TIMING DETECTORS FOR PROTON TAGGING AT THE LHC*

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(Received August 20, 2014)

We present the physics motivation of detecting intact protons in the final state at the LHC in the ATLAS and CMS experiments, as well as the importance of timing measurement, in particular, to reject pile-up background. Different kinds of timing detectors being studied are presented briefly.

DOI:10.5506/APhysPolBSupp.7.735
PACS numbers: 13.85.–t, 11.25.Wx, 12.15.–y, 12.38.–t

1. Physics with proton tagging at the LHC

The Large Hadron Collider (LHC) will collide protons with a center-of-mass energy of 13 TeV starting in 2015, and the idea is to detect and measure intact protons after collisions in the ATLAS and CMS-TOTEM experiments. For this sake, special detectors will be hosted in Roman pots and will be installed close to the beam at about 210–220 m from the interaction point. This allows us to detect and measure precisely the intact protons after interaction and scattered at the very small angles (see Fig. 1). Two kinds of

* Presented at the Workshop on Picosecond Photon Sensors for Physics and Medical Applications, Clermont-Ferrand, France, March 12–14, 2014.

detectors are used, namely pixel silicon detectors located at 206 and 214 m, and timing detectors at 214 m in order to measure respectively the proton position and time of flight with a precision of 10–15 μm and 10–15 ps. The diffractive mass acceptance of these detectors stands typically between 400 and 1400 GeV. The key requirements for the pixel silicon detectors is a spatial resolution of 10 (30) μm in x (y) directions, and an angular resolution better than 1 μrad. For this sake, double-sided 3D 50 $\times$ 250 micron pixel detectors with slim-edge dicing will be used.

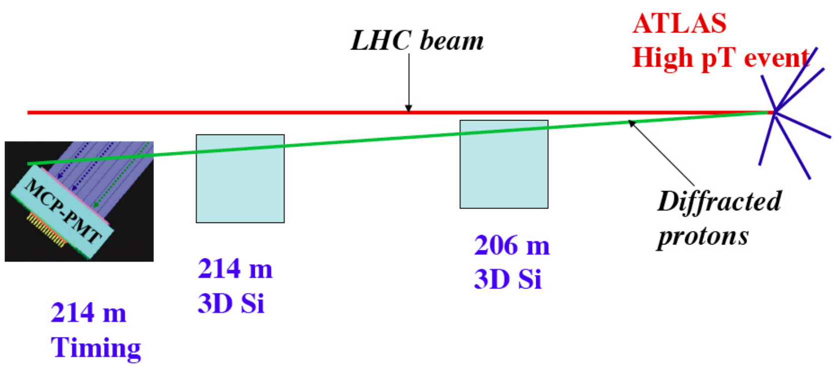

Fig. 1. Scheme of the AFP proton detector in ATLAS. The same detector is implemented on the other side of ATLAS.

In addition to standard QCD measurement in order to understand better the structure of the Pomeron [1], one of the main motivations for running these detectors at the highest luminosities at the LHC is to look for quartic anomalous couplings between γ and W, Z bosons and γ [2]. The search for quartic $WW\gamma\gamma$ anomalous couplings was performed after a full simulation of the ATLAS detectors [4] and requesting two protons to be tagged on both sides of ATLAS/CMS, the presence of high p_{T} leptons above 300 GeV for the leading one — we only consider leptonic decays of the W bosons — high diffractive mass object $M > 800$ GeV. The pile-up events are suppressed by requesting a low number of tracks fitted to the vertex of the W boson pairs. After all requirements, we obtain less than 0.4 event of background for 35 events of signal for an anomalous coupling value of $a_0^W = 5.10^{-6}$ GeV^{-2} for 300 fb^{-1} and a pile-up of 50. This means that the "standard" LHC methods to look for quartic $\gamma\gamma WW$ anomalous couplings are improved by about two orders of magnitude by detecting intact protons. A resolution of the timing detector of about 10 ps discussed in the following was requested to obtain this high sensitivity.

Of special interest is the search for quartic anomalous $\gamma\gamma\gamma\gamma$ couplings [3]. These couplings allow us to probe in a model independent way the existence of charged or neutral particles with unprecedented precision. For these kinds of events, two photons are detected in the central ATLAS/CMS detectors and the two intact protons in the dedicated forward proton detectors. If discovered at the LHC, $\gamma\gamma\gamma\gamma$ quartic anomalous couplings might be related to the existence of extra-dimensions in the universe, which might lead to new insights in the theory of inflation in cosmology since this could happen via extra-dimensions or a reinterpretation of some experiments in atomic physics. As an example, the Aspect photon correlation experiments might be interpreted via the existence of extra-dimensions. Photons could communicate through extra-dimensions and the deterministic interpretation of Einstein for these experiments might be true if such anomalous couplings exist. From the point of view of atomic physics, the results of the Aspect experiments would depend on the distance of the two photon sources.

One of the main backgrounds is due to diphoton exclusive production from the Standard Model and inclusive and exclusive productions of dileptons and dijets where the dileptons and dijets are identified wrongly as photons. Additional backgrounds at high masses are mainly due to pile-up events. Like for the $\gamma\gamma WW$ study, the detection of high p_{T} (γ with $p_{\mathrm{T}} > 200,\ 100$ GeV) and high diffractive mass (above 600 GeV) is requested. The idea to remove the background especially dominated by pile-up events is to compare the kinematic information computed using the central and the forward proton detectors. Events are then selected requesting a matching between mass and rapidity computed using the two photons or the intact proton in the final state. After this requirement, we obtain no background for 300 fb^{-1} considering 50 pile-up events per bunch crossing for 15 signal events for a coupling $\zeta = 2 \times 10^{-13}$ GeV^{-4} as an example. In this configuration, the 95% C.L. sensitivity is 3.5×10^{-14}. The sensitivity to quartic $\gamma\gamma\gamma\gamma$ anomalous couplings goes down to 7×10^{-15} GeV^{-4} for 3000 fb^{-1} and 200 pile-up events reaching the values of beyond Standard Model theories that predict couplings of the order of 10^{-14}–10^{-13} GeV^{-4}. It is worth noticing that timing detectors were not used in this study but might be used to remove additional beam induced backgrounds that are not present in the simulation.

2. Pixelisation of timing detectors and pile-up

The main source of background in the timing detectors is due to pile-up events. Intact protons may obviously originate from the diffractive and photon-exchange events but also from additional soft interactions (pile-up). For instance, a non-diffractive WW event can be superimposed with two single diffractive soft events with intact protons and it is important to be able to distinguish this background from the event where both protons originate from the WW vertex. In order to suppress this background, it is useful to measure precisely the proton time of flights in order to know if the protons originate from the main event hard vertex or not.

Two parameters to build a detector are important to reject pile-up:

— the precision of the proton time of flight, which is the timing detector resolution. Typically, a measurement of 10 ps gives a precision of 2.1 mm on the vertex position,

— the pixelisation of the timing detector: at highest luminosity, the number of intact protons per bunch crossing is high and in order to compute the time of flight of each proton, it is needed to have enough pixelisation or space resolution so that each proton can be detected in different cells of the timing detector. If two protons with different time of flight fall in the same cell, the information is lost.

In order to study the required pixelisation of the timing detector, we simulated 10 million minimum bias events (non-diffractive, single diffractive and double diffractive events) using the PYTHIA generator. The protons were transported through the LHC magnets up to the proton detectors. Events are characterised as no tagged (NT), single tagged (ST) and double tagged (DT) depending on the number of protons in the forward proton detector acceptance. For one minimum bias event, we get a probability of 97% NT, p =1.6% ST, and q =0.01% DT. The multinomial distribution was adopted to simulate pile-up since we assume that the different interactions are independent [6]. For a given number of pile-up proton N, the probability to have N_{L} (N_{R}) protons tagged in the left (right)-hand side only, N_{B} protons on both sides and N_{N} protons not tagged reads

$$P(N_{\mathrm{B}}, N_{\mathrm{L}}, N_{\mathrm{R}}, N_{\mathrm{N}}) = \frac{N!}{N_{\mathrm{B}}!N_{\mathrm{L}}!N_{\mathrm{R}}!N_{\mathrm{N}}!} p^{N_{\mathrm{L}}} q^{N_{\mathrm{B}}} p^{N_{\mathrm{R}}} (1-2p-q)^{N_{\mathrm{N}}} \tag{1}$$

and the probability of no proton tagged, of at least one proton tagged on the left-hand side, and of at least one proton tagged on both sides reads

$$P_{\text{no hit}} = P(0,0,0,N) = (1-2p-q)^N\,, \tag{2}$$

$$P_{\text{hit left}} = \sum_{N_{\mathrm{L}}=1}^{N} P(0,N_{\mathrm{L}},0,N-N_{\mathrm{L}}) = (1-p-q)^N - (1-2p-q)^N\,, \tag{3}$$

$$P_{\text{double hit}} = 1 - P_{\text{no hit}} - 2P_{\text{hit left}} = 1 + (1-2p-q)^N - 2(1-p-q)^N\,. \tag{4}$$

The hit probabilities can then be calculated for various pile-up values (see Table I). For a pile-up $\mu = 50$ (100) for instance, the probability of no tag is 19% (3.6%). The detector needed to detect intact protons has a coverage of about 2 cm $\times$ 2 cm and is located 15σ from the beam. The inefficiency of such a detector assuming 20×8 pixels is given in Table II. The numbers displayed in the table correspond to the probability of getting one proton or more in a given pixel for $\mu = 100$ or a 20×8 pixellised detector. The upper limit on the inefficiencies is of the order of 8% for the pixels closest to the

TABLE I

No tag, single tag on the left- or right-hand side (same by definition) and double tagged probability.

μ	$P_{\rm N}$	$P_{\rm S,left}$	$P_{\rm S,right}$	$P_{\rm D}$
0	0.97	0.016	0.016	9.9e-05
50	0.189	—	0.248	0.316
100	0.036	—	0.155	0.655
300	0.	—	0.007	0.986

TABLE II

Probability of more than 1 proton to fall in a given pixel of the timing detector.

Inefficiencies — 20×8 pixel design — $\mu = 100$

Row/ Column	1	2	3	4	5	6	7	8	9	10
8	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
7	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
6	0.038	0.002	0.	0.	0.	0.	0.	0.	0.	0.
5	0.067	0.077	0.051	0.006	0.001	0.001	0.001	0.001	0.001	0.
4	0.001	0.001	0.015	0.049	0.042	0.024	0.012	0.006	0.004	0.003
3	0.	0.	0.	0.001	0.007	0.019	0.022	0.018	0.013	0.008
2	0.	0.	0.	0.	0.	0.002	0.006	0.010	0.012	0.011
1	0.	0.	0.	0.	0.	0.	0.001	0.003	0.005	0.007

Row/ Column	11	12	13	14	15	16	17	18	19	20
8	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
7	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
6	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
5	0.001	0.001	0.001	0.001	0.001	0.	0.	0.	0.	0.
4	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.
3	0.006	0.004	0.003	0.003	0.002	0.002	0.001	0.001	0.001	0.
2	0.010	0.008	0.006	0.004	0.004	0.003	0.003	0.002	0.002	0.
1	0.008	0.008	0.007	0.006	0.005	0.004	0.004	0.003	0.003	0.

bins, but is found negligible for pixels further away which measure higher mass diffractive objects. For comparison, the inefficiencies for $\mu = 50$ are about half, and vertical bar detectors lead to larger inefficiencies between 10% and 20% on a large part of the detector (a 7 bar detector with 2 mm width for the first bar and 3.25 mm for other bars, leads to inefficiencies between 8% and 19% for the first 6 bars). It is also worth mentioning that this study only includes physics backgrounds and not beam-induced backgrounds which are not in the simulation. Recent results from TOTEM show that the beam-induced backgrounds have the tendency to be high and located in the pixels closest to the beam [5], and this is why a full pixelised detector is preferable to bars.

3. Timing detectors and readout chip

A fast timing system that can precisely measure the time difference between outgoing scattered protons is a key component of the forward proton detector. The final timing system should have the following characteristics:

— 10 ps or better resolution (which leads to a factor 40 rejection on pile-up background);

— Efficiency close to 100% over the full detector coverage;

— High rate capability (there is a bunch crossing every 25 ns at the nominal LHC);

— Enough segmentation for multi-proton timing;

— Level trigger capability.

The first proposed timing system consisted of a quartz-based Cherenkov detector [7] coupled to a microchannel plate photomultiplier tube (MCP-PMT), followed by the electronic elements that amplify, measure, and record the time of the event along with a stabilized reference clock signal. The QUARTIC detector consists of an array of 8×4 fused silica bars ranging in length from about 8 to 12 cm and oriented at the average Cherenkov angle. The beam tests lead to a time resolution per bar of the order of 34 ps.

At high luminosity of the LHC, as we already mentioned, higher pixelisation of the timing detector will be required. For this sake, a R&D phase concerning timing detector developments based on silicon detectors [9], and diamonds [10] has started. In parallel, a new timing readout chip has been developed in Saclay. It uses waveform sampling methods which give the best possible timing resolution. The aim of this chip called SAMPIC0 [8] (see Fig. 2) is to obtain sub 10 ps timing resolution, 1 GHz input bandwidth, no dead time at the LHC, and data taking at up to 10.2 Gigasamples per second. The cost per channel is estimated to be of the order of $10 which is a considerable improvement to the present cost of a few $1000 per channel for a standard TDC converter, allowing us to use this chip in medical applications such as PET imaging detectors. The holy grail of imaging 10 picosecond PET detector seems now to be feasible: with a resolution better than 20 ps, image reconstruction is no longer necessary and real-time image formation becomes possible. The results on timing resolution using for the first time a Si detector read out by SAMPIC0 and lit with a laser are shown in Fig. 3 and lead to a promising resolution of 30 ps per channel. Beam tests are foreseen towards autumn to further test SAMPIC0 together with a diamond and Si detector.

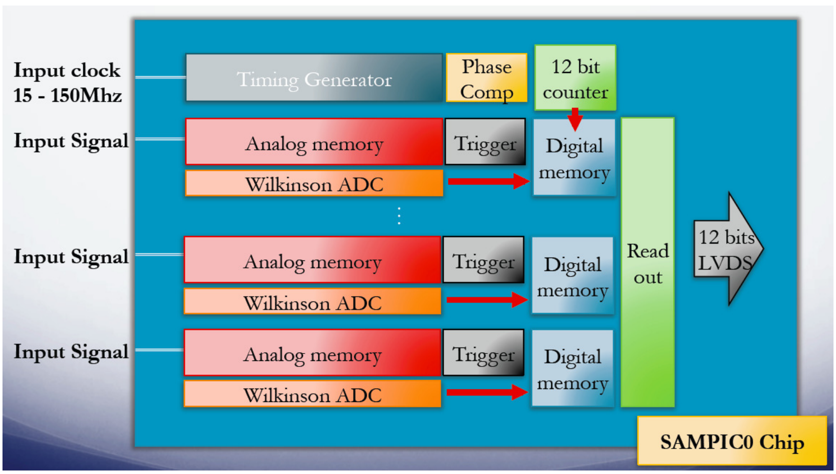

Fig. 2. Scheme of the SAMPIC0 chip.

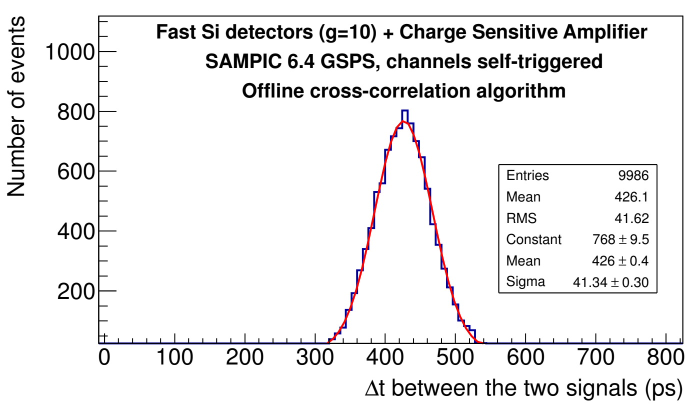

Fig. 3. Preliminary results on timing resolution using SAMPIC0 and a Si detector using a laser.

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