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The Search for Squarks, Gluinos, and Stop Squarks in DØ

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Searches through data collected by DØ at Fermilab during the 1992-1993 $p\bar{p}$ collider run for the supersymmetric partners to the quark and gluon, the squark and gluino, including a low mass scalar top squark, are reviewed. A set of classic searches were conducted for missing E_T plus jets signatures. No evidence of positive signals is reported, but limits are set on the squark and gluino masses.

INTRODUCTION

Searches were conducted for the SUSY partners of quarks and gluons, the squarks $\tilde{q}$ and gluinos $\tilde{g}$ including the supersymmetric partner to the top quark, $\tilde{t}$, under the framework of a supergravity-GUT inspired Minimal Supersymmetric Standard Model (MSSM) (1). In such models, the SUSY parameters can be reduced to five, chosen at the low energy scale to be: the squark and gluino masses, the Higgs mass mixing parameter, μ, the charged Higgs mass, m_{H^+}, and the ratio of the two vacuum expectation values of Higgs doublets, tanβ. With the addition of the top quark mass, all supersymmetric mass relations, couplings and mixings are calculable. The model enforces conservation of R-parity which implies sparticles be produced in pairs, and that the Lightest Supersymmetric Particle (LSP) must be absolutely stable (2).

Early limits were set under the assumption that all squarks have the same mass. This was justified by a model that argued all scalar particles share a common mass at the energy scale where SUSY is broken. The degeneracy among squarks is broken only slightly by the small differences in electroweak interactions between left and right states and the different Yukawa interactions of the various families. A heavy top quark (3) means *its* Yukawa interactions become substantial and can drive top squark masses lower than all other squarks. Mass-splitting by left/right mixing may split the mass eigenstates even further, making one state, $\tilde{t}_1$, the lightest of all (4).

In our squark/gluino analysis, top squark production was not simulated; only the remaining five flavors of left and right handed squarks were assumed to be mass degenerate. A different set of cuts was applied in a separate search for a possibly lighter top squark.

EVENT SELECTION OF BOTH ANALYSES

The Data Set

Data corresponding to a total integrated luminosity of 13.5 ± 0.7 pb^{-1} were collected by the DØ detector during its 1992-1993 run. DØ is a general purpose detector consisting of a central tracking system and nearly hermetic liquid argon calorimeter surrounded by a toroidal muon spectrometer. A detailed description can be found elsewhere (5). Events for these analyses were collected using a set of missing E_T ($\not\!\!E_T$) triggers: one requiring 30 GeV $\not\!\!E_T$ in hardware and 35 GeV in software, plus additional (prescaled) triggers with a softer (20/25 GeV) $\not\!\!E_T$ requirement but either a one or three 20 GeV jet requirement.

The Single Interaction Cut

To ensure unambiguous $\not\!\!E_T$ assignments, we demanded events be identified as having only one primary vertex. An algorithm that combined timing information from a set of trigger counters together with reconstructed scalar E_T and the number of vertices found by tracking was used to select single interaction events (6). Its use effectively reduced our data set to a *single interaction equivalent luminosity* of either 7.2 ± 0.4 pb^{-1} (for an initial squark/gluino search) or 7.4 ± 0.4 pb^{-1} (for the top squark search and an updated squark/gluino search). The different analyses being reported here were performed on different streams of the data, accounting for the slight difference in luminosity.

Angular Correlation Cuts

Badly mismeasured jets can produce false $\not\!\!E_T$, but such events usually show a correlation between the jet and $\not\!\!E_T$ directions. If a jet is identified as the leading object in an event by an overestimate of its energy, a false $\not\!\!E_T$ signal will be induced in a direction opposite to that of the jet. Jets with underestimated energy will tend to be aligned with the fake $\not\!\!E_T$. This is cited as the source of the clumping of events visible in the upper left-hand corner of Fig. 1, a feature not reproduced by either the SUSY signal or any of the expected physics backgrounds. This effect is observed not only on events from our $\not\!\!E_T$ triggers, but even those from a low E_T threshold single jet trigger (used to study detector induced background) when mild $\not\!\!E_T$ cuts are applied offline. DØś squark/gluino searches (7,8) remove this dense corner by requiring $\sqrt{(\pi - \Delta\phi(\not\!\!E_T, jet1))^2 + (\Delta\phi(\not\!\!E_T, jet2))^2} > 0.5$. The $\tilde{t}$ search simply applied a one-dimensional cut against high $\Delta\phi(\not\!\!E_T, jet1)$ values. In both searches additional cuts were made against jets aligned (within $\delta\phi = 0.1$) with the direction of the $\not\!\!E_T$.

THE SEARCH FOR SQUARKS AND GLUINOS

Selection Cuts from Two Analyses

Though the relative rates of $\tilde{q}$ and $\tilde{g}$ production, as well as details of their decay modes, depend strongly on the input parameters to the model, in general their decays cascade

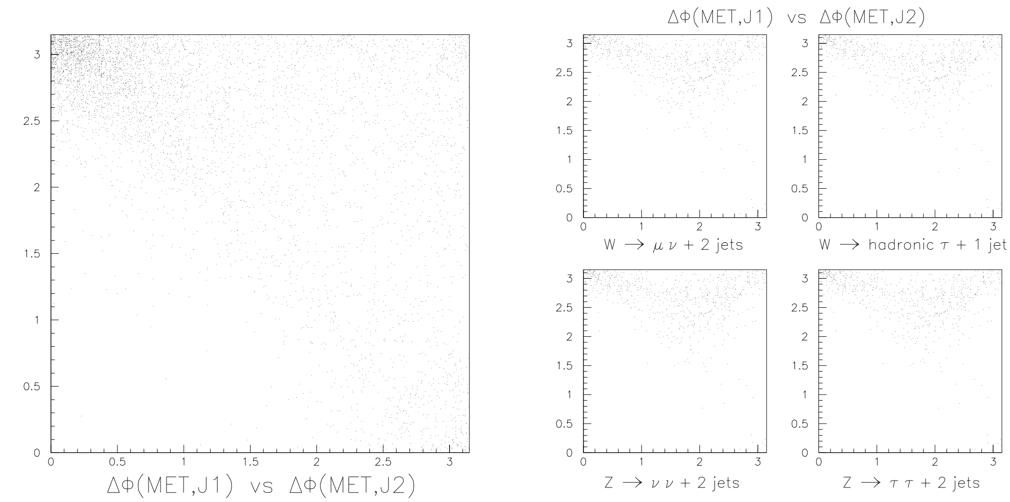

FIG. 1. The opening angle between $\not{E}_T$ and the leading jet runs up the ordinate, its angle with the next leading jet along the abcissa. At left are events from a low E_T threshold single jet trigger, after an offline $\not{E}_T > 15$ GeV cut has been applied. At right are some Monte Carlo of vector boson backgrounds.

through intermediate state charginos and neutralinos to a final state consisting of an LSP and several jets. The event signature sought is large $\not{E}_T$ plus three or more jets.

Inherent in this search was the assumption that all squarks (excluding top) are mass degenerate. The common slepton $\tilde{\ell}$ mass was set equal to the squark mass. The MSSM parameter values were fixed at $m_{H^+} = 500$ GeV$/c^2$, $\tan\beta = 2$, $\mu = -250$ GeV$/c^2$ (with $m_t = 140$ GeV$/c^2$), while we varied both the squark mass $m_{\tilde{q}}$ and gluino mass $m_{\tilde{g}}$. Results of this search were not sensitive to either the choice of m_H^+ or m_t.

This summary includes the final results of a completed analysis searching for 3 jets plus $\not{E}_T$ (11) and the preliminary results of a competing 4-jet search. Selection cuts for the 3-jet search are listed in Table 1. Once some final jet clean up cuts were applied to reject clusters

TABLE 1. The final selection cuts of the 3-jet analysis.

Cut	# of events passing
trigger/offline filter	9625
single interaction	3730
$\not{E}_T > 75$ GeV	107
3 jets, $\not{E}_T > 25$ GeV, jet quality	32
Reject jet-$\not{E}_T$ azimuthal correlation	22
No e with $E_T > 20$ GeV, No μ with $E_T > 15$ GeV	17
Reject 1 event with $\not{E}_T$ due to cosmic ray, and 2 with $\not{E}_T$ due to incorrect vertex	**14**

TABLE 2. An alternate set of cuts for the 4-jet analysis.

Cut	# of events passing
trigger/offline filter	9163
single interaction	3347
4 jets, $E_T > 20$ GeV, jet quality Reject jet-$\not{E}_T$ azimuthal correlation	223
$\not{E}_T > 65$ GeV	**5**

formed around noisy calorimeter cells, 17 candidate events remained. Scanning displays of this final set revealed one case of a cosmic ray interacting within the calorimeter. When reconstructed as a jet from the nearby interaction vertex, this excess contribution of energy inflated the $\not{E}_T$ sufficiently to pass our cut. In addition, two events were found where the the hard scattering vertex from which the jets originate was missed, in favor of a distant soft scatter vertex. When these events were reconstructed with the correct primary vertex, each failed the 75 GeV $\not{E}_T$ cut. Rejecting these anomalies left a final sample of 14 surviving candidate events.

A competing set of analysis cuts (8) (Table 2) was able to relax the $\not{E}_T$ requirement by imposing a 4 jet requirement. After making the same jet quality and correlation cuts against fake $\not{E}_T$ events on a comparable initial data set, 223 events survived the 4 jet cut. Only 5 candidates remained once the $\not{E}_T$ requirement is applied.

Background

To estimate the vector boson associated background, we generated W/Z plus n jet samples using the Monte Carlo (MC) generator VECBOS (9), interfaced with ISAJET (10) to dress up the final parton states. VECBOS allowed us to specify n, the number of primary jets associated with the vector boson production. Since ISAJET also allows control over the decay of the tau, we were careful to count its hadronic decays as contributing to the jet total. Events were then passed through a GEANT simulation of the DØ detector (13), reconstructed and subjected to our selection criteria.

Improvements in error estimates for both the luminosity (12) and the single interaction algorithm, as well as a new procedure for treating systematic errors in general, provide updates on the published (11) estimates for the 3-jet analysis. A total of 14.2 ± 4.4 W/Z events are expected to make it into our final 3-jet candidate sample, 5.2 ± 2.2 are predicted under the 4-jet cuts.

To estimate the contribution from Standard Model multijet production, we fit the $\not{E}_T$ spectrum of a set of single low jet E_T triggers, and then determined the fraction of such events that passed our selection cuts, as a function of $\not{E}_T$. We predict a total of 0.42 ± 0.37 events in our 3-jet sample from this source. 1.6 ± 0.9 events are predicted in the 4-jet sample, though this background is not subtracted in the final 4-jet analysis (leading to a slightly conservative lower mass limit).

The combined background is consistent with the observed candidates in each case. Thus, we observe no excess of events unexplained by the Standard Model.

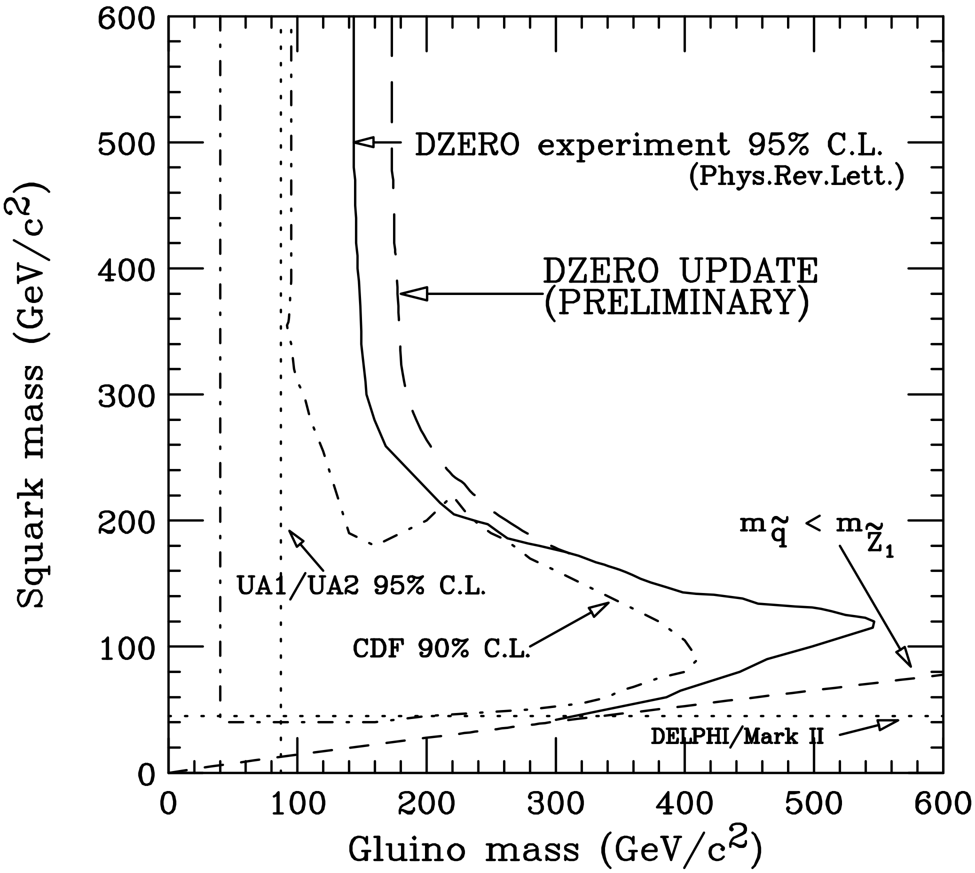

FIG. 2. Squark and gluino mass limits. The long dashes mark the upper bound on the *preliminary* DØ 95% confidence level excluded region (note how it has expanded beyond the PRL (11) result (solid line). UA1, DELPHI, and CDF limits are shown for comparison. The dashed line identifies the model excluded region where the squark mass is lighter than the LSP.

Mass Limits

Events were generated for a grid of $\tilde{q}/\tilde{g}$ mass pairs using ISASUSY (14) and run through a simulation of our trigger. Like the Monte Carlo background events described above, these were then processed through a GEANT simulation of the detector and reconstructed. Signal efficiencies were determined by applying the event selection cuts, and interpolating between grid points.

Figure 2 shows the region in the $m_{\tilde{g}}$-$m_{\tilde{q}}$ plane excluded by our search at the 95% confidence level. The line marked *preliminary* shows how far the 4-jet and newly updated 3-jet analyses will push our exclusion contour. In the limit of $m_{\tilde{q}} >> m_{\tilde{g}}$ gluino pair production dominates over other processes and the gluino decay patterns become insensitive to further increase in squark mass. In this region we obtain an asymptotic limit of $m_{\tilde{g}} > 173$ GeV/c^2. In the case of equal squark and gluino masses, the limit is $m_{\tilde{g}} = m_{\tilde{q}} > 229$ GeV/c^2.

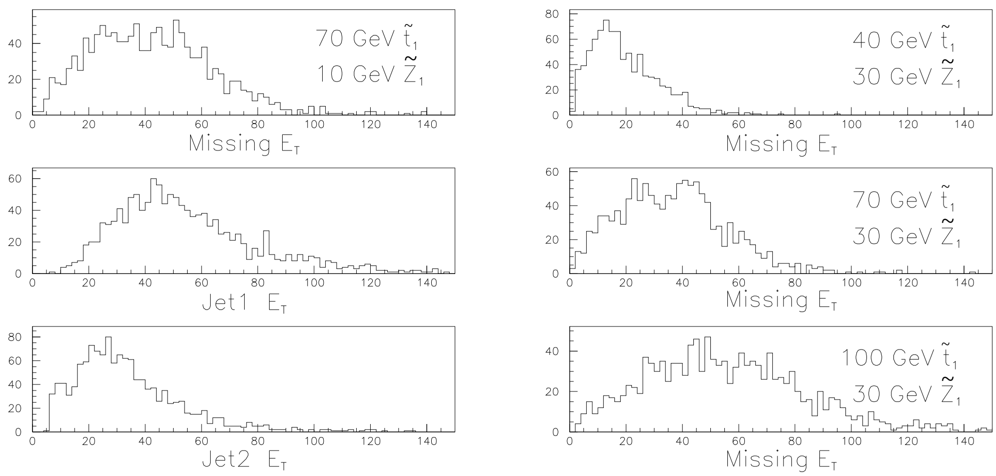

FIG. 3. The jet E_T's are seen to be healthy (left) in this sample of $m_{\tilde{t}_1} = 70$ GeV/c^2 $m_{Z_1} = 10$ GeV/c^2 ISAJET events. The $\not\!\!E_T$ is respectable, although scanning the region to be searched (right) shows $\not\!\!E_T$ to be rather feeble for low $m_{\tilde{t}_1}$.

A SEARCH FOR LIGHT TOP SQUARKS

Introduction

If kinematically accessible, the top squark is expected to decay through $\tilde{t}_1 \to b\tilde{W}_1$. If, however, $m_{\tilde{W}_1} > m_{\tilde{t}_1} + m_b$, the chargino becomes virtual and three-body decays $\tilde{t}_1 \to bl\tilde{\nu}$ or $\tilde{t}_1 \to b\nu\tilde{l}$ become accessible *unless* sleptons and sneutrinos are *also* heavier than $\tilde{t}_1$. Under this additional assumption, top squarks will dominantly decay via $\tilde{t}_1 \to c\tilde{Z}_1$ yielding an event signature of two acollinear jets with $\not\!\!E_T$ (16).

Top squark production cross section is via gluon fusion and $q\bar{q}$ annihilation (17) and thus fixed by QCD in terms of $m_{\tilde{t}_1}$; its decay topology is determined by $m_{\tilde{Z}_1}$, the mass of the lightest neutralino. Thus the search is through a two-parameter phase space in $m_{\tilde{Z}_1}$ vs $m_{\tilde{t}_1}$. The region to be explored is the lower half-plane defined by the near-diagonal $m_{\tilde{t}_1} < m_{\tilde{Z}_1} + m_c$, hemmed in by $m_{\tilde{t}_1} > m_{\tilde{Z}_1} + m_b + m_W$ (to restrict competing 3-body decays).

The results of the $\tilde{t}_1$ search reported here are preliminary.

Signal

Signal events were generated using ISAJET 7.13 (10), which incorporates the latest implementation of ISASUSY (14). These files were processed through a GEANT simulation of the DØ detector (13) and reconstructed. Kinematic distributions sampled from the middle of the parameter space to be probed (Figure 3, left) show that the leading jets are fairly high in E_T, and the $\not\!\!E_T$ is large. The latter claim, however, does not hold over the full range of the region to be explored (Figure 3, right). Although it means sacrificing the rejection

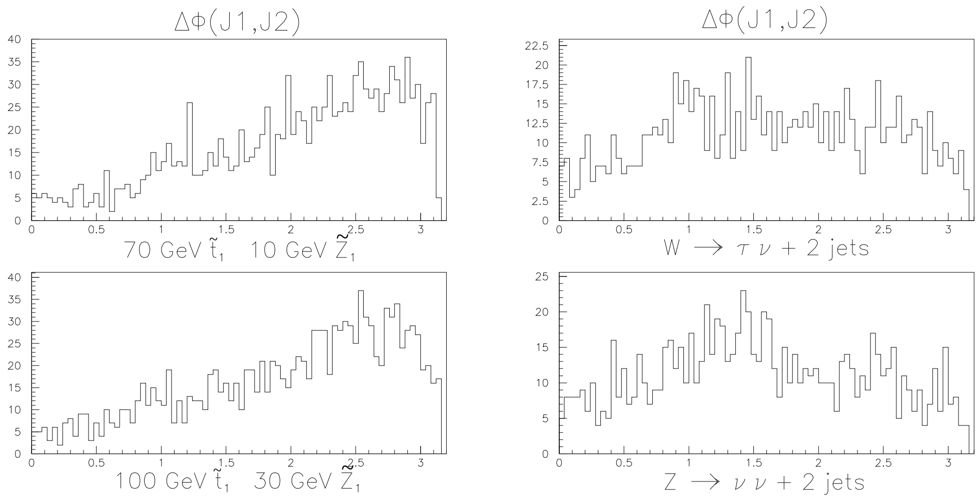

FIG. 4. The opening angle between the two leading jets tends toward higher values in the signal, though most of our background sources show relatively flat distributions.

power of a high $\not{E}_T$ cut, a relatively low cut will allow coverage of more of the parameter space. Trigger thresholds fixed this cut at 40 GeV.

Event Selection

Leptons are not primarily part of our signal, but appear only incidentally insofar as charm jets are in the final state. These tend to be low E_T objects. We gain some rejection against the vector boson background by discriminating against events with high-E_T electrons or muons.

The presence of two LSP's in the event suggests that the two leading jets in our signal be acollinear. But distributions of the opening angle between them (Fig.4) shows that angle tends to large values. A cut of $\Delta\phi(j1,j2) > 90^o$ preserves 70-75% of the signal. Background distributions tend to be flat.

Standard Model multijet events tend to be mostly back-to-back jet pairs. Thus we must also cut against two leading jets with an opening angle close to π. Monte Carlo distributions suggest an effective cut can be made at $\Delta\phi(j1,j2) < 165^o$.

Our final selection cuts of

$$\not{E}_T > 40 \text{ GeV}$$
$$E_T^{jet2} > 30 \text{ GeV}$$
$$90^o < \Delta\phi(j_1,j_2) < 165^o$$
$$10^o < \Delta\phi(j_1,\not{E}_T) < 125^o$$
$$10^o < \Delta\phi(j_{3,4},\not{E}_T)$$

with a *VETO* against events with:

$$E_T^{\mu} > 10 \text{ GeV}$$
$$E_T^{el} > 10 \text{ GeV}$$

leave a total of two candidates in the single interaction missing E_T triggers.

TABLE 3. Expected Vector Boson backgrounds to the $\tilde{t}$ signal.

Background Process	Expected # of events
$W \to e\bar{\nu}$	$0.52 \pm .30$
$W \to \mu\bar{\nu}$	0.84 ± 0.42
$W \to \tau\bar{\nu}$	0.99 ± 0.64
$Z \to \nu\bar{\nu}$	0.37 ± 0.32
$Z \to \mu\bar{\mu}$	0.06 ± 0.05
$Z \to \tau\bar{\nu}$	0.08 ± 0.05
TOTAL	2.86 ± 0.93

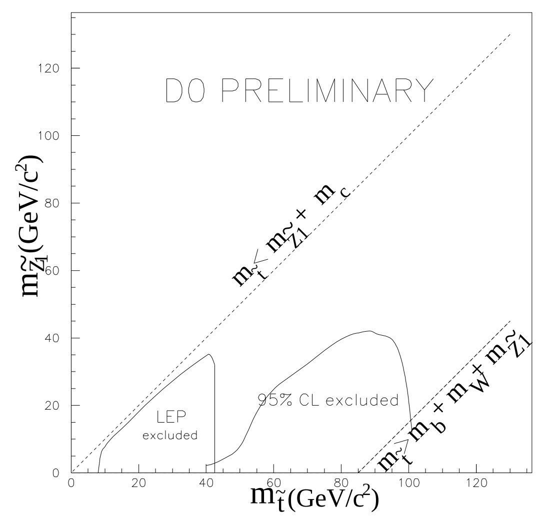

FIG. 5. The 95% Confidence Level contour. For comparison, the latest exclusion contour from OPAL(18) is shown.

Background

In addition to Standard Model multijet production with faked $\not{E}_T$ signals, the major backgrounds, as in the $\tilde{q}$ and $\tilde{g}$ search, come from vector boson associated background. These were generated as described in the $\tilde{q}$ and $\tilde{g}$ search. Table 3 lists the expected background from this source. For our final selection cuts the contribution from multijet production is predicted to be negligible.

Results

With 2 candidates, our preliminary background subtracted 95% Confidence Level exclusion contour is shown in Fig. 5. This contour intersects the $m_{\tilde{t}_1} = m_{\tilde{Z}_1} + m_b + m_W$ line at 106 GeV$/c^2$. The gap between the LEP limit and our own exclusion region is due to the limitation of the $\not{E}_T$ trigger threshold. The 1994-95 data run now includes a customized filter which employs some of the offline cuts against low-E_T jets aligned with $\phi(\not{E}_T)$ permitting the $\not{E}_T$ cut to be lowered to 25 GeV, which may allow us to cover this area more completely. The region between $m_{\tilde{t}_1} = m_{\tilde{Z}_1} + m_c$ and our excluded area requires additional statistics.

CONCLUSIONS

We have analyzed 7.4 ± 0.4 pb^{-1} of data (the *single interaction equivalent*) luminosity of the entire 1992-93 DØ run and observe no excess of squark and gluino events in the framework of the MSSM. We also see no evidence of $\tilde{t}_1 \rightarrow c + \tilde{Z}_1$ signatures. In each case the number of events is consistent with Standard Model predictions.

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