Research Article

Dynamic Alignment of the Forward-Proton Detectors at the LHC

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Received 26 April 2012; Accepted 1 July 2012

Academic Editor: Luca Stanco

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The dynamic alignment method of the forward proton detectors proposed by the CDF collaboration is reviewed. The applicability of the method at the LHC is discussed.

1. Introduction

A typical collision of protons at the LHC consists of parton-parton interaction. This causes the colour charge flow between the protons and leads to the creation of colour dipoles. In consequence, the dipoles radiate, filling the detector with particles. However, in a fraction of events the protons interact coherently, either electromagnetically—by exchanging a photon, or strongly—via an exchange of a colour singlet object named Pomeron. From such a collision one or both protons may emerge intact and may lose a part of its/their energy and be scattered at very small angles into the accelerator beam pipe. Exchange of a colour singlet object may result in a suppression of particle radiation in some regions of the phase space—the so-called rapidity gap.

When both protons stay intact, and the two emitted photons or Pomerons interact with each other producing a state in the central part of the rapidity space, the event is called the central exclusive production (CEP) [1]. Various objects can be produced in such a process: particles (χ_c , Higgs boson, J/ψ) or systems of particles (these may be: a pair of leptons, photons, jets, SUSY particles, etc.). At hadron colliders, such processes provide a unique opportunity to measure all particles of the final state. This leads to kinematic constraints,

and results in a good resolution of the centrally produced system mass reconstruction in a wide range of masses [2]. The tagging of protons emerging from such an interaction can be done with detectors that are inserted into the beam pipe far away from the interaction point (typically several dozens or even hundreds of metres).

At the LHC, such detectors are installed around the ATLAS interaction point (IP1)—ALFA (absolute luminosity for ATLAS) and the CMS interaction point (IP5)—TOTEM (total cross-section, elastic scattering, and diffraction dissociation). However, both detector systems are designed to work during dedicated LHC runs with a special machine tune (the so-called high β^* optics), when the luminosity is a few orders of magnitude smaller than the nominal $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Therefore, ATLAS and CMS collaborations plan to install additional detectors that will be able to work in the standard LHC tune environment: the AFP (ATLAS Forward-Proton) detectors and the HPS (high precision spectrometer).

Forward-proton detectors can measure the position and direction of the scattered proton trajectory. From that measurement, the fractional momentum loss $\xi = (E_0 - E')/E_0$ (E_0 is the initial proton energy, E' is the scattered proton energy) and the four-momentum transfer $-t \approx p_T^2 = p_x^2 + p_y^2$ can be reconstructed (actually, t denotes hereafter its absolute value). A crucial element of the reconstruction resolution is a proper alignment of the detectors, that is, precise knowledge of their positions. One should note that the positions of the detectors (their distance from the beam centre) have to be adjusted according to the actual beam conditions—the detectors must be movable. For instance, at early stages of the run, when the beam can be unstable, the detectors are situated in their home positions. Later, they are inserted into the beam pipe and placed in the immediate vicinity of the beam. As the positions of the detectors need to be established on the run-by-run basis, one needs a data-driven method of aligning forward-proton detectors.

2. Dynamic Alignment Method

The dynamic alignment method [3, 4] has been used by CDF for their RPS (Roman pot spectrometer) detector. For a given time period, a sample of single diffractive events was collected. Then, the four-momentum transfer, t' (henceforth primed variables denote the reconstructed values and unprimed variables denote the true values of the observables), was reconstructed assuming different detectors positions. In particular, one is interested in the value of the t' distribution at $t' = 0$

$$S = \left. \frac{d\sigma}{dt'} \right|_{t'=0}. \quad (2.1)$$

Naturally, the value of the reconstructed four-momentum transfer is affected by the assumed positions of the detectors. Thus, S is a function of the detector misalignment. The dynamic alignment method assumes that S reaches the maximum for perfectly aligned detectors. Below, a simplified justification of this method is given.

As mentioned before, the detectors measure the trajectories of scattered particles, that is, the trajectory position (x, y) and its elevation angles (slopes) (s_x, s_y) . In the simplest case there are two detector stations per beam placed at the distances of z_1 and z_2 from the IP. Since both measure the proton trajectory positions (x_1, y_1) at z_1 and (x_2, y_2) at z_2 , and are spaced

by the distance $L = z_2 - z_1$ then the trajectory parameters at the mid point, $z = (z_1 + z_2)/2$, are:

$$x = \frac{x_1 + x_2}{2}, \quad y = \frac{y_1 + y_2}{2}, \quad s_x = \frac{x_2 - x_1}{L}, \quad s_y = \frac{y_2 - y_1}{L}. \quad (2.2)$$

The misalignment of such detectors has four degrees of freedom for both stations and both directions: Δx_1 , Δy_1 , Δx_2 , and Δy_2 . In fact, one should include also a possible misalignment of the z detector position and skewness of the coordinate system, but in a real experimental environment they are negligible. It will prove to be helpful to use the global

$$\Delta x = \frac{\Delta x_1 + \Delta x_2}{2}, \quad \Delta y = \frac{\Delta y_1 + \Delta y_2}{2}, \quad (2.3)$$

and the relative

$$\delta x = \Delta x_2 - \Delta x_1, \quad \delta y = \Delta y_2 - \Delta y_1, \quad (2.4)$$

misalignments, instead of Δx_1 , Δy_1 , Δx_2 , and Δy_2 .

A large fraction of protons tagged in forward detectors originates from single diffractive processes (i.e., single diffractive dissociation). The four-momentum transfer distribution of these events is exponential as follows

$$\frac{d\sigma}{dt} = \sigma_0 b e^{-bt}, \quad (2.5)$$

where σ_0 is the single diffraction cross-section and b is the nuclear slope. The scattered proton momentum (at the IP) is unfolded from the measured values of (x, y, s_x, s_y) . In particular:

$$p_x = f(x, y, s_x, s_y), \quad p_y = g(x, y, s_x, s_y). \quad (2.6)$$

Next, these values are used to calculate the four-momentum transfer. However, if the detectors are misaligned, the unfolded momentum is affected as follows:

$$p'_x = p_x + \Delta p_x, \quad p'_y = p_y + \Delta p_y, \quad (2.7)$$

where

$$\begin{aligned} \Delta p_x &\approx \frac{\partial f}{\partial x} \Delta x + \frac{\partial f}{\partial y} \Delta y + \frac{\partial f}{\partial s_x} \frac{\delta x}{L} + \frac{\partial f}{\partial s_y} \frac{\delta y}{L}, \\ \Delta p_y &\approx \frac{\partial g}{\partial x} \Delta x + \frac{\partial g}{\partial y} \Delta y + \frac{\partial g}{\partial s_x} \frac{\delta x}{L} + \frac{\partial g}{\partial s_y} \frac{\delta y}{L}. \end{aligned} \quad (2.8)$$

As $t \approx p_x^2 + p_y^2$ and $t' \approx (p'_x)^2 + (p'_y)^2$, one can obtain the reconstructed four-momentum transfer distribution (assuming that Δp_x and Δp_y are proton momentum independent):

$$\frac{d\sigma}{dt'd\varphi'} = \frac{\sigma_0 b}{2\pi} e^{-b(t' - 2\sqrt{t'}\Delta p \cos(\varphi' - \alpha) + \Delta p^2)}, \quad (2.9)$$

where Δp , φ' , and α are such that

$$p'_x = \sqrt{t'} \cos \varphi', \quad p'_y = \sqrt{t'} \sin \varphi', \quad \Delta p_x = \Delta p \cos \alpha, \quad \Delta p_y = \Delta p \sin \alpha. \quad (2.10)$$

Expanding $\exp(2b\sqrt{t'}\Delta p \cos(\varphi' - \alpha))$ into a power series, one obtains

$$S = \left. \frac{d\sigma}{dt'} \right|_{t'=0} = \sigma_0 b e^{-b\Delta p^2}. \quad (2.11)$$

This shows that S reaches its maximal value for the perfect alignment.

At this point some important remarks have to be made. Firstly, in order to reconstruct the t distribution at $t = 0$, such events must fall into the acceptance of the detector. As will be discussed later, it is not always the case. Secondly, the derivation presented above assumes that Δp_x and Δp_y are constant (not dependent on the proton momentum), that is, higher derivatives of f and g are zero. This assumption is needed only to obtain the analytic formula for S , but is not crucial for the method. However, there are restrictions on the possible variation of Δp_x and Δp_y —on the average, they must be substantially different from zero; otherwise, the net effect cancels. Thirdly, the fact that S reaches the maximum for the perfect alignment does not mean that by the maximisation of S one aligns the detectors. This is because maximisation of S is equivalent to the request of $\Delta p_x = 0$ and $\Delta p_y = 0$. There is no unique solution of these two equations, as there are four unknown misalignment degrees of freedom. However, when the matrix of partial derivatives of f and g :

$$\begin{pmatrix} \partial_x f & \partial_x g \\ \partial_y f & \partial_y g \\ \partial_{sx} f & \partial_{sx} g \\ \partial_{sy} f & \partial_{sy} g \end{pmatrix} \quad (2.12)$$

has two rows that are negligible and the remaining two rows form a matrix with a non-vanishing determinant, the method provides a direct alignment for variables corresponding to non-negligible rows. Otherwise, one needs another method that will provide the two missing constraints.

Finally, one must remember that there are additional experimental effects that influence the measurement. Such factors (e.g., spatial resolution of the detectors and beam angular spread) cause random smearing of the reconstructed four-momentum transfer, leading to statistical errors of the obtained t' distribution. Thus, for a given number of collected single diffractive events, there is a limit on the alignment precision.

Table 1: Approximate ranges of $f(x, y, x', y')$ and $g(x, y, x', y')$ derivatives for the standard LHC tune (V6.5, collision [12]).

	$f(x, y, x', y')$	$g(x, y, x', y')$
∂_x	$(-2 \pm 4) \cdot 10^1$	$(-1 \pm 1) \cdot 10^2$
∂_y	0	0
$(1/L)\partial_{sx}$	$(2.5 \pm 1) \cdot 10^3$	$(4 \pm 2.5) \cdot 10^2$
$(1/L)\partial_{sy}$	0	$(-3 \pm 2) \cdot 10^3$

3. Alignment at the LHC

In this section, the dynamic alignment method applicability at the LHC is presented; the forward-proton detectors in the ATLAS experiment are considered—the ALFA [5] and the AFP detectors [6].

The ALFA detector consists of two Roman pot stations placed on each side of the IP at the distances of 237.4 and 241.5 metres. Each pot allows vertical insertion of position sensitive and triggering detectors into the beam pipe. The detectors use scintillating fibres to measure the scattered proton position.

The main purpose of ALFA is to measure the elastic proton-proton scattering in the Coulomb amplitude dominance region. This is needed for precise calculations of the scattering amplitude and hence a precise determination of the LHC luminosity. For that purpose a special high β^* machine optics will be used. In consequence, single diffractive events with $t = 0$ will not be within the detectors acceptance for all possible proton momentum losses [7]. Therefore, the dynamic alignment method cannot be used for the ALFA detectors.

The AFP detectors are currently at the well-advanced R&D stage and are planned to be installed during the 2013/14 LHC shutdown [6]. Similarly as in the ALFA experiment, two detector stations per outgoing beam are planned—they will be positioned symmetrically at 206 and 214 metres away from the ATLAS IP. However, instead of the Roman Pots, the Hamburg movable beam pipe mechanism [8, 9] will be used to position the detectors in vicinity of the proton beam. Each station will consist of six silicon-pixel detector planes for the proton position measurement. This will provide the spatial resolutions of $10\mu\text{m}$ and $30\mu\text{m}$ in x and y directions, respectively. In addition, the stations at 214 metres station will be equipped with a fast-timing detector (with a resolution of several picoseconds) necessary for the pile-up background reduction.

As has been discussed in Section 2, the derivatives of the p_x and p_y unfolding functions (f and g) with respect to x , y , s_x , and s_y are crucial for the method. Therefore, they were calculated for single diffractive events generated with Pythia 6.4 [10], transported with FPTrack [11] to the AFP positions, and then unfolded as in [2]. The ranges of these derivatives are given in Table 1.

In the proton transport, the Coulomb multiple scattering and the spatial resolution effects were taken into account. The multiple scattering in the first station material resulted the average angular deflection of the trajectory of about $0.5\mu\text{rad}$ which lead to the trajectory displacement at the second station smaller than the apparatus spatial resolution. The multiple scattering due to the dead material in the second station was neglected since its effects were negligible for the measurement and unfolding accuracies.

Figure 1: Reconstructed four-momentum distribution for different values of the relative horizontal misalignment (δx).

It can be seen that in the first column the most significant element is the ∂_{sx} , and in the second column the most important is the ∂_{sy} . Therefore, for both columns the ∂_x and ∂_y rows can be neglected. The remaining ∂_{sx} and ∂_{sy} rows form a matrix with a nonzero determinant, which depends only on the most significant elements in each column. This shows that the dynamic alignment method will work for the AFP detectors. However, contrary to the situation of the CDF detectors, the method is sensitive to the relative alignment and not to the global one.

This is illustrated in Figures 1 and 2, where the reconstructed four-momentum transfer distributions are presented for different values of δx and δy : $0 \mu\text{m}$, $\pm 30 \mu\text{m}$, and $\pm 50 \mu\text{m}$. Indeed, the simulation confirms the conclusions drawn from the analysis of f and g derivatives. The four-momentum-transfer distribution at $t' = 0$ decreases when a relative misalignment is introduced. Such a behaviour is not observed in case of the global misalignment. This results from the fact that ∂_x and ∂_y columns in Table 1 are practically negligible. Also, as can be seen in Figures 1 and 2, the sensitivity to the relative misalignment in the vertical direction is smaller than that for the horizontal one.

A comment on the practical significance of the above discussed method is in place here. As it was mentioned the spatial resolution of the detector is $10 \mu\text{m} \times 30 \mu\text{m}$. Obviously these numbers define the required alignment precision needed to fully exploit the physics potential of the AFP detectors. It has been estimated that a relatively small integrated luminosity of $30 \mu\text{b}^{-1}$ is sufficient to obtain the required precision of the relative alignment of the detectors using the presented method. This corresponds to the data collection time

Figure 2: Reconstructed four-momentum distribution for different values of the relative vertical misalignment (δy).

ranging from few seconds to few minutes depending on the instantaneous luminosity of the LHC.

4. Conclusions

The dynamic alignment method for the forward-proton-tagging detectors proposed by the CDF Collaboration was reviewed. A simplified mathematical justification of this method was given and its applicability to the detectors in the ATLAS Experiment was discussed. It was shown that the method works differently than at the Tevatron, where it allowed the *global* alignment determination. At the LHC, the method can be successfully used for the *relative* alignment of the AFP detectors, whereas it will not work for the ALFA stations.

References

- [1] M. G. Albrow, T. D. Coughlin, and J. R. Forshaw, "Central exclusive particle production at high energy hadron colliders," *Progress in Particle and Nuclear Physics*, vol. 65, no. 2, pp. 149–184, 2010.
- [2] R. Staszewski and J. Chwastowski, "Transport simulation and diffractive event reconstruction at the LHC," *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 609, no. 2-3, pp. 136–141, 2009.
- [3] K. Goulianos, "The forward detectors of CDF and $D\phi$," in *Proceedings of the 13th International Conference on Elastic and Diffractive Scattering (Blois Workshop): Moving Forward into the LHC Era*, M. Deile, D. d'Enterria, and A. De Roeck, Eds., pp. 442–448, Geneva, Switzerland, July 2009.

- [4] M. Gallinaro, "Diffractive and exclusive measurements at CDF," in *Proceedings of the 14th International Workshop on Deep Inelastic Scattering (DIS '06)*, Tsukuba, Japan, April 2006.
- [5] S. Franz and P. Barrillon, "ATLAS ALFA-measuring absolute luminosity with scintillating fibres," *Nuclear Instruments and Methods in Physics Research A*, vol. 610, no. 1, pp. 35–40, 2009.
- [6] ATLAS Collaboration, ATLAS Letter of Intent Phase-I Upgrade, CERNLHCC- 2011-012 LHCC-I-020, C. Royon et al., AFP: A Proposal to Install Proton Detectors at 220 m around ATLAS to Complement the ATLAS High Luminosity Physics Program, ATL-COM-LUM-2011-006, December 2011.
- [7] M. Trzebiński, R. Staszewski, and J. Chwastowski, LHC High β^* Runs: Transport and Unfolding Methods, arXiv:1107.2064 [physics.ins-det].
- [8] U. Schneekloth, Private communication.
- [9] M. G. Albrow, R. B. Appleby, M. Arneodo et al., "The FP420 R&D project: higgs and new physics with forward protons at the LHC," *Journal of Instrumentation*, vol. 4, p. T10001, 2009.
- [10] T. Sjöstrand, S. Mrenna, and P. Z. Skands, "PYTHIA 6.4 physics and manual," *Journal of High Energy Physics*, vol. 05, p. 026, 2006.
- [11] P. Bussey, <http://ppewww.physics.gla.ac.uk/~bussey/FPTRACK/>.
- [12] LHC Optics Web Home, <http://cern.ch/lhcoptics>.