# THE AFP PROJECT*

R. Staszewski

on behalf of the ATLAS Collaboration

The Henryk Niewodniczański Institute of Nuclear Physics
Polish Academy of Sciences
Radzikowskiego 152, 31-342 Kraków, Poland.

(Received April 29, 2011)

AFP is a project to extend the diffractive physics programme of the ATLAS experiment by installing new detectors that will be able to tag forward protons scattered at very small angles. This will allow us to study Single Diffraction, Double Pomeron Exchange, Central Exclusive Production and photon–photon processes. This note presents the physics case for the AFP project and briefly describes the proposed detector system.

DOI:10.5506/APhysPolB.42.1615
PACS numbers: 13.85.–t

## 1. Introduction

In the high energy $pp$ collisions at the LHC most attention is usually paid to the central rapidity region, *i.e.* where the most of the particles are produced and where the most of the high $p_{\mathrm{T}}$ signal of new physics is expected. However, the energy emitted in such interactions is distributed mainly in the forward direction and usually most of it disappears in the accelerator beampipe (see Fig. 1).

Forward physics is devoted to studies of high rapidity regions and includes many interesting topics like elastic scattering, diffraction, low-$x$ QCD and Central Exclusive Production, photon–photon interaction, the two last being the main motivation for the AFP project.

## 2. Central exclusive production

Central Exclusive Production (CEP) is a very interesting class of processes in which the two interacting protons are not destroyed during the interaction but survive into the final state (intact protons, forward protons).

* Presented at the Cracow Epiphany Conference on the First Year of the LHC, Cracow, Poland, January 10–12, 2011.

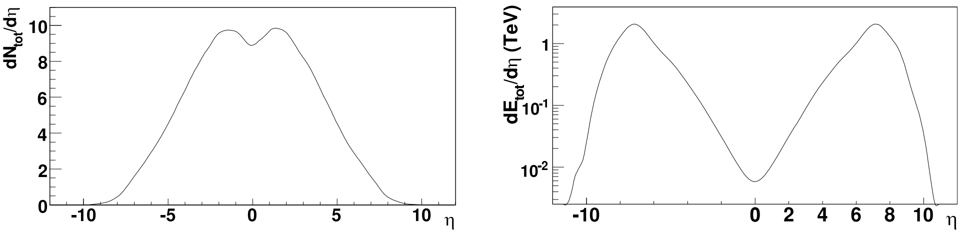


Fig. 1. Multiplicity (left) and energy (right) distributions in proton–proton collisions at $\sqrt{s} = 14$ TeV (adapted from [1]).

Such situation takes place, for example, during elastic scattering, but can happen also in quasi-elastic processes when, apart from the two protons, there is an additional particle (or particles) in the final state.

This is a very rare situation and can take place only when the protons interact coherently via an emission of a color singlet object. Such interaction can be of an electromagnetic or a strong nature, occurring via a photon or a Pomeron exchange, respectively. In hard processes the Pomeron exchange is usually modeled, at the lowest order, by an exchange of a colorless two-gluon system. Feynman diagrams for two important examples are presented in Fig. 2 — exclusive production of jets (left) and the Higgs boson (right). One can notice a similar structure: two gluons are emitted from each proton, one of the gluons is involved in the hard subprocess ($gg \to gg$ or $gg \to H$), the second one screens the process. Since no color is exchanged between the protons and the central state (jets or Higgs), it is possible that the protons stay intact after the interaction. It is important to point out that in the Central Exclusive Production, contrary to the Double Pomeron Exchange processes, there are no Pomeron remnants in the final state.

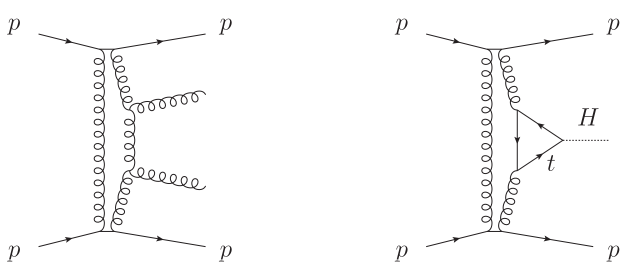


Fig. 2. Feynman diagrams of exclusive jets (left) and Higgs (right) production.

The exclusive jet production has already been studied at the Tevatron [2] and there is a hope for observing the exclusive Higgs at the LHC. This would have several advantages over the "standard" searches. First of all, the exclusive $b\bar{b}$ jets production (background to exclusive $H \to b\bar{b}$) is suppressed by the $J_z = 0$ selection rule [3]. Secondly, for such a process it is possible to detect all particles in the final state, provided the forward protons are detected. In such a way the kinematics of the event is fully constrained, which leads to a good resolution for the Higgs mass measurement in a wide range of masses [4]. Thirdly, observing the Higgs in the exclusive production mode indicates strongly that it is a $0^{++}$ particle, since the amplitudes for other spin states are much smaller. The drawback of this approach for the Standard Model (SM) Higgs is a very small production cross-section, which is predicted (with very large uncertainty [5]) to be of the order of a femtobarn. However, in supersymetry (SUSY) scenarios the cross-section can be much bigger.

As mentioned before the exclusive production can be not only a strong, but also an electromagnetic interaction. A Feynman diagram, for an example of such a process, is shown in Fig. 3 (left). One can see the photons that are emitted from the protons, interact with each other and produce a lepton pair. This kind of process is called a photon–photon interaction and the same mechanism can lead to production of pairs of $W$ bosons, sparticles, *etc.* Since these are the QED processes, they are well understood and the prediction for cross-sections have very small uncertainty. Therefore, they can be used for a precise luminosity determination at the LHC [6]. Also, similarly to the exclusive Higgs case, the detection of the outgoing protons can give a precise determination of the central system mass, which can be used for SUSY studies [7].

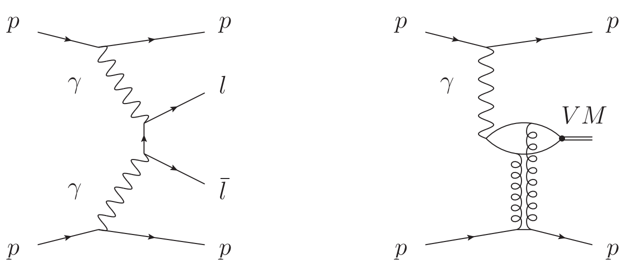


Fig. 3. Feynman diagrams of diphoton exchange (left) and exclusive photoproduction (right) processes.

There exists also a third possibility of the exclusive process. This is the exclusive photoproduction and it combines the electromagnetic and strong interactions. Here, one of the protons emits a photon that interacts with the Pomeron emitted by the second proton, see Fig. 3 (right). The result is a vector meson and two intact protons in the final state.

## 3. Anomalous gauge bosons couplings

A particularly interesting exclusive process that could be studied at the LHC is the production of $W$ boson pairs. A complete review of this process can be found in [8, 9], only the main points are outlined in this note. As mentioned above, a $WW$ pair can be produced in a photon–photon process, see Fig. 4 (left). The cross-section is calculated as a convolution of the photon–photon luminosity $\mathcal{L}_{\gamma\gamma}$ and the subprocess cross-section $\hat{\sigma}_{\gamma\gamma\to WW}$

$$\sigma_{pp\to pW^+W^-p} = \int \mathcal{L}_{\gamma\gamma}\hat{\sigma}_{\gamma\gamma\to WW} \,.$$

At tree level both the triple $\gamma WW$ (*e.g.* Fig. 4, centre) and the quartic $\gamma\gamma WW$ (*e.g.* Fig. 4, right) SM couplings contribute to the subprocess cross-section. This ensures the unitarity of the SM at high energies due to cancellations between these diagrams and gives the cross-section of 95.6 fb at $\sqrt{s} = 14$ TeV.

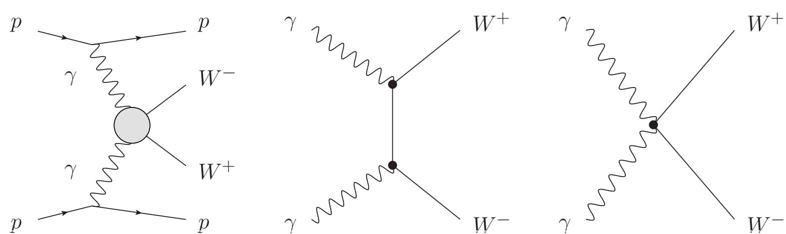


Fig. 4. The Feynman diagram of exclusive $W^+W^-$ production in photon–photon interaction (left) and diagrams contributing to the $\gamma\gamma\to W^+W^-$ subprocess via triple $\gamma WW$ (centre) and quartic $\gamma\gamma WW$ (right) SM couplings.

Measurements of this process will allow to test the existence of the SM quartic $\gamma\gamma WW$ couplings, which can give an insight into the electroweak symmetry breaking mechanism. Also, it is expected in Beyond Standard Model (BSM) theories (especially in Higgsless and extra-dimension models) that the cross-section for exclusive $WW$ production is larger than in the SM.

Such BSM effects can be described in terms of anomalous couplings of the gauge bosons. This is done by adding into the SM Lagrangian new (anomalous) terms that are responsible for the modified interactions. The cross-section for the $WW$ production in the photon–photon channel rise very quickly with the anomalous couplings values. Currently, the best limits on these values come from the OPAL Collaboration [10]. With the AFP detectors one can constrain the values of the couplings by four orders of magnitude and reach the values predicted by Higgsless and extra-dimension models.

## 4. AFP — the experimental setup

A crucial ingredient for all the studies described above is to have an experimental possibility to detect forward protons. Such protons are scattered at a very small angles, of the order of microradians, and into the accelerator beampipe. Therefore, to measure the protons one needs detectors that are placed inside the machine beampipe. Such measurements are quite difficult but it has been shown at HERA, Tevatron and RHIC that they are possible [2, 11, 12, 13]. Although the ATLAS experiment already has such detectors (these are the ALFA stations [14]), their purpose is to measure the elastic scattering process and they can work only during special, very low luminosity LHC runs with a dedicated, high $\beta^*$, machine tune. AFP is an upgrade project for the ATLAS experiment aiming to install additional detectors that will be able to detect forward protons during the normal LHC runs. The primary goal for the new detectors is to study the Central Exclusive Production, especially the exclusive $WW$ production.

A forward proton, which is scattered into the beampipe, goes through the LHC magnets together with the proton beam. However, due to the energy loss in the interaction, its momentum is smaller than the nominal one. Therefore, in the magnetic fields of the LHC magnets its trajectory is bent more than that of the protons of the beam. The transverse distance between the beam and the forward proton increases with the distance from the Interaction Point (IP), see Fig. 5, and at some point the forward proton hits the beampipe. Before this happens the proton is separated enough from the beam to be tagged by dedicated detectors.

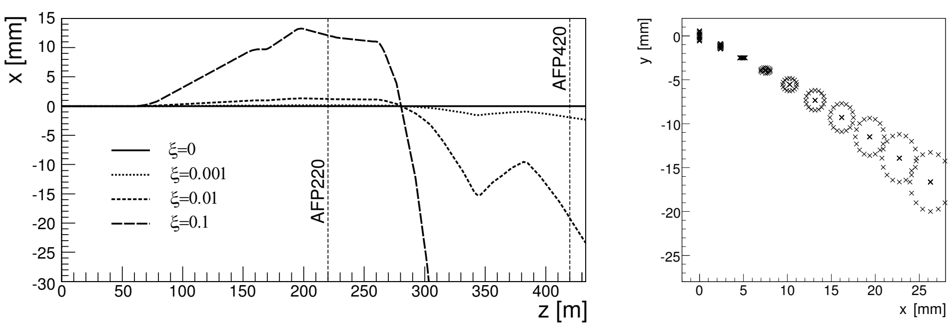


Fig. 5. Left: Simulated horizontal trajectory of a 7 TeV proton and protons with tree different values of reduces energy loss. Right: The position in AFP220 of scattered protons. Moving from left to right, different ellipses correspond to increasing values of $\xi$, the centers of ellipses correspond to $t = 0.0$ GeV$^2$, while the ellipses correspond to $t = 0.5$ GeV$^2$.

The AFP [15] project assumes installation of eight stations with such detectors around the ATLAS IP. The installation is planned in two phases:

(1) AFP220 — stations at 216 and 224 m (on both sides of the IP),

(2) AFP420 — stations at 416 and 424 m (on both sides of the IP).

The first phase of the installation (AFP220) is planned for the long LHC shutdown starting in 2012. These detectors can be used for the studies of exclusive production of jets and anomalous couplings. The second phase (AFP420) is more complicated from the technical point of view, because 420 m is already the LHC cold region and to install the detectors one needs to interfere with the machine liquid helium system.

The AFP420 stations are needed for the low mass Higgs studies, but are not necessary for the anomalous couplings study. Therefore, the second phase of the AFP project will be possibly performed only if the SM Higgs is discovered and the uncertainty for its production in the exclusive mode is more constrained. The second phase could be considered also in the case of supersymmetry discovery.

To perform the measurement of forward protons one needs detectors that are placed inside the accelerator beampipe. The smaller the distance between the active detector area and the beam the better the acceptance that can be obtained. However, one must realize that in the beginning of most runs the beam is "hot", which means that it can be unstable. To be able to perform the measurements the detectors need to be movable — it must be possible to adjust their position (*i.e.* their distance from the beam) appropriately to the beam conditions. The AFP project assumes the use of the Hamburg movable beampipe mechanism to adjust the horizontal position of the detectors, see Fig. 6.

For the measurement of the proton position the required resolution is 10 $\mu$m in the horizontal and 30 $\mu$m in vertical direction. Additional important requirements for the detectors are: high efficiency, small dead space at the edge of the sensors (active edge) and sufficient radiation hardness. A silicon tracking detector fulfilling these requirements will be placed in each AFP station. Such detector will consist of five layers of active detectors that will together give the required resolution.

At the LHC one needs to remember about the pile-up. Not only will the bunch crossings occur every 25 ns, but also in each of them there will be many independent *pp* interactions. For studies of the Central Exclusive Production it must be possible to tell if both protons observed in the AFP detectors come from the same interaction (the same vertex) or it is just a random coincidence of two intact protons coming from two different, independent *pp* collisions. For this purpose additional detectors are needed — fast timing

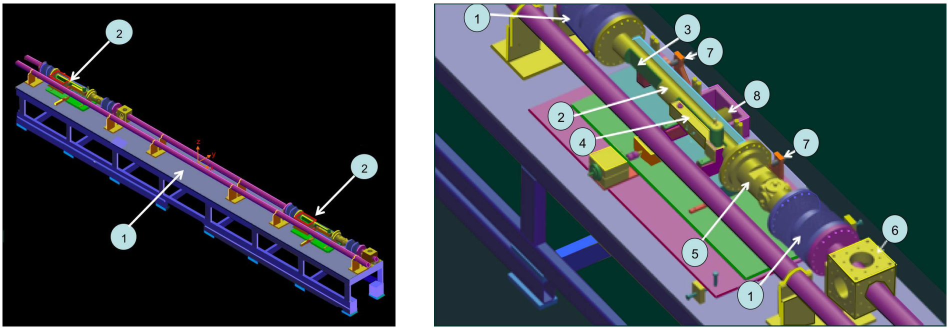

Fig. 6. Left: Schematic view of the AFP220 setup: (1) detector arm with support table, (2) detector sections at 216 and 224 metres. Right: Top view of one detector section: (1) bellows, (2) moving pipe, (3) Si-detector pocket, (4) timing detector, (5) moving BPM, (6) fixed BPM, (7) LVDT position measurement system, (8) emergency spring system.

detectors with resolution of a few picoseconds. With such detectors it is possible to measure the proton time of flight from the vertex to the AFP station so precisely that it will be possible to reconstruct the longitudinal position of the interaction vertex with resolution of a few millimeters. Such measurement performed for both protons will help to distinguish the signal from the pile-up background.

Two different designs of timing detectors are considered. The first one, QUARTIC (see Fig. 7, left), consists of a matrix of quartz bars. A proton traversing the detector creates Cherenkov light that propagates along the

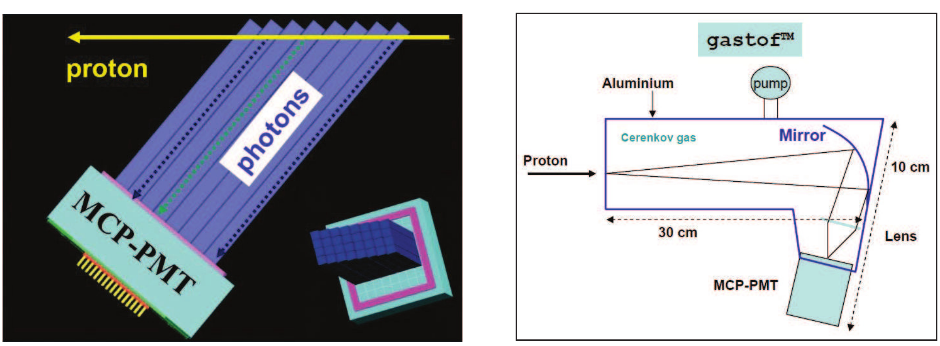


Fig. 7. Left: A schematic side view of the proposed QUARTIC time-of-flight counter, which shows Cerenkov photons being emitted and channeled to the MCP-PMT as the proton traverses the eight fused silica bars in one row. The inset shows a rotated view with all four rows visible. Right: A schematic view of the proposed GASTOF time-of-flight counter.

bars to the photomultiplier. In the second detector, GASTOF, a gas is used as the active material and the created Cherenkov light is focused by a mirror and then detected by a photomultiplier (see Fig. 7, right).

Kinematics of a forward proton is often described by means of the reduced energy loss $\xi$

$$\xi = \frac{\Delta E}{E_0} = \frac{E_0 - E}{E_0}\,,$$

where $E_0$ is the nominal energy of the beam, $E$ is the energy after the interaction and $\Delta E$ is the energy that proton lost in the process. For the Central Exclusive Production there is a simple approximate relation between the reduced energy losses of both protons ($\xi_1$ and $\xi_2$) and the mass $M$ of the centrally produces particle/system (missing mass)

$$M^2 = s\xi_1\xi_2\,,$$

where $s = (2E_0)^2$ is the centre of mass energy squared.

Both sets of detector stations (AFP220 and AFP420) are needed to cover a wide range of $\xi$. The AFP220 stations can detect protons with $\xi$ between 0.02 and 0.2, whereas the AFP420 stations accept $0.002 < \xi < 0.02$. The lower endpoints of these intervals depend on the distance between the detector and the beam (the smaller the distance, the smaller the minimal $\xi$). Fig. 8 (left) presents the acceptance of the AFP220. For the Central Exclusive Production the acceptances of both protons can be translated into the acceptance as a function of the centrally produced mass, see Fig. 8 (right). Three different signatures are considered in this plot:

(1) AFP220+AFP220 — both protons are detected by AFP220 stations,

(2) AFP420+AFP420 — both protons are detected by AFP420 stations,

(3) AFP220+AFP420 — one proton is detected by the AFP220 station and the second one by the AFP420 station.

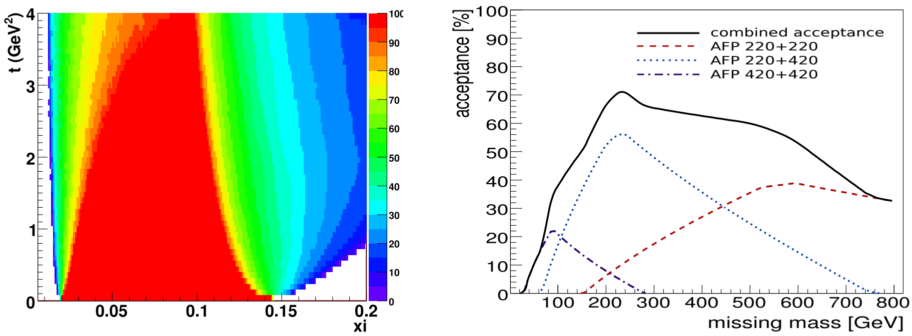


Fig. 8. Left: Acceptance of the AFP220 stations on beam 1 as a function of $\xi$ and $t \approx p_{\mathrm{T}}^2$. Right: Acceptance of the AFP detectors as a function of the missing mass.

## 5. Summary

Central Exclusive Production and photon–photon interactions in *pp* collisions are very interesting processes to study at the LHC. Uncertainties of the theoretical calculations are quite large, thus measurements of *e.g.* exclusive jets could lead to better understanding of the strong interactions ruling these processes. Other possible results are determination of the Higgs boson quantum numbers and probing new physics via the gauge bosons anomalous couplings.

For all these to happen, new dedicated detectors are needed to tag the forward protons. The AFP project of such an upgrade of the ATLAS experiment has been presented. In the first phase it postulates installation of four stations on both sides of the central ATLAS detector. Each station will consist of a silicon detector measuring the proton position and the timing detector that measures TOF of the scattered proton with picoseconds precision. The detectors will be placed in the Hamburg movable beampipe.

At the time of writing this note the Technical Proposal of the AFP was being reviewed by the ATLAS Collaboration. If the project is accepted, the AFP220 stations will be installed in the tunnel during the next long LHC shutdown.

## REFERENCES


[1] D.G. d'Enterria, `arXiv:0708.0551 [hep-ex]`.

[2] [CDF Collaboration], *Phys. Rev.* **D77**, 052004 (2008).

[3] V.A. Khoze, A.D. Martin, M.G. Ryskin, *Eur. Phys. J.* **C14**, 525 (2000); *Eur. Phys. J.* **C23**, 311 (2002).

[4] R. Staszewski, J. Chwastowski, *Nucl. Instrum. Methods* **A609**, 136 (2009) [`arXiv:0906.2868 [physics.ins-det]`].

[5] A. Dechambre, O. Kepka, C. Royon, R. Staszewski, *Phys. Rev.* **D83**, 054013 (2011).

[6] M.W. Krasny, J. Chwastowski, K. Slowikowski, *Nucl. Instrum. Methods* **A584**, 42 (2008).

[7] N. Schul, K. Piotrzkowski, *Nucl. Phys. Proc. Suppl.* **179-180**, 289 (2008).

[8] O. Kepka, C. Royon, *Phys. Rev.* **D78**, 073005 (2008).

[9] E. Chapon, C. Royon, O. Kepka, *Phys. Rev.* **D81**, 074003 (2010).

[10] [OPAL Collaboration], *Phys. Rev.* **D70**, 032005 (2004).

[11] G. Wolf, *Rep. Prog. Phys.* **73**, 116202 (2010).

[12] [pp2pp Collaboration], *Phys. Lett.* **B647**, 98 (2007).

[13] S.L. Bueltmann *et al.*, *Phys. Lett.* **B579**, 245 (2004).

[14] ATLAS Luminosity and Forward Physics Community: ATLAS TDR 018, CERN/LHCC/2008-004.

[15] [AFP Collaboration], Letter of Intent for ATLAS FP: A Project to Install Forward Proton Detectors at 220 m and 420 m Upstream and Downstream of the ATLAS Detector, http://jenni.web.cern.ch/jenni/AFP.loi_atlas.pdf