Verification of hadron interaction models of cosmic rays at 10^{17} eV by the LHCf experiment

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Abstract. Ultra high energy cosmic rays (UHECR) have been studied by extensive air shower experiments such as AGASA, HiRes and AUGER. However implication of their data depends on model of air shower development at such high energy where yet no experimental verification is available. The LHCf experiment will provide unique data to calibrate existing hadron interaction models at 10^{17} eV in the very forward region which will reduce model uncertainty in UHECR experiments. Experimental overview and expected results are presented.

Keywords: Cosmic ray, high energy interactions, LHC, extensive air showers
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INTRODUCTION

Ultra high energy cosmic rays (UHECRs) of which energy above 10^{19} eV have great scientific interest since their origin, propagation and interactions are unknown and may yield information about new physics. There has been a big progress in recent observational studies in UHECR's by very large extensive air shower experiments such as AGASA, HiRes and AUGER. The one of interesting issues is existence of UHECR's beyond GZK cut-off. Ten years ago AGASA reported that the UHECR's at the highest energy may extend beyond GZK cut-off[1]. However results from the HiRes experiment or the Auger experiments show consistent results existence of the GZK cut-off feature[2, 3]. Possible energy scale uncertainty among the group has been discussed as a source of this discrepancy.

Chemical composition of the UHECRs is also an important issue since it is relevant to their origin and also to their energy per nucleon. The Auger group has reported correlation of arrival direction of the highest energy events to the distribution of active galactic nuclei (AGN)[4]. This would suggest that the primaries above 4×10^{19} eV are likely mostly protons because they can travel through nearby inter-galactic space almost without deviation by magnetic fields. On the other hand, the elongation rate or the muon yield measured by Auger would suggest that the primary composition is a mixture of protons and heavy nuclei (Fe)[5]. If it turns out that the highest energy primaries have significant Fe composition then the "GZK-cut off"-like feature could perhaps be interpreted as photo-dissociation by cosmic microwave background (CMB) photons. One must need a consistent understanding of all measurements to give definitive answer to the mystery of UHECR's.

Determination of energy or composition of UHECR's depends on a model for air shower development. There are two key quantities at the primary interaction vertices

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which determine the development of air showers; the total inelastic cross section and the particle production energy spectra at very forward angles. It is known that a large part of air showers particles originate from secondary particles produced at a very forward region, since most of the energy flow from collisions concentrate in the very forward direction. In this region non-perturbative aspects of small-x partons plays an important role. Therefore an experimental input is needed to calibrate a model. However only data from the UA7 experiment taken at the S$p\bar{p}$S has been available so far for calibration of the forward neutral pion production spectrum at 10^{14} eV [6].

The LHC, corresponding 10^{17}eV at a laboratory frame, gives a great opportunity to test hadronic interaction models for very forward region at the near UHECR's energy. Inelastic cross section at this energy will be measured by Roman-pot projects planned in the ATLAS or TOTEM [7, 8] experiments. On the other hands, the LHCf experiment is aiming to measure neutral particles at zero degree of 7 TeV proton collisions with small dedicated calorimeters covering pseudo-rapidity $8.7 < |\eta| < \infty$. These data will verify various hadron interaction models such as QGSJET, DPMJET, SYBILL and EPOS at interesting energy for cosmic ray physics above the knee to GZK region. Here we briefly introduce the LHCf experiment. More detail information can be found in the LHCf TDR [9].

THE LHCF EXPERIMENT

There are two massive iron shields, TAN, located $\pm$140m apart from IP1. The two small EM calorimeters (Detector-1 and Detector-2) will be installed in each TAN at the crotch of the Y-shape beam vacuum chambers embedded inside the TAN. At this location, the inner beam separation dipole has swept away all the charged secondary particles so that only neutral particles such as γ-rays from π^0 decays, neutrons or neutral kaons reach the detector. In the case of 7 + 7 TeV collisions, their flux is mostly concentrated within a few cm around the center of the neutral particle flux arriving from the IP, which is the direction of the proton beam at collision projected to the detector plane.

Both the LHCf detectors employ two imaging shower calorimeters. The Detector-1 has two towers of diamond shaped tungsten sampling calorimeters (2cm$\times$2cm and 4cm$\times$4cm) stacked vertically. Each tower consists of 22 tungsten plates ($2X_0$) interleaved with plastic scintillators. The Detector-2 is similar but has rectangle shapes (2.5cm$\times$2.5cm and 3.2cm$\times$3.2cm) in cross section. Each tower has 44 X_0 and 1.3 interaction length. In addition Detector-1 and Detector-2 have 4 layers of scintillating fibers and Si strip detectors providing incident position of showers with accuracy of 200 μm and 75 μ, respectively. The incident positions are used not only to determine P_T but also to correct shower leakage due to small aperture of the calorimeters. Energy resolution is achieved to be $3\%/\sqrt{E(TeV)} + 1.2\%$ for EM showers by this correction. Hadronic showers can be discriminated by measuring the longitudinal shape of shower development. Although the calorimeter has only 1.7 interaction length, energy resolution of hadron showers is still expected to be about 30% at 6TeV by selecting early developing showers. These basic performance has been well confirmed by test beam experiment at CERN-SPS H4 beam line[10].

The LHCf experiment is aiming to measure forward production spectra for inclusive

γ's, π^0's and neutrons to discriminate existing hadronic interaction models or to provide experimental inputs for model tuning. Here we briefly discussed π^0 measurement. Detail description including other channels can be found elsewhere [9].

The π^0 mass can be reconstructed in the invariant mass distribution of two γ's, one each hitting the two tower calorimeters. The expected mass resolution is about 5% after taking into account 5% energy resolution and 0.2 mm position resolution.

Figure 1 shows energy distribution of π^0 events for Detector-2 at the center of the neutral particle flux, i.e. at 0 degree. Here 3 different distributions expected from various interaction models, QGSJET II, DPMJET3 and SIBYLL are shown. One can see the differences in the shape of energy distributions among these models. We tested discrimination based only on the differences in the shape of energy spectra. Here we defined the χ^2 as,

$$\chi^2(\alpha,\beta) = \sum_i \frac{(\alpha N_i^{data}(\beta) - N_i^{model})^2}{(\sigma_i^{data})^2 + (\sigma_i^{model})^2} \tag{1}$$

where $N_i^{data}(\beta) = N(\beta E_{\pi^0})$ is i-th bin of the energy spectrum of π^0's scaled by factor of β for a reference model, $N_i^{model} = N(E_{\pi^0})$ is i-th bin of energy spectrum of π^0's for tested models, α is a normalization factor, β is a scale factor for the energy scale, σ_i^{data} and σ_i^{model} are statistical errors of the i-th bin for the reference model and the tested model, respectively.

Here we conservatively set α and β as free parameters. We compared QGSJET II for reference with DPMJET3 and SIBYLL as tested models. The minimum-χ^2 values obtained for the DPMJET3 and SIBYLL models are χ^2=106, χ^2=83, respectively with DOF=15. On the other hand if we compared DPMJET3 as a reference model with SIBYLL as a tested model, The minimum-$\Delta\chi^2$ was obtained as χ^2=28. Therefore we can discriminate these models sufficiently with shapes of E_{π^0} distributions.

The π^0 mass peak can be also used for the absolute calibration of the energy scale. It also helps for rejection of beam-gas interactions by giving a constraint for location of the neutral pion production vertex.

Measurement of energy spectrum of very forward neutrons is a compartmental to measurement electro-magnetic components. Figure 2 shows the energy spectra measured by LHCf taking into account 30% energy resolution. Even with 30% energy resolution there are significant differences between the models.

STATUS AND FUTURE

Construction of detectors has been done and calibrated by 100-220 GeV electron, proton and muon beams at the CERN SPS H4 beam-line in the summer 2007. The detectors weree finally installed in the TANs during Jan to Feb 2008.

The LHCf experiment is scheduled to take data in the commissioning phase of the LHC machine. The first operation of LHC in colliding beam mode is envisioned at 5TeV+5TeV collisions in late 2008 with low luminosity ($\sim 10^{30}$cm^{-2}s^{-1}) with 43 equally spaced bunches per beam ($\sim 2\mu$sec between bunches). In 2009 LHC will increase energy up to 7TeV+7TeV collisions. The LHCf is being scheduled to take data shortly during these early commissioning mode of LHC operation.

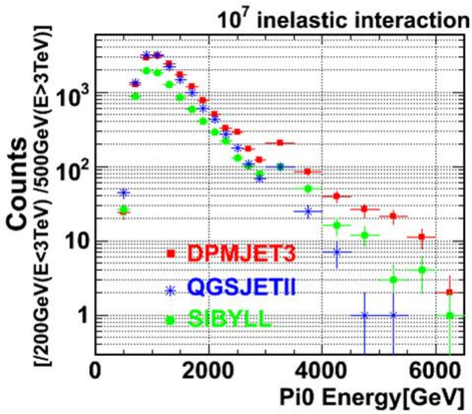

FIGURE 1. Energy distribution of π^0's measured by Detector-2 at 0 degree. Here 3 different distributions expected from DPMJET3, QGSJET II, SIBYLL (from top to bottom) are shown. Note that binning above 3 TeV is different to cope with different statistics.

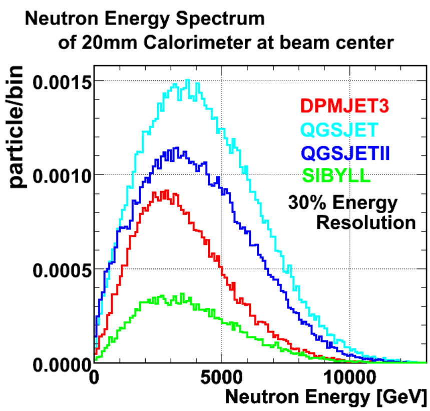

FIGURE 2. Energy distribution of neutrons measured by the 2cm$\times$2cm calorimeter of detector-1 at 0 degree. Here 30 % energy resolution is taken into account by simple Gaussian convolution. Here 4 different distributions expected from QGSJET, QGSJET II, DPMJET3 and SIBYLL (from top to bottom) are shown.

As we will see below operating with such low luminosity still assures an adequate event rate for LHCf. Event rate of γ's is about 500 Hz even at very low luminosity $\sim 10^{29}\text{cm}^{-2}\text{s}^{-1}$. Those for π^0s and neutrons are about 5 Hz at the same luminosity. Thus quite quick measurements can provide enough statistics for the analysis. The LHCf experiment will give an indispensable calibration data for UHECR physics.

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