# Unraveling the neutral flavor-changing properties of the top quark at a future electron-positron collider

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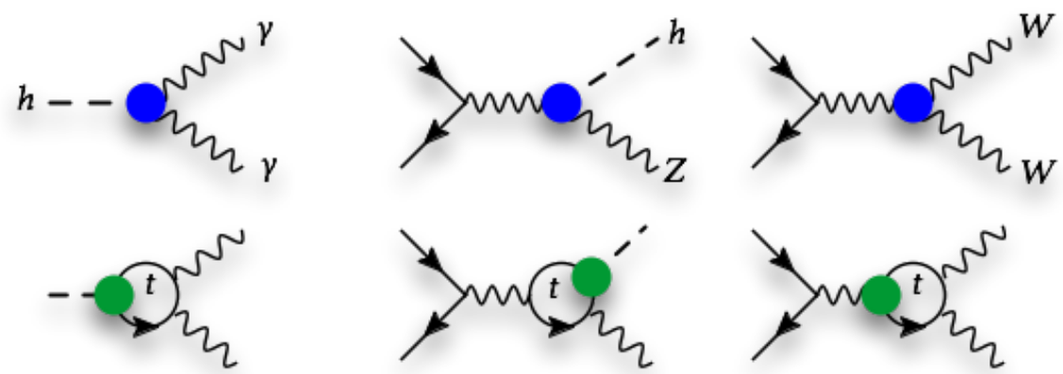
FCPPL proposal, with Gauthier Durieux, Benjamin Fuks, Yi-Ming Liu, Hua-Sheng Shao, Liaoshan Shi, Yusheng Wu

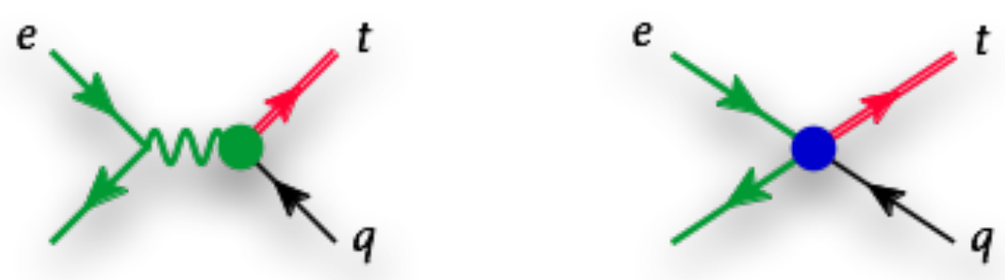
# Top physics at a ee collider below 350 GeV

- 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 interactions
    (may cover unexplored parameter space by LHC…)



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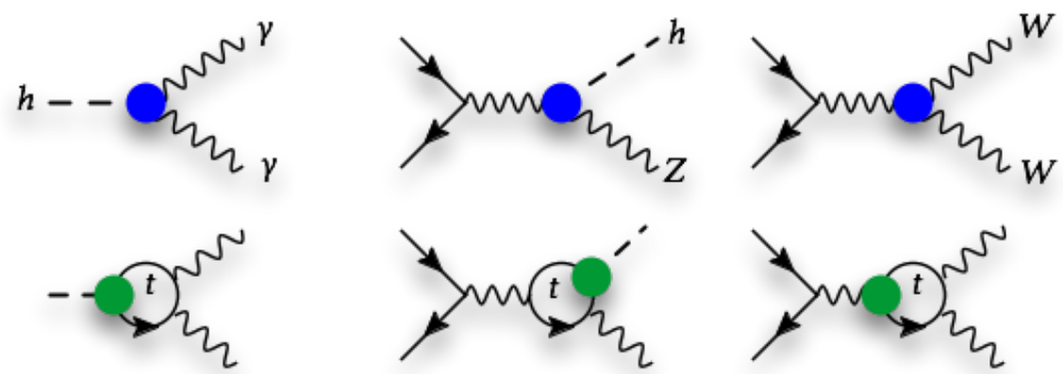


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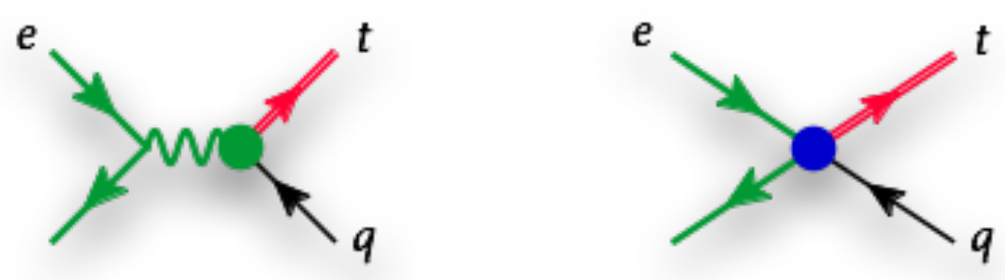


This talk

# Top flavor changing interactions (Top FCNC)

# Top FCNC

- Neutral couplings that involve one top quark and one light quark.
- Forbidden in the SM (by GIM mechanism) **Definite sign of BSM**.

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

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

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

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

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

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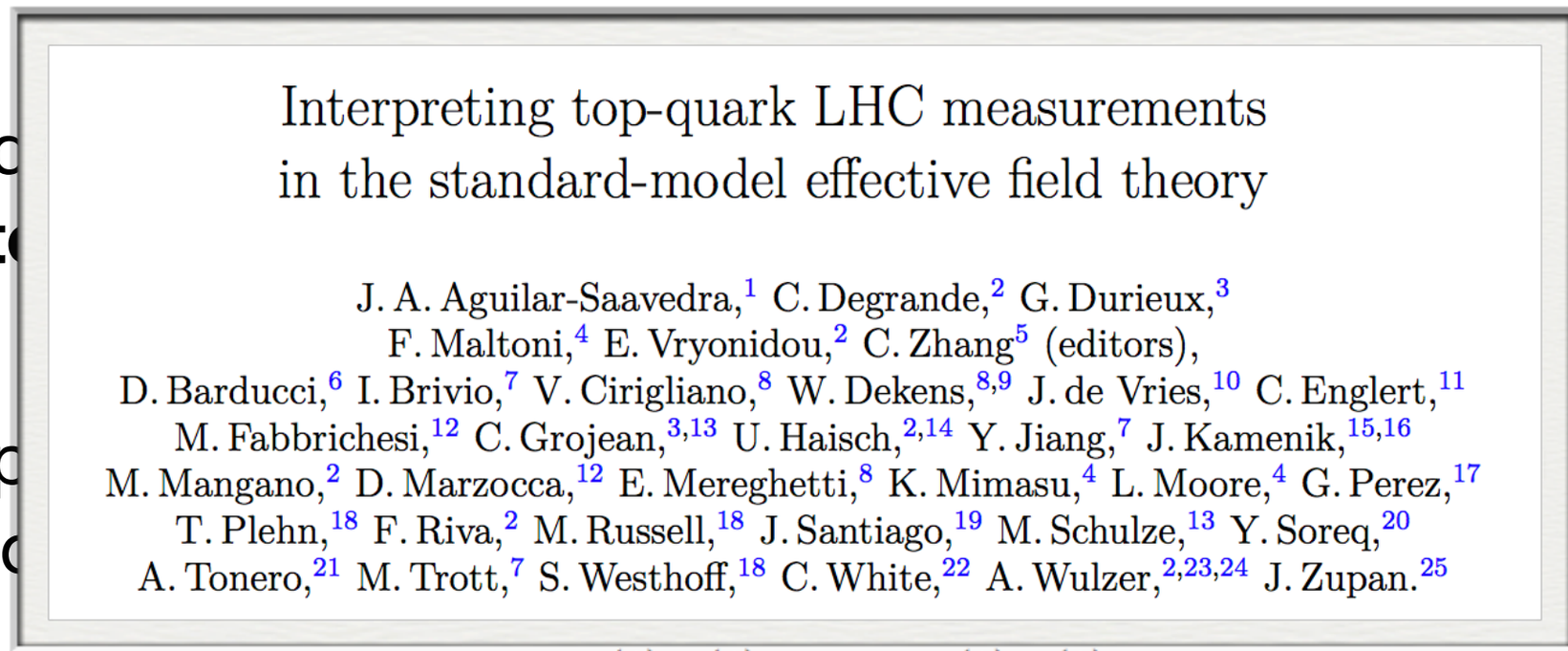

Interpreting top-quark LHC measurements in the standard-model effective field theory

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

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

## Warsaw basis operators

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

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Left-handed q

Right-handed q

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

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

## 28 DoFs relevant for ee

CP even

CP odd

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

Sufficient to focus on 7 parameters

Left-handed q

Right-handed q

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

28 DoFs relevant for ee

$$c_{\varphi q}^{-(3+a)},\quad c_{uA}^{(a3)},\quad c_{uZ}^{(a3)},\quad c_{lequ}^{S(1,a3)},\quad c_{lequ}^{T(1,a3)},\quad c_{lq}^{-(1,3+a)},\quad c_{eq}^{(1,3+a)},$$

$$c_{\varphi u}^{(3+a)},\quad c_{uA}^{(3a)},\quad c_{uZ}^{(3a)},\quad c_{lequ}^{S(1,3a)},\quad c_{lequ}^{T(1,3a)},\quad c_{lu}^{(1,3+a)},\quad c_{eu}^{(1,3+a)},$$

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

$$c_{\varphi u}^{I(3+a)},\quad c_{uA}^{I(3a)},\quad c_{uZ}^{I(3a)},\quad c_{lequ}^{SI(1,3a)},\quad c_{lequ}^{TI(1,3a)},\quad c_{lu}^{I(1,3+a)},\quad c_{eu}^{I(1,3+a)}$$

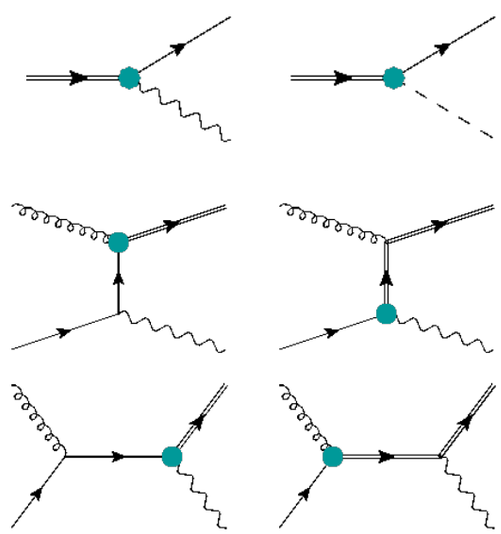
# Top FCNC: 2-fermion and 4-fermion operators

28 DoFs relevant for ee

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

## 2-fermion FCNC

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



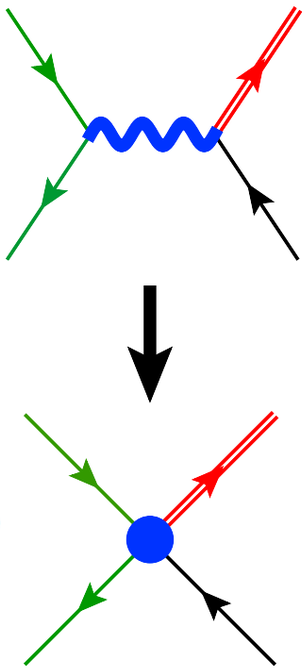
# Top FCNC: 2-fermion and 4-fermion operators

28 DoFs relevant for ee

$$c_{\varphi q}^{-(3+a)},\quad c_{uA}^{(a3)},\quad c_{uZ}^{(a3)},$$
$$c_{\varphi u}^{(3+a)},\quad c_{uA}^{(3a)},\quad c_{uZ}^{(3a)},$$
$$c_{\varphi q}^{-I(3+a)},\quad c_{uA}^{I(a3)},\quad c_{uZ}^{I(a3)},$$
$$c_{\varphi u}^{I(3+a)},\quad c_{uA}^{I(3a)},\quad c_{uZ}^{I(3a)},$$

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

4-fermion FCNC

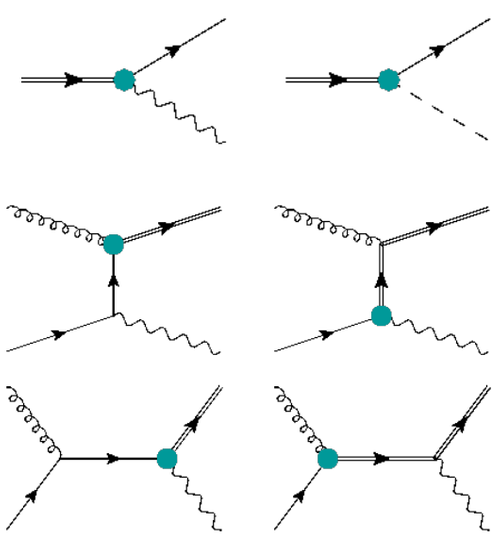


$$\mathcal{L}_{tcee} = \frac{1}{\Lambda^2}\sum_{i,j=L,R}\Big[V_{ij}\,(\bar{e}\gamma_\mu P_i e)\,(\bar{t}\gamma^\mu P_j c) + S_{ij}\,(\bar{e}P_i e)\,(\bar{t}P_j c) + T_{ij}\,(\bar{e}\sigma_{\mu\nu}P_i e)\,(\bar{t}\sigma_{\mu\nu}P_j c)\Big]\,,$$

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

2-fermion FCNC

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



| 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)

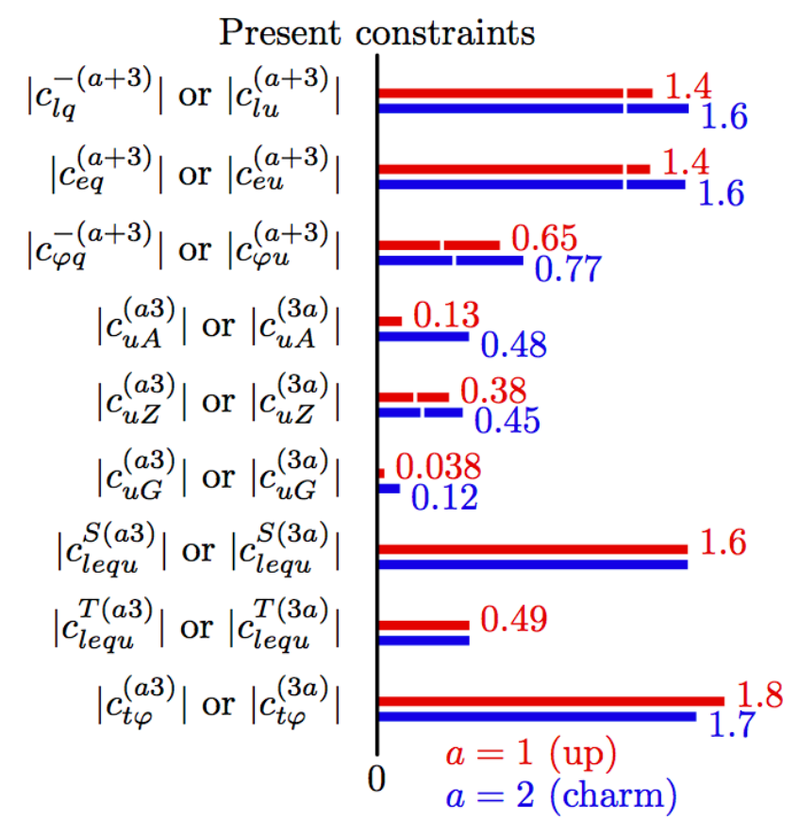
**[DELPHI, CERN–PH–EP/2010–056]**

**See also [Chala, Santiago, Spannowsky '18] for LHC**

# 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

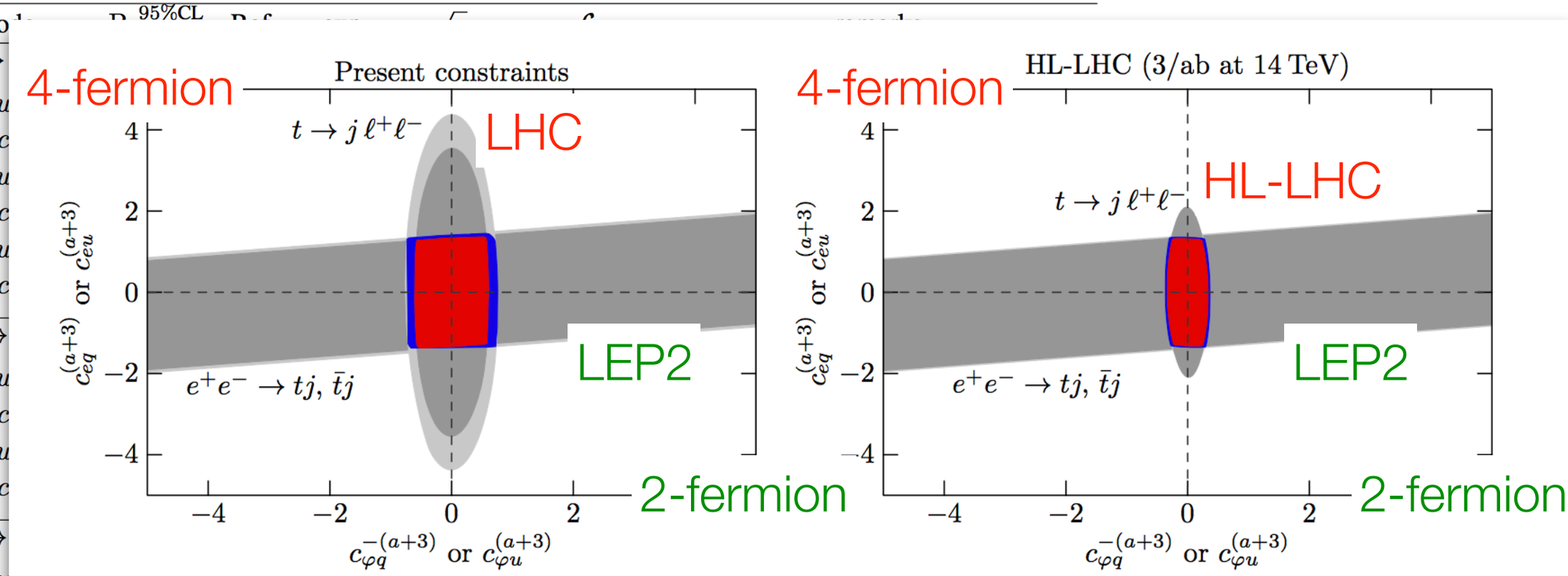
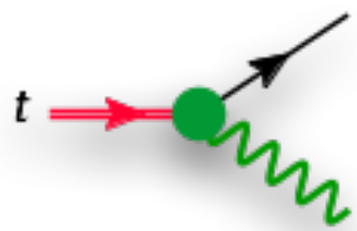
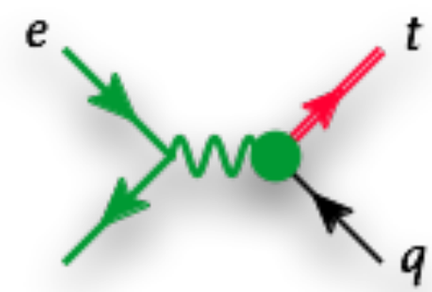
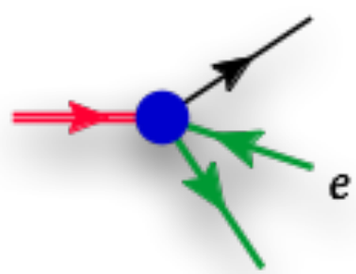
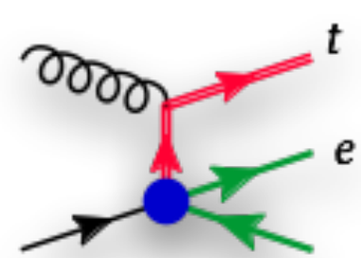
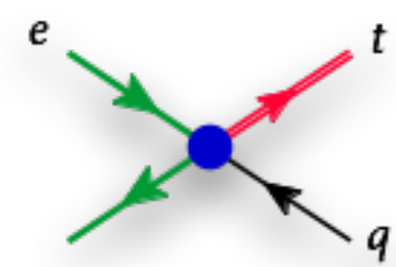
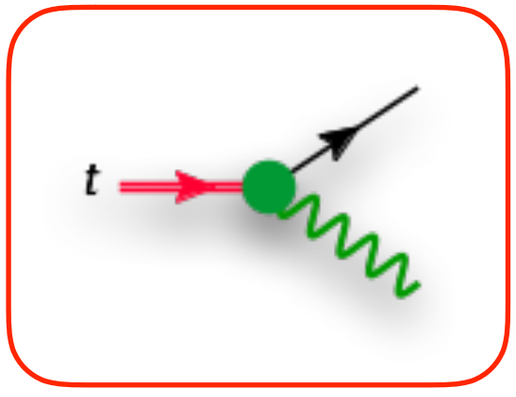
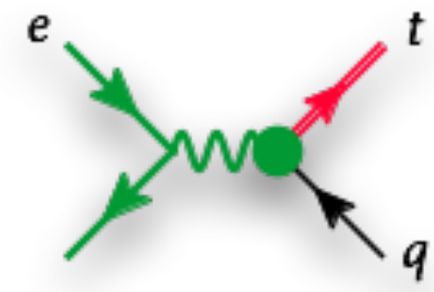
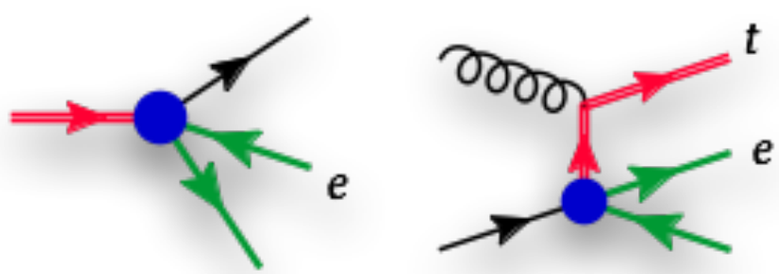
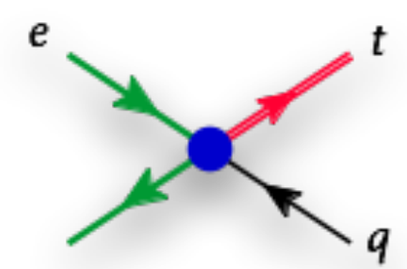



Fig. 59: Current (left) and prospective HL-LHC (right) 95% C.L. limits on top-quark FCNC operator coefficients in a two-dimensional plane formed by two- ($x$ axis) and four-fermion ($y$ axis) operator coefficients. Other parameters are marginalized over, within the constraints obtained when all measurements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

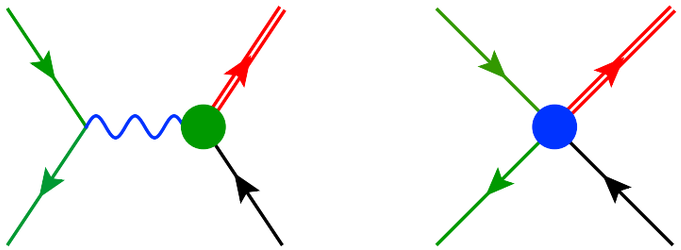
[HL/HE-LHC yellow report]

| | LHC | ee collider |
|---|---|---|
| 2-fermion OP |  |  |
| 4-fermion OP |   |  |
| | Phase space suppression | $E^4/\mathbf{mz}^4$ scaling enhancement |

| | LHC | ee collider |
|---|---|---|
| 2-fermion OP |  |  |
| 4-fermion OP |  <br>Phase space suppression |  <br>$E^4/\mathbf{mz}^4$ scaling enhancement |

# 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]**



# Top FCNC: MC tool

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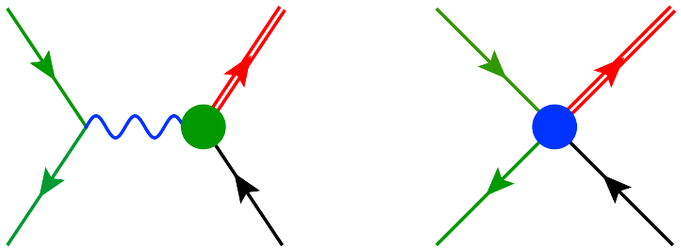
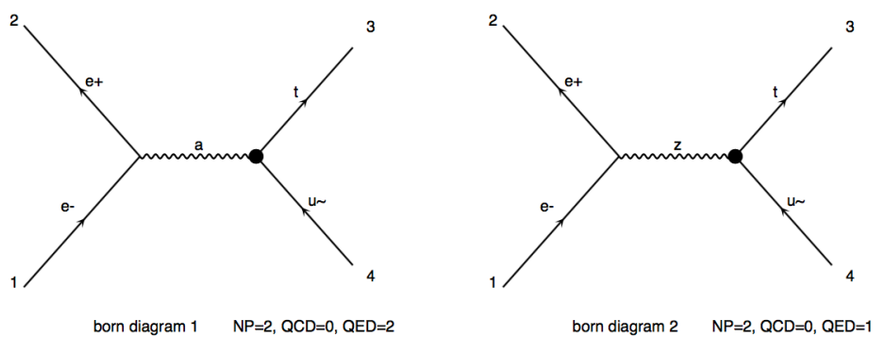
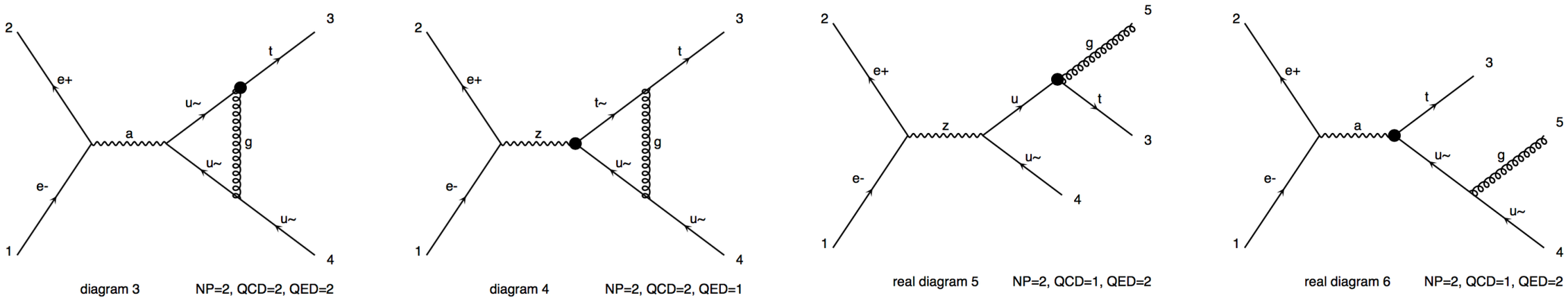


- QCD corrections: FCNC specific UFO. Need 4f implementation
  http://feynrules.irmp.ucl.ac.be/wiki/TopFCNC **[Degrande, Maltoni, Wang, CZ '14]**

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

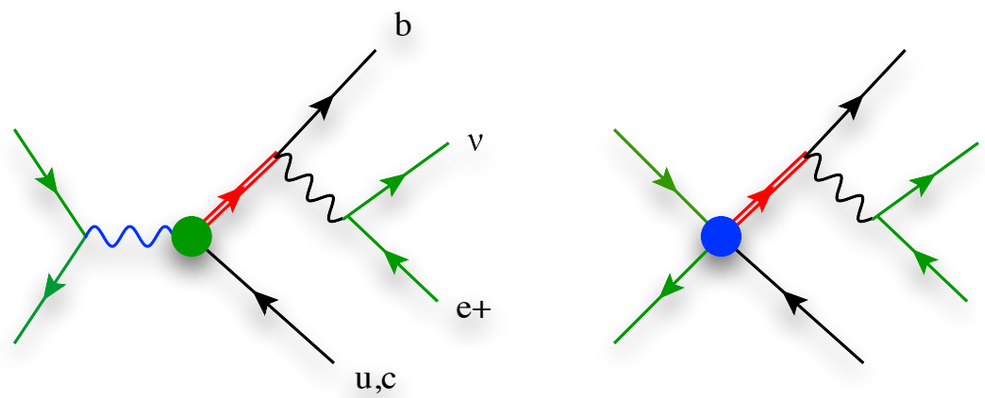


# Some **very preliminary** results for CEPC

Produced by Liaoshan Shi

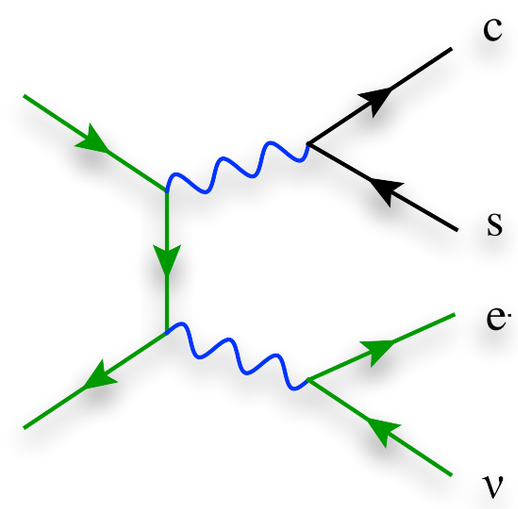
- CEPC scenario, 240 GeV, 5 $ab^{-1}$
- Signal and Backgrounds both simulated at LO+PS, with MadGraph5 and Pythia8
- FCNC implementation: **`dim6top`**
- Detector effects: Delphes with CEPC card
- Signal:

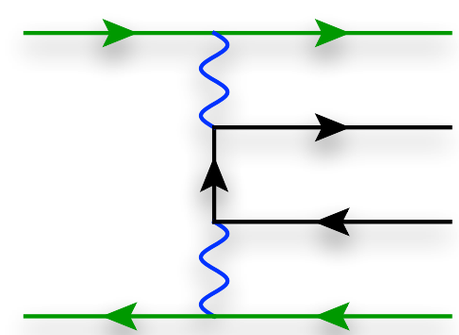



$$m_{top,rec} \approx 172.5 \text{ GeV}$$

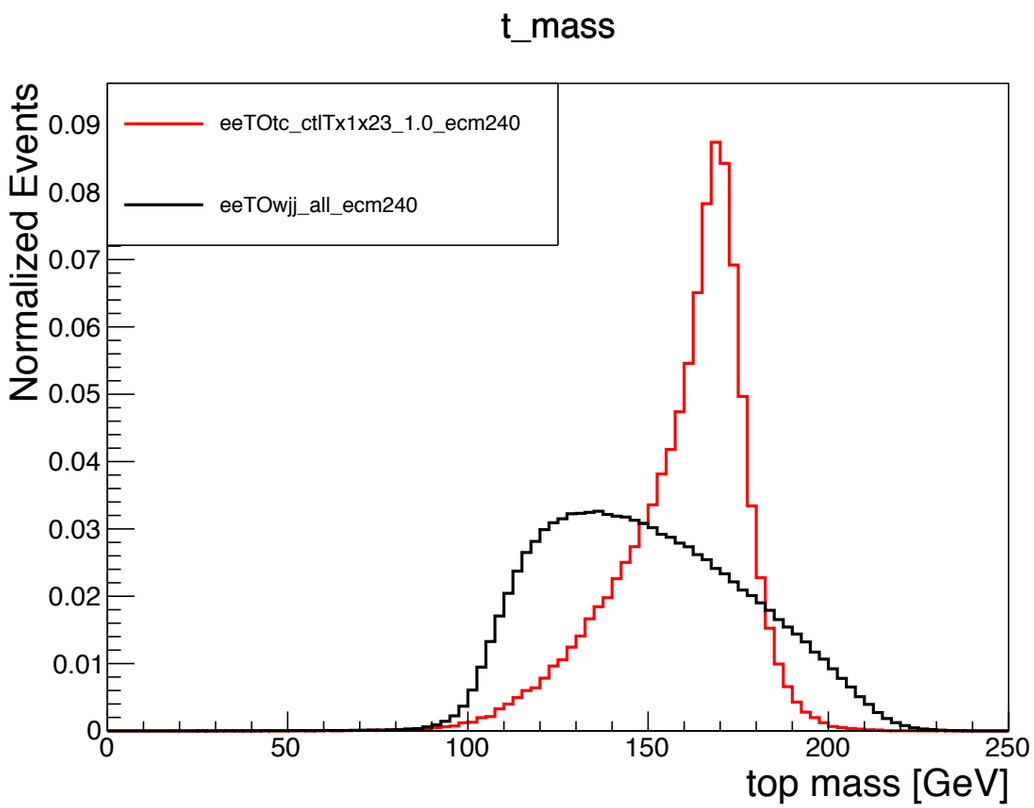
$$E_{j,rec} \approx \frac{s - m_t^2}{2\sqrt{s}} \approx 58 \text{ GeV}$$

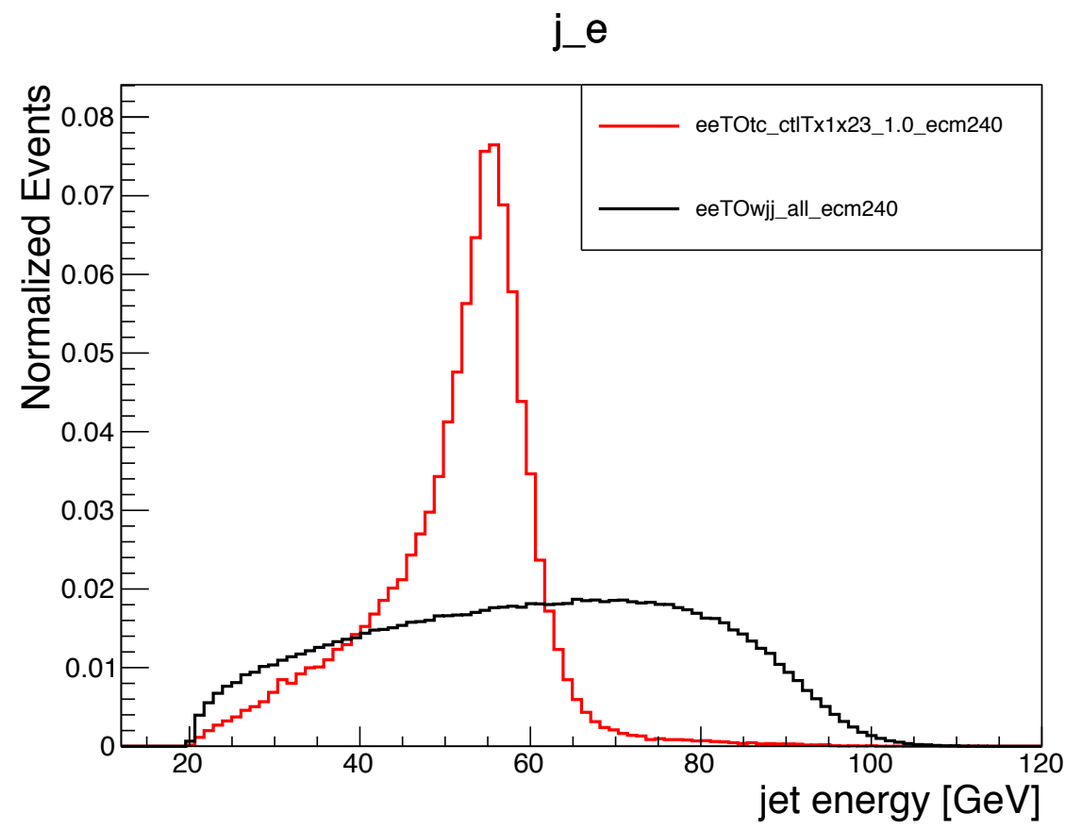
- Background: Wjj dominant

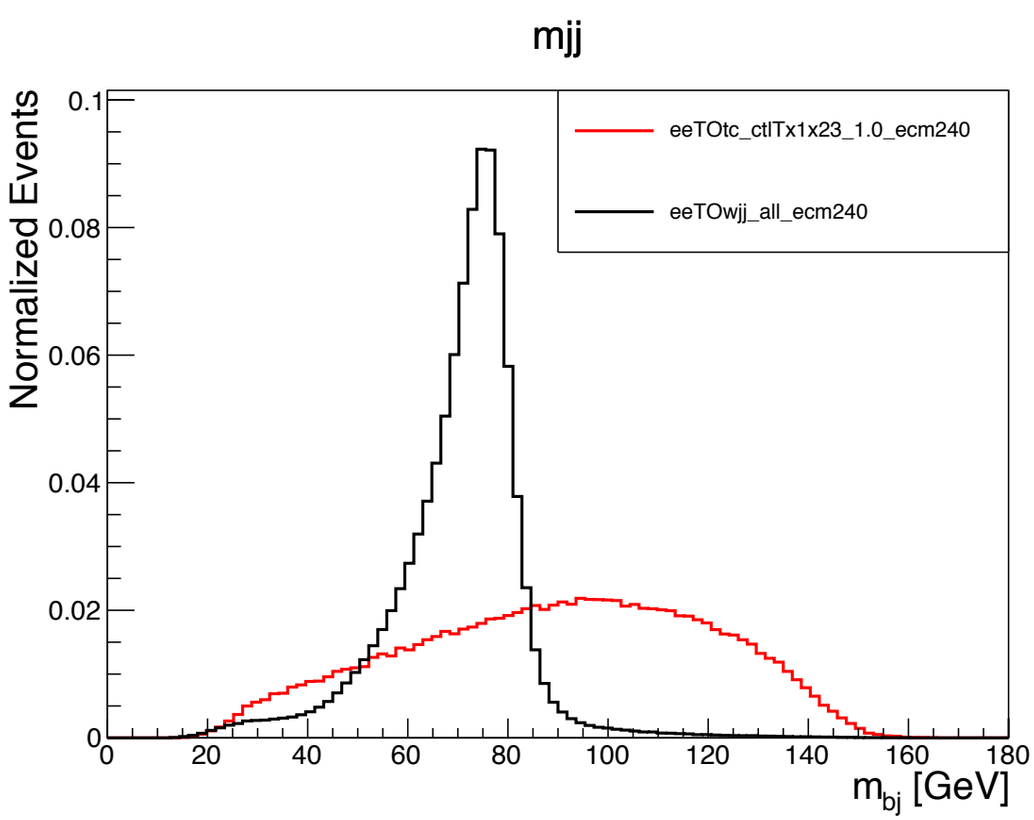


$$m_{jj} \approx 80.4 \text{ GeV}$$




- Signal selection:

  1 lepton, 1 b-jet, 1 non-b jet

  $\not{E} > 30$ GeV

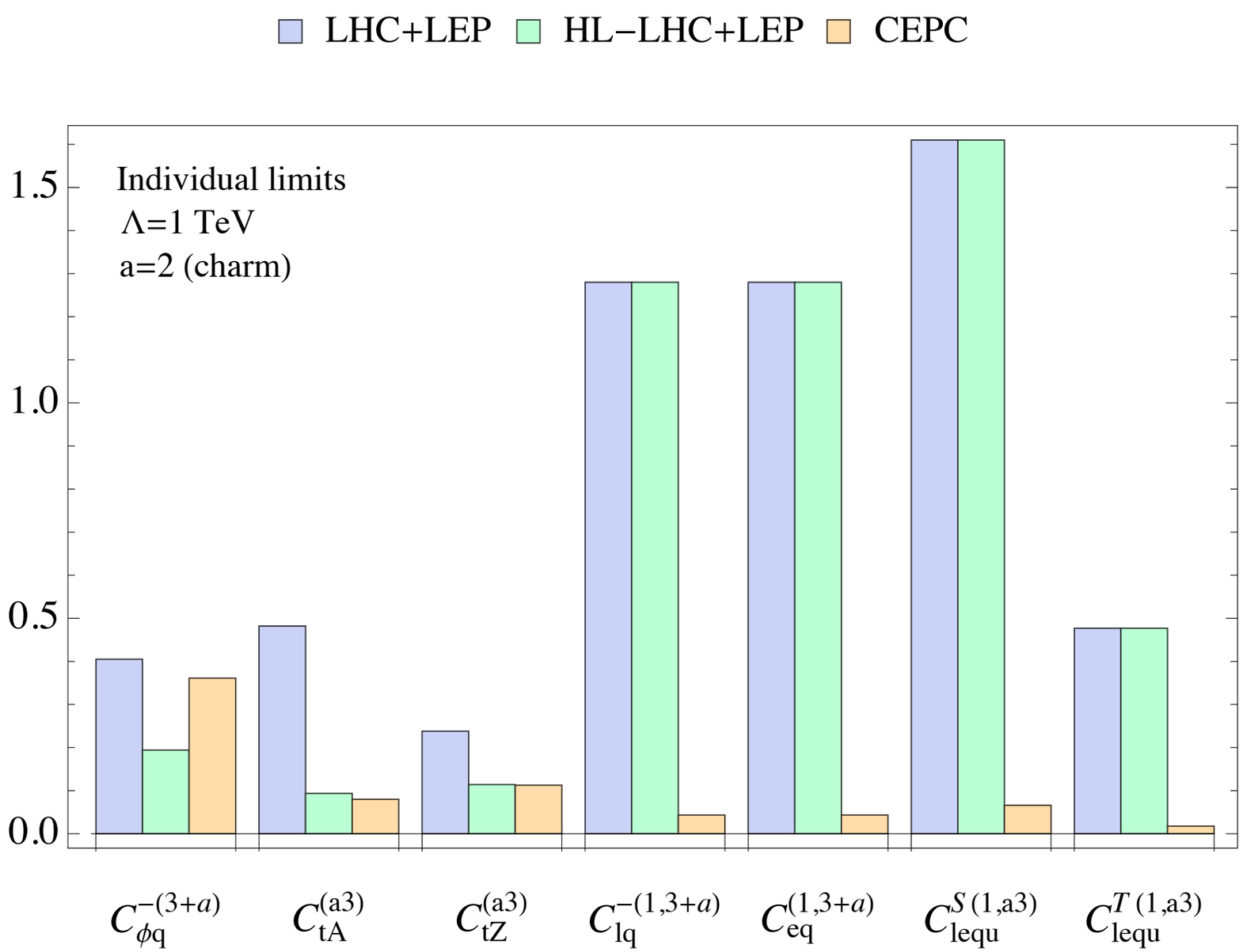
  $E_j < 60$ GeV

  $m_{jj} > 100$ GeV

  $m_{top} < 180$ GeV

- Stat.~3%. Ignore systematics

- 95% CL upper limit on fiducial xsec: 0.0144 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



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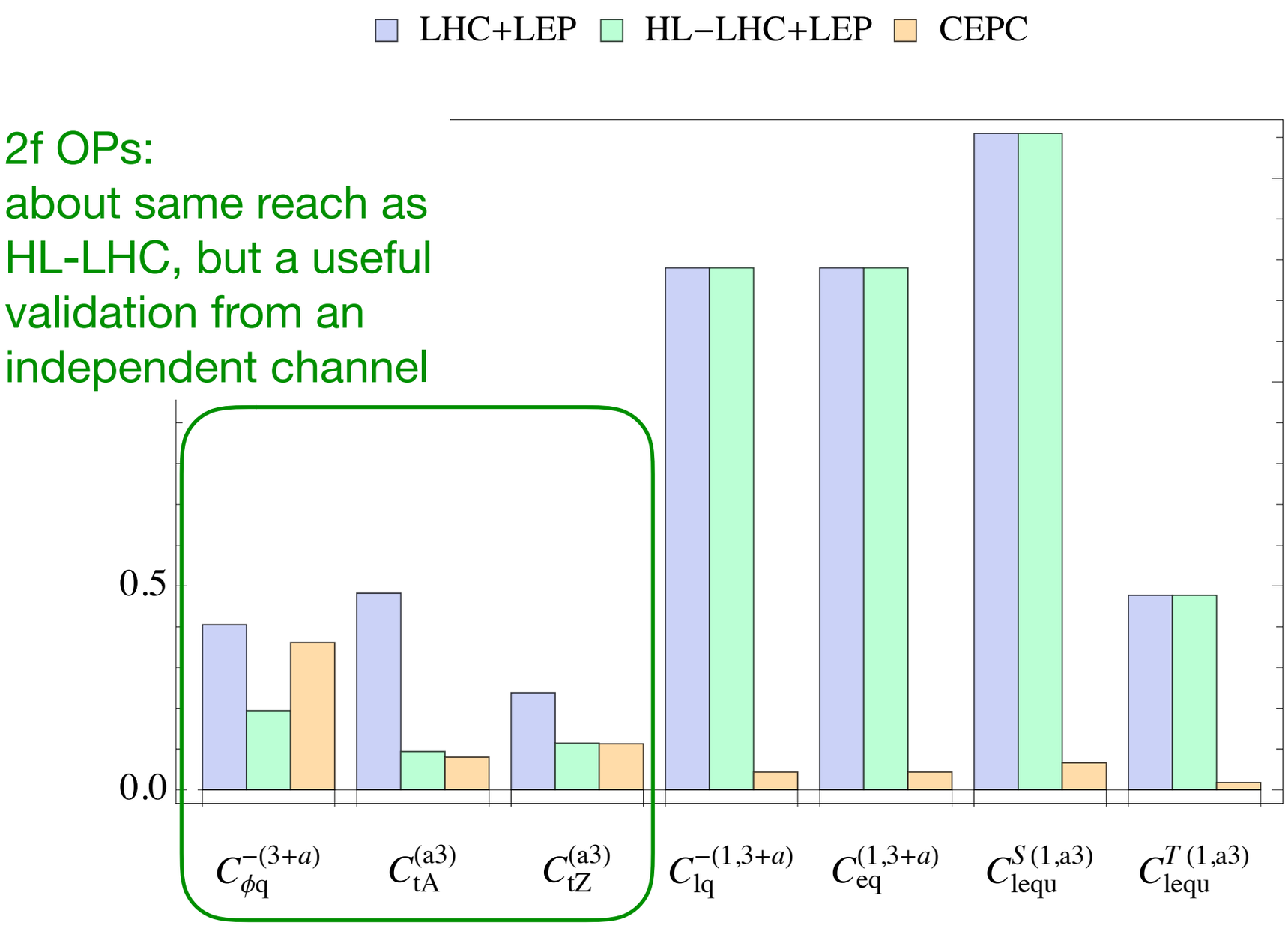

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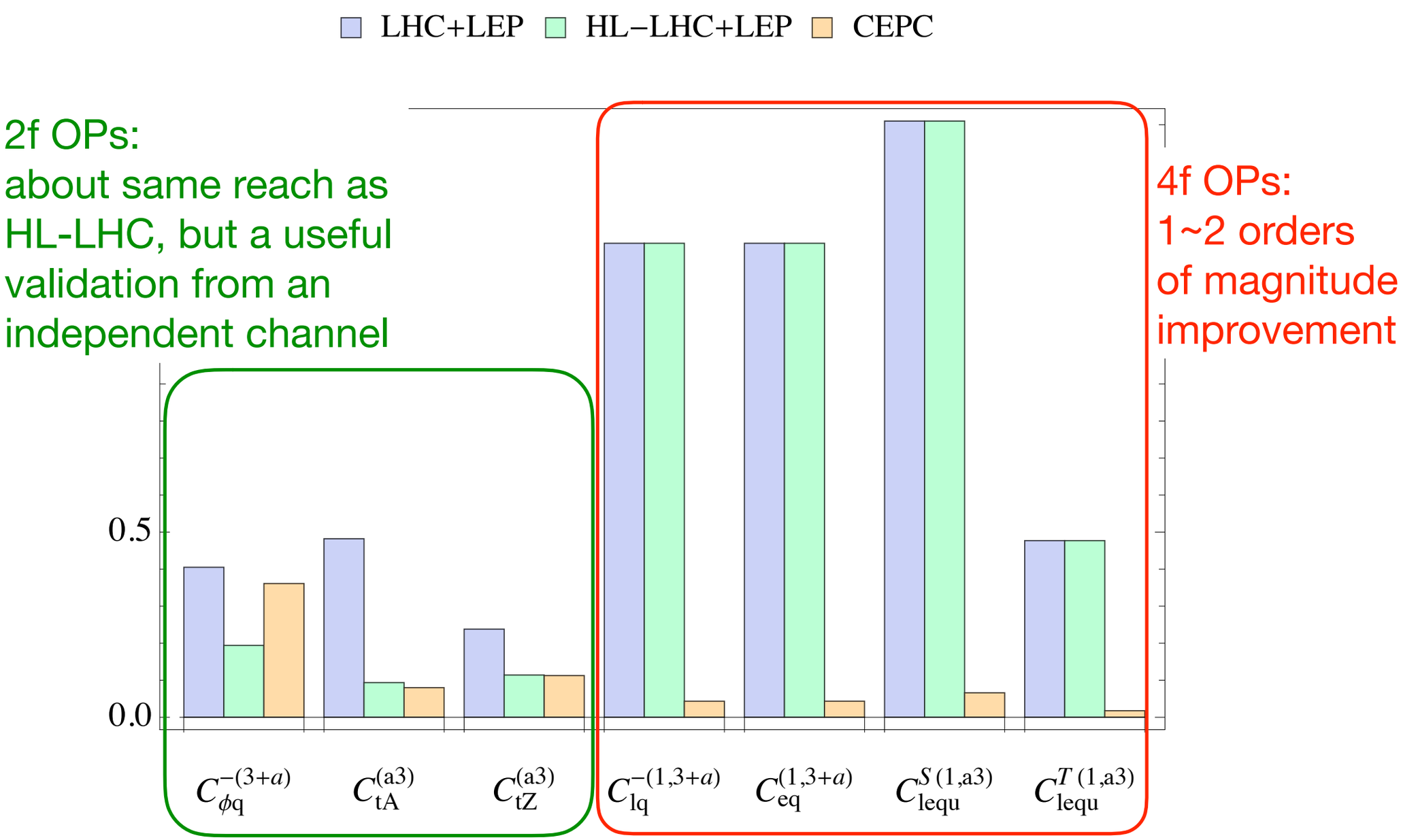
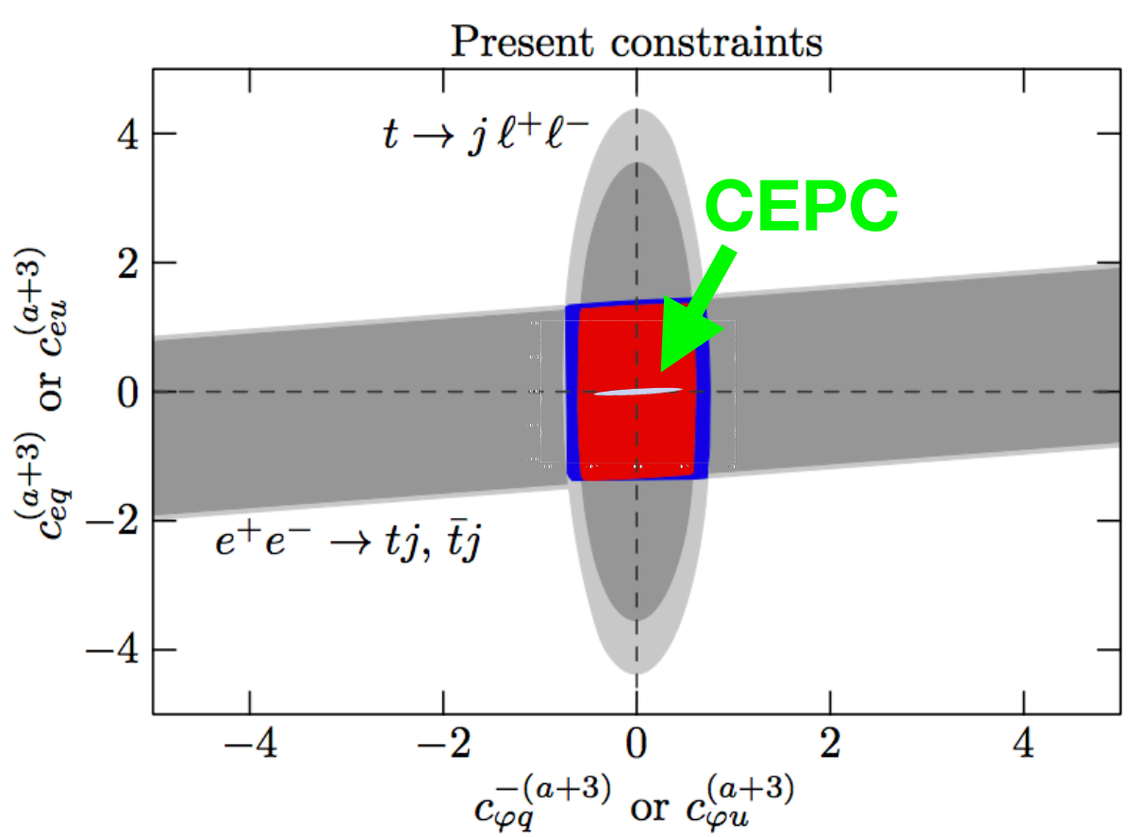
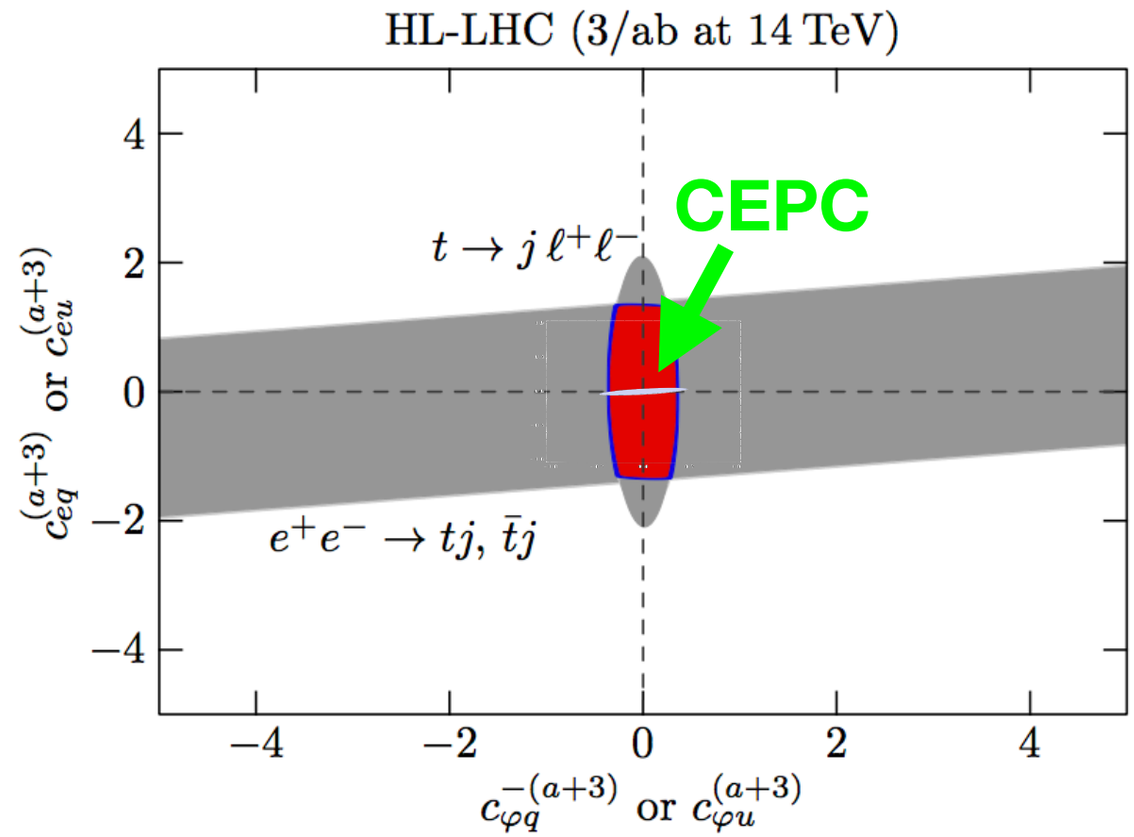
- Convert into 95% 7-D bound in the dim-6 parameter space




Present constraints
$t \to j\,\ell^+\ell^-$
CEPC
$e^+e^- \to tj,\ \bar{t}j$
$c_{eq}^{(a+3)}$ or $c_{eu}^{(a+3)}$
$c_{\varphi q}^{-(a+3)}$ or $c_{\varphi u}^{(a+3)}$


HL-LHC (3/ab at 14 TeV)
$t \to j\,\ell^+\ell^-$
CEPC
$e^+e^- \to tj,\ \bar{t}j$
$c_{eq}^{(a+3)}$ or $c_{eu}^{(a+3)}$
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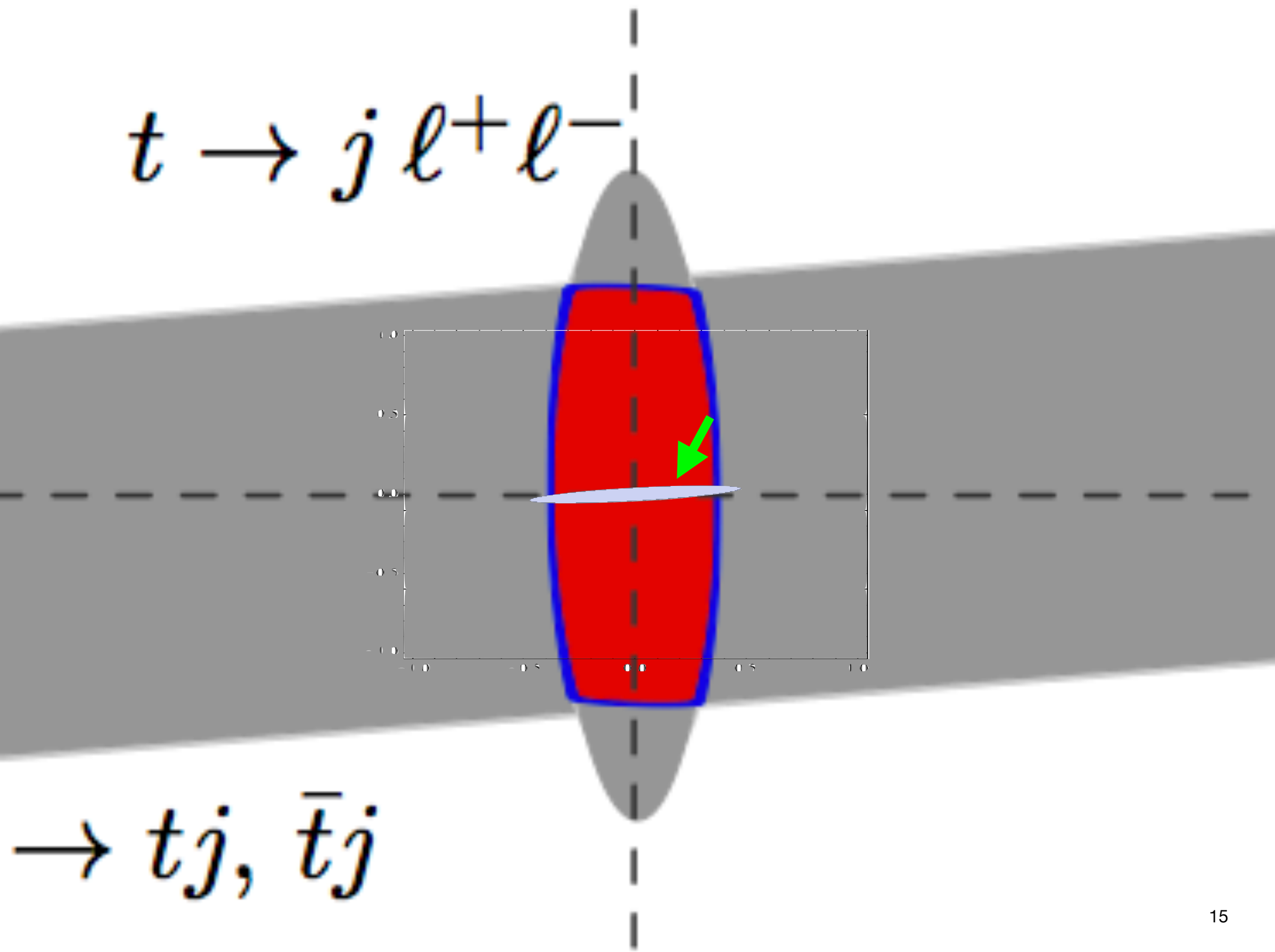
$$t \to j\,\ell^+\ell^-$$



$$\to t j,\ \bar{t} j$$

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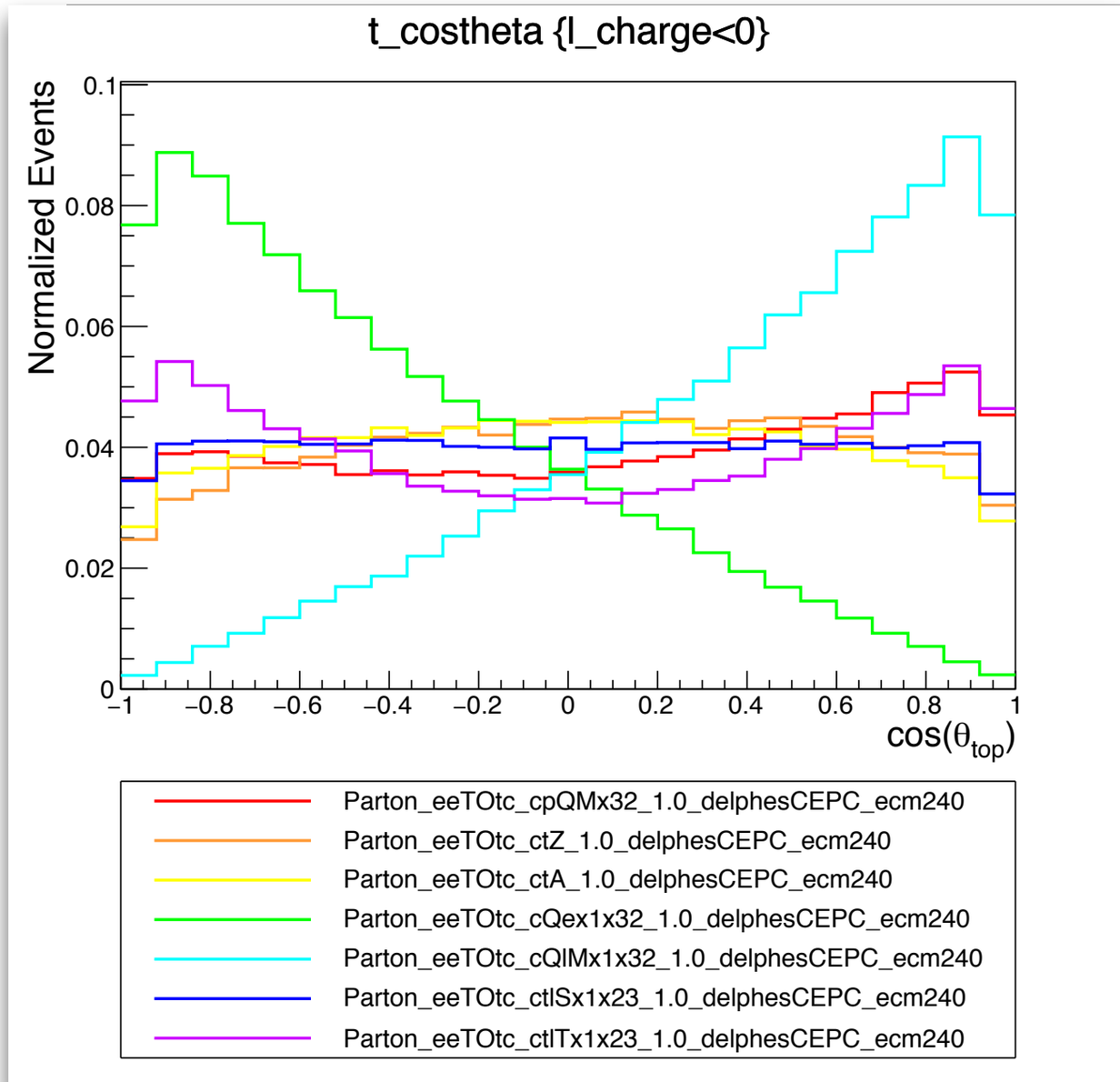
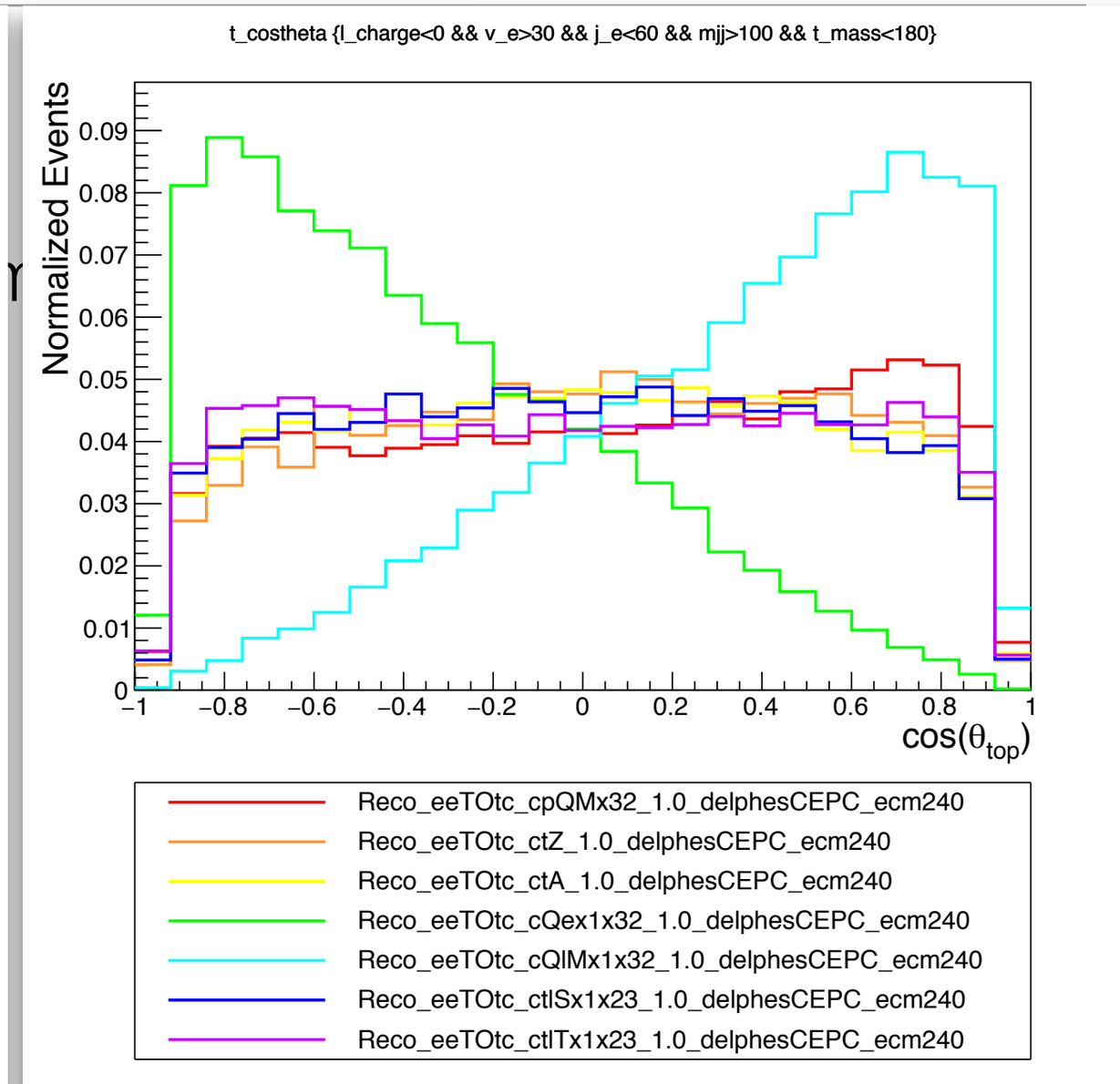

t_costheta {l_charge<0}
Normalized Events
0.1
0.08
0.06
0.04
0.02
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
cos(θtop)
Parton_eeTOtc_cpQMx32_1.0_delphesCEPC_ecm240
Parton_eeTOtc_ctZ_1.0_delphesCEPC_ecm240
Parton_eeTOtc_ctA_1.0_delphesCEPC_ecm240
Parton_eeTOtc_cQex1x32_1.0_delphesCEPC_ecm240
Parton_eeTOtc_cQlMx1x32_1.0_delphesCEPC_ecm240
Parton_eeTOtc_ctlSx1x23_1.0_delphesCEPC_ecm240
Parton_eeTOtc_ctlTx1x23_1.0_delphesCEPC_ecm240


t_costheta {l_charge<0 && v_e>30 && j_e<60 && mjj>100 && t_mass<180}
Normalized Events
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
cos(θtop)
Reco_eeTOtc_cpQMx32_1.0_delphesCEPC_ecm240
Reco_eeTOtc_ctZ_1.0_delphesCEPC_ecm240
Reco_eeTOtc_ctA_1.0_delphesCEPC_ecm240
Reco_eeTOtc_cQex1x32_1.0_delphesCEPC_ecm240
Reco_eeTOtc_cQlMx1x32_1.0_delphesCEPC_ecm240
Reco_eeTOtc_ctlSx1x23_1.0_delphesCEPC_ecm240
Reco_eeTOtc_ctlTx1x23_1.0_delphesCEPC_ecm240

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  - Template fit, MVA, etc.
  - **Statistically optimal observable** to obtain the best sensitivity in theory. **[G. Durieux, the CLIC Potential for New Physics, CERN YR, 18]**
- Higher CoM energies, improvements from top pair production with FCNC decays, etc…

# Conclusion

- Future ee colliders are ideal for testing top-quark flavor-changing interactions.
- In particular it explores the parameter space that cannot be probed by the HL/HE-LHC.
- Preliminary results for the reach of CEPC seems promising. We continue to improve.

Thank you

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

## minimize the one-sigma ellipsoid in EFT parameter space

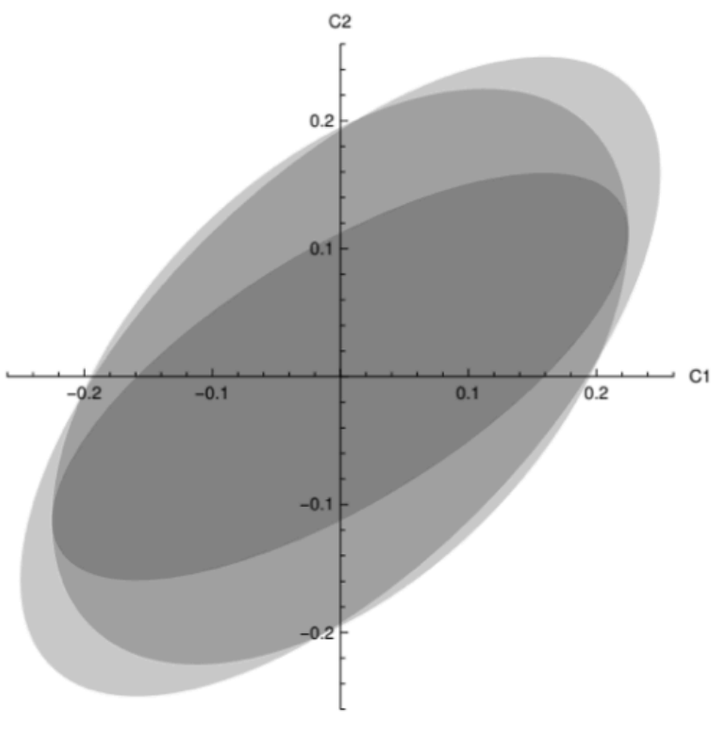
(*joint efficient* set of estimators, saturating the Cramér-Rao bound: $V^{-1} = I$,like MEM)

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]