The Measurement of Forward Particle Production at LHC

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Abstract—**The measurement of particle production cross-sections in the very forward region is essential for understanding cosmic ray phenomena. Our experiment (LHCf) will measure the neutral-pion production cross-section at the LHC. The "laboratory" equivalent energy of the 7+7 TeV proton collisions in the LHC is 10^{17}eV. In this paper some of the details of the LHCf experiment are introduced.**

I. Introduction

IN cosmic ray physics, a long-standing puzzle has existed over the composition of primary cosmic rays. One example was seen in the discussions in the 1980's concerning whether or not the nuclear interaction process changes in the very high energy region. For example, the Chacaltaya emulsion chamber group asserted that in the very high energy region, ≥1 PeV, nuclear interaction processes must be changed. An alternative interpretation, proposed by the Mt. Fuji group, was that the emulsion chamber experiments can be understood if the highest energy primary cosmic rays are dominated by heavy nuclei rather than protons. One way of investigating this is to study the spatial development of air showers. The showers initiated by heavy primaries develop quickly and decay rapidly in comparison with showers induced by protons.

Since the interpretation of cosmic ray data is dependent on the hadron production cross section for neutral-pions in the very forward region, the UA7 experiment was performed (by some of us) at the SPS p-pbar collider in the late 1980's [5]. We used the Roman pot [1] of the UA4 collaboration [2] and installed shower calorimeters inside and outside the beam pipe. The shower counters were made of tungsten plates and silicon strip sensors [3]. The corresponding "laboratory equivalent primary energy" was 1.5×10^{14} eV and the production cross-section of neutral pions in the very forward region with Feynman X variable $X_F \geq 0.1$ was measured. The measurement of particle production in the very forward region of colliders presents significant challenges. It is worthwhile to mention here that our experimental technique has been mentioned in the early proposal of the GLAST experiment and has triggered US people to write a proposal to NASA, using the silicon calorimeter for a space experiment in order to measure high energy gamma rays in GeV region [4].

The results of UA7 experiment [5] have shown that the pion production cross-section in the very forward region does not change drastically in the energy region between 10^{12} and 10^{14} eV. Feynman scaling was shown to be valid in the very forward region in the above energy range. We combined the UA7 results with the data obtained by the UA5 collaboration, after removing the leading particles observed by the UA5 spark chamber, and have shown that the two data sets are smoothly connected [6].

II. New Challenge at the Large Hadron Collider

Again we need to make the same type of experiment as UA7 at the LHC. New problems have appeared in high energy cosmic rays in the more than ten years since UA7. One main problem is again related with the composition of primary cosmic rays at very high energy 10^{17}-10^{19}eV. Another is a well known problem of whether or not cosmic rays beyond the GZK cut-off exist.

Cosmic rays enter at the top of the atmosphere and produce nuclear cascade showers. In an electro-magnetic cascade the shower maximum X_{max} can be written in units of radiation length as $X_{max} \approx \ln(E_0/\varepsilon)$ where E_0 is the primary energy and ε is the critical energy in air (82.4 MeV). However in the case of nuclear cascade showers, the shower maximum depends on the nuclear interaction model. If the experimental data on shower development is modeled by the Monte Carlo simulation code SYBILL, then the primary composition of cosmic rays does not change in the energy range 2×10^{14} - 3×10^{19} eV[7]. However if the shower development is modeled by the simulation code DPMJET v2.5, then the composition of primary cosmic rays

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must change drastically above 10^{16}eV, from proton dominant to heavy nuclei dominant. Thus the conclusion on the composition of primary cosmic rays is completely dependent on the model. Therefore it is very important to establish the production cross-section of neutral pions emitted in the very forward region with the Feynman variable $X_F \geq 0.1$ and the laboratory equivalent energy $>10^{16}$eV.

Another important problem is in the energy region of the highest energy cosmic rays, $E_0 \geq 10^{20}$ eV. It is expected that cosmic rays with energy greater than $4\text{x}10^{19}$eV are not confined in our galactic halo, even if the halo is filled by a ~ 3 micro Gauss magnetic field. If the magnetic field does not exist in the halo but only in the galactic disk, it is even more difficult to imagine that cosmic rays with energy greater than $4\text{x}10^{19}$eV have a galactic origin.

There is also difficulty imagining that super high energy cosmic rays have an extra galactic origin. The proton spectrum is expected to have a high energy cutoff ~ 10^{20}eV owing to inelastic interactions with the 3K cosmic background radiation (the Grisen-Zatsepin-Kuzmin cut off).

However the AGASA air shower experiment has reported air showers with energy exceeding 10^{20}eV. On the other hand the Hi Res experiment reports a declining feature of the energy spectrum in the highest energy region[8] which is consistent with the GZK cut-off.

The difference between the cosmic ray energy spectra of AGASA and Hi Res may arise from systematic errors between the two different detection methods. AGASA measured air showers with a surface array detector while Hi Res used a total photon detection technique that measured atmospheric fluorescence. The total photon detection method is independent of the nuclear interaction model in principle, but is subject to other experimental biases such as the attenuation of photons in the atmosphere due to the amount of the aerosol and/or an ambiguity determining the position of the shower center. A surface detector like AGASA has an unavoidable systematic error owing to the dependence of shower development on the nuclear interaction model. In fact if we could shift the energy scale of the AGASA results downward by 20% then the two experimental results would coincide. To understand and resolve this problem, we need to perform a "new UA7 experiment", LHCf, at the LHC, using the highest energy accelerator in the world.

III. *The LHCf experiment*

We will install two 44 radiation length compact tungsten calorimeters at zero degree collision angle on both sides of and 140m away from the beam intersection point of IP1 (Arm #1 and Arm #2). The shower calorimeters will use scintillation fiber or silicon strip detectors for identification of the shower center. To minimize the probability of multiple high energy photons in a single tower calorimeter, the calorimeters have been segmented into two towers with transverse cross-sections 2cmx2cm, and 4cmx4cm for the Arm #1 detector (Fig.1) and 2.5cmx2.5cm and 3.2cmx3.2cm for the Arm #2 detector.

At +/-140m from the collision points of LHC, the vacuum beam pipe splits from a single common beam pipe facing the IP into two beam pipes facing the arcs (the Y vacuum chambers). The LHCf detectors are installed in the 96mm gap between the two beam pipes and at zero degree collision angle. The proton beams and secondary charged particles are bent by the D1 beam separation dipole magnet located +/-82 m from the IP. Only neutral particles such as photons, neutrons and neutral kaons are incident on the detectors +/- 140m from the IP and inside the TAN neutral particle absorber instrumentation slot. Normally a luminosity monitor BRAN will be installed in this slot behind 30cm of Cu absorber. During the time LHCf is installed the 30cm Cu absorber will be exchanged with the 44 radiation length W calorimeters. LHCf will be replaced with the Cu absorber when the luminosity exceeds $10^{30}\text{cm}^{-2}\text{s}^{-1}$.

The LHCf experiment will carried out during the initial low luminosity commissioning of the LHC, when the luminosity is $L = 5\text{x}10^{28}\text{-}1\text{x}10^{30}/\text{cm}^2\text{sec}$. According to our simulations, after an exposure of 2 minutes @ $L = 10^{29}/\text{cm}^2\text{sec}$, we will obtain an significant scientific results. For obtaining reliable data on neutral pions, we will need about an hour of exposure time. By then we will have collected about 50,000 neutral pions and this is enough data for the cosmic ray simulation codes.

Fig. 1. The Arm #1 detector. The signals deposited in the plastic scintillators are transferred by the optical fibers to the photomultipliers.

IV *A possible scenario for 2007-2008*

The LHCf detector #1 was prepared in July 2006. The detector was shipped to CERN and exposed at the CERN SPS H4 beam line (Fig. 2). For the first step, the calorimeter was exposed to a muon beam and the pulse height of minimum ionizing particles was recorded with 1,000V bias on the Hamamatsu photomultipliers R7400U. The high voltage was then reduced to 450V and the calorimeter was exposed to an electron beam to produce electromagnetic showers. The decrease in photomultiplier gain from 1000V to 450V was measured with a N_2 laser and found to be a factor of 150. Thus the number of minimum ionizing shower particles in each scintillator was recorded and compared with em shower theory. The LHCf detector #1 is scheduled to be installed in the beam tunnel in January 2007 at its 140m location from IP1. The LHCf detector #2 is scheduled to be installed in October 2007.

During initial LHC commissioning with a single proton beam we will see neutral particles from beam-gas collisions. Then we will estimate the location of the center of the proton beam and obtain the residual gas distribution in the +/- 82m straight section of the beam pipe between the D1 magnets by applying the two photons mapping into one neutral pion technique. During LHC commissioning with two beams the double arm system will be very useful for identifying "the first evidence" of beam-beam collisions since we are considering introducing a classical coincidence trigger system to suppress beam-gas collisions.

An estimate of the LHC luminosity L will be obtained assuming the inelastic cross-section is 80 ± 16mb. The acceptance of our detector is completely geometrical, so if the Monte Carlo code is correct, we can infer luminosity L from the counting rate of the photons with 20 % error bars. However the production cross-section in the very forward region is unknown at the high collision energies of LHC and therefore a systematic error must be associated with this estimate.
By itself the LHCf counting rate will give a measurement of relative luminosity that can be correlated with measurements of relative luminosity with the BRAN detectors in the TAN. In order for LHCf to measure absolute forward cross-sections an independent method of measuring absolute luminosity must be used. One possibility is to use machine measurements of bunch intensity and rms beam size to estimate absolute luminosity (van der Meer method). Later, after the LHCf experiment has been completed, the TOTEM collaboration and the forward group of ATLAS will obtain absolute measurements of the total pp cross-section which can be used for normalization of the forward cross-sections measured by LHCf. We hope that we will be able to obtain to obtain scientifically important data using the LHC by early 2008.

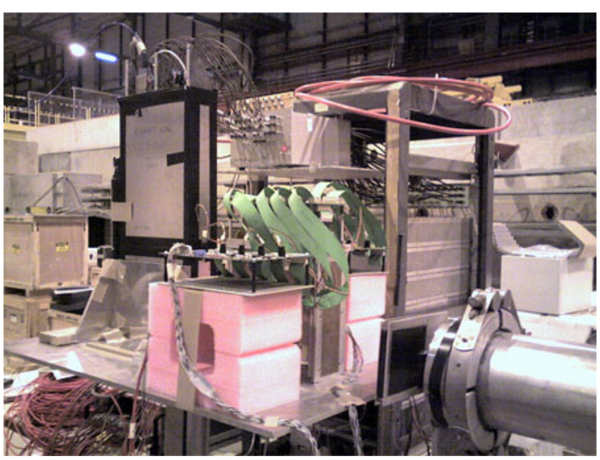

Fig. 2. A photograph of the beam test of the LHCf detector in the SPS H4 beam line. The LHCf detectors are inside the aluminum box with black tape for suppression light leaks. (The left side photo)

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NOTE IN ADD:

The LHCf proposal has been officially approved by the CERN LHC committee and Research Board in July 2007. The details of the development on this project can be seen in other papers.[10]-[14]. The details of the project can be found in the CERN archives: http://doc.cern.ch/ and put LHCf, then they are found out at

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