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Elastic scattering, diffraction and forward physics at the LHC

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The 6 LHC experiments are equipped with detectors placed in the forward regions of the 4 interaction points. The first part of this article reviews the status of these detectors in the very moment the first proton-proton collisions take place. The second part is dedicated to review the main forward physics processes at the LHC and how they can be measured by the experimental apparatus.

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1. Introduction

In particle physics at the colliders, the forward regions are those placed at very small angles with respect to the beam line (more precisely but, in a sense, arbitrarly, at pseudorapidities[1] $\eta >$ 3). In the proton-proton interactions at the LHC[1] the forward regions are characterized by a hadron particle density decreasing with η and a very high hadron energy flux (fig.1, left). The experimental apparatus installed by the six LHC experiments (ALICE[2], ATLAS[3], CMS[4], LHCb[5], LHCf[6] and TOTEM[7]) will cover almost completely the central and forward regions, reaching an unprecedented pseudorapidity range of roughly 20 units (fig. 1, right). The detection of forward particles open up the possibility of sheding new light on basic aspects of QCD and electro-weak physics; the physics processes which will be studied comprehend elastic scattering, soft and hard diffraction, low-x QCD, γ-p interactions, Higgs production.

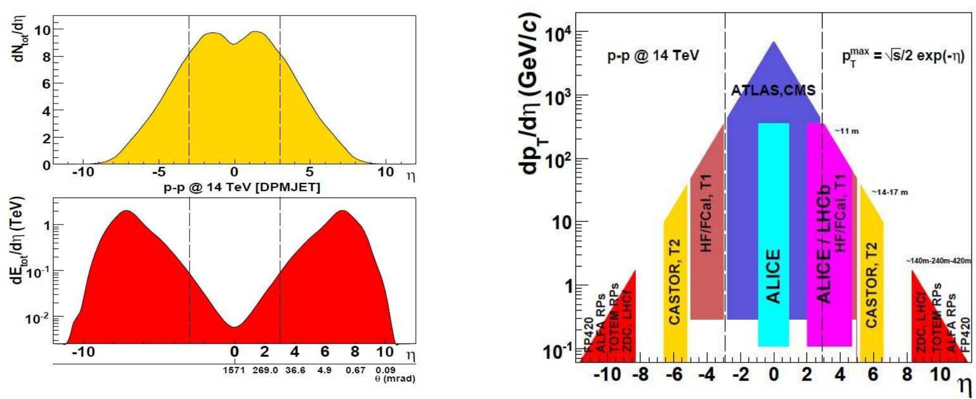

Figure 1: Left: hadron particle and energy density at the LHC nominal energy $\sqrt{s} = 14$ TeV (from DPM-JET3 [8]). Right: approximate $p_T - \eta$ coverage of the LHC experiments[9].

2. Forward detectors

The four LHC interaction points (IP) have been instrumented with detectors in the forward regions using several different technologies. In the following a short description of the forward detectors is given, as well as their (roughly approximated) pseudorapidity coverage:

- IP1: ATLAS is equipped in the forward region with the FCAL calorimeter ($3 < |\eta| < 5$), with LUCID Cerenkov detector, mainly intended for the measurement of the instantaneous luminosity ($5.5 < |\eta| < 6$), and with a zero degree electromagnetic and hadronic calorimeter (ZDC) placed in the TAN region, for the calorimetry of the neutral particles. Moreover, special insertions of the beam pipe, called Roman Pots, have been installed at $\sim$ 200m from the IP to house scintillator fiber detectors (ALFA project) in order to detect protons scattered elastically (the detectors will be probably installed during 2010).

[1]pseudorapidity can be considered as the limit at very low mass of the particle rapidity and is related to the angle θ by $\eta = -log(tan(\theta/2))$

The LHCf experiment is dedicated to measurements connected to the cosmic ray physics and has installed two zero degree calorimeters in the TAN regions for the calorimetry of γ's and of neutral hadrons.

- IP2: ALICE is equipped with a muon spectrometer on the negative side ($-4 < \eta < -2.5$) with a few additional forward detectors ($-4 < \eta < -1$ and $1 < \eta < 5$).

- IP5: CMS and TOTEM provide an almost full coverage of ~ 20 pseudorapidity units. In the forward part: TOTEM-T1 tracker, which will be installed in 2010 depending on CMS and LHC schedule, and CMS-HCAL calorimeter ($3 < |\eta| < 5$), TOTEM-T2 tracker and CMS-CASTOR calorimeter, which has installed only one side ($5 < |\eta| < 7$), CMS-ZDC in the TAN region and two TOTEM Roman Pot stations per side at 147m and 220m from the IP (only the stations at 220m are at the moment equipped with edgeless silicon detectors for the proton detection[10]).

- IP8: LHCb is a one side forward spectrometer optimized for B-physics, equipped with trackers, calorimeters and imaging Cerenkov detectors in the pseudorapidity range $2 < \eta < 5$.

3. Total cross section and elastic scattering

A precise measurement of the total p-p cross section σ_{tot} and of the elastic scattering over a large range in the squared four-momentum transfer t is of primary importance for distinguishing between different models of soft proton interactions.

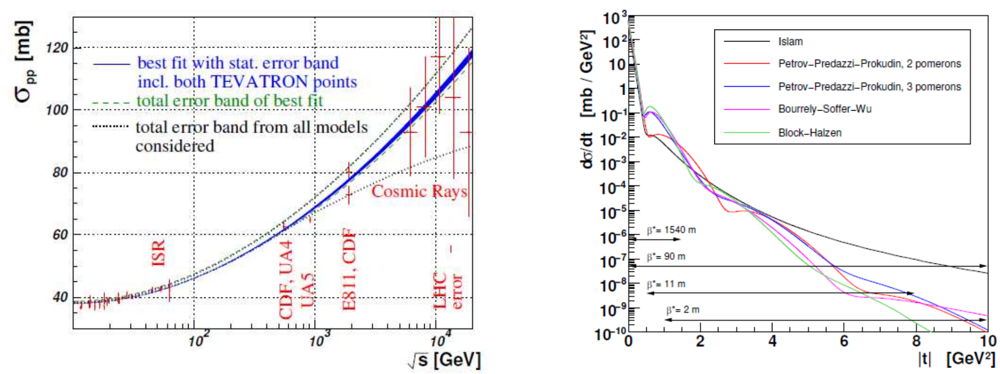

Figure 2: Left: previous measurements of the total p-p cross section and extrapolation to the LHC energy[11]. Right: elastic scattering cross section as a function of t and TOTEM acceptance with different machine optics[7].

The large uncertainties of the cosmic-ray data and the 2.6 standard-deviations discrepancy between the two final results from the Tevatron[12, 13] make an extrapolation to higher energies uncertain, leaving a wide range for the expected value of the total cross section at the LHC energy of $\sqrt{s} = 14$ TeV, typically from 90 to 130 mb, depending on the model used for the extrapolation (fig. 2, left). TOTEM will measure σ_{tot} without depending on the measurement of the luminosity, taking advantage of the optical theorem, performing the simultaneous measurement of the total inelastic N_{in} and elastic rate N_{el}, as well as the extrapolation to the optical point t=0 of dN_{el}/dt, using special high β^* dedicated optics which allow the detection of the elastic protons with very low t (fig.2, right):

$$\sigma_{tot} = \frac{16\pi(dN_{el}/dt)_{t=0}}{(1+\rho^2)(N_{el}+N_{in})}$$

where ρ is the ratio of the real and imaginary part of the forward amplitude at t=0. The expected best precision, achievable with a high β^* optics is 1-2%. Moreover, with different beam optics and running conditions, TOTEM will cover the $|t|$ range from $2 \cdot 10^{-3}$ GeV^2 to about 10 GeV^2 (fig.2, right).

The different method used by ATLAS consists in measuring the elastic scattering down to such small t-values that the total cross section becomes sensitive to the electromagnetic amplitude via the Coulomb interference term[14]. If the Coulomb region can be reached, using special LHC optics, an additional constraint is available from the electromagnetic amplitude that describes the elastic scattering at small t values. In the best available conditions and with a special high β^* optics, the expected uncertainty is of $\sim$3%.

4. Diffraction

Diffractive events represent $\sim$30% of the p-p interactions and are characterized by the fact that the incoming proton(s) emerge from the interaction intact or are excited into a low mass state. Diffractive processes, for proton energy losses up to a few per cent, are mediated by an exchange with quantum numbers of the vacuum, the so-called Pomeron, now understood in terms of partons from the proton; for larger energy losses, mesonic exchanges become important. The topology of diffractive events is characterized by a gap in the rapidity distribution of final-state hadrons caused by the lack of colour and effective spin of the exchanged object. Comparison between HERA and Tevatron data has shown that such rapidity gaps are suppressed in case of p-p interaction, due to the rescattering of proton remnants which eventually fill the gaps[15]. The probability of having a gap is $\sim$10% at the Tevatron and is expected to be less than 5% at the LHC. The measurement of the cross sections of the different diffractive processes (such as single $pp \to pX$, or central $pp \to pXp$ diffraction) and of the gap survival probability are of fundamental importance to understand the dynamics of hadron-hadron interactions, providing a better understanding of the so-called underlying event and, in general, of the huge QCD background which affects most of the precision measurements at the LHC.

At low luminosity the t and mass dependence of the diffractive cross sections can be measured by TOTEM by measuring the fractional proton momentum loss ξ (e.g. in single diffraction $M_X = \sqrt{s\xi}$). At higher luminosity ($\mathscr{L} \sim 10^{32}$cm^{-2}s^{-1}), the measurements by all the LHC experiments of hard processes in diffractive events, with di-jets, vector bosons or heavy quarks in the final state, provide access to the diffractive proton distribution functions dPDF's.

For what concerns the Higgs sector, the central exclusive diffraction is quite a promising production channel, especially at low Higgs mass, since, although there are big uncertainties on the predicted cross sections ($\mathscr{O}(fb)$), the selection rules coming from diffraction would highly suppress the QCD background. The small cross sections expected need the LHC operated in high luminosity runs and new detectors to be installed to detect protons scattered in those scenarios. AFP[16] and FP420[17] projects are studying the feasibility of such detectors.

5. Low-x physics

Proton is to be considered as a dynamic object and its parton distributions can be described in terms of kinematic variables such as x (the fractional momentum carried by the parton) and Q^2 (the energy scale of the collision between two partons). At the LHC the experiments will have the chance to widely increase the kinematic region already investigated in previous experiments (fig.3, left). Moreover, it has been shown that the gluon density $xG(x,Q^2)$ grows rapidly for decreasing x. As long as the densities are not too high, this growth is described by DGLAP[18] or by BFKL[19] evolution equations which govern, respectively, parton radiation in Q^2 and x. Eventually, at high enough center-of-mass energies (i.e. at very small x), the gluon density will be so large that gluon-gluon fusion effects will become important [20] and thus a regime of saturated parton densities is expected for small enough x values. Since the minimum x probed with the production of a particle of trasverse momentum p_T is $x_{min} = 2p_T/\sqrt{s}\cdot e^{-\eta}$, the forward detectors become the ideal tool to probe the small x region. The study of forward jets in ATLAS, CMS and LHCb will allow to access x values down to 10^{-5} and to gather useful information to distinguish among different PDF's and among different underlying event models. Another way to probe low x values is using Drell-Yan lepton pair production at high rapidities; CMS/TOTEM, ATLAS and LHCb will be sensitive to masses of a few GeV, near to the saturation energy scale at the LHC which is of ~ 3 GeV, and thus sensitive to saturation effects. The study of meson hadroproduction can be also used to study low x regimes (e.g. J/Ψ forward production in ALICE can probe x values down to 10^{-6}). QCD evolution at low x can be investigated by ATLAS and CMS by means of so-called Mueller-Navelet di-jets, which are characterized by a big rapidity gap between them. In fact, BFKL expects much larger yield of high E jets in the forward direction than DGLAP and it expects a strong azimuthal decorrelation between jets for larger gaps (fig.3, right).

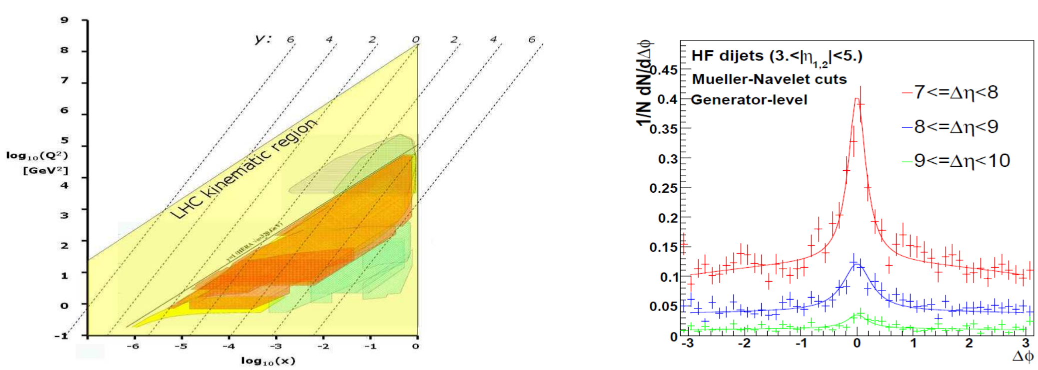

Figure 3: Left: kinematic region accessible at the LHC in the x-Q^2 plane (with darker colors are indicated regions already investigated by previous experiments). Right: azimuthal decorrelation in Mueller-Navelet jet pairs as expected in the BFKL evolution model (by CMS[21]).

6. Forward physics and cosmic rays

High energy cosmic rays ($E \sim 10^{15} \div 10^{20}$ eV) are studied by several experiments (for example Auger[22]) measuring the extensive air showers they produce interacting with the Earth atmosphere. The simulation of these interactions is done by means of hadronic Monte Carlo's which are then used in data analysis to establish the mass and the energy of the primary particle (usually protons or light nuclei). The core of such codes is dominated by forward and soft QCD physics and their predictions for the LHC p-p interactions are quite different in the forward region. Since the nominal LHC energy is roughly equivalent to a 100 PeV fixed target interaction, the measurements of the forward multiplicity and energy flow done by the LHC experiments (mainly LHCf) can be used to discriminate among different MC models.

7. Conclusions and acknowledgements

At the LHC start the six experiments have installed, or plan to install in the very next months, several detectors in the forward regions. The resulting coverage, unprecedented at a collider, will allow measurements of fundamental importance (mainly) in the field of QCD physics; moreover, due to the high cross sections involved, many studies will profit of the low luminosity scenarios expected in the first months of LHC operations.

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