Role of the Top Quark in the Quest for BSM Physics

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45 years after the creation of the Standard Model of weak interactions, we still have no understanding of its central feature:

The Standard Model has a gauge symmetry SU(2)xU(1) which is spontaneously broken. Why should this be so ?

Even after the discovery of the Higgs boson, this question remains. Why is the Higgs potential unstable at the origin ? How do we compute this potential ?

The Standard Model is unable to answer this question.

The other remarkable feature of the Standard Model is the top quark.

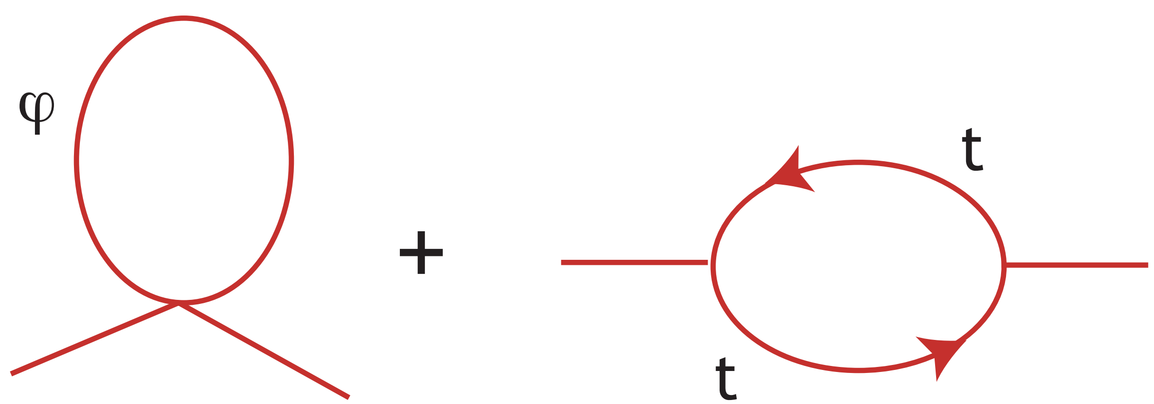
The top quark is 35 times heavier than any other quark or lepton. In the Standard Model, it receives its mass through the Yukawa coupling y_t . Its value is

$$\alpha_t = \frac{y_t^2}{4\pi} = 1/13$$

This coupling, which links the top quark and the Higgs field, is the largest coupling in the Standard Model aside from α_s .

It is tempting to suggest that this is a clue to the mystery.

One of the clues that there must be new physics behind the Higgs boson is the "gauge hierarchy problem": In the Standard Model, the Higgs field mass has quadratically divergent radiative corrections, with contributions of opposite sign.



$$\mu^2 = \mu^2_{\text{bare}} + \frac{\lambda}{8\pi^2}\Lambda^2 - \frac{3y_t^2}{8\pi^2}\Lambda^2 + \cdots$$

To make a predictive theory of electroweak symmetry breaking, we need to compute μ^2; thus we need to control or cancel these corrections. The largest coefficient here is proportional to α_t .

The solutions proposed for this problem are to two types:

First, a weak-coupling solution:

There is a better field theory in which the contributions on the previous slide cancel as the result of a symmetry. The most popular example is supersymmetry. The cancellations require new particles, including top quark partners.

Second, a strong-coupling solution:

The Higgs field and the top quark are composites of more elementary constituents. Then we must find Higgs and top excitations and resonances.

These alternatives are connected to the question of whether α_t is a small or a large coupling:

1. α_t is a perturbative coupling, the top quark is mass is the typical mass expected in the Standard Model (other quark and lepton masses are small). Effects on the top quark properties are of order

$$\frac{\alpha_t}{4\pi}\frac{q^2}{M^2}$$

OR

2. α_t is large enough to signal nonperturbative physics in the top sector. Then effects on the top quark properties are of order

$$\frac{q^2}{M^2} \quad \text{(only)}$$

In supersymmetry, the top quark is not a major player in electroweak symmetry breaking. That role is given to the top squark which might be much heavier than the top. The effects of new physics on the top quark are usually small.

Fortunately, all supersymmetry theorists are in Melbourne this week, so I can show this slide (from Top2015):

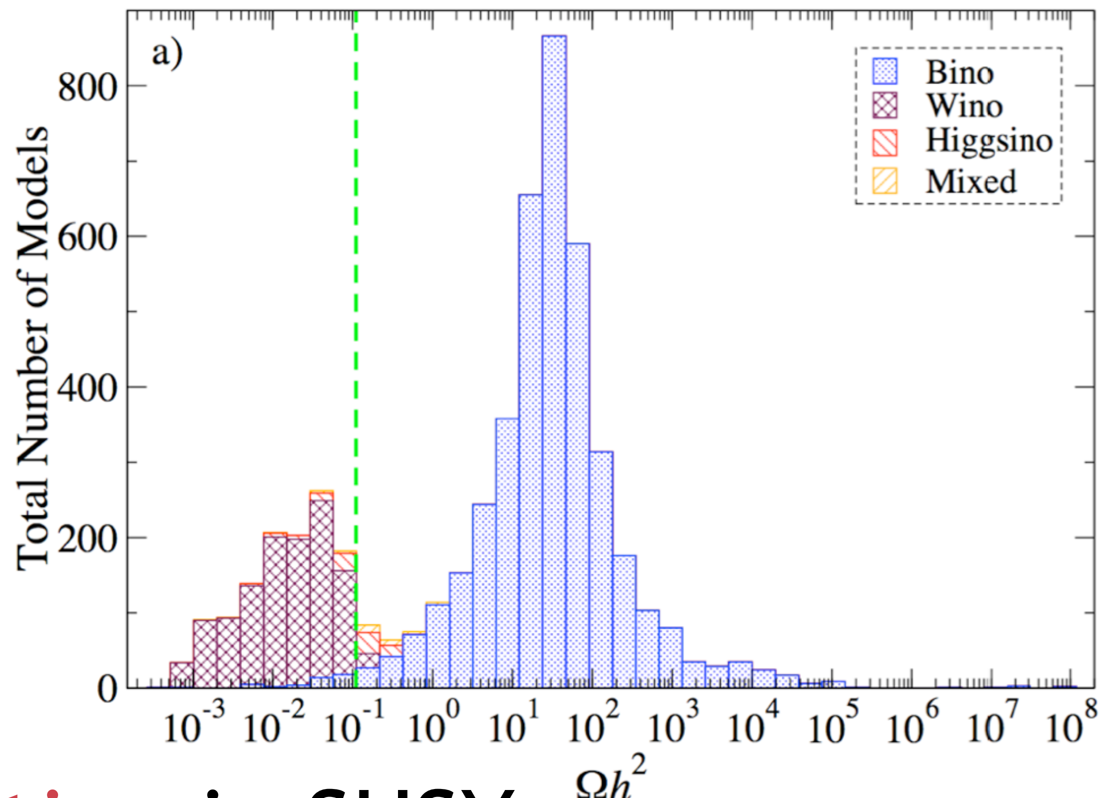
SUSY is OVER-RATED:

1. For SUSY to be at the TeV scale, 3 unrelated parameters must have approximately equal values:

$$m_{\tilde{g}} \ , \quad \mu \ , \quad \text{zero of } M_{Hu}(Q)$$

Nelson

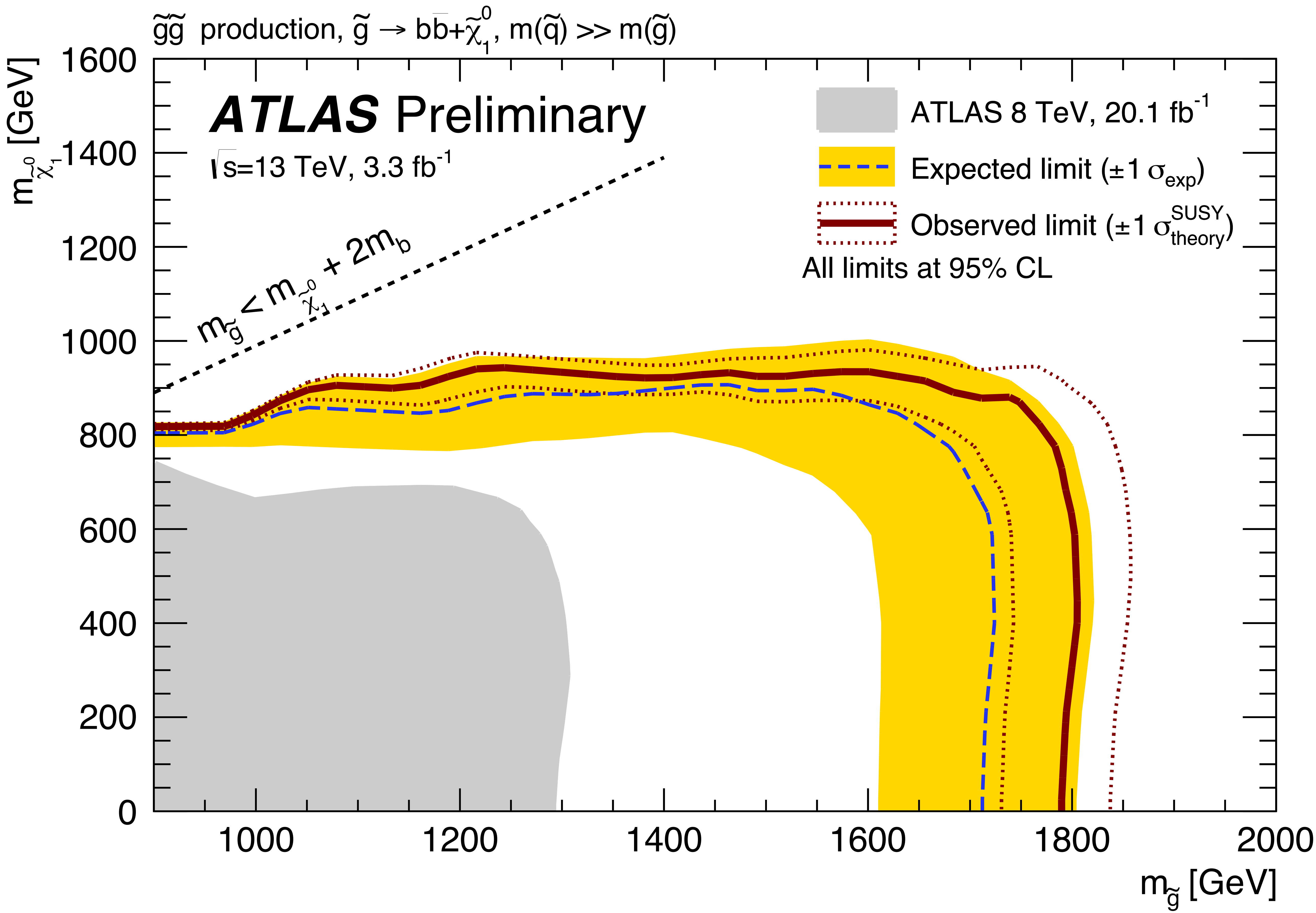
2. Value of the dark matter density in a scan of SUSY models:



Baer, Box, Summy

3. Grand unification in SUSY:

LO: perfect! NNLO: not so much ...



$\tilde{g}\tilde{g}$ production, $\tilde{g} \rightarrow b\bar{b}+\tilde{\chi}_1^0$, $m(\tilde{q}) >> m(\tilde{g})$
ATLAS Preliminary
$\sqrt{s}$=13 TeV, 3.3 fb^{-1}
ATLAS 8 TeV, 20.1 fb^{-1}
Expected limit ($\pm 1\ \sigma_{exp}$)
Observed limit ($\pm 1\ \sigma_{theory}^{SUSY}$)
All limits at 95% CL
$m_{\tilde{g}} < m_{\tilde{\chi}_1^0} + 2m_b$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{g}}$ [GeV]
0
200
400
600
800
1000
1200
1400
1600
1000
1200
1400
1600
1800
2000

However, I feel that there are cautions about considering the top quark and the Higgs boson to be nonperturbative objects.

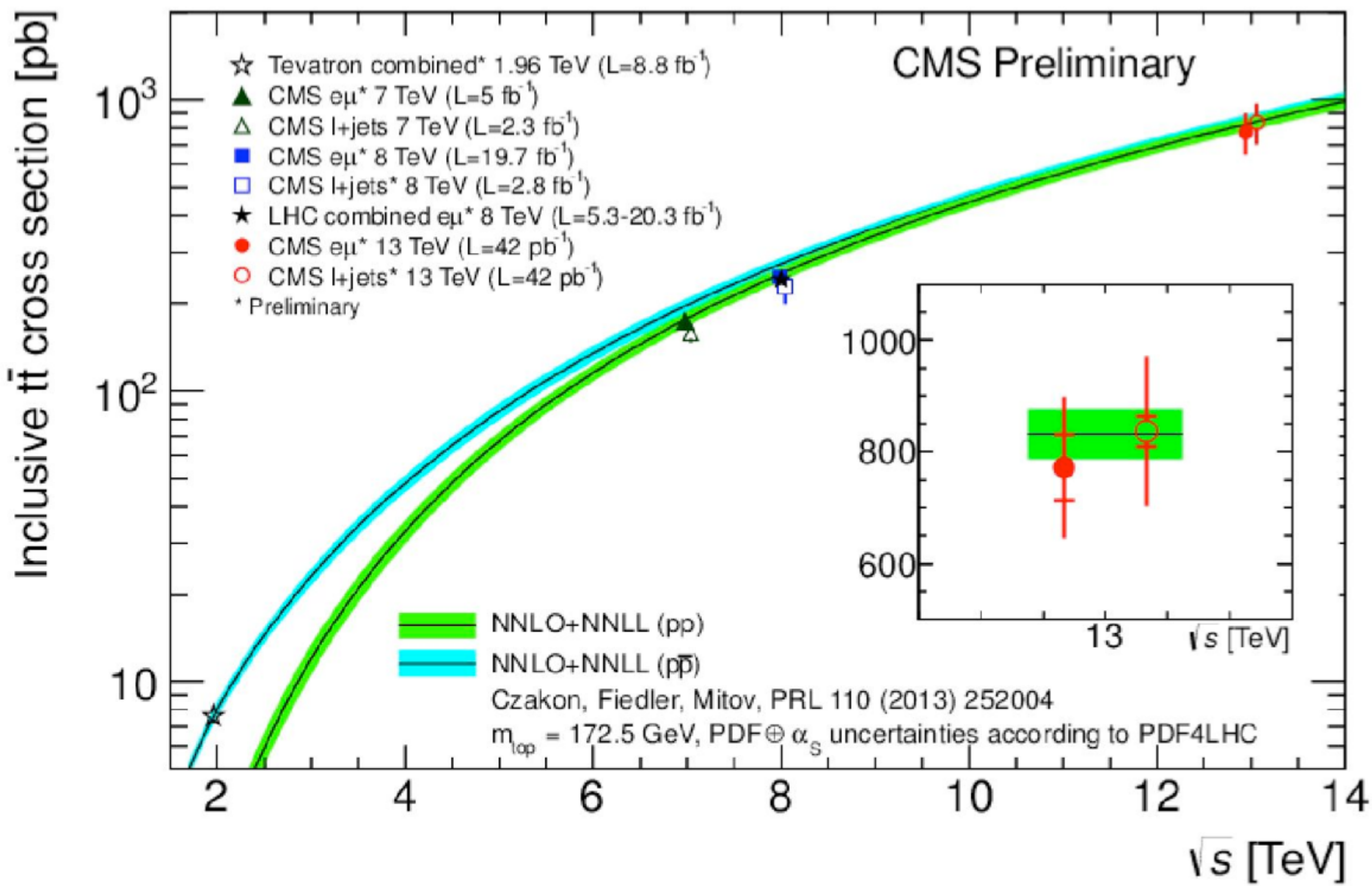
The Higgs boson mass is small compared to $v = 246$ GeV, a sign of a perturbative coupling.

Measurements of the top quark properties at hadron colliders are in excellent agreement with the Standard Model.

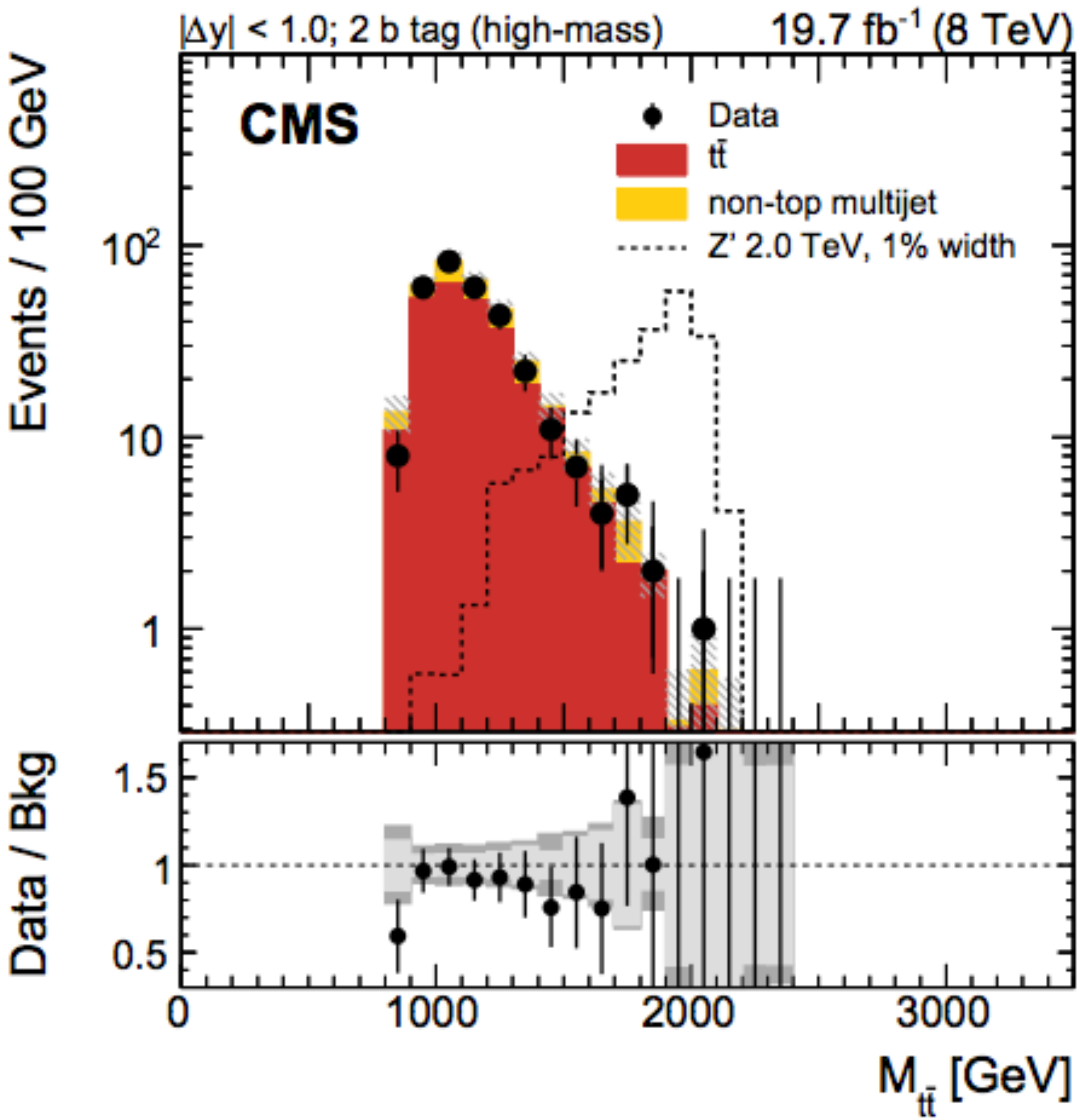
b_L is in the same SU(2)xU(1) multiplet as top, and

$$R_b(Z \to b\bar{b}) = 0.21629 \pm 0.00066$$

within 0.3% (1σ) of the Standard Model expectation.



CMS Preliminary
Tevatron combined* 1.96 TeV (L=8.8 fb-1)
CMS eμ* 7 TeV (L=5 fb-1)
CMS l+jets 7 TeV (L=2.3 fb-1)
CMS eμ* 8 TeV (L=19.7 fb-1)
CMS l+jets* 8 TeV (L=2.8 fb-1)
LHC combined eμ* 8 TeV (L=5.3-20.3 fb-1)
CMS eμ* 13 TeV (L=42 pb-1)
CMS l+jets* 13 TeV (L=42 pb-1)
* Preliminary
NNLO+NNLL (pp)
NNLO+NNLL (pp̄)
Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
m_top = 172.5 GeV, PDF ⊕ α_S uncertainties according to PDF4LHC
Inclusive tt̄ cross section [pb]
√s [TeV]



(also, no peak at 750 GeV)

There are two ideas that are important in building composite models of Higgs and top consistent with these constraints:

Higgs as a Goldstone boson of new strong interactions, which can then be at 10 TeV.

Higgs as the 5th component of a gauge field in 5 dimensions (Gauge-Higgs unification).

These ideas are connected in the context of Randall-Sundrum 5d models in “warped space”, 5d anti-de Sitter space between flat 4d boundaries.

Through the AdS/CFT correspondence, a 4d strongly interacting conformal theory can be viewed as a weakly coupled theory in 5d AdS.

A scale transformation in 4d is a translation in the 5th dimension z of AdS.

An AdS theory with boundaries is then a theory that is approximately conformally invariant over a range of energy scales, from that of the IR brane to that of the UV brane.

When the conformal symmetry is broken by the presence of 4d boundaries, the mass spectrum of the model becomes discrete.

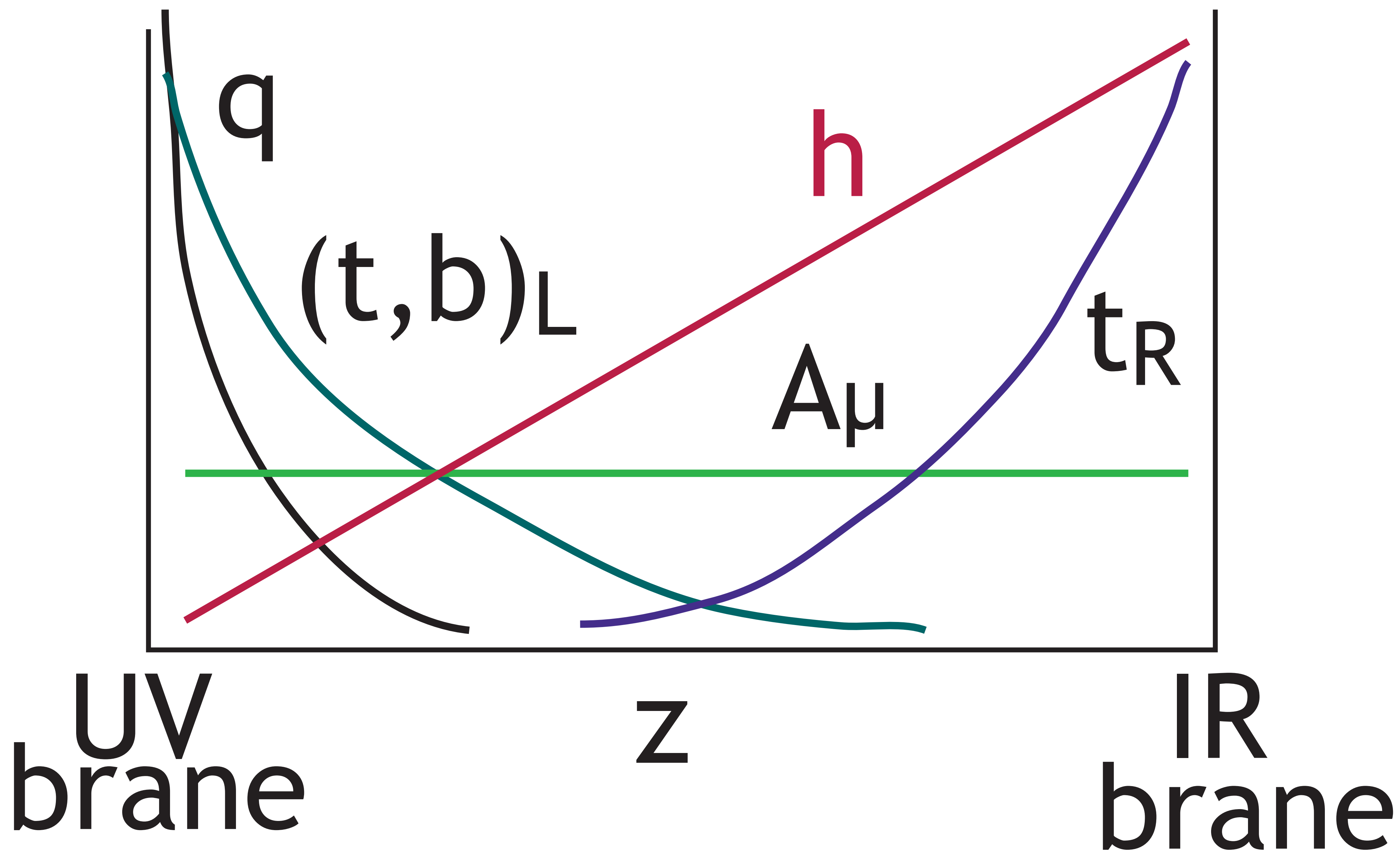
The bound states of the 4d strong interaction theory are modeled as the Kaluza-Klein excitations of the 5d theory.

It is possible to choose boundary conditions so that some fields have zero mass in 4d. These will be

5d Dirac fermions $\rightarrow$ 4d chiral fermions
gauge bosons $\rightarrow$ 4d gauge bosons and symmetries
gauge bosons $\rightarrow$ 4d Goldstone bosons

This gives us the ingredients to build a model that extends the Standard Model with 4d strong coupling dynamics.

The zero modes have specific forms in z that affect the discussion to follow. These forms can be tailored, to some extent, as part of the model definition.



Using this 5d picture for visualization, we can enumerate many phenomena that could result from strong interactions of Higgs and top.

These observables form a web.   To fully understand the underlying theory, we will want to measure as many as possible.

Precision electroweak observables:

$$A_e \ , \ A_{FB}(Z) \ , \ m_W \ , \ \Gamma_Z$$

These mainly constrain the A, W, Z KK states; typically these will be above 3 TeV

b precision observables:

$$\Gamma(Z \to b\bar{b}) \ , A_{FB,b}(s)$$

It is possible that these have anomalies growing as

$$s/M^2$$

to a few percent at 500 GeV. (The smallness of $\Gamma(Z \to b\bar{b})$ may also be explained by a custodial symmetry (Agashe, Contino, da Rold, Pomarol).)

t and b KK recurrences:

These also would be at 3-5 TeV masses;

also expect g recurrences decaying to $t\bar{t}$

Non-zero mode members of the t and b 5d multiplets (vector-like T and B).

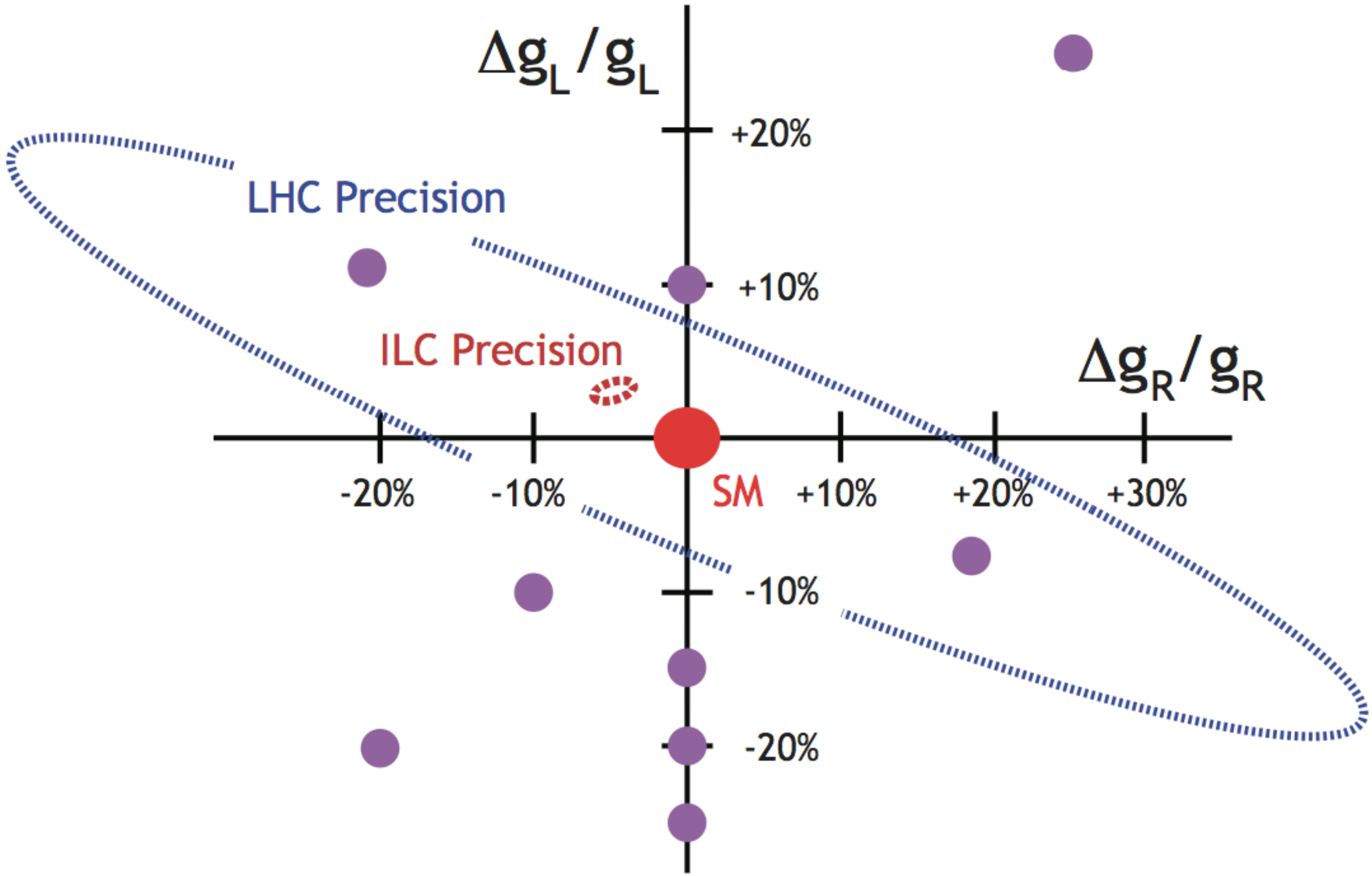
These could potentially be lighter, at the 1-2 TeV mass scale. These are the states directly responsible for cancelling the UV quadratic divergence from t. In most models, these mix with t, and the cancellation is an identity on the mixing angles.

Precision t observables:

Mixing of t and T changes the Z quantum numbers of the t, in general differently for t_L and t_R. At some level, a t anomalous magnetic moment could also be induced. The sensitivity to these shifts in the $t\bar{t}Z$ couplings will be discussed extensively in this workshop.

Effects of order s/M^2, where $M \sim 3-4 \text{ TeV}$, would also be seen in $e^+e^- \to t\bar{t}$ and $gg \to t\bar{t}$. This might be visible at LHC as a perturbation of the spectrum (or, in the best case, a resonance).

LHC and ILC opportunities to measure the t_L and t_R form factors for coupling to the Z:



models collected by Richard and Wulzer

Precision Higgs-top observables:

The presence of t form factors and new T states affects three distinct Higgs-top observables:

$$g(tth) \qquad pp\ , \quad e^+e^- \to t\bar{t}h$$

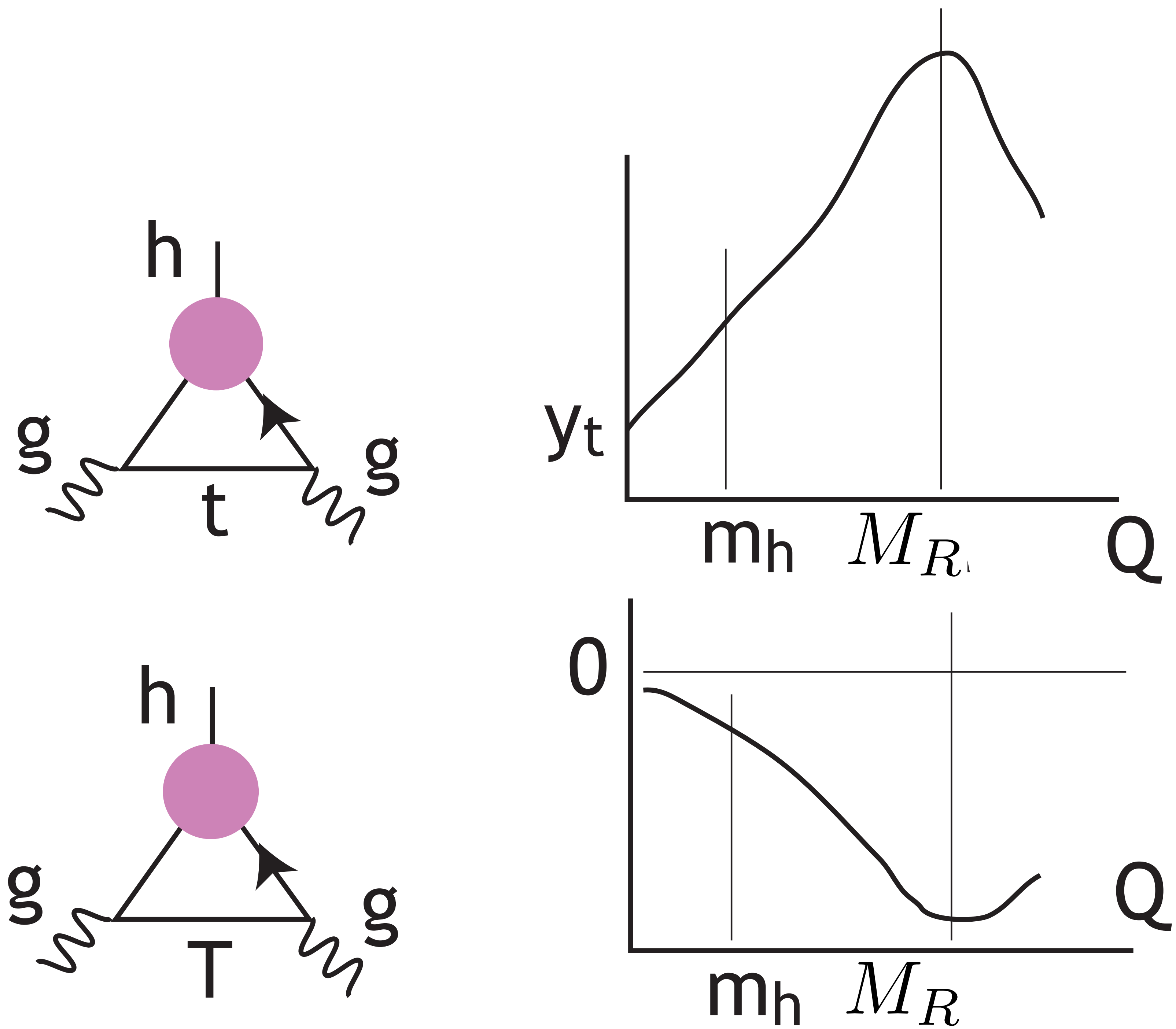
$$g(hgg) \qquad \Gamma(h \to gg)$$

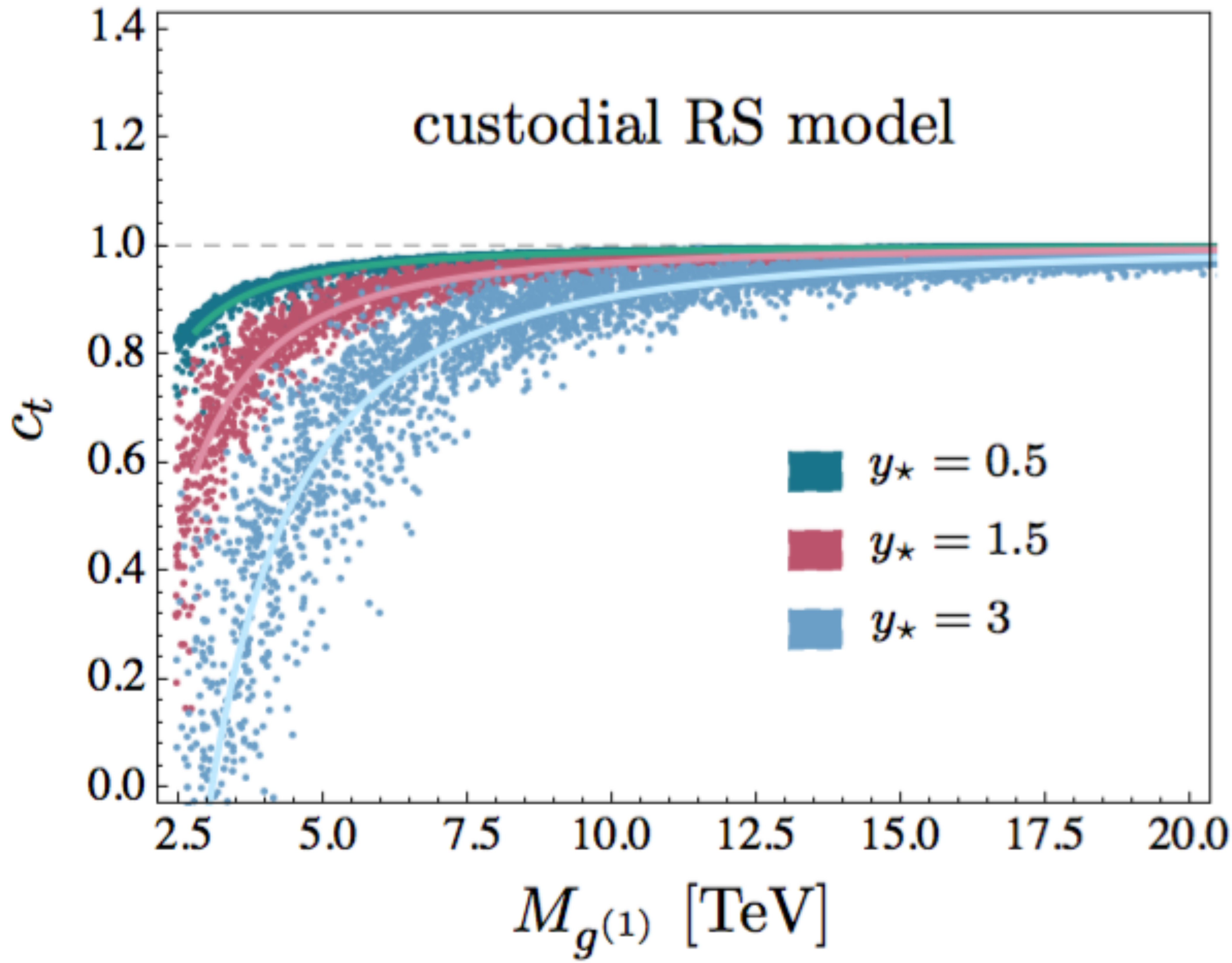
$$pp \to h + g \text{ or } q \text{ at high } p_T$$

To disentangle the origin of coupling anomalies, all three need to be measured with high precision.

Only LC can realize the first two of these measurements with high precision, so this gives an interesting example of LHC/ILC complementarity.

t, T form factors

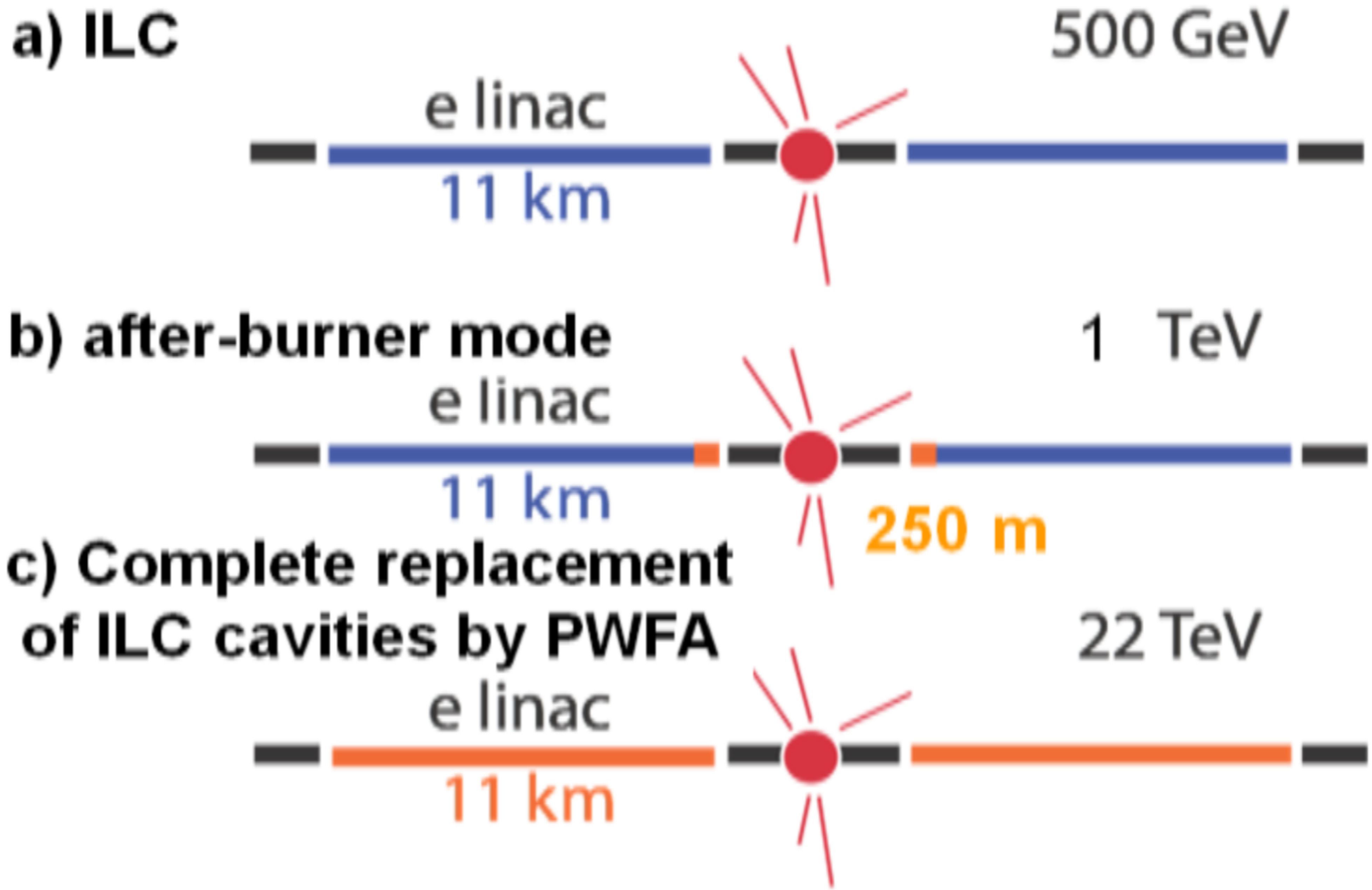




Malm, Neubert, and Schmell

Over the long term, the crucial tests of these models will involve the discovery of the T and B partners and the KK recurrences.   This will require a very high-energy collider.

Though currently, most of the emphasis for this issue is on the capabilities of a 100 TeV pp collider (in the Geneva region or China), one should not forget the possibility of searching for these resonances as a future stage of the ILC accelerator laboratory.



Delahaye et al, IPAC 2014

(assumes 1 GeV/m effective gradient with staging)

Conclusions:

Is the top quark a weakly coupled or a strongly coupled particle ?

The second case gives a rich array of models of electroweak symmetry breaking and BSM physics. These models are less challenged than supersymmetry by the current LHC results. We need to take them seriously.

These models suggest a wide range of observables that can be measured at the LHC and the ILC. In particular, The sensitivity of ILC precision observables goes well beyond the reach of the LHC to discover new particles.

Thus, top quark observables form an important element of the projected ILC experimental program.

We need to be prepared carry out these measurements with the highest precision possible.