Vol. 1 (2008) *Acta Physica Polonica B Proceedings Supplement* No 2

COLLIDER SEARCHES FOR PHYSICS BEYOND THE STANDARD MODEL*

Jane Nachtman

for the CDF and D0 Collaborations

Fermi National Accelerator Laboratory, PO Box 500 Batavia, IL 60510-5011, USA
and
University of Iowa, Iowa City, IA 52242-1479, USA

(Received January 8, 2008)

On the eve of the LHC startup, I review the current results from the highest energy colliders in operation, the Tevatron and HERA. Searches for physics beyond the Standard Model are presented, encompassing a wide variety of models and methods.

PACS numbers: 12.60.–i

1. Introduction

High energy physics is on the threshold of discovery, as we await the turn-on of the CERN's Large Hadron Collider (LHC) next year. The current energy frontier is at Fermilab's Tevatron and DESY's HERA accelerators, where new results push the boundary of our understanding of nature. There are many signals of new physics that are unique to HERA, or that can be observed at the Tevatron more readily than at LHC. Physicists working on analysis of the data are pushing hard to explore the possibilities to try to make a discovery in advance of the LHC startup.

The Tevatron accelerator is located at Fermi National Accelerator Laboratory, colliding protons and anti-protons at a center-of-momentum energy of 1.96 TeV. There are two collision points, where the Collider Detector at Fermilab (CDF) and D0 detectors are located. The Tevatron has currently delivered almost $3\,\mathrm{fb}^{-1}$ of data to each of the CDF and D0 detectors. With two more years of operation remaining, datasets of up to $8\,\mathrm{fb}^{-1}$ per experiment are expected. The integrated luminosity as a function of time illustrates the remarkable achievements from the Tevatron accelerator, as the machine continues to be upgraded to reach its final configuration.

* Presented at the Symposium "Physics in Collision", Annecy, France, June 26–29, 2007.

Results presented at this conference are mainly from analysis of 1–2 fb^{-1} of data, with the remainder in progress and preparations for analysis of the full dataset in mind.

The HERA accelerator at DESY accelerates electrons (or positrons) to an energy of 27.5 GeV and protons to an energy in the range of 460 to 920 GeV, depending on the accelerator configuration, governed by the physics program, giving a range of center-of-momentum energies for this versatile machine. The HERA accelerator concludes its operation this week, ending a successful run for the Zeus and H1 experiments, who have presented many new results in this conference. The combined dataset size of the H1 and Zeus experiments totals 1 fb^{-1}. As the HERA results were largely covered by Iris Abt and Thi Nguyet Trinh at this conference, they will not be covered here.

2. Searches for Supersymmetry

The search for SUSY has been ongoing for many years, and SUSY models continue in popularity, in spite of the lack of experimental evidence. SUSY predicts a new particle "super-partner" for every Standard Model particle, differing by one-half in spin. Therefore, the SUSY partners of Standard Model fermions are bosons, and Standard Model bosons are fermions in their Supersymmetric manifestation. The theory of Supersymmetry solves several issues in the Standard Model, and many SUSY models which could explain Dark Matter predict signatures accessible at current colliders. Coincidentally, the low-mass SUSY particles which could be observed at the Tevatron prove to be among the best Dark Matter candidates. SUSY provides a Dark Matter candidate in the lightest neutralino — it is neutral, colorless, and does not decay. This leads to the classic signature of missing energy observed in the detector. Tevatron searches typically look for evidence of SUSY particles which decay to the lightest neutralino. The Tevatron experiments have a broad program of searches for SUSY, covering a variety of signatures, models, and indirect/direct searches.

2.1. Search for chargino-neutralino production

Associated production of a chargino and (second lightest) neutralino, decaying to W and Z plus the lightest neutralino is one of the flagship analyses for discovery of SUSY at the Tevatron. When the W and Z decay leptonically, the signature is three leptons plus missing energy from the neutralino and neutrino, giving a very clear signal which has low Standard Model background. The trilepton signature can also be attained from decays of the chargino and neutralino through real or virtual sleptons.

CDF and D0 have developed a suite of searches for trilepton events [1,2], with combinations of electrons, muons, and tracks (which can substitute for the third lepton). Tau leptons are more difficult to detect, as there is a larger background from misidentified jets. However, accepting a track in place of the third lepton can recoup some of the tau acceptance. A range of kinematic properties of the events is considered, to take into account as many possible theoretical scenarios as possible. When more energetic leptons are considered, the searches are relatively easier, as more problematic backgrounds are smaller. However, the low-energy searches must be carefully considered, in order to retain sensitivity in as much of SUSY parameter space as possible. Another analysis which searches for only two leptons, but requires the leptons to have the same sign, can gain signal acceptance with somewhat higher backgrounds.

Control regions, regions of kinematic parameter space where the signal is expected to be small while the Standard Model is large, are chosen to enhance particular backgrounds and test the prediction of the shape and normalization. Both CDF and D0 show kinematic distributions to prove that their control regions are understood, giving confidence that if a signal were to be present, it would be recognized as such.

The CDF and D0 analyses do not see a significant excess of trilepton events thus far, and combine all trilepton analyses in order to set limits on mSUGRA-inspired models with up to $1.1\,\mathrm{fb}^{-1}$ [2]. Limits are often expressed as cross section limits as a function of chargino mass, which can be easily interpreted with different SUSY parameters. Both D0 and CDF test a variety of models, where the experiments have the most sensitivity to models with high leptonic branching ratios of the chargino and second neutralino, and large mass differences between these partices and the lightest neutralino, to which they decay. CDF and D0 chose models which are similar in order to facilitate combination of results; these models have high leptonic branching ratios. The CDF model uses a fixed value of m_0 to fix the slepton mass to be slightly larger than the second-lightest neutralino, so the slepton mass remains constant throughout, and gives a lower limit on the chargino mass of $127\,\mathrm{GeV}/c^2$. The D0 analysis adjusts the value of m_0 such that the slepton mass is slightly greater than the mass of the second-lightest neutralino, and scales as the gaugino masses change. The resulting lower limit on the chargino mass is $145\,\mathrm{GeV}/c^2$.

In the CDF analysis which searched for a pair of leptons with the same charge, a small excess was observed in 1 fb^{-1} of data. With a looser version of the selection criteria, 34 ± 4 events are expected and 44 are observed. With a tighter version of the selection criteria, 8 ± 1 events are expected and 13 are observed. This small excess was mainly observed at high transverse momenta, and more data is needed to see if this interesting result is sustained.

The trilepton analyses are just beginning to probe new parameter space not accessible by the LEP experiments, and much more data is expected from the Tevatron. Both CDF and D0 have calculated their projected sensitivity to SUSY using the trilepton analyses. The CDF projected sensitivity is calculated based on the current $1\,\mathrm{fb}^{-1}$ expected sensitivity. For a dataset with an integrated luminosity of $8\,\mathrm{fb}^{-1}$, chargino masses of up to almost $190\,\mathrm{GeV}/c^2$ can be probed, assuming no changes to the existing analyses [1]. The D0 expected sensitivity is calculated assuming improvements to the analysis as more data is analyzed. For a dataset with an integrated luminosity of $8\,\mathrm{fb}^{-1}$, chargino masses of up to almost $240\,\mathrm{GeV}/c^2$ can be probed, with the improved analyses [2]. The D0 analysis found that at high chargino masses, new decay modes open up which spoil the trilepton signature, leading to reduced sensitivity.

2.2. Searches for squarks and gluinos

At the Tevatron, a large production cross section is expected for squarks and gluinos, so these searches could yield the first evidence of Supersymmetry. Squarks and gluinos can be produced in pairs or in association, and the decay modes depend on the masses. High mass particles will decay in a cascade down to the lightest neutralino, leading to multiple energetic jets and large missing energy. The number of jets resulting from the decay depend on the SUSY particle masses, so searches for $N = 2, 3$, or 4 jets can be optimized for regions of SUSY parameter space. The search for squark/gluino production leading to energetic jets and large missing transverse energy is one of the most powerful and general SUSY searches possible at the Tevatron; it is also one of the most difficult due to the large QCD background (which can be reduced to low levels after all analysis selection is applied). Careful comparison of the missing transverse energy and scalar sum of the transverse energy of the jets is required to proceed with confidence with this analysis.

No excess of events was found in the CDF and D0 searches for missing transverse energy plus jets; limits on squark and gluino production can be calculated. For $m_{\tilde{q}}\ m_{\tilde{g}}$, D0 (CDF) sets a limit at $m_{\tilde{g}} > 402$ (380) GeV/c^2. For any $m_{\tilde{q}}$, D0 (CDF) sets a limit at $m_{\tilde{g}} > 309$ (230) GeV/c^2. It should be noted that these calculations use the nominal values for signal cross sections, without reducing it for systematic errors, which has an impact on the values of the squark and gluino mass limits, the level of which is analysis dependent.

D0 has derived projections for the sensitivity achievable with the full Run II dataset and improvements to the analysis such as improved jet energy scale. For 8/fb, and at $m_{\tilde{q}}\ m_{\tilde{g}}$, D0 is sensitive to $m_{\tilde{g}} < 410\,\mathrm{GeV}/c^2$. For any $m_{\tilde{q}}$, D0 is sensitive to $m_{\tilde{g}}$ up to $320\,\mathrm{GeV}/c^2$.

3. Long-lived particles

Several models predict long-lived particles: charged or neutral particles which can decay inside or outside of the detector. The charged particles (CHAMP) appear as if they were slow muons, and neutral particles which finally decay inside the detector lead to such signatures as "delayed photons" and "delayed jets".

CDF's Charged Massive stable Particle (CHAMP) analysis [1] looks for the unique signature of a slow, heavy, muon-like object which has a long Time-of-Flight measurement and in additon large ionization energy loss, dE/dX. Control datasets are used to validate the measurement technique. The track momentum and the velocity from the CDF time-of-flight measurement are used to derive the mass of the candidates, which are taken from the high-p_{T} muon dataset. No candidates were found with reconstructed mass greater than $120\,\mathrm{GeV}/c^2$, leading to a 95% C.L. exclusion limit on a stable stop model, of $M_{\mathrm{stop}} > 250\,\mathrm{GeV}/c^2$.

CDF's Delayed Photon analysis [1] relies on the electromagnetic calorimeter timing detector, which is able to precisely measure the photon arrival time. The typical collision event will have an arrival time centered at zero, while events where the misreconstructed photon comes from the beam halo precede the collision, and photons misreconstructed from cosmic rays are independent of time. The signal is from a hypothesized Gauge-Mediated SUSY Breaking model, where the lightest neutralino does not decay immediately, but still decays within the detector to a photon and a gravitino, which is the lightest SUSY particle. The data shown in points is $570\,\mathrm{pb}^{-1}$ of CDF data with electromagnetic calorimeter timing information available. The analysis is sensitive to a range of neutralino lifetimes up to 25 ns, and the absence of evidence of long-lived neutralinos allows a limit to be placed on the neutralino mass *versus* the neutralino lifetime which exceeds the limits from ALEPH for short neutralino lifetimes.

Models of "split-SUSY" predict SUSY scalars that are heavy compared to SUSY fermions, leading to long-lived gluinos. If these particles are produced, they will stop in the calorimeter and decay at a later time. D0's analysis [2] is sensitive to a decay time between 10 μsec to 100 hours after the collision. This technically difficult analysis requires a detailed understanding of many subtle effects in the data; the analysis looks for events with calorimeter energy and nothing else. The good agreement of the data with the predicted background allows cross section limits to be derived as a function of the gluino mass for various gluino decay times.

4. Extra dimensions

In recent years theories have emerged which hypothesize more than four dimensions of spacetime. These "extra" dimensions must be confined. Large Extra Dimension (LED) models predict the size of the extra dimensions to be approximately $10\,\mu$m; for example, ADD models which predict a continuous spectrum of Kaluza–Klein modes. Small Extra Dimension models, for example Randall–Sundrum models, predict towers of Kaluza–Klein modes which are experimentally observed as mass resonances with spacing of $\mathcal{O}(\mathrm{TeV})$.

CDF reports a search for monojet plus missing energy events [1], where they have developed a range of kinematic selections to improve sensitivity and keep the analysis as model independent at possible. The LED signal would be manifested as a continuous spectrum in missing energy. As the data agrees with the Standard Model prediction, limits on ADD models can be derived. The analysis sets limits on the number of Extra Dimensions, where the CDF result exceeds the LEP combined limit for large numbers of Extra Dimensions.

Randall–Sundrum (RS) models predict that evidence of gravitons may be accessible at Tevatron energies. As RS gravitons have spin 2, the branching ratio to photons is twice that to electrons. A new D0 analysis [2] maximizes the acceptance by looking for electromagnetic calorimeter objects without a track requirement. The analysis finds good agreement between the total background from instrumental and Standard Model sources and $1.1\,\mathrm{fb}^{-1}$ of data. Limits derived on the graviton mass range from 240 to 865 GeV$/c^2$, depending on the value of the coupling.

5. Fourth generation, extra gauge bosons, compositeness and leptoquark searches

More collider searches for new particles include analyses looking for evidence of a fourth generation of particles (t' and b'), new gauge bosons (Z' and W'), compositeness (excited electrons and neutrinos), and leptoquarks.

CDF reports a limit on b' production [1] which is derived from a signature -based search for Z bosons with additional jets. This data-driven analysis uses Z events with low jet multiplicity (< 3) to estimate the Standard Model prediction for the production of Z events with higher jet multiplicity (> 2). After validating the method, and applying to a model for $b' \to Z + b$, a limit of $m_{b'} > 270\,\mathrm{GeV}/c^2$ is derived.

Searches for $Z' \to e^+e^-, \mu^+\mu^-$ from CDF [1] and D0 [2] look for events with high p_{T}, same-flavor leptons, optimized for a high-mass Z'. The main Standard Model Contribution is from the Drell–Yan process. No significant excess is observed in 1.3/fb of CDF di-electron data.

CDF searches for W' were covered in a previous presentation by Catalin Ciobanu, so would not be discussed here. D0 has also searched for $W' \to e\nu$ in 900/pb of data [2], using the lower transverse mass distribution for normalization, and the higher transverse mass distribution for the search, which yielded a limit of $m_{W'} > 965\,\mathrm{GeV}/c^2$.

A new search from D0 for excited leptons in the channel $p\bar{p} \to ee^* \to ee\gamma$ examines the $e\gamma$ mass spectrum for a resonance [2]. No evidence for e^* production was found, and cross section limits were derived for various values of the compositeness scale Λ.

Searches for leptoquarks (LQ) are performed at the Tevatron and HERA. Leptoquarks, new bosons carrying lepton and baryon numbers, are predicted by many models, and could be pair produced at the Tevatron. D0 reports a new search for second-generation leptoquarks [2], which has a signture of energetic muons plus jets. Reconstructing m_{LQ} yields a high-mass expectation of $6.4 \pm 0.7 \pm 0.8$ and an observation of 6 events (for $m_{\mathrm{LQ}} = 200\,\mathrm{GeV}/c^2$). The good agreement with prediction leads to limits of $m_{\mathrm{LQ}} > 210\,\mathrm{GeV}/c^2$.

6. Signature-based and global searches

In an effort to be independent of models predicting physics beyond the Standard Model and so not miss something unexpected, a program of signature-based and global searches has been developing. The idea is to look for anomalies in the Standard Model production; for example, the excess observed in the W's by H1 (see Iris Abt's presentation) and the suite of analyses from CDF looking for diphoton + X [1]. These signature-based searches provide useful input to experimental physicists in developing new analyses, and for theoretical physicists in developing new models that they wish to test experimentally.

Global searches attempt to take a broad look at "everything", or at least everything possible with caveats. There is less model dependence for the signal, although some assumptions must be made to carry out the analysis. However, there is a greater reliance on Standard Model modeling of background, which has to be carried out on a global scale rather than for a specific channel. The lack of optimization for a specific signal means that sensitivity is sacrificed in order to retain global sensitivity to the unexpected. A search in the D0 Run I data [3] was performed on a subset of channels, and some of the current analyses build on that foundation.

6.1. Global search at H1

The H1 collaboration has released a global search result [4] with $159\,\mathrm{pb}^{-1}$ of e^-p data. In their analysis, they search for energetic ($p_{\mathrm{T}} > 20\,\mathrm{GeV}/c$), isolated particles: e, μ, ν, γ, and jets, looking at combinations of these objects in 23 final states. The level of agreement between the predicted and the observed number of events in the data is very good.

Besides the number of events, kinematic quantities are scanned for agreement between prediction and observation. The sum of transverse momentum and the invariant mass of the objects in the event is examined, and the agreement is quantified in terms of the probability to observe an excess or deficit at the level given, taking into account the number of places searched. Although a small number of disagreements are observed, the overall probability does not indicate the presence of physics beyond the Standard Model.

6.2. Global search at CDF

CDF's global search analysis [1] is divided into two parts. In the Vista analysis, the bulk features of the high-p_T data are examined in a model-independent manner. Objects considered are e, μ, τ, γ, jets, and b-tagged jets, and are combined into exclusive final states. The global comparison of kinematic quantites over all final states is used to derive a correction model for the Standard Model, which automatically takes into account higher-order corrections and known deficiencies in the simulation. Data and the Standard Model are compared in 16486 kinematic distributions in 344 final states, taking the trials factor into account. After this analysis, the probability of observing the largest discrepance (or greater) that is observed, is 8%.

The second piece of CDF's global analysis is the Sleuth program, which is a "quasi-model-independent" search of the high Σp_T tails. The premise is that new physics would likely show up here, indepedently of the details of the model. The analysis starts with the final states examined by the Vista analysis, where similar final states are merged to increase the statistical significance. The analysis is quantified by the probability to observe the most interesting (most unlikely) positive deviation from the prediction in the high Σp_T tail, incorporating the trials factor into the calculation. Although several interesting final states were observed none were significant enough to warrant a claim of new physics. However, the significance of an interesting final state could jump to a much higher level with the addition of more data.

7. Conclusion

The Tevatron and HERA experiments have probed a wide variety of signatures and models, and have shown many interesting results today. As the Tevatron still has most of its expected data to deliver, there will be many more results to come, and hopefully some surprises.

REFERENCES

[1] See `http://www-cdf.fnal.gov/physics/exotic/exotic.html`
[2] See `http://www-d0.fnal.gov/Run2Physics/WWW/results/np.htm`
[3] [D0 Collaboration], *Phys. Rev. Lett.* **86**, 3712 (2001).
[4] [H1 Collaboration], *Phys. Lett.* **B602**, 14 (2004).