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THE ATLAS AND CMS EXPERIMENTS AT THE LHC*

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The Large Hadron Collider LHC will start operating, at CERN, Geneva, Switzerland in 2008. CMS and ATLAS are the two general purpose detectors that will collect data at the LHC. A brief overview of the ATLAS and CMS detector is given, followed by the status of the construction, installation and commissioning. Next, a quick tour on what could be the first physics measurements and search results for new physics at the LHC will be given.

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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. In order to support the 7 TeV proton beams, in total 1232 8.4 Tesla superconducting dipoles and 736 quadrupoles are installed in the underground tunnel of 26.6 km circumference.

The dipoles magnets installation in the tunnel has been completed in March 2007. The interconnecting of the magnets and installation of other components was completed early 2008. A first octant sector has been cooled down to 1.9 degrees Kelvin in 2007. First collisions at 14 TeV (or perhaps a bit less in energy) are expected for summer/fall 2008.

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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.

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	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

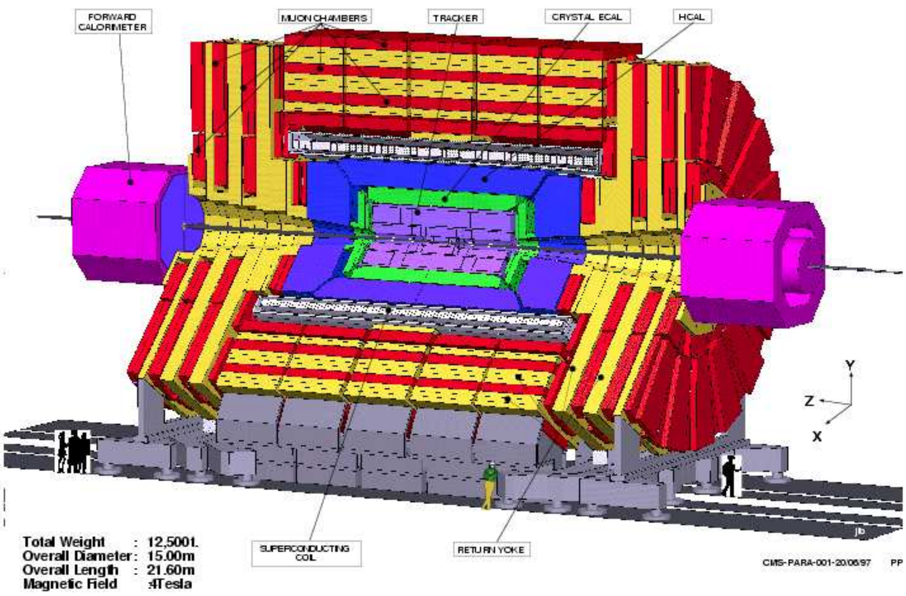

Fig. 1. Three dimensional view of the CMS detector, and its detector components.

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, shown in Fig. 1. Interaction point 1 is the cavern of the ATLAS experiment shown in Fig. 2. ATLAS and CMS are general multi-purpose 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. A detailed review of the capabilities of CMS have been recently reported in the so called Physics TDRs [4, 5].

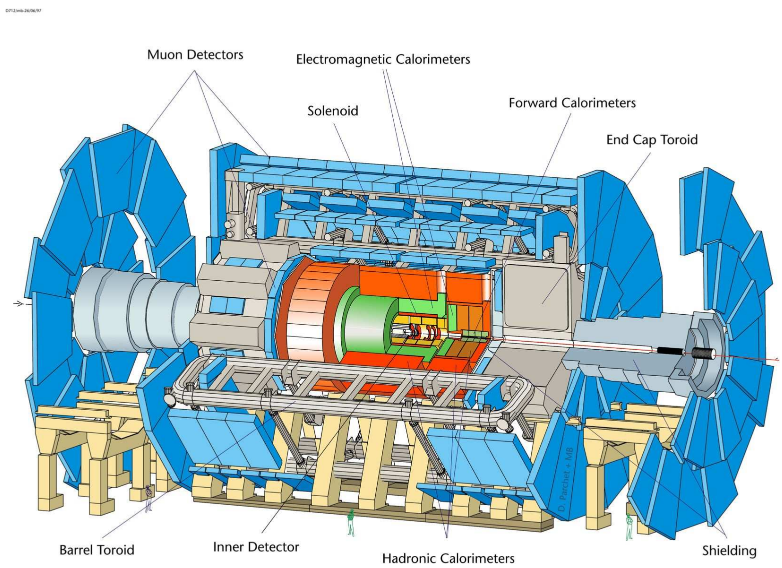

Fig. 2. Three dimensional view of the ATLAS detector, and its detector components.

2. The LHC experiments

Two experiments ATLAS (A Toroidal LHC Apparatus) and CMS (Compact Muon Solenoid) are in the final assembly phase. They will provide efficient and precise measurements of electrons, muons, taus, neutrinos, photons, light flavour jets, b-jets and the missing transverse momentum. A brief summary of the main design choices is given in the following. The main features of the two experiments are summarised in Table II.

TABLE II

Main features of the ATLAS and CMS detectors.

	ATLAS	CMS
Magnet(s)	Air-core toroids + solenoid Calorimeters in field-free region 4 magnets	Solenoid Calorimeters inside field 1 magnet
Tracker	Si pixels and strips TRT → particle identification $B = 2\,\mathrm{T}$ $(\sigma/p_{\mathrm{T}} \sim 3.4 \times 10^{-4} p_{\mathrm{T}}(\mathrm{GeV}) \oplus 0.01)$	Si pixels and strips No particle identification $B = 4\,\mathrm{T}$ $(\sigma/p_{\mathrm{T}} \sim 1.5 \times 10^{-4} p_{\mathrm{T}}(\mathrm{GeV}) \oplus 0.008)$
EM calo	Lead-liquid argon $\sigma/E \sim 10\%/\sqrt{E(\mathrm{GeV})}$ Longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 3-5\%/\sqrt{E(\mathrm{GeV})}$ No longitudinal segmentation
HAD calo	Fe-scintillator + Cu-liquid argon $\geq 10\ \lambda$ $\sigma/E \sim 50\%/\sqrt{E(\mathrm{GeV})} \oplus 0.03$	Brass-scintillator $\geq 7.2\ \lambda$ + tail catcher $\sigma/E \sim 100\%/\sqrt{E(\mathrm{GeV})} \oplus 0.05$
Muons	Chambers in air $\sigma/p_{\mathrm{T}} \sim 7\%$ at 1 TeV spectrometer alone	Chambers in return yoke (Fe) $\sigma/p_{\mathrm{T}} \sim 5\%$ at 1 TeV combining spectrometer tracker

CMS is centred around one magnet, a big solenoid, which contains the inner detector and the calorimeters and provides a magnetic field of 4 T in the inner detector volume. ATLAS has four magnets: a solenoid sitting in front of the electromagnetic calorimeter and producing a field of 2 T in the inner cavity, and external barrel and end-cap air-core toroids. The general structure of the two detectors is determined by this basic design choice.

Both detectors reconstruct the tracks from the interaction vertex using inner detectors built of layers of silicon pixel and silicon strip detectors immersed in the solenoidal magnetic field. These detectors provide a high precision measurement of the vertex position and of the track momenta. While the CMS tracking detector is all silicon, the ATLAS inner detector in addition contains a Transition Radiation Detector (TRT) at larger radii. Excellent momentum resolution is expected for both experiments as shown in Table II. Due to the lower magnetic field the expected momentum resolution in ATLAS is a factor of about two worse than that of CMS. However, the Transition Radiation Detector provides electron/pion separation capabilities. Thanks to silicon strip and pixel detectors, both experiments will be able to perform b quark tagging using impact parameter measurements and the reconstruction of secondary vertices.

The CMS electromagnetic calorimeter is a high-resolution lead tungstate ($PbWO_4$) crystal detector. The ATLAS calorimeter is a lead-liquid argon sampling calorimeter, therefore with a worse intrinsic energy resolution. However, thanks to a very fine lateral and good longitudinal segmentation, the ATLAS calorimeter potentially has more robust particle identification capabilities.

In both experiments the hadronic calorimeters are sampling detectors with scintillator or liquid-argon as active medium. The ATLAS hadronic calorimeter offers a better energy resolution because it is thicker (the CMS hadronic calorimeter is constrained in space as dictated by the external solenoid dimensions) and has a finer sampling. CMS will be using particle flow techniques to improve the resolution of the calorimeter response. For both experiments the calorimetric coverage is extended down to a rapidity of $|\eta| < 4.9$ in order to ensure hermetic coverage for the measurement of missing transverse momentum, and to allow the detection of forward jets.

Finally, the external Muon spectrometer of CMS consists of chamber stations embedded into the saturated iron of the solenoid return yoke, thus achieving a design where a single magnet provides the necessary bending power for precise tracking in the inner detector and in the muon spectrometer. ATLAS has a spectrometer in air, where multiple scattering is minimised, and therefore offers the possibility of good standalone (*i.e.* without the inner detector contribution) muon momentum measurement with three stations of high-precision tracking chambers at the inner and outer radius and in the middle of the air-core toroid. The expected momentum resolution is better than 10% for muons of $p_{\mathrm{T}} = 1\,\mathrm{TeV}/c$ in both experiments.

For CMS essentially all components are lowered and installed except for the pixel detector and the ECAL endcaps. The pixel detector should be installed and be ready for day one, but it is still open if both ECAL endcaps will be ready in time for the first collisions. For ATLAS the last big component, a small wheel, was lowered in the cavern on February 29, 2008. The wall wheels of the muon detector are still being assembled. Both experiments are now in a frantic campaign to commission the detector and get it as operational as possible before the first collisions come. Cosmics are a welcome tool for such studies, and beam halo or beam-gas collisions will take that role by middle of 2008.

The challenges at the LHC are enormous. The total inelastic cross section at the LHC is expected to be close to 80 mb. The LHC will operate at a bunch crossing rate of 40 MHz, but only 80 % of the bunches will be filled. The instantaneous luminosity in the first two years after start-up is expected to be $L = 2\times10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and subsequently upgraded to $L = 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in a second phase. The average number of inelastic non-difractive interactions per bunch crossing are, respectively, 4 and 20 events. These form the so called pile-up interactions, discussed later.

A complex trigger system is needed to reduce the 10^8–10^9 interaction rate, to a data recording rate of 100–200 Hz. CMS and ATLAS have $\sim 10^8$ channels that are checked each bunch crossing. The design data-size per event is about 1 MB. At start-up it is essential to allow for a larger event size, up to 1.5 MB per event, in order to be able to thoroughly study and understand the detector performance.

At the LHC more than 10 PetaBytes of data will be produced per year. These data need to be stored, processed and be accessible from all over the world. LHC experiments count on the computing GRID to play that role. The Grid will consist of more than 100,000 processors, multi-PentaByte disk and tape storage. The Grid is based on a Tier Architecture.

Apart from the general purpose detectors, there are 5 more experiments at the LHC. ALICE is a central detector like ATLAS and CMS, but specialised to study ion-ion collisions. LHCb convers a forward area roughly between 2 and 4 of pseudo-rapidity on one side of the interaction point. LHCb is tailored to study CP violation in the B sector and rare B decays. They may also have a window on direct observation of new physics particularly for signatures with displaced vertices.

These four experiments discussed so far cover the central regions of the 4 interaction points at the LHC. Three additional experiments co-occupy an interaction region with one of these experiments. TOTEM aims to measure the total and elastic cross section, using forward detectors (Roman Pots), in the CMS forward region. LHCf is a zero degree calorimeter located at 147 m away from the ATLAS interaction point, and aims to measure fast forward pizeros, for the tunning of cosmic ray Monte Carlo programs. Finally, the MOEDAL experiment consist of a foil covering LHCb, to detect heavily charged particles, such as monopoles.

The ATLAS and CMS experiments themselves have some extensions planned for the forward region. ATLAS plans Roman Pots in the region around 200 m away from the interaction region (like TOTEM) and some forward tagging detector (LUCID) which could be used to select events with a rapidity gap. CMS plans to install a calorimeter to increase the total acceptance of the detector to 6.5 units in rapidity on both sides. Both experiments also include zero degree calorimeters and are presently evaluating a project for near beam detectors at 420 m away from the interaction point (FP420). The latter would allow to detect exclusive central production of Higgs or other particles, as discussed in the Higgs section.

3. First physics

3.1. Early measurements

According to the schedule of the machine, the first delivered luminosity will be of order of $10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, *i.e.* much lower than the values mentioned before. It is expected that at this point there will be no problem with pile-up, due to the lower bunch currents, and the trigger will have a large acceptance for all medium and high p_{T} processes. Nevertheless Table I shows clearly that even with, say 10 pb^{-1} of integrated luminosity, there will be already a large number of di-jet, W, Z and top quark events.

The first events the LHC experiments will detect are soft hadronic events, sometimes also misnamed minimum bias events. Soft hadronic events are collisions of the type $pp \to X$ with X a final state of hadrons with an average p_{T} of a few hundred MeV/c, up to tails of a few GeV/c. These events saturate the total hadronic cross section, and they come in a number of varieties: elastic events, which will not be seen in the CMS central detector, difractive events, and inelastic non-difractive events. These events will make the bulk of the so called pile-up events when going to higher luminosity. Pile up comes from the fact that the bunch–bunch collision cross section at the LHC is larger that the total hadronic cross section. As a result at a luminosity of *e.g.* $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ on average 3.5 collisions will be produced per bunch–bunch crossing. All these events with different vertices are overlaid and form a background to the hard scattering event of interest. Often the difractive events are neglected in the soft hadronic sample used for pile-up studies. This is a mistake, but the overall effect is not very large since difractive events have less activity in the central detector compared to the non-difractive ones: on average they increase the charged particle density by 10% while they constitute in fact 30–40% of the cross section.

Minimum bias events on the other hand are a detector operational definition for an ensemble of events, introduced by the collider experiments in the 80's. Minimum bias reflects the fact that these events were triggered in a way to have the smallest possible bias in the selection. Typically it required some minimum central and forward activity seen in the detector. Hence these selections were efficient for inclusive non-difractive events, but less so for difractive ones, and zero for elastic events.

Our knowledge on what to expect at the LHC for soft hadronic events is limited and based on phenomenological models and Monte Carlo programs. In fact the predictions for the charged particle density in pp collisions at 14 TeV differ by 20–30% between different models or assumptions, see Fig. 3 Hence probably one of the very first physics papers at the LHC will be the measurement of the charged particle density in soft pp collisions. These are studies that can be performed with the smallest of luminosities, but of course need a reasonably well understood tracker.

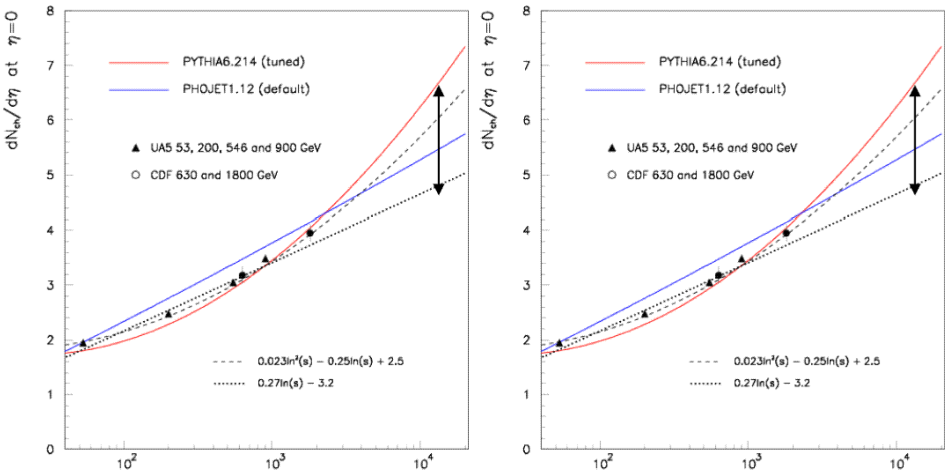

Fig. 3. Expected charged particle density (left) and rapidity distribution of charged particles (right) as predicted by several models for pp collisions at 14 TeV. The precision of pseudo-data is shown as well.

Next we will see the first hard scattering events, in form of jets and di-jet events. Jet cross section measurements are a must for each new collider. The high E_{T} part of the jet spectrum could contain signals for new physics. Even with 10 pb^{-1} we expect already O(100) di-jet events with a jet $E_{\mathrm{T}} > 1$ TeV. An important aspect to study with these first data is the behaviour of the so called underlying event (UE). This is the (somewhat arbitrary) activity in the event which is not associated with the hard scattering process. It contains the break-up of the proton remnants and their colour connections with the central activity, possible (softer) extra scatterings in the event and often also the initial and final state radiation. Tevatron has shown that the limited knowledge of the UE can cause important systematic uncertainties for precisions measurements such as the top mass determination, and this is just one of the reasons to understand the UE better. Again, this can be best studied at the initial luminosity where there will be no pile-up effects.

With time and accumulated luminosity many QCD topics will be studied, such as the aforementioned jet studies, extraction of parton density information, jet shape studies, diffractive studies, BFKL studies and perhaps even the extraction of α_{s}.

3.2. High mass probes

From Table I it can be seen that already with 10 pb^{-1} we expect of the order of $10^6 W$, $10^5 Z$ and 10^4 top quark pairs to be produced. Taken into account projected efficiencies, this leads to event samples of order 10^3

top events. It should be clear that before the LHC experiments can launch into a dedicated search for new physics they will first have to *rediscover the Standard Model*, by measuring the cross sections of these particles and more. It is shown that with perhaps 100 pb^{-1} or less already a good top mass peak can be observed, with a relatively simple analysis requiring 4 jets and a lepton (thus catching the $tt \to qqbl\nu b$ decay). The cross section could be measured with perhaps 20% precision or better. Note that the top cross section is a factor 100 larger than at the Tevatron and the NLO/LO calculation of the cross section is ~ 2.

Next will be the measurement of the more complicated topologies, such as tt+$n$jets, W+$n$jets, Z+$n$jets. These topologies are important background channels for *e.g.* SUSY searches and need therefore to be well measured and characterised.

4. 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 optimised 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 III shows the possible discovery channels for the Higgs at the LHC in the low mass range ($M_H < 200$ 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.

TABLE III

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	—	—	—

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% depending on the mass, with high luminosity. We will discuss in the following a few of the main channels.

4.1. $H \to \gamma\gamma$

The $H \to \gamma\gamma$ decay has been recognised from the very early studies of LHC physics as the most promising inclusive signature for Higgs masses ranging from the LEP limit to approximately 150 GeV/c^2.

The signal would appear as a narrow peak in the invariant mass of a photon pair over a continuum background. This background has two components: the irreducible QCD $\gamma\gamma$ production and a reducible component from γ–jet and jet–jet production where one or both of the hadronic jets are misidentified as a photon. Even after the reducible background is reduced well below the irreducible $\gamma\gamma$ background this channel is quite challenging due to the low branching fraction for photons and to the high QCD cross-section. For an integrated luminosity of 20 fb^{-1} and for a Higgs mass of 120 GeV^2 one expects approximately 300–400 signal events for a background of 7000–8000 events. In order to optimise the signal to background ratio the signal peak has to be as narrow as possible. Two components affect the width of the peak: the energy resolution for the photons and the resolution on the direction of the two photons. The distribution of the photon–photon invariant mass over the background for three Higgs masses is shown in Fig. 4.

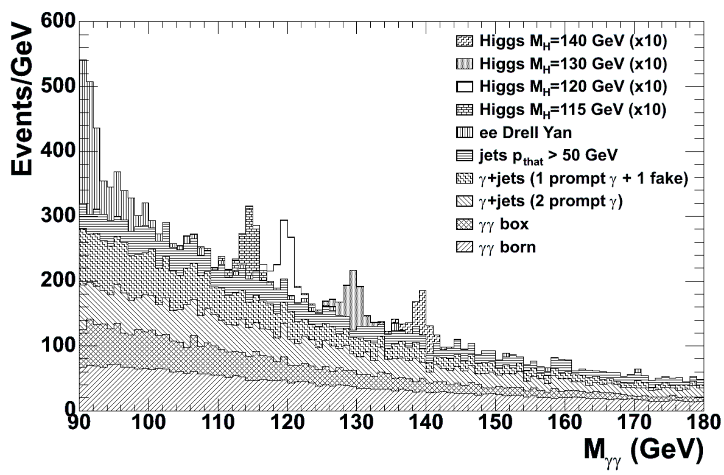

Fig. 4. Diphoton invariant mass spectrum after the selection for the cut-based analysis. Events are normalised to an integrated luminosity of 1fb^{-1} and the Higgs signal, shown for different masses, is scaled by a factor 10.

The background evaluation is performed through the study of the side-bands of the peak, and is, therefore, not affected by uncertainties on the theoretical cross-section. With a simple cut-based analysis, the CMS experiments quotes a 5σ discovery potential for Higgs masses between 115 and $145\,\mathrm{GeV}/c^2$ for an integrated luminosity of $30\,\mathrm{fb}^{-1}$.

A more sophisticated analysis based on neural networks to exploit the kinematic differences in signal and background was performed. An improvement in significance is observed which, under the condition that an adequate understanding of the kinematic distributions for background is achieved, would give a strong hint for Higgs discovery already in the first year of good running. Using this technique the amount of data needed to discover a Higgs particle with mass with $130\,\mathrm{GeV}/c^2$ or less is 8–10 fb^{-1}.

4.2. $H \to ZZ(^*)$ decay

One of the most promising roads towards a discovery at the LHC of the Higgs boson postulated in the SM is via single production followed by a cascade decay into charged leptons, $H \to ZZ^{(*)} \to l^+l^-l^+l^-$. The branching ratio for the $H \to ZZ^{(*)}$ decay SM is sizeable for any m_H value above $130\,\mathrm{GeV/c^2}$. It remains above 2% for $m_H \leq 2 \times M_W$ with a peak above 8% around $m_H \simeq 150\,\mathrm{GeV/c^2}$, and rises to values of 20 to 30% for $m_H \geq 2 \times m_Z$. The Z bosons have a 10% probability to yield a pair of charged leptons. Thus, the decay chain $H \to ZZ^{(*)} \to l^+l^-l^+l^-$ (in short $H \to 4l$) offers a possibly significant and very clean and simple multi-lepton final state signature for the SM Higgs boson at the LHC. The anti-correlation of the Z spin projections in the $H \to ZZ$ decay and the polarisation of each Z boson can be used to constrain, and eventually determine, the spin and CP quantum numbers of the Higgs resonance for Higgs masses larger than $200\,\mathrm{GeV/c^2}$. Furthermore, the $ZZ^{(*)}$ and $WW^{(*)}$ decay modes are related via SU(2) and the combination of channels could allow for cancellation of some systematic uncertainties in a determination of the Higgs coupling. The $H \to ZZ \to ll$jetjet channel is used for heavy Higgses.

CMS has recently revisited this channel in detail in the physics TDR. Backgrounds from $ZZ^{(*)}$, $t\bar{t}$ and $Zb\bar{b}$ associated production are used. The decay channels into 4 electrons, 4 muons and 2 electrons + 2 muons have been studied, all taking into account the present trigger thresholds for multi-lepton channels.

For the 4 electron channel the signal after all cuts is shown in Fig. 5, and for the 4 muon the results are shown in Fig. 6. Finally also the mixed lepton flavour channel $Z \to ee\mu\mu$ has been studied. Fig. 7 shows the result. Including this channel enhances the statistical power by roughly a factor of two. The combined discovery reach of the $H \to ZZ$ channel is shown in Fig. 10.

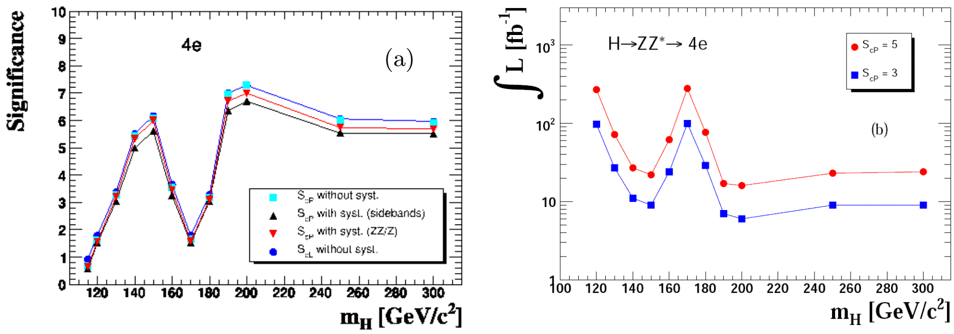

Fig. 5. (a) Significance for an integrated luminosity of 30fb^{-1}as a function of the Higgs boson mass without and with systematics included in both options of $ZZ^{(*)}$ normalisation to the measured sidebands or the measured single Z production cross-section. (b) luminosity needed for a 3σ observation and 5σ discovery with the systematics included using $ZZ^{(*)}$ normalisation to the Z cross-section.

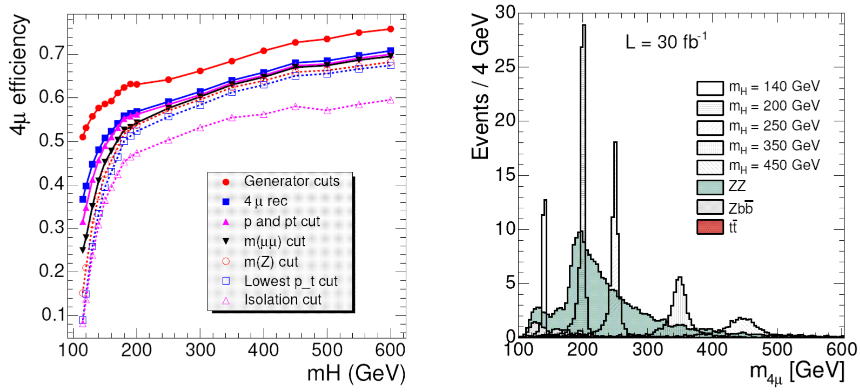

Fig. 6. Left: $H \to \mu\mu$ efficiency *versus* mH after different cuts are — Right: reconstructed four-muon invariant mass distribution, for an integrated luminosity of 30fb^{-1}, for background (shaded histograms) and several Higgs signals (hatched), after the selection criteria are applied.

4.3. $H \to WW(^{*})$ decay

The Higgs decay into two Ws and subsequently into two leptons ($H \to WW \to \ell\nu\ell\nu$) is the discovery channel for Higgs boson masses between $2m_W$ and $2m_Z$ [6]. In this mass range, the Higgs to WW branching ratio is close to one, leading to a large number of events. The signal is characterised by two leptons in the final state with opposite charge, missing energy and no jet. The leptons, either electrons or muons, are required to have $p_{\rm T} > 20$ GeV$/c$ and $|\eta| < 2$. However, since no narrow mass peak can be reconstructed, good

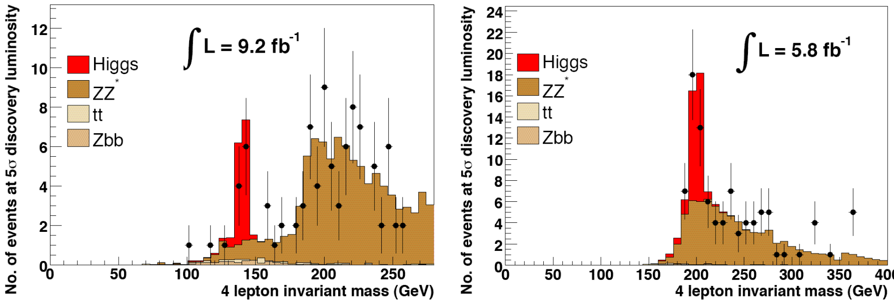

Fig. 7. Number of expected events for signal and background for an integrated luminosity corresponding to a discovery significance of 5σ, for Higgs boson masses of 140 and 200 GeVc^2. The results of a simulated experiment are also shown to illustrate the statistical power of the analysis and the determination of the background normalisation from data.

understanding of the background together with a high signal to background ratio is needed. The most important backgrounds, which give a similar signature as the signal are the continuum WW production and the $t\bar{t}$ and tWb production. To reduce these backgrounds, one has to require a small opening angle between the leptons in the transverse plane and apply a jet veto.

The selection is optimised for a Higgs mass of 165 GeV$/c^2$, where we have the largest sensitivity for a discovery. A dedicated optimisation for the $e^+e^-\nu\nu$ final state in the mass range of $130 \leq M_H \leq 150$ GeV$/c^2$ has been performed. An example signal for 10 b^{-1} is shown in Fig. 8. It turns out that this channel has the highest sensitivity, if the Higgs is close in mass to the WW threshold. A discovery is possible with 1 fb^{-1}if the mass of the Higgs is around 160 GeVc^2.

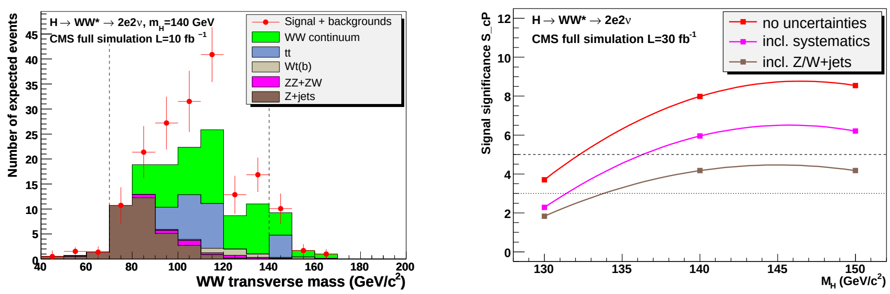

Fig. 8. Left: the reconstructed WW transverse mass for a 140 GeVc^2 Higgs signal selection with 10fb^{-1}. The dashed lines show the window of events entering in the signal significance. Right: the signal significance as function of the Standard Model Higgs mass and for an integrated luminosity of 30fb^{-1}.

4.4. Exclusive Higgs production

Recently [7, 8] the possibility to produce a Higgs particle in a rather clean environment at the LHC has been extensively discussed: the central exclusive production (CEP). The diagram to produce the Higgs is shown in Fig. 9 $pp \to pHp$. The protons remain intact and can be detected by near-beam detectors. Presently the LHC experiments are not equipped to detect these protons but the FP420 R&D collaboration is completing its proposal to instrument the region at 420 m away from the interaction region [9]. With these detectors the protons of CEP Higgs particles in the mass range of $70 < M_H < 150\,\mathrm{GeV}/c^2$ can be detected.

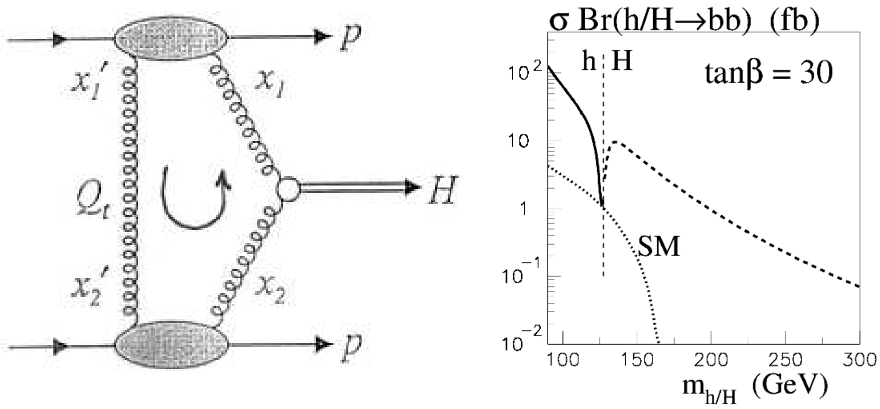

Fig. 9. Left: Diagram for the CEP process. Right: Cross-section for SM and MSSM exclusive Higgs production.

These protons allow to measure the mass of the centrally produced system with a precision of 1–2 GeV/c^2 via the missing mass to the incoming beam particles: $M^2 = (p_1 + p_2 - p'_1 - p'_2)^2$ with (p_1, p_2) and (p'_1, p'_2) the 4-vectors of the incoming and outgoing protons respectively. In fact by detecting and tagging the process through the outgoing protons, it is possible to tag Higgs production regardless of the decay product, similar to HZ production at a linear e^+e^- collider. Moreover, the CEP requirement suppresses the QCD backgrounds processes such as exclusive $gg \to bb$ in leading order. This lead to the promise that the decay mode $H \to bb$ could be observed above background in CEP. Furthermore, to a very good approximation the central system is constrained to be a colour singlet, $J_Z = 0$ state, and, due to the strongly constraint three particle final state, the measurement of azimuthal correlations between the two scattered protons will allow to determine the CP quantum numbers of the produced central system [10].

The downside of this process is that the cross section is relative small as shown in Fig. 9: a few fb for the SM Higgs. The process can however be by a factor 10 or more larger in the MSSM for relatively high tanβ as shown in Fig. 9 and recently also discussed in [11]. Recent studies [12] show that the Standard Model Higgs measurement will be challenging in CEP for the $H \to bb$ mode. However, the decay mode $H \to WW^{(*)}$ is measurable for masses up to about 140 GeV/c^2 [13]. About 10 events are expected for 30 fb^{-1} after trigger and detector cuts, with essentially no background.

4.5. Higgs summary

The experimental reach of the CMS experiment at the LHC is shown in Fig. 10 for the most significant channels. A few fb^{-1} will be sufficient to discover the SM Higgs if the mass is around 165 GeVc^2 or if the mass of the Higgs is between 200 and 400 GeVc^2. For Higgs masses around 120–130 GeVc^2 of the order of 10 pb^{-1} will be needed. Reversely Fig. 11 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.

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 will measure with full luminosity (100–300 fb^{-1}):

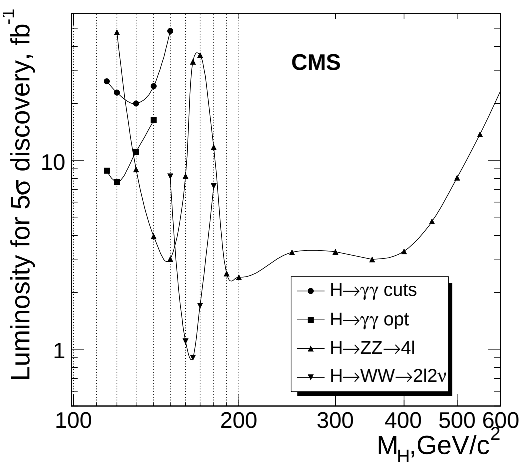

Fig. 10. The integrated luminosity needed for the 5σ discovery of the inclusive Higgs boson production $pp \to H + X$ with the Higgs boson decay modes $H \to \gamma\gamma$, $H \to ZZ \to 4l$, and $H \to WW \to 2l2\nu$.

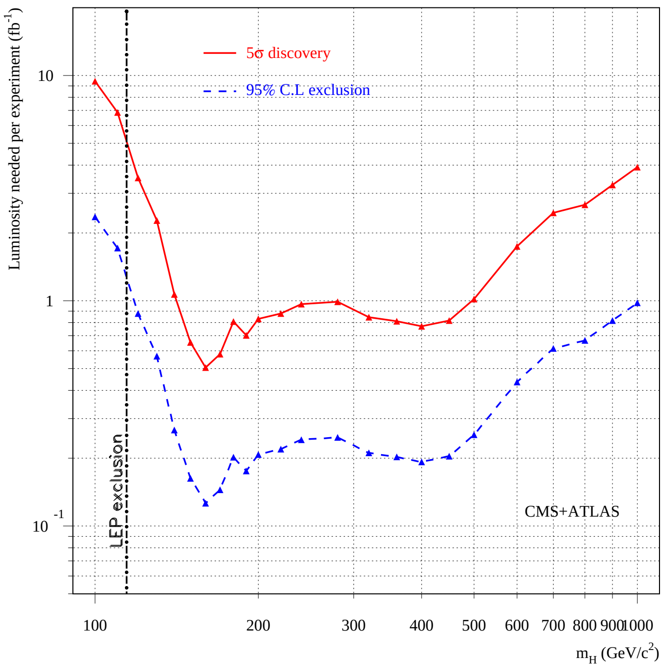

Fig. 11. The prospects for discovering a Standard Model Higgs boson in initial LHC running, as a function of its mass, combining the capabilities of ATLASand CMS.

- The Higgs mass with 0.1–1% precision,
- the Higgs width, for $m_H > 200\,\mathrm{GeV}/c^2$ 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 $m_H > 200\,\mathrm{GeV}/c^2$,
- 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. *Eg.* the channel $ttH, H \to bb$ will be difficult to observe even with $60\,\mathrm{pb}^{-1}$.

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.

5. 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 .... 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, valley physics, *etc.* All these scenarios, if they are realized in Nature, will leave measurable traces in collisions at the LHC.

Will new discoveries show up easily a the LHC? As said before 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. 12 shows a di-lepton resonance at a mass of $1\,\mathrm{TeV}/c^2$ showing up in the di-lepton spectrum. The background (that will need to be understood) 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. Moreover, several cross check channels exist and can be inspected for similar signals. If this happens, LHC could be lucky and already see signals of new physics very early on. Such a resonance could be a new

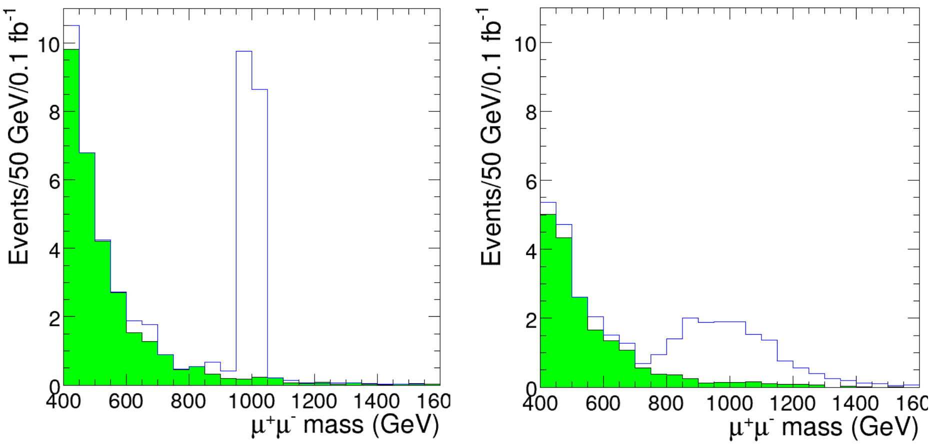

Fig. 12. Histograms of the $\mu^+\mu^-$ invariant mass for $1\,\mathrm{TeV}/c^2$ Z' plus background (open histogram) and for background only (shaded histogram), at the event-generator level (left) and for events selected by the triggers and reconstructed assuming the "first data" misalignment scenario (right). The number of events per bin is normalised to an integrated luminosity of $0.1\mathrm{fb}^{-1}$.

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.

5.1. Supersymmetry

Supersymmetry predicts that each known particle has a sparticle partner with the same couplings but spin difference of 1/2, ie 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 GeVc^2 to 1 TeV$/c^2$. Hence about 100 000 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 (2008, 2009) of LHC operation.

In scenarios with so called R-parity conservation, ie 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

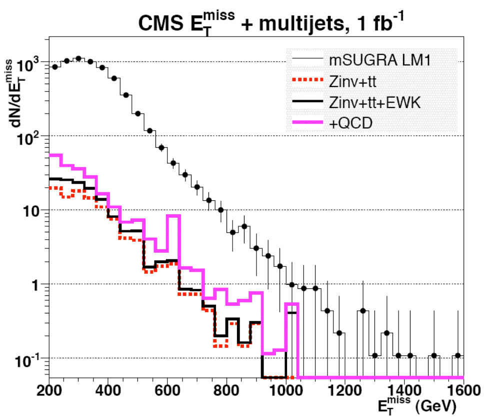

Fig. 13. SUSY (CMS benchmark point LM1) signal and Standard Model background distributions for missing transverse energy.

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. 13 show an example of an $E_{\rm T}$ spectrum of a SUSY signal with SM backgrounds.

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 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. Fig. 14 shows that 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. 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 [14]. Clearly this region will be probed already with the first data.

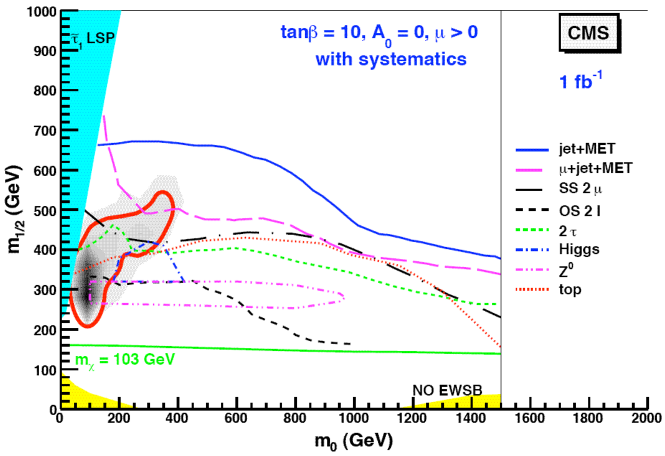

Fig. 14. Regions of the $m_0 - m_{1/2}$ plane showing the CMS reach with 1 fb^{-1}. The dark region represents the most favoured fit to precision data (see text).

Clearly 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. 15. 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.

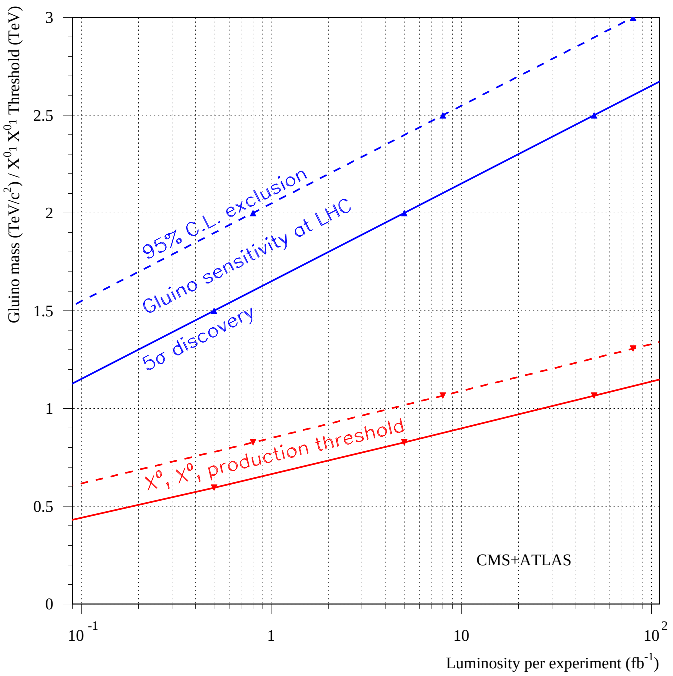

Fig. 15. The reach for gluino detection at the LHC and the corresponding threshold for the production of pairs of the lightest neutralinos at linear colliders, as function of the LHC luminosity per experiment.

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 [15] that for a favourable low mass SUSY point masses can be reconstructed with a precision of a few %, with integrated luminosities of order of O(100) pb^{-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 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 a the LHC, but recently several proposal have emerged [16, 17] and recent progress is reported in [18].

5.2. Other BSM signatures

Extra dimensions are string theory inspired signatures. They come in a wide variety of models [19]. 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 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. 12. Recently also the production of top quarks resonances has been emphasised as a useful signature.

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 [20], 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 very spheric events with lots of high E_{T} jets and leptons. An example of an event is shown in Fig. 16. 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.

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. More detailed studies can be found in the CMS physics TDR [4].

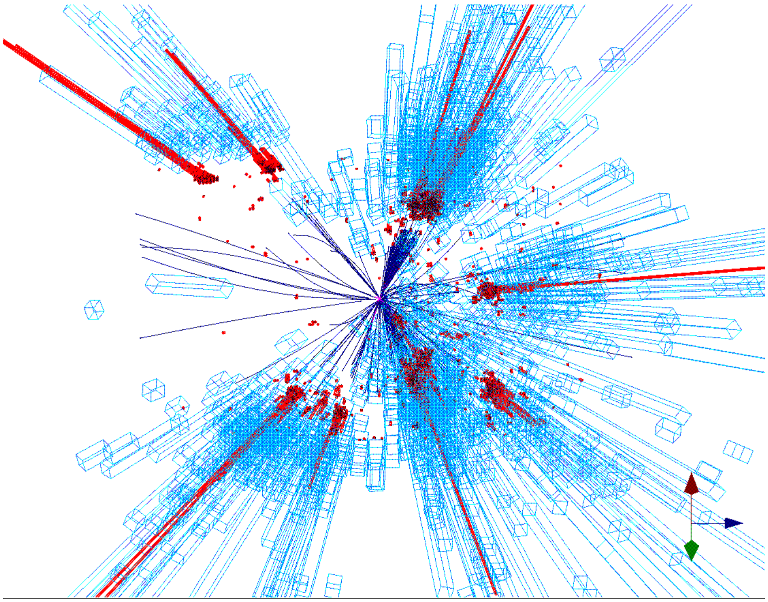

Fig. 16. A black hole, produced in the CMS detector, which evaporates in a large number of jets, high p_{T} leptons, photons *etc.*

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 [21, 22], extended SUSY models [23], or as exotic as hidden valley models [24]. 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 .... .

6. 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. After a dedicated period of detector commissioning the first Standard Model "rediscovery" measurements will be made, in terms of jets, vector bosons and top quarks. 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 finally know!

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