DISSERTATION PROPOSAL (26th June 2004):

Search for neutral, long-lived particles using the EMTiming system at CDF Run II

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Introduction

The idea that the universe is ultimately built up by indivisible particles came up as early as in Greek philosophy 2000 years ago. Since then scientists of all branches strove to find these "atoms" of nature which is culminating today in "elementary particle physics." With particle accelerators as the Tevatron at Fermilab we have the opportunity to create new, heavy particles from the collision of two light, abundant particles, by virtue of their mass and their kinetic energy. Based on the so found particles one succeeded to formulate a theory in the middle of last century, called "Standard Model", which describes their number, masses and other properties up to highest precision. Motivated by philosophical and calculational difficulties however this model is regarded as not a complete description of the particle world, but rather a low energy approximation of a super-theory. Most incarnations of which predict "new" particles, mostly heavier than the one already observed. Yet none of these particles has ever been seen...

With the measurement of an unusual event in the early 90's (the "CDF $ee\gamma\gamma\not{E}_T$ event", [1]) events with photon final states received more and more attention. As it turned out, major theories which predict new particles, like supersymmetry (SUSY), might easily be observable in those kinds of events. The Tevatron Collider at Fermilab produces the highest collision energy and is thus preferable to search for new particles. Since the electromagnetic calorimeter on the Collider Detector at Fermilab (CDF) has recently been equipped with a timing system for photons (EMTiming), we propose to use the data collected by Run II to search for neutral, long-lived particles which decay to photons using their time of arrival.

After having introduced the theory motivation and the detector tools in more detail, we introduce the discriminating variable for the analysis. Then we estimate with a Monte Carlo simulation a quasi-model-independent sensitivity to pure neutral particle pair production as it would be expected at the Tevatron. We will then estimate the expected 95% C.L. exclusion regions for the GMSB model as a function of the neutralino mass and lifetime. We find that a combination of single-photon and diphoton analyses should allow the Tevatron in Run II to easily extend the exclusion regions from LEP at high neutralino masses and lifetimes and cover much, if not all, of the theoretically favored $m_{\tilde{G}} < 1$ keV/c^2 parameter space for masses less than 150 GeV/c^2. In other words, we will show that we can use the EMTiming system to search for neutral long-lived particles in a mass-lifetime region that has never been explored before. Moreover we can exclude large parts of one of the favored SUSY models (for natural parameter assumptions).

I. THEORY

A. Supersymmetry

The Standard Model (SM) has been the favored particle physics model for many years. This model describes the inter particle interactions and the distribution of particle masses at high energies. Nevertheless it is considered an incomplete description of the particle world, as it suffers from the "Hierarchy" (or "Naturalness" problem) [2], which can elegantly be solved by "Supersymmetry" (SUSY) [3, 4]. This is an important and well examined extension of the SM which postulates a symmetry between fermions and bosons. As we will see later SUSY models also have a broad impact on cosmological models [5]. Since experiments cannot confirm the symmetry, e.g. the supersymmetric counterparts to the SM particles are not found at the same masses, the symmetry must be broken. The way this symmetry is broken distinguishes the SUSY models into Supergravity (SUGRA) [6], Anomaly Mediated SUSY Breaking (AMSB) [7] and Gauge Mediated SUSY Breaking (GMSB) [8], to name the most important ones. All of these have in common that SUSY can be broken at low energies (few TeV), so that the predicted new particles ("New Physics") may be accessible by current and future accelerators like Tevatron (FNAL) and LHC (CERN). Up to date none of the predicted particles have been found.

B. Minimal Supersymmetric Model (MSSM)

This is the basic SUSY Model, which e.g. mSUGRA and GMSB are based upon [3]. SM fermions/bosons get bosonic/fermionic SUSY partners, where the fermionic degrees of freedom equal the bosonic degrees of freedom: The counterparts of quarks and leptons are squarks and gluinos (spin-0), one for each chirality eigenstate. The SUSY partners of the gauge-bosons (Z_0, $W^{\pm}$) are gauginos (spin-1/2) and the fermionic partners of the two complex Higgs doublets are higgsinos. Since the Higgs's give rise to the Z and W masses by growing a vacuum expectation value, we finally have 5 Higgs particles (4 scalars $H^{\pm}$, h_0 and H_0 and one pseudoscalar A_0). The corresponding mass eigenstates called charginos as a mixture of charged and neutralinos as a mixture of neutral gauginos and higgsinos. The mixture (photino, higgsino, wino/zino) decides over the dominating decay process of the gaugino/higgsino. One of the drawbacks is that it has 106 unknown parameters: 26 masses, 37 angles and 43 phases. But these parameters are severely restricted by Flavor Changing Neutral Currents (FCNC) and CP-violation constraints and their number is strongly reduced after SUSY breaking. It appears to be that if the SUSY-breaking mechanism is too closely coupled to the SM particles, some of the SUSY particles are lighter than their SM-partners, which cannot be true. Consequently SUSY must be broken in a "hidden sector", with the intermediate states called "messengers" and the SM sector "visible". The nature of the hidden sector is what distinguishes the SUSY models. A possible natural extension of the MSSM is localized SUSY, or Supergravity in which the hidden and the visible sector are mixed by gravitational interaction. The 5 free parameters, at the SUGRA (or grand unification) scale, are: a common scalar mass m_0, the universal gaugino mass $m_{1/2}$, the universal cubic soft breaking mass (A-term) A_0, $\tan(\beta)$ (at the electroweak scale) and the sign of the Higgs mixing parameter μ. An alternative ansatz that solves the above mentioned constraints by definition is SUSY breaking which is mediated by the flavor blind gauge interactions.

C. Gauge Mediated Supersymmetry Breaking (GMSB)

GMSB [8] breaks SUSY at a relatively low energy of a few TeV and consists of 6 free parameters: the SUSY breaking scale Λ, the messenger mass scale M_M, the number of SU(5) messenger fields N_M, $\tan(\beta)$, $\mathrm{sgn}(\mu)$ and the gravitino scale c_{Grav}.

Phenomenologically the most striking feature is that the gravitino, $\tilde{G}$, is the lightest SUSY particle (LSP). In general, the scalar and the gaugino masses have roughly the same size. For the simplest choice of 1 pair of messenger fields $\mathrm{N_m} = 1$, the neutralino $\tilde{\chi}_1^0$ is the next-to-lightest SUSY particle (NLSP) if $\tan(\beta)$ is small. For larger multiplicities the right-handed sleptons are the NLSP. The stau $\tilde{\tau}$ is the NLSP for large $\tan(\beta)$.

Furthermore GMSB has a considerable impact on cosmological models [9]. Both gravitino and neutralino are candidates for dark matter. Since the gravitino is a very weakly interacting particle, it is thus unlikely to self-annihilate, with a mass in the range eV$-$GeV, it might contribute too much to the mass density of the universe, causing it to "overclose". This severely restricts the mass of the gravitino to $<$ 1 keV, if one avoids unnatural assumptions like an additional entropy production mechanism below the reheating temperature during the early cosmological evolution.

GMSB is an interesting model from an experimentalist's point of view, since it predicts the LSP to have a mass of down to a few eV. While the gravitino is too a weakly interacting particle to be detected, this opens the possibility to observe decay processes from heavier SUSY particles to the gravitino under emission of a SM-particle. Over a large parameter range the neutralino $\tilde{\chi}_1^0$ is the NLSP. Its electroweak eigenstate is mostly photino, so the decay process would be $\tilde{\chi}_1^0 \to \gamma\tilde{G}$ with a branching ratio of $\sim$ 100%. The decay length of the neutralino scales as:

$$c\tau \sim 130 \cdot (\frac{100\mathrm{GeV}/c^2}{m_{\tilde{\chi}}})^5 (\frac{\sqrt{F}}{100\mathrm{TeV}})^4 \mu\mathrm{m}$$

with the gravitino mass $m_{\tilde{G}} \sim 2.5 \cdot (\frac{\sqrt{F}}{100\mathrm{TeV}})^2\,\mathrm{eV}/c^2$ [10]. Thus the decay length can be macroscopic of the order of meters leading to lifetimes of nanoseconds (insert e.g. $m_{\tilde{G}} = 1\mathrm{keV}/c^2$ and $m_{\tilde{\chi}} = 90\mathrm{GeV}/c^2$).

II. TOOLS

A. Tevatron and the CDF Detector

We will conduct our analysis at the Tevatron at Fermi National Laboratory. The Tevatron is with a center-of-mass energy of currently $\sqrt{s}$ = 1.96 TeV in Run II the world's highest energy proton-antiproton-synchrotron. Its collision rate is 1.7 MHz with 396 ns separated bunches and an inelastic $p\bar{p}$ cross section of $\sim$ 60 mb. It produces collisions in two multi-purpose detectors CDF and DØ, with an integrated luminosity in Run II of $\sim 550\,\mathrm{pb}^{-1}$ [11].

CDF II [12] is a general purpose solenoidal detector which combines precision charged particle tracking with fast projective calorimetry and fine grained muon detection. Tracking systems are contained in a superconducting solenoid, 1.5 m in radius and 4.8 m in length, which generates a 1.4 T magnetic field parallel to the beam axis. Calorimetry and muon systems are outside the solenoid.

A silicon microstrip detector (SVX II) and a cylindrical drift chamber (COT) track charged particles in the range $|\eta| < 1.0$, where η is the pseudorapidity [13]. The SVX consists of two components: a micro-vertex detector for impact parameter measurements, and for the forward region $1 \leq |\eta| \leq 2$ two silicon layers at intermediate radii for p_T resolution and b-tagging, and a stand-alone silicon tracking over the full region $|\eta| \leq 2$ which is assisted by the Intermediate Silicon Layer (ISL) at a radius of 22 cm. The COT, consisting of small drift cells, encompasses the volume between 44 cm and 132 cm radius. With four axial and stereo superlayers it can provide 96 track measurements. The scintillator-based EM and HAD calorimeters lie between 150 cm and 350 cm radius. At the outermost position is the muon detector.

A three-level triggering DAQ system selects good runs from 20 kHz of data in level 1 to 70 Hz in level 3, $\sim$ 20 MB/s are streamed on tape.

B. Subdetectors of CDF which are important for further study

Here I'll give a short description of detector elements that are used for photons [12, 14]. The CDF calorimeter systems have played a key role by measuring electron, photon and jet energies. They are subdivided into projective towers in η ($\Delta\eta \sim 15°$) and ϕ ($\Delta\phi \sim 0.1°$) which point to the nominal $p\bar{p}$ interaction point at the center of the detector. The central region ($|\eta| < 1.1$) consists of central electromagnetic (CEM), central hadronic (CHA) and wall hadronic (WHA) calorimeters. The CEM has a thickness of 19 radiation lengths (X_0) and is equipped at a depth of 6 radiation lengths (at the typical position of the shower maximum) and at a radius of 184.15 cm with a layer of crossed wire and strip gas chambers (Central EM Shower Detector, CES) to measure the transverse shape of the EM shower. At a radius of 168.29 cm, between the solenoid and the CEM, is located another layer of wire chambers (Central Preshower, CPR), which is used as a pre-shower detector (with the solenoid 1.1 X_0 depth) acting as the converting material. In the plug region ($1.1 < |\eta| < 3.64$) consists of plug EM calorimeter (PEM) with a thickness of 20 X_0.

C. EMTiming

During the last summer shutdown to Run IIb the detector experienced several upgrades. The most important addition for this study is the "EMTiming" system [12], a timing system in the EM calorimeter. The motivation for the installation was twofold: (a) to help reject photons from cosmic ray and beam halo sources and (b) to provide a handle to search for supersymmetric events with photons in the final states, i.e., to confirm or deny that unusual events like the $ee\gamma\gamma\not\!\!E_T$ event are from the primary vertex. The timing system in the hadronic calorimeter (HAD) has been previously used to measure the arrival time of the leakage energy of EM particles, which was quite powerful in rejecting backgrounds, but not very efficient at low energies (20% at $E_T = 20$ GeV and 100% at 80 GeV). The EMTiming system is especially efficient for particles which deposit most of their energy in the EM calorimeter and little or no energy in the HAD.

The EMTiming uses a technique similar to the hadron TDC system (HADTDC). Both have the same hardware designs: The signal comes out of the phototube (PMT) and is collected with the tubes from the rest of the wedge on a transition board which is on the backside of a calorimeter readout VME crate. All the lines are passed into an Amplifier Shaper Discriminator (ASD) which effectively turns the signal into and LVDS digital pulse suitable for use by a TDC. The signal is then sent out to a TDC which is read out into the event. In the central EM calorimeter there are 960 PMTs with 20 PMTs/wedge and 48 wedges; the DAQ reads out 96 channels from the TDC. Tests have shown that the resolution of the system is less than 1 ns [15].

The installation in the plug has been successfully finished during the last summer shutdown and it will be continued with the central part during this summer, so that the system is fully operational at the end of this year.

III. SIMULATION OF THE SEARCH

We will begin with a study of the kinematic properties of events that contain long-lived particles which decay to photons and compare them to photons produced at the collision. A suitable variable to describe this distinction is the measured difference between the time after which the photon arrives at the face of the detector, and the time a prompt photon would virtually need to reach the same final position. This time difference for a prompt photon, from SM sources, is exactly 0 but is always > 0 for photons from delayed decays, as from SUSY/GMSB, if we neglect the measurement resolution. We call this difference Δs:

$$\Delta s \equiv (t_f - t_i) - \frac{|\vec{x}_f - \vec{x}_i|}{c} \tag{1}$$

where $t_f - t_i$ is the time between the collision and the arrival time of the photon, and $|\vec{x}_f - \vec{x}_i|$ is the distance between the final position of the photon and the collision point. The situation is visualized in Fig. 1. All four variables can be measured by the CDF detector [16] and give a system resolution of $\sigma_{\text{EMTiming}} \sim 1.0$ ns. Thus we expect to be sensitive to long-lived particles with lifetimes of the order of nanoseconds.

Since in most models of new physics pair production dominates at the Tevatron, we choose direct GMSB neutralino pair production to estimate a quasi-model-independent sensitivity of the system to long-lived particles, and examine its dependency on neutralino mass and lifetime. To choose analysis final states we consider three issues: 1) with neutralino lifetimes of the order of nanoseconds it is possible that one or both of the neutralinos leave the detector before they decay, and 2) with gravitinos or the neutralino leaving the detector, missing transverse energy, $\not\!\!E_T$, should also help separate signal from SM backgrounds and 3) to ensure that our background estimates are reliable we have chosen selection requirements from analyses which have already been performed at CDF and DØ [17]. Published papers by CDF and DØ show three interesting types of searches with these criteria: $\gamma\gamma + \not\!\!E_T$ [18], exclusive $\gamma + \not\!\!E_T$ ($\gamma + \not\!\!E_T + 0$ jets) [19] and $\gamma + \not\!\!E_T +$ jets [20]. Since there are no jets at the parton level in direct neutralino

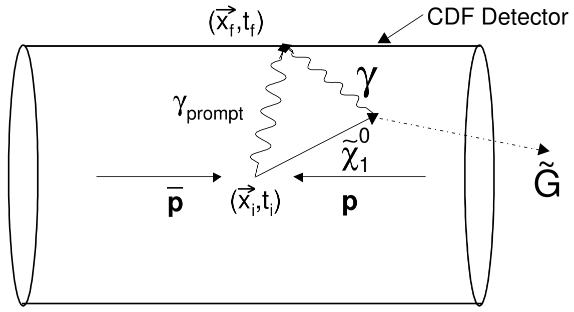


Figure 1: A schematic diagram of an event that consists of a long-lived neutralino decaying to a photon and a gravitino. The neutralino emanates from the collision at $(\vec{x}_i, t_i)$ and after a time τ it decays. While the gravitino leaves the detector the photon travels to the detector wall and deposits energy in the EM calorimeter where its final location $\vec{x}_f$ and arrival time t_f can be measured at CDF. A prompt photon would have traveled directly from $\vec{x}_i$ to $\vec{x}_f$ which can also be measured. The difference between the actual time the neutralino/photon needed, $\Delta t = t_f - t_i$, and the time a prompt photon would have needed, $\frac{|\vec{x}_f - \vec{x}_i|}{c}$, is defined as Δs. The SM typically produces prompt photons which have $\Delta s = 0$ ns, whereas photons from delayed decays from SUSY have $\Delta s > 0$ ns, assuming a perfect measurement.

pair production, we consider analyses with final states $\gamma\gamma + \not{E}_T$ and $\gamma + \not{E}_T + 0$ jets. To estimate the sensitivity for "full" GMSB neutralino production, which means including all relevant subprocesses such that the neutralinos are part of cascades from gauginos and squarks, we consider a $\gamma\gamma + \not{E}_T$ and a $\gamma + \not{E}_T +$ jets analysis.

Throughout our results sections we will compare the sensitivity to the signal both with and without the EM-Timing system by looking at the ratio of the cross section limits for the respecting analysis. We further compare our results with the results from the ALEPH experiment at LEP [22], which have completed direct searches for neutral, long-lived particles decaying to photons using photon pointing. We conclude that the Tevatron should significantly expand LEP's exclusion region towards higher neutralino lifetime and masses in Run II, and should cover a majority of the parameter space for masses up to 150 GeV/c^2 which is theoretically favored in cosmological models ($m_{\tilde{G}} < 1$ keV/c^2) [9].

From a simple Monte Carlo simulation it became clear that with a cut on Δs we can effectively filter out events which contain photons from long-lived particles, with lifetimes greater than roughly $2 \cdot \Delta s$, and reject most of the prompt SM photons. Further, the lower the momentum of the decaying particle is, the higher is the probability that it decays in the detector and thus the higher is the overall efficiency of the system, independent of the Δs cut. Now we want to look at the sensitivity of the system towards quasi-model-independent neutral particle pair production, i.e., taking into account possible SM background sources.

A. Neutralino Pair Production

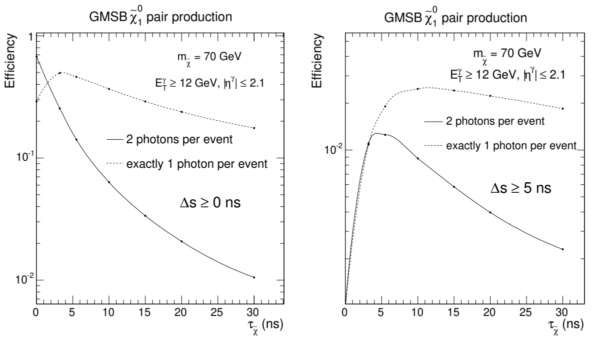
1. Analysis Methods and their Efficiency as a Function of Neutralino Mass and Lifetime

Here we estimate our sensitivity to heavy, neutral, long-lived particles which decay to photons in as model-independent a manner as possible. We do so by looking at a simple GMSB model of direct neutralino pair production and decay: $p\bar{p} \to \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \gamma\tilde{G}\gamma\tilde{G}$. We use a simple detector simulation, modified for the use of timing information. We accept photons with a pseudorapidity $|\eta| \leq 2.1$ and a transverse energy $E_T \geq 12$ GeV according to the CDF fiducial region and trigger [12]. We first look at the efficiency of the timing system with an infinite resolution as a function of neutralino mass and lifetime for different Δs restrictions. Then we discuss background estimations, take into account a timing resolution of 1.0 ns and find the sensitivities for the model predictions for both the single- and diphoton analysis.

Figure 2 shows the efficiency versus $\tau_{\tilde{\chi}}$ for a neutralino mass of 70 GeV/c^2 for events with $\Delta s \geq 0$ ns (photons from neutralinos remaining in the detector) and events with a $\Delta s \geq 5$ ns, separated into single- and diphoton events. For all four distributions there is an efficiency maximum in the lifetime region between 4 and 9 ns. At lower lifetimes the probability that the neutralino stays in the detector is quite big, so the diphoton final state dominates. For any $\Delta s > 0$ requirement the efficiency is zero at $\tau_{\tilde{\chi}} = 0$ ns, since all photons have $\Delta s = 0$. At a lifetime of about 3 ns, independent of the Δs cut, single-photon events become dominant. At high lifetimes the efficiency approaches zero for both analyses as most of the neutralinos leave the detector. Hence, in order to have sensitivity in as much lifetime range as possible, we consider both $\gamma + \not{E}_T$ and $\gamma\gamma + \not{E}_T$ analyses. Note that in contrast to this the timing efficiency is essentially constant as a function of neutralino mass at a fixed lifetime. But this depends strongly on the production mechanism, specifically the shape of the momentum distribution of the produced neutralino.

2. Backgrounds and Sensitivity to Neutralino Pair Production

We now estimate the sensitivity of our system to quasi-model-independent pair production of neutral particles. We simulate this with the neutralino pair production introduced in the previous section, but now taking into account SM backgrounds, more realistic cuts and the timing resolution. We consider separately single-photon and diphoton events and present our sensitivity as 95% C.L.



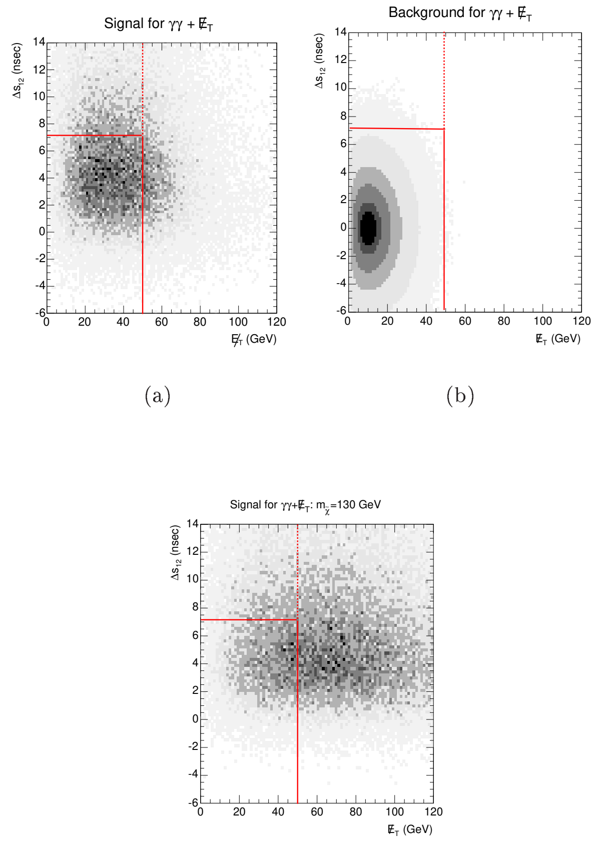
(a) (b)

Figure 2: The efficiency for events to pass the various Δs-cuts (assuming perfect measurements) as a function of the neutralino lifetime at constant mass ($m_{\tilde{\chi}}$= 70 GeV/c^2), separated into single- and diphoton-events at $\Delta s \geq 0$ ns and 5 ns. For any $\Delta s > 0$ the efficiency is zero at $\tau = 0$ ns, since all photons would have $\Delta s = 0$. For high τ neutralinos have a higher probability to leave the detector. For any Δs one can find an efficiency maximum at about 5-10 ns. Single-photon events are preferred towards higher Δs and higher lifetime, due to increasing probability for a photon to leave the detector. Thus we expect a $\gamma\gamma + \not{E}_T$ analysis preferable for very low lifetimes, and a $\gamma + \not{E}_T$ analysis for higher lifetimes.

cross section limits for either case assuming no signal in the data, comparing our results with the results of no EMTiming system available to estimate the effect of the EMTiming system over the kinematics. Throughout this section we use a Δs resolution of 1.0 ns. The expected cross section limits are calculated following [23] with the number of events observed "in the data" fluctuating around an expected mean background rate according to Poisson statistics. The cross section limit is, for a certain luminosity, a function of background events and signal acceptance, where both in turn are functions of specified cuts (e.g. Δs and $\not{E}_T$ cuts in the $\gamma\gamma + \not{E}_T$ case). By varying the cuts we find a signal acceptance and number of background events that, after smearing by systematic errors, minimize the cross section limit.

3. $\gamma\gamma + \not{E}_T$

A $\gamma\gamma + \not{E}_T$ analysis is expected to have the best sensitivity for low neutralino lifetimes. We follow the analysis in [18] which is summarized in Table I. The background for this analysis consists of QCD events with fake $\not{E}_T$ [24]. To allow us to extend our results to large values of $\not{E}_T$ we model the $\not{E}_T$ from QCD with a resolution of 10 GeV, i.e. we assume a measurement uncertainty of the transverse energy of all particles of 10 GeV in each x- and y-direction; this reproduces well the numbers in [18]. We select signal events in which both photons have $E_T > 12$ GeV and $|\eta| < 1$. Since all photons

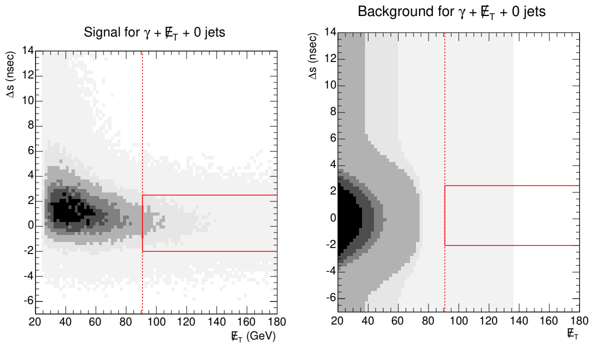


(a) (b)

(c)

Figure 3: The distribution of Δs_{12} and $\not{E}_T$ for signal and background in the $\gamma\gamma + \not{E}_T$ analysis. The distributions are (a) from direct $\tilde{\chi}_1^0$- pair production, with $m_{\tilde{\chi}} = 70$ GeV/c^2 and $\tau_{\tilde{\chi}} = 10$ ns, (b) QCD background and (c) direct $\tilde{\chi}_1^0$-pair production, with $m_{\tilde{\chi}} = 130$ GeV/c^2 and $\tau_{\tilde{\chi}} = 10$ ns. The solid and dashed lines show the cuts with and without EMTiming system usage respectively that give the smallest 95% C.L. cross section limit. In (c) the mass is so large that there is only small additional acceptance from allowing large Δs_{12} events which is why the sensitivity is not improved in this mass region.

from QCD are promptly produced, we model them with a mean $\Delta s = 0$ ns, and a resolution of 1.0 ns (see Fig. 3). We found that adding the Δs values $\Delta s_{12} = \Delta s_1 + \Delta s_2$, and selecting signal events with *either* large $\not{E}_T$ *or* large Δs_{12}, either of which is not SM-like, maximizes the separation of signal and background. The position of the cuts are optimized for each mass and lifetime to minimize the 95% C.L. cross section limit as a function of Δs_{12} and $\not{E}_T$. We find both the Δs_{12} and $\not{E}_T$ cuts are relatively stable at 7 ns and 50 GeV for non-zero lifetimes.



(a) (b)

Figure 4: The distribution of Δs and $\not{E}_T$ for signal and background in the $\gamma + \not{E}_T + 0$ jets analysis. The distributions are (a) from direct $\tilde{\chi}_1^0$- pair production, with $m_{\tilde{\chi}} = 70$ GeV/c^2 and $\tau_{\tilde{\chi}} = 10$ ns, and (b) from SM background. The solid and dashed lines show the cuts with and without EMTiming system usage respectively that give the smallest 95% C.L. cross section limit.

4. $\gamma + \not{E}_T + 0$ jets

From our efficiency considerations we expect a $\gamma + \not{E}_T + 0$ jets analysis to yield the best sensitivity at longer lifetimes, since the signal does not produce jets at the parton level. We follow the analysis in [19] which is summarized in Table II with the background consisting of QCD, Zγ and cosmic ray sources. The baseline sample requires the highest E_T photon to have $E_T > 25$ GeV and $|\eta| \leq 1$, a minimum $\not{E}_T$ of 25 GeV, and no jets with or additional photons with $E_T > 15$ GeV. Since photons from cosmic ray sources hit the detector with no correlation between the arrival time and the time of collision, we expect them to be randomly distributed over time and model this with a flat random distribution in Δs. As in the previous section the Δs of all other SM sources is dominated by the timing resolution of 1.0 ns. The $\not{E}_T$ for the backgrounds are modeled according to the shapes in [19], and extrapolated to large values using an exponential fit. The expected background and signal shapes are shown in Fig. 4. The final cuts on $\not{E}_T$ and Δs are applied to sort out events with a large $\not{E}_T$ *and* whose photon has a Δs within a lower bound and an upper bound: $\Delta s_1 \leq \Delta s \leq \Delta s_2$, to reject photons from SM background as well as from cosmic ray sources. Both cuts are chosen to minimize the 95% C.L. cross section limit for each mass and lifetime case. We find the optimized values around $\Delta s_1 = -2.0$ ns, $\Delta s_2 = 2.0$ ns and $\not{E}_T = 80$ GeV. However, Δs_2 could vary up to 3 ns for high lifetimes, $\not{E}_T$ up to 120 GeV for higher masses. Without timing information we found the optimal $\not{E}_T$ cut mostly higher at around 100 GeV.

Table I: Background and baseline selection criteria used for the $\gamma\gamma + \not{E}_T$ analysis [18].

Baseline selection requirements:
$E_T^{\gamma_1/\gamma_2} > 12$ GeV
$\vert\eta^{\gamma_1/\gamma_2}\vert < 1$
Backgrounds:
2577 events / 100 pb^{-1} from QCD
$\Delta s_{12} = \Delta s^{\gamma_1} + \Delta s^{\gamma_2}$, $\overline{\Delta s_{12}} = 0$ ns with resolution $\sigma_{\Delta s_{12}} = 1.41$ ns
$\not{E}_T$: Rayleigh distribution (Square-root of the sum of 2 Gaussians squared) with $\sigma = 10$ GeV
Optimization:
Accept events in which the photon has *either* a $\not{E}_T$ greater than the optimized $\not{E}_T$- cut *or* a Δs_{12} greater than the optimized Δs_{12}- cut.

Table II: Background and baseline selection criteria for the $\gamma + \not{E}_T + 0$ jets analysis [19].

Baseline selection requirements:
$E_T^{\gamma} > 25$ GeV
$\vert\eta^{\gamma}\vert < 1.0$
$\not{E}_T > 25$ GeV
No jets with $E_T^j > 15$ GeV
Backgrounds:
12.6 events / 100 pb^{-1} from $Z\gamma \to \nu\bar{\nu}\gamma$, W$\gamma$, $W \to e\nu$, QCD and cosmics [19]
Non-cosmics: $\Delta s = 0$, $\overline{\Delta s_{12}} = 0$ ns with resolution $\sigma_{\Delta s} = 1.0$ ns
Cosmics: 57.2% of total background, flat distribution in Δs
$\not{E}_T$ distribution according to [19]
Optimization:
accept events where the event has a $\not{E}_T$ greater than the optimized cut *and* whose photon Δs is within a range of cuts $\Delta s_1 \leq \Delta s \leq \Delta s_2$.

5. Results

Figure 5 shows the ratio of the lower of the 95% C.L. cross section limits of the two analyses with EMTiming system usage and without in two dimensions for a luminosity of 2 fb^{-1}. In this plot we see four trends: 1) As a function of lifetime the cross section limits rise since the probability that the neutralinos decay in the detector goes down, 2) at high lifetimes the timing handle is better able to separate the signal from the backgrounds and produces better limits relative to kinematics alone, 3) as a function of mass the cross section decreases as more and more events pass the kinematic threshold, and 4) at low masses the timing handle is better able to separate the signal from the backgrounds because the momentum distribution happens be lower on average (see Fig. 3c

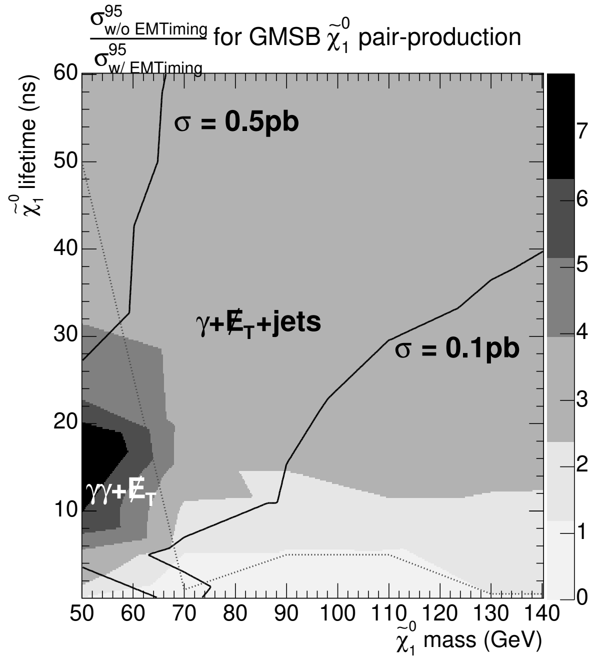


Figure 5: This plot combines the $\gamma\gamma + \not\!\!E_T$ and $\gamma + \not\!\!E_T$+ 0 jets- analysis predictions for $\tilde{\chi}^0_1$- pair production for 2 fb^{-1} of data. The contours of constant cross section limit are shown as the solid lines, and the separation line between the regions where the two different analyses provide the best sensitivity is given by the dotted line; the $\gamma + \not\!\!E_T$+ 0 jets- analysis shows better cross section limits than a $\gamma\gamma + \not\!\!E_T$ analysis in the mass and lifetime range above the dashed line. The shaded regions delineate the contours of the ratio of the 95% C.L.- cross-section limits on between with and without EMTiming information. The ratio is greatest for a low neutralino mass and a lifetime of 10-20 ns, and lowest for a high mass and low lifetime.

which shows an example where the kinematics are such that there is only small additional acceptance from allowing large Δs_{12} events). In general the $\gamma\gamma + \not\!\!E_T$ analysis yields lower cross sections when the mass or the lifetime is low. The ratio is greatest in this region and occurs at a mass around 50 GeV/c^2 and a lifetime of 10-20 ns. The $\gamma + \not\!\!E_T + 0$ jets analysis yields lower cross section limits for the rest of the considered lifetime range and masses, but it is important to note that the course of the separation line of the analyses depends on the production momentum distribution of the neutralino. Unfortunately this analysis cannot be applied to searches for long-lived NLSP neutralinos in a true GMSB model with the preferred production processes as there the neutralinos are produced as part of cascades from gaugino pairs which contain jets. Therefore we do a separate analysis for a full GMSB production in the next section.

B. GMSB Neutralino Production

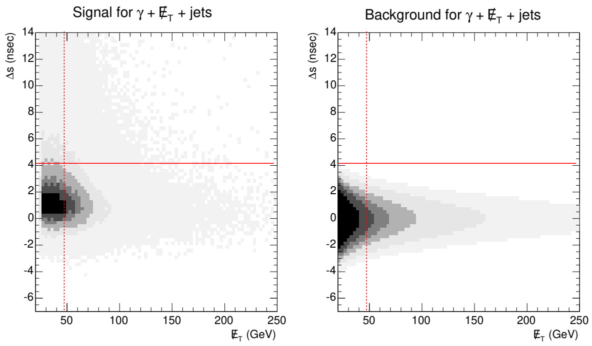
We next consider the sensitivity to full GMSB production with the timing system where we allow all processes to contribute to the final state according to their predicted cross sections. The GMSB parameters ($M_M = 2\Lambda$, $\tan(\beta) = 15$, $\text{sgn}(\mu) = 1$, $\text{N}_\text{M} = 1$, c_{Grav} and Λ unrestricted) are chosen in the range where the neutralino is the NLSP; neutralino mass and lifetime are varied via M_M and c_{Grav}. Again we consider a single-photon and a diphoton analysis. The $\gamma\gamma + \not\!\!E_T$ analysis methodology is identical to the case of neutralino pair production, but the single-photon analysis must be modified to allow jets as here the neutralinos are part of cascades from gauginos which produce additional particles which, in general, could be identified jets. We thus use a $\gamma + \not\!\!E_T$ + jets analysis.

1. $\gamma + \not\!\!E_T$ + jets

A $\gamma + \not\!\!E_T$ + jets analysis should be most sensitive to neutralinos with long lifetime which are produced in association with other particles in the final state such as from gaugino pair production. We follow the analysis in [20] which is summarized in Table III with the backgrounds dominated by QCD and W+jets [26]. The baseline selection requirements are that the primary (highest E_T) photon is required to have $E_T > 25$ GeV and $|\eta| = [0, 1.1]$ or [1.5, 2.0], $\not\!\!E_T > 25$ GeV, ≥ 2 jets of $E_T > 20$ GeV and $|\eta| < 2.0$. The expected $\not\!\!E_T$ of the background is modeled according to [20], and since the backgrounds are from SM we take a mean $\Delta s = 0$ ns with a resolution of 1.0 ns. The signal and background shapes are shown in Fig. 6. We find that the optimal final selection requirements accept events in which the event has a large $\not\!\!E_T$ *or* the photon a large Δs. Again, both cuts are optimized to minimize the 95% C.L. cross section limit for each mass and lifetime case. For without-timing usage we find the $\not\!\!E_T$ cut to be around 50 GeV for around 70 GeV/c^2, varying up to 110 GeV for masses around 150 GeV/c^2. For with-timing usage we find only a Δs cut around 4 ns which is stable for all masses and lifetimes, and no $\not\!\!E_T$ cut other than the baseline $\not\!\!E_T > 25$ GeV (except for $\tau_{\tilde{\chi}} = 0$ ns where the diphoton analysis shows better sensitivity). While it is outside of our ability to predict, one might find further optimization is possible by further lowering the baseline selection requirements.

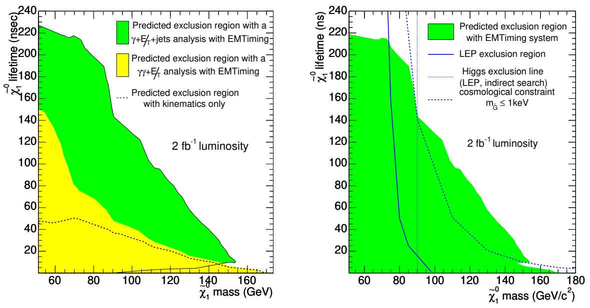
2. Results

A comparison of the cross section limits with the production cross sections in the GMSB model at a luminosity of 2 fb^{-1} gives a mass vs. lifetime exclusion region shown in Fig. 7. As expected timing has the biggest effect at low masses and high lifetimes. We have also indicated the exclusion regions from LEP from both direct



(a) (b)

Figure 6: The distribution of Δs and $\not\!\!E_T$ for signal and background in the $\gamma + \not\!\!E_T +$ jets analysis. The distributions are (a) from GMSB $\tilde{\chi}_1^0 \to \gamma\tilde{G}$ production, with $m_{\tilde{\chi}} = 70$ GeV$/c^2$ and $\tau_{\tilde{\chi}} = 10$ ns, and (b) from SM background. The solid and dashed lines show the cuts with and without EMTiming system usage respectively that give the smallest 95% C.L. cross section limit.



(a) (b)

Figure 7: Plot (a) shows the 95% C.L. exclusion regions as a function of neutralino lifetime and mass for a GMSB model at 2 fb^{-1} luminosity for the the $\gamma\gamma + \not\!\!E_T$ and a $\gamma + \not\!\!E_T +$ jets analysis separately. The region below the dashed line is the exclusion region from kinematics alone, i.e., where no timing information is used. Figure b) shows the full exclusion region combining the two analyses. The Tevatron should be able to significantly extend the sensitivity beyond the direct and indirect search limits from LEP [22] and cover much of the theoretically favored region from cosmological constraints ($m_{\tilde{G}} < 1$ keV$/c^2$) [9] for masses below 150 GeV$/c^2$.

Table III: Background and baseline selection criteria used for the $\gamma + \not\!\!E_T +$ jets analysis [20].

Baseline selection requirements:
$E_T^\gamma > 20$ GeV
$\lvert\eta^\gamma\rvert < 1.1$ and $1.5 < \lvert\eta^\gamma\rvert < 2.0$
$\not\!\!E_T > 25$ GeV
$\geq$2 jets with $E_T^j > 20$ GeV and $\lvert\eta^j\rvert < 2.0$
Backgrounds:
320 events / 100 pb^{-1} from QCD and W+jets [20]
$\overline{\Delta s_{12}} = 0$ ns with resolution $\sigma_{\Delta s} = 1.0$ ns
$\not\!\!E_T$ distribution from [20], extrapolated to large $\not\!\!E_T$
Optimization:
Accept events in which the photon has *either* an $\not\!\!E_T$ greater than the cut *or* a Δs greater than the cut.

and indirect searches [22], and the line $m_{\tilde{G}} = 1$ keV$/c^2$, below which is the theoretically preferred region from cosmological constraints [9]. LEP effectively excludes all neutralino masses under 80 GeV$/c^2$ up to high lifetimes, with a small extension to 100 GeV$/c^2$ for lifetimes below 20. For 2 fb^{-1}, Run II, the Tevatron should significantly extend the sensitivity at large mass and lifetimes, covering most of the lifetimes for $m_{\tilde{G}} < 1$ keV$/c^2$ up to a mass of around 150 GeV$/c^2$. If Run II is extended beyond 2 fb^{-1}, these results could be significantly further extended to cover the small window between 80 and 100 GeV$/c^2$ as well as extending to higher masses.

C. Factors that might change the cross section limit

Two issues might have major effects on the presented cross section limits: cosmic photons in the background sample of the single-photon analysis and a change in the timing resolution. In the $\gamma + \not\!\!E_T +$ jets analysis following [20] we have neglected the contribution from cosmic ray background, i.e. cosmic photons crossing the detector, since the probability of an event with two jets overlapping with a photon from a cosmic ray is small, and should mostly be removed with simple topology cuts with very high efficiency. In our study we estimate that at a neutralino mass of 110 GeV$/c^2$ and a lifetime of 40 ns the cross section limit rises about one order of magnitude at a fraction of 10% of cosmic photons in the background sample. We used here the same analysis style as in the $\gamma + \not\!\!E_T + 0$ jets case. The fraction presumably depends on Neutralino mass and lifetime but has not been further examined.

In all the analyses we have also assumed a Δs resolution of 1.0 ns. A study of the expected 95% C.L. cross section limits as a function of the system resolution at $m_{\tilde{\chi}} = 70$ GeV$/c^2$ and $\tau_{\tilde{\chi}} = 60$ ns at 2 fb^{-1} luminosity for a $\gamma + \not\!\!E_T +$jets analysis showed that a timing resolution of 1.0 ns significantly improves the cross section limit over kinematics alone for this mass-lifetime combination by a factor of 20. This factor however increases/decreases towards higher/lower lifetimes, due to a better/worse separation between signal and background, and also depends on which analysis is being used. Comparing both effects, a loss in timing resolution from 1.0 ns to 1.2 ns has a similar effect on the cross section limit as an increase of cosmic background to 10%.

IV. CONCLUSION AND OUTLOOK

The prospects for using the new EMTiming System at CDF in the search for neutral, long-lived particles which decay to photons, as one can find in supersymmetric models, have been studied. We find that the kinematic requirements and the EMTiming system provide excellent rejection against SM backgrounds in a complementary fashion. As the mass increases the kinematics are more important and the sensitivity gets better. For a given mass, as the lifetime increases more and more of the neutralinos leave the detector and the overall sensitivity goes down, but the EMTiming system provides additional rejection power and allows for significant exclusions even at large lifetimes.

While the region where EMTiming produces the most additional rejection is already excluded by LEP, the additional handle it provides will allow the Tevatron in Run II to produce the world's most stringent limit at masses above 80 GeV$/c^2$ at high lifetimes and has the potential to cover the entire region for $m_{\tilde{G}} < 1$ keV$/c^2$ up to a neutralino mass of around 150 GeV$/c^2$ if Run II is extended only slightly beyond 2 fb^{-1}.

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