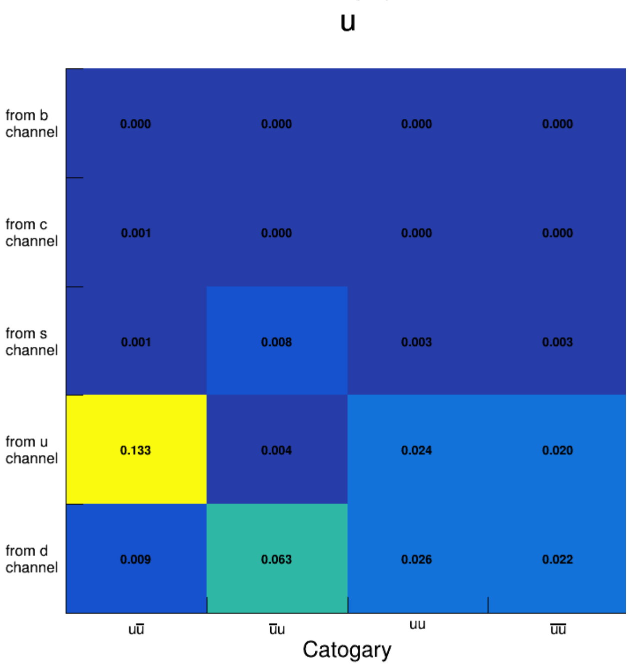
A $h\bar{h}$ event can be tagged as: AB, here *Primary* and *Secondary* represent A and B, respectively.

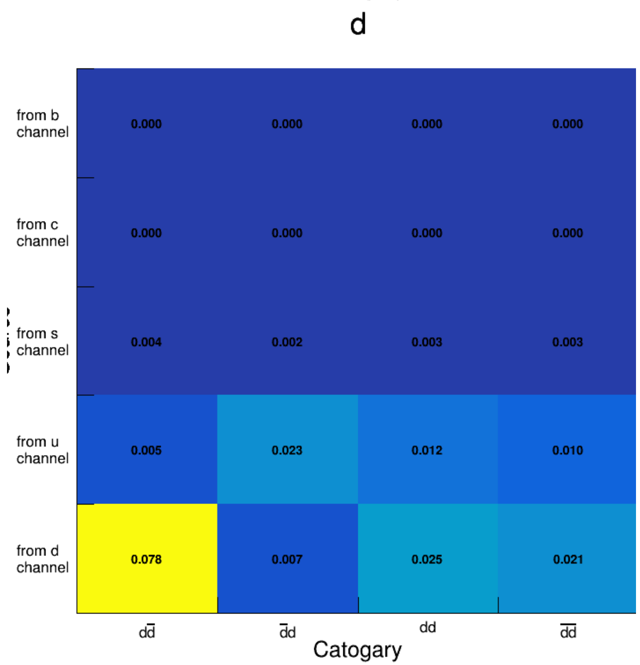
For each matrix, sum of all elements is 1.



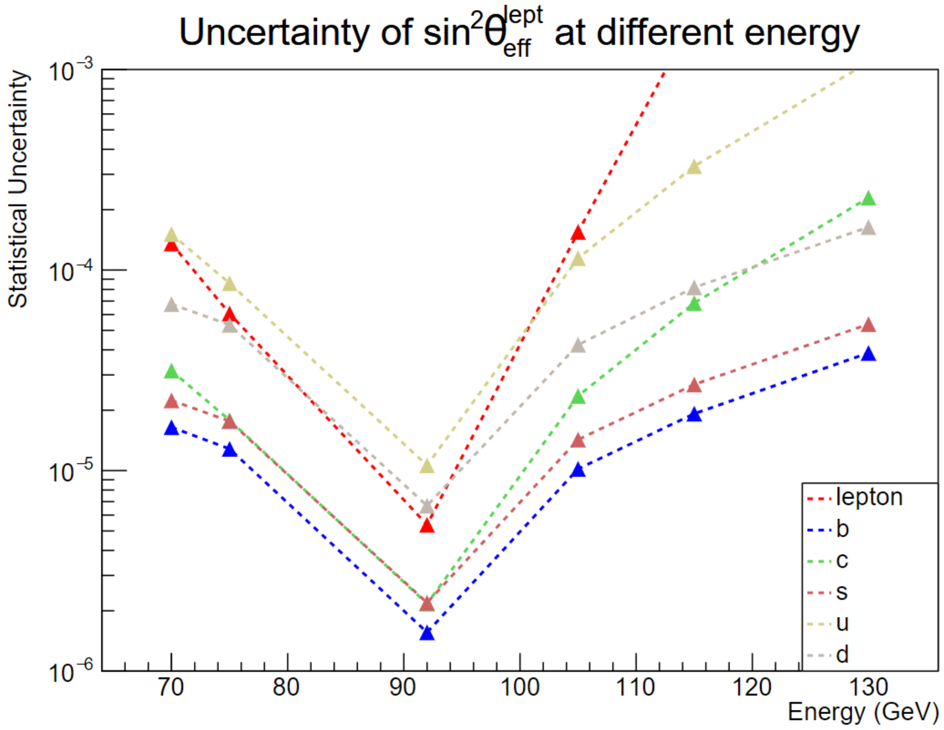








$e^+e^- \to h\bar{h}$ events can be tagged and classified into different categories. Considering contamination from other channels (note that different channel has different branch ratio), the sample component is shown in matrix.



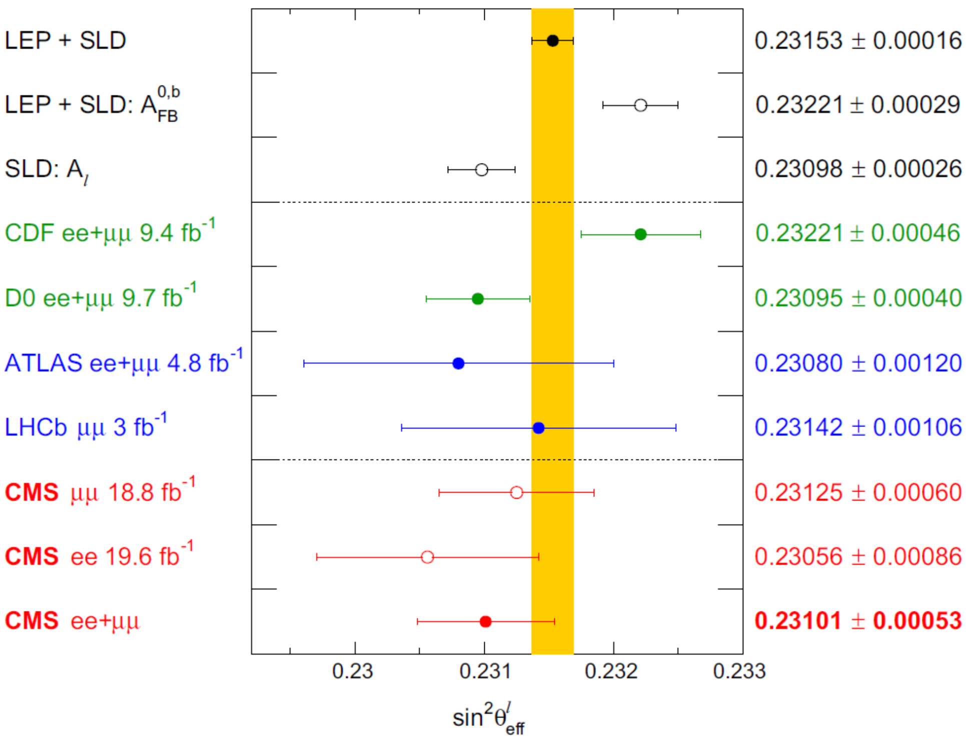
$\sqrt{s}$	l	b	c	s	u	d
70	1.4×10^{-4}	1.6×10^{-5}	3.2×10^{-5}	2.2×10^{-5}	1.5×10^{-4}	6.8×10^{-5}
75	6.1×10^{-5}	1.3×10^{-5}	1.8×10^{-5}	1.8×10^{-5}	8.6×10^{-5}	5.3×10^{-5}
92	5.4×10^{-6}	1.6×10^{-6}	2.2×10^{-6}	2.2×10^{-6}	1.1×10^{-5}	6.7×10^{-6}
105	1.5×10^{-4}	1.0×10^{-5}	2.4×10^{-5}	1.4×10^{-5}	1.1×10^{-4}	4.2×10^{-5}
115	1.8×10^{-3}	1.9×10^{-5}	6.8×10^{-5}	2.7×10^{-5}	3.2×10^{-4}	8.2×10^{-5}
130	3.6×10^{-3}	3.9×10^{-5}	2.3×10^{-4}	5.4×10^{-5}	1.1×10^{-3}	1.6×10^{-4}

Formula for the estimation of the statistical uncertainty on $\sin^2\theta^l_{eff}$

$$\Delta \sin^2\theta^l_{eff} = \frac{1}{S} \cdot \sqrt{\frac{1-(A^{obs}_{FB})^2}{(1-2f)^2 \cdot \epsilon \cdot N_0}}$$

$\sin^2\theta^l_{eff}$ measurement at lepton/hadron collider

- LEP&SLAC (precision~0.1%)
  - LEP: 0.23188 ± 0.00021
  - SLAC: 0.23098 ± 0.00026
  - Statistical dominant
- Tevatron
  - 0.23148 ± 0.00033 (DØ+CDF)
  - Statistic & PDF dominant
- LHC
  - PDF, QCD & systematic dominant
  - Aiming for ~0.00010 in the future



Tevatron:

$$\sin^2\theta^l_{eff} = 0.23148 \pm 0.00027(stat.) \pm 0.00005(syst.) \pm 0.00018(PDF)$$

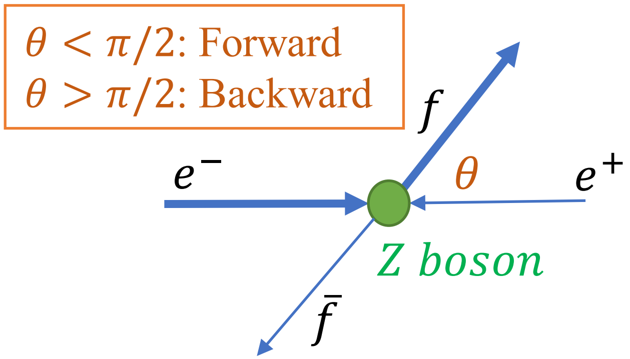
CMS 8TeV:

$$\sin^2\theta^l_{eff} = 0.23101 \pm 0.00036(stat.) \pm 0.00018(syst.) \pm 0.00016(theo.) \pm 0.00031(PDF)$$

Estimation on experimental systematics

- Systematics from efficiency determination:
  - Cancelled out in the ratio-type definition of AFB, no propagation
- Systematics from charge mis-ID estimation:
  - Can be precisely measured from data-driven method
- Other systematics (from LEP):
  - Electron channel: t-channel & s-t interference (0.00085)
  - Lepton channel: QED calculation (0.00006)
  - B quark channel: QCD calculation (0.00007)

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



- B quark systematics: Preliminary study found it may significantly reduce

Supplementary result from P_τ measurement

- The only channel for which the polarization can be determined

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

- $P_\tau = P_\tau(\cos\theta, \sin^2\theta_{eff})$

- Measurement of P_τ rely on the kinematic spectrum of different tau decay modes.

- Statistical: 2.15×10^{-6} (one month data)
- Systematic: $\mathcal{O}(10^{-4})$ for LEP

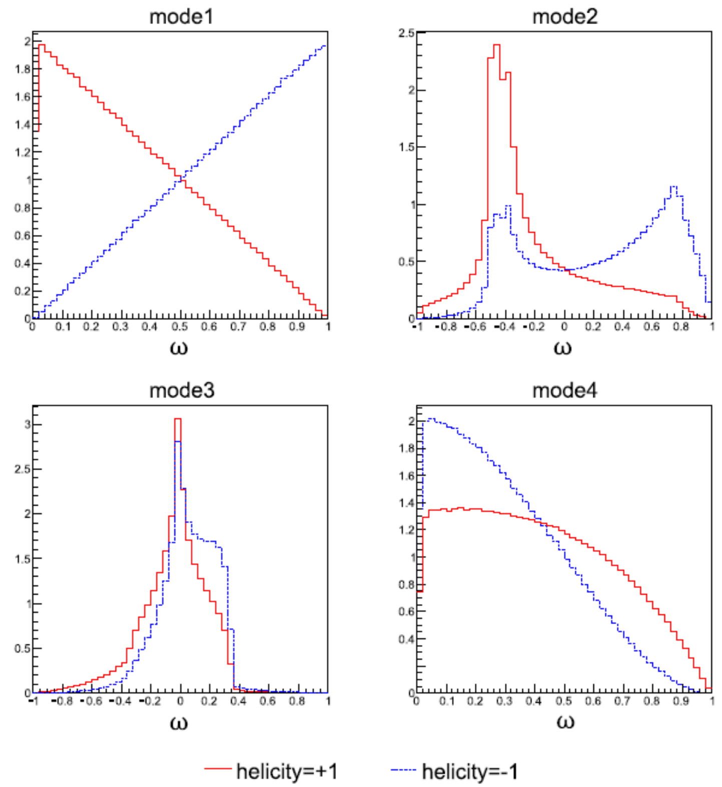


Fig. 5. (color online) Kinematic spectrum of different tau decay modes. The red solid line and blue dashed line represent the kinematic spectrum of taus with *helicity* = +1 and −1, respectively. All the spectra are generated using PYTHIA8 generator and tauola interface.