Kinematics reconstruction for ATLAS Forward Proton detectors

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Abstract

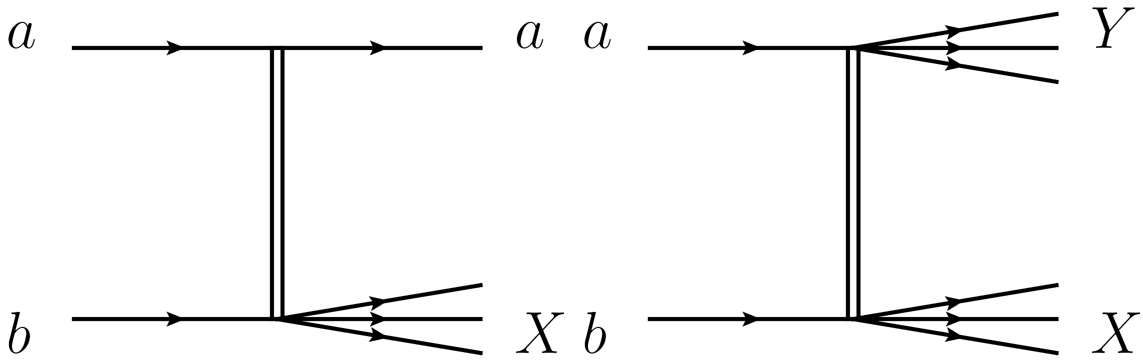
In this paper, purpose of ATLAS Forward Proton detectors was described. Kinematics reconstruction method for forward protons was explained. Results of kinematics reconstruction of protons measured by detector were shown.

Contents

1 Introduction

One of the goals of physics programme at Large Hadron Collider [1] is the measurement of diffractive processes. Those processes take place in proton-proton interactions and are result of the exchange of a colour singlet called pomeron. In the result, both protons survive and lose portion of their energy. The examples of such processes are shown on Fig. 1. Two distinctive signatures are used for experimental measurements of diffraction, namely the large rapidity gap - an area in rapidity, where there are no particles - and an intact forward protons. Scattering angles of intact protons are very small, in order of micro-radians, which makes them impossible to be detected by central detector. These protons can be described with the use of three kinematic variables, namely: the transverse momentum p_T,the azimuthal angle φ and the relative energy loss ξ, which is defined as: $\xi = (E_{beam} - E_{proton})/E_{beam}$, where: E_{beam} is the energy of beam and E_{proton} is the energy of intact proton.

Measurement of these protons can only be performed at large distances from interaction point and very close to the centre of the beam. This can be achieved with help of the dedicated forward detectors, such as ATLAS Forward Proton (AFP) [2].



(a) Single diffraction (b) Double diffraction

Figure 1: Examples of diffractive processes at LHC.

2 ATLAS Forward Proton detectors

The AFP (ATLAS Forward Proton) detectors programme aims to measure very forward protons, which are outside central detector acceptance. To achieve this, the detectors are placed 205 and 217 m away from the ATLAS interaction point, on each outgoing beam.

For today, only one (A) arm is installed and fully operational. Near station (205 m) is equipped with three planes of 3D Silicon pixel detectors, while far station (217 m) with four planes of 3D Silicon pixel detectors and with time-of-flight (ToF) Quartz Cherenkov detector (Fig. 2). Each plane consist of array of 336 by 80 pixels, each of size of 50 by 250 μm. Also, each plane is shifted with respect to other planes in station and additionally, each plane is tilted along z-axis by $\sim 14°$. Given those circumstances, final resolution of pixel detector is equal to $\sim$ 10 μm in horizontal axis and $\sim$ 30 μm in vertical axis and for ToF detector: 10 ps. Second arm is planned to be installed in the beginning of 2017.

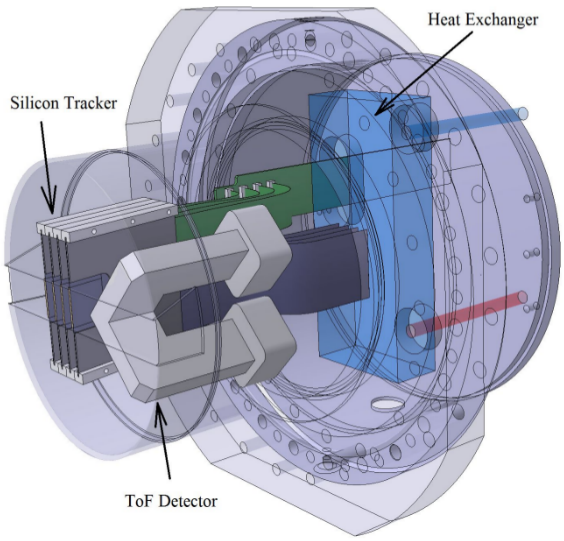
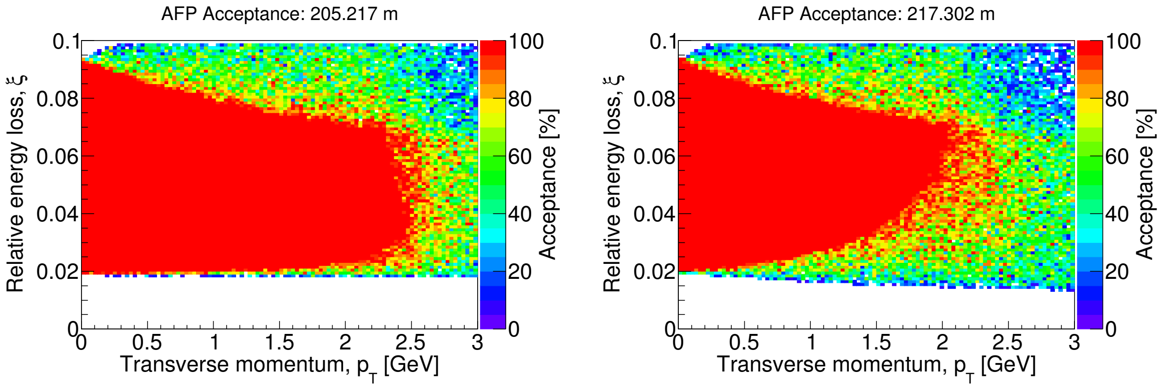


Figure 2: Visualization ATLAS Forward Proton far station (217 m).

From the measurement of position of the same proton on both stations on the same arm (proton tagging), it is possible to extract the information about proton's initial energy and transverse momentum. In addition, information from ToF detectors from both arms will help to determine exact position of interaction vertex. This will hopefully allow to get full spectra of information from both AFP and ATLAS detectors.

Not all scattered protons can be measured in the AFP detectors. Such protons can be too close to the centre of the beam to be detected or it can hit LHC elements, such as magnets or collimators. In order to identify kinematic region where protons can be measured, one can use acceptance plots, as a function of ξ and p_T. These plots for both near and far stations are presented in Fig. 3. In these plots, distance from the beam was set to $d = 2.5$ mm. To precisely reconstruct proton kinematics, one need to know exact distance from the beam. This information can be extracted from dedicated alignment methods.



(a) Acceptance plot for near station

(b) Acceptance plot for far station

Figure 3: Acceptance plot for near and far AFP station, for optics $\beta^* = 0.40$ m.

3 Proton kinematics reconstruction

In order to reconstruct values of relative energy loss and transverse momentum of scattered proton, one can parametrize transport of proton by following equation [3]:

$$\alpha = A_\alpha + B_\alpha x_{IP} + C_\alpha y_{IP} + D_\alpha z_{IP} + E_\alpha x'_{IP} + F_\alpha y'_{IP} + G_\alpha z_{IP} x'_{IP} + H_\alpha z_{IP} y'_{IP} \quad (1)$$

where: $\alpha \in (x, y, x', y')$ are variables measured by detectors and $A_\alpha, \ldots, H_\alpha$ are the polynomials dependent on relative energy loss ξ of ranks:

$$A_\alpha = \sum_{n=0}^{N_{A_\alpha}} a_\alpha^n \xi^n \quad (2)$$

$$\vdots$$

$$H_\alpha = \sum_{n=0}^{N_{H_\alpha}} h_\alpha^n \xi^n$$

Polynomials coefficients can be received with the help of the proton tracking program, such as FPTracker.

3.1 Proton tracking

FPTracker is a set of C++ libraries, which allow fast proton through the LHC magnetic lattice[1]. Between ATLAS interaction point and the AFP detectors there are many elements, such as magnets or collimators, on which proton can be stopped. Fragment

[1]The composition of the accelerator magnets

of the LHC magnetic lattice is presented on Figure 4. Both AFP stations are placed between fifth (Q5) and sixth (Q6) quadrupole magnet.

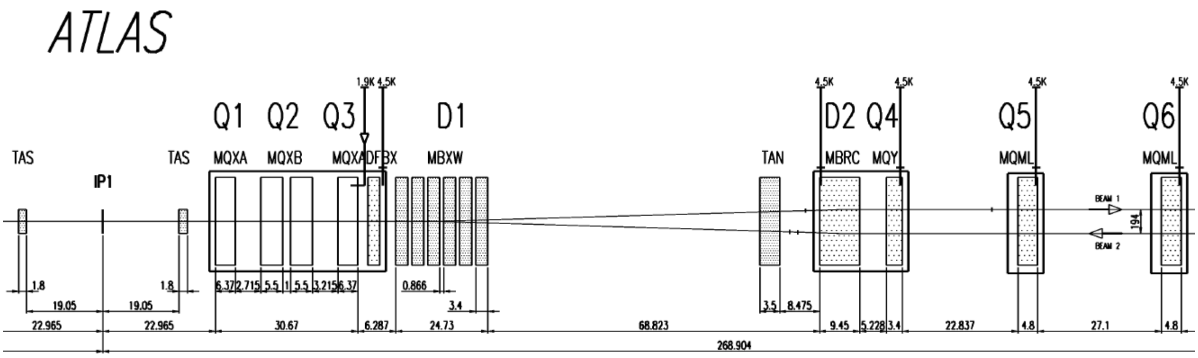


Figure 4: LHC magnetic lattice in vicinity of ATLAS.

First, optics files need to be prepared in *twiss* format, which is recognized by FPTracker. This can be achieved with the use of MAD-X software [4]. Once the optics files are prepared, FPTracker can be used.

3.2 Parametrization algorithm

Parametrization algorithm is split on three parts:

1. Reading constants from configuration file and finding coefficients for all polynomials with various degrees,
2. Validating parametrization,
3. Writing chosen parametrization.

3.2.1 Coefficients evaluation

In the beginning configuration file is read, in which one must specify initial conditions of beam and point to optics directory. Coefficient evaluating is a three-part process, based on equation 1:

- Solving the equation: $\alpha = A_\alpha$, and fitting polynomial to it,
- Fitting the line to equations: $\alpha = A_\alpha + B_\alpha x_{IP}, \ldots, \alpha = A_\alpha + F_\alpha y'_{IP}$ with different: $x_{IP}, \ldots, y_{IP}$ to obtain slopes, then fitting polynomials to them,
- Fitting slope of $\alpha - B_\alpha x_{IP} - E_\alpha x'_{IP} = A_\alpha + G_\alpha z_{IP} x'_{IP}$ and $\alpha - C_\alpha y_{IP} - F_\alpha y'_{IP} = A_\alpha + H_\alpha z_{IP} y'_{IP}$ with different x'_{IP}, y'_{IP}, then fitting polynomials to obtained slopes.

For each iteration, a single proton with known initial position and momentum is tracked to the position of detector.

3.2.2 Validating and saving parametrization

Next step is validating obtained parametrization. This is achieved with the help of any high energy physics Monte Carlo event generator, capable of generating processes which can be measured with the AFP detectors. In this case, Pythia8 [5] was used. To correctly validate parametrization, a set of at least 50 thousands events is needed. Initial positions of protons are smeared in the same way as the LHC beam is for given optics at interaction point. Once validation is complete one can check which set of parameters fits the best in terms of accuracy and efficiency. Then the final parametrization is saved.

Once parametrization is complete there is no need to repeat it, unless used optics is changed or user desires to.

3.3 Unfolding procedure

Data from the detectors is stored in form of events in xAOD files. Those files contain all information about events, especially position of tracks in both AFP stations, which are reconstructed from hits on detector. To iterate over events in xAOD files, one can use RootCore with a set of additional libraries allowing to read AFP data format. On each iteration, every event is checked in terms of cuts. Valid events are those in which there are only two tracks, first in near station, second in far station. This ensures that those tracks belong to single proton.

Input parameters of unfolding algorithm are position of tracks in both stations - which are effectively position and slope of proton in vertical and horizontal axis and also vertex coordinates. There are two methods of extracting ξ. First, finding the root of function with bisection method, which is dedicated for AFP detectors:

$$f_1(\xi) = (x - A_x - B_x x_{IP} - D_x z_{IP})(E_{x'} + G_{x'} z_{IP}) - (x' - A_{x'} - B_{x'} x_{IP} - D_{x'} z_{IP})(E_x + G_x z_{IP}) \tag{3}$$

Second, minimalization of χ^2 function:

$$\chi^2(p) = \frac{(x_1^D - x_1(p))^2}{\sigma_x^2} + \frac{(y_1^D - y_1(p))^2}{\sigma_y^2} + \frac{(x_2^D - x_2(p))^2}{\sigma_x^2} + \frac{(y_2^D - y_2(p))^2}{\sigma_y^2} \tag{4}$$

where (x_1^D, y_1^D) are coordinates of proton measured by the first station and $(x_1(p), y_1(p))$ are coordinates calculated from transport parametrization. In this paper, first method will be used.

Relative energy loss reconstruction is solely dependent on vertical axis components of initial state and measured positions. Since in principle vertical components are independent of horizontal ones and vice-versa, slopes can be reconstructed with two equations:

$$x'_{IP} = \frac{x - A_{x'} - B_{x'} x_{IP} - D_{x'} z_{IP}}{E_{x'} + G_{x'} z_{IP}} \tag{5}$$

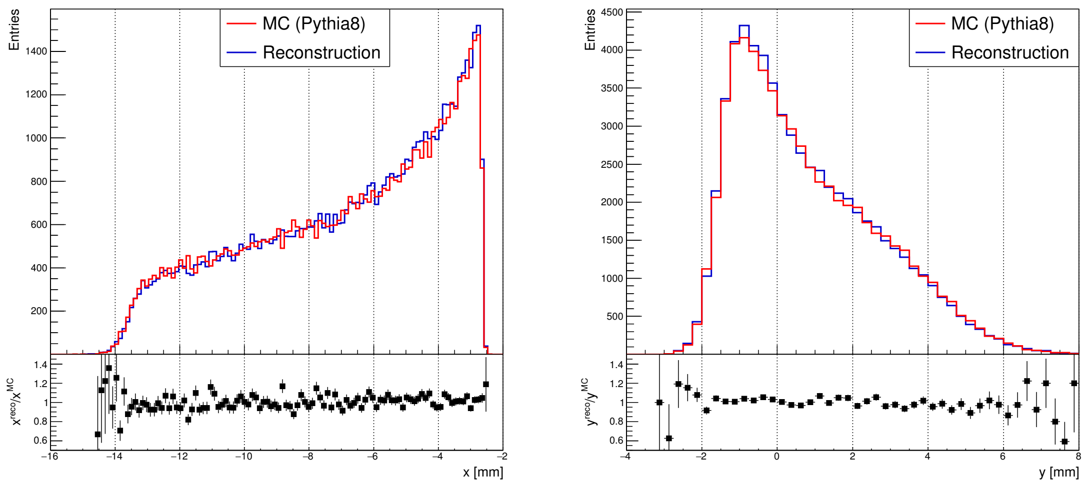
$$y'_{IP} = \frac{y - A_{y'} - B_{y'}y_{IP} - D_{y'}z_{IP}}{E_{y'} + G_{y'}z_{IP}} \tag{6}$$

With those three reconstructed variables, one can evaluate complete set of information of protons initial kinematics. Since second arm of the AFP detector is not installed, there is no information about initial vertex, thus it was set to $(0, 0, 0)$.

4 Results

4.1 Pythia testing

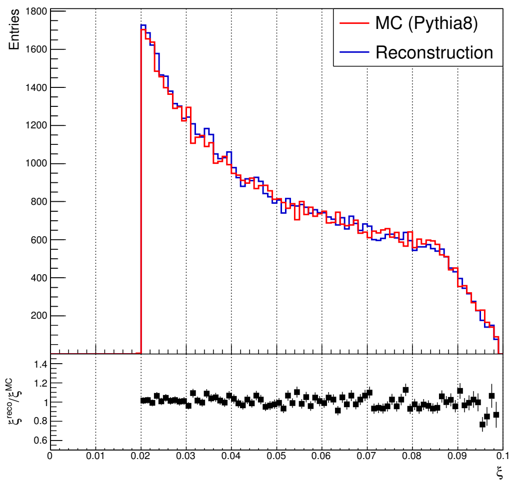
For testing purpose, a set of 2.5 million single diffractive events was generated with Pythia. All protons with $\xi < 0.02$ were discarded - cannot be measured by detector. The rest of protons were tracked with the use of FPTracker to the position of the first AFP station, then based on each proton momentum, their positions were extrapolated to second station. Protons that reached the detectors were split to two halves, first - set as reference, second half - reconstructed. Initial states of protons from first half were compared to states received from reconstruction (Fig. 6). Additionally, protons with reconstructed kinematics were tracked to compare positions (Fig. 5).



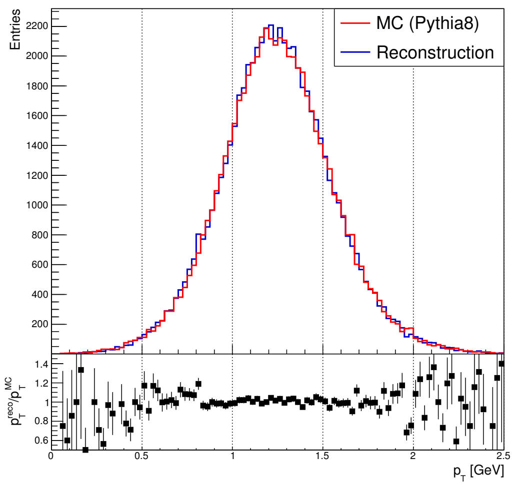
(a) Horizontal position distribution (b) Vertical position distribution

Figure 5: Comparison of position of tracked protons from Pythia and tracked protons with reconstructed kinematics.

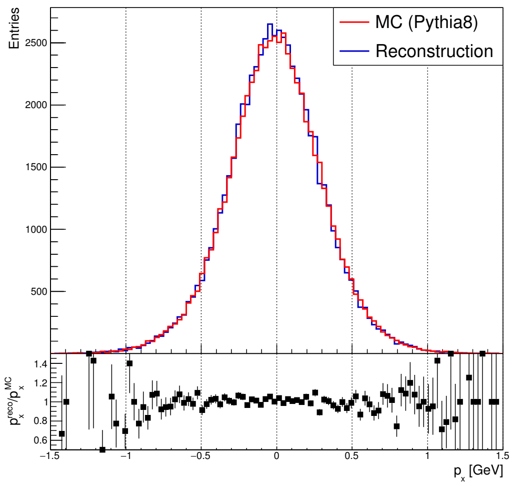
From those plots one can see, that reconstruction algorithm works very well for Pythia simulation, results are accurate.



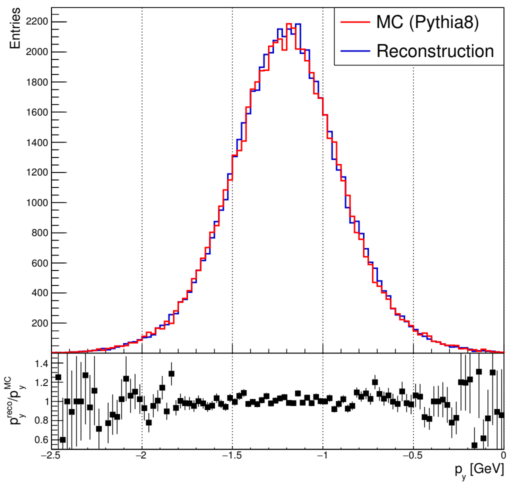
(a) Relative energy loss distribution



(b) Transverse momentum distribution



(c) Horizontal momentum distribution



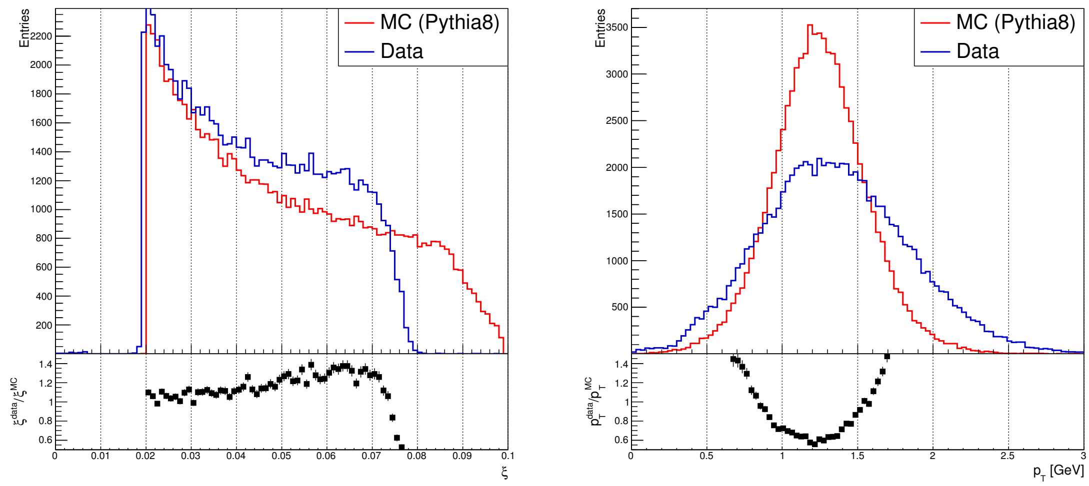
(d) Vertical momentum distribution

Figure 6: Comparison of kinematics of scattered proton from Pythia and reconstructed kinematics.

4.2 Data from detector

For the next step, data from run 296423 was used. First of all, tracks position from data are in ATLAS coordinate system, those must be converted to beam coordinate system. This can be partially achieved with help of dedicated alignment method. Translation in vertical direction was set to: 96.75 mm. This value was obtained from early result of Paweł Buglewicz's work, here at DESY. In horizontal direction there is no alignment method, thus translation value was set arbitrary to: -5.75 mm.

Comparison of relative energy loss and transverse momentum between reconstructed protons and initial states from Pythia are shown on Fig. 7. All plots are normalized to the same number of events.



(a) Relative energy loss distribution

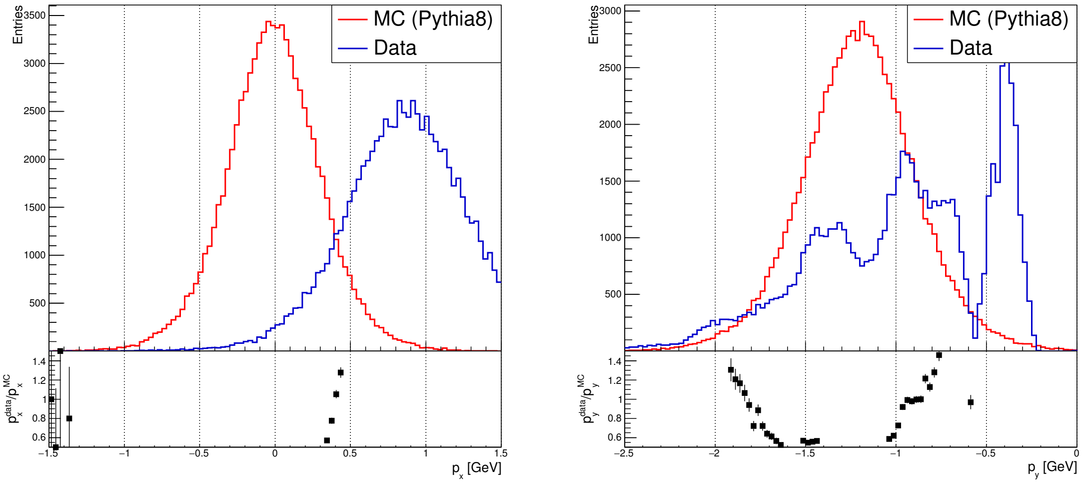
(b) Transverse momentum distribution

Figure 7: Comparison of relative energy loss and transverse momentum distributions of protons from Pythia and protons with reconstructed kinematics from data.

One can see that energy distribution is not described very well. Also, transverse momentum distribution is not completely accurate. Looking at both components of transverse momentum may give a hint (Fig. 8). One can see that both horizontal and vertical components are not correctly reconstructed. Necessary corrections were applied:

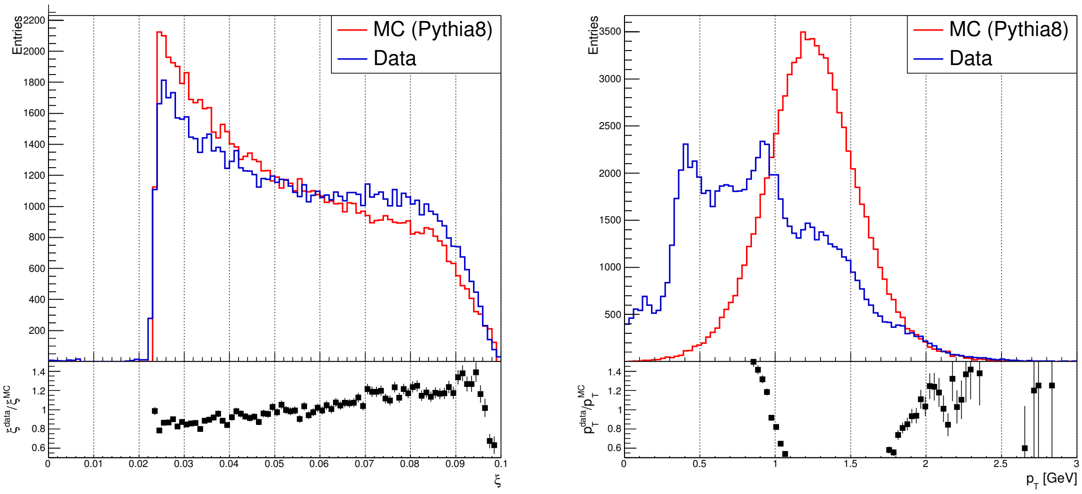
- All tracks from first stations were translated in horizontal axis by value of -0.49 mm.
- Additional cuts on Pythia data, events with $\xi < 0.0235$ were discarded.

Results of those corrections are shown on Fig. 9. Relative energy loss is better reconstructed than before. Unfortunately, transverse momentum distribution looks much worse. But, if one take a look at transverse momentum components distribution shown on Fig. 10, horizontal component is reconstructed well and vertical one changed a little.



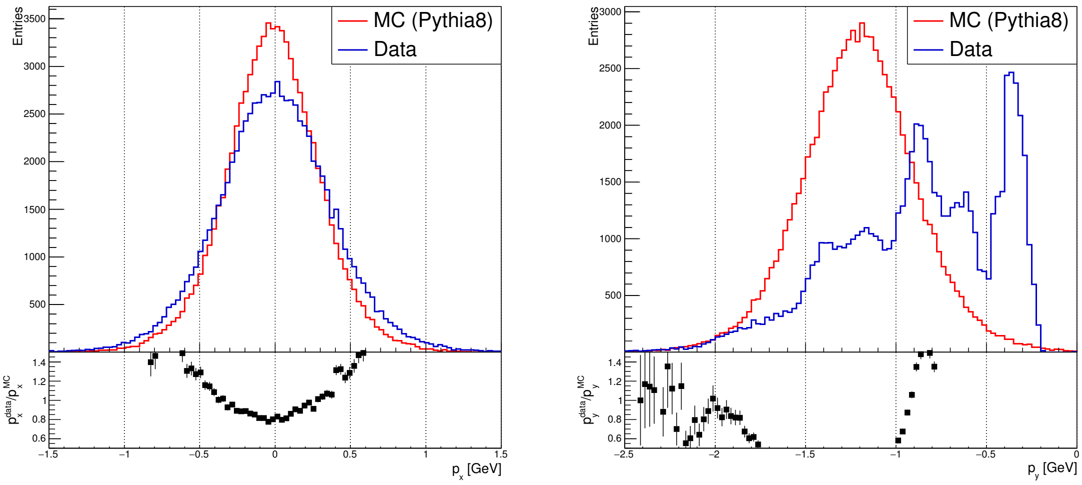
(a) Horizontal momentum distribution (b) Vertical momentum distribution

Figure 8: Comparison of transverse momentum components distributions of protons from Pythia and protons with reconstructed kinematics from data.



(a) Relative energy loss distribution (b) Transverse momentum distribution

Figure 9: Comparison of relative energy loss and transverse momentum distributions of protons from Pythia and protons with reconstructed kinematics from data after corrections.



(a) Horizontal momentum distribution

(b) Vertical momentum distribution

Figure 10: Comparison of transverse momentum components distributions of protons from Pythia and protons with reconstructed kinematics from data after corrections.

5 Summary

Reconstruction method presented in this paper was proved to be insufficient to fully reconstruct kinematics of protons measured with the AFP detectors. Whole method of reconstructing energy was based on vertical component of measurements. Thus, naturally, vertical momentum was correctly reconstructed, while horizontal one was not.

References

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[5] T. Sjöstrand *et al.*, *"An Introduction to PYTHIA 8.2"*, Comput. Phys. Commun. **191**, 159 (2015).