Discovering SUSY

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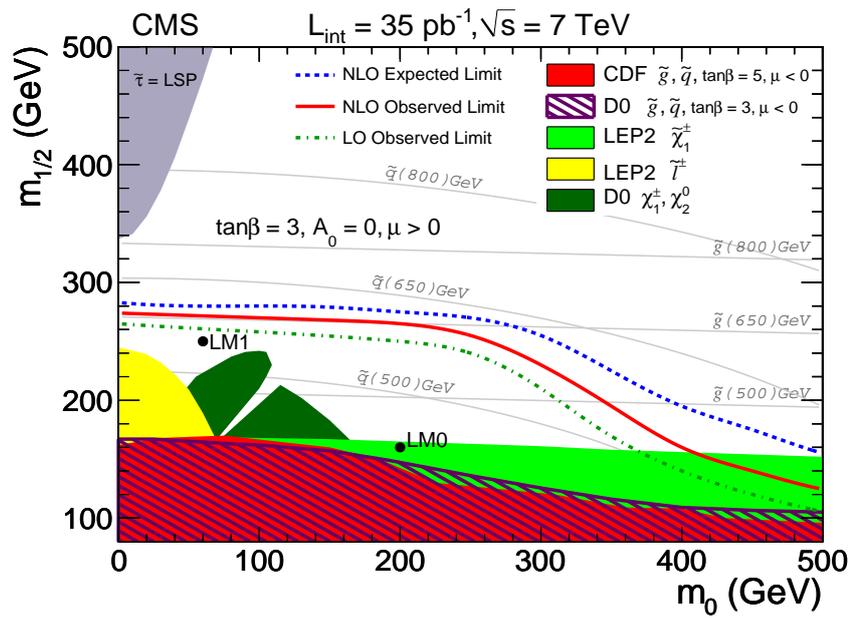
Figure 1: Exclusion plot from CMS (Figure 5 in [1])

1 Introduction

The main purpose of our work was obtaining the data to compare with the results of CMS paper [1]. We were looking for the processes where one can find the trace of SUSY particle neutralino. Quantum numbers of neutralino allows it to be an appropriate dark matter particle candidate. So, our first aim was to choose the parameters of the theory we were working within so that neutralino could be found in the final state of some process. We chose the so-called CMSSM framework where we have fixed 3 of 5 parameters ($\tan\beta = 3, A_0 = 0, \mu > 0$). After that step one can plot all possible theories on the $(m_0, m_{1/2})$ plane (fig.1).

In the CMSSM framework superparticles can decay into lighter superparticles emitting ordinary particles, conserving the so-called R-parity. In a simple way that means that in the final state one can observe only the lightest SUSY particle. And our next step was to choose the area on the plane $(m_0, m_{1/2})$ where neutralino is the lightest. We used program Suspect2 to make it. On the 1 the shadow area in the left-upper corner is forbidden for us because neutralino is not the lightest in that sector. The process under consideration was the proton-proton scattering into two jets and missing energy. We used MadGraph program to calculate it. In this program proton is complex and consists of quarks and gluons with their structure functions. Structure function is responsible for the possibility to find the corresponding particle in the proton. In the final state MadGraph gets quarks which in reality are hadronized and are not observable. So the scheme for the process is

$$pp \rightarrow jj + E_T \tag{1}$$

In the original Standard Model the same process is legal (fig.2). So we had to subtract the
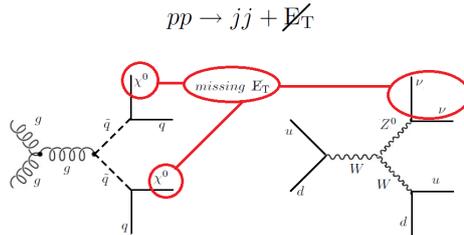
$$pp \rightarrow jj + \not{E}_T$$

Figure 2: Processes in two theories

background from the cross-section we had obtained. We used only two jets in the final state approximation because in the low m_0 area it is good approximation and it's the simplest process with the trace of SUSY to calculate.

Constrained Minimal Supersymmetric Standard Model

The Minimal Supersymmetric Extension of Standard Model (MSSM) has 105 parameters which makes scanning over possible values of all parameters practically impossible. One solution for this problem is to use a supersymmetric model with a restricted parameter space, such as the Constrained Minimal Supersymmetric Standard Model (CMSSM). The CMSSM has 5 parameters - universal scalar and gaugino mass parameters m_0 and $m_{1/2}$, universal trilinear soft SUSY breaking parameter A_0, ratio of the vacuum expectation values of the two Higgs doublets in supersymmetry - $tan\beta$ and sign of the Higgs mixing parameter μ. From these 5 in CMSSM, the values for all the parameters in MSSM can be calculated.
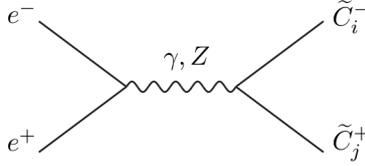
The plot

Figure 3: Electron-positron collision with 2 charginos final state

The values $tan\beta = 3$, $A_0 = 0$ and $\mu > 0$ have been fixed as reasonable values for a useful supersymmetric theory, leaving a parameter space of m_0 and $m_{1/2}$. The plot on Figure 1) shows the results obtained by the CMS Collaboration for integrated luminosity of $35pb^{-1}$ and centre of mass energy $7TeV$ along with previous experimental results. The discussion is based on the article [1] Coloured areas on the plot present exclusion regions from CDF, D0 and LEP2 experiments. For example, the light green area is obtained by colliding electrons and positrons in LEP2, with the final state consisting of charginos, as in Figure 3 The purple are in the top left corner of the plot is excluded for other reasons. Namely, in this region of the parameter space the stau is the lightest supersymmetric particle (LSP) instead of the neutralino. This region is unavailable for testing in the current case as we are studying processes with neutralinos in final state and if neutralino is not the LSP it will decay into lighter particles and not appear in final state.

New exclusion limits have been calculated from the results by the CMS experiment, shown as the red line. The expected limit (blue line) based on Monte Carlo simulations differs somewhat from the observations because observed results exceed the prediction of Standard Model background.

The mass parameters m_0 and $m_{1/2}$ do not directly correspond to particle masses. The masses of squarks and gluinos for different parameter values are shown with grey lines. As can be seen from the plot, the experiment excludes squark masses under about 600 GeV.

2 Suspect

Suspect is a Fortran code that calculates the SUSY and Higgs particle spectrum in the Minimal Supersymmetric Standard Model (MSSM). It uses renormalization group equations to relate the values of the parameters at low and high energy scales.

$$\left[M\frac{\partial}{\partial M} + \beta(g) + n\gamma \right] G^{(n)}(x_1, x_2, \ldots, x_n; M, g) = 0 \tag{2}$$

Since SUSY has 124 parameters, the parameter space has to be restricted. One possibility is to use minimal SUper GRAvity (mSUGRA). The theory of supergravity arises from coupling local SUSY to gravity, so mSUGRA is MSSM coupled to gravity. The nonzero mass of gravitino brakes the symmetry. mSUGRA has only five physical parameters

$$
\begin{array}{ll}
m_0 & \text{Gaugino mass} \\
m_{1/2} & \text{Scalar mass} \\
A_0 & \text{Higgs-sfermion-sfermion coupling constant} \\
\tan\beta & \text{Ratio of the VEVs of the two Higgs} \\
\text{sign}(\mu) & \text{Sign of the bilinear Higgsino coupling constant}
\end{array}
\tag{3}
$$

Using renormalization group equations, Suspect calculates the values of the MSSM parameters at low energies from these parameters.

3   Our Procedure

One of the goals for this project has been to calculate the cross section for certain points of the plot from the CMS paper and thereby determine whether the points are excluded or not. To obtain this goal the following procedure has been used:
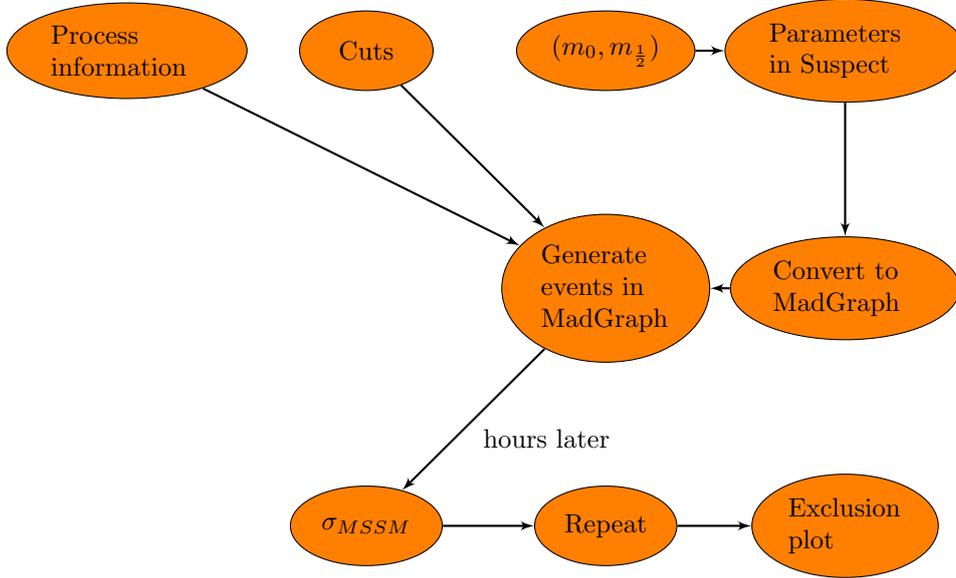
Process information:
In MadGraph edit *proc_card.dat*, so we have the correct process, model and constituents of the protons and jets. Then run *./bin/newprocess* where MadGraph makes all 3312 Feynmann diagrams for this specific proces.

Cuts:
Edit *run_card.dat*, so the protons have the right energy and we choose appropiate cuts for the events we want to consider. Number of events is chosen to be 10000.

$(\mathbf{m_0}, \mathbf{m_{\frac{1}{2}}}) \rightarrow$ Parameters in Suspect:
Fix $\tan \beta$, A_0 and $\text{sign}(\mu)$ as in the CMS paper, and choose a point $(m_0, m_{\frac{1}{2}})$ to calculate cross section for. Use these 5 CMSSM parameters as input in Suspect by editing *suspect2_lha.in* and run *./suspect2*. Then Suspect calculates all the parameters needed for the MSSM model.

Convert to MadGraph:
MadGraph cannot directly read the output from Suspect why MadGraphs homepage provides a "param_card calculator" to convert it. First rename *suspect2_lha.out* to *suspect2_lha.spc*, then upload it and press "send". Replace the old *param_card.dat* file with this new one in MadGraph.

Generate events in MadGraph $\rightarrow \sigma_{\mathbf{MSSM}}$:
Now MadGraph has all 3 kinds of information needed to generate the events. Run *./bin/generate_events* and a few hours later the calculated cross section appears. This cross section is then compared to our exclusion limit on approximately 0.2 pb.

Repeat $\rightarrow$ Exclusion plot:
Repeat the previous procedure for new points $(m_0, m_{\frac{1}{2}})$, but with the same "Process information" and "Cuts". These points are then plotted into the plot from the CMS paper, and the exclusions are compared with the exclusion line.

4 Stau LSP region

To have a better understanding of this "cmssm exclusion graph", and a first contact with the program "Suspect", we decided to try to reproduce the Stau LSP region. This region in the $(m_0, m_{1/2})$ plane, is forbidden because for the following value:

$$\tan \beta = 3 \text{ and } A_0 = 0 ,$$

the stau is lighter than neutralino.

4.1 Why is it forbidden?

This area is excluded in the CMSSM model, because if the stau is lighter than the neutralino, it will be possible for the neutralino tho decay in stau. The stau will have then no possibility to decay, conserving the R-number and the fact that the stau is charged and the LSP contradict with the fact that the Dark Matter can't be charged.

4.2 Estimation of the stau LSP region

For six differents values of m_0, we took some values of $m_{1/2}$, to obtain, at each point in the $(m_0, m_{1/2})$ plane, the mass of the neutralino and the mass of the stau. With a basic fitting, we find for a given m_0 the value of $m_{1/2}$ where the two mass are equal. We did the same for several value of m_0 and we find the following graphes.
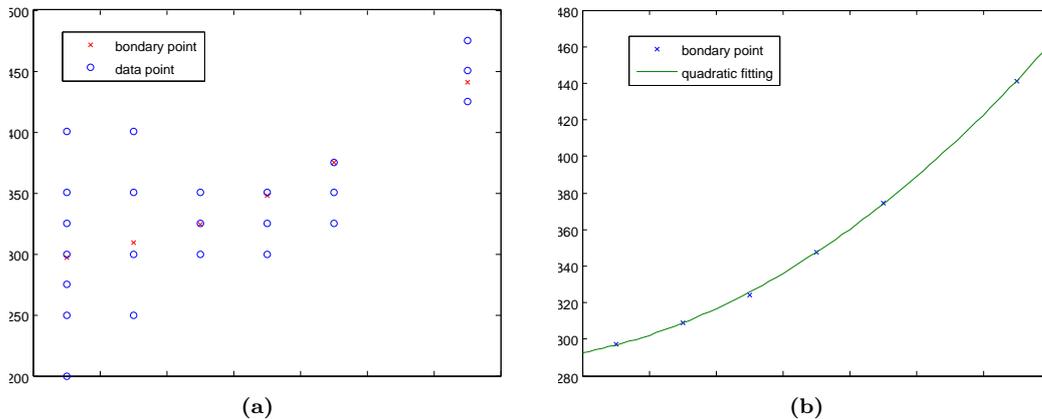

Figure 4: Datapoints and fitting

5 MadGraph Input

In order to calculate the cross sections for our process, given various regions of MSSM parameter space, MadGraph is employed. The two routines MadGraph calls to perform this calculation, namely "*newprocess*" and "*generate_events*", require certain inputs such that the relevant cross sections can be produced.

In the case of the newprocess routine, one is required to specify the exact process of interest. In the context of this analysis, we demand the process

$$pp \rightarrow 2j + 2\tilde{\chi}_1^0 \tag{4}$$

where protons and jets are defined as displayed in Table 5. It is necessary to set the constituents of protons and jets in this way, since they are not in themselves fundamental particles. Using these inputs, *newprocess* calculates the amplitudes for all subprocesses relevant to the process shown in 4.

The next routine *generate_events* uses these matrix elements calculated by *newprocess* as input. In addition to this, the parameters associated with the particular region of parameter space being considered are required. This is the output acquired from SuSpect. Finally, information regarding the run must be supplied, such that MadGraph possesses details regarding the energy at the centre of mass, the number of events desired, and any selection cuts which are implemented. Once all of this information is obtained, the events themselves are generated, and the production cross section can be extracted.

6   Run Settings & Selection Cuts

In particle physics experiments such as CMS, any potential new physics signal will always be obscured by Standard Model (SM) background processes. In order to identify such a signal it is necessary to remove these SM backgrounds from data as much as reasonably possible. This can be achieved by setting certain selection criteria on events, exploiting the characteristics of signal processes. These selection cuts are carefully chosen such that the SM backgrounds are filtered out without excessive deterioration of the signal. The motivation for and effect of such cuts can be seen in Figure 7. This illustrates the effect of a H_T cut (where $H_T = \sum_{i=1}^{njet} E_T^i$). One can see that the SM backgrounds are decreasing continuously with increasing H_T, where as the two sample CMSSM SUSY models have a broad peak in the region where H_T is a few hundred GeV. By placing a cut at high H_T in this way the backgrounds are substantially reduced without rejecting an excessive number of signal processes.

Since the process in question has n hadronic jets in the final state (where $n = 2$ in this study, and $n \geq 2$ for the CMS study) and missing transverse energy (E_T^{miss}) due to escaping LSPs, it makes sense to select events with jets with high transverse momentum (p_T. CMS set cuts on the E_T and η of the jets to select hadronically energetic events with transverse jets. A list of the criteria implemented by CMS and the approximation to those cuts used in this study can be found in Table 6. At CMS it is also necessary to enforce that there be no isolated leptons or photons in the event. Of course, in this study given that the process of interest is explicitly set in newprocess, such cuts are not important here.

7   Significance

The following report will give a short draft about significance and confidence levels in particle physics. We want to take as an example the exclusion of a model. In our case this is the mSUGRA model which we want to exclude in certain regions of the model parameters m_0 and $m_{1/2}$. We compare here to known measurements or the Standard Model (cf. the paper by the CMS Collaboration). The new physics model can be excluded if it gives rise to a signal which we do not find in the data or a Standard Model event generation. More precisely, we try to keep the probability P that our measurement can be interpreted as a statistical fluctuation of the new physics model as low as possible. The probability 1-P will then represent the region where we would have seen a signal, but as we do not, the model can be excluded here to a certain confidence level corresponding to P.

Mathematically, one starts from a null hypothesis. In case of exclusion, the hypothesis is to assume that the new physics model gives the correct distribution of observables. In this model,

the number of events of a certain type during a certain period of time (a certain integrated luminosity) will be Poisson distributed by the nature of the experiment, but, for large numbers N, can be approximated by a Gaussian. Thus, imposing a certain probability P, one can get a critical cross-section, i.e. the size the signal needs to have at least.

More precisely, P gives the probability for, in case of fulfilled null hypothesis, measure a signal (= difference between measurement and null hypothesis expectation) of a certain size or larger. Thus, the value of P is gives by the integral over an outer tail of the normalized Gaussian distribution. The confidence level can also be expressed as the number of standard deviations (sigma) where this integral starts, so one usually talks about 1-P confidence or about n sigma confidence level.

Object	Possible constituents
Proton	$u\ \bar{u}\ d\ d\ g$
Jet	$u\ \bar{u}\ d\ d\ c\ \bar{c}\ s\ \bar{s}\ g$

Figure 5: *Proton and jet definitions input to MadGraph.*

CMS selection	Cut input to run settings
$E_T > 50$ GeV	$p_T > 50$ GeV
E_T 2 leading jets > 100 GeV	
$|\eta| > 3$	$|\eta| > 3$
$|\eta|$ leading jet > 2.5	
$H_T > 350$ GeV	$H_T > 350$ GeV

Figure 6: *List of cuts implemented in CMS jets and E_T^{miss} SUSY analysis and those used to approximate the CMS results herein.*
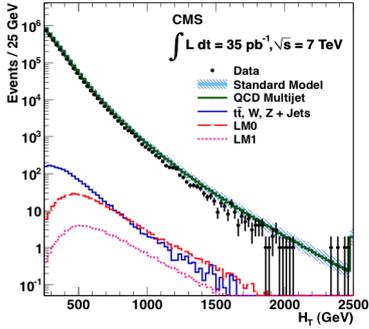

Figure 7: *H_T distribution for all standard model backgrounds and two SUSY signal samples with tow different CMSSM parameter sets, normalised to an integrated luminosity of 35 pb^{-1} [1].*
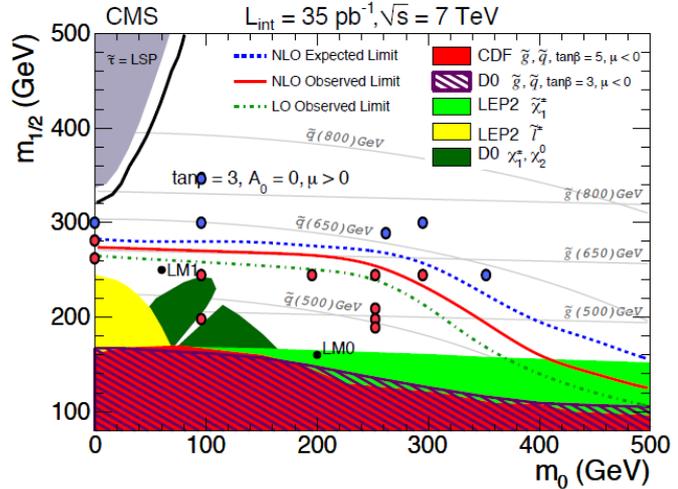

Figure 8: Our result

8   Conclusion

Let's summarize our results. We've made some calculations to compare with CMS plot (fig.1). We've chosen CMSSM to work in. Our first step was to choose the appropriate area on the $(m_0, m_{1/2})$ plane. We used Suspect2 program to make the restrictions on the area where neutralino is not the lightest SUSY particle. Our border doesn't coincide with the line in CMS paper but the inaccuracy is about 10% and it is not enough to worry about, it's just

a program inaccuracy and different programs can make different results within the margin of error. Besides, we constrained the area of high m_0 values because in that case the two jets approximation doesn't work properly. So the area we were working in can be identified on the exclusion plot as the region where the gluon masses are higher than than the squark masses. Each of us has processed several points on the $(m_0, m_{1/2})$ plane. And each point took about 3 hours to be calculated. We've calculated the cross-section of the $pp \rightarrow jj + E_T$ process subtracting the background contribution and have compared this value with the critical one obtained by the Monte-Carlo method. We've plotted our results over the original CMS plot (fig.8).

If the cross-section at some point is less than the critical one at this point SUSY can be alive. We've marked these points with blue colour. And points, where SUSY dies are marked with red colour. The line corresponding to the critical cross-section is the dashed blue line on the plot and as one can see we have good coincidence with the CMS work. The inaccuracy can be produced by the fact we used only two jets in the final state. Summing up, we have calculated exclusion limits with good equivalence with the CMS work.

References

[1] The CMS Collaboration. arXiv:1101.1628v2 [hep-ex] 4 Apr 2011