Measuring top squark interactions with standard model particles via associated production

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A new particle's interactions can be measured at colliders, by observing its associated production with standard model particles. We focus on the case of a collider-stable right-handed top squark and study the LHC sensitivities to its couplings to the photon, Z, and the Higgs boson. Such measurements determine the top squark's charge, mixing angle, and coupling to the electroweak symmetry breaking sector. Determining these couplings can provide strong evidence for the supersymmetric solution to the hierarchy problem. Our analysis shows that the LHC has great prospects for measuring the photon and Higgs couplings but will require a very high luminosity to measure the Z coupling.

The LHC era is well underway and the next particle physics discovery could be imminent. Determining the fundamental significance of a new particle requires measurements of its properties, some easier than others. For example, its mass is straightforward to measure by kinematics, but determining its spin is challenging. The interactions of the new particle, specifically what it couples to and how strongly, are also quite difficult to measure for the following reasons. The production of a new particle is typically dominated by one type of coupling (e.g. QCD interaction for a colored particle), and it is extremely subtle to extract the dependence on subdominant couplings from the production rate. On the other hand, the decays of the particle can only tell us the ratios of different coupling strengths from branching ratios, with no information on their overall scale.

One can overcome this by considering the "associated production" of the new particle with a known particle. The method is extremely general: given an LHC process producing a new particle X, we consider the higher order diagram where the X particle radiates a standard model (SM) particle Y via the coupling λXXY. This associated Y production has a rate proportional to λ^2, thereby allowing us to measure λ. For example, in the SM, measurements of the associated production of $W + \gamma$ [1,2] and $t\bar{t} + h$ [3–5] can be used to measure the charge of the W and the top quark's coupling to the Higgs, respectively.

In this letter, we consider such measurements in theories with supersymmetry (SUSY), specifically for the *top squark* (or *stop*), i.e. the SUSY partner of the top quark, denoted as $\tilde{t}$. The stop couplings to γ, Z, and h are all potentially measurable. The rate of associated $\tilde{t}\tilde{t}^*$ production with a photon determines the charge of the top squark, verifying it is an up-type squark. The $\tilde{t}\tilde{t}^* + Z$ rate determines the mixing angle between the two stop gauge eigenstates. Finally, the associated production with a Higgs determines how strongly the top squark couples to the source of electroweak symmetry breaking (EWSB).

Extracting these couplings from the observed rates requires knowledge of the stop masses as well as a method of identifying the stops. To demonstrate our procedure and factor out coupling measurements from these issues, we consider a case where the stop is stable on collider time scales. Then, a stop hadronizes into a long-lived massive QCD bound state, an *R-hadron* [6], where its mass can be measured by ionization and time-of-flight measurements in the detector [7]. As long as its lifetime is short on cosmological scales, the *R*-hadron is only limited by collider searches. Moreover, *R*-hadrons have no irreducible SM backgrounds and can be identified with a high efficiency. As a further simplification we use a very minimal SUSY spectrum, namely, a single stop, with all other supersymmetric particles assumed heavy enough that their production rates are small compared to the stop production. This guarantees that there are no additional sources of Z's or Higgses from cascade decays.

Coupling measurements via associated production of a new particle are general and not restricted to the top squark. There is, however, a deep theoretical motivation for measuring the stop couplings: it allows one to experimentally verify that SUSY solves the hierarchy problem of the EWSB scale. SUSY relates the stop-Higgs coupling to the top-Higgs coupling so that the quadratically divergent contribution of the top quark to the Higgs mass-squared parameter is precisely cancelled by that of the top squark. Thus, the stop coupling measurements will test this cancellation that allows the EWSB scale to be naturally lower than the Planck scale. Our method is complementary to the "sum rule" approach to verifying SUSY naturalness [8] as well as the tests of other supersymmetric relations among interactions [9,10]. Our method can also be used to test the naturalness of Little Higgs models, in addition to other approaches [11–14].

The rest of the paper is as follows: we first review the interactions of top squarks to SM particles and choose

benchmark coupling values. We then analyze the benchmark in detail to determine expected sensitivities of our procedure at the LHC. Finally, we conclude.

I. SUSY RELATIONS AND THE BENCHMARK

In this section, we discuss stop interactions with SM particles with the goal of determining benchmark coupling values. In the Minimal Supersymmetric Standard Model (MSSM), there are two gauge eigenstates for the stops, $\tilde{t}_L$ and $\tilde{t}_R$, SUSY partners to the SM fields, t_L and t_R. Mass eigenstates come from diagonalizing the stop mass matrix in the $\tilde{t}_L$-$\tilde{t}_R$ basis:

$$m_{LL}^2 = m_L^2 + m_t^2 + \left(\frac{g^2}{8} - \frac{g'^2}{24}\right)v^2 \cos 2\beta, \quad (1)$$

$$m_{LR}^2 = m_{RL}^2 = -(A_t \sin\beta + y_t \mu \cos\beta)\frac{v}{\sqrt{2}}, \quad (2)$$

$$m_{RR}^2 = m_R^2 + m_t^2 + \frac{g'^2}{6}v^2 \cos 2\beta. \quad (3)$$

The parameters, assumed to be real, are $m_{L,R}^2$, the soft SUSY breaking masses of the stops, A_t, the coefficient of the scalar trilinear coupling $H_u \tilde{q}_{3L} \tilde{t}_R$, and μ, the Higgsino mass parameter. The SM parameters are the $SU(2)_L \times U(1)_Y$ couplings g and g', the top quark mass m_t, and the EWSB vacuum expectation value $v^2 = v_u^2 + v_d^2 \simeq (247 \text{ GeV})^2$, where $v_{u,d}/\sqrt{2} \equiv \langle H_{u,d}^0 \rangle$. Finally, the SUSY top Yukawa coupling y_t is fixed through $m_t = y_t v_u/\sqrt{2}$, and $\tan\beta \equiv v_u/v_d$. For a review, see Ref. [15]. The mass eigenstates $\tilde{t}_{1,2}$, ordered in increasing mass, are $\tilde{t}_1 = \tilde{t}_L \cos\theta_t + \tilde{t}_R \sin\theta_t$, $\tilde{t}_2 = \tilde{t}_L \sin\theta_t - \tilde{t}_R \cos\theta_t$.

As mentioned earlier, we will now focus on the interactions of $\tilde{t}_1$ only, assuming that $\tilde{t}_2$ is sufficiently heavy and decoupled. We will comment in the conclusions on the complications due to $\tilde{t}_2$.

The $\tilde{t}_1$ couplings relevant for single γ/Z emission are

$$\mathcal{L}_{\text{gauge}} = i\left(\frac{2}{3}eA_\mu + g_{\tilde{t}_1 \tilde{t}_1 Z}Z_\mu\right)(\partial^\mu \tilde{t}_1^*)\tilde{t}_1 + \text{c.c.},$$

$$g_{\tilde{t}_1 \tilde{t}_1 Z} = e\left[\left(-\frac{1}{2}\cot\theta_W + \frac{1}{6}\tan\theta_W\right)\cos^2\theta_t\right.$$
$$\left. + \frac{2}{3}\tan\theta_W \sin^2\theta_t\right]. \quad (4)$$

Furthermore, for each of these gauge boson couplings, there is a 4-point vertex including a gluon, which we include when we generate inclusive event samples.

The stop couplings to the Higgs are more complicated, due to the mixing of the two Higgs fields, H_u and H_d. Again, for the purpose of demonstrating the principle, we take the lightest Higgs eigenstate h to be aligned with the direction of the vacuum, (v_u, v_d), in the H_u-H_d space. This is the case in the decoupling limit, where the other Higgs bosons A^0, H^0, $H^\pm$ are much heavier than h. The coupling of $\tilde{t}_1$ to h is then given by

$$\mathcal{L}_{\text{Higgs}} = -\lambda_{\tilde{t}_1 \tilde{t}_1 h}h|\tilde{t}_1|^2,$$

$$\lambda_{\tilde{t}_1 \tilde{t}_1 h}v = 2m_t^2 - \frac{1}{2}(m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)\sin^2 2\theta_t$$

$$+ 2v^2\left[\left(\frac{g^2}{8} - \frac{g'^2}{24}\right)\sin^2\theta_t + \frac{g'^2}{6}\cos^2\theta_t\right]\cos 2\beta. \quad (5)$$

Here, we see that, for small mixing ($\theta_t \to 0$ or $\pi/2$) and gauge couplings (g, $g' \to 0$), $\lambda_{\tilde{t}_1 \tilde{t}_1 h} \approx 2m_t^2/v = y_t^2 v$. This contribution comes from the quartic coupling between stops and Higgs bosons, $y_t^2|H_u^0|^2(|t_L|^2 + |t_R|^2)$, that is required by SUSY to cancel the top quark contribution to the Higgs mass quadratic divergence. Thus, measuring a coupling of this size would be strong evidence that SUSY solves the naturalness problem of EWSB. On the other hand, the mixing term in Eq. (5) tends to cancel this contribution and, for large enough stop mass differences, dominates the trilinear coupling. In that case, testing SUSY naturalness requires measuring both stop masses and the mixing angle in order to isolate the interesting contribution from the Higgs-Higgs-stop-stop quartic coupling.

As a benchmark, we take the case where the lightest stop is right handed ($\theta_t = \pi/2$). This determines that $g_{\tilde{t}_1 \tilde{t}_1 Z} \approx 0.11$ and $\lambda_{\tilde{t}_1 \tilde{t}_1 h} \approx 230$ GeV for moderately large $\tan\beta$. For other scenarios, these couplings can be larger. For instance, the Z coupling goes from 0.11 to -0.27 as θ_t varies from $\pi/2$ to 0. The Higgs trilinear can also be much larger; with nontrivial mixing and splitting between the stops the coupling can become an order of magnitude larger than the $2m_t^2/v$ value. Therefore, our benchmark provides conservative estimates of the sensitivities to the stop couplings to
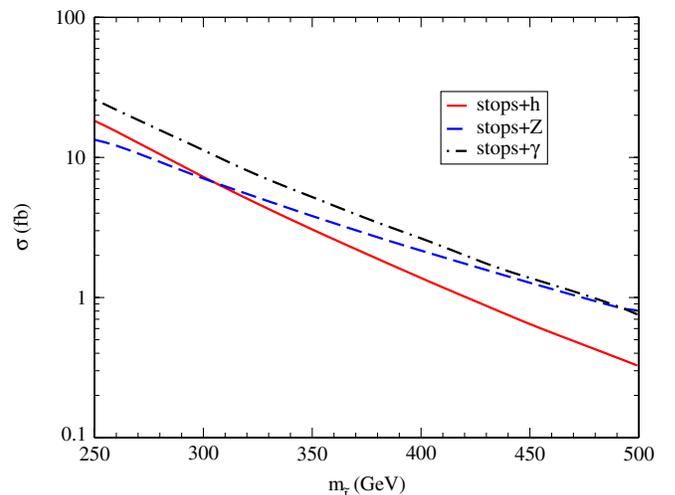

FIG. 1 (color online). The associated production cross sections as a function of stop mass with the benchmark couplings at the LHC with 14 TeV center of mass energy. A Higgs mass of 120 GeV was used. Photons were required to have $p_T > 10$ GeV. The backgrounds from initial state radiation have been subtracted for each final state.

Z and h. For the benchmark values, we determine the collider rates of associated production of γ, Z, h with the $\tilde{t}_R$. See Fig. 1 for the values.

II. COLLIDER ANALYSIS

To perform our collider analysis, we follow the recent CMS and ATLAS R-hadron analyses [16,17]. Triggering is a crucial issue in an R-hadron search, where CMS employs muon, jet, and calorimetric missing E_T (MET) triggers, while ATLAS only uses the last option. Since R-hadrons are minimum-ionizing particles, they will cause an imbalance of calorimetric transverse energy. At production, R-hadrons can hadronize as neutral or charged and can change charge through interactions with the detector material, see [18]. Thus, they can appear as completely neutral with no track in the inner detector. Even if they become charged on the way out and reach the muon system, reconstruction will likely fail without an associated track. If instead, it hadronizes as a charged particle, reconstruction difficulties can still arise if they neutralize while traversing the detector or if they undergo charge oscillations, leading to oppositely curved tracks in the muon system. Furthermore, since R-hadrons are heavy, they are not ultrarelativistic and may not make their way to the outer parts of the detector within the same bunch crossing.

Because of the added subtleties of triggering on R-hadrons as heavy muons (which requires that the R-hadron retain its charge all the way through the detector), and given the high efficiency of the MET trigger used by ATLAS, we choose to implement this trigger for our analysis. We estimate the trigger threshold for the 14 TeV LHC run by doubling that used at 7 TeV [17], requiring the calorimetric MET of the event (neglecting the small contribution from the R-hadrons) to be greater than 80 GeV. Furthermore to be reconstructed, at least one of the R-hadrons must: I) hadronize as a charged particle (assuming this charge is retained in the tracker), II) have a velocity in the range $0.2 < \beta\gamma < 1.5$, III) have $p_T > 50$ GeV and $|\eta| < 1.7$, and IV) have $\Delta R > 0.5$ to the nearest jet with $E_T > 50$ GeV, where p_T is the transverse momentum, $\eta \equiv \ln[\cot(\theta/2)]$ the pseudorapidity, and $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$ the η-ϕ distance. Such requirements are adopted from the recent ATLAS search [17]. We use a subroutine supplied on the Pythia [19] webpage to determine the stop charge fractions upon hadronization and find that the probability for exactly one (two) of the R-hadrons to be charged to be 0.48 (0.33). We assume that these probabilities are independent of the kinematics of the event. We assume that when one R-hadron satisfies these criteria, reducible SM backgrounds become negligible.

We generate parton level events at leading order using the usrmod functionality of MADGRAPH [20,21] for three choices of $m_{\tilde{t}}$, at 320, 360, and 400 GeV, which are above the current limits [16,17]. For each mass point, we use the MLM matching procedure in MADGRAPH to generate

samples of $\widetilde{tt}^*$ + jet(s), $\widetilde{tt}^*$ + $b\bar{b}$ (including a SM Higgs signal with $m_h = 120$ GeV), $\widetilde{tt}^*Z$ + jet, and $\widetilde{tt}^*\gamma$ + jet. We then pass the events through Pythia for showering and hadronization and PGS [22] to simulate detector effects. We use the default ATLAS parameter set for PGS, with a cone jet algorithm of $\Delta R = 0.7$. Since stable colored particles are difficult to handle with these tools, we modify the parton level events such that the stops are treated as particles with no SM charges and reinsert them into the event record in the offline analysis.

For the Higgs search, we use the $\widetilde{tt}^*$ + jet(s) sample as background and $\widetilde{tt}^*$ + $b\bar{b}$ as both signal and background since in addition to Higgs production this sample includes QCD and electroweak sources of b quark production. We demand two heavy flavor tags in each event, with the following tagging procedure: for each b parton in the event, we find the highest $p_T > 20$ GeV PGS jet, within $\Delta R = 0.7$ of the parton. We assume a flat b-tag rate of 0.6 for such jets and a 0.02 mistag rate for light jets [23].

Looking at the distribution of the invariant mass of two b-tagged jets in the range [80–160] GeV, see, for example, Fig. 2, we chose to analyze the [96–128] GeV mass window. For this bin, the measured coupling's 1σ error determined from the change in the log-likelihood is $\frac{\delta\lambda}{\lambda} = \frac{\sqrt{S+B}}{2S}$. We require a measurement of the Higgs coupling to an accuracy of 25%, $\frac{S}{\sqrt{S+B}} = 2$, where we treat the events that have a Higgs resonance at parton level as signal. The target luminosity for this criterion can be found in Table I.

In order to study the coupling of the stop to the photon, we use the $\widetilde{tt}^*\gamma$ + jet as signal and the $\widetilde{tt}^*$ + jet(s) sample as background, where we assume a flat rate of 5×10^{-4} as the probability of a jet faking a photon. We also generate a $\widetilde{tt}^*\gamma$ + jet sample where the stops have no electric charge, i.e. the photons come from initial state radiation (ISR)
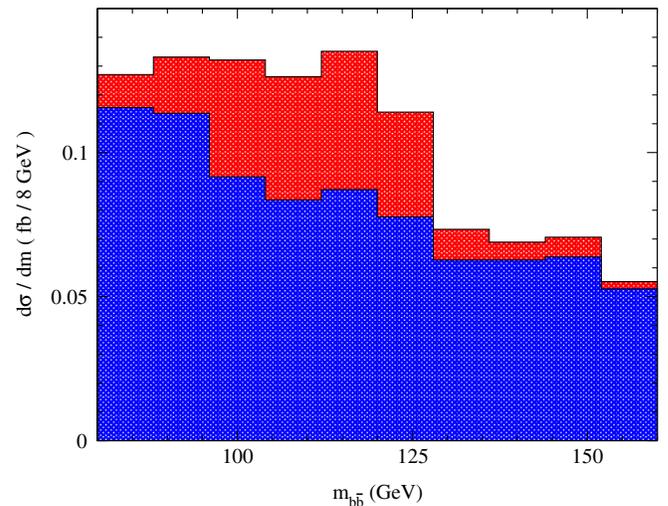

FIG. 2 (color online). The invariant mass of b-jet pairs in association with top squarks of $m_{\tilde{t}} = 320$ GeV. The signal of a 120 GeV Higgs is stacked on top of the background.

TABLE I. Luminosity (in fb^{-1}), followed by S/B for that luminosity in parentheses, required to measure the benchmark stop couplings to Higgs, γ and Z with a statistical error of 25%. For the Higgs and Z, the luminosity required for a coupling twice as large is also listed.

$m_{\tilde{t}}$	Higgs	$2 \times$ Higgs	γ	Z	$2 \times Z$
320	71 $\left(\frac{11.8}{23.1}\right)$	9 $\left(\frac{6.0}{2.9}\right)$	6 $\left(\frac{8.3}{8.9}\right)$	1050 $\left(\frac{14.3}{36.5}\right)$	121 $\left(\frac{6.6}{4.2}\right)$
360	135 $\left(\frac{12.4}{26.0}\right)$	17 $\left(\frac{6.1}{3.2}\right)$	12 $\left(\frac{9.1}{11.8}\right)$	3600 $\left(\frac{20.1}{80.6}\right)$	360 $\left(\frac{8.0}{8.1}\right)$
400	282 $\left(\frac{13.9}{34.2}\right)$	33 $\left(\frac{6.5}{4.0}\right)$	19 $\left(\frac{9.2}{12.0}\right)$	4330 $\left(\frac{18.1}{63.6}\right)$	450 $\left(\frac{7.5}{6.6}\right)$

only. We consider these ISR photons as part of the background. By studying another sample with the stops having twice their normal electric charge, we find that the cross section of signal, obtained from subtracting the background sample from the signal + background sample, scales like the stop charge squared, demonstrating that photons from stops do not significantly interfere with ISR. We use the same trigger criteria as described above and accept only photons with $|\eta| < 2.5$ and $p_T > 50$ GeV. We find that a second trigger (100 GeV photon +50 GeV MET) has negligible effect on the analysis.

While the p_T distribution of the signal and background look very similar, the fake and ISR photons have a flat distribution in η, while the photons emitted from stops peak at central values and cut off at $|\eta| \sim 2$, see Fig. 3. Therefore, in a realistic analysis, the $|\eta| > 2$ could be used as a sideband, but here we take the whole range. For the stop charge measurement, the fake and ISR photons are background, and those produced off stops are signal. Table I lists the luminosity needed to measure the stop charge to 25%, showing it is possible to measuring the charge for an R-hadron in early data.
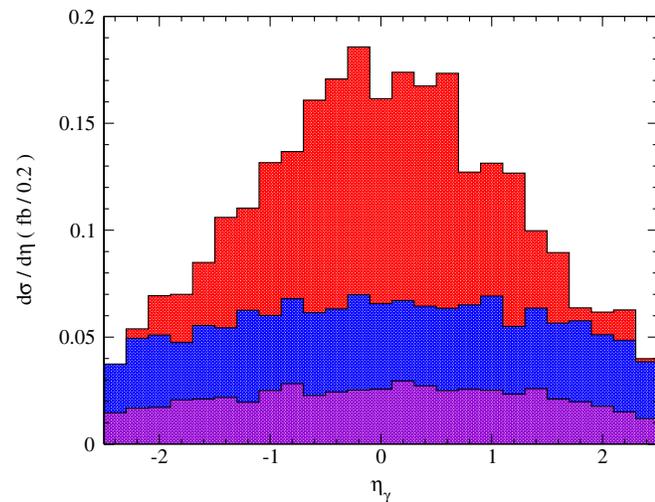
Finally in order to measure the Z coupling to the stop, we use the $\tilde{t}\tilde{t}^*Z$ + jet sample and consider leptonic Z decays. We use a trigger based on the presence of an oppositely charged e or μ pair, where both leptons have $p_T > 25$ GeV, $|\eta| < 2.5$ and an invariant mass within 6 GeV of m_Z. Backgrounds for this final state are assumed negligible. Unfortunately, unlike the γ search, there is no simple kinematic variable that distinguishes Z's from ISR versus those produced off stops. Plus, the small Z branching ratio to leptons leaves little statistics to cut on a differential distribution, forcing us to rely on Monte Carlo and do a simple counting experiment.

We treat Z's from ISR as background, and as in the photon case, we verify that there is no significant interference between ISR and emission from stops. As shown in Table I, we find that an integrated luminosity of $O(\text{ab}^{-1})$ is needed to measure the Z coupling with 25% accuracy. Prospects for a coupling twice as large, close to that of a $\tilde{t}_L$, are much more promising but still require $\gtrsim 100$ fb^{-1}. Note that due to limited statistics, our results are more uncertain for this case than the others.

Uncertainties: The 25% error on these couplings is only statistical and does not take into account systematics. The uncertainty from the Higgs mass will be small, since it will be measured to $\sim 1\%$ in its diphoton decay [3,4], given ~ 30 fb^{-1}. The mass resolution of a stop R-hadron is expected to be $\sim 12\%$ [16], and conservatively, we assume the mass can be measured to 5%. Propagating this uncertainty into the signal cross section, using Fig. 1, leads to systematic uncertainties of 10%–15% in the couplings. Finally, further uncertainties due to efficiencies and K-factors as well as other experimental errors require rigorous experimental and theoretical analyses to be quantified.

III. CONCLUDING REMARKS

In this note, we have studied the LHC capabilities to measure top squark couplings to the photon, Higgs and Z boson, assuming a simplified scenario of a long-lived top squark. For conservative values of these couplings, those of a right-handed stop, we found the Higgs and photon couplings can be measured with $\lesssim 100$ fb^{-1}, while the Z coupling requires $O(\text{ab}^{-1})$. This suggests that, with enough data, it is possible to identify an R-hadron by its charge as an up-type squark and argue that it is a top squark through its strong Higgs coupling. Moreover, the benchmark Higgs coupling comes dominantly from the supersymmetric generalization of the top quark Yukawa. A measurement consistent with this value would be strong evidence that the top squark's couplings are supersymmetric and that supersymmetry is solving the hierarchy problem.

It is worth exploring these measurements in scenarios where the top squarks promptly decay into top quarks and a neutralino. Since top quarks produce a bottom-jet each, there are combinatorial issues for the Higgs measurement,

FIG. 3 (color online). The η distribution of photons, with $p_T > 50$ GeV, produced in association with top squarks of $m_{\tilde{t}} = 320$ GeV. Stacked from top to bottom are signal, ISR photons, and the jet fake background.

which could benefit from existing top squark studies [24,25]. The photon measurement is also affected by similar complexities. Another issue is the potential contamination from decays of the heavier top squark (or sbottom). Such events could be distinguished by the additional cascade decay products. In cases where these heavy particles are relevant, there are additional handles on the stop mixing angle, such as the heavy stop mass and the SUSY Higgs mass prediction.

To conclude, this measurement technique can be applied to any new particle that has a large direct production rate at the LHC. We hope it will become experimentally useful as the LHC era evolves.

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Note added in proof.—During the process of this project, we learned of independent work by M. Luty and D. Phalen that considers similar Higgs signals produced with *R*-hadrons [26]. After this paper was submitted for publication, a CMS note [27] has appeared, which places a preliminary lower bound of 515 GeV on the mass of a stop *R*-hadron. While this is higher than all benchmark masses considered in this paper, our method is general and can apply to nonminimal SUSY theories as well as non-SUSY theories, as we have emphasized in the introduction. However, coupling measurements for the case of promptly decaying stops remains promising. As briefly discussed in the conclusions, there are additional complications for this phenomenology, but could be potentially overcome by existing techniques in the literature.

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