PROCEEDINGS OF SCIENCE

Top Production and Search for SUSY at LHC

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Top quark production is discussed in the framework of SUSY searches with the two general-purpose detectors at LHC, ATLAS and CMS. Top quark appears both in signal and in backgrounds, so knowing top quark features is crucial for the analysis.

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1. Introduction

Although the standard model (SM) of the elementary particles explains precisely the data from the colliders, there are some remaining fundamental questions raised by the SM itself that don't have any explanation. For example radiative loop corrections to the higgs mass like in figure 1 give

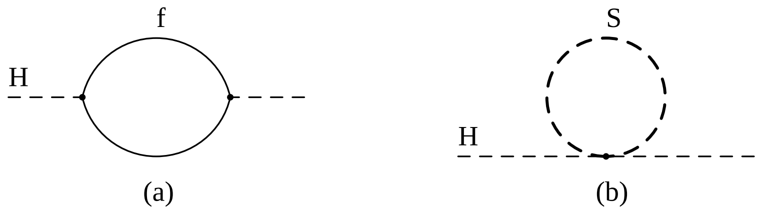


Figure 1: Loops affecting the squared Higgs mass from (a) fermions trilinear couplings, (b) scalars quartic couplings [1].

a correction

$$\Delta m_H^2|_f = \frac{\lambda_f^2}{8\pi^2}[-\Lambda^2 + 6m_f^2 ln\frac{\Lambda}{m_f}] \tag{1.1}$$

where Λ is the upper limit of the momentum. The leading term diverges quadratically (The **Quadratic Divergency Problem**). This divergence can be removed by introducing a cut-off scale on momentum. Its value is the higher limit of energy up to which SM is valid. Usually this limit is $M_{Pl} \equiv (8\pi G_{Newton})^{-1/2} = 2.4 \times 10^{18}$ GeV, at which gravity has a strength comparable to the other interactions and SM must be modified. This enormous disparity of scales between electroweak and M_{Pl} is not natural and is called the **hierarchy problem** [1]. If another scalar exists which couples to the Higgs by a quartic interaction of the form $-\lambda_S|H|^2|S|^2$ (see figure 1(b)), it contributes to the Higgs mass by:

$$\Delta m_H^2|_S = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 ln\frac{\Lambda}{m_S}] \tag{1.2}$$

It also generates a quadratic divergence, but because of Fermi statistics, its sign is opposite to the one of the fermions. Assuming there are two scalar partners for every fermion with couplings $\lambda_S = \lambda_f^2$ the quadratic divergencies cancel exactly.

To solve the hierarchy problem this theory should contain nearly degenerate fermions and scalars and adequately chosen couplings. It is exactly what **supersymmetry** (SUSY) postulates, the existence of supersymmetric partners for every SM particle, which have exactly the same quantum numbers and mass, but differ by 1/2 in their spin.

The super partners of the fermions are called with same name starting with "s", e.g stop, and the superpartners of bosons are called with same name ending with "ino", e.g wino.

SUSY particles have not been discovered yet, so they are not at the same mass as their SM partners. It means that supersymmetry is a broken symmetry and SUSY particles are heavier. There are different mechanisms to break this symmetry softly (without generating quadratic divergencies). Here we consider a very constrained scenario where gravity is responsible for SUSY breaking and the Z^0 mass is produced by radiative electroweak symmetry breaking. This model is called **mSUGRA**. The particle masses and branching ratios in mSUGRA are defined completely by only 5 parameters:

m_0 common scalar mass at the Grand Unification Theories (GUT) scale.

$m_{1/2}$ common gaugino mass at GUT scale.

A_0 common trilinear coupling at GUT scale.

tanβ ratio of the vacuum expectation values for H_u and H_d.

sign(μ**)** μ is the higgs mixing parameter.

In the followings the search for SUSY in two main experiments (ATLAS [2] and CMS [3]) at the Large Hadron Collider (LHC) [4] which is going to start data taking in summer 2007 will be reviewed by two examples emphasizing the role of the top quark as both signal and background.

2. Mass measurement for stop in ATLAS

In a study [5] ATLAS considers a benchmark point in mSUGRA (SPS5) which is characterized with the following parameters:

$$m_0 = 150\ GeV,\ m_{1/2} = 300\ GeV,\ A_0 = -1000\ GeV,\ tan\beta = 5,\ \mu > 0 \tag{2.1}$$

They use the gluino decay to stop squark $\tilde{g} \rightarrow \tilde{t}_1 t \rightarrow tb\tilde{\chi}_1^{\pm}$ (BR = 38%) with hadronic decay of top ($t \rightarrow bW \rightarrow bjj$) to reconstruct the kinematic endpoint of the top-bottom (tb) invariant mass. The relevant masses in this benchmark are as follow (all in GeV/c^2):

$$\begin{array}{cccc} m(\tilde{g}) = 719 & m(\tilde{t}_1) = 236 & m(\tilde{q}_L) = 644 & m(\tilde{q}_R) = 621 \\ m(\tilde{\chi}_1^{\pm}) = 226 & m(\tilde{\chi}_2^0) = 226 & m(\tilde{\chi}_1^0) = 120 & \end{array} \tag{2.2}$$

To maximize the statistics, they look at the inclusive production of a gluino with a light squark. The light squark decays to another quark plus a gaugino. Because of the large difference between the mass of squark and gauginos ($>$ 400 GeV/c^2), this quark will appear as a very hard jet. They use ATLFAST [6], a parameterized simulation of the ATLAS detector, to simulate the detector response. To isolate the signal and suppress the backgrounds, the following selection cuts are applied:

1. $E_T^{miss} > 200$ GeV, because of two $\tilde{\chi}_1^0$'s in every event.
2. no isolated electrons or muons (in this benchmark point the relevant gauginos mostly decay to τ).
3. at least three light jets with $p_T(j_1) > 300$ GeV/c (originating from $\tilde{q}$) , $p_T(j_2, j_3, ..) > 30$ GeV/c (two light jets from W decay) and $|\eta| < 3$.
4. only two b-jets with $30 < p_T(b_1) < 50$ GeV/c (the mass difference between $\tilde{t}_1$ and $\tilde{\chi}_1^{\pm}$ is only 10 GeV/c^2) and $30 < p_T(b_2) < 150$ GeV/c (The upper limit on $p_T(b_2)$ is introduced to suppress the SUSY backgrounds).

To find the tb invariant mass distribution, first the top quark must be reconstructed. Excluding the most energetic jet, all jj combinations are made, if $|M_{jj} - m_W| < 15$ GeV/c^2 (W region) they are combined with two b-jets. The closest bjj combination to m_t is chosen as the top quark if after scaling the four momentum of jets in jj to have $m_{jj} = m_W$, still $|M_{bjj} - m_t| < 30$ GeV/c^2. The top-bottom invariant mass was reconstructed if the remaining b-jet had $p_T < 50$ GeV/c and was closer than 2 *rad* to the direction of the reconstructed top quark. To estimate the combinatorial background from SUSY events with fake W, jet pairs with the invariant masses within $|M_{jj} - (m_W \pm 30)| <$ 15 GeV/c^2 (A and B regions) were scaled linearly to the zone $|M_{jj} - m_W| < 15$ GeV/c^2 and the same procedure for top and top-bottom mass reconstruction was repeated. Assuming half of these events represent the number of fake W events, background fractions in top and top-bottom mass distributions were estimated. Background distributions estimated with this method are presented in figures 2 and 3.

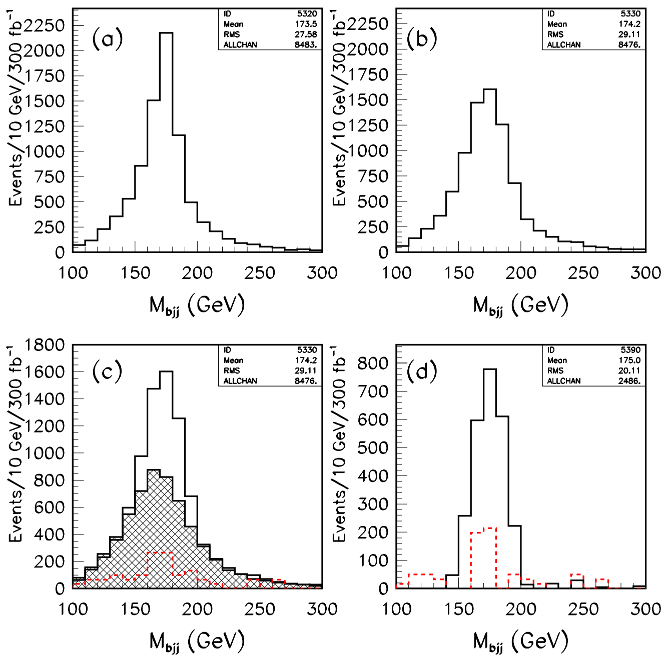


Figure 2: M_{bjj} (a) for the events from W region before jet four momentum scaling, (b) after jet energy scaling but before W sideband subtraction, (c) same as (b) but with the fake W background estimated by the sideband method (the hatched histogram) and (d) after W sideband subtraction from the distribution (b). Dashed lines in (c) and (d) refer to the remaining $t\bar{t}$ background events.

After applying this method the signal to the remaining $t\bar{t}$ events becomes $S/B \approx 12$. In this case the total number of events in the spectrum is ~ 1300 corresponding to an integrated luminosity of 300 fb^{-1}. About 1000 of these events are coming from the real signal and the rest comes from other SUSY channels or $t\bar{t}$ events faking the signal.

Finally to extract the endpoint of this distribution and put a constraint on the masses of the involved SUSY particles the distribution was fitted with a combination of a Gaussian smeared triangular shape function and a linear function, to consider the remaining background behind the endpoint. The result (figure 4) from fit is:

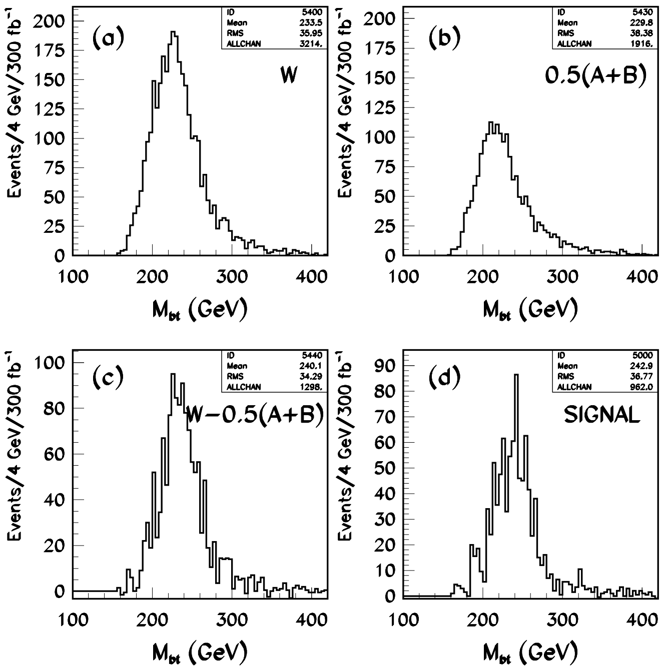


Figure 3: Top-bottom invariant mass spectrum (a) for W region, (b) for the fake W background estimated by the sideband method (A and B regions), (c) after W sideband subtraction (a) - (b) and (d) same as (c) when only signal events $\tilde{g} \to \tilde{t}_1 t \to tb\tilde{\chi}_1^{\pm}$ are used.

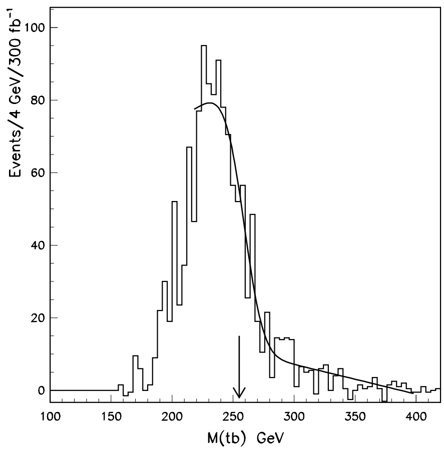


Figure 4: Fitted Top-bottom invariant mass distribution. The arrow shows the calculated endpoint position.

$$(M_{tb}^{max})^{fit} = 258.6 \pm 0.3(stat) \pm 2.6(sys) \text{ GeV}/c^2 \tag{2.3}$$

which is consistent with the theoretical value of 255 GeV/c^2. The systematics uncertainty only includes 1% uncertainty on the jet energy scale.

3. Inclusive search for SUSY in top quark final states in CMS

In CMS an inclusive search for SUSY is done by looking for events with a top quark in the final states [7]. For illustration a test point LM1 within the mSUGRA scenario is used. This point is defined by $m_0 = 60$, $m_{1/2} = 250$, $A_0 = 0$, $tan\beta = 10$ and $\mu > 0$. The masses of the relevant particles are

$$\begin{array}{ccc} m(\tilde{g}) = 611 & m(\tilde{t}_1) = 412 & m(\tilde{t}_2) = 576 \\ m(\tilde{\chi}_1^0) = 120 & m(\tilde{b}_1) = 514 & m(\tilde{b}_2) = 535 \end{array} \tag{3.1}$$

In this point, the top quark can be produced inclusively in the decay of the $\tilde{t}$, $\tilde{b}$ and $\tilde{g}$. The $\tilde{g}$ can also decay inclusively to $\tilde{t}_1$ and $\tilde{b}$ and increase the number of generated top quarks from the sparticles. The SUSY events have a large E_T^{miss}, so the idea is to see the excess in the number of the extracted top quarks, when a hard cut is applied on the missing transverse energy. To simulate the detector response, the full simulation based on GEANT4 [8], is used . To extract the top quark, a two constraints kinematic fit is utilized [9]. It is very useful because firstly it has a quantitative feature to reject the fake top quarks (χ^2 probability, see figure 5) and also it can improve the kinematic

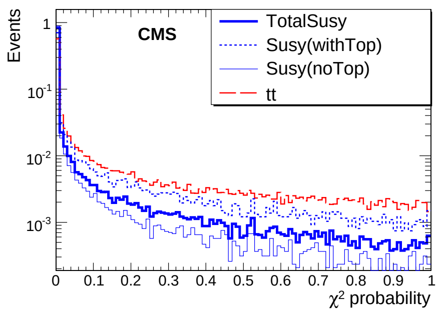


Figure 5: χ^2 probability distribution for 200K events of the inclusive LM1 sample and 100K events of the inclusive $t\bar{t}$ sample. All plots are normalized to 1 to make the shape comparison easier. The fake top quarks (SUSY events without a generated top quark 'Susy(noTop)') are concentrated in the low probability region.

features of the reconstructed top quark. Figure 6 shows the difference between the energy of the reconstructed (fitted) top quark and the generated top quark, when the generated top quark which is closer than $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.5$ to the reconstructed top quark decays hadronically and all its three partons have $E_T > 30$ GeV and $|\eta| < 2.5$.

The main background is semileptonic $t\bar{t}$ when there is a potentially high value for E_T^{miss} and a hadronically decaying top quark. In these events E_T^{miss} and the fitted top quark are almost back-to-back in the transverse plane. This feature is used to suppress the $t\bar{t}$ background. The cuts were optimized both to suppress the SM background and also increase the ratio of the SUSY events with a generated top quark 'SUSY(withTop)' against the SUSY events without a generated top quark 'SUSY(noTop)', although these two sources are used as the number of extracted signal events. In order to do the mentioned suppressions the following cuts are applied:

1. At least one b-jet with $E_T^{Corrected} > 30$ GeV and $|\eta| < 2.5$, when $E_T^{Raw} > 20$ GeV.

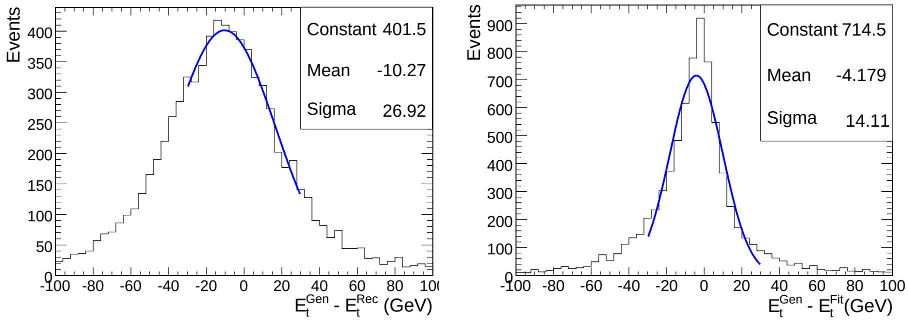
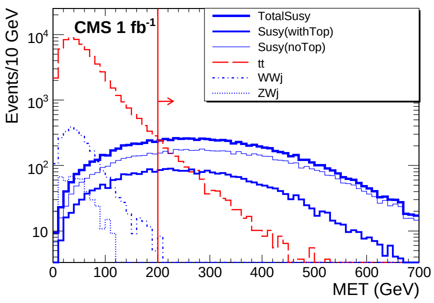


Figure 6: The difference between the energy of the reconstructed/fitted top and the generated top. Fitted jet combinations pass the probability cut(χ^2 probability > 0.05). The central parts of the distributions(-30,30) are fitted with a gaussian function(thick-blue lines) to emphasize and quantify the improvement in the resolution. The fit improves the resolution of the energy of the W and top quark by 37% and 48%, respectively. It also improves the bias. Distributions are made by 100k events of the inclusive $t\bar{t}$ sample.

2. At least three non *b*-jets with the same cuts as *b*-jets. (to reduce SM backgrounds.)

3. $E_T^{miss} > 200$ GeV. See figure 7. (to reduce SM backgrounds.)



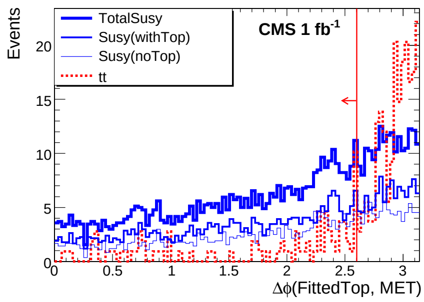


Figure 7: Missing Transverse energy for different samples. The distributions are made after applying the cut 2.

Figure 8: $\Delta\phi$ between the fitted top and the missing transverse energy. The distributions are made after applying the cut 4.

4. A convergent fit with χ^2 probability > 0.15. This cut is the most important cut to increase the ratio of SUSY(withTop) against the SUSY(noTop).

5. $\Delta\phi$ between the fitted top quark and the $E_T^{miss} < 2.6$. Figure 8 shows the distribution of this quantity for different samples.

6. at least one isolated electron or muon with $P_T > 5$ GeV/c and $|\eta| < 2.5$. This cut is introduced to suppress the QCD backgrounds.

After applying these cuts, the only remaining background is $t\bar{t}$. The ratio of the SUSY signal against the SM background is > 3, and more than 65% of the extracted SUSY events have a generated top quark 'SUSY(withTop)'. The 5 σ discovery is achievable with less than 100 pb^{-1} provided the uncertainty is statistics dominated. Figure 9 shows the distributions of missing transverse energy and the extracted top quark for different samples. It can be seen that the SUSY signal is well above the standard model ($t\bar{t}$) background. The analysis will be repeated with a higher statistics for the QCD backgrounds.

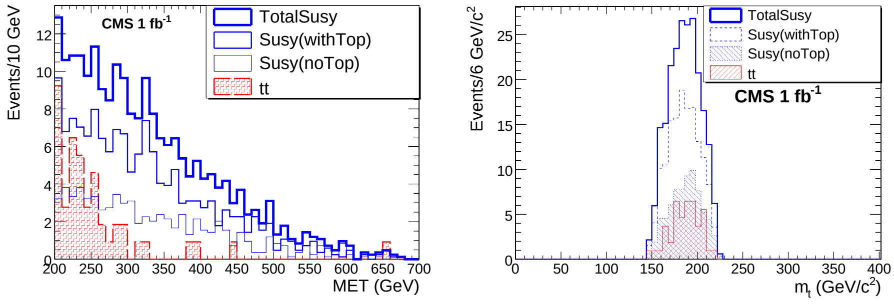


Figure 9: Missing transverse energy (left) and the extracted top quark (right) after applying all cuts.

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