

Forward physics with tagged protons at the LHC: QCD and anomalous couplings *

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Abstract

We present some physics topics that can be studied at the LHC using proton tagging. We distinguish the QCD (Pomeron structure, BFKL analysis...) from the exploratory physics topics (Higgs boson, anomalous couplings between photons and W/Z bosons).

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In this short report, we discuss some potential measurements to be performed using proton tagging detectors at the LHC. We can distinguish two kinds of measurements. The first motivation of these detectors is to probe the structure of the colorless exchanged object, the Pomeron, in terms of quarks and gluons, in order to constrain further its structure in a domain of energy unexplored until today. We can also mention tests of the Balitsky Fadin Kuraev Lipatov (BFKL) evolution equation [1] using gap between jets in diffractive events. The second motivation is to explore more rare events such as the production of the Higgs boson and the search for beyond standard model physics such as quartic anomalous couplings between photons and W/Z bosons and photons. We assume in the following intact protons to be tagged in dedicated detectors located at about 210 m for ATLAS (220 m for CMS) as described at the end of this report.

1 Inclusive diffraction measurement at the LHC

In this section, we discuss potential measurements at the LHC that can constrain the Pomeron structure. The Pomeron structure in terms of quarks and gluons has been derived from QCD fits at HERA and at the Tevatron and it is possible to probe this structure and the QCD evolution at the LHC in a completely new kinematical domain. All the following studies have been performed using the

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Forward Physics Monte Carlo (FPMC), a generator that has been designed to study forward physics, especially at the LHC. It aims to provide a variety of diffractive processes in one common framework, *i.e.* single diffraction, double pomeron exchange, central exclusive production and two-photon exchange [2].

1.1 Dijet production in double Pomeron exchanges processes

The high energy and luminosity at the LHC allow the exploration of a completely new kinematical domain. One can first probe if the Pomeron is universal between ep and pp colliders, or in other words, if we are sensitive to the same object at HERA and the LHC. Tagging both diffractive protons in ATLAS and CMS will allow the QCD evolution of the gluon and quark densities in the Pomeron to be tested and compared with the HERA measurements. In addition, it is possible to assess the gluon and quark densities using the dijet and $\gamma + jet$ productions [3]. The different diagrams of the processes that can be studied at the LHC are shown in Fig. 1, namely double pomeron exchange (DPE) production of dijets (left), of $\gamma+jet$ (middle), sensitive respectively to the gluon and quark contents of the Pomeron, and the jet gap jet events (right).

The dijet production in DPE events at the LHC is sensitive to the gluon density in the Pomeron. In order to quantify how well we are sensitive to the Pomeron structure in terms of gluon density at the LHC, we display in Fig. 2, top, the dijet cross section as a function of the jet p_T . The central black line displays the cross section value for the gluon density in the Pomeron measured at HERA including an additional survival probability of 0.03. The yellow band shows the effect of the 20% uncertainty on the gluon density taking into account the normalisation uncertainties. The dashed curves display how the dijet cross section at the LHC is sensitive to the gluon density distribution especially at high β . For this sake, we multiply the gluon density in the Pomeron from HERA by $(1 - \beta)^\nu$ where ν varies between -1 and 1. When ν is equal to -1 (resp. 1), the gluon density is enhanced (resp. decreased) at high β . From Fig. 2, we notice that the dijet cross section is indeed sensitive to the gluon density in the Pomeron and we can definitely check if the Pomeron model from HERA and its structure in terms of gluons is compatible between HERA and the LHC. This will be an important test of the Pomeron universality. This measurement can be performed for a luminosity as low as 10 pb^{-1} since the cross section is very large (typically, one day at low luminosity without pile up at the LHC). It is worth noticing that this measurement will be limited by systematic uncertainties (not the statistical ones). Typically, if the jet energy scale is known with a precision of 1%, we expect the systematics on the jet cross section mainly due to jet energy scale and jet p_T resolution to be of the order of 15%.

However, from this measurement alone, it will be difficult to know if the potential difference between the expectations from HERA and the measurement at the LHC are mainly due to the gluon density or the survival probability since the ratio between the curves for the different gluons (varying the ν parameters) are almost constant.

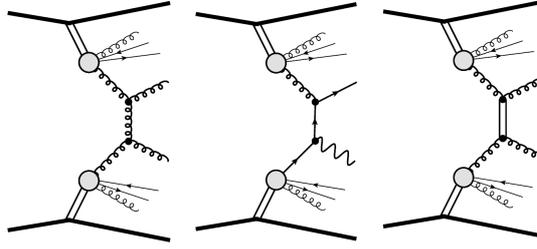


Figure 1: Inclusive diffractive diagrams. From left to right: jet production in inclusive double pomeron exchange, γ +jet production in DPE, jet gap jet events

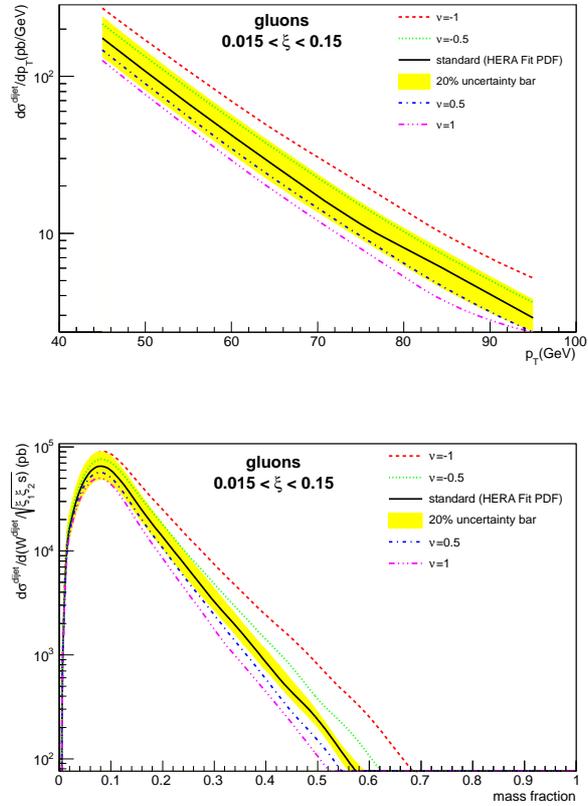


Figure 2: Top: DPE di-jet cross section as a function of jet p_T at the LHC. Bottom: DPE di-jet mass fraction distribution. The different curves correspond to different modifications of the Pomeron gluon density extracted from HERA data (see text).

An additional observable more sensitive to the gluon density in the Pomeron is displayed in Fig. 2, bottom. This is the so called dijet mass fraction, the ratio of the dijet mass to the total diffractive mass computed as $\sqrt{\xi_1 \xi_2 S}$ where $\xi_{1,2}$ are the proton fractional momentum carried by each Pomeron and \sqrt{S} the center-of-mass energy of 14 TeV. We note that the curves corresponding to the different values of ν are much more spaced at high values of the dijet mass fraction, meaning that this observable is indeed sensitive to the gluon density at high β . This is due to the fact that the dijet mass fraction is equal to $\sqrt{\beta_1 \beta_2}$ where $\beta_{1,2}$ are the Pomeron momentum fraction carried by the parton inside the Pomeron which interacts. The measurement of the dijet cross section as a function of the dijet mass fraction is thus sensitive to the product of the gluon distribution taken at β_1 and β_2 . It is worth mentioning that exclusive dijet events will contribute to this distribution at higher values of the dijet mass fraction above 0.6-0.7 [4].

1.2 Sensitivity to the Pomeron structure in quarks using γ + jet events

Fig. 3 displays possible observables at the LHC that can probe the quark content in the Pomeron. Fig. 3, top, displays the γ +jet to the dijet cross section ratios as a function of the leading jet p_T for different assumptions on the quark content of the Pomeron, d/u varying between 0.25 and 4 in steps of 0.25. We notice that the cross section ratio varies by a factor 2.5 for different values of u/d and the ratio depends only weakly on the jet p_T except at low values of jet p_T , which is due to the fact that we select always the jet with the highest p_T in the dijet cross section (and this is obviously different for the γ + jet sample where we have only one jet most of the time). The aim of the jet p_T distribution measurement is twofolds: is the Pomeron universal between HERA and the LHC and what is the quark content of the Pomeron? The QCD diffractive fits performed at HERA assumed that $u = d = s = \bar{u} = \bar{d} = \bar{s}$, since data were not sensitive to the difference between the different quark component in the Pomeron. The LHC data will allow us to determine for instance which value of d/u is favoured by data. Let us assume that $d/u = 0.25$ is favoured. If this is the case, it will be needed to go back to the HERA QCD diffractive fits and check if the fit results at HERA can be modified to take into account this assumption. If the fits to HERA data lead to a large χ^2 , it would indicate that the Pomeron is not the same object at HERA and the LHC. On the other hand, if the HERA fits work under this new assumption, the quark content in the Pomeron will be further constrained. The advantage of measuring the cross section ratio as a function of jet p_T is that most of the systematic uncertainties due to the determination of the jet energy scale will cancel. This is however not the case for the jet energy resolution since the jet p_T distributions are different for γ +jet and dijet events.

Fig. 3, bottom, displays the γ +jet to dijet cross section ratio as a function of the diffractive mass M computed from the proton ξ measured in the forward detectors $M = \sqrt{\xi_1 \xi_2 S}$ where ξ_1 and ξ_2 are the momentum fractions of the

proton carried by each Pomeron and measured in the proton detectors. The advantage of this variable is that most of systematic uncertainties due to the measurement of the diffractive mass cancel since the mass distributions for γ +jet and dijet are similar. The typical resolution on mass is in addition very good of the order of 2 to 3%. The statistical uncertainties corresponding to 300 pb⁻¹, three weeks of data taking at low pile up, are also shown on the Figure. This measurement will be fundamental to constrain in the most precise way the Pomeron structure in terms of quark densities, and to test the Pomeron universality between the Tevatron and the LHC.

Let us notice that the measurement can be performed with 100 pb⁻¹ (about one week of data taking), but this would increase the statistical uncertainties in Fig. 3 of about 40%. It would still be possible to distinguish between extreme models. 300 pb⁻¹ is the optimal luminosity for this measurement in order to get a more precise measurement. Working at higher pile up will require new strategies to be developed, by using for instance fast timing detectors allowing us to measure the proton time-of-flight and thus to determine if the protons originate from the main hard interaction or from pile up.

1.3 Soft colour interaction models

Soft color interaction models (SCI) describe [5] additional interactions between colored partons below the conventional cutoff for perturbative QCD. These are based on the assumption of factorization between the conventional perturbative event and the additional non-perturbative soft interactions. Soft exchanges imply that the changes in momenta due to the additional exchanges are very small, whereas the change in the event's color topology due to exchanges of color charge can lead to significant observables, e.g. rapidity gaps and leading beam remnants. The probability to obtain a leading proton at the LHC in the context of SCI models depends on the color charge and the kinematic variables of the beam remnant before hadronization. We find an overall good agreement between Herwig/DPE and Pythia/SCI for the prediction of the ratio between γ +jet and jet+jet cross sections, but the distribution of this ratio as a function of the total diffractive mass distributions may allow to distinguish between the Herwig/DPE and Pythia/SCI models because the latter leads to a more flat dependence on the total diffractive mass, as shown in Fig. 3, bottom.

1.4 Jet gap jet production in double Pomeron exchanges processes

This process is illustrated in Fig 1, right [6, 7]. Both protons are intact after the interaction and detected in AFP at 210 m, two jets are measured in the ATLAS central detector and a gap devoid of any energy is present between the two jets. This kind of event is important since it is sensitive to QCD resummation dynamics given by the BFKL [1] evolution equation. This process has never been measured to date and will be one of the best methods to probe these resummation effects, benefitting from the fact that one can perform the

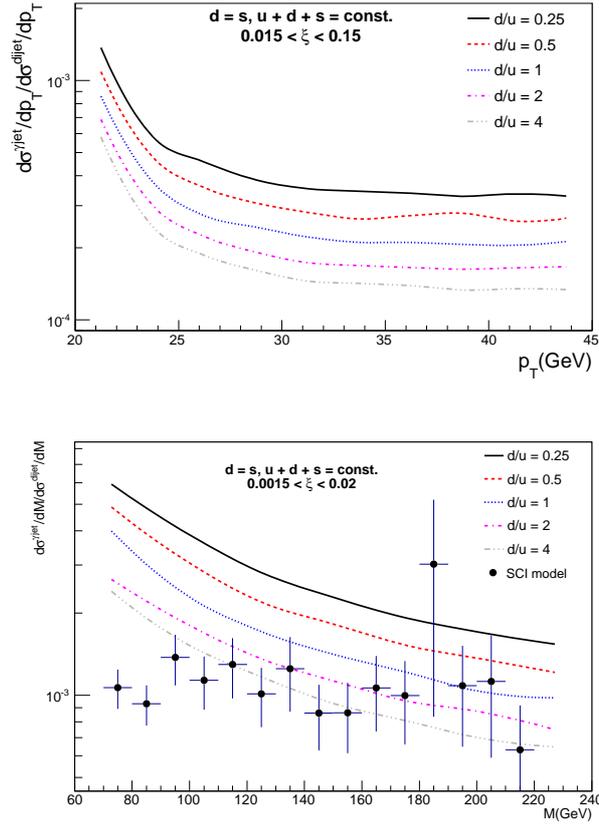


Figure 3: DPE γ + jet to di-jet differential cross section ratio, for the acceptance of the 210m proton detectors. Top: as a function of jet p_T , for different values of d/u . Bottom: as a function of diffractive mass, compared in addition to expectations from SCI models.

measurement for jets separated by a large angle (there is no remnants which ‘pollute’ the event). As an example, the cross section ratio for events with gaps to events with or without gaps as a function of the leading jet p_T is shown in Fig 4 for 300 pb^{-1} . The measurement has to be performed at medium luminosity at the LHC so that the gap between the jets is not “polluted” by pile up events. The presence of few pile up events in average is still possible for this measurement since central gaps can be identified using central tracks fitted to the main vertex of the event. It is worth noticing that the ratio between the jet gap jet and the dijet cross sections in DPE events is of the order of 20% which is much higher than the expectations for non-diffractive events. This is due to the fact that the survival probability of 0.03 at the LHC does not need to be applied for diffractive events.

2 Exclusive jet and Higgs boson production at the LHC

The Higgs and jet exclusive production in both Khoze Martin Ryskin [8] (KMR) and CHIDE [9] models have been implemented in FPMC [2]. The exclusive Higgs cross section for a Higgs boson mass of 126 GeV is of the order of 3 fb.

There are two main sources of uncertainties in exclusive models: the gap survival probability which will be measured using the first LHC data (in this study we assume a value of 0.03 at the LHC for a center-of-mass energy of 14 TeV), the unintegrated gluon density which appears in the exclusive cross section calculation and which contains the hard and the soft part (contrary to the hard part, the soft one is not known precisely and originates from a phenomenological parametrisation) [10, 8].

In addition, it is possible to measure the exclusive jet cross section (see the process in Fig. 6) at high jet p_T at the LHC benefitting from the high luminosity accumulated. The expectation is shown in Fig. 5 for the ATLAS experiment as an example. The results of the measurement are shown as black points for a luminosity of 40 fb^{-1} and 23 pile up events, assuming the protons to be detected in AFP at 210 m [15]. The expected contributions from background (non-diffractive, single diffractive with pile up and double pomeron exchange events) are shown as well as the exclusive jet one in yellow. The statistical significance of the measurement is up to 19σ .

3 Exclusive WW and ZZ production

In the Standard Model (SM) of particle physics, the couplings of fermions and gauge bosons are constrained by the gauge symmetries of the Lagrangian. The measurement of W and Z boson pair productions via the exchange of two photons allows to provide directly stringent tests of one of the most important and least understood mechanism in particle physics, namely the electroweak symmetry breaking.

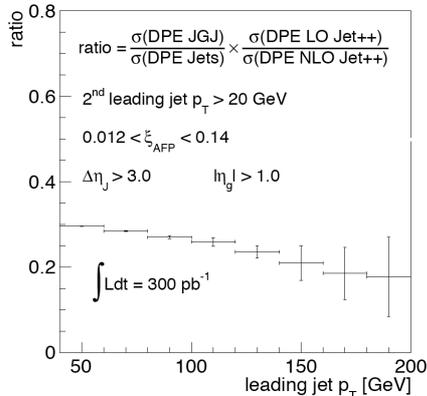


Figure 4: Ratio of DPE Jet gap jet events to standard DPE dijet events as a function of the leading jet p_T [6].

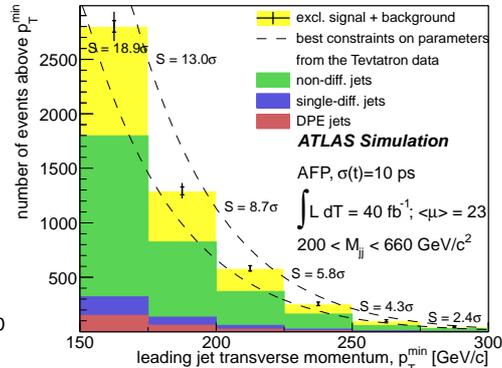


Figure 5: Measurement of the exclusive jet production at high jet p_T at the LHC in the ATLAS experiment [15].

3.1 Photon exchange processes in the SM

The process that we intend to study is the W pair production shown in Fig. 7 induced by the exchange of two photons [11]. It is a pure QED process in which the decay products of the W bosons are measured in the central detector and the scattered protons leave intact in the beam pipe at very small angles and are detected in AFP.

After simple cuts to select exclusive W pairs decaying into leptons, such as a cut on the proton momentum loss of the proton ($0.0015 < \xi < 0.15$) — we assume the protons to be tagged in AFP at 210 and 420 m — on the transverse momentum of the leading and second leading leptons at 25 and 10 GeV respectively, on $\cancel{E}_T > 20$ GeV, $\Delta\phi > 2.7$ between leading leptons, and $160 < W < 500$ GeV, the diffractive mass reconstructed using the forward detectors, the background is found to be less than 1.7 event for 30 fb^{-1} for a SM signal of 51 events [11].

3.2 Quartic anomalous couplings

The parameterization of the quartic couplings based on [12] is adopted. The cuts to select quartic anomalous gauge coupling WW events are similar as the ones we mentioned in the previous section, namely $0.0015 < \xi < 0.15$ for the tagged protons corresponding to the AFP detector at 210 and 420 m, $\cancel{E}_T > 20$ GeV, $\Delta\phi < 3.13$ between the two leptons. In addition, a cut on the p_T of the leading lepton $p_T > 160$ GeV and on the diffractive mass $W > 800$ GeV are requested since anomalous coupling events appear at high mass. Fig 8 displays the p_T distribution of the leading lepton for signal and the different considered

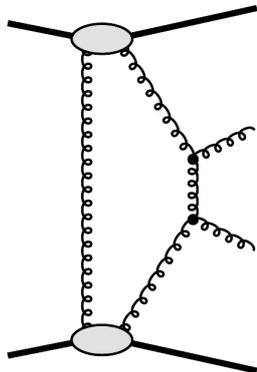


Figure 6: Exclusive jet production.

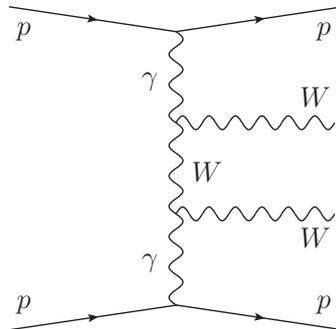


Figure 7: Diagram showing the two-photon production of W pairs.

Couplings	OPAL limits [GeV ⁻²]	Sensitivity @ $\mathcal{L} = 30$ (200) fb ⁻¹	
		5 σ	95% CL
a_0^W/Λ^2	[-0.020, 0.020]	5.4 10 ⁻⁶ (2.7 10 ⁻⁶)	2.6 10 ⁻⁶ (1.4 10 ⁻⁶)
a_C^W/Λ^2	[-0.052, 0.037]	2.0 10 ⁻⁵ (9.6 10 ⁻⁶)	9.4 10 ⁻⁶ (5.2 10 ⁻⁶)
a_0^Z/Λ^2	[-0.007, 0.023]	1.4 10 ⁻⁵ (5.5 10 ⁻⁶)	6.4 10 ⁻⁶ (2.5 10 ⁻⁶)
a_C^Z/Λ^2	[-0.029, 0.029]	5.2 10 ⁻⁵ (2.0 10 ⁻⁵)	2.4 10 ⁻⁵ (9.2 10 ⁻⁶)

Table 1: Reach on anomalous couplings obtained in γ induced processes after tagging the protons in AFP compared to the present OPAL limits. The 5 σ discovery and 95% C.L. limits are given for a luminosity of 30 and 200 fb⁻¹ [11]

backgrounds. After these requirements, we expect about 0.7 background events for an expected signal of 17 events if the anomalous coupling is about four orders of magnitude lower than the present LEP limit [13] ($|a_0^W/\Lambda^2| = 5.4 \cdot 10^{-6}$) or two orders of magnitude lower with respect to the D0 and CDF limits [14] for a luminosity of 30 fb⁻¹. The strategy to select anomalous coupling ZZ events is analogous and the presence of three leptons or two like sign leptons are requested. Table 1 gives the reach on anomalous couplings at the LHC for luminosities of 30 and 200 fb⁻¹ compared to the present OPAL limits [13]. It is possible to reach the values expected in extra-dimension models. The tagging of the protons using the ATLAS Forward Physics detectors is the only method at present to test so small values of quartic anomalous couplings.

The search for quartic anomalous couplings between γ and W bosons was performed again after a full simulation of the ATLAS detector including pile

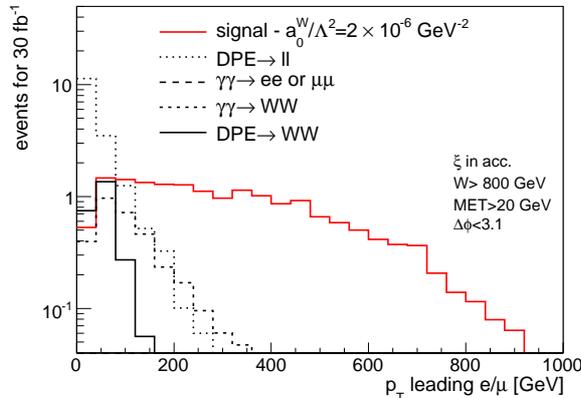


Figure 8: Distribution of the transverse momentum of the leading lepton for signal and background after the cut on W , \cancel{E}_T , and $\Delta\phi$ between the two leptons [11].

up [15] assuming the protons to be tagged in AFP at 210 m only. Integrated luminosities of 40 and 300 fb^{-1} with, respectively, 23 or 46 average pile-up events per beam crossing have been considered. In order to reduce the background, each W is assumed to decay leptonically (note that the semi-leptonic case in under study). The full list of background processes used for the ATLAS measurement of Standard Model WW cross-section was simulated, namely $t\bar{t}$, WW , WZ , ZZ , W +jets, Drell-Yan and single top events. In addition, the additional diffractive backgrounds mentioned in the previous paragraph were also simulated. The requirement of the presence of at least one proton on each side of AFP within a time window of 10 ps allows us to reduce the background by a factor of about 200 (50) for $\mu = 23$ (46). The p_T of the leading lepton originating from the leptonic decay of the W bosons is required to be $p_T > 150 \text{ GeV}$, and that of the next-to-leading lepton $p_T > 20 \text{ GeV}$. Additional requirement of the dilepton mass to be above 300 GeV allows us to remove most of the diboson events. Since only leptonic decays of the W bosons are considered, we require in addition less than 3 tracks associated to the primary vertex, which allows us to reject a large fraction of the non-diffractive backgrounds (e.g. $t\bar{t}$, diboson productions, W +jet, etc.) since they show much higher track multiplicities. Remaining Drell-Yan and QED backgrounds are suppressed by requiring the difference in azimuthal angle between the two leptons $\Delta\phi < 3.1$. After these requirements, a similar sensitivity with respect to fast simulation without pile up was obtained.

Of special interest will be also the search for anomalous quartic $\gamma\gamma\gamma\gamma$ anomalous couplings which is now being implemented in the FPMC generator. Let us notice that there is no present existing limit on such coupling and the sensitiv-

ity using the forward proton detectors is expected to be similar as the one for $\gamma\gamma WW$ or $\gamma\gamma ZZ$ anomalous couplings. 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 a reinterpretation of some experiments in atomic physics. As an example, the Aspect photon correlation experiments [16] 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.

4 Forward Proton Detectors in ATLAS and CMS

In this section, we describe the proposal to install the ATLAS Forward Proton (AFP) detector in order to detect intact protons at 206 and 214 meters on both side of the ATLAS experiment [15] (similar detectors will be installed around CMS by TOTEM/CMS). This one arm will consist of two sections (AFP1 and AFP2) contained in a special design of beampipe or in more traditional roman pots. In the first section (AFP1), a tracking station composed by 6 layers of Silicon detectors will be deployed. The second station AFP2 will contain another tracking station similar to the one already described and a timing detector. In addition, a similar structure could be installed at about 420 m from the ATLAS interaction point. The aim of this setup, mirrored by an identical arm placed on the opposite side of the ATLAS interaction point, will be to tag the protons emerging intact from the pp interactions so allowing ATLAS to exploit the program of diffractive and photon induced processes described in the previous sections.

4.1 Movable beam pipes and roman pots

In order to detect intact protons in the final state. two kinds of detectors (roman pots and movable beam pipes) are possible. Roman pots have been used already in many experiments at the SPS, HERA, Tevatron and LHC colliders and we will concentrate here on the new idea of movable beam pipes. The idea of movable Hamburg beam pipes is quite simple [17]: a larger section of the LHC beam pipe than the usual one can move close to the beam using bellows so that the detectors located at its edge (called pocket) can move close to the beam by about 2.5 cm when the beam is stable (during injection, the detectors are in parking position). In its design, the predominant aspect is the minimization of the thickness of the portions called floor and window (see Fig. 9). Minimizing the depth of the floor ensures that the detector can go as close to the beam as possible allowing us to detect protons scattered at very small angles, while minimizing the depth of the thin window is important to keep the protons intact and to reduce the impact of multiple interactions. Two configurations exist for the movable beam pipes: the first one at 206 m from the ATLAS interaction

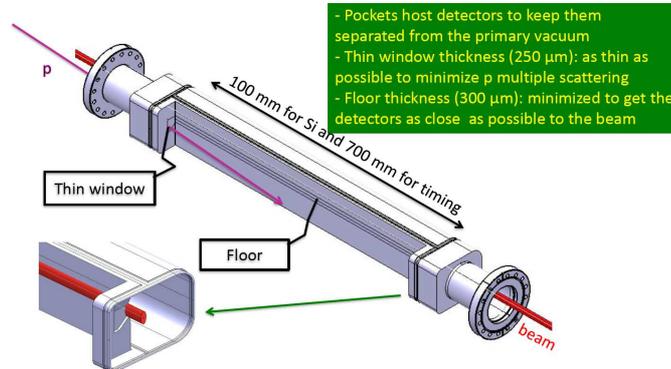


Figure 9: Scheme of the movable beam pipe.

point hosts a Si detector (floor length of about 100 mm) and the second one (floor length of about 400 mm) the timing and the Si detectors. While it is still being discussed if the movable beam pipe or the roman pot solution will be chosen at 210 m (the RF pickup using movable beam pipes is still under study and might be an issue for the LHC stability if it is too high), it is clear that movable beam pipes are favoured at 420 m since not enough space is available at this position and new cryostats have been developed to host these movable beam pipes in the cold region at 420 m. The usage of roman pots at 420 m would require a costly cryogenic bypass to be installed to isolate the region where roman pots would be installed.

4.2 3D Silicon detectors

The purpose of the tracker system is to measure points along the trajectory of beam protons that are deflected at small angles as a result of collisions. The tracker when combined with the LHC dipole and quadrupole magnets, forms a powerful momentum spectrometer. Silicon tracker stations will be installed in Hamburg beam pipes or roman pots at ± 206 and ± 214 m from the ATLAS interaction point (and also at 420 m later if these additional detectors are approved).

The key requirements for the silicon tracking system at 220 m are:

- Spatial resolution of ~ 10 (30) μm per detector station in x (y)
- Angular resolution for a pair of detectors of about $1 \mu\text{rad}$
- High efficiency over the area of $20 \text{ mm} \times 20 \text{ mm}$ corresponding to the distribution of diffracted protons
- Minimal dead space at the edge of the sensors allowing us to measure the scattered protons at low angles

- Sufficient radiation hardness in order to sustain the radiation at high luminosity
- Capable of robust and reliable operation at high LHC luminosity

The basic building unit of the AFP detection system is a module consisting of an assembly of a sensor array, on-sensor read-out chip(s), electrical services, data acquisition and detector control system. The module will be mounted on the mechanical support with embedded cooling and other necessary services. The sensors are double sided 3D 50×250 micron pixel detectors with slim-edge dicing built by FBK and CNM companies. The sensor efficiency has been measured to be close to 100% over the full size in beam tests. A possible upgrade of this device will be to use 3D edgeless Silicon detectors built in a collaboration between SLAC, Manchester, Oslo, Bergen... A new front-end chip FE-I4 has been developed for the Si detector by the Insertable B Layer (IBL) collaboration in ATLAS [18]. The FE-I4 integrated circuit contains readout circuitry for 26 880 hybrid pixels arranged in 80 columns on $250 \mu\text{m}$ pitch by 336 rows on $50 \mu\text{m}$ pitch, and covers an area of about $19 \text{ mm} \times 20 \text{ mm}$. It is designed in a 130 nm feature size bulk CMOS process. Sensors must be DC coupled to FE-I4 with negative charge collection. The FE-I4 is very well suited to the AFP requirements: the granularity of cells provides a sufficient spatial resolution, the chip is radiation hard enough (up to a dose of 3 MGy), and the size of the chip is sufficiently large that one module can be served by just one chip.

The dimensions of the individual cells in the FE-I4 chip are $50 \mu\text{m} \times 250 \mu\text{m}$ in the x and y directions, respectively. Therefore to achieve the required position resolution in the x -direction of $\sim 10 \mu\text{m}$, six layers with sensors are required (this gives $50/\sqrt{12}/\sqrt{5} \sim 7 \mu\text{m}$ in x and roughly 5 times worse in y). Offsetting planes alternately to the left and right by one half pixel will give a further reduction in resolution of at least 30%. The AFP sensors are expected to be exposed to a dose of 30 kGy per year at the full LHC luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

4.3 Timing detectors

A fast timing system that can precisely measure the time difference between outgoing scattered protons is a key component of the AFP detector. The time difference is equivalent to a constraint on the event vertex, thus the AFP timing detector can be used to reject overlap background by establishing that the two scattered protons did not originate from the same vertex as the the central system. The final timing system should have the following characteristics [19]:

- 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

Fig. 10 shows a schematic overview of the first proposed timing system, consisting of a quartz-based Cerenkov detector 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 Cerenkov angle. A proton that is sufficiently deflected from the beam axis will pass through a row of eight bars emitting Cerenkov photons providing an overall time resolution that is approximately $\sqrt{8}$ times smaller than the single bar resolution of about 30 ps, thus approaching the 10 ps resolution goal. Prototype tests have generally been performed on one row (8 channels) of $5 \text{ mm} \times 5 \text{ mm}$ pixels, while the initial detector is foreseen to have four rows to obtain full acceptance out to 20 mm from the beam. The beam tests lead to a time resolution per bar of the order of 34 ps. The different components of the timing resolution are given in Fig. 11. The upgraded design of the timing detector has equal rate pixels, and we plan to reduce the the width of detector bins close to the beam, where the proton density is highest.

At higher luminosity of the LHC (phase I starting in 2019), higher pixelisation of the timing detector will be required. For this sake, a R&D phase concerning timing detector developments based on Silicon photomultipliers (SiPMs), avalanche photodiodes (APDs), quartz fibers, diamonds 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 SAMPIC [20] (see Fig. 12) is to obtain sub 10 ps timing resolution, 1GHz input bandwidth, no dead time at the LHC, and data taking at 2 Gigasamples per second. The cost per channel is estimated to be of the order for \$10 which a considerable improvement to the present cost of a few \$1000 per channel, 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.

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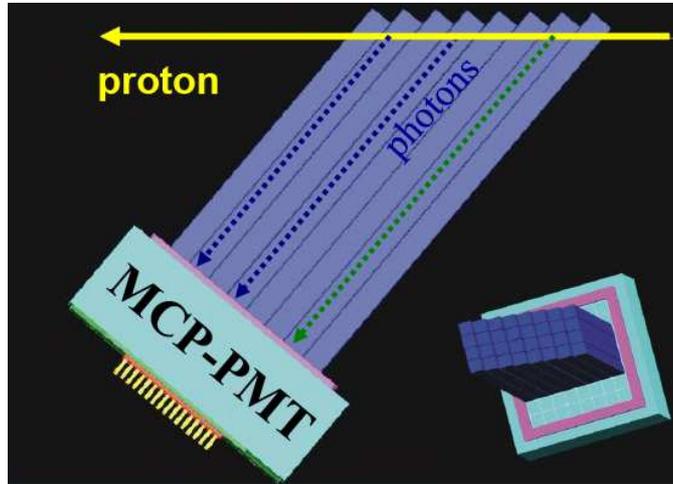


Figure 10: A schematic diagram of the QUARTIC fast timing detector.

Component	$\delta t(\text{ps})$ Current	$\delta t(\text{ps})$ Projected (8 ch + cable)	Improve ment	$\delta t(\text{ps})$ Phase 0 (8 channels)
Radiator (fused silica bar) ~10 pe's	22	22	Optimize radiator	17
MCP-PMT (64 channel 25 um Planacon)	20	20	10 um tube	15
CFD	5	5	-	5
HPTDC	16	16	-	15
Reference Clock	-	3	-	3
Total/bar	34	34		28
Cable		15%	retune CFD	5%
Total/ detector	14	14	-	10

Figure 11: Different components of the timing detector resolution [19].

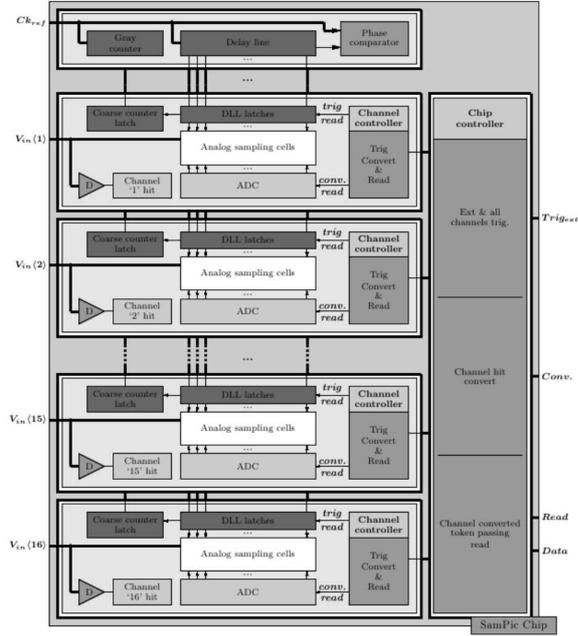


Figure 12: Scheme of the sampic chip.

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