PROCEEDINGS OF SCIENCE

New Physics Searches

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1. Introduction

The Standard Model of particle physics is an extremely successful description of nature and has been tested in numerous measurements to a very high precision. Nevertheless, it is known to be incomplete, since for instance it cannot provide a quantum theory of gravity, describe massive neutrinos or give an explanation for dark matter. There are several indications that new physics might enter at the TeV scale, including the hierarchy problem or weakly interacting massive particles as dark matter candidates.

Searches for new physics at colliders with access to the TeV scale are therefore of high priority. Currently, the proton-antiproton collider Tevatron (Fermilab, USA) is the only collider in operation that can directly produce such massive particles. As of summer 2009, the Tevatron has delivered an integrated luminosity corresponding to 7 fb^{-1} at a centre-of-mass energy of 1.96 TeV, and is expected to add 2-3 fb^{-1} per year. So far a dataset of about 4.2 fb^{-1} has been analyzed by the two experimental collaborations CDF and DØ. In both experiments, an extensive program of searches for various signatures of new physics has been deployed, which will be reviewed in the following with an emphasis on recent results.

While the Tevatron experiments can probe mass scales of up to 1 TeV in exceptional cases, the limited centre-of-mass energy does not allow to reach the TeV scale in many of the proposed models. The proton-proton collider LHC at CERN has been designed to reach centre-of-mass energies of up to 14 TeV, and is expected to resume operation at the end of 2009. For the 2010 physics run, the machine will operate at a reduced centre-of-mass energy of 7–10 TeV, with an expected integrated luminosity corresponding to about 100 pb^{-1}. It is well documented that both general purpose detectors ATLAS and CMS are able to discover new physics at the TeV scale in a vast number of models. In this review, selected examples of recent updates in preparation for the 2010 run will be discussed.

2. Searches for Supersymmetry

A supersymmetric extension of the Standard Model addresses many of its shortcomings and predicts a supersymmetric partner for every Standard Model particle. To solve the hierarchy problem and to provide a dark matter candidate, masses of at least some of the supersymmetric partners must be of the order of the electroweak scale. Searches for supersymmetric particles have been conducted at both Tevatron experiments in a large variety of models. In the following, recents results are presented for models with a stable lightest supersymmetric particle (LSP), which is expected to escape detection, leading to final states with large missing transverse energy.

2.1 Squarks and Gluinos

The supersymmetric partners of the quarks and the gluon, the scalar "squarks" and the fermionic "gluino", couple strongly and are therefore expected to be produced at a high rate if kinematically accessible. They decay into jets and the LSP, potentially with additional leptons from cascade decays via intermediate states. Inclusive searches for jets and missing transverse energy are performed by both CDF and DØ, optimized in final states with two, three or more jets. At large

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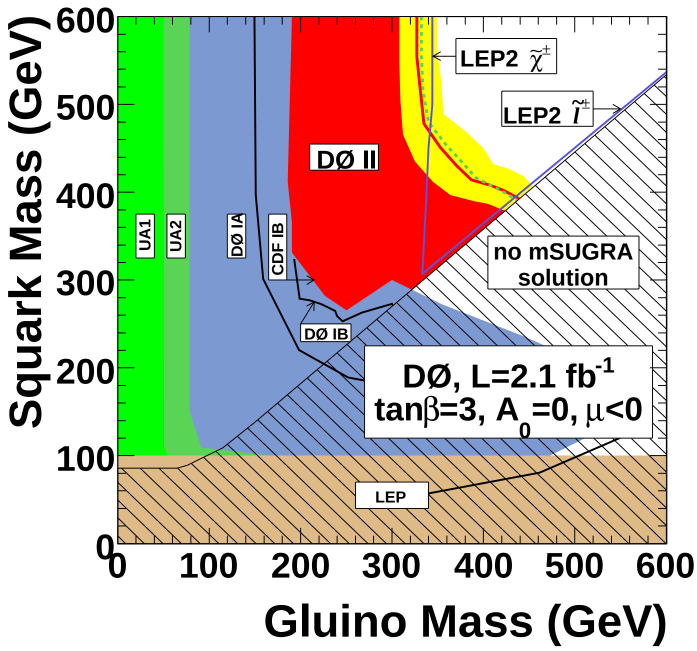

Figure 1: Limits on squark and gluino masses within the minimal SUGRA model with $\tan\beta$=3, A_0 and $\mu < 0$ based on the DØ analysis with an integrated luminosity of 2.1 fb^{-1} [1].

missing transverse energy, backgrounds are dominated by Z+jets production with the Z-boson decaying into neutrinos. The delicate modeling of gluon radiation has been verified in vector boson plus jets production with decays into charged leptons. Both experiments do not observe any excess, and therefore place upper limits on the production cross sections of squarks and gluinos. Within a specific model, these can be translated into mass limits, as shown in Fig. 1 for the minimal SUGRA model.

While the inclusive searches for squarks and gluinos start to be limited by parton luminosities, exclusive searches for particular squark flavours and decay chains are still limited by statistics. Searches for third generation squarks are of particular interest, since sbottom and stop quarks are expected to be the lightest squark states due to mixing effects. The DØ collaboration has presented new results in search for sbottom quarks, decaying to b-jets and the LSP. The analysis is very similar to the inclusive search, except that b-tagging can be used to significantly suppress backgrounds from vector boson plus jets production. Since no excess is observed, new limits have been set on sbottom masses as a function of LSP mass (see Fig. 2 left).

For stop quarks within reach of the Tevatron, the equivalent decay channel via a top quark is not open. Alternative decay channels include the loop-induced decay to charm quark plus LSP, the decay to bottom quark and chargino, as well as the decay to bottom quark, lepton and sneutrino. Depending on the chargino and sneutrino masses, any of the three decay modes can be dominant. Tevatron searches for all these channels have been completed, resulting in limits in the plane of stop quark masses vs. LSP mass (see Fig. 2 right and Fig. 3).

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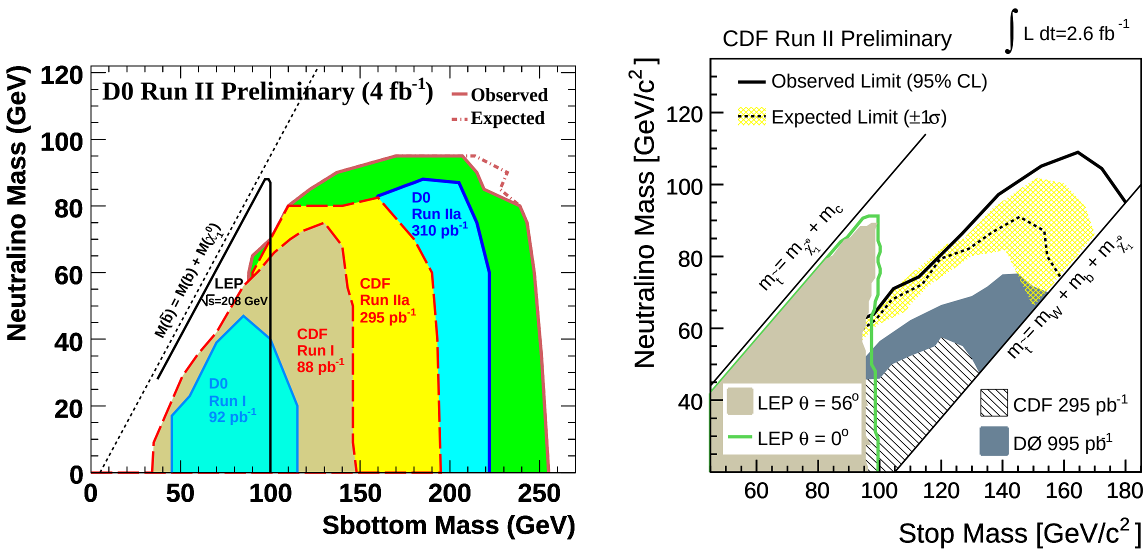

Figure 2: Limits on sbottom (left) and stop (right) quark mass as a function of the mass of the lightest Neutralino, assuming a branching ratio of 100% into b+LSP or c+LSP, respectively [2][3].

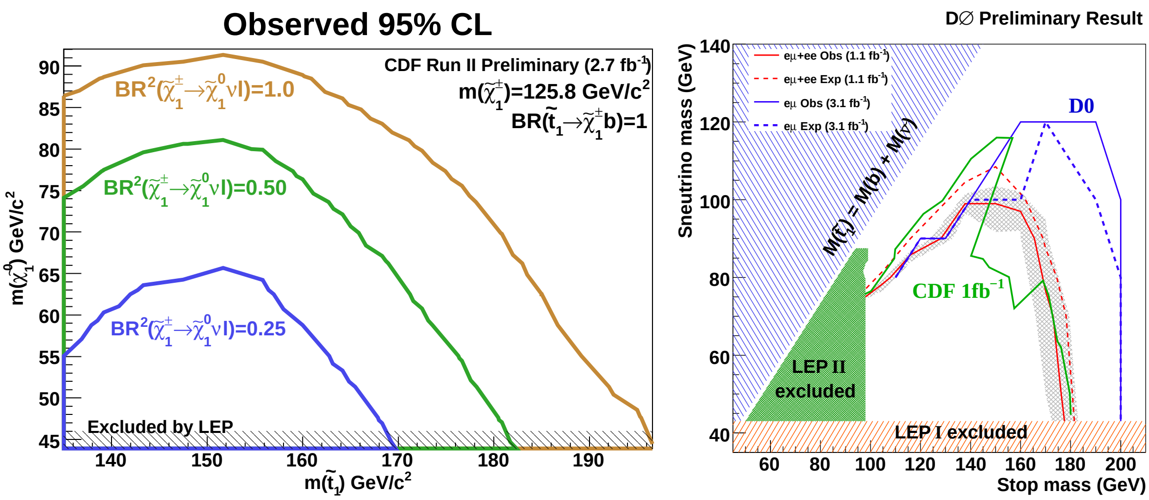

Figure 3: Left: limits on stop quark mass as a function of the mass of the lightest Neutralino assuming a branching ratio of 100% into b+chargino for various choices of the leptonic branching fraction of the chargino [4]. Right: Limits on stop quark mass as a function of the mass of the sneutrino assuming a branching ratio of 100% into b+l+sneutrino [5].

2.2 Charginos and Neutralinos

With squarks and gluinos potentially beyond the kinematic reach of the Tevatron, searches for Charginos and Neutralinos, the fermionic supersymmetric partners of the charged and neutral gauge and Higgs bosons, are alternative potential discovery modes. Charginos and Neutralinos can be detected in their leptonic decays, leading to final states with three charged leptons and missing transverse energy. They are produced via the electroweak interaction, such that the search is statistically limited to relatively small masses. This results in low transverse momenta for the

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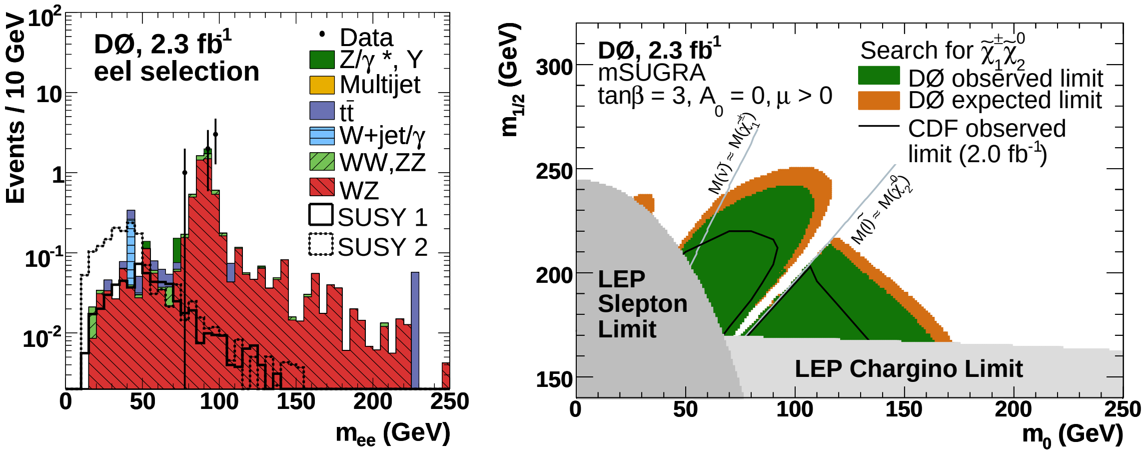

Figure 4: Left: Distribution of the invariant dielectron mass for data (points), background (shaded histogram) and Supersymmetry (open histogram) after all cuts of the trilepton analysis. Right: Regions in the (m_0,$m_{1/2}$)-plane excluded by the trilepton analysis for the minimal SUGRA model ($\tan\beta$=3, A_0=0 and $\mu>0$) [6].

decay products, presenting challenges in particular for the efficient detection of the third charged lepton. Both CDF and DØ collaborations have developed a large number of trilepton analyses, designed to cover all possible lepton flavour combinations, and tuned for optimal efficiencies down to very low transverse momenta. After requiring three leptons and $\not{E}_t$, backgrounds are dominated by WZ production, which can be separated from the signal using kinematics (see Fig. 4 left).

No significant excess has been observed, allowing to place limits on the production rate of trilepton events. Within a specific model, these limits can be translated into mass limits, as shown in Fig. 4 right for the minimal SUGRA model.

2.3 Prospects for LHC

As has been documented in numerous studies, the supersymmetry discovery potential for the LHC with a centre-of-mass energy of 14 TeV is excellent. For the initial physics run in 2010, a relatively modest dataset of about 100–200 pb^{-1} is expected, at a reduced centre-of-mass energy of up to 10 TeV. Over the course of the last year, both ATLAS and CMS collaborations have re-optimized their analyses for this dataset. As shown in Fig. 5 left, the discovery reach for the inclusive searches in jets plus $\not{E}_t$ plus 0/1/2 leptons already extends well beyond the regions probed at the Tevatron. For parameter regions accessible with the dilepton+jets analysis, first information on the masses of supersymmetric particles could be extracted by a fit to the dilepton mass distribution. According to a recent CMS study, the endpoint of the dilepton spectrum (see Fig. 5 right) from the decay of the second lightest neutralino could be determined with an accuracy of 4% (200 pb^{-1} at $\sqrt{s}$=10 TeV).

3. Searches for new High-Mass States

In addition to searches for new physics based on predictions of specific models, both Tevatron collaborations are conducting a vast number of analyses in search for generic signatures of new particles. This includes searches for new high-mass states as predicted in many extensions of the

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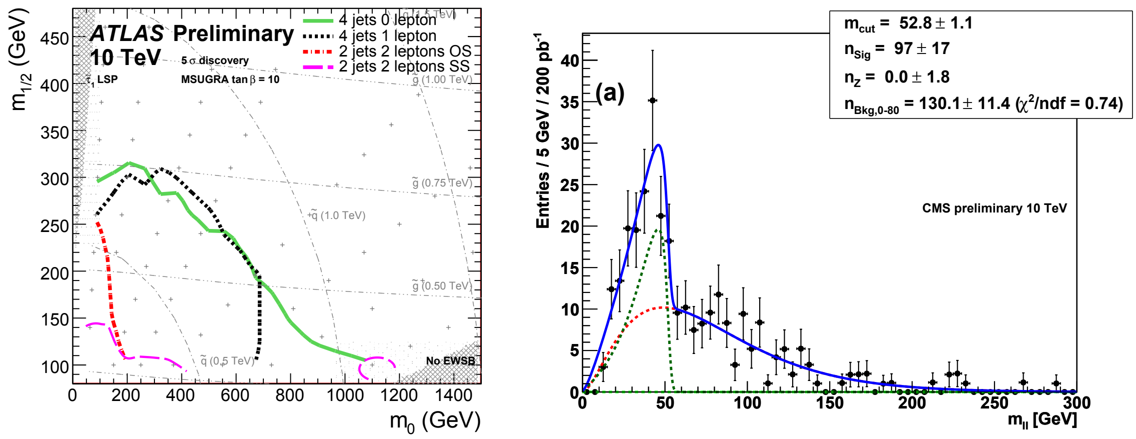

Figure 5: Left: 5σ discovery reach of inclusive Supersymmetry searches at ATLAS in the minimal SUGRA model for a dataset of 200 pb^{-1} at $\sqrt{s}$=10 TeV [7]. Right: Fits to the dilepton mass spectrum for a supersymmetry signal ("LM0" benchmark point) on top of background in the CMS dilepton+jets analysis based on a dataset of 200 pb^{-1} at $\sqrt{s}$=10 TeV [8].

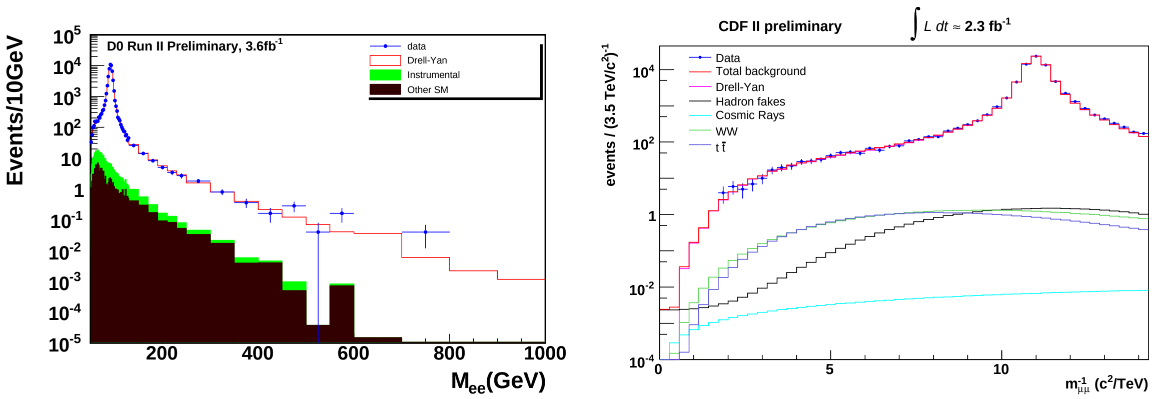

Figure 6: Distribution of the (inverse) invariant dielectron (dimuon) mass for data (points) in comparison with the background expectation (histogram) in Tevatron searches for heavy dilepton resonances [9].

Standard Model. They can be categorized into resonances decaying into difermion or diboson final states (e.g. extra gauge bosons or Kaluza-Klein excitations of Gravitons), and heavy states decaying into lepton plus quark (e.g. Leptoquarks), quark plus W-boson (e.g. 4th generation quarks) as well as lepton plus photon (e.g. excited fermions).

In all cases, a signal would manifest itself as a bump in the invariant mass distribution of the decay products. As an example, Figs. 6 and 7 show the dielectron/dimuon and ditop invariant mass distributions. The data are very well consistent with background expectation from Drell-Yan and $t\bar{t}$ continuum production, allowing to set limits on the presence of high-mass resonances up to mass scales of 1 TeV. Current mass limits in reference models for all final states are collected in Table 1.

For most of the singly-produced resonances, the Tevatron analyses are probing the TeV region and are now severely limited by the parton luminosities. With its significantly higher centre-of-mass energy, the LHC will be able to quickly probe masses beyond the kinematic reach of the

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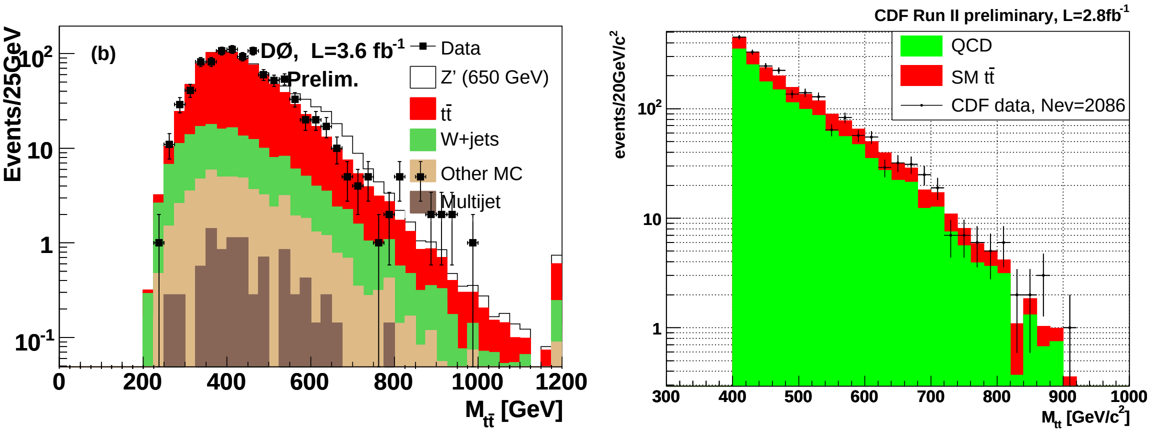

Figure 7: Distribution of the invariant top-antitop quark mass reconstructed in the lepton+jets (left) and all-hadronic (right) channel for data (points) in comparison with the expectation from background (shaded histogram) as obtained in Tevatron searches for $t\bar{t}$-resonances [10].

	Sequential V'								RS-Grav. (k/M_{Pl}=0.1)		
X→	eν	ee	$\mu\mu$	eμ	$\tau\tau$	qq	$t\bar{t}$	tb	$\gamma\gamma$	WW/WZ	ZZ
Limit (GeV)	1000	966	1030	910[1]	399	840	820	800	900	606	490

	Leptoquarks β=1					Sequential f'		Excited f*	
X→	eq	μq	bτ	qν	bν	b'→tW	t'→qW	eγ	$\mu\gamma$
Limit (GeV)	256	316	210	205	252	325	311	796	853

[1] reviewers extrapolation

Table 1: Tevatron mass limits for new high-mass states X decaying to various combinations of fermions and bosons. Limits are evaluated within the reference models indicated in the table (for detailed specifications see [11]).

Tevatron.

4. Exotic Signatures

A number of extensions of the Standard Model predict signals with very specific, unusual signatures that would be missed by the standard generic searches and therefore require dedicated analyses. Many such searches for exotic signatures have been performed at the Tevatron [11], out of which just one recent representative result will be discussed here.

Recent observations by a number of experiments can be interpreted as hints for the annihilation signal of dark matter. To explain all available data, a new class of models has been constructed, postulating a dark, hidden sector containing in particular a light dark photon. Dark matter can then annihilate into a pair of dark photons, which decay into Standard Model fermions with branching fractions strongly depending on the dark photon mass. The DØ collaboration has developed a search for light dark photons produced in decay chains of supersymmetric particles, leading to final states with two dark photons and missing transverse energy. The dark photons decay into electrons or muons, which due to the low dark photon mass are almost collinear in the detector. The

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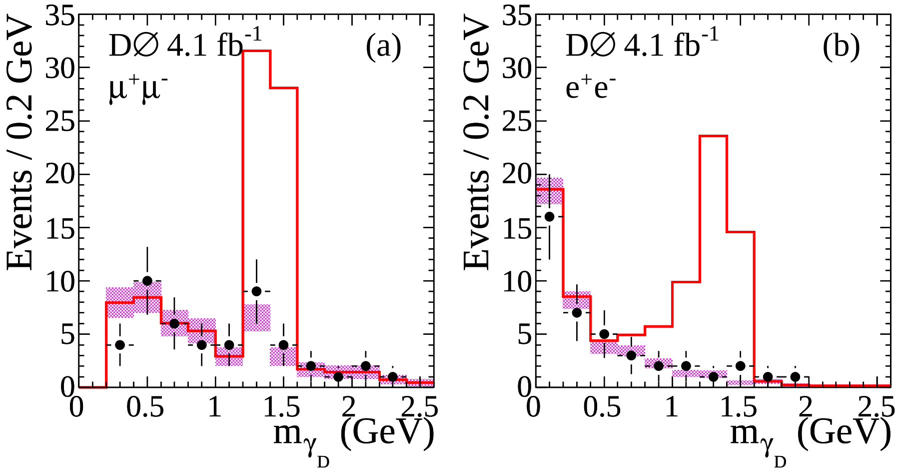

Figure 8: Distribution of invariant dimuon (left) and dielectron (right) mass for data (points), background (histogram with shaded uncertainty band) and a dark photon signal (open histogram) in the search for light dark photons [12].

detection of such a collinear lepton pair requires modification of the standard lepton identification procedures. The resulting invariant mass spectra are shown in Fig. 8. No excess is observed, which is translated into upper limits on the dark photon production cross section.

For the LHC, both ATLAS and CMS collaborations have been reviewing and improving their trigger capabilities to ensure that exotic signatures will be picked up by the trigger systems. In the case of long-lived particles, which are a generic prediction of a large number of models, this effort has lead to the implementation of new dedicated triggers in preparation for data-taking in 2010. For instance, CMS will run a trigger on jets with low transverse momentum in time periods without beam or between bunch crossings [13]. This provides sensitivity to detect delayed decays of long-lived gluinos, which are stopped in the calorimeter and decay later at a random time. As another example, ATLAS has developed new triggers to detect decays of long-lived neutral particles into jets. Depending on the lifetime, the decay will occur in different parts of the detector, which results in signatures ranging from trackless jets to high multiplicity in the muon system without inner detector tracks or calorimeter activity (see Fig. 9).

5. Summary

A vast number of signatures and models for new physics has been tested by the two Tevatron experiments CDF and DØ. No evidence for any deviation from the Standard Model has been found, resulting in limits that in many cases are close to the kinematic reach of the Tevatron. The LHC is expected to provide access to new mass regimes already within its first year of physics running in 2010, with the exciting prospects of an early discovery if masses of new particles are small.

6. Acknowledgments

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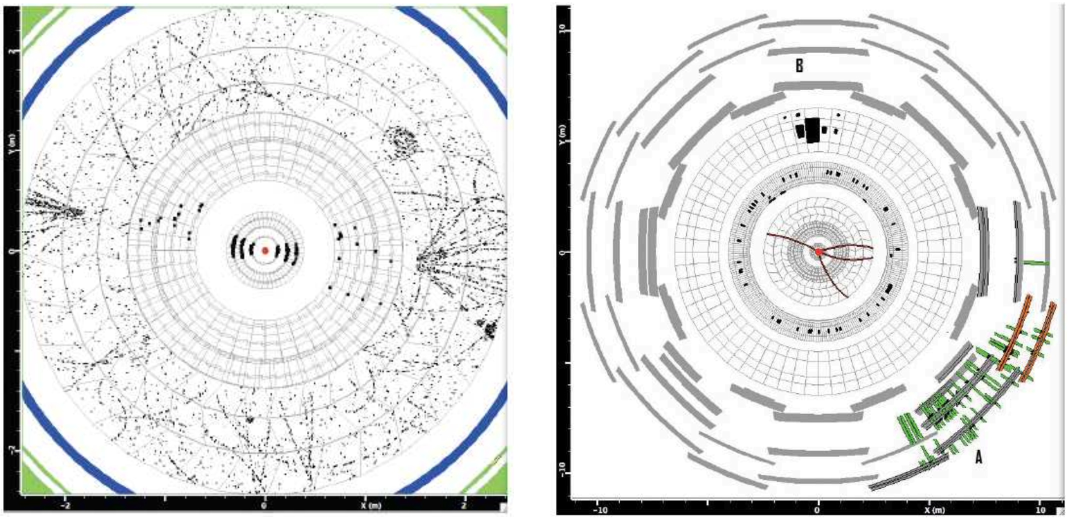

Figure 9: Event displays of the decays of long-lived neutral particles into jets in the ATLAS detector. Left: decays in the outer layers of the tracking system (trigger signature: trackless jets). Right: decay inside the calorimeter (trackless jet) or in the muon system (high muon multiplicity without tracks or jets) [14].

results, as well as express his gratitude to Todd Adams, Oliver Buchmüller, Arnaud Duperrin, Paul de Jong, Greg Landsberg, Monica D'Onofrio, Giacomo Polesello, Jeffrey Richman, Albert de Roeck, Eduardo Ros, Pierre Savard and Tom Wright for their support in preparing this presentation.

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