LHCf Measurements of Very Forward Particles at LHC

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The LHC forward experiment (LHCf) is specifically designed for measurements of the very forward (η>8.4) production cross sections of neutral pions and neutrons at Large Hadron Collider (LHC) at CERN. LHCf started data taking in December 2009, when the LHC started to provide stable collisions of protons at $\sqrt{s}$=900 GeV. Since March 2010, LHC increased the collision energy up to $\sqrt{s}$=7 TeV. By the time of the symposium, LHCf collected 113k events of high energy showers (corresponding to ~7M inelastic collisions) at $\sqrt{s}$=900 GeV and ~100M showers (~14 nb^{-1} of integrated luminosity) at $\sqrt{s}$=7 TeV. Analysis results with the first limited sample of data demonstrate that LHCf will provide crucial data to improve the interaction models to understand very high-energy cosmic-ray air showers.

1. INTRODUCTION

The development of very high-energy cosmic-ray observation in the last decade has dramatically improved the quality of the observation data [1] [2] [3] [4]. However we have not yet obtained consistent interpretation about the nature of the very high-energy cosmic-rays. One of the reasons of this puzzle is the uncertainty of the hadron interaction at the energy range where we could not test with the man-made accelerators so far. Even in the available accelerator energy, we do not have enough data about the very forward cross sections that are important to understand the air shower development. Among hadron collider data, we have only UA7 [5] for π^0 at $\sqrt{s}$=630 GeV and ISR data [6] for neutrons at $\sqrt{s}$=70 GeV.

LHC, however, provides us the best opportunity to study hadron interaction at $\sqrt{s}$=14 TeV, corresponding to 10^{17} eV at the laboratory system. LHCf is specifically designed for measurements of the very forward (η>8.4) production cross sections of neutral pions and neutrons at LHC. These measurements will set crucial anchor points to constrain the hadron interaction models to extrapolate into higher energy.

In this paper, after introduction of the LHCf experiment and operation at LHC in 2009 and 2010, some results from the early data are presented.

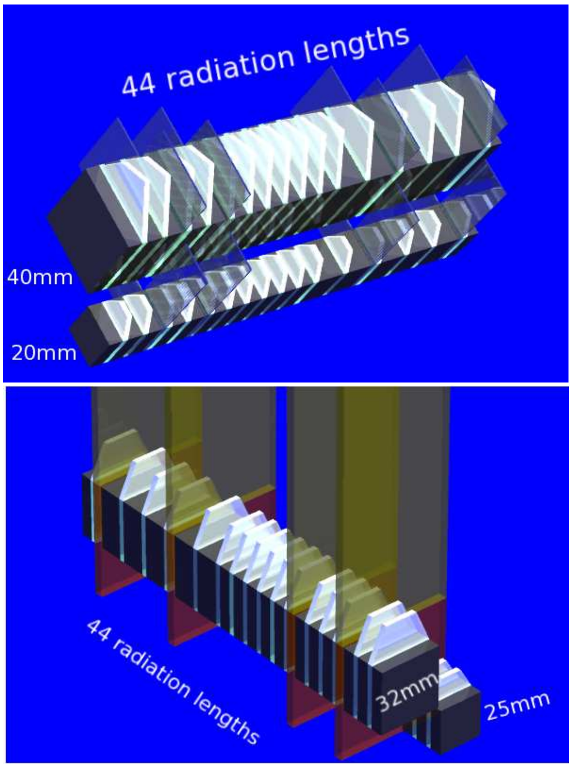

Figure 1: Schematic views of the LHCf detectors (Arm1 and Arm2 in top and bottom, respectively). Plastic scintillators (light green) are interleaved with tungsten (dark gray) layers. Four layers of position sensitive layers (SciFi in Arm1 indicated by light Gray and silicon strip detector in Arm2 indicated by brown) are inserted.

2. THE LHCF EXPERIMENT

The LHCf detectors are installed in the slot of the TANs (Target Neutral Absorber) located ±140 m from the ATLAS interaction point (IP1) and measure the neutral particles arriving from the IP. Inside TAN the beam vacuum chamber makes a Y shaped transition from a single common beam tube facing the IP to two separate beam tubes joining to the arcs of LHC. Charged particles from the IP are swept aside by the inner beam separation dipole D1 before reaching the TAN. This unique location covers the pseudo-rapidity range from 8.4 to infinity (zero degree).

The LHCf detectors are two independent shower calorimeters, named Arm1 and Arm2 installed at the IP8 side and the IP2 side of IP1, respectively. Both detectors consist of a pair of small sampling and imaging calorimeters, which we call a 'tower' hereafter, made of 16 layers of plastic scintillators (3 mm thickness) interleaved with tungsten converters (7 mm for the first 11 layers and 14 mm for the rest). The longitudinal size is 230 mm or 44 X_0 (1.7 λ) in units of radiation length (hadron interaction length). The transverse

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sizes of the towers are 20 mm×20 mm and 40 mm× 40 mm in Arm1, and 25 mm×25 mm and 32 mm× 32 mm in Arm2. Usually the smaller towers cover the zero degree, however, it is adjustable using the vertical manipulators. Four X-Y layers of position sensitive detectors, scintillating fiber (SciFi) belts in Arm1 and microstrip silicon sensors in Arm2, are inserted in order to provide incident positions of the showers. The schematic views of the detectors are shown in Figure 1.

The calorimeters are designed to have energy and position resolutions better than 5% and 0.2 mm, respectively, for electromagnetic showers with energy >100 GeV. Because of the small aperture of the towers, the frequency of multi particle hits in a single tower is reduced to a reasonable level. The double tower structure allows us to detect gamma-ray pairs from the decay of π^0's with a single gamma-ray induced shower in each tower. By reconstructing the invariant mass of gamma-ray pairs, we can identify the π^0's and hence measure their energy spectrum.

Expected energy spectra of gamma-rays at $\sqrt{s}$=14 TeV collisions based on Monte Carlo (MC) simulation using various interaction models are shown in Figure 2. In this plot, statistical errors are taken into account assuming the total number of inelastic collisions to be 10^7 that corresponds to 0.1 nb^{-1} of integrated luminosity. Only short operation of LHCf at the commissioning phase of LHC can provide statistically sufficient data to evaluate existing interaction models.

More detail of scientific goal, technical detail and performance of the detectors are found in [7] [8] [9] [10] [11] [12] [13].

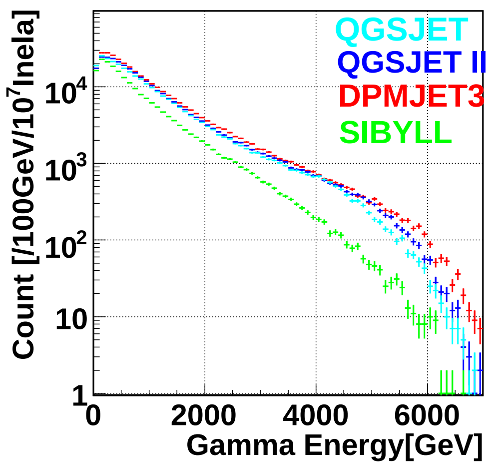

Figure 2: Expected energy spectra of gamma-rays to be measured by LHCf at LHC 14 TeV collisions. Four different models widely used in the cosmic-ray studies are used as generators. Assumed statistics of 10^7 inelastic collisions can be achieved with a very short operation of LHC even at the commissioning phase.

3. OPERATION AT LHC

LHC has succeeded first physics collisions (stable beams) on 6 December 2009 at $\sqrt{s}$=900 GeV. They provided total 0.5M collisions at IP1 in 2009. After a winter shutdown, LHC succeeded collisions at $\sqrt{s}$=7 TeV on 30 March 2010 and is gradually increasing the luminosity. At the time of the ISVHECRI symposium, the integrated luminosity reached at 14 nb^{-1}. Meanwhile they provided 15 times more collisions at $\sqrt{s}$=900 GeV than 2009.

LHCf has successfully started data taking at the first collision and is accumulating data at all stable beam condition. (Note: LHCf has finished operation at this energy at the middle of July 2010 and removed the detectors from the LHC tunnel.) LHCf has accumulated 113k and 100M high energy shower events (>10 GeV approximately) at 900 GeV and 7 TeV collisions, respectively. The trigger of the LHCf detectors is based on the signals from one of the beam monitors (BPTX) and existence of high energy shower in any of the calorimeters. During 2009-2010, LHC has always operated with at least one non crossing bunch (having no pair bunch in the other beam) in both beams. Any high energy particles associated with passage of such bunches at IP1 are thought to be collision products of beam and residual gas in the beam pipe, thus background in our measurement.

4. RESULTS

4.1. Data Processing

In the analyses presented here, we used only early data set. In the 900 GeV analyses, we used data taken in 2009, that will increase about 15 times when we include all data taken in 2010. In the 7 TeV analyses, we used data taken only in Mach 2010, that corresponds to about 1% of all data taken by the time of the symposium. (Only for Figure 5, we used more data.)

For each shower, incident position is determined using the information of the position sensitive layers. The particles fell within 2 mm from the calorimeter edge are removed from the analysis to sustain sufficient energy resolution [12] [13]. After correcting the non-uniformity of the scintillating photon collection based on the position information, the ADC value is converted to the energy deposit and summed up over the layers. Energy of the incident particle is determined from this summation based on the MC simulation tested below 200 GeV. In this energy determination, conversion factor for gamma-rays is applied to all particles, therefore the assigned energy so far is 'gamma-ray equivalent energy.' After the shower leakage correction [12], particles having more than 40 GeV are used in the analyses in the following sections.

For MC simulations, we used various models as generators of the collision particles. Transport from the collision to the detectors in the beam pipe and the detector simulation were carried out using the EPICS package [14]. In the analyses of MC data, same process as data is applied. In the plots compared with data, the entry of MC simulation is normalized to the entry of experimental data.

4.2. Results for 900 GeV Collisions

According to the models, roughly 50% of the particles detected by the LHCf calorimeters is gamma-rays and the rest is hadrons (mainly neutrons and some K^0 in lower energy). To identify electromagnetic and hadronic showers, we defined a simple parameter called '$L_{90\%}$.' $L_{90\%}$ is the longitudinal position in radiation length measured from the entrance of the tower where 90% of total energy deposit is contained. Figure 3 shows the $L_{90\%}$ distributions of the 900 GeV data and the MC simulation using QGSJET2 as a generator. Clear double peak structure is due to the electromagnetic and hadronic showers. The peak with smaller (larger) $L_{90\%}$ is caused by electromagnetic (hadronic) showers.

From the first look of Figure 3, we can expect followings. Detail study of the $L_{90\%}$ performance and other particle identification methods are in progress. 1) MC simulation reasonably reproduces the $L_{90\%}$ distribution. 2) The gamma-ray/hadron ratio predicted by QGSJET2 agrees well with the experimental result. 3) By cutting at around $L_{90\%}$= 20 r.l., we can obtain best particle identification. In the further analyses, we applied criteria indicated by the red band in the figure. This is slightly smaller than 20 r.l. to enhance the purity of gamma-ray sample (actually 90% purity accoding to the MC simulation) and weak energy dependence is also introduced.

Energy spectra of gamma-ray like and hadron like events after applying the particle ID criteria are shown in Figure 4. The data is from the Arm1 detector after combining the results of two towers. With this limited statistics, there is no difference between Arm1 and Arm2. Because of the weak beaming in forward at this lower energy collisions, there are also no difference in the spectra between small and large towers.

Considering the statistical errors and conservative systematic error at this early stage, the measured spectra and the prediction by QGSJET2 have a good agreement.

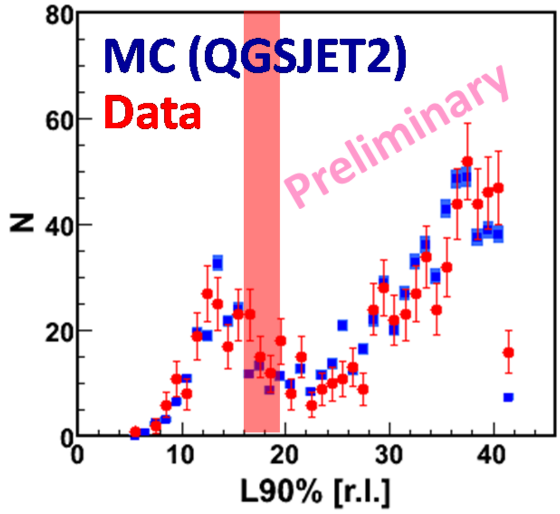

Figure 3: Distribution of the particle ID parameter $L_{90\%}$. Red plots are the results of the 900 GeV collisions while the blue rectangles are prediction by MC simulation using QGSJET2 as a generator. A red band from 16 to 20 radiation lengths indicates the criteria for particle ID. Weak energy dependence (smaller in lower energy, and vice versa) is expressed as a band.

4.3. Results for 7 TeV Collisions

In the analyses of 7 TeV data, we first applied same particle ID as the 900 GeV analysis. In case of 7 TeV collisions, gamma-ray pairs decayed from π^0's produced at collisions can hit two towers at the same time. Using the energy and position information of these gamma-rays and assuming their parents decayed at IP, the invariant mass of the gamma-ray pairs can be reconstructed and clear peak at the π^0 mass is found as shown in Figure 5. We can see the combinatorial background that makes background in the π^0 analysis is reasonably small. By selecting the events around the peak, the energy spectrum of π^0's is also reconstructed. We have observed π^0 candidates with energy over 3 TeV.

Energy spectra of gamma-ray like and hadron like events are also shown in Figure 6. Here the spectra measured in the Arm2 detector are separated in the results of two different towers. Red and blue markers are events associated with the crossing and non-crossing bunches, respectively. From these plots, we can conclude the contamination from the beam-gas background was 2 orders of magnitude below the signal level and negligible.

When we compare the spectra between small (25 mm) and large (32 mm) towers, harder spectra in the small tower (covering zero degree) are seen both in gamma-ray like and hadron like spectra. This suggests a strong beaming of the high energy particles in very forward that was not seen in the 900 GeV data.

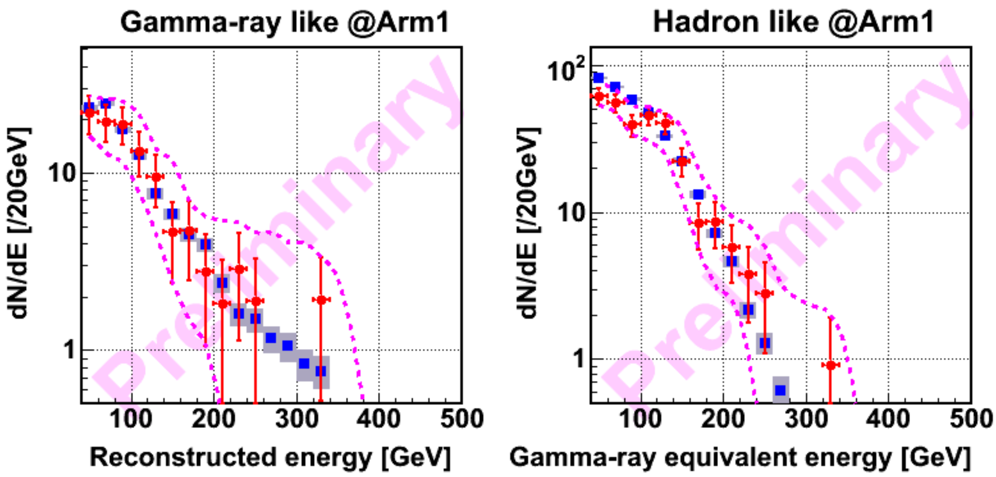

Figure 4: Energy spectra at 900 GeV collisions measured by the LHCf Arm1 detector and prediction by the QGSJET2 model. The spectra of gamma-ray (hadron) like events are shown in left (right). In the total experimental error shown by the dashed lines, conservative systematic error is included.

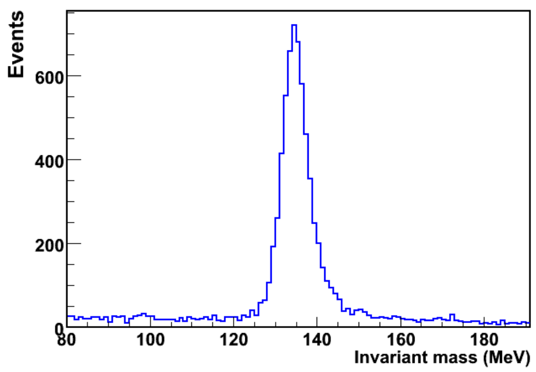

Figure 5: Invariant mass distribution of gamma-ray pairs measured in the Arm2 detector. A clear peak at 135 MeV is due to the decay of π^0 produced at collision and immediately decayed. Very low level of combinatorial background is also remarkable.

5. FUTURE PLAN

LHCf plans to finish operation at 7 TeV collisions before the luminosity reaches at 10^{31} cm^{-2}s^{-1} because radiation damage to the plastic scintillators becomes severe and multiple collisions at a single bunch crossing (pile-up) reduce the quality of data.

LHC is planning to increase its beam energy up to 7 TeV (collision energy of 14 TeV) in 2013 and LHCf is assured to take data at this energy. By taking data at three different energies (900 GeV, 7 TeV and 14 TeV), we can discuss energy dependence of the hadron interaction and it is useful to extrapolate into the cosmic-ray energy range. An example of such study is demonstrated in Figure 7, where some expected X_F spectra of gamma-rays are plotted for three different collision energies (7 TeV, 10 TeV and 14 TeV) and two major models (Sybill and QGSJET2). Though Sybill predicts a beautiful scaling over three energies, QGSJET2 predicts softening of the spectrum. LHCf will clarify such energy dependence at the operation in 2013.

To be able to fit any commissioning program of LHC at 14 TeV collisions, LHCf has started an upgrade work to replace the plastic scintillators with crystal scintillators (GSO) those are known to be radiation hard.

6. SUMMARY

LHCf is a dedicated experiment at LHC to measure the cross sections of the very forward neutral particle emission. The measurements of LHCf are expected to set a crucial anchor point to constrain the hadron interaction models used in the study of cosmic-ray air showers. LHCf has successfully started operation when LHC started to provide stable collisions in December 2009. By the time of the symposium, LHC has delivered about 7M inelastic collisions at 900 GeV and 14 nb^{-1} at 7 TeV collision at IP1. LHCf has accumulated data during all these collisions.

In this paper, we presented analysis results using the limited sample of data. In 900 GeV analysis, we demonstrated a simple parameter for particle ID, $L_{90\%}$, reasonably agrees with the prediction of QGSJET2 both in the distribution shape and gamma-ray/hadron ratio. Using this particle ID parameter, we derived energy spectra (gamma-ray equivalent) of gamma-ray like events and hadron like events. Within large error bars with the limited statistics and conservative systematic errors, the energy spectra also agree between data and MC. We will complete the analysis of all data and compare with the other major models.

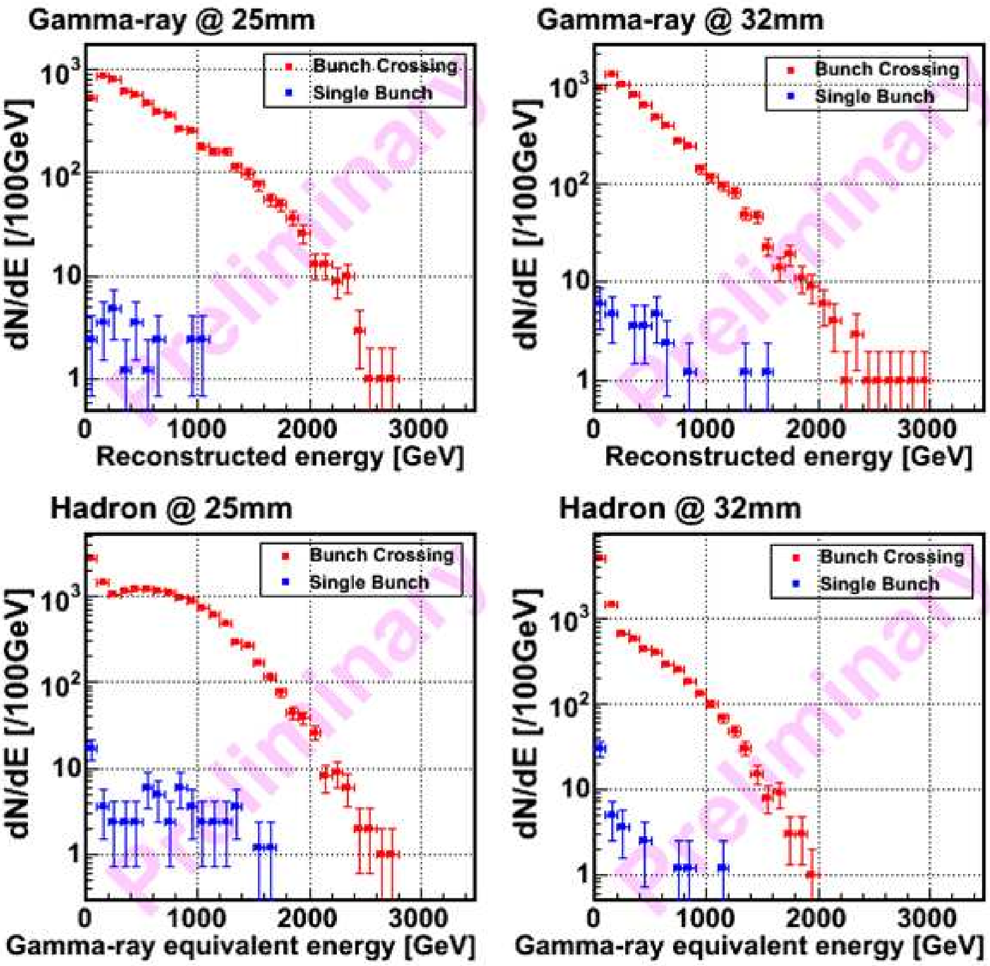

Figure 6: Energy spectra for gamma-ray like and hadron like events measured in the Arm2 detector. Left plots are the results of the small tower covering zero degree while the right plots are results at non-zero angle measured with the large tower. Red plots are events associated with the crossing bunched while the blue plots are events associated with the non-crossing bunches.

One of the impressive results in 7 TeV collisions is a detection of π^0's. Thanks to the double tower structure and the excellent energy and position resolutions, we can reconstruct the invariant mass of gamma-ray pairs. In the distribution of the invariant mass, a clear peak at the π^0 mass is detected. We have already detected π^0 candidates with energy above 3 TeV. The amount and energy spectra of π^0 are essential to understand how much fraction of hadron interaction is carried into electromagnetic showers.

Energy spectra of 7 TeV collision data are also presented only using 1% of total data set. We could demonstrate, using the crossing and non-crossing bunch configurations at LHC, that the contamination from the collisions between beam and residual gas is two orders of magnitude below the beam-beam collisions. The comparison of spectra between towers shows strong beaming (hard spectrum) in the small tower covering zero degree.

LHCf will finish operation when the luminosity reaches at $10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ to avoid severe radiation damage and pile-up events. [Detectors were removed on 20-July 2010.] LHCf will come back when LHC increases the beam energy up to 7 TeV (collision energy of 14 TeV) planned in 2013. The data of LHCf at three (or more at intermediate energies) different energies will be very useful to construct future hadron interaction models those are used in the study of cosmic-ray air showers at much higher energy than LHC.

Acknowledgments

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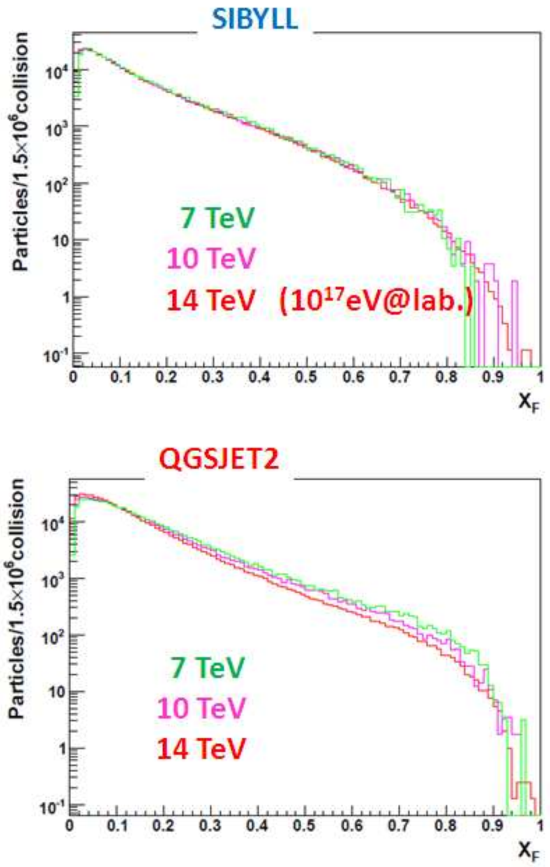

Figure 7: Feynman X distributions (energy spectra normalized by the beam energy) of gamma-rays at three different collision energies (7 TeV, 10 TeV and 14 TeV) to be measured by the LHCf calorimeters. The top and bottom plots are the predictions using the Sybill and QGSJET2 generators, respectively. Sybill predicts an energy scaling while QGSJET2 predicts softening at higher energy. Such energy dependence can be testes when LHC increases the beam energy in 2013.

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