Tevatron Searches for New Physics with Photons and Jets

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The DØ and CDF experiments have each collected more than 8 fb^{-1} in Run II of Fermilab's Tevatron, and have many recent search results which use up to 5.2 fb^{-1}. Here I summarize the results of a variety of searches for physics beyond the Standard Model with an emphasis on searches for very exotic phenomena. I will present the status of model-inspired searches for several signatures of supersymmetry, as well as several other searches for several "hidden-valley" inspired models, all of which contain photons and jets in the final state.

1 Introduction

Despite its enormous success at explaining the interactions of the known particles, we are certain that the Standard Model (SM) is incomplete. We now have overwhelming evidence that the universe contains mostly dark matter, yet the SM provides no explanation for it. Among the models on the market, Supersymmetry (SUSY) is favored by many, in part because it naturally has a dark matter candidate in the lightest supersymmetric particle (LSP). Recently though, a class of models has been proposed that can generally be described as "hidden-valley" (HV) models. These are characterized by the general feature that they propose relatively light particles one might expect to have already discovered, but haven't been because some mechanism prevents them from interacting with the SM particles, except gravitationally. These models therefore also can naturally provide a solution to the dark matter puzzle. Most collider experiments sensitive to new higher energy scales have searched for SUSY in a variety of final states, and the Tevatron is no exception. Hidden-valley models are relatively recent, and searches for them at colliders are just emerging. I will discuss several searches for SUSY and HV models at the CDF and DØ experiments at the Tevatron with 2.6-5.2 fb^{-1}.

2 Searches for Sbottom with b jets and $\not\!\!E_T$

In the MSSM, if $\tan\beta$ is large, there is a large mass splitting in the third generation. This leads to relatively low masses for the lightest scalar bottom quark (sbottom) state. In an R-parity conserving scenario, sbottoms are expected to be produced at the Tevatron in pairs via gluon-gluon fusion or qqbar annihilation. The sbottom is then kinematically required to decay into bottom and the lightest neutralino (assumed to be the LSP), leading to final states which include two b-jets and substantial missing transverse energy (MET) from the undetected LSP.

Both Tevatron experiments have searched for bbottom in events with jets, $\not\!\!E_T$, and b-tags.

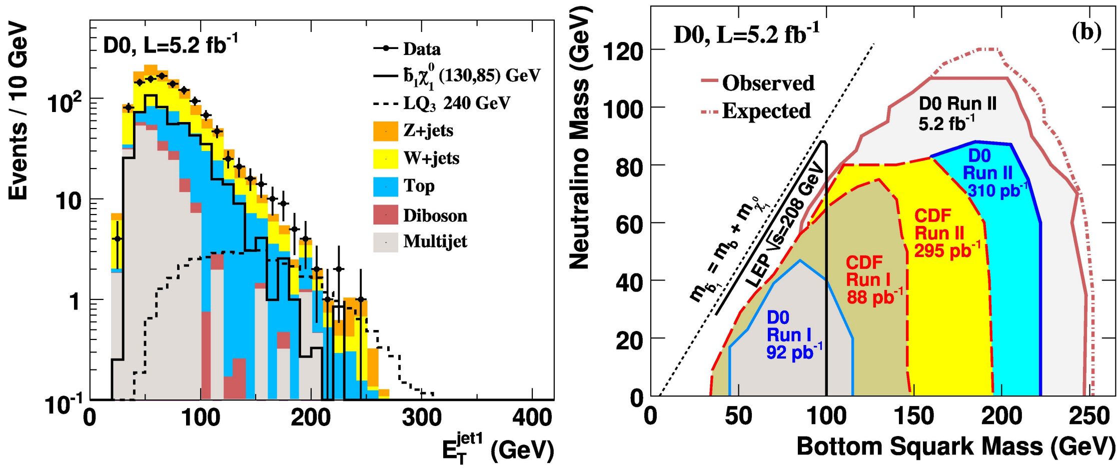

Figure 1: The E_T of the leading jet (left) and limits in the $m_{\chi_1^0}$-$m_{\tilde{b}}$ neutrino and a b quark plane (right).

The CDF collaboration has searched in 2.65 fb^{-1} of Run II data[1], and measures the dominant background in this search from light-flavor jets misidentified as b-jets with control samples in data. Events are required to have a good primary vertex, and track activity consistent with energy measured in the calorimeter. Events with exactly two well-measured jets with $E_T > 25$ GeV, not pointing along either jet direction, and no isolated high-p_T tracks are selected for final analysis. The final selection criteria are optimized for two signal regions in $\Delta M = M_{\tilde{b}_1} - M_{\tilde{\chi}_1^0}$, the mass difference between the sbottom and the neutralino. The background predictions for the two regions are 133.8 ± 25.2 events and 47.6 ± 8.3 events for the high and low ΔM regions respectively. In the data, 139 events are observed in the high ΔM region and 38 in the low ΔM region. In the absence of any excess, limits are set in the neutralino-sbottom mass plane.

DØ has performed an updated search[2], which uses 5.2 fb^{-1} of Run II data. This search is also for pair production of scalar bottom quarks, and is also interpreted in the context of scalar third-generation leptoquarks. As in the CDF analysis, scalar bottom quarks are assumed to decay to a neutralino and a b quark. Events are selected by requiring two or three jets with $p_T > 20$ GeV/c, and no identified isolated electrons or muons. The $\not\!\!E_T$ is required to be greater than 40 GeV, and not aligned with the direction of any jet. A neural network b-tagging algorithm is employed to identify heavy-flavor jets, two of the jets are required to be consistent with originating from a b quark. A final selection on the kinematics of the event, including the p_T of the leading jet, $\not\!\!E_T$, and the scalar sum of the jets E_T and $\not\!\!E_T$, H_T, is optimized for the smallest expected cross section limit for each signal mass considered.

In the absence of a significant excess, this search has set 95% C.L. lower limits on their production in the ($m_{\tilde{b}}$, $m_{\chi_1^0}$) mass plane, such as $m_{\tilde{b}} > 247$ GeV/c^2 for a massless neutralino, and $m_{\chi_1^0} > 110$ GeV/c^2 for $160 < m_{\tilde{b}} < 200$ GeV/c^2. The E_T of the leading jet and limits in the $m_{\chi_1^0} - m_{\tilde{b}}$ plane are shown in Figure 1. Limits are also placed on third generation leptoquarks, which are assumed to decay to a tau neutrino and a b quark. The 95% C.L. lower limit on the mass of a charge-1/3 third-generation scalar leptoquark is 247 GeV/c^2.

3 Search for Scalar top with c jets and $\not\!\!E_T$

CDF has also searched for direct stop quark production, where the stop decays to a charm quark and a neutralino. In this search, the neutralino is assumed to be the LSP, and R-parity conservation is assumed. Therefore, the stop signature is two c jets and large missing transverse energy from the LSP escaping detection.

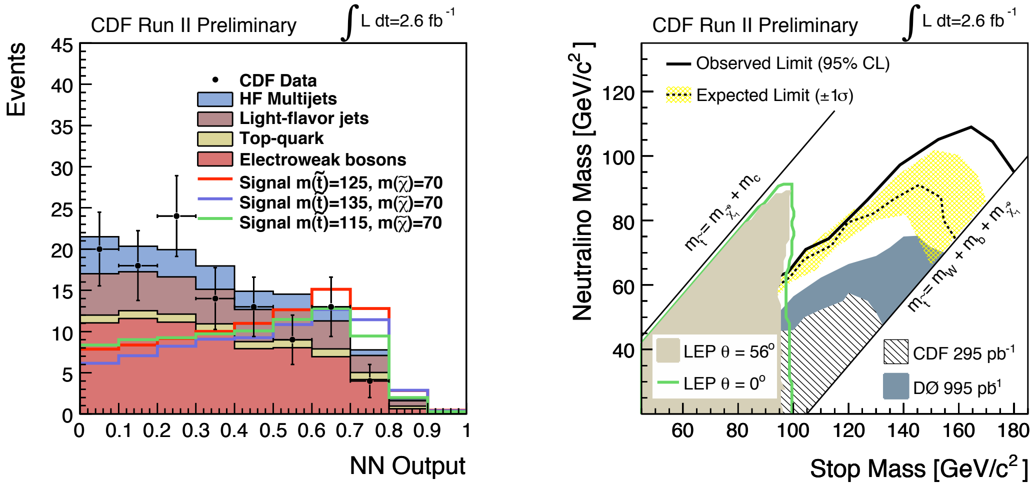

Figure 2: Output discriminant from the heavy-flavor multi-jet neural network (left) and the 95% C.L. limits in the $m_{\chi_1^0} - m_{\tilde{t}}$ mass plane (right).

Events are selected by requiring at least two well-measured jets with $E_T > 25GeV$ and $\not{E}_T > 50$ GeV. A neural network is used to reject heavy flavor multi-jet events, and a second two-dimensional neural network is employed to select charm jets. The background contribution from heavy-flavor production and light quark jets misidentified as heavy flavor are estimated from the data. This search is optimized for a stop mass of 125 GeV/c^2, and a neutralino mass of 70 GeV/c^2. The predicted background is 132.0 ± 24.4 events, and 115 events are observed. For a neutralino mass of 70 GeV/c^2, and $m_{\tilde{t}}$ ranging from 115 to 125 GeV/c^2, the expected signal ranges from 82.4 to 90.2 events. No excess is observed and limits are set in the $m_{\chi_1^0}$ and $m_{\tilde{t}}$ plane, shown in Figure 2.

4 Search for Gauginos in GMSB

After the observation in Run 1 by CDF of a two electron, two photons, and $\not{E}_T$ candidate event, a class of supersymmetry models with gauge-mediated SUSY breaking became of particular theoretical interest. These models solve the "naturalness problem" and provide a low-mass dark matter candidate. In this search, a scenario where the lightest neutralino, χ_1^0, decays almost exclusively to a photon and a weakly interacting, stable gravitino is considered. The gravitino escapes the detector without depositing any energy, and therefore can generate significant $\not{E}_T$. At the Tevatron, production of gaugino pairs would then result in two photons, $\not{E}_T$, and possibly other products of the cascade decay.

CDF has performed a search [3] for this signature with 2.6 fb^{-1} of Run II data. This search is optimized for neutralino lifetimes of order a few ns or less, and utilizes a timing system allowing the photon arrival time to be measured. A detailed model of the $\not{E}_T$ resolution is employed to reject backgrounds from instrumental and non-collision sources, enhancing the sensitivity for large χ_1^0 masses. This model enables a per-event figure of merit to be computed, allowing events where the $\not{E}_T$ is more likely to be the result of a mis-measured jet or other poorly reconstructed object to be rejected, while retaining with high efficiency events with well-measured real $\not{E}_T$.

Events are selected by requiring two photons with $E_T > 20$ GeV. The $\not{E}_T$ significance of events is required to be greater than 3, and the total sum E_T of the observed jets and $\not{E}_T$ in the event is required to be more than 200 GeV. Finally, the two photons are required to not be back-to-back by requiring the angle between them to be less than $\pi - 0.35$ radians. After

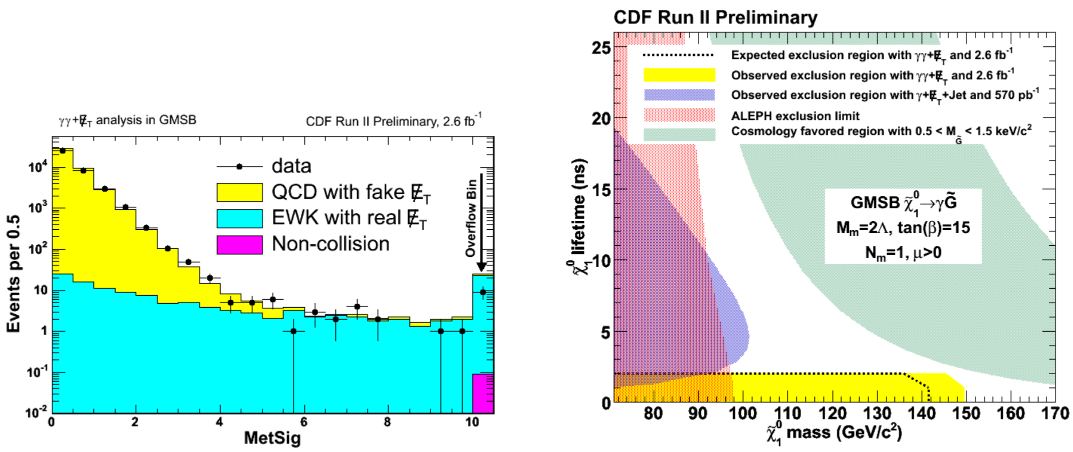

Figure 3: The $\not\!\!E_T$ significance, showing the separation power for mismeasured QCD and electroweak sources of $\not\!\!E_T$ (left), and the limits in the $m_{\chi_1^0}$ and χ_1^0 lifetime plane (right).

all selection, the dominant background originates from electroweak production of a Z^0 with two photons, where the Z^0 decays to neutrinos and results in significant $\not\!\!E_T$. The total predicted background in this search is 1.4 ± 0.4 events, and zero are observed. Limits are set at 95% C.L. in the $m_{\chi_1^0}$ and χ_1^0 lifetime plane, shown in Figure 3. For a short-lived neutralino with lifetime less than a nanosecond, the limit is 150 GeV/c^2.

5 Search for Hidden Valley Dark Photons

Recently, a subset of HV models with SUSY have emerged which may simultaneously explain anomalies of the observed spectra of high-energy cosmic ray positrons and electrons, and provide a solution to the origin of Dark Matter. They propose a scenario where dark matter can annihilate to pairs of so-called dark photons, which then would potentially themselves decay to pairs of e^+e^- or $\mu^+\mu^-$ through their mixing with the SM photon. At the Tevatron, gaugino production could lead to cascade decays of charginos and neutralinos which could include decays to both SM photons and these dark photons, whose favored mass range is on the order of 1 GeV. The signature, then, will be a SM photon, two opposite charge leptons spatially close to each other in the detector, and $\not\!\!E_T$ from the escaping LSP. DØ has searched for this signature with 4.1fb^{-1} of Run II data[4].

Events are selected by requiring a single photon and two leptons. The proximity of the leptons to each other requires a careful treatment of the isolation requirement placed on the leptons. The main background is QCD with photon conversions producing pairs of leptons. After selection, the dilepton invariant mass is used as a signal discriminant, where the signal would appear as an excess at the dark photon mass. No significant excess is observed, and exclusion limits are set on the lightest chargino mass as a function of the dark photon mass, shown in Figure 4.

6 Search for Hidden Valley Long-lived Particles

Another class of HV models predicts a new, confining gauge group, weakly coupled to the SM. Stable configurations of HV hadrons, "v-hadrons" in this model, can be long-lived. In one benchmark model, the SM Higgs boson mixes with the HV Higgs boson. In this scenario, the SM Higgs could decay, through the mixing with the HV Higgs, to pairs of v-hadrons. The v-hadrons then preferentially couple to the heavier SM quarks due to a helicity suppression

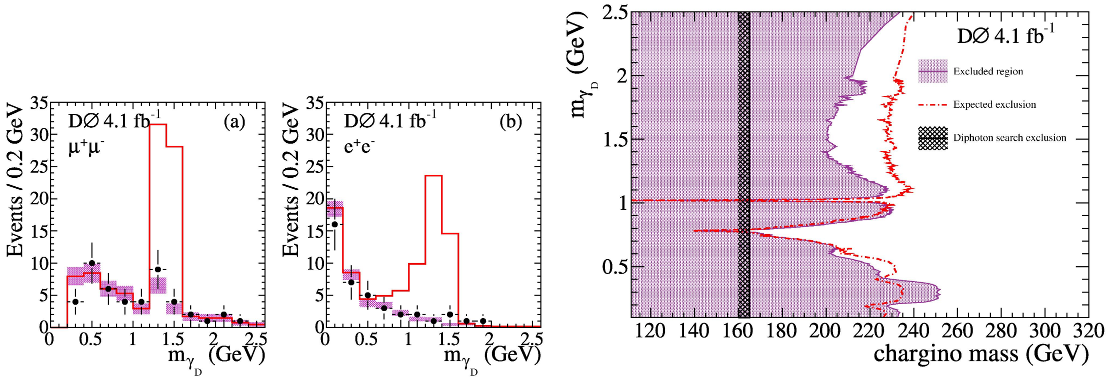

Figure 4: Dark Photon mass for the muon and electron channels with hypothetical signal shown in solid line(left), and limits in the dark photon mass - chargino mass plane (right).

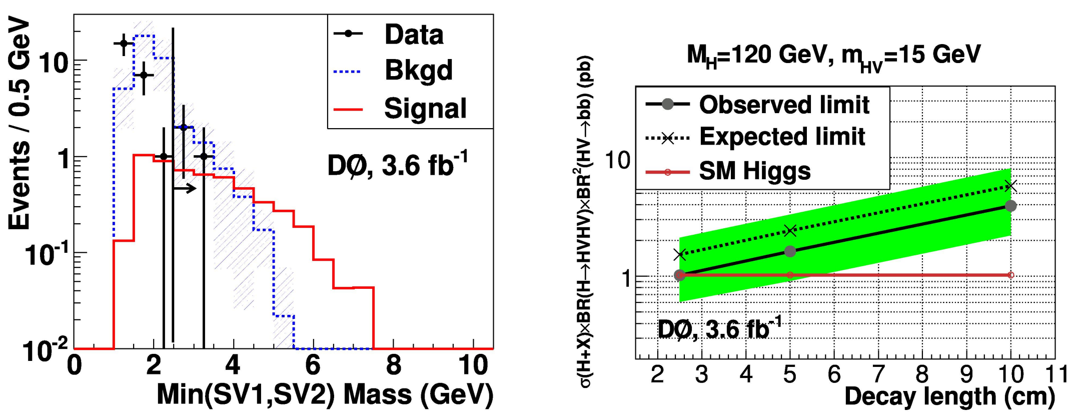

Figure 5: The smallest secondary vertex mass in the event (left), and limits on the SM Higgs boson production cross section, for a v-hadron mass of 15 GeV/c^2 (right).

mechanism. The resulting signature is highly-displaced secondary vertices with a large number of tracks from the b-quark decays. This has been searched for by DØ with 3.6 fb^{-1} [5].

Events are selected by searching for at least two separated four-track secondary vertices, with an impact parameter in the transverse plane, $L_{xy} > 1.6$ cm. The secondary vertex mass and collinearity are used to select the signal region. No excess is observed in data. Assuming the Higgs always decays to dark-sector v-hadrons, which themselves always decay to $b\bar{b}$ pairs, limits are set on SM Higgs boson production, shown in Figure 5.

7 Conclusions

The CDF and DØ experiments are searching many models and signatures for evidence of new physics. None is observed yet, but both experiments have now recorded more that 8 fb^{-1}, and should have results with this doubling of the data soon. Much of the Run II data is yet to be analyzed, and additional data continues to increase sensitivity to new physics signals.

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