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Pb + Pb at 1000 TeV with CMS at LHC

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Abstract. Pb + Pb collisions with an energy of 1140 TeV are planned for the Linear Hadron Collider (LHC) at CERN starting in 2008. The Compact Muon Solenoid (CMS) is designed for precision measurements of Higgs bosons and SUSY particles with masses up to 1 TeV, which could be expected from 14 TeV p + p collisions. These same design features will allow CMS to make precision measurements of Pb + Pb reactions. A large fraction of the Pb + Pb reaction products go into the very forward (HF) calorimeter which covers the pseudorapidity region $3.0 \leq | \eta | \leq 5.0$. The HF is a non-compensating calorimeter made of quartz fibers in iron, which has excellent spatial and temporal resolution.

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1. Introduction

The Large Hadron Collider (LHC) will allow the study of Pb + Pb collisions at an energy that is thirty times the maximum energy available for Au + Au collisions with the Relativistic Heavy Ion Collider (RHIC). The plans at present are for the LHC to be used for heavy-ion studies only six weeks each year, starting in 2008. The rest of the accelerator time will be used for p + p studies.

Plans for the accelerator and the detectors are given in technical reports and other documents that can be found by starting at www.cern.ch. Here we present, not a summary of the reports, but rather an account of some of the interesting features of these remarkable devices.

There are just four locations in the LHC tunnel where the counter-rotating beams are made to intersect. Three of these are instrumented with massive detectors with the acronyms, CMS, ALICE, and ATLAS. ALICE (A Large Ion Collider Experiment at CERN), is designed especially for heavy-ion reactions. CMS (Compact Muon Solenoid), was designed primarily for p + p studies, but is also an excellent device for heavy-ion studies. CMS and ALICE are complimentary. CMS has better hermiticity; it makes quantitative

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measurements on every particle that is emitted at an angle greater than 0.8° with respect to the beam. ALICE has superior particle identification, but over smaller solid angles. ALICE will also study p + p, but with a luminosity that is reduced by a factor of 10^4 in order to allow time to clear the tracks from the large gas volume of the TCP (time projection chamber, a key feature of ALICE). ATLAS (A Toroidal LHC ApparatuS) is designed for p + p with some special features such as a liquid-argon calorimeter. It will also be used with heavy ions. To understand unusual types of events, it is essential that they be observed in more than one experiment. Electronic anomalies can create a variety of bizarre effects. The redundancy is not a luxury but is crucial for the overall success of the LHC nuclear-physics program.

This paper will concentrate on CMS with emphasis on its heavy-ion capabilities and on HF, its far-forward calorimeter whose design has been a major project at the University of Iowa.

2. LHC

The LHC will feature proton-proton collisions with $\sqrt{s}$ = 14 TeV, with luminosity 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and Pb + Pb with an energy of 5.5 TeV per charge for a total of 1140 TeV at 10^{27} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The LHC is being constructed in the tunnel of the recent Large Electron Positron Collider (LEP) that follows a 27-km circular path under the city of Geneva and part of France. For Pb + Pb the bunch crossing time is 125 ns (each bunch is only 7.5 cm long). For p + p the time is only 25 ns, which is less time than a muon spends traveling through CMS.

The LHC has many remarkable features. The total energy stored in the two proton beams is 334 MJ. The average power required to generate the beam is small because the rings need to be refilled only two or three times a day. There is, however, 7.2 kW of synchrotron radiation from the two proton beams. The LHC rings accelerate protons from 450 GeV to 7 TeV. The beams are prepared for injection into the LHC by a sequence of four accelerators, Linac, Booster, PS and SPS. The superconducting magnets in the LHC are supplied with liquid helium by eight 18 kW cryogenic plants.

3. Pb + Pb

At LHC energies the electromagnetic fields around colliding lead nuclei are huge. For two lead nuclei passing each other at a center to center distance of 20 fm, the magnetic field becomes greater than 2×10^{20} gauss at the point midway between the two nuclei. Many years ago Edward Teller commented that if magnetic monopoles are possible, they are most likely to be found in such high-energy, heavy-ion collisions. The nuclear cross section for Pb + Pb is 7.8 barn, which is essentially the geometric size of the nuclei. However, the cross section is 225 barn for a lead nucleus breaking apart in the electromagnetic field of the other nucleus. The equivalent photon spectrum of the passing nucleus has components up to 100 GeV. There is an additional, large electromagnetic effect that does not destroy the lead nucleus but does take it out of the beam. The intense electromagnetic field makes electron-positron pairs with an electron being captured into a Bohr orbit of one of the nuclei. With only 91 charges, it is lost from the beam after it encounters the first magnet. The cross section for this process is 204 barn. Summing these cross sections gives a total of 437 barn for taking lead out of the beam. Some of the products of these processes will find their way into the superconducting magnets along the beam line, thereby putting a limit on the maximum allowed luminosity. One suggestion for increasing the average luminosity is to start with a large, but somewhat defocused, beam so that the maximum allowed luminosity is not exceeded. Then as beam is lost, it can be focussed more sharply to maintain the maximum luminosity as long as possible.

CMS and ALICE are prepared to deal with charged particle multiplicities as high as dN/dy = 8000 (the number per unit rapidity). Some models predict maximum multiplicities as much as four times smaller, but the large extrapolation from measured values at lower energy results in considerable uncertainty.

Heavy ion collisions at LHC energies will explore regions of temperature and particle density significantly beyond those reachable at RHIC. The higher density of produced partons allows a more rapid thermalization, and therefore a larger ratio of the lifetime of the quark-gluon plasma to the thermalization time. The longer lifetime of an equilibrium quark-gluon plasma state widens the time window available for probing it experimentally [1–3].

The early stages can best be studied by using probes that do not interact strongly, such as real photons, virtual photons (the Drell-Yan process), and the gauge bosons, $W^{\pm}$ and Z^0, all of which CMS can measure with precision.

For Pb + Pb at LHC energies the cross section for producing heavy quarks is large, 5 mb for $c\bar{c}$ pairs and 190 μb for $b\bar{b}$ pairs. The average central Pb + Pb collision will produce 152 J/$\psi(c\bar{c})$ and 6 $\Upsilon(b\bar{b})$. Much can be learned about the quark-gluon plasma from the suppression (or enhancement) of J/ψ and Υ production and from the ratio of the excited states of Υ as a function of its transverse momentum [4]. The mass resolution for Υ is 40 MeV in CMS (using the decay into muons), which is more than adequate for resolving the Υ excited states.

Much of the new physics to be learned from heavy ions at the LHC will depend on measurements of jets. It is important that all of the jets be measured and that their energy and angle be well determined. CMS with its hermetic coverage for all angles greater than 0.8° to the beam is an ideal detector for studying the jets.

4. CMS

CMS, Fig. 1, was originally designed as a general-purpose proton-proton detector that could operate well, even at the highest luminosity of the LHC. CMS is a massive undertaking that involves over 1800 scientists and engineers from 151 institutions in 31 countries. The main design goals of CMS are:

- precision muon measurements up to the highest energies available
- the best possible electromagnetic calorimetry

- high quality central tracking
- hermetic calorimetry

The hermeticity can use some additional explanation. CMS will make precision measurements of the transverse momentum (p_T) of all hadrons, photons, and charged particles with $\eta < 5$ ($> 0.8°$ with respect to the beam), except for muons which are not detected for $\eta > 3$. Any unbalanced p_T would be due to neutrinos or to previously unknown neutral objects. One expected decay product of a massive Higgs is a $W^{\pm}$ which often decays into a charged lepton and a neutrino. A high-energy muon, along with the appropriate amount of missing p_T, would be a clear signature of the $W^{\pm}$. The small amount of transverse momentum carried by particles with $\eta < 5$ can be estimated from the amount of undetected energy. For heavy ions, a small calorimeter at zero degrees measures the considerable amount of energy (but no p_T) that is sometimes carried by spectator neutrons.

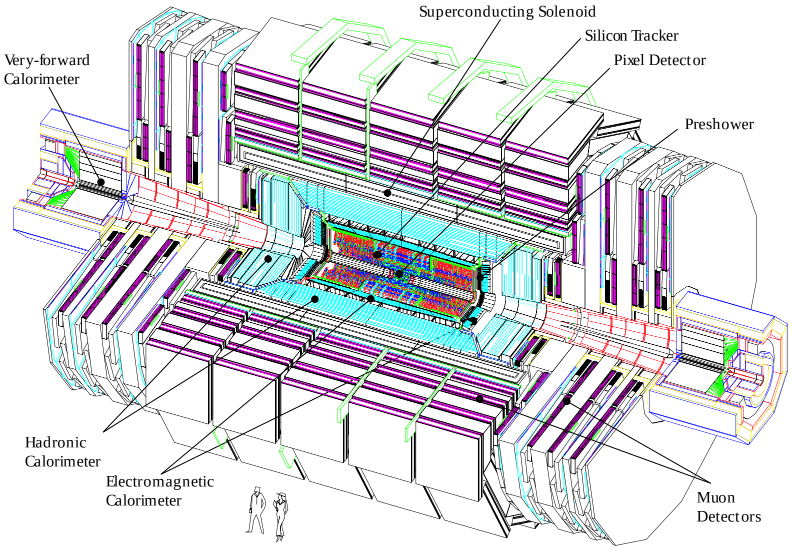

Fig. 1. The CMS detector: a cut away view showing its components.

4.1. Solenoid

The solenoid, the S in CMS, is 5.9 m in diameter and 13 m long with a field of 4.0 T that is parallel to the beam direction. It is the world's largest super conducting magnet with a stored energy sufficient to melt 19 tons of gold. The coil is large enough to contain all of the calorimetry out to $\eta = 3$ (5.7° with respect to the beam). Although most of the magnetic flux is constrained to CMS, the stray fields are large enough so that careful shielding is required for all of the electronics in the CMS underground vault. In the underground control room, 35 m from CMS, the field is 5 gauss.

4.2. Central Tracker

In the center of the magnet is a 2.6 m diameter, 6 m long volume of silicon detectors for tracking the reaction products as they leave the interaction region. Closest to the beam, at a radius of 4.7 cm, are silicon pixel detectors with 100 μm x 150 μm pixels. Interpolation between pixels allows a position resolution of about 20 μm. Altogether there are 40 million pixels. Silicon strip detectors are used farther out where position resolution is not as critical.

4.3. ECAL

An electromagnetic calorimeter surrounds the silicon tracker. It consists of over 80,000 scintillating crystals of $PbWO_4$, each 2.2 cm x 2.2 cm and 23 cm long. The length provides 25.8 radiation lengths, $X_\circ$, sufficient to stop virtually all photons and electrons. In the endcap region, where the crystals are parallel to the beam axis, there is a preshower detector that distinguishes between a single photon and a pair of photons from the decay of a π^0. The preshower consists of two orthogonal planes of silicon strip detectors, placed after 2 $X_\circ$ and 1 $X_\circ$ of lead radiators respectively. It can separate two photons that are only 300 μm apart.

4.4. HCAL

Surrounding the electromagnetic calorimeter, and still inside of the magnet, is the central hadronic calorimeter. It consists of the hadron barrel (HB) and hadron endcap (HE). It is a sampling calorimeter made of scintillator/copper plates. The copper absorber plates are 5 (8) cm thick in the barrel (endcap). The active elements are 4 mm thick plastic scintillator tiles read out using wavelength-shifting plastic fibers followed by clear optical waveguide fibers. The photosensors at the end of the fibers are hybrid photodiodes (HPDs). An HPD is a new device consisting of a fiber-optic entrance window onto which a multi-alkali photocathode is deposited. This is followed by a gap of a few millimeters over which a large applied electric field accelerates photoelectrons onto a pixellated silicon diode. The applied voltage is 10 to 15 kV, with the HPD oriented so that the electrons travel along the magnetic field lines. This arrangement provides a linear response over a large dynamic range from minimum ionizing muons up to 3 TeV hadron showers.

4.5. Muon system

A thick muon detector system surrounds the solenoid (out to $\eta = 3$). It consists of slabs of iron interspersed with three different kinds of gas detectors. Muon identification is ensured by the large thickness of absorbing material which can not be traversed by any particle other than a muon or a neutrino. The iron absorber serves a dual purpose; it is also the return yoke for the magnet. Some of the gas detectors provide excellent timing resolution, 3 ns, while others provide the excellent position resolution needed to provide the desired momentum resolution. Some of the detectors need to function well in magnetic fields as up to 4 T.

To provide the position resolution, the location of the detectors must be known with an accuracy of 0.1 mm. This is not easy because some the iron to which the detectors are attached moves by as much as 14 mm when the magnetic field is turned on. The reason the iron moves is easy to understand after noting that the overall magnetic force on the first endcap disk, which weighs 900 metric tons, is about 7000 metric tons. The position of the gas detectors needs to be known, not only with respect to each other, but also with respect to the silicon tracker. The muon detector spectrometers are instrumented with optical alignment systems to constantly monitor the position and deformations of the muon chambers during their operation. This is done with video cameras that observe light sources mounted on the muon chambers.

4.6. Very Forward Calorimeter

The far-forward calorimeter (HF) covers the pseudorapidity range $3 < \eta < 5$ (5.7° to 0.8° with respect to the beam axis) and is located at the ends of CMS, starting at a distance of 11 m from the interaction point. Because of its extreme forward angle, HF receives a large fraction of the reaction products. Simulations for p + p show that, for an average event, 760 GeV go into HF and only 100 GeV into the rest of CMS.

HF consists of 600 μm diameter fibers that are parallel to the beam in an iron matrix and arranged in a rectangular array with a spacing of 5 mm. Half of the fibers go the entire 165 cm from the back to the front of the iron. The other half stop at a distance 22 cm (12.5 $X_\circ$ in iron) from the front face. The long fibers measure both electromagnetic and hadronic showers, while the short fibers measure only the hadronic part. The fibers are collected together in bundles and read out by photomultiplier tubes.

The light in the transparent fibers is mostly from Čerenkov radiation by fast electrons generated in electromagnetic showers. For hadrons 80% of the light is from photons from π^0 decay. Because of the large π^0 energy these photons have essentially the same direction as the original π^0.

Nearly all other detector types now in use are not adequately precise and robust for use in such a severe environment [5]. The main constraints and conditions that apply to this region are:

- *High radiation levels:* The radiation expected is measured in mega-grays. Radiation damage of detector components, especially in the very forward region, is a major concern.

- *Fast signal collection:* The high particle densities and the short time between bunch-bunch crossings constrain the acceptable signal duration, especially for protons for which the time is only 25 ns. In an optimized design the entire signal from HF should occur within less than 25 ns.

- *Insensitivity to neutrons:* In standard calorimeters used in this energy range, neutrons produced by the particle being detected deliver their energy at large radial distances, such as 30 cm, from the path of the incoming particle and after time delays much longer than 25 ns.

- *Insensitivity to activation products:* Induced radioactivity may also have a large impact on measurements, to the extent that it may give rise to a calorimetric signal. Should this be the case, pedestals of electronic channels will depend not only on the instantaneous luminosity, but also on the luminosity history.

The nature of Čerenkov light gives rise to several important benefits:

- In contrast with molecular fluorescence processes, Čerenkov radiation is much faster with a typical time constant of less than 1 ns. Instrumental effects broaden the signals, but they are still much less than 25 ns.
- Neutral particles, particularly neutrons, and non-relativistic charged particles, including most particles produced by induced radioactivity, do not produce Čerenkov light and thus do not give rise to noise.
- The mass dependence of the Čerenkov threshold implies that electrons and positrons produced in the shower development largely dominate the signals.

Hadron showers, thus, register predominantly through the electromagnetic shower core. This has a twofold benefit. First, the instrumented depth needed is substantially less than that required for full containment of the hadron showers. Second, the lateral dimension of the shower signal depends on the Molière radius and not the much larger nuclear interaction length, which governs the lateral development of hadron showers in calorimeters based on dE/dx measurements. These two quantities typically differ by almost an order of magnitude which results in hadron showers in this type of calorimeter being considerably narrower than in other types of calorimeter. For Pb + Pb, where many jets have energies measured in TeVs, the extreme collimation of jets is only helpful for disentangling multi-jet events if the hadronic shower width is narrower than the intrinsic jet width. This condition is satisfied in HF.

Hadron shower dimensions in copper are less than in most materials—even lead. Because of the low Z, neutron production is only one third that of tungsten or lead. The shower dimensions in iron are about 15% larger than for copper (because of its lower density), but iron is used for HF to achieve less residual radioactivity.

Quartz was chosen as the active medium because of its radiation resistance. For particles with $\beta \approx 1$ in quartz, Čerenkov light is emitted in a cone at an angle of 46° to the direction of the particle. However, the shower particles contributing to the calorimeter signal are, to a large extent, isotropically distributed. Orienting the fibers at an angle of 46° with respect to the incoming photons increases the light at the end of the fiber by only a factor of two.

The valuable features of the Čerenkov calorimeter come with a price [6]. The signal size for electromagnetic showers is strictly proportional to the incoming energy. For hadron showers the response is smaller and and is not linear with energy. Only about half of the energy in a hadron shower is electromagnetic, and the fraction increases with energy. There is also a small difference between the electromagnetic fraction for pions and protons of the same energy. The energy resolution for protons of a single energy is about 10% and improves slowly with energy. A calculation the energy of a jet from the light produced requires an estimate of the number of photons, pions, and protons in the jet.

However, excellent energy resolution is not the most important requirement in the forward region. Accurate measurements of the angle between two jets or the angle between the jet direction and the beamline are at least as important. These are used to compute physically relevant quantities such as the missing transverse energy and the invariant mass of jet-jet systems.

For Pb + Pb, HF allows the elimination of all background events, such as Pb + air [7]. Figure 2 shows that the two ends of HF must receive almost the same amount of energy if the event is real. Note that this condition does not hold for p + p but could still be useful for intermediate mass ions.

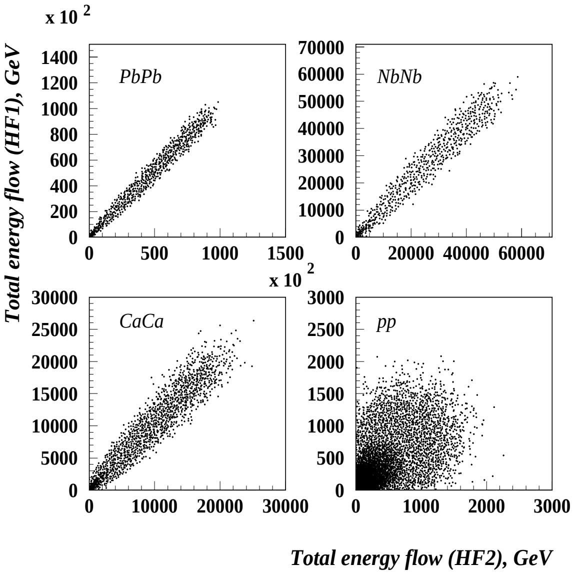

Fig. 2. Correlation plots between the total energy received by the two parts of HF (at opposite ends of CMS) for Pb-Pb, Nb-Nb, Ca-Ca, and p-p collisions at $\sqrt{s}$ = 5.5A TeV.

4.7. ZDC

The two ZDCs (Zero Degree calorimeters) are located ±140 m from the center of CMS. At this distance the spectator neutrons form a 1.0 cm radius beam. The detector is between the two beam pipes with only 1.45 cm of copper in front of the detector. This small detector adds considerably to the hermiticity of CMS. Twenty neutrons in each detector is 10% of the total reaction energy. The design of the ZDC is similar to that of HF with quartz fibers embedded in a metal matrix. For the ZDC the metal is tungsten because the nuclear interaction length for tungsten is smaller than for any other ordinary metal, only 9.6 cm, and the total available length is only 1.0 m.

5. Conclusions

With thirty times the energy available at RHIC, the study of Pb + Pb collisions at the LHC will show us a new aspect of reality. The longer lifetime of an equilibrium quark-gluon plasma will widen the time window available for probing it experimentally. For the first time we will be able to study in detail the interaction of B quarks with the quark-gluon plasma. However, the most interesting features will be those that are not expected. The CMS detector, with its extensive muon acceptance and $\approx 4\pi$ calorimetric coverage, will make significant and, in some respects, unique contributions to the study of heavy-ion collisions. The quartz fiber design of the very-forward calorimeter will allow it to withstand the enormous doses of radiation; and, with its narrow hadronic showers, it will be able to resolve jets that would completely overlap in other types of detectors.

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