The “Top Priority” at the LHC

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Abstract

The LHC will be a top-quark factory. With 80 million pairs of top quarks and an additional 34 million single tops produced annually at the designed high luminosity, the properties of this particle will be studied to a great accuracy. The fact that the top quark is the heaviest elementary particle in the Standard Model with a mass right at the electroweak scale makes it tempting to contemplate its role in electroweak symmetry breaking, as well as its potential as a window to unknown new physics at the TeV scale. We summarize the expectations for top-quark physics at the LHC, and outline new physics scenarios in which the top quark is crucially involved.

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I. BRIEF INTRODUCTION

The top quark plays a special role in the Standard Model (SM) and holds great promise in revealing the secret of new physics beyond the SM. The theoretical considerations include the following:

- With the largest Yukawa coupling $y_t \sim 1$ among the SM fermions, and a mass at the electroweak scale $m_t \sim v/\sqrt{2}$ (the vacuum expectation value of the Higgs field), the top quark is naturally related to electroweak symmetry breaking (EWSB), and may reveal new strong dynamics [1].

- The largest contribution to the quadratic divergence of the SM Higgs mass comes from the top-quark loop, which implies the immediate need for new physics at the Terascale for a natural EW theory [2], with SUSY and Little Higgs as prominent examples.

- Its heavy mass opens up a larger phase space for its decay to heavy states $Wb$, $Zq$, $H^{0,\pm}q$, etc.

- Its prompt decay much shorter than the QCD scale offers the opportunity to explore the properties of a “bare quark”, such as its spin, mass, and couplings.

Top quarks will be copiously produced at the LHC. The production and decay are well understood in the SM. Therefore, detailed studies of the top-quark physics can be rewarding for both testing the SM and searching for new physics [3].

II. TOP QUARK IN THE STANDARD MODEL

In the SM, the top quark and its interactions can be described by

$$-\mathcal{L}_SM = m_t \bar{t}t + \frac{m_t}{v} H\bar{t}t + g_s \bar{t}\gamma^\mu t G^a_\mu + e Q_t \bar{t}\gamma^\mu t A_\mu$$

$$+ \frac{g}{\cos \theta_w} \bar{t}\gamma^\mu (g_V + g_A \gamma^5) t Z_\mu + \frac{g}{\sqrt{2}} \sum_q V_t q \bar{t}\gamma^\mu P_L q W^-_\mu + h.c. \tag{1}$$

Besides the well-determined gauge couplings at the electroweak scale, the other measured parameters of the top quark are listed in Table [3].
TABLE I: Experimental values for the top quark parameters [4].

| Parameter | Value |
|-----------|-------|
| $m_t$ (pole) | $(172.7 \pm 2.8)$ GeV |
| $|V_{tb}|$ | $> 0.78$ |
| $|V_{ts}|$ | $(40.6 \pm 2.6) \times 10^{-3}$ |
| $|V_{td}|$ | $(7.4 \pm 0.8) \times 10^{-3}$ |

The large top-quark mass is important since it contributes significantly to the electroweak radiative corrections. For instance, the one-loop corrections to the electroweak gauge boson mass can be cast in the form

$$\Delta r = -\frac{3 G_F m_t^2}{8 \sqrt{2} \pi^2 \tan^2 \theta_W} + \frac{3 G_F M_W^2}{8 \sqrt{2} \pi^2} \left( \ln \frac{m_H^2}{M_Z^2} - \frac{5}{6} \right).$$

(2)

With the $m_t$ value in Table I, the best global fit in the SM yields a Higgs mass $m_H = 89^{+38}_{-28}$ GeV [4]. The recent combined result from CDF and D0 at the Tevatron Run II gave the new value [5]

$$m_t = 171.4 \pm 2.1 \text{ GeV}.$$  

(3)

The expected accuracy of $m_t$ measurement at the LHC is better than 1 GeV [6], with errors dominated by the systematics.

To directly determine the left-handed $V-A$ gauge coupling of the top quark in the weak charged current, leptonic angular distributions and $W$ polarization information would be needed [7]. No direct measurements are available yet for the electroweak neutral current couplings, $g_V^t = T_3/2 - Q_t \sin^2 \theta_W$, $g_A^t = -T_3/2$ and $Q_t = +2/3$, although there are proposals to study them via the associated production processes $t\bar{t}\gamma$, $t\bar{t}Z$ [8]. The indirect global fits however indicate the consistency with these SM predictions [4].

A. Top-Quark Decay in the SM

Due to the absence of the flavor-changing neutral currents at tree level in the SM (the Glashow-Iliopoulos-Maiani mechanism), the dominant decay channels for a top quark will be through the weak charged-currents, with the partial width given by

$$\Gamma(t \to W^+ q) = \frac{|V_{tq}|^2 m_t^3}{16 \pi v^2} (1 - r_W)^2 (1 + 2r_W) \left[ 1 - \frac{2 \alpha_s}{3 \pi} \left( \frac{2\pi^2}{3} - \frac{5}{2} \right) \right],$$

(4)

where $r_W = \frac{M_W^2}{m_t^2}$. The subsequent decay of $W$ to the final state leptons and light quarks is well understood. Two important features are noted:
Since $|V_{tb}| \gg |V_{td}|, |V_{ts}|$, a top quark will predominantly decay into a $b$ quark. While $V_{ts}, V_{td}$ may not be practically measured via the top-decay processes, effective $b$-tagging at the Tevatron experiments has served to put a bound on the ratio

$$\frac{B(t \rightarrow Wb)}{B(t \rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2},$$

that leads to the lower bound for $|V_{tb}|$ in Table I.

Perhaps the most significant aspect of Eq. (4) is the numerics:

$$\Gamma(t \rightarrow W^+ q) \approx 1.5 \text{ GeV} \approx 1.5 \times 10^{-24} \text{ s} > \Lambda_{QCD} \sim 200 \text{ MeV}. \quad (6)$$

This implies that a top quark will promptly decay via weak interaction before QCD sets in for hadronization [10]. So no hadronic bound states (such as $\bar{t}t, \bar{t}q$, etc.) would be observed. The properties of a “bare quark” may be accessible for scrutiny.

It is interesting to note that in the top-quark rest frame, the longitudinal polarization of the $W$ is the dominant mode. The ratio between the two available modes is

$$\frac{\Gamma(t \rightarrow b_L W_{\lambda=0})}{\Gamma(t \rightarrow b_L W_{\lambda=-1})} = \frac{m_t^2}{2M_W^2}. \quad (7)$$

**B. Top-Quark Production in the SM**

1. $\bar{t}t$ production via QCD

Historically, quarks were discovered via their hadronic bound states, most notably for the charm quark via $J/\psi(\bar{c}c)$ and bottom quark via $\Upsilon(\bar{b}b)$. Due to the prompt decay of the top quark, its production mechanisms and search strategy are quite different from the traditional one.

The leading processes are the open flavor pair production from the QCD strong interaction, as depicted in Fig. [11] The contributing subprocesses are from

$$q\bar{q}, gg \rightarrow \bar{t}t. \quad (8)$$

The cross sections have been calculated rather reliably to the next-to-leading order [12] and including the threshold resummations [13, 14], as given in Table [11]
FIG. 1: Top-quark pair production in hadronic collisions via QCD interaction. This figure is taken from Ref. [11].

TABLE II: Cross sections, at next-to-leading-order in QCD, for top-quark production via the strong interaction at the Tevatron and the LHC [14]. Also shown is the percentage of the total cross section from the quark-antiquark-annihilation and gluon-fusion subprocesses.

|           | $\sigma_{\text{NLO}}$ (pb) | $q\bar{q} \rightarrow t\bar{t}$ | $gg \rightarrow t\bar{t}$ |
|-----------|-----------------------------|-------------------------------|-----------------------------|
| Tevatron ($\sqrt{s} = 1.8$ TeV $p\bar{p}$) | $4.87 \pm 10\%$ | 90\% | 10\% |
| Tevatron ($\sqrt{s} = 2.0$ TeV $p\bar{p}$) | $6.70 \pm 10\%$ | 85\% | 15\% |
| LHC ($\sqrt{s} = 14$ TeV $pp$) | $803 \pm 15\%$ | 10\% | 90\% |

Largely due to the substantial gluon luminosity at higher energies, the $t\bar{t}$ production rate is increased by more than a factor of 100 from the Tevatron to the LHC. Assuming an annual luminosity at the LHC of $10^{34}$ cm$^{-2}$ s$^{-1}$ $\Rightarrow$ 100 fb$^{-1}$/year, one expects to have 80 million top pairs produced. It is truly a “top factory”. In Fig. 2(a), we plot the invariant mass distribution, which is important to understand when searching for new physics in the $t\bar{t}$ channel. Although the majority of the events are produced near the threshold $m(t\bar{t}) \sim 2m_t$, there is still a substantial cross section even above $m(t\bar{t}) \sim 1$ TeV, about 5 pb. This is illustrated in Fig. 2(b), where the integrated cross section is given versus a minimal cutoff on $m(t\bar{t})$ and decay branching fractions of one top decaying hadronically and the other leptonically have been included.

It should be noted that the forward-backward charge asymmetry of the $t\bar{t}$ events can be generated by higher order corrections, reaching $10 - 15\%$ at the partonic level from QCD [15] and 1\% from the electroweak [16].
FIG. 2: (a) Invariant mass distribution of $t\bar{t}$ at the LHC and (b) integrated cross section versus a minimal cutoff on $m(t\bar{t})$. Decay branching fractions of one top decaying hadronically and the other leptonically ($e, \mu$) have been included.

2. Single top production via weak interaction

As discussed in the last section, the charged-current weak interaction is responsible for the rapid decay of the top quark. In fact, it also participates significantly in the production of the top quark as well [17]. The three classes of production processes, $s$-channel Drell-Yan, $t$-channel $Wb$ fusion, and associated $Wt$ diagrams, are plotted in Fig. 3. Two remarks are in order:

- The single top production is proportional to the quark mixing element $|V_{tb}|^2$ and thus provides the direct measurement for it, currently $0.68 < |V_{tb}| \leq 1$ at the 95% C.L.

- The $s$-channel and $t$-channel can be complementary in the search for new physics such as a $W'$ exchange [19].

For the production rates [20, 21, 22, 23, 24], the largest of all is the $t$-channel $Wb$ fusion. It is nearly one third of the QCD production of the $t\bar{t}$ pair. Once again, it is mainly from the enhancement of the longitudinally polarized $W$. The total cross sections for these processes at Tevatron [23] and LHC energies [24] are listed in Table III [20, 21, 22]. We see the typical change of the production rate from the Tevatron to the LHC: A valence-induced process (DY-
FIG. 3: Single top-quark production in hadronic collisions via the charged-current weak interaction. This figure is taken from Ref. [11].

Type) is increased by about an order of magnitude; while the gluon- or $b$-induced processes are enhanced by about a factor of 100.

TABLE III: Cross sections, at next-to-leading-order in QCD, for top-quark production via the charged current weak interaction at the Tevatron and the LHC.

|               | $\sigma$(pb) | $s$-channel | $t$-channel | $Wt$ |
|---------------|--------------|-------------|-------------|------|
| Tevatron ($\sqrt{s} = 2.0$ TeV $p\bar{p}$) | 0.90 ± 5%   | 2.1 ± 5%   | 0.1 ± 10%  |
| LHC ($\sqrt{s} = 14$ TeV $pp$)          | 10.6 ± 5%   | 250 ± 5%   | 75 ± 10%  |

3. Top quark and Higgs associated production

Of fundamental importance is the measurement of the top-quark Yukawa coupling. The direct probe to it at the LHC is via the processes

$$q\bar{q}, \ g g \rightarrow t\bar{t}H.$$  \hfill (9)

The cross section has been calculated to the next-to-leading-order (NLO) in QCD [26, 27] and the numerics are given in Table II. The cross section ranges are estimated from the uncertainty of the QCD scale.

The production rate at the LHC seems quite feasible for the signal observation. It was claimed [28] that a 15% accuracy for the Yukawa coupling measurement may be achievable with a luminosity of 300 fb$^{-1}$. Indeed, the decay channel $H \rightarrow \gamma \gamma$ should be useful for the search and study in the mass range of $100 < m_H < 150$ GeV [29, 30]. However, the potentially large backgrounds and the complex event topology, in particular the demand on
TABLE IV: Total cross section at the NLO in QCD for top-quark and Higgs associated production at the LHC [27].

| $m_H$ (GeV) | 120 | 150 | 180 |
|------------|-----|-----|-----|
| $\sigma$ (fb) | $634\text{--}719$ | $334\text{--}381$ | $194\text{--}222$ |

the detector performance, make the study of the leading decay $H \to bb$ very challenging [31].

III. NEW PHYSICS IN TOP-QUARK DECAY

The high production rate for the top quarks at the LHC provides a great opportunity to seek out top-quark rare decays and search for new physics Beyond the Standard Model (BSM). Given the annual yield of 80 million $t\bar{t}$ events plus 34 million single-top events, one may hope to search for rare decays with a branching fraction as small as $10^{-6}$.

A. Charged Current Decay: BSM

The most prominent examples for top-quark decay beyond the SM via charged-currents may be the charged Higgs in SUSY or with an extended Higgs sector, and charged technicolor particles

$$t \to H^+b, \quad \pi_T^+b. \quad (10)$$

Experimental searches have been conducted at the Tevatron [32], and some simulations are performed for the LHC as well [3, 33]. It is obvious that as long as those channels are kinematically accessible and have a sizable branching fraction, the observation should be straightforward. In fact, the top decay to a charged Higgs may well be the leading channel for $H^\pm$ production.

More subtle new physics scenarios may not show up with the above easy signals. It may be desirable to take a phenomenological approach to parameterize the top-quark interactions beyond the SM [7, 34], and experimentally search for the deviations from the SM. Those “anomalous couplings” can be determined in a given theoretical framework, either from loop-induced processes or from a new flavor structure. One can write the interaction terms
as

\[ \mathcal{L}_{CC} = \frac{g}{\sqrt{2}} \left( \bar{t}(1 + \delta_L)\gamma^\mu P_L q W^-_\mu + \bar{t}\delta_R \gamma^\mu P_R q W^-_\mu \right) + h.c. \] (11)

The expected accuracy of the measurements on \( \delta_{L,R} \) is about 1% \cite{3,34}, thus testing the top-quark chiral coupling.

B. Neutral Current Decay: BSM

Although there are no Flavor-Changing Neutral Currents (FCNC) at tree level in the SM, theories beyond the SM quite often have new flavor structure, most notably for SUSY and technicolor models. New symmetries or some alignment mechanisms will have to be utilized in order to avoid excessive FCNC. It is nevertheless prudent to keep in mind the possible new decay modes of the top quark such as the SUSY decay channel

\[ t \rightarrow \tilde{t}\chi^0. \] (12)

Generically, FCNCs can always be generated at loop level. It has been shown that the interesting decay modes

\[ t \rightarrow Zc, \ Hc, \ \gamma c, \ gc \] (13)

are highly suppressed \cite{35,36} with branching fractions typically \( 10^{-13} \) -- \( 10^{-10} \) in the SM, and \( 10^{-7} \) -- \( 10^{-5} \) in the MSSM. It has been shown that the branching fractions can be enhanced significantly in theories beyond the SM and MSSM, reaching above \( 10^{-5} \) and even as high as 1\% \cite{37}.

One may again take the effective operator approach to parameterize the interactions. After the electroweak symmetry breaking, one can write them as \cite{38,39,40}

\[ \mathcal{L}_{NC} = \frac{g}{2\cos\theta_w} \sum_{\tau=\pm,q=c,u} \kappa_\tau \bar{t}\gamma^\mu P_\tau q Z_\mu + h.c. \] (14)

\[ + g_s \sum_{q=c,u} \frac{\kappa_9}{\Lambda} \bar{t} \sigma^{\mu\nu} T^a t G^a_{\mu\nu} + eQ_t \sum_{q=c,u} \frac{\kappa_7}{\Lambda} \bar{t} \sigma^{\mu\nu} t A_{\mu\nu} + h.c. \] (15)

The sensitivities for the anomalous couplings have been studied at the LHC by the ATLAS Collaboration \cite{41}, as listed in Table V.
TABLE V: 95% C.L. sensitivity of the branching fractions for the top-quark decays via FCNC couplings at the LHC [41].

| Channel | 10 fb$^{-1}$ | 100 fb$^{-1}$ |
|---------|--------------|--------------|
| $t \rightarrow Zq$ | $3.1 \times 10^{-1}$ | $6.1 \times 10^{-5}$ |
| $t \rightarrow \gamma q$ | $4.1 \times 10^{-5}$ | $1.2 \times 10^{-5}$ |
| $t \rightarrow gq$ | $1.3 \times 10^{-3}$ | $4.2 \times 10^{-4}$ |

IV. TOP QUARKS IN RESONANT PRODUCTION

The most striking signal of new physics in the top-quark sector is the resonant production via a heavy intermediate state $X$. With some proper treatment to identify the top decay products, it is possible to reconstruct the resonant kinematics. One may thus envision fully exploring its properties in the c.m. frame.

A. $X \rightarrow t\bar{t}$, $t\bar{b}$

Immediate examples of the resonant states include Higgs bosons [42], new gauge bosons [43], Kaluza-Klein excitations of gluons [44] and gravitons [45], Technicolor-like dynamical states [1, 3, 46] etc.

The signal can be generically written as

$$\sigma(pp \rightarrow X \rightarrow t\bar{t}) = \sum_{ij} \int \int dx_1dx_2 f_i(M^2_X, x_1)f_j(M^2_X, x_2)$$

$$\times \frac{4\pi^2(2J + 1)\Gamma(X \rightarrow ij)B(X \rightarrow t\bar{t})}{s M_X^2}.$$  \hspace{1cm} (16)

Thus the observation of this class of signals depends on the branching fraction of $X \rightarrow t\bar{t}$ as well as its coupling to the initial state partons. Figure 4 quantifies the observability for a bosonic resonance (spin 0,1,2) for a mass up to 2 TeV at the LHC via $q\bar{q}, gg \rightarrow X \rightarrow t\bar{t}$. The vertical axis gives the normalization factors ($\omega$) for the cross section rates needed to reach a $5\sigma$ signal with a luminosity of 10 fb$^{-1}$. The normalization $\omega = 1$ defines the benchmark for the spin 0, 1 and 2 resonances. They correspond to the SM-like Higgs boson, a $Z'$ with electroweak coupling strength and left (L) or right (R) chiral couplings to SM fermions, and the Randall-Sundrum graviton $\tilde{h}$ with the couplings scaled with a cutoff scale.
FIG. 4: Normalization factor versus the resonance mass for the scalar (dashed) with a width-mass ratio of 20%, vector (dot-dashed) with 5%, and graviton (solid) 2%, respectively. The region above each curve represents values of $\omega$ that give $5\sigma$ or greater statistical significance with 10 fb$^{-1}$ integrated luminosity.

as $\Lambda^{-1}$ for $\tilde{h}q\bar{q}$, and $(\Lambda \ln(M_{pl}^*/\Lambda))^{-1}$ for $\tilde{h}gg$, respectively. We see that a $Z'$ or a graviton should be easy to observe, but a Higgs-like broad scalar will be difficult to identify in the $t\bar{t}$ channel.

It is of critical importance to reconstruct the c.m. frame of the resonant particle, where the fundamental properties of the particle can be best studied. It was demonstrated that with the semi-leptonic decays of the two top quarks, one can effectively reconstruct the events in the c.m. frame. This relies on using the $M_W$ constraint to determine the missing neutrino momentum, while it is necessary to also make use of $m_t$ to break the two-fold ambiguity for two possible $p_z(\nu)$ solutions. Parity and CP asymmetries can be studied.

Top-quark pair events at the high invariant mass are obviously important to search for and study new physics. In this new territory there comes a new complication: When the top quark is very energetic, $\gamma = E/m_t \sim 10$, its decay products may be too collimated to be individually resolved by the detector – recall that the granularity of the hadronic calorimeter at the LHC is roughly $\Delta \eta \times \Delta \phi \sim 0.1 \times 0.1$. This is a generic problem relevant to any fast-moving top quarks from heavy particle decays (see the next sections).
The interesting questions to be addressed may include:

- To what extent can we tell a “fat top-jet” from a massive QCD jet due to showering?
- To what extent can we tell a “fat W-jet” from a massive QCD jet?
- Can we make use of a non-isolated lepton inside the top-jet ($b\ell\nu$) for the top-quark identification and reconstruction?
- Can we do $b$-tagging for the highly boosted top events?

These practical issues would become critical to understand the events and thus for new physics searches. Detailed studies including the detector effects will be needed to reach quantitative conclusions.

B. $T \rightarrow tZ, tH, bW$

In many theories beyond the SM, there is a top-quark partner. These are commonly motivated by the “naturalness” argument, the need to cancel the quadratic divergence in the Higgs mass radiative correction, most severely from the top-quark loop. Besides the scalar top quark in SUSY, the most notable example is the Little Higgs theory [50]. If there is no discrete symmetry, the top partner $T$ will decay to SM particles in the final state, leading to fully reconstructable fermionic resonance.

It was pointed out [51] that the single $T$ production via the weak charged-current may surpass the pair production via the QCD interaction due to the longitudinal gauge boson enhancement for the former and the phase space suppression for the latter. This is shown in Fig. 5. Subsequent simulations [52] performed by the ATLAS collaboration demonstrated the clear observability for the signals above the backgrounds at the LHC for $T \rightarrow tZ, bW$ with a mass $M_T = 1 \text{ TeV}$, as seen in Fig. 6.

V. TOP-RICH EVENTS FOR NEW PHYSICS

Although the top-quark partner is strongly motivated for a natural electroweak theory, it often results in excessively large corrections to the low energy electroweak observables. In order to better fit the low energy measurements, a discrete symmetry is often introduced,
FIG. 5: Production of the top-quark partner $T$ in pair and singly at the LHC versus its mass. The Yukawa coupling ratio $\lambda_1/\lambda_2$ has been taken to be 2 (upper dotted curve) 1 (solid) and 1/2 (lower dotted), respectively. The $T\bar{T}$ pair production via QCD includes an NLO $K$-factor (dashed curve).

such as the R-parity in SUSY, KK-parity in UED, and T-parity in LH [53]. The immediate consequence for collider phenomenology is the appearance of a new stable particle that may provide the cold dark matter candidate, and results in missing energy in collider experiments.\footnote{Alternatively, the breaking of the R-parity [54] or the T-parity [55] would lead to different collider phenomenology [56].}

A. $T\bar{T}$ pair production

The top partner has similar quantum numbers to the top quark, and thus is commonly assigned as a color triplet. This leads to their production in QCD

\[ q\bar{q}, \ g\bar{g} \rightarrow T\bar{T}. \]  

(17)

The production cross section is shown in Fig. 7 for both spin-0 and spin-1/2 top partners. Although there is a difference of a factor of 8 or so (4 from spin state counting and the
FIG. 6: Observability for the decays (a) $T \rightarrow tZ$ and (b) $T \rightarrow bW$ at the ATLAS [52].

rest from threshold effects) in the cross sections, it is still challenging to tell a scalar and a fermionic partner apart [57, 58, 59] due to the lack of definitive features.

Due to the additional discrete symmetry, the top partner cannot decay to a SM particle alone. Consequently, $T \rightarrow tA^0$, leading to $t\bar{t}$ pair production plus large mixing energy. The crucial parameter to characterize the kinematical features is the mass difference $\Delta M_{TA} = m_T - m_A$. For $\Delta M_{TA} \gg m_t$, the top quark as a decay product will be energetic and qualitatively different from the SM background. But if $\Delta M_{TA} \approx m_t$, then the two will have very little difference, making the signal difficult to separate out. Depending on the top-quark decay, we present two classes of signals.

1. $t\bar{t}$ pure hadronic decay

For both $t\bar{t}$ to decay hadronically [58, 60], the signal will be 6 jets plus missing energy. While it has the largest decay rate, the backgrounds would be substantial as well. With judicious acceptance cuts, the signal observability for $\Delta M_{TA} > 200$ GeV was established, as seen in Fig. 8. Possible measurements of the absolute mass scale and its spin of the top partner were considered [57, 58], but the determination remains difficult.
FIG. 7: Leading order total cross section for the top partner $T\bar{T}$ production at the LHC versus its mass \cite{57}. Both spin-0 and spin-1/2 top partners are included. The QCD $t\bar{t}$ and the SM $t\bar{t}Z$ backgrounds are indicated by the horizontal lines.

2. $t\bar{t}$ semi-leptonic decay

If one of the $t\bar{t}$ decays hadronically and the other decays leptonically, the signal may be cleaner. It turns out that if the mass difference $\Delta M_{T_A}$ is sizable, then requiring large missing transverse energy may be sufficient to suppress the background. However, if $\Delta M_{T_A} \sim m_t$, then the $E_T$ for the signal is not much different from the background. On the other hand, the fact that the $t\bar{t}$ kinematics can be fully reconstructed in the SM implies that the reconstruction for the signal events would be distinctive due to the large missing mass. Indeed, the reconstructed $m_t^r$ based on the $E_T$ will be far away from the true $m_t$, and mostly result in an unphysical value. If we impose

$$|m_t - m_t^r| > 110\text{ GeV},$$

we can reach optimal signal identification. The summary plot for the statistical significance (the number of $\sigma$) is given in Fig. \[9\] at the LHC with an integrated luminosity of 100 fb$^{-1}$, where the left panel is for a fermionic $T$, and the right is a scalar $\tilde{t}$, both decaying to $t+$ a missing particle.
FIG. 8: Contour in $m_{\tilde{t}} - m_N$ for $\tilde{t} \to tN$ for the statistical significance of a scalar $\tilde{t}$ at the LHC with an integrated luminosity of 100 fb$^{-1}$. Purely hadronic decays are considered.

B. Exotic top signatures

Searching for exotic events related to the top quark can be rewarding. First, there exists a variety of natural electroweak models with distinctive top partners that should not be overlooked for collider phenomenology. Second, potentially large couplings of the top quark to new physics may result in multiple top quarks from new particle decays. Finally, the exotic events have less SM background contamination, and thus may stand out for discovery even at the early phase of the LHC. We briefly list a few recent examples.

- Multiple top quarks and $b$-quarks in the final state may help to search for new heavy particles in the electroweak sector and can be distinctive from the SM backgrounds [61].

- Heavy top partners and other KK fermions in the RS model may lead to unique top-quark and $W$-boson signatures [62].

- New exotic colored states may predominantly couple to heavy quarks and thus lead
FIG. 9: Contour in $m_T - m_A$ for $T \rightarrow tA$ for the statistical significance at the LHC with an integrated luminosity of 100 fb$^{-1}$. Left panel is for a fermionic $T$, and the right is a scalar $\tilde{t}$, both decaying to a top plus a missing particle.

- to multiple top quarks in the final state [63].

- Composite models for the right-handed top-quark may lead to $tt\bar{t}t$ signals at the LHC [64].

- Like-sign top quark pairs may indicate new dynamics [65].

VI. SUMMARY AND OUTLOOK

The LHC will be a true top-quark factory. With 80 million top-quark pairs plus 34 million single tops produced annually at the designed high luminosity, the properties of this particle will be studied to a great accuracy and the deep questions related to the top quark at the Terascale will be explored to an unprecedented level. Theoretical arguments indicate that it is highly likely that new physics associated with the top quark beyond the SM will show up at the LHC. This article only touches upon the surface of the rich top quark physics, and is focused on possible new physics beyond the SM in the top-quark sector. The layout of this article has been largely motivated by experimental signatures for the LHC. Interesting
signatures covered here include

- Rare decays of the top quark to new light states, or to SM particles via the charged and neutral currents through virtual effects of new physics.
- Top quark pair production via the decay of a new heavy resonance, resulting in fully reconstructable kinematics for detailed studies.
- Top quark pair production via the decay of pairly produced top partners, usually associated with two other missing particles, making the signal identification and the property studies challenging.
- Multiple top quarks, $b$ quarks, and $W^\pm$'s coming from theories of electroweak symmetry breaking or an extended top-quark sector.

The physics associated with top quarks is rich, far-reaching, and exciting. It opens up golden opportunities for new physics searches, while brings in new challenges as well. It should be of high priority in the LHC program for both theorists and experimentalists.

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