HERA, LHC and Cosmic Rays

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At high energy, cosmic rays can only be studied by measuring the extensive air showers which they produce in the atmosphere of the Earth. The development of extensive air showers strongly relies on the physics of forward region of hadronic interactions. Measurement of forward particle production at HERA and LHC colliders constrain the physics used in hadronic interaction models and allow for more reliable determinations of the cosmic ray energy and composition.

1 Introduction

The origin and nature of cosmic rays (CRs) with energies between 10^{15} eV and the Greisen-Zatsepin-Kuzmin (GZK) cutoff at about 10^{20} eV remains a central open question in high-energy astrophysics (more details in the contributions at this conference [1–3]). At these energies the flux of CRs is so low that it cannot be measured directly using particle detectors. Therefore all CR measurements of higher energy are based on analyzing the secondary particle showers, called extensive air showers (EAS), which they produce in the atmosphere of the Earth. To interpret the characteristics of EAS in terms of primary particle type and energy, detailed modeling of the various interaction and decay processes of the shower particles is needed (for details see [4, 5]). In particular, the elemental composition of the CR flux reconstructed form air shower data depends very much on the assumptions on hadronic multiparticle production. Knowing the CR composition is essential for understanding the phenomena such as the *knee* and *ankle*, the changes of the power-law index of CR flux distribution at about 3×10^{15}eV and 3×10^{18}eV (see figure 1), and for confirming or ruling out models proposed for the sources of ultra-high energy CRs.

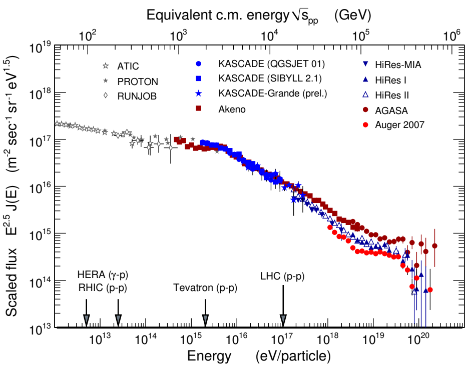

Figure 1: The flux of cosmic rays in the energy range from 10^{12} eV. In addition, the equivalent energies of colliders, referring to proton-proton collisions, are indicated by arrows.

Here, we discuss the relation between hadronic multiparticle production and EAS observables and the constraints given by accelerator data. Due to the huge difference between the energy ranges accessible at colliders and in the CR experiments it is very difficult to make direct comparison of their measurements. Nevertheless, it is possible to relate particle production processes in CR interactions to those studied in collider experiments. The current understanding of interaction processes is realised in the Monte Carlo (MC) event generators, which describe the interactions of the primary in the upper atmosphere. Such event generators allow us to study hadron production at colliders as in CR interactions [6]. The event generators combine theoretical predictions with phenomenological models and parameterisations and have to be tuned by comparing their predictions to measurements at accelerators. Considering the underlying theory and models entering MC programs, almost all data measured at colliders are relevant for understanding of very high energy cosmic ray interactions [7], e.g. limits on physics beyond the Standard Model, parton densities, low-x dynamics and saturation, reliability and range of applicability of perturbative QCD, transition between soft and hard physics, heavy flavour production, etc. In particular, the lack of experimental data on forward hadron production is one of the main source of model uncertainties, as the bulk of the primary particle production is dominated by forward and soft QCD interactions [8]. When extrapolated to energies around the GZK-cutoff, the current MCs predict energy and multiplicity flows differing by factors as large as three, with significant inconsistencies in the forward region. Thus, the modeling of CR interactions strongly depends on the input from accelerator experiments. The measurements of leading proton and neutron distributions from HERA experiments are the highest energy data available at present ($E_{lab} \approx 5 \times 10^{13}$ eV). These data provide important input for CR model tuning. The measurement of forward particle production in pp, pA and AA collisions at LHC ($E_{lab} \approx 10^{17}$ eV) will provide further strong constraints on these models and allow for more reliable extrapolations of the CR energy and composition around the GZK cut-off.

2 Forward Baryons at HERA

In ep scattering at HERA, a significant fraction of events contains a low-transverse momentum baryon carrying a large fraction x_L of the incoming proton energy. Although a fraction of these *leading baryons* may result from the hadronisation of the proton remnant, the t-channel exchange of colour singlet virtual particles is expected to contribute significantly [9–12]. In this picture, the proton fluctuates into a virtual meson-baryon state; the virtual photon subsequently interacts with a parton from the pion, leaving a fast forward baryon in the final state (figure 2). The production of leading neutron in the virtual exchange model occurs through the exchange of isovector states, and π^+ exchange is expected to dominate. For leading proton production, isoscalar exchanges also contribute, including diffractive Pomeron mediated interactions (more details in the contribution at this conference [13]).

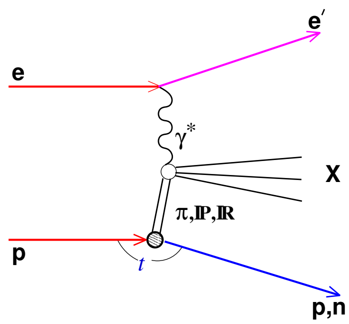

Figure 2: Leading baryon production $ep \to eXN$ via the colour singlet exchange processes.

To measure the forward baryons the H1 and the ZEUS experiments have been equipped with dedicated detectors. Forward protons were measured with position sensitive detectors (Roman Pots) placed along the proton beam downstream of the interaction point. Leading neutrons were measured with lead-scintillator forward calorimeters (FNC) at the zero-degree point; magnet apertures limited neutron detection to scattering angles less than 0.75 mrad

The cross section of leading proton production in DIS normalised to the inclusive DIS cross section $(1/\sigma_{tot} \cdot d\sigma_{LP}/dx_L)$ as function of x_L is shown in figure 3 as well as the exponential slope b of squared transverse momentum (p_T^2) distribution [14]. The rate of leading protons is approximately flat up to the diffractive peak, where it increases by a factor of about six. In the left side of figure 3 the distributions are compared to the predictions of MC models DJANGO and RAPGAP [15, 16]. which are based on standard fragmentation. These models don't reproduce either the flat dependence of the cross section versus x_L below the diffractive peak at $x_L \sim 1$ or the magnitude and dependence of b on x_L. The same data are compared to a Regge-based model [17] incorporating the isovector and isoscalar exchanges, and including the Pomeron for diffraction. A good description of the x_L distribution and the slopes is obtained by adding a substantial contribution of isoscalar Reggeon exchanges, which turn out to be the dominant processes below the diffractive peak.

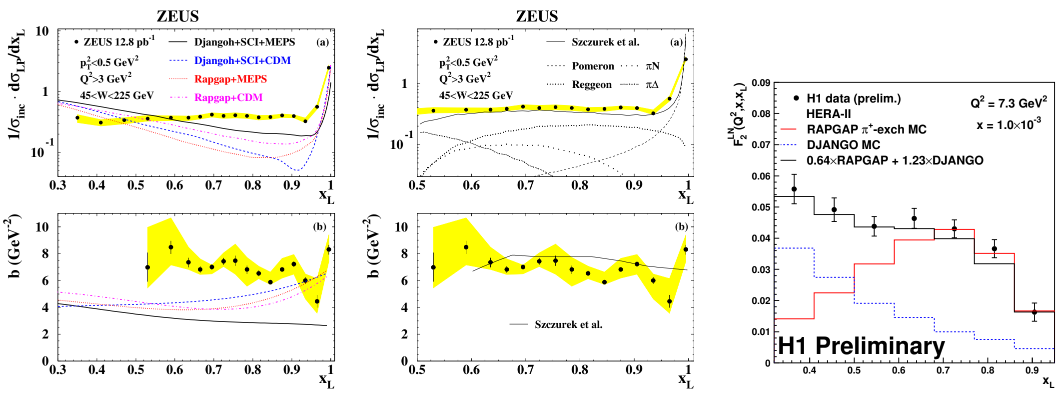

Figure 3: Normalized LP cross section and exponential slope b of LPs in DIS as function of x_L, compared to Monte Carlo models (left) and a Regge-based model [17] (center). (Right) leading neutron x_L distribution compared with Monte Carlo simulation which represents an optimised mixture of exchange and fragmentation models.

The leading neutron x_L cross section is compared in right side figure 3 to the prediction of RAPGAP MC model, which here simulates the neutron production via π^+ exchange and the DJANGO MC for inclusive DIS [18]. The DJANGO model which incorporates only standard fragmentation can not describe the observed LN yield, while the mixture of the standard fragmentation and π-exchange models gives a better description of the shape of the x_L distribution.

3 Forward Particles at HERA and Cosmic Rays

The measurements of forward particles at HERA may provide valuable information for the physics of ultra-high energy CRs. The models used for the CR analyses can make predictions for HERA kinematics, which can be compared to the experimental measurements. Below the comparisons are presented with the several models of hadronic interaction commonly used to simulate air showers: EPOS 1.6 [19, 20], QGSJET 01 [21], QGSJET II [22–24], and SIBYLL 2.1 [25–27].

Comparison of the leading proton and the leading neutron spectra measured at HERA with the predictions of the CR models are shown in figures 4 and 5 [28]. As expected, the HERA measurements are sensitive to the differences between the models and can be used for the tuning of model parameters.

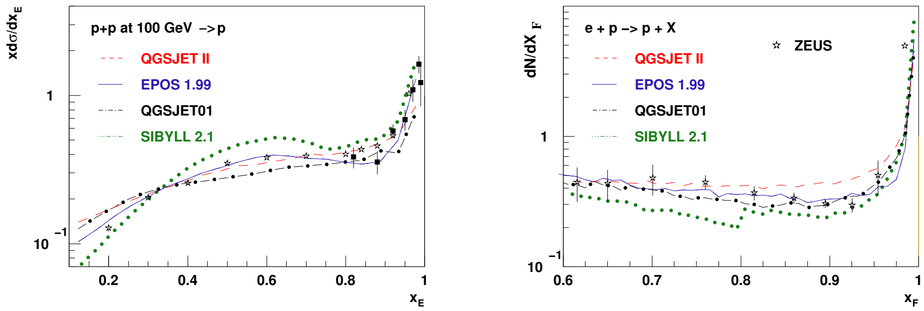

Figure 4: Comparison of the leading proton spectra measured at HERA with the predictions of cosmic ray interaction models [28].

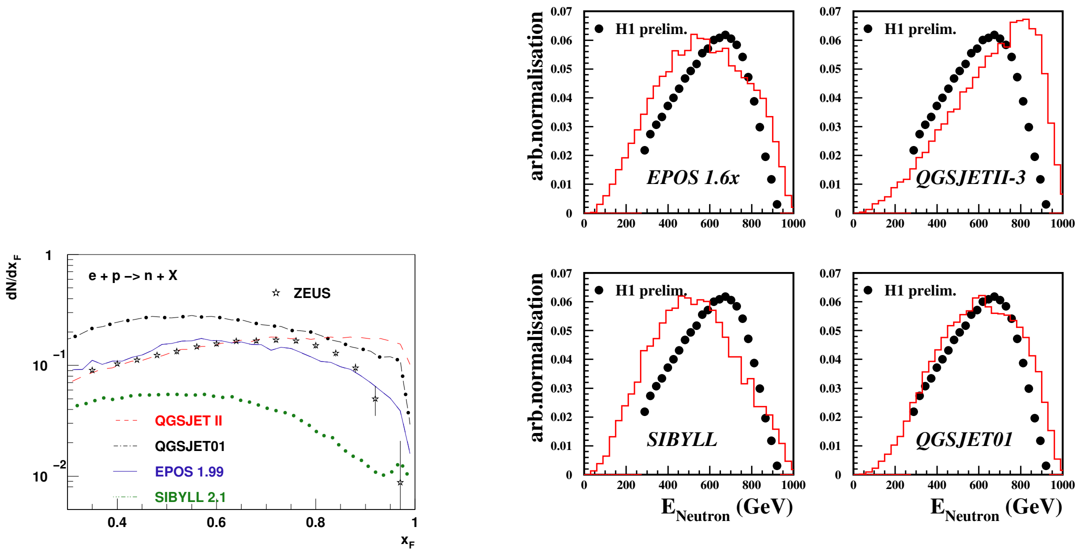

Figure 5: Comparison of leading neutron production energy distribution at HERA with the predictions of the cosmic ray interaction models [28].

4 LHC and Cosmic Rays

The coming energy frontier for hadron collisions will be reached by the LHC collider. The LHC will open up a phase space for particle production in an unprecedented range spanning about 20 units (see left side of figure 6). As a general feature, particle production in hadronic collisions is peaked at central rapidities, whereas most of the energy is emitted at very low angles. The subdetectors of the two large experiments ATLAS and CMS (ATLAS LUCID and CMS CASTOR calorimeters, the Zero-Degree-Calorimeters, ATLAS Roman Pots) and two independent experiments LHCf and TOTEM are capable of measuring very forward particles. Coverage of each experiment in pseudo-rapidity is also indicated in figure 6 by arrows. Because each experiment has different capability (charged or neutral particle measurement, hadron or electromagnetic calorimeter, calorimeter or tracker, infinite or finite pseudo-rapidity coverage, aperture, position/energy resolutions), they provide complementary data for total understanding of the very forward particles.

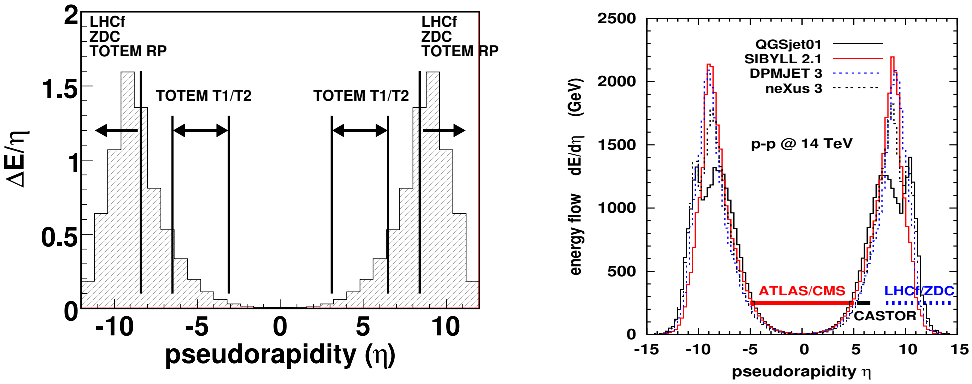

Figure 6: Left:Approximate p_T-η coverage of LHC detectors. Right:Pseudo-rapidity energy distribution for pp at the LHC predicted by four MC models commonly used in ultra-high energy cosmic rays physics.

Right side of figure 6 compares the predictions of QGSJET [21], DPMJET [29], NEXUS [30] and EPOS [19, 20] for the energy flow ($dE/d\eta$) in pp collisions at $\sqrt{s} = 14\ TeV$. In the range covered by detectors like CASTOR or TOTEM (around $|\eta| \approx 6$) and ZDC or LHCf (beyond $|\eta| \approx 8$, for neutrals), the model predictions differ by up to 60%.

The LHCf experiment [31] placed at 140m from interaction point is dedicated for the very forward neutral particle measurements for the efficient cosmic ray model tuning. LHCf will take the data in the early stage of the LHC commissioning. Figure 7 shows the comparison of models for the neutral particle distributions (neutrons, π^0) [28]. The figure demonstrates the potential of LHCf experiment to distinguish the models.

A good test of the fundamental properties of the hadronic interaction models is provided by the multiplicity distribution of charged particles. Figure 8 shows the MC model predictions for the different multiplicity distributions at LHC [28]. The discrepancies at LHC energy range can be larger than a factor of two in the shape of distributions. The charged multiplicity distribution will be one of the first measurements of the LHC experiments and provide reliable constrain for CR interaction models.

Measurement of forward particle production in pp, pA, and AA collisions will thus provide strong constraints on these models and allow for more reliable determinations of the CR energy and composition at the highest energies.

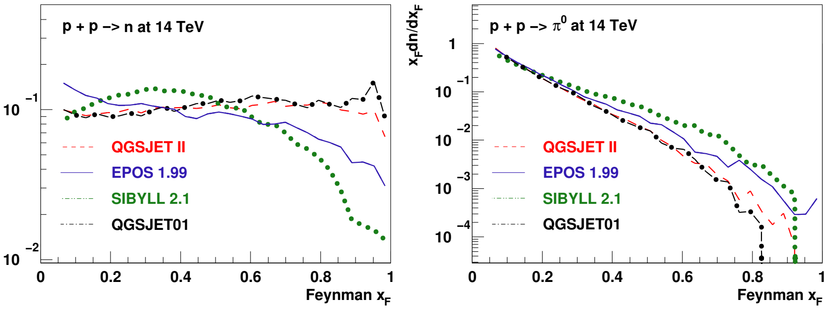

Figure 7: Feynman-x_F distribution of forward neutrons and π^0 from pp collision at 14 TeV [28].

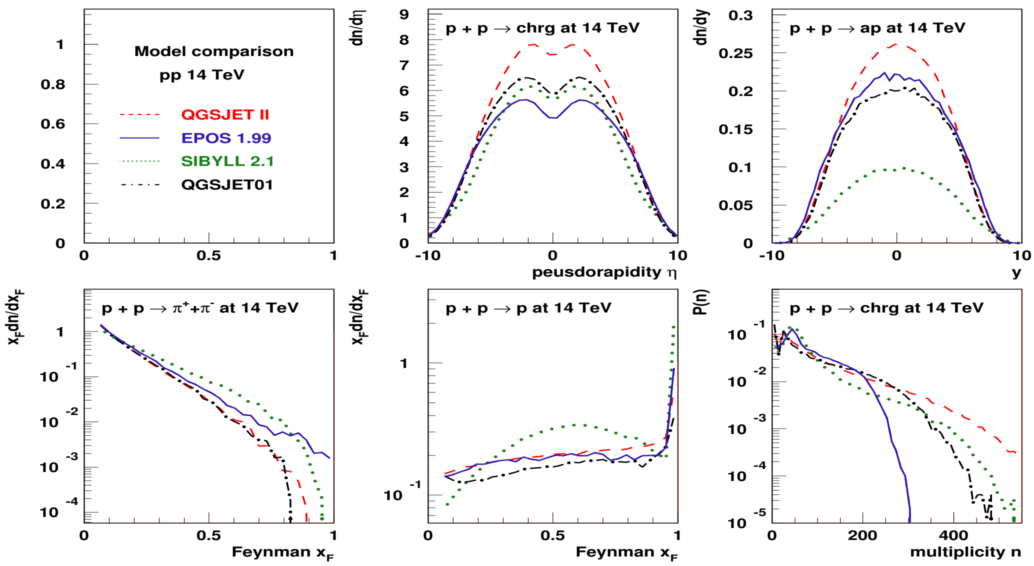

Figure 8: Multiplicity distribution of pp collision at 14 TeV energy calculated with EPOS 1.99, QGSJET II, QGSJET 01 and SIBYLL 2.1 Monte Carlo models [28].

5 Conclusions

The energy and mass of the primary ultra-high energy cosmic rays are obtained with the help of Monte Carlo models of hadronic interaction. These models strongly depend on the experimental measurements at collider experiments, in particular in the forward region.

The HERA experiments provide a wealth of measurements of leading baryon production in ep interactions. These measurements give an important input for an improved theoretical understanding of the proton fragmentation mechanism and help to reduce the uncertainties in the model predictions for cosmic ray showers. Forward measurements at LHC in pp, pA and AA collisions will provide further strong constraints to calibrate and tune these models and make more reliable predictions for the cosmic rays energy and composition.

Acknowledgments

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