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EXOTIC PHYSICS AT THE LHC WITH CASTOR IN CMS

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Cosmic-rays sometimes produce showers of unusual composition that contain particles with energy-loss profiles different from all known particles. The Large Hadron Collider (LHC) will produce, for the first time, nuclear collisions at the extremely high energy characteristic of the cosmic-ray events. The CASTOR detector, a part of the huge CMS experiment, is designed for detailed studies of the products corresponding to the cores of cosmic-ray showers. It will cover angles of 0.1° to 0.7° from the beam. It will be divided azimuthally into 16 segments and longitudinally into 18 segments. It is assumed that cosmic ray showers are caused by nuclei, protons through iron, hitting the atmosphere. If CASTOR does not find events that can be identified with the anomalous cosmic-ray events, this assumption may need to be reconsidered. Pb-Pb collisions with the LHC will have an energy 28 times that of Au-Au collisions studied at RHIC. With this huge increase in energy a wealth of new phenomena is almost assured. Because of the much larger mass number, Pb-Pb events can be expected to show exotic phenomena that is beyond the reach of cosmic rays.

1. Introduction

The original motivation for CASTOR (Centauro And Strange Object Research)^{1,2} was to study, in the laboratory using heavy-ion beams from the LHC, unexplained types of events seen in cosmic rays. The physics program for CASTOR as part of CMS now goes well beyond the study of cosmic-ray related phenomena. It will also be used for diffractive and low-x physics in pp and pA collisions. It will test the

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nonperturbative region of QCD at Björken- x as small as $\sim 10^{-6} - 10^{-7}$ and allow a detailed study of the Color Glass Condensate for which there is some evidence in RHIC data.³ In addition there is the tantalizing possibility of finding something completely new.

CASTOR is a calorimeter for detecting particles at 0.1° to 0.7° from the beam direction ($|\eta| = 6.6$ to 5.2) with 16-fold azimuthal segmentation and 18-fold segmentation in the longitudinal direction. CASTOR, along with Totem-T2⁴ a small tracking detector in front of CASTOR, is a complete unit producing data that can be studied independent of the rest of CMS. The data for a single event from this unit is orders of magnitude smaller than that for a full CMS event. The smaller data sets can be analyzed by a single physicist, whereas the analysis of full CMS data is much more demanding. A massive computer network will allow access to CASTOR data by any interested physicist.

CMS (Compact Muon Solenoid) is one of the two large multipurpose experiments at the Large Hadron Collider (LHC) now under construction at CERN. When the LHC begins operation in 2007-2008, it will be the highest energy machine for both proton-proton and heavy-ion collisions in the world, with p-p at 14 TeV (7 times larger than currently available, p- \bar{p} at Fermilab) and Pb-Pb collisions at center-of-mass energies per nucleon pair of 5.5 TeV. The factor of 28 increase in nucleus-nucleus center-of-mass energy, compared to the most powerful existing machine (0.2 TeV Au-Au at RHIC), will be the largest jump ever in the history of the field.

2. Cosmic Ray “Exotic” Phenomena

The CASTOR project was inspired by unusual events with an abnormal ratio of hadrons to photons, either a strongly pronounced⁵ or a strongly reduced⁶ hadronic component. Such events, characterized by abnormal hadron dominance (reduction), seen both in multiplicity and in energy content, are called *Centauros* (*anti-Centauros*). Centauros have been detected in emulsion chamber experiments at Mt. Chacaltaya and in the Pamirs, at energies above $\sim 10^{15}$ eV. Hadron-rich families constitute a few percent of all high energy events, and the data reveal the existence of several types of Centauro species such as: Centauros of original type, Mini-Centauros and Chirons.

The other exotic phenomenon is the so-called *strongly penetrating component*, which often accompanies the hadron-rich events. The strongly penetrating component has two forms. At first, it was observed in the form of strongly penetrating cascades, clusters of showers or the so-called “halo”.⁷ A second pattern shows an anomalously strong penetrability of some objects in their passage through the atmosphere. This phenomenon manifests itself by the characteristic energy deposition pattern of shower development in deep chambers (calorimeters), which shows a slow attenuation, a strong penetrating power and many maxima. These various features may be related and perhaps are different manifestations of the same phenomenon.

The Centauro-related phenomena are described in the review.⁷

3. Possible Explanations

The possibility that fluctuations in normal air showers mimic Centauro-like exotic events has been studied and excluded by many authors. It is believed that Centauro-related phenomena cannot be due to any kind of statistical fluctuations in the hadronic content of normal events and/or in the development of nuclear-electromagnetic showers. Although many unconventional models have been proposed to explain these phenomena, their interpretation still remains an open question. The opinion that the likely mechanism for Centauro production is the formation of a quark-gluon plasma has been incorporated in many proposed models. New ideas are based on the DCC (Disoriented Chiral Condensate)⁸ mechanism or the evaporation of mini-black holes.⁹ Most of the models are not able to explain simultaneously all features of the Centauro-like events and they are mainly concentrated on the interpretation of the basic Centauro anomaly, i.e. the extreme hadron-rich composition. The exceptions are strange quark matter (SQM) based scenarios, which give the possibility of a simultaneous explanation of both the hadron-rich composition and the unusual features of the strongly penetrating component. According to the SQM fireball model,^{10,11} Centauro arises through the hadronization of a QGP fireball of high baryochemical potential, produced in the forward direction in nucleus-nucleus collisions. Strangelet formation via a mechanism of strangeness distillation is possible and the hypothesis that strangelets can be identified as the strongly penetrating particles has been checked by simulations.¹¹ The simulations show that transition curves, produced by strangelets during their passage through the chamber, resemble the experimentally detected long many-maxima cascades. The new results obtained in remeasurement of the Centauro I also support the SQM scenario.¹² Different models proposed to explain Centauro-related phenomena are described and discussed in.^{7,13}

The SQM, initially proposed by E. Witten, has been the subject of many recent theoretical works. Its existence could have strong cosmological consequences because it is a candidate for dark matter and because the appearance of events above the GZK energy threshold could be explained by assuming the presence of strangelets in the primary cosmic ray spectrum.

4. CASTOR

CASTOR^{1,2} is a tungsten/quartz Čerenkov detector that is $\sim 10.2 \lambda_i$ in length and azimuthally symmetric around the beam pipe. Tungsten, with its short nuclear interaction length (9.6 cm), is used because of the limited available space and the high energy of the particles to be detected. The large ratio of the nuclear interaction length to the radiation length in tungsten ($\lambda_i/X_o = 27.4$) facilitates the study of structures appearing in the longitudinal development of cascades caused by successive interactions or decays of strongly penetrating objects.

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The quartz plates are tilted at 45° in order to efficiently capture the Čerenkov light. This angle also makes the detector insensitive to particles coming from the rear, caused by beam-gas collisions from beam packets passing through CASTOR on the way to the interaction point. CASTOR is azimuthally divided into 16 semi-octants and longitudinally into 18 segments and is located 14 m from the interaction point and covers the pseudorapidity range $5.2 < \eta < 6.6$. Photomultiplier tubes measure the Čerenkov light produced in the quartz plates by relativistic, charged shower particles. Multiplicity information from the Totem-T2 tracker, placed in front of CASTOR, will complement the CASTOR calorimeter measurements.

Prototypes of sections of CASTOR have been constructed and tested with electron, pion and muon beams at the CERN-SPS, giving satisfactory results.^{14,15} Several options and different technical solutions have been investigated. Tests using quartz fibers and quartz plates showed that quartz plates give more light with better energy resolution. The width of the transverse size of the hadronic cascade has a standard deviation $\sigma_H = 5.2$ mm. The electromagnetic cascade is considerably smaller, having $\sigma_{EM} = 1.9$ mm, in agreement with Monte Carlo simulations.

5. Exotic Physics at the LHC

The LHC will be the first accelerator to effectively probe the very high energy cosmic ray domain, close to the end of the cosmic ray spectrum (the “ankle” region). Both experimental data and model predictions indicate that the forward rapidity region is the most favorable place for the production and detection of the above mentioned exotic phenomena. Favorable conditions for exotic event production are expected for the pseudorapidity region $\sim 5 < \eta < 7$ where the standard event generators (HIJING, VENUS) predict the formation of a high baryochemical potential in central Pb+Pb collisions at energy $\sqrt{s_{NN}} = 5.5$ TeV. Recent results from the BRAHMS experiment at RHIC support the expectation of the existence of a baryon peak at forward rapidities. The proposed new form of QCD matter called the Color Glass Condensate motivated by HERA and RHIC data³ should also be checked at the LHC in the forward direction, where one can reach much smaller values of Bjorken- x than is accessible with present colliders.

A study of detector sensitivity to new effects and the choice of optimal parameters has been made using the Monte Carlo event generator CNGEN,¹⁶ which embodies the SQM fireball model. The exotic species generated in central Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV, have been passed through the calorimeter by means of the GEANT program supplemented by the algorithm for strangelets passing through the apparatus.¹⁷ In^{7,17} the detector performance has been studied for the calorimeter divided into 8 azimuthal sectors and longitudinally into 80 sampling units in each sector, and covering the pseudorapidity range $5.6 < \eta < 7.2$. Different kinds of novel phenomena, such as: Centauros, narrow pion clusters (DCC), stable and unstable strangelets, have been simulated for a wide range of parameters expected with LHC energies. The analysis showed that for deep calorimeters with

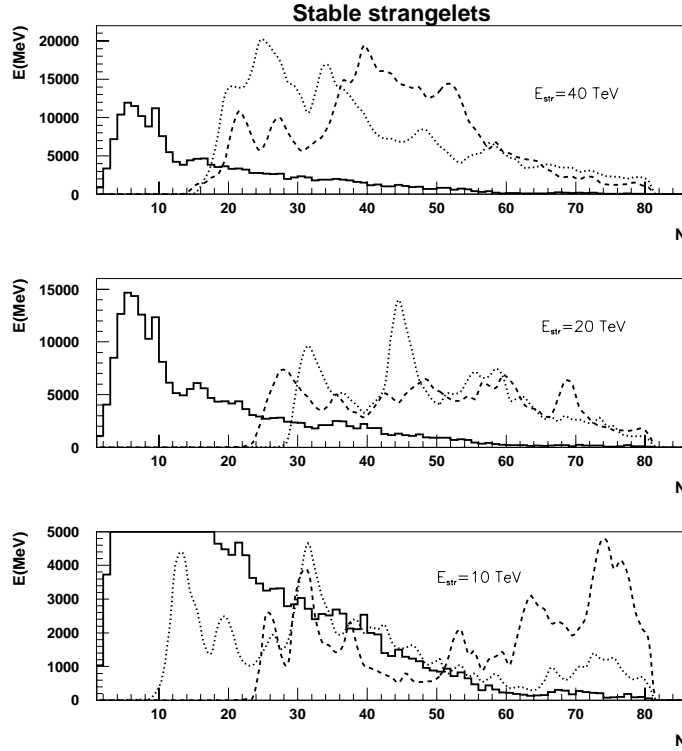


Fig. 1. Energy-loss curves for stable strangelets with energies $E_{str} = 10-40$ TeV and baryon number $A_{str} = 15-40$ (dashed and dotted lines). Energy deposit (MeV) in each of the 80 calorimeter layers, in the octant containing a strangelet, is shown. Full line histograms show the HIJING estimated background for the full energy less the strangelet energy.¹³

fine longitudinal segmentation different exotic species produce characteristic signals that may be distinguished from conventional background.^{7,18} Energy-loss curves for strangelets in a CASTOR-type calorimeter are characterized by strong penetrating power with many maxima. *The energy deposition pattern in a deep calorimeter provides an excellent signature of exotic phenomena.* Two examples of energy-loss curves for stable strangelets are shown in each pane of Fig. 1.

In a calorimeter divided into 16 azimuthal sectors and longitudinally into 18 readout units the strangelet energy-loss curves have a wave-like structure.^{2,19} Simultaneous investigation of fluctuations in the longitudinal development of the energy loss profile and the azimuthal asymmetry allow the extraction of the strangelet signal from the conventional background at a level of about 3σ even for low energy (~ 7 TeV) strangelets. A substantial part of Centauro decay products ($\sim 60\% - 70\%$) and strangelets ($\sim 8\% - 10\%$) are found to fall into the CASTOR acceptance.

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