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NEW PHYSICS IN THE FIRST YEAR OF THE LHC*

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In 2009 the LHC will start its long awaited operation to explore the Tera-scale energy region. The opportunities for new physics discoveries at the LHC are reviewed.

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1. Introduction

The Large Hadron Collider (LHC) [1], is a proton–proton collider being installed in the Large Electron Positron (LEP) tunnel at the CERN Laboratory (the European Laboratory for Particle Physics near Geneva, Switzerland). It will be a unique tool for fundamental physics research and the highest energy accelerator in the world for many years following its completion. The LHC will provide two proton beams, circulating in opposite directions, at an energy of 7 TeV each (center-of-mass $\sqrt{s} = 14$ TeV). These beams upon collision will produce an event rate about 1,000 times higher than that presently achieved at the Tevatron $p\bar{p}$ collider. Collisions at an initial center-of-mass energy of about 10 TeV are expected for fall 2009.

The physics potential of the LHC is unprecedented: it will allow to study directly and in detail the TeV scale region. The LHC is expected to elucidate the electroweak symmetry breaking mechanism (EWSB) and to provide evidence of physics beyond the Standard Model (SM) [2]. The LHC will be also a Standard Model precision measurements instrument, mainly due to the very high event rates as shown in Table I.

The proton beams cross at interaction points along the ring where detectors that measure the particles produced in the collisions are installed. Interaction point 5 hosts the CMS detector. Interaction point 1 is the cavern of the ATLAS experiment. ATLAS and CMS are general multi-purpose

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detectors, with the mission to discover, or exclude within the SM, the Higgs particle in the full range of interest, and thus shed light on the mechanism of electroweak symmetry breaking [3,4]. Furthermore, the LHC will be the first machine that allows to study the Tera-energy scale, and has excellent chances to discover physics beyond the SM. The broad capabilities of CMS and ATLAS are tailored for the detection of these phenomena and particles.

TABLE I

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

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

2. LHC status

The LHC machine has been completed in 2008. The start-up of the LHC on September 10 was really good: the beam was circulating in the machine for 30 minutes within days. However, on September 19 an unfortunate incident happened. An electrical resistive zone built up and led to an electric arc in the cryogenics part in one of the 8 arcs of the LHC. This created a rupture in the helium enclosure of the magnets and led to considerable damage that needs to be repaired: 53 dipoles and 14 quadrupoles (SSS) moved to the surface to be inspected and repaired. To avoid such accidents in future the safety margin of the machine will be increased by a factor 8 to 40 for Helium relief devices. As of December 5 a new schedule has been announced for the LHC. It is an aggressive schedule: it foresees a full cooldown of the LHC by the end of July 2009. This could lead to multi-TeV collisions October–November 2009. Since February 2009 also the energy of the machine has been defined: 5 TeV per beam for the first year. What will be the luminosity? The machine is expected to run from end of 2009 till summer/fall 2010, and allow the experiments to collect 200 pb^{-1}.

3. Searches for new physics at the LHC

One of the most important tasks of the LHC is the search for new physics beyond the Standard Model. New physics is expected — but not guaranteed — around the TeV scale. It can provide answers to questions such as stabilising the Higgs mass, the hierarchy problem, unification of gauge couplings, dark matter... Two popular extensions of the Standard Model are supersymmetry and extra dimensions. However, there is whole plethora of possibilities *e.g.* Little Higgs models, split supersymmetry, new gauge bosons, technicolor, compositness, leptoquarks, unparticles, hidden valley physics, *etc.* All these scenarios, if they are realized in Nature, will leave measurable traces in collisions at the LHC.

Typically many signature channels are used for searches for New Physics. Typical signals are:

- Di-leptons (like sign/same sign).
- Leptons + MET (Missing E_{T}).
- Photons + MET.
- Multi-jet events.
- Mono/Multi-jets +MET (a few 10 to a few 100 GeV).
- Multi jets + leptons + MET.
- b/τ final states.

Also new unusual signatures have been proposed and are searched for such as

- Large displaced vertices.
- Heavy ionising particles (heavy stable charged particles).
- Non-pointing photons.
- Special showers in the calorimeters.
- Unexpected jet structures.
- Very short tracks (stubs).

New physics signatures are being studied for since many years in the LHC experiments. The ATLAS physics TDR is now exactly 10 years old, similarly to many of the CMS analysis notes on the early sensitivity studies. Since then the studies have been done with full simulation and the detectors are closer to the real experimental set-up. Improved signal and backgrounds studies have been performed, using more complex and complete generators, NLO (QCD/EW) corrections and so on. The studies are now much more concentrating on first data luminosities ie 10–100 pb^{-1}. The studies are now also made for detectors with start-up conditions (energy calibration, misalignment of the detectors). Even more than before, special attention to the trigger is given. Data driven methods are used to estimate backgrounds for discoveries. In a few cases, real *in situ* measured background estimates (cosmics, beam halo) are used. The recent information is culminated in the CMS physics TDR [4] and follow up papers, and in the so called CSC notes from ATLAS [5].

4. Early discoveries

Will new discoveries show up easily at the LHC? For most scenarios it will be imperative that the Standard Model processes are well measured and understood at the LHC, before we can go into 'discovery mode' with high confidence. There are, however, exceptions: Fig. 1 shows a di-lepton resonance at a mass of 1 TeV/c^2 showing up in the di-lepton spectrum. The background is Drell–Yan pair production. But the mere fact that it sticks out as a peak and not just a global enhancement of the background is extremely helpful for a fast discovery. If this happens, LHC could be lucky and already see signals of new physics very early on. Such a resonance could

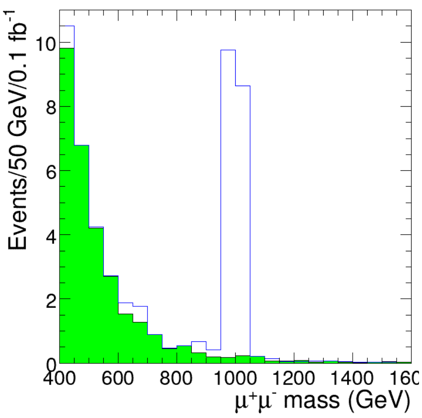

Fig. 1. Histograms of the $\mu^+\mu^-$ invariant mass for 1 TeV/c^2 Z' plus background (open histogram) and for background only (shaded histogram), at the event-generator level. The number of events per bin is normalised to an integrated luminosity of 0.1 fb^{-1}.

be a new gauge boson, or a signal from a variety of new physics models, such as the Little Higgs model, extra dimensions *etc.* So after the discovery a careful characterisation and analysis of these new states, with a lot more integrated luminosity, will be in order.

A huge cross-sections at the LHC is that of QCD di-jet production. *E.g.* for 1 fb^{-1} we expect about 10000 events with transverse energy $E_{\rm T} >$ 1 TeV and about 100 events with $E_{\rm T} > 2$ TeV. Understanding QCD at 14 TeV (or 10 TeV for that matter) will be one of the first physics topics at the LHC. Jan Kwiecinski would have most certainly be eagerly waiting for these data now and would help towards understanding the QCD of it. He will be missed.

QCD topics to be addressed are Parton Density Functions, jet shapes, minimum bias event characteristics, the underlying event, jet shape studies, diffraction, BFKL and low-x studies, and even new physics. Indeed already with first data there is good sensitivity to new physics. This is shown in Fig. 2 for the ratio of di-jets with η smaller and larger than 0.7, as function of the di-jet mass. The effects on the ratio from contact interactions is shown as well as the statistical precision of the measurements for 10 pb^{-1}.

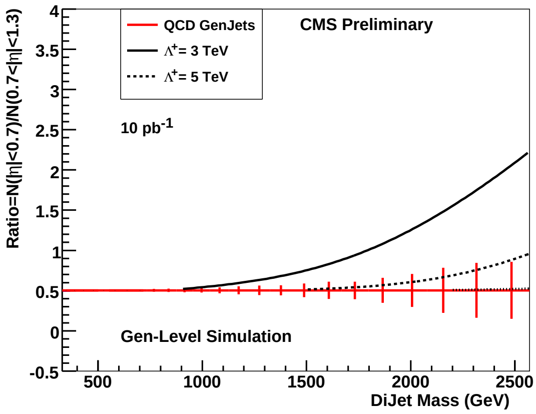

Fig. 2. Ratio of central to forward di-jet events as function of the di-jet invariant mass. The curves show the QCD prediction as well as the prediction for contact interactions for two scales. The error bars show the sensitivity for 10 pb^{-1}.

5. Supersymmetry

Supersymmetry predicts that each known particle has a sparticle partner with the same couplings but spin difference of 1/2, *i.e.* fermions have boson partners and *vice versa*. Low energy supersymmetry leads to expect these particles to be produced at present and future colliders. So far the Tevatron has not found any evidence for sparticles, but since their masses in the most conservative SUSY models are expected — at least in part — to be well below a few TeV, they should show up at the LHC. In fact they could show up very rapidly at the turn on of the machine: cross-sections roughly vary from 100 pb to 10 fb for sparticle masses varying from 500 GeV/c^2 to

1 TeV$/c^2$. Hence about 100000 to 10 sparticles can be produced with 1 fb^{-1} of data. If the sparticle masses are below 1 TeV$/c^2$ then the first signatures could already be observed in the first years (2009, 2010) of LHC operation.

In scenarios with so called R-parity conservation, *i.e.* where the SUSY quantum number is conserved at each vertex, the lightest supersymmetric particle cannot decay any further and is stable. It turns out that this (neutral) weakly interacting particle makes up for a good dark matter candidate if dark matter is due to thermal relics. These particles will be produced in the LHC collisions and typically appear at the end of the decay chain of the heavier sparticles. Although these particles escape detection, like neutrinos, it will be possible to infer some of their properties at the LHC, like a broad measurement of the sparticle mass. The escaping particles will lead to so called missing transverse momentum $E_{\rm T}$. This is a notoriously difficult measurement at the experiment and it will take some time to fully control that. Fig. 3 shows an example of a missing $E_{\rm T}$ spectrum of a SUSY signal with SM backgrounds.

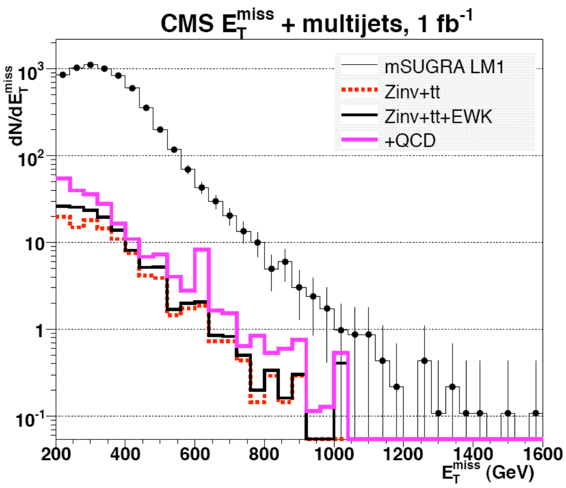

Fig. 3. SUSY (CMS benchmark point LM1) signal and Standard Model background distributions for missing transverse energy.

Besides missing $E_{\rm T}$, the SUSY events will contain generally high $p_{\rm T}$ jets and leptons, likely excess of b-jets and τ-leptons, and will leave clear footprints for their discovery. Obviously the Standard Model processes that could lead to similar final states (perhaps partially due to misidentified objects) will need to be controlled well. The reach in SUSY parameter space that can be covered by the early measurements is typically studied for benchmark scenarios. A recent result is shown in Fig. 4 which displays the reach for different final state signatures, as function of two mSUGRA model parameters, namely the Universal scalar and gaugino masses: m_0 and $m_{1/2}$. The early reach of the LHC will be large, as already anticipated from the cross-sections given above.

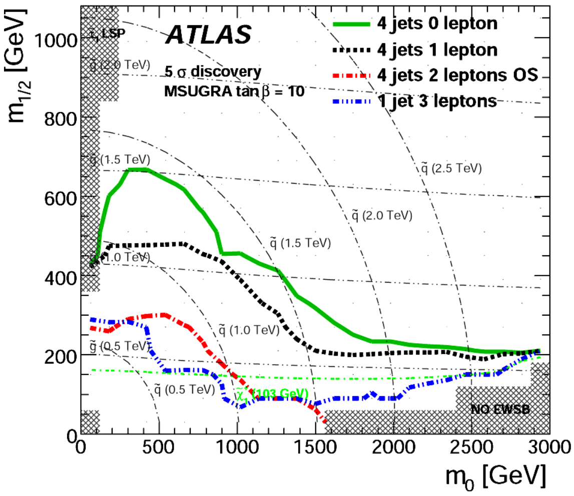

Fig. 4. Reach in Supersymmetry for different event signatures for an integrated luminosity of 0.1 fb^{-1}.

Fig. 5 shows a so called weather forecast for SUSY at the LHC. The dark region at low m_0 shows the "preferred" region based on a fit of present precision data and heavy flavour variables within the constrained MSSM [6]. Clearly this region will be probed already with the first data.

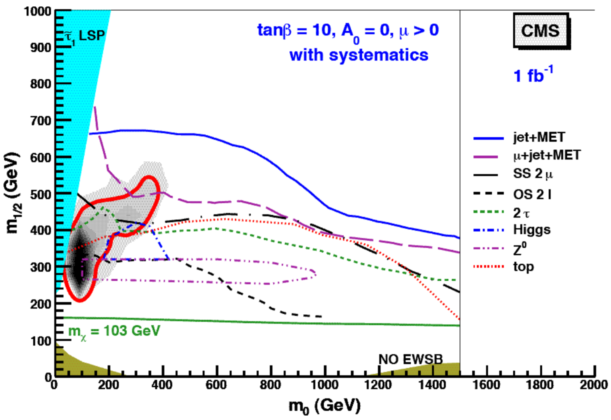

Fig. 5. Regions of the $m_0 - m_{1/2}$ plane showing the CMS reach with 1 fb^{-1}. The dark region represents the most favoured fit to precision data (see text).

As the integrated luminosity will increase, the sensitivity will increase as well. Reversely, when no excess of any of the possible signatures is observed, the LHC will exclude higher and higher masses for *e.g.* gluinos. In constrained models such as mSUGRA this leads to expect that also the lower limit on gaugino masses increases. This is demonstrated in Fig. 6. In the context of such a constrained model, the fact that the LHC would not yet have seen any sign of gluino production with an integrated luminosity of 1fb^{-1} would be rather bad news for a future TeV-scale linear collider.

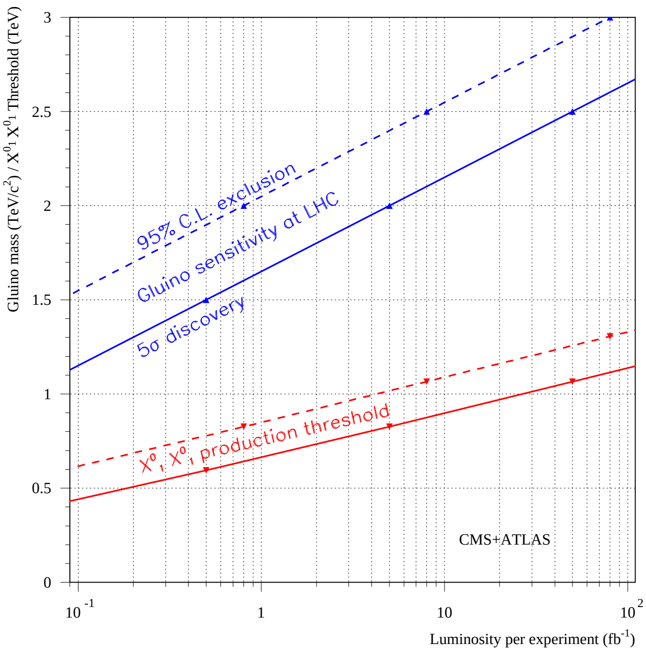

Fig. 6. The reach for gluino detection at the LHC and the corresponding threshold for the production of pairs of the lightest neutralinos at linear colliders, as function of the LHC luminosity per experiment.

The discovery of SUSY via the observation of sparticle candidates would be the first step in a program to unveil the underlying theory. Next a characterisation of the signals and candidate sparticle properties is needed. The decay chains will be analysed in detail and so called kinematic end points of particle distributions will be used to extract information on particle masses. It was shown [7] that for a favourable low mass SUSY point masses can be reconstructed with a precision of a few %, with integrated luminosities of the order of $\mathcal{O}(100)$ fb^{-1}. A general fit of the SUSY model parameters to the measured sparticle masses can be used to extract the dark matter density, to maybe as precise as $\mathcal{O}(10\%)$ in favourable regions of SUSY space.

An important element in deciding whether the new particles one observes are indeed the long-sought sparticles, is the confirmation that they have the right spin number, *e.g.* the partners of the fermions should have spin zero. Accessing spin information is not simple at the LHC, but recently several proposal have emerged [8, 9] and a recent method is reported in [10].

6. Other BSM signatures

As was shown in Section 3, an easy signature would be new gauge bosons, such as Z'. These can be most easily found in the di-lepton final state such as e^+e^- and $\mu^+\mu^-$. Fig. 7 shows the luminosity required for a 5σ discovery of a Z' signal for various Z' models. Already with the data of the first year the LHC should extend the search of the Tevatron. When such a resonance is seen, which is compatible with a Z', the question will arise whether the charged partner, the W', is present as well. Fig. 8 shows the sensitivity for W' detection in the decay channel $W' \to e\nu$. The discovery potential as function of the mass of the boson is as large as for the Z'.

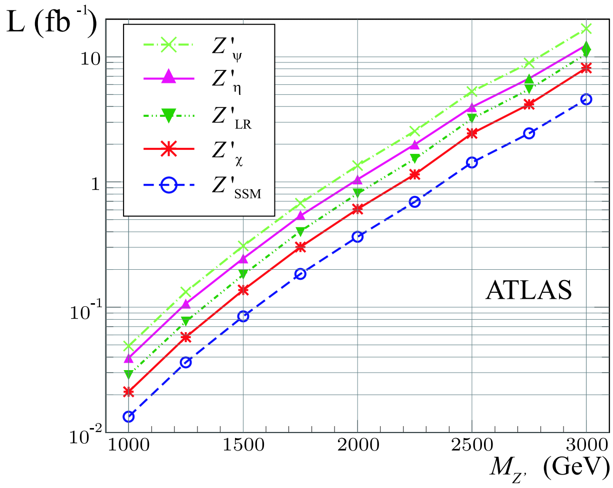

Fig. 7. Luminosity required for a 5σ discovery of a Z' signal for various Z' models.

Recent developments in models point to the prominent role of top production. In particular RS models of extra dimensions, the light SM fermions are anticipated to live near the Planck brane, and heavy (top) near the TeV brane. Hence the RS decays preferably into top pairs (or gauge bosons pairs and ZH). Decaying TeV resonances lead, however, to highly boosted tops and the jets typically appear as one fat jet with internal structure. It is an experimental challenge to detect these top quarks in the data.

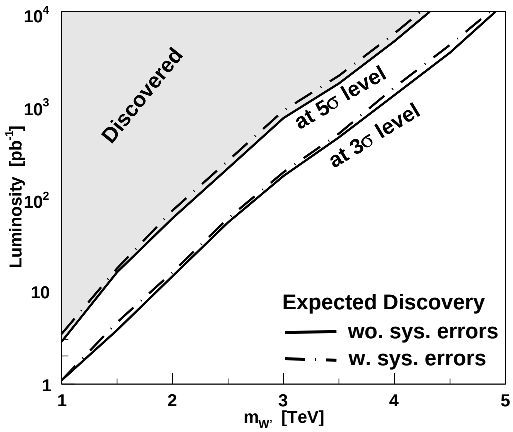

Fig. 8. Luminosity needed to make a 5σ (3σ) discovery of a W' in the decay channel $e\nu$.

Leptoquarks are new particles with lepton and quark quantum numbers. They decay into a quark and lepton. The branching fraction into a final state with a charged lepton is noted by β. Fig. 9 shows the minimum β that can be reached with 5σ as function of the leptoquark mass, for leptoquark decays into electrons and muons.

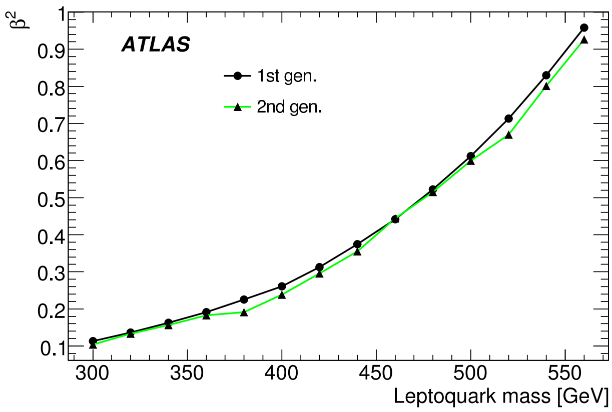

Fig. 9. Leptoquark reach with for first and second generation LQ decays for β^2 versus the LQ mass, for an integrated luminosity of 0.1 fb^{-1}.

Recently the 4-th family got a revival in interest. In fact the LHC could quickly surpass the present Tevatron limits of ($m_{b'} > 199$ GeV) and ($m_{t'} > 311$ GeV). As an example, Fig. 10 shows the sensitivity to b' quark searches in the channel $b' \to tW$. Early data will allow to reach masses of the order of 500 GeV. This by itself is interesting as in the SM the 4-th family quarks should be lighter than about 550 GeV, imposed by unitarity.

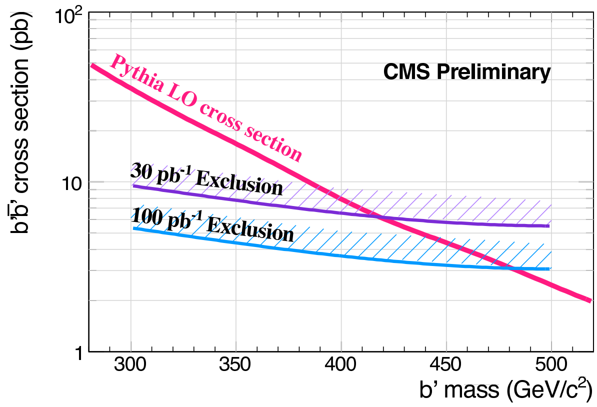

Fig. 10. 95% C.L. exclusion limits for the detection of heavy b' quarks in the tW decay, for 30 and 100 pb^{-1} of integrated luminosity.

Extra dimensions are string theory inspired signatures. They come in a wide variety of models [11]. For several of these models only gravity can move in these extra dimensions, but in TeV^{-1} and UED models more, possibly even all particles can experience more than the traditional 3+1 extra dimensions.

There are several different signatures that the LHC can look for, to find extra dimensions. First the ADD or large extra dimensions can produce spectacular events which consist of one very high energy jet or photon, balanced by a graviton which escapes detection like a neutrino and leaves a large amount of missing E_{T}. The sensitivity for the monojet searches is shown in Fig. 11.

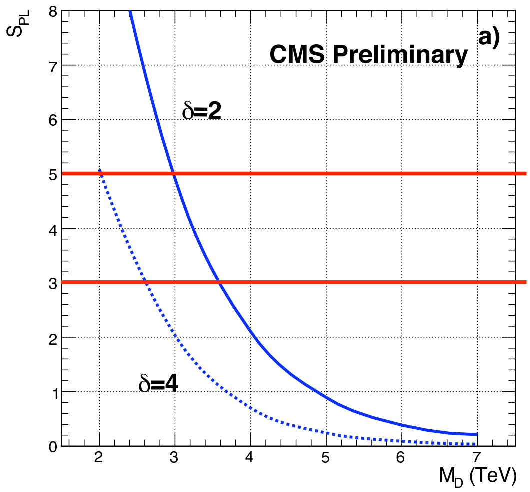

Fig. 11. Sensitivity for a 5σ discovery of monojet events in CMS as function of the mass M_D, for 2 and 4 extra dimensions δ, for an integrated luminosity of 0.1 fb^{-1}.

The Randall–Sundrum (RS) extra dimensions, on the other hand, lead to the production of di-photon and di-lepton spin-2 resonances. The latter will show a signal as shown *e.g.* in Fig. 1. Note that also ADDs can be detected in di-lepton and di-photon spectra looking at angular correlations.

In so called TeV^{-1} extra dimensions also the gauge bosons can go in the extra dimensions. This leads to spin-1 resonances in di-lepton invariant mass distributions. Moreover these states can interfere with the DY background, leading to sometimes very complicated di-lepton spectra.

Finally in universal extra dimensions, all particles can go in the extra dimension(s), leading to a spectrum of Kaluza–Klein states with a partner for each known particle (and possible higher KK states as well). Such a KK particle spectrum looks very much like a SUSY sparticle spectrum. There are some ways of differentiating these two scenarios with data, like production rates and spin measurements [12], which illustrates the importance of having spin sensitive measurements at the LHC.

For all the above scenarios the LHC will be able to discover these phenomena, up to several TeV in the relevant mass or energy scale of the specific model.

An interesting possibility in the ADD and RS models where gravity can go into the extra dimension, is the possible formation of back holes. This may happen as the result of the $4+n$ dimensional Schwarzschild radius which is around 10^{-19} m for a TeV scale black hole. The event signatures could be spectacular, like events with lots of high $E_{\rm T}$ jets and leptons. An example of an event is shown in Fig. 12. The integrated luminosity needed for a 5σ discovery of black holes is shown in Fig. 13. The lifetime of these black holes is very short, roughly 10^{-27} secs, so there should be no fear that these can cause any damage.

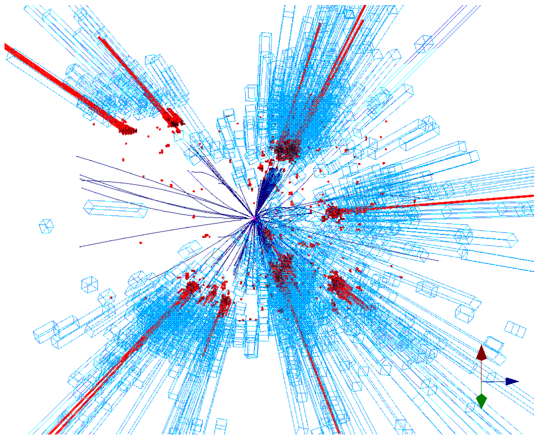

Fig. 12. A black hole, produced in the CMS detector, which evaporates in a large number of jets, high $p_{\rm T}$ leptons, photons *etc.*

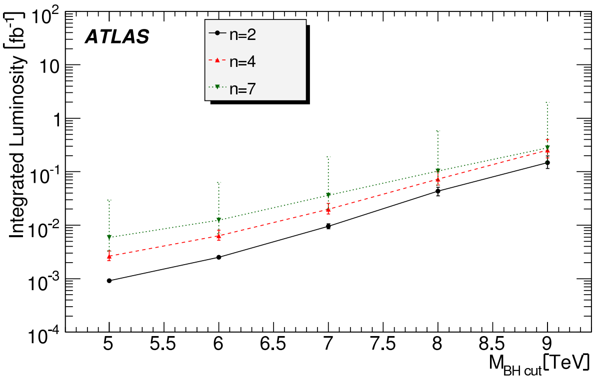

Fig. 13. Integrated luminosity needed for a 5σ discovery of black hole production as function of the black hole mass and number of extra dimensions.

7. New signatures

As said there are many more scenarios for new physics, and so far for all of them, if the signatures are in the domain of a few TeV or less, they can be detected and measured at the LHC.

Recently several scenarios were proposed (or re-discovered by the experiments) that can lead to entirely new types of signatures. These include mostly semi-stable particles either from SUSY models [13, 14], extended SUSY models [15], or as exotic as hidden valley models [16]. In some of these scenarios particles will get stuck in the detector, sit there for a while (seconds, hours, days) and then decay. It is a challenge for the experiments to be ready for these scenarios in particular for the trigger part. However, so far the experiments are found to be up to the challenge... For example Fig. 14 shows the luminosity needed for observing 3 events (in absence of background) for different scenarios of new physics that lead to heavy stable charged particles. This includes KK taus, gluinos, stable stops and GMSB staus. The prospects are excellent! Now let us see what Nature really has in store for us...

8. The role of theory and phenomenology

The LHC will be a precision and hopefully discovery machine, producing no doubt a lot of beautiful measurements. But LHC will need a strong support from theorists. The ultimate precision can only be reached if all theoretical tools are in place in time. Here I will list just a few of the important issues that would benefit from more theoretical development:

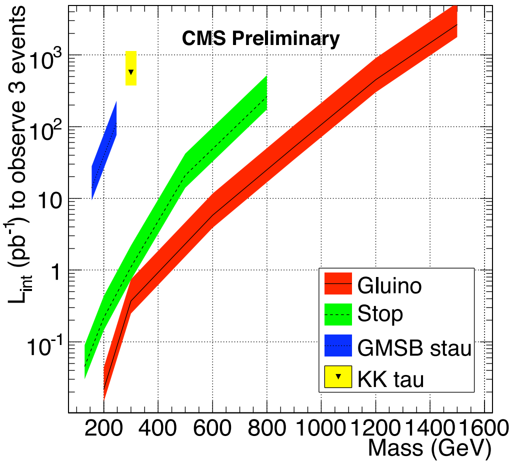

Fig. 14. Luminosity needed for a discovery requiring 3 events (for no background) for various heavy stable charged particles in CMS.

- Precision predictions of standard candle cross-sections (*e.g.* W, Z, Drell–Yan) at 14 TeV.
- Estimates of SM processes that are backgrounds to new physics, and quantifying their uncertainties. Examples: QCD multijets events, W, Z, t ... + njets, diboson production ...
- Tuned Monte Carlo programs for SM processes: ME+parton showers, PDF4MCs.
- Monte Carlo programs for some new physics signals (EDs, new signatures, still many are missing).
- Higher order calculations: both QCD and electroweak corrections.
- New phenomenology/signatures to look for; Experiments have *e.g.* to make sure the trigger is well prepared.
- Discriminating variables to discriminate among different theories: what are the footprints?
- Characterising new physics: *e.g.* getting spin information from particles, CP.
- Prepare tools to interprete the new signals in an as model independent way as possible using tools such as MARMOSET, perhaps others? Resolving degeneracies between possible inverse mapping scenarios.
- Prepare/complete tools to test new model phase space with current constraints.

All these tools will take time to get in place, so we have the prospect of fruitful collaboration between theory and experiment for many years to come.

9. Summary

The first physics at the LHC promises to be very interesting. The hunt for a discoveries will be on soon. New physics signatures could in fact show up very early. Will this be the case at the LHC? In 2009/10 we will get a first glimpse of that.

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