# Probing top-quark flavor changing coupling at the CEPC

Cen Zhang

Institute of High Energy Physics

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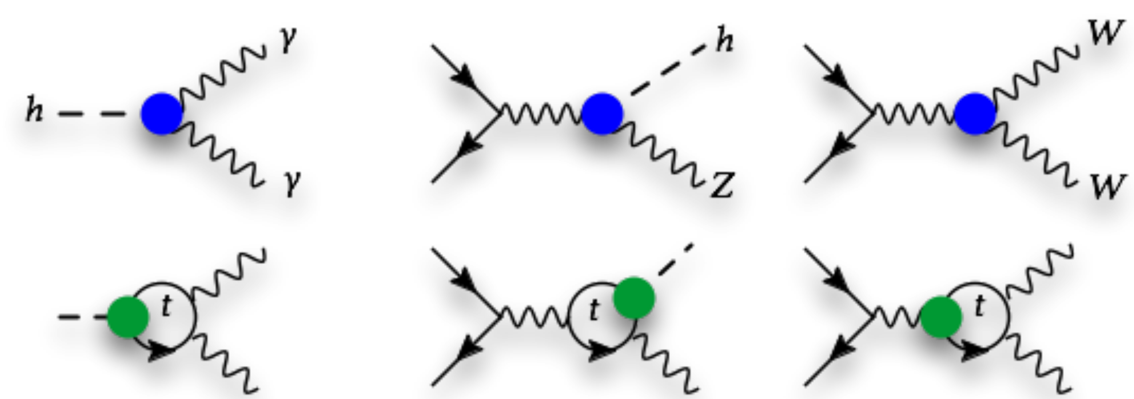
Based on 1906.04573 with Liaoshan Shi,
and going FCPPL project with Gauthier Durieux, Benjamin Fuks, Yi-Ming Liu, Hua-Sheng Shao, Liaoshan Shi, Yusheng Wu

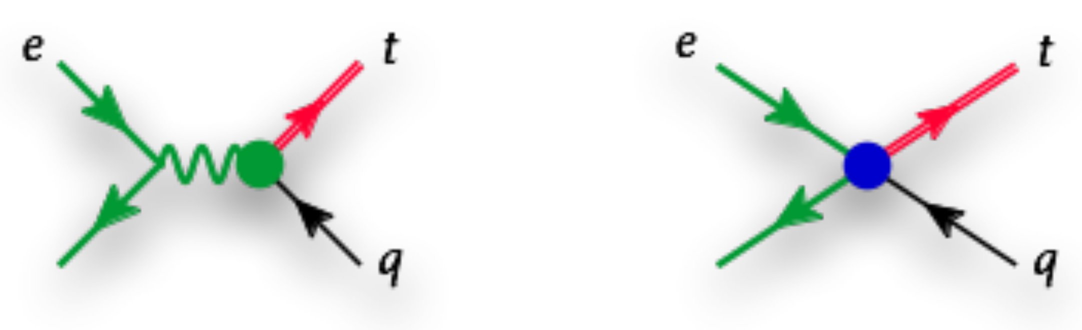
# Top physics at an ee collider below 350 GeV?

- At future Higgs factories, Ecm is optimized for Higgs. e.g. CEPC @ 240 GeV. What about top physics?
- Instead of producing pairs of on-shell tops, we might:
  - Study virtual tops

    [Durieux, Gu, Vryonidou, CZ '18]




  - Produce single top
    i.e. through flavor changing neutral current (FCNC)
    (may cover unexplored parameter space by LHC…)



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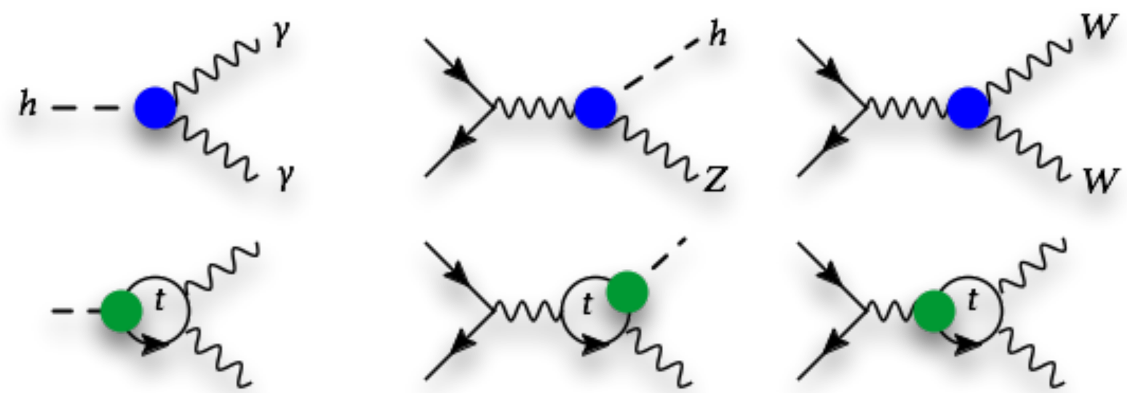


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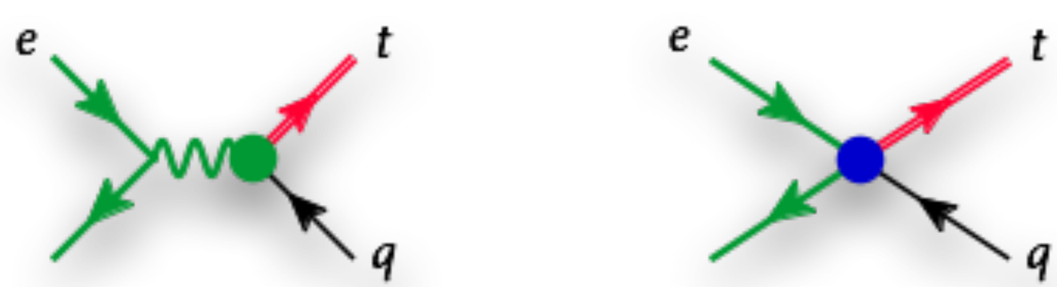


This talk

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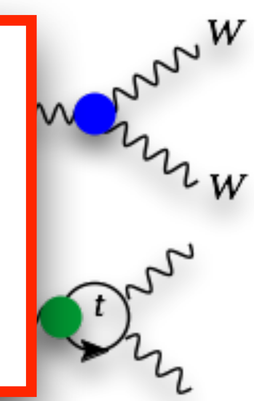
    [Durieux, G

- No fancy theory idea, just routine works
- But top FCNC is important, and in any case we need to know the prospects

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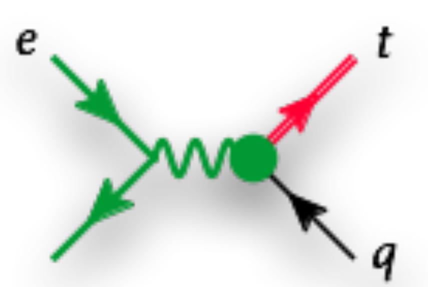
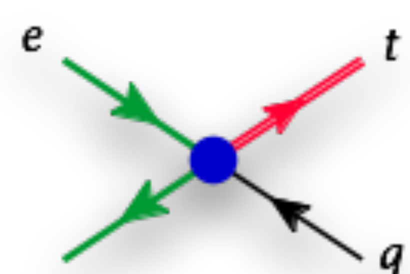
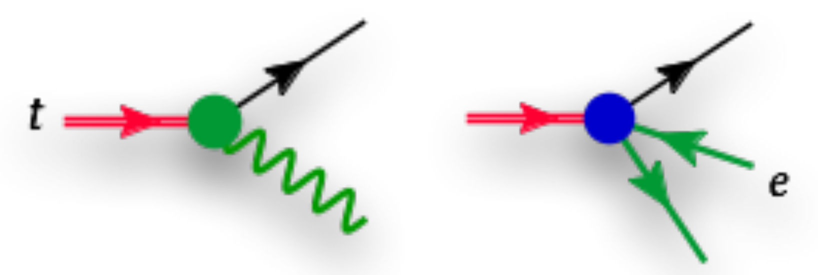



This talk

# Top FCNC

- Neutral couplings that involve one top quark and one light quark.




- Forbidden in the SM (by GIM mechanism) **Definite sign of BSM**.

| | $\text{Br}^{\text{SM}}$ | $\text{Br}^{\text{exp}}$ |
|---|---|---|
| $t \to cg$ | $\sim 10^{-11}$ | $\lesssim 10^{-4*}$ |
| $t \to c\gamma$ | $\sim 10^{-12}$ | $\lesssim 10^{-3*}$ |
| $t \to cZ$ | $\sim 10^{-13}$ | $\lesssim 10^{-4}$ |
| $t \to ch$ | $\sim 10^{-14}$ | $\lesssim 10^{-3}$ |

- A complete and systematic description of FCNC interactions based on **Standard Model Effective Field theory**:

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i^{(6)} O_i^{(6)}}{\Lambda^2} + \sum_i \frac{f_i^{(8)} O_i^{(8)}}{\Lambda^4} + \cdots$$

Leading dim-6 FCNC operators are classified in the TOP WG EFT notes.

[Aguilar-Saavedra et al. ’18]

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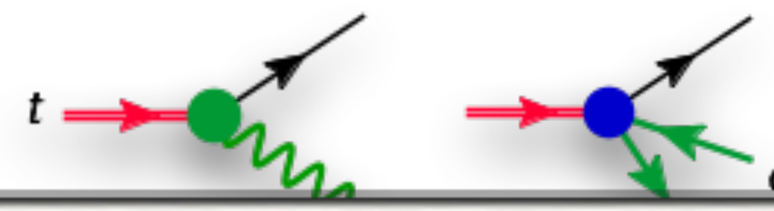


Interpreting top-quark LHC measurements in the standard-model effective field theory

J. A. Aguilar-Saavedra,[1] C. Degrande,[2] G. Durieux,[3]
F. Maltoni,[4] E. Vryonidou,[2] C. Zhang[5] (editors),
D. Barducci,[6] I. Brivio,[7] V. Cirigliano,[8] W. Dekens,[8,9] J. de Vries,[10] C. Englert,[11]
M. Fabbrichesi,[12] C. Grojean,[3,13] U. Haisch,[2,14] Y. Jiang,[7] J. Kamenik,[15,16]
M. Mangano,[2] D. Marzocca,[12] E. Mereghetti,[8] K. Mimasu,[4] L. Moore,[4] G. Perez,[17]
T. Plehn,[18] F. Riva,[2] M. Russell,[18] J. Santiago,[19] M. Schulze,[13] Y. Soreq,[20]
A. Tonero,[21] M. Trott,[7] S. Westhoff,[18] C. White,[22] A. Wulzer,[2,23,24] J. Zupan.[25]

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# Top FCNC

[Aguilar-Saavedra et al. '18]

[G. Durieux, the CLIC Potential for New Physics, CERN YR, 18]

## Warsaw basis operators

**[B. Grzadkowski et al. 10]**

$$O_{u\varphi}^{(ij)} = \bar{q}_i u_j \tilde{H}\,(H^\dagger H),$$
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## Relevant D.o.F for tops

**[Aguilar-Saavedra et al. ’18]**

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## 28 DoFs relevant for ee->tj

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CP even

| | | | | | | |
|---|---|---|---|---|---|---|
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Left-handed q

Right-handed q

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$$O_{\varphi u}^{(ij)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_i\gamma^\mu u_j),$$
$$O_{\varphi ud}^{(ij)} = (\tilde{H}^\dagger i D_\mu H)(\bar{u}_i\gamma^\mu d_j),$$
$$O_{uW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{H} W^I_{\mu\nu}$$
$$O_{dW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I d_j)\,H W^I_{\mu\nu},$$
$$O_{uB}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}u_j)\tilde{H} B_{\mu\nu},$$
$$O_{uG}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}T^A u_j)\,\tilde{H} G^A_{\mu\nu}.$$

$$O_{lq}^{1(ijkl)} = (\bar{l}_i\gamma^\mu l_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{lq}^{3(ijkl)} = (\bar{l}_i\gamma^\mu\tau^I l_j)(\bar{q}_k\gamma^\mu\tau^I q_l),$$
$$O_{lu}^{(ijkl)} = (\bar{l}_i\gamma^\mu l_j)(\bar{u}_k\gamma^\mu u_l),$$
$$O_{eq}^{(ijkl)} = (\bar{e}_i\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{eu}^{(ijkl)} = (\bar{e}_i\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_l),$$
$$O_{lequ}^{1(ijkl)} = (\bar{l}_i e_j)\;\varepsilon\;(\bar{q}_k u_l),$$
$$O_{lequ}^{3(ijkl)} = (\bar{l}_i\sigma^{\mu\nu}e_j)\;\varepsilon\;(\bar{q}_k\sigma_{\mu\nu}u_l),$$
$$O_{ledq}^{(ijkl)} = (\bar{l}_i e_j(\bar{d}_k q_l)(\bar{u}_k\gamma^\mu u_l),$$

## Relevant D.o.F for tops

[Aguilar-Saavedra et al. '18]

$$c_{\varphi q}^{-[I](3+a)} \equiv {}^{[\Im]}_{\Re}\{C_{\varphi q}^{1(3a)} - C_{\varphi q}^{3(3a)}\},$$
$$c_{\varphi u}^{[I](3+a)} \equiv {}^{[\Im]}_{\Re}\{C_{\varphi u}^{(3a)}\},$$
$$c_{uA}^{[I](3a)} \equiv {}^{[\Im]}_{\Re}\{c_W C_{uB}^{(3a)} + s_W C_{uW}^{(3a)}\},$$
$$c_{uA}^{[I](a3)} \equiv {}^{[\Im]}_{\Re}\{c_W C_{uB}^{(a3)} + s_W C_{uW}^{(a3)}\},$$
$$c_{uZ}^{[I](3a)} \equiv {}^{[\Im]}_{\Re}\{-s_W C_{uB}^{(3a)} + c_W C_{uW}^{(3a)}\},$$
$$c_{uZ}^{[I](a3)} \equiv {}^{[\Im]}_{\Re}\{-s_W C_{uB}^{(a3)} + c_W C_{uW}^{(a3)}\},$$

$$c_{lq}^{-[I](1,3+a)} \equiv {}^{[\Im]}_{\Re}\{C_{lq}^{-(113a)}\},$$
$$c_{eq}^{[I](1,3+a)} \equiv {}^{[\Im]}_{\Re}\{C_{eq}^{(113a)}\},$$
$$c_{lu}^{[I](1,3+a)} \equiv {}^{[\Im]}_{\Re}\{C_{lu}^{(113a)}\},$$
$$c_{eu}^{[I](1,3+a)} \equiv {}^{[\Im]}_{\Re}\{C_{eu}^{(113a)}\},$$
$$c_{lequ}^{S[I](1,3a)} \equiv {}^{[\Im]}_{\Re}\{C_{lequ}^{1(113a)}\},$$
$$c_{lequ}^{S[I](1,a3)} \equiv {}^{[\Im]}_{\Re}\{C_{lequ}^{1(11a3)}\},$$
$$c_{lequ}^{T[I](1,3a)} \equiv {}^{[\Im]}_{\Re}\{C_{lequ}^{3(113a)}\},$$
$$c_{lequ}^{T[I](1,a3)} \equiv {}^{[\Im]}_{\Re}\{C_{lequ}^{3(11a3)}\}.$$

## 28 DoFs relevant for ee->tj

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| CP even | $c_{lq}^{-(1,3+a)}$, | $c_{eq}^{(1,3+a)}$, | $c_{\varphi q}^{-(3+a)}$, | $c_{uA}^{(a3)}$, | $c_{uZ}^{(a3)}$, | $c_{lequ}^{S(1,a3)}$, | $c_{lequ}^{T(1,a3)}$, | Left-handed q |
| | $c_{lu}^{(1,3+a)}$, | $c_{eu}^{(1,3+a)}$, | | | | $c_{lequ}^{S(1,3a)}$, | $c_{lequ}^{T(1,3a)}$, | |
| CP odd | $c_{lq}^{-I(1,3+a)}$, | $c_{eq}^{I(1,3+a)}$, | | | | $c_{lequ}^{SI(1,a3)}$, | $c_{lequ}^{TI(1,a3)}$, | |
| | $c_{lu}^{I(1,3+a)}$, | $c_{eu}^{I(1,3+a)}$, | $c_{\varphi u}^{I(3+a)}$, | $c_{uA}^{I(3a)}$, | $c_{uZ}^{I(3a)}$, | $c_{lequ}^{SI(1,3a)}$, | $c_{lequ}^{TI(1,3a)}$, | Right-handed q |

Sufficient to focus on 7 parameters at a time

# Top FCNC

[Aguilar-Saavedra et al. '18]

[G. Durieux, the CLIC Potential for New Physics, CERN YR, 18]

## Warsaw basis operators

**[B. Grzadkowski et al. 10]**

$$O_{u\varphi}^{(ij)} = \bar{q}_i u_j \tilde{H}\,(H^\dagger H),$$
$$O_{\varphi q}^{1(ij)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_i\gamma^\mu q_j),$$
$$O_{\varphi q}^{3(ij)} = (H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_i\gamma^\mu\tau^I q_j),$$
$$O_{\varphi u}^{(ij)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_i\gamma^\mu u_j),$$
$$O_{\varphi ud}^{(ij)} = (\tilde{H}^\dagger iD_\mu H)(\bar{u}_i\gamma^\mu d_j),$$
$$O_{uW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{H}W^I_{\mu\nu}$$
$$O_{dW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I d_j)\,HW^I_{\mu\nu},$$
$$O_{uB}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}u_j)\tilde{H}B_{\mu\nu},$$
$$O_{uG}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}T^A u_j)\,\tilde{H}G^A_{\mu\nu}.$$
$$O_{lq}^{1(ijkl)} = (\bar{l}_i\gamma^\mu l_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{lq}^{3(ijkl)} = (\bar{l}_i\gamma^\mu\tau^I l_j)(\bar{q}_k\gamma^\mu\tau^I q_l),$$
$$O_{lu}^{(ijkl)} = (\bar{l}_i\gamma^\mu l_j)(\bar{u}_k\gamma^\mu u_l),$$
$$O_{eq}^{(ijkl)} = (\bar{e}_i\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{eu}^{(ijkl)} = (\bar{e}_i\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_l),$$
$$O_{lequ}^{1(ijkl)} = (\bar{l}_i e_j)\ \varepsilon\ (\bar{q}_k u_l),$$
$$O_{lequ}^{3(ijkl)} = (\bar{l}_i\sigma^{\mu\nu} e_j)\ \varepsilon\ (\bar{q}_k\sigma_{\mu\nu} u_l),$$
$$O_{ledq}^{(ijkl)} = (\bar{l}_i e_j(\bar{d}_k q_l)(\bar{u}_k\gamma^\mu u_l),$$

## Relevant D.o.F for tops

**[Aguilar-Saavedra et al. '18]**

$$c_{\varphi q}^{-[I](3+a)} \equiv {}^{[\Im]}_{\Re}\{C_{\varphi q}^{1(3a)} - C_{\varphi q}^{3(3a)}\},$$
$$c_{\varphi u}^{[I](3+a)} \equiv {}^{[\Im]}_{\Re}\{C_{\varphi u}^{(3a)}\},$$
$$c_{uA}^{[I](3a)} \equiv {}^{[\Im]}_{\Re}\{c_W C_{uB}^{(3a)} + s_W C_{uW}^{(3a)}\},$$
$$c_{uA}^{[I](a3)} \equiv {}^{[\Im]}_{\Re}\{c_W C_{uB}^{(a3)} + s_W C_{uW}^{(a3)}\},$$
$$c_{uZ}^{[I](3a)} \equiv {}^{[\Im]}_{\Re}\{-s_W C_{uB}^{(3a)} + c_W C_{uW}^{(3a)}\},$$
$$c_{uZ}^{[I](a3)} \equiv {}^{[\Im]}_{\Re}\{-s_W C_{uB}^{(a3)} + c_W C_{uW}^{(a3)}\},$$
$$c_{lq}^{-[I](1,3+a)} \equiv {}^{[\Im]}_{\Re}\{C_{lq}^{-(113a)}\},$$
$$c_{eq}^{[I](1,3+a)} \equiv {}^{[\Im]}_{\Re}\{C_{eq}^{(113a)}\},$$
$$c_{lu}^{[I](1,3+a)} \equiv {}^{[\Im]}_{\Re}\{C_{lu}^{(113a)}\},$$
$$c_{eu}^{[I](1,3+a)} \equiv {}^{[\Im]}_{\Re}\{C_{eu}^{(113a)}\},$$
$$c_{lequ}^{S[I](1,3a)} \equiv {}^{[\Im]}_{\Re}\{C_{lequ}^{1(113a)}\},$$
$$c_{lequ}^{S[I](1,a3)} \equiv {}^{[\Im]}_{\Re}\{C_{lequ}^{1(11a3)}\},$$
$$c_{lequ}^{T[I](1,3a)} \equiv {}^{[\Im]}_{\Re}\{C_{lequ}^{3(113a)}\},$$
$$c_{lequ}^{T[I](1,a3)} \equiv {}^{[\Im]}_{\Re}\{C_{lequ}^{3(11a3)}\}.$$

## 28 DoFs relevant for ee->tj

| | | | | | | |
|---|---|---|---|---|---|---|
| $c_{lq}^{-(1,3+a)}$, | $c_{eq}^{(1,3+a)}$, | $c_{\varphi q}^{-(3+a)}$, | $c_{uA}^{(a3)}$, | $c_{uZ}^{(a3)}$, | $c_{lequ}^{S(1,a3)}$, | $c_{lequ}^{T(1,a3)}$, |
| $c_{lu}^{(1,3+a)}$, | $c_{eu}^{(1,3+a)}$, | | | | $c_{lequ}^{S(1,3a)}$, | $c_{lequ}^{T(1,3a)}$, |
| $c_{lq}^{-I(1,3+a)}$, | $c_{eq}^{I(1,3+a)}$, | | | | $c_{lequ}^{SI(1,a3)}$, | $c_{lequ}^{TI(1,a3)}$, |
| $c_{lu}^{I(1,3+a)}$, | $c_{eu}^{I(1,3+a)}$, | $c_{\varphi u}^{I(3+a)}$, | $c_{uA}^{I(3a)}$, | $c_{uZ}^{I(3a)}$, | $c_{lequ}^{SI(1,3a)}$, | $c_{lequ}^{TI(1,3a)}$, |

Sufficient to focus on 7 parameters at a time

CP even

CP odd

a=1: tuV/tull

a=2: tcV/tcll

Left-handed q

Right-handed q

# Top FCNC: 2-fermion and 4-fermion operators

28 DoFs relevant for ee

$$
\begin{array}{lllllll}
c_{\varphi q}^{-(3+a)}, & c_{uA}^{(a3)}, & c_{uZ}^{(a3)}, & c_{lequ}^{S(1,a3)}, & c_{lequ}^{T(1,a3)}, & c_{lq}^{-(1,3+a)}, & c_{eq}^{(1,3+a)}, \\
c_{\varphi u}^{(3+a)}, & c_{uA}^{(3a)}, & c_{uZ}^{(3a)}, & c_{lequ}^{S(1,3a)}, & c_{lequ}^{T(1,3a)}, & c_{lu}^{(1,3+a)}, & c_{eu}^{(1,3+a)}, \\
c_{\varphi q}^{-I(3+a)}, & c_{uA}^{I(a3)}, & c_{uZ}^{I(a3)}, & c_{lequ}^{SI(1,a3)}, & c_{lequ}^{TI(1,a3)}, & c_{lq}^{-I(1,3+a)}, & c_{eq}^{I(1,3+a)} \\
c_{\varphi u}^{I(3+a)}, & c_{uA}^{I(3a)}, & c_{uZ}^{I(3a)}, & c_{lequ}^{SI(1,3a)}, & c_{lequ}^{TI(1,3a)}, & c_{lu}^{I(1,3+a)}, & c_{eu}^{I(1,3+a)}
\end{array}
$$

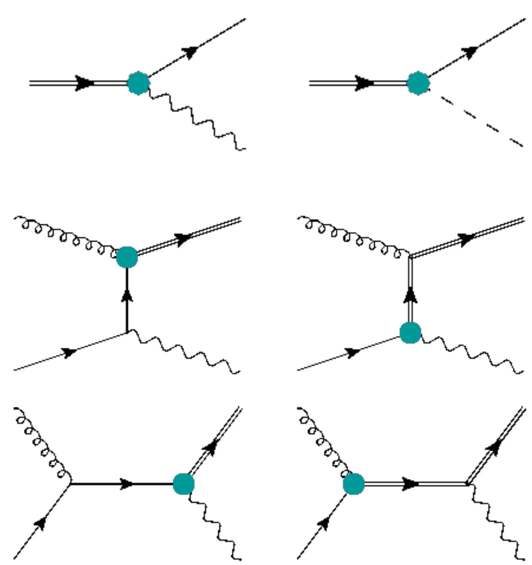
# Top FCNC: 2-fermion and 4-fermion operators

28 DoFs relevant for ee

| | | | | | | |
|---|---|---|---|---|---|---|
| $c_{\varphi q}^{-(3+a)}$, | $c_{uA}^{(a3)}$, | $c_{uZ}^{(a3)}$, | $c_{lequ}^{S(1,a3)}$, | $c_{lequ}^{T(1,a3)}$, | $c_{lq}^{-(1,3+a)}$, | $c_{eq}^{(1,3+a)}$, |
| $c_{\varphi u}^{(3+a)}$, | $c_{uA}^{(3a)}$, | $c_{uZ}^{(3a)}$, | $c_{lequ}^{S(1,3a)}$, | $c_{lequ}^{T(1,3a)}$, | $c_{lu}^{(1,3+a)}$, | $c_{eu}^{(1,3+a)}$, |
| $c_{\varphi q}^{-I(3+a)}$, | $c_{uA}^{I(a3)}$, | $c_{uZ}^{I(a3)}$, | $c_{lequ}^{SI(1,a3)}$, | $c_{lequ}^{TI(1,a3)}$, | $c_{lq}^{-I(1,3+a)}$, | $c_{eq}^{I(1,3+a)}$ |
| $c_{\varphi u}^{I(3+a)}$, | $c_{uA}^{I(3a)}$, | $c_{uZ}^{I(3a)}$, | $c_{lequ}^{SI(1,3a)}$, | $c_{lequ}^{TI(1,3a)}$, | $c_{lu}^{I(1,3+a)}$, | $c_{eu}^{I(1,3+a)}$ |

## 2-fermion FCNC

$$\bar{q}\gamma^\mu q \quad \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi,$$
$$\bar{q}\gamma^\mu \tau^I q \quad \varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi,$$
$$\bar{u}\gamma^\mu u \quad \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi,$$
$$\bar{q}\sigma^{\mu\nu} u\, \tilde{\varphi} \quad B_{\mu\nu},$$
$$\bar{q}\sigma^{\mu\nu}\tau^I u\, \tilde{\varphi} \quad W^I_{\mu\nu},$$

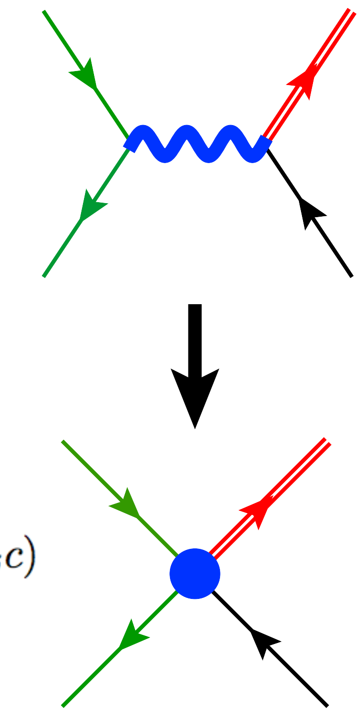


# Top FCNC: 2-fermion and 4-fermion operators

28 DoFs relevant for ee

$$
\begin{array}{lll}
c_{\varphi q}^{-(3+a)}, & c_{uA}^{(a3)}, & c_{uZ}^{(a3)}, \\
c_{\varphi u}^{(3+a)}, & c_{uA}^{(3a)}, & c_{uZ}^{(3a)}, \\
c_{\varphi q}^{-I(3+a)}, & c_{uA}^{I(a3)}, & c_{uZ}^{I(a3)}, \\
c_{\varphi u}^{I(3+a)}, & c_{uA}^{I(3a)}, & c_{uZ}^{I(3a)},
\end{array}
\qquad
\begin{array}{llll}
c_{lequ}^{S(1,a3)}, & c_{lequ}^{T(1,a3)}, & c_{lq}^{-(1,3+a)}, & c_{eq}^{(1,3+a)}, \\
c_{lequ}^{S(1,3a)}, & c_{lequ}^{T(1,3a)}, & c_{lu}^{(1,3+a)}, & c_{eu}^{(1,3+a)}, \\
c_{lequ}^{SI(1,a3)}, & c_{lequ}^{TI(1,a3)}, & c_{lq}^{-I(1,3+a)}, & c_{eq}^{I(1,3+a)}, \\
c_{lequ}^{SI(1,3a)}, & c_{lequ}^{TI(1,3a)}, & c_{lu}^{I(1,3+a)}, & c_{eu}^{I(1,3+a)}
\end{array}
$$

4-fermion FCNC

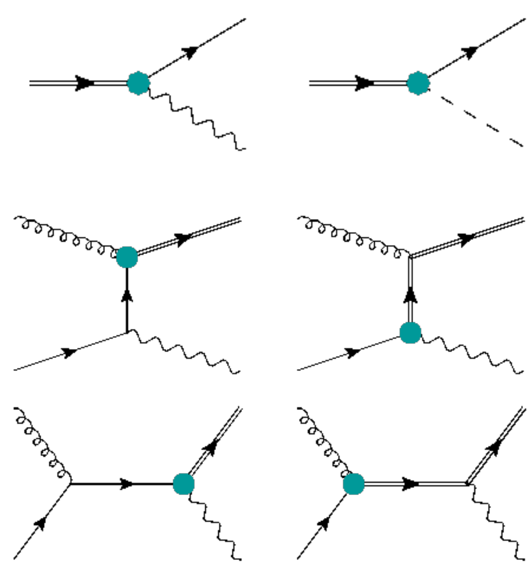


$$
\mathcal{L}_{tcee} = \frac{1}{\Lambda^2}\sum_{i,j=L,R}\Big[V_{ij}\,(\bar e\gamma_\mu P_i e)\,(\bar t\gamma^\mu P_j c) + S_{ij}\,(\bar e P_i e)\,(\bar t P_j c) + T_{ij}\,(\bar e\sigma_{\mu\nu}P_i e)\,(\bar t\sigma_{\mu\nu}P_j c)\Big],
$$

**[Bar-Shalom, Wudka '99]**

2-fermion FCNC

$$
\begin{array}{ll}
\bar q\gamma^\mu q & \varphi^\dagger i\overleftrightarrow{D}_\mu\varphi, \\
\bar q\gamma^\mu\tau^I q & \varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi, \\
\bar u\gamma^\mu u & \varphi^\dagger i\overleftrightarrow{D}_\mu\varphi, \\
\bar q\sigma^{\mu\nu}u\,\tilde\varphi & B_{\mu\nu}, \\
\bar q\sigma^{\mu\nu}\tau^I u\,\tilde\varphi & W^I_{\mu\nu},
\end{array}
$$



| Scenario | Hadronic topology | | | | Semi-leptonic topology | | | | Combined topologies | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | obs. | $-1\sigma$ | exp. | $+1\sigma$ | obs. | $-1\sigma$ | exp. | $+1\sigma$ | obs. | $-1\sigma$ | exp. | $+1\sigma$ |
| $SVT$ | 1218 | 1268 | 1180 | 1097 | 1315 | 1406 | 1301 | 1203 | 1402 | 1468 | 1366 | 1264 |
| $S$ | 577 | 604 | 556 | 520 | 647 | 647 | 603 | 555 | 685 | 693 | 641 | 593 |
| $V$ | 953 | 1003 | 933 | 863 | 997 | 1069 | 997 | 921 | 1073 | 1141 | 1068 | 980 |
| $T$ | 1069 | 1117 | 1045 | 969 | 1124 | 1232 | 1142 | 1052 | 1204 | 1300 | 1210 | 1114 |

Table 5: Observed and expected 95% CL lower limits on $\Lambda$ (GeV)

**[DELPHI, CERN–PH–EP/2010–056]**

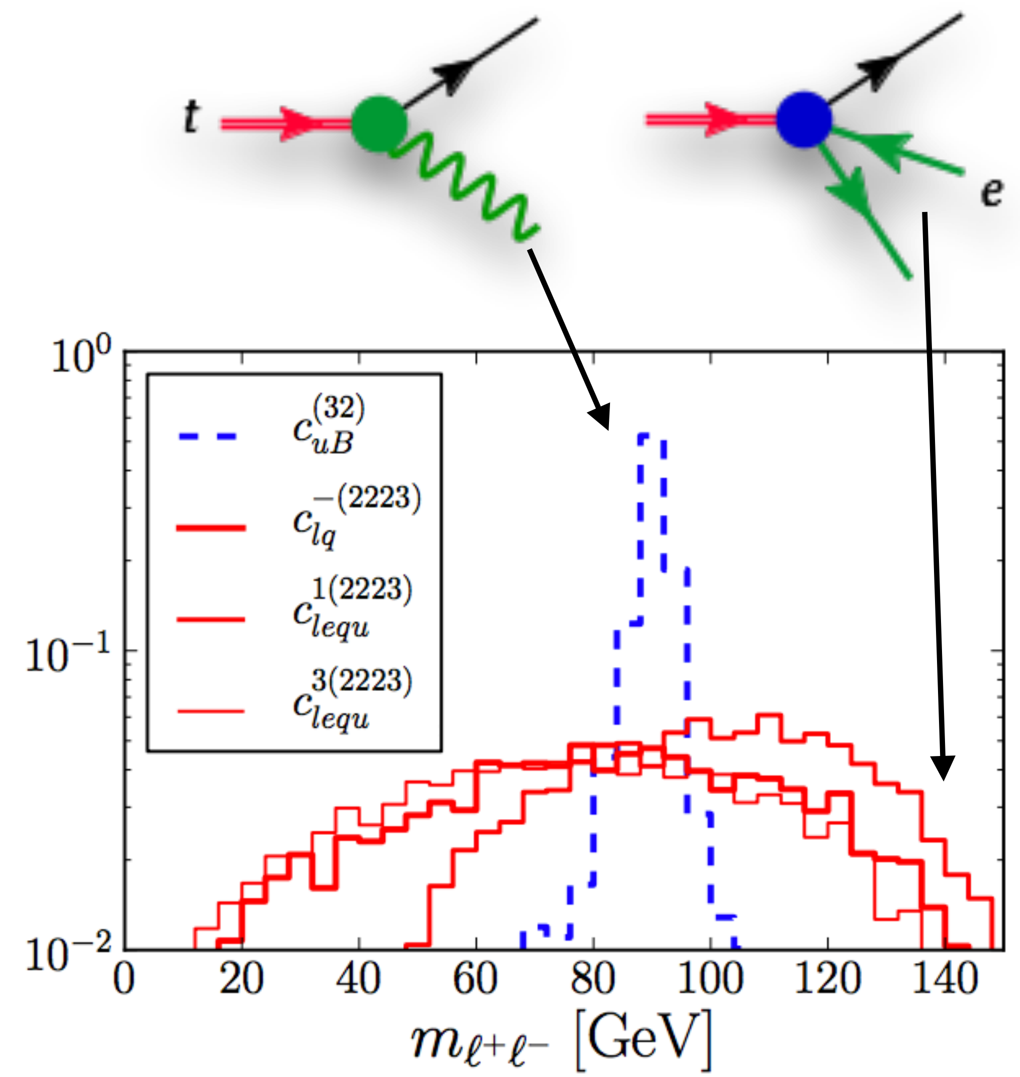
# Top FCNC: 2-fermion and 4-fermion operators

- Currently no dedicated search for 4f eetq couplings at the LHC/Tevatron
- Recasting existing bound from t>qZ (->ee) suffer from the $M_{ee}$ mass window cut.
- Best official bounds are from LEP2
- Recast limits from LHC:

| | $c_{lq}^{-(2223)}$ | $c_{eq}^{(2223)}$ | $c_{lu}^{(2223)}$ | $c_{eu}^{(2223)}$ | $c_{lequ}^{1(2223)}$ | $c_{lequ}^{1(2232)}$ | $c_{lequ}^{3(2223)}$ | $c_{lequ}^{3(2232)}$ |
|---|---|---|---|---|---|---|---|---|
| CR1 | **8.4** (1.2) | **8.4** (1.2) | **8.4** (1.2) | **8.4** (1.2) | **18** (2.7) | **18** (2.7) | **2.3** (0.35) | **2.3** (0.35) |
| NEW | 3.1 (1.0) | 3.1 (1.0) | 3.1 (1.0) | 3.1 (1.0) | 6.8 (2.2) | 6.8 (2.2) | 0.87 (0.28) | 0.87 (0.28) |

Table 2: Bounds on $c$ for $\Lambda = 1$ TeV, asuming one operator at a time, using the different signal regions defined in the text. The numbers without (within) parenthesis stand for the LHC13 (HL-LHC). The boldface indicates limits using actual data. These numbers can be obtained from the master equation (2.14) using the coefficients in Table 1 and the upper bound on the following number of signal events: $s_{\max}^{CR1} = 143$ (315) and $s_{\max}^{NEW} = 18$ (179), where again the number in brackets correspond to HL-LHC projections. The projected bounds on the coefficients get a factor of $\sim 3$ weaker for systematic uncertainties of 10 %.

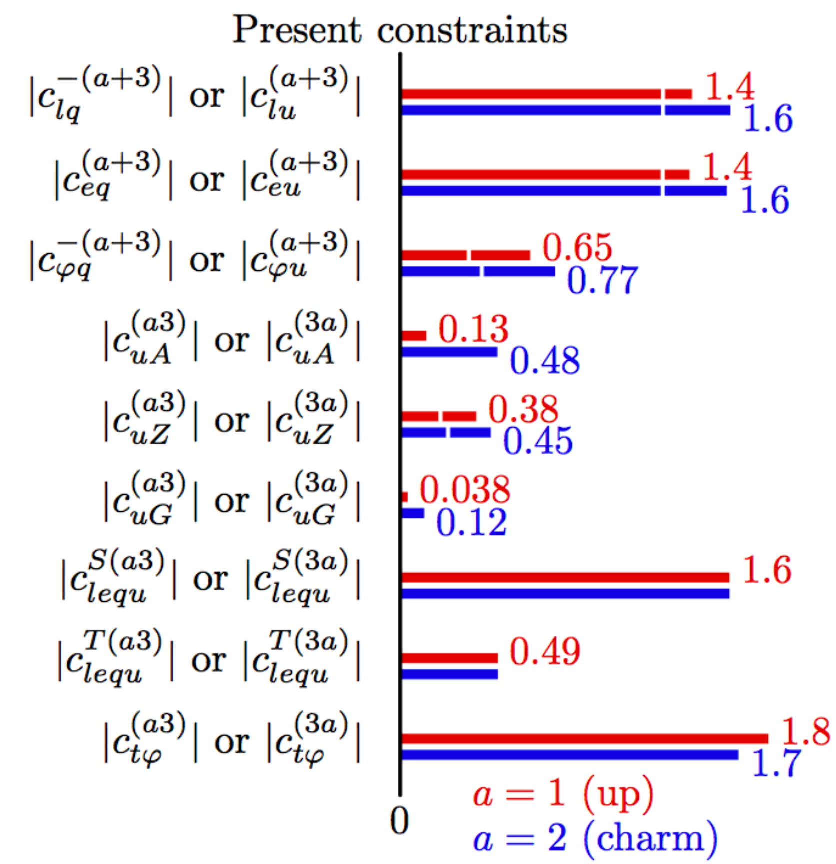
[Chala, Santiago, Spannowsky '18]



# Top FCNC: current limits

| Mode | $\mathrm{Br}^{95\%\mathrm{CL}}$ | Ref. | exp. | $\sqrt{s}$ | $\mathcal{L}$ | remarks |
|---|---|---|---|---|---|---|
| $t \to qZ$ | | | | | | |
| $u$ | $\mathbf{1.7 \times 10^{-4}}$ | [1176] | ATLAS | 13 TeV | $36.1\,\mathrm{fb}^{-1}$ | decay, $\lvert m_{\ell\ell} - m_Z \rvert < 15$ GeV |
| $c$ | $\mathbf{2.4 \times 10^{-4}}$ | | | | | |
| $u$ | $2.4 \times 10^{-4}$ | [1177] | CMS | 13 TeV | $35.9\,\mathrm{fb}^{-1}$ | production plus decay |
| $c$ | $4.5 \times 10^{-4}$ | | | | | |
| $u$ | $2.2 \times 10^{-4}$ | [1178] | CMS | 8 TeV | $19.7\,\mathrm{fb}^{-1}$ | production, $76 < m_{\ell\ell} < 106$ GeV |
| $c$ | $4.9 \times 10^{-4}$ | | | | | |
| $t \to qg$ | | | | | | |
| $u$ | $0.40 \times 10^{-4}$ | [1179] | ATLAS | 8 TeV | $20.3\,\mathrm{fb}^{-1}$ | $\sigma(pp \to t) \times \mathrm{Br}(t \to bW) < 3.4$ pb |
| $c$ | $\mathbf{2.0 \times 10^{-4}}$ | | | | | |
| $u$ | $\mathbf{0.20 \times 10^{-4}}$ | [1180] | CMS | 7, 8 TeV | $5.0, 17.9\,\mathrm{fb}^{-1}$ | in $pp \to tj$ |
| $c$ | $4.1 \times 10^{-4}$ | | | | | |
| $t \to q\gamma$ | | | | | | |
| $u$ | $\mathbf{1.3 \times 10^{-4}}$ | [1175] | CMS | 8 TeV | $19.8\,\mathrm{fb}^{-1}$ | $\sigma(pp \to t\gamma) \times \mathrm{Br}(t \to bl\nu) < 26$ fb |
| $c$ | $\mathbf{17 \times 10^{-4}}$ | | | | | $\sigma(pp \to t\gamma) \times \mathrm{Br}(t \to bl\nu) < 37$ fb |
| $t \to qh$ | | | | | | |
| $u$ | $\mathbf{19 \times 10^{-4}}$ | [1181] | ATLAS | 13 TeV | $36.1\,\mathrm{fb}^{-1}$ | multilepton channel |
| $c$ | $\mathbf{16 \times 10^{-4}}$ | | | | | |
| $u$ | $55 \times 10^{-4}$ | [1182] | CMS | 8 TeV | $19.7\,\mathrm{fb}^{-1}$ | multilepton, $\gamma\gamma$, $b\bar{b}$ |
| $c$ | $40 \times 10^{-4}$ | | | | | |
| $u$ | $47 \times 10^{-4}$ | [1183] | CMS | 13 TeV | $35.9\,\mathrm{fb}^{-1}$ | $b\bar{b}$ |
| $c$ | $47 \times 10^{-4}$ | | | | | |

[HL/HE-LHC yellow report]




[Durieux, Kitahara, CZ ’18]

# Top FCNC: current limits

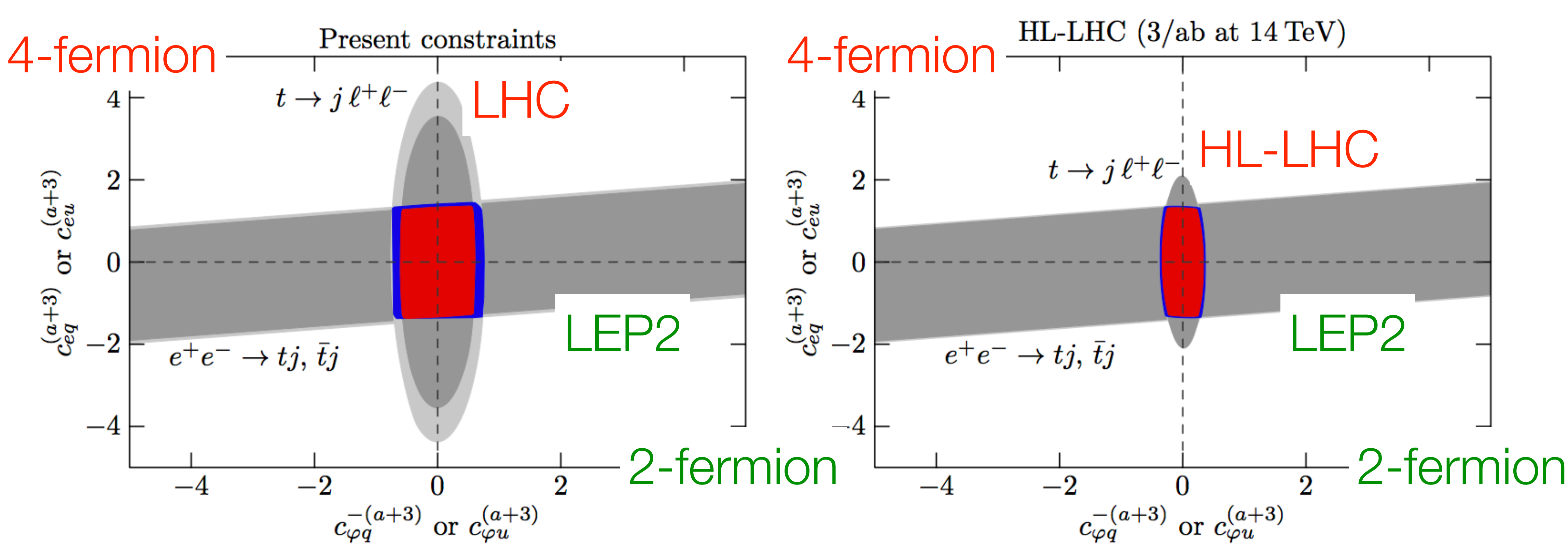


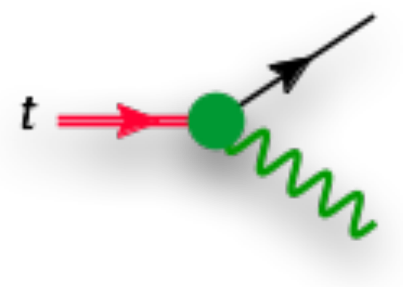

Fig. 59: Current (left) and prospective HL-LHC (right) 95% C.L. limits on top-quark FCNC operator coefficients in a two-dimensional plane formed by two- ($x$ axis) and four-fermion ($y$ axis) operator coefficients. Other parameters are marginalized over, within the constraints obtained when all measurements are included. Red and blue regions are the combined constraints for top-up and top-charm FCNCs. The impact of $t \to j\ell^+\ell^-$ and $e^+e^- \to tj, \bar{t}j$ measurements is displayed separately in dark and light gray colors for top-up and top-charm FCNCs, respectively.

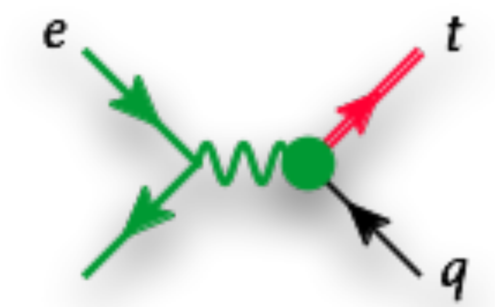
[HL/HE-LHC yellow report]

LHC

ee collider

2-fermion OP

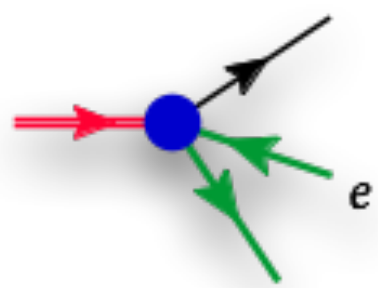


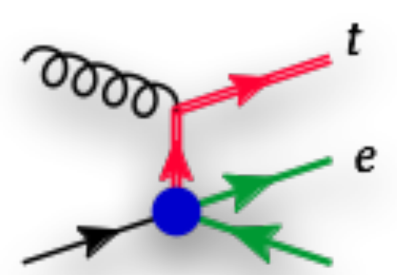



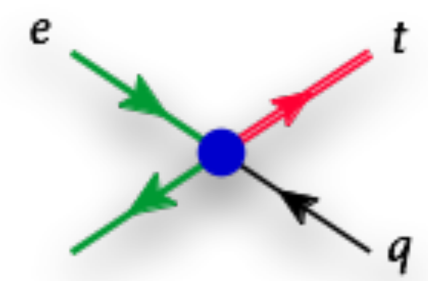

2f: 8.1e-5 GeV

2f: 1.8 fb

4-fermion OP



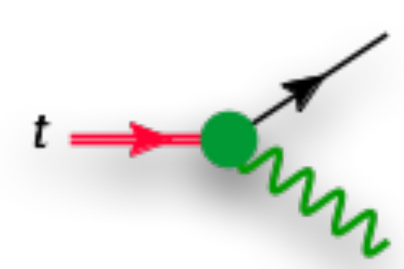
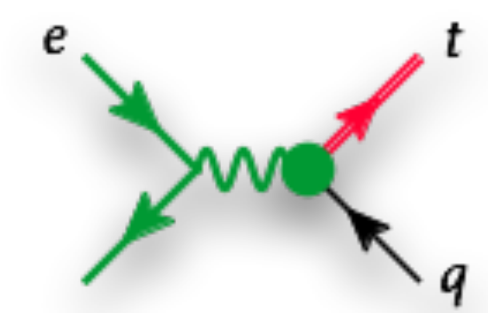
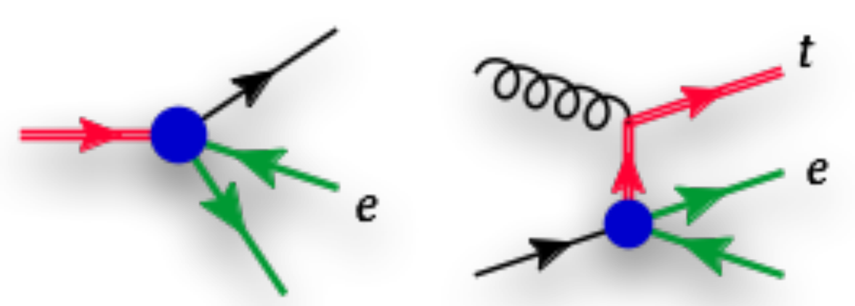
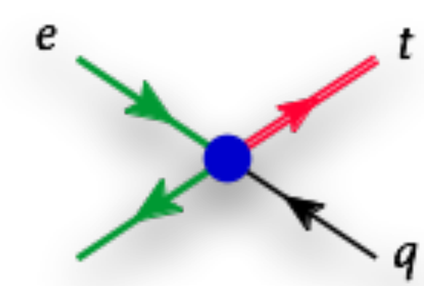




Phase space suppression

$E^4/m_Z^4$ scaling enhancement

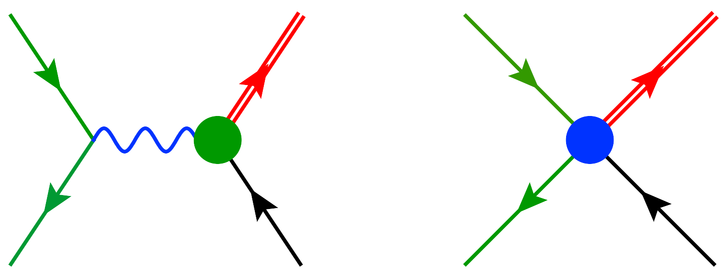
4f: 3.2e-6 GeV

4f: 120 fb

| | LHC | ee collider |
|---|---|---|
| 2-fermion OP |  2f: 8.1e-5 GeV |  2f: 1.8 fb |
| 4-fermion OP |  Phase space suppression<br>4f: 3.2e-6 GeV |  $E^4/m_Z^4$ scaling enhancement<br>4f: 120 fb |

# Top FCNC: MC tool

- Leading order, MadGraph+UFO
  - One model for all top operators: **`dim6top`**
    https://feynrules.irmp.ucl.ac.be/wiki/dim6top [Durieux, CZ '19]



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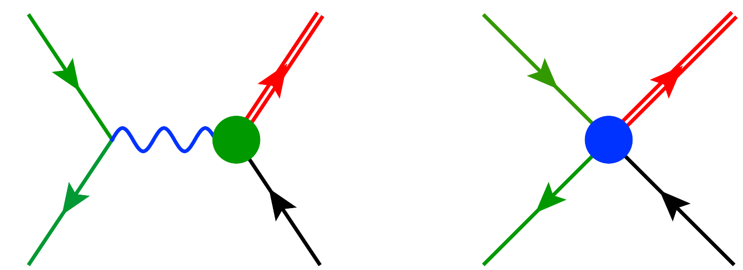
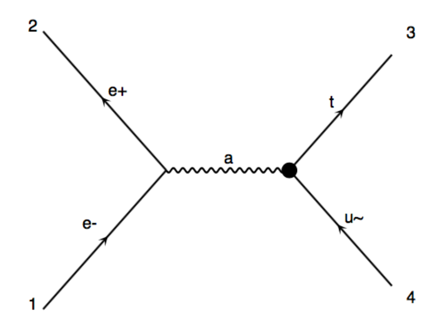
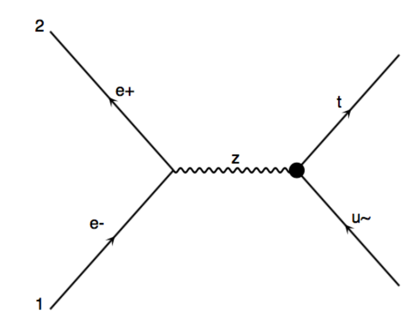


- QCD corrections: FCNC specific UFO. Need 4f implementation
  http://feynrules.irmp.ucl.ac.be/wiki/TopFCNC [Degrande, Maltoni, Wang, CZ '14]

```
MG5_aMC>import model TopFCNC
MG5_aMC>generate e- e+ > t j NP=2 [QCD]
MG5_aMC>output
MG5_aMC>launch
```




born diagram 1 NP=2, QCD=0, QED=2




born diagram 2 NP=2, QCD=0, QED=1

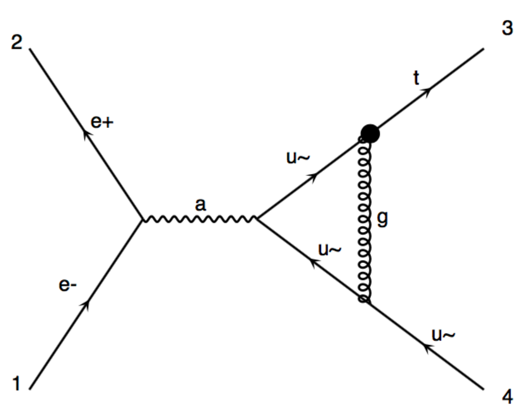



diagram 3 NP=2, QCD=2, QED=2

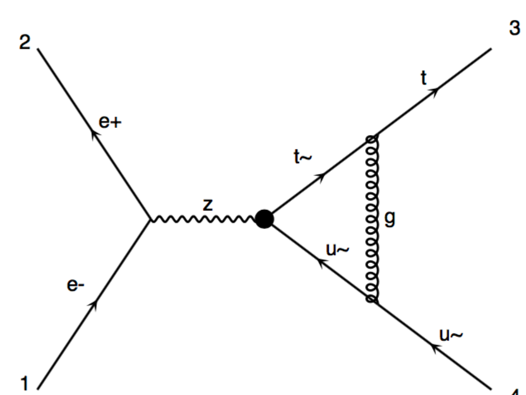
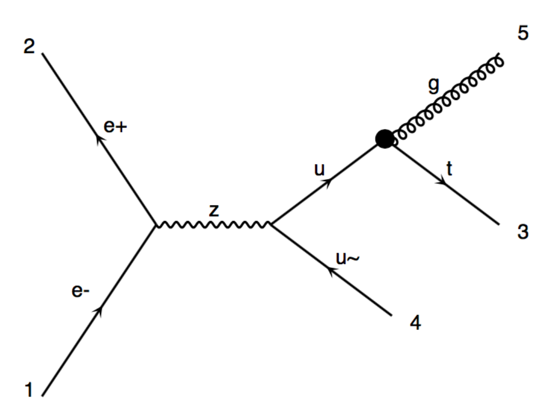
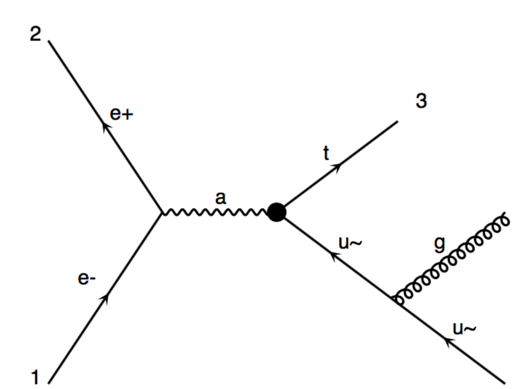



diagram 4 NP=2, QCD=2, QED=1




real diagram 5 NP=2, QCD=1, QED=2

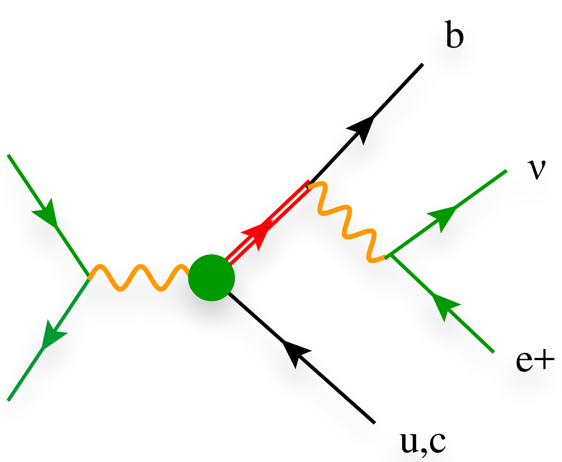


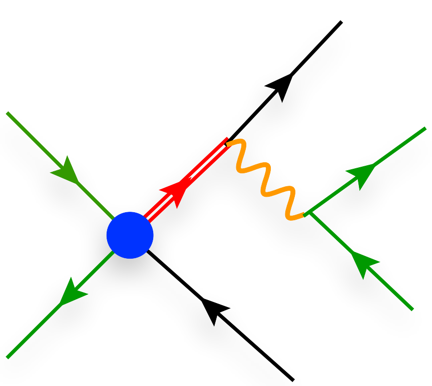

real diagram 6 NP=2, QCD=1, QED=2

# Results for CEPC

Produced by Liaoshan Shi (who will answer all hard questions)

- CEPC scenario, 240 GeV, 5.6 $ab^{-1}$
- Signal and backgrounds both simulated at LO+PS, with MadGraph5 and Pythia8
- FCNC implementation: **`dim6top`**
- Detector effects: Delphes with CEPC card
- Signal:

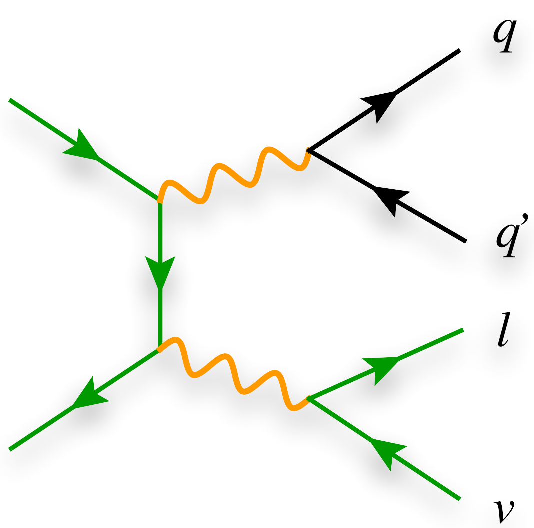


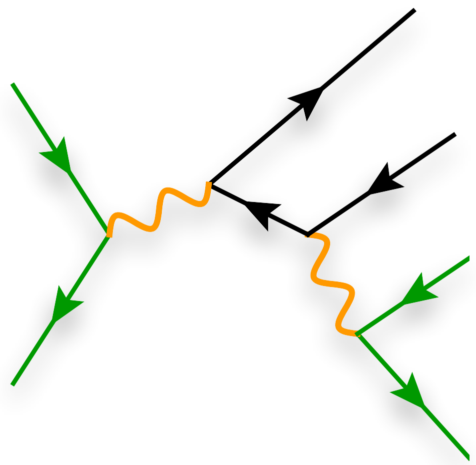



$$m_{top,rec} \approx 172.5 \text{ GeV}$$

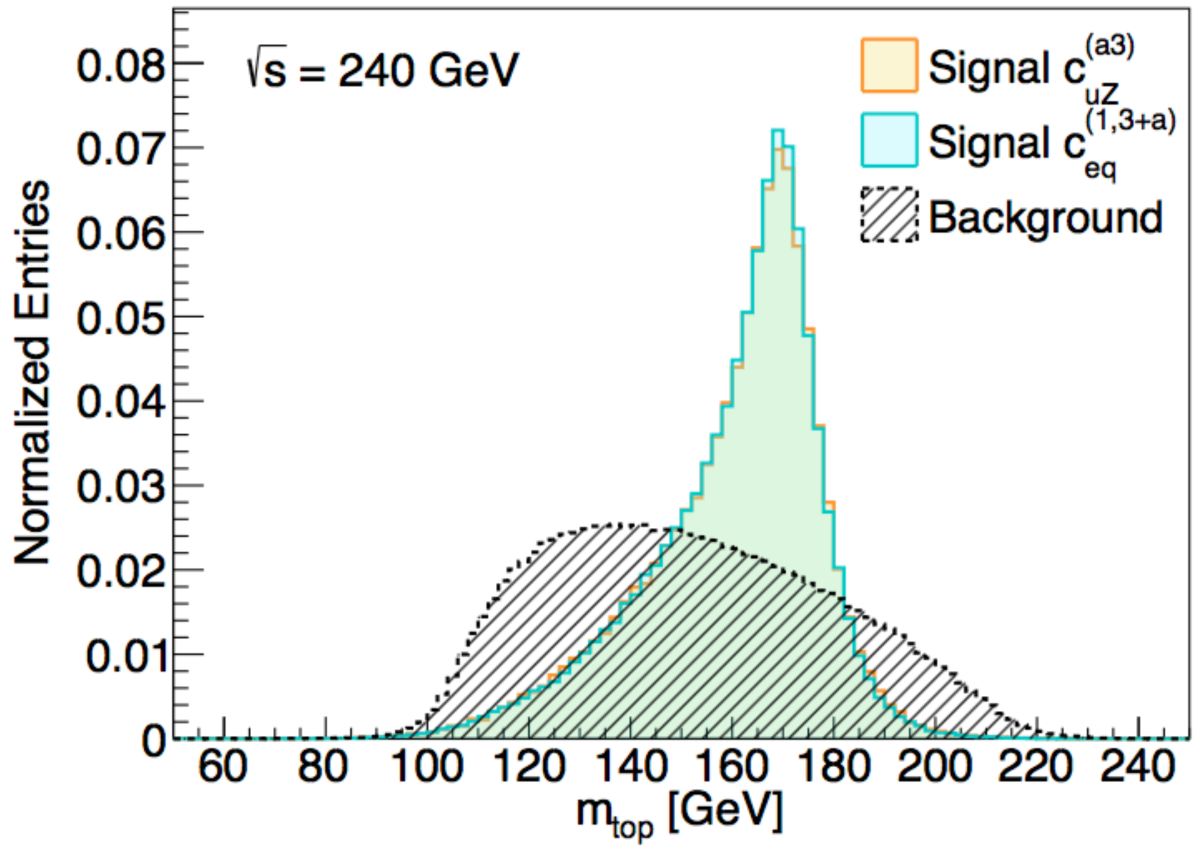
$$E_{j,rec} \approx \frac{s - m_t^2}{2\sqrt{s}} \approx 58 \text{ GeV}$$

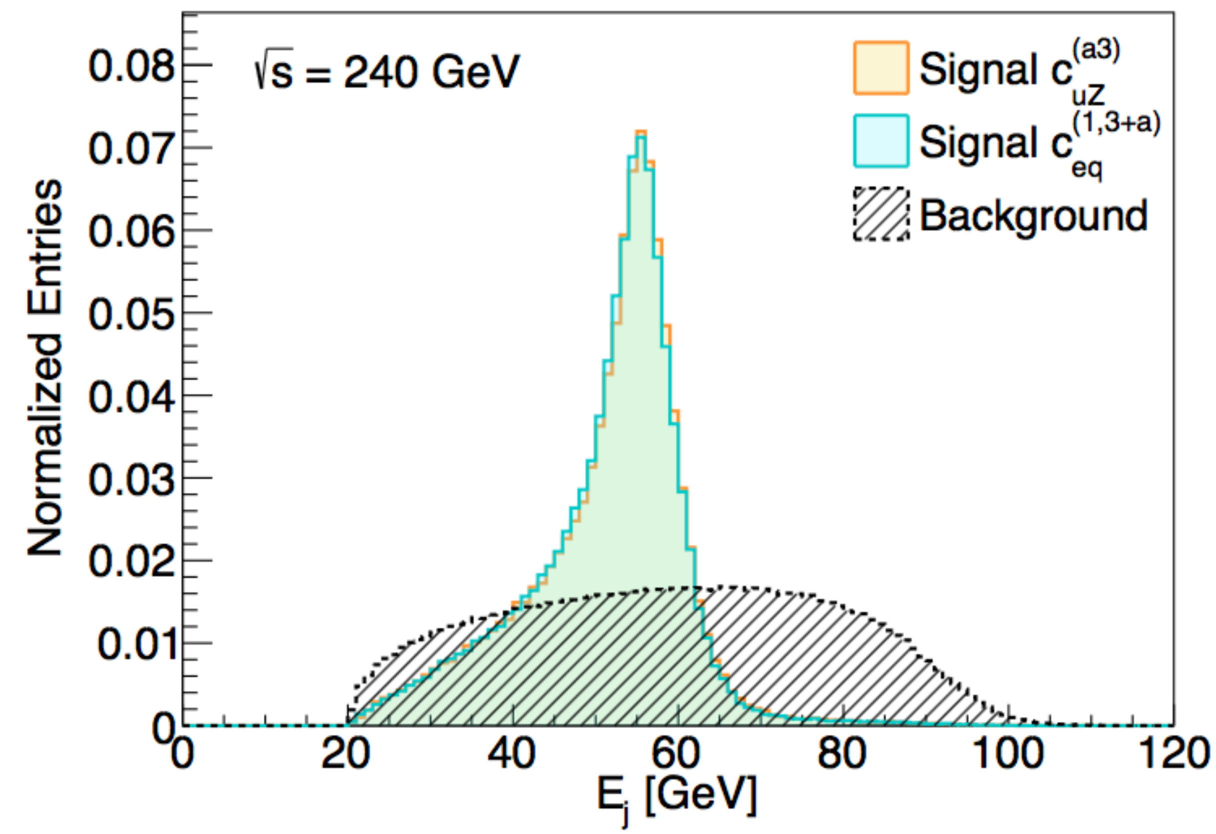
- Background: Wjj dominant

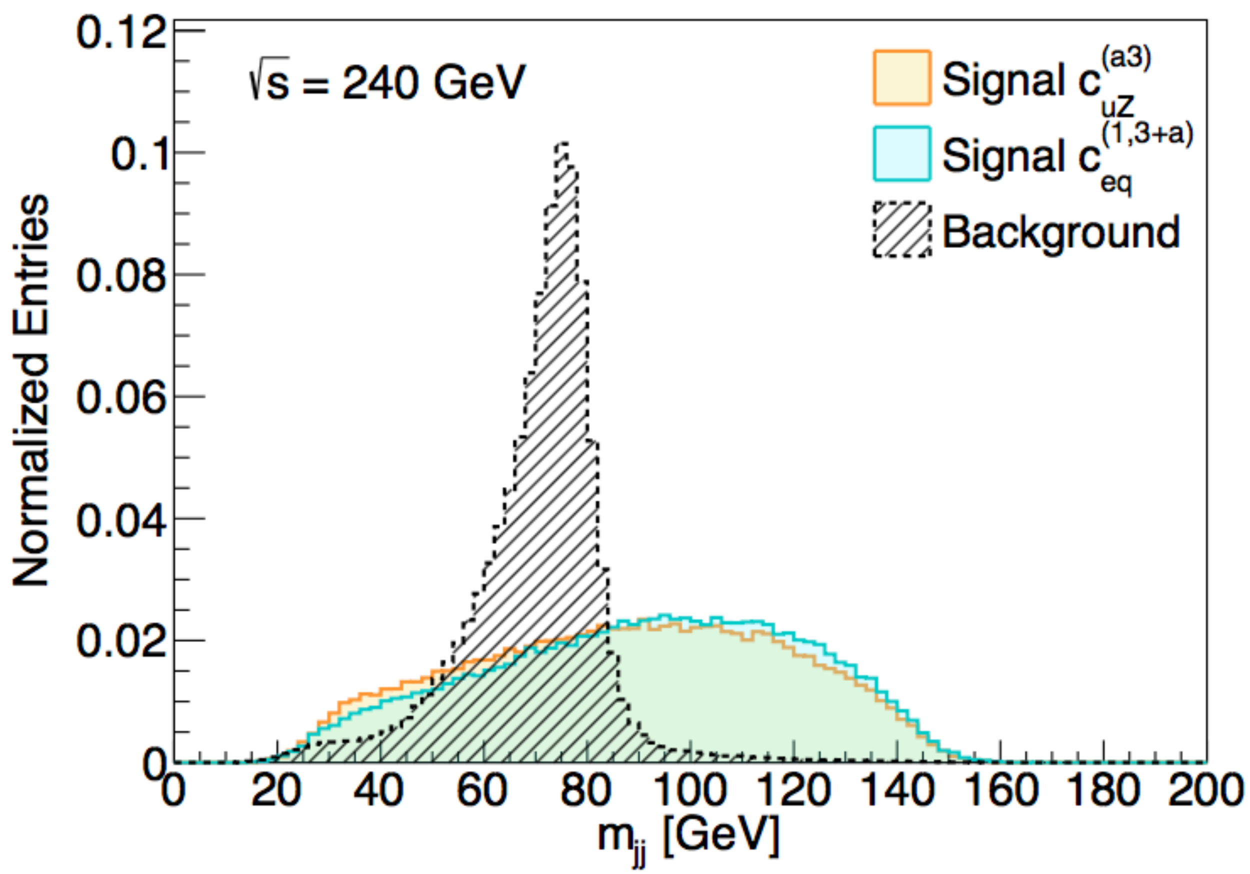


$$m_{jj} \approx 80.4 \text{ GeV}$$




# Baseline:

$E_j < 60$ GeV ,

$m_{jj} > 100$ GeV ,

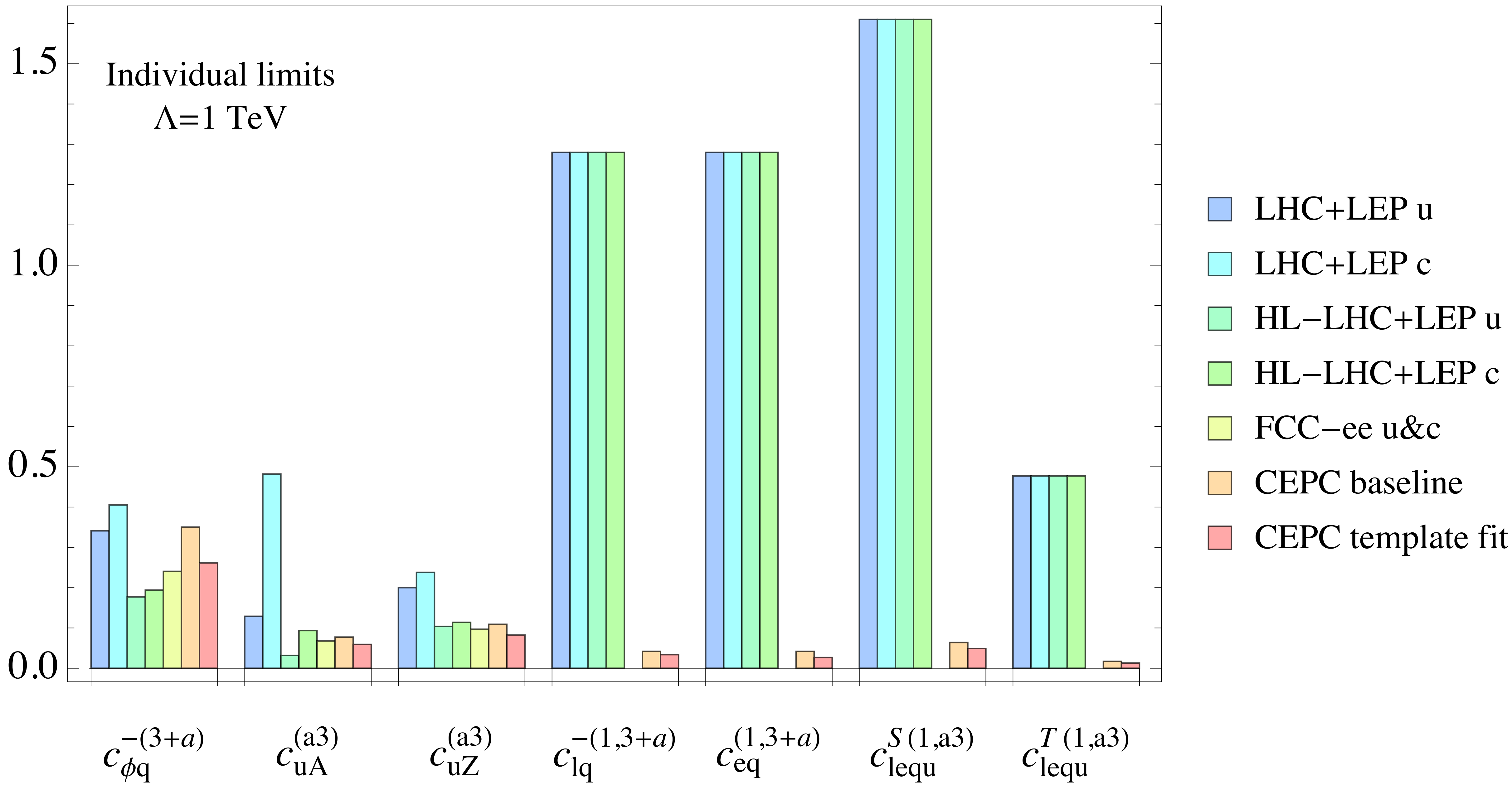
$m_{top} < 180$ GeV .

Exactly 1 *b*-tagged jet

1400 events at 5.6 $ab^{-1}$

95% CL limit on xsec: 0.0134 fb

- Xsec dependence from simulation of 28 sampling points in the space of C's
- Convert into 95% 7-D bound in the dim-6 parameter space




FCC-ee: 4f operator limits are not available; 2f slightly better [H. Khanpour et al. '14]

CLIC: 380 GeV run + polarization, 3~4 times better on 4f

Larger energy -> better limits [G. Durieux, the CLIC Potential for New Physics, CERN YR, 18]

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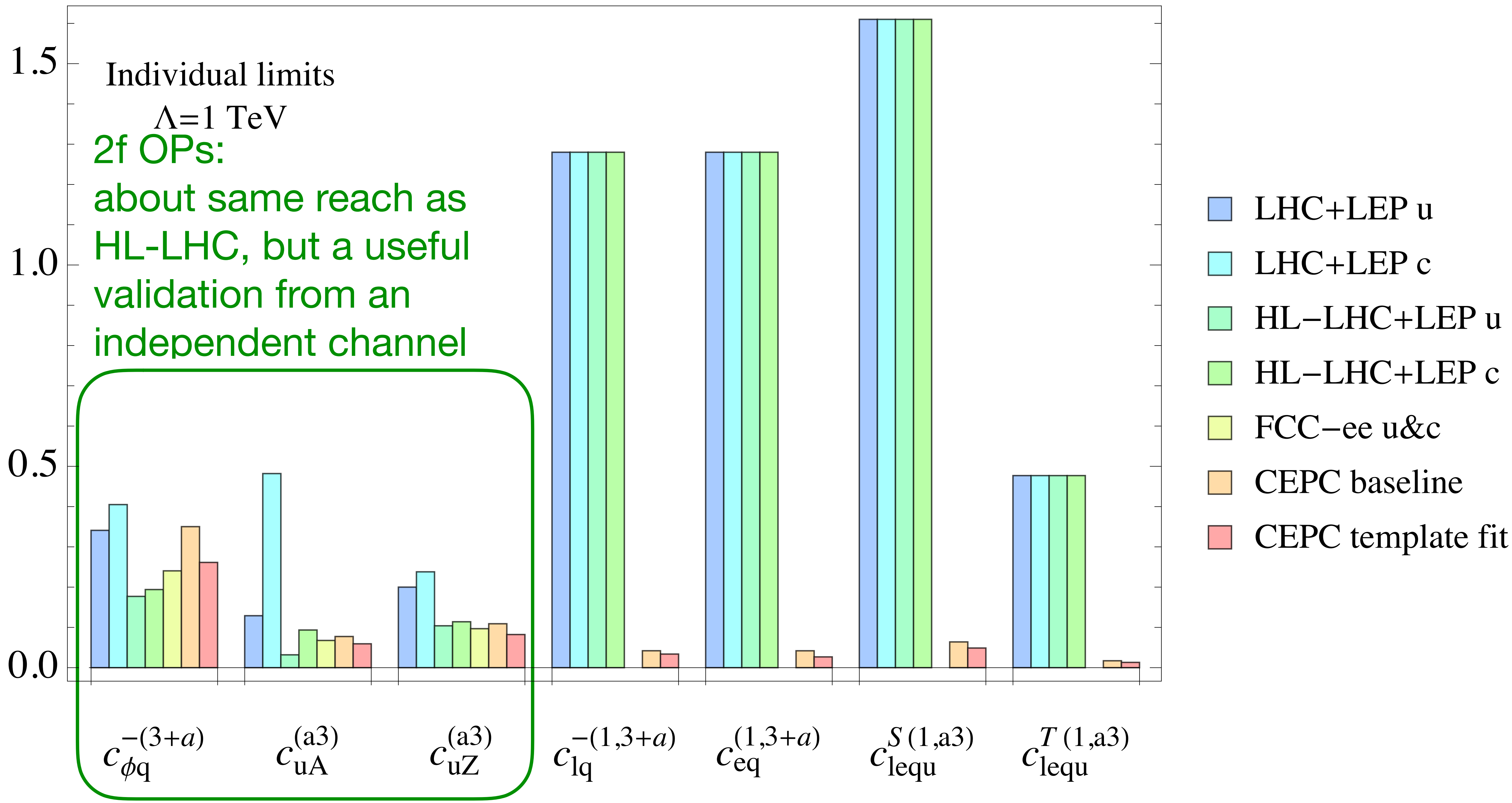


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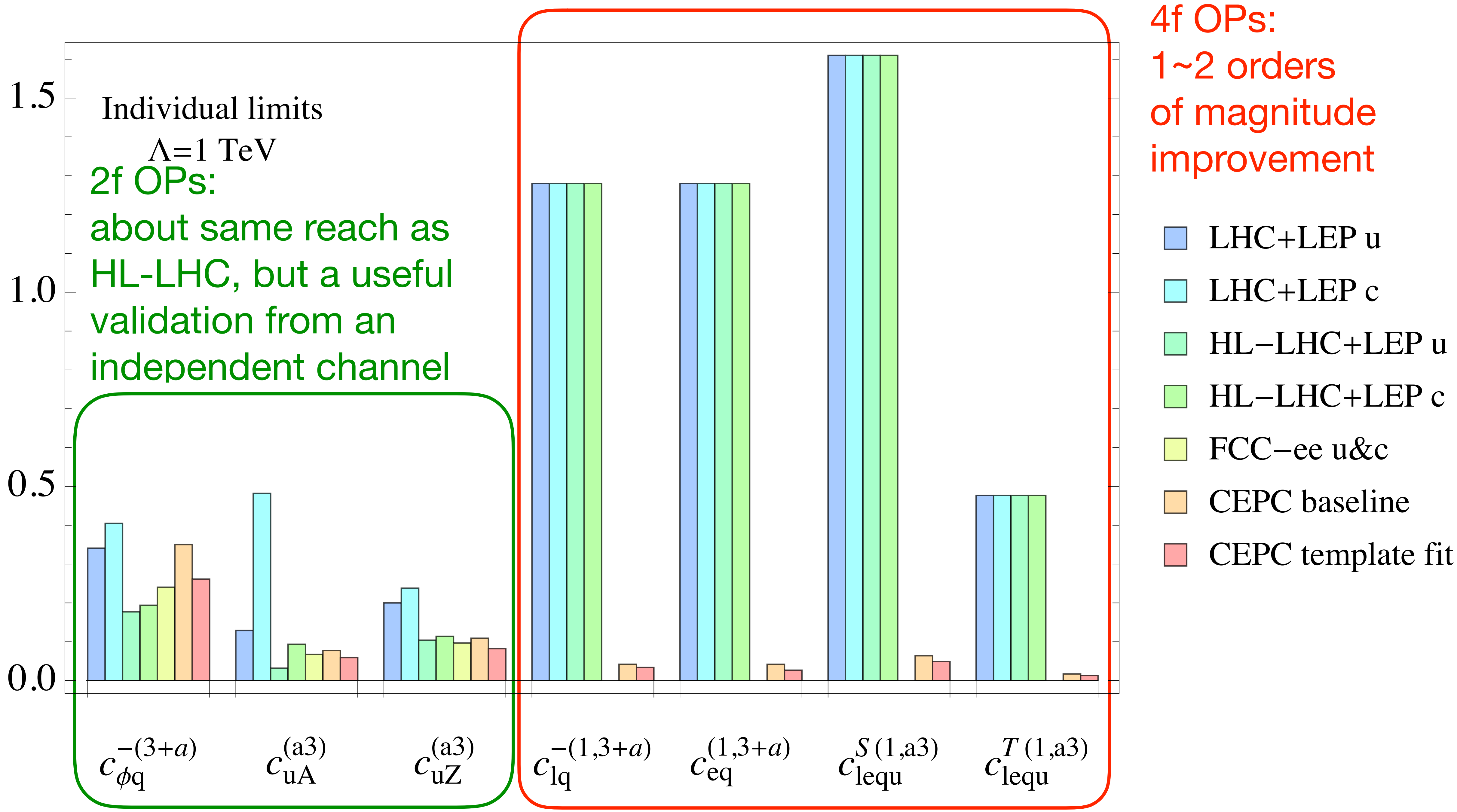


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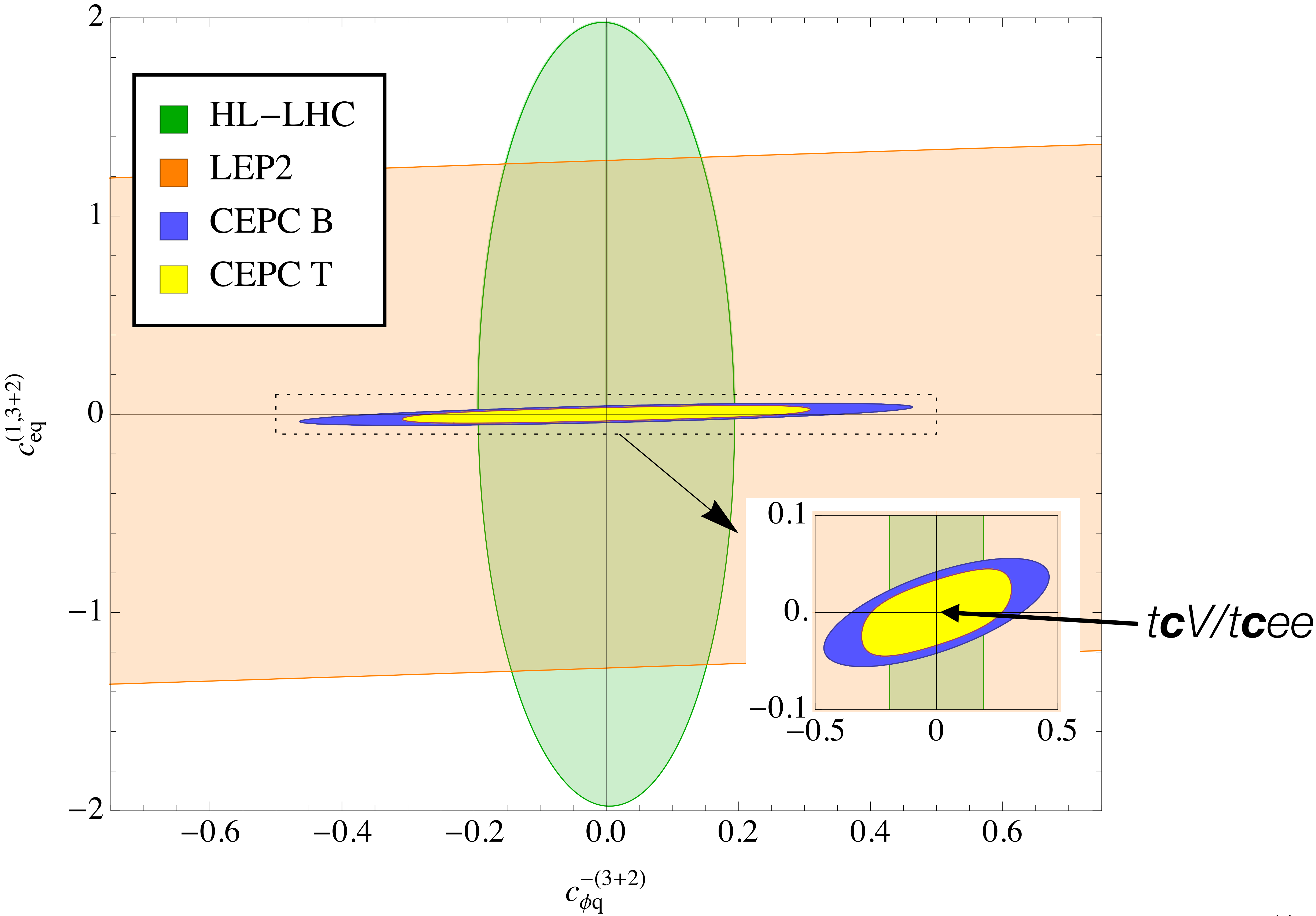

HL−LHC
LEP2
CEPC B
CEPC T
2
1
0
−1
−2
$c_{eq}^{(1,3+2)}$
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
$c_{\phi q}^{-(3+2)}$
0.1
0.
−0.1
−0.5
0
0.5
$tcV/tcee$

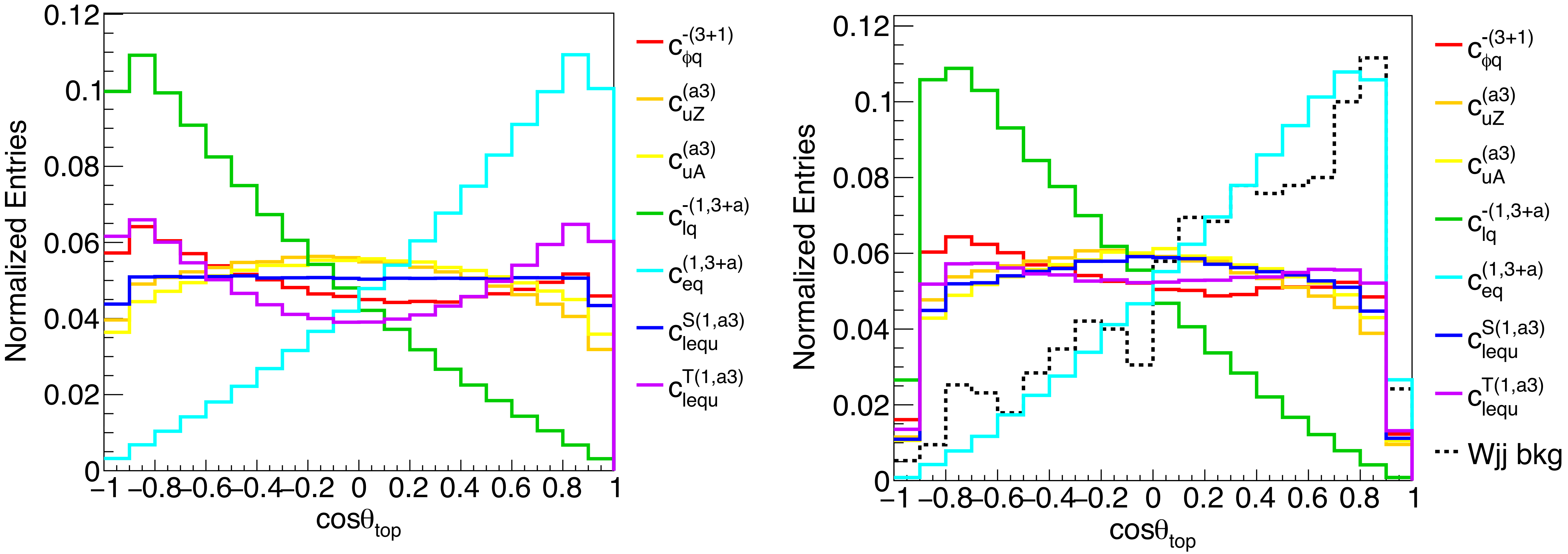
- Two ways to improve:
  - Charm tagging:
    for signal from eetc, the signal is ***b,c,l,v*** while the main background is ***c,s,l,v*** where the c fakes the b. So choose a c-tagged jet improves S/B.

  ➡ **Improve sensitivity on a=2 operators.**

  - Angular distribution:
    Signal produced by different operators with different Lorentz structures can be distinguished by angular distribution

  ➡ **Improve the discrimination power** between different operators

# Angular distribution

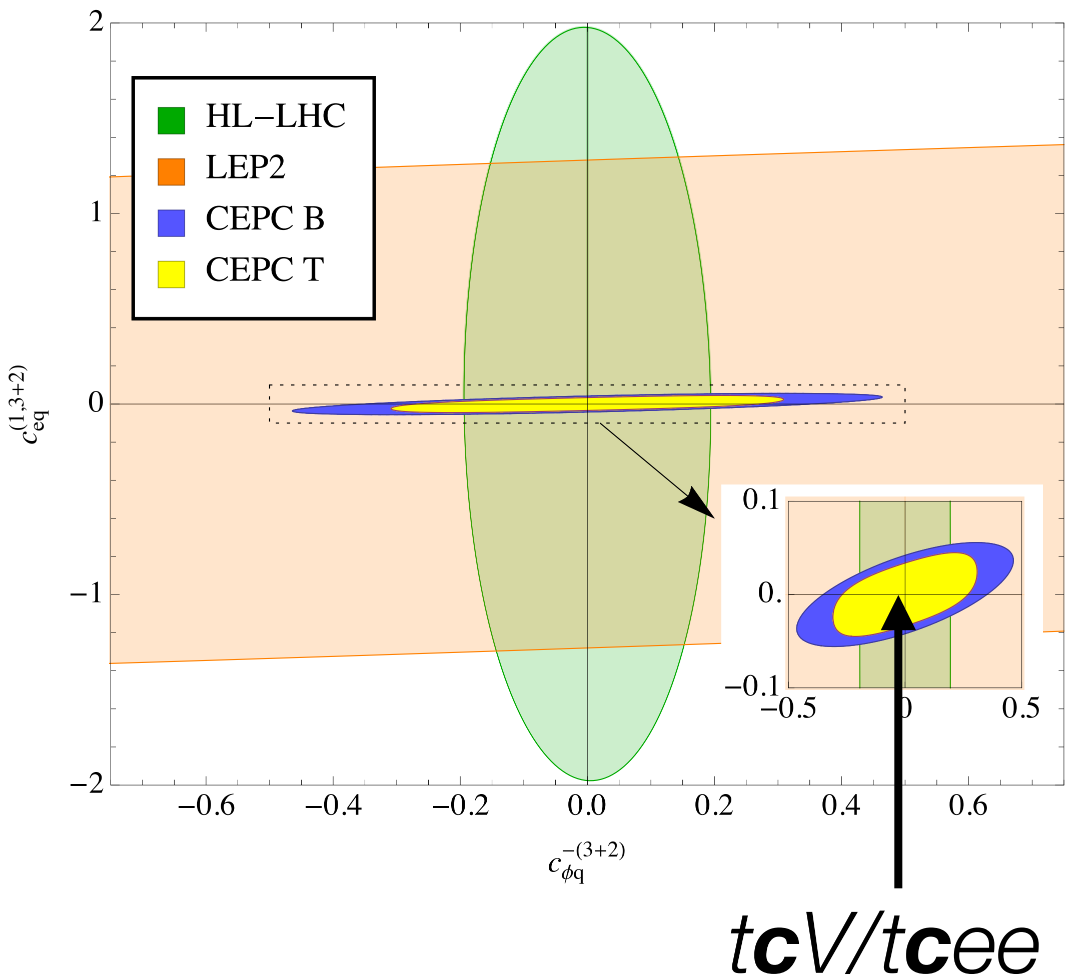



Template fit:

4 bins in $Q_l \times \cos\theta_{top}$ + charm tagging

# Improvement from c-jet tagging

## If no signal is observed



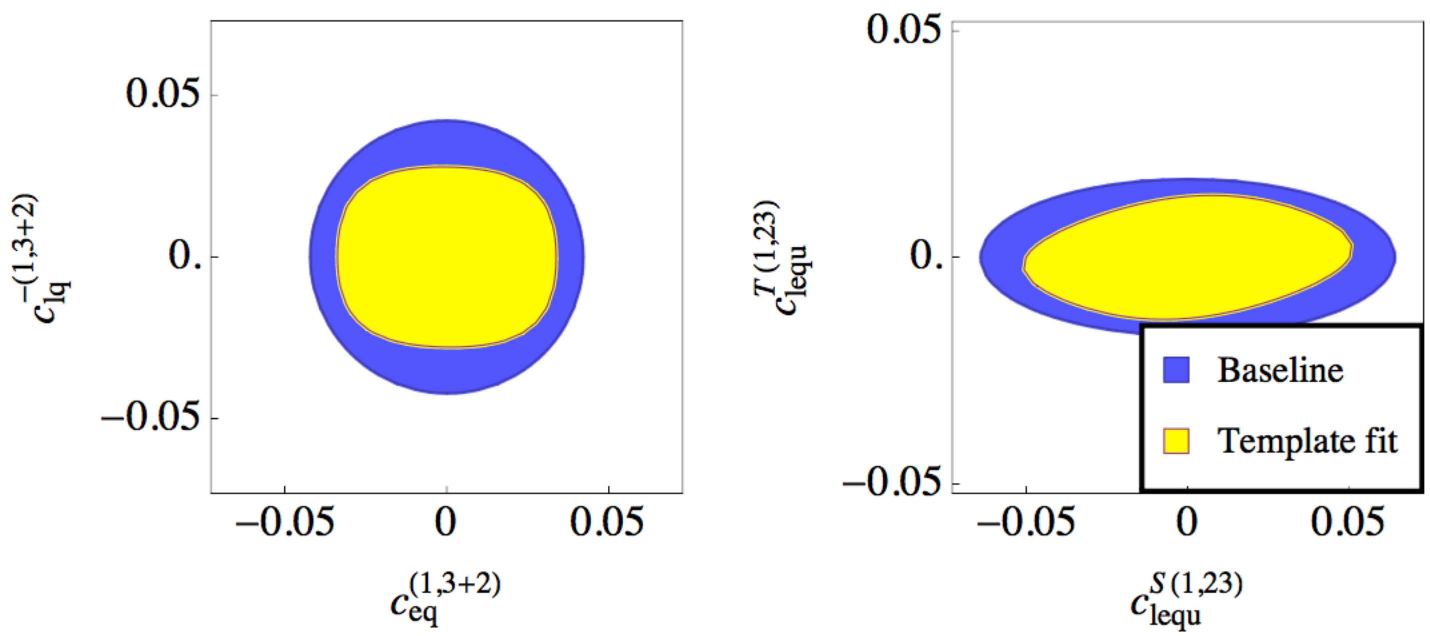




Fig. 8. Two-dimensional limits on four-fermion coefficients, at 95% CL, under the SM hypothesis, with other coefficients turned off. The template fit approach improves the sensitivity.

# Discriminating between operators

## Using angular observable

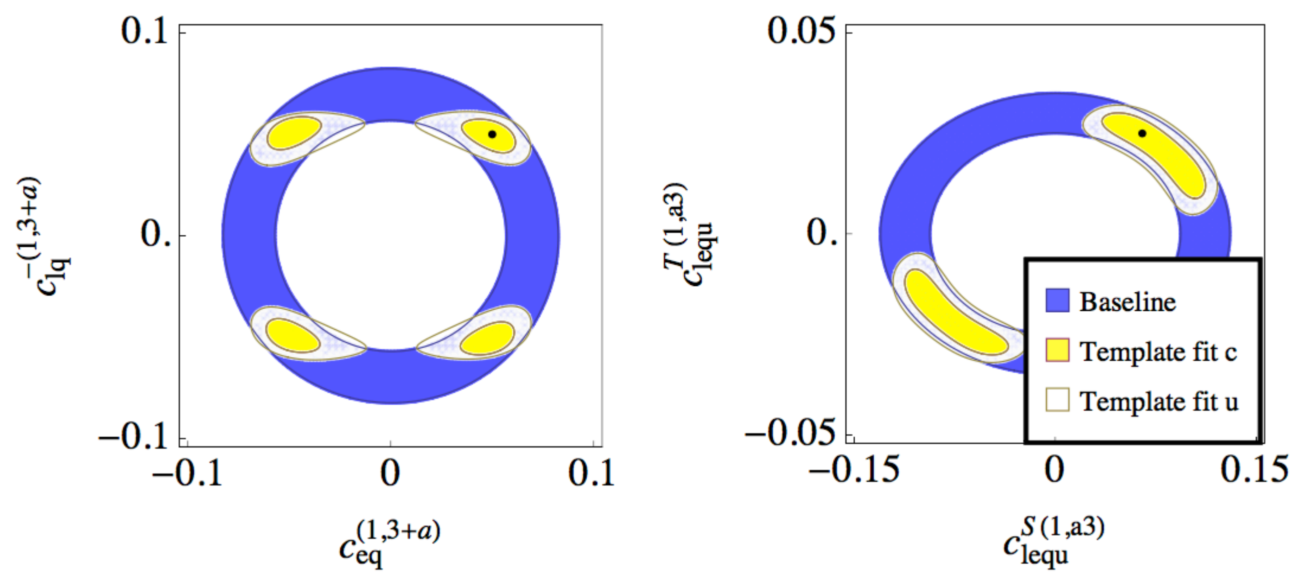



Fig. 9. Two-dimensional limits on four-fermion coefficients, at 95% CL, with other coefficients turned off. Two hypotheses are considered. Left: $c_{eq}^{(1,3+a)} = c_{lq}^{-(1,3+a)} = 0.05$. Right: $c_{lequ}^{S(1,a3)} = 0.065$, $c_{lequ}^{T(1,a3)} = 0.025$. Both points are labeled by a black dot in the plots. The template fit helps to pinpoint the coefficients. Better precision is obtained for operators involving a charm-quark (i.e. $a = 2$).

## Using c-tagging

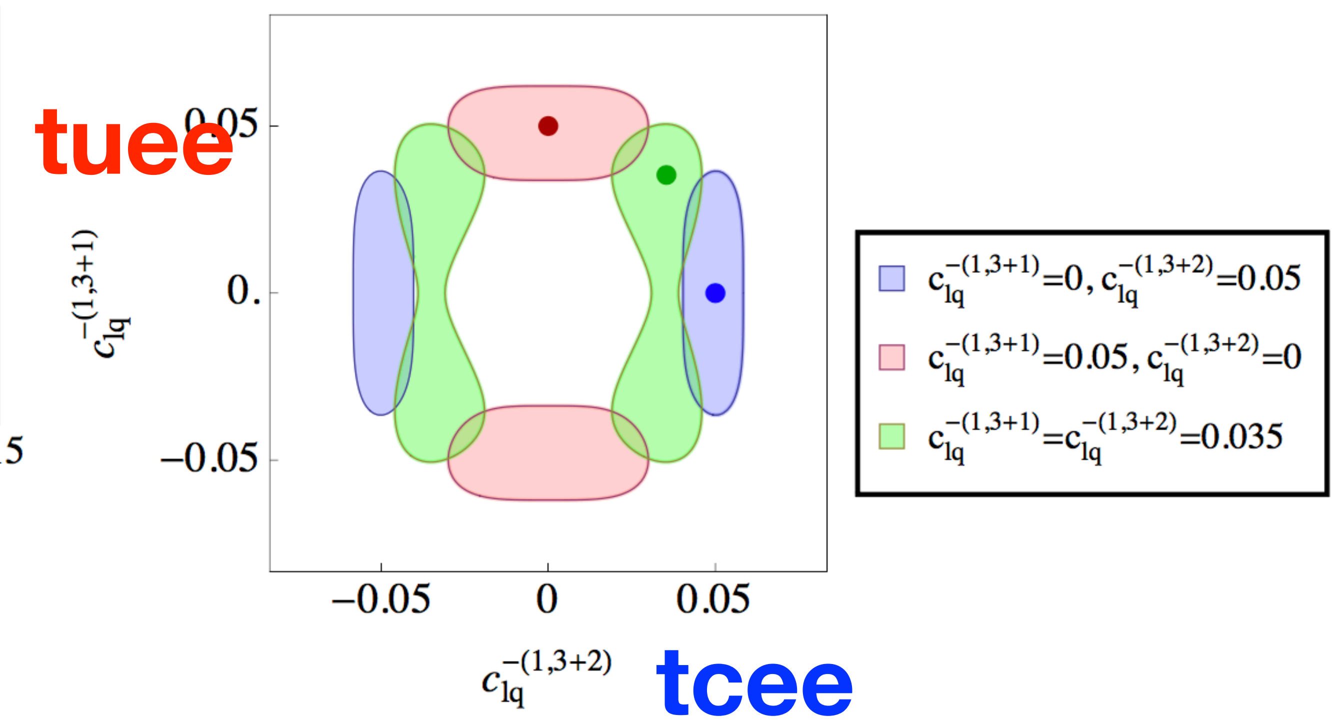



Fig. 10. Two-dimensional limits on $c_{lq}^{-(1,3+a)}$ coefficients with $a = 1$ and $a = 2$, at 95% CL. Other coefficients are turned off. Three hypotheses are considered. The template fit helps to identify the light-quark flavor involved in the FCN coupling.

In contrast with LHC:
No such info from top decay

# For future:

- Improve the sensitivity:
  - Better signal/background simulation, e.g. NLO for 4f etc.
  - Understand the signal of OP with different Lorentz structures.
  - Template fit, MVA, etc.
  - **Statistically optimal observable** to obtain the best sensitivity in theory.
- Higher CoM energies, improvements from top pair production with FCNC decays, etc…

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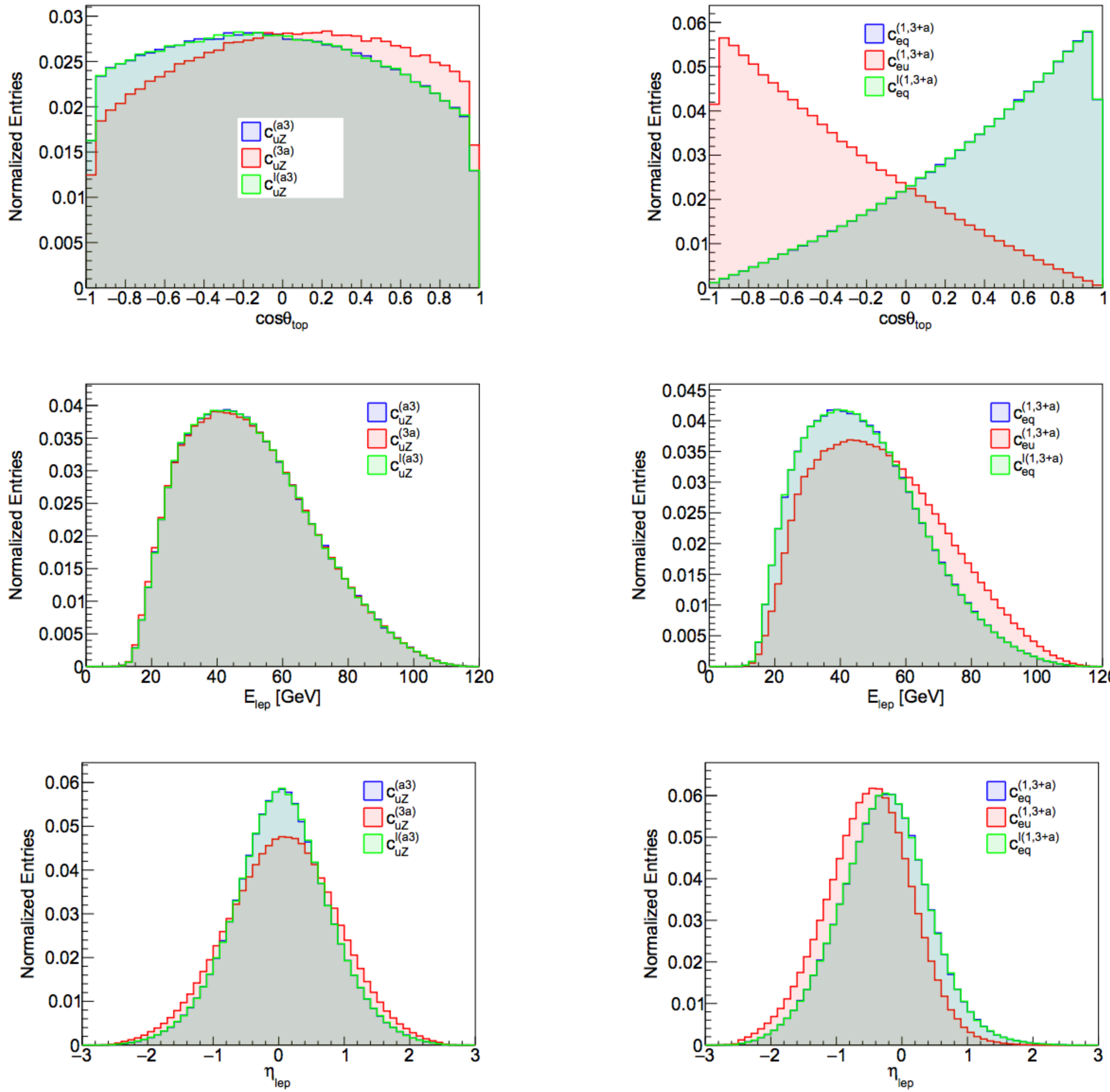
# Conclusion

- Future ee colliders are ideal for testing top-quark flavor-changing interactions.
- In particular it explores the parameter space that will be left uncovered by the HL/HE-LHC.
- Results for the potential at CEPC is promising. We continue to improve.

Thank you


Normalized Entries
cosθ_top
E_lep [GeV]
η_lep
c_uZ^(a3)
c_uZ^(3a)
c_uZ^I(a3)
c_eq^(1,3+a)
c_eu^(1,3+a)
c_eq^I(1,3+a)

[Atwood,Soni, '92] [Diehl,Nachtmann, '94]

minimize the one-sigma ellipsoid in EFT parameter space

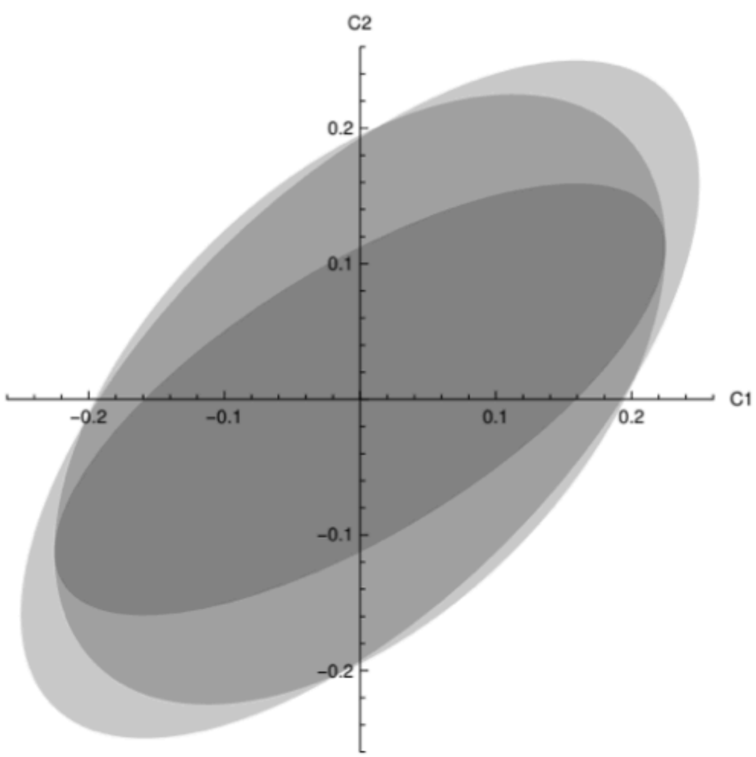
(*joint efficient* set of estimators, saturating the Cramér-Rao bound: $V^{-1} = I$,like MEM)

For small $C_i$, with a phase-space distribution $\sigma(\Phi) = \sigma_0(\Phi) + \sum_i C_i\, \sigma_i(\Phi)$,

the stat. opt. obs. are the average values of $O_i(\Phi) = \sigma_i(\Phi)/\sigma_0(\Phi)$.

The associated covariance at $C_i = 0$, $\forall i$ is

$$\mathrm{cov}(C_i, C_j)^{-1} = \epsilon\mathcal{L} \int \mathrm{d}\Phi\, \frac{\sigma_i(\Phi)\sigma_j(\Phi)}{\sigma_0(\Phi)}.$$




e.g. $\sigma(\phi) = 1 + \cos(\phi) + C_1 \sin(\phi) + C_2 \sin(2\phi)$

1. asymmetries: $O_i \sim \mathrm{sign}\{\sin(i\phi)\}$
2. moments: $O_i \sim \sin(i\phi)$
3. statistically optimal: $O_i \sim \dfrac{\sin(i\phi)}{1+\cos\phi}$

$\Longrightarrow$ area ratios 1.9 : 1.7 : 1

Previous applications in $e^+e^- \to t\,\bar{t}$, on different distributions:

[Grzadkowski, Hioki '00] [Janot '15] [Khiem et al '15]