Journal of Physics: Conference Series

Year-1 (heavy-ion) physics with CMS at the LHC

To cite this article: Edwin Norbeck *et al* 2010 *J. Phys.: Conf. Ser.* **230** 012044

Journal of Physics: Conference Series **230** (2010) 012044 doi:10.1088/1742-6596/230/1/012044

Year-1 (Heavy-Ion) Physics with CMS at the LHC

Edwin Norbeck and Yasar Onel (for the CMS collaboration)

University of Iowa, Iowa City, IA 52242, USA

E-mail: `edwin-norbeck@uiowa.edu`

Abstract. The plans for the CERN LHC heavy ion program in 2010 are for collisions of lead ions during the month of November at an energy about half of the final 5.5 TeV/nucleon. The advanced preparations are mostly for extrapolations of the measurements at the maximum energy previously available, Au + Au at 0.2 TeV/nucleon. Because of the large increase in energy, surprises can be expected. One new feature made possible by the increased energy and the excellent muon energy resolution of CMS will be the study of the yields of the excited states of the upsilon meson as a function of angle and centrality. Although the main emphasis will be on the QGP formed by the overlapping parts of the Pb ions, the spectator parts and the electromagnetic field outside of the ions, γ-Pb and $\gamma\gamma$, are also important.

1. Introduction

This paper will discuss some of the plans and expectations for the heavy ion data from CMS [1]. Much of the material presented here is discussed in greater detail in [2]. Up to the time of the first Pb-Pb runs in November of 2010, the LHC [3] will feature p-p at $\sqrt{s} = 7$ TeV, which is half of the final 14 TeV. The same magnet settings for Pb will give $\sqrt{s_{\rm NN}} = 2.75$ TeV. At this energy, CMS will need to be prepared to deal with up to 572 TeV of energetic particles.

Initially the LHC Pb-Pb studies will be mostly extrapolations of the Au-Au program at RHIC. Because of the large increase in energy, a factor of 14, the experimental results may prove to be much more interesting than simple extrapolations. Examples of the extrapolations are high $p_{\rm T}$ suppression and jet quenching, azimuthal distributions (v2), and flow and temperature from energy spectra, all as functions of beam energy and impact parameter. At RHIC energies the quark-gluon plasma (QGP) is a low viscosity fluid, not a gas. The properties of the QGP at an energy 14 time larger may be quite different. New physics can also be expected from the spectator matter and from reactions of the intense photon field surrounding the Pb ions.

It is expected that the Pb-Pb collision rate during year-1 will be around 100 Hz. Although one would like a larger collision rate to be able to get better statistics for rare processes, the low rate does have advantages. The low rate will allow all minimum bias events to be written to mass storage. Unexpected event types that would be ignored by carefully prepared triggers are preserved for later discovery by enterprising physicists.

2. Ratios to p-p particle yields

Much of the RHIC data is presented as ratios of Au-Au to p-p particle yields. Accurate p-p yields at the $\sqrt{s_{\rm NN}}$ of the same energy as for the heavy-ion reactions are therefore essential to the heavy-ion program. The short, low energy p-p runs at $\sqrt{s} = 0.9$ and 2.36 TeV in 2009 are of considerable value to the heavy-ion program. They provide information about the variation with

Journal of Physics: Conference Series **230** (2010) 012044 doi:10.1088/1742-6596/230/1/012044

energy of transverse-momentum (p_T) and pseudorapidity (η) distributions, which are needed for the computer codes that predict the outcome of heavy-ion collisions. The 0.9 TeV data, which can be compared with other measurements, show that the CMS measurements are valid. The distributions at the energies needed for the heavy-ion calculations will be interpolated between the 2.36 TeV data and the 7.0 TeV data measured in 2010. It is fortunate for the heavy-ion program that the LHC did not start with p-p at $\sqrt{s}$ = 14.0 TeV. The Pb-Pb measurements will eventually be at $\sqrt{s_{\rm NN}}$ = 5.5 TeV, but the measurements in 2010 are expected to be in the neighborhood of $\sqrt{s_{\rm NN}}$ = 2.75 TeV. As was demonstrated at RHIC, it is good to have heavy ion measurements at more than one energy.

The energy for p-p will be 7 TeV for the first year or so because that energy does not require upgrading of the superconducting magnets. The $\sqrt{s_{\rm NN}}$ = 2.75 TeV Pb-Pb experiments would use the same magnetic field settings. It is interesting to note that, in principle, the Pb-Pb luminosity could be larger at the lower energy. The Pb-Pb luminosity must be kept below the value for which the debris from the interaction point causes excessive heating of some superconducting magnet. The breakup of one Pb nucleus in the electromagnetic field of the other Pb nucleus and the pickup of an electron out of the cloud of electron-positron pairs have cross sections of hundreds of barns, and these effects increase with energy.

3. Limiting fragmentation

The spectrum of particles emitted at small angles with respect to the beam has the same shape independent of the reaction and the energy. This feature is demonstrated by plots of $\eta' = \eta$ - $y_{\rm beam}$ for small values of η'. The curves have the same shape for heavy-ion reactions for $\sqrt{s_{\rm NN}}$ = 20 GeV to $\sqrt{s_{\rm NN}}$ = 200 GeV. At the present time there is no good explanation for this phenomenon, also known as extended longitudinal scaling, so it will be most interesting to see if it holds with additional factors of 14 and 28 in energy.

4. Smaller x

The Bjorken x is essentially the momentum fraction that can be studied. Reaching small values of x requires a large energy and a small angle. As x approaches zero one might expect the number of low energy gluons to diverge. Because gluons can change into quarks, this effect would result in particle production rates to exceed unitarity at sufficiently high energy and small angles. This does not happen because, at a sufficiently high density, the gluons interact to form a classical field, described by the Color Glass Condensate (CGC) model. The values of x accessible with CMS using the full Pb beam energy will be almost two orders of magnitude smaller than at RHIC. Possible CGC effects that have been observed at RHIC will be studied in detail with CMS.

5. Hard probes

The large increase in the cross section for heavy quarks and other heavy objects can be seen in figure 1. Of these, the upsilon in its various excited state is of particular interest and will be considered in the next section. The accuracy of the CMS tracking (10 μm radially) is good enough to see the distance that a b meson travels before it decays. Even with central Pb-Pb collisions, the occupancy is expected to be at the level of 1% in the pixel detectors of the inner tracker and less than 20% in the outer silicon strip detectors [4].

Most of the hard probes have such short lifetimes that they leave the interaction region in the form of jets. A major data analysis task is the recognition of a jet and an accurate as possible measurement of its energy. Even with the high precision detectors of CMS, the energy resolution does not allow the separation of W jets from Z jets. The jets must be somehow separated from the large background, which is of the order of 5000 charged particles per unit of η. (The predicted numbers range from 1500-8000 at mid-rapidity.) There are two related

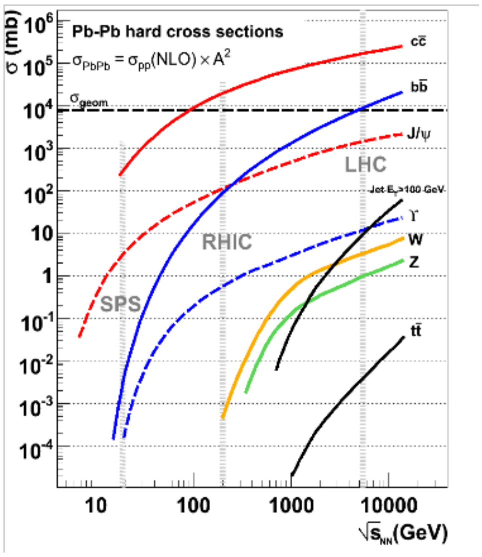

Figure 1. The cross section as a function of energy for the production of a number of interesting heavy objects using the Pb-Pb reaction.

problems. A jet can be hidden in the background, and a fluctuation in the background can be interpreted as a jet. Figure 2 shows the efficiency and purity as a function of jet energy using Monte Carlo simulations and the current jet finding programs. The efficiency is the probability that a real jet will be recognized, and the purity is the probably that a configuration that the program considers to be a jet is an actual jet and not a fake.

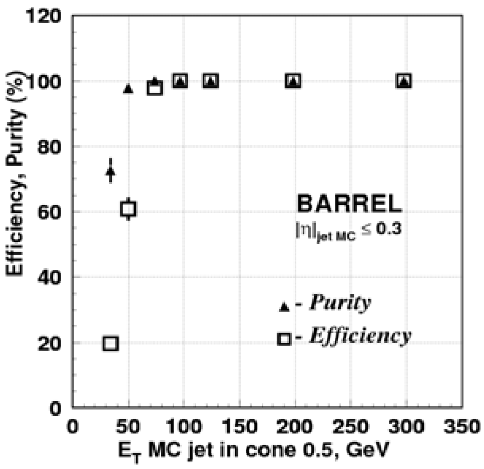

Figure 2. The efficiency and purity of the jets found by the jet finding programs assuming $dN_{ch}/d\eta = 5000$.

6. Upsilon states from muon energy spectra

The Compact Muon Solenoid (CMS) has exceptional capabilities for measuring muons. Figure 3 shows the nature of the measurements. The muons are first tracked through layers of silicon inside a homogeneous 3.8 T solenoidal magnetic field. Next they pass through the lead tungstate crystals of the electromagnetic calorimeter and then through the hadronic calorimeter, most of which is inside the magnet and consists of bronze absorbers and scintillating plastic. Beyond that is the part of CMS devoted exclusively to muons. It is made of thick layers of iron, shown in red, interleaved by a variety of detectors. The iron also provides a return path for the solenoidal magnetic field. Elaborate provisions are made to ensure that the position of every detector in

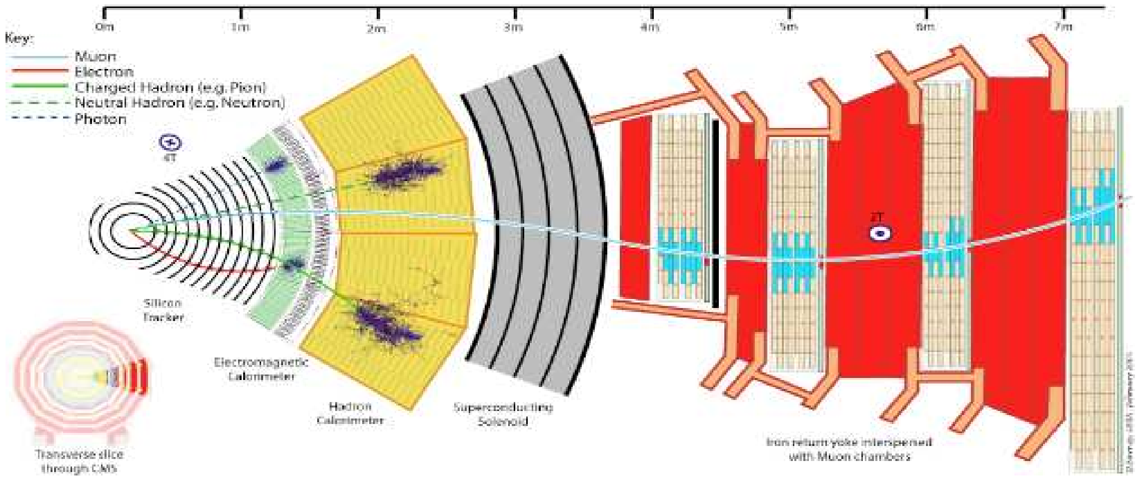

Figure 3. Schematic drawing showing how neutrons near mid rapidity are measured in CMS. The drawing does not show the part of the hadronic calorimeter just outside of the superconducting magnet.

the muon system is known to within a small fraction of a millimeter. This is made even more difficult by centimeter size elastic deformations caused by the magnetic field.

Figure 4 shows the excellent resolution of the first three upsilon states in CMS using muons from the decay $\Upsilon \rightarrow 2\mu$. The calculations made use of the known characteristics of CMS and actual measurements of cosmic ray muons. The calculations do not include the melting of the

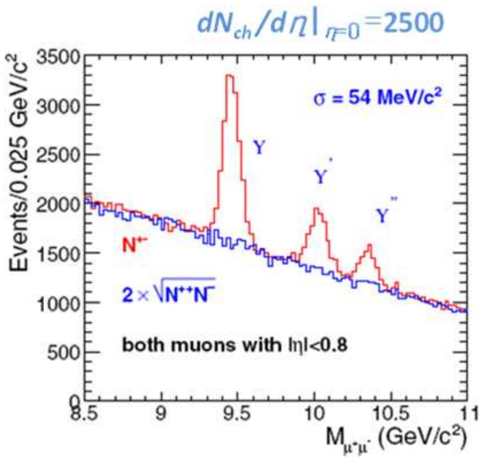

Figure 4. Invariant mass spectra of $\mu^+\mu^-$pairs in the Υ mass range. This simulation does not take into account the partial melting of the excited states in the hot quark gluon plasma.

excited states in the hot quark gluon plasma. If the third state melts completely, the third peak would be only from excited upsilons formed at the surface. Much can be learned about the geometry of the hot interaction region by looking at the relative amplitude of the three peaks as a function of centrality, the angle with respect to the reaction plane, and other variables. With configurations for which there are large differences in the amplitude of the three peaks, the good resolution of the peaks is essential. Such excellent energy resolution is not available in any other experiment.

7. Ultraperipheral reactions

There is an extremely large electromagnetic field around the Pb ion. A number that is easy to remember is 2×10^{20} gauss for the magnetic field midway between two Pb ions passing at 20 fm at the full $\sqrt{s_{\rm NN}} = 5.5$ TeV.

The physics of ultraperipheral collisions at the LHC has been described in a 171 page document [5]. Here there is space only for a brief introduction. The Lorentz contracted electromagnetic field around a relativistic Pb ion can interact as a high energy photon. The equivalent photon spectrum flux increases with Z^2, which provides for Pb a $Z^2 \sim 7000$ enhancement factor compared to electron or proton beams. The first factor of Z is from Coulomb's law and the second from the Bio-Savart law. For photon-photon reactions the increase is proportional to Z^4. Photoproduction has been extensively studied at RHIC; but the LHC offers a much larger number of higher energy photons. Over a certain range, the radiation field of all 82 protons in the lead nucleus is coherent. The requirement of coherence places an upper limit on the maximum photon energy, which increases linearly with beam energy. At RHIC the maximum energy available from photon-photon collisions is about 6 GeV. For year-1 at the LHC the energy is 100 GeV, and with full energy Pb-Pb it is 200 GeV. The reaction $\gamma\gamma \rightarrow \Upsilon$ is well within the LHC energy range. The energy spectrum should look like figure 4, but with less background. With direct photoproduction of heavy quarks, the only contribution is from $\gamma g \rightarrow Q\bar{Q}$, thereby providing a measurement of the gluon distribution in the Pb nucleus along with nuclear shadowing effects. The total luminosity during year-1 will not be sufficient for many detailed studies, but measurements at $\sqrt{s_{\rm NN}}$ of both 2.75 TeV and 5.5 TeV should help identify the extent of various background processes.

The large cross sections for the breakup of the Pb nucleus, mostly from γ-Pb, are sufficiently calculable that they can be used in luminosity determinations. A measurement of the rate for the production of one or more neutrons in both ZDCs (zero degree calorimeters) should provide a luminosity measurement with an accuracy of 2%[5].

8. CMS at small angles

The tracker and muon chambers cover the pseudorapidity region $\mid \eta \mid < 2.5$. Larger values of $\mid \eta \mid$ are covered by calorimeters, all of which have both electromagnetic and hadronic parts. With p-p at the design luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ there can be two dozen interactions in one beam crossing. The tracker can localize a reaction to within 20 μm along the beam direction, which is more than enough to allow matching of each track to the interaction that produced it. For the calorimeters at $\mid \eta \mid > 2.5$ there is no direct way of knowing the source of a detected particle, but with heavy ions there are never two interactions in one beam crossing so that the small angle detectors are fully useful.

The construction details of these forward angle calorimeters are given in [1]. In all of them, charged particles are detected by photomultiplier tubes (PMTs) viewing Čerenkov light in pure quartz (radiation resistant synthetic fused silica). The absorber material is either iron or tungsten. As of this writing, all of these calorimeters are deciding how to deal with the occasional spurious large signal caused by charged particles hitting the front window of the PMTs.

9. Stranglets

Cosmic ray studies at mountain observatories [6] show an abundance of events that can be interpreted as light nuclei containing a number of strange quarks, so that the ratio Z/A is small compared with ordinary nuclei. These objects, sometimes called stranglets, (also called MEMOs, metastable exotic multihypernuclear objects [7])are found in the cores of cosmic ray showers and are thought to be the result of collisions of cosmic iron or nickel with nitrogen or oxygen at the top of the atmosphere. The center of mass energy per nucleon of the collisions is in the same range as with the LHC. In a heavy ion collision, there are two parts, a hot interaction region and a non-overlapping region that gives rise to spectator matter that continues undeviated from the original beam direction. A recent paper [8] has shown that there is essentially zero probability that a bound nuclear system could come out of the hot interaction region. For small Pb-Pb impact parameters the spectators are disintegrated into neutrons and protons so that the number of neutrons observed in a zero degree calorimeter (ZDC) is proportional to the amount of spectator matter. At a sufficiently large impact parameter, the number of neutrons is no longer proportional to the amount of spectator matter because some of the spectator neutrons are bound with protons into small nuclear systems. If the objects seen in cosmic rays are stranglets, they are formed from spectator nuclei that have somehow become infiltrated with strange quarks from the hot interaction region. With a large iron nucleus incident on a small nitrogen nucleus there is a large amount of spectator matter.

Stranglets would appear in the CMS ZDC as an abnormally large signal. The impact parameter can be measured by other parts of CMS so that the expected number of neutrons in the ZDC will be known. A stranglet of A nucleons would add to the ZDC signal like A additional neutrons. The ZDC sits between the beam lines, 140 m from the center of CMS, so that a stranglet would need to have Z/A well under the 92/208 of lead in order to not be swept aside by the beam magnets. The electromagnetic part of the ZDC is divided horizontally into five equal sections. The spectator neutrons will mostly be incident on the middle section. A stranglet would most likely go through the section closest to the outgoing beam and leave an easily observable amount of energy.

The observation of stranglets in the ZDC may have to wait for $\sqrt{s_{\rm NN}} = 5.5$ TeV runs. The larger energy will increase the number of strange quarks produced in the interaction region, and the relativistic γ factor will be twice as large. The lifetime of a stranglet is likely to be short—of the order of the lifetime of a Λ^0. The extra factor of two in the time dilatation effect may be necessary for an adequate number to reach the ZDC. The mountain top observatories could observe much shorter lifetimes because the γ factor for cosmic iron is huge compared with the γ factor with colliding beams at the same $\sqrt{s_{\rm NN}}$.

The ZDC of the ALICE experiment [9] may be a better device for observing stranglets. In addition to the part between the beam lines, ALICE has a part on the other side of the outgoing beam line. This outer part would be able to see stranglets with $Z/A < 1/2$ but $> 92/208$. Also, the distance that the stranglet must travel is smaller with ALICE, only 116 m instead of 140 m.

An extensive search by the STAR experiment at RHIC failed to find a single stranglet candidate [10]. These results are not surprising. The experiment looked only at the 4% most central collisions for which there would be no bound spectator nuclei. It is also possible that at the RHIC energy there are not a sufficient number of strange quarks produced to convert a spectator nucleus into a stranglet.

References

[1] CMS Collaboration 2008 *JINST* **3** S08004
doi:10.1088/1748-0221/3/08/S08004
[2] CMS Collaboration 2007 *J. Phys. G: Nucl. Part. Phys.* **34** 2307
[3] Evans L (ed.) and Bryant P (ed.) 2008 *JINST* **3** S08001
doi:10.1088/1748-0221/3/08/S08001
[4] CMS Collaboration 2006 "Detector performance and software" CERN/LHCC 2006-001 CMS TDR 8.1
[5] Baltz A *et al* 2008 *Phys. Reports* **458** 1-171
[6] Gladysz-Dziaduś E 2003 *Phys. Part. Nucl* **34** 285-347
[7] Schaffner-Bielich J, Greiner G, Diener A and Stöcker H 1997 *Phys. Rev.* C **55** 3038-46
[8] Ellis J *et al* 2008 *J. Phys. G: Nucl. Part. Phys.* **35** 115004
[9] 1999 "Zero-Degree Calorimeter Technical Design Report" CERN/LHCC 99-5
[10] STAR Collaboration 2007 *Phys. Rev.* C **76** 011901(R)