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SEARCHES FOR NEW PHYSICS WITH LEPTONS IN THE FINAL STATE AT THE LHC

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Final states including leptons are most promising to detect early signs of new physics processes when the Large Hadron Collider will start proton-proton collisions at the centre of mass energy of 14 TeV. The reach for Supersymmetry and Extra Dimension models for integrated luminosities ranging from 1 to 10 fb^{-1} is reported. Preliminary results indicate that already with 1 fb^{-1} of data new phenomena can be detected.

By the end of 2008 the ATLAS[1] and CMS[2] experiments at the LHC expect to collect between 0.5 and 1 fb^{-1} of data each, which should make possible the first searches for new phenomena over the Standard Model (SM) background. All such searches would require the precision measurement of the SM processes with detailed understanding of the detector performance, reconstruction algorithms and triggering. Leptons, electrons and muons, have better reconstruction efficiency and energy resolution than taus, jets and missing transverse energy ($\not{E}_T$). They also provide a clean triggering and a high background reduction. Above all, leptons may indicate signatures of new physics, such as decays of massive strongly interacting particles to leptons accompanied by jets and $\not{E}_T$ and decays of new massive resonances to di-lepton pairs. In this report, the preliminary discovery limits for Supersymmetry (SUSY) and Extra Dimension (ED) models estimated over a wide range of parameter space are presented.

Inclusive SUSY reach with leptons

Supersymmetry[3] is described by models which provide a realistic SUSY-breaking scheme. One of the general approaches is given by the Minimal Supergravity[4] (mSUGRA) model with only 5 free parameters: a common scalar (m_0) and fermion ($m_{1/2}$) masses, a trilinear coupling (A_0) and Higgs sector parameters ($\tan\beta$, $sgn\,\mu$) at the Grand Unification (GUT) scale. In mSUGRA, assuming R-parity[3], new supersymmetric particles are produced in pairs and the lightest one (LSP) is stable and neutral. At the LHC, the SUSY production is dominated by strongly interacting squarks and gluinos ($M_{SUSY} \sim m_{\tilde{q},\tilde{g}}$), which have long decay cascades with the jet emission. The cascade ends with the LSP, which is not detected. Therefore, a generic supersymmetry signature is a multi-jet final state with large $\not{E}_T$. The main backgrounds are QCD and $t\bar{t}$, W, Z with QCD-jet associated production processes, which should be estimated by using an exact LO evaluation of partonic matrix elements matched with parton showers at the hard process scale[5]. In SUSY cascades, leptons are produced in decays of charginos or neutralinos (e.g. $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l^+ l^-$, $\tilde{\chi}_1^+ \to \tilde{\nu}_l l^+$) and the final state consists of $n \leq 4$ leptons (+ jets + $\not{E}_T$). Pairs of leptons can have the

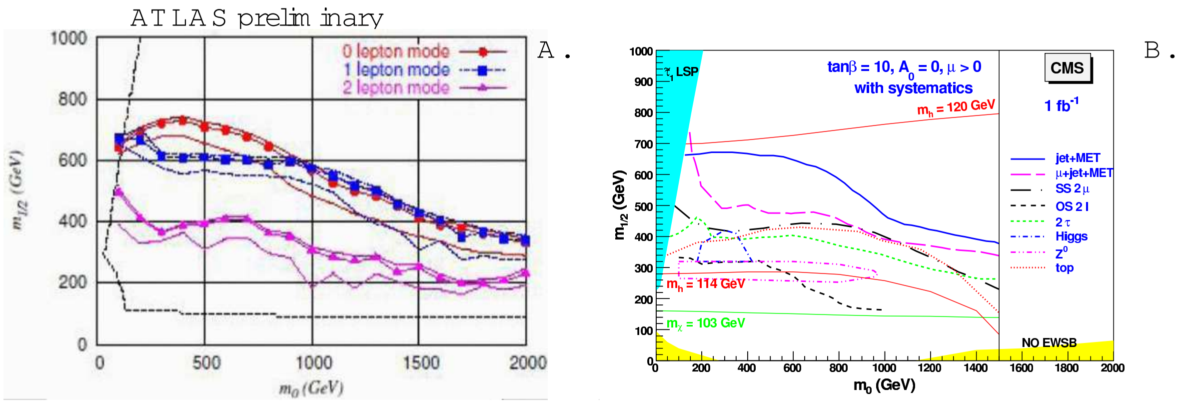

Figure 1: The mSUGRA discovery reach in m_0-$m_{1/2}$ plane for fixed $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$ for 1 fb^{-1} with systematic uncertainties denoted by dash lines for the (A) and with uncertainties already included for CMS (B).

same or opposite sign (SS or OS). Considering signatures with at least one lepton, substantially reduces the QCD background. The inclusive SUSY searches employ the following strategy. First, experimental signatures are studied for a limited number of test points of mSUGRA parameter space (in m_0-$m_{1/2}$ plane for fixed A_0, $\tan\beta$, sgn μ) using the full detector simulation and reconstruction (S&R) software. Next, the results are extended to other points of the parameter space using fast S&R. In order to obtain the best signal to background (S/B) ratio the SUSY selection cuts are optimised for each point. The expected discovery reach is evaluated for parameter sets having at least five standard deviation (5σ) signal significance[6].

The ATLAS collaboration studied the mSUGRA model with $n \leq 2$ leptons in the final state. The cuts have been optimised with fast S&R for $m_0 = 100$–2000 GeV, $m_{1/2} = 100$–1500 GeV, $\tan\beta = 5, 10, 30, 50$, $A_0 = 0$ and $\mu > 0$ model parameters using the SUSY-sensitive observables: $\not{E}_T$, $p_T^{1^{st}\,jet}$, $p_T^{4^{th}\,jet}$, Sphericity$_T$. The background consists of the following SM processes[5]: $t\bar{t}$+N(0-3)jets, W($\to l\nu$)+N(2-5)jets, Z($\to ll;\ \nu\nu$)+N(2-5)jets, N(2-6) QCD jets. The large cut on $\not{E}_T$ (e.g. > 400 GeV) effectively removes the SM background in the wide $m_{1/2}$ region due to mass splitting between the heaviest and the lightest SUSY particles. The major theoretical uncertainties of background cross-sections arise from the low parton p_T cut and the small renormalization scale. Experimental uncertainties of luminosity (5%), $\not{E}_T$ scale (5%) and jet energy scale (5%) are considered. The resulting discovery reach, defined by at least 10 signal events and $S/\sqrt{B} > 5$ for 1 fb^{-1}, is shown in Fig.1A. By including uncertainties the discovery potential curves are lower on $m_{1/2}$ by about 50 GeV for all channels. Therefore, ATLAS searches for $n \leq 1$ lepton channels are sensitive up to $M_{SUSY} \sim 1.4$ TeV or $m_{1/2} \sim 700$ GeV.

The CMS experiment analysed several signatures characteristic for mSUGRA[6] with the full S&R and the event selection criteria optimised for SUSY. The discovery potential for integrated luminosity of 1 fb^{-1} is presented in Fig.1B. The curves show limits with all systematic uncertainties included. The inclusive channels, jet+$\not{E}_T$ and μ+jet+$\not{E}_T$ yields the best results and allow to probe an existence of SUSY to the same level of $M_{SUSY} \sim 1.5$ TeV as ATLAS obtained for $n \leq 1$ lepton channels. Other experimental signatures in the same range of parameters may help to confirm the discovery. The parameters of mSUGRA can be recovered later from the measurement of several observables such as the reconstructed masses of SUSY particle.

Four-lepton signal from Universal Extra Dimensions

The CMS collaboration studied 4-lepton signatures in the context of Universal Extra Dimensions[7] (UED) model. The phenomenology of UED is very similar to that of SUSY, although the origin of UED comes from the sub-millimetre ED model of the ADD[8] type. In UED, all SM fields are allowed to propagate along EDs. Therefore, each SM particle has Kaluza-Klein (KK) excitations with the same spin contrary to SUSY particles. In the minimal scenario with only one ED:

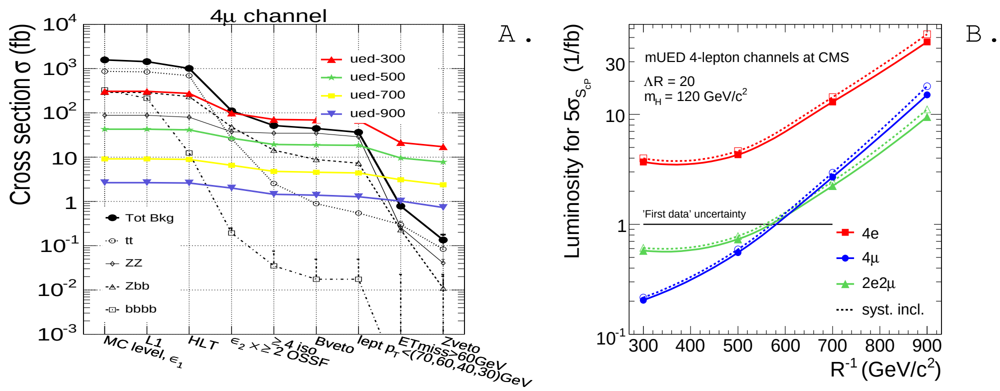

Figure 2: The CMS search for mUED signal with the 4-lepton final state. A. Signal selection efficiency in the 4-muon channel. B. The mUED 4-lepton discovery potential as a function of the ED size, R^{-1}.

mUED [R^{-1}, ΛR], where R^{-1} is a size of the ED and Λ an effective cut-off scale, the KK excitations exhibit highly degenerate masses even after radiative corrections. The KK-quarks decay to the lightest and stable KK-photons in a long chain ($q^{KK} \to Z^{KK} q; Z^{KK} \to l^{KK} l; l^{KK} \to \gamma^{KK} l$) producing soft leptons and jets in the detector. Therefore, the 4-lepton final state is considered the best to eliminate the SM background. The CMS study[9] has been performed with the full S&R for four sets of mUED parameters ($\Lambda R = 20$ and $R^{-1} = 300, 500, 700, 900$ GeV) and for three leptonic channels: 4μ, 4e and 2e2μ. Two same-flavour OS isolated lepton pairs were required in the offline selection in advance of the b-tagging and Z-veto rejections (Fig. 2A). The discovery potential for mUED in terms of the integrated luminosity needed to achieve signal significance of 5σ (Fig.2B) extends up to $R^{-1} = 600$ GeV for 1 fb^{-1} data. The systematic uncertainties due to a limited understanding of the detector performance during initial phase of the LHC data taking may shift the sensitivity of mUED discovery up to 1 fb^{-1}.

Di-lepton resonances from Z^0 bosons and Randall-Sundrum Gravitons

The spin-0 Z^0 gauge bosons and spin-2 KK excitations of the graviton with masses of the order of 1 TeV are predicted by many EDs and GUT's theories. At LHC, such resonances are produced directly and promptly decay into pairs of same-flavour OS leptons. Their masses can be measured from peaks in the invariant mass distribution in the tails of the SM background processes. This signature has been studied in the CMS experiment.

The dominant background arises from the Drell-Yan (D-Y) lepton pair production, whereas contributions from $t\bar{t}$ and the vector boson pair production (ZZ; WZ; WW) are significantly smaller and are highly suppressed by selection cuts. The K-factors related to the NNLO perturbative QCD calculations are used to correct cross-sections in function of the di-lepton mass for the D-Y and the new boson production. Theoretical uncertainties due to a choice of the PDF set and various experimental uncertainties are also considered including effects of the misalignment of the muon system in the early (< 1 fb^{-1}) and the late (> 100 fb^{-1}) phase of the LHC data taking periods. The momentum resolution of the detector plays a key role in separating the signal from the background. New reconstruction algorithms have been developed to increase the lepton reconstruction efficiency. For highly energetic electrons, their energy deposited as an isolated electromagnetic super-cluster is corrected for the energy leaking into a hadronic calorimeter and for electronics saturation effects. For very high-p_T muons, the track fitting in the tracker and the muon system are optimised to detect and correct effects of their energy lost. The results of the CMS analyses[6] obtained with the full S&R of signal and background are presented in Fig.3. Both, the Z^0_{SSM} boson originated from the so-called Sequential SM and Z^0_ψ from one of the GUT's models[10] can be discovered using 1 fb^{-1} of data (above the Tevatron limit of 1 TeV) up to $M_{Z^0} \approx 2.6$ TeV (Fig.3A). Graviton excitations, G^*, are

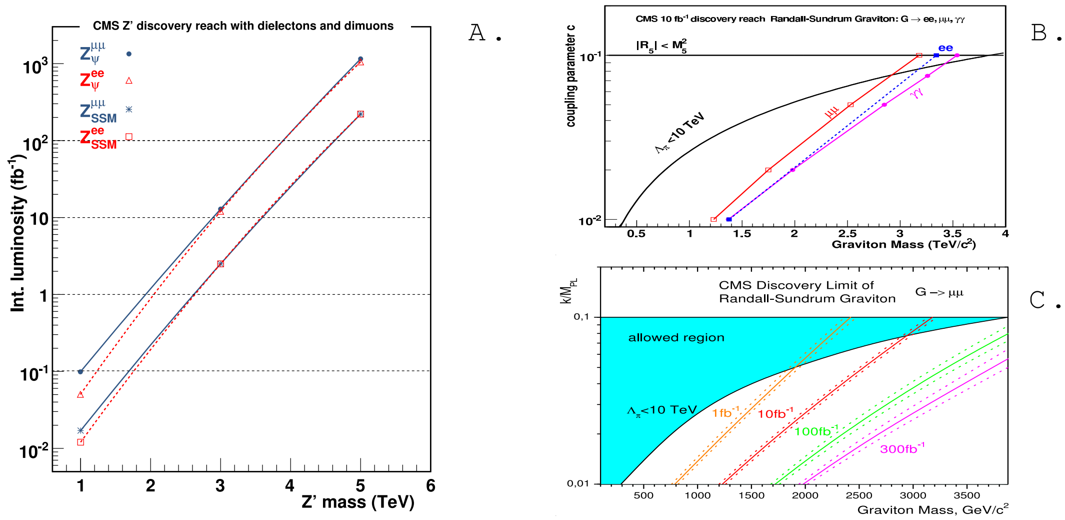

Figure 3: A. The luminosity required for 5σ discovery as a function of Z^0 mass. B. The comparison of RS graviton discovery reach for $10\ \mathrm{fb}^{-1}$ for different channels. C. The RS graviton discovery limits with systematic uncertainties (dash lines) for the muon channel.

predicted by the Randall-Sundrum[11] (RS) model in which only one ED is seen by the gravity whereas all SM fields live in the 3-dimensional Universe. Couplings and the width of G are given by the parameter $c = k/M_{Planck}$, where $k \sim M_{Planck}$ is a mass scale factor. In Fig.3B the RS graviton discovery reach corresponding to $10\ \mathrm{fb}^{-1}$ is shown for three decay channels. The muon channel has the lowest discovery potential due to momentum resolution effects. Although, the photon channel has the branching ratio almost two times larger then leptonic ones its reach is comparable to the electron channel due to QCD and prompt photon irreducible backgrounds. From Fig.3C one can see that $1\ \mathrm{fb}^{-1}$ of data should be sufficient to discover RS gravitons decaying to muons with mass up to $M_G \geq 2.4$ TeV. Experimental methods have been proposed to measure the spin of such new resonances[6].

Summary

Leptons provide the cleanest signature for exotic searches with the first LHC data. Thus, inclusive searches with leptons are very promising for verifying theoretical predictions for physics beyond the Standard Model. Recent studies on the discovery potential for SUSY performed by the ATLAS and CMS collaborations are consistent with each other and demonstrate that probing the production of squarks and gluinos with masses of the order of 1.5 TeV is possible with integrated luminosity as low as $1\ \mathrm{fb}^{-1}$. With $1\ \mathrm{fb}^{-1}$ the searches for EDs can set discovery limits at the level of: $R^{-1} = 600$ GeV for mUED model, $M_G \geq 2.4$ TeV for the RS graviton, and $M_{Z^0} \geq 2.6$ TeV for massive Z^0 bosons.

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