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Early physics with ATLAS and CMS

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Abstract. The status of the CMS and ATLAS experiments is given, as it is end of 2007. A quick tour of possible new physics is presented.

Keywords. Large hadron collider; ATLAS; CMS; Higgs; beyond the Standard Model.

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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 (centre-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 centre-of-mass energy of about 10 TeV are expected for summer/fall 2008.

The physics potential of the LHC is unprecedented: it will allow one 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 1.

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

Process	Events/s	Events/yr
$W \to e\nu$	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 $p_{\mathrm{T}} > 200$ GeV	10^2	10^9

Table 2. Production and decay modes for Higgs particles with mass less than 200 GeV that have been studied at the LHC.

	Production			
Decay	Inclusive	VBF	WH/ZH	ttH
$H \to \gamma\gamma$	yes	yes	yes	yes
$H \to bb$	–	–	yes	yes
$H \to \tau\tau$	–	yes	–	
$H \to WW^{(*)}$	yes	yes	yes	–
$H \to ZZ, Z \to ll$	yes	–	–	–
$H \to Z\gamma, Z \to ll$	low σ	–	–	–

A detailed review of the capabilities of CMS has been recently reported in the so-called physics TDRs [4,5].

2. Searching the Higgs particle

One of the key questions in particle physics is the origin of electroweak symmetry breaking. Eg. why is the photon massless while the Z is very massive? The most elegant explanation within the SM is a Higgs field with at least one scalar particle, the Higgs boson. The LHC search reach has been largely optimized for finding the SM Higgs particle, or excluding its existence. Production mechanisms are: the gg channel, the vector boson fusion channel (VBF), the vector boson associated channel WH/ZH, and the top associated channel ttH. Table 2 shows the possible discovery channels for the Higgs at the LHC in the low mass range ($M_{\mathrm{H}} < 200$ GeV/c^2). In the intermediate and high mass range, in particular, the channels $H \to WW, H \to ZZ$ are important with leptonic decays, but at high mass also with jet decays of the vector bosons.

The decay channels $H \to \gamma\gamma$ and $H \to ZZ$ are the golden decay channels and will allow an extraction of the Higgs mass with a precision ranging from 0.1 to 1%

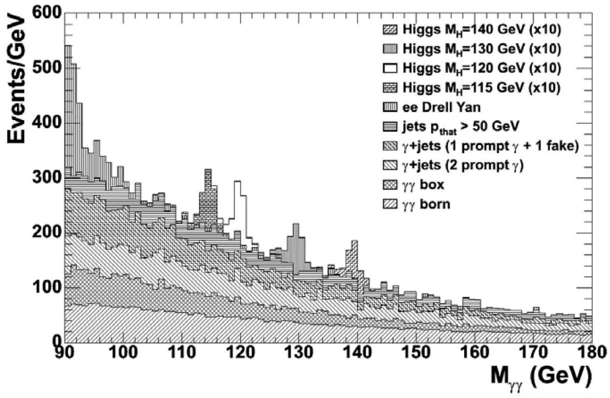

Figure 1. Diphoton invariant mass spectrum after the selection for the cut-based analysis. Events are normalized to an integrated luminosity of 1 fb^{-1} and the Higgs signal, shown for different masses, is scaled by a factor 10.

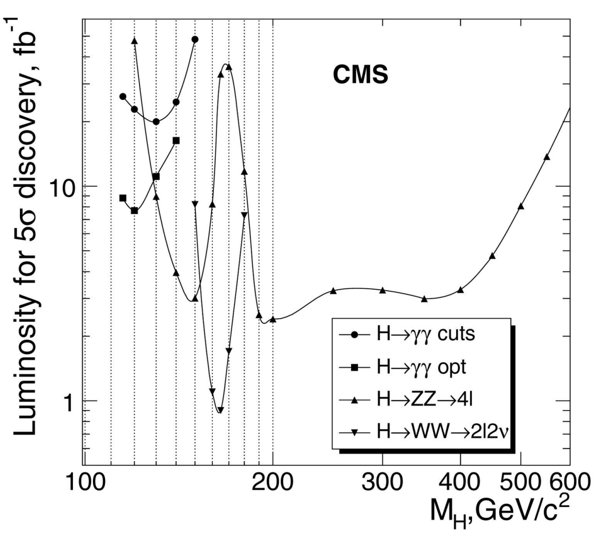

Figure 2. The integrated luminosity needed for the 5σ discovery of the inclusive Higgs boson production $pp \to H + X$ with the Higgs boson decay modes $H \to \gamma\gamma$, $H \to ZZ \to 4l$ and $H \to WW \to 2l2\nu$.

depending on the mass, with high luminosity. The spectrum for the $H \to \gamma\gamma$ decay with backgrounds is shown in figure 1.

The experimental reach of the CMS experiment at the LHC is shown in figure 2 for the most significant channels. A few fb^{-1} will be sufficient to discover the SM Higgs if the mass is around 165 GeV/c^2 or if the mass of the Higgs is between 200 and 400 GeV/c^2. For Higgs masses around 120–130 GeV/c^2 of the order of 10 pb^{-1} will be needed. Reversely figure 3 shows what luminosity is needed to exclude with combined CMS and ATLAS data the Higgs hypothesis as function of mass. Clearly the first fb^{-1} will already be very revealing.

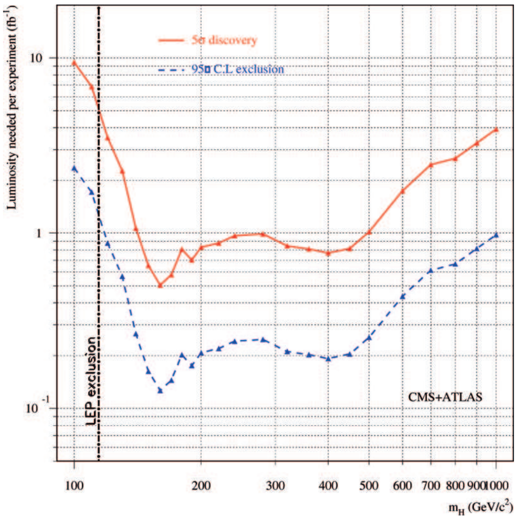

Figure 3. The prospects for discovering a Standard Model Higgs boson in the initial LHC running, as a function of its mass, combining the capabilities of ATLAS and CMS.

Hence the Higgs program at the LHC looks as follows. The SM Higgs will be discovered in the full region up to 1 TeV or its existence will be excluded with $O(10)$ fb^{-1} or less. If no Higgs is observed, other new phenomena in the WW scattering should be observed around 1 TeV. The LHC with full luminosity (100–300 fb^{-1}) will measure the Higgs mass with 0.1–1% precision, the Higgs width, for $m_{\rm H} > 200$ GeV/c^2 with 5–8% precision, the Higgs cross sections times branching ratios with 5–20% precision, ratios of couplings with 10–30% precision, absolute couplings only with additional assumptions, spin information in the ZZ channel for $m_{\rm H} > 200$ GeV/c^2 and CP information from exclusive central production $pp \to pHp$.

The latest studies [4] also have been teaching us that some channels may be more difficult than originally anticipated, e.g. the channel $ttH, H \to bb$ will be difficult to observe even with 60 pb^{-1}.

But in general we will get a pretty good picture of the Higgs at the LHC. Even more detailed information can be extracted from a high energy e^+e^- collider.

3. Beyond the Standard Model

The second most important task 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 stabilizing the Higgs mass, the hierarchy problem, unification gauge couplings, dark matter etc. 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, technicolour, compositness, leptoquarks, unparticles, valley physics, etc. All these scenarios, if they are realized in Nature, will leave measurable traces in collisions at the LHC.

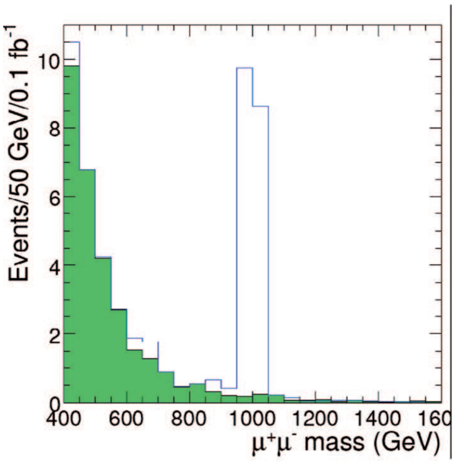

Figure 4. Histograms of the $\mu^+\mu^-$ invariant mass for 1 TeV/c^2 Z' plus background (open histogram) and for background only (shaded histogram), at the event-generator level. The number of events per bin is normalized to an integrated luminosity of 0.1 fb^{-1}.

Will new discoveries show up easily a 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: figure 4 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 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 characterization and analysis of these new states, with a lot more integrated luminosity, will be in order.

3.1 *Supersymmetry*

Supersymmetry predicts that each known particle has an 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 one to expect these particles to be produced at the 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 1,00,000 to 10 sparticles can be produced with 1 fb^{-1} of data. If the sparticle masses are below 1 TeV/c^2 then

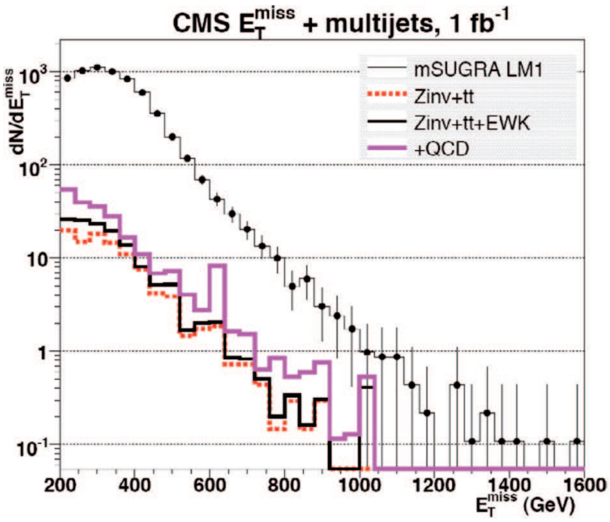

Figure 5. SUSY (CMS benchmark point LM1) signal and Standard Model background distributions for missing transverse energy.

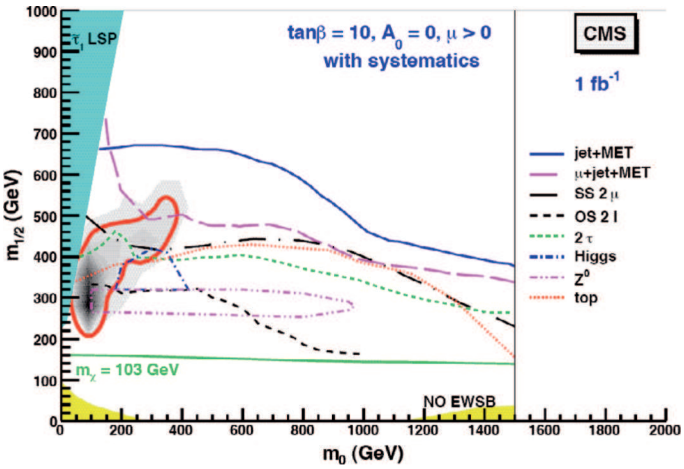

Figure 6. Regions of the m_0–$m_{1/2}$ plane showing the CMS reach with 1 fb^{-1}. The dark region represents the most favoured fit to precision data (see text).

the first signatures could already be observed in the first years (2008, 2009) of LHC operation.

In scenarios with the 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, like a broad measurement of the sparticle mass at the LHC. The escaping particles will lead to the so-called missing transverse momentum E_{T}. This is a notoriously difficult measurement at the experiment and it will take some time to fully control that. Figure 5 shows an example of a missing E_{T} spectrum of a SUSY signal with SM backgrounds.

Besides missing E_{T}, the SUSY events will contain generally high p_{T} jets and leptons, probably 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 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. Figure 6 shows the reach for different final state signatures, as a 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. The dark region at low m_0 shows the 'preferred' region based on a fit of the present precision data and heavy flavour variables within the constrained MSSM [6]. Clearly this region will be probed already with the first data.

Clearly, as the integrated luminosity will increase, the sensitivity will also increase. Reversely, when excess of any of the possible signatures is not observed, the LHC will exclude higher and higher masses, for e.g. gluinos. In constrained models such as mSUGRA, this leads one to expect that the lower limit on gaugino masses also increases. This is demonstrated in figure 7. 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 $1\mathrm{fb}^{-1}$ would be rather bad news for a future TeV-scale linear collider.

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 characterization of the signals and candidate sparticle properties is needed. The decay chains will be analysed in detail and the 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 $O(100)$ 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 may be as precise as $O(10\%)$ 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 proposals have emerged [8,9] and recent progress is reported in [10].

3.2 *Other BSM signatures*

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

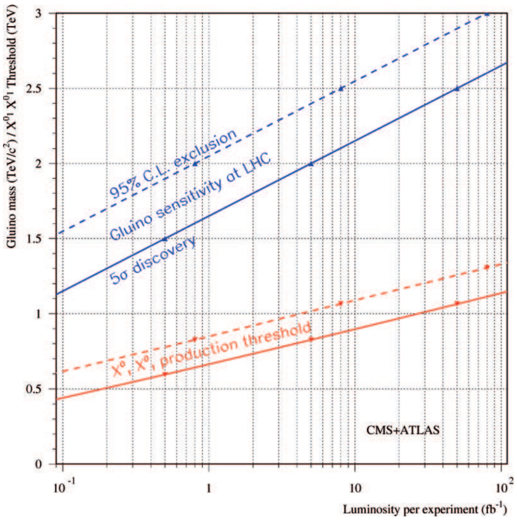

Figure 7. The reach for gluino detection at the LHC and the corresponding threshold for the production of pairs of the lightest neutralinos at linear colliders, as a function of the LHC luminosity per experiment.

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 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 in figure 4. Recently the production of top quarks resonances has been emphasized as a useful signature.

In the 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 black holes. This may happen as a 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 very spheric

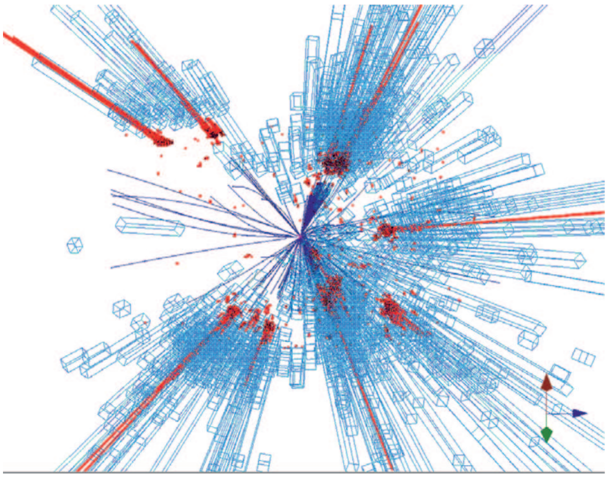

Figure 8. A black hole, produced in the CMS detector, which evaporates in a large number of jets, high p_{T} leptons, photons, etc.

events with lots of high E_{T} jets and leptons. An example of an event is shown in figure 8. The lifetime of these black holes is very short, roughly 10^{-27} s, and so there should be no fear that these can cause any damage.

As said there are many more scenarios for new physics, and all of them, if the signatures are in the domain of a few TeV or less, can be detected and measured at the LHC. More detailed studies can be found in the CMS physics TDR [4].

Recently, several scenarios were proposed (or re-discovered by the experiments) that can lead to entirely new types of signatures. These include mostly semistable 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. Let us see what Nature really has in store for us.

4. 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 developments:

- 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. e.g. QCD multjets events, $W, Z, t.. + n$ jets, 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 to make sure that the trigger is well prepared.
- Discriminating variables to discriminate among different theories: What are the footprints?
- Characterizing new physics: e.g. getting spin information from particles, CP measurements.
- Prepare tools to interpret the new signals in a model-independent way as far as possible using tools such as MARMOSET [17], 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.

5. Summary

In the current schedule, the CMS and ATLAS detectors will be largely ready for the first collisions in summer 2008. The first physics at the LHC promises to be very interesting. The hunt for finding the Higgs will be on but the potential to discover it at an early stage depends strongly on its mass. New physics signatures could also show up very early. Will this be the case at the LHC? In 2008/09 we will get a first glimpse.

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