Top and Higgs interplay beyond the Standard Model

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The physics of the top quark is a missing and generally misunderstood aspect of the physics of e+e- linear colliders.

Not all, but many, models of new physics beyond the SM predict modifications of the electroweak couplings of the top quark. This leaves a significant opportunity for the discovery of BSM physics in the precision study of the top quark.

The effects are intimately connected to the mechanism of top quark mass generation. Thus they are connected to the BSM theory of the HIggs boson and its properties. These effects are potentially an independent source of information about the origin of electroweak symmetry breaking and the generation of the fermion mass hierarchy.

The large mass of the top quark raises an important question that is not often asked about the SM:

Is the top quark a light quark or a heavy quark?

That is, can the top quark interaction with electroweak symmetry breaking be treated simply in perturbation theory, or does the top quark couple to new strong interactions ?

The value of the top quark Yukawa coupling is

$$\alpha_t = \frac{y_t^2}{4\pi} = \frac{1}{12.6}$$

(smaller than the QCD coupling). The typical size of radiative corrections from new physics is then

$$\frac{\alpha_t}{2\pi}\ \frac{m_t^2}{M^2} < 0.1\%$$

This is correct for typical SUSY models and 2-Higgs-doublet models.

However, it might be that the Higgs boson is composite at some energy scale. In such models, there are strong interaction effects at high energies. These can couple to the top quark and can play a role in generating to large top quark mass.

Three distinct scenarios can come in to play:

Mixing of the top quark with heavy top quark partners.

Mixing of the $t\bar{t}$ system with a high-mass resonance.

New BSM interactions coupling the top quark with other fermions.

All of these effects can potentially enter in the effective Lagrangian with a coefficient

$$\frac{m_t^2}{M^2} \sim 1\%$$

These effects are not easy to observe in proton-proton collisions.

The bulk of top quark pair production is through $gg \to t\bar{t}$. The $t\bar{t}g$ coupling is constrained by the QCD Ward identity. SMEFT effects enter at dimension 8.

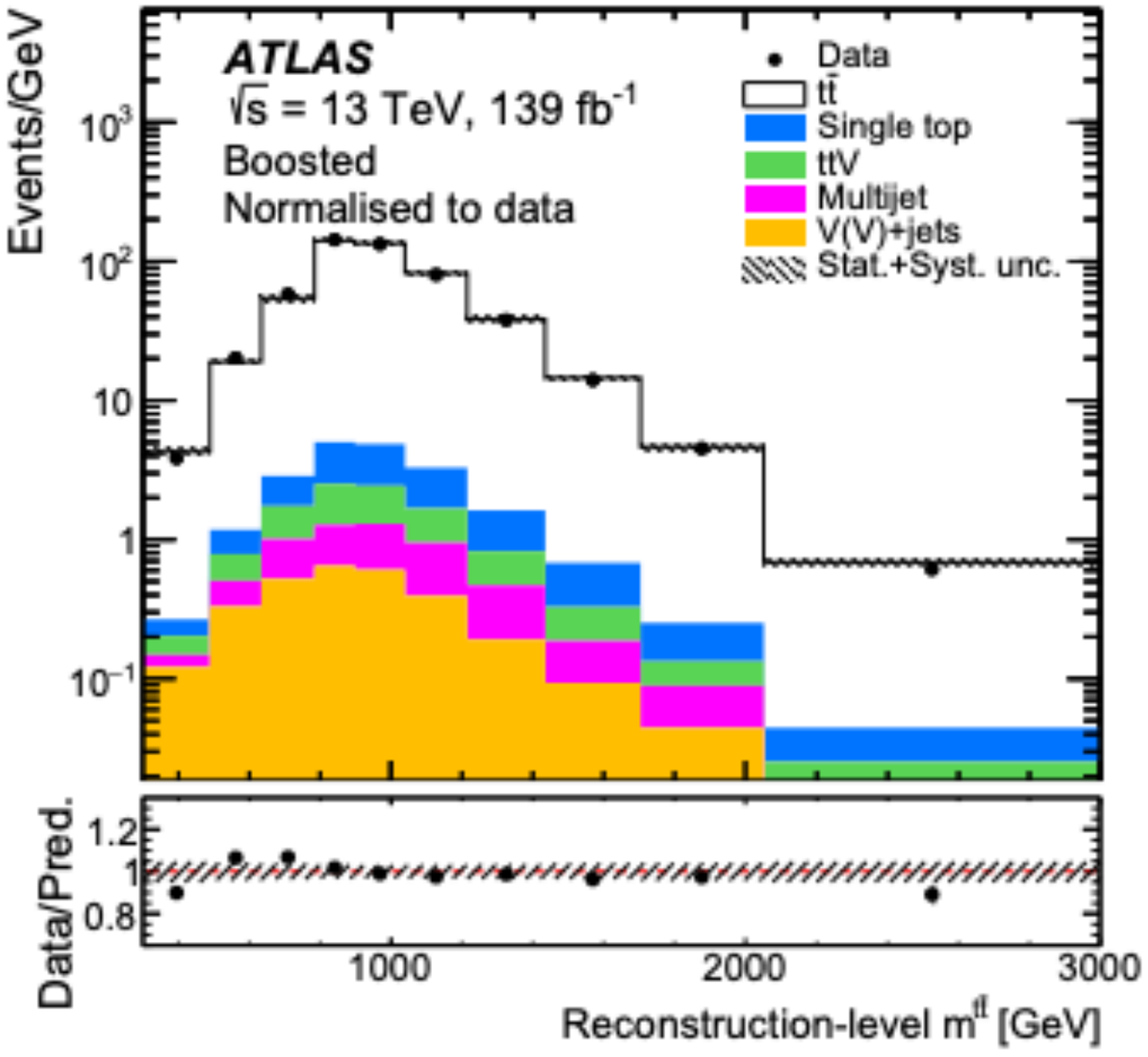
Coupling of the t to the Z and W have backgrounds from single top + V production and single top + WZ. Currently, the uncertainty in the relevant SMEFT couplings are ~ $(1/\mathrm{TeV}^2)$. Expectations from de Blas et al., arXiv/2206.08326 are

$$\Delta\ c_{tW} \sim 0.1\ (\text{HL-LHC}) \quad 0.02\ (\text{ILC } 500)$$

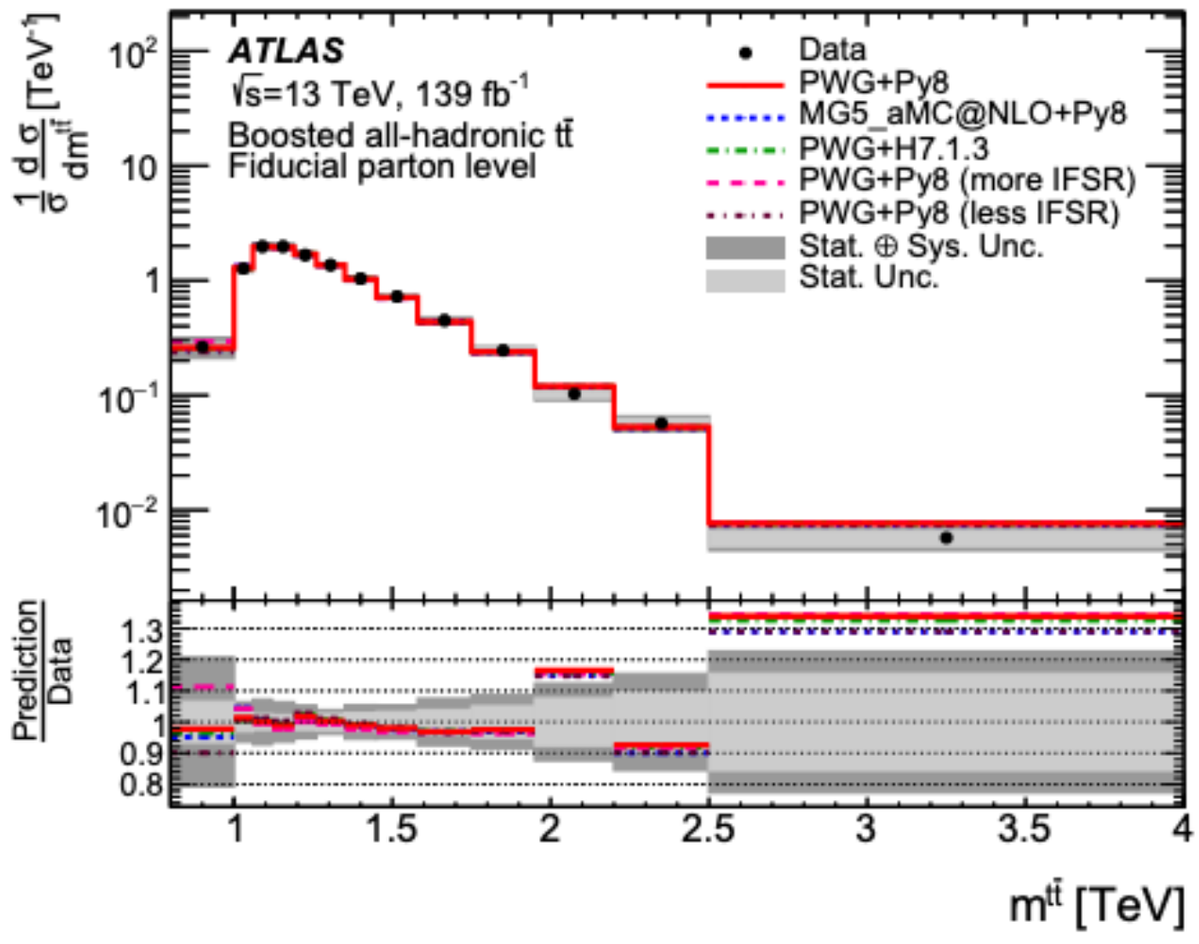
$$\Delta\ c_{eQ} \sim 0.3\ (\text{HL-LHC}) \quad 0.003\ (\text{ILC } 500)$$

LHC has difficulty distinguishing L vs. R-handed couplings. At ILC, this is straightforward using beam polarization.

pp collisions can search for $t\bar{t}$ resonances. But the search range is limited, and the theory cross section is uncertain due to modelling effects and the dependence on the g parton distribution at large x.



arXiv:2202.12134



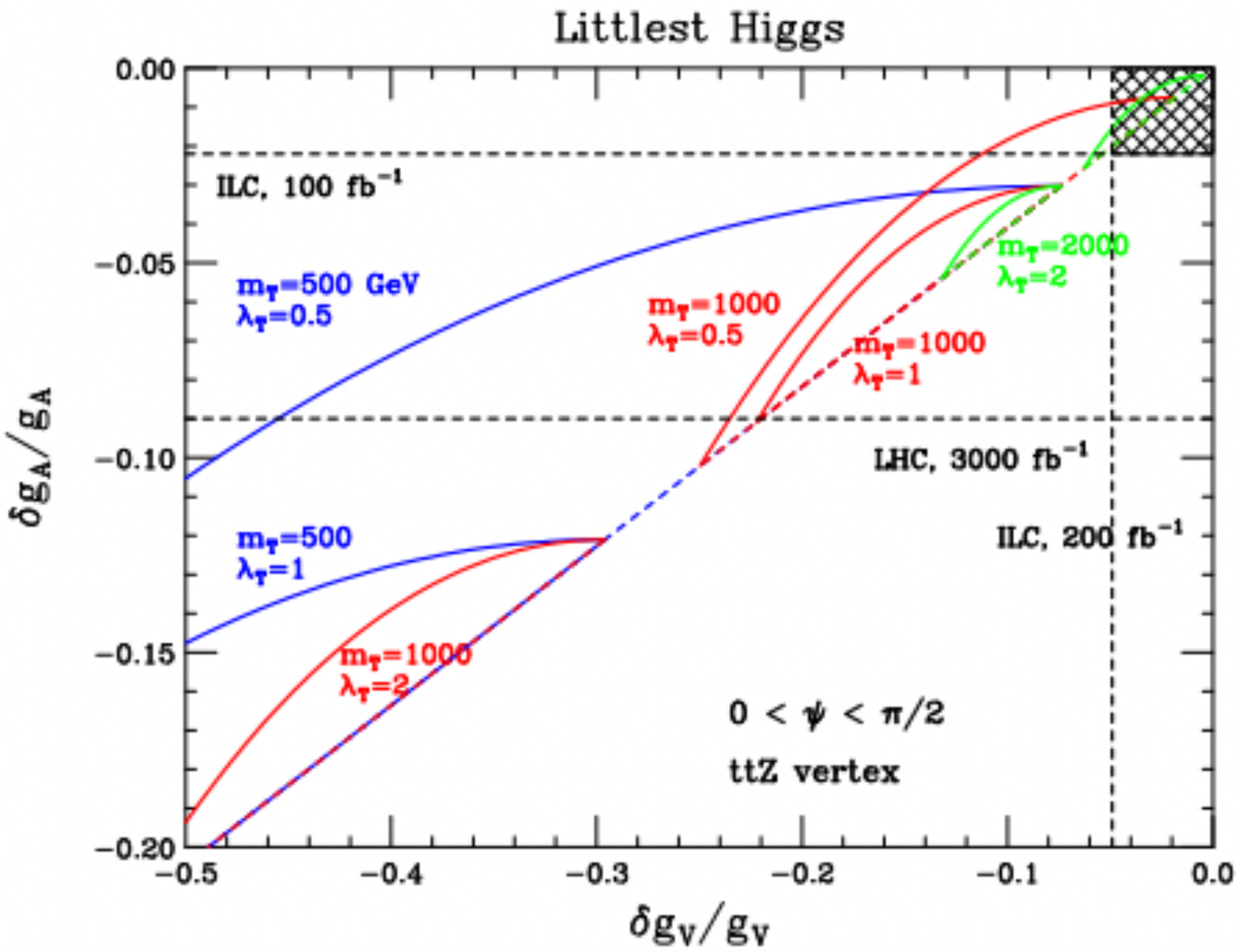
arXiv:2205.02817

In Little Higgs models, the top quark is a mixture of a chiral and a vectorlike heavy quark.

In the Higgs potential, the loop effects of these two quarks cancel at large momentum, to solve the hierarchy problem.

The top quark couplings to W and Z are decreased by the effect of mixing.

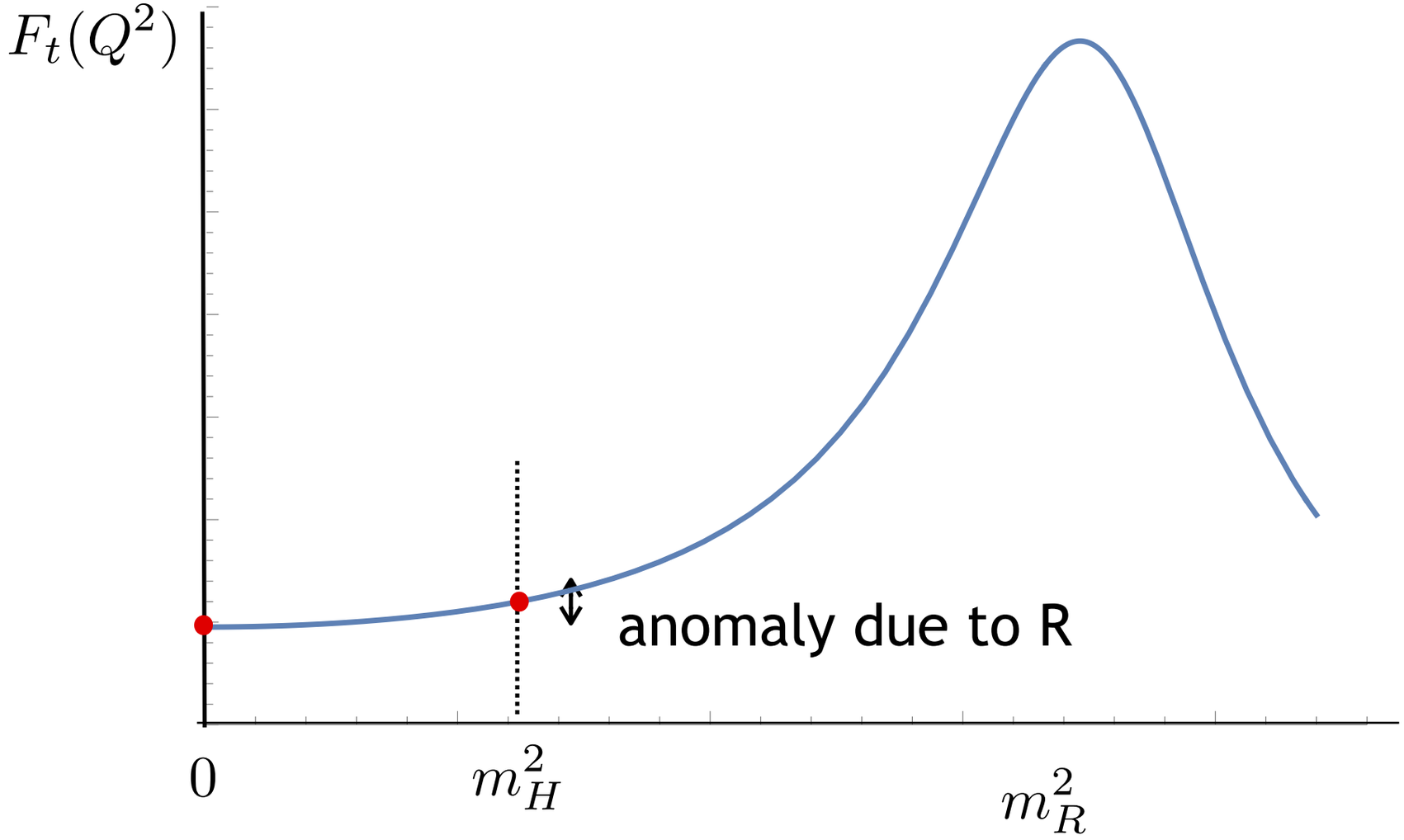
Effects of mixing of t with T in Little Higgs models:



Berger, Perelstein, and Petriello, hep-ph/0512053

Excuse me that the plot is dated; we now talk about 4000 fb-1 total integrated luminosity at 500 GeV.

If the top is composite with a $t\bar{t}$ resonance at a high mass, the top quark will have a form factor:



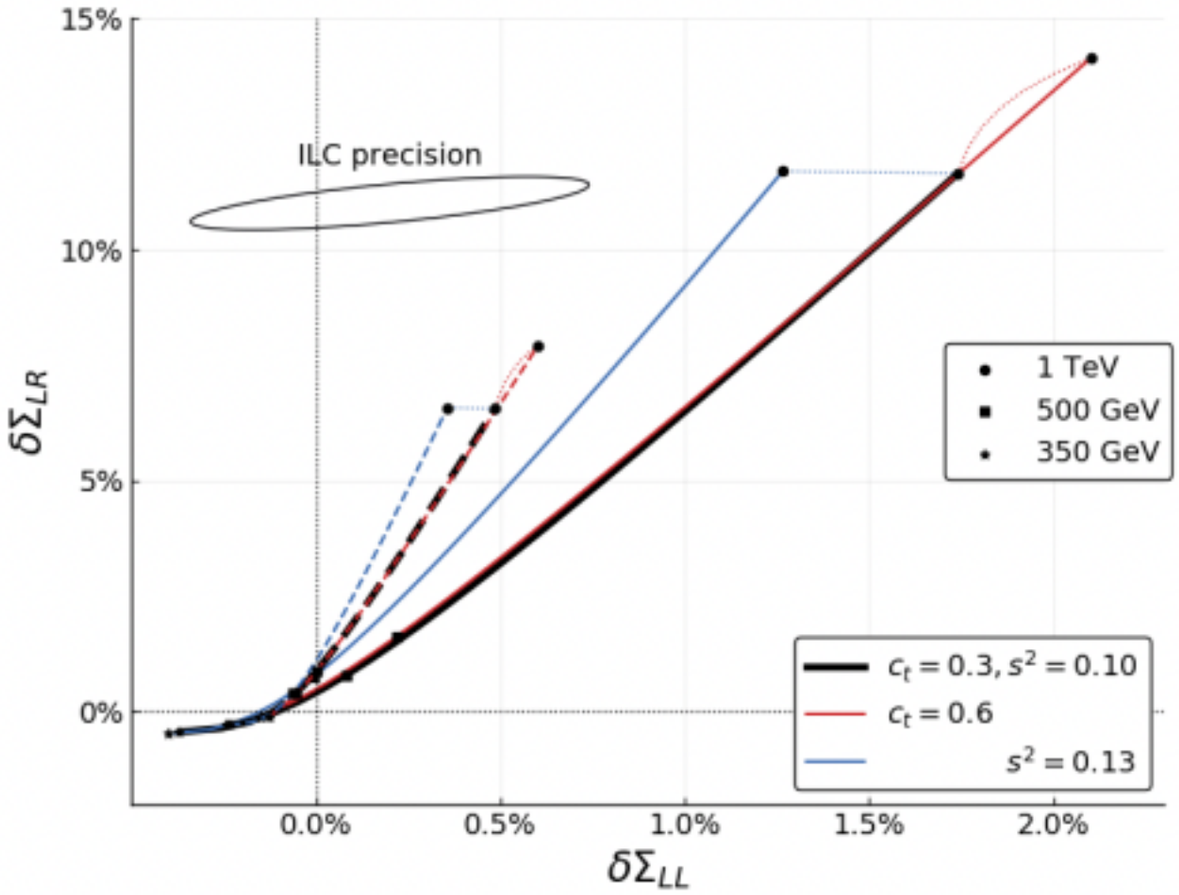
This is an m_H^2/m_R^2 correction, visible as a difference in the top quark Yukawa coupling from the value predicted from m_t .

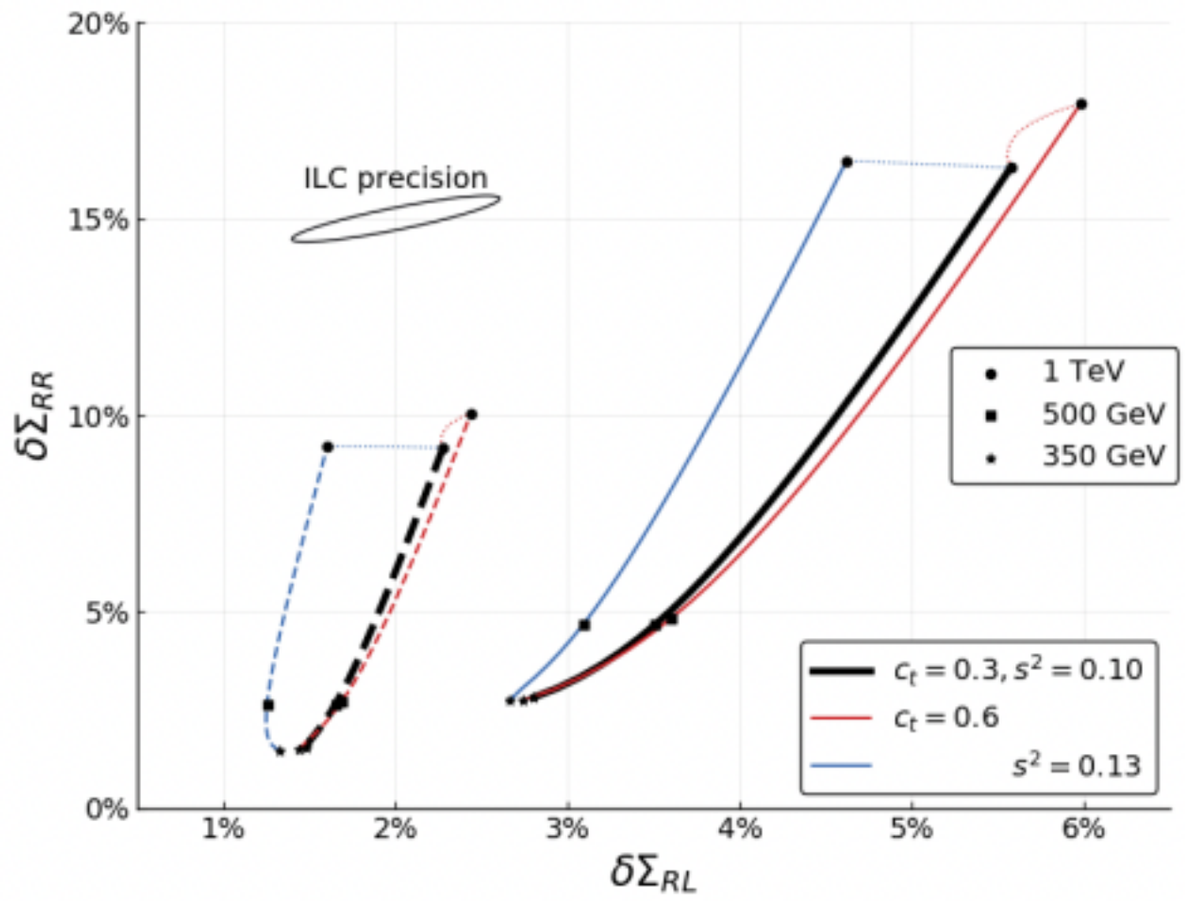
In models with extra dimensions, the recurrences of the γ and Z will create new couplings that can link top quark to light fermion initial states such as e^+e^-. This effect generates effective 4-fermion contact interactions, which can have general chiral structure.

The relevant class of models includes Randall-Sundrum models with gauge bosons in the 5-d bulk. These models are dual to 4-d strongly interacting models in which the heavy strong interaction resonances have chiral couplings. This gives another interpretation of observed BSM contact interactions.

An important question is: Which couples more strongly to the KK recurrences, or, equally well, which is more composite, t_L or t_R?

effect of contact interactions in a particular Randall-Sundrum 5-d model:



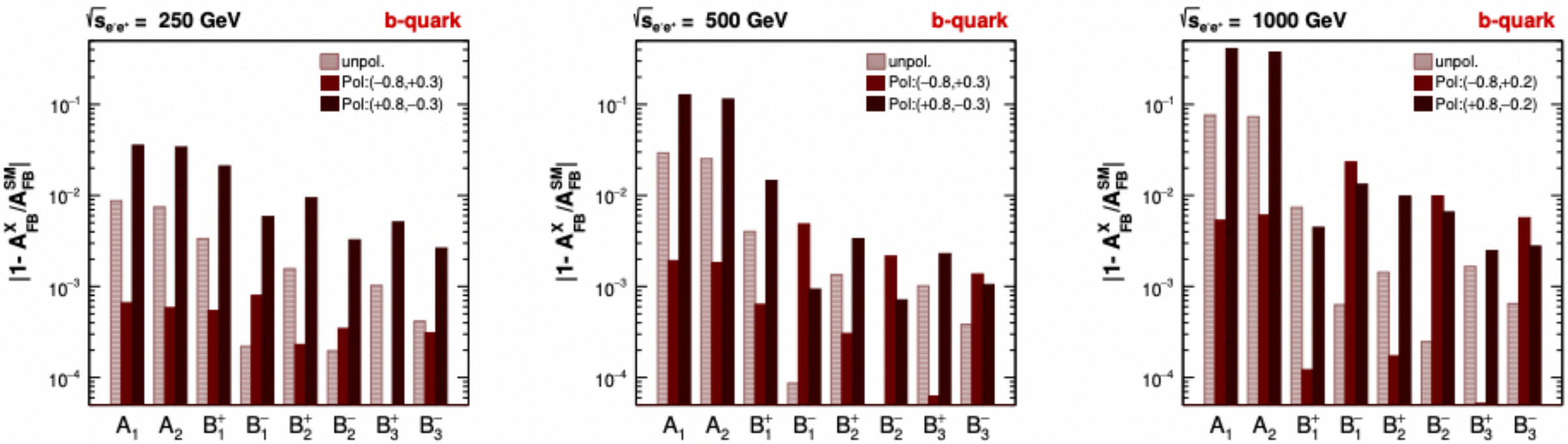


MEP and Yoon, arXiv:1811.07877

ILC precisions from Amjad et al. arXiv:1505.06020

These effects are also visible in $e^+e^- \to b\bar{b}$, even in the 250 GeV run.

But, the effects are much larger in higher energy running.



Analysis of the gauge-Higgs unification model of Hosotani et al. by Irles et al, arXiv:2403.09144

All of these effects are reflected in a SMEFT fit to the data on top quark pair production.

mixing effects and $t\bar{t}$ vector/axial form factors

$$c_{\phi Q}^{(1)}, c_{\phi Q}^{(3)}, c_{\phi t}$$

$t\bar{t}$ scalar form factor

$$c_{t\phi}$$

four fermion contact interactions

$$c_{lQ}^{(1)}, c_{lQ}^{(3)}, c_{lt}, c_{et}$$

For a proper physics interpretation, it is important that these operator effects be distinguished from one another.

Unfortunately, the effects of the form factor or mixing-type operator coefficients $c_{\phi t}$ are the essentially same as the effects of the four-fermion coefficients c_{et} at any given energy in $e^+e^- \to t\bar{t}$ above the $t\bar{t}$ threshold.

Fortunately, these terms have different CM energy-dependence, with the form factor operators effects staying constant while the contact interaction effects increase as $(E_{cm})^2$. Thus it is important to have substantial running at 2 CM energies well above the $t\bar{t}$ threshold.

If we are to carry out searches for all types of BSM models at a Higgs factory, this set of measurements in $e^+e^- \to t\bar{t}$ must be included.

We should not miss this additional opportunity that a Higgs factory gives us to find evidence for BSM physics and to clarify its nature.