Physics Opportunities at the Large Hadron Collider

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Abstract. In about two years time the LHC is scheduled to deliver its first pp collisions at a centre of mass energy of 14 TeV. The LHC is expected to open up the discovery of new physics at the TeV scale, and give the final answer on the Standard Model Higgs. The LHC will however also be a tool for precision physics. Furthermore LHC is also a pA and AA collider. This report summarizes some of the physics opportunities of the LHC.

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INTRODUCTION

The construction at CERN of the Large Hadron Collider (LHC), which will collide protons at a centre of mass (CM) system energy of 14 TeV, is ramping up well. At the time of writing (December '05) about 200 out of the 1232 dipoles have been installed in the tunnel and an instalation rate of 20 dipoles per week has been achieved [1]. According to the present schedule LHC will be closed and set up for beam on July 2007[1]. The first beam in the machine can be expected in August 2007. First collisions at 14 TeV are expected for October/November 2007, followed by a short pilot run with perhaps an integrated luminosity of up to a few tens pb^{-1}. The first physics run in 2008 should yield one to a few fb^{-1}, reaching luminosities in the range of $0.5 - 2.0 \cdot 10^{33}$ cm$^{-2}s^{-1}$. Depending on the evolution of the machine we expect to collect 200-300 pb^{-1} per experiment in roughly 6 years time, with a peak luminosity of 10^{34} cm$^{-2}s^{-1}$. Note: the above integrated luminosity guesses are mine, not official numbers released by the machine group.

The experiments CMS, ATLAS, ALICE, LHCb and TOTEM are preparing for first beam in 2007. Major components have been produced, shipped to CERN and are being installed in the interaction regions during the last 12 months.

The main physics mission of the LHC is to explore directly the highly-motivated TeV-scale, say the final word about the SM Higgs mechanism and test TeV-scale New Physics predictions. Also the LHC will be a great tool for studies on QCD [2], B-physics, heavy ions, EW precision measurements etc.

Over the years the ATLAS and CMS experiments have demonstrated their discovery potential for key processes, such as the discovery of the Higgs particle or supersymmetry. A summary can be found in the ATLAS physics TDR[3] and e.g. topical papers

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[1] More information on the LHC dashboard: http://lhc-new-homepage.web.cern.ch/lhc-new-homepage

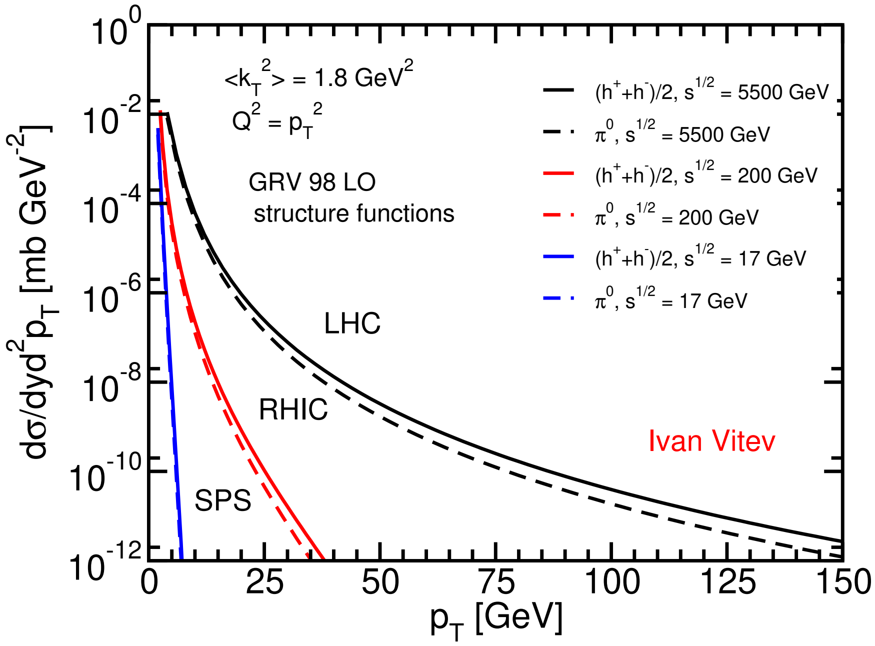

FIGURE 1. The transverse momentum distributions of charged particles or pions for different CM system energies of heavy ion collisions

by CMS [4]. Recent ideas such as extra dimensions, bosonic SUSY, exclusive central Higgs production, black holes, little Higgs scenarios, etc... have been studied, as well as the reachable precision for EW measurements, Higgs properties, and supersymmetry benchmark points. If low energy new physics sets in, then also LHCb can detect deviations in (rare) b-decay production rates.

ALICE will study systematically the new dense matter systems through AA heavy ion collisions, and comparisons with pA and pp. Recent data from the Relativistic Heavy Ion Collider (RHIC) show that this new state of matter is more remarkable than predicted – raising many new questions – and seems to behave like a perfect liquid; see discussion in another talk at this conference [5]. At the LHC in particular event shapes and high p_T probes will be used to study this new dense state of matter at the highest energies. Among others the meltdown of the J/ψ and Υ, and effects of high p_T particle and jet quenching will be studied. Fig. 1 shows the increased range of high p_T particles expected at the LHC compared to present machines.

Note that also ATLAS and CMS have embraced heavy ions in their physics program. The LHC could be ready for heavy ions already from 2008 onwards if the pre-accelerator chain is upgraded (new source, improved vacuum in the PS, and most important of all the conversion from LEAR to LEIR). Typically one month of heavy ion running/year can be expected.

The TOTEM experiment aims to measure the total pp cross sections, the elastic cross section and the diffractive components of the cross section. It will make use of Roman Pot detectors up to about 200 meter distance from the interaction point, which can approach the beamline very closely, up to a few milimeters distance, to tag the forward protons. TOTEM uses the same interaction region as CMS, and common running of the detectors is foreseen. Recently also a 6th experiment has been proposed, namely LHCf, which consists of an electromagnetic detector to measure photons and neutral pions emitted at zero degrees from the interaction point. If approved, the detector will be installed at 140 m distance from the (ATLAS) interaction point, at a place where the 2 proton beams are separated in their own individual beampipes. The results of this experiment will be important for the study of cosmic rays.

In this report we will in the following mostly discuss the physics program of the experiments ATLAS and CMS.

PRECISION MEASUREMENTS

The event rates at the LHC are very large, even at startup luminosity. Some examples are shown in Table 1[6]. The LHC will be a W factory, a Z factory, a top factory, and – if these exist– a Higgs and SUSY factory...

TABLE 1. Aproximate event rates for some physics processes at the LHC for a luminosity of $2 \cdot 10^{33}\mathrm{cm}^{-2}s^{-1}$. For this table, one year is equivalent to 20 fb^{-1}.

Process	Events/s	Events/year
$W \to e\nu$	40	$4 \cdot 10^{8}$
$Z \to ee$	4	$4 \cdot 10^{7}$
$t\bar{t}$	1.6	$1.6 \cdot 10^{7}$
$b\bar{b}$	10^{6}	10^{13}
$\tilde{g}\tilde{g}$ (m = 1 TeV)	0.002	10^{4}
Higgs (m= 120 GeV)	0.08	$8 \cdot 10^{5}$
Higgs (m= 800 GeV)	0.0012	$1.2 \cdot 10^{4}$
QCD jets $P_T > 200$ GeV	10^{2}	10^{9}

TABLE 2. Most sensitive production and decay channels for the SM Higgs boson search[8].

Production/Decay	Incl.	qqH	WH/ZH	ttH
Low mass region, $M_H < 200\mathrm{GeV}/c$				
$H \to \gamma\gamma$	Yes	Yes	Yes	Yes
$H \to$ bb			Yes	Yes
$H \to \tau\tau$		Yes		
$H \to WW \to l\nu l\nu$	Yes	Yes	Yes	
$H \to ZZ^{*} \to 4l, l = e, \mu$	Yes			
Intermediate mass region, 200 <$M_H < 700\mathrm{GeV}/c$				
$H \to WW \to l\nu l\nu$	Yes			
$H \to ZZ \to 4l, l = e, \mu$	Yes			
High mass region, 700 <$M_H < 1000\mathrm{GeV}/c$				
$H \to WW \to l\nu qq$	Yes	Yes		
$H \to ZZ \to 2l2\nu$	Yes	Yes		

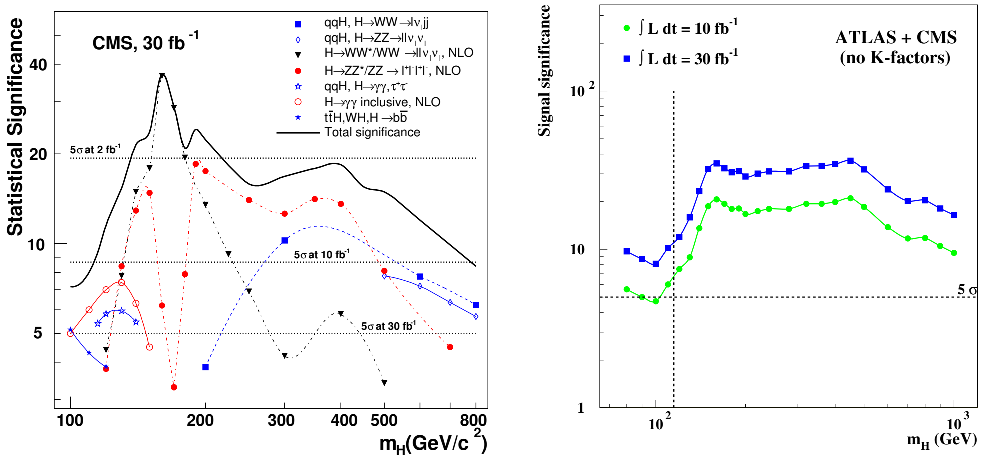

FIGURE 2. (left) CMS discovery potential for the SM Higgs boson in the whole mass range; (right) Expected statistical significance for the detection of the SM model Higgs with 10 and 30 fb^{-1} for both ATLAS and CMS together.

Examples of current estimates of precision measurements include [7]:

- Measure ΔM_W down to 15 MeV
- Measure ΔM_{top} down to 1 GeV, $V_{tb} \sim 10\%$, $BR(t \to bH^+) \sim 3\%$, rare top decays e.g. branching ratios down to $t \to u\gamma$: $0.4 - 2.5 \times 10^{-5}$
- Triple Gauge Couplings [9] to a few permille ($\lambda_\gamma, \lambda_Z$) or a few per cent ($\Delta\kappa$)
- Precision on $\sin^2\theta_{\rm eff}^{\rm lept}$ down to 10^{-4}

Note that it will be a non-trivial task to achieve these results. Typical challenges are the luminosity precision (2-5%), PDF uncertainties (from HERA or from the LHC itself), theoretical uncertainties (radiative corrections, QCD HO), and experimental precision e.g. on the calorimeter energy scales (1% for jets, 0.02% for EM objects). However, when achieved, the top and W-boson mass precisions quoted above will pinpoint the Higgs mass down to within 30%, a nice consistency check with the hopefully direct measurements of this boson.

The LHC will be also a factory of QCD jets with large E_T. Typically for 1 fb^{-1} of data the LHC will produce 10k events which have a jet with an E_T larger than 1 TeV. Understanding QCD at 14 TeV will be one of the first topics at the LHC. Topics such as PDFs, jet shape, underlying event, minimum bias events, α_s extraction, diffraction, BFKL studies, low-x studies and the search for new physics in jet channels, will be addressed. Besides there is a whole b-quark physics program that opens. A dedicated experiment for this program is LHCb, that will select interesting decays for B-hadrons produced in the region of $2 < \eta < 5$ and $p_T > 2$ GeV. The B-cross section for this region is about 200 μbarns. Therefore LHCb will operate at a luminosity of $2 \cdot 10^{32}$cm^{-2}s^{-1} in order to deal with the huge event rate.

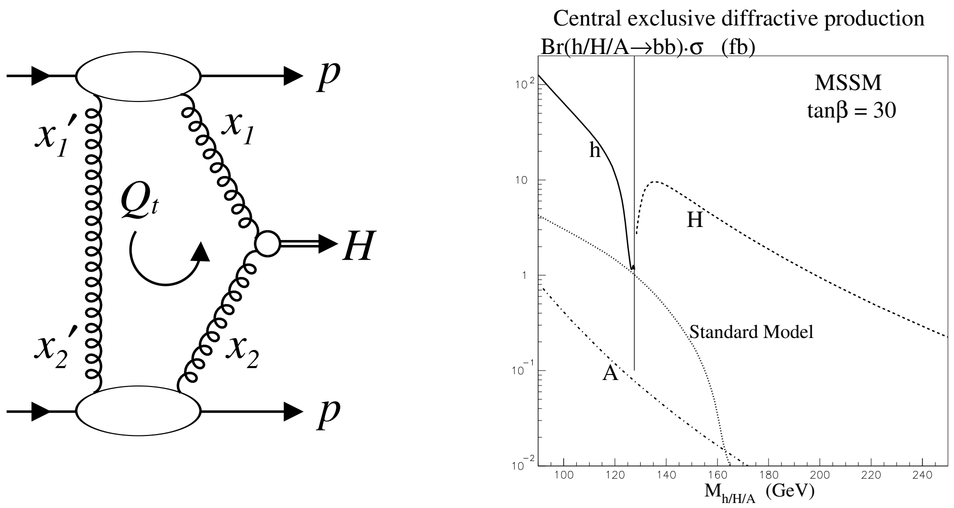

FIGURE 3. (left) Schematic diagram of the central exclusive diffractive production of the Higgs; (right) The cross section times the $b\bar{b}$ branching ratio predicted for central exclusive diffractive production, for the SM and MSSM with $\tan\beta = 30$.

HIGGS SEARCHES AND MEASUREMENTS

The search for the Higgs particle is one of the most important tasks for ATLAS and CMS at the LHC. The mass range to discover the Standard Model Higgs at the LHC ranges from the present negative search limits at LEP (114.4 GeV) till approximately 1 TeV. Table 2 gives an overview on the production modes and decays under study at the LHC. A summary of the significance of the different channels is given in Fig. 2a. For the region around 120 GeV the most promising channels to date are the fusion processes or the decays into two photons. The most prominent decay mode $H \to b\bar{b}$ is not accessible in the inclusive mode: the background is several orders of magnitude larger and the mass resolution in this channel is 10-15%. In the heavy mass range where the channel $H \to ZZ$ opens, this will be the channel with the best sensitivity up to a Higgs mass of about 700 GeV. In particular $H \to ZZ \to 4$ leptons will be the gold plated channel above $M_H = 180$ GeV/c^2.

New studies on the Higgs include $qqH, H \to WW^* \to l\nu l\nu$ and $qqH, H \to \tau\tau \to l + \tau_{jet}, ll$. The significance is found to be larger than 5σ in the range of $140 < M_H < 200$ GeV for 10 fb^{-1}. With these new channels each experiment will be able to discover the Higgs already with a luminosity of 10 fb^{-1} for a low Higgs mass, see Fig. 2b.

New studies also include the search for invisible Higgs decays, ie. the Higgs decays in light neutral sparticles, gravitons,.. At the LHC the channel $qq \to qqH$ can be used, where the two forward jets are tagged in the forward region (roughly $3 < \eta < 5$) and the event contains a large missing E_T.

New channels under study also include the central exclusive production $p + H + p$. This process, shown in Fig. 3, allows, when tagged, to use the protons to reconstruct the (missing) Higgs mass, and has a measurable cross section of a few fb [11]. For the MSSM Higgs and high $\tan\beta$ values the cross sections can however be a factor 20 larger,

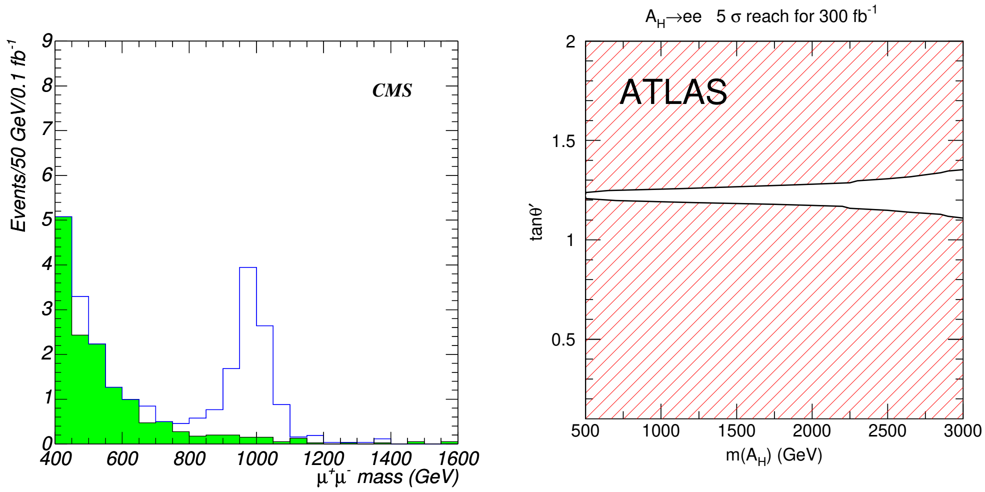

FIGURE 4. (left) A $Z' \rightarrow \mu\mu$ plus background spectrum at generator level, scaled to 100 pb^{-1} equivalent luminosity; (right) The accessible region (shaded) in the channel $A_H \rightarrow e^+e^-$ as a function of mass and the mixing angle $\tan\theta'$

as shown in Fig.3. This channel would allow for the ultimate test on whether the newly discovered particle is a Higgs boson and measure the CP numbers of a low mass Higgs, otherwhise only possible for the $H \rightarrow ZZ$ mode at masses above 200 GeV.

In summary, with the additional channels, the LHC has a 5σ discovery potential over the full range up to 1 TeV already with 10 fb^{-1} of luminosity, as shown in Fig. 2b. Hence LHC will give the final word on the Standard Model Higgs. The luminosity needed to cover this full range could be delivered by 2009 or so.

The next question is how well the Higgs properties can be measured. With the full statistics (300 fb^{-1}) it is expected that the mass can be measured rather precisely: $\Delta M/M = 0.1-1\%$ in a large range. The width becomes directly measurable for Higgses with masses larger than $2 \cdot m_Z$ with a precision of 5-8%. Below one can only get indirect access to the width [10] with a precision of perhaps 20%, but it relies on some assumptions. Cross sections times branching ratios can be measured with a precision in the range of 5-20%. Ratios of couplings can be measured directly to a precision of 10-30% [12]. The Higgs self-coupling measurement will presumably remain elusive at the LHC, perhaps there is a chance at the SLHC with 3000 fb^{-1} to make a measurement with an accuracy of 20-30% [13].

BEYOND THE STANDARD MODEL

We have reasons to believe that New Physics may show up at the TeV scale. These reasons are the stabelizing of the Higgs mass, the hierarchy problem, the unification of the gauge couplings, dark matter, etc. Recent popular contenders are supersymmetry and extra dimensions.

New physics could already show up very early. An example is shown in Fig.4: a mass peak is seen around 1 TeV in the invariant mass of two high E_T muons, due to the presence of a Z'. Only an integrated luminosity of 100 pb^{-1} is necessary for this discovery, ie an amount that could already be available for the pilot run. The main question will be then to disentangle what it is: a Z', a new gauge boson in the context of a Little Higgs model, a RS resonance,...

Fig.4 shows the discovery reach for scenarios with new gauge bosons: the Little Higgs model This model predicts a partner for every particle in the SM, with a mass in the TeV range. The partner of the photon is the A_H and the discovery reach at the LHC is shown in Fig.4 [14]. Note that for some values of the angle θ', which is like the Weinberg angle in this model with extended gauge symmetry group, the cross sections to produce this particle will be too small, and it will go undetected.

The Randall Sundrum (RS) model [15] is a scenario of extra dimensions (ED), with one extra dimension with strong curvature, separating the brane on which we live from the Plank brane where gravity lives. The phenomenology of this model predicts Kaluza-Klein (KK) excitations that appear as resonances in the TeV region and which decay e.g. in muon, electron or photon pairs. The reach for the LHC is shown in Fig.5.

For large EDs [16] the typical signal is a jet plus large missing E_T, carried by a graviton that escapes detection. The reach in the new scale for the discovery of such ED's depends on the number of extra dimensions δ, as is shown in Fig. 5, and extends up to 9 TeV for two extra dimensions.

If the true Planck scale is effectively in the range of a few TeV, one of the possible consequences of large EDs is the production of black holes. These occur when the impact parameter of the partonic collisions is smaller than the Schwarzschild radius in the 4+δ space. The results would be spectacular events, which are mostly spherical and contain many high energy jets, leptons and photons. The rate at the LHC can be as large as one black hole produced per second. Fortunately these black holes live only about 10^{-27} seconds and thus the detector (and the rest of the planet) is quite safe. Beyond the Planck scale even more exotic phenomena may pop up, an example being transplanckian effects [17] through small transverse momentum graviton exchange, which will produce di-jets with an invariant mass in the multi-TeV range.

If supersymmetry is produced in Nature, heavy sparticles produced at the LHC will have many, mostly complicated, decay chains [18]. The LHC will be able to detect supersymmetry for masses of colored particles up to roughly 2.5 TeV, as shown in Fig 6a, from relatively simple signals. To disentangle all information hidden in the LHC data will however be tedious.

To extract quantities, e.g. the masses of sparticles, direct reconstruction methods at the LHC are hampered by the lightest neutral sparticle that escapes detection, at least in R-parity conserving models. Experiments at the LHC therefore typically rely on kinematic end-points of e.g. dilepton spectra from decays to constrain the masses. A full analysis of the benchmark point B'[19] is given in the LHC/ILC report[20] and shows that with 100 fb^{-1} the masses of the sparticles can be reconstructed with a statistical precision of a few %, by combining many endpoint data. These measurements will allow to check whether e.g. the neutralino in the model is consistent with dark matter[19]. Fig. 6 shows the calculated CDM density from the SUSY particle measurements, compared with the measurement of WMAP.

Recently [21] scenarios where proposed where the LHC will detect indeed new particles eg. with a 'SUSY production signature' characterized by 4 leptons and large

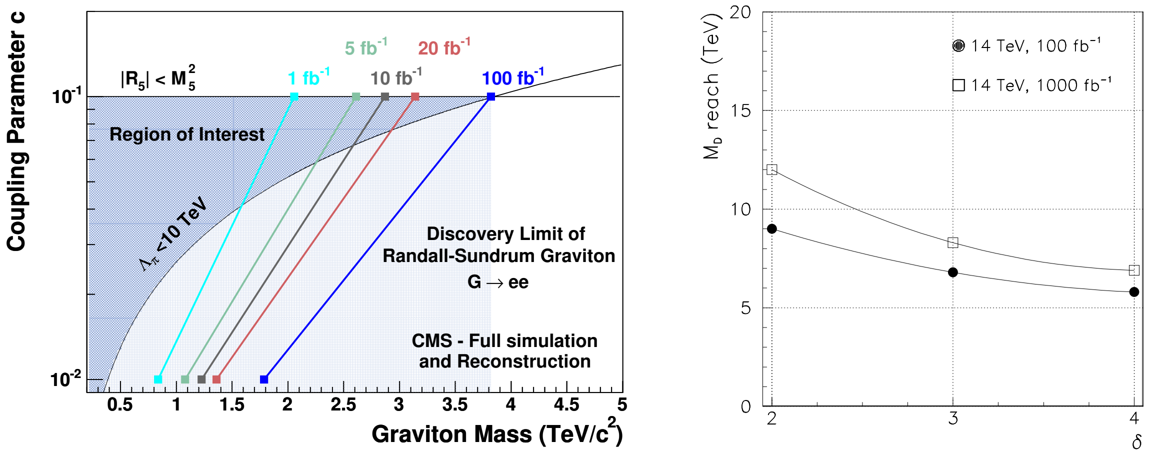

FIGURE 5. (left) Discovery range of CMS for Randal-Sundrum gravitons decaying into electrons; (right) The 5σ discovery limits for the large ED scale M_D for 2,3 and 4 extra dimensions δ, for ATLAS with different luminosities.

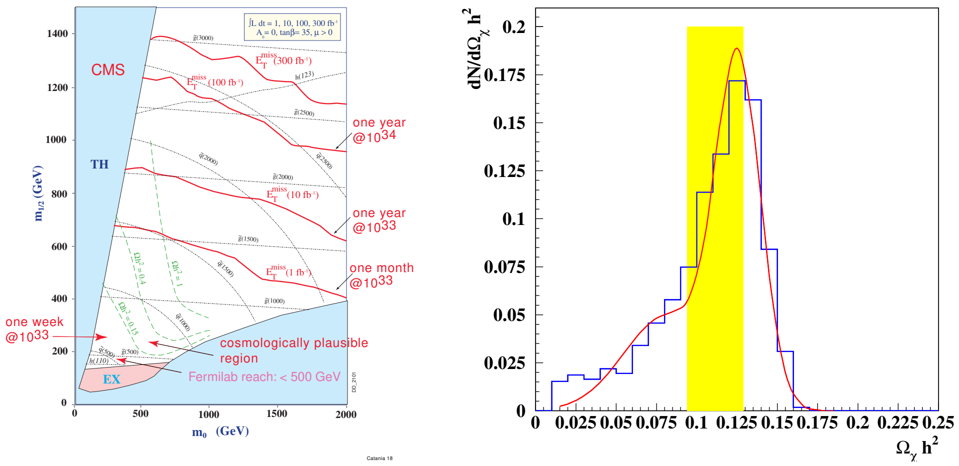

FIGURE 6. (left) Expected 5σ discovery range for E_T^{miss} + jets final states for $\tan\beta = 35$, for various integrated luminosities; (right) Probability density functions for the dark matter density as can be determined at the LHC. The left-hand distribution shows dark matter densities calculated from post-LEP benchmark model B' [19] by first fitting to invariant mass edges with model-independent SUSY particle masses, and then fitting CMSSM parameters to the measured mass distributions, before using those parameter values to calculate $\Omega_\chi h^2$. The range $0.094 < \Omega_\chi h^2 < 0.129$, favoured by WMAP, is shown for comparison.

missing E_T. These new particles belong to a mass spectrum, of which the LHC can measure the coloured members. It looks very much like SUSY, but in fact it is a KK tower pattern from a model with Universal Extra Dimensions (UED). Handles which allow to distinguish this scenario from SUSY are measurements of the spin of the sparticles, the absence of heavy Higgs bosons, and repetition of these patterns at higher energies. An example is shown in Fig.7[23] where a spin asymmetry variable is used is

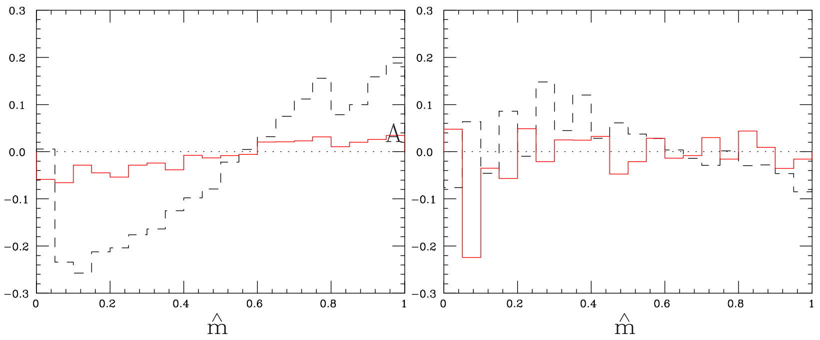

FIGURE 7. Detector-level charge asymmetries with respect to the jet + lepton rescaled invariant mass, for the (a) UED and (b) SUSY mass different mass spectra. Dashed: SUSY. Solid:UED[23].

proposed in [22]. It shows that in some scenarios one can distinguish, but not always. Generally, more variables that are sensitive to the spin of the new particles, are needed.

Finally, considerable attention recently went into new special signatures for the LHC, in particular split supersymmetry and SUSY scenarios with peculiar characteristics of the NLSP: Gravitiono Dark Matter Scenarios and Gauge Mediated SUSY Breaking models.

In split SUSY scenarios, it is assumed that nature is fine tuned and SUSY is broken at some very high scale. The only light particles are the Higgs and the gauginos. As a consequence the gluino can live long: seconds, minutes, or even years! When produced it will colour neutralize with gluons or quarks, forming a R-hadron. Such a hadron will behave as a slow, heavy particle, containing a heavy gluino. It will have unusual interactions with material such as the one of the calorimeters of the detectors and behave somewhere in between a minimum ionizing and hadronic showering particle. To detect it needs to a special analysis of these data.

In some models/phase space of mSUGRA the gravitino is the LSP. Then the NLSP (neutralino, stau lepton) can live long. In case the NLSP is the stau then this will look like a heavy lepton moving through the detector loosing energy on the way. This lepton can actually be stopped in the detector or the walls of the cavern. Then suddenly, some time later, it will decay and release a few hundered GeV of energy. Scenarios are now been worked out which will allow to detect these particles if produced at the LHC[24, 25].

SUMMARY

The LHC is likely to be the first window into the 'new world' at the TeV scale and we all hope this will be a discovery machine. The experiments will be ready to for these discoveries. However the LHC will be also a machine for precision measurements, QCD studies and the study of hot dense matter. It will set the scene of High Energy Physics for many years to come.

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