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CMS - Concept and Physics Potential

C.-E. Wulz

*Institut für Hochenergiephysik der Österreichischen Akademie der Wissenschaften,
Nikolsdorfergasse 18, A-1050 Vienna, Austria*

CMS Collaboration

Abstract

CMS (Compact Muon Solenoid) will be one of two general purpose detectors at the CERN Large Hadron Collider. Its main feature is a strong solenoidal magnetic field ensuring high momentum resolution for charged particles. The detector consists of an inner tracker with an embedded pixel detector, a crystal electromagnetic calorimeter, a copper-scintillator hadron calorimeter and a dual muon system made up of tracking chambers and special trigger chambers. Forward calorimetry is also foreseen.

The discovery potential of CMS for the Standard Model Higgs, the SUSY Higgses and other supersymmetric particles is presented.

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CMS Concept and Physics Potential

Claudia-Elisabeth Wulz

*Institut für Hochenergiephysik, Österreichische Akademie der Wissenschaften,
Nikolsdorfergasse 18, A-1050 Vienna, Austria*

Abstract. CMS (Compact Muon Solenoid) will be one of two general purpose detectors at the CERN Large Hadron Collider. Its main feature is a strong solenoidal magnetic field ensuring high momentum resolution for charged particles. The detector consists of an inner tracker with an embedded pixel detector, a crystal electromagnetic calorimeter, a copper-scintillator hadron calorimeter and a dual muon system made up of tracking chambers and special trigger chambers. Forward calorimetry is also foreseen.

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FIGURE 1. General view of CMS.

INTRODUCTION

CMS (Compact Muon Solenoid) is a general purpose experiment designed to explore physics at the planned Large Hadron Collider (LHC) at CERN. It is expected to go into operation in 2005. Proton-proton collisions as well as heavy ion collisions will be available. More than 150 institutions with 1700 physicists and engineers are presently taking part in the collaboration.

The design concept of CMS was first presented at the LHC Workshop at Aachen in 1990 [1]. It is based on a strong solenoidal magnetic field of 4 Tesla generated by a superconducting coil. The inner tracking system, the electromagnetic calorimeter, and the hadron calorimeter with the exception of a tail catcher in the central region, are inside the magnetic field volume. The muon chambers are embedded in the return iron yoke. Forward and Very Forward Calorimetry complete the apparatus in order to detect non-interacting particles.

A perspective view of CMS is shown in Fig. 1.

DETECTOR SETUP

Following the completion of the Technical Design Reports [2–6] of all subdetectors the CMS layout has been essentially finalized in April 1998.

The long superconducting coil is the heart of CMS. It provides a solenoidal field of 4 Tesla parallel to the beam direction. It is essential that the coil be completed before most other detector parts. The design is well advanced and real construction has started. The finished magnet is expected to be tested in 2003.

Inner Tracking

The active volume of the CMS inner tracker is a cylinder with a radius of 115 cm and a length of 270 cm on each side of the interaction point. Three different detectors well suited to the high, medium and low occupancy regions have been chosen to satisfy the stringent resolution and granularity requirements: a silicon pixel detector up to a radius of approximately 20 cm, a silicon strip detector in the region between 20 and 60 cm, and Micro Strip Gas Chambers (MSGC's) from 70 to 120 cm. The setup is shown in Fig. 2. The tracker geometry has been chosen such that typically 13 high resolution measurement planes for high- p_T tracks are available up to $|\eta| \approx 2$, gradually falling off to a minimum of 8 planes at $|\eta| \approx 2.5$. Overall, the silicon and MSGC trackers consist of more than ten thousand independent detector modules instrumented with 12×10^6 channels. The occupancy of each channel will be about 1 to 2 percent at high luminosity.

High- p_T isolated tracks are reconstructed with a transverse momentum resolution of better than $\delta p_T/p_T \approx (15p_T \oplus 0.5)\%$, with p_T in TeV, in the central region of $|\eta| \leq 1.6$, degrading to $\delta p_T/p_T \approx (60p_T \oplus 0.5)\%$ as $|\eta|$ approaches 2.5.

FIGURE 2. The CMS Inner Tracker.

Electromagnetic Calorimeter

CMS has chosen an electromagnetic calorimeter made out of scintillating lead tungstate crystals (PbWO_4) because it offers the best prospects of identifying and measuring precisely the energies of photons and electrons in a hostile environment with a magnetic field of 4 Tesla, a time of 25 ns between bunch crossings and radiation doses of 1 to 2 kGy per year at maximum LHC luminosity. The choice was based on the considerations that PbWO_4 has a short radiation length of 0.89 cm and Molière radius of 2.19 cm and a short light decay time. The initial drawback of low light yield has been overcome by progress in crystal growth and through the development of large-area silicon avalanche photodiodes. The geometrical coverage extends to $|\eta| = 3$. Precision energy measurement of photons and electrons will be carried out to $|\eta| = 2.63$. A total thickness of about 26 radiation lengths at $|\eta| = 0$ is required to limit the longitudinal shower leakage of high-energy electromagnetic showers to a reasonable level. This corresponds to a crystal length of 23 cm in the barrel region. In the endcap region a $\gamma - \pi_0$ separating preshower detector corresponding to $3 X_0$ of lead allows the use of slightly shorter crystals.

For the energy range of about 25 to 500 GeV, typical for photons from the $H \rightarrow \gamma\gamma$ decay, the energy resolution can be parametrized as:

$$(\sigma/E)^2 = (a/\sqrt{E})^2 + (\sigma_n/E)^2 + c^2$$

where a is the stochastic term, σ_n the noise, and c the constant term. Fig. 3 shows the different contributions to the energy resolution. Depending on luminosity a

FIGURE 3. Energy resolution of the CMS electromagnetic calorimeter.

mass resolution of 650 to 700 MeV can be obtained for a 100 GeV Standard Model Higgs decaying into two photons.

Hadron Calorimeter

Together with the electromagnetic calorimeter the hadron calorimeter will be essential to measure jets and missing energy, crucial for the discovery of many new particles or phenomena. The targeted energy resolution is:

$$\sigma/E = 65\%/\sqrt{E} \oplus 5\% \text{ (E in GeV)}.$$

In addition to the barrel and endcap hadron calorimeters (HB, HE) extending to $|\eta| \approx 3$ a separate forward calorimeter (HF) covering the region $3 < |\eta| < 5$ is foreseen to maximize hermeticity (Fig. 4). HB and HE are sampling calorimeters consisting of 4 mm thick plastic scintillator tiles read out with wavelength-shifting plastic fibres inserted between copper plates. The barrel hadron calorimeter has only 5.15 nuclear interaction lengths at $\eta = 0$. To ensure adequate sampling depth the first muon absorber layer is instrumented with scintillator tiles to form a tail catcher.

The HF calorimeter which has to withstand high radiation doses uses quartz fibres as the active medium, embedded in a copper absorber matrix. It is not only important for the measurement of missing energy as required for example in Standard Model and SUSY Higgs searches or top quark physics, but also for forward jet detection needed in the search for the heavy Higgs boson in the TeV mass region.

In order to get an idea of the physics performance the process $t \rightarrow Wb$ with W decaying into jets was simulated. The obtained dijet mass resolution was 12 GeV with pileup and 8 GeV without.

FIGURE 4. rz-projection of CMS.

Muon System

In the barrel region the muon system consists of drift chambers with bunch crossing identification capability (DTBX) to reconstruct muon tracks and of resistive plate chambers (RPC) to detect muon hits for trigger purposes. In the forward region the cathode strip chambers (CSC) perform the tasks of reconstructing the tracks. RPC's are also available.

The chambers are arranged in four stations interleaved with the iron return yoke plates as shown in Fig. 4. They are arranged in concentric cylinders around the beam line in the barrel region, and in disks perpendicular to the beam in the endcaps. The momentum resolution of charged tracks for the muon system alone and combined with the inner tracker at $\eta = 0.1$ is shown in Fig. 5.

Trigger and Data Acquisition

At LHC the collision rate will be 40 MHz. 16 million channels will have to be processed in total. One event is expected to contain 1 Mbyte of data on average. Filtered events will be written to a storage medium with a frequency of 100 Hz. The trigger system has therefore to perform a sizable reduction of data. The first-level trigger, a partly programmable hard-wired system, will run at a frequency of

FIGURE 5. Momentum resolution of charged tracks.

100 kHz in pipeline mode. Data at the level one trigger stage will be stored in 500 readout memories with 200 Gbyte storage capacity. The event builder is a large switching network with a total throughput of about 500 Gbit per second. The following event filter consists of a set of high performance commercial processors organized into many farms convenient for on-line and off-line applications. The farms replace the traditional second and higher level triggers. One event will be processed by a single CPU.

PHYSICS PERFORMANCE

CMS has been designed in order to give answers to or shed light on the most important open questions in high energy physics. The understanding of the origin of mass is certainly one of the major problems. Other problems are the verification of Grand Unification Theories, the explanation of dark matter and the matter-antimatter asymmetry in the universe. CMS can also probe if there are really only three generations of quarks and leptons, if elementary particles of today have substructure or if the quark-gluon plasma exists.

We will concentrate here only on Standard Model Higgs [7] and supersymmetry searches [8]. CMS's B-physics capabilities are described in another contribution to these proceedings [9]. Heavy ion physics will not be dealt with either.

Standard Model Higgs searches

In the framework of the Standard Model particles acquire mass through the interaction with the Higgs field. This implies the existence of the Higgs boson. Theory does not predict its mass, but it does predict production rates and decay modes as a function of the Higgs mass. CMS has been optimized to detect the Higgs over the

FIGURE 6. Standard Model Higgs in CMS.

entire possible mass range. The most promising channels after taking into account branching ratios and background are (l denotes either electron or muon):

- $H \rightarrow \gamma\gamma$ for $80 \text{ GeV} < m_H < 140 \text{ GeV}$
- $H \rightarrow ZZ^* \rightarrow 4l$ for $130 \text{ GeV} < m_H < 200 \text{ GeV}$
- $H \rightarrow ZZ \rightarrow 4l$ for $200 \text{ GeV} < m_H < 700 \text{ GeV}$
- $H \rightarrow ZZ \rightarrow 2l + 2\nu$ for $0.5 \text{ TeV} < m_H < 1 \text{ TeV}$
- $H \rightarrow WW \rightarrow \ell\nu jj$ for $m_H \approx 1 \text{ TeV}$
- $H \rightarrow ZZ \rightarrow lljj$ for $m_H \approx 1 \text{ TeV}$

It should be noted that in the lower mass region ($m_H < 130$ GeV) the branching ratio for $H \rightarrow b\bar{b}$ is close to one, but due to the large dijet background this channel seems only usable together with an additional lepton signature (e.g. $pp \rightarrow WH \rightarrow l\nu b\bar{b}$).

Fig. 6 depicts Higgs signals for the different mass ranges.

For the $H \rightarrow \gamma\gamma$ channel the diphoton mass resolution is essential. Calorimeter granularity is crucial for photon isolation measurements to suppress the $\pi^0 \rightarrow \gamma\gamma$ background. The $\gamma\gamma$ mass resolution at $m_{\gamma\gamma} \approx 100$ GeV is better than 1%, resulting in a signal to background ratio of approximately 1/20.

In the mass range $130 \text{ MeV} < m_H < 700$ GeV the most promising channel is the Higgs decay to two Z's, one of them being off-shell for masses smaller than 200 GeV. The detection relies on the excellent performance of the muon chambers, the tracker and the electromagnetic calorimeter. For $m_H < 170$ GeV a mass resolution of about 1 GeV should be achieved.

For the highest Higgs masses, in the range 0.5 to 1 TeV, high luminosity is needed. One also has to exploit decays of Z's and W's into jets and neutrinos. Hadron calorimeter performance is very important. At the very highest masses, above 800 GeV, the signal to background ratio has to be improved by requiring a central jet veto. Thus the $t\bar{t}$ and Z,W to jets backgrounds are reduced considerably. At the highest luminosities one must also take into account pile-up from minimum bias events. Double forward jet tagging will be necessary.

To summarize, CMS can detect a Standard Model Higgs boson in the entire mass range, from the LEP2 limit up to approximately 1 TeV with a significance of at least 5σ .

Supersymmetry searches

Supersymmetry predicts a number of particles in addition to the Standard Model ones. Fermions have boson super-partners and bosons have fermion super-partners. We use the minimal supergravity-inspired standard model (mSUGRA) with a stable lightest supersymmetric particle (LSP) as a benchmark model [10]. The particle spectrum one expects consists of squarks ($\tilde{q}$), gluinos ($\tilde{g}$), sleptons ($\tilde{l}$), neutralinos ($\tilde{\chi}_i^0$ [i=1,4]) and charginos ($\tilde{\chi}_j^\pm$ [j=1,2]). There is also a Higgs sector with five SUSY Higgses, three neutral (h^0, H^0, A^0) and two charged ones ($H^\pm$).

mSUGRA is determined by only five parameters, the universal scalar (m_0) and gaugino masses ($m_{1/2}$), the SUSY breaking universal trilinear coupling A_0 , the ratio of the vacuum expectation values of the Higgs fields $\tan\beta$ and the sign of the Higgsino mixing parameter $\text{sign}(\mu)$.

Squarks and Gluinos

The total SUSY particle production cross-section is dominated by strongly interacting gluinos and squarks, which through their cascade decays can produce many

jets and leptons with missing energy due to escaping LSP's and possibly neutrinos. Due to these escaping particles a complete mass reconstruction of squarks and gluinos is impossible. However, the presence of SUSY can be established by an excess of events of a given topology over known Standard Model backgrounds such as $t\bar{t}$, $W + \text{jets}$, $Z + \text{jets}$, WW , ZZ , ZW , $Zb\bar{b}$ and QCD. In order to establish the limits of the SUSY reach in the $(m_0, m_{1/2})$ parameter space the signal was generated at more than 100 points. $\tan\beta = 2$, $A_0 = 0$ and $\mu < 0$ have been assumed. Fig. 7 shows the expected sparticle reach in various channels, for signatures containing leptons in different charge combinations. For 10^5pb^{-1} integrated luminosity the ultimate mass reach for gluinos would be $m_{\tilde{g}} \approx 2.5 \text{ TeV}$ for small m_0 (below 400 GeV) and up to 2 TeV for any reasonable value of m_0 (below 2000 GeV). Squark masses can be probed for values in excess of 2 TeV. The cosmologically interesting region within the relic neutralino dark matter density contour of $\Omega h^2 \leq 1$ can be probed entirely already with an integrated luminosity around 10^3pb^{-1} .

FIGURE 7. Expected sparticle reach in various channels.

Chargino/neutralino pair production

Direct production of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ with leptonic decays of both sparticles gives three high- p_T isolated leptons accompanied by missing energy. These events have no jet activity except from initial-state QCD radiation. A central jet veto is therefore appropriate. WZ, ZZ and $Zb\bar{b}$ backgrounds can be removed by a Z mass cut. Other backgrounds are $t\bar{t}$, $b\bar{b}$ and SUSY channels ($\tilde{g}$, $\tilde{q}$, $\tilde{l}$, $\tilde{\chi}^0$, $\tilde{\chi}^\pm$). From Fig. 8 it can be

5 σ significance contours at different luminosities

FIGURE 8. Chargino/neutralino pair production.

concluded that $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ direct production can be investigated up to $m_{1/2} \approx 170$ GeV for all m_0 with $10^5 pb^{-1}$ and $m_{1/2} \approx 150$ GeV with $10^4 pb^{-1}$. With $10^5 pb^{-1}$ the discovery region extends up to $m_{1/2} \approx 420$ GeV for $m_0 < 120$ GeV. It is possible to measure the mass of the lightest neutralino for $m_0 \gtrsim 160$ GeV by using the fact that the dilepton mass distribution has a sharp cutoff which is approximately equal to the mass of $\tilde{\chi}_1^0$ for the three-body decay process $\tilde{\chi}_2^0 \rightarrow l\tilde{\chi}_1^0$ [11].

Sleptons

To search for direct slepton production the most appropriate signature is 2 leptons + missing energy + no jets. Backgrounds are expected to come from $\tau\tau$, WW, $t\bar{t}$, $b\bar{b}$ and other SUSY channels. Fig. 9 shows the slepton mapping of the mSUGRA parameter space. With $10^4 pb^{-1}$ luminosity, CMS is sensitive up to $m_{\tilde{l}_L} \approx 160$ GeV. With $10^5 pb^{-1}$ the reach extends up to $m_{\tilde{l}_L} \approx 340$ GeV for all allowed LSP masses (< 200 GeV), and up to $m_{\tilde{l}_L} \approx (340...440)$ GeV if $m_{LSP} \approx (0.45...0.6) m_{\tilde{l}_L}$ for a given $m_{\tilde{l}_L}$.

FIGURE 9. Slepton mapping of mSUGRA parameter space.

SUSY Higgs searches

The principal decay modes of the five SUSY Higgses are the following:

- $h, H \rightarrow \gamma\gamma$
- $h \rightarrow \gamma\gamma$ in Wh , $t\bar{t}H \rightarrow l\gamma\gamma$ events
- $H \rightarrow ZZ, ZZ^* \rightarrow 4l^\pm$
- $h, H, A \rightarrow \tau\tau \rightarrow l^\pm + h^\pm + E_T^{miss}$
- $h, H, A \rightarrow \tau\tau \rightarrow e + \mu$
- $h, H, A \rightarrow \mu^+ \mu^-$
- $H^\pm \rightarrow \tau\nu$ from $t\bar{t}$

For the first three channels the procedures used in the Standard Model Higgs search can be repeated. A summary plot of the significance contours for SUSY Higgses for 10^5 pb^{-1} and assuming no stop mixing is shown in Fig. 10.

FIGURE 10. 5σ significance contours for SUSY Higgses.

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