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Nuclear and Particle Physics Proceedings 279–281 (2016) 130–138

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Results and Perspectives in Forward Physics with ATLAS

B. Giacobbe on behalf of the ATLAS Collaboration

Istituto Nazionale di Fisica Nucleare, Sezione di Bologna, Italy

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Abstract

A review of the ATLAS forward physics results is given with particular emphasis on the aspects of relevance for the cosmic rays community. These include proton-proton cross section measurements at $\sqrt{s} = 7$ TeV, diffractive physics studies using rapidity gaps, measurements of energy flow as a function of pseudorapidity, and the first cross section measurement performed in the recently started Run 2 at $\sqrt{s} = 13$ TeV. The ATLAS future perspectives will also be discussed, focused on the phase 1 upgrade project AFP, underlying its potential for a wide forward physics program both at low and high luminosity.

Keywords: Forward Physics, Cosmic Rays, Monte Carlo, Hadronic Cross Section, Diffraction

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1. Introduction

One of the still open items in cosmic ray physics is the interpretation of the cosmic particle flux spectrum measured by the experiments. The observation of cosmic rays spreads over a very large energy interval (up to 10^{20} eV) and, in particular for the ultra-high energy range, it is performed by large area experiments at the earth-surface observing the showers produced by primary cosmic particles interacting with the atmosphere. At $E \sim 10^{16}$ eV the spectrum shows a steepening, known as the *knee*, while at $E \sim 10^{19}$ eV an additional feature appears, called the *ankle* (see Figure 1). The knee is usually associated with the maximum particle acceleration of galactic origin, while the ankle with extragalactic sources. The results from the various experiments in this energy region show important discrepancies both in terms of absolute flux and in terms of mass composition of the primary particles. The energy and mass composition of the primaries is determined from the energy and shape of the shower, as measured at the surface of the earth, through hadronic Monte Carlo (MC) simulations of the shower development in the atmosphere. The involved processes are dominated by forward, soft QCD interactions, poorly known at these energies. From Figure 1 one can see that the proton-proton interactions at the LHC at $\sqrt{s} = 7$ and 13 TeV, correspond to the energy range of cosmic rays at the knee. Detailed measurements of the proton-proton interaction in the forward region are therefore a valuable input for the cosmic rays community as they can be used to tune the parameters of the models used for the description of the cosmic showers. In this context, ATLAS has performed a wide set of measurements, including the proton-proton cross sections (both total, elastic and inelastic), the energy flow distribution as a function of the particles pseudorapidity, and jet production. Such a program can be perfomed thanks to a large set of forward detectors (described in section 2) aimed to detect particles emerging from the pp interaction close or even inside the beam-pipe at large pseudorapidity. In sections 3 and 4 the pp cross section measurements are described using different techniques, while in section 5 the energy flow measurement is discussed. In section 6 the future perspectives of forward physics in ATLAS are discussed including the new AFP detector, which represents one of the major ATLAS upgrades for the LHC Run 2.

http://dx.doi.org/10.1016/j.nuclphysbps.2016.10.019

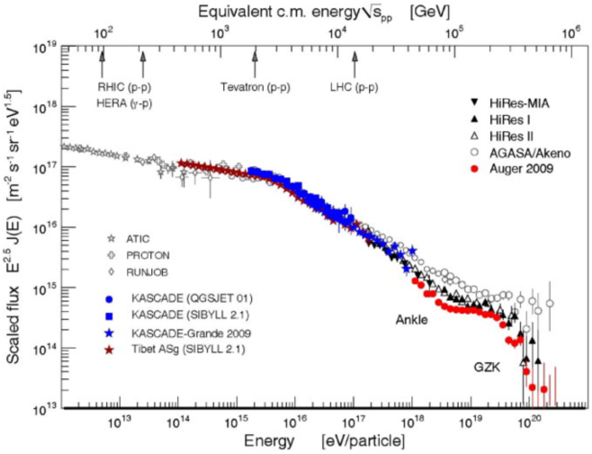

Figure 1: Energy distribution of cosmic rays above 10^{12} eV. At $E \sim 10^{16}$ eV and $E \sim 10^{19}$ eV respectively, the knee and the ankle are visible. The equivalent pp-collider center of mass energy is shown in the upper horizontal axis. The LHC center of mass energy in Run 1 is explicitly reported. In Run 2, LHC decided at the end to run at a center of mass energy of 13 TeV instead of 14 TeV. Taken from Ref. [1].

2. The ATLAS Forward Detectors

ATLAS (Ref. [2]) is a multi-purpose detector operating at the Large Hadron Collider (LHC), designed to study proton-proton interactions at the TeV scale. ATLAS can perform a wide set of forward physics measurements thanks to the various dedicated subdetectors, covering the range of large pseudorapidity. LUCID and BCM are dedicated to the luminosity determination, and are not discussed in this paper (all details can be found in Ref. [3]), as well as the Zero Degree Calorimeter (ZDC) dedicated to heavy ions physics. ALFA (Absolute Luminosity for ATLAS, Ref. [4]) is designed to measure small-angle proton scattering at a pseudorapidity $|\eta| > 8.2$ [1]. It is composed by two stations, located at 238 and 241 meters on both sides of the interaction point (IP). The detectors are housed into Roman Pots which can be moved inside the beam pipe, close to the proton beam, without breaking the LHC vacuum, in order to detect protons at scattering angles as low as 10 μrad. Elastically scattered protons are detected in the Main Detectors (MDs) made of scintillating fibers with a measured spatial resolution of about 30 μm and an efficiency to detect protons of 93% per fiber. Additional Overlap Detectors are attached to the MDs in order to measure their relative distance. The detectors are complemented by trigger counters. The Minimum Bias Trigger Scintillator detector (MBTS, Ref. [3]) is composed by high efficiency scintillation counters, placed at about 3.6 meters on both sides of the IP, and covers a pseudorapidity interval $2.1 < |\eta| < 3.8$. Each module is organised into 2 disks (inner and outer) each composed by 8 independent sectors. The light produced by each counter is guided into a photomultiplier tube by wavelength-shifting optical fibers. The detector shows an efficiency for inelastic events close to 100%.

3. Proton-Proton Cross Sections at $\sqrt{s}$ = 7 TeV

The total proton-proton cross section is a fundamental parameter of strong interactions, defining the size of the interaction region as a function of the energy. Quantum chromodinamics (QCD) cannot at present provide a precise calculation of the cross section, as large distance, non-perturbative interactions are involved in the collision process, but only estimations or bounds can be set based on high-energy scattering relations. Among these the optical theorem relates the imaginary part of the forward-elastic scattering amplitude to the total cross section, thus relating the elastic cross section at zero momentum transfer to the total cross section:

$$\sigma^2_{\rm tot} = \frac{16\pi(\hbar c)^2}{1+\rho^2}\frac{d\sigma_{\rm el}}{dt}|_{\rm t\to 0} \tag{1}$$

In general the total cross section $\sigma_{\rm tot}$ can be decomposed into an elastic ($\sigma_{\rm el}$) and an inelastic ($\sigma_{\rm inel}$) parts. The inelastic component is further made of a non-diffractive component $\sigma_{\rm ND}$ (dominated by exchange of color degrees of freedom) and a diffractive one $\sigma_{\rm D}$ (where the particles exchanged by the interacting protons are colorless). Experimentally, the elastic events can be identified by observing the two interacting protons emerging intact and practically udeflected from the IP (protons tag). On the other hand, in diffractive events one proton (single-diffraction, SD) or both (double-diffraction, DD) dissociate into a mixture of low diffractive mass particles of mass $M_{\rm X}$. The typical experimental signature of single diffractive events is the presence of one intact proton in one side of the detector and some activity, due to the products of the dissociated proton, on the opposite side, with an empty region separating them (rapidity gap). Rapidity gaps also characterize double diffractive events where both ends of the detector detect the products of the two dissociated protons.

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[1] ATLAS uses a right-handed coordinate system with its origin at the nominal IP in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Cylindrical coordinates (r,ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -ln\ tan(\theta/2)$.