SMEFT for tops at ee collides: 2t, 1t and 0t

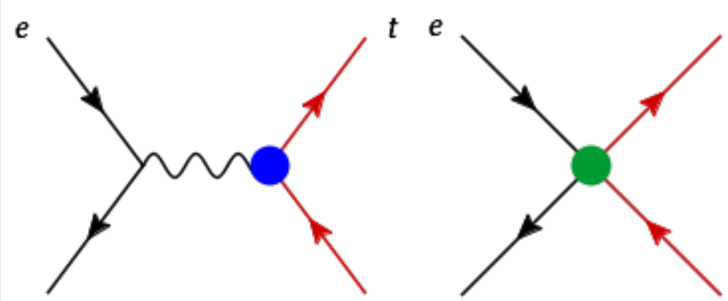
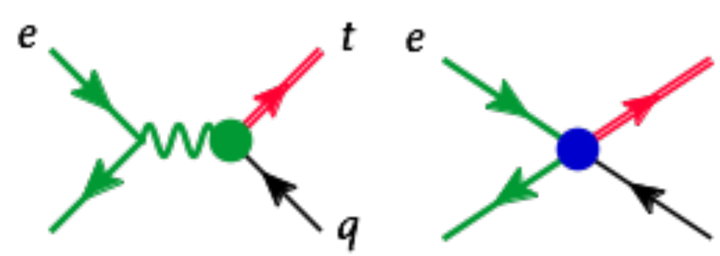
Cen Zhang

Institute of High Energy Physics

CEPC workshop
CHEP Beijing, Nov. 19 2019

Based on
1807.02121 with G. Durieux, M. Perelló, M. Vos;
1906.04573 with L. Shi (and ongoing FCPPL project) with G. Durieux, B. Fuks, H.-S. Shao, L. Shi, Y. Wu;
1804.09766 & 1809.03520 with G. Durieux, J. Gu, E. Vryonidou.

- Original title: **Theory prediction for ttbar in SMEFT**
- but it might be interesting to cover something more relevant for a CEPC workshop… So

	Process	Diagrams	Physics	TH prediction
2t	$e^+e^- \to t\bar{t}$ >350 GeV		Top-EW couplings	SMEFT @ NLO in QCD
1t	$e^+e^- \to tj, \bar{t}j$ via top FCNC 240 GeV		Search for FCNC	NLO in QCD ISR (+BS)
0t	Virtual tops 240 GeV		Indirectly probe tops (below 350 GeV)	EW loop corrections

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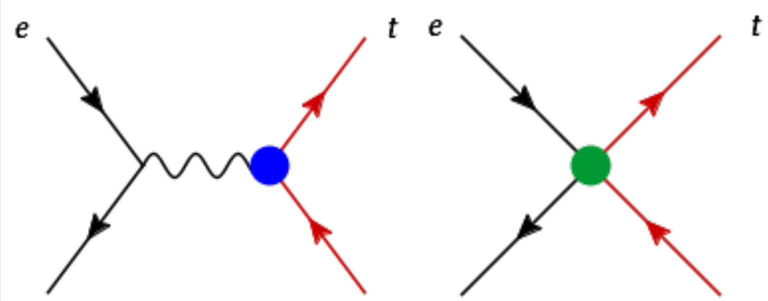
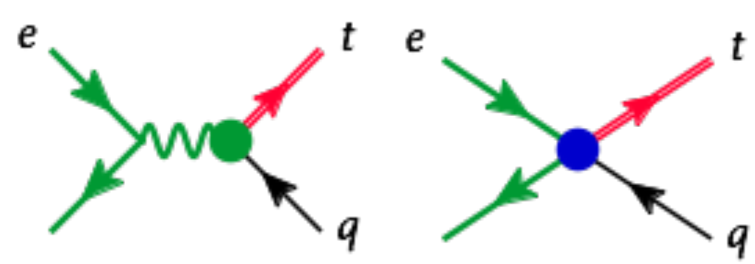
2t	$e^+e^- \to t\bar{t}$ >350 GeV		Top-EW couplings	SMEFT @ NLO in QCD
1t	$e^+e^- \to tj, \bar{t}j$ via top FCNC 240 GeV		Search for FCNC	NLO in QCD ISR (+BS)
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Automated with MG5

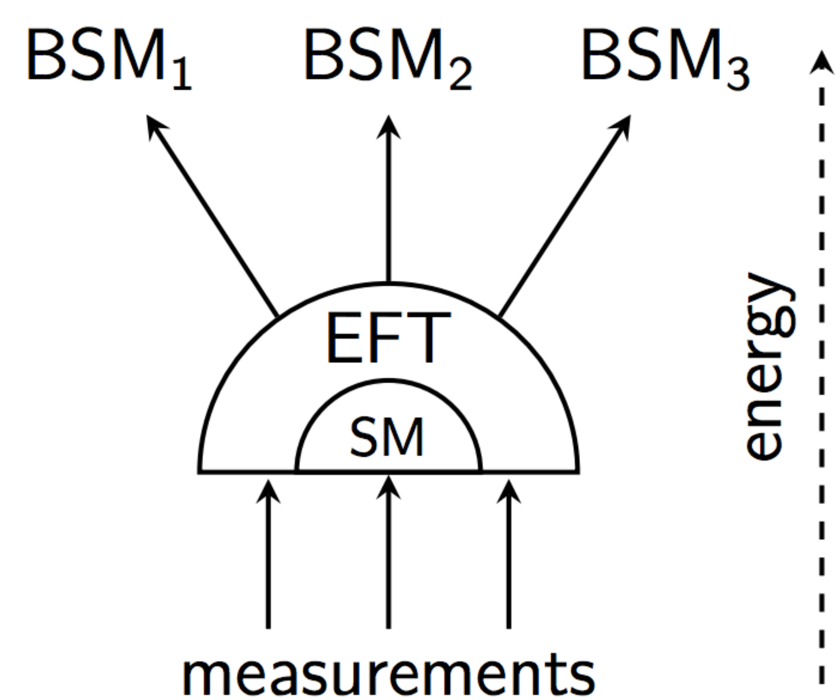
SMEFT

systematically parametrizes the theory space in direct vicinity of the SM

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

- based on SM fields and symmetries
- in a low-energy limit
- systematic (and renormalizable) when global

(...) if one writes down the most general possible Lagrangian, including all terms consistent with assumed symmetry principles, (...) the result will simply be the most general possible S-matrix consistent with analyticity, perturbative unitarity, cluster decomposition and the assumed symmetry. [*Phenomenological Lagrangians*, Weinberg '79]



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- based on SM fields and symmetries
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Identify SM deviations through precise measurements

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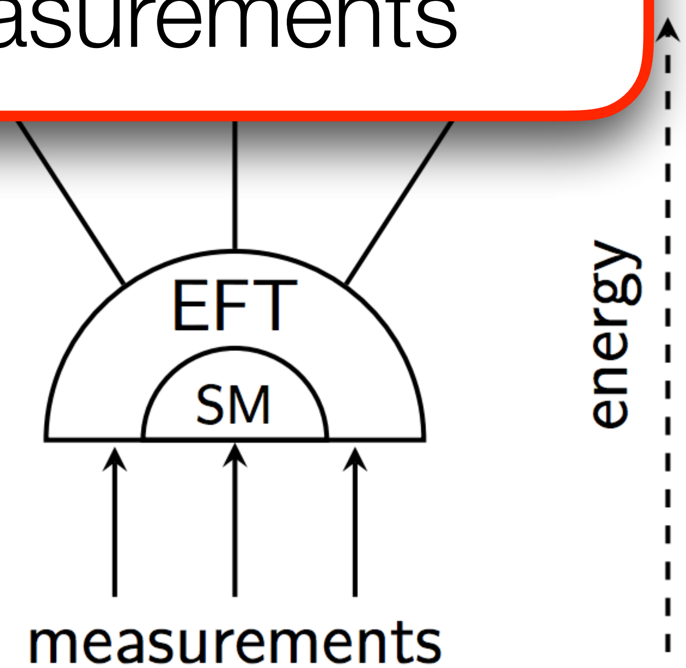
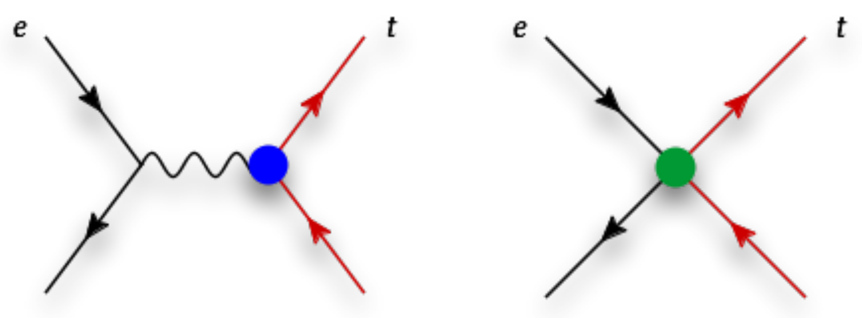
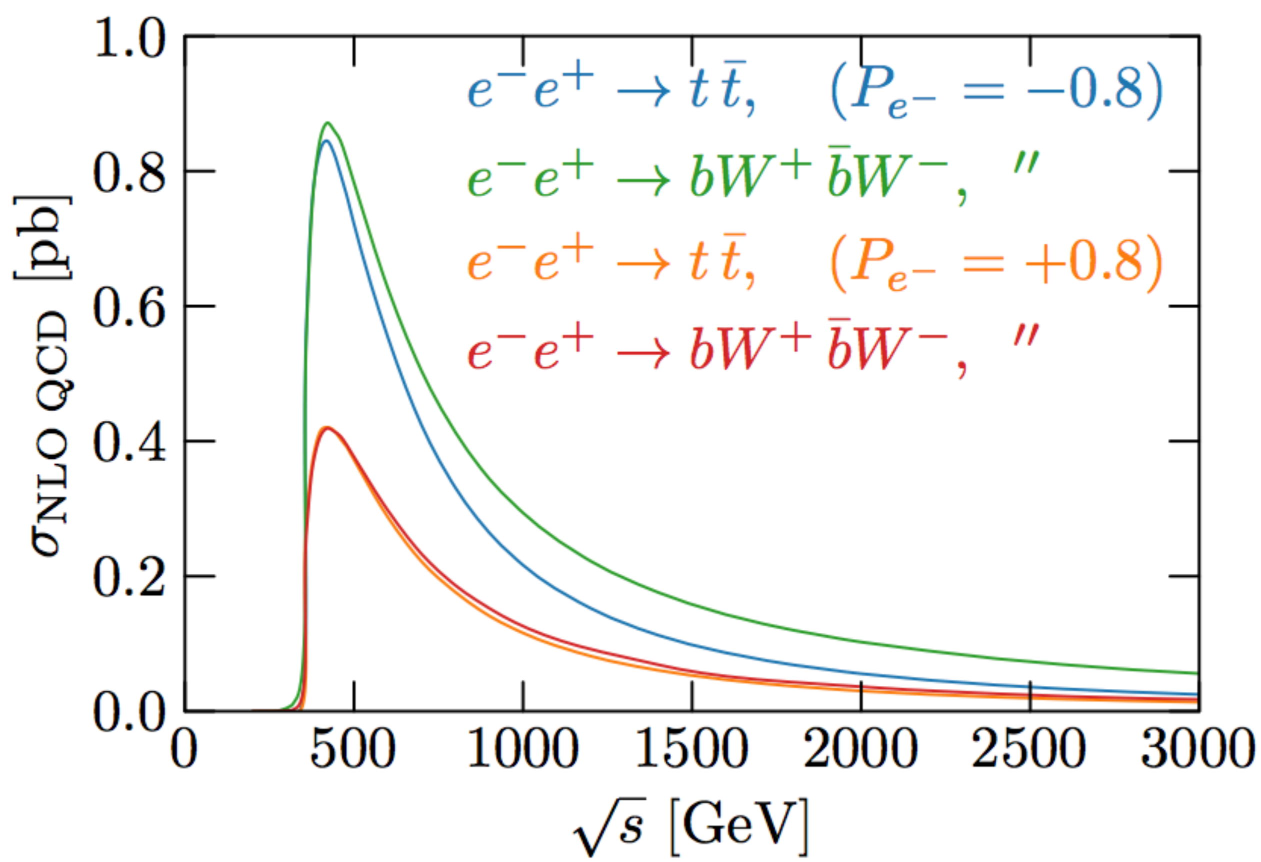
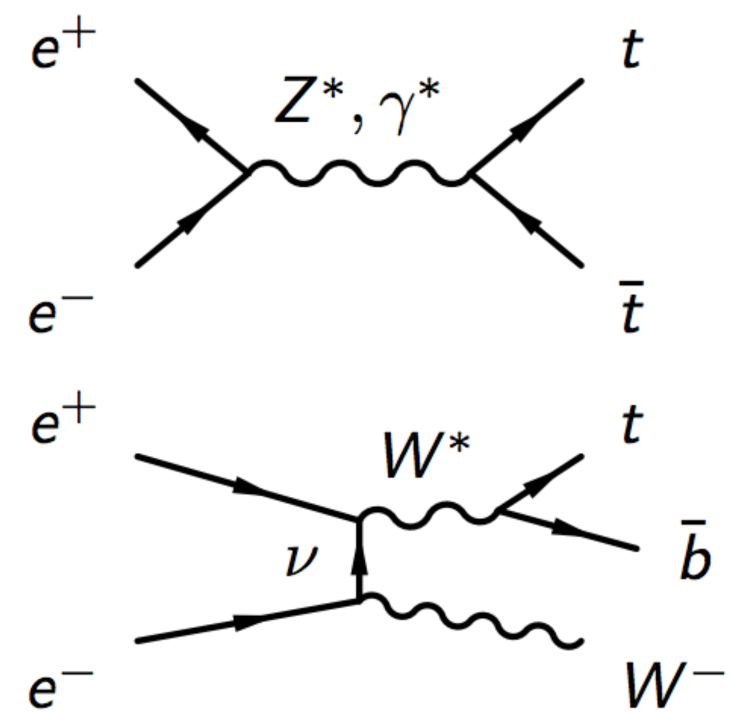


2t: ttZ, ttγ, and ttee



Top pair production





$+\ W^+W^- \to t\,\bar{t}$
catching up at multi-TeV
w/ unitarity breaking effects
[Grojean, Wulzer, You, Zhang]

- σ peaked at about 380 GeV
- enhanced for a left-handed beam
- fall-off as $1/s$
- single-top contribution increasingly important

Top EW couplings

$$\mathcal{L}_{\mathrm{EFT}} = \sum_i \frac{C_i}{\Lambda^2} O_i$$

Two-quark operators:

Scalar: $O_{u\varphi} \equiv \bar{q} u \, \tilde{\varphi} \quad \varphi^\dagger \varphi,$

Vector:

$O^1_{\varphi q} \equiv \bar{q}\gamma^\mu q \quad \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi \quad \equiv O^+_{\varphi q} + O^V_{\varphi q} - O^A_{\varphi q},$

$O^3_{\varphi q} \equiv \bar{q}\gamma^\mu \tau^I q \quad \varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi \quad \equiv O^+_{\varphi q} - O^V_{\varphi q} + O^A_{\varphi q}$ (CC also)

$O_{\varphi u} \equiv \bar{u}\gamma^\mu u \quad \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi \quad \equiv O^V_{\varphi q} + O^A_{\varphi q}$

$O_{\varphi ud} \equiv \bar{u}\gamma^\mu d \quad \tilde{\varphi}^\dagger i\overleftrightarrow{D}_\mu \varphi,$ (CC only, m_b int.)

Tensor:

$O_{uB} \equiv \bar{q}\sigma^{\mu\nu} u \, \tilde{\varphi} \, g_Y B_{\mu\nu}, \quad \equiv O_{uA} - \tan\theta_W O_{uZ}$

$O_{uW} \equiv \bar{q}\sigma^{\mu\nu}\tau^I u \, \tilde{\varphi} \, g_W W^I_{\mu\nu}, \quad \equiv O_{uA} + \mathrm{cotan}\,\theta_W O_{uZ}$ (CC also)

$O_{dW} \equiv \bar{q}\sigma^{\mu\nu}\tau^I d \, \tilde{\varphi} \, g_W W^I_{\mu\nu},$ (CC only, m_b int.)

$O_{uG} \equiv \bar{q}\sigma^{\mu\nu} T^A u \, \tilde{\varphi} \, g_s G^A_{\mu\nu}.$ (NLO only)

Two-quark–two-lepton operators:

Scalar:

$O^S_{lequ} \equiv \bar{l} e \quad \varepsilon \quad \bar{q} u,$ (CC also, m_e int.)

$O_{ledq} \equiv \bar{l} e \quad \bar{d} q,$ (CC only, m_e int.)

Vector:

$O^1_{lq} \equiv \bar{l}\gamma_\mu l \quad \bar{q}\gamma^\mu q \quad \equiv O^+_{lq} + O^V_{lq} - O^A_{lq},$

$O^3_{lq} \equiv \bar{l}\gamma_\mu \tau^I l \quad \bar{q}\gamma^\mu \tau^I q \quad \equiv O^+_{lq} - O^V_{lq} + O^A_{lq},$ (CC also)

$O_{lu} \equiv \bar{l}\gamma_\mu l \quad \bar{u}\gamma^\mu u \quad \equiv O^V_{lq} + O^A_{lq},$

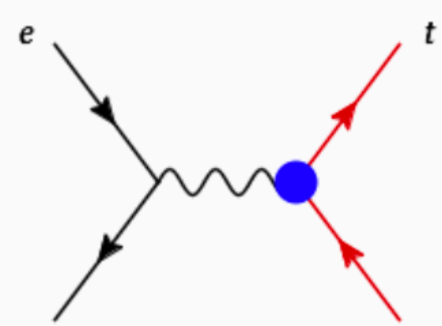
$O_{eq} \equiv \bar{e}\gamma^\mu e \quad \bar{q}\gamma_\mu q \quad \equiv O^V_{eq} - O^A_{eq},$

$O_{eu} \equiv \bar{e}\gamma_\mu e \quad \bar{u}\gamma^\mu u \quad \equiv O^V_{eq} + O^A_{eq},$

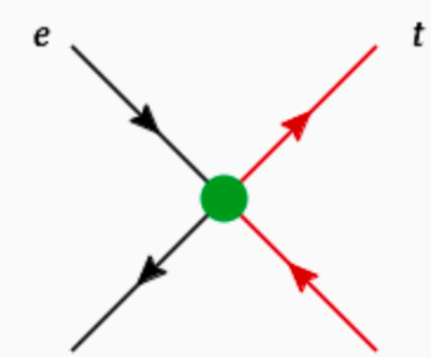
Tensor: $O^T_{lequ} \equiv \bar{l}\sigma_{\mu\nu} e \quad \varepsilon \quad \bar{q}\sigma^{\mu\nu} u.$ (CC also, m_e int.)

Top EW couplings

Two-fermion (vertex) Op



Four-fermion Op



(Axial-)Vector like $O^V_{\varphi q}, O^A_{\varphi q}$

- Sensitivity independent of energy.

Dipole (CP-even) $\mathrm{Re}O_{uA}, \mathrm{Re}O_{uZ}$

- $\sim E$ in amplitude, but suppressed by interference at *tt* level (cross section and A^{FB})
- $\sim E^2$ sensitivity can be obtained with OO

Dipole (CP-odd) $\mathrm{Im}O_{uA}, \mathrm{Im}O_{uZ}$

Left-handed *ee* O^V_{lq}, O^A_{lq}

Right-handed *ee* O^V_{eq}, O^A_{eq}

- E^2 dependence in general observables.
- Similar to the V-A vertex operators. Need at least two different CoM energies to distinguish.

Optimal observable

minimize the one-sigma ellipsoid in EFT parameter space

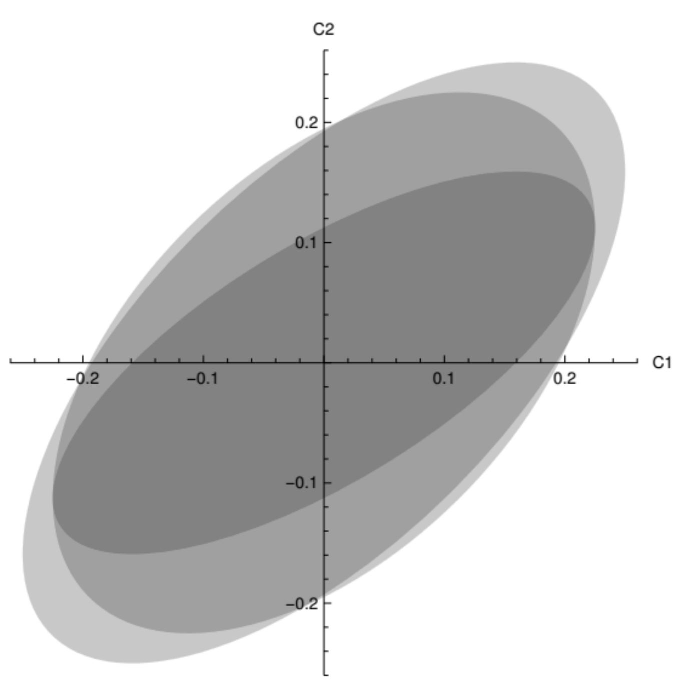
(*joint efficient* set of estimators, saturating the Cramér-Rao bound: $V^{-1} = I$,like MEM)

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

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



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

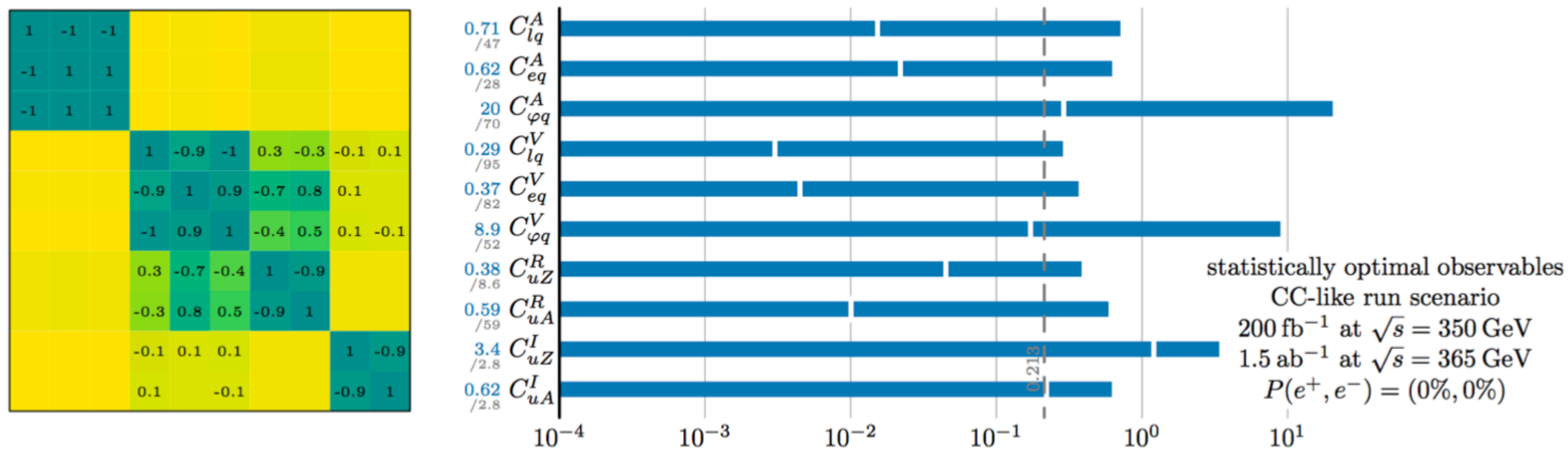
1. asymmetries: $O_i \sim \text{sign}\{\sin(i\phi)\}$
2. moments: $O_i \sim \sin(i\phi)$
3. statistically optimal: $O_i \sim \dfrac{\sin(i\phi)}{1 + \cos\phi}$

$\Longrightarrow$ area ratios 1.9 : 1.7 : 1

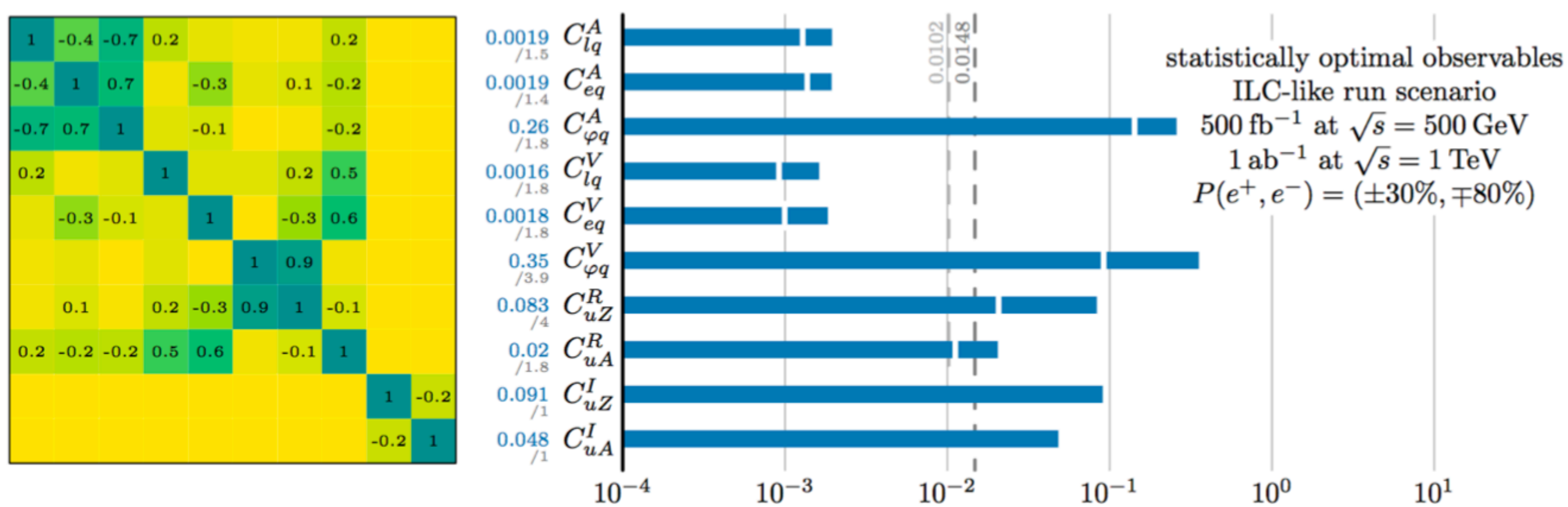
Previous applications in $e^+e^- \to t\,\bar{t}$, on different distributions:

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

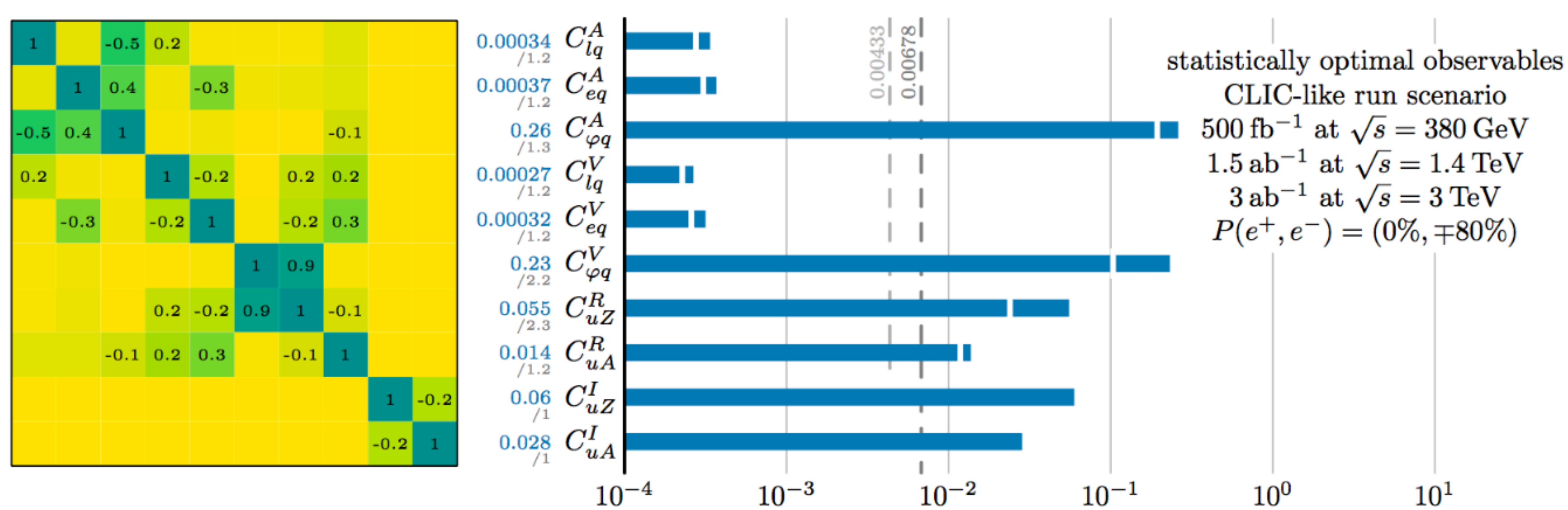
FCC-ee
- 200 fb^{-1} at 350
- 1.5 ab^{-1} at 365
- No polarization



ILC
- 500 fb^{-1} at 500
- 1.0 ab^{-1} at 1000
- (-.3,+.8)&(+.3,-.8) equally shared



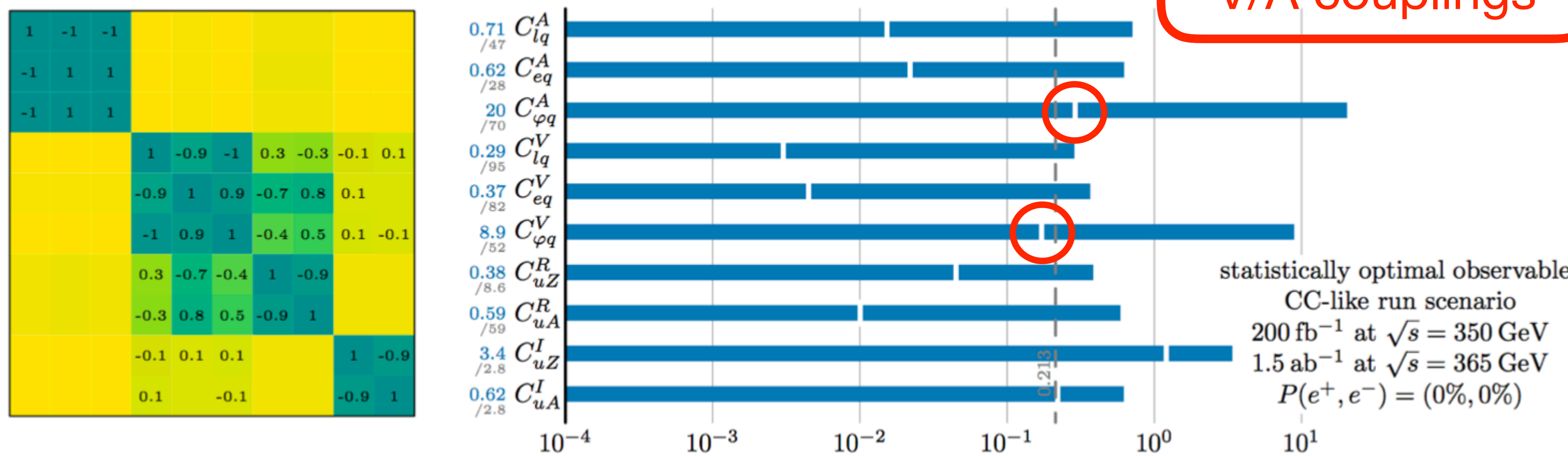
CLIC
- 500 fb^{-1} at 380
- 1.5 ab^{-1} at 1400
- 3.0 ab^{-1} at 3000
- (0,+.8)&(0,-.8) equally shared



V/A couplings

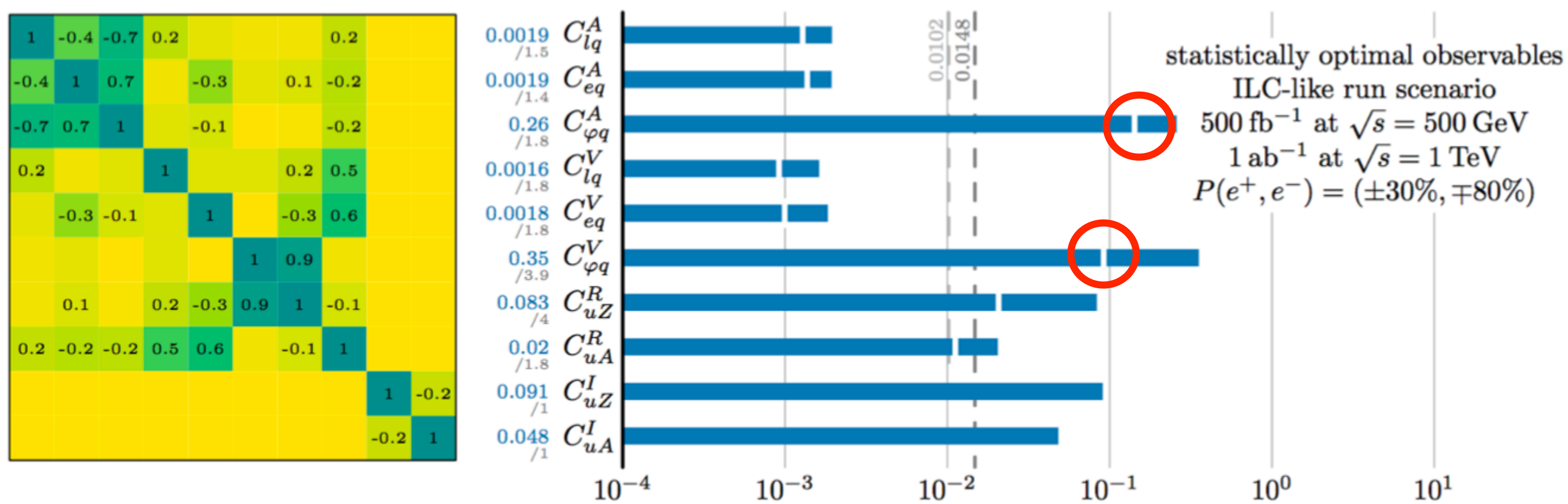
FCC-ee

- 200 fb^{-1} at 350
- 1.5 ab^{-1} at 365
- No polarization



ILC

- 500 fb^{-1} at 500
- 1.0 ab^{-1} at 1000
- (-.3,+.8)&(+.3,-.8) equally shared



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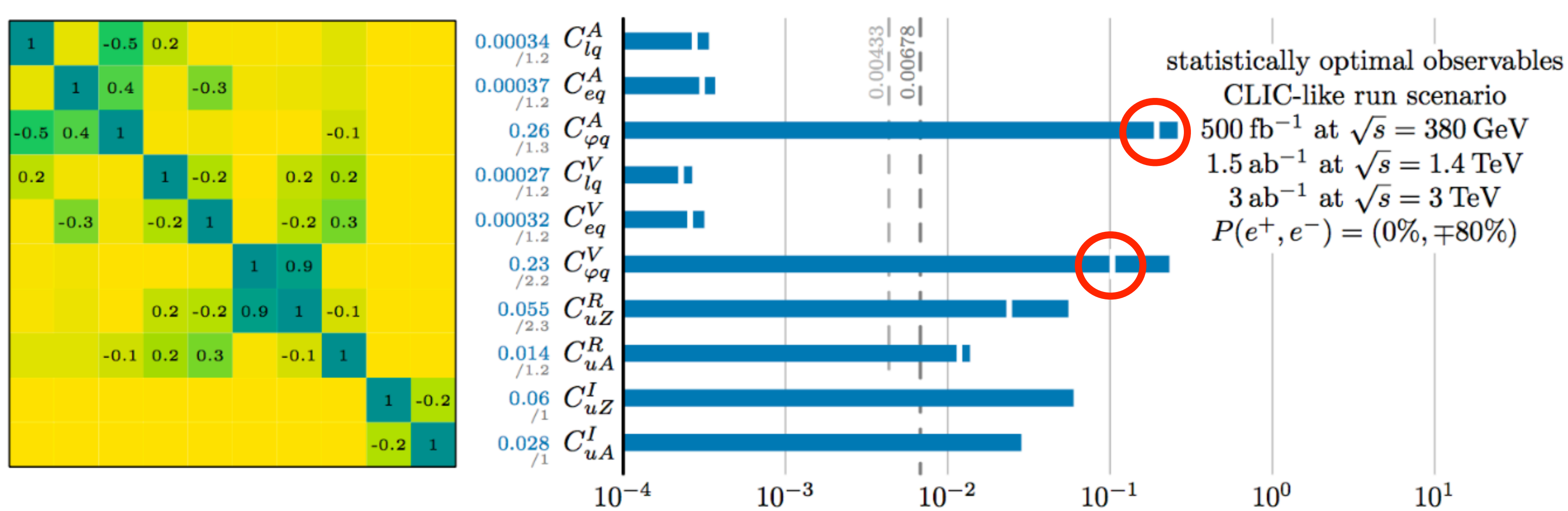
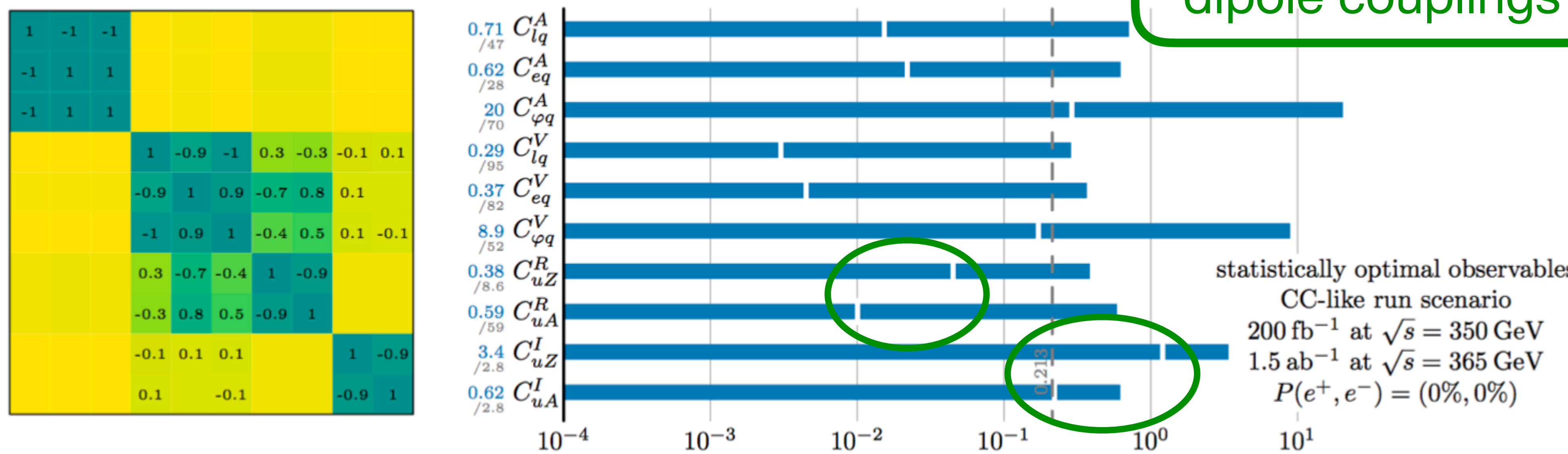
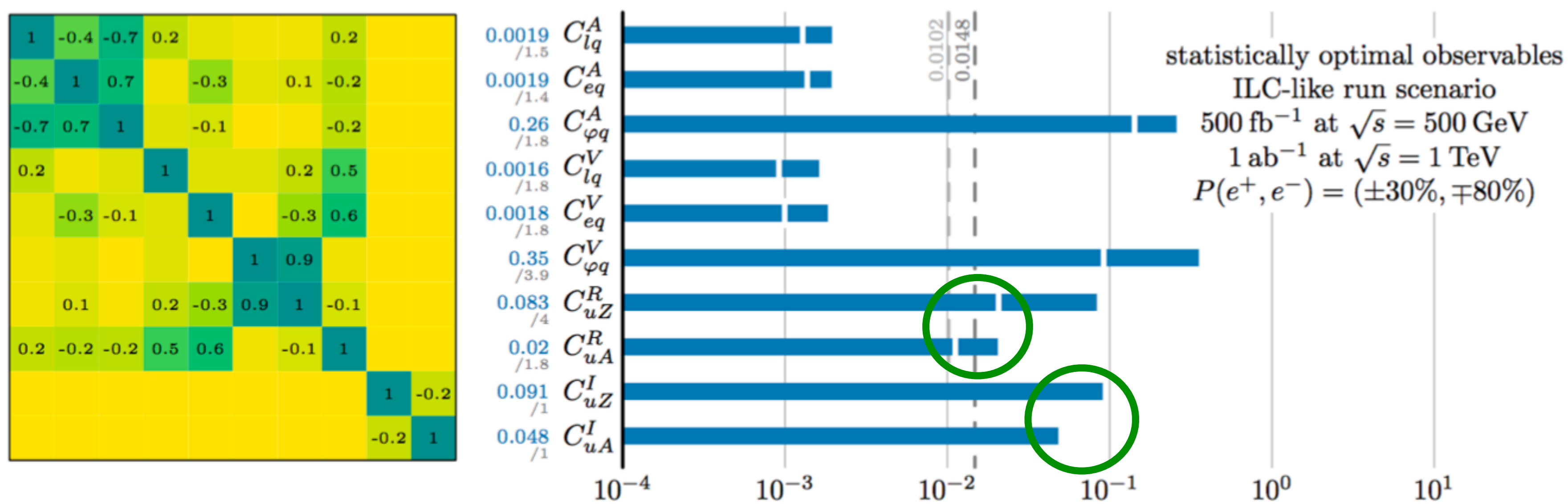


dipole couplings

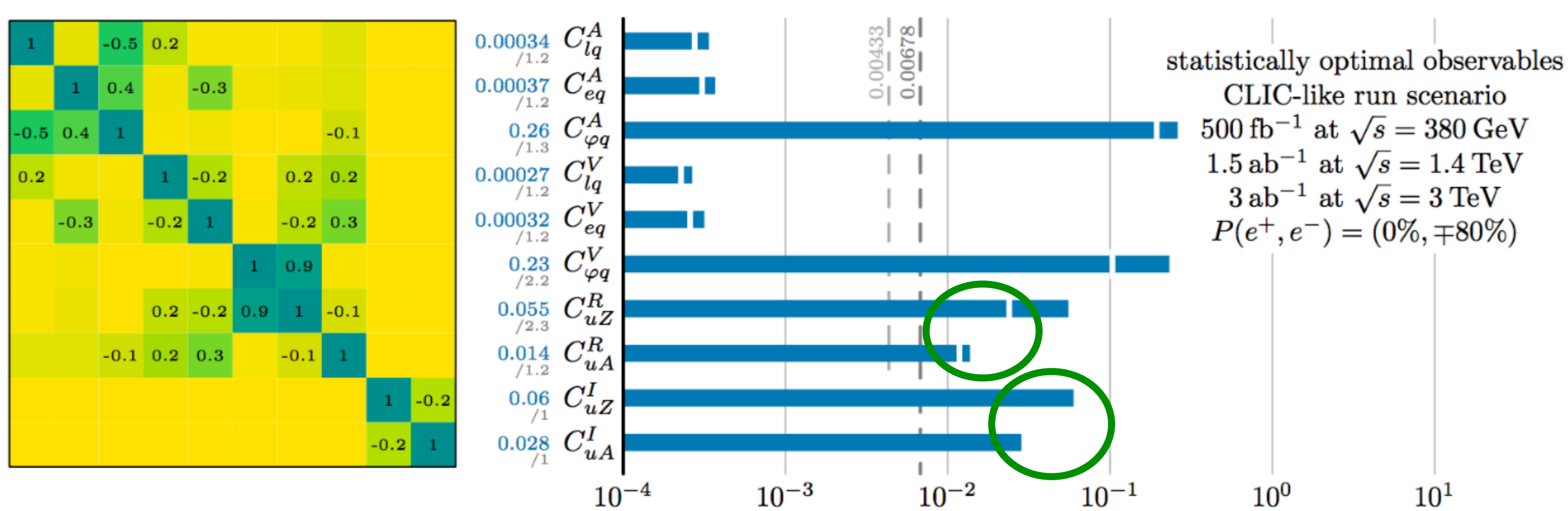
FCC-ee
- 200 fb^{-1} at 350
- 1.5 ab^{-1} at 365
- No polarization



ILC
- 500 fb^{-1} at 500
- 1.0 ab^{-1} at 1000
- (-.3,+.8)&(+.3,-.8) equally shared

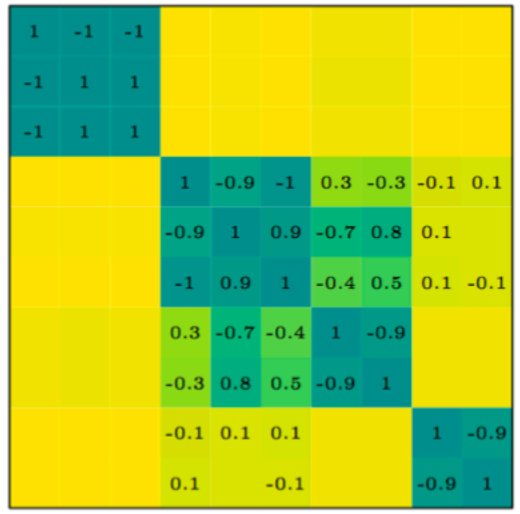


CLIC
- 500 fb^{-1} at 380
- 1.5 ab^{-1} at 1400
- 3.0 ab^{-1} at 3000
- (0,+.8)&(0,-.8) equally shared



Four fermion

FCC-ee
- 200 fb^{-1} at 350
- 1.5 ab^{-1} at 365
- No polarization



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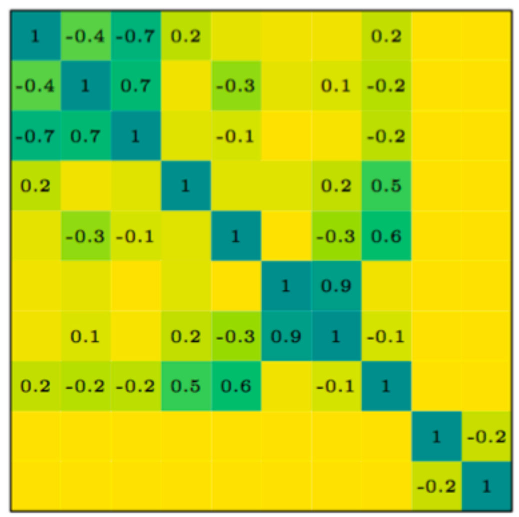

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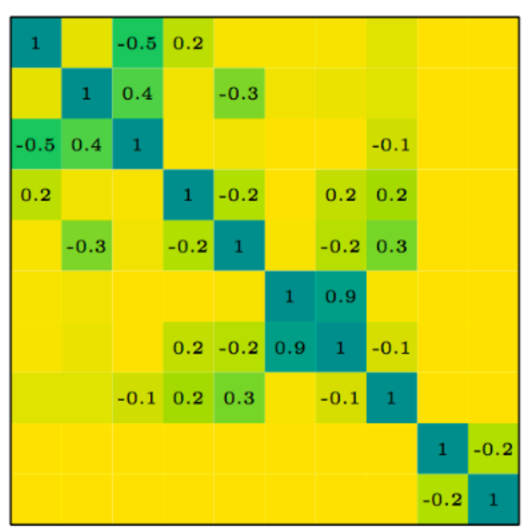

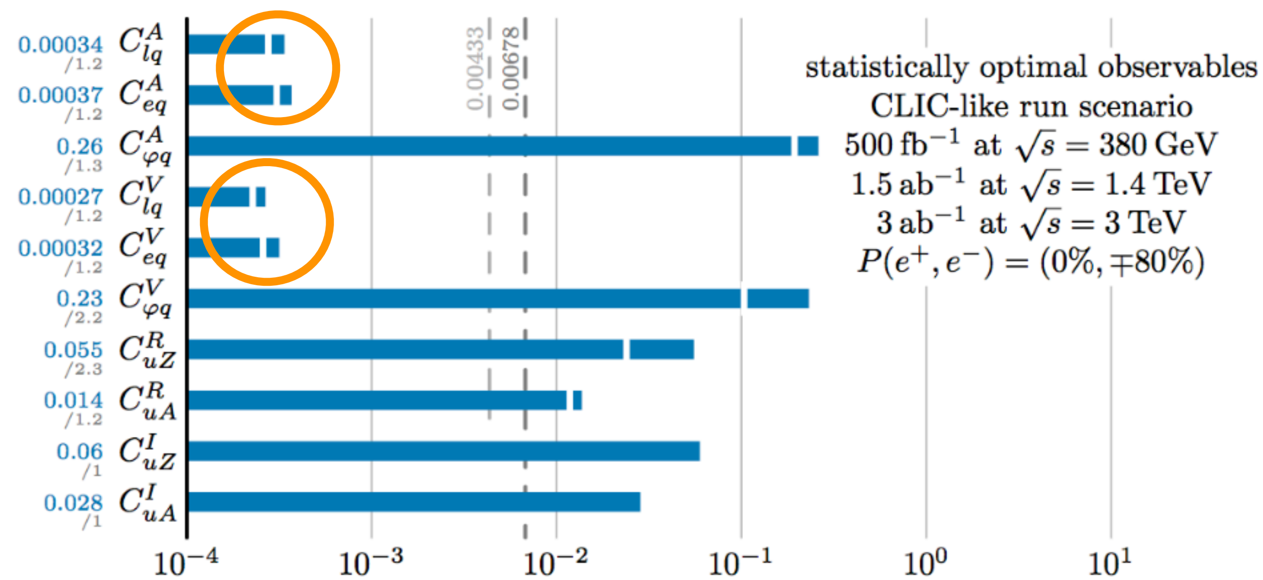

Higher energy runs are useful:

- Individual limits on 2-fermion (axial-)vector operators are not improved, but degeneracies with 4-fermion operators are resolved with energy lever arm.
  - At least a factor of three better than the most optimistic HL-LHC prospects.
- Dipole operators can be slightly better.
  - 2 orders of magnitude better than HL-LHC prospects.
- 4-fermion operators are significantly improved.
  - CC-like scenario would probes four-fermion operator couplings a factor of a few smaller, and a ILC- or CLIC-like scenarios two to four orders of magnitude smaller (comparing *qqtt* at LHC with *eett* at e^+e^-)
- Flat directions are reduced.

SMEFT prediction at NLO for $e^+e^- \to t\bar{t}$

central value (k-factor below) +scale up% ±Monte Carlo% −scale down%

pol	$\sqrt{s}$ [GeV]	SM	C_{lq}^A	C_{eq}^A	$C_{\varphi q}^A$	C_{lq}^V	C_{eq}^V	$C_{\varphi q}^V$	C_{uZ}^R	C_{uA}^R	C_{uZ}^I	C_{uA}^I	C_{uG}^R
00	380	835 +3% ±0.01% −2% (1.38)	64.5 +3% ±0.3% −3% (1.46)	−56.6 −3% ±0.7% +3% (1.46)	3.72 +3% ±0.9% −3% (1.47)	−1010 −2% ±0.04% +3% (1.38)	−666 −2% ±0.06% +3% (1.38)	−13.7 −2% ±0.2% +3% (1.38)	48.9 +3% ±0.2% −2% (1.38)	288 +3% ±0.04% −2% (1.38)	0.00271 +4% ±2000% −3% (—)	−0.226 −4% ±50% +5% (—)	−0.271 −0.3% ±100% +0.3% (—)
00	500	648 +1% ±0.01% −1% (1.14)	267 +2% ±0.1% −1% (1.2)	−236 −1% ±0.2% +2% (1.2)	8.5 +2% ±0.08% −1% (1.2)	−1250 −1% ±0.03% +1% (1.13)	−834 −1% ±0.04% +1% (1.13)	−9.45 −1% ±0.4% +1% (1.14)	38.3 +1% ±0.4% −1% (1.13)	236 +1% ±0.04% −1% (1.13)	0.144 +10% ±60% −9% (—)	0.112 +5% ±200% −4% (—)	−0.136 −30% ±200% +20% (—)
00	1000	181 +0.6% ±0.02% −0.5% (1.06)	510 +0.8% ±0.2% −0.6% (1.08)	−449 −0.7% ±0.3% +0.8% (1.08)	3.98 +0.9% ±0.3% −0.7% (1.09)	−1280 −0.4% ±0.05% +0.5% (1.05)	−859 −0.4% ±0.1% +0.5% (1.05)	−2.29 −0.3% ±0.7% +0.3% (1.03)	10.7 +0.2% ±0.7% −0.2% (1.02)	68.8 +0.2% ±0.08% −0.2% (1.02)	−0.00765 −30% ±900% +20% (—)	−0.0094 −50% ±900% +40% (—)	0.665 +10% ±0.4% −9% (—)
00	1400	93.4 +0.5% ±0.03% −0.4% (1.05)	550 +0.6% ±0.3% −0.5% (1.07)	−480 −0.5% ±0.3% +0.6% (1.06)	2.16 +0.6% ±0.3% −0.5% (1.06)	−1280 −0.4% ±0.06% +0.4% (1.04)	−860 −0.3% ±0.2% +0.4% (1.04)	−1.17 −0.4% ±0.9% +0.5% (1.04)	5.43 +0.09% ±0.9% −0.08% (1.01)	35.4 +0.06% ±0.1% −0.07% (0.993)	−0.0194 −10% ±300% +10% (—)	−0.0458 −6% ±100% +8% (—)	0.474 +10% ±5% −9% (—)
00	3000	20.4 +0.4% ±0.02% −0.3% (1.04)	577 +0.4% ±0.2% −0.3% (1.04)	−508 −0.4% ±0.3% +0.4% (1.04)	0.494 +0.4% ±0.1% −0.3% (1.04)	−1270 −0.3% ±0.09% +0.4% (1.04)	−856 −0.3% ±0.1% +0.4% (1.04)	−0.251 −0.3% ±0.5% +0.3% (1.03)	1.16 +0.4% ±1% −0.5% (0.954)	7.57 +0.4% ±0.2% −0.5% (0.951)	0.000148 +900% ±10000% −1000% (—)	−0.0563 −6% ±30% +8% (—)	0.203 +10% ±6% −9% (—)
+−	380	579 +3% ±0.01% −2% (1.38)	64.7 +3% ±0.3% −3% (1.46)	—	2.06 +3% ±0.8% −3% (1.46)	−1010 −2% ±0.04% +3% (1.38)	—	−32.3 −2% ±0.06% +3% (1.38)	116 +3% ±0.03% −2% (1.38)	174 +3% ±0.03% −2% (1.38)	0.00654 +2% ±200% −2% (—)	−0.0393 −3% ±100% +3% (—)	−0.151 −0.003% ±100% +0.05% (—)
+−	500	441 +1% ±0.02% −1% (1.14)	267 +2% ±0.09% −1% (1.2)	—	4.8 +2% ±0.2% −1% (1.2)	−1260 −1% ±0.03% +1% (1.13)	—	−22.6 −1% ±0.03% +1% (1.13)	92.1 +1% ±0.05% −1% (1.13)	142 +1% ±0.05% −1% (1.13)	−0.0599 −4% ±100% +5% (—)	−0.178 −1% ±80% +2% (—)	0.298 +9% ±30% −8% (—)
+−	1000	121 +0.5% ±0.03% −0.5% (1.05)	511 +0.8% ±0.08% −0.7% (1.08)	—	2.24 +0.8% ±0.1% −0.7% (1.09)	−1280 −0.4% ±0.05% +0.5% (1.05)	—	−5.63 −0.4% ±0.04% +0.5% (1.05)	26.1 +0.2% ±0.06% −0.1% (1.02)	41.2 +0.2% ±0.05% −0.2% (1.02)	−0.0107 −60% ±300% +50% (—)	0.0532 +10% ±90% −8% (—)	0.474 +10% ±2% −9% (—)
+−	1400	62.1 +0.5% ±0.04% −0.4% (1.05)	550 +0.6% ±0.1% −0.5% (1.06)	—	1.22 +0.6% ±0.3% −0.5% (1.06)	−1280 −0.3% ±0.07% +0.4% (1.04)	—	−2.85 −0.3% ±0.08% +0.4% (1.04)	13.4 +0.06% ±0.1% −0.08% (0.993)	21.2 +0.08% ±0.2% −0.09% (0.991)	0.0184 +9% ±300% −7% (—)	0.0136 +9% ±200% −10% (—)	0.342 +10% ±9% −8% (—)
+−	3000	13.6 +0.4% ±0.03% −0.3% (1.04)	577 +0.4% ±0.2% −0.3% (1.04)	—	0.28 +0.4% ±0.1% −0.4% (1.04)	−1270 −0.3% ±0.1% +0.4% (1.04)	—	−0.614 −0.3% ±0.06% +0.4% (1.04)	2.85 +0.5% ±0.4% −0.6% (0.949)	4.52 +0.4% ±0.3% −0.5% (0.952)	0.00756 +2% ±100% −1% (—)	−0.00757 −4% ±100% +5% (—)	0.133 +10% ±6% −9% (—)
−+	380	256 +3% ±0.02% −2% (1.38)	—	−57.1 −3% ±0.2% +3% (1.47)	1.6 +3% ±0.1% −3% (1.47)	—	−666 −2% ±0.04% +3% (1.38)	18.7 +3% ±0.03% −2% (1.38)	−67.1 −2% ±0.05% +3% (1.38)	114 +3% ±0.05% −2% (1.38)	0.00526 +5% ±200% −4% (—)	−0.0465 −3% ±70% +3% (—)	0.000268 +100% ±50000% −100% (—)
−+	500	208 +1% ±0.02% −1% (1.14)	—	−235 −1% ±0.07% +2% (1.2)	3.73 +2% ±0.9% −1% (1.21)	—	−835 −1% ±0.03% +1% (1.13)	13.2 +1% ±0.06% −1% (1.13)	−53.8 −1% ±0.04% +1% (1.13)	94.2 +1% ±0.04% −1% (1.13)	−0.0211 −1% ±200% +1% (—)	−0.224 −1% ±30% +1% (—)	0.144 +10% ±6% −8% (—)
−+	1000	60.5 +0.6% ±0.03% −0.5% (1.06)	—	−448 −0.7% ±0.1% +0.8% (1.08)	1.73 +0.8% ±0.1% −0.7% (1.08)	—	−863 −0.4% ±0.03% +0.5% (1.05)	3.32 +0.5% ±0.04% −0.4% (1.05)	−15.4 −0.1% ±0.07% +0.2% (1.02)	27.6 +0.2% ±0.08% −0.2% (1.02)	−0.0105 −20% ±200% +30% (—)	0.0106 +7% ±300% −5% (—)	0.237 +10% ±4% −8% (—)
−+	1400	31.3 +0.5% ±0.03% −0.4% (1.05)	—	−483 −0.5% ±0.1% +0.6% (1.06)	0.942 +0.6% ±0.1% −0.5% (1.06)	—	−860 −0.3% ±0.07% +0.4% (1.04)	1.69 +0.4% ±0.1% −0.4% (1.04)	−7.92 −0.06% ±0.1% +0.05% (0.994)	14.2 +0.07% ±0.1% −0.09% (0.992)	−0.00889 −10% ±200% +10% (—)	−0.0414 −3% ±70% +3% (—)	0.16 +10% ±1% −9% (—)
−+	3000	6.9 +0.4% ±0.02% −0.3% (1.04)	—	−509 −0.4% ±0.2% +0.4% (1.04)	0.216 +0.4% ±0.1% −0.4% (1.04)	—	−857 −0.3% ±0.1% +0.4% (1.04)	0.364 +0.4% ±0.07% −0.3% (1.04)	−1.67 −0.6% ±0.3% +0.5% (0.943)	3.04 +0.4% ±0.2% −0.5% (0.953)	0.0122 +10% ±50% −9% (—)	−0.00327 −9% ±200% +7% (—)	0.0698 +10% ±5% −8% (—)

Table 8. Linear effective field theory dependence of the total $e^+e^- \to t\,\bar{t}$ cross section [fb]. The +−, and −+ labels specify the helicities of the electron and positron, respectively. Any mixted polarization can be optained through $(1-P_{e^-})(1+P_{e^+})[-+] + (1+P_{e^-})(1-P_{e^+})[+-]$. In particular, for unpolarized beams, denoted as 00, the sum of +− and −+ contributions is obtained. Note the large Monte-Carlo uncertainties affecting most of the smallest values.

SMEFT prediction at NLO for $e^+e^- \to t\bar{t}$

central value$^{+\text{scale up}\%}_{-\text{scale down}\%}$ ±Monte Carlo%.
k-factor

pol	$\sqrt{s}$ [GeV]	SM	C^A_{lq}	C^A_{eq}	$C^A_{\varphi q}$	C^V_{lq}	C^V_{eq}	$C^V_{\varphi q}$	C^R_{uZ}	C^R_{uA}	C^I_{uZ}	C^I_{uA}	C^R_{uG}
00	380	$835^{+3\%}_{-2\%}$ ±0.01% (1.38)	$64.5^{+3\%}_{-3\%}$ ±0.3% (1.46)	$-56.6^{-3\%}_{+3\%}$ ±0.7% (1.46)	$3.72^{+3\%}_{-3\%}$ ±0.9% (1.47)	$-1010^{-2\%}_{+3\%}$ ±0.04% (1.38)	$-666^{-2\%}_{+3\%}$ ±0.06% (1.38)	$-13.7^{-2\%}_{+3\%}$ ±0.2% (1.38)	$48.9^{+3\%}_{-2\%}$ ±0.2% (1.38)	$288^{+3\%}_{-2\%}$ ±0.04% (1.38)	$0.00271^{+4\%}_{-3\%}$ ±2000% (—)	$-0.226^{-4\%}_{+5\%}$ ±50% (—)	$-0.271^{-0.3\%}_{+0.3\%}$ ±100% (—)
00	500	$648^{+1\%}_{-1\%}$ ±0.01% (1.14)	$267^{+2\%}_{-1\%}$ ±0.1% (1.2)	$-236^{-1\%}_{+2\%}$ ±0.2% (1.2)	$8.5^{+2\%}_{-1\%}$ ±0.08% (1.2)	$-1250^{-1\%}_{+1\%}$ ±0.03% (1.13)	$-834^{-1\%}_{+1\%}$ ±0.04% (1.13)	$-9.45^{-1\%}_{+1\%}$ ±0.4% (1.14)	$38.3^{+1\%}_{-1\%}$ ±0.4% (1.13)	$236^{+1\%}_{-1\%}$ ±0.04% (1.13)	$0.144^{+10\%}_{-9\%}$ ±60% (—)	$0.112^{+5\%}_{-4\%}$ ±200% (—)	$-0.136^{-30\%}_{+20\%}$ ±200% (—)
00	10									$68.8^{+0.2\%}_{-0.2\%}$ ±0.08% (1.02)	$-0.00765^{-30\%}_{+20\%}$ ±900% (—)	$-0.0094^{-50\%}_{+40\%}$ ±900% (—)	$0.665^{+10\%}_{-9\%}$ ±0.4% (—)
00	14									$35.4^{+0.06\%}_{-0.07\%}$ ±0.1% (0.993)	$-0.0194^{-10\%}_{+10\%}$ ±300% (—)	$-0.0458^{-6\%}_{+8\%}$ ±100% (—)	$0.474^{+10\%}_{-9\%}$ ±5% (—)
00	30									$7.57^{+0.4\%}_{-0.5\%}$ ±0.2% (0.951)	$0.000148^{+900\%}_{-1000\%}$ ±10000% (—)	$-0.0563^{-6\%}_{+8\%}$ ±30% (—)	$0.203^{+10\%}_{-9\%}$ ±6% (—)
+−	38									$174^{+3\%}_{-2\%}$ ±0.03% (1.38)	$0.00654^{+2\%}_{-2\%}$ ±200% (—)	$-0.0393^{-3\%}_{+3\%}$ ±100% (—)	$-0.151^{-0.003\%}_{+0.05\%}$ ±100% (—)
+−	50									$142^{+1\%}_{-1\%}$ ±0.05% (1.13)	$-0.0599^{-4\%}_{+5\%}$ ±100% (—)	$-0.178^{-1\%}_{+2\%}$ ±80% (—)	$0.298^{+9\%}_{-8\%}$ ±30% (—)
+−	10									$41.2^{+0.2\%}_{-0.2\%}$ ±0.05% (1.02)	$-0.0107^{-60\%}_{+50\%}$ ±300% (—)	$0.0532^{+10\%}_{-8\%}$ ±90% (—)	$0.474^{+10\%}_{-9\%}$ ±2% (—)
+−	14									$21.2^{+0.08\%}_{-0.09\%}$ ±0.2% (0.991)	$0.0184^{+9\%}_{-7\%}$ ±300% (—)	$0.0136^{+9\%}_{-10\%}$ ±200% (—)	$0.342^{+10\%}_{-8\%}$ ±9% (—)
+−	30									$4.52^{+0.4\%}_{-0.5\%}$ ±0.3% (0.952)	$0.00756^{+2\%}_{-1\%}$ ±100% (—)	$-0.00757^{-4\%}_{+5\%}$ ±100% (—)	$0.133^{+10\%}_{-9\%}$ ±6% (—)
−+	38									$114^{+3\%}_{-2\%}$ ±0.05% (1.38)	$0.00526^{+5\%}_{-4\%}$ ±200% (—)	$-0.0465^{-3\%}_{+3\%}$ ±70% (—)	$0.000268^{+100\%}_{-100\%}$ ±50000% (—)
−+	500	$208^{+1\%}_{-1\%}$ ±0.02% (1.14)	—	$-235^{-1\%}_{+2\%}$ ±0.07% (1.2)	$3.73^{+2\%}_{-1\%}$ ±0.9% (1.21)	—	$-835^{-1\%}_{+1\%}$ ±0.03% (1.13)	$13.2^{+1\%}_{-1\%}$ ±0.06% (1.13)	$-53.8^{-1\%}_{+1\%}$ ±0.04% (1.13)	$94.2^{+1\%}_{-1\%}$ ±0.04% (1.13)	$-0.0211^{-1\%}_{+1\%}$ ±200% (—)	$-0.224^{-1\%}_{+1\%}$ ±30% (—)	$0.144^{+10\%}_{-8\%}$ ±6% (—)
−+	1000	$60.5^{+0.6\%}_{-0.5\%}$ ±0.03% (1.06)	—	$-448^{-0.7\%}_{+0.8\%}$ ±0.1% (1.08)	$1.73^{+0.8\%}_{-0.7\%}$ ±0.1% (1.08)	—	$-863^{-0.4\%}_{+0.5\%}$ ±0.03% (1.05)	$3.32^{+0.5\%}_{-0.4\%}$ ±0.04% (1.05)	$-15.4^{-0.1\%}_{+0.2\%}$ ±0.07% (1.02)	$27.6^{+0.2\%}_{-0.2\%}$ ±0.08% (1.02)	$-0.0105^{-20\%}_{+30\%}$ ±200% (—)	$0.0106^{+7\%}_{-5\%}$ ±300% (—)	$0.237^{+10\%}_{-8\%}$ ±4% (—)
−+	1400	$31.3^{+0.5\%}_{-0.4\%}$ ±0.03% (1.05)	—	$-483^{-0.5\%}_{+0.6\%}$ ±0.1% (1.06)	$0.942^{+0.6\%}_{-0.5\%}$ ±0.1% (1.06)	—	$-860^{-0.3\%}_{+0.4\%}$ ±0.07% (1.04)	$1.69^{+0.4\%}_{-0.4\%}$ ±0.1% (1.04)	$-7.92^{-0.06\%}_{+0.05\%}$ ±0.1% (0.994)	$14.2^{+0.07\%}_{-0.09\%}$ ±0.1% (0.992)	$-0.00889^{-10\%}_{+10\%}$ ±200% (—)	$-0.0414^{-3\%}_{+3\%}$ ±70% (—)	$0.16^{+10\%}_{-9\%}$ ±1% (—)
−+	3000	$6.9^{+0.4\%}_{-0.3\%}$ ±0.02% (1.04)	—	$-509^{-0.4\%}_{+0.4\%}$ ±0.2% (1.04)	$0.216^{+0.4\%}_{-0.4\%}$ ±0.1% (1.04)	—	$-857^{-0.3\%}_{+0.4\%}$ ±0.1% (1.04)	$0.364^{+0.4\%}_{-0.3\%}$ ±0.07% (1.04)	$-1.67^{-0.6\%}_{+0.5\%}$ ±0.3% (0.943)	$3.04^{+0.4\%}_{-0.5\%}$ ±0.2% (0.953)	$0.0122^{+10\%}_{-9\%}$ ±50% (—)	$-0.00327^{-9\%}_{+7\%}$ ±200% (—)	$0.0698^{+10\%}_{-8\%}$ ±5% (—)

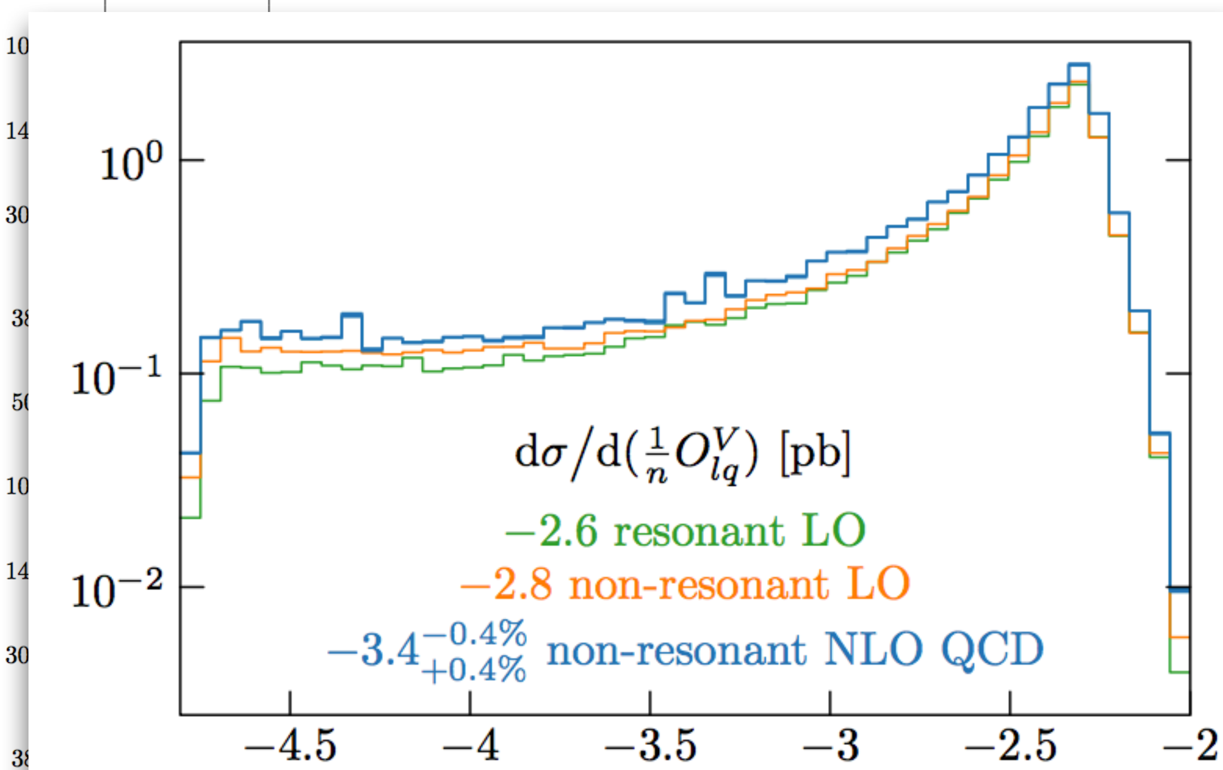

Table 8. Linear effective field theory dependence of the total $e^+e^- \to t\,\bar{t}$ cross section [fb]. The $+-$, and $-+$ labels specify the helicities of the electron and positron, respectively. Any mixted polarization can be optained through $(1-P_{e^-})(1+P_{e^+})[-+] + (1+P_{e^-})(1-P_{e^+})[+-]$. In particular, for unpolarized beams, denoted as 00, the sum of $+-$ and $-+$ contributions is obtained. Note the large Monte-Carlo uncertainties affecting most of the smallest values.

The SMEFT @ NLO UFO

http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

Standard Model Effective Theory at Next-to-Leading-Order in QCD

Céline Degrande, Gauthier Durieux, Fabio Maltoni, Ken Mimasu, Eleni Vryonidou & Cen Zhang

A complete implementation of the SMEFT compatible with NLO QCD predictions.

The implementation is based on the Warsaw basis of operators and includes all degrees of freedom consistent with the following symmetry assumptions:

- CP-conservation.
- $U(2)_Q \times U(2)_u \times U(3)_d \times U(3)_L \times U(3)_e$ flavor symmetry.

The CKM matrix is approximated as a unit matrix. The flavor symmetry imposes that only the top quark is massive. The model therefore implements the 5-flavor scheme for PDFs. The bosonic operators are implemented as in the Warsaw basis employing the M_Z, M_W, G_F scheme of Electroweak input parameters.

The Standard Model input parameters that need to be specified are:

M_Z, M_W, G_F, M_H, M_t, $\alpha_S(M_Z)$

The fermionic degrees of freedom (2 & 4 fermion operators) are defined according to the common standards and prescriptions established by the LHC TOP WG for the EFT interpretation of top-quark measurements at the LHC (see the dim6top page for more information). This model has been validated at LO with the dim6top implementation.

A new coupling order, `NP`, is added to the model for the SMEFT interactions. It is assigned through the universal cutoff parameter, `Lambda`, which takes a default value of 1 TeV^{-2} and can be modified along with the Wilson coefficients in the param card.

The definitions.pdf document specifies the operators definitions, normalisations and coefficient names in the UFO model

Usage notes

Restriction cards

Because of the mixture of LO/NLO compatible operators included in the model, restriction cards must be used to access the SMEFT interactions.

Default loading of the model

```
> import model SMEFTatNLO_U2_2_U3_3_cG_4F_LO_UFO
```

will load the pure SM without any effective operators.

The `LO` restriction card should be used when importing the model for LO generation:

```
> import model SMEFTatNLO_U2_2_U3_3_cG_4F_LO_UFO-LO
```

For NLO QCD generation, the `NLO` restriction card should be used when importing the model:

```
> import model SMEFTatNLO_U2_2_U3_3_cG_4F_LO_UFO-NLO
```

This invokes a restricted set of operators for which the required counterterms are implemented.

(missing 4F and 3G operators)

The SMEFT @ NLO UFO

http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

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The CKM matrix is approximated as a unit matrix. The flavor symmetry imposes that only the top quark is massive. The model therefore implements the 5-flavor scheme for PDFs. The bosonic operators are implemented as in the Warsaw basis employing the M_Z, M_W, G_F scheme of Electroweak input parameters.

The Standard Model input parameters that need to be specified are:

M_Z, M_W

The fermionic ... ark
measuremen...

A new coupli... dified along
with the Wils...

The definit...

```
MG5_aMC>import model SMEFTatNLO_U2_2_U3_3_cG_4F_LO_UFO-NLO
MG5_aMC>generate p p > t t H~ QCD=2 QED=1 NP=2 [QCD]
MG5_aMC>output
MG5_aMC>launch
```

Usage notes

Restriction ca...

Because of the mixture of LO/NLO compatible operators included in the model, restriction cards must be used to access the SMEFT interactions.

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> import model SMEFTatNLO_U2_2_U3_3_cG_4F_LO_UFO
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```

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```
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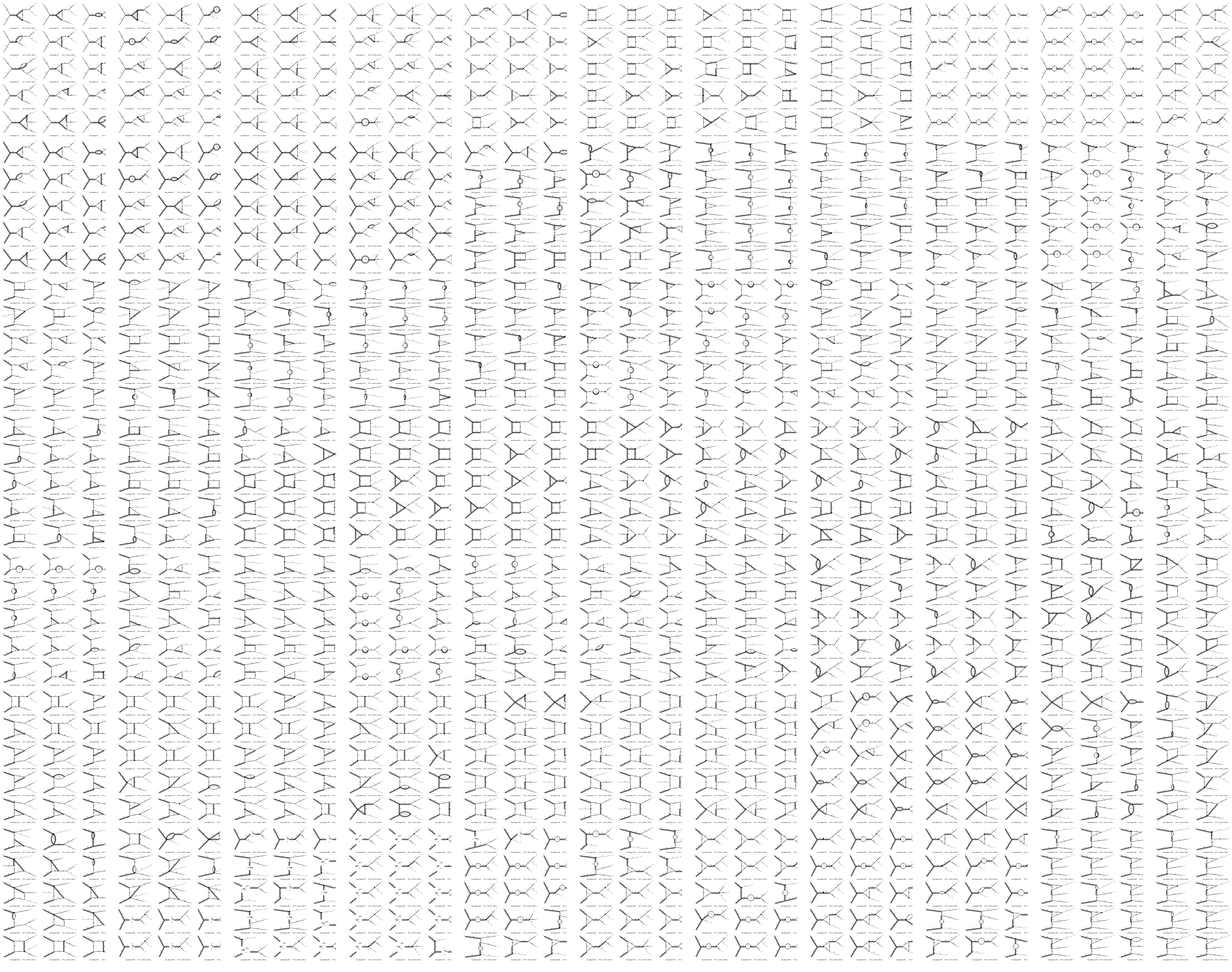
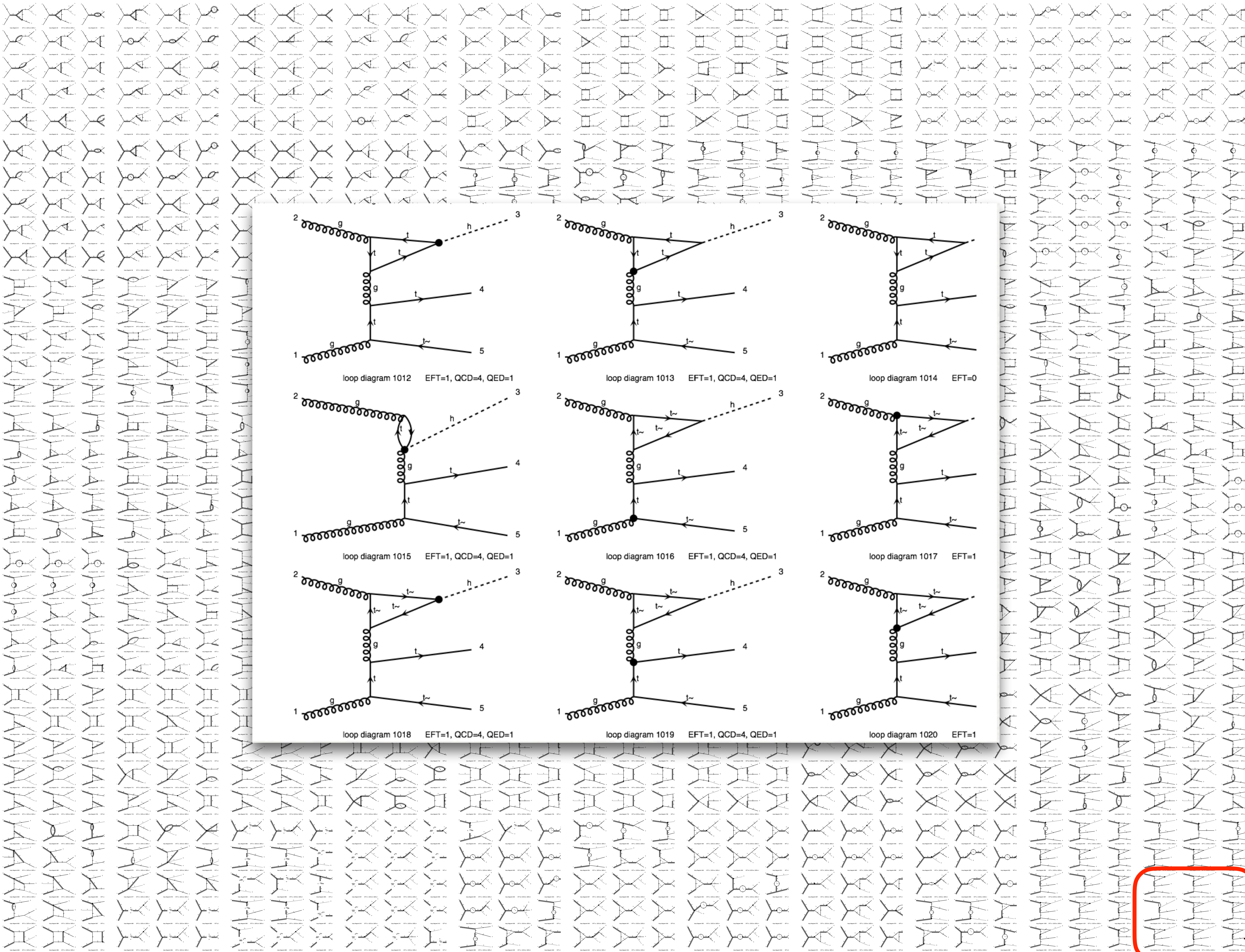
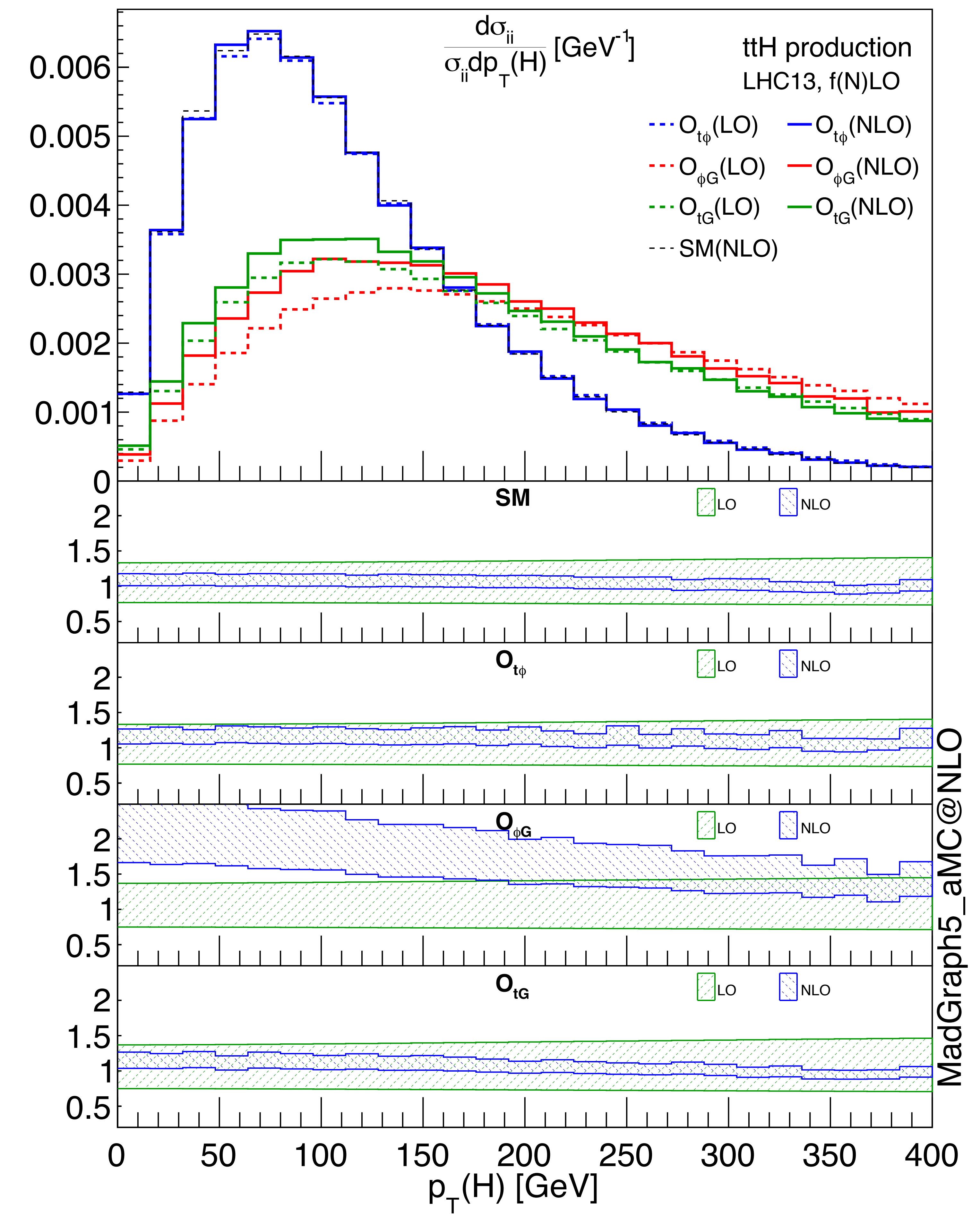
```

This invokes a restricted set of operators for which the required counterterms are implemented.

(missing 4F and 3G operators)

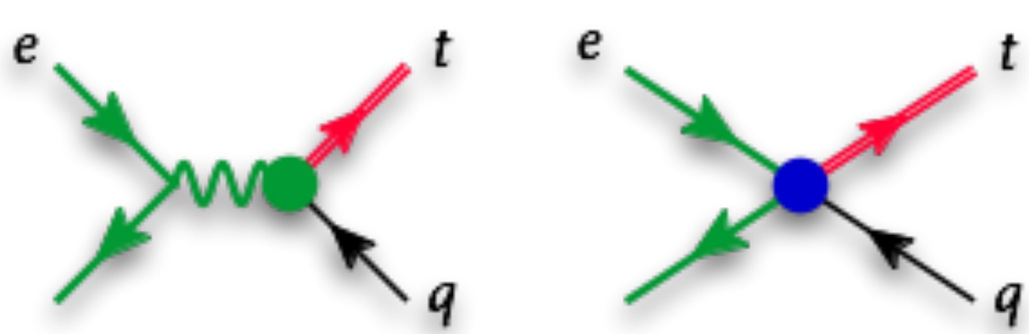



loop diagram 1012 EFT=1, QCD=4, QED=1
loop diagram 1013 EFT=1, QCD=4, QED=1
loop diagram 1014 EFT=0
loop diagram 1015 EFT=1, QCD=4, QED=1
loop diagram 1016 EFT=1, QCD=4, QED=1
loop diagram 1017 EFT=1
loop diagram 1018 EFT=1, QCD=4, QED=1
loop diagram 1019 EFT=1, QCD=4, QED=1
loop diagram 1020 EFT=1

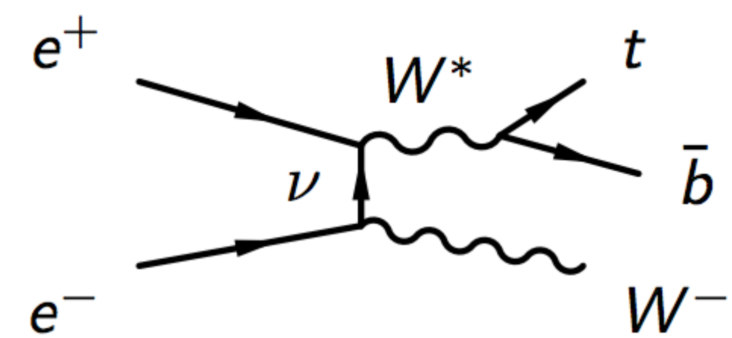


$\frac{d\sigma_{ii}}{\sigma_{ii} dp_T(H)}$ [GeV^{-1}]
ttH production
LHC13, f(N)LO
$O_{t\phi}$(LO)
$O_{t\phi}$(NLO)
$O_{\phi G}$(LO)
$O_{\phi G}$(NLO)
O_{tG}(LO)
O_{tG}(NLO)
SM(NLO)
SM
$O_{t\phi}$
$O_{\phi G}$
O_{tG}
LO
NLO
MadGraph5_aMC@NLO
p_T(H) [GeV]

1t: top FCNC

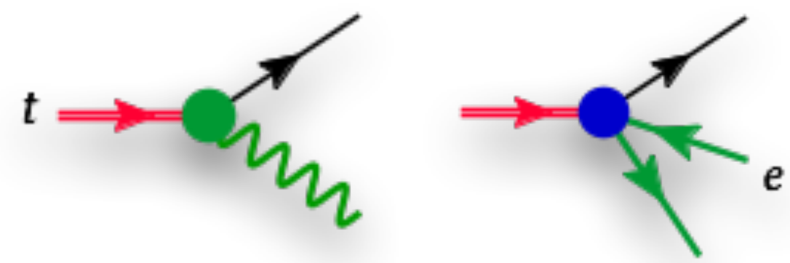


(not this)



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 **SMEFT.**

- Leading dim-6 FCNC operators are classified in the TOP WG EFT notes. [Aguilar-Saavedra et al. ’18]

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]

$$O_{u\varphi}^{(ij)} = \bar{q}_i u_j \tilde{H}\,(H^\dagger H),$$
$$O_{\varphi q}^{1(ij)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_i\gamma^\mu q_j),$$
$$O_{\varphi q}^{3(ij)} = (H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_i\gamma^\mu \tau^I q_j),$$
$$O_{\varphi u}^{(ij)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_i\gamma^\mu u_j),$$
$$O_{\varphi ud}^{(ij)} = (\tilde{H}^\dagger iD_\mu H)(\bar{u}_i\gamma^\mu d_j),$$
$$O_{uW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{H}W^I_{\mu\nu}$$
$$O_{dW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I d_j)\,HW^I_{\mu\nu},$$
$$O_{uB}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu} u_j)\tilde{H}B_{\mu\nu},$$
$$O_{uG}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}T^A u_j)\,\tilde{H}G^A_{\mu\nu}.$$

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

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]

$$
\begin{aligned}
O_{u\varphi}^{(ij)} &= \bar{q}_i u_j \tilde{H}\,(H^\dagger H),\\
O_{\varphi q}^{1(ij)} &= (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_i\gamma^\mu q_j),\\
O_{\varphi q}^{3(ij)} &= (H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_i\gamma^\mu \tau^I q_j),\\
O_{\varphi u}^{(ij)} &= (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_i\gamma^\mu u_j),\\
O_{\varphi ud}^{(ij)} &= (\tilde{H}^\dagger i D_\mu H)(\bar{u}_i\gamma^\mu d_j),\\
O_{uW}^{(ij)} &= (\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{H} W^I_{\mu\nu}\\
O_{dW}^{(ij)} &= (\bar{q}_i\sigma^{\mu\nu}\tau^I d_j)\,H W^I_{\mu\nu},\\
O_{uB}^{(ij)} &= (\bar{q}_i\sigma^{\mu\nu} u_j)\tilde{H} B_{\mu\nu},\\
O_{uG}^{(ij)} &= (\bar{q}_i\sigma^{\mu\nu}T^A u_j)\,\tilde{H} G^A_{\mu\nu}.
\end{aligned}
$$

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

Relevant D.o.F for tops

[Aguilar-Saavedra et al. ’18]

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

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

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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$$O_{\varphi ud}^{(ij)} = (\tilde{H}^\dagger iD_\mu H)(\bar{u}_i\gamma^\mu d_j),$$
$$O_{uW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{H}W^I_{\mu\nu}$$
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$$O_{uB}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}u_j)\tilde{H}B_{\mu\nu},$$
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$$O_{lq}^{1(ijkl)} = (\bar{l}_i\gamma^\mu l_j)(\bar{q}_k\gamma^\mu q_l),$$
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$$O_{eu}^{(ijkl)} = (\bar{e}_i\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_l),$$
$$O_{lequ}^{1(ijkl)} = (\bar{l}_i e_j)\ \varepsilon\ (\bar{q}_k u_l),$$
$$O_{lequ}^{3(ijkl)} = (\bar{l}_i\sigma^{\mu\nu} e_j)\ \varepsilon\ (\bar{q}_k\sigma_{\mu\nu} u_l),$$
$$O_{ledq}^{(ijkl)} = (\bar{l}_i e_j(\bar{d}_k q_l)(\bar{u}_k\gamma^\mu u_l),$$

Relevant D.o.F for tops

[Aguilar-Saavedra et al. '18]

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

28 DoFs relevant for ee->tj

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

Top FCNC

[Aguilar-Saavedra et al. ’18]

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$$O_{\varphi ud}^{(ij)} = (\tilde{H}^\dagger iD_\mu H)(\bar{u}_i\gamma^\mu d_j),$$
$$O_{uW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{H}W^I_{\mu\nu}$$
$$O_{dW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I d_j)\,HW^I_{\mu\nu},$$
$$O_{uB}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}u_j)\tilde{H}B_{\mu\nu},$$
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$$O_{eq}^{(ijkl)} = (\bar{e}_i\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{eu}^{(ijkl)} = (\bar{e}_i\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_l),$$
$$O_{lequ}^{1(ijkl)} = (\bar{l}_i e_j)\;\varepsilon\;(\bar{q}_k u_l),$$
$$O_{lequ}^{3(ijkl)} = (\bar{l}_i\sigma^{\mu\nu}e_j)\;\varepsilon\;(\bar{q}_k\sigma_{\mu\nu}u_l),$$
$$O_{ledq}^{(ijkl)} = (\bar{l}_i e_j(\bar{d}_k q_l)(\bar{u}_k\gamma^\mu u_l),$$

Relevant D.o.F for tops

[Aguilar-Saavedra et al. ’18]

$$c_{\varphi q}^{-[I](3+a)} \equiv \overset{[\Im]}{\Re}\{C_{\varphi q}^{1(3a)} - C_{\varphi q}^{3(3a)}\},$$
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$$c_{uA}^{[I](3a)} \equiv \overset{[\Im]}{\Re}\{c_W C_{uB}^{(3a)} + s_W C_{uW}^{(3a)}\},$$
$$c_{uA}^{[I](a3)} \equiv \overset{[\Im]}{\Re}\{c_W C_{uB}^{(a3)} + s_W C_{uW}^{(a3)}\},$$
$$c_{uZ}^{[I](3a)} \equiv \overset{[\Im]}{\Re}\{-s_W C_{uB}^{(3a)} + c_W C_{uW}^{(3a)}\},$$
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$$c_{lq}^{-[I](1,3+a)} \equiv \overset{[\Im]}{\Re}\{C_{lq}^{-(113a)}\},$$
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$$c_{lu}^{[I](1,3+a)} \equiv \overset{[\Im]}{\Re}\{C_{lu}^{(113a)}\},$$
$$c_{eu}^{[I](1,3+a)} \equiv \overset{[\Im]}{\Re}\{C_{eu}^{(113a)}\},$$
$$c_{lequ}^{S[I](1,3a)} \equiv \overset{[\Im]}{\Re}\{C_{lequ}^{1(113a)}\},$$
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28 DoFs relevant for ee->tj

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

CP even

CP odd

Left-handed q

Right-handed q

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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$$O_{lq}^{1(ijkl)} = (\bar{l}_i\gamma^\mu l_j)(\bar{q}_k\gamma^\mu q_l),$$
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$$O_{eq}^{(ijkl)} = (\bar{e}_i\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_l),$$
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$$O_{ledq}^{(ijkl)} = (\bar{l}_i e_j(\bar{d}_k q_l)(\bar{u}_k\gamma^\mu u_l),$$

Relevant D.o.F for tops

[Aguilar-Saavedra et al. ’18]

$$c_{\varphi q}^{-[I](3+a)} \equiv {}^{[\Im]}_{\Re}\{C_{\varphi q}^{1(3a)} - C_{\varphi q}^{3(3a)}\},$$
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$$c_{uZ}^{[I](3a)} \equiv {}^{[\Im]}_{\Re}\{-s_W C_{uB}^{(3a)} + c_W C_{uW}^{(3a)}\},$$
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$$c_{eq}^{[I](1,3+a)} \equiv {}^{[\Im]}_{\Re}\{C_{eq}^{(113a)}\},$$
$$c_{lu}^{[I](1,3+a)} \equiv {}^{[\Im]}_{\Re}\{C_{lu}^{(113a)}\},$$
$$c_{eu}^{[I](1,3+a)} \equiv {}^{[\Im]}_{\Re}\{C_{eu}^{(113a)}\},$$
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28 DoFs relevant for ee->tj

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Sufficient to focus on 7 parameters at a time

CP even

CP odd

Left-handed q

Right-handed q

Top FCNC

[Aguilar-Saavedra et al. '18]

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Relevant D.o.F for tops

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

$$c_{lq}^{-[I](1,3+a)} \equiv \overset{[\Im]}{\Re}\{C_{lq}^{-(113a)}\},$$
$$c_{eq}^{[I](1,3+a)} \equiv \overset{[\Im]}{\Re}\{C_{eq}^{(113a)}\},$$
$$c_{lu}^{[I](1,3+a)} \equiv \overset{[\Im]}{\Re}\{C_{lu}^{(113a)}\},$$
$$c_{eu}^{[I](1,3+a)} \equiv \overset{[\Im]}{\Re}\{C_{eu}^{(113a)}\},$$
$$c_{lequ}^{S[I](1,3a)} \equiv \overset{[\Im]}{\Re}\{C_{lequ}^{1(113a)}\},$$
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28 DoFs relevant for ee->tj

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

Sufficient to focus on 7 parameters at a time

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

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

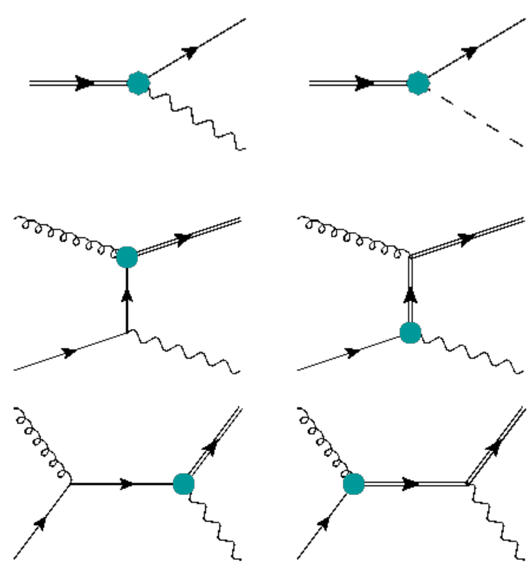
Top FCNC: 2-fermion and 4-fermion operators

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

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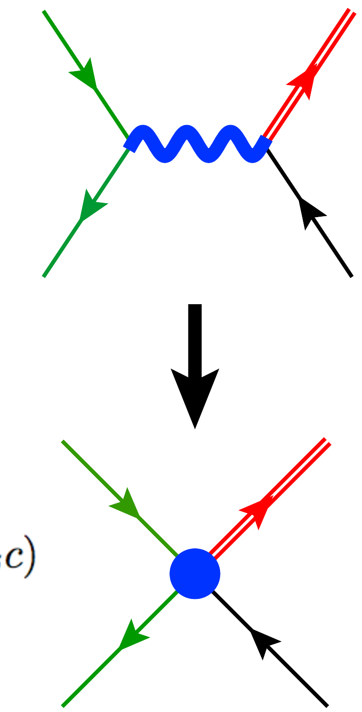
$$c_{\varphi u}^{I(3+a)},\quad c_{uA}^{I(3a)},\quad c_{uZ}^{I(3a)},$$

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

4-fermion FCNC

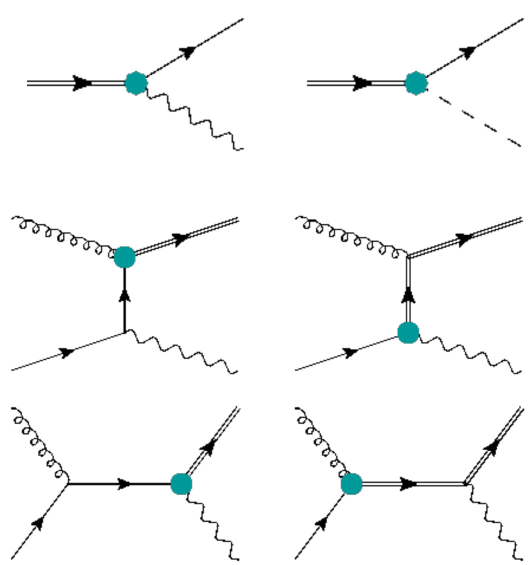


$$\mathcal{L}_{tcee} = \frac{1}{\Lambda^2}\sum_{i,j=L,R}\Big[V_{ij}\,(\bar{e}\gamma_\mu P_i e)\,(\bar{t}\gamma^\mu P_j c) + S_{ij}\,(\bar{e}P_i e)\,(\bar{t}P_j c) + T_{ij}\,(\bar{e}\sigma_{\mu\nu}P_i e)\,(\bar{t}\sigma_{\mu\nu}P_j c)\Big],$$

[Bar-Shalom, Wudka '99]

2-fermion FCNC

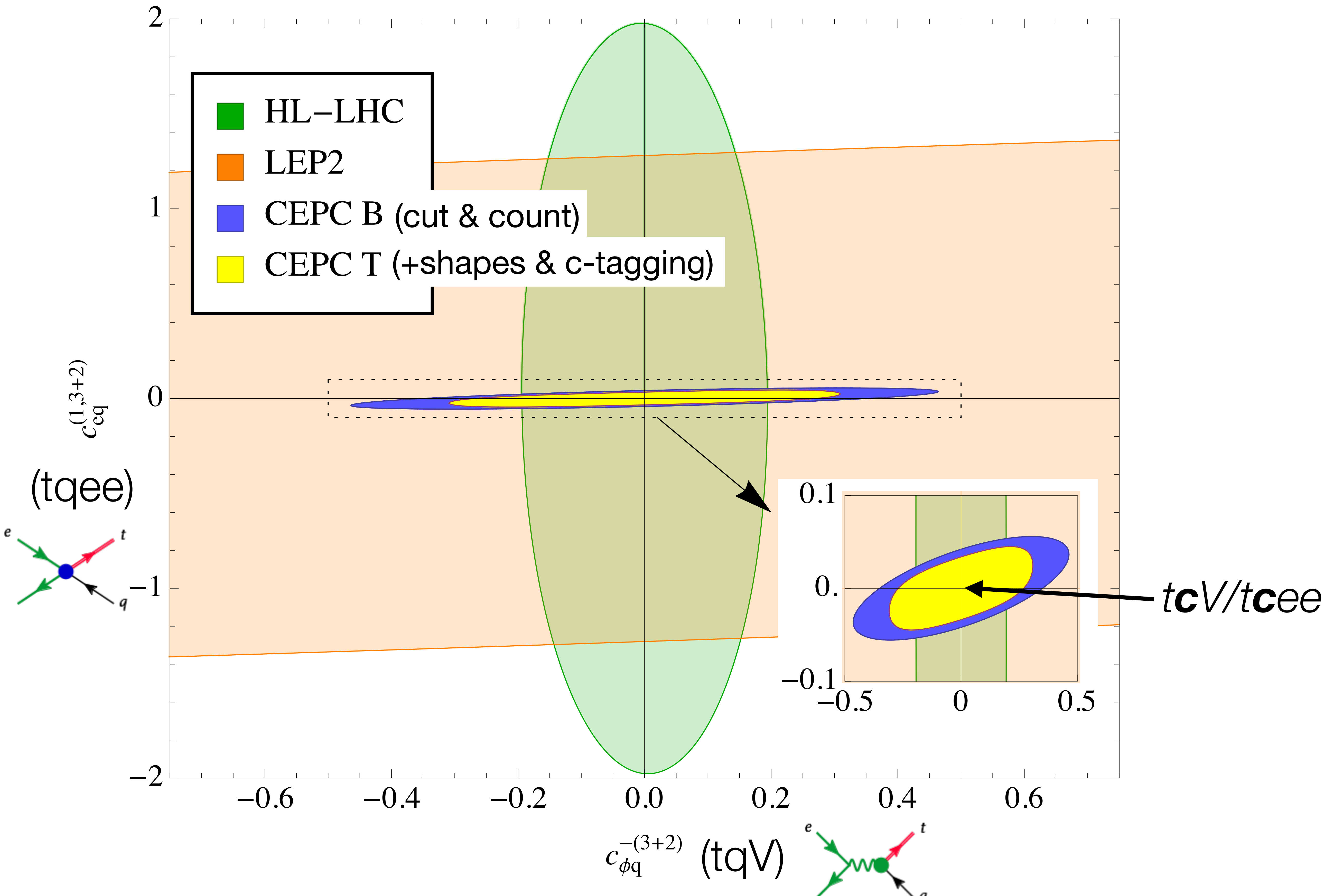
$$\bar{q}\gamma^\mu q \quad \varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi,$$
$$\bar{q}\gamma^\mu\tau^I q \quad \varphi^\dagger i\overleftrightarrow{D}^I_\mu\,\varphi,$$
$$\bar{u}\gamma^\mu u \quad \varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi,$$
$$\bar{q}\sigma^{\mu\nu}u\,\tilde{\varphi}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



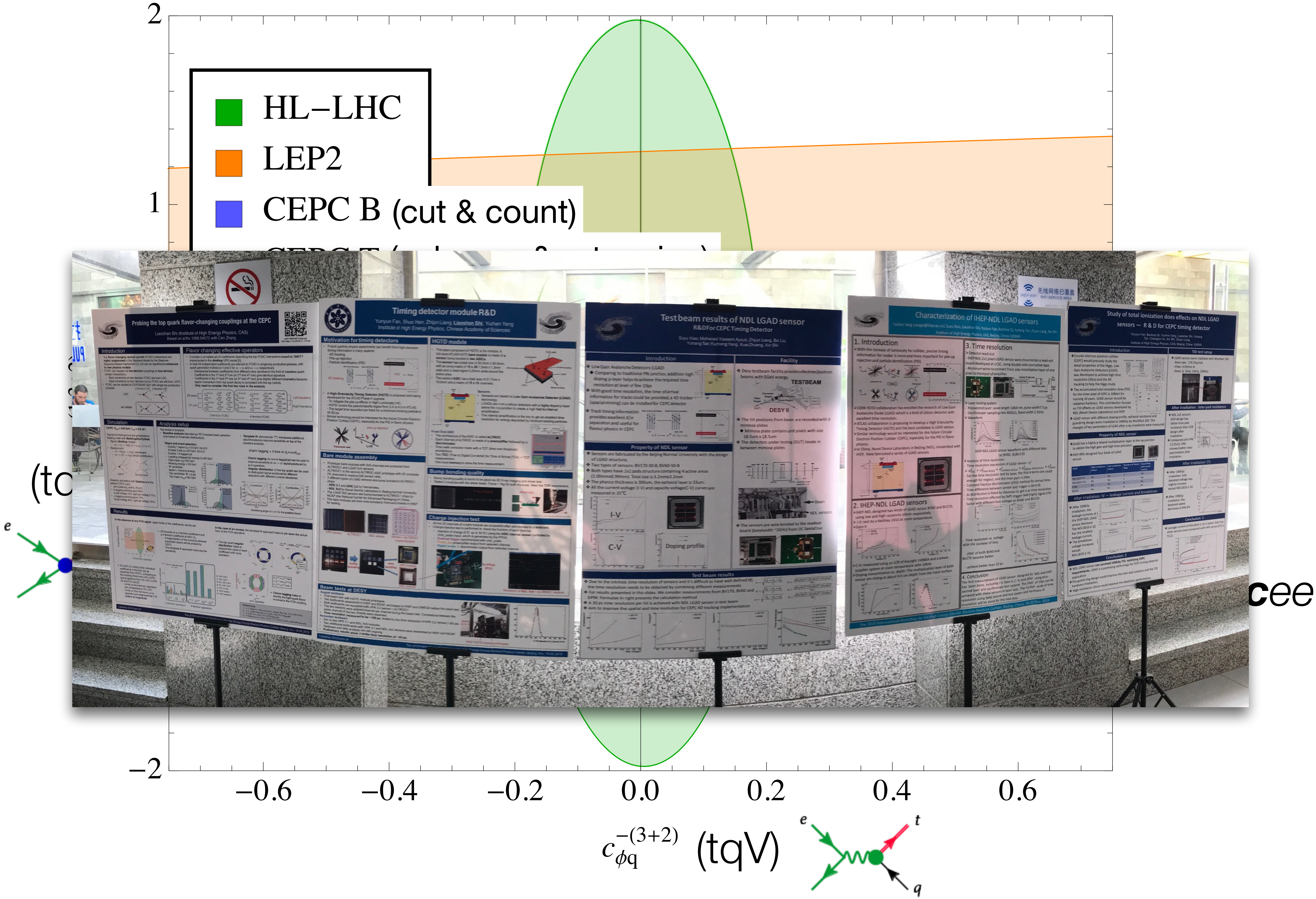
Scenario	Hadronic topology				Semi-leptonic topology				Combined topologies			
	obs.	-1σ	exp.	$+1\sigma$	obs.	-1σ	exp.	$+1\sigma$	obs.	-1σ	exp.	$+1\sigma$
SVT	1218	1268	1180	1097	1315	1406	1301	1203	1402	1468	1366	1264
S	577	604	556	520	647	647	603	555	685	693	641	593
V	953	1003	933	863	997	1069	997	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 Λ (GeV)

[DELPHI, CERN–PH–EP/2010–056]



See Liaoshan's poster for more results and details



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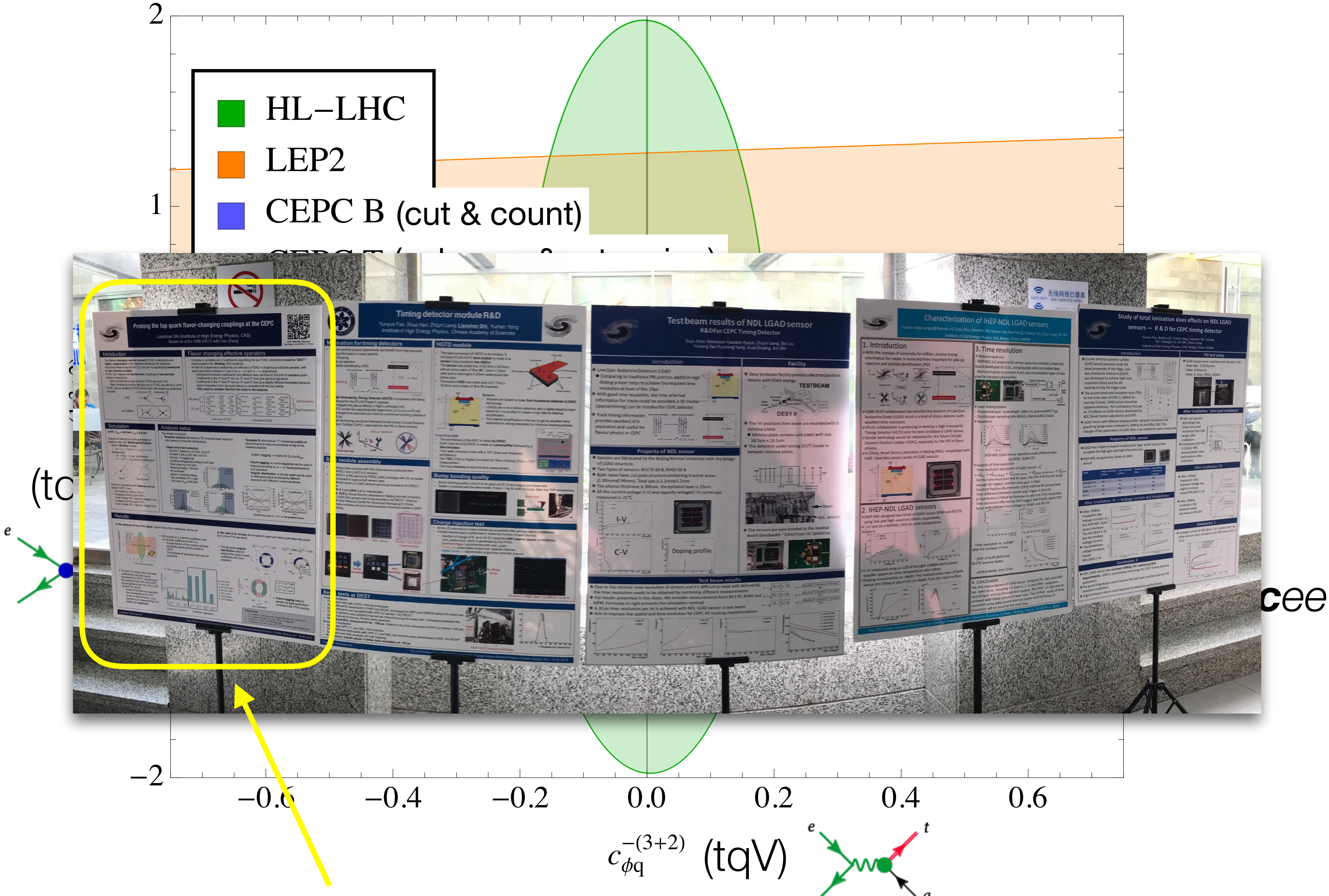
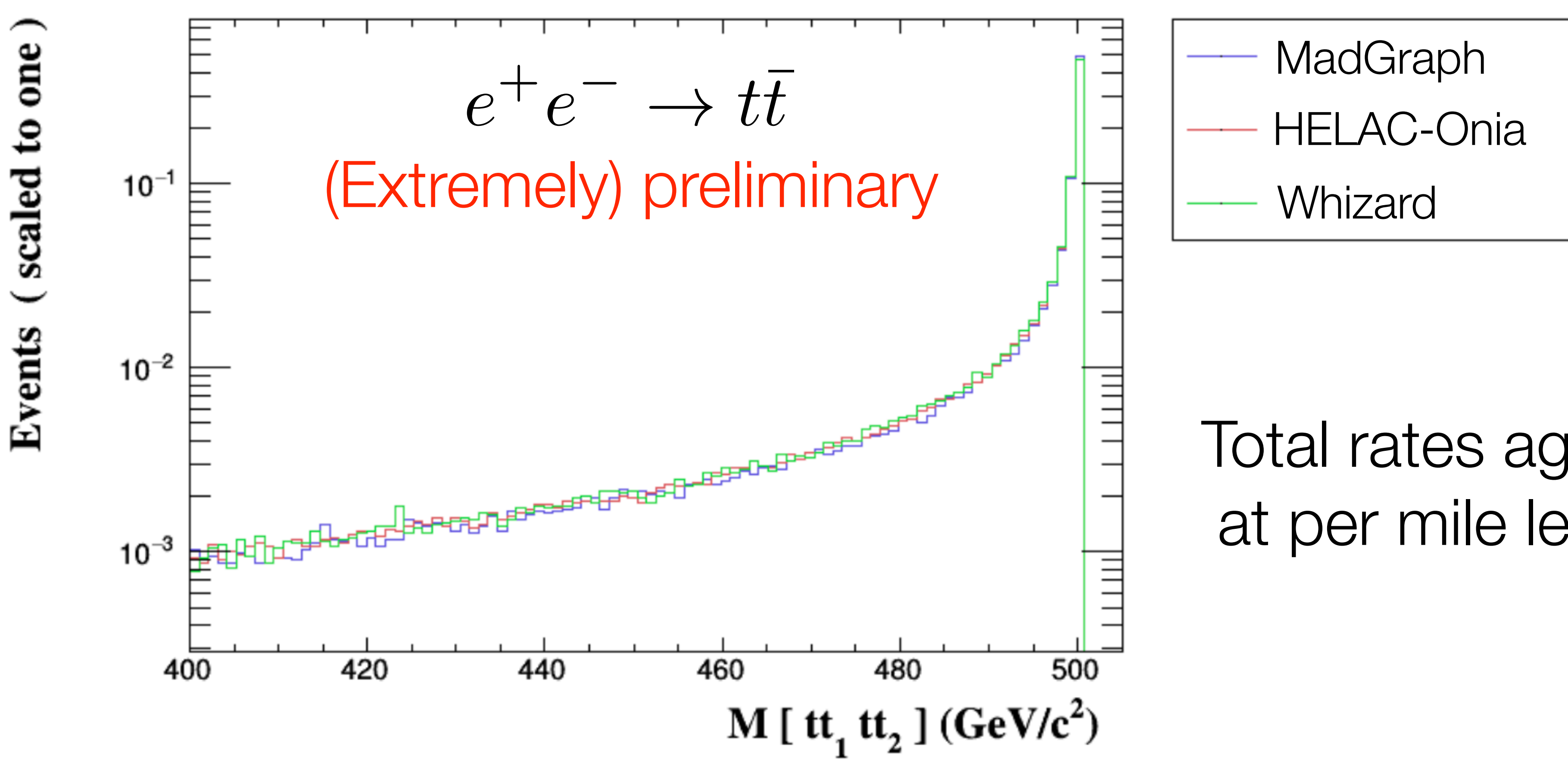


See Liaoshan's poster for more results and details

Theory prediction

- NLO QCD for FCNC operators, consistent with LHC TOP WG. Based on [Degrande, Maltoni, Wang, CZ ’14]. Four-fermion operators added.
- Extending to other ee colliders, FCCee, ILC, …
- ISR and beamstrahlung will be taken care of by a new MG branch (in development)



Total rates agree at per mile level

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  With Gauthier Durieux, Benjamin Fuks, Hua-Sheng Shao, Liaoshan Shi
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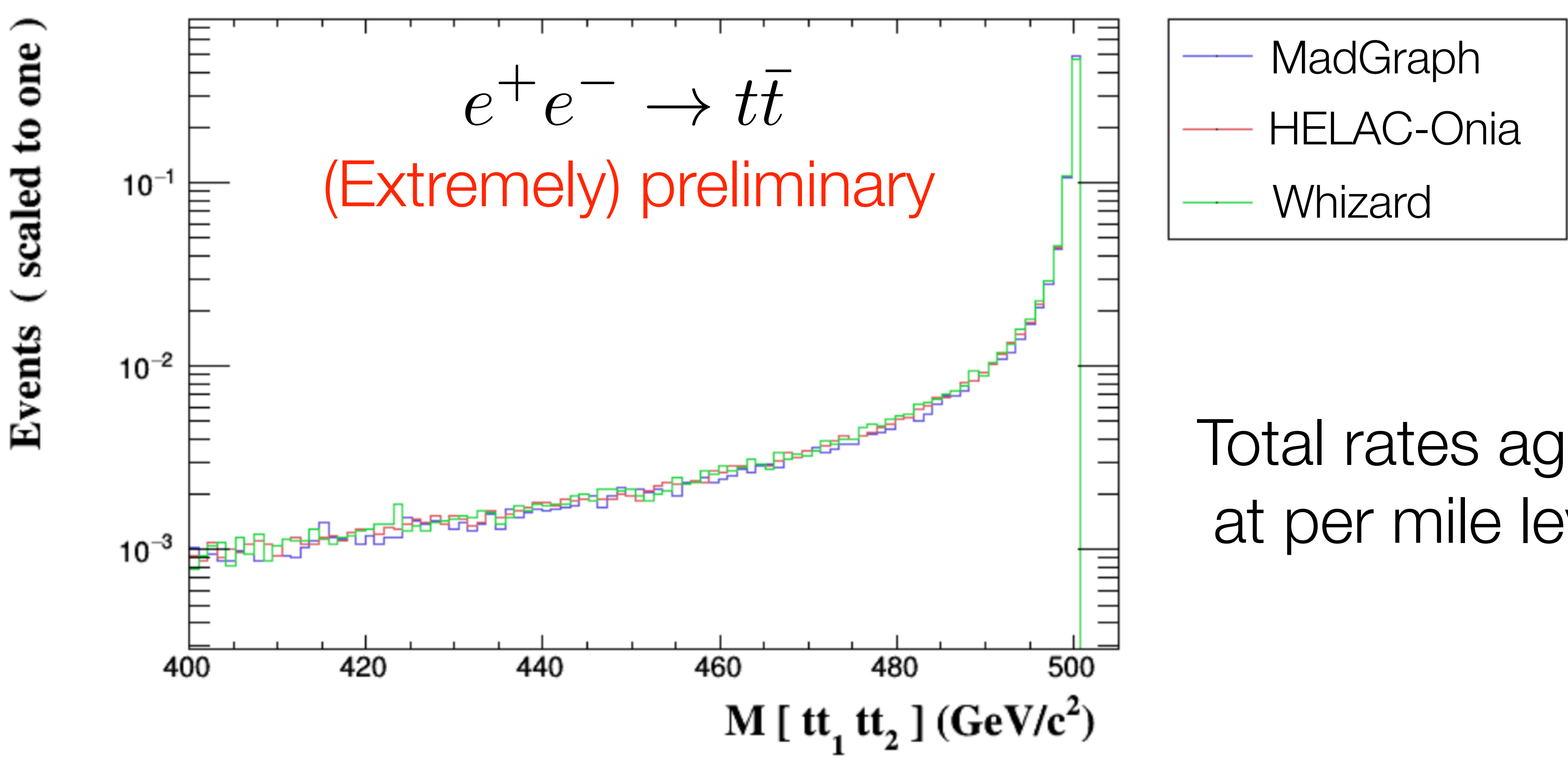
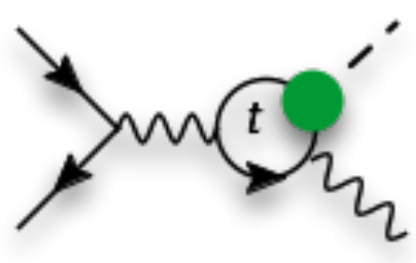
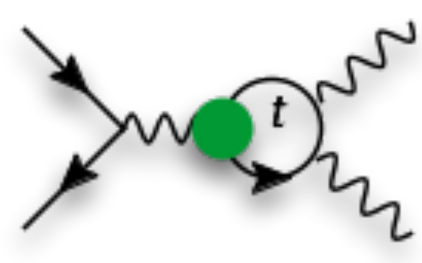
  by Stefano Frixione, Marco Zaro, Xiaoran Zhao



Total rates agree at per mile level

0t: tops below 350 GeV

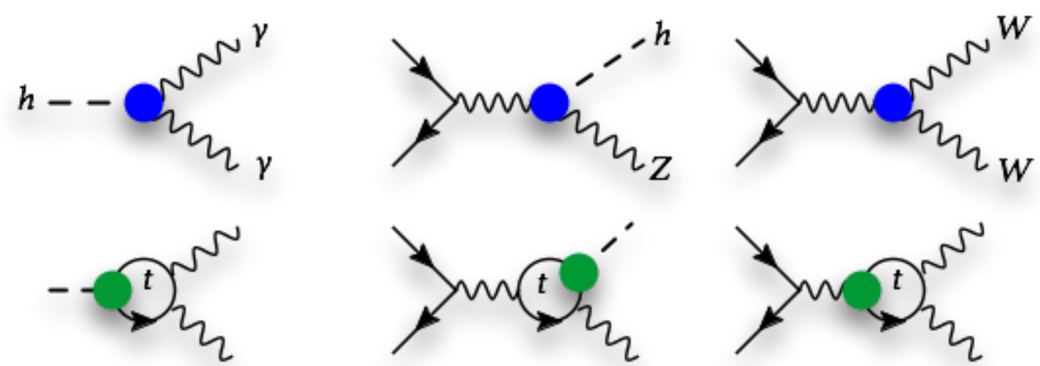




Top loops

Top operators entering at one loop lead to complication in future precision Higgs measurements.

- Higgs/diboson channels can reach ~1% or even better precision with future lepton collider. When this happens, we want to be able to disentangle
  - **H coupling tree level** and
  - **Top coupling loop level**?



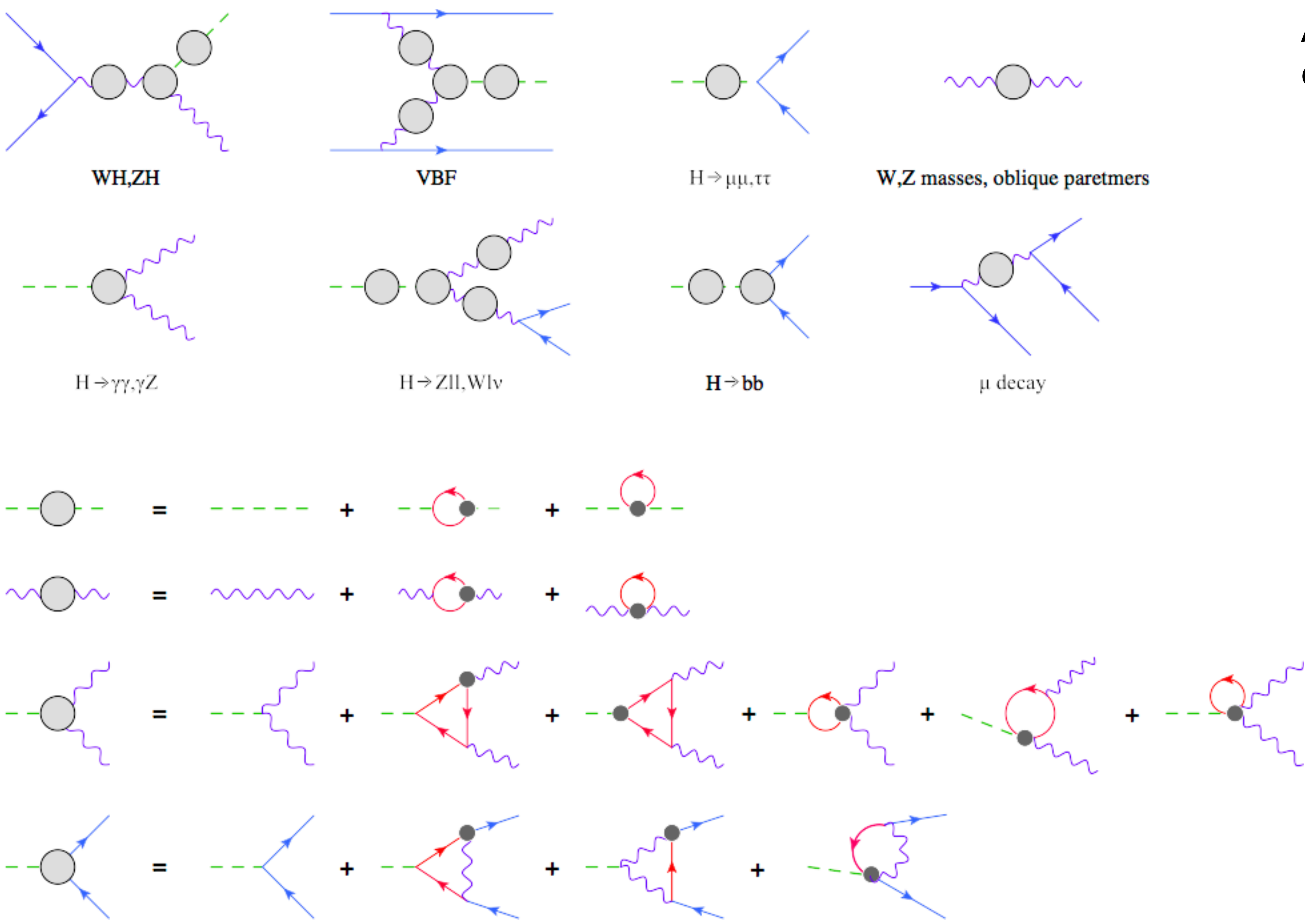
- At future CC even below ttbar threshold, it's possible to probe top EW couplings with good precision (better than HL-LHC).
- Strong correlation between top/H couplings -> top uncertainty will downgrade precision on H couplings.

Automatic EW NLO based on reweighting

Top coupling at one loop:

[Vryonidou, CZ ’18]

All dim-6 top loop contributions in Higgs



RG mixing

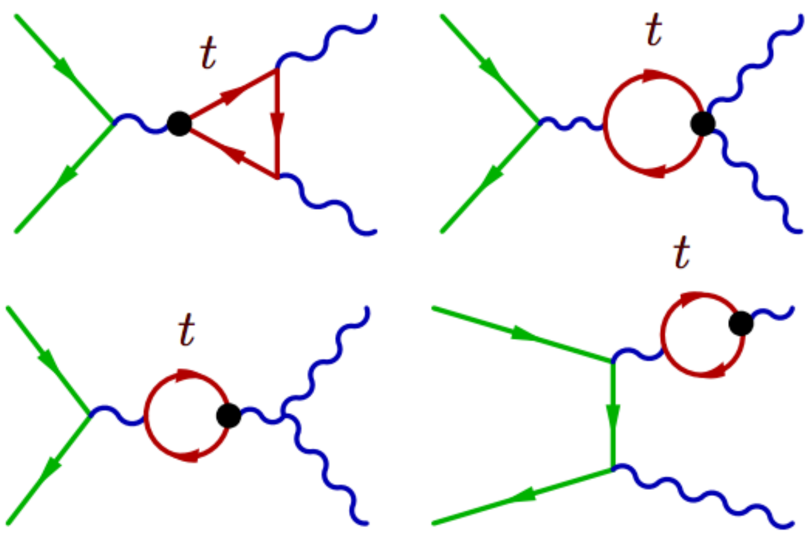
	$O_{\varphi t}$	$O^{(+)}_{\varphi Q}$	$O^{(-)}_{\varphi Q}$	$O_{\varphi tb}$	O_{tW}	O_{tB}	$O_{t\varphi}$
$O_{\varphi WB}$	$\frac{1}{3s_W c_W}$	$\frac{1}{3s_W c_W}$	$-\frac{1}{6s_W c_W}$	0	$-\frac{5y_t}{2ec_W}$	$-\frac{3y_t}{2es_W}$	0
$O_{\varphi D}$	$-6\frac{y_t^2}{e^2}$	$3\frac{y_t^2-y_b^2}{e^2}$	$3\frac{y_t^2-y_b^2}{e^2}$	$-6\frac{y_t y_b}{e^2}$	0	0	0
$O_{\varphi\Box}$	$-\frac{3}{2}\frac{y_t^2}{e^2}$	$-\frac{3y_t^2+6y_b^2}{2e^2}$	$\frac{6y_t^2+3y_b^2}{2e^2}$	$3\frac{y_t y_b}{e^2}$	0	0	0
$O_{\varphi W}$	0	$\frac{1}{4s_W^2}$	$-\frac{1}{4s_W^2}$	0	$\frac{3y_t}{2es_W}$	0	0
$O_{\varphi B}$	$\frac{1}{3c_W^2}$	$\frac{1}{12c_W^2}$	$\frac{1}{12c_W^2}$	0	0	$\frac{5y_t}{2ec_W}$	0
O_W	0	$\frac{1}{es_W}$	$-\frac{1}{es_W}$	0	0	0	0
O_B	$\frac{4}{3ec_W}$	$\frac{1}{3ec_W}$	$\frac{1}{3ec_W}$	0	0	0	0
$O_{b\varphi}$	0	$-\frac{y_b}{2c_W^2} + y_b\frac{8\lambda-3y_t^2-5y_b^2}{4e^2}$	$y_b\frac{-4\lambda+3y_t^2+7y_b^2}{4e^2}$	$\frac{3y_t}{4s_W^2} - y_t\frac{2\lambda+y_t^2-6y_b^2}{2e^2}$	$\frac{y_t y_b}{2es_W}$	0	$\frac{3y_t y_b}{4e^2}$
$O_{\mu\varphi}$	0	$-\frac{3y_\mu(y_t^2+y_b^2)}{2e^2}$	$\frac{3y_\mu(y_t^2+y_b^2)}{2e^2}$	$\frac{3y_t y_b y_\mu}{e^2}$	0	0	$\frac{3y_t y_\mu}{2e^2}$
$O_{\tau\varphi}$	0	$-\frac{3y_\tau(y_t^2+y_b^2)}{2e^2}$	$\frac{3y_\tau(y_t^2+y_b^2)}{2e^2}$	$\frac{3y_t y_b y_\tau}{e^2}$	0	0	$\frac{3y_t y_\tau}{2e^2}$

agrees with **[R. Alonso et al., ’13,’14]**

$e^+e^- \rightarrow W^+W^-$

- $e^+e^- \rightarrow W^+W^-$: Dim-6 contribution to γWW leads to anomaly.
- In our scheme (KKS) this is reflected by the R2 dependence on the "reading point" when tracing the top loop. E.g.

$$O^{(-)}_{\varphi Q}: \quad \frac{e^3 v^2}{48\pi^2 s_W^2 \Lambda^2} \begin{cases} \epsilon^{\mu\nu\rho\sigma}(p_{2\sigma} - p_{3\sigma}) & \gamma \\ \epsilon^{\mu\nu\rho\sigma}(p_{3\sigma} - p_{1\sigma}) & W^+ \\ \epsilon^{\mu\nu\rho\sigma}(p_{1\sigma} - p_{2\sigma}) & W^- \end{cases}$$



- This is fixed by adding a Wess-Zumino-Witten term.

Global fit

[Durieux, Gu, Vryonidou, CZ ’18]

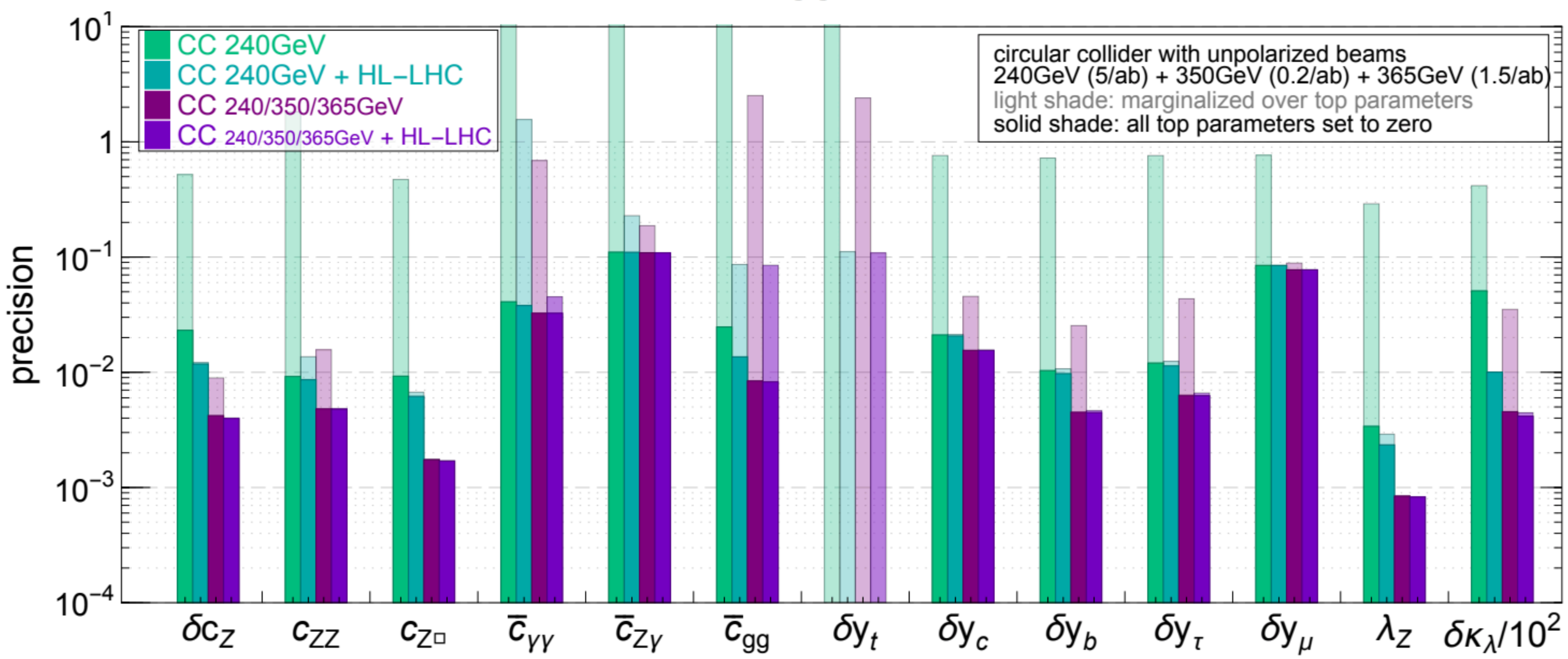
- **Below tt threshold:** CEPC 240 GeV 5 ab^{-1}
- **Above tt threshold:** FCC-ee 350 GeV 0.2 ab^{-1}, and 365 GeV 1.5 ab^{-1}

- **Higgs** ZH, WW fusion, all decay channels.
  Based on [Durieux, Grojean, Gu, Wang, ’17]
- **Diboson** Angular distributions.
- **Precision tests** Assuming oblique new physics and a factor of 5 improvements.
- **Top** ttbar with statistical optimal observable.
  Based on [Durieux, Perello, Vos, CZ, ’18]

Global fit at future ee collider: H/top interplay

- How does the top-coupling uncertainties downgrade the H precision at future CC?
- Global H + top loop fit

light shades: 12 Higgs op. floated + 6 top op. floated
dark shades: 12 Higgs op. floated + 6 top op. $\to 0$



Uncertainties on the top have a big effect on the Higgs

- Higgsstr. run: insufficient
- Higgsstr. run $\oplus$ $e^+e^- \to t\bar{t}$: large y_t contaminations in various coefficients
- Higgsstr. run $\oplus$ top@HL-LHC: large top contaminations in $\bar{c}_{\gamma\gamma,gg,Z\gamma,ZZ}$
- Higgsstr. run $\oplus$ $e^+e^- \to t\bar{t}$ $\oplus$ top@HL-LHC: top contam. in $\bar{c}_{gg}$ only

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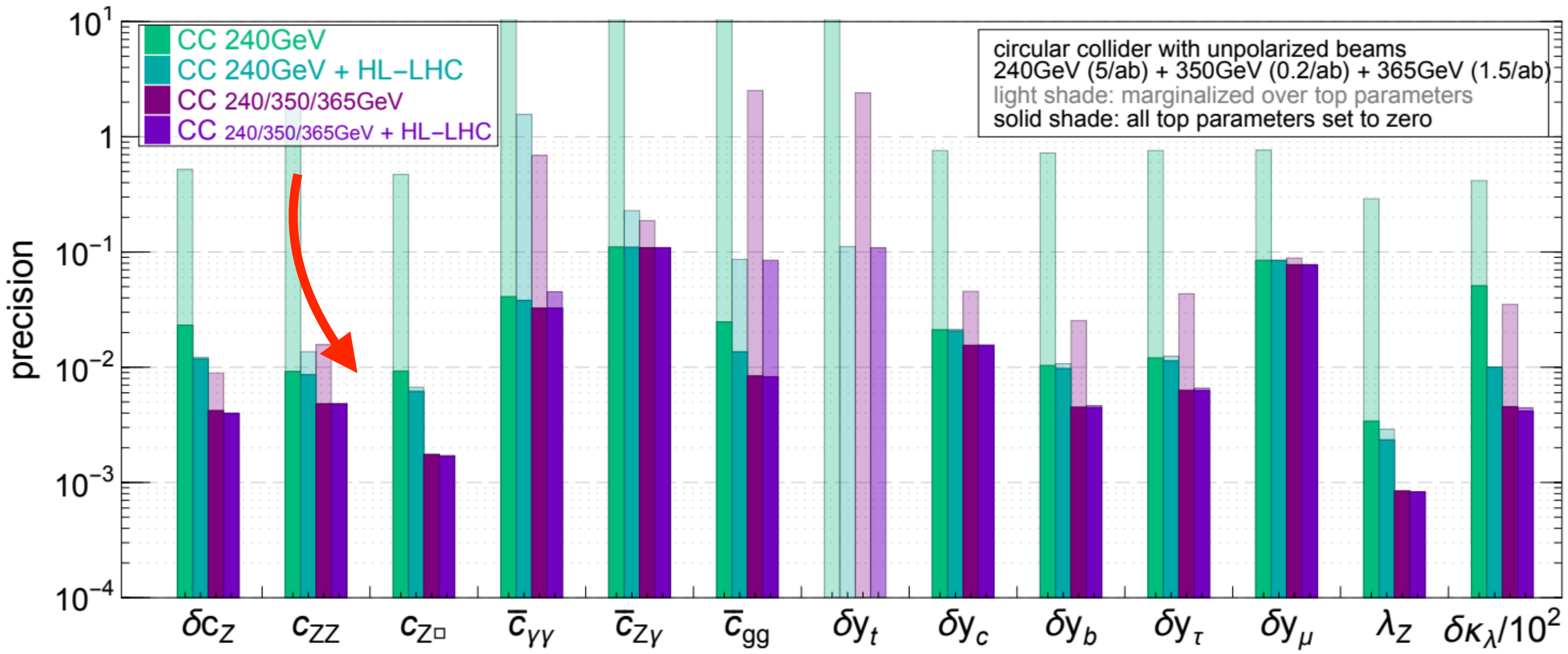

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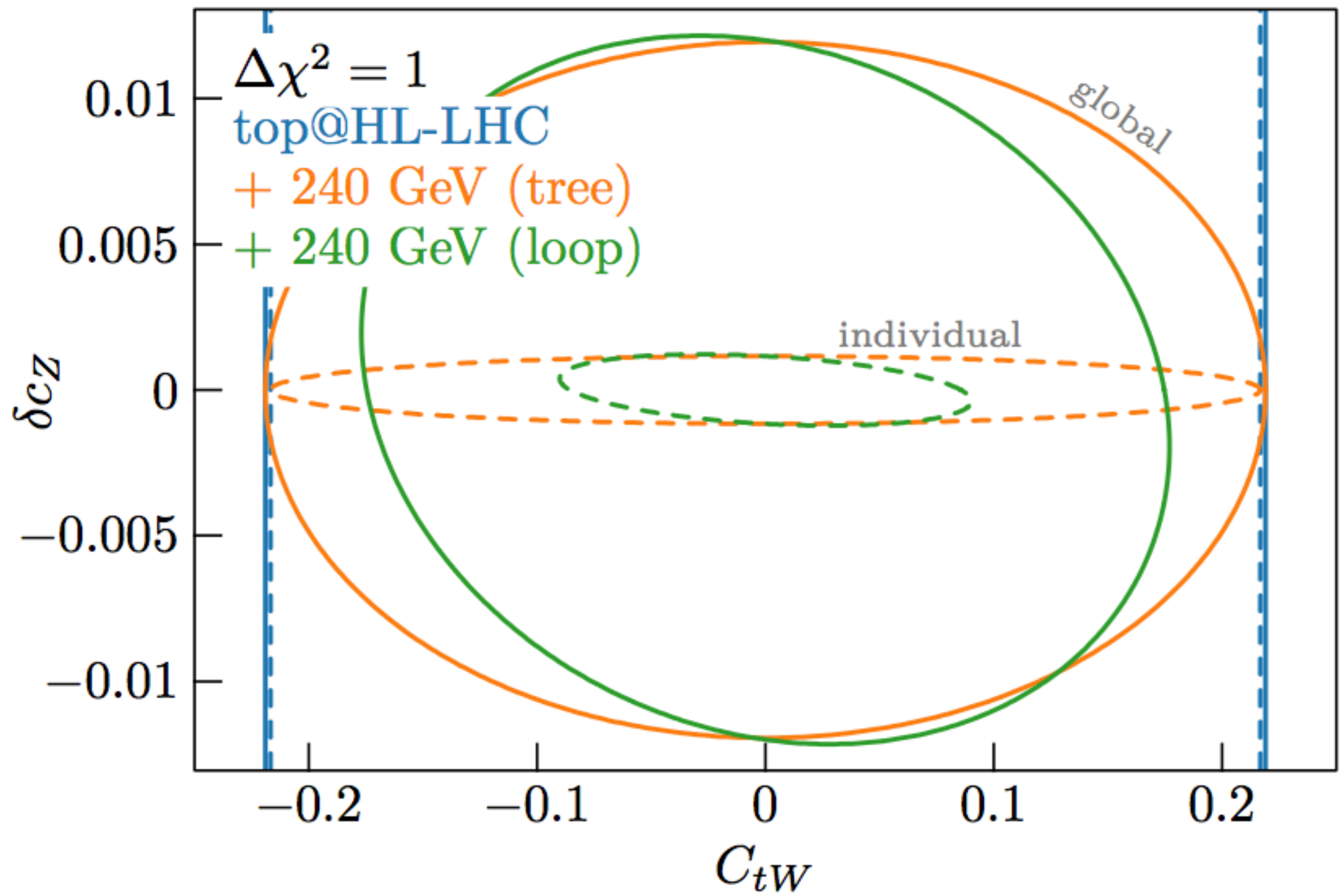
Global fit at future ee collider: indirect top limits

- HL-LHC gives the **blue limits**.
- A global fit of Higgs data in CC, at LO, will give the **orange contours**, vertical direction.
- A global fit of Higgs data in CC, at NLO including top loops, will also constrain top couplings, giving the **green contours**, both vertical and horizontal.
- Constraining power ~ a factor of 3, reflected by the individual case (dashed line).

On a linear scale, in the $(C_{tW}, \delta c_Z)$ plane:



- extra parameter space covered thanks to loop sensitivity
- room for improvement between glo. and ind. constraints

Conclusion

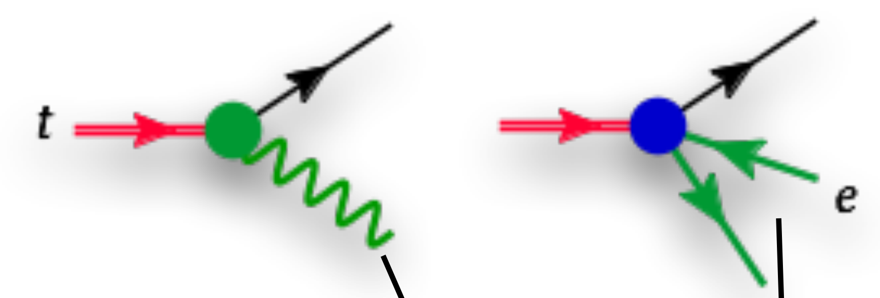
- Clean and global EFT analyses for top couplings are feasible at future lepton colliders, leading to direct or indirect constraints, with limited model dependence.
  - **ttbar production**: statistically optimal observables are theoretically well-motivated and experimentally amenable. Lepton colliders would cover orders of magnitude of unexplored top-quark EFT parameter space.
  - **Single top FCNC**: 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.
  - **Virtual tops**: Top-couplings can be probed indirectly at e+e– colliders, even below tt threshold. Individual reach is better than HL-LHC. Strong correlation between Top- and Higgs-couplings is however present, downgrading precisions on both sectors.
- **Fully automated tools** are available for SMEFT (also other BSM models), including NLO QCD prediction, EW loop corrections, and (on-going) ISR+ beamstrahlung.
- Accurate TH predictions for not only SM background but also BSM signals can be obtained, with no almost cost from the user side.

Thank you

Backups

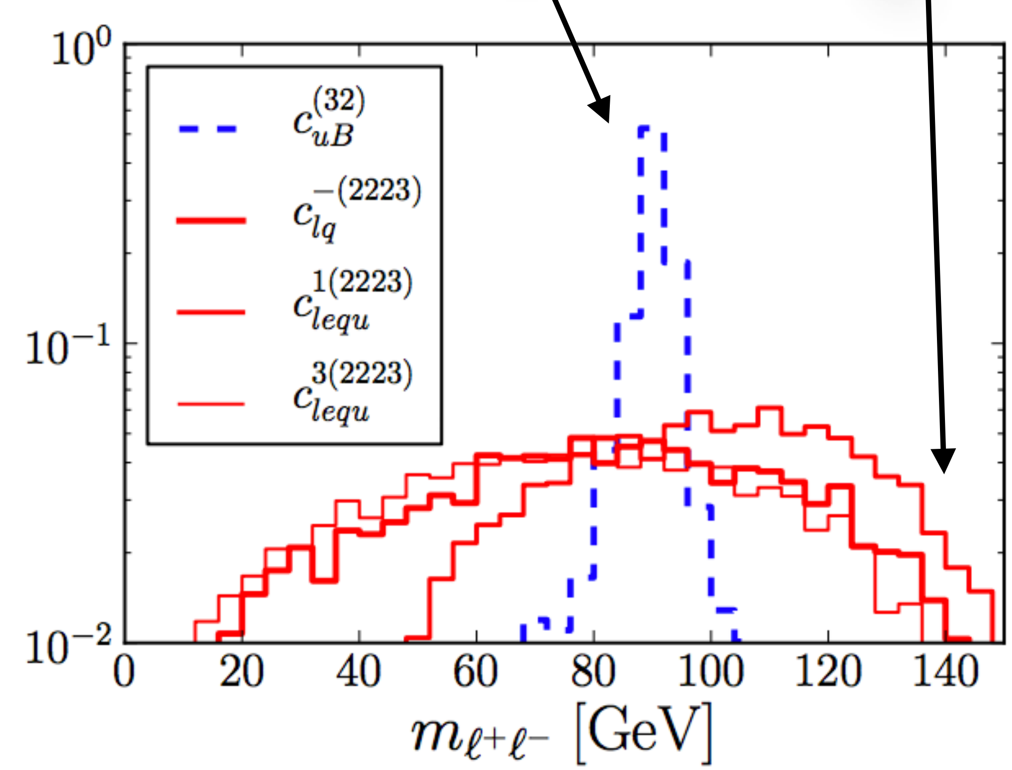
Top FCNC: 2-fermion and 4-fermion operators

- 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: $s_{\rm max}^{CR1} = 143$ (315) and $s_{\rm max}^{NEW} = 18$ (179), where again the number in brackets correspond to HL-LHC projections. The projected bounds on the coefficients get a factor of ~ 3 weaker for systematic uncertainties of 10%.

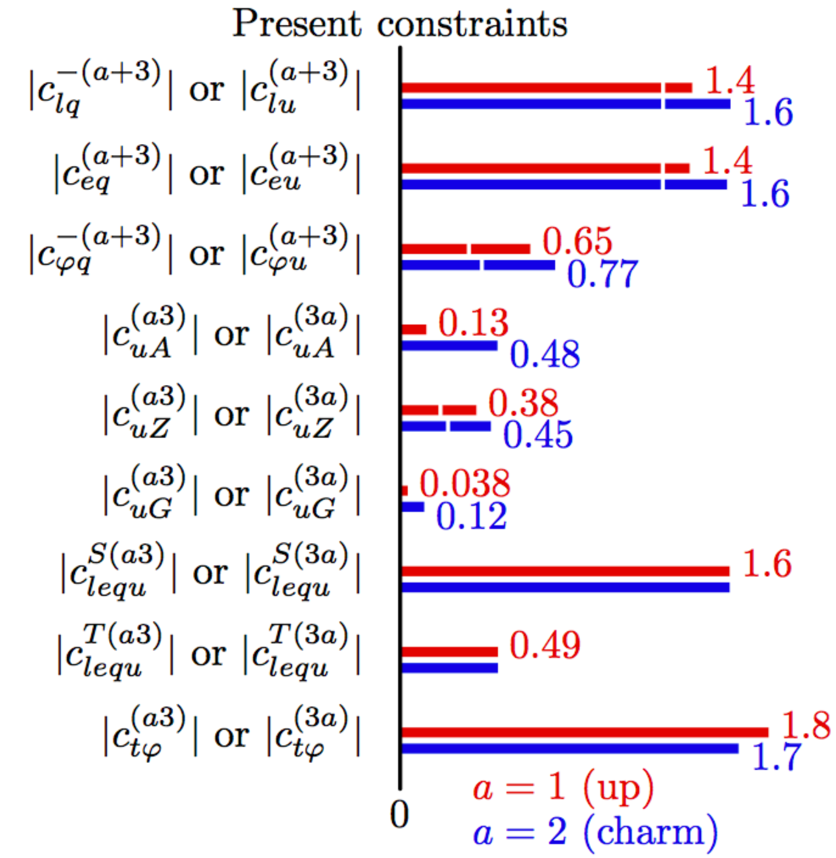


[Chala, Santiago, Spannowsky '18]

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	2.4×10^{-4}	[1177]	CMS	13 TeV	$35.9\,\mathrm{fb}^{-1}$	production plus decay
c	4.5×10^{-4}					
u	2.2×10^{-4}	[1178]	CMS	8 TeV	$19.7\,\mathrm{fb}^{-1}$	production, $76 < m_{\ell\ell} < 106$ GeV
c	4.9×10^{-4}					
$t \to qg$						
u	0.40×10^{-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	4.1×10^{-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	55×10^{-4}	[1182]	CMS	8 TeV	$19.7\,\mathrm{fb}^{-1}$	multilepton, $\gamma\gamma$, $b\bar{b}$
c	40×10^{-4}					
u	47×10^{-4}	[1183]	CMS	13 TeV	$35.9\,\mathrm{fb}^{-1}$	$b\bar{b}$
c	47×10^{-4}					

[HL/HE-LHC yellow report]



[Durieux, Kitahara, CZ ’18]

Top FCNC: current limits

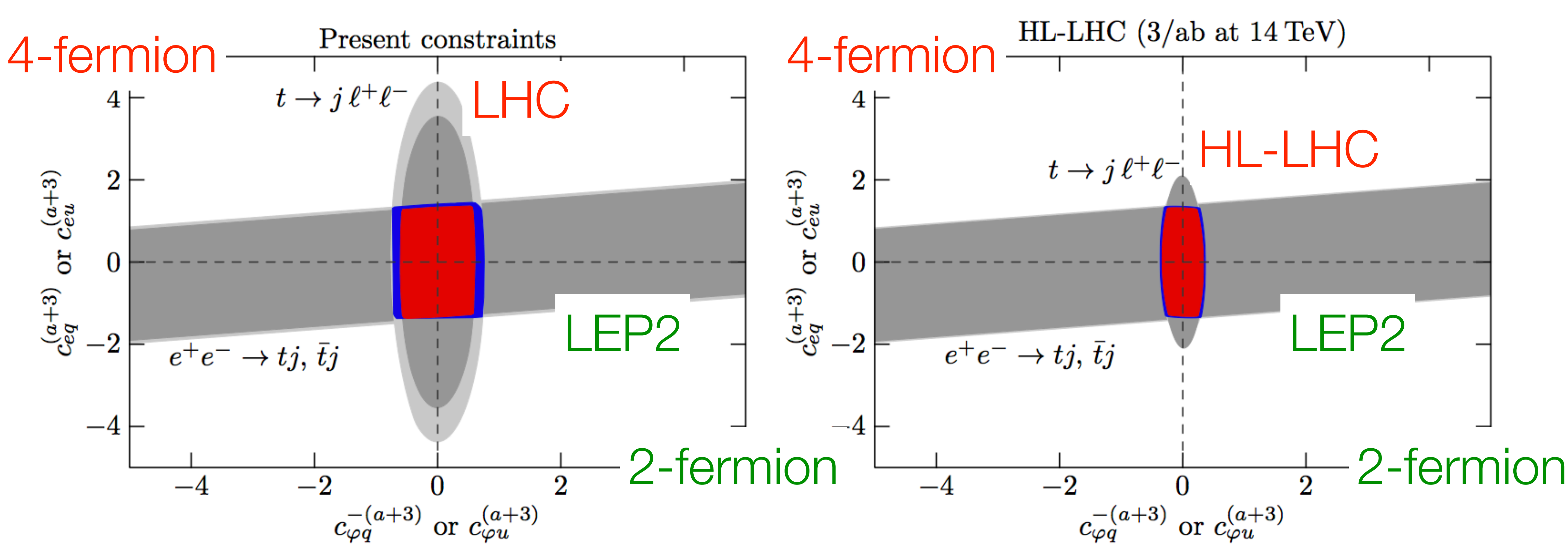


Fig. 59: Current (left) and prospective HL-LHC (right) 95% C.L. limits on top-quark FCNC operator coefficients in a two-dimensional plane formed by two- (x axis) and four-fermion (y axis) operator coefficients. Other parameters are marginalized over, within the constraints obtained when all measurements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

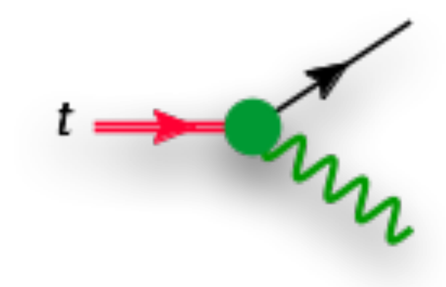
[HL/HE-LHC yellow report]

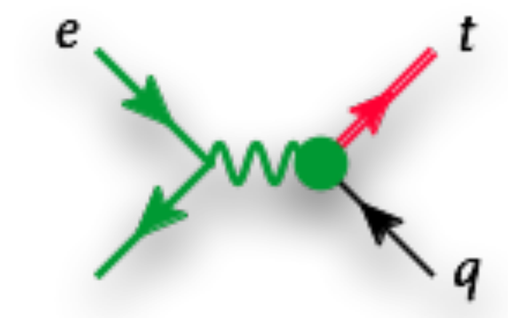
Taking
$C=1$, $\Lambda=1$ TeV:

LHC

ee collider

2-fermion OP

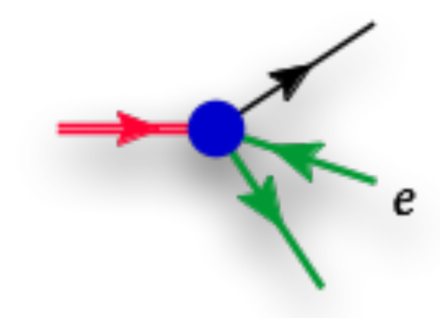


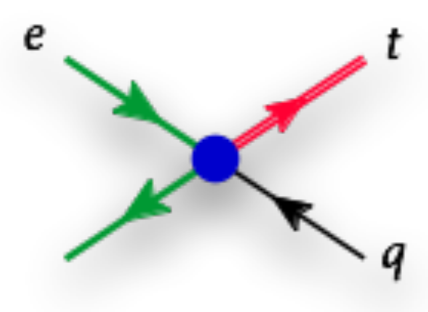


2f: 8.1e-5 GeV

2f: 1.8 fb

4-fermion OP





Phase space suppression

E^4/m_Z^4 scaling enhancement

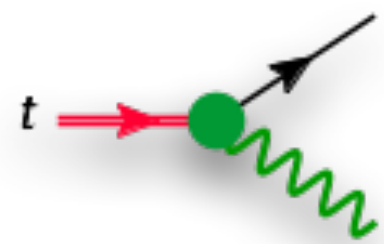
4f: 3.2e-6 GeV

4f: 120 fb

Taking $C=1$, $\Lambda=1$ TeV:	LHC	ee collider

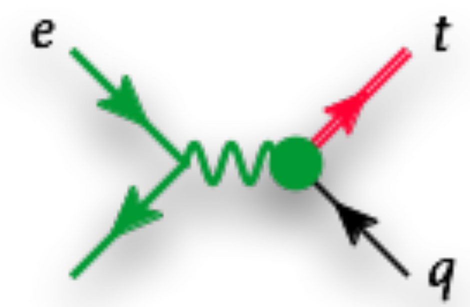
2-fermion OP

LHC:



2f: 8.1e-5 GeV

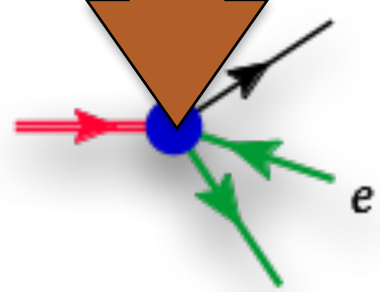
ee collider:



2f: 1.8 fb

4-fermion OP

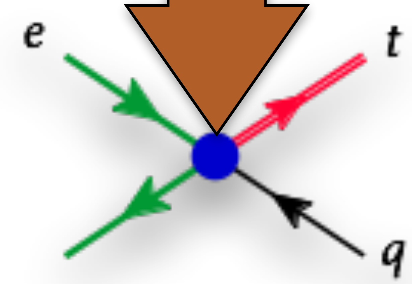
LHC: 0.04



Phase space suppression

4f: 3.2e-6 GeV

ee collider: ~70

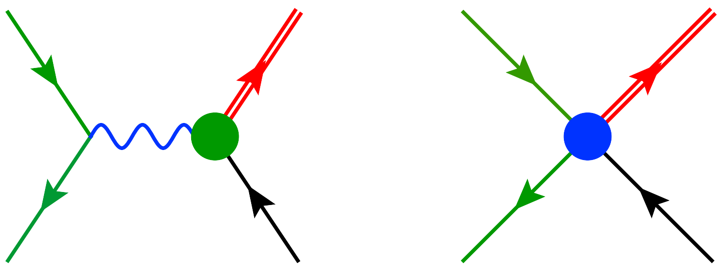


E^4/m_Z^4 scaling enhancement

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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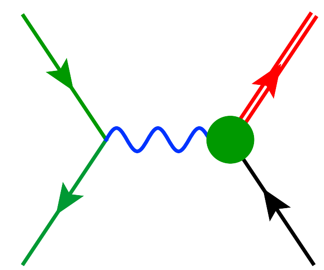
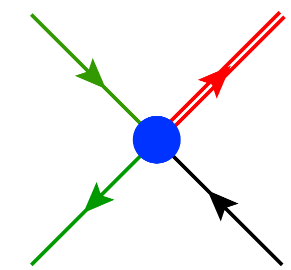
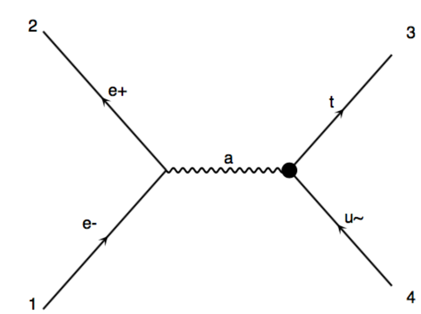


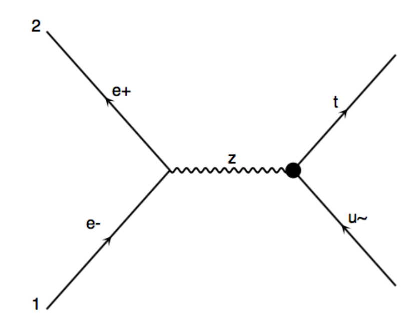


- QCD corrections: FCNC specific UFO. Need 4f implementation
  http://feynrules.irmp.ucl.ac.be/wiki/TopFCNC [Degrande, Maltoni, Wang, CZ '14]

```
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

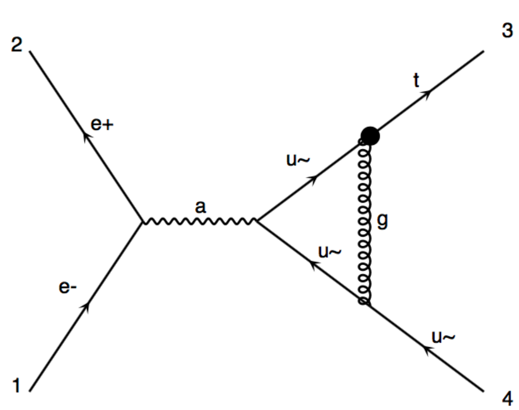


diagram 3 NP=2, QCD=2, QED=2

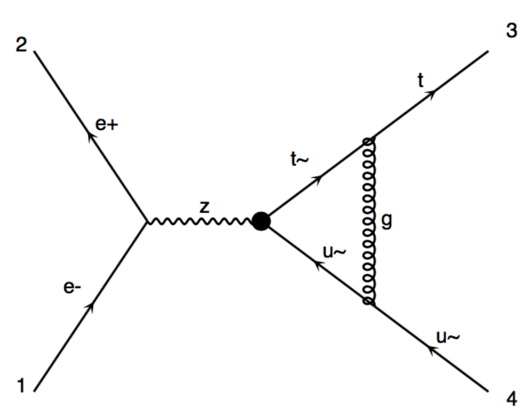
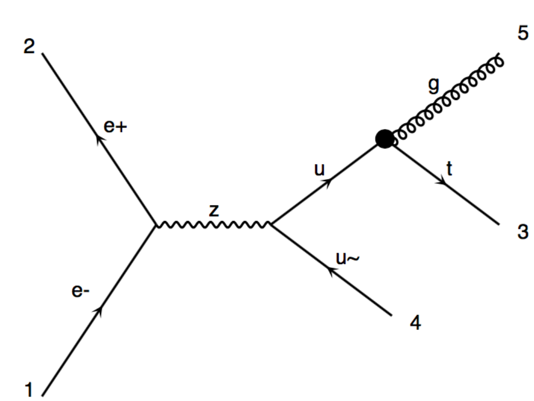
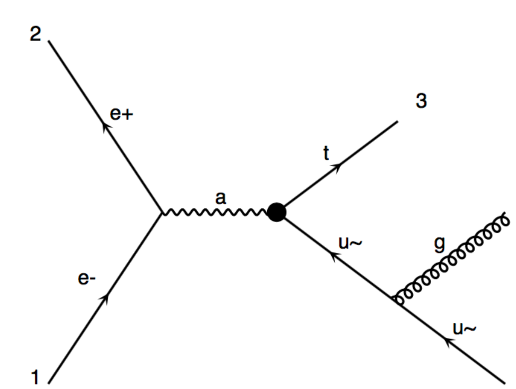


diagram 4 NP=2, QCD=2, QED=1

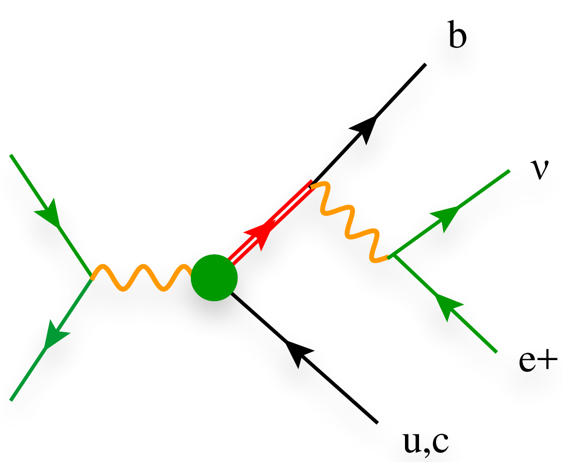


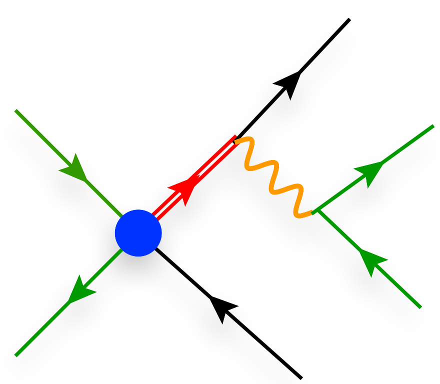
real diagram 5 NP=2, QCD=1, QED=2



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

- 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:

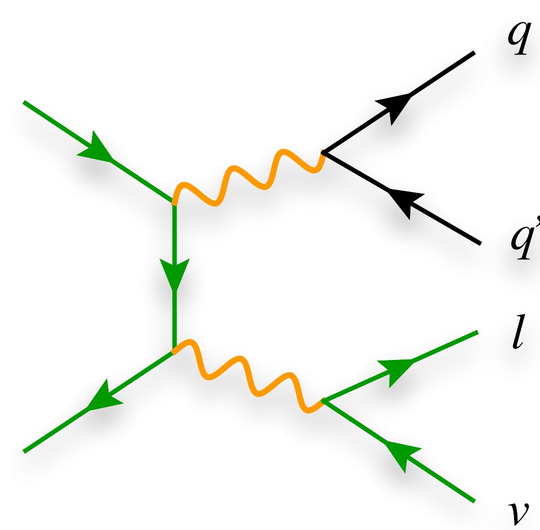


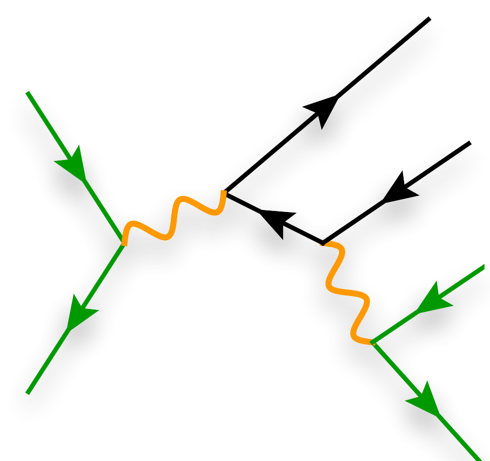


$$m_{top,rec} \approx 172.5 \text{ GeV}$$

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

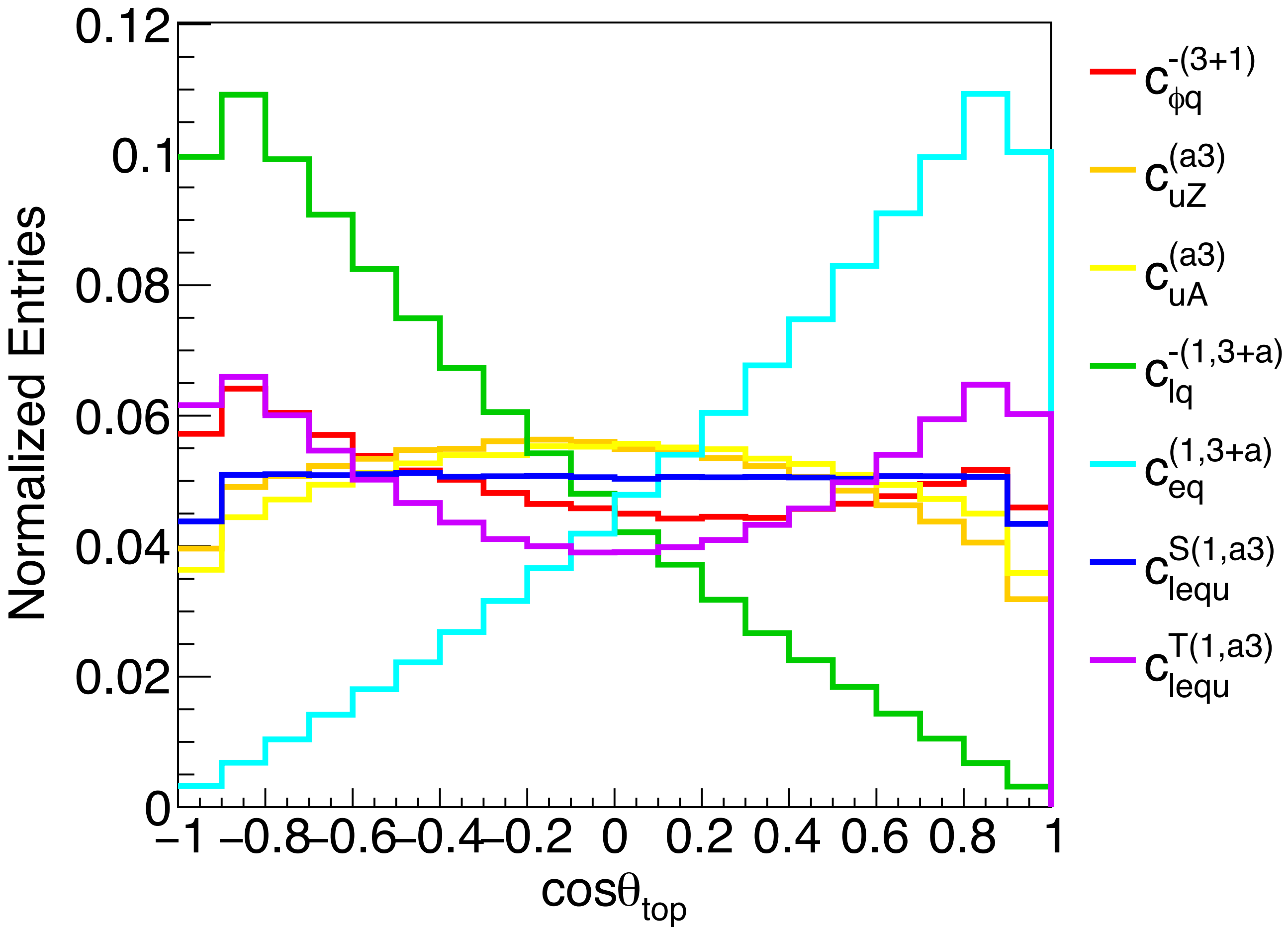
- Background: Wjj dominant

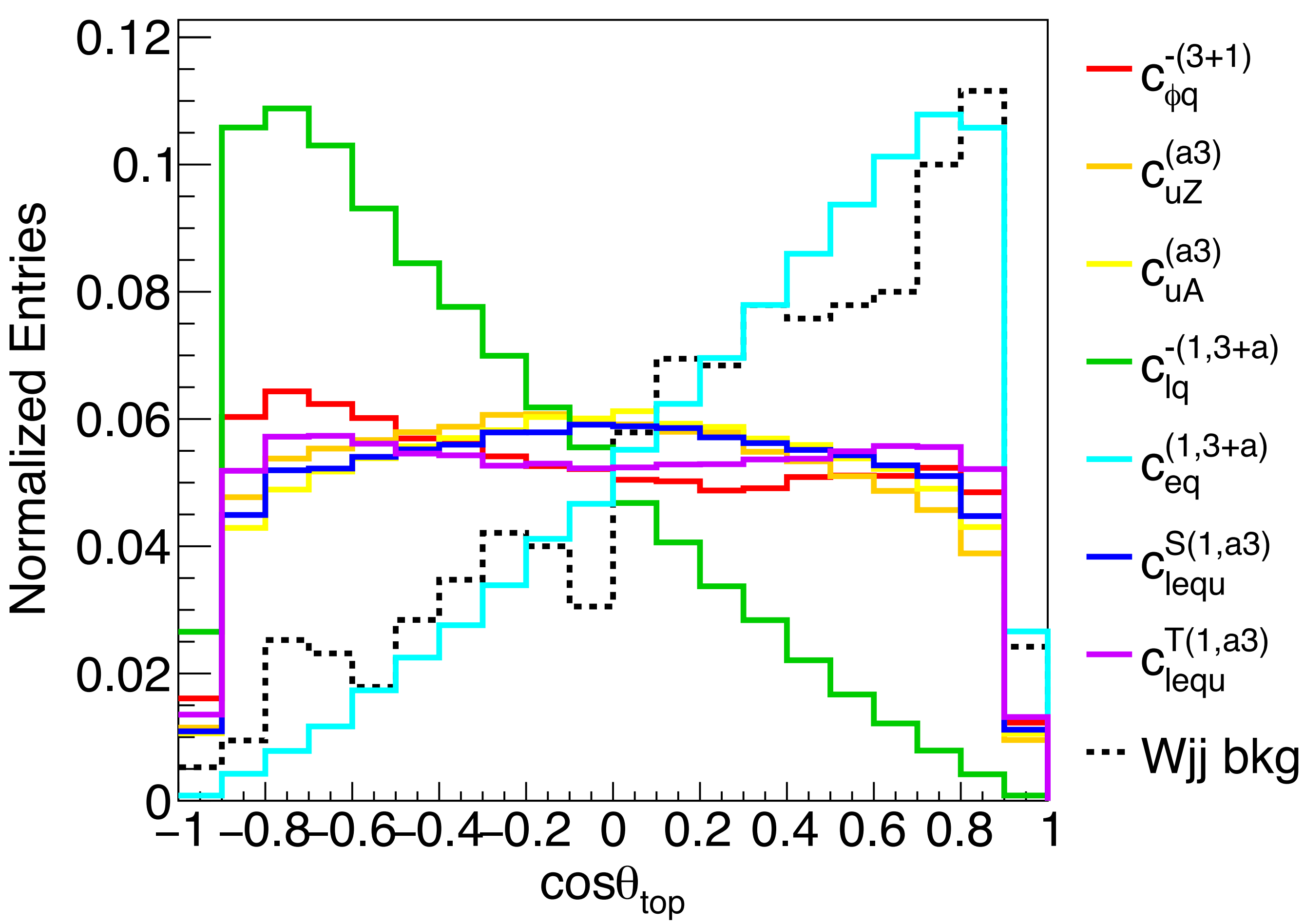




$$m_{jj} \approx 80.4 \text{ GeV}$$

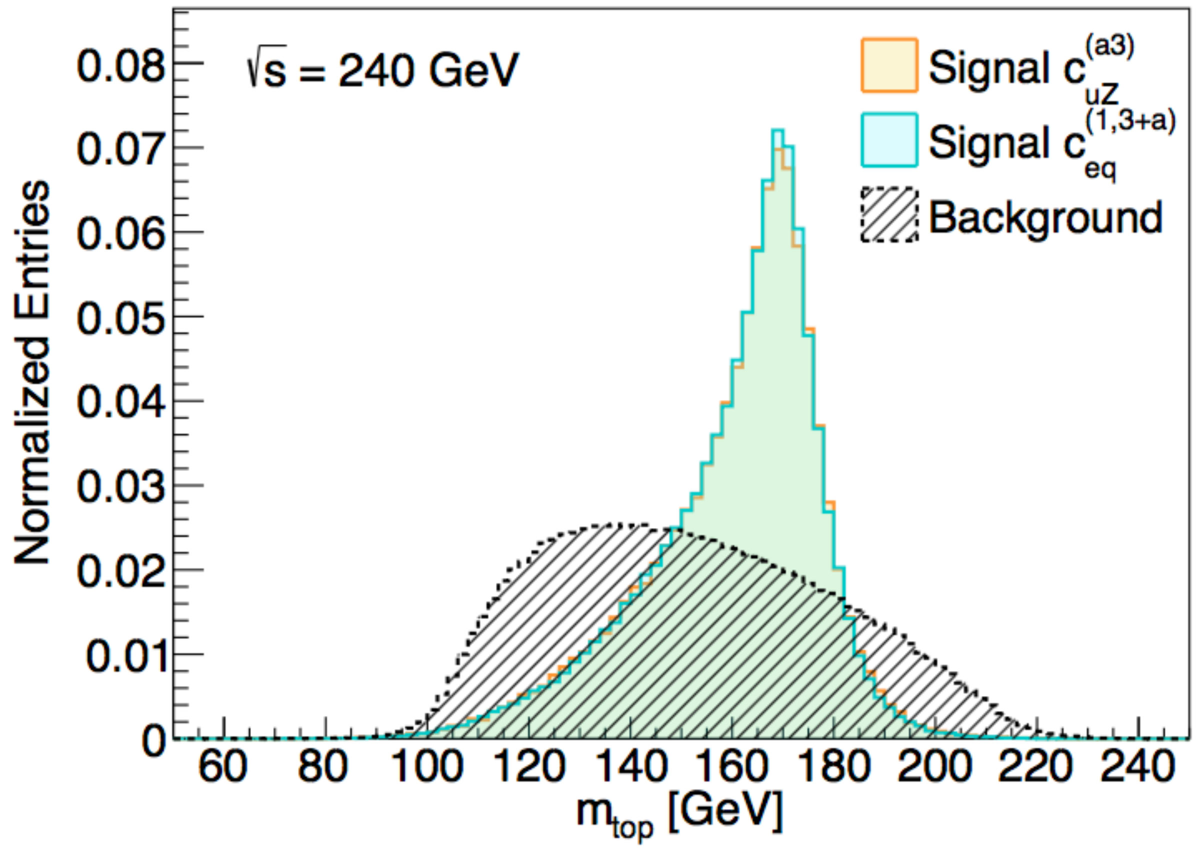
Angular distribution

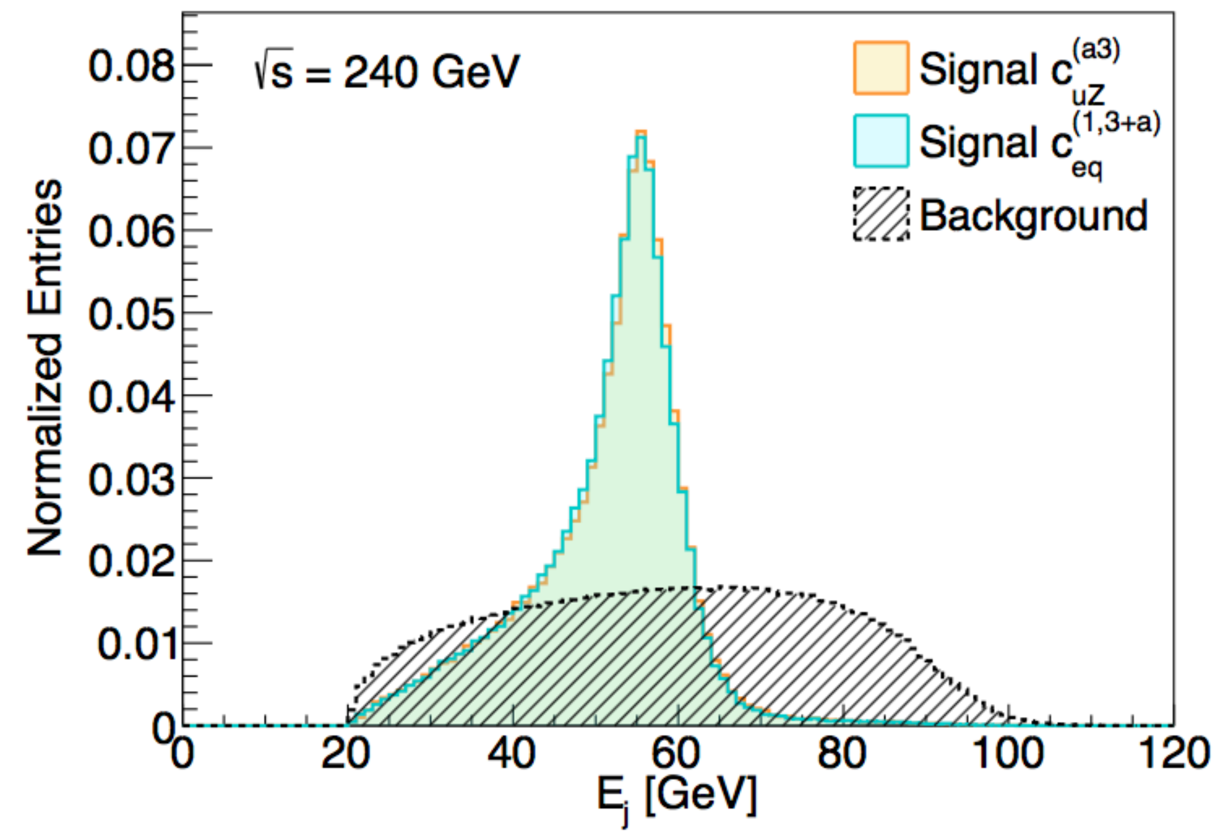


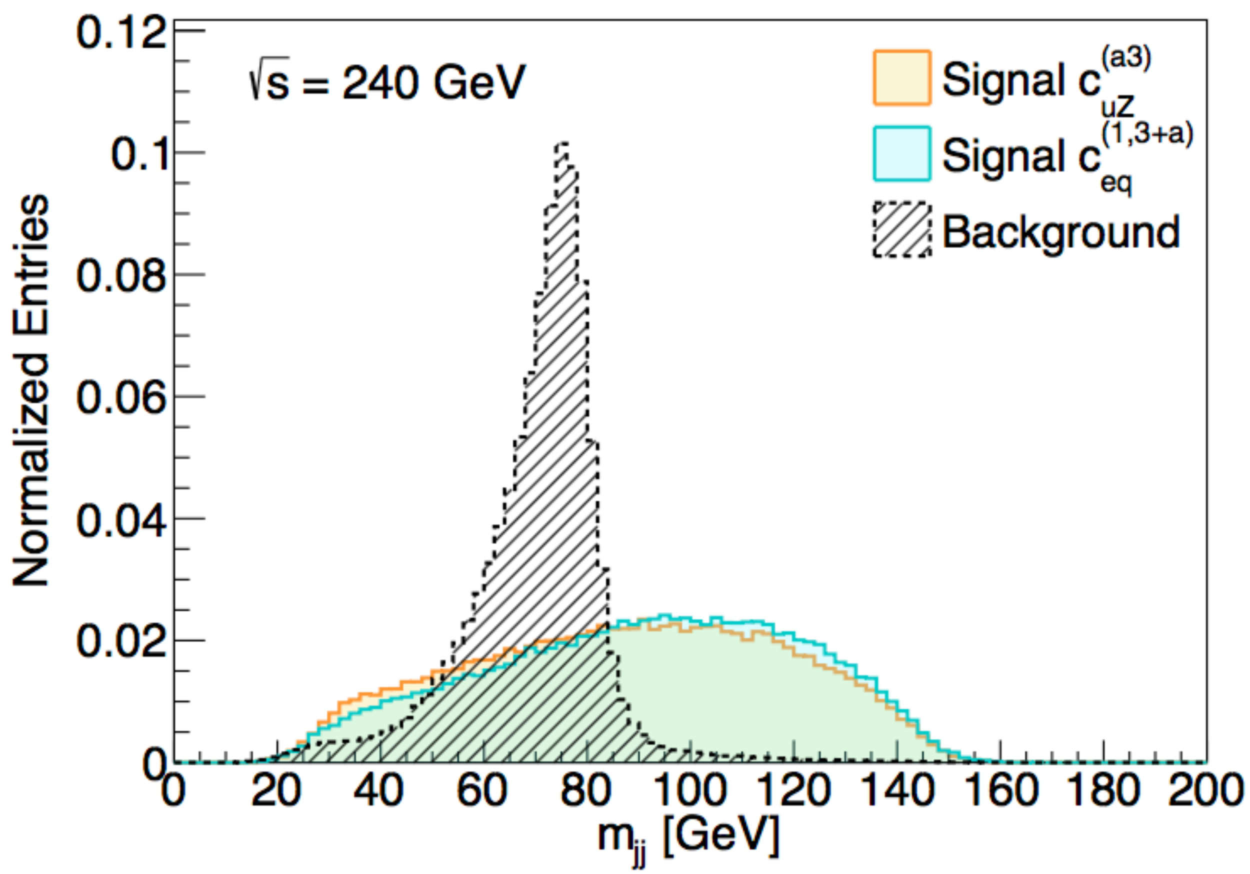


Template fit:

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







Baseline:

$E_j < 60$ GeV ,

$m_{jj} > 100$ GeV ,

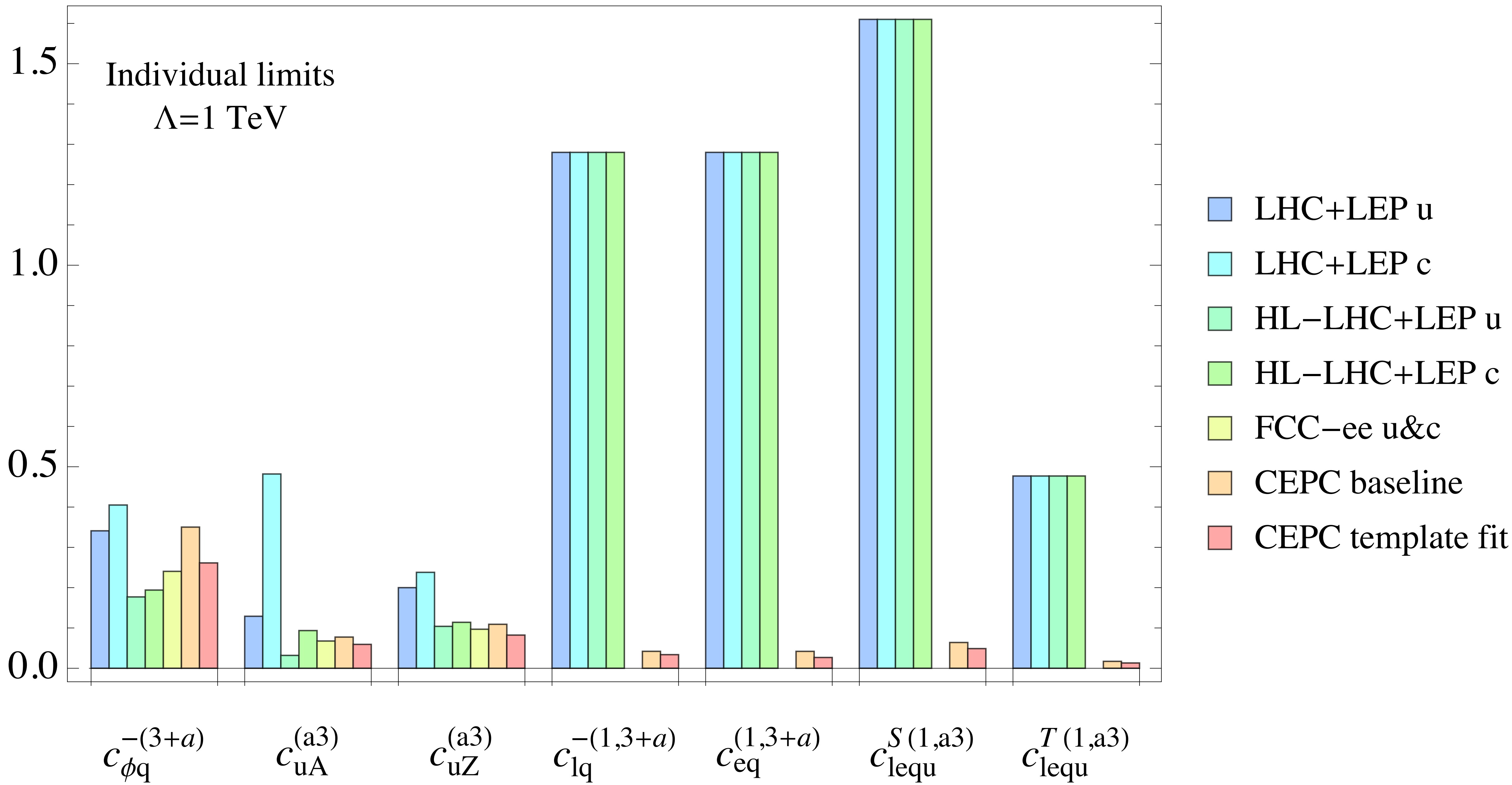
$m_{top} < 180$ GeV .

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 (0.0134 fb)



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]

LHeC: similar limits [W. Liu, H. Sun 1906.04884]

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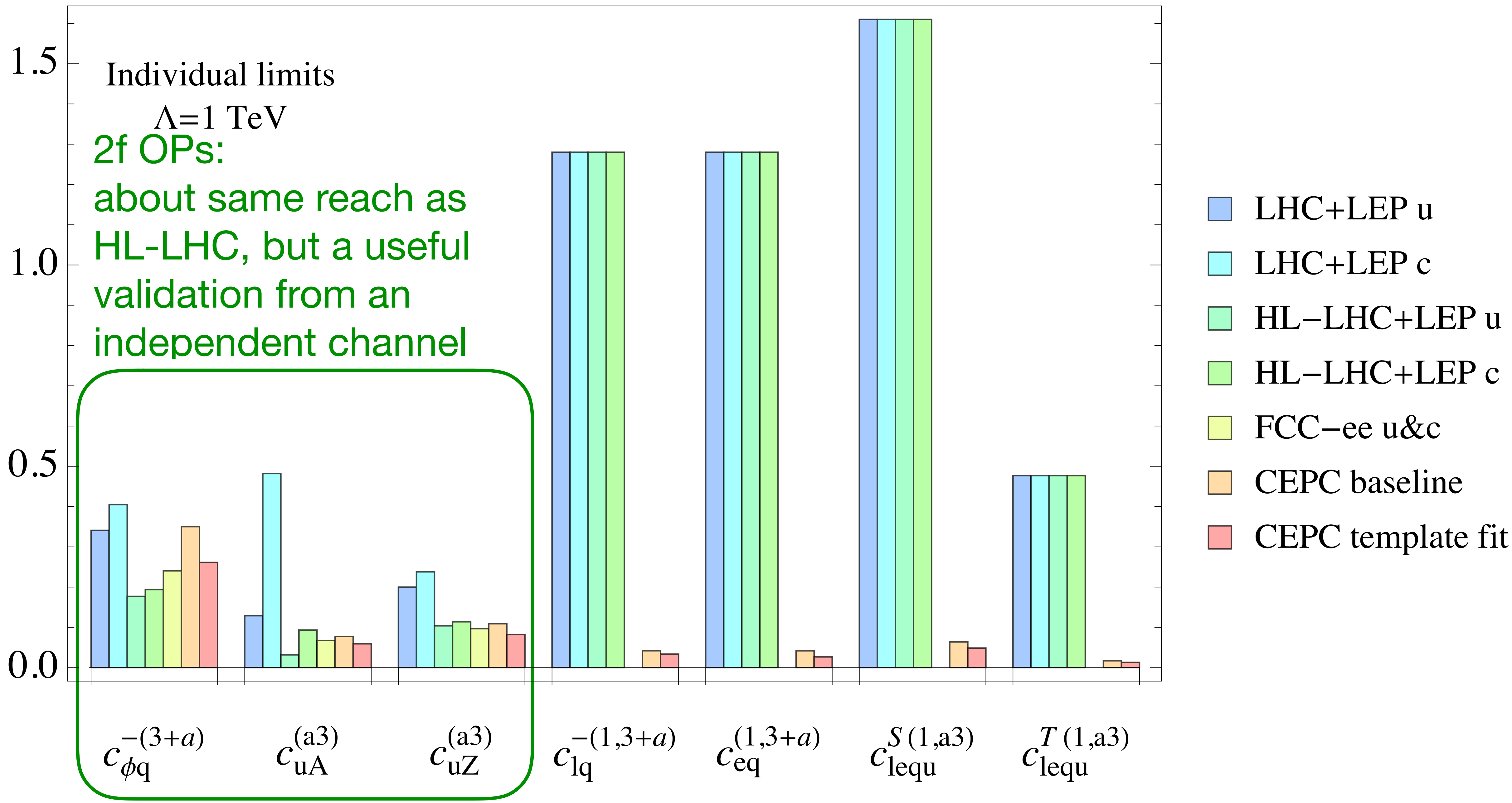

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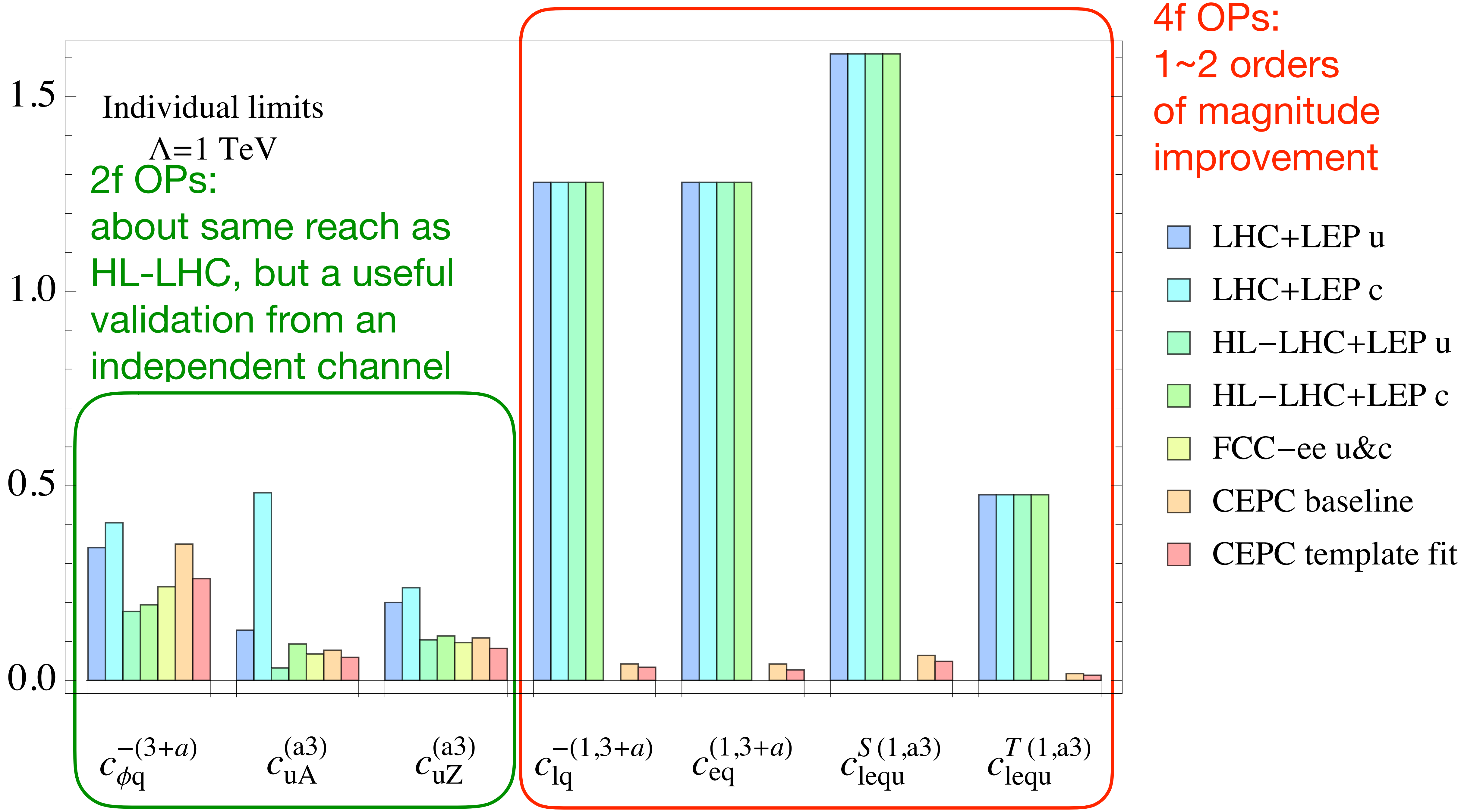

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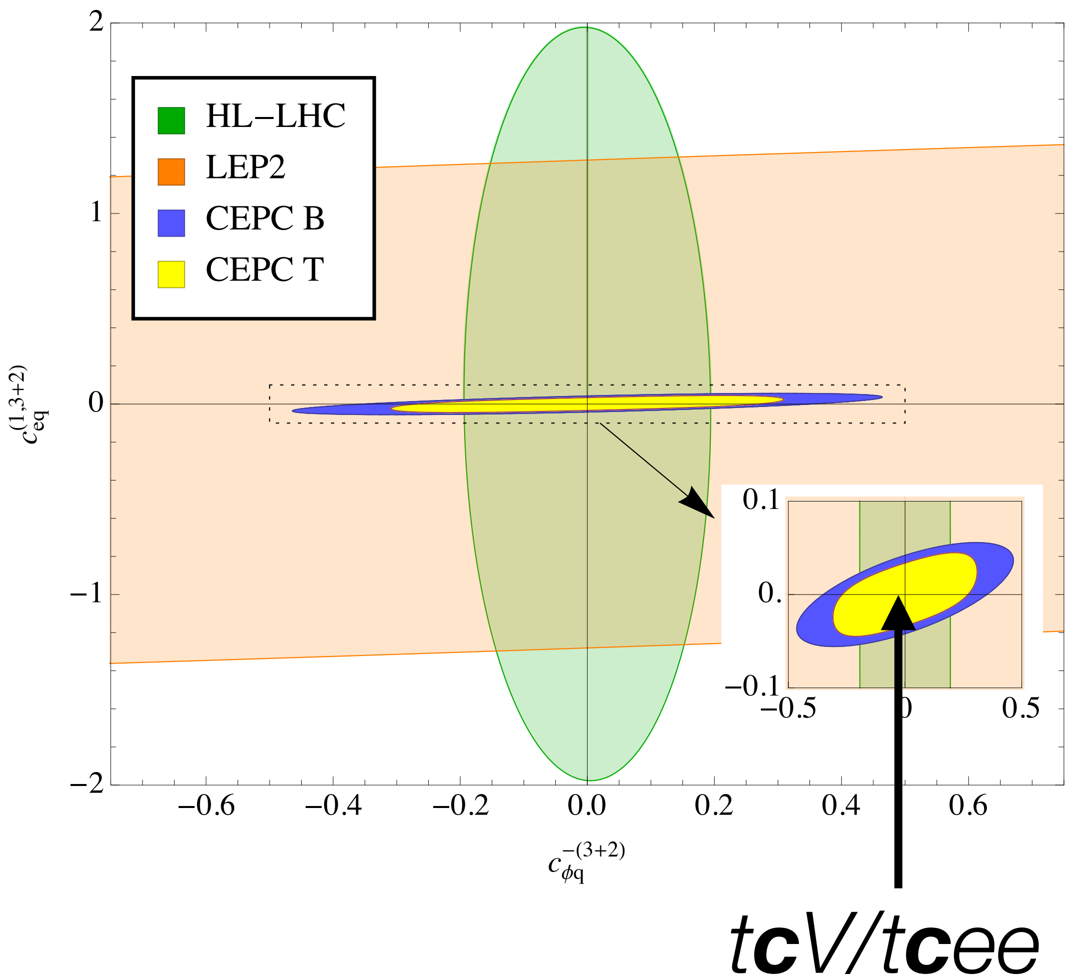
Improvement from c-jet tagging

If no signal is observed



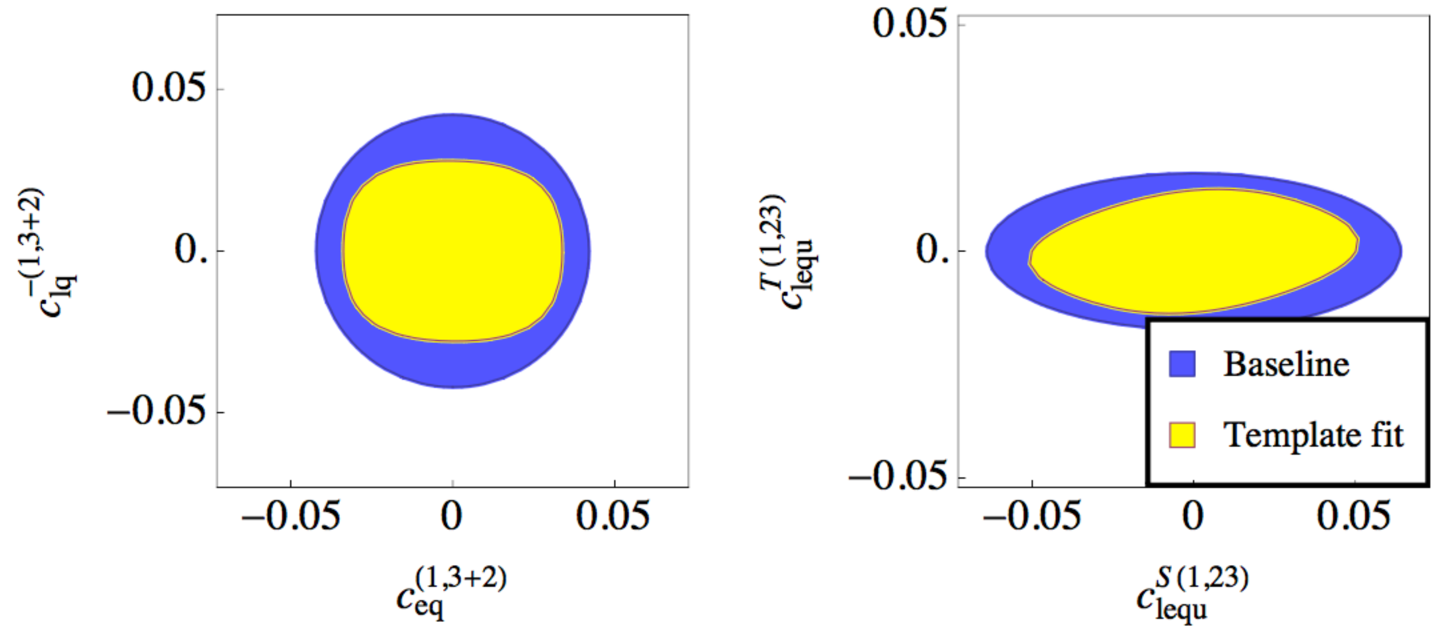


Fig. 8. Two-dimensional limits on four-fermion coefficients, at 95% CL, under the SM hypothesis, with other coefficients turned off. The template fit approach improves the sensitivity.

Discriminating between operators

Using angular observable

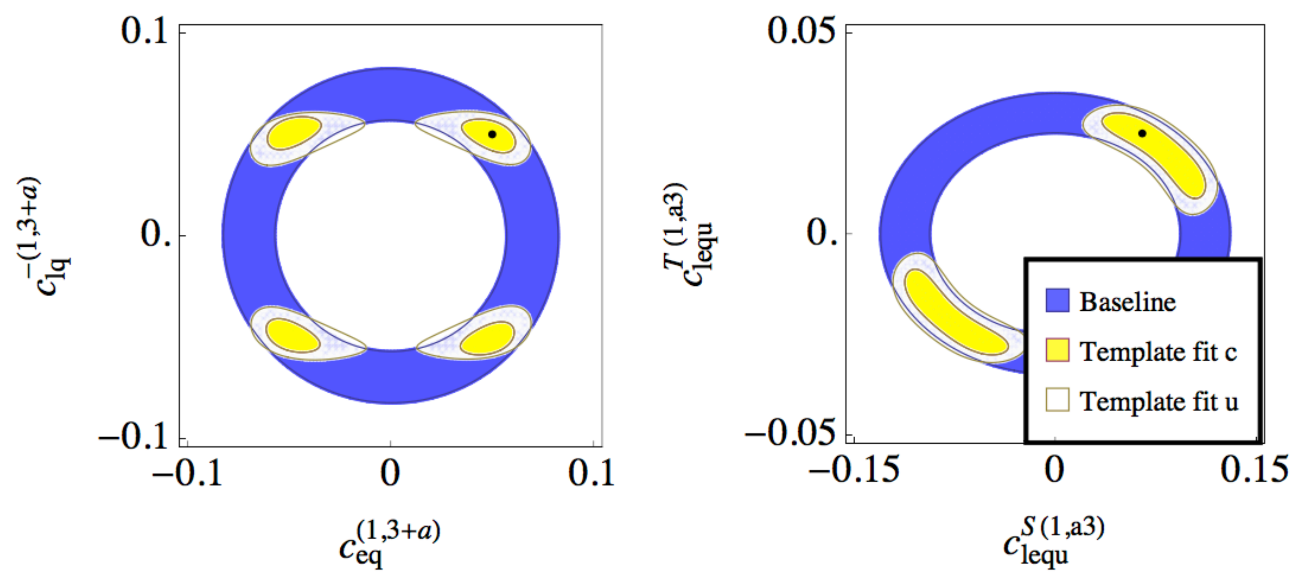


Fig. 9. Two-dimensional limits on four-fermion coefficients, at 95% CL, with other coefficients turned off. Two hypotheses are considered. Left: $c_{eq}^{(1,3+a)} = c_{lq}^{-(1,3+a)} = 0.05$. Right: $c_{lequ}^{S(1,a3)} = 0.065$, $c_{lequ}^{T(1,a3)} = 0.025$. Both points are labeled by a black dot in 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

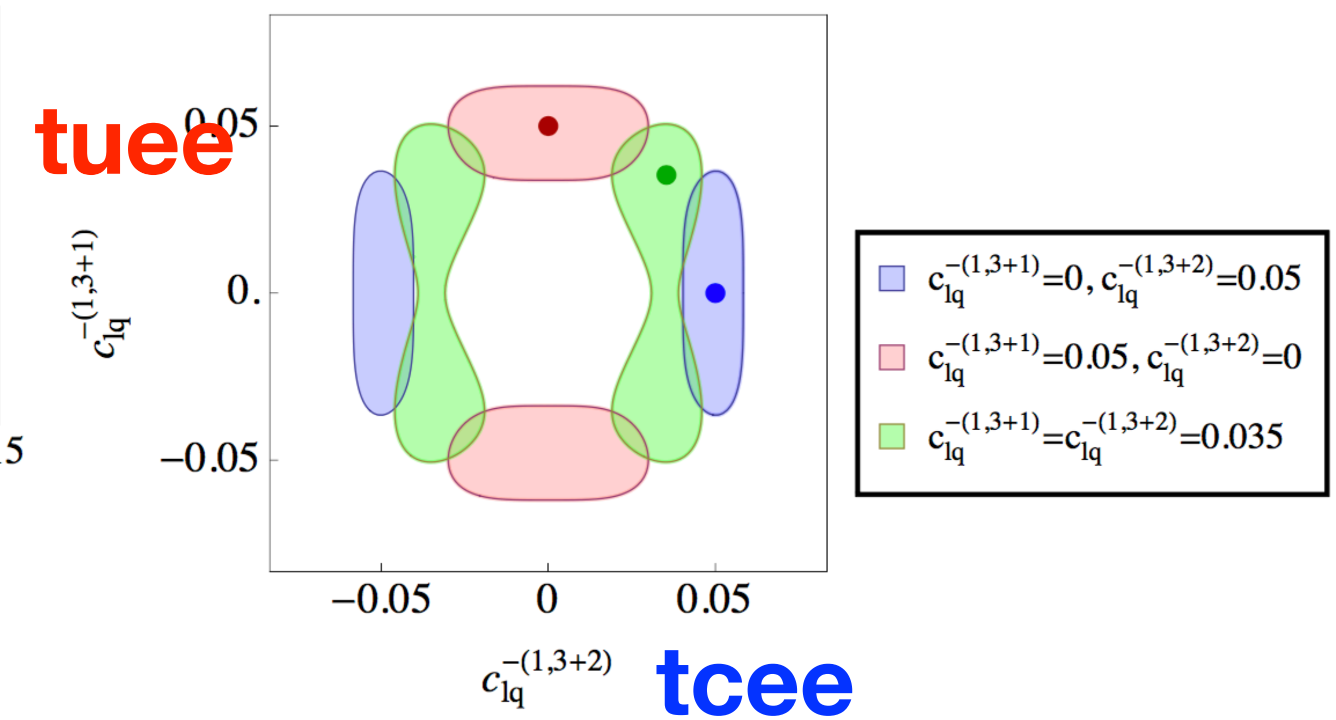


Fig. 10. Two-dimensional limits on $c_{lq}^{-(1,3+a)}$ coefficients with $a = 1$ and $a = 2$, at 95% CL. Other coefficients are turned off. Three hypotheses are considered. The template fit helps to identify the light-quark flavor involved in the FCN coupling.

In contrast with LHC:
No such info from top decay

Lorentz structures

V, A

$$O_{\varphi q}^{1(ij)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_i\gamma^\mu q_j),$$
$$O_{\varphi q}^{3(ij)} = (H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_i\gamma^\mu\tau^I q_j),$$
$$O_{\varphi u}^{(ij)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_i\gamma^\mu u_j),$$
$$O_{\varphi ud}^{(ij)} = (\tilde{H}^\dagger iD_\mu H)(\bar{u}_i\gamma^\mu d_j),$$

Dipole

$$O_{uW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{H}W^I_{\mu\nu}$$
$$O_{dW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I d_j)\,HW^I_{\mu\nu},$$
$$O_{uB}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}u_j)\tilde{H}B_{\mu\nu},$$
$$O_{uG}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}T^A u_j)\,\tilde{H}G^A_{\mu\nu}.$$

V,A - V,A

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

S-S, T-T

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

Lorentz structures

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Dipole

V,A - V,A

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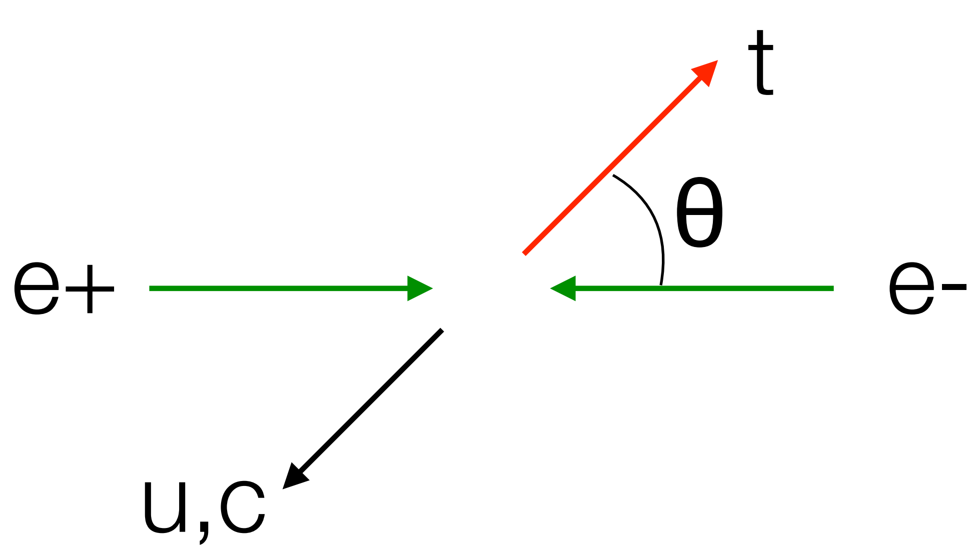
$$O_{lequ}^{3(ijkl)} = (\bar{l}_i \sigma^{\mu\nu} e_j)\, \varepsilon\, (\bar{q}_k \sigma_{\mu\nu} u_l),$$
$$O_{ledq}^{(ijkl)} = (\bar{l}_i e_j (\bar{d}_k q_l)(\bar{u}_k \gamma^\mu u_l),$$

S-S, T-T



Lorentz structures

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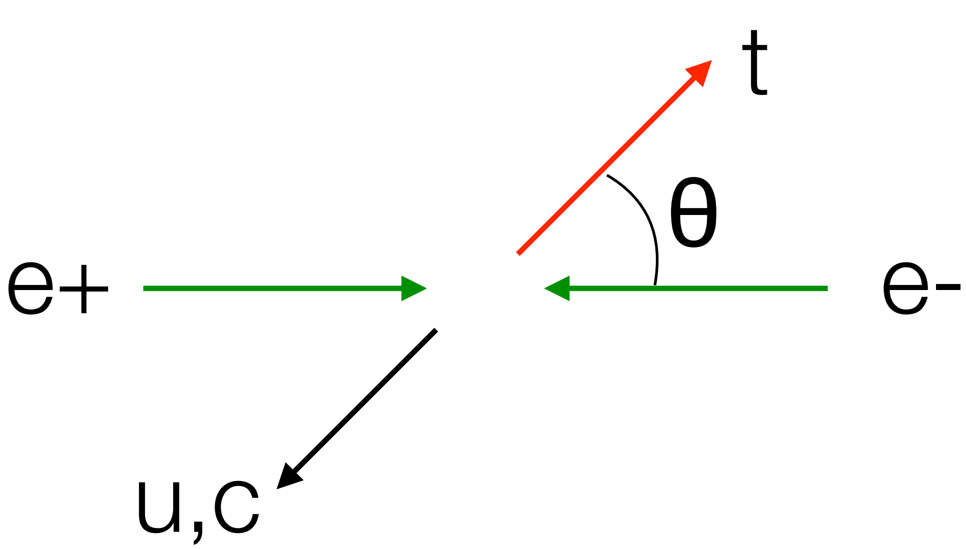
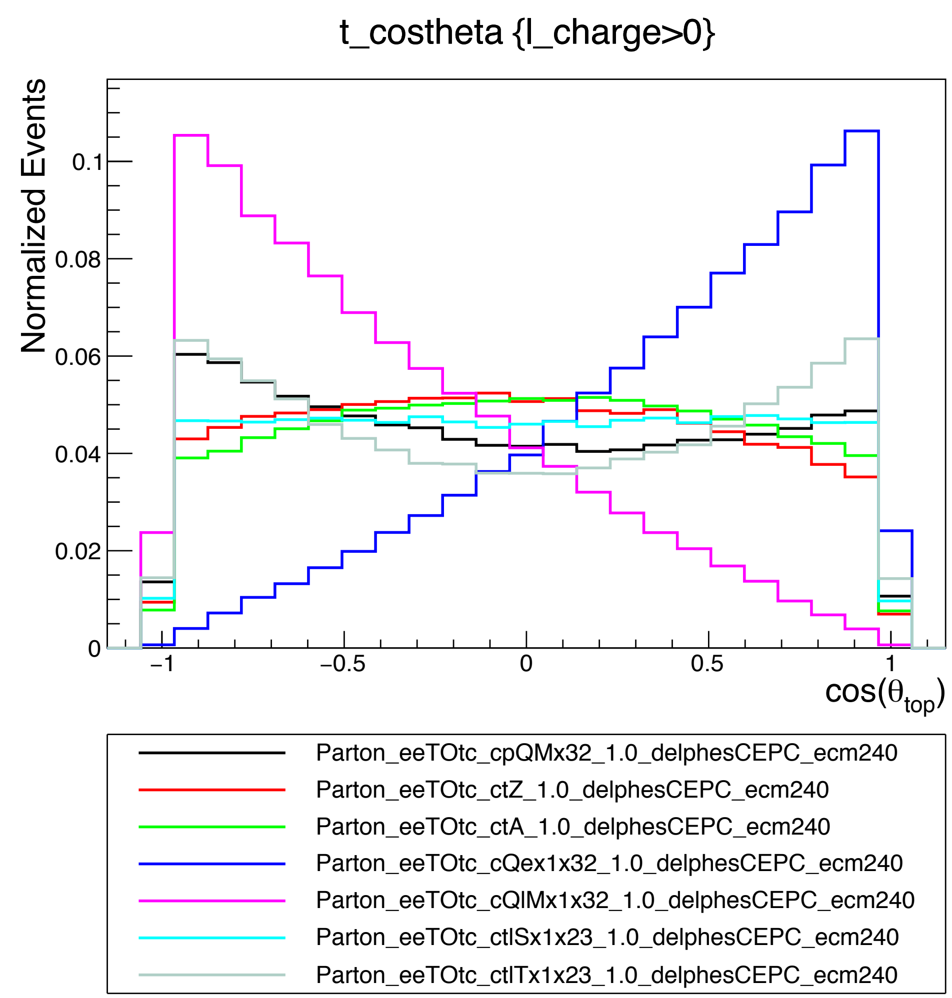
$$O_{lequ}^{3(ijkl)} = (\bar{l}_i\sigma^{\mu\nu}e_j)\;\varepsilon\;(\bar{q}_k\sigma_{\mu\nu}u_l),$$
$$O_{ledq}^{(ijkl)} = (\bar{l}_i e_j(\bar{d}_k q_l)(\bar{u}_k\gamma^\mu u_l),$$

S-S, T-T



Discrimination power from distribution.



A second energy, or ttbar with FCNC decay will help.

ttbar uncertainties

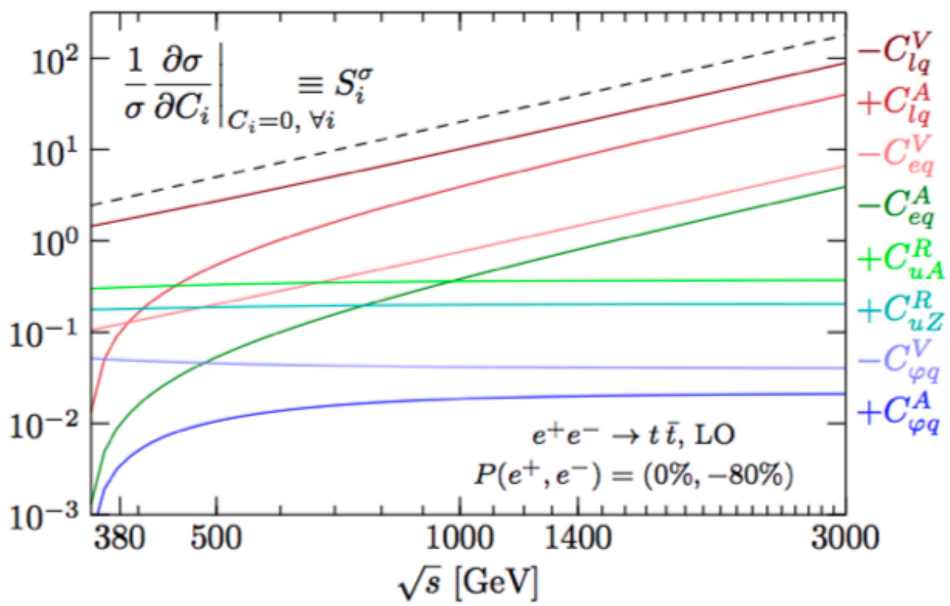
$\sqrt{s}$ [GeV]	350	365	380	500	1000	1400	3000
acceptance times efficiency [%]	-	-	64-67[8]	$\sim$ 50	-	37-39	33-37
equivalent $t\bar{t}$ event fraction [%]	10	10	10	10	6	6	5

Table 5. Summary of the efficiencies obtained in Refs. [1, 21] (first row) and effective rate fractions available for analysis used in this study (second row). When multiplied by the $e^+e^- \to t\,\bar{t}$ cross section for the nominal centre-of-mass energy and the integrated luminosity, these yield the number of events available for analysis.

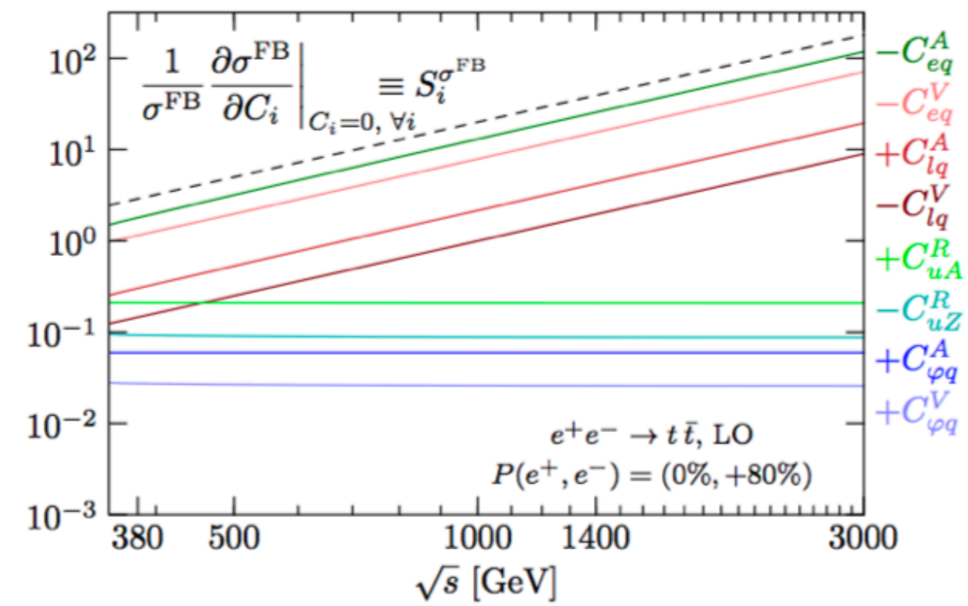
- Full-detector simulation performed by ILC and CLIC collaborations.
- Good reconstruction can be obtained with moderate quality cuts.
- Systematics expected to be controlled to the level of statistics.

Sensitivities

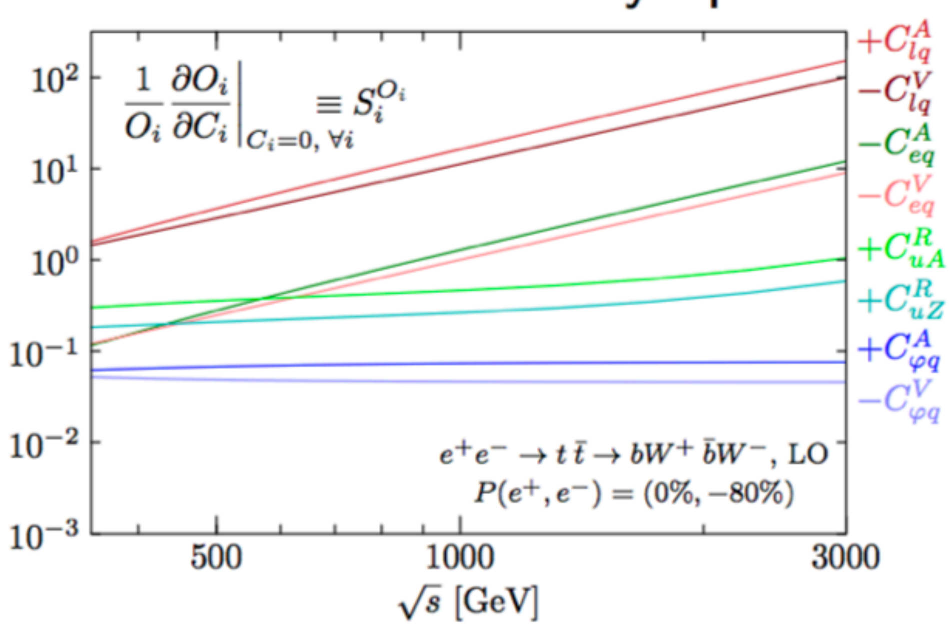
Total cross section (left pol.):

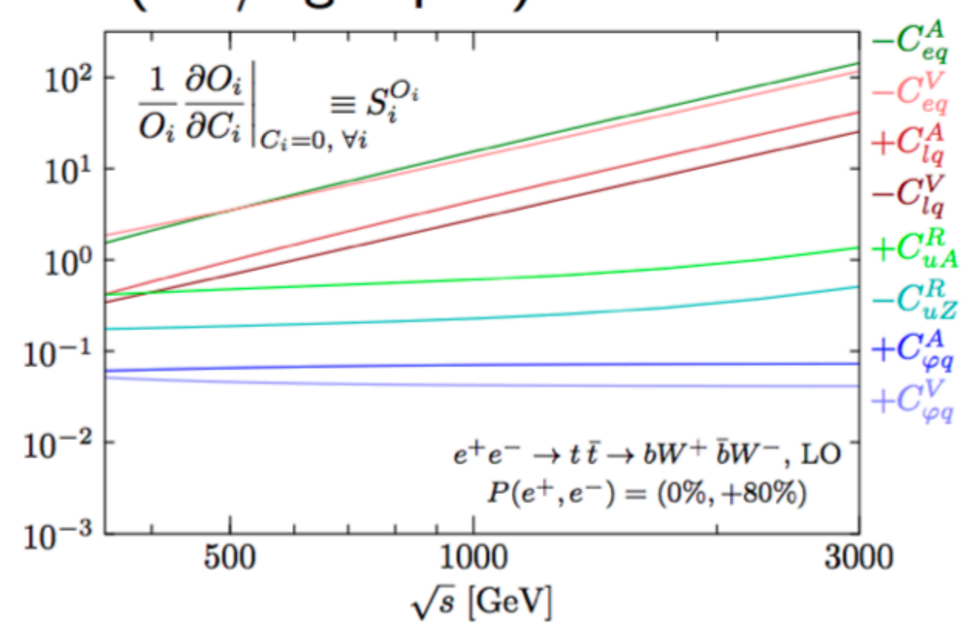


FB-integrated cross section (right pol.):



Statistically optimal observable (left/right pol.)



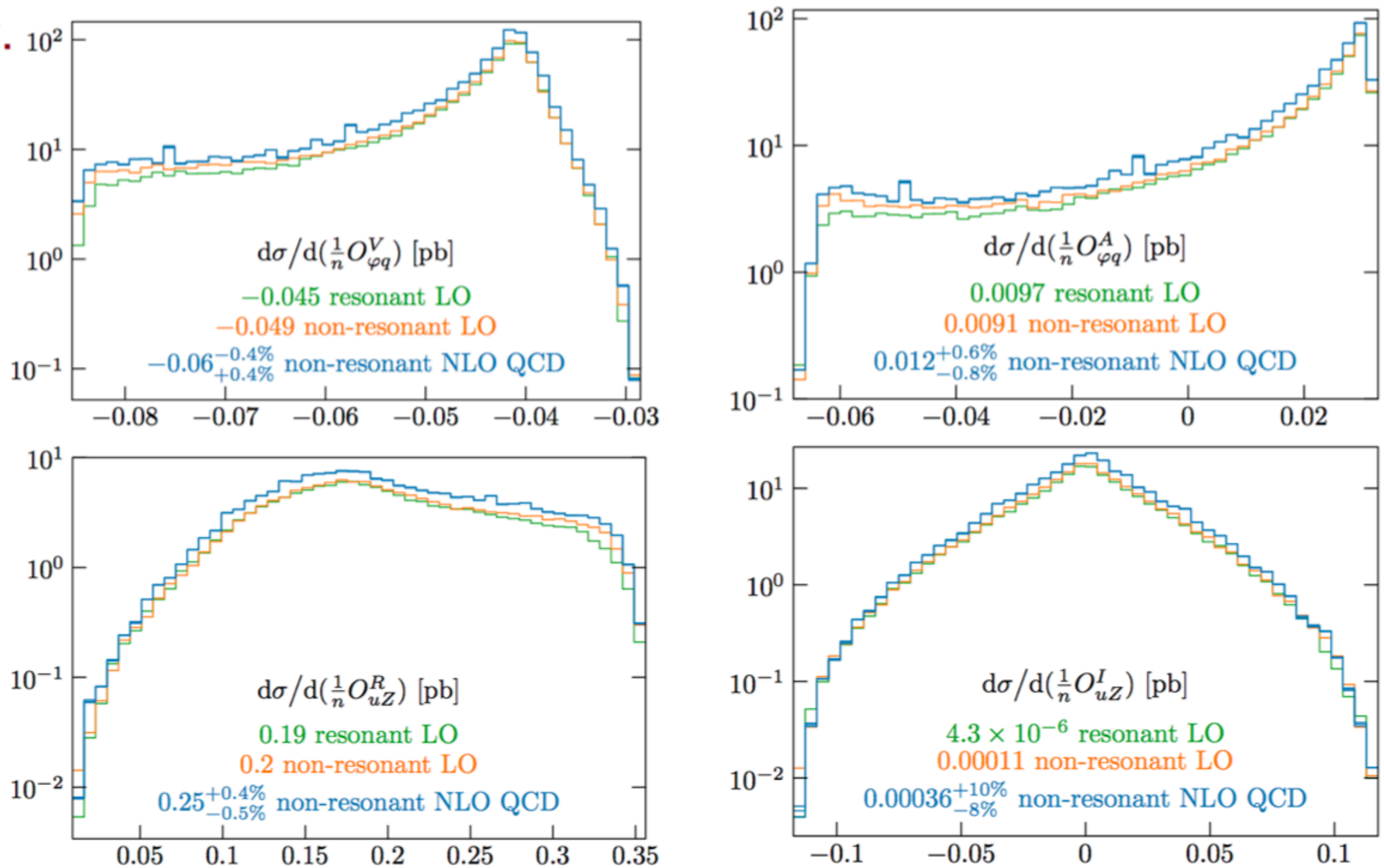


TH robustness

Non-resonant and NLO QCD effects can be studied

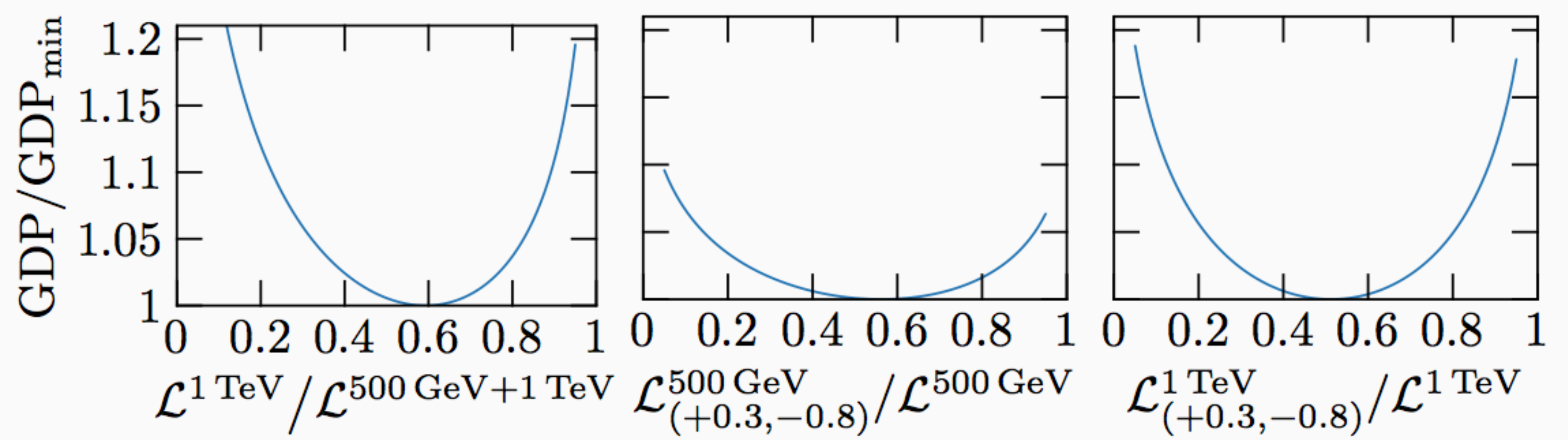
- mostly flat k factor (24% at $\sqrt{s} = 500$ GeV)
- couple-of-percent shape effects, excepted on axial operators ($O(10)\%$)

e.g.



$\sqrt{s} = 500$ GeV, $P(e^+, e^-) = (+30\%, -80\%)$,
quoted average values of distribution are $\bar{O}_i/\mathcal{L}$ in pb,
QCD scale variation from $m_t/2$ to $2m_t$

Optimization



- ILC: the optimal repartition of 1.5 ab^{-1} in total is the following:

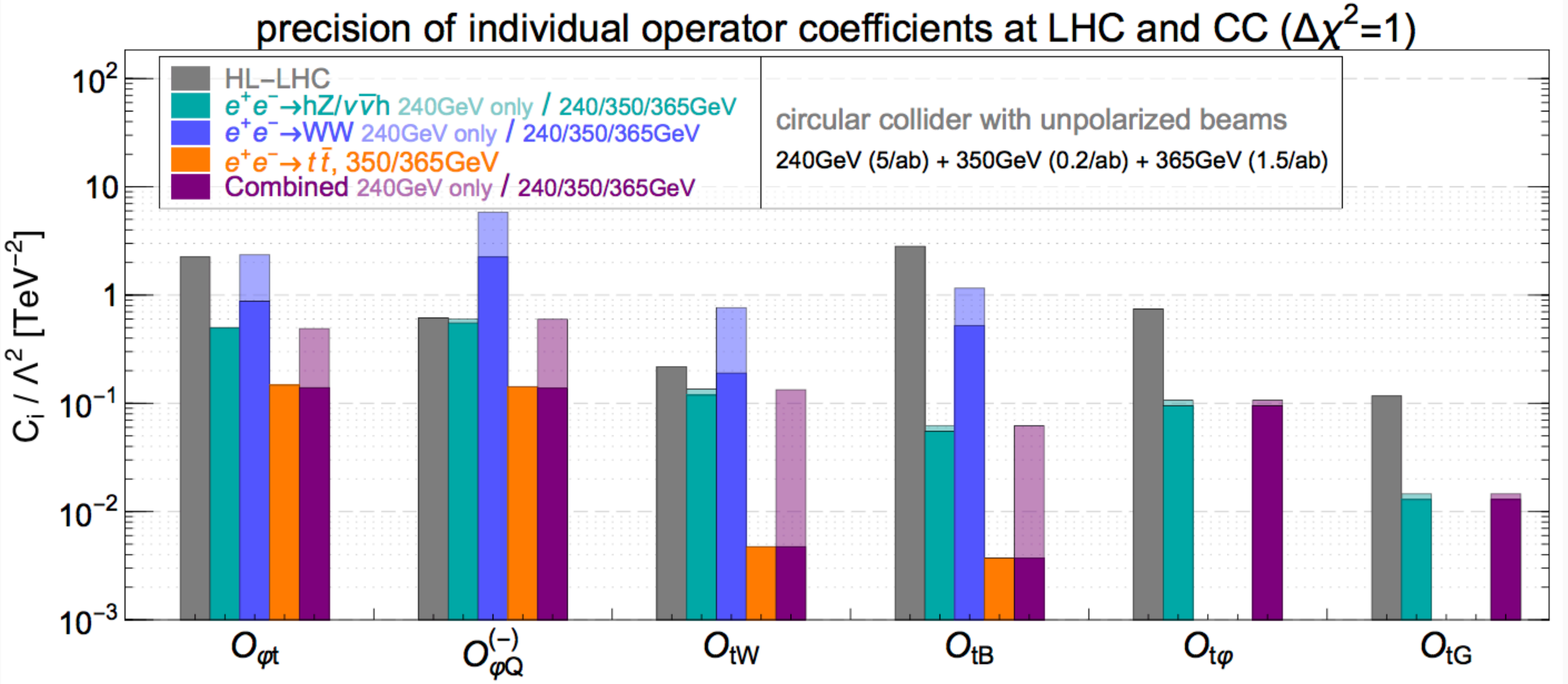
$\sqrt{s} = 500\,\mathrm{GeV}$	610 fb^{-1}	57% with $P(e^+, e^-) = (+30\%, -80\%)$
1 TeV	890 fb^{-1}	51% 〃

- It requires about 4.6 ab^{-1} shared between $\sqrt{s} = 380$ and 500 GeV runs to achieve the same performance:

$\sqrt{s} = 380\,\mathrm{GeV}$	1.5 ab^{-1}	57%	with $P(e^+, e^-) = (+30\%, -80\%)$
500 GeV	3.1 ab^{-1}	51%	〃

Individual limits

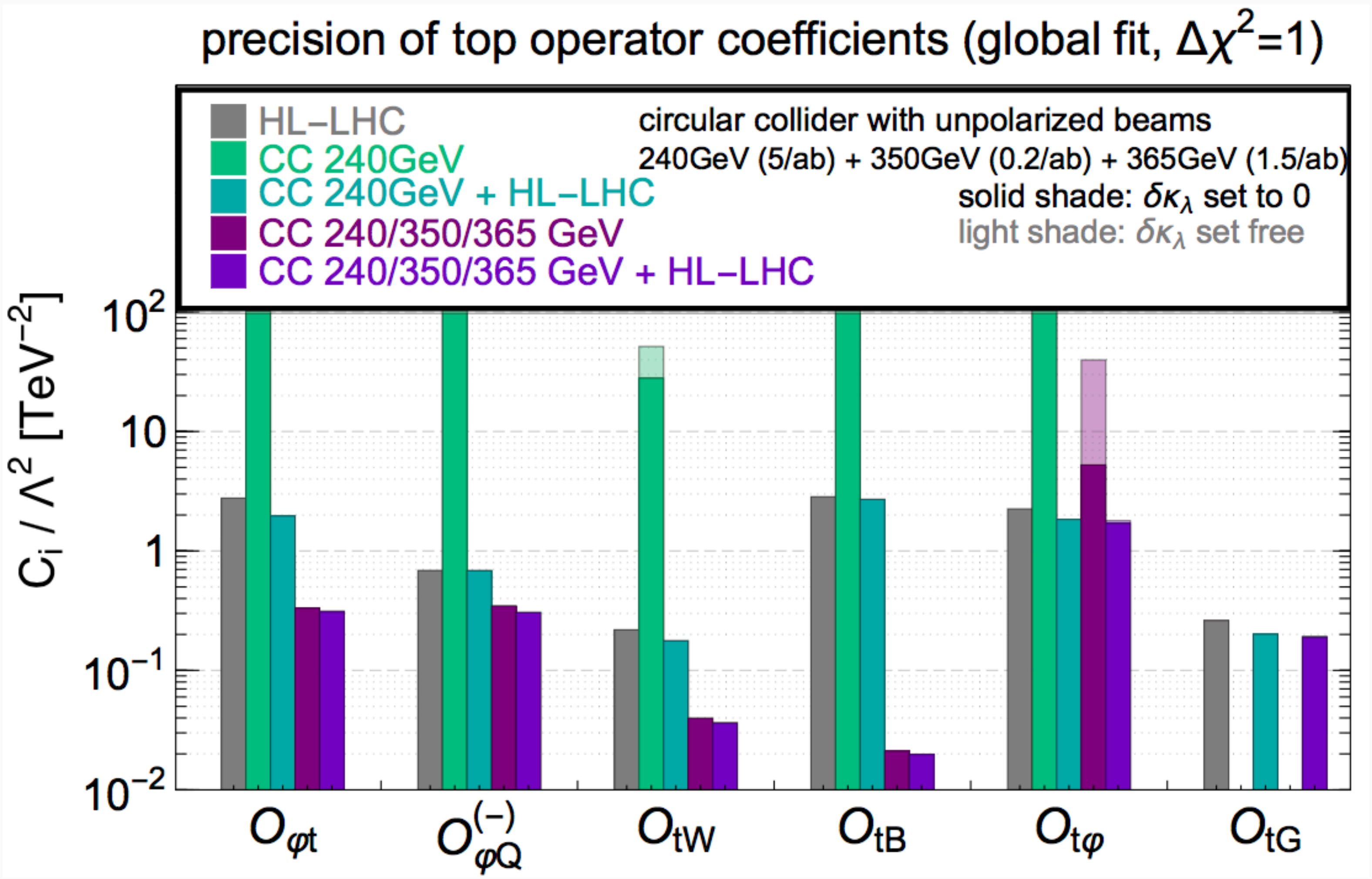
Individual one-sigma reach, one at a time



- Good sensitivity to top couplings below $t\bar{t}$ threshold.
- Loop suppression of top-quark operator contributions is compensated by the high precision of lepton collider.
- Still $ee \to tt$ above 350 GeV provides best sensitivity.
- Diboson sensitivity increases with energy.

Marginalized limits: Top

Global one-sigma precision reach on top-quark operators



- Indirect bounds are much worse. In particular, large degeneracies if only run at 240 GeV.
- Correlations between Top/Higgs, e.g. $C_{t\varphi}$, C_{tB} and $\bar{c}_{\gamma\gamma}$; $C_{t\varphi}$, C_{tG} and $\bar{c}_{gg}$.

Marginalized limits: Higgs

Consider $H \to \gamma\gamma$ on C_{tB} and $\bar{c}_{\gamma\gamma}$

- $H \to \gamma\gamma$ imposes a strong constraint, but also leaves a flat direction.
- Including loop corrections to all other measurements lift this flat direction, but not strong enough to eliminate the degeneracy.
- HL-LHC is too weak.
- $ee \to tt$ at 350/365 will fix C_{tB} which in turn improves $\bar{c}_{\gamma\gamma}$.