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Top at Future Colliders

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As the heaviest fermion, the top quark is bound to tell us something about electroweak symmetry breaking and the origin of mass, and may even play a special role. In this talk I first review the role of the top quark in the Standard Model and in new physics scenarios. I then discuss what we have to learn from top physics studies in present and future high energy experiments.

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1. Introduction: Top in the Standard Model

It is remarkable that the top quark discovery is more than ten years behind us now. In the interim we have made a great deal of progress in learning whether the particle discovered by CDF and D0 is indeed the Standard Model (SM) top. To establish its identity we need to confirm its properties: charge $+2/3e$, spin and weak isospin equal to 1/2, color triplet, correct CKM matrix elements, and SM gauge couplings to the photon, W and Z bosons, and gluon. So far, all is consistent with the SM. Yet we hope that top is not entirely as described in the SM, because we hope and expect to see new physics in the near future, especially new physics associated with electroweak symmetry breaking. The top quark's huge mass of nearly 175 GeV makes it a unique laboratory for this new physics, for reasons we will see below.

The top quark is produced in pairs at hadron colliders via the strong interaction. At the Tevatron, the dominant process in $q\bar{q} \to t\bar{t}$ via an intermediate gluon. Top pair production at the higher-energy LHC is dominated by $gg \to t\bar{t}$. In both cases the production process is sensitive to the top quark's coupling to the gluon At an e^+e^- collider, top pair production occurs via $e^+e^- \to \gamma^*, Z \to t\bar{t}$ and is sensitive to the $t\gamma$ and tZ couplings. Tops can also be produced singly via an electroweak process. Single top production at hadron colliders proceeds via three different processes, characterized by the role of the W boson (s-channel, t-channel, and tW associated production). Each is sensitive to the tWb coupling.

The top quark decays to a W boson and a b quark nearly 100% of the time in the SM, and the decay is therefore also sensitive to the tWb coupling. The width for top decay is quite large: $\Gamma_t = 1.4$ GeV at next to leading order in the SM. This width is much larger than the characteristic hadronization scale Λ_{QCD}, and therefore top decays before hadronizing, and passes its spin information to its decay products. Although Γ_t is large compared to Λ_{QCD}, it is smaller than typical experimental resolutions for top reconstruction, which means that the top width and the magnitude of the tWb coupling cannot be measured directly. What can be measured in top decay is the structure of the tWb coupling, which in the SM is $V-A$. And of course the top mass itself is measured from kinematic reconstruction of the top quark's decay products. Top decay modes other than Wb are suppressed in the SM by CKM elements or occur only through loops.

Other SM interesting SM top processes include top pairs produced in association with a Higgs boson, at the LHC or ILC, which is sensitive to the top Yukawa coupling, and $t\bar{t}\gamma$ and $t\bar{t}Z$ production which are, respectively, sensitive to the top couplings to the photon and Z boson.

2. Electroweak Symmetry Breaking, Top, and New Physics

In the Standard Model, the Higgs mechanism breaks the electroweak symmetry, giving mass to the weak gauge bosons, and also gives mass to the fermions via a Yukawa interaction. The coupling of the Higgs to a fermion f (Yukawa coupling) is

$$\lambda_f = m_f \sqrt{2}/v$$

where $v = 246$ GeV is the Higgs vacuum expectation value. The top quark is the heaviest fermion and therefore has the largest Yukawa coupling with $\lambda_t \approx 1$. This value may be a coincidence, or it may be telling us that top plays a special role in electroweak symmetry breaking (EWSB). EWSB is considered to be unsatisfying, at best, in the SM. The biggest problem is that the Higgs mass gets quadratically divergent radiative corrections from loops, with

$$\Delta m_h^2 \propto \Lambda^2$$

where Λ is the momentum cutoff in the loop integrals. The top quark contribution dominates these corrections. In the SM, this cutoff is $\Lambda \sim M_{Pl} \sim 10^{19}$ GeV, the scale where gravity becomes strong. But we expect the Higgs mass to be on the scale of the weak interactions, or a couple of hundred GeV. This hierarchy in scales leads to fine-tuning over 17 orders of magnitude, which is deemed unnatural.

Fortunately there are many candidate solutions to the hierarchy problem. The solutions come in roughly three classes. In the first, new particles are introduced to cancel SM divergences. The cancellation requires the new particles to be related to the SM particles via symmetries (hence the "partner" nomenclature for the new particles). In these models, if we require fine-tuning to be no more than about 10%, this implies a scale for the top quark partners of the order of 2 TeV. Because the other SM particles contribute less to the Higgs mass corrections, they can typically have more massive partners than that of the top. This means that the first TeV-scale new physics is very likely associated with top. Examples of models in this class are Supersymmetry and Little Higgs models.

In the second class of solutions to the hierarchy problem, new strong dynamics enters at the TeV scale, thereby lowering the cutoff and eliminating fine-tuning. Now the Higgs is typically composite, and is no longer a fundamental degree of freedom. In these models top typically enters uniquely due to its large mass. Examples of this class of solution include Technicolor and its descendents.

In recent years a third kind of solution to the hierarchy has come along which involves modifying spacetime itself, typically by introducing extra space dimensions to lower the cutoff scale Λ. Λ is still the scale at which gravity becomes strong, but now gravity becomes strong on the TeV scale, so the models are not fine tuned at all and there is no hierarchy of scales. Example in this class include ADD (Arkani-Hamed, Dimopolous, and Dvali), RS (Randall-Sundrum), UED (Universal Extra Dimensions), and Higgsless models.

Each of the above solutions (in all three classes) typically gives rise to new TeV-scale physical degrees of freedom which can potentially be produced at the LHC and/or ILC. Each also affects top phenomenology. And each must reproduce the astounding success of the SM, especially in precision electroweak measurements.

2.1 Supersymmetry

Supersymmetric (SUSY) models contain two Higgs doublets, which give rise to five physical Higgs bosons. Each SM particle gets a partner with opposite spin-statistics (e.g. squarks, sleptons, gluinos, gauginos, etc.) to cancel the Higgs mass divergences. SUSY has a number of attractive features, including the fact that gauge coupling unification is possible and top's large mass gives EWSB automatically. The lightest squark is typically "stop," the partner of the top. SUSY models have many parameters (>100), but they are predictive. In some models, including the Minimal Supersymmetric Standard Model (MSSM), the discrete symmetry R-parity requires SUSY partners to be pair produced. R-parity also implies that the lightest SUSY partner is stable, and therefore a dark matter candidate.

Top plays a prominent role in SUSY. The lightest Higgs mass increases with the top quark mass; indeed, if top were not so heavy the lightest SUSY Higgs may have been observable at LEP2. As for top phenomenology proper, SUSY modifies the top Yukawa coupling, which can be measured in $t\bar{t}H$ production at the LHC and ILC. Top also can appear in cascade decays of heavy partners. And two of the Higgs bosons are charges, with couplings to top and bottom. If the charged Higgs is light enough, it can potentially be seen in top decays through the process $t \rightarrow H^{+}b$.

2.2 Little Higgs Models

In Little Higgs Models, the Higgs field is a Nambu-Goldstone boson of a broken global symmetry. The structure of the symmetry breaking is designed to ensure cancellation of quadratic divergences in m_H without SUSY. In fact the Higgs mass divergences are cancelled by particles with the same spin-statistics as in the SM. The simplest version of these models, called the Littlest Higgs, features several new TeV-scale particles, most notably a vector-like top quark partner T with a mass of about 1-2 TeV. There are also partners to the electroweak gauge bosons as well as a new weak triplet scalar field. In general, Little Higgs models' symmetry group and new particle content are model-dependent. Some models feature a discrete symmetry called T-parity to solve the "little hierarchy problem" (that the 1-2 TeV scale for new physics required by the Higgs mass corrections differs from the 5-7 TeV scale required by precision electroweak measurements). In models with T-parity, the new particles must be pair produced (and do not appear in tree-level exchange processes) and the lightest partner must be stable and is therefore a dark matter candidate.

As for phenomenology, the new T, W', and Z' particles (and any other predicted new particles, if they exist) should be produced at the LHC or ILC. Top phenomenology is particularly affected. The vector-like T can mix with the SM t_L, modifying its couplings to the SM W and Z (both magnitude and structure of the couplings). If there are new gauge bosons and no T-parity, they also mix to modify the top couplings to the W and Z. Top also appears in heavy T decays, via $T \rightarrow tH$ and $T \rightarrow tZ$. In addition, the models predict relations between the masses, couplings, and symmetry breaking scale, which are experimentally testable.

2.3 Technicolor and its Descendents

Technicolor-type models introduce new strong dynamics above the TeV scale to break the electroweak symmetry. Recent versions which account for the large top mass include top-color assisted Technicolor (TC2), in which a new interaction couples preferentially to the third generation. TC2 predicts the existence of new heavy color-octet gauge bosons called topgluons which couple to top, as well as a new $U(1)$ gauge boson called the topcolor Z'. These new gauge bosons can appear in $t\bar{t}$ resonant production, and the LHC can potentially reach masses of 4-5 TeV.

2.4 Modified Spacetime

Modified spacetime models are different form the others in a number of ways, one of which is that top is not so special in them! However top phenomenology is still affected: Top pairs can be produced via s-channel production new Kaluza-Klein particles which these models predict, and top couplings to SM gauge bosons are also modified.

3. Conclusions

Top is unique as a laboratory for studying EWSB and new physics. Its huge mass may be a clue that it is special, and it plays an important role in the SM and beyond. We have many candidates for new physics signals at the LHC and ILC, and much to learn from studying the top quark.