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Working group report: Dictionary of Large Hadron Collider signatures

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Abstract. We report on a plan to establish a 'Dictionary of LHC Signatures', an initiative that started at the WHEPP-X workshop in Chennai, January 2008. This study aims at the strategy of distinguishing 3 classes of dark matter motivated scenarios such as R-parity conserved supersymmetry, little Higgs models with T-parity conservation and universal extra dimensions with KK-parity for generic cases of their realization in a wide range of the model space. Discriminating signatures are tabulated and will need a further detailed analysis.

Keywords. Large Hadron Collider; dark matter; discrimination; underlying theory.

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1. Introduction

The particle physics community is eagerly awaiting the start-up of the LHC. The measurements at this proton–proton collider with a centre of mass system energy of 14 TeV will shed light on the origin of electroweak symmetry breaking and are expected to provide collider signatures of dark matter (DM), thus directly revealing new physics beyond the Standard Model (BSM).

The identification of BSM signals at the LHC and establishing the underlying theory will become a central question after the discovery. Correctly identifying the new physics scenario from the data will be a very important task and due to the very many possible scenarios, it is likely to be a very difficult or perhaps even unsolvable puzzle. However, among the many compelling BSM scenarios proposed so far, only a few provide a stable DM candidate (with a correct relic density) and at the same time solve the hierarchy and fine-tuning problem of the SM Higgs sector. Hence, we turn our attention in this paper to those BSM models that fulfill these requirements.

The idea of this study, which started off at WHEPP X is to design a strategy on how to distinguish three representative BSM candidates, namely, supersymmetry with conserved R-parity (SUSY) [1], the littlest Higgs model [2] with T-parity (LHT) [3] and universal extra dimensions with KK-parity (UED) [4]. In fact, for all these models, one expects very similar event topologies at the LHC, with new particles produced in pairs which then subsequently decay in (long) cascades to the lightest stable DM particle which escapes detection. For each scenario we choose generic regions in the parameter space, each characterized by specific features of the DM particle properties. The regions selected are allowed by the cosmological constraints on the relic density; e.g. for SUSY this means the so-called bulk, co-annihilation, focus point and resonant annihilation region (funnel corridor).

The final goal of this study is to classify generic properties and signatures of each class of models and find the strategy for discriminating the underlying model. In this paper we report the plan towards this final goal and present qualitative arguments for the different signatures that will be used. This classification and the strategy are discussed in the next section.

Similar questions have been studied in the context of the so-called inverse problem of supersymmetry at the LHC [5], and footprints for SUSY models [6]. A recent study [7] aims to discriminate SUSY, and to a lesser extent also LHT and UED models, using a variety of different kinematical observables related to the spin difference of the underlying theories, by using tailored benchmark points particularly suitable for the LHC start-up. In the present study we extend the classes of various observables and will attempt to establish a strategy for more generic regions of the parameter space for every class of these BSM scenarios. The results themselves will be reported in a follow-up report, following the full study which will also take into account experimental issues, applied to the comprehensive list of observables listed below.

2. Generic LHC signatures of the BSM and their powers of discrimination

Generic properties and signatures of the SUSY, LHT and UED models are the following.

2.1 *Spin statistics*

SUSY superpartners have a different spin compared to their partners, while LHT and UED are theories with 'bosonic' supersymmetry, where the SM particle and its heavy partner have the same spin. This difference can be probed effectively by the following observables:

- *Difference of the total cross-section*: This has been discussed in refs [8–10]. It was shown in [9] that the cross section of chargino–neutralino production in SUSY is typically one order of magnitude lower than the cross-section of the analogous particle production ($W_{\rm H}Z_{\rm H}$) in LHT. Note however, that for total cross-sections one needs to control the theoretical uncertainties, such as parton distributions, renormalization and factorization scale uncertainties, etc. Alternatively, one needs to find effects which may be less sensitive to these uncertainties. The experimental issues of relevance to this measurement are the systematics in the luminosity measurement, the lepton identification and trigger efficiency, the jet energy scale and energy and momentum resolution. Note that the experimental cuts can modify the expected relative rates of different models.
- *Various angular correlations between final state particles*: This issue has been discussed in refs [7,11–15]. The invariant lepton mass distributions as well as the lepton–quark invariant mass distributions were shown to be capable of discriminating between SUSY and UED models, even for similar masses of the heavy partners in both the models [13]. Since a direct spin measurement is impossible due to the LSP in the final state, such correlation studies are the only handle. However, this is a very challenging measurement. Choice of a particular final state as well as that of particles therein to study the correlations plays a crucial role, particularly since the combinatorics can sometimes completely smear out the differences. The angular, energy and momentum resolution of the measurement also plays a very important role.
- *Polarization of the final state SM particles*: Polarization of the top quarks and taus, is reflected in their decay products and is experimentally accessible. The same experimental issues that affect the study of angular correlations are important here as well. The polarization may be used to determine the character of the DM particle and hence the underlying model parameters [16–18] as well as to sharpen the search strategies [19]. In stau co-annihilation region of SUSY, the final state signatures will be exhibited by very soft τ leptons. In this case, the polarization of τ can be used very effectively to reduce the background from QCD jets [20].
- *Difference in the direct and indirect DM detection rates*: The DM detection rates in the DM search experiments can play a very important role in this discrimination between models as discussed, in ref. [15,21,22]. The ratio of positron rates to the sum of the electron and positron rates from DM annihilation in galactic halo, is an observable which allows discrimination among all the BSM models we study: SUSY, LHT and UED. Even though these rates will not be measured at the LHC, we include these in our study, since they will come from experiments with the same (LHC) time line, stressing a very important complementarity between LHC and DM search experiments to decipher the underlying theory.

2.2 *Heavy partner content*

Even though LHT and UED are both 'bosonic' supersymmetries, their heavy partner content differs significantly. Since LHT has no heavy partner of gluon, one expects less QCD-induced events in the LHT scenario, as compared to SUSY and UED.

2.3 *Existence of higher level modes*

The higher level modes, e.g., the second KK modes, appear only in UED scenarios and do not exist in SUSY or LHT models. Hence, it is important to identify comprehensive particle spectrum as precisely as possible. These measurements will be affected by the experimental resolution of all measurable quantities, viz. energy and momentum of leptons, the jet energy as well as the the missing transverse energy $\not\!\!E_{\mathrm{T}}$, hence the calibration and alignment of the detectors.

2.4 *Majorana vs. Dirac nature of the heavy neutral fermion partners*

The character of the heavy neutral fermions is clearly an important distinguishing feature among these models. In LHT or UED models Majorana fermions are absent, whereas in all usual formulation of supersymmetric theories, neutralinos and gluinos are Majorana fermions [22a]. These serve as a source of like-sign lepton signatures. One of the observables which reflects this difference is the $N_{l^+l^+}/N_{l^-l^-}$ ratio as well as the ratio between multilepton rates and just $\not\!\!E_{\mathrm{T}}+$ jets, *viz.*, $R = N(\not\!\!E_{\mathrm{T}} + \text{jets})/N(l's + \not\!\!E_{\mathrm{T}} + \text{ jets})$. In the case of LHT and UED, the $N_{l^+l^+}/N_{l^-l^-}$ ratio is fixed by parton density functions and the mass of the heavy quarks produced in the t-channel reactions initiated by two valence quarks in the initial state. For example, this ratio is between 3.5 and 5 for the respective heavy quark mass between 0.3 and 1 TeV [25], while in SUSY this ratio is diluted by the same sign leptons originating from cascade gluino decays. The ratio R mentioned above is larger in SUSY compared to LHT because of the presence of gluino in SUSY models. We plan to study this ratio for the case of UED scenario. The systematics of these measurements will be affected by the lepton charge mis-identification probability and any lepton sign-dependent systematics.

2.5 *b-jet and τ multiplicity*

For example, in the SUSY focus point region the b-jet multiplicity is enhanced due to Higgsino nature of neutralino and suppressed mass of the lightest stop-quark as compared to the first and second squark generations. In fact top multiplicity may also be used effectively. This measurement will be strongly affected by the b- and τ-tagging efficiency and purity.

2.6 *Single production of the heavy partner of the top*

In LHT single heavy top production is possible. Also single KK2 (2nd KK mode) heavy top can be produced through KK2 parity violating coupling in UED [13]. There is no such analog in SUSY.

2.7 *The number of DM co-annihilation channels*

The number of DM co-annihilation channels in the early Universe can be considerably larger in the case of UED scenario as compared to SUSY or LHT scenarios. The set of UED co-annihilating channels can include co-annihilation of KK photon with KK leptons, KK quarks, KK scalars, KK W/Z and KK gluons simultaneously. This degeneracy then would lead to an enhanced number of decays of soft particles, resulting from several degenerate states.

2.8 *Various kinematical observables*

We will also include possible significant kinematical variables, some of which have been analysed in previous studies.

- number of leptons versus number of jets counts including same-sign and opposite sign leptons of various flavours,
- invariant and transverse masses of multilepton states,
- kinematical edges,
- event topology, including event shape variables as acoplanarity, sphericity.

The comparison of generic features of SUSY, LHT and UED stated above is summarized in table 1.

3. Experimental issues

Before one embarks on the study of distinguishing among the BSM models, one will have to also establish how well these chosen signals can be discriminated from the SM backgrounds. This will be an inherent part of our study. The experimental issues involved in the signal extraction are related to the missing E_{T} measurement, the reconstruction of hadronic, b- and τ-jets, and the lepton identification, which are discussed here.

Missing E_{T} ($\not\!\!E_{\mathrm{T}}$) is primarily reconstructed from the energy deposits in the calorimeter and the reconstructed muon tracks. Apart from the hard scattering process of interest, many other sources, such as the underlying event, multiple interactions, pile-up and electronic noise lead to energy deposits and/or fake muon tracks. Classifying these energy deposits into various types (e.g. electrons, taus

Table 1. Discriminating signatures between SUSY (MSSM), LHT and UED. See description in the text. 'YES' or 'NO' mean presence or absence of the particular signature respectively, 'SS' stands for 'same-sign leptons'.

Variables	SUSY (MSSM)	LHT	UED
Spin	Heavy partners differ in spin by 1/2	Heavy partners have the same spin, no heavy gluon	Heavy partners have the same spin
Higher level modes	NO heavy partners	NO heavy partners	YES heavy partners
$N_{l^+l^+}/N_{l^-l^-}$	$R_{\text{SUSY}} < R_{\text{LHT}}$	R_{LHT}	$R_{\text{UED}} \simeq R_{\text{LHT}}$
SS leptons rates	From several channels: SS heavy fermions, Majorana fermions	Only from SS heavy fermions	Only from SS heavy fermions
$R = \frac{N(\not{E}_{\text{T}}+\text{jets})}{N(l's+\not{E}_{\text{T}}+\text{ jets})}$	R_{SUSY}	$R_{\text{LHT}} < R_{\text{SUSY}}$	R_{UED} to be studied
b-jet multiplicity	Enhanced (FP)	Not enhanced	Not enhanced
Single heavy top	NO	YES	YES via KK2 decay
Polarization $tt+\not{E}_{\text{T}}$ effects $\tau\tau+\not{E}_{\text{T}}$	To be studied To be studied	To be studied To be studied	To be studied To be studied
Direct DM detection rate	high (FP) low (coann.)	Low (bino-like LTP)	Typically low for γ_1(5D) DM [22] Typically high for γ_H(6D) DM [22]

or jets) and calibrating them accordingly, is the essential key for optimal $\not{E}_{\text{T}}$ measurement. In addition, the loss of energy in regions of inactive material and dead detector channels make the $\not{E}_{\text{T}}$ measurement a real challenge.

The $\not{E}_{\text{T}}$ reconstruction algorithm starts from the energy deposits in calorimeter cells or clusters of cells ('raw $\not{E}_{\text{T}}$'). The raw $\not{E}_{\text{T}}$ is then cleaned up from a number of sources of fake $\not{E}_{\text{T}}$: hot cells, overlay of beam-halo, cosmics, detector malfunctions, detector hermiticity. Overall, the reconstruction of $\not{E}_{\text{T}}$ is a challenging task and it requires a good understanding of the calorimeter response and the topology of different signatures. The $\not{E}_{\text{T}}$ resolution roughly scales with $\sqrt{\sum E_{\text{T}}}$, where $\sum E_{\text{T}}$ is the scalar sum of the energies of the particles in the final state, for $\sum E_{\text{T}} < 1.5$ TeV.

For the reconstruction of hadronic jets, a seeded fixed-cone reconstruction algorithm with a cone size $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.4$ is presently used for search studies for BSM physics. For future studies also the SISCone (seedless infra-red safe cone) jet algorithm and the fast K_{T} algorithm are considered. If one neglects the noise term, the jet energy resolution varies between 50 and $100\%/\sqrt{E(\text{ GeV})}$. Both experiments have strong capabilities for the identification of b-jets and τ-jets in a wide range of transverse momentum for $|\eta| < 2.5$. For a b-tagging efficiency of 60 % and transverse momentum $20 < p_{\mathrm{T}} < 100$ GeV a rejection of above 100 and about 10 may be achieved against light and c-jets, respectively, with degradation of the performance for $p_{\mathrm{T}} > 100$ GeV. For a τ-jet efficiency of 50%, the rejection against hadronic jets improves with p_{T}, reaching rejection values of $O(10^2) - O(10^3) GeV$.

Electrons are reconstructed as objects that have a track in the inner tracker and an electromagnetic cluster in the EM calorimeter. The calorimeter is designed to contain almost all of the energy of a high p_{T} (TeV range) electron, and has an energy resolution of $2–10\%/\sqrt{E(\text{GeV})}$, depending on the experiment. The inner tracker has an intrinsic p_{T} resolution of a few times $10^{-4} p_{\mathrm{T}}(\text{TeV/c})$, which is limited by early bremsstrahlung in its material. In order to separate isolated electrons originating from interesting events, from QCD background (hadrons, jets and photons) with similar topology, several of their characteristics are exploited. The EM cluster in the calorimeter is required to match with a track in the inner tracker and the ratio of its energy over its momentum measured by the tracker (E/p) to be that of an electron. Cuts on the longitudinal (and lateral) shape of the shower are applied, and minimal energy is allowed to be deposited in the hadronic calorimeter.

Muons are reconstructed as objects that have a track in the muon spectrometer and a corresponding ('matched') track in the inner tracker. In the case of ATLAS, the good resolution of the muon spectrometer provides the possibility to trigger and reconstruct muons in 'stand alone' mode (no matching with the inner detector involved). The momentum resolution is maintained high for both experiments. For muon p_{T} in the TeV range, the resolution is limited by detector alignment in the case of ATLAS and can be kept at $\sigma/p_{\mathrm{T}} \approx 10\%$, whereas in the case of CMS it is limited by energy losses in the iron yoke, and it varies between 15–30%. In combination with the inner detector track the resolution is improved to 5%. The muon detection and reconstruction efficiencies for both experiments are high (above 95%). The charge misidentification probability varies between 10^{-3} and 10^{-2} for muons below 100 GeV p_{T} and between 10^{-2} to few times 10^{-1} for muons above 500 GeV, increasing with rapidity. Finally the expected fake rate for muons, even for the high luminosity case, can be maintained to the % level, while it is an order of magnitude lower for low luminosity.

4. Strategy

For the signature analysis we will investigate details of each particular class of models as discussed above. A set of significant signatures (the aim of our study) for each model will be classified as shown in table 1. For example, for MSSM a preliminary and still incomplete version of such a classification is shown in table 2.

Every 'YES' entry in table 2 means that the particular final state has the potential of being able to discriminate among (or pinpoint to) different regions of the MSSM space, consistent with DM constraints. For example, while the b-jets multiplicity (N b-jets in table 2) may allow to separate the SUSY signal from the SM in all the regions of the MSSM parameter space, the amount of enhanced b-jet multiplicity is very large particularly in the focus point region.

Table 2. DM-motivated models and signatures. Only the MSSM is listed here. The following signatures: $\not{E}_T$+jets, top polarization, top-quark multiplicity are planned to be studied. OSL and SSL stand for opposite-sign leptons, and same-sign leptons respectively.

	SUSY (MSSM)			
Signatures and observables	Focus point	Co-ann.	A-res.	Bulk
$1\ \ell$ + jets + $\not{E}_T$	YES	YES	YES	YES
OSL + jets + $\not{E}_T$	YES	YES	YES	YES
SSL + jets + $\not{E}_T$	YES	YES	YES	YES
$3\ \ell$ + jets + $\not{E}_T$	YES	YES	YES	YES
$4\ \ell$ + jets + $\not{E}_T$	YES	YES	YES	YES
N b-jets	Enhanced	YES	YES	YES
H+$\not{E}_T$+jets from cascades				
$H \to \gamma\gamma, b\bar{b}$	YES	NO	NO	NO
$H \to VV, t\bar{t}$	NO	NO	NO	NO
Soft taus	YES	Enhanced	NO	NO
Tau polarization	YES	YES	YES	YES
$N_{l^+l^+}/N_{l^-l^-}$	$\sim 1:1$	$< R_{\rm LHT}$	$< R_{\rm LHT}$	$\ll R_{\rm LHT}$
DD rates, $\sigma(Z1p)$	Enhanced	Suppr.	Suppr.	Part. enhanced
ID rates, $\langle\sigma v\rangle(v \to 0)$	Enhanced	Suppr.	Suppr.	Part. enhanced

For mSUGRA, for example, the polarization of τ leptons produced in the decay of $\tilde{\tau}_1\tilde{\tau}_1$ can be used very effectively to sharpen up SUSY signature; for the co-annihilation region where one expects soft τ's, the fact that τ's from SUSY decays are polarized, can be used very effectively to reduce SM background from the soft QCD jets.

Another example of the powerful discrimination between different DM-motivated SUSY regions are the dark matter direct detection (DD) rates which are proportional to neutralino scattering cross-section off the nuclei, usually expressed in terms of $\sigma(Z1p)$ as well as indirect dark matter detection rates (ID) related to average of DM annihilation rate times velocity in zero velocity limit, $\langle\sigma v\rangle(v \to 0)$.

For each entry with a 'YES' in table 2, the most important contributing processes will be listed and studied in more detail. Similar tables will be worked out for the LHT and UED.

In very recent work [7], the authors aimed to distinguish a quite specific benchmark points for these theories with high cross-section in the first month of the LHC run. We plan on using analogous tables for LHT and UED models together with table of 'comparison', table 1 to create a 'dictionary of LHC signatures' and examine a strategy to discriminate all three classes of theories for generic cases of their realization in wide range of the model space. This will be the main difference and novelty of our study in comparison with earlier ones.

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