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Alignment-related effects in forward proton experiments at the LHC

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ABSTRACT

The activity in the field of diffractive physics at the Large Hadron Collider has been constantly increasing. This includes the planning for additional dedicated apparatus – horizontal forward proton detectors. This work focuses on the problems related to the alignment of such devices. The effects of the misalignment of the detectors on their geometric acceptance and on the reconstruction of the proton kinematics are studied. The requirements for the alignment precision are inferred for different types of possible measurements.

1. Introduction

Studies of Standard Model physics are an important part of the Large Hadron Collider experimental programme. One of the least understood branches of the Standard Model is diffraction and, in particular, hard diffractive processes.

Diffraction in soft hadron collisions is a well-established phenomenon. The existence of hard diffractive interactions was confirmed for the first time at the CERN SPS collider in the UA8 experiment. Later, the HERA experiments, H1 and ZEUS, measured a significant contribution of diffraction to many processes, including DIS. This was followed by another interesting observation at the Tevatron, where the extrapolations based on HERA measurements led to the overestimation of the hard diffractive cross-section by a factor of about 10. Although today these issues are considered to be reasonably well understood, the experience gained shows that agreement of LHC results with expectations should not be taken for granted.

Two properties are typically used to discriminate between diffractive and non-diffractive interactions. In non-diffractive events colour charge is exchanged between the interacting protons,[1] leading to the break-up of the protons and to enhanced production of hadrons in the forward region. By contrast, in the case of diffractive interactions a colour singlet is exchanged between the colliding protons, and forward production of particles is suppressed. As a result, the rapidity distribution of final state particles in diffractive events contains regions completely devoid of particles – the so-called large rapidity gaps.

The size of the rapidity gap is anti-correlated to the energy transferred from the diffractively scattered proton and, in consequence, to the diffractive mass. Moreover, rapidity gaps can be present also in non-diffractive events, where they can emerge due to fluctuations of the distance between neighbouring particles. The size of such a gap has a steeply falling exponential distribution. The size of the gap in diffractive events drops more slowly, which makes the rapidity gap selection method appropriate for events with large gaps, *i.e.* small diffractive masses. For diffractive processes with large masses in the final state the use of this method is problematic. In addition, the high pile-up environment of the LHC makes it impossible for calorimeters to be used in the rapidity gap reconstruction.

The second method used to measure diffraction is based on the fact that the exchange of a colour singlet may leave the proton intact. Such a proton is characterised by a very steep distribution of the scattering angle. In fact, at the LHC, the scattered diffractive protons remain inside the beam pipe and traverse the magnetic structures of the accelerator accompanying the proton bunch. However, the kinematics of the diffractive protons is slightly different from that of the protons of the beam (greater transverse momentum or lower longitudinal momentum). Because of this the trajectories of such protons recede from the beam orbit. At a far enough distance from the interaction point (more than 100 m), the diffractive protons may depart far enough from the beam core to be detected.

Measurements of diffractively scattered protons in the vicinity of the beam require dedicated detectors. To access small scattering

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[1] Although diffractive interactions are possible in any hadron–hadron collision, in this work we focus on proton–proton interactions at the LHC.

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angles, the detectors have to be placed inside the accelerator beam pipe. Moreover, it must be possible to adjust the distance between the detector and the beam during the operation. This is because the minimal distance depends on the actual condition of the beam. Typically, during beam injection and acceleration, when the beams are unstable, the detectors must be retracted into the parking positions. This is possible by using a dedicated system – the Roman pot [1] or the Hamburg movable beam pipe [2,3]. Depending on the nature of the studied process, the detectors can be designed to move in the machine plane (horizontal detectors) or along the normal to this plane (vertical detectors).

The procedures of inserting and retracting the detectors imply that the positions of the detectors will vary from one data taking period to another. This makes the apparatus alignment more difficult than for other detectors, since it needs to be performed more frequently – typically for each run. In order to develop the alignment methods, one needs to know the precision needed to perform the physics measurement. The answer to this problem is the subject of this paper.

2. The AFP detectors

Presently at the LHC, the proton tagging detectors are installed at Point 1 (ALFA) [4] and Point 5 (TOTEM) [5]. The CMS and TOTEM collaborations plan to install additional horizontal detectors: recently, the CT-PPS (CMS-TOTEM Precision Proton Spectrometer) project [6] has been approved. In addition to the existing vertical detectors around LHC Point 1, the installation of horizontal stations – the AFP (ATLAS Forward Proton) detectors [7] – is considered. In this paper the alignment for the AFP detectors will be studied; however, the results for the TOTEM horizontal pots and CT-PPS should be similar.

The ultimate aim of the AFP detectors is to measure diffractive and two-photon processes during the periods when the LHC will work with standard settings, *i.e.* low β^*, high luminosity. It is planned to use horizontally inserted detectors placed symmetrically w.r.t. the interaction point at 204 m (near station) and 212 m (far station). The AFP stations will contain silicon pixel detectors [8] with the foreseen spatial resolution of 10 μm in the horizontal direction and 30 μm in the vertical direction, respectively. The far stations will be also equipped with precise timing detectors with the resolution of 30 ps.

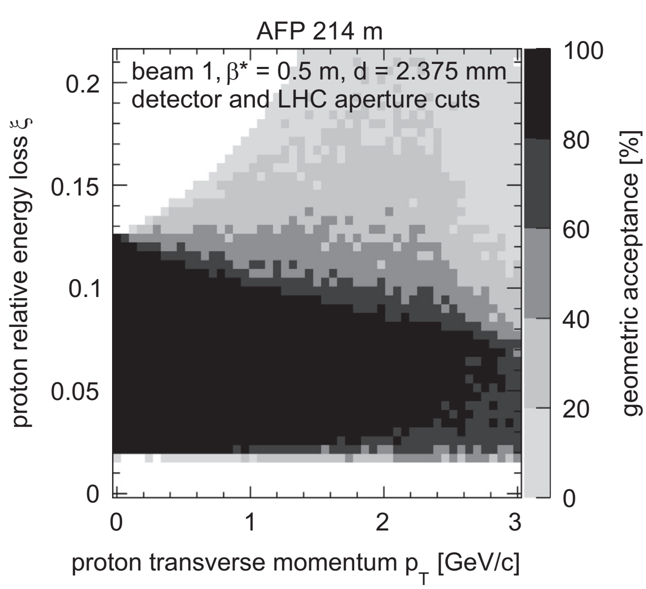

Fig. 1. Acceptance of the AFP detectors.

The protons scattered diffractively at the interaction point traverse the fields of the LHC magnets together with the beam. For the AFP detectors the magnets are: three quadrupole magnets (Q1, Q2, and Q3 – the inner triplet), two dipole magnets (D1 and D2 – separating the incoming and outgoing beams) and two additional quadrupole magnets (Q4 and Q5). The trajectory of a scattered proton depends on its momentum and the position of the interaction vertex. Tracking of the proton through the magnetic lattice can be simulated with dedicated tools, such as the Mad-X [9] or the FPTrack [10] programs.

For the nominal LHC optics ($\beta^* = 0.55$ m) with beam energy $p_0 = 7$ TeV and beam emittance of 3.5 μm rad, one can calculate the transverse size and the angular spread of the beam. For example, at 212 m from the interaction point the beam width equals 140 μm and 430 μm in the horizontal and vertical directions, respectively. The information about the beam transverse size at the detector location is of particular interest. This is because the detectors cannot approach the beam too closely, due to the radiation hazard for both the detectors themselves and the magnets located behind them, which is due to the hadronic showers generated in the Roman pot material. The actual distance between the detector edge and the beam position depends on the beam intensity and the amount of the halo background. A realistic distance value is between 10 and 20 times the width of the beam at the appropriate location (σ), depending on the intensity and condition of the beam.

The distance between the detector and the beam is of principal importance for the calculation of the detector geometric acceptance, which defines the range of the scattered proton momenta accessible to the detectors. Since the considered physics processes are symmetric in the azimuthal angle, it makes sense to inspect the geometric acceptance as a function of two parameters. A common choice is the transverse momentum value, p_T, and the relative momentum loss of the proton, $\xi = 1 - p/p_0$, where p is the scattered proton momentum.

The acceptance of the AFP detectors as a function of the scattered proton p_T and ξ for the nominal settings of the LHC magnets and the beam–detector distance of 15σ is presented in Fig. 1. One can see that high acceptance is obtained for $\xi \in [0.02; 0.13]$, *i.e.* high diffractive mass. To get acceptance for low masses, one needs different LHC optics and vertical detectors. On the other hand, the AFP detectors provide very good p_T acceptance, allowing the measurements of the full spectrum.

3. Reconstruction of proton kinematics

The aim of the forward proton measurement is twofold. First, one can simply check whether such a proton was present in the event, which would imply the diffractive nature of the process. Second, measurements of the proton trajectory can be used to determine its momentum, which can be used in the analysis. In this section we briefly describe the method used for proton kinematics reconstruction with the AFP detectors.

The parameters describing the scattered proton trajectory in the vicinity of the forward proton detector – the position and elevation angles (x, y, x', y') – depend on the momentum of the proton emerging from the interaction (p_x, p_y, p_z) as well as on the interaction vertex position (x_0, y_0, z_0). In the most general case, it would be impossible to reconstruct the momentum of a scattered proton from its trajectory measurement, because the trajectory is described by four parameters, while it depends on six: vertex position and proton momentum. However, in the case of the nominal LHC optics, the beam spot size is very small. This makes the vertex dependence sub-leading to the momentum dependence and allows the reconstruction of the momentum.