CASTOR: CENTAURO AND STRANGE OBJECT RESEARCH EXOTIC ASPECTS OF FORWARD PHYSICS AT THE LHC*

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CASTOR, a unique experimental design to probe the forward rapidity region at the LHC, is presented. Motivation and possibilities to search for a QGP, via unconventional signatures and in a region largely left unexplored by current and future high energy heavy ion experiments, are discussed.

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1. Introduction

Current and future high energy heavy ion experiments are concentrated mainly on a study of the high temperature baryon-free midrapidity region. The potentially very rich field of novel phenomena expected to appear in the baryon-rich environment motivates to complement the CERN heavy ion program and to investigate the forward phase space at the LHC. Such theoretical ideas as the existence of a critical endpoint on the phase diagram [1] or appearance of different quark condensates and phase transitions between them attract a lot of attention. Colour superconductivity, colour superfluidity [2] or change of the order of phase transition at the endpoint should lead to characteristic experimental consequences. Also some experimental results, coming from cosmic rays and also accelerator experiments encourage to study particle production at small angles. The proposed new form

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of QCD matter called the Colour Glass Condensate (CGC), motivated by HERA and RHIC data [3] should be checked at the LHC, where in the forward direction one can reach much smaller values of Bjorken-x than these accessible in the present colliders.

The CASTOR project was inspired by the anomalous observations registered in cosmic ray experiments. The physics programme of the project, initially dedicated to study different extreme fluctuations expected to appear in the forward region in Pb+Pb collisions at the LHC, has been recently enriched and CASTOR will contribute not only to heavy ion studies, but also to diffractive and low-x physics in pp and pA collisions. It will give the opportunity to test a nonperturbative region of QCD at Bjorken-x as small as $\sim 10^{-6}$–10^{-7}.

The purpose of this work is to describe of the primary goal of the project, *i.e.* looking for a Quark Gluon Plasma (QGP) via some novel, unconventional signatures.

2. Centauro-like phenomena in cosmic ray experiments

The exotic phenomena which inspired the CASTOR project were discovered in mountain cosmic ray experiments at Mt. Chacaltaya and in the Pamirs. Typical detectors used in these experiments, being sandwiches of a lead absorber and sensitive layers (X-ray films or nuclear emulsions) consist of upper and lower chambers, and sometimes the carbon target between them. The upper chamber mainly detects the electromagnetic component, generated in the interaction of a cosmic ray particle with an air nucleus, in the atmospheric layer above the apparatus. In the lower part of the detector, mainly hadrons are registered. Usually, a part of the event seen in the upper detector is several times larger than its continuation into the lower detector. In a "normal" event, registered in such apparatus, the hadronic component constitutes less than 30 % of the total visible energy. Thus, the events with the contrary situation, were a big surprise. The puzzling events, called *Centauros, characterised by strongly reduced (sometimes close to zero) electromagnetic component and abnormal hadron dominance*, seen both in a multiplicity and in an energy content, have been detected at energies above $\sim 10^{15}$ eV. Hadron-rich families constitute a few percent of all high energy events and the experimental data reveal the existence of several types Centauro species such as: Centauros of original type, Mini-Centauros and Chirons [4, 5].

The first Centauro I, found in 1973, has been recently remeasured. The big surprise was the finding [6, 7] that the group of cascades detected in the upper chamber flies at a slightly different direction than the cascades in the lower chamber. Using the standard procedure of analysis, the "upper" showers cannot be classified as belonging to the family detected in the lower chamber. The recent discussions [6–8], and especially conclusions from [7], which exclude the trivial apparatus origin of this effect, make Centauros much more puzzling species than it was thought before.

The second exotic phenomenon, so-called *the strongly penetrating component* is *very frequently accompanying the hadron-rich events*. This phenomenon manifests itself by the characteristic energy deposition pattern revealed in shower development in the deep chambers indicating the slow attenuation, strong penetrative power and many maxima structure. The existence of such anomalous cascades, firstly observed among the secondaries in the Centauro-like event in 1981 [9] has been confirmed in [10].

Some unconventional models succeed in explanation of a hadron rich composition of Centauros (see [5, 8]), but only the model of the strange quark-matter (SQM) fireball [11] supplemented with the idea of formation [12] and passage of strangelets through the matter [13] explains simultaneously both phenomena. According to this model Centauro arises through the hadronization of a QGP fireball of very 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 [12, 13]. The SQM, containing a comparable fraction of u, d and s quarks, initially proposed by E. Witten, is recently the subject of many theoretical works. Its existence could have strong cosmological consequences because it is a candidate for dark matter and many cosmic ray anomalies are proposed to be explained by assuming the presence of strangelets in cosmic ray spectrum [14].

3. Exotic physics at the LHC

The LHC will be the first accelerator to effectively probe the very high energy cosmic ray domain. We expect favourable conditions for exotic events production in central Pb+Pb collisions at energy $\sqrt{s} = 5.5\ A$TeV, where the standard event generators (HIJING, VENUS) predict the formation of the baryon rich environment at $\sim 5 < \eta < 7$ [15, 16]. Recent results from the BRAHMS experiment at RHIC [17] support our expectation of the existence of a baryon peak at forward rapidities.

The CASTOR detector [18] is a deep calorimeter ($\sim 10.2\ \lambda_i$), azimuthally symmetric around the beam pipe (Fig. 1). It will be azimuthally divided into 16 semi-octants and longitudinally segmented into layers, each consisting of a tungsten absorber plate followed by a quartz plate as active medium. The signal is the Cherenkov light produced in the quartz plates as they are traversed by relativistic charged particles in the showers. The layers are inclined at 45° relative to the impinging particles in order to maximize the Cherenkov light yield. The light propagates along the plates to the outer edge of the calorimeter where it is collected by air light guides and transmitted to photomultipliers (PMTs). The calorimeter is the subdetector of the CMS-LHC experiment. It will be placed at about 14 m from the interaction point to cover the range where the baryon density is expected to be large and hermetically closing the CMS acceptance range up to 13 η units. The CMS experiment supplemented by CASTOR and TOTEM experiments will be the largest acceptance system among the LHC experiments. Multiplicity information from the T2-TOTEM tracker, placed in front of the CASTOR, will complement the CASTOR calorimeter measurements.

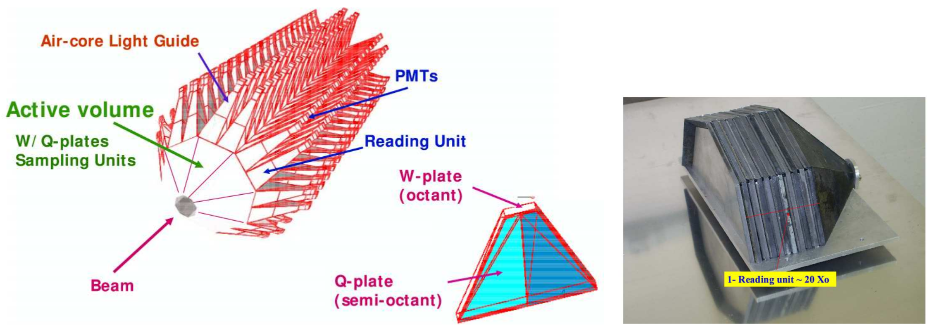

Fig. 1. Scheme of the CASTOR calorimeter and photo of the electromagnetic prototype I [18].

A study of detector sensitivity to new effects and the choice of optimal parameters have been done by means of our Monte Carlo event generator CNGEN [19], embodying the SQM fireball model. The exotic species generated in central Pb+Pb collisions at $\sqrt{s} = 5.5$ ATeV, have been passed through the calorimeter by means of the GEANT program supplemented with our algorithm of strangelets passage through the apparatus [20].

In [5, 16, 20] 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 a pseudorapidity range $5.6 < \eta < 7.2$. We have simulated different kinds of novel phenomena, such as: Centauros, narrow pion clusters (DCC), stable and unstable strangelets, in a wide range of parameters expected for the LHC energies. The analysis showed that the strangelet transition curves in the CASTOR-type deep calorimeters are characterised by strong penetrative power and many maxima structure, and may be distinguished from conventional background. It was concluded that *the energy deposition pattern in a deep calorimeter can be an excellent signature of a QGP state decaying in different exotic ways.*

Recently the new simulations have been performed for the modified version of the calorimeter covering the pseudorapidity range $5.2 < \eta < 6.5$, divided into 16 azimuthal sectors, and longitudinally into 18 RUs in each sector. The left panel of Fig. 2 shows the pseudorapidity distribution of the decay products of the Centauro fireball of a temperature $T_{\mathrm{fb}} = 250$ MeV. In this case about 60 % of Centauro decay products and about 8 % of strangelets fall into the detector acceptance. The two-dimensional lego histogram illustrates a probability of strangelet production as a function of η and energy. Strangelets with energies up to 20 TeV can be produced. At temperature $T_{\mathrm{fb}} = 300$ MeV, even 30 TeV strangelets can be produced.

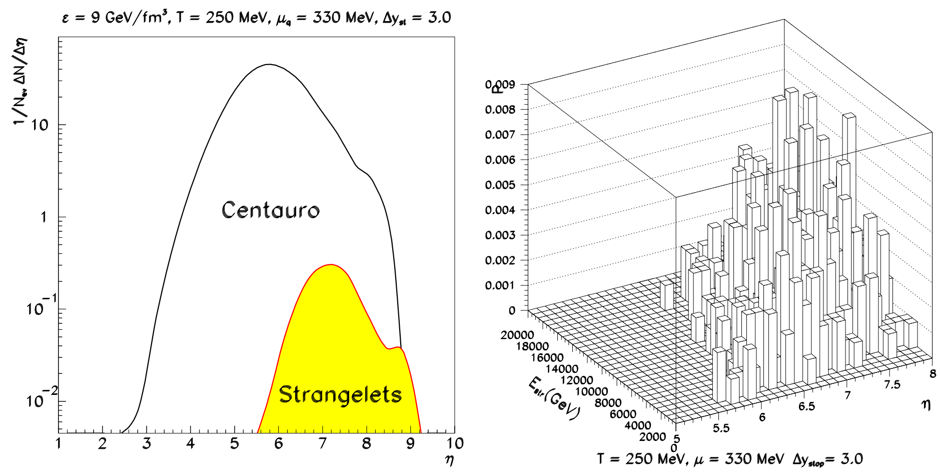

Fig. 2. Pseudorapidity distribution of Centauro decay products and strangelets (left panel) and probability of a strangelet production as a function of energy and pseudorapidity (right panel).

Fig. 3 shows a fraction of strangelets with energies sufficiently high to be detected and recognised in the calorimeter, calculated in two pseudorapidity ranges: $5.2 < \eta < 6.5$ (right panel) and $5.3 < \eta < 6.8$ (left panel). Three curves correspond to different assumed energy densities, all lower than the maximal one expected at the LHC ($\epsilon_{\mathrm{max}} \sim 30$ GeV/fm^3). For the stopping power δy_{stop} between $\sim$ 2–3.5, corresponding to a rapidity shift of a Centauro fireball $\Delta y_{\mathrm{fb}} \sim$ 0.5–2.0, we will be able to detect from several up to $\sim$ 25% (for $5.2 < \eta < 6.5$) and 35 % (for $5.3 < \eta < 6.8$) of strangelets produced via the decay of a Centauro fireball.

Strangelet transition curves reveal the wave-like structure and may be distinguished from conventional background if their energy is higher than $\sim$ 7 TeV [18]. Examples of transition curves produced by low energy strangelets [21] are shown in Fig. 4. Signals produced by three different strangelets

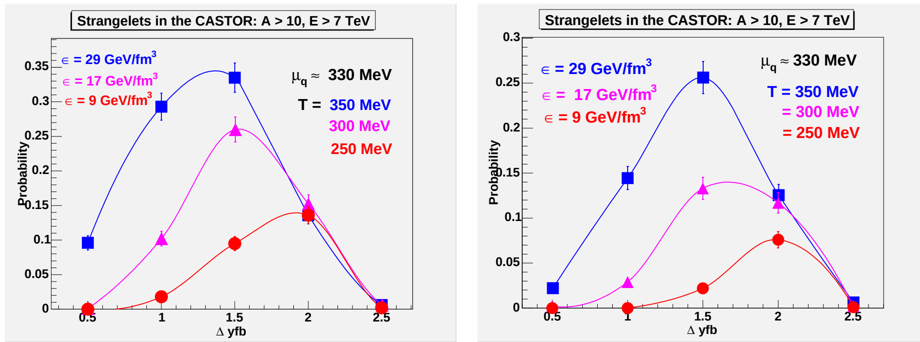

Fig. 3. Probability of production of detectable strangelets in two different ranges ($5.3 < \eta < 6.8$ — left panel, $5.2 < \eta < 6.5$ — right panel), as a function of rapidity shift of a Centauro fireball.

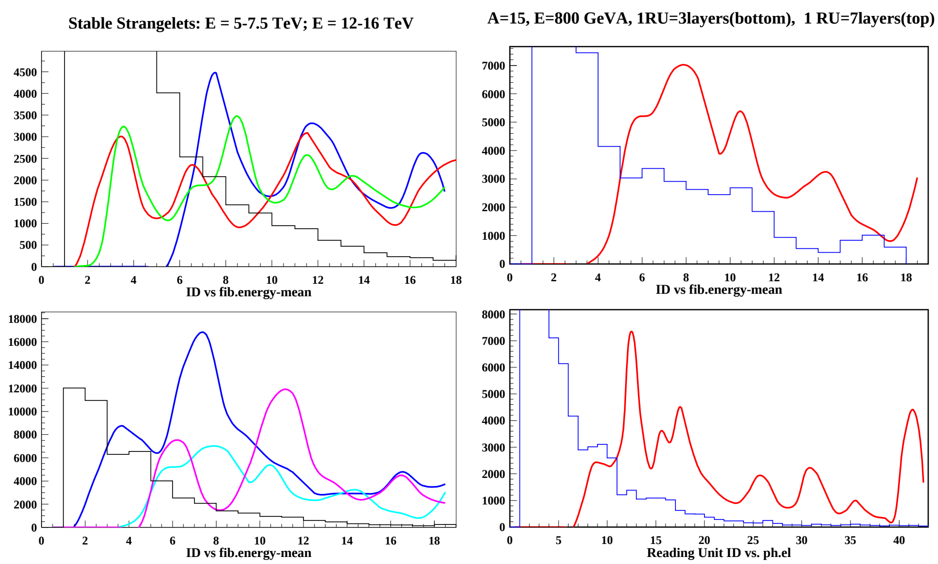

Fig. 4. Energy deposit (MeV) in calorimeter layers, in the sector containing a strangelet. Left panel: Smooth colour lines show signals produced by different strangelets with energies 5–7.5 TeV (upper) or 12–16 TeV (lower). Histograms correspond to the HIJING estimated background. Right panel: Comparison of signals produced by the same strangelet in one azimuthal sector divided into 18 and 42 readout units [21].

with energies 12–16 TeV, shown at the left lower panel of Fig. 4 (smooth colour lines), are high above the HIJING generated background (histogram). Also much lower energy strangelets ($\sim$ 5–7 TeV) give apparent signals at the end of the calorimeter (left upper panel). Comparison of transition curves produced by the same strangelet in a calorimeter divided into 18 and 42 longitudinal segments shows that the many maxima structure is more pronounced in the design with finer longitudinal segmentation (right panel of Fig. 4).

The CASTOR calorimeter electromagnetic prototype I and the prototype II, consisting of electromagnetic and hadronic sections of the total length $\sim 4.3\lambda_{\rm int}$, have been constructed and tested with electron, pion and muon beams at the CERN-SPS, giving the satisfactory results [18,22]. The electromagnetic prototype I, tested in 2003, consisted of four readout units (Fig. 1), arranged side-by-side in four azimuthal sectors. Several options and different technical solutions have been investigated. In particular, comparison of the sector with quartz fibres and quartz plates indicates that a calorimeter with quartz plates is a promising option. Fig. 5 shows a good linearity of response with energy for both sectors. Energy resolution of the sector with quartz plates $\sigma/E \sim 36\%/\sqrt{E}$ (right panel), means that we would measure electromagnetic energy hitting the CASTOR in Pb+Pb collisions at the LHC well below 0.5 %.

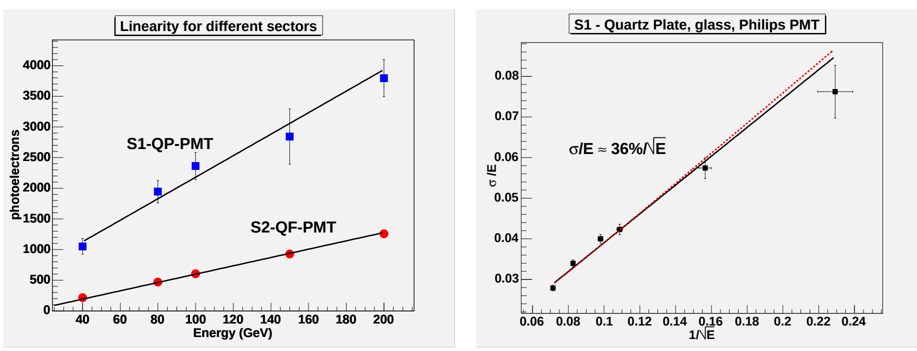

Fig. 5. Linearity in the sectors with quartz fibres and quartz plates (left panel). Relative energy resolution in the sector with quartz plates (right panel). Two fits are shown: $\sigma/E = p_0 + p_1/\sqrt{E}$ — solid line; $\sigma/E = p_0 \oplus p_1/\sqrt{E} \oplus p_2/E$ — dashed line ($\oplus$ means that the terms have been added in quadrature) .

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