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Beyond Standard Model Physics

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There are many recent results from searches for fundamental new physics using the TeVatron, the SLAC b-factory and HERA. This talk quickly reviewed searches for pair-produced stop, for gauge-mediated SUSY breaking, for Higgs bosons in the MSSM and NMSSM models, for leptoquarks, and v-hadrons. There is a SUSY model which accommodates the recent astrophysical experimental results that suggest that dark matter annihilation is occurring in the center of our galaxy, and a relevant experimental result. Finally, model-independent searches at D0, CDF, and H1 are discussed.

1. Introduction

It is somewhat misleading to use the terms 'New Physics' or 'Beyond Standard Model Physics' for results that explicitly search for signatures that would result from extensions to the standard model. In almost any precision measurement of the production, properties or decays of already-known property, there is the possibility of an unusual result can be explained with an extension to the standard model. In a certain sense then, nearly every result being shown here this week is a search for new physics. In particular, Lee Roberts will be giving a presentation on searches for 'New Physics' in low energy experiments.

However even restricting the discussion to analyses that search directly for extensions to the standard model at high energy colliders would create a discussion that goes on for far too long. With great regret, I have had to trim my selection of topics very sharply. There is just too much good work done here to give each study adequate coverage. In particular, there has been a great deal of excellent work preparing for the analysis of the imminent flood of data from the LHC. I can only refer the reader to the parallel sessions of this conference.

The bulk of the recent results are from the TeVatron, which has been performing quite well. Although most of the results described here are based on smaller datasets, just under $7\,\mathrm{fb}^{-1}$ have been delivered to each experiment at this time. Results from the CDF and D0 collaborations are collected at [1].

Certain characteristics of hadron collisions are common to all or nearly all searches for exotic phenomena in them. The copious production of multijet "QCD" events is suppressed with detectors designed to reject fake electrons and muons (hereafter referred to as leptons, ℓ), kinematic cuts and isolation cuts that require that the identified lepton not be surrounded by other activity in the detector. Multijet background is rarely, if ever, modeled effectively with Monte Carlo simulation techniques. For the many searches which select highly energetic leptons or momentum imbalance in the final state, the following known physics processes typically produce significant backgrounds: the Drell-Yan process $p\overline{p}\rightarrow\ \gamma^*/Z\ \rightarrow\ell^+\ell^-$, $\gamma^*/Z\ \rightarrow\tau^+\tau^-$, $W^\pm\ \rightarrow\ \ell^\pm\nu$, and $t\bar{t}$ production. The diboson production processes $p\overline{p}\rightarrow\ VV$ with $V\ \in\ \{\gamma, Z, W\}$ have lower production cross-sections but also create unusual signatures which are of interest in many searches.

sJust as limiting as backgrounds are the kinematic facts of life in hadron colliders. In $p\overline{p}$ (or pp) collisions, the component of the initial-state momentum along the collision axis is not known and kinematic calculations can only be done in the plane perpendicular to the collision. I will use $\not{E}_T$ to indicate the opposite of the observed sum of particle momenta in this transverse plane, and p_T to indicate the momentum of an object projected onto this transverse plane.

2. About Supersymmetry

As many of the results discussed here are based on supersymmetric (SUSY) extensions of the standard model, a short introduction is appropriate. In no way however can this replace the many excellent existing reviews and introductions, some of which may be found in reference [2, 3].

SUSY provides solutions to several existing dilemmas in the standard model. One is the "$\mathrm{M}_H$problem". The propagator for a Higgs scalar with fermionic couplings $\mathcal{L}\ =\ -\lambda_f H f\bar{f}$ has one loop correction terms that contribute to the mass in amount $\Delta\mathrm{M}_H^2\ =\ -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2$, where$\Lambda_{\ UV}$ is a cutoff scale corresponding to the point where our existing understanding of nature's particle content becomes inadequate. Our difficulty is that we have no clear value for$\Lambda_{\ UV}$ short of the Plank scale, resulting in large negative contributions to m_H. However, if for every fermion there is a corresponding scalar field S with interaction $\mathcal{L}\ =\ -\lambda_s|h|^2|S|^2$, then the corresponding scalar loop diagram introduces canceling mass contributions $\Delta_H^2\ =\ \frac{\lambda_S}{16\pi^2}[\Lambda_{UV}^2\ +\ \ldots]$.

A second outstanding problem in the standard model is the dark matter problem. The lightest neutral sparticle often makes a good dark matter candidate.

Finally, the coupling constants for the strong, weak and electromagnetic forces vary with the energy scale of the interaction according to the renormalization group. In the minimal supersymmetric extension to the standard model (MSSM), the coupling constants evolve out to reach similar values at the scale of 10^{16} GeV, which does not happen in the standard model. Quoting [3], "While the apparent unification of gauge couplings at [this scale] might just be an accident, it may also be taken as a strong hint in favor of a grand unified theory or superstring models, both of which can naturally accommodate gauge coupling unification below M_P."

Because the SUSY mass spectrum evidently differs from that of the standard model particle content, there must be SUSY-breaking terms in the Lagrangian. The primary constraint on these terms is that they not reintroduce ultraviolet divergences of the sort we were glad to be rid of earlier. This is not a very tight constraint; there are at least 105 new free parameters in the most general form of the symmetry breaking Lagrangian. What this does is provide a flexible framework in which different models of symmetry breaking can be inserted and investigated. Of the many different physical concepts that can and have been inserted into the SUSY breaking Lagrangian, two of the most studied ones are the mSUGRA and the GMSB models. We have recent results in both of these SUSY breaking models.

The generality of the SUSY breaking Lagrangian is perhaps why the SUSY hypothesis has had such a long run. After all, SUSY was proposed in the early 1970s, when the standard model was still a novel model, and much of its particle content was unknown. For nearly 4 decades, theorists have been able to write Lagrangians of all sorts into this framework and work out the their possible implications.

R-parity is a hypothesized quantum number which differentiates standard model particles from SUSY particles. All of the searches presented here assume the conservation of R-parity, so that each SUSY particle is produced in conjunction with the corresponding SUSY anti-particle.

In SUSY, 2 Higgs doublets

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \qquad H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \qquad (1)$$

coupling respectively to down- and up- type fermions are required in order to prevent triangle anomalies. The ratio of the vacuum expectation values of the two neutral fields, $\tan\beta = \langle H_u^0\rangle/\langle H_d^0\rangle$ is one of the key parameters of supersymmetry, or indeed of any 2 doublet model. Analyses that apply Bayesian methods to a random samplings of parameter space [5] strongly favor larger values of $\tan\beta$ at least in the context of mSUGRA and similar SUSY-breaking models.

The SUSY partners to the Higgs fields are the spin 1/2 Higgsinos:

$$\tilde{H}_d = \begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{pmatrix} \qquad \tilde{H}_u = \begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix} \qquad (2)$$

The charged components of the Higgsino fields can form linear admixtures with the wino to create 2 charginos, $\tilde{\chi}^\pm$. The convention is that $m(\tilde{\chi}_1^\pm) < m(\tilde{\chi}_2^\pm)$. $\tilde{\chi}$, without subscript, refers the lightest of the mixtures. The neutral components of the Higgsino fields form linear admixtures with the zino and photino to create 4 neutralinos, $\tilde{\chi}_i^0$.

Returning to the scalars, after electroweak symmetry breaking, two doublet models yield 5 Higgs bosons: two CP-even neutral scalars h and H, a CP-odd neutral A and a pair of charged scalars, $H^\pm$.

No discussion at length about SUSY is complete without mentioning that the MSSM at least is under some pressure from experimental results from the electroweak symmetry breaking sector. The lightest neutral MSSM Higgs boson h must have a mass below 135 GeV [3, 4] and experimental lower bounds [6] have come to approach this level.

3. Searches for $\tilde{t}$

We have recent search results for the pair production of the SUSY partner to the top quark in $p\overline{p}$ collisions. There are 3 decay channels under study. In all 3 cases, limits are placed in a plane where the horizontal axis is the mass of the pair-produced $\tilde{t}$ and vertical axis is the mass of the final state SUSY particle.

The first channel is $\tilde{t} \to b\tilde{\chi}^+; \tilde{\chi}^+ \to \tilde{\nu}\ell^+$. R-parity conservation means that the charge conjugate process occurs on the other side of the event, where a $\overline{\tilde{t}}$ decays similarly. The signature is an $\ell^+\ell^-$ pair with $\not{E}_T$ from the escaping neutrinos. There are 2 b-jets in the final state, but both the D0 and CDF collaborations found kinematic selection sufficient. The recent D0 result [7] uses $3.1\,\mathrm{fb}^{-1}$ in the $e-\mu$ channel in conjunction with earlier $1.1\,\mathrm{fb}^{-1}$ $e-\mu$ and $e-e$ results. The CDF result [8] is based on $1.0\,\mathrm{fb}^{-1}$ in all 3 dilepton channels. Limits are drawn in the $m(\tilde{\nu})$ *vs.* $m(\tilde{t})$ plane and extend up to $m(\tilde{\nu}) \simeq 120$ GeV.

The second channel is $\tilde{t} \to b\tilde{\chi}^+; \tilde{\chi}^+ \to \tilde{\chi}^0(W^+/H^+/G^+)$ where the remaining charged gauge boson decays semileptonically. This channel was originally of interest when measured values of $m(t)$ seemed to be a little lower in the dilepton channel. It is possible if $m(\tilde{t}) < m(t)$ for the SUSY process to contaminate the $t\overline{t}$ dilepton channel and pull down the apparent t quark mass. With 4 undetected particles in the final state (the $\tilde{\chi}^0$ is taken to be stable), the kinematics are very underconstrained, even in the trans-

verse plane. However, one may use a weighted sum of possible solutions to the kinematic problem to estimate $m(\tilde{t})$. CDF has set limits [9] on $m(\tilde{\chi}^0)$ as a function of $m(\tilde{t})$ (up to 197 GeV) and the assumed $\mathrm{Br}(\tilde{\chi}^{\pm}\to\tilde{\chi}^0\nu\ell^{\pm})$ using $2.7\,\mathrm{fb}^{-1}$.

The third channel to be studied is $\tilde{t} \to c\tilde{\chi}^0$. As the lifetime of charm hadrons typically is shorter than that of bottom hadrons, and as the transverse momentum of the charged products of charm decays typically is less than that of bottom decays, obtaining a pure sample of charm decays with impact parameter tagging is very difficult. The CDF collaboration has developed a 2 output, 22 input neural network that distinguishes (at one output) between charm and bottom jets. The other output distinguishes between charm and light or τ jets. Cutting on the sum of the two outputs, they set limits [10] in the $m(\tilde{\chi}^0)$ *vs.* $m(\tilde{t})$ plane extending up to $m(\tilde{t}) = 180\,\mathrm{GeV}$.

4. Trifermion SUSY Searches

SUSY allows a number of channels leading to 3 leptons in the final state, as shown in Figure 1. There are relatively few backgrounds, but the cross-section for production times the branching ratio for decay into any particular combination of leptons is small. Depending on the particular values of the SUSY-breaking parameters (here, the mSUGRA breaking is used) it may happen that the mass of the charginos or neutralinos produced at the $q\overline{q}$ vertex is only a little larger than the mass of the escaping $\tilde{\chi}^0_1$, in which case a low momentum lepton is produced. For the high values of $\tan\beta$ that are of particular interest, $\tau^{\pm}$ leptons are often produced, and are detected by their decays to electrons or muons that are also of lower momentum. To increase sensitivity then, it is common to not attempt to identify the lepton of third lowest p_T, but rather to just ask for a charged particle that is isolated from any jets that appear in the event. Robert Forrest and Todd Adams have presented the CDF [11] and D0 [12] results in this conference.

Another final state with three fermions produced via SUSY diagrams has been investigated by CDF [13]. Suppose that in the top diagram of Figure 1 the W materializes as a $q\overline{q}$ pair, creating 2 jets. The resulting event then appears as a WZ pair with $\not{E}_T$. In the standard model, hadronically decaying Ws with $Z \to\ell^+\ell^-$do not have $\not{E}_T$ except as a result of mismeasurement, so this is a relatively clean final state. While it has to be admitted that the existing sensitivity is not really comparable to what might reasonably be expected in SUSY, there are several reasons why large improvements can be expected in the future. To date, only $Z \to e^+e^-$has been investigated, and b-jet identification has not been employed although a large $t\overline{t}$ background is present. Also, the present result is based on $2.7\,\mathrm{fb}^{-1}$ of data at one of the two TeVatron experiments; a final sample some 7 or 8 times larger than this could occur.

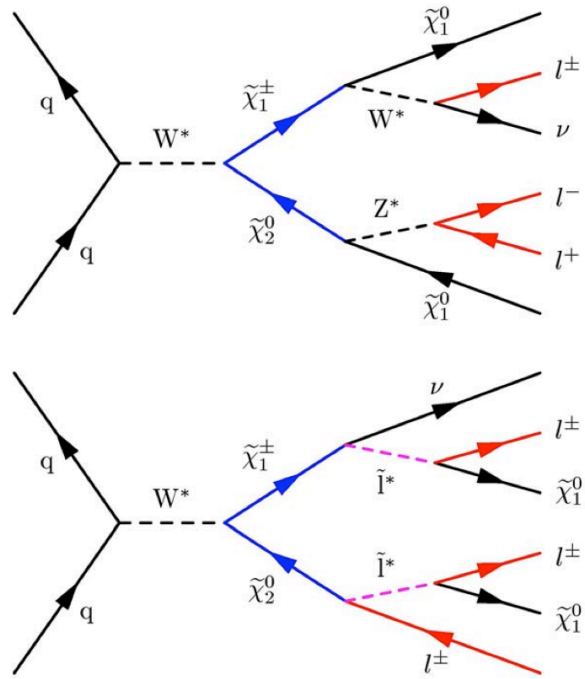

Figure 1: Some of the ways in which SUSY creates trilepton signatures in $p\overline{p}$ collisions.

5. Gauge Mediated Supersymmetry Breaking

In order to give different mass spectra to SUSY *vs.* standard model particles using gauge interactions, one can postulate the existence of new fields, called messengers, that couple the standard model and SUSY particles to an ultimate source of symmetry breaking. In these GMSB models, the lightest neutral SUSY particle is nearly always the gravitino, which is an interesting dark matter candidate for masses on the scale of a few keV. For the collider experimentalist, the way to think of various versions of this model is to categorize them in terms of their next-to-lightest SUSY particle (NLSP). Whatever particular SUSY particles might be created at the hard scattering vertex, they will cascade down to the NLSP (assuming R-parity conservation) which will after some lifetime go to an undetected gravitino. The nature of the NLSP will then determine what type of events to look for in the dataset.

When the NLSP is the lightest neutralino and $m(\tilde{\chi}^0) < \mathrm{M}_Z$, its decay produces a photon in conjunction with the gravitino. If the $\tilde{\chi}^0_1$ lifetime is on the order of 10 ns, the arrival of the γ will be delayed because of the flight path, as shown in Figure 2. The

CDF detector has 0.5 ns time resolution in its EM calorimeter, which makes this type of search feasible. In addition to the delayed photon, the search requires a jet and $\not\!\!E_T$. Limits up to $m(\tilde{\chi}^0) > 191\,\mathrm{GeV}$ for $\tau(\tilde{\chi}^0) > 5\,\mathrm{ns}$ were obtained and a detailed description of the analysis was published in 2008 [14].

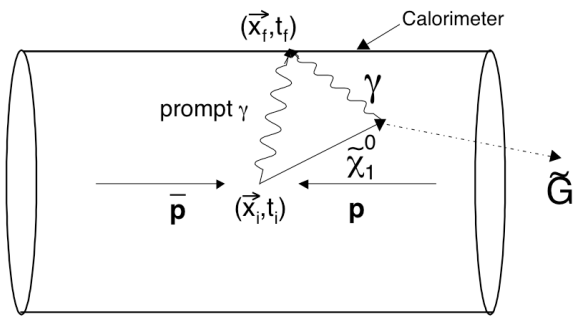

Figure 2: Why photons from $\tilde{\chi}^0 \to \gamma\tilde{G}$ arrive late in the electromagnetic calorimeter of a large collider experiment.

When the lifetime of the neutralino is on the order of a few ns or less, the delayed photon technique will not work. However, as a consequence of R-parity, there should be 2 SUSY cascades in the event leading to 2 NLSP $\tilde{\chi}^0$ decays to $\gamma\tilde{G}$. In this conference, Eunsin Lee has reported on a search [15] for GMSB at CDF which requires 2 photons with high p_T along with $\not\!\!E_T$ from the gravitinos. Limits up to $m(\tilde{\chi}^0) > 149\,\mathrm{GeV}$ for $\tau(\tilde{\chi}^0) < 1\,\mathrm{ns}$ were obtained.

6. MSSM Higgs

In the large $\tan\beta$ limit, the mass and couplings of the A boson approach the mass and couplings of one of the two CP-even bosons h or H. If $A \to H$ and $m(H)$ is large, one has the "decoupling" limit, where h becomes in many ways rather similar to the standard model Higgs. If $A \to h$, $m(A)$ would not be not too large and hadron colliders can search for the A in the modes $A \to \tau^+\tau^-$, $bA \to b\tau^+\tau^-$ and $bA \to bbb$. The Abb and $A\tau\tau$ couplings are enhanced relative to the experimentally difficult Att and $A\nu\nu$ couplings by a factor of $\tan^2\beta$ and so limits on the maximum possible value of $\tan\beta$ can be set as a function of $m(A)$. John Conway and Flera Rizatdinova in this conference have discussed the recent TeVatron results. At this time, values of $\tan\beta$ over $\simeq 30$ are ruled out [16, 17] at $m(A) \simeq 130\,\mathrm{GeV}$; if these results are scaled by the expected final Run II luminosity and $\tan^2\beta$, it is reasonable to guess that the TeVatron experiments will ultimately be able to set limits as low as $\tan\beta \simeq 20$. More detailed studies of the potential reach of the TeVatron and the LHC have been done recently [18].

7. NMSSM Higgs

Given the increasing restrictions on the available parameter space of the minimal supersymmetric extension of the standard model, it is natural to consider a nearly-minimal SUSY extension. In the NMSSM SUSY model, the smallest possible combination of fields is added to the known standard model fields and their SUSY partners. Neutral weak isospin singlet fermion and corresponding complex scalar fields are introduced. The resulting physical content of the theory includes a new light pseudoscalar, a, which (in the manner characteristic of Higgs bosons) decays into the heaviest kinematically available particles. For $m(a)$ above $2M_\mu$, $a \to \mu\mu$ is possible and has a nearly 100% branching ratio. If $m(a)$ is over $\simeq 3$ times the pion mass, hadronic decays become dominant; when $m(a) > 2M_\tau$, the decay into $\tau^+\tau^-$ becomes the dominant mode. Interest in this model was increased [19] by the unusual dimuon mass spectrum observed in $\Sigma \to p\mu^+\mu^-$ by the HyperCP [20] experiment.

In e^+e^- colliders, the Υ may decay to $a\gamma$ and there should be a narrow peak in the γ energy spectrum for events where a $\tau^+\tau^-$ or $\mu^+\mu^-$ pair has been identified. A search using this method was performed earlier by the CLEO collaboration [21] which set limits on $\mathrm{Br}(\Upsilon(1S)\to a\gamma) \times \mathrm{Br}(a\to\mu^+\mu^-)$ on the scale of a few times 10^{-6} in the range of about 250 MeV to 3.5 GeV, and also upon $\mathrm{Br}(\Upsilon(1S)\to a\gamma) \times \mathrm{Br}(a\to\tau^+\tau^-)$ on the scale of a few times 10^{-5} in the range of about 5 to 9 GeV. More recently, BaBar [22] examined their data for evidence of this process, using the case where one τ decayed to $e\nu\overline{\nu}$ and the other decayed to $\mu\nu\overline{\nu}$. They set limits on $\mathrm{Br}(\Upsilon(3S)\to a\gamma) \times \mathrm{Br}(a\to\tau^+\tau^-)$ on the scale of a few times 10^{-5} in the range of about 4 GeV to just under 10 GeV.

In a hadron collider, a pair of a bosons would be produced as the result of the decay of an h. From LEP II, we have a very general limit [23] that the mass of any new scalar coupling to the Z, including the h, must have a mass over 82 GeV, and so the a is produced in a hadron collider with a high boost. That in turn means that its decay into, say, a $\mu^+\mu^-$ pair will produce particles with a small opening angle. For $m(a) < 2\mathrm{M}\tau$ the two tracks can be difficult to resolve in the r-ϕ plane. D0 [24] has searched for the a in the case $2\mathrm{M}\tau < m(a)$ using the modes $aa \to \mu\mu\mu\mu$ and $aa \to \mu\mu\tau\tau$. The branching ratios are substantially lower than for $aa \to \tau\tau\tau\tau$ but the signature is clearer. Andy Haas has discussed the special reconstruction criteria needed for these collinear leptons in this conference. Limits on $\sigma(p\overline{p} \to h) \times \mathrm{Br}(h\to aa)$ of a few pb are obtained.

8. Leptoquarks

Because silicon vertex detectors can identify jets produced by fragmenting b quarks, it is possibile to search for third generation leptoquarks at hadron colliders. An LQ-$\overline{LQ}$ pair would produce events containing 2 b jets and a large $\not\!\!E_T$ from the 2 ν_τ. As Sergey Uzunan described at this conference, this is the same signature as that which one might expect from pair production of $\tilde{b}$, with subsequent $\tilde{b} \to b\chi^0$ decays. Limits can then be set [25] upon both models as a result of what is basically a single search method. As a search for $\tilde{b}$, limits up to $m(\tilde{b}) > 250\,\mathrm{GeV}$ are obtained; as a search for leptoquarks, $m(\mathrm{LQ}_3) > 252\,\mathrm{GeV}$ is obtained.

The best way to find a leptoquark, at least a first generation one, is to take a lepton and accelerate it to high energy and then arrange for it to collide with a quark, similarly accelerated. This is exactly what HERA did, collecting just under $0.8\,\mathrm{fb}^{-1}$ of $e^{\pm}p$ data at $\sqrt{s} = 300 - 319\,\mathrm{GeV}$, $0.3\,\mathrm{fb}^{-1}$ of which had polarized $e^{\pm}$. The ZEUS [26] collaboration measured the Q^2 distribution in their data and compared it to the standard model prediction. The (very small) difference was then compared against deviations that would be created by first generation leptoquarks, resulting in limits on $m(LQ)/\lambda(LQ)$ of $0.5-1.9\,\mathrm{TeV}$, where $\lambda(LQ)$ is the coupling of the leptoquark to the fermions. Using the same technique they were also able to set limits on large extra dimensions and contact interactions with the same Q^2 distribution. The H1 collaboration worked with different kinematic variables, specifically, M and y; their results [27] are not straight lines on the $\lambda(LQ)$ *vs.* $m(LQ)$ plane. If the couplings are taken to be $\lambda(LQ) = \sqrt{4\pi\alpha_{em}}$, the H1 analysis rules out leptoquark masses below 275 to 325 GeV, depending on the type of leptoquark.

9. Hidden Valley Scenarios

As my long time friend and one of our kind hosts here in Detroit Dave Cinabro once accurately pointed out, "When somebody writes a paper that says he looked for something and he did not find it, well then, you have to believe him." Another, more common, reaction to a null search is to imagine that the imagined new phenomena still actually does in fact exist, but at some higher energy scale which is at least for the moment experimentally inaccessible. Hidden Valley scenarios are predicated on a third possible response: the new phenomena still does exist at a relatively low mass scale, but is so weakly coupled to the standard model phenomenology as to render it invisible, or at least, hard to see.

One can postulate a wide range of fields that could exist in such a hidden sector; "hidden valleys" is really a class of models rather than than a specific model. In the simplest example of such a model [28] the valley is populated with two electrically neutral quarks which are confined into so-called "v-hadrons". Some of these particles may be stable, providing dark matter candidates; big-bang nucleosynthesis considerations suggest that at least one v-hadron has to have a lifetime much less than 1 sec. A Z' that couples to both the hidden valley particles and the standard model ones is included in this model, with a mass in the $1 \sim 6\,\mathrm{TeV}$ range.

Andy Haas, in this conference, has presented D0's search [29] for v-hadrons that are produced by mixing with a Higgs boson and have a long lifetime; their decay is mediated by the Z' and produces a pair of b jets that emanate from a vertex that is between 1.6 and 20 cm distant from the $p\overline{p}$ interaction point. The large background from material interactions is suppressed by comparing the locations of the jet vertices with the known material distribution in the detector. Limits on $\sigma(p\overline{p} \to HX) \times \mathrm{Br}(H \to HV\overline{HV}) \times \mathrm{Br}^2(HV \to b\overline{b})$ as low as 1 pb are obtained.

10. Supersymmetric Hidden Valley Dark Matter Model

In recent years, a number of experiments have reported results that could be interpreted as dark matter annihilation to e^+e^- pairs near the center of the Milky Way. Additionally, the DAMA experiment reports an annual modulation in their NaI(Tl) detector which may be interpreted as a signal from a dark matter galactic halo. While there is no shortage of more mundane explanations for these results, some authors [30] have taken a more adventuresome approach. They begin with the assumption that all of these results are in fact due to new physics and then ask what would that new physics look like.

They come to the surprising conclusion that dark matter is on the $0.5 - 0.8\,\mathrm{TeV}$ mass scale and that it annihilates to standard model particles with "sizeable" cross-sections. With such a large mass, it is natural to speculate that a new symmetry prevents the rapid decay of such states. However, these states might couple to light ($\mathcal{O}(1\,\mathrm{GeV})$) particles, known as "dark photons" (γ_D). They also have found that such a picture can be implemented in a SUSY framework with GMSB. In that case a clear signature for $p\overline{p}$ collider searches occurs through processes such as that shown in Figure 3; a high energy γ would appear in conjunction with $\not\!\!E_T$ and a collinear $\mu^+\mu^-$ pair from the γ_D decay.

The low mass, high boost and decay into $\mu^+\mu^-$ pairs of the dark photon means that one may use the same reconstruction techniques as were applied in searching for the NMSSM a in hadron colliders. The D0 collaboration has set limits [31] on $m(\tilde{\chi}^0)$

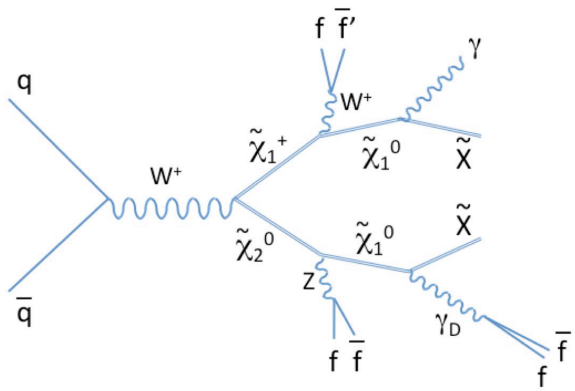

Figure 3: A dark photon production diagram in $p\overline{p}$ collisions.

as a function of $m(\gamma_D)$ in the range $0.1 < m(\gamma_D) < 2.5\,\mathrm{GeV}$

11. Model Independent Searches

Much of the motivation for searching for new physics beyond the standard model stems from our dissatisfaction with the many aspects of the standard model which we find so surprising. Indeed, were it not for such astonishments as parity violation, the J/ψ observation, the large value of M_t and many others, the standard model would surely have been easier to figure out! While we do hope and expect that getting the correct extension to the standard model will somehow reduce our overall level of astonishment, history warns us that such an outcome is not at all certain. With this in mind, it behooves us to try to conduct searches for new physics without the guidance of models that are at least in part constructed so as to reduce our astonishment.

The basic scheme for the modern model-independent search begins by defining a large number of final states. The definition is usually made in terms of the particle content of the final state, where particles are defined by the detection capabilities of the experiment's apparatus. So for example, final states with low p_T electrons would typically evade detection in hadron colliders, and such final states can not be included. Particles that require unusual reconstruction schemes are typically not included in the list of possible final states. Particles that are found by vertexing their decay products (such as K^0_S or D^{*+}) have by and large not been included to date, although there is no specific reason why they could not be. One consequently should not think of a model-independent search as being exactly the same as a search for "everything"; it is not quite that, at least to date.

For each entry on the list of possible final states, the standard model processes contributing to the final state are identified and modeled. The data are then compared against this predicted background, and cases where the data appear at a higher rate than the known physics rate are flagged. Cases where the data appear at a lower rate are also interesting, both as a check on the method and in case there might be new physics amplitudes that interfere destructively with known amplitudes. In assessing the statistical significance of any departure of reality from prediction, it is important to allow for the fact that the more comparisons you make, the more likely it is that the most discrepant result will be at or beyond any particular level of significance.

There are different ways to compare the data to the predicted rates of known physics. There might be a different total number of events. Distributions of kinematic variables for the data and the expectation can be compared with an overall quality of fit statistic, such as the Komolgov-Smirnov statistic. The distribution of a kinematic variable, such as a reconstructed mass, can be scanned for bumps. Or one might scan the distributions of GeV dimensioned kinematic variables such as p_T or reconstructed mass from low to high values, and look for discrepancies in the event counts above the scan point.

This type of analysis has been completed at the CDF [32], D0 [33] and H1 [34] experiments, although not all three have utilized the full range of possible comparison methods. Jim Linnemann, in this conference, has presented the D0 model independent search. Table I shows the results of comparisons at the level of simple event count comparisons of data with expected background levels. The H1 collaboration chose to express their results in terms of number of seen events *vs.* the expected backgrounds; to facilitate comparison with the CDF and D0 results I have calculated a corresponding number of standard deviations.

Table I Significance of event count discrepancies in 3 model independent searches. See text regarding treatment of H1 results.

CDF ($2.0\,\mathrm{fb}^{-1}$)		**H1** ($0.5\,\mathrm{fb}^{-1}$)		**D0** ($1.1\,\mathrm{fb}^{-1}$)	
$\gamma\tau$	2.2σ	$\nu 4j$	$< 3.0\sigma$	$\mu jj\not{E}_T$	9.3σ
$\mu\tau$	1.7σ	$e4j$	$< 2.4\sigma$	$\mu j\gamma\not{E}_T$	6.6σ
$e\tau\not{E}_T$	1.7σ	eee	$\sim 2.0\sigma$	$\mu^+\mu^-\ \not{E}_T$	4.4σ
		$\mu\nu$	$\sim 1.5\sigma$	$\mu^+\mu^-\ \gamma$	4.4σ

The statistically significant deviations in the channels flagged by the D0 analysis are attributed to defects in the modeling of the rate at which jets fake as photons, trigger simulation shortcomings, and p_T resolution effects in the D0 tracking system which effect muon measurement.

Significantly, there is no overlap in the channels found by all 3 experiments.

Acknowledgments

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