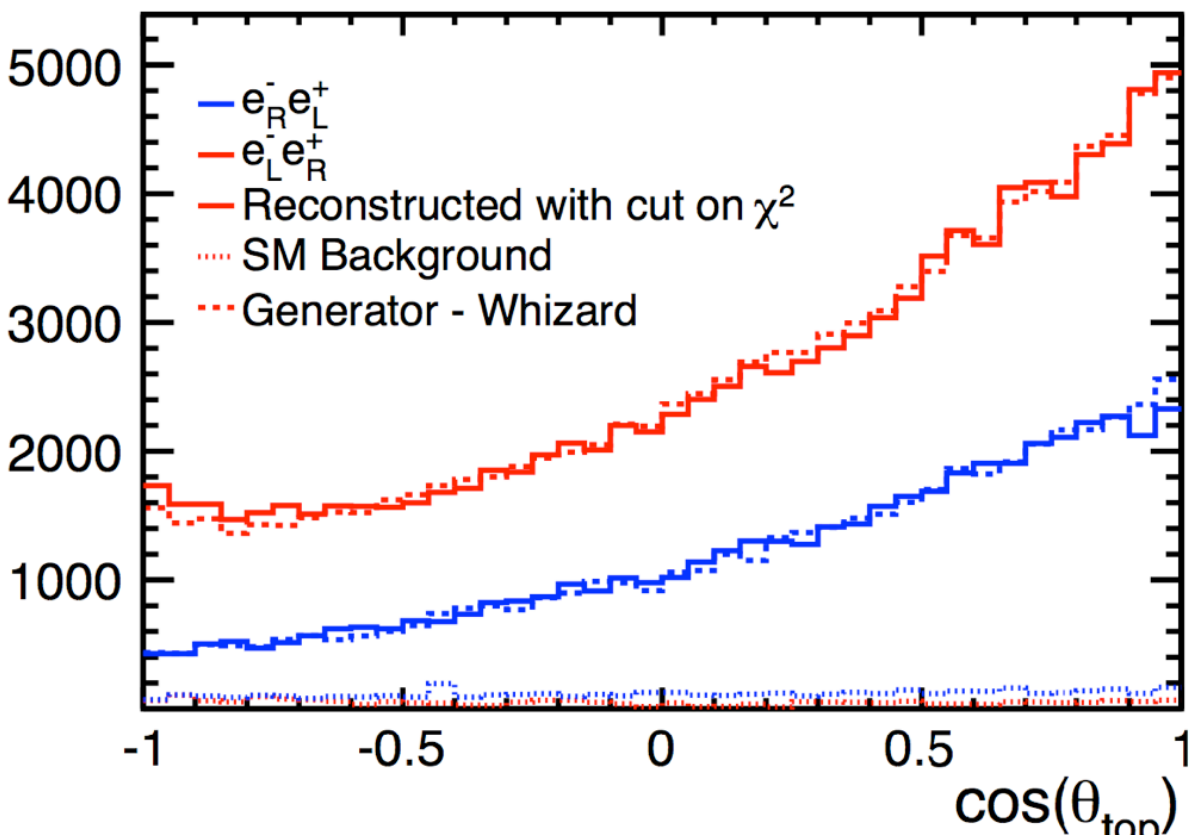
Precision Top Quark Measurements at Linear Colliders



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LCWS 2015
November 2015

In discussion of the physics case for future e+e- colliders, the top quark is often unappreciated.

Some people think that e+e- running at 250 GeV is quite sufficient.

Thus, we need to discuss the importance of the top quark in the LC program.

The study of the top quark is now often considered a part of precision QCD rather than as a source of information about physics beyond the Standard Model. For example, in ATLAS and CMS, the main activity of the Top Physics group is top cross sections and properties.

There is enough truth in this idea to confuse people.

Part of the issue is that we do not know whether the top quark is a heavy quark or an ordinary quark, in a sense that I will make precise below.

Outline of this talk:

SM part:

Top quark mass at hadron and lepton colliders
$t\bar{t}$ threshold in e+e-
Top quark observables above threshold

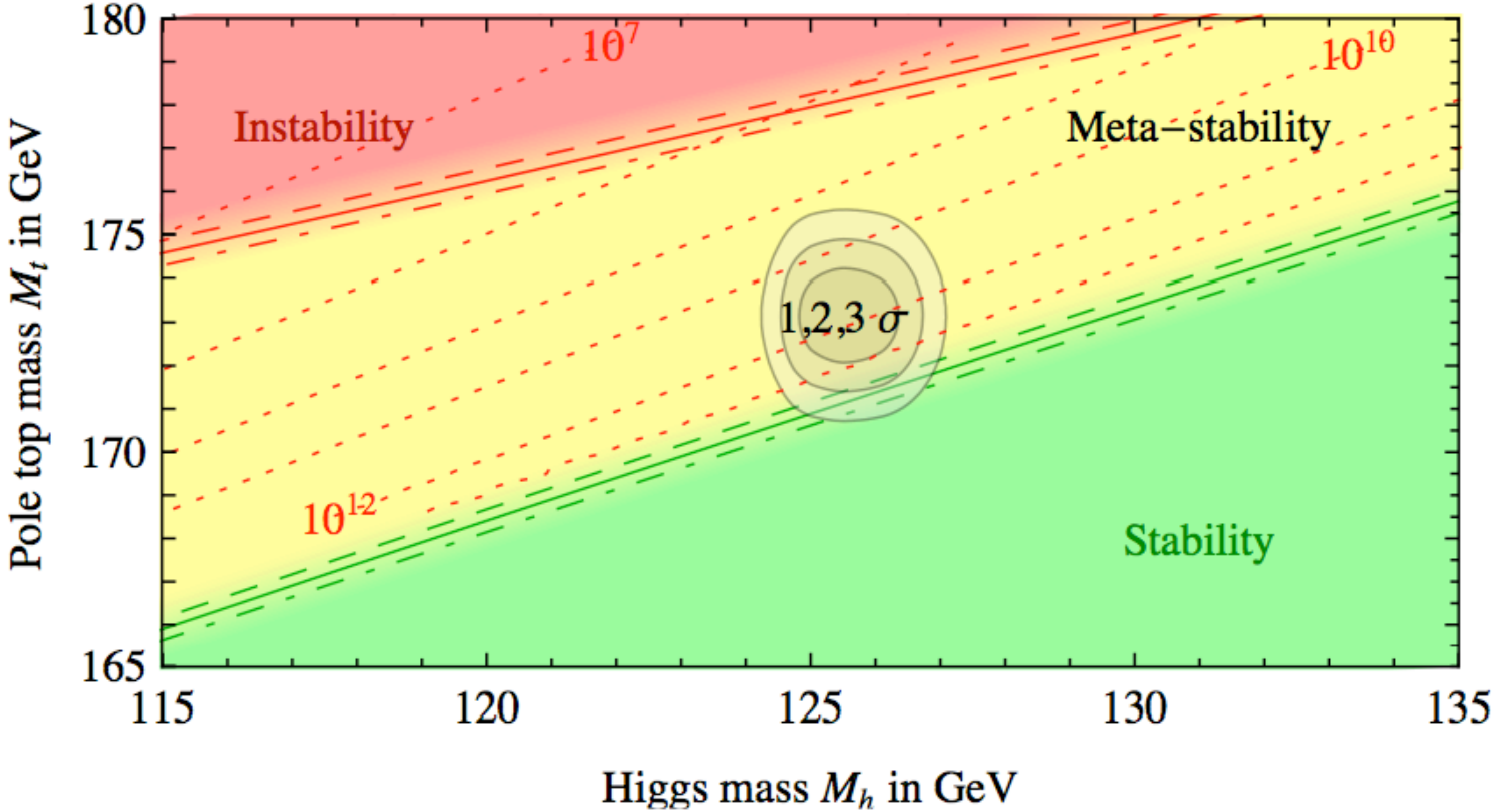
BSM part:

Is the top quark heavy or ordinary ?
Does composite Higgs imply composite top ?
3 probes of top quark compositeness
3 probes of the top/Higgs relation

As the precision of our understanding of the Standard Model has increased, this theory has called for higher accuracy in the top quark mass.

The most striking example is the quirk of the Standard Model that its vacuum is apparently unstable due to top quark loops. The critical value of the top quark pole mass is very close to the observed value.

Precision electroweak analysis requires an accuracy on m_t of about 200 MeV.



$m_t = 173.1 \pm 0.7$ GeV ; **critical value:** $m_t = 171.1$ GeV

Degrassi et al.

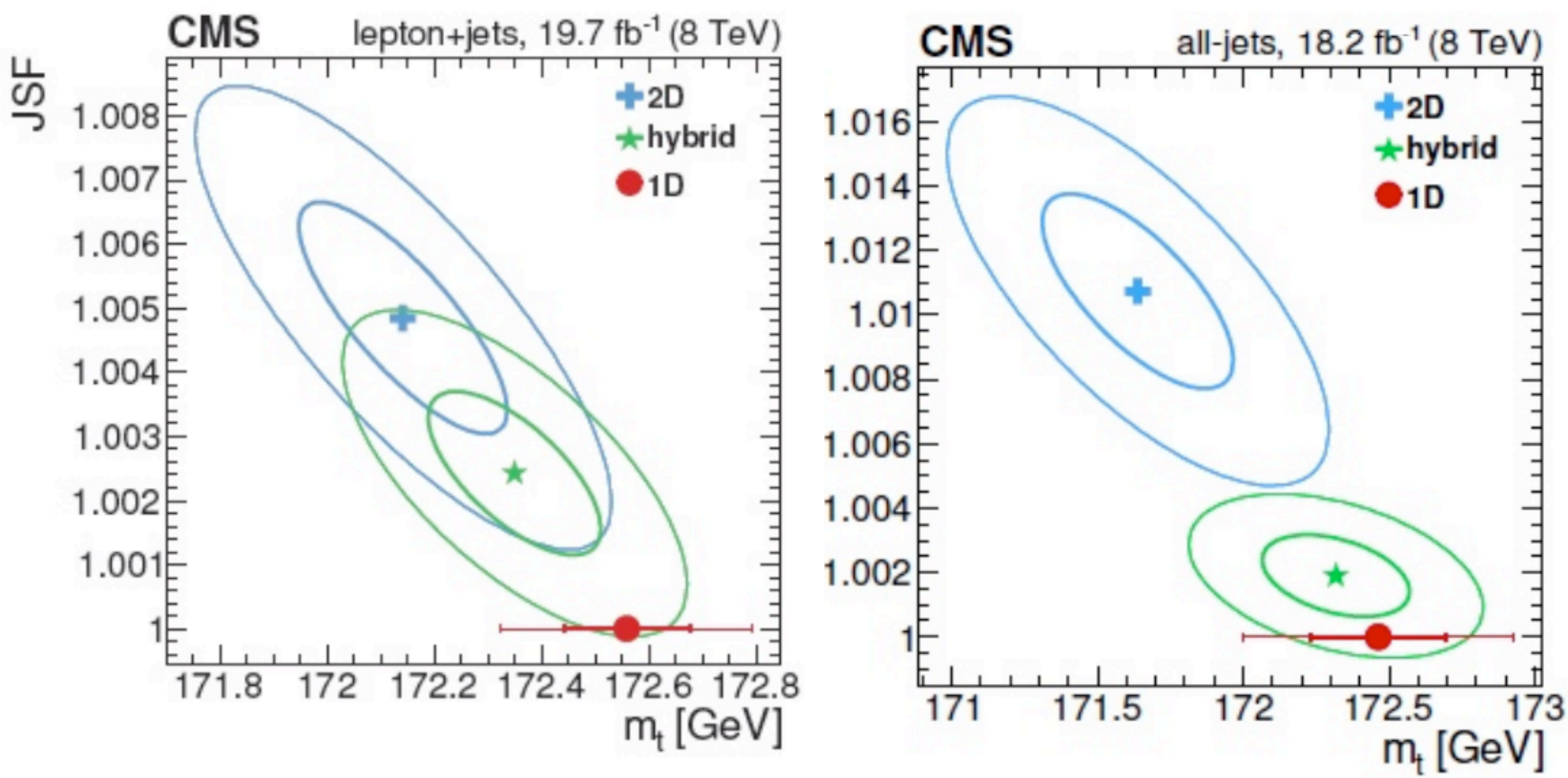
The accuracy on m_t expected from HL-LHC is about 500 MeV. Several factors make this difficult to achieve:

Current m_t errors are based on a definition of m_t as a parameter in PYTHIA. Definitions of m_t aware of QCD corrections exist but have lower statistics and less analyzing power.

Measurements of m_t at hadron colliders depend crucially on the jet energy scale. Can this be controlled below 1%?

What we really need to contact fundamental theory is the $\overline{MS}$ top quark mass. Hadron colliders measure the pole mass. The difference has an intrinsic error and a nonperturbative contribution.

effect of the jet energy scale:
blue: Tevatron method fitting a 2-jet mass to m_W
green: best estimate from jet calibration



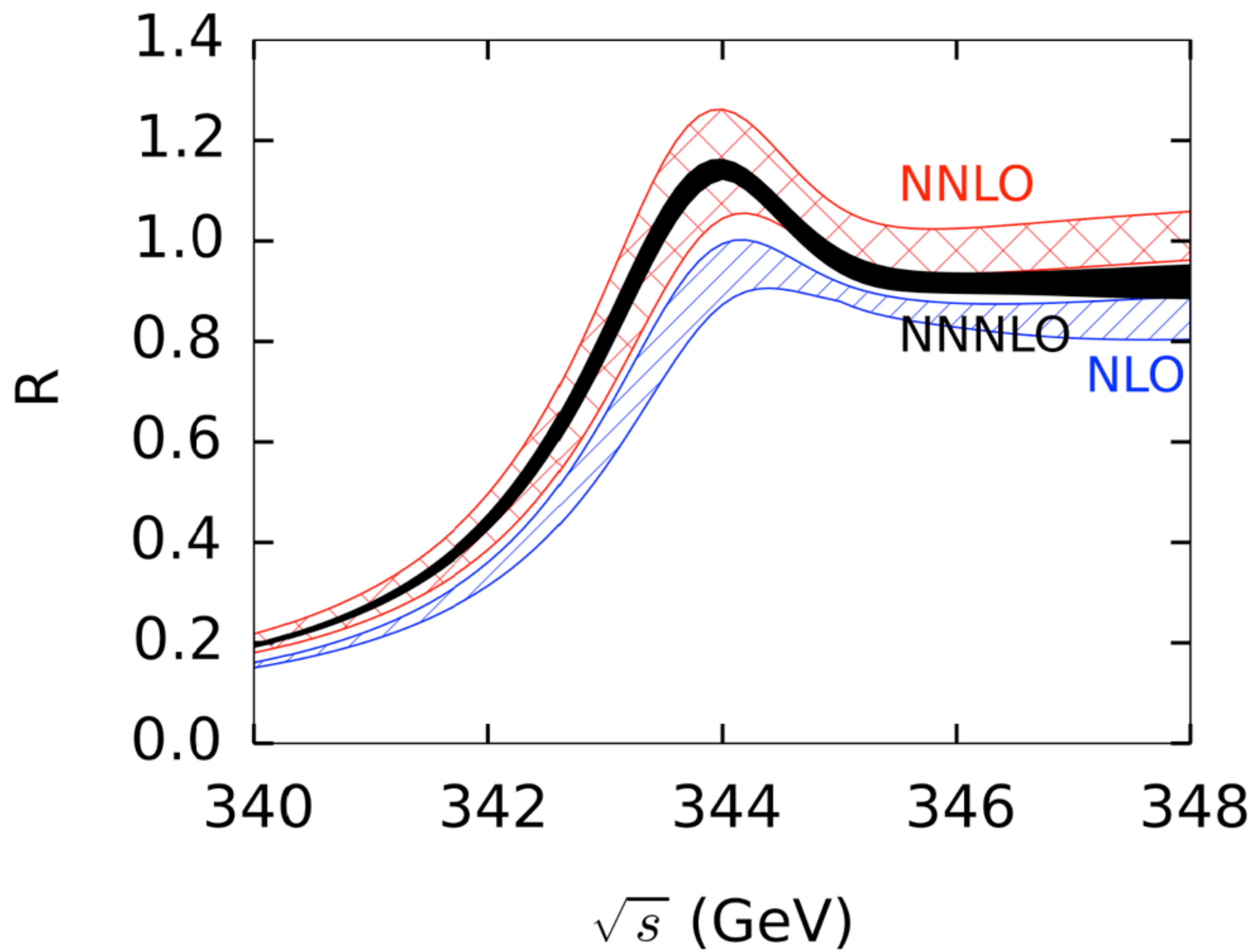
Conversion to the $\overline{MS}$ mass: the perturbative parts are now know to 4 loops

-- Marquard, Smirnov, Smirnov, Steinhauser

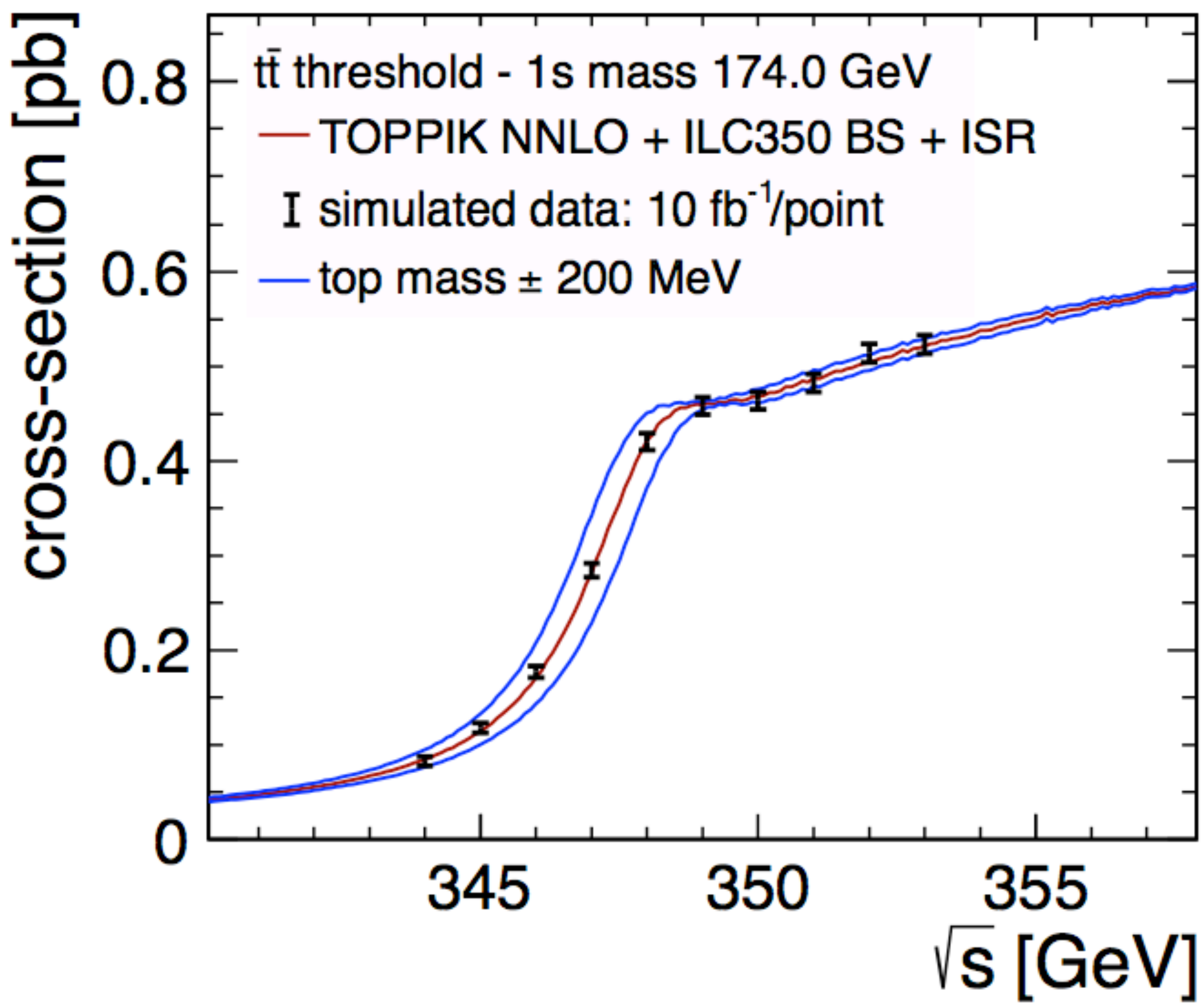
pole mass to $\overline{MS}$ mass: estimated error of 200 MeV

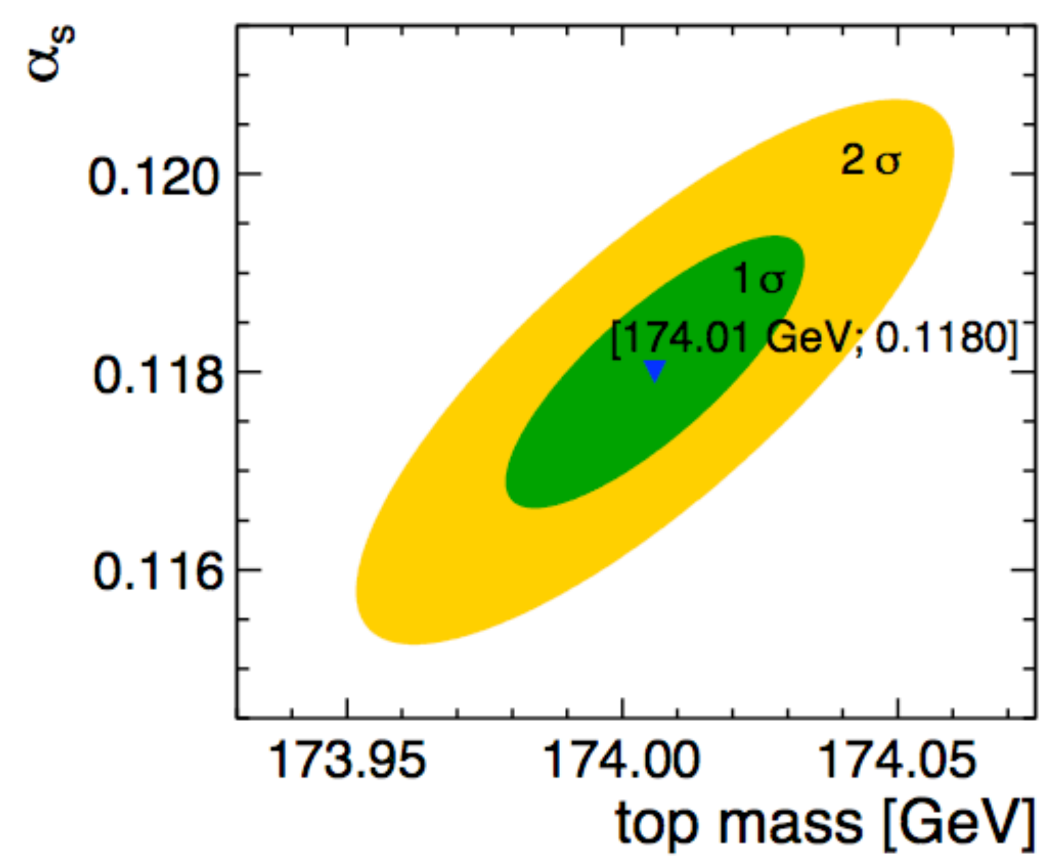
1S mass to $\overline{MS}$ mass: estimated error of 7 MeV

Another important development in precision QCD in the past year is the completion of the N^3LO theory of the $t\bar{t}$ threshold in e+e- annihilation by Beneke, Kiyo, Marquard, Penin, Piclum, and Steinhauser.



ILC and CLIC studies show that this threshold shape will be measured with impressive accuracy.

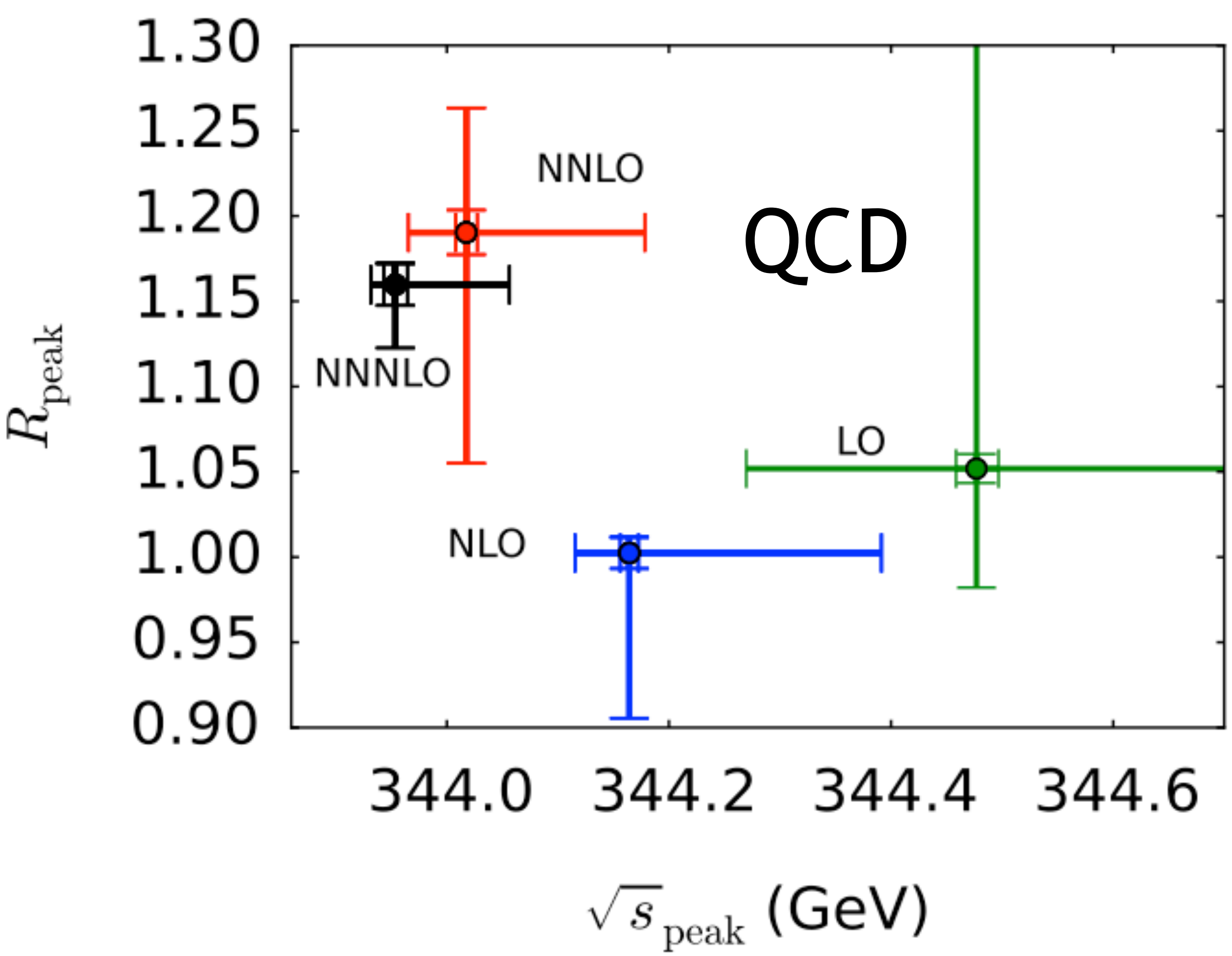


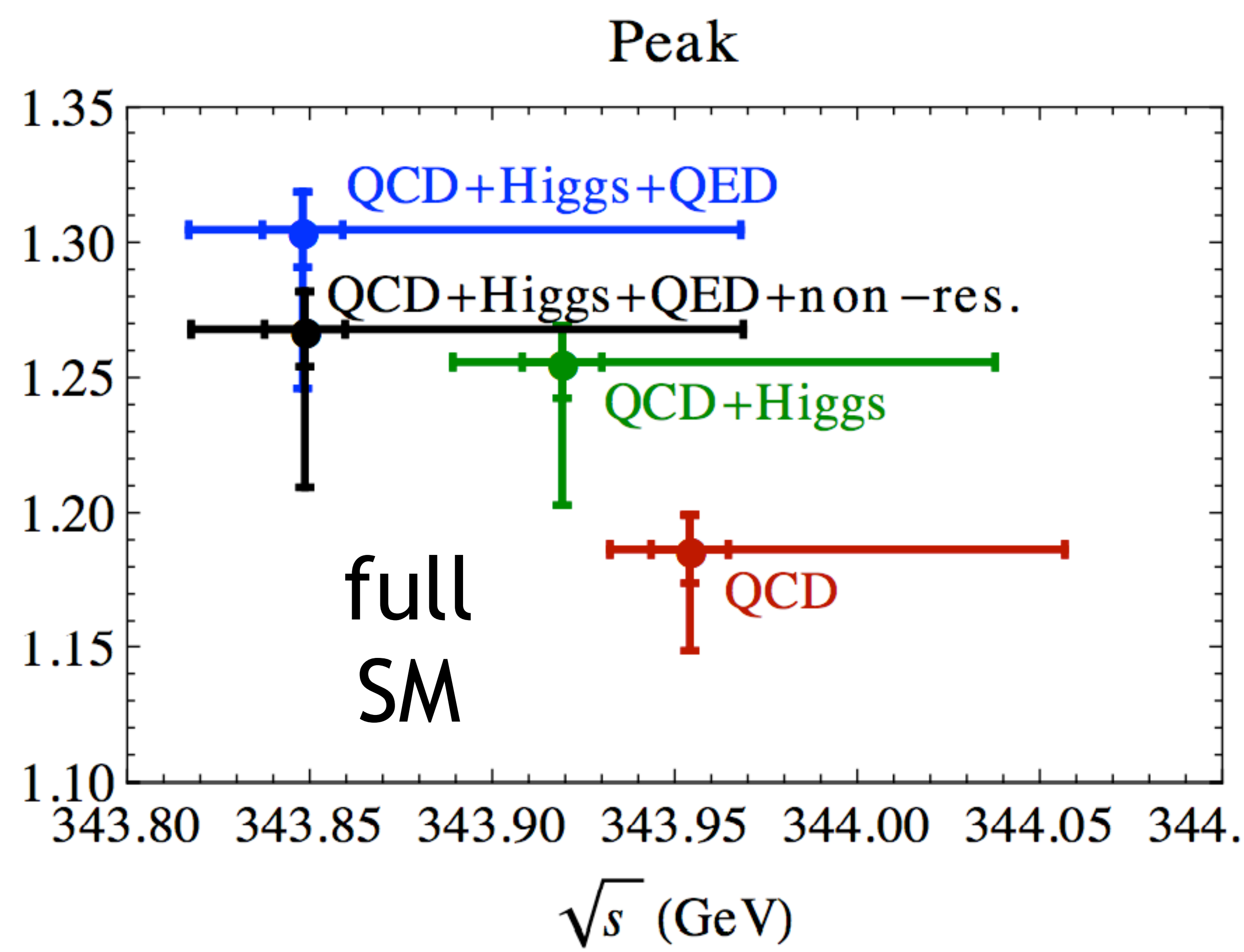


Seidel, Simon, Tesar

Precision comparison of theory and experiment for the threshold will be a landmark test of QCD.

However, the remaining theoretical uncertainty is still sizable and dominates expected experimental errors for m_t (50 MeV) and $g(ht\bar{t})$ (20%).

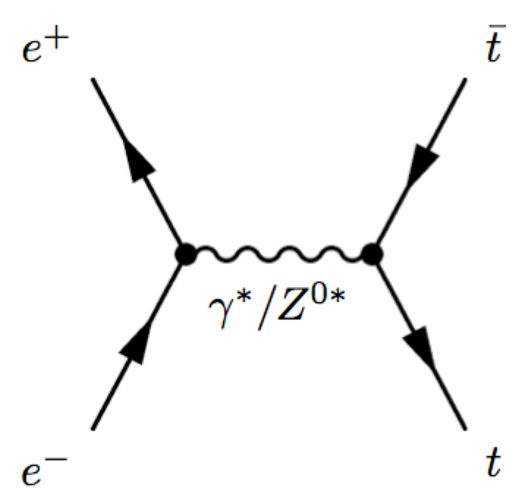


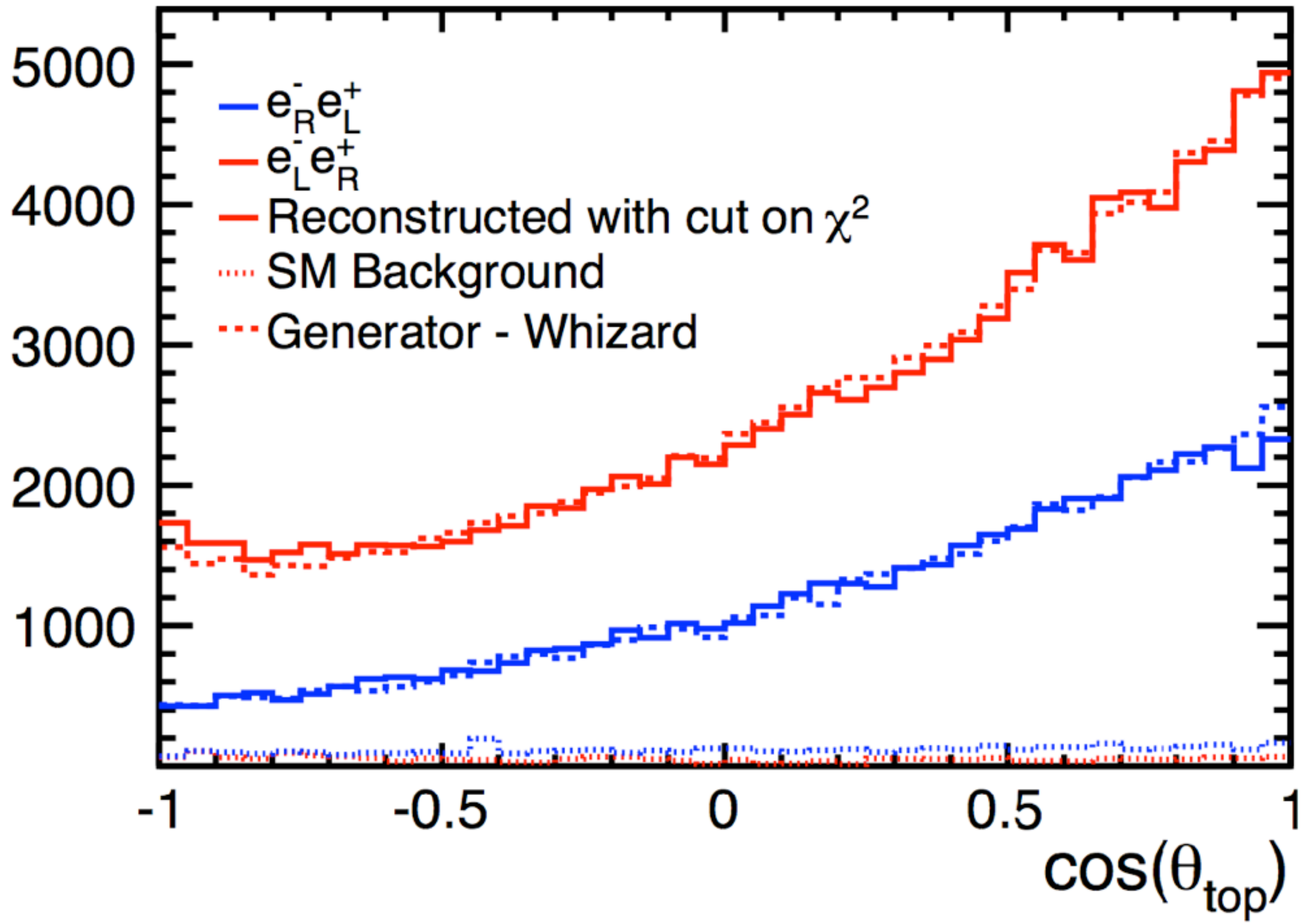


Finally, I should remind you of some properties of $e^+e^- \to t\bar{t}$ above threshold.

The important properties are

events are fully reconstructable,
all final parton angles can be measured
production is from γ-Z interference,
asymmetries are of order 1
decay is by weak interactions,
asymmetries are of order 1





5000
4000
3000
2000
1000
$e^-_R e^+_L$
$e^-_L e^+_R$
Reconstructed with cut on χ^2
SM Background
Generator - Whizard
-1
-0.5
0
0.5
1
$\cos(\theta_{top})$

This enables very accurate measurements of the form factors for top quark production and decay:

	Initial	Full program
Γ_t	3%	3%
g_L^γ	0.8%	0.6%
g_R^γ	0.8%	0.6%
g_L^Z	0.8%	0.6%
g_R^Z	0.8%	0.6%
F_2^γ	0.001	0.001
F_2^Z	0.002	0.002

Amjad et al.

This will enormously improve the precision of our knowledge of the top quark over what will be possible at the HL-LHC.

Why is it important to do this ?

Is the top quark a heavy quark or an ordinary quark ?

The top quark is the heaviest particle of the SM.

Thus - within the SM - its coupling to the Higgs field is the largest of any particle, even the Higgs boson itself.

But also, within the SM, $\alpha_t = \frac{y_t^2}{4\pi} = 1/13$

$$c.f. \qquad \alpha_s = 1/9 \qquad \alpha_b = 1/40,000$$

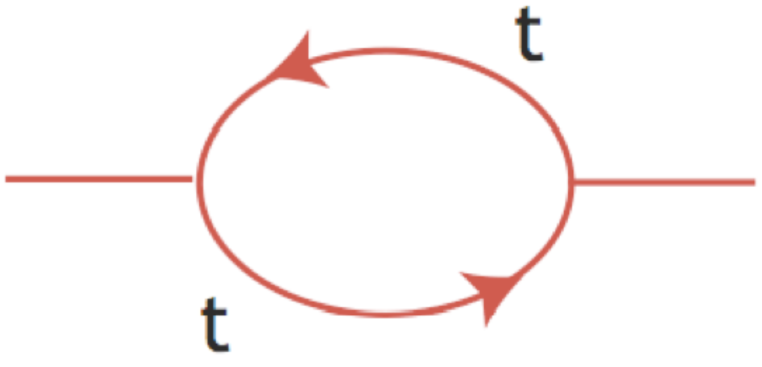
It could be that the top quark is a quark of ordinary mass, and all other quarks are puny.

Another way to ask this question:

Is the top quark responsible for the spontaneous breaking of electroweak symmetry ?

It is tempting that the top quark gives a negative contribution to the Higgs field mass parameter

$$\mu^2 = \mu^2_{bare} - \frac{3\alpha_t}{2\pi}\Lambda^2 + \cdots$$



But, this contribution is divergent and needs renormalization.

Really, in the the SM, there is no explanation for electroweak symmetry breaking. It is put in by hand.

Can we find an explanation outside the SM ?

We now know that there is no heavier fermion than the top quark that is chiral under SU(2)xU(1). A heavier quark doublet would multiply $\sigma(pp \to gg \to h)$ by a factor 9 !

However, it is possible that heavier particles exist that do not require electroweak symmetry breaking to acquire mass. These particles, taken together with the top quark, can make a model that explains electroweak symmetry breaking.

The structure of the model depends on whether the top quark is heavy or ordinary.

One possible approach is supersymmetry.

In supersymmetry, the usual approach to electroweak symmetry breaking relies on the couplings of the top squarks to the Higgs field. The top quark is a minor partner.

Similarly, corrections to the top properties are of the order of

$$\frac{\alpha_t}{4\pi}\frac{m_t^2}{m_{SUSY}^2} \sim 10^{-3}$$

However, there are alternatives to supersymmetry to generate new interactions at the TeV energy scale.

An idea that remains attractive is that the Higgs boson is composite, and that the interactions that bind the Higgs constituents are also responsible for driving electroweak symmetry breaking.

This is compatible with the property of the Higgs boson as a light, weakly coupled particle if this particle is a Goldstone boson of a symmetry-breaking at some higher mass scale.

Compositeness of the top quark brings with it the prediction of new particles:

vectorlike top quark T (mass m_T)

vector resonance R coupling to $t\bar{t}$ (mass m_R)

These particles are needed to give a finite and calculable theory of the Higgs mass parameter, and also contribute to t vector/axial-vector couplings.

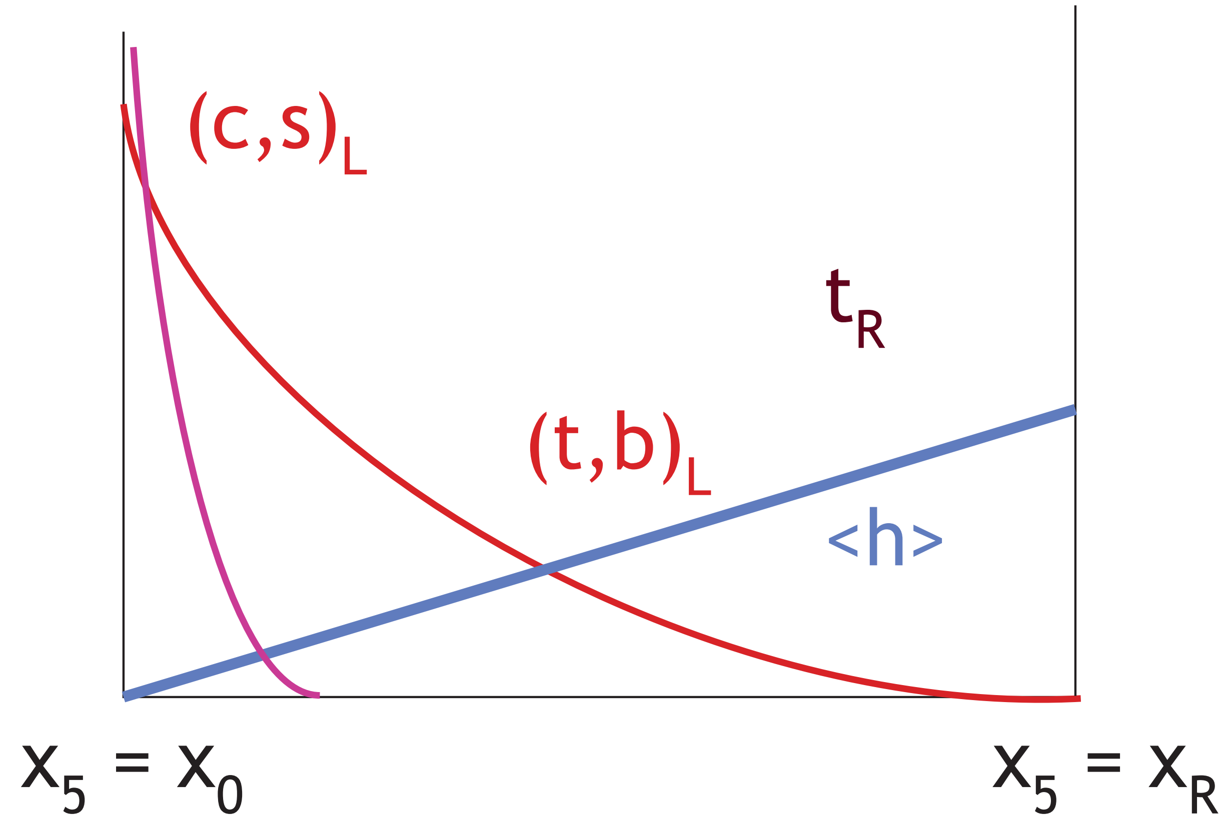
Little Higgs models are based on an effective field theory treatment of the Goldstone bosons. To implement the higher symmetries of Little Higgs models, these always include vectorlike T quarks, e.g.,

$$Q_L = (t, b, T)_L$$

Another way to understand these states is to model the new strong interactions by a warped 5th dimension (Randall-Sundrum construction)

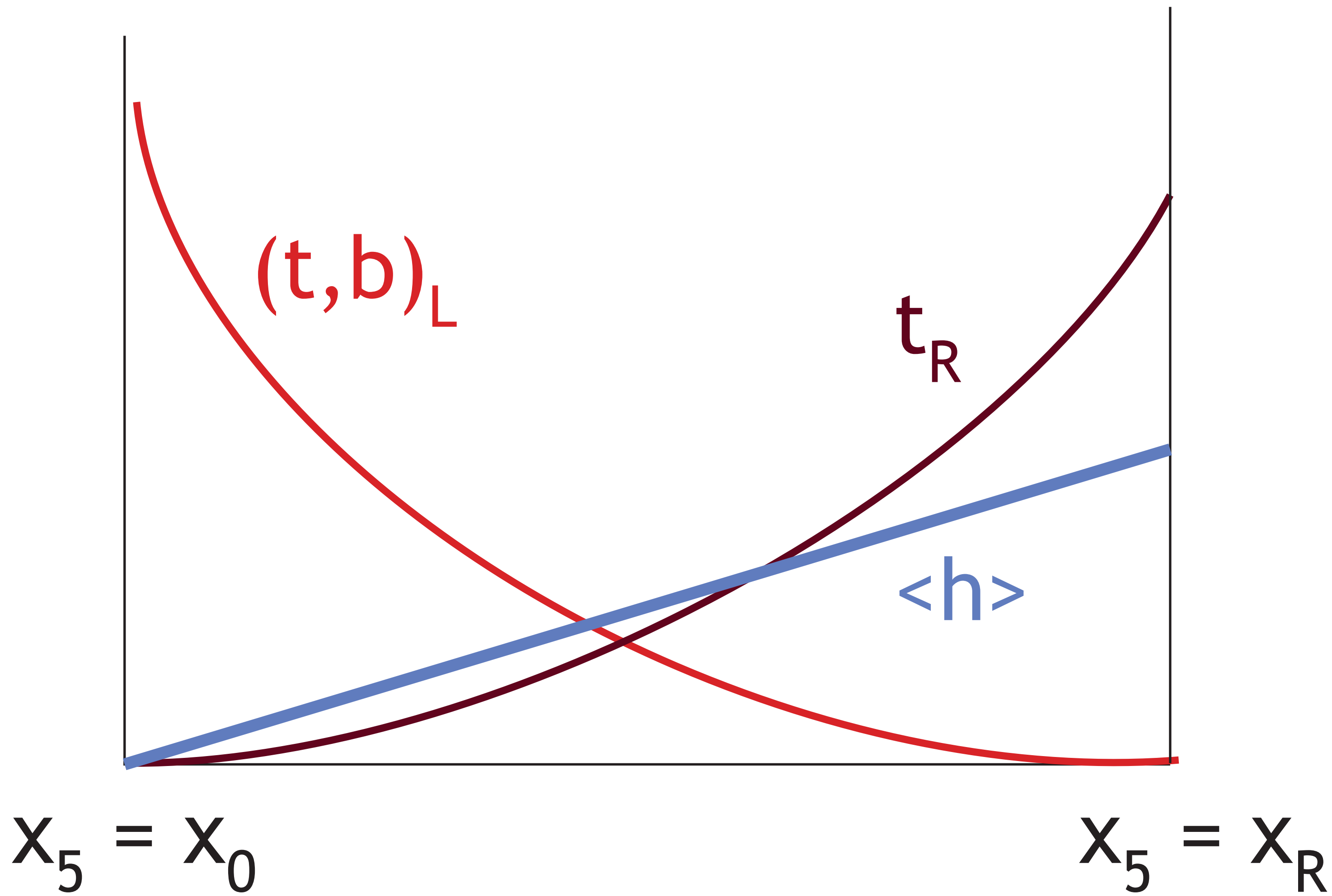
curved (AdS) 5th dimension with

UV physics near $x^5 = x_0 = x_R \exp[-k\pi R]$
IR physics near $x^5 = x_R$
and Higgs localized near $x^5 = x_R$



The $(t,b)_L$ doublet must be elementary, to satisfy precision electroweak constraints ($\Gamma(Z \to b\bar{b})$).

Then t_R must be highly composite, to provide good overlap with the Higgs vev in the 5th dimension



To test this idea, it is crucial to measure the L/R structure of t electroweak couplings.

Parametric dependence of top quark F_1 form factors on the masses of new particles:

$$F_{1V}^{\gamma}(q^2) = 1 + A\frac{q^2}{m_R^2} + \cdots$$

$$F_{1A}^{\gamma}(q^2) = 0 + B\frac{q^2}{m_R^2} + \cdots$$

$$F_{1L}^{Z} = \frac{\frac{1}{2} - \frac{2}{3}s_w^2}{c_w^2 s_w^2} + C\frac{4m_t^2}{m_R^2} + D\frac{q^2}{m_R^2}$$

$$F_{1R}^{Z} = \frac{-\frac{2}{3}s_w^2}{c_w^2 s_w^2} + E\frac{4m_t^2}{m_R^2} + F\frac{q^2}{m_R^2}$$

and

$$F_1^{g}(q^2) = 1 + G\frac{q^2}{m_R^2} + \cdots$$

(probably below the level of LHC pdf errors; but LHC might see the R resonance)

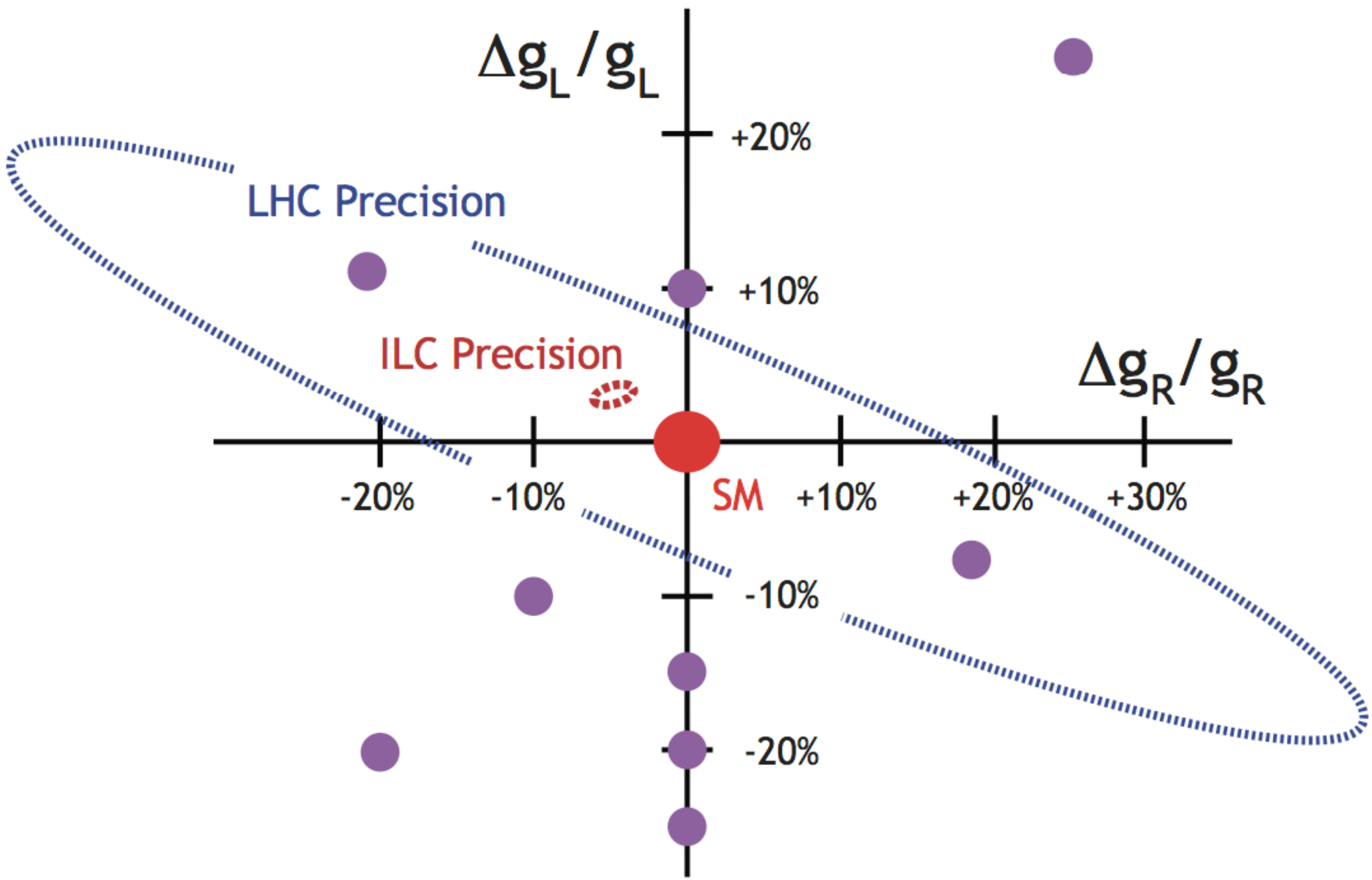
Methods to search for this physics:

LHC search for T HL-LHC expectation $m_T \sim 1.8 \text{ TeV}$

LHC search for R HL-LHC expectation $m_R \sim 6 \text{ TeV}$

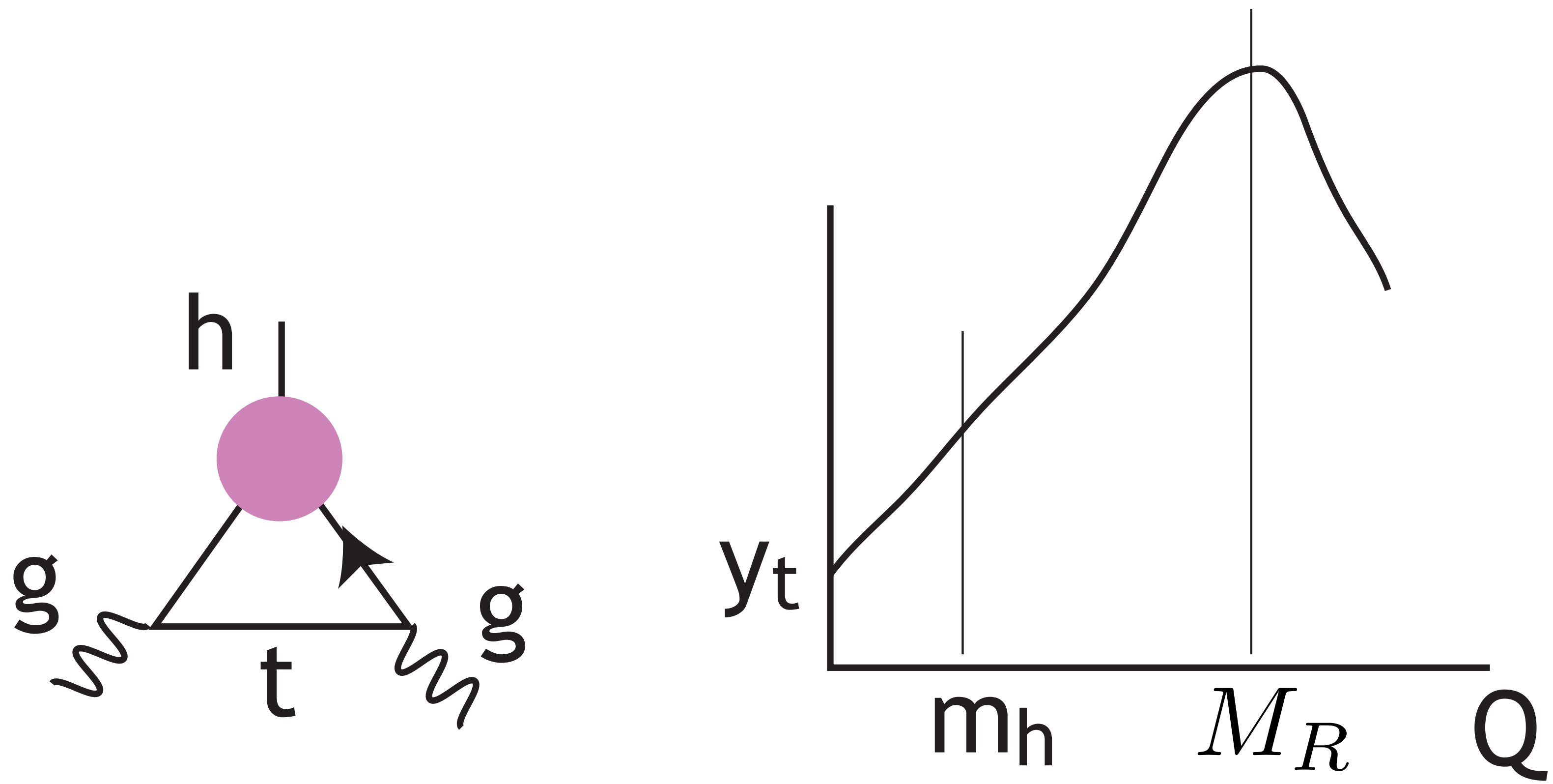
Complementary to these, ILC can measure the values of the $q^2 = 0$ $t\bar{t}Z$ couplings. In models, large effects are predicted. The ILC reach expectation is $m_R \sim 15 \text{ TeV}$.

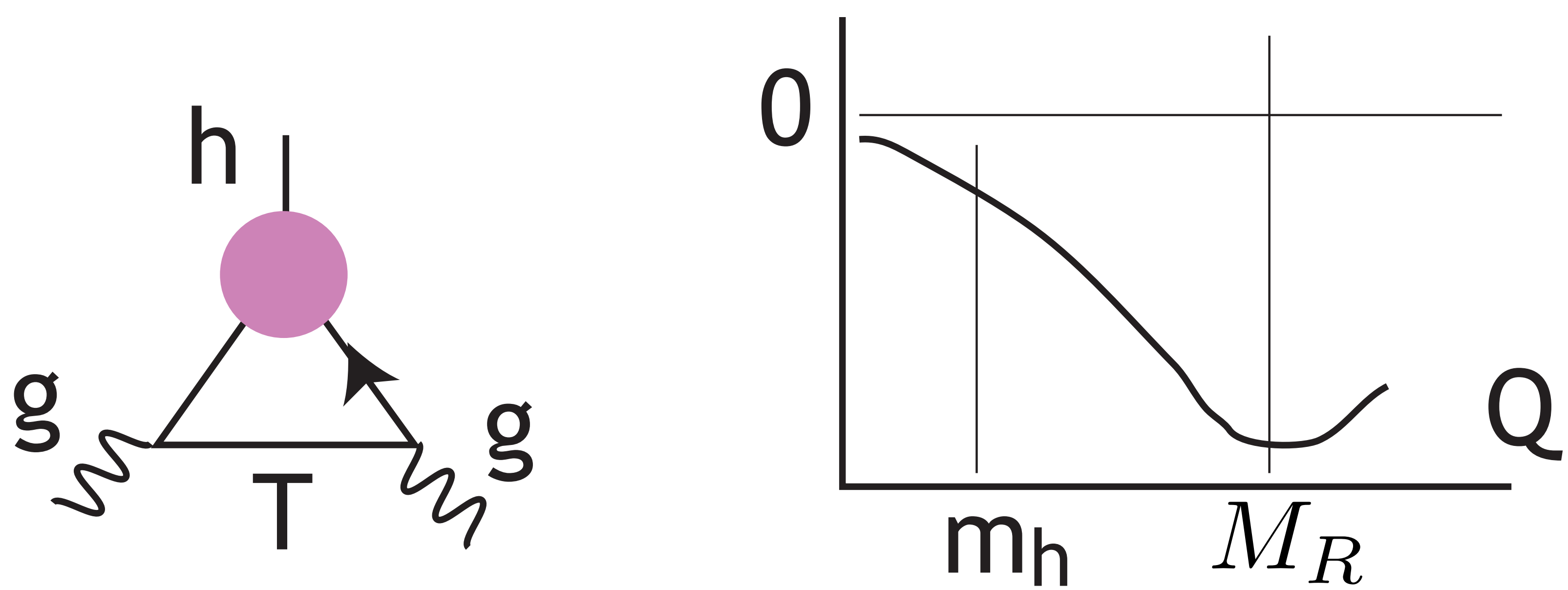
LHC and ILC opportunities to measure the t_L and t_R form factors for coupling to the Z:



models collected by Richard and Wulzer

It is also important to note that T, R modify the Higgs couplings of top. In particular, the hgg is affected in two different ways:





To disentangle possible modifications of the tth coupling from the influence of the T quarks, it is important to make three orthogonal measurements with high precision:

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

$$g(hgg) \quad \text{in} \quad \Gamma(h \to gg)$$

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

Only LC can realize the first two of these measurements with high precision.

Does the top quark have a crucial role in the physics of the TeV energy scale ?

It many models, it is so. In these cases, the properties of new TeV interactions are manifest in the detailed properties of the top quark.

We are not yet sensitive to these effects through hadron collider physics. We need the high precision and new observables that come from studying top in e+e- annihilation.

The top quark needs to be front and center in the physics case for Linear Colliders.