Top quark FCNC at CEPC

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CEPC Flavor Physics/New Physics/Detector Technology Workshop

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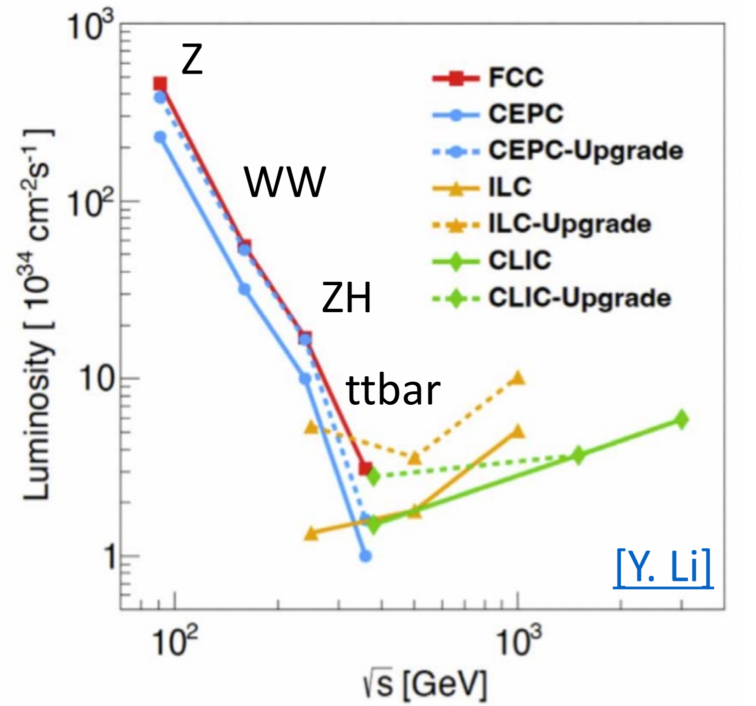
Based on on arXiv:1906.04573 with Cen Zhang

Introduction

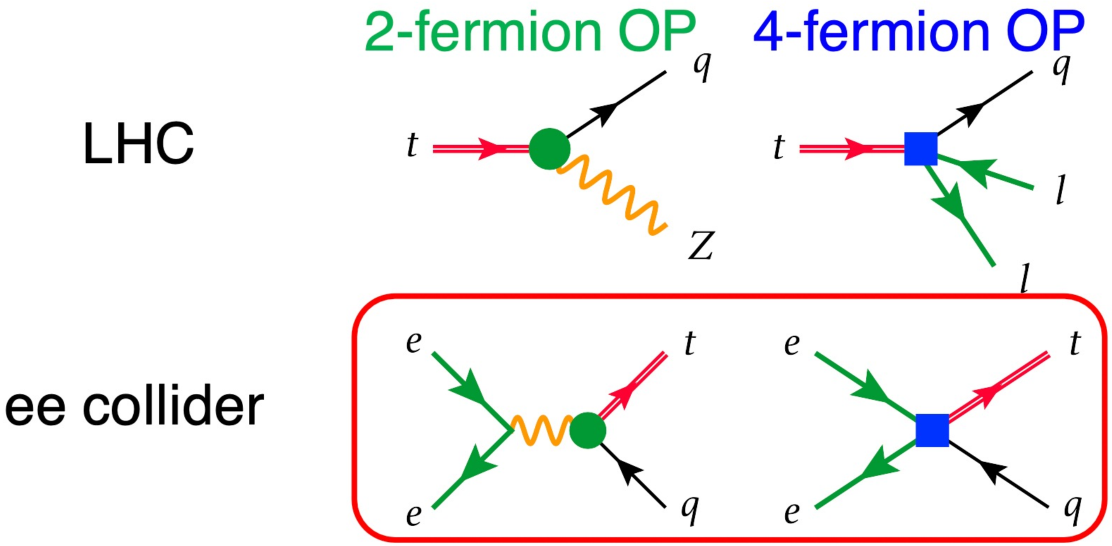
- CEPC is proposed to run as a Higgs factory at 240 GeV.
- Can potentially upgrade to run at 360 GeV to produce ttbar for top quark physics.
- Can we do some top quark physics below the ttbar production threshold?
  - The Top FCNC interactions can be probed via single top production at 240 GeV.



Top FCNC

- Top FCNC interactions are highly suppressed in SM by GIM mechanism.
  - Any observation will be a clear sign of new physics.
- FCNC can happen via 2-fermion or 4-fermion interactions:

	$\mathrm{Br}^{\mathrm{SM}}$
$t \to cg$	$\sim 10^{-11}$
$t \to c\gamma$	$\sim 10^{-12}$
$t \to cZ$	$\sim 10^{-13}$
$t \to ch$	$\sim 10^{-14}$



Current constraints

[HL/HE YR, 1812.07638]

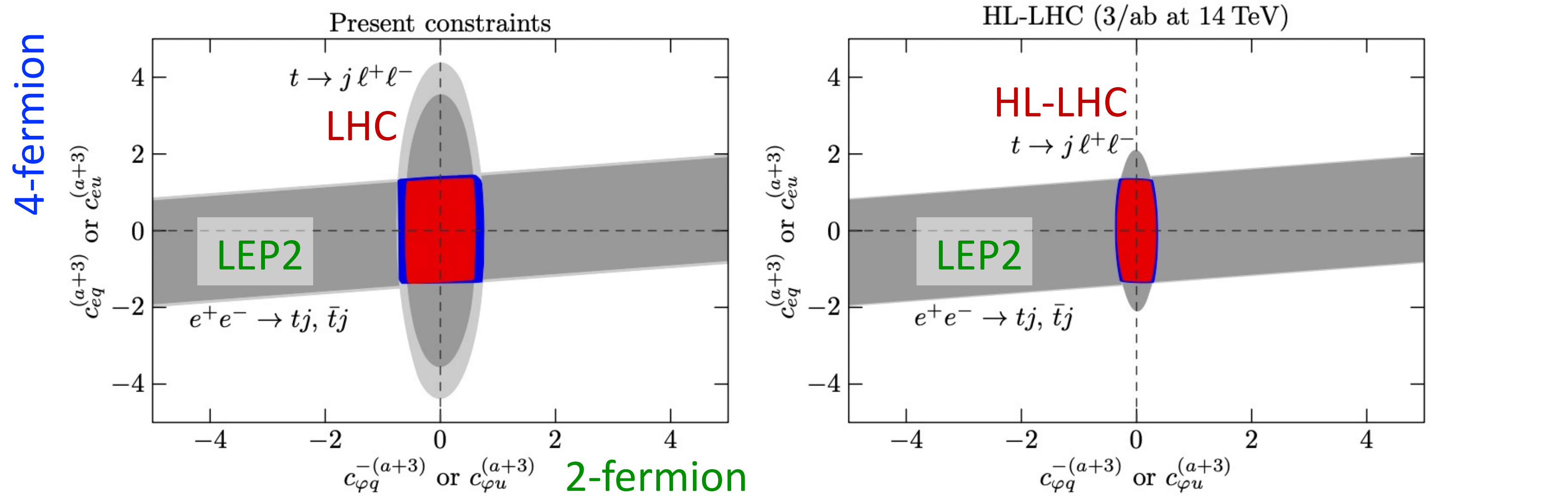


Fig. 59: Current (left) and prospective HL-LHC (right) 95% C.L. limits on top-quark FCNC operator coefficients in a two-dimensional plane formed by two- (x axis) and four-fermion (y axis) operator coefficients. Other parameters are marginalized over, within the constraints obtained when all measurements 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.

- Best constraints on 2-fermions FCNC are from LHC.
- Best constraints on 4-fermion (eetq) FCNC are still from LEP2.

Flavour changing effective operators

- Consider a complete set of coefficients describing the top FCNC interactions based on SMEFT implemented in the dim6top UFO model.
- In total 56 independent coefficients are relevant in single top production process.

2-fermion FCNC			4-fermion FCNC			
$c_{\varphi q}^{-(3+a)}$	$c_{uZ}^{(a3)}$	$c_{uA}^{(a3)}$	$c_{lq}^{-(1,3+a)}$	$c_{eq}^{(1,3+a)}$	$c_{lequ}^{S(1,a3)}$	$c_{lequ}^{T(1,a3)}$
$c_{\varphi u}^{(3+a)}$	$c_{uZ}^{(3a)}$	$c_{uA}^{(3a)}$	$c_{lu}^{(1,3+a)}$	$c_{eu}^{(1,3+a)}$	$c_{lequ}^{S(1,3a)}$	$c_{lequ}^{T(1,3a)}$
$c_{\varphi q}^{-I(3+a)}$	$c_{uZ}^{I(a3)}$	$c_{uA}^{I(a3)}$	$c_{lq}^{-I(1,3+a)}$	$c_{eq}^{I(1,3+a)}$	$c_{lequ}^{SI(1,a3)}$	$c_{lequ}^{TI(1,a3)}$
$c_{\varphi u}^{I(3+a)}$	$c_{uZ}^{I(3a)}$	$c_{uA}^{I(3a)}$	$c_{lu}^{I(1,3+a)}$	$c_{eu}^{I(1,3+a)}$	$c_{lequ}^{SI(1,3a)}$	$c_{lequ}^{TI(1,3a)}$

Quark generation index: a=1 for ee→tu, a=2 for ee→tc

Flavour changing effective operators

- Consider a complete set of coefficients describing the top FCNC interactions based on SMEFT implemented in the dim6top UFO model.
- In total 56 independent coefficients are relevant in single top production process.

- Interference between rows vanishes in the limit of massless quark.

→ Sufficient to focus on 7 parameters at a time.

2-fermion FCNC			4-fermion FCNC			
$c_{\varphi q}^{-(3+a)}$	$c_{uZ}^{(a3)}$	$c_{uA}^{(a3)}$	$c_{lq}^{-(1,3+a)}$	$c_{eq}^{(1,3+a)}$	$c_{lequ}^{S(1,a3)}$	$c_{lequ}^{T(1,a3)}$
$c_{\varphi u}^{(3+a)}$	$c_{uZ}^{(3a)}$	$c_{uA}^{(3a)}$	$c_{lu}^{(1,3+a)}$	$c_{eu}^{(1,3+a)}$	$c_{lequ}^{S(1,3a)}$	$c_{lequ}^{T(1,3a)}$
$c_{\varphi q}^{-I(3+a)}$	$c_{uZ}^{I(a3)}$	$c_{uA}^{I(a3)}$	$c_{lq}^{-I(1,3+a)}$	$c_{eq}^{I(1,3+a)}$	$c_{lequ}^{SI(1,a3)}$	$c_{lequ}^{TI(1,a3)}$
$c_{\varphi u}^{I(3+a)}$	$c_{uZ}^{I(3a)}$	$c_{uA}^{I(3a)}$	$c_{lu}^{I(1,3+a)}$	$c_{eu}^{I(1,3+a)}$	$c_{lequ}^{SI(1,3a)}$	$c_{lequ}^{TI(1,3a)}$

Quark generation index: a=1 for ee→tu, a=2 for ee→tc

Flavour changing effective operators

- Consider a complete set of coefficients describing the top FCNC implemented in the dim6top UFO
- In total 56 independent coefficients are relevant in single top production process.

- 1st and 3rd row (or 2nd and 4th row) only differ by a CP phase and give identical signature.
- 1st and 2nd row (or 3rd and 4th row) give slightly different kinematics because lepton momentum from top quark decay is correlated with the top helicity.

→Only need to consider the first two rows in the analysis.

	2-fermion FCNC			4-fermion FCNC				
CP even	$c_{\varphi q}^{-(3+a)}$	$c_{uZ}^{(a3)}$	$c_{uA}^{(a3)}$	$c_{lq}^{-(1,3+a)}$	$c_{eq}^{(1,3+a)}$	$c_{lequ}^{S(1,a3)}$	$c_{lequ}^{T(1,a3)}$	Left-handed q
CP even	$c_{\varphi u}^{(3+a)}$	$c_{uZ}^{(3a)}$	$c_{uA}^{(3a)}$	$c_{lu}^{(1,3+a)}$	$c_{eu}^{(1,3+a)}$	$c_{lequ}^{S(1,3a)}$	$c_{lequ}^{T(1,3a)}$	Right-handed q
CP odd	$c_{\varphi q}^{-I(3+a)}$	$c_{uZ}^{I(a3)}$	$c_{uA}^{I(a3)}$	$c_{lq}^{-I(1,3+a)}$	$c_{eq}^{I(1,3+a)}$	$c_{lequ}^{SI(1,a3)}$	$c_{lequ}^{TI(1,a3)}$	Left-handed q
CP odd	$c_{\varphi u}^{I(3+a)}$	$c_{uZ}^{I(3a)}$	$c_{uA}^{I(3a)}$	$c_{lu}^{I(1,3+a)}$	$c_{eu}^{I(1,3+a)}$	$c_{lequ}^{SI(1,3a)}$	$c_{lequ}^{TI(1,3a)}$	Right-handed q

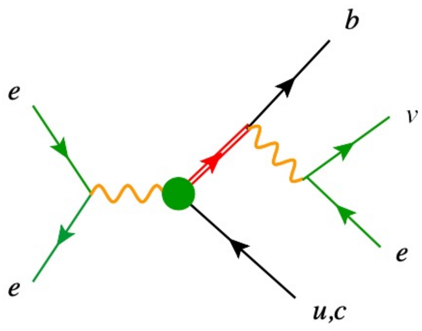
Quark generation index: a=1 for ee→tu, a=2 for ee→tc

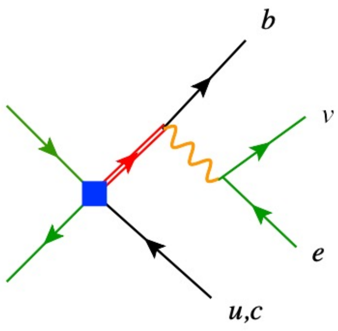
Analysis setup – event generation

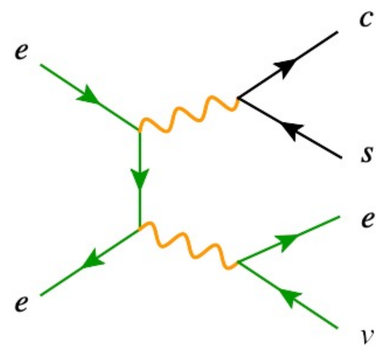
- CEPC (CDR) scenario: E_{cm} = 240 GeV, L_{int} = 5.6 ab^{-1}
- Only consider leptonic delay of the W boson from the top quark.
- Event generation: leading order with MadGraph5 + Pythia8:

Signal (dim6top model):
ee→tj→lvbj (l = e, mu; j = u, c)

Background:
ee→WW→lvqq (dominant)
ee→ZZ→llbb/llcc (small contribution)

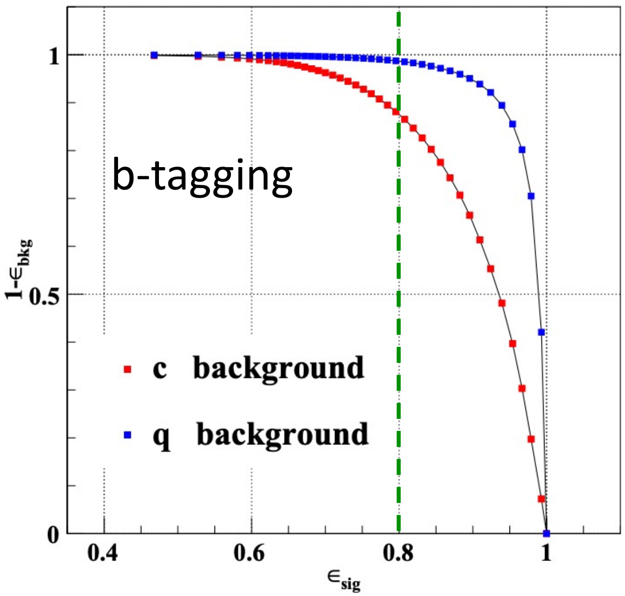


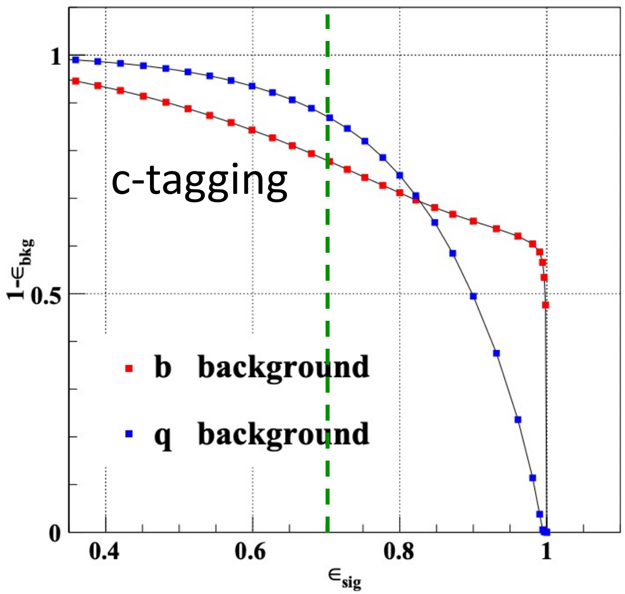




Analysis setup – simulation

- Fast simulation: Delphes with CEPC card
  - Jet clustering: anti-kT R=0.5
  - b-tagging working point 80% (c-jet mistag 10%, light jet mistag 0.1%)
  - c-tagging working point 70% (b-jet mistag 20%, light jet mistag 12%)

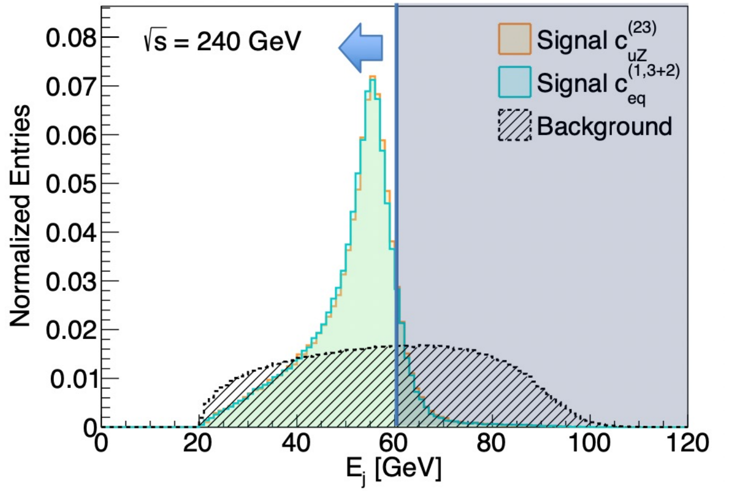




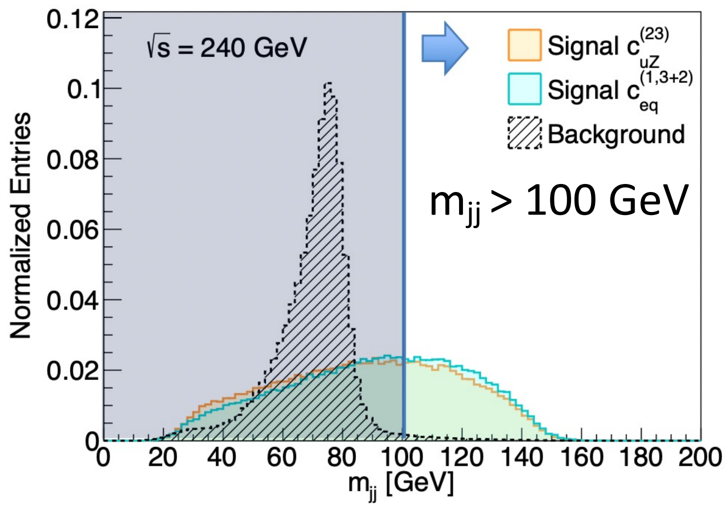
[arXiv:1806.04879]

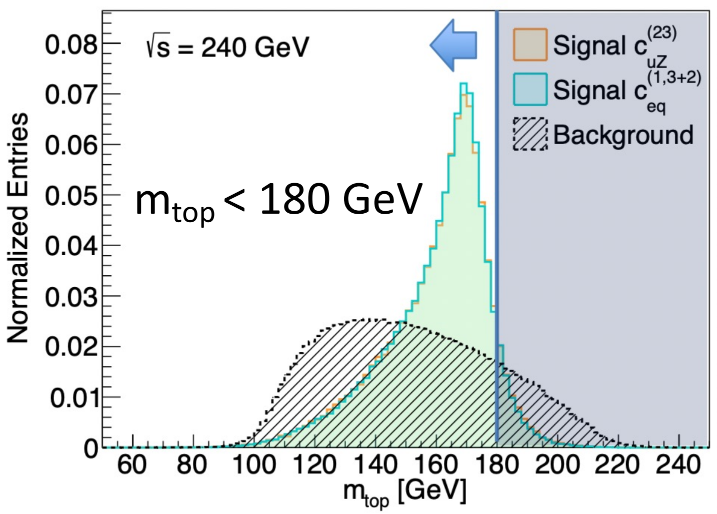
Baseline analysis

- Object and event selection:
  - Exactly 1 lepton pT>10 GeV, |eta|<3.0
  - Missing energy > 30 GeV
  - ≥2 jets pT>20 GeV, |eta|<3.0
  - Exactly 1 b-tagged jet



Leading untagged jet energy < 60 GeV



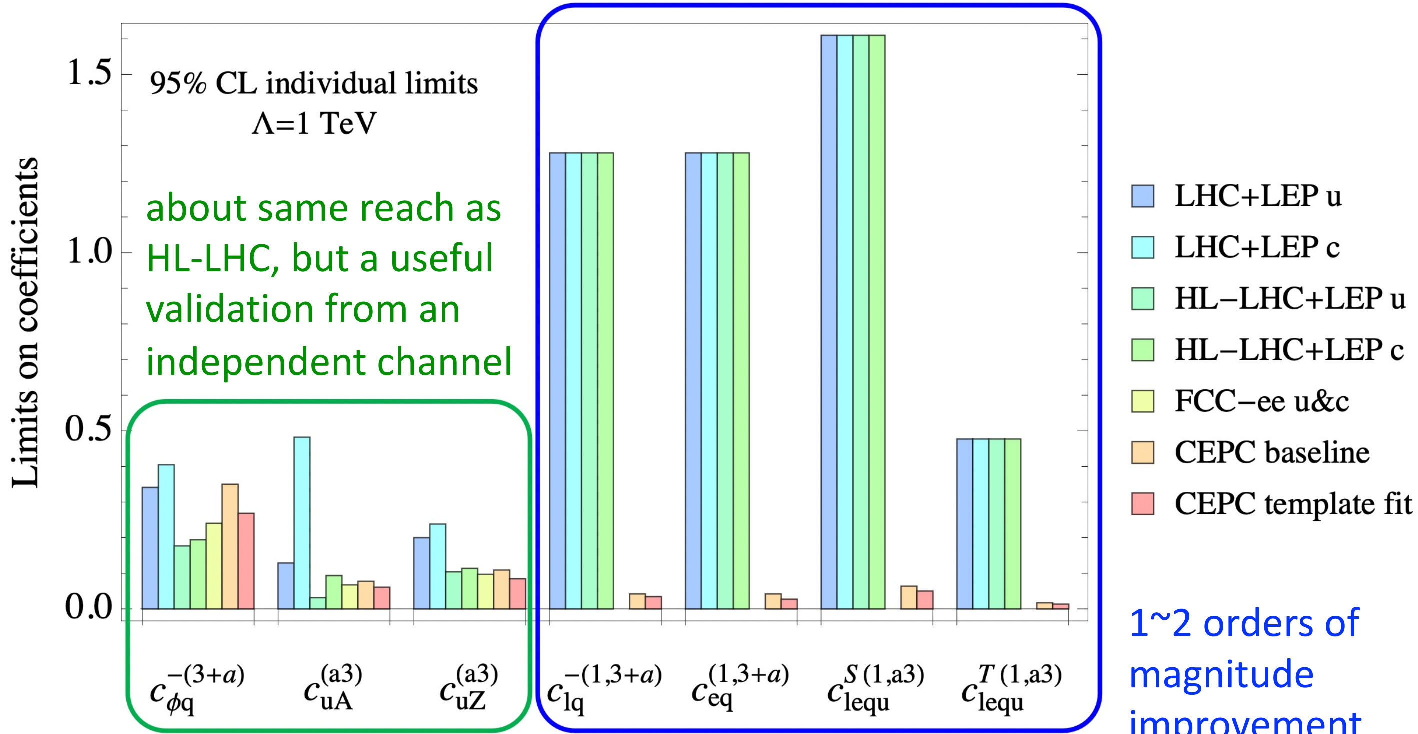


1400 events at 5.6 ab^{-1} → 95% CL limit on xsec: 0.0134 fb

Constraints on individual operators

If no signal is observed:
convert the limit on xsec to bounds in the dim-6 parameter space.

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



1~2 orders of magnitude improvement

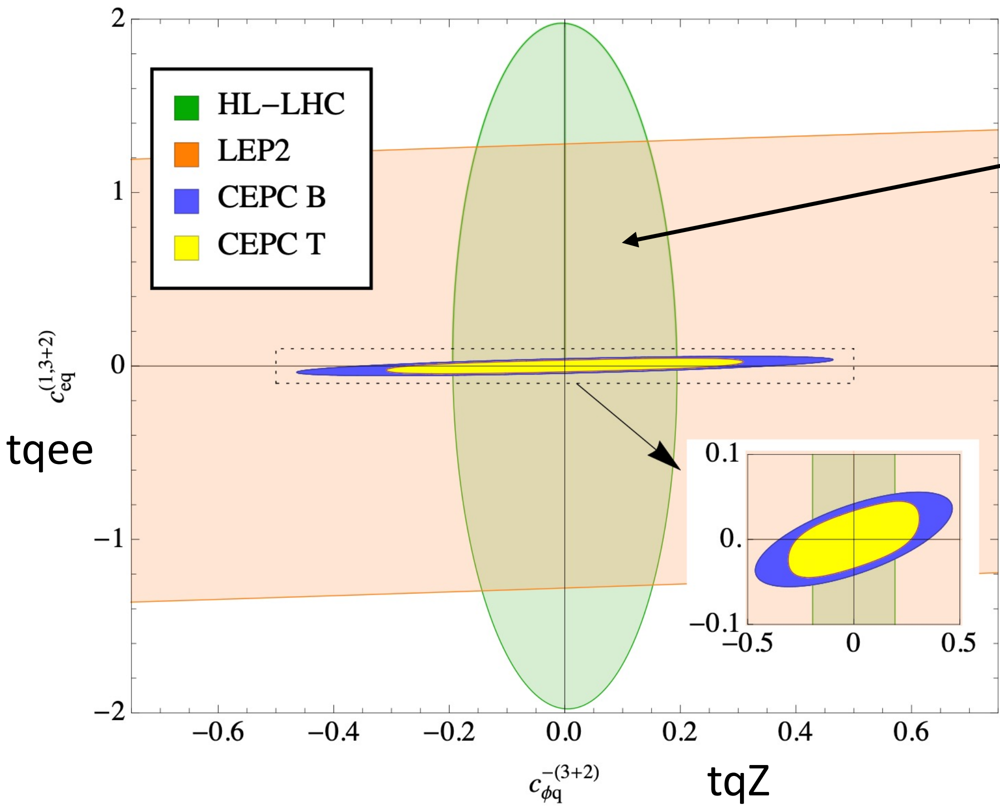
2-fermion operators 4-fermion operators

* Similar results for the second row of the coefficients

Constraints on 2f VS 4f operators

If no signal is observed:
convert the limit on xsec to bounds in the dim-6 parameter space.

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



Probe parameter space that will be left uncovered by the HL-LHC

Complementary between HL-LHC and CEPC

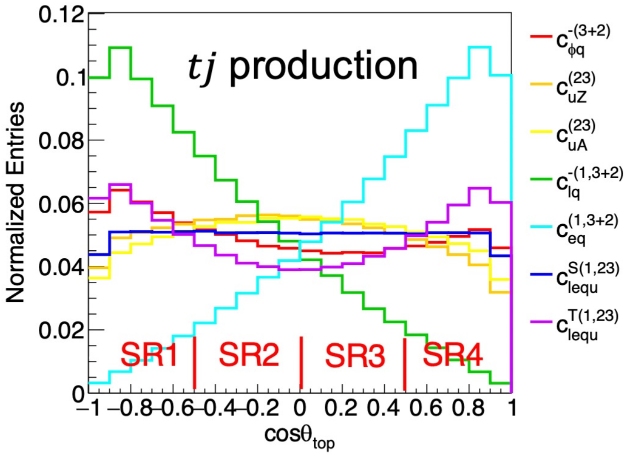
* Similar results for the second row of the coefficients

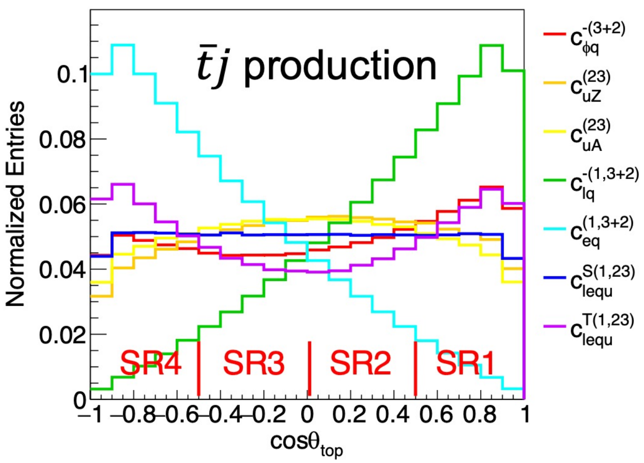
Improvement with additional discriminators

- Introduce additional discriminators to improve sensitivity on top of the baseline analysis (denoted as "template fit"):

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

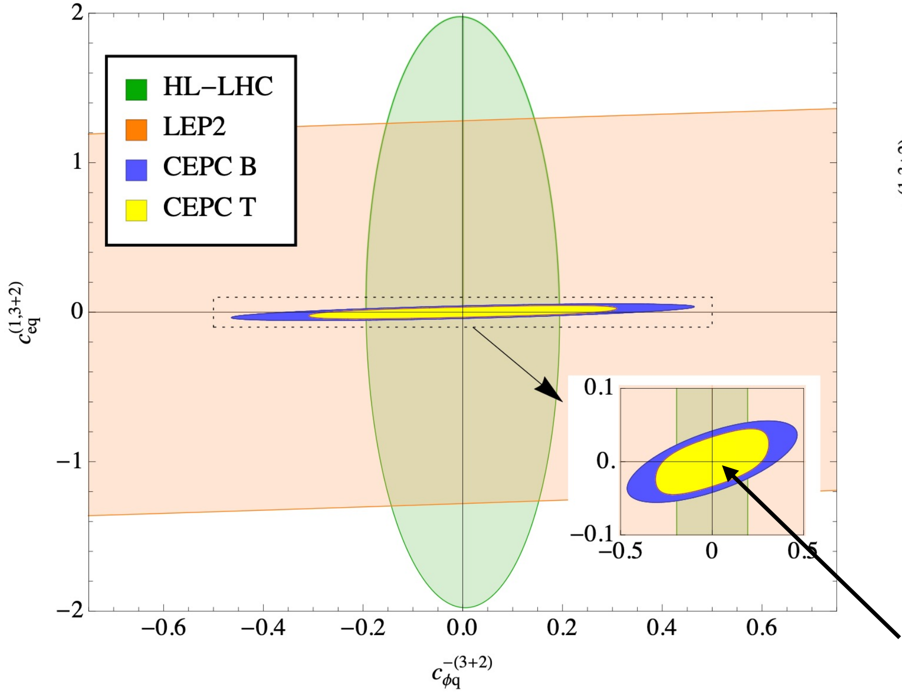
  - **c-jet tagging** on non-b-tagged jet to improved sensitivity to ee→tc signal produced by a=2 operators (i.e. tcV/tcee).
  - **Production angle** of the top quark to distinguish signal produced by operators with different Lorentz structures.





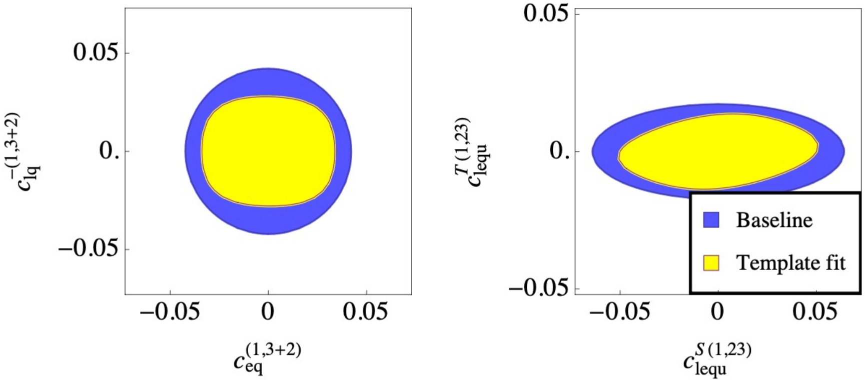
Using c-jet tagging

If no signal is observed:
convert the limit on xsec to bounds in the dim-6 parameter space.



tcV/tcee

2D limit of a 2f and a 4f coefficients



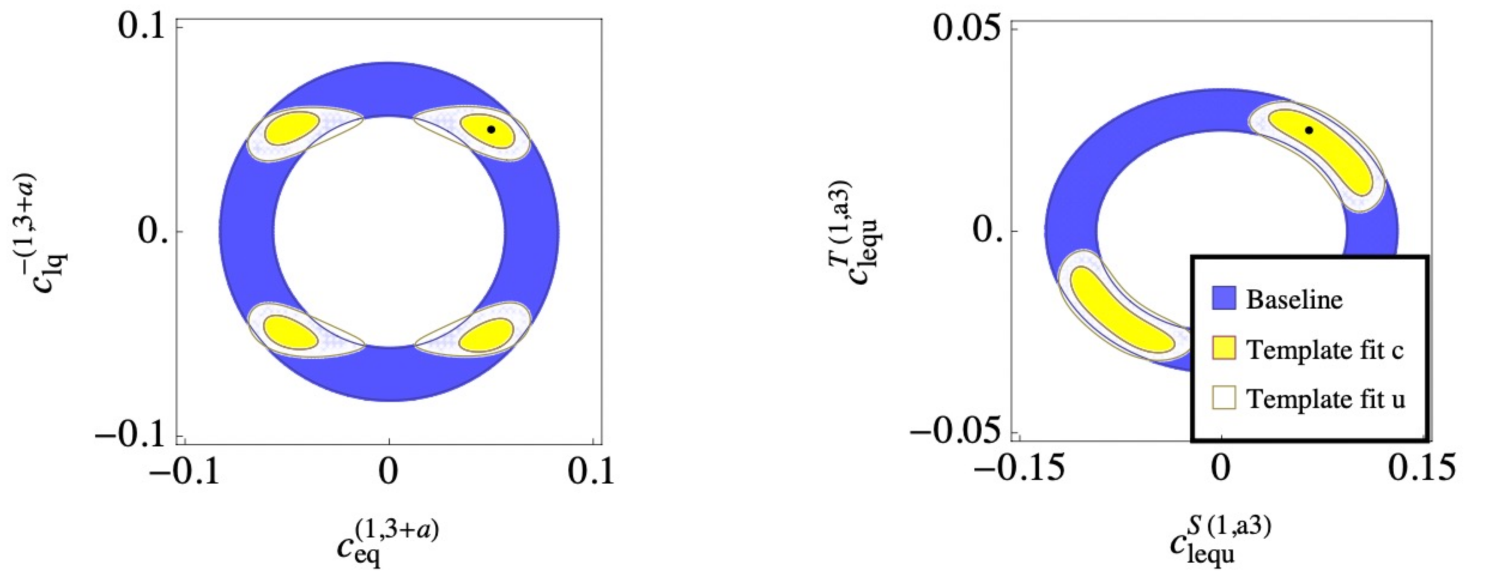
2D limits of the 4f coefficients

- c-jet tagging improves the constraints of the operator coefficients for a = 2.

Using angular observable

If there is an excess – two hypotheses are considered:

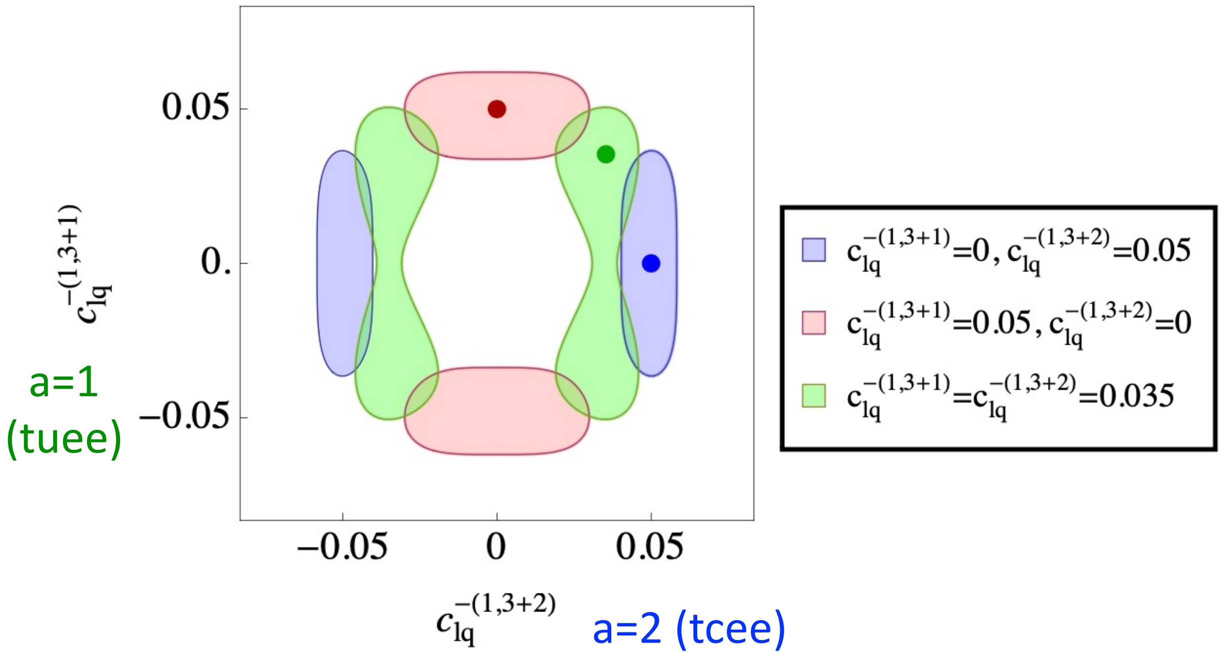
$$c_{eq}^{(1,3+a)} = c_{lq}^{-(1,3+a)} = 0.05 \qquad c_{lequ}^{S(1,a3)} = 0.065,\ c_{lequ}^{T(1,a3)} = 0.025$$



- The angular observable helps to pinpoint the coefficient.
- Benefit from the c-tagging, better precision is obtained for operators involving a charm quark (i.e. a=2)

Using c-jet tagging

If there is an excess – three hypotheses are considered:

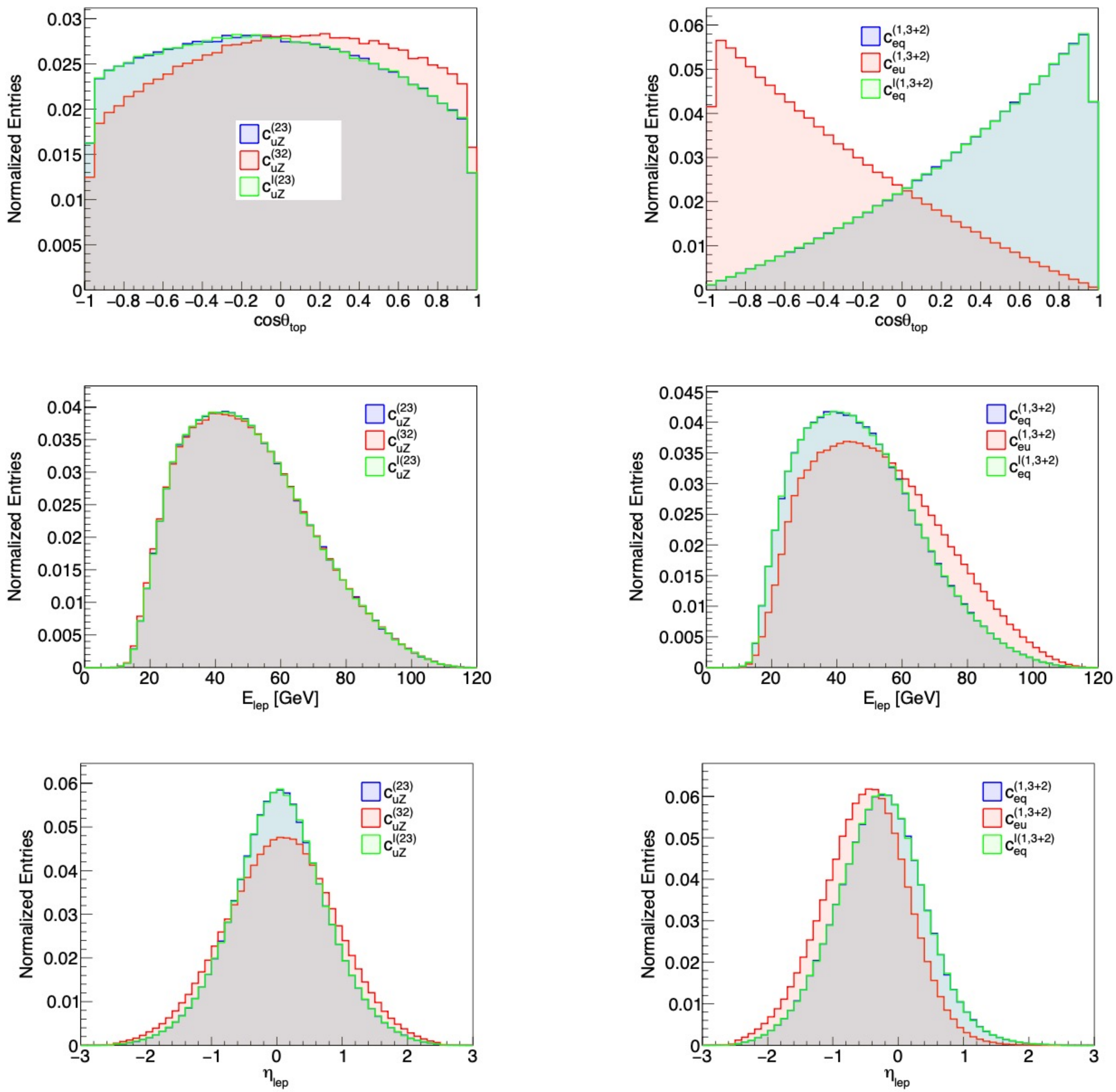


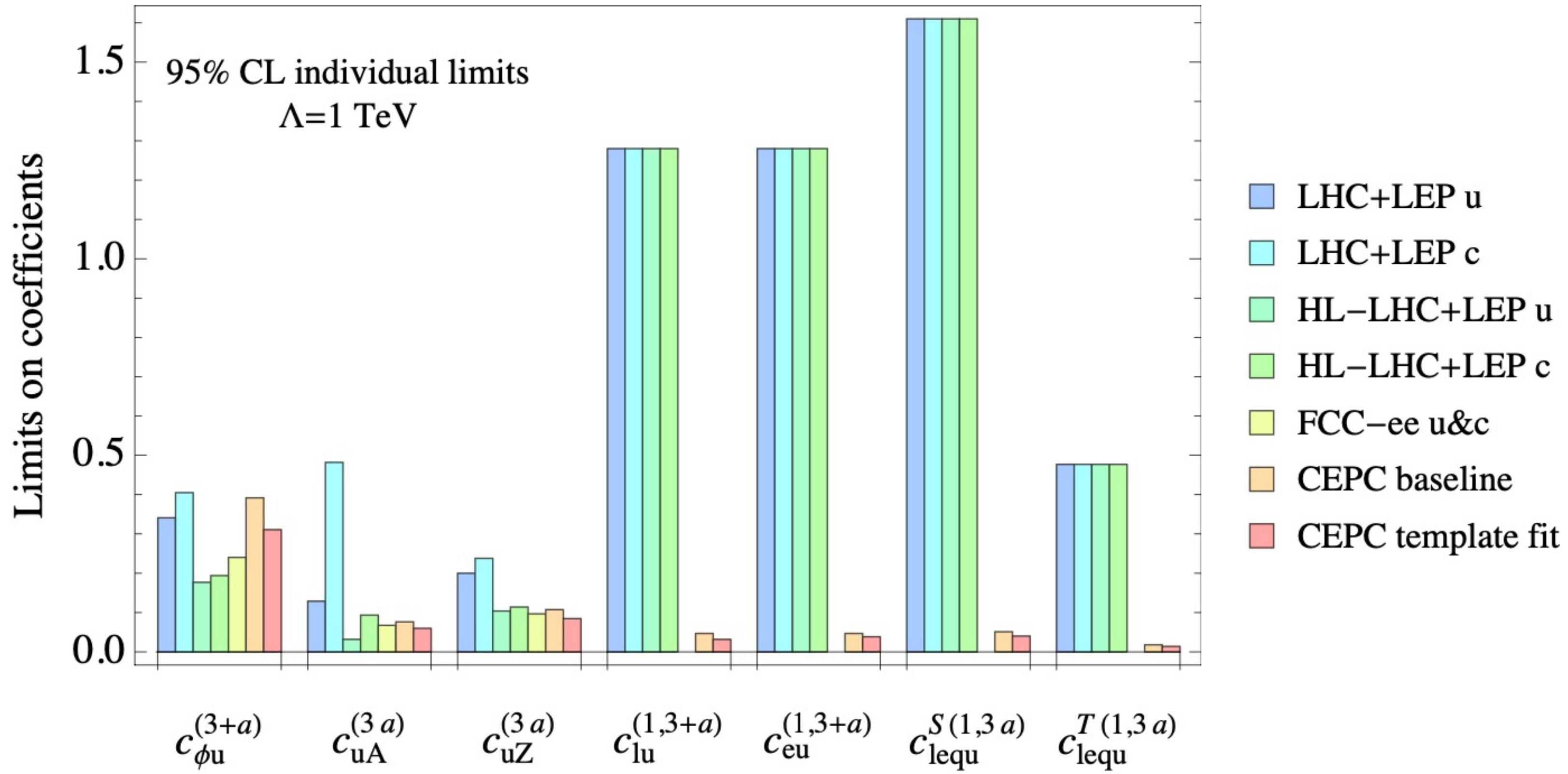
- 2D limits on a 4f coefficient with a=1 and a=2.
- c-jet tagging helps to identify the quark flavour involved in the FCN coupling.

Conclusion

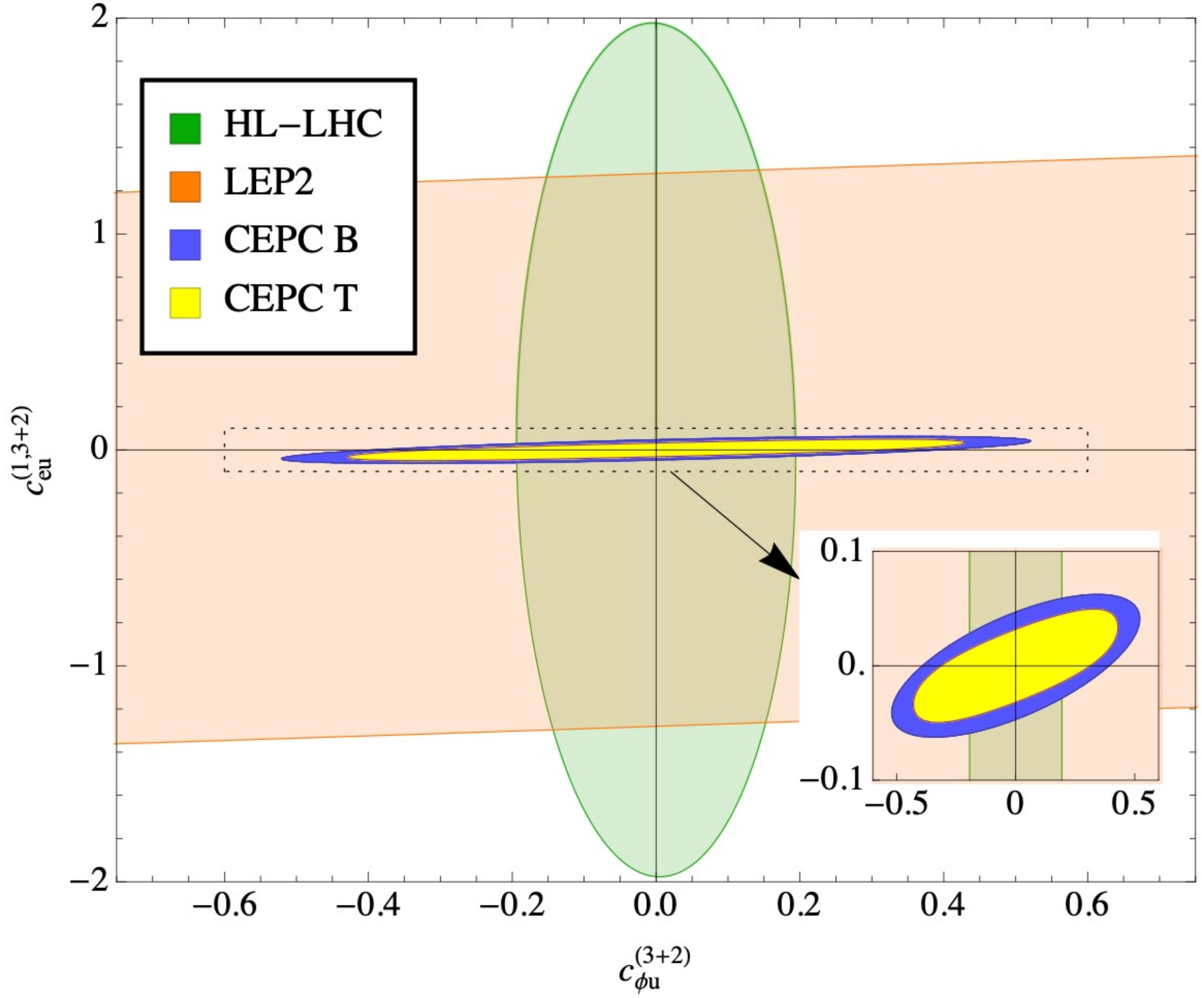
- CEPC, prosed as a Higgs factory, is also an ideal machine to test the top-quark flavour-changing interactions.
- In particular as a ee collider it has very good sensitivity on 4-fermion operators, and will explore the parameter space not covered by HL-LHC.
- Estimation of the sensitivity of CEPC @ 240 GeV based on the CDR scenario looks promising.
- c-tagging and angular observable can further improve the sensitivity and helps to pinpoint the coefficients if there is an excess.

BACKUP


Normalized Entries
cosθ_top
c_uZ^(23)
c_uZ^(32)
c_uZ^I(23)
c_eq^(1,3+2)
c_eu^(1,3+2)
c_eq^I(1,3+2)
E_lep [GeV]
η_lep



95% CL individual limits
Λ=1 TeV
Limits on coefficients
1.5
1.0
0.5
0.0
$c_{\phi u}^{(3+a)}$
$c_{uA}^{(3\,a)}$
$c_{uZ}^{(3\,a)}$
$c_{lu}^{(1,3+a)}$
$c_{eu}^{(1,3+a)}$
$c_{lequ}^{S\,(1,3\,a)}$
$c_{lequ}^{T\,(1,3\,a)}$
LHC+LEP u
LHC+LEP c
HL−LHC+LEP u
HL−LHC+LEP c
FCC−ee u&c
CEPC baseline
CEPC template fit


HL−LHC
LEP2
CEPC B
CEPC T
2
1
0
−1
−2
$c_{eu}^{(1,3+2)}$
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
$c_{\phi u}^{(3+2)}$
0.1
0.
−0.1
−0.5
0
0.5