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Heavy-Ion Reactions at Forward Angles with CMS (LHC)

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Abstract. Reactions seen only in cosmic rays will be studied by three forward angle, $\theta < 5.7°$ ($| \eta |> 3$), detectors at CMS. These detectors look at Čerenkov radiation from quartz fibers embedded in a heavy-metal matrix to deal with the exceptionally large particle fluxes

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1. Introduction

The LHC (Large Hadron Collider), being constructed in the former LEP tunnel at CERN, will feature p + p collisions at $\sqrt{s}$ = 14 TeV at the very high luminosity of 10^{34} cm^{-2}s^{-1} and Pb + Pb at $\sqrt{s}$ = 5.5 TeV/nucleon at a luminosity of 10^{27} cm^{-2}s^{-1}. The lead beam will be run only about six weeks each year, but, because of the high luminosity, the number of collisions per year will be about the same as with the gold beam at RHIC.

CMS [1, 2] (Compact Muon Solenoid) is one of two large, general-purpose detectors located at intersection points in the LHC tunnel. Most of the cost of CMS is for the complex central region, -3 < η < 3, discussed in the next paper [3], but the components closer to the beam are also important parts of CMS.

Table 1 shows the three small angle ($\eta > 3$) detectors associated with CMS. Each of these detectors is designed with different physics goals. There are some phenomena that are expected to occur only in this baryon-rich, high-rapidity region.

Table 1. Three detectors at forward angles in CMS

HF	5.7 to 0.8°	$3 < \|\eta\| < 5$
CASTOR	0.6° to 0.1°	$5.3 < \|\eta\| < 6.9$
ZDC	0° $\eta = \infty$	$y = 8.67$

An additional detector in this angular range is TOTEM [4]. It will not be discussed here because it is designed to be used during p + p runs during the early stages with low luminosity. If available, however, it could also be used for all A + A studies.

The reaction products at very small angles to the beam become more important as the energy increases in colliding-beam experiments. For Pb + Pb collisions at the LHC the number of particles per unit of η is approximately constant out to $\eta = 5$ and then falls off. However, the amount of solid angle per unit of η falls off so rapidly for large η that the number of particles per unit solid angle continues to increase as the angle to the beam decreases.

To subtend large pseudo-rapidities, it is essential that the detectors be at a considerable distance from the interaction point. The front of HF is 11 meters from the IP. This makes HF, covering a pseudo-rapidity range 3–5, a large device, 2.2 m in diameter. For CASTOR, subtending $\eta = 5.3$–6.9, the outer angle of $0.5°$ is so small that, even at 15 m, its outer diameter is under 30 cm.

The pseudorapidity, η, is often used interchangeably with the rapidity, y, but these two quantities diverge at far forward angles. Rapidity (defined so that the shape of a rapidity distribution is invariant under Lorentz transformations) is

$$y = \frac{1}{2}\,\ell n\left(\frac{1+\beta\cos\theta}{1-\beta\cos\theta}\right)$$

where $\beta = v/c$ and θ is the angle with respect to the beam. One gets η by setting $\beta = 1$ so that η depends only on θ. Figure 1 shows y(η) for a particle moving with the same velocity as the LHC lead beam. It is helpful to note that $\eta \approx$ y as long as $v_z \approx$ c $\cos(\theta)$. The two quantities become different as $\cos(\theta)$ becomes sufficiently close to unity that the difference between c and β becomes significant.

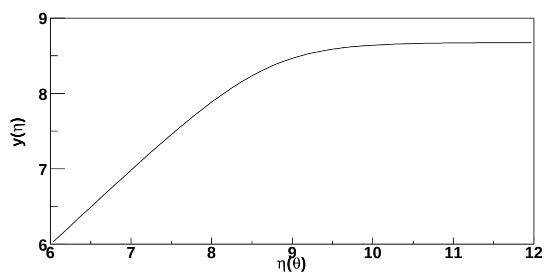

Fig. 1. Rapidity of a beam velocity particle as a function of pseudorapidity.

2. Čerenkov Sampling Calorimetry

All three detectors consist of quartz fibers in a heavy metal matrix. There are several compelling reasons for using this type of detector [2, 5].

The diameter of hadron showers is substantially smaller than in detectors that measure total ionization (almost every other type of detector). Without this reduction on shower diameter the three forward angle detectors would produce little useful physics.

With quartz-fiber detectors a hadron shower has about the same radius as an electromagnetic shower, which is of the order of the Molière radius, 1.69 cm for Fe and 0.93 cm for W. With most other detectors it is of the order of the nuclear interaction length, 16.8 cm for Fe and 9.6 cm for W.

The quartz fibers confer additional advantages. The light production is instantaneous, faster than any scintillator; and the quartz can be made highly resistant to radiation damage.

Nearly all of the Čerenkov light is from electron-positron pairs and Compton scattered electrons from the interaction of photons with the heavy metal. The quartz fiber devices are excellent electromagnetic calorimeters that are linear with energy and have good energy resolution. They can detect hadrons because the interactions of high-energy hadrons result in pions. It is the photon pairs from the neutral pions that eventually result in Čerenkov light.

Čerenkov light is highly directional; but because the electrons and positrons that produce the light are almost isotropic, the orientation of the fibers in the metal matrix has only a small effect on the amount of light collected. Rotating the fibers to the Čerenkov angle of approximately 45° from the direction of the incoming hadrons only doubles the amount of light collected.

3. HF

The Hadron Forward calorimeter [2,6] functions both as an electromagnetic calorimeter and as a hadronic calorimeter. Only half of the quartz fibers extend to the front of the detector so that they can collect Čerenkov light from incident photons and electrons. The other half of the fibers starts 22 cm back from the front face, well beyond the reach of purely electromagnetic events (22 cm = $12.5 \times X_\circ$ for iron). The spacing of the fibers in the iron matrix is 5 mm which allows the showers to be sampled by many fibers. Each of the HF modules, one at each end of CMS, contains half a million quartz fibers viewed with 2000 phototubes.

Neutrinos and other non-interacting products that may be formed at LHC energies can not be observed directly in CMS, but they can be observed as missing transverse momentum. With a maximum angle of 5.7° the maximum transverse momentum carried by a single particle hitting HF is small. None the less, HF accounts for a large fraction of the total transverse momentum because of the large number and large kinetic energy of the particles.

4. CASTOR

The CASTOR detector, fig. 2, surrounds the beam pipe and is azimuthally divided into eight octants. Each octant is a stack of 210 3 mm thick tungsten plates, separated by planes of quartz fibers. The layers are oriented 45° from the beam axis. Air-core light guides carry Čerenkov light from multiple layers to avalanche photodiodes. The addition of CASTOR [7] makes CMS nearly hermetic in transverse

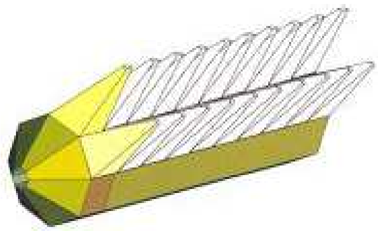

Fig. 2. Schematic of CASTOR showing two rows of internally reflecting air light guides. The interaction point is to the left.

energy (CASTOR gets about 6% of the transverse energy). A good estimate of the missing transverse energy helps with the interpretation of missing transverse momentum. The importance of this function can not be overstated, but here we will focus on the possibility that CASTOR will produce spectacular new physics, as suggested by its name, CASTOR (Centauro And Strange Object Research). CASTOR was originally associated with the ALICE experiment but is now part of CMS.

The LHC will allow, for the first time, laboratory measurements of high-energy heavy-ion events that have heretofore been seen only in cosmic rays. These include centauro events [8] which are characterized by a small particle multiplicity and almost no electromagnetic component. There are also strange hadron-rich events with a strongly penetrating component whose cascades in the detector display a characteristic shape with many maxima and slow attenuation. Other, related types of events have colorful names such as mini-centauro and binocular [9]. Such events should be seen in the far-forward region characterized by a large concentration of baryons. This region is covered by CASTOR and the high η part of HF.

A model for such events has been developed that allows simulations of such events in the CASTOR detector [8]. In this model centauro events arise through the hadronization of a quark-gluon plasma of very high baryochemical potential. The fireball initially consists of u and d quarks and gluons. The high baryochemical potential inhibits the creation of $u\bar{u}$ and $d\bar{d}$ quark pairs but not $s\bar{s}$ pairs. This leads to a strong suppression of pions and hence of photons. As the fireball evolves, "strangeness distillation" occurs through emission of kaons (K^+) [10], resulting in relatively cold, nearly neutral, multi-strange-quark-matter droplets, sometimes called "strangelets" [11]. Figure 3 [12] shows the simulated longitudinal energy deposition of a centauro event and a strangelet compared to a normal event as predicted by the HIJING code. The peak on the left (the front part of CASTOR) in the normal event is from photons. This peak is absent in the centauro event.

CASTOR is well suited for the search for Disoriented Chiral Condensates (DCC) [13]. An important goal of high-energy, heavy-ion research is to probe for the possible existence of chiral symmetry restoration. If this happens the hot and dense nuclear matter formed in a collision may, as it expands and cools, settle into a vacuum state that is quite different from the normal ground state. The decay of the resulting DCC is predicted to have a neutral pion fraction very different

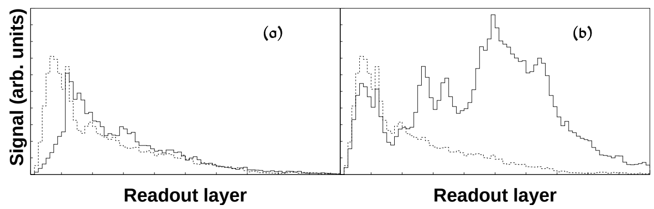

Fig. 3. (a) 140 TeV centauro event, (b) 40 TeV strangelet. The dotted line is a typical, normal event predicted by the HIJING code.

from that which would occur in the absence of DCC production. CASTOR, which makes detailed measurements of the longitudinal energy deposition, is well suited to measuring this neutral pion fraction.

CASTOR can function as an excellent beam-position monitor, with its eightfold azimuthal segmentation surrounding the beam pipe. This, and other considerations have lead to requests to use CASTOR also for lower luminosity (L = 1–3$\times10^{33}$ $cm^{-2}s^{-1}$) pp runs. For these runs considerable radiation damage will occur even with quartz fibers. Experiments are planned to determine a suitable heat treatment regime for annealing out radiation damage. It would be relatively easy to alternate heating wires with quartz fibers in the fiber planes between the tungsten sheets.

5. ZDC

The Zero Degree Calorimeter will measure the number of spectator neutrons from heavy-ion reactions. It will be located between the two separated beam lines at a distance of 140 m from the interaction point (on both ends of CMS). The space available for the ZDC is limited to a width of 8 cm and a length of less than 100 cm. The distribution of spectators have been calculated for Pb + Pb [14]. The diameter of the neutron beam at the ZDC is a centimeter or so, caused by beam divergence and Fermi motion of the neutrons in the lead nucleus.

Some spectator neutrons occur even for the most central collisions [15]. These are from the outer edge where the density is so low that the interaction probability is small. The number of spectator neutrons increases with impact parameter out to about 10 fm. With larger impact parameters the number of neutrons decreases because the fraction of the neutrons that remain bound in charged fragments becomes larger. These charged fragments are swept away by the beam magnets and do not reach the ZDC.

Several groups have proposed ZDC designs featuring radiation resistant quartz fibers in tungsten. Some designs have fibers parallel to the beam, as with HF and the NA50 experiment at the CERN SPS [16]; others have fibers at 45° as in CASTOR and the ZDCs at RHIC [17]. As with CASTOR, there are good reasons to use the ZDC for pp as well as with heavy ions. We estimate that with pp, the dose in parts of the ZDC would be of the order of 50 Grad/year, enough to cause unacceptable darkening in even the most radiation resistant quartz fibers. The detailed design may depend on results from studies of thermal annealing of quartz fibers. There is also a design under consideration that would use gas detectors, which would not be subject to radiation damage.

6. Conclusions

At LHC energies important physics will be missed if the very high rapidity region is excluded from the measurements. For $\eta > 3$ (angles less than $5.7°$) the extremely high particle fluxes require detectors that have the minimum possible hadron shower diameter and are resistant to radiation and very fast. Detectors that measure the amount of Čerenkov light in quartz fibers embedded in a heavy metal matrix are superior to almost all other types of detectors in this environment.

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