Search for an LSP Gluino from Stop Decay

DELPHI collaboration

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Abstract

In some supersymmetric models, the gluino ($\tilde{g}$) could be light and stable, and would hadronize to form R-hadrons. Data collected by the DELPHI detector at centre-of-mass energy of 189 to 202 GeV corresponding to an integrated luminosity of 384 pb^{-1} have been used to search for R-hadrons from stop decay. The observed number of events is in agreement with the Standard Model predictions. Results are presented in terms of excluded regions in the plane $(m_{\tilde{t}_1}, m_{\tilde{g}})$.

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1 Introduction

This paper presents the search for R-hadrons ($R^0, R^\pm$) from the stop decay $\tilde{t}_1 \rightarrow c\tilde{g}$ performed on the data samples collected by the DELPHI detector in 1998 and 1999, corresponding to an integrated luminosity of 158. pb $^{-1}$ at an energy of 189 GeV, 25.9 pb $^{-1}$ at 192 GeV, 76.4 pb $^{-1}$ at 196 GeV, 83.4 pb $^{-1}$ at 200 GeV and 40.6 pb $^{-1}$ at 202 GeV.

In minimal supergravity supersymmetry models (mSUGRA), the gaugino masses (M_i) are supposed to evolve from a common value $m_{1/2}$ at the GUT scale. In such models, the M_i are proportional to the corresponding coupling constants (α_i) and the gluino is naturally heavier than the other gauginos.

$$M_1 : M_2 : M_3 \sim \alpha_1 : \alpha_2 : \alpha_3$$

Nevertheless, as pointed out in recent studies [1], models exist where the M_i do not follow this relation. M_3 could be lighter than the other gaugino masses, and in this case, the gluino is the Lightest Supersymmetric Particle (LSP). The same can happen in Gauge Mediated Supersymmetry Breaking (GMSB) [2].

In this paper, R-parity conservation is assumed. The gluino is the LSP and thus stable. The event topology depends strongly on how the gluino hadronizes to form R-hadrons. It could either fragment to neutral R^0 states ($\tilde{g}g, \tilde{g}u\bar{u}, \dots$) or to charged $R^\pm$ states ($\tilde{g}u\bar{d}, \dots$). The parameter P describes the probability that a gluino fragments to a charged R-hadron. Depending on this probability, the topology of events containing R-hadron changes. For $P = 1$, R-hadrons are identified by an anomalous ionizing energy loss in the tracking chambers. For $P = 0$, gluino hadronizes into neutral states which reach the calorimeters where they deposit a part of their energy. In this last scenario, the LSP signature of missing energy is no more valid. The phenomenology depends on the model used to calculate the energy loss in the calorimeters.

Due to important off-diagonal terms in the mass matrix, the lightest stop, scalar partner of the top quark is expected to be light. The stop decay into $t\tilde{g}$ is kinematically forbidden at LEP2. Therefore, the dominant decay is $\tilde{t}_1 \rightarrow c\tilde{g}$. The topology of such events is two c-quark jets plus two gluino "jets".

2 The DELPHI detector

The description of the DELPHI detector and its performance have already been summarised in references [3, 4]. We only present here the part relevant for this analysis.

Charged particles are reconstructed in a 1.2 T magnetic field by a system of cylindrical tracking detectors. The closest to the beam is the Vertex Detector (VD) which consists of three cylindrical layers of silicon detectors at radii 6.3 cm, 9.0 cm and 11.0 cm. They allow the measurement of the coordinates in the $R\phi$ plane. In addition, the inner and the outer layers are double-sided giving the z coordinate. The VD covers polar angles from 24° to 156°. The Inner Detector (ID) is a drift chamber with radius 12 cm and outer radius 22 cm covering polar angles between 15° and 165°. The principal tracking detector of DELPHI is the Time Projection Chamber (TPC). It is a cylinder of 30 cm inner radius, 122 cm outer radius and 2.7 m length. Each end-plate is divided into 6 sectors, with 192 sense wires to allow the dE/dx measurement, and with 16 circular pad rows

which provide 3-dimensional track reconstruction. The TPC covers polar angles from 20° to 160° . Finally, the Outer Detector (OD) consists of drift cells at radii between 192 cm and 208 cm, covering polar angles between 43° and 137° . In addition, two planes of drift chambers perpendicular to the beam axis (Forward Chambers A and B) are installed in the encaps covering polar angles $11^\circ < \theta < 33^\circ$ and $147^\circ < \theta < 169^\circ$.

The electromagnetic calorimeters are the High density Projection Chamber (HPC) in the barrel region ($40^\circ < \theta < 140^\circ$) and the Forward Electromagnetic Calorimeter (FEMC) in the endcaps ($11^\circ < \theta < 36^\circ$ and $144^\circ < \theta < 169^\circ$). In the forward and backward regions, the Scintillator Tile Calorimeter (STIC) extends the coverage down to 1.66° from the beam axis. The radiation length are respectively 18, 20 and 27 in the HPC, the FEMC and the STIC. In the crack between the HPC and the FEMC, 40° taggers made of single layer scintillator-lead counters can be used to veto electromagnetic particles that escape detection. Finally, the hadron calorimeter (HCAL) covers polar angle between $11^\circ < \theta < 169^\circ$. The iron thickness in the HCAL is 110 cm which corresponds to 6.6 nuclear interaction lengths.

3 R-hadron simulation

The flavor changing decay $\tilde{t}_1 \rightarrow c\tilde{g}$ goes through one-loop diagrams. So $\tilde{t}_1$ is expected to be long-lived and to hadronize before its decay. A modified version of the SUSYGEN [5] generator was used to simulate this process. Special care was taken to introduce hard gluon radiation off scalar stop at the matrix-element level and to treat the stop hadronization as a non-perturbative strong interaction effect. A detailed description of this hadronization model can be found in [6]. Such a model, based on the Peterson function [7], was also used to perform the gluino hadronization into R-hadrons. Figure 1 summarizes the stop production and the two fragmentation steps. The final hadronization was performed using the JETSET program [8].

Figure 1: Hadronization scheme for stop pair production and for the decay into $c\tilde{g}$.

It is now important to understand how a neutral R-hadron state will manifest into the detector. For that, we use the results of authors in reference [1]. The energy loss in the

reaction $R_0N \rightarrow R_0X$ is given by:

$$\Delta E = \frac{m_X^2 - m_N^2 + |t|}{2m_N} \quad (1)$$

where $|t|$ is the usual momentum transfer invariant for the R^o and m_X is the mass of the system produced in the $R_0N \rightarrow R_0X$ collision. The form for $\frac{d\sigma}{d|t|dm_X}$ is taken to:

$$\frac{d\sigma}{d|t|dm_X} \propto \begin{cases} 1, & \text{if } |t| \leq 1 \text{ GeV}^2 \\ 0, & \text{if } |t| > 1 \text{ GeV}^2 \end{cases} \quad (2)$$

The average energy loss in the reaction $R_0N \rightarrow R_0X$ is then given by:

$$\langle \Delta E \rangle = \frac{\int_{m_N}^{\sqrt{s}-m_{R^o}} dm_X \int_{|t|_{\min}(m_X)}^{|t|_{\max}(m_X)} d|t| \Delta E \frac{d\sigma}{d|t|dm_X}}{\int_{m_N}^{\sqrt{s}-m_{R^o}} dm_X \int_{|t|_{\min}(m_X)}^{|t|_{\max}(m_X)} d|t| \frac{d\sigma}{d|t|dm_X}} \quad (3)$$

The average number of collisions of a R^o state in the calorimeters is given by the number of equivalent iron λ_T interaction lengths that characterizes the calorimeter. In DELPHI, the electromagnetic calorimeters thickness represents around 1 λ_T while this value is 6.6 λ_T for the hadronic calorimeter. We adopt a correction factor for the interaction length of 9/16 as suggested in [1]: a factor $C_A/C_F = 9/4$ comes from the color octet nature of the R^o constituents increasing the σ_{R^oN} cross section as compared to $\sigma_{\pi N}$, while a factor $\langle r_{R^o}^2 \rangle / \langle r_\pi^2 \rangle = 1/4$ takes into account the relative size of the R-hadron as compared to standard hadrons. Neutral R-hadrons should undergo 4.3 collisions in DELPHI calorimeters. Figure 2 shows the total energy loss by R^o after 4 collisions in iron.

It should be noticed that we choose a neutral R-hadron interaction model which gives significant energy raise, such that the decay $\tilde{t}_1 \rightarrow c\tilde{g}$ really differs from the standard decay $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$. This is a conservativ way in the search for R-hadrons at LEP, since the neutral R-hadron signal is more difficult to extract from QCD and WW pair backgrounds when the interaction models predicts higher energy loss in the calorimeters.

The R^o are subsequently treated in the DELPHI detector simulation as K_L^0 with energy calculated from the previous formula. The charged R-hadrons are treated as heavy muons to reproduce the anomalous dE/dx signature. In this case, only the tracking informations are used to calculate the R-hadron momentum.

4 Data and Monte-Carlo samples

The total integrated luminosity collected by the DELPHI detector at centre-of-mass energy from 189 to 202 GeV is 384 pb⁻¹ (table 1).

The e⁺e⁻ interactions leading to four-fermions final states are generated using the EXCALIBUR [9] program. The processes e⁺e⁻ → eνq $\bar{q}$ and e⁺e⁻ → Z^oee with electrons below the angular cut imposed by excalibur are generated with GRC4F [10]. The two-fermions final states are generated with PYTHIA [8] for e⁺e⁻ → q $\bar{q}$ (nγ), KORALZ [11] for e⁺e⁻ → τ⁺τ⁻(γ), e⁺e⁻ → μ⁺μ⁻(γ) and e⁺e⁻ → νν(γ), BHWIDE [12] for e⁺e⁻ → e⁺e⁻(γ). TWO GAM [13] is used to simulate γγ interactions leading to hadronic final states, while

Figure 2: Average energy loss by neutral R-hadrons in DELPHI as a function their initial energy for different mass cases.

	$\sqrt{s}$ (GeV)	Luminosity (pb^{-1})
1998	189.	158.
1999	192.	25.9
	196.	76.4
	200.	83.4
	202.	40.6

Table 1: Integrated luminosity and centre-of-mass energy of the data collected by the DELPHI detector in 1998 and 1999.

BDKRC [14] is used for leptonic final states. In all cases, the final hadronization of the particles is performed with the JETSET [8] program.

The Monte-Carlo samples used to simulate the Standard Model processes and the supersymmetric signals are passed in DELSIM [15], the official program simulating the full detector response. They are subsequently processed with the same reconstruction program as the real data. The number of generated events is always several times higher than the corresponding luminosities.

5 Preselection

In a first step, reconstructed charged particles are required to have momenta above 100 MeV/c with $\Delta p/p < 1$, where Δp is the momentum error, and impact parameter below 4 cm in the transverse plane and below 4 cm/ $\sin(\theta_{particles})$ in the beam direction. A cluster in the calorimeters is selected as neutral particles if the cluster energy is greater than 500 MeV in the HPC, 400 MeV in the FEMC, 300 MeV in the STIC and 900 MeV in the HAC.

In the second step of the analysis, hadronic events are selected. A common preselection for

the charged and neutral R-hadron searches is applied to remove most of the background coming from soft $\gamma\gamma$ interactions leading to hadronic final states. To select hadronic events, the number of charged particles is required to be greater than six and the number of tracks in the Time Projection Chamber greater than four. At least one charged particle must have transverse momentum greater than 2 GeV/c. The transverse energy has to be greater than 4 GeV. Because of the $\sin^2(\theta)$ dependence of the stop differential cross-section, the largest part of the signal energy is expected in the barrel region of the detector. Thus, it is required that the cosine of the polar angle of the thrust axis is in the region $[28^\circ, 162^\circ]$ and that the fraction of energy in the STIC is lower than 10 %. Then, events having more than 20 % of their energy in 40° cones around the z axis and no charged particle with transverse momentum greater than 4 GeV/c are removed. Finally, to reject the $e^+e^- \rightarrow q\bar{q}\gamma$ background where a high energy photon is emitted, it is required that the energy of the most energetic neutral cluster is lower than 30 GeV.

6 Charged R-hadron search

The ionisation loss (dE/dx) in the Time Projection Chamber allows to identify heavy and stable charged particles. Figure 3 shows the behavior of the ionizing energy loss as a function of the particle momentum for different mass cases. Two regions can be defined where heavy ionizing particles differ from the standard particles having masses between 5×10^{-4} GeV/c² and 1 GeV/c² : the low dE/dx and the high dE/dx regions.

In a first step, loose criteria to select Charged R-hadron candidates were defined as follows. The charge track momentum has to be above 10 GeV/c. The track is required to be reconstructed using the Time Projection Chamber to allow dE/dx measurement. To ensure a correct measurement of the ionization loss, at least 80 wires signals (out of 192) are required. It is asked that each event must have at least two $R^\pm$ candidates. Then, all the tracks of the event are clustered into two and four jets using the Durham algorithm [16].

At this step, the main backgrounds are $e^+e^- \rightarrow q\bar{q}$ and $e^+e^- \rightarrow W^+W^-$. The data Monte-Carlo comparison is shown in table 3 and in figure 4.

As the ionizing energy loss depends strongly on the mass of the particle, the analysis is separated into three mass windows in the plane $(m_{\tilde{t}_1}, m_{\tilde{g}})$. The first one corresponds to charged R-hadron masses below 30 GeV/c², the second one to masses between 30 and 60 GeV/c², and the last one to masses greater than 60 GeV/c².

R-hadron masses below 30 GeV/c²:

In this mass window, the gluino fragmentation is soft, leading to high energy fragmented particles. Charged R-hadrons also have high momentum and are characterized by a low dE/dx value.

The final selection is performed by requiring at least one $R^\pm$ candidate with momentum greater than 20 GeV/c and dE/dx below what is expected for a particle of mass 3 GeV/c².

R-hadron masses between 30 GeV/c² and 60 GeV/c²:

For this mass range the R-hadrons have lower momentum and a part of the signal falls in the dE/dx band between 1.2 and 1.6 mip where the background is high. $R^\pm$

can either be tagged by low or high dE/dx values. The fragmentation is also harder leading to few fragmented particles.

It is required that events must have at least two $R^\pm$ candidates in the region between what is expected for a particle of mass $30 \text{ GeV}/c^2$ and $60 \text{ GeV}/c^2$, with either dE/dx greater than 1.7 mip or below what is expected for a particle of mass $1 \text{ GeV}/c^2$.

R-hadron masses above $60 \text{ GeV}/c^2$:

In this case, R-hadrons have lower momentum, and because of their high masses, they are easily tagged by high dE/dx values. The gluino also takes most of the initial stop energy and because of the hard fragmentation process for this range of masses, the energies of the charm quarks and of the fragmented jets are small.

The events must contain at least two $R^\pm$ candidates with dE/dx above 1.7 mip and higher than what is expected for a particle of mass $50 \text{ GeV}/c^2$.

7 Neutral R-hadron search

As a neutral R-hadron with mass above $20 \text{ GeV}/c^2$ does not deposit more than 4 GeV in the calorimeters, the topology of the events in the neutral R-hadron search depends mainly on the mass difference between the stop and the gluino (ΔM). Thus, the analysis is separated into two mass windows: $\Delta M \leq 20 \text{ GeV}/c^2$ and $\Delta M > 20 \text{ GeV}/c^2$.

"Degenerate" mass-case: $\Delta M \leq 20 \text{ GeV}/c^2$:

In this mass window, the gluino has a mass greater than $30 \text{ GeV}/c^2$ and do not deposit a large amount of energy. The main background comes from $\gamma\gamma$ interactions leading to hadronic final states. A sequential cut analysis to isolate the neutral R-hadron signal is performed.

First, the fraction of energy in the STIC has to be lower than 5 %, the energy in the FEMC lower than $0.125\sqrt{s}$, and the fraction of energy in 45° cones around the z axis lower than 10 %. The polar angle of the missing momentum is required to point in the barrel region $[37^\circ, 143^\circ]$. Then, the transverse missing momentum has to be higher than $4 \text{ GeV}/c$. Events should have missing energy and we require the visible energy to be between 5 % and 25 % of $\sqrt{s}$. Finally, the acoplanarity between the two reconstructed jets has to be higher than 20° . Table 4 and figure 5 shows the Monte-Carlo comparison to the data at different steps of the analysis.

Non-Degenerate mass-case: $\Delta M > 20 \text{ GeV}/c^2$:

In this mass region, the R-hadron signal is more difficult to isolate from QCD backgrounds and hadronic WW pair decays.

First, the fraction of energy in the STIC has to be lower than 5 %, the energy in the FEMC lower than $0.125\sqrt{s}$, and the fraction of energy in 45° cones around the z axis lower than 10 %. The polar angle of the missing momentum is required to point in the barrel region $[28^\circ, 152^\circ]$. Then, the transverse missing momentum has to be higher than $4 \text{ GeV}/c$.

A neural network method [17] is used for the final selection. The neural network structure defined in this analysis consists of: 10 input variables, 10 hidden nodes and 3 output nodes. The 10 input variables are :

- the charged energy: E_{char}
- the visible mass: M_{vis}

- the effective centre-of-mass energy [18]: $\sqrt{s'}$
- the ratio: P_t^{mis}/E_{vis}
- the opening angle between the two jets: $\theta_{jet1-jet2}$
- the acoplanarity
- the WW distance: $dist_{WW} = MIN \left(\sqrt{\frac{(M_1-M_2)^2}{\sigma_-^2} + \frac{(M_1+M_2-2M_W)^2}{\sigma_+^2}} \right)$
 where MIN is the minimum over the 4 jet combinations when forcing the events into four jets. M_1 and M_2 are the di-jet masses. The values $M_W = 80.4$ GeV is used for the W mass while $\sigma_- = 9.5$ GeV and $\sigma_+ = 4.8$ GeV are taken for the resolutions on the sum and on the difference of the di-jet masses. $dist_{WW}$ is peaked to 0 for WW events.
- the first and third Fox-Wolfram momenta : $H_{10} + H_{30}$
- the momentum of the most energetic track: P_{ch}^{max}
- the energy of the most energetic neutral cluster: E_{ne}^{max}

Events for a large spectrum of squark and gluino masses were presented to the network in order not to overtrain the network to a specific mass pair. The 3 output nodes are linked to the three categories of events which the neural network should discriminate: the supersymmetric signal, the $q\bar{q}(n\gamma)$ and the four-fermions backgrounds together, and the $\gamma\gamma$ interactions leading to hadronic final states.

Output node	node 1	node 2	node 3
Signal	1	0	0
$q\bar{q}\gamma$ 4-fermions	0	1	0
$\gamma\gamma \rightarrow$ hadrons	0	0	1

Table 2: Description of the training method for the neural networks.

Finally, the output of the signal node is required to be higher than 0.915 Table 5 and figure 6 shows the Monte-Carlo comparison to the data at different steps of the analysis.

8 Results

The final numbers of events selected by the neutral and charged R-hadron analysis are shown in tables 6 and 7 respectively. The signal efficiencies are calculated for 57 points in the plane $(m_{\tilde{t}_1}, m_{\tilde{g}})$ for stop masses between 50 and 95 GeV/c² and then interpolated with a step of one GeV/c². These efficiencies are shown in figures 7 and 8. For the charged R-hadron search, these efficiencies run from around 20 % to 70 %. Low sensitivity area in the plane $(m_{\tilde{t}_1}, m_{\tilde{g}})$ correspond to charged R-hadron signals where the dE/dx takes standard values between 1.2 and 1.6 mip. The efficiencies in the neutral R-hadron search are lower, running from 5 % to 35 %. The low values obtained for low gluino masses come from the fact that in this region the signal is QCD or WW-like.

The results of the analysis are in agreement with the Standard Model predictions. Limits are derived at 95 % confidence level using the ALRMC program [19]. The stop pair production cross sections are calculated for two cases using the SUSYGEN [5] program. In the first case, the lightest stop ($\tilde{t}_1$) is purely left; this corresponds to the maximal cross-section. In the second one, the stop mixing angle is put to 56° ; this corresponds to the Z^0 decoupling and approximately to the minimal cross-section. We always suppose 100 % branching ratio for the stop decay into $c\tilde{g}$. Figure 9 show the excluded regions in the plane $(m_{\tilde{t}_1}, m_{\tilde{g}})$ for $P = 1$ which corresponds to gluino fragmentation into charged R-hadrons, while Figure 10 is for $P = 0$ which corresponds to gluino fragmentation into neutral R-hadrons. We also look at intermediate cases. Figure 11 shows the excluded regions for $P = 0.75 - 0.50 - 0.25$. Since signals where one of the gluino fragments to a charged R-hadron state, while the second fragments to a neutral state have not been generated, the visible cross section is given by:

$$\sigma_{vis} = \sigma(e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1^*) [P^2 + (1-P)^2] \quad (4)$$

For pure left-handed stops, limit at 95 % CL on the stop mass is defined for a mass difference between the stop and the gluino greater than 5 GeV/c² and for a gluino mass greater than 10 GeV/c². This limit is 75. GeV/c² for $P = 0.$, 71. GeV/c² for $P = 0.25$, 81. GeV/c² for $P = 0.50$, 88. GeV/c² for $P = 0.75$ and 90. GeV/c² for $P = 1$.

9 Conclusion

In the data samples of 384 pb⁻¹ taken by the DELPHI detector in 1998 and in 1999, the search for R-hadrons appearing in stop decay is performed. Charged R-hadrons are identified on the basis of abnormal ionizing energy loss, while neutral R-hadron interactions in the calorimeters of DELPHI are simulated from specific interaction cross section model. No deviation from Standard Model predictions is seen and excluded regions at 95 % CL are derived in the plane $(m_{\tilde{t}_1}, m_{\tilde{g}})$.

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Figure 3: Ionization energy loss as a function of the momentum of the particle for different mass cases (GeV/c^2). The dE/dx is expressed in units of energy loss for a minimum ionizing particle.

	189 GeV		192 GeV	
cut	Observed	Backgrounds	Observed	Backgrounds
Preselection	11663	11205. $\pm$ 30.	1803	1811. $\pm$ 6.0
$P_{ch}^1 > 10GeVc$	9597	9322. $\pm$ 22.	1460	1499. $\pm$ 5.7
$P_{ch}^2 > 10GeVc$	6476	6220. $\pm$ 18.	969	997.7 $\pm$ 5.2
dE/dx quality	1010	1042. $\pm$ 8.0	148	169.3 $\pm$ 2.3

	196 GeV		200 GeV	
cut	Observed	Backgrounds	Observed	Backgrounds
Preselection	5295	5088. $\pm$ 11.	5527	5382. $\pm$ 12.
$P_{ch}^1 > 10GeVc$	4405	4213. $\pm$ 9.8	4602	4447. $\pm$ 11.
$P_{ch}^2 > 10GeVc$	2983	2819. $\pm$ 8.7	3130	3010. $\pm$ 9.8
dE/dx quality	477	474.3 $\pm$ 3.8	500	504.8 $\pm$ 4.2

	202 GeV	
cut	Observed	Backgrounds
Preselection	2611	2540. $\pm$ 5.2
$P_{ch}^1 > 10GeVc$	2171	2115. $\pm$ 4.4
$P_{ch}^2 > 10GeVc$	1491	1462. $\pm$ 4.0
dE/dx quality	256	251.6 $\pm$ 1.8

Table 3: Comparison between data and Monte-Carlo at the preselection level for charged R-hadron analysis.

Figure 4: Data Monte-Carlo comparison at the preselection level for the charged R-hadron analysis. Histogrammes combine results from 189 to 202 GeV.

	189 GeV		192 GeV	
cut	Observed	Backgrounds	Observed	Backgrounds
Preselection	11663	11205. $\pm$ 30.	1803	1811. $\pm$ 6.0
$E_{stic}/E_{vis} < 0.05$	11287	10824. $\pm$ 29.	1754	1752. $\pm$ 6.0
$E_{emf}/\sqrt{s} < 0.125$	8835	8437. $\pm$ 28.	1345	1365. $\pm$ 5.8
$E_{45^\circ}/E_{vis} < 0.1$	2877	2777. $\pm$ 17.	388	442.9 $\pm$ 3.8
$ \cos(\theta_{P_{mis}}) < 0.8$	2071	1988. $\pm$ 13.	290	325.5 $\pm$ 3.3
$P_t^{mis} > 4\text{GeV}/c$	1855	1783. $\pm$ 11.	262	294.6 $\pm$ 3.1
$0.05 < E_{vis}/\sqrt{s} < 0.25$	32	21.14 $\pm$ 3.39	3	4.08 $\pm$ 0.30
$Acop. \geq 20^\circ$	3	5.93 $\pm$ 1.63	1	0.62 $\pm$ 0.09

	196 GeV		200 GeV	
cut	Observed	Backgrounds	Observed	Backgrounds
Preselection	5295	5088. $\pm$ 11.	5527	5382. $\pm$ 12.
$E_{stic}/E_{vis} < 0.05$	5124	4924. $\pm$ 11.	5350	5201. $\pm$ 12.
$E_{emf}/\sqrt{s} < 0.125$	3962	3833. $\pm$ 10.	4106	4024. $\pm$ 12.
$E_{45^\circ}/E_{vis} < 0.1$	1231	1194. $\pm$ 6.6	1253	1252. $\pm$ 7.3
$ \cos(\theta_{P_{mis}}) < 0.8$	935	884.3 $\pm$ 5.5	926	942.7 $\pm$ 6.2
$P_t^{mis} > 4\text{GeV}/c$	839	792.4 $\pm$ 5.1	847	844.0 $\pm$ 5.7
$0.05 < E_{vis}/\sqrt{s} < 0.25$	22	12.34 $\pm$ 0.89	16	14.58 $\pm$ 1.03
$Acop. \geq 20^\circ$	5	1.96 $\pm$ 0.29	1	2.38 $\pm$ 0.33

	202 GeV	
cut	Observed	Backgrounds
Preselection	2611	2540. $\pm$ 5.2
$E_{stic}/E_{vis} < 0.05$	2541	2456. $\pm$ 5.2
$E_{emf}/\sqrt{s} < 0.125$	1959	1892. $\pm$ 4.9
$E_{45^\circ}/E_{vis} < 0.1$	593	583.5 $\pm$ 3.1
$ \cos(\theta_{P_{mis}}) < 0.8$	447	439.0 $\pm$ 2.5
$P_t^{mis} > 4\text{GeV}/c$	412	394.3 $\pm$ 2.3
$0.05 < E_{vis}/\sqrt{s} < 0.25$	4	7.08 $\pm$ 0.50
$Acop. \geq 20^\circ$	2	1.09 $\pm$ 0.16

Table 4: Comparison between data and Monte-Carlo after each cut of the first neutral R-hadron analysis: $m_{\tilde{t}_1} - m_{\tilde{g}} < 20 \text{ GeV}/c^2$.

Figure 5: Data Monte-Carlo comparison for the first window of the neutral R-hadron analysis ($m_{\tilde{t}_1} - m_{\tilde{g}} < 20 \text{ GeV}/c^2$) after the cut $E_{45^\circ}/E_{vis} < 0.1$. Histogrammes combine results from 189 to 202 GeV.

	189 GeV		192 GeV	
cut	Observed	Backgrounds	Observed	Backgrounds
Preselection	11663	11205. $\pm$ 30.	1803	1811. $\pm$ 6.0
$E_{stic}/E_{vis} < 0.05$	11287	10824. $\pm$ 29.	1754	1752. $\pm$ 6.0
$E_{emf}/\sqrt{s} < 0.125$	7258	6989. $\pm$ 26.	1083	1097. $\pm$ 5.4
$E_{40^\circ}/E_{vis} < 0.1$	3997	3852. $\pm$ 20.	577	619.8 $\pm$ 4.4
$ \cos(\theta_{P_{mis}}) < 0.88$	2705	2613. $\pm$ 15.	400	427.2 $\pm$ 3.6
$P_t^{mis} > 4\text{GeV}/c$	2390	2307. $\pm$ 12.	355	380.8 $\pm$ 3.4
NN output ≥ 0.915	9	6.46 $\pm$ 0.50	4	1.45 $\pm$ 0.15

	196 GeV		200 GeV	
cut	Observed	Backgrounds	Observed	Backgrounds
Preselection	5295	5088. $\pm$ 11.	5527	5382. $\pm$ 12.
$E_{stic}/E_{vis} < 0.05$	5124	4924. $\pm$ 11.	5350	5201. $\pm$ 12.
$E_{emf}/\sqrt{s} < 0.125$	3175	3064. $\pm$ 9.7	3279	3198. $\pm$ 11.
$E_{40^\circ}/E_{vis} < 0.1$	1735	1681. $\pm$ 7.7	1772	1758. $\pm$ 8.5
$ \cos(\theta_{P_{mis}}) < 0.88$	1239	1174. $\pm$ 6.2	1222	1253. $\pm$ 7.0
$P_t^{mis} > 4\text{GeV}/c$	1095	1034. $\pm$ 5.6	1098	1103. $\pm$ 6.3
NN output ≥ 0.915	6	5.11 $\pm$ 0.30	6	5.89 $\pm$ 0.34

	202 GeV	
cut	Observed	Backgrounds
Preselection	2611	2540. $\pm$ 5.2
$E_{stic}/E_{vis} < 0.05$	2541	2456. $\pm$ 5.2
$E_{emf}/\sqrt{s} < 0.125$	1544	1507. $\pm$ 4.5
$E_{40^\circ}/E_{vis} < 0.1$	842	820.7 $\pm$ 3.6
$ \cos(\theta_{P_{mis}}) < 0.88$	605	587.6 $\pm$ 2.9
$P_t^{mis} > 4\text{GeV}/c$	543	518.4 $\pm$ 2.5
NN output ≥ 0.915	4	1.81 $\pm$ 0.11

Table 5: Comparison between data and Monte-Carlo after each cut of the second neutral R-hadron analysis: $m_{\tilde{t}_1} - m_{\tilde{g}} > 20 \text{ GeV}/c^2$.

Figure 6: Data Monte-Carlo comparison for the second window of the neutral R-hadron analysis ($m_{\tilde{t}_1} - m_{\tilde{g}} > 20 \text{ GeV}/c^2$) after the cut $E_{40^\circ}/E_{vis} < 0.1$. Histogrammes combine results from 189 to 202 GeV.

	$\Delta M \leq 20$		$\Delta M > 20$	
$\sqrt{s}$	Observed	Backgrounds	Observed	Backgrounds
189	3	5.93 ± 1.63	9	6.46 ± 0.50
192	1	0.62 ± 0.09	4	1.46 ± 0.15
196	5	1.96 ± 0.29	6	5.11 ± 0.30
200	1	2.36 ± 0.33	6	5.89 ± 0.34
202	2	1.09 ± 0.16	4	1.81 ± 0.11

Table 6: Final number of events selected by the neutral R-hadron analysis.

	$m_{\tilde{g}} \leq 30.$		$30. < m_{\tilde{g}} < 60.$		$m_{\tilde{g}} \geq 60.$	
$\sqrt{s}$	Observed	Backgrounds	Observed	Backgrounds	Observed	Backgrounds
189	4	5.03 ± 0.56	0	0.185 ± 0.055	0	0.213 ± 0.096
192	1	0.84 ± 0.18	0	0.031 ± 0.012	0	0.014 ± 0.008
196	4	2.35 ± 0.29	0	0.095 ± 0.049	0	0.003 ± 0.002
200	0	2.42 ± 0.31	0	0.046 ± 0.010	0	0.030 ± 0.014
202	2	0.99 ± 0.12	0	0.020 ± 0.008	0	0.010 ± 0.003

Table 7: Final number of events selected by the charged R-hadron analysis.

Figure 7: Charged R-hadron detection efficiency (%) in the plane $(m_{\tilde{t}}, m_{\tilde{g}})$.

Figure 8: Neutral R-hadron detection efficiency (%) in the plane $(m_{\tilde{t}}, m_{\tilde{g}})$.

Figure 9: Excluded regions at 95 % confidence level for the charged R-hadron analysis in the plane $(m_{\tilde{t}}, m_{\tilde{g}})$. The shaded region shows the excluded region for the stop mixing angle which corresponds to the Z^0 decoupling. For a pure left-handed stop the unfilled region enclosed by a curve is also excluded.

Figure 10: Excluded regions at 95 % confidence level for the neutral R-hadron analysis in the plane $(m_{\tilde{t}}, m_{\tilde{g}})$. The shaded region shows the excluded region for the stop mixing angle which corresponds to the Z^0 decoupling. For a pure left-handed stop the unfilled region enclosed by a curve is also excluded.

Figure 11: Excluded regions at 95 % confidence level for the R-hadron analysis in the plane $(m_{\tilde{t}}, m_{\tilde{g}})$. First histogramme corresponds to $P = 0.75$, the second one to $P = 0.50$ and the last one to $P = 0.25$. The shaded region shows the excluded region for the stop mixing angle which corresponds to the Z^0 decoupling. For a pure left-handed stop the unfilled region enclosed by a curve is also excluded.