SMEFT for top quarks at LHC and e+e- colliders

M. E. Peskin
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Topics for this talk :

What are the important effects for top quarks in BSM physics ?

What SMEFT operators realize these for LHC ?

What SMEFT operators realize these for e+e- Higgs factories ?

What should be the archival result of SMEFT fits at LHC ?

Warning: I am one of those conservative people who does not believe that SMEFT fitting beyond linear terms in cross sections is meaningful. So I will always be talking about order $1/M^2$ or dimension 6 SMEFT.

What are the most important effects for top quarks in BSM physics?

Corrections to SM top quark amplitudes can be small or large, according to whether the top quark is an "ordinary" quark or a heavy quark.

Elementary Higgs boson / ordinary quark :

these effects are small, of order $(\alpha_w/4\pi)(v^2/M^2)$

Composite Higgs boson / "partially composite" top quark :

these effects are larger, of order 1 x (v^2/M^2)

effects in this case:

vector resonances coupling to $t\bar{t}$, leading to :

contact interactions $\bar{q}\gamma_\mu q\,\bar{t}\gamma^\mu t, \quad \bar{\ell}\gamma_\mu\ell\,\bar{t}\gamma^\mu t$
resonant enhancement of $Z_\mu\bar{t}\gamma^\mu t, \quad W_\mu\bar{b}\gamma^\mu t$
resonant enhancement of

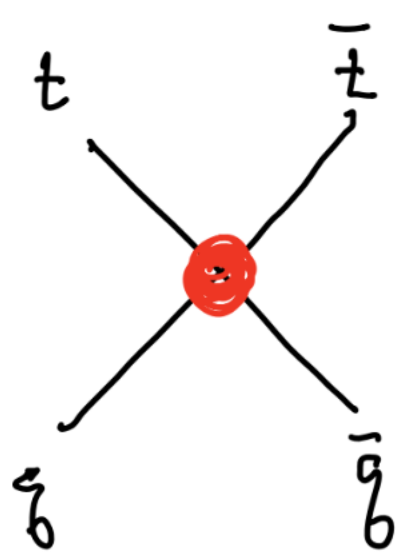
vectorlike top quark partners, leading to :

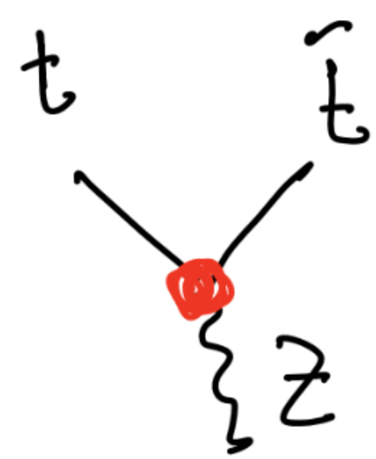
mixing effects on $Z_\mu\bar{t}\gamma^\mu t, \quad W_\mu\bar{b}\gamma^\mu t$
loop decrement of Hgg, overall rescaling of H couplings

This may be our best opportunity to find evidence for BSM physics at energies that we know how to access.

LHC : 3 billion top quark pairs in the HL-LHC program

Higgs factories : Systematic errors at parts per mil for measurement of top quark properties (at CM energies of 400 GeV and above).





Associated SMEFT operators: for LHC:

Q is a 3rd generation quark, q is a lighter quark

$$\overline{q}\gamma^\mu q \; \overline{Q}\gamma_\mu Q$$

or insert $\tau^i \cdots \tau^i$, $t^a \cdots t^a$

14 of these in all , 11 more with all quarks 3rd generation,

plus 9 operators with 3rd generation + bosons, including

$\Phi^\dagger \Phi \; \overline{Q} \cdot \Phi Q$ Yukawa correction

$\Phi^\dagger \overleftrightarrow{D}_\mu \Phi \; \overline{Q}\gamma^\mu Q$ Z vertex correction

$\Phi^\dagger \overleftrightarrow{D}_\mu \tau^i \Phi \; \overline{Q}\gamma^\mu \tau^i Q$ W vertex correction

$\overline{Q}\sigma^{\mu\nu}\tau^i Q \; W^i_{\mu\nu}$

$\overline{Q}\sigma^{\mu\nu} Q \; B_{\mu\nu}$ magnetic moment corrections

$\overline{Q}\sigma^{\mu\nu} t^a Q \; G_{\mu\nu}$

Harland et al. 1901.05965

Associated SMEFT operators: for e+e- :

7 operators with 3rd generation quarks and leptons

$$\bar{e}\gamma^{\mu}e\ \overline{Q}\gamma_{\mu}Q$$

or insert $\tau^{i}\cdots\tau^{i}$

plus 9 operators with 3rd generation + bosons, including

$\Phi^{\dagger}\Phi\ \overline{Q}\cdot\Phi Q$ Yukawa correction

$\Phi^{\dagger}\overleftrightarrow{D}_{\mu}\ \Phi\ \overline{Q}\gamma^{\mu}Q$ Z vertex correction

$\Phi^{\dagger}\overleftrightarrow{D}_{\mu}\ \tau^{i}\Phi\ \overline{Q}\gamma^{\mu}\tau^{i}Q$ W vertex correction

$\overline{Q}\sigma^{\mu\nu}\tau^{i}Q\ W^{i}_{\mu\nu}$

$\overline{Q}\sigma^{\mu\nu}Q\ B_{\mu\nu}$ magnetic moment corrections

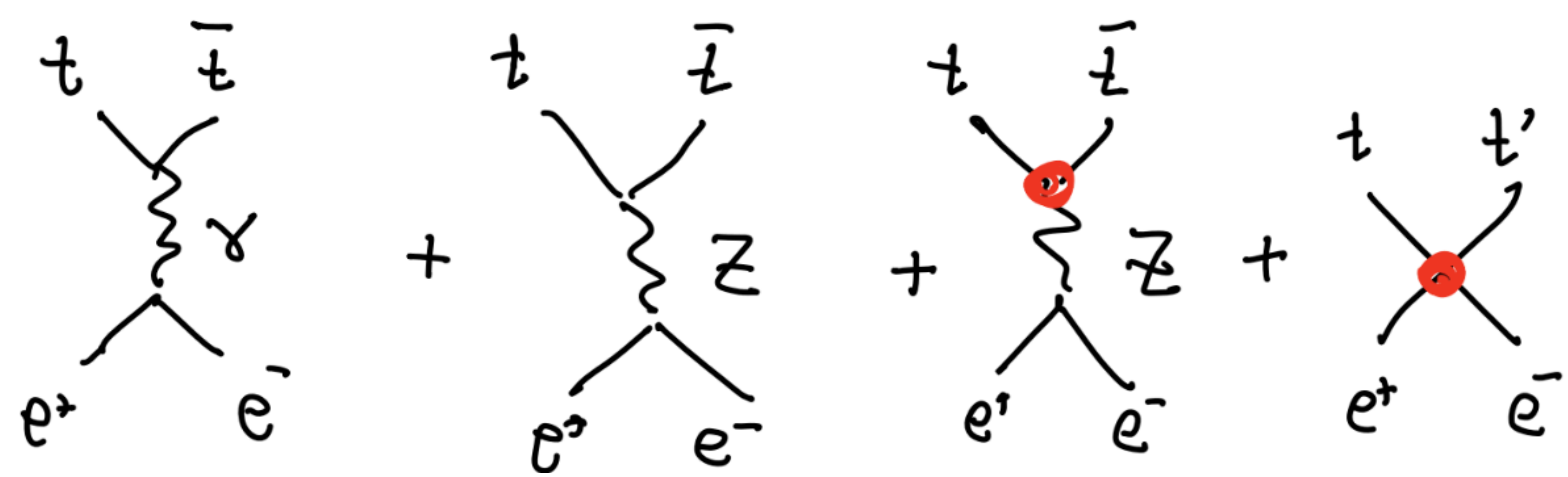
$\overline{Q}\sigma^{\mu\nu}t^{a}Q\ G_{\mu\nu}$

2 (with b) strongly constrained by precision electroweak

Durieux et al. 2205.02140

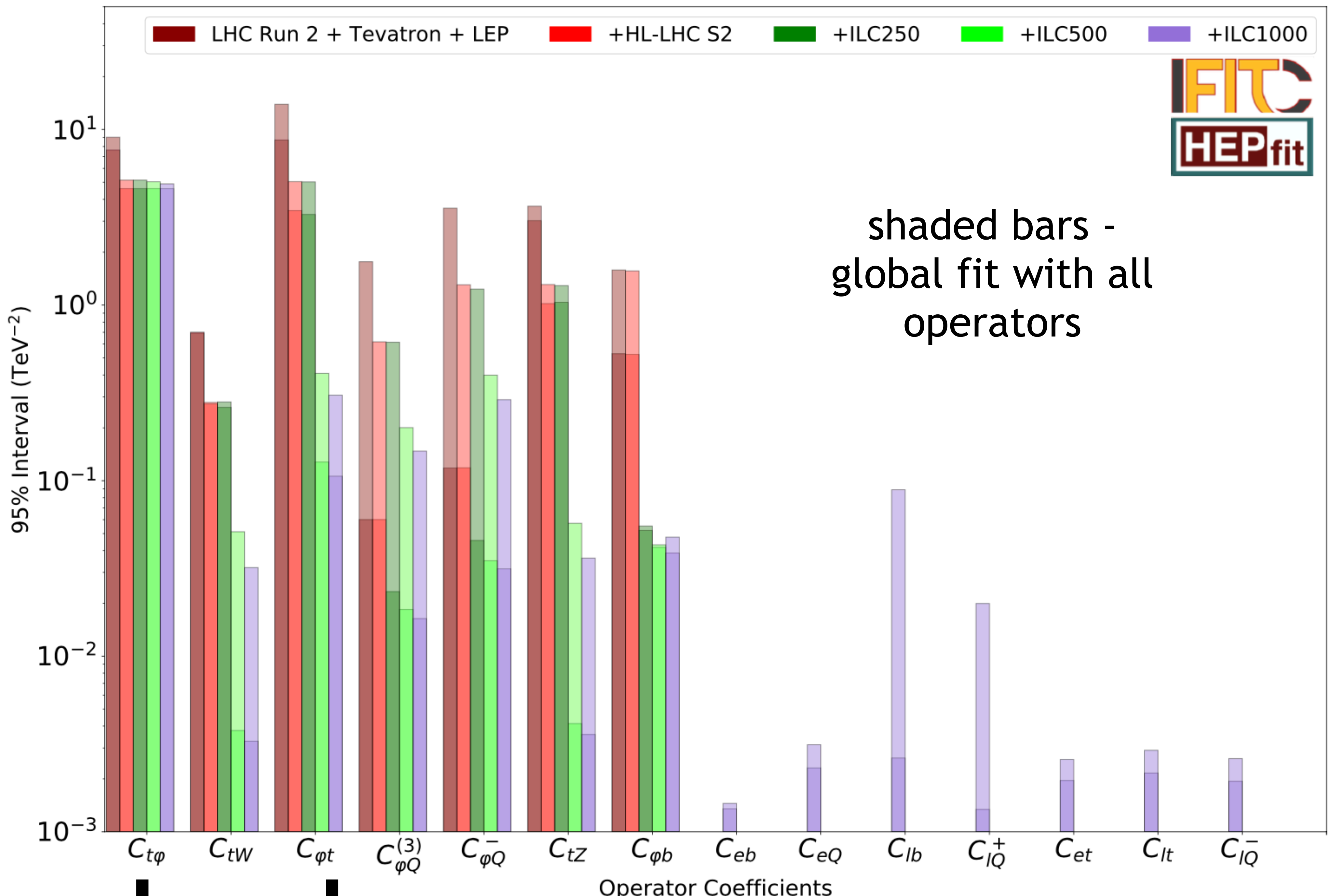
At LHC, the ttZ vertex is observed in $gg \to \bar{t}tZ$. This is a rarer process, and the Z is in a limited momentum range.

In e+e- , the ttZ vertex is part of the dominant top quark production process. Electron (+ positron) beam polarization can distinguish the operators with different helicity fermions. The process also has a large forward-backward asymmetry, separately measurable for each polarization setting.



A problem with this is that the Z vertex and 4-fermion operators have degenerate effects at fixed CM energy. This requires running at multiple CM energies > 400 GeV.

Improvement of LHC constraints in the ILC program   Durieux et al 2205.02140

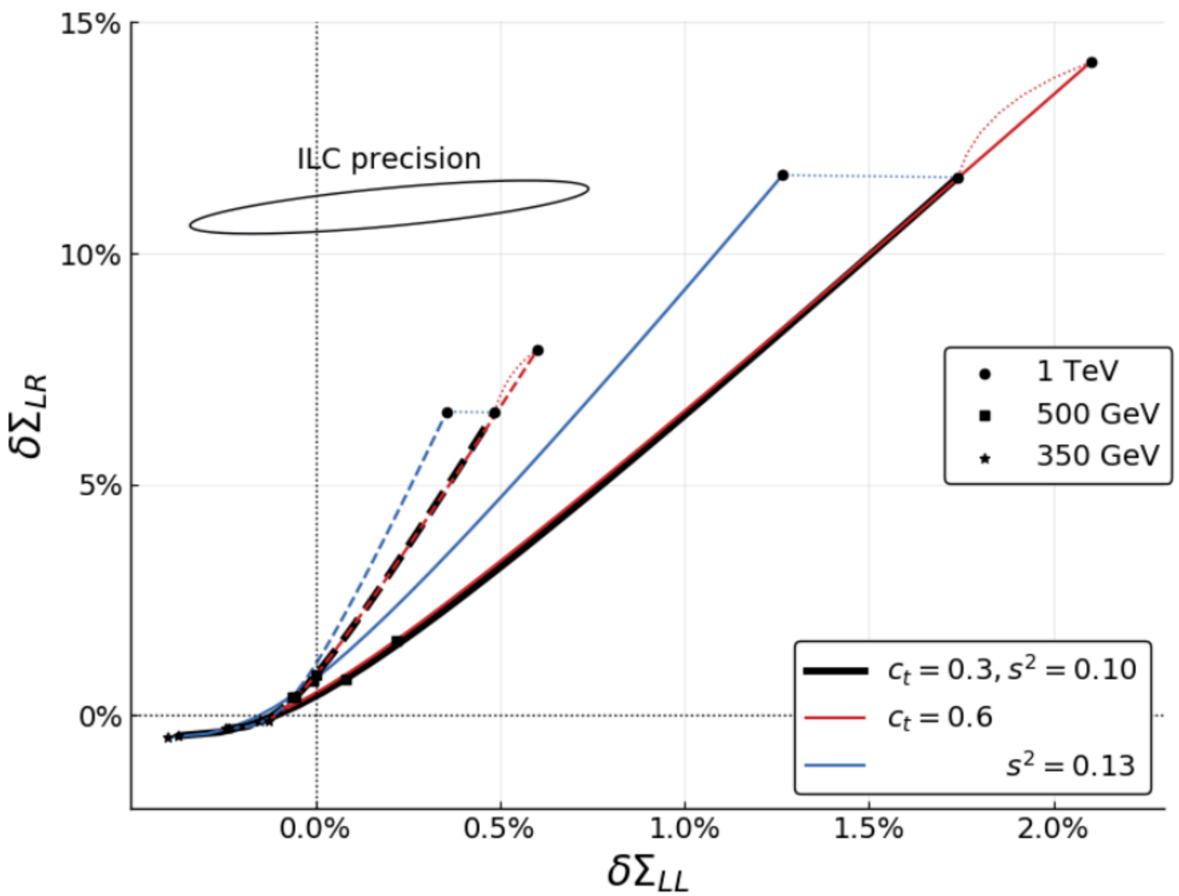


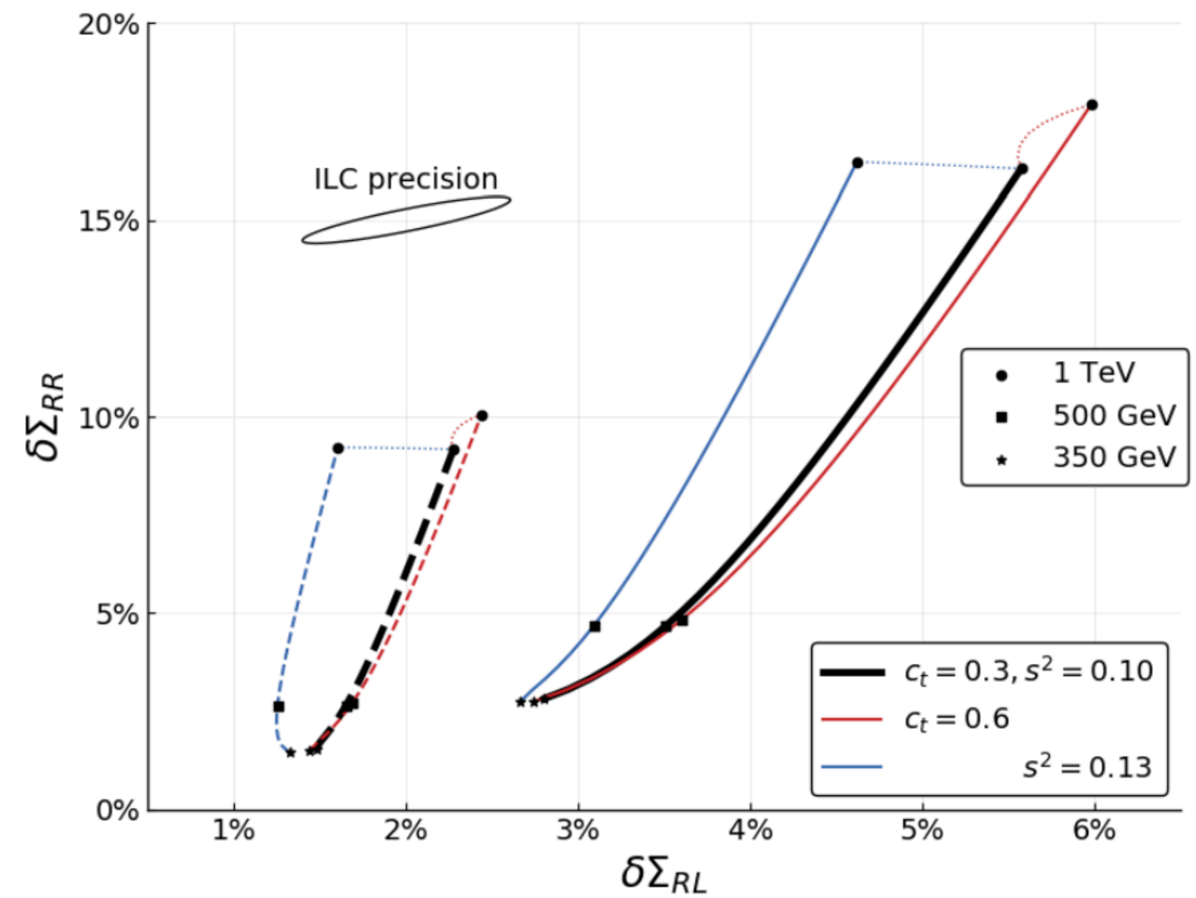
ttZ coupling

contact interactions

ttH coupling :   2.8% at 550 GeV
1%   at 1 TeV

some BSM predictions for helicity-dependent $e^+e^- \to t\bar{t}$ cross sections





(error ellipses based on ILC full simulation)

Yoon and MEP, arXiv:1811.078777

Both HL-LHC and (high energy) Higgs factories will have constraints on top-boson operators, and it will be useful to combine these. This will require care, but it should be straightforward.

Combining the limits (or values) for 4-fermion contact interactions will be more difficult. The operators are different, and for LHC the light quark helicity states included in the operator will not be determined. Probably (if no discovery), the limits will be $\Lambda > 100$ TeV, so these will be strong constraints on models with Higgs compositeness.

Lindsey asked me: What is the desired end product of LHC SMEFT analyses to give information to future accelerators ? Here I apply my prejudice that only SMEFT analysis to order $1/M^2$ are meaningful.

This calls for a pure linear fit, which is much easier than a linear plus quadratic fit. In that case, what is needed is the best-fit set of deviations from the Standard Model and the inverse covariance matrix, in the complete Warsaw basis of operators.

Many of the deviations will be zero, for operators to which we do not have sensitivity. And, many elements of the inverse covariance matrix will be zero. Thus, the full inverse covariance matrix will not be invertible.

My viewpoint is that I am fine with this.

Today, we should truncate the theory to the subspace of the Warsaw basis on which the inverse covariance matrix is nonzero. Then, by fiat, we make this matrix invertible. From the inverse, we can quote errors and correlations. This is a way to clearly state the best knowledge we have now.

Future colliders will bring new measurements that will fill in some zeros, and also improve constraints on parameters to which we are sensitive at LHC. Both of these are an improvement in our knowledge.

To repeat:

Precision studies of the top quark provide an important opportunity to discover signals of BSM physics at energies that we know how to access. We shouldn't miss it.

HL-LHC has a tremendous opportunity here. But also e+e- colliders can go further:

leading sensitivity to modifications of the ttZ coupling

sensitivity to contact interactions involving tt

helicity-dependent information on the structure of contact interactions

This does require e+e- in the energy region 400 GeV - 1 TeV. Will we have it?