Some aspects of flavor physic at CEPC

Qin Qin (Uni. Siegen)

International workshop on CEPC

Outline

* A glance at flavor measurements at CEPC
* Two examples
  - Lepton flavor violating Higgs, Z and tau decays
  - Anomalous weak dipole moments of tau
* Summary

A glance at CEPC

* **Higgs involved** (1 million Higgs bosons)
    - Hff and Hff' couplings
* **Z involved** (10 - 100 billion Z bosons)
    - Zff and Zff' couplings
* **Heavy hadron decays** (CEPC vs Belle II)

b-hadron species	Fraction in decays of $Z^0 \to b\bar{b}$	Number of b-hadron at Z^0 peak	Fraction in $\Upsilon(4S)/(5S)$ decays	Number of b-hadron at $\Upsilon(4S)/(5S)$
B^0	0.404 ± 0.009	0.6×10^{10}	0.486 ± 0.006 ($\Upsilon(4S)$)	4.9×10^{10}
B^+	0.404 ± 0.009	0.6×10^{10}	0.514 ± 0.006 ($\Upsilon(4S)$)	5.1×10^{10}
B_s	0.103 ± 0.009	0.02×10^{10}	0.201 ± 0.030 ($\Upsilon(5S)$)	0.6×10^{10}
b baryons	0.089 ± 0.015	0.02×10^{10}	–	–

No chance for mesons, unless other advantages (tau reconstruction).

A glance at CEPC

* Higgs couplings CEPC > ...
* Z couplings CEPC > ...
* heavy baryon production and decays
  CEPC > ...
* tau production and decays CEPC ? Belle II

Lepton flavor violation
(1st example)

* Induced by SUSY, extra dimension ...

* Exp. hints of lepton non-uni. in B decays

- $R(D^*) \equiv \mathcal{B}[B \to D^* \tau\nu]/\mathcal{B}[B \to D^* \ell\nu]$ $\mathbf{3.4}\sigma$

- $R(D) \equiv \mathcal{B}[B \to D \tau\nu]/\mathcal{B}[B \to D \ell\nu]$ $\mathbf{2.3}\sigma$

- $R_K \equiv \mathcal{B}[B \to K\mu\mu]/\mathcal{B}[B \to Kee]_{q^2 \in [1,6]\mathrm{GeV}^2}$ $\mathbf{2.6}\sigma$

- $R_{K^*}^{\mathrm{low}} \equiv \mathcal{B}[B \to K^*\mu\mu]/\mathcal{B}[B \to K^*ee]_{q^2 \in [0.045,1.1]\mathrm{GeV}^2}$ $\mathbf{2.1}\sigma$
  $R_{K^*}^{\mathrm{high}} \equiv \mathcal{B}[B \to K^*\mu\mu]/\mathcal{B}[B \to K^*ee]_{q^2 \in [1.1,6]\mathrm{GeV}^2}$ $\mathbf{2.4}\sigma$

Lepton flavor violation
(1st example)

* Induced by SUSY, extra dimension ...

* Exp. hints of lepton non-uni. in B decays

  - $R(D^*)$, $R(D)$, R_K, R_{K^*}, ...

* LFV Higgs decay appeared and disappeared

  - $H \to \tau\mu$

    CMS: $\mathcal{B}[H \to \tau\mu] = (0.84^{+0.39}_{-0.37})\%$ (1502.07400) $\Rightarrow$ $(-0.76^{+0.81}_{-0.84})\%$ (CMS PAS HIG-16-005)

    ATLAS: $\mathcal{B}[H \to \tau\mu] = (0.53 \pm 0.51)\%$ (1604.07730)

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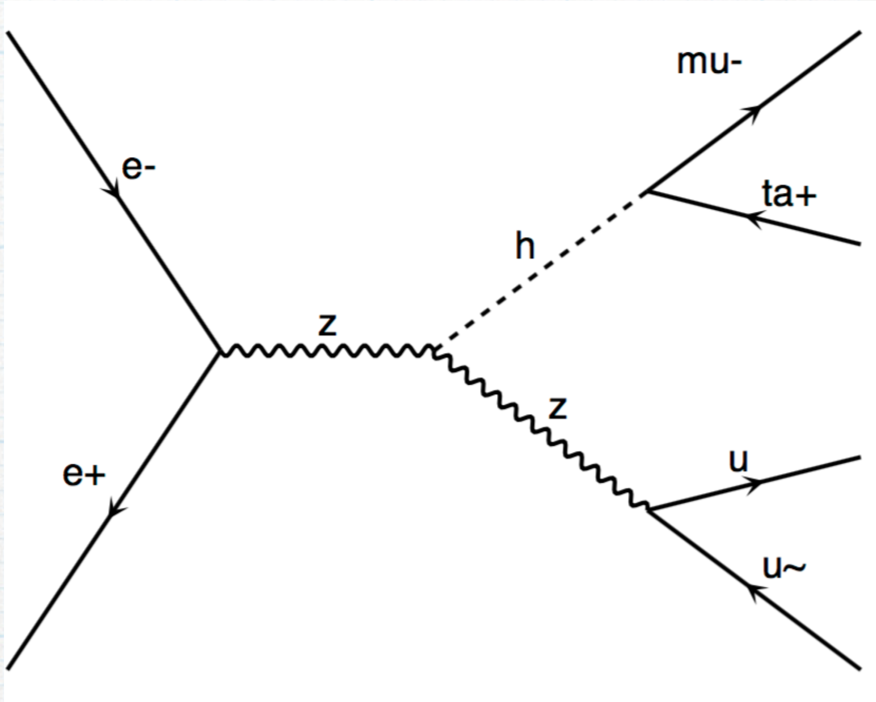
To probe LFV with cleaner channels.

Lepton flavor violation (Higgs)

- 3 channels
  - $H \to e^{\pm}\mu^{\mp}, e^{\pm}\tau^{\mp}, \mu^{\pm}\tau^{\mp}$
- Reconstruct tau by mu or e + missing energy
- Reconstruct Z by dijet



The dominant production process at the Higgs factory (240 -250 GeV)

Why such choices?

- $\mathcal{B}(Z \to jj) \sim 70\%$;
- Ensure lepton flavor changing vertices: if rebuilding τ by $e + \not{E}_T$ in $H \to e\tau$, $eejj$ will cause large background.

Lepton flavor violation (Higgs)

* **MadGraph:** generator for signals
* **Whizard:** generator for background See Kilian's talk
* **Pythia:** hadronization
* **Delphes:** fast simulation

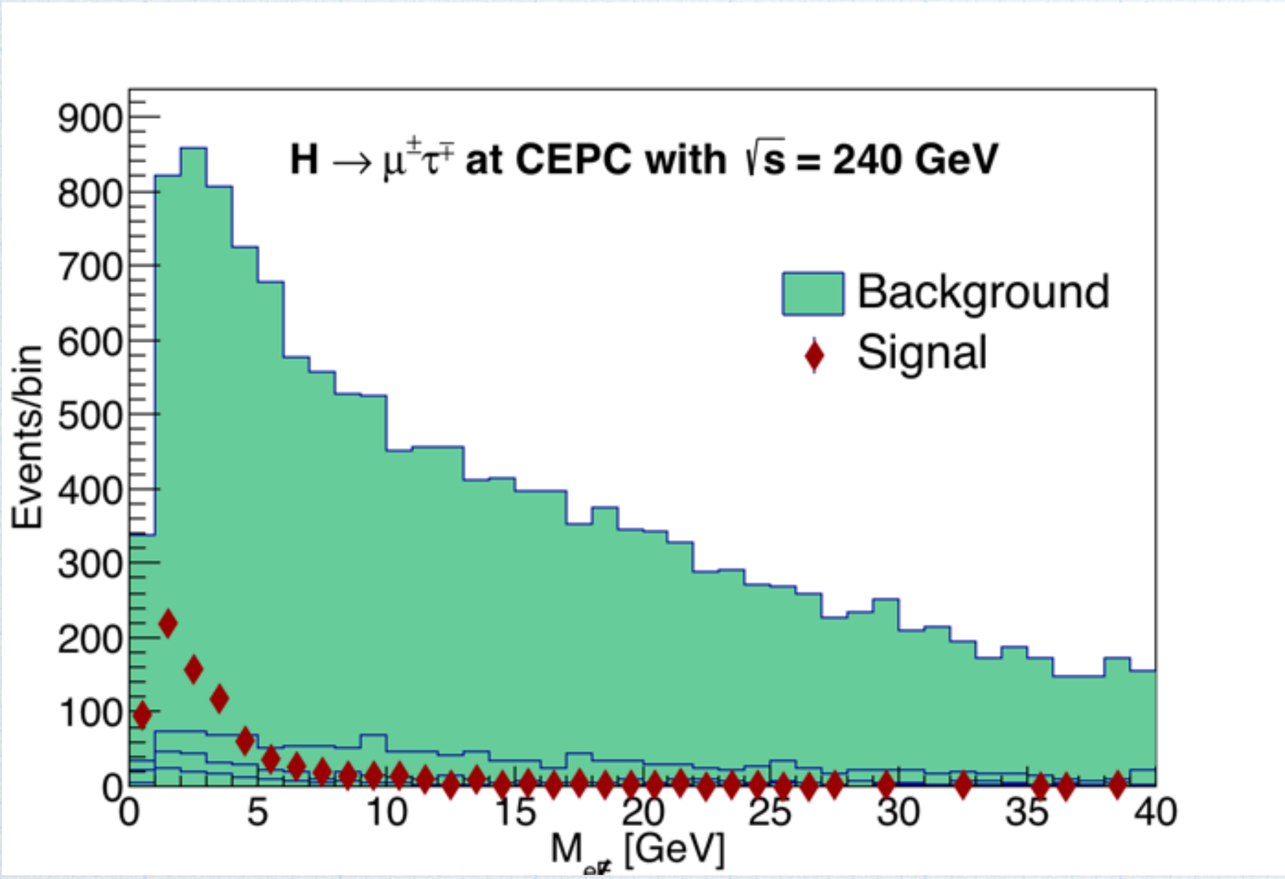
Four-fermion background

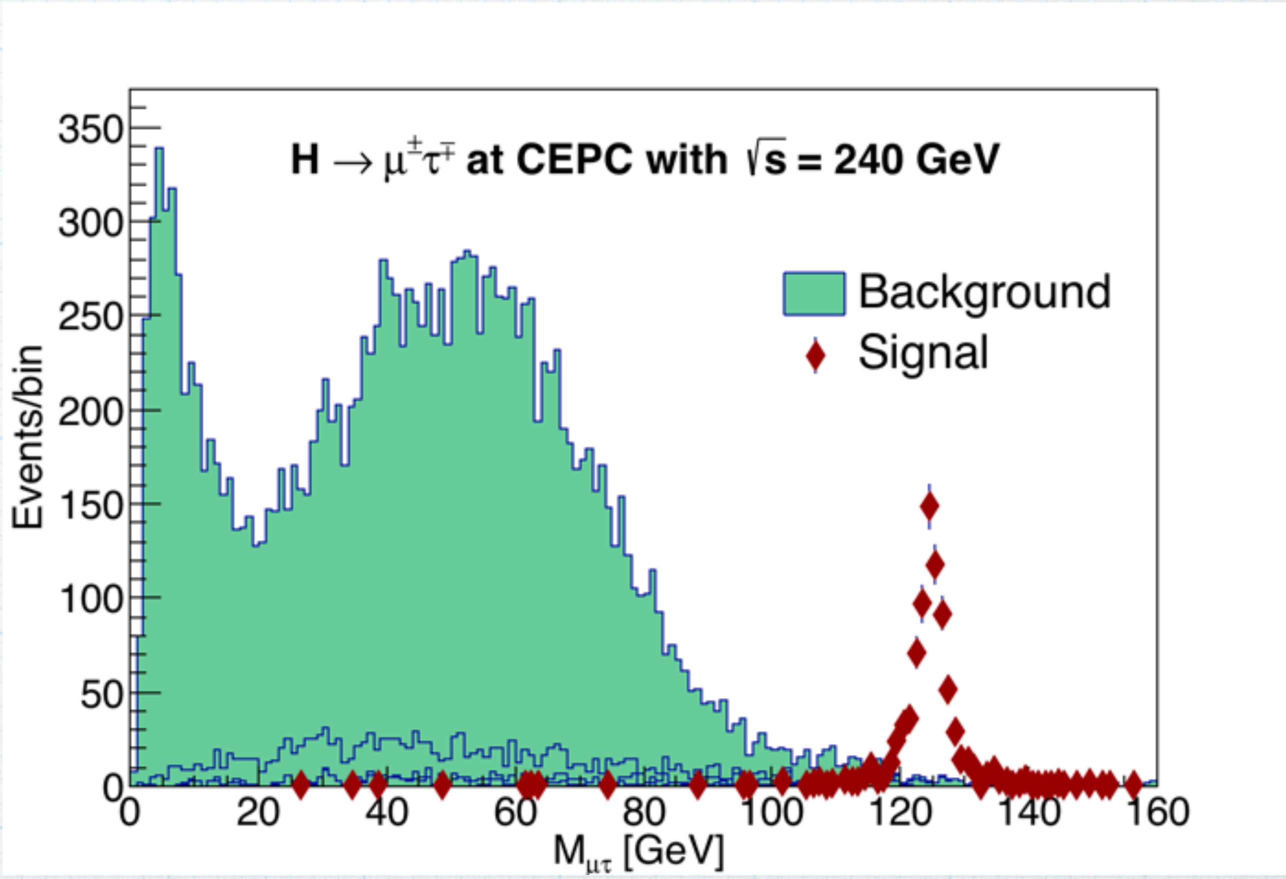
Category[a]	**cross section** [fb]	**Event No.** [10000]
SZ_ll	342	171
SZ_ql	452	226
ZZ_ll	18.8	9.4
ZZ_ql	233	117
ZZ_qq	830	415
SW_ql	667	333
WW_ql	1792	896

- SZ_ll: $e^+e^-\tau^+\tau^-$;
- SZ_ql: e^+e^-jj;
- ZZ_ll: $\mu^+\mu^-\tau^+\tau^-$, $\tau^+\tau^-\tau^+\tau^-$;
- ZZ_ql: $\mu^+\mu^-jj$, $\tau^+\tau^-jj$;
- ZZ_qq: $cc\bar{c}\bar{c}$, $dd\bar{d}\bar{d}$, $d\bar{d}b\bar{b}$, $bb\bar{b}\bar{b}$, $u\bar{u}s\bar{s}$, $u\bar{u}b\bar{b}$, $s\bar{s}b\bar{b}$;
- SW_ql: $e^+\nu_e\bar{c}s$;
- WW_ql: $\tau^+\nu_\tau\bar{u}d$, $\mu^-\bar{\nu}_\mu c\bar{s}$, $\mu^-\bar{\nu}_\mu u\bar{d}$.

Lepton flavor violation (Higgs)

* To set cuts





Signal and background events with cuts of Higgs->mu,tau

Cuts	SZ_ll	SZ_ql	ZZ_ll	ZZ_ql	ZZ_qq	SW_ql	WW_ql	**signal**
$N_{e,\mu}$=1, N_j=2	5684	1248	1464	16504	1945	1063	1627	856
$60 < m_{jj} < 100$	1578	428	606	13504	412	320	518	736
$m_{e\not{E}} < 5$	26	16	84	2706	30	5	0	583
$120 < m_{\mu\tau} < 130$	0	0	2	3	0	0	0	522

Lepton flavor violation (Higgs)

Signal and background events with cuts of Higgs->e,mu

Cuts	SZ_ll	SZ_ql	ZZ_ll	ZZ_ql	ZZ_qq	SW_ql	WW_ql	**signal**
$N_{e,\mu}$=1, N_j=2	5684	1248	1464	16504	1945	1063	1627	5617
$70 < m_{jj} < 100$	1099	267	408	12277	321	221	461	4216
$117 < m_{e\mu} < 127$	1	0	0	0	0	0	0	4115

Signal and background events with cuts of Higgs->e,tau

Cuts	SZ_ll	SZ_ql	ZZ_ll	ZZ_ql	ZZ_qq	SW_ql	WW_ql	**signal**
$N_{e,\mu}$=1, N_j=2	5684	1248	1464	16504	1945	1063	1627	868
$66 < m_{jj} < 94$	1119	290	448	11828	412	320	518	693
$m_{\mu E_M} < 4$	423	95	41	1892	30	5	0	530
$121 < m_{e\tau} < 130$	9	1	0	0	0	0	0	479
$\|\eta_e\| < 2$	5	0	0	0	0	0	0	456

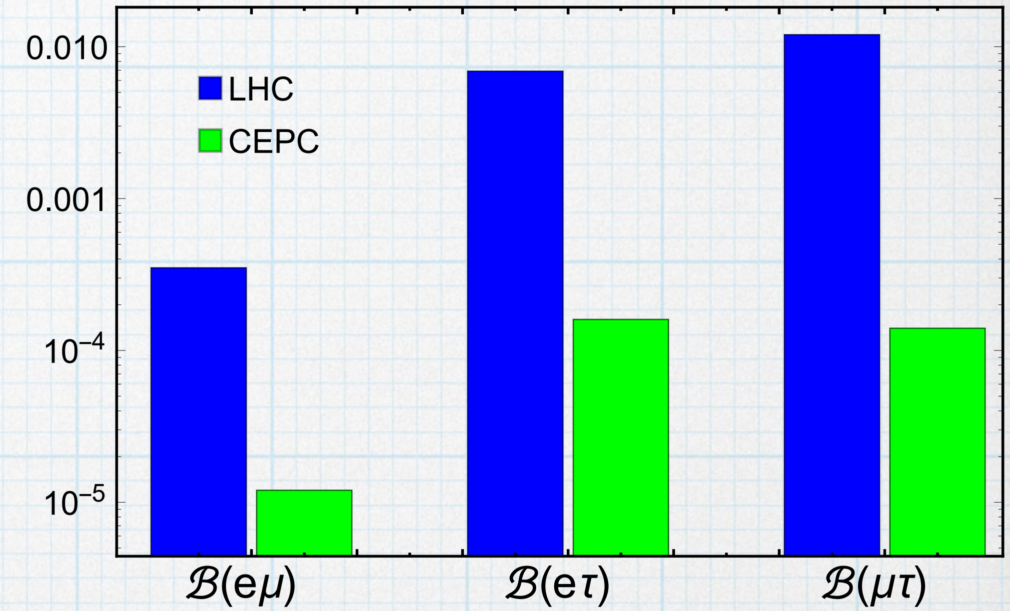
Lepton flavor violation (Higgs)

$$\mathcal{L}^{H\to\mu^\mp\tau^\pm} = -Y_{\mu\tau}\bar{\mu}_L H\tau_R - Y_{\tau\mu}\bar{\tau}_L H\mu_R + h.c.,$$

$$\Gamma(H\to\mu^\mp\tau^\pm)_{m_{\mu,\tau}\to 0} = \frac{m_H}{8\pi}(|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2)$$

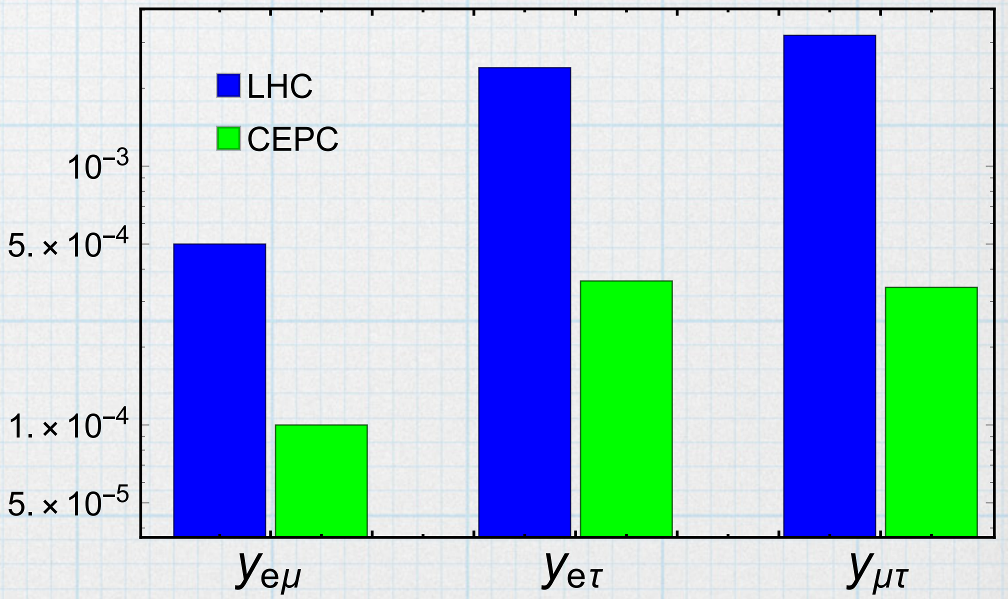
Current and expected CEPC bounds on the branching ratios

Channels	$\mu^\mp\tau^\pm$	$e^\mp\tau^\pm$	$e^\mp\mu^\pm$
ATLAS bound	1.43%	1.04%	
CMS bound	1.2%	0.69%	3.5×10^{-4}
CEPC bound	1.4×10^{-4}	1.6×10^{-4}	1.2×10^{-5}



Current and expected CEPC bounds on the couplings

Channels	$\mu^\mp\tau^\pm$	$e^\mp\tau^\pm$	$e^\mp\mu^\pm$
ATLAS bound	3.5×10^{-3}	2.9×10^{-3}	
CMS bound	3.2×10^{-3}	2.4×10^{-3}	5.4×10^{-4}
CEPC bound	3.4×10^{-4}	3.6×10^{-4}	1.0×10^{-4}



Lepton flavor violation (Higgs)

* Constraints to EFT

- $Y_{ij} = \frac{v^2}{\sqrt{2}\Lambda^2} C_{ij},\ C_{ij} \sim 1 \quad \Longrightarrow \Lambda \gtrsim 25\ \text{TeV}$
- $Y_{ij} = \frac{v^2}{\sqrt{2}\Lambda^2} C_{ij},\ C_{ij} \sim \sqrt{m_i m_j}/v \Longrightarrow \Lambda \gtrsim 0.6\ \text{TeV}$

(Cheng-Sher Ansatz)

* Constraints to RS models with a proper setup

- $Y_{ij} = \frac{v^2}{\sqrt{2}\Lambda^2} C_{ij},\ C_{ij} \sim \max(m_i, m_j)/v \Longrightarrow M_{\text{KK}}(\Lambda) \gtrsim 2.5\ \text{TeV}$

Lepton flavor violation (Z)

$$\mathcal{L}^{Z\to\mu^\mp\tau^\pm} = g^L_{\mu\tau}\mu_L \not{Z}\tau_L + g^R_{\mu\tau}\bar{\mu}_R\not{Z}\tau_R + h.c.$$

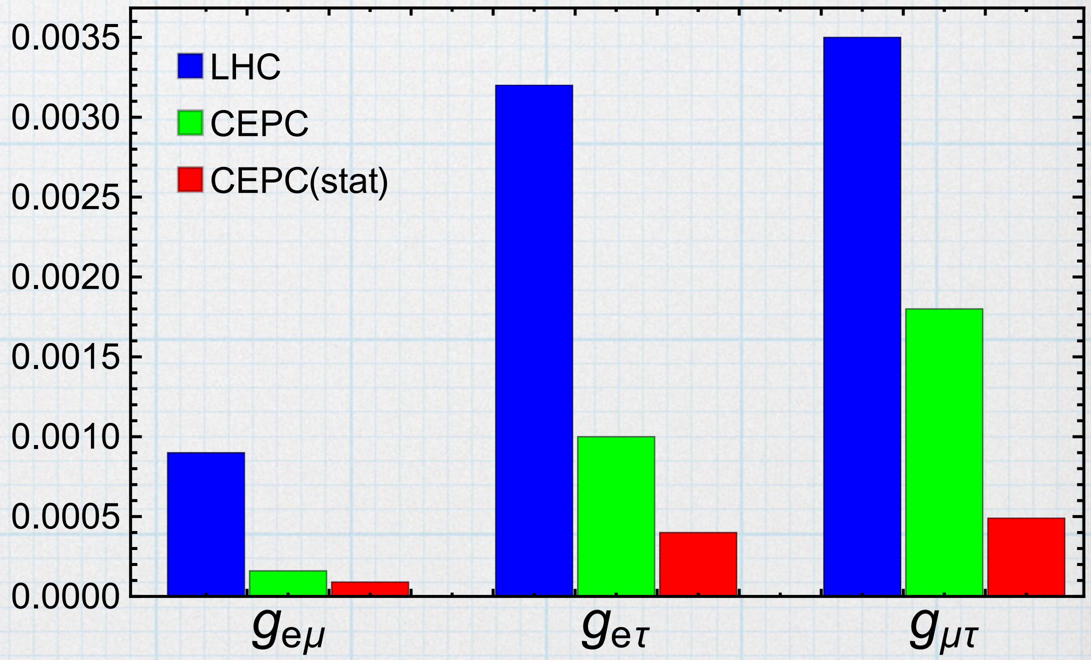
$$\Gamma(Z\to\mu^\mp\tau^\pm)_{m_{\mu,\tau}\to 0} = \frac{m_Z}{12\pi}(|g^L_{\mu\tau}|^2 + |g^R_{\mu\tau}|^2)$$

In estimation of the CEPC bounds (10 billion Z^0, about 0.2 ab^{-1}, or one year running with $10^{34}\ cm^{-2}s^{-1}$),

- the statistic uncertainties will be smaller than 2%,
- the systematic uncertainties are assumed to be 5%.

Channels	$\mu^\mp\tau^\pm$	$e^\mp\tau^\pm$	$e^\mp\mu^\pm$
current bound	3.5×10^{-3}	3.2×10^{-3}	0.9×10^{-3}
CEPC bound	1.8×10^{-3}	1.0×10^{-3}	1.6×10^{-4}
CEPC bound (only stat. unc.)	4.9×10^{-4}	4.0×10^{-4}	0.9×10^{-4}

Current (PDG2016) vs CEPC (rough estimates) bounds (95% CL) on the coefficients $g\equiv\sqrt{|g_L|^2+|g_R|^2}$



Lepton flavor violation (tau)

* There might be chances for CEPC

  - B factories: 10^9 taus;
  - CEPC: $10^9 \sim 10^{10}$ taus; ← High speed, high reconstruction eff.
  - Belle II: 10^{11} taus.

	$\tau \to 3\mu$	$\tau \to \mu\gamma$	$\tau \to \mu\pi^+\pi^-$	$\tau \to \mu K\bar{K}$	$\tau \to \mu\pi$	$\tau \to \mu\eta^{(\prime)}$
$O^{4\ell}_{S,V}$	✓	–	–	–	–	–
O_D	✓	✓	✓	✓	–	–
O^q_V	–	–	✓ (I=1)	✓(I=0,1)	–	–
O^q_S	–	–	✓ (I=0)	✓(I=0,1)	–	–
O_{GG}	–	–	✓	✓	–	–
O^q_A	–	–	–	–	✓ (I=1)	✓ (I=0)
O^q_P	–	–	–	–	✓ (I=1)	✓ (I=0)
$O_{G\tilde{G}}$	–	–	–	–	–	✓

- **for photon induced $\tau \to \mu$ transitions**

$$\mathcal{L}_{\rm eff}^{(D)} = -\frac{m_\tau}{\Lambda^2}\left[\left(C_{DR}\bar{\mu}\sigma^{\mu\nu}P_L\tau + C_{DL}\bar{\mu}\sigma^{\mu\nu}P_R\tau\right)F_{\mu\nu} + h.c.\right],$$

- **for gluon induced $\tau \to \mu$ transitions**

$$\mathcal{L}_{\rm eff}^{(G)} = -\frac{m_\tau G_F}{\Lambda^2}\frac{\beta_L}{4\alpha_s}\Big[\left(C_{GR}\bar{\mu}P_L\tau + C_{GL}\bar{\mu}P_R\tau\right)G^a_{\rho\sigma}G_a^{\rho\sigma} + \left(C_{\tilde{G}R}\bar{\mu}P_L\tau + C_{\tilde{G}L}\bar{\mu}P_R\tau\right)G^a_{\rho\sigma}\tilde{G}_a^{\rho\sigma} + h.c.\Big],$$

- **for four-lepton operators with $\tau \to \mu$ transitions**

$$\begin{aligned}\mathcal{L}_{\rm eff}^{(4\ell)} = -\frac{1}{\Lambda^2}\Big[&\left(C_{SLL}(\bar{\mu}P_L\tau)(\bar{\ell}P_L\ell) + C_{SRR}(\bar{\mu}P_R\tau)(\bar{\ell}P_R\ell)\right)\\ &+ \left(C_{SLR}(\bar{\mu}P_L\tau)(\bar{\ell}P_R\ell) + C_{SRL}(\bar{\mu}P_R\tau)(\bar{\ell}P_L\ell)\right)\\ &+ \left(C_{VLL}(\bar{\mu}\gamma^\mu P_L\tau)(\bar{\ell}\gamma_\mu P_L\ell) + C_{VRR}(\bar{\mu}\gamma^\mu P_R\tau)(\bar{\ell}\gamma_\mu P_R\ell)\right)\\ &+ \left(C_{VLR}(\bar{\mu}\gamma^\mu P_L\tau)(\bar{\ell}\gamma_\mu P_R\ell) + C_{VRL}(\bar{\mu}\gamma^\mu P_R\tau)(\bar{\ell}\gamma_\mu P_L\ell\right) + h.c.\Big],\end{aligned}$$

- **for lepton-quark operators with $\tau \to \mu$ transitions**

$$\begin{aligned}\mathcal{L}_{\rm eff}^{(\ell q)} = -\frac{1}{\Lambda^2}\sum_{q=u,d,s}\Big[&(C^q_{VR}\bar{\mu}\gamma^\rho P_R\tau + C^q_{VL}\bar{\mu}\gamma^\rho P_L\tau)\bar{q}\gamma_\rho q\\ &+ (C^q_{AR}\bar{\mu}\gamma^\rho P_R\tau + C^q_{AL}\bar{\mu}\gamma^\rho P_L\tau)\bar{q}\gamma_\rho\gamma_5 q\\ &+ m_\tau m_q G_F(C^q_{SR}\bar{\mu}P_L\tau + C^q_{SL}\bar{\mu}P_R\tau)\bar{q}q\\ &+ m_\tau m_q G_F(C^q_{PR}\bar{\mu}P_L\tau + C^q_{PL}\bar{\mu}P_R\tau)\bar{q}\gamma_5 q\\ &+ m_\tau m_q G_F(C^q_{TR}\bar{\mu}\sigma^{\rho\nu}P_L\tau + C^q_{TL}\bar{\mu}\sigma^{\rho\nu}P_R\tau)\bar{q}\sigma_{\rho\nu}q + h.c.\Big].\end{aligned}$$

Lepton flavor violation (tau)

* Constrain the tau-mu-gamma WCs by
  - the tau to muon gamma decay
  - the tau to 3 muon decay

$$\mathcal{L}_{\rm eff}^{(D)} = -\frac{m_\tau}{\Lambda^2}\left[\left(C_{DR}\bar{\mu}\sigma^{\mu\nu}P_L\tau + C_{DL}\bar{\mu}\sigma^{\mu\nu}P_R\tau\right)F_{\mu\nu} + h.c.\right]$$

$$\Gamma(\tau^- \to \mu^-\gamma)_{m_\mu\to 0} = \frac{m_\tau^5}{4\pi\Lambda^4}\left(|C_{DR}|^2 + |C_{DL}|^2\right)$$

$$\mathcal{B}[\tau \to 3\mu] \approx 1.4\times 10^{-3}\left(|C_{DR}|^2 + |C_{DL}|^2\right) \quad (\Lambda = 1\text{TeV})$$

Channels	$\tau \to \mu\gamma$	$\tau \to 3\mu$
current b.d. on $\mathcal{B}$	4.4×10^{-8}	2.1×10^{-8}
current b.d. on C_D	2.7×10^{-4}	3.9×10^{-3}
CEPC b.d. on $\mathcal{B}$	1.7×10^{-8}	3.9×10^{-9}
CEPC b.d. on C_D	1.6×10^{-4}	1.7×10^{-3}

Current and CEPC bounds (90% CL) on the coefficient $C_D \equiv \sqrt{|C_{DL}|^2 + |C_{DR}|^2}$

- N_τ: $\sim 10^9$ at B factories, $\sim 10^{10}$ at CEPC
- assuming same tau reconstruction efficiency
- statistic uncertainty dominant
- direct constraint is more stringent

Anomalous dipole moments of tau

(2nd example)

* **More sensitive to new physics**
  - Effects proportional to fermion mass

$$\Gamma^{\mu}_{Z} \ni -e\frac{\alpha^W_\tau}{2m_\tau}\sigma^{\mu\nu}q_\nu + ie\frac{d^W_\tau}{2m_\tau}\gamma_5\sigma^{\mu\nu}q_\nu$$

* **Weak moments at Z factories**
  - PDG values are still given by LEP1 (Z pole)

$$\frac{e}{2m_\tau}\mathrm{Re}(d^W_\tau) < 0.50\times 10^{-17} e\mathrm{cm}, \frac{e}{2m_\tau}\mathrm{Im}(d^W_\tau) < 1.1\times 10^{-17} e\mathrm{cm}, \text{(weak dipole moment)}$$

$$\mathrm{Re}(\alpha^W_\tau) < 1.1\times 10^{-3}, \mathrm{Im}(\alpha^W_\tau) < 2.7\times 10^{-3}, \text{(weak anomalous magnetic dipole moment)}$$

* **EM moments at Z and Higgs factories**
  - Anomalous magnetic moment

$$-0.052 < g_\tau - 2 < 0.058 \text{ (LEP1)} \Rightarrow -0.052 < g_\tau - 2 < 0.013 \text{ (LEP2, PDG)}$$

  - Electric dipole moment (EDM, CP violation)

$$-2.2 < \mathrm{Re}(d_\tau) < 4.5\ (10^{-17} e\mathrm{cm}), -2.5 < \mathrm{Im}(d_\tau) < 0.8\ (10^{-17} e\mathrm{cm}), \text{(Belle, PDG)}$$

$$|d_\tau| < 7.2\times 10^{-20} e\mathrm{cm}, \text{(Super B, 75 ab}^{-1}\text{)}$$

Anomalous dipole moments of tau

* Definition of the weak moments in currents

$$\Gamma^\mu_Z \ni ie\left[v_\tau\gamma^\mu - a_\tau\gamma^\mu\gamma_5 + i\frac{\alpha^w_\tau}{2m_\tau}\sigma^{\mu\nu}q_\nu + i\frac{d^w_\tau}{2m-\tau}\gamma_5\sigma^{\mu\nu}q_\nu\right]$$

* Effects of the moments in observables

$$\frac{d\sigma}{d\cos\theta_\tau}(s_1,s_2) = R_{00} + \sum_{\mu=1-3} R_{\mu 0}s_1^\mu + \sum_{\nu=1-3} R_{0\nu}s_2^\nu + \sum_{\mu,\nu=1-3} R_{\mu\nu}s_1^\mu s_2^\nu$$

For example

$$R_{13} + R_{31} \propto -\frac{\sqrt{s}}{2m_\tau}\sin\theta_\tau\cos\theta_\tau(|a_e|^2 + |v_e|^2)\mathrm{Im}(a_\tau^*\alpha^w_\tau)$$
$$-2\left(\frac{\sqrt{s}}{2m_\tau} - \frac{2m_\tau}{\sqrt{s}}\right)\sin\theta_\tau\mathrm{Re}(v_e a_e^*)\mathrm{Im}(v_\tau^*\alpha^w_\tau)$$

Linear dependence.

Anomalous dipole moments of tau

* Naive estimation of the CEPC precision

$$\frac{e}{2m_\tau}\mathrm{Re}(d_\tau^w) < 1.3 \times 10^{-19} e\mathrm{cm}, \quad \frac{e}{2m_\tau}\mathrm{Im}(d_\tau^w) < 2.8 \times 10^{-19} e\mathrm{cm},$$

$$\mathrm{Re}(\alpha_\tau^w) < 2.8 \times 10^{-5}, \mathrm{Im}(\alpha_\tau^w) < 6.8 \times 10^{-5}, (\mathrm{CEPC@Z\ with\ 0.2\ ab^{-1}})$$

An optimised version might come close to the SM prediction $\alpha_\tau^W = -(2.10 + 0.61i) \times 10^{-6}$ [hep-ph/9411289]

* Anomalous moments in the effective theory

Dim-6 operators

$$\mathcal{O}_B = \frac{\alpha'}{2\Lambda^2}\bar{L}_L H \sigma_{\mu\nu}\tau_R B^{\mu\nu},$$
$$\mathcal{O}_W = \frac{\alpha}{2\Lambda^2}\bar{L}_L \frac{\sigma_i}{2} H \sigma_{\mu\nu}\tau_R W_i^{\mu\nu}$$

→

$$\kappa_\tau^W = -(s_w c_w \alpha_\tau^w + s_w^2 \alpha_\tau^\gamma)$$
$$\left(\mathcal{L} \ni \frac{1}{\sqrt{2}}\kappa_\tau^W \frac{g}{2m_\tau}\bar{\nu}_\tau \sigma_{\mu\nu}\tau_R W_+^{\mu\nu} + h.c.\right)$$

Combine W decays to set bounds.

Summary

* CEPC is an ideal machine for measurements of Higgs and Z couplings (and tau relevant observables)
* Precision of the LFV Higgs decay rates will be improved significantly by CEPC, and also the LFV Z decay rates and anomalous weak moments of tau
* Competition on LFV tau decays and EDM of tau with Belle II

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Thank you for the attention!