Proton tagging at high luminosities at LHC

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Abstract
We show that forward proton taggers at the LHC installed at 220 and 420 m from ATLAS and / or CMS give access to a very rich forward physics program including possibilities to study the diffractive structure of proton or Higgs boson production in central exclusive diffraction processes, and also the photon-photon and photon-proton physics. The focus is put on projects aiming at tagging scattered protons at high luminosities at the LHC.

1 Introduction

There has been a great attention recently being devoted to the possibility of complementing the standard LHC physics menu by adding forward proton detectors to the ATLAS [1] and CMS [2] detectors. As a general and well-known feature of the hadronic production at LHC, the particle multiplicity is peaked in the central region, while most of the energy flows very forward and undetected by the main detector. In order to have a chance to explore the very rich forward physics it is necessary to instrument the forward region of the main detectors. The forward detector projects around the interaction point (IP) of ATLAS (IP1) and CMS (IP5) outside the main detectors are summarized as follows:

- 14 m:
  T2 GEM trackers of the Totem project [3]. Each of them contains 10 aligned detector half-planes with 512 strips. The acceptance is $5.2 < |\eta| < 6.5$ and resolution is $\Delta\phi \times \Delta\eta = 0.06 \times 0.017\pi$. Installation is foreseen in 2007.
- 16 m:
  CASTOR (Centauros and Strange Object Research) [4] calorimeter at CMS side is composed of tungsten/quartz planes with Cerenkov radiation as a measuring principle and with separate electromagnetic (20.1 X_0) and hadronic (9.5 λ_I) sections. It is an octagonal cylinder (length of 1.5 m, diameter of 36 cm) with 16-fold segmentation in ϕ and 14-fold segmentation in z. The acceptance is $5.2 < |\eta| < 6.6$. The construction is two-staged: the first CASTOR will be installed in 2008, the second one in 2009.

  Two LUCID (Luminosity measurement using Cerenkov Integrating Detector) [5] detectors at ATLAS side consist each of 168 gasfilled (C4F10 gas) aluminum tubes with Cerenkov radiation as a measuring principle. It is a cylinder (length of 1.5 m, diameter of 13.7 cm) with 168 tubes and 1176 fibers. The acceptance is $5.5 < |\eta| < 6.2$. The construction is also staged: a partial detector is being build in 2007, the full detector later.

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- 140 m:
  ZDC (Zero Degree Calorimeter) at CMS side [6] is a tungsten/quartz Cerenkov calorimeter with separate electromagnetic (19 X_0) and hadronic (5.6 λ_I) sections. The acceptance for neutral particles (γ, π^0, n) is for $\eta > 8.1$ (100% for $\eta > 9.3$). The installation is planned for 2007.

  ZDC at ATLAS side [7] is a tungsten/quartz Cerenkov calorimeter with separate electromagnetic (29 X_0) and hadronic (3.4 λ_I) section. It has 3-fold segmentation in z for hadronic section; quartz rods in electromagnetic and first hadronic module provide transverse coordinate measurement. The acceptance for neutral particles is for $\eta > 8$. The installation of one side is planned for 2007/2008 and the completion should be phased with the LHCf detector.

  The LHCf [8] tungsten-scintillator/silicon calorimeters share the location with the ATLAS ZDC in the 140 m region.
- 220 m:
  Roman Pots from the Totem project at CMS side are formed by two units separated by 4 m and each consisting of 2 vertical and one horizontal pot approaching the beam down to 10σ+250 μm = 1.5 mm. Each pot has 5+5 planes of edgeless silicon detectors. It reaches a spatial resolution of 20 μm per plane. The overall proton acceptance for CEP processes varies with beam optics: it is almost 90% in the range $10^{-3} < -t < 0.3$ GeV^2 and $10^{-4} < \xi < 0.2$ for $\beta^* = 1540$ m, while for $\beta^* = 0.5$ m (the highest instantaneous luminosity) it is around 40% in the range $10^{-3} < -t < 10$ GeV^2 and almost 100% in the range $0.02 < \xi < 0.2$ where ξ is the fractional proton momentum loss. The installation should be completed in 2007.

  Roman Pots of the RP220 project at ATLAS side [9] should contain just horizontal pots with silicon strip or 3D silicon detectors with foreseen spatial resolution of 10–15 μm and active edge of 30–60 μm in the case of the silicon strip option. The installation is foreseen to happen in 2010.
- 240 m:
  ALFA (Absolute Luminosity For ATLAS) [10] contains two vertical stations approaching the beam down to 1.5 mm. It is composed of 10+10 planes of scintillating fiber detectors with spatial resolution of 30 μm and the insensitive region smaller than 100 μm. The ALFA system is foreseen to be installed in the 2008/2009 shutdown.
- 420 m:
  FP420 [11] is an R&D collaboration formed to study the possibility to adapt 15 m long cryostat using moving beam pipe at both, ATLAS and CMS side. It is designed to operate at the highest luminosity optics for which the 3D silicon detectors is the best solution to stand high radiation levels. The detectors yield $\Delta p/p = 10^{-4}$ and hence the mass resolution of about 1%. The overall proton acceptance for CEP processes is almost 100% in the range $0.002 < \xi < 0.02$ giving the exclusive central system in a mass range $30 < M < 200$ GeV. The acceptance is around 40% in the range $10^{-3} < -t < 10$ GeV^2. A timing detector with at least 10 ps is necessary to install to suppress the pile-up background. The installation is foreseen in 2010.

In the following, an emphasis is put on the two projects aiming at installing forward proton taggers for high luminosities, namely the FP420 and RP220. In the sections 2–5, common aspects for both projects are discussed, followed then by sections about the status of both projects.

2 Physics motivation for forward proton taggers at high luminosities

The use of forward proton tagging will provide an exceptionally clean environment to search for new phenomena at the LHC and to identify their nature. Of particular interest in this context is Central Exclusive Production (CEP), $pp \to p \oplus \phi \oplus p$ (where $\oplus$ denotes a rapidity gap), which gives access to the generalized (or skewed) PDFs. At the highest available luminosities, CEP may become a discovery channel for particles with appropriate quantum numbers that couple to gluons. The CEP of a SM (or MSSM) Higgs boson is an attractive and at the same time a challenging process. It is attractive for two reasons: firstly, if the outgoing protons remain intact and scatter through small angles then, to a good approximation, the central system ϕ must be produced in a spin 0, CP even state, therefore allowing a clean determination of the quantum numbers of any observed resonance. Secondly, from precise measurements of proton momentum losses, ξ_1 and ξ_2, the mass of the central system can be measured much more precisely than from the dijet method, by the so-called missing mass method, $M^2 = \xi_1 \xi_2 s$, which is independent of the decay mode. The simplest decay mode from an experimental perspective is the WW decay mode, in which one (or both) of the W bosons decay leptonically. With standard single and double lepton trigger thresholds at ATLAS or CMS, approximately 6 events are expected for Higgs boson mass around 160 GeV with luminosity of 30 fb^{-1} [12]. In the $\mathrm{b\bar{b}}$ decay mode, the quantum number selection rules in CEP strongly suppress the QCD b-jet background, nevertheless severe requirements necessary to get rid of the pile-up background make the event yield rather modest. In certain regions of the MSSM parameter space the cross section for the CEP of the lightest Higgs boson is significantly enhanced and possibly making the $\mathrm{b\bar{b}}$ decay mode the discovery channel [13]. Another interesting feature coming from the MSSM studies is that the Higgs boson mass spectrum gets broader with increasing $\tan\beta$ which from a certain value of $\tan\beta$ may serve as a distinguishing criterion between the SM and MSSM signals [13].

Forward proton tagging at high luminosities will also give access to a rich QCD program. The proton structure can be investigated via the diffractive process $pp \to pX$ and $pp \to pXp$ where X includes a dijet system, vector bosons or heavy quarks. These reactions give access to the diffractive PDFs as well as to the so-called rapidity gap survival probability. The latter is closely linked to soft rescattering and the features of the underlying event at LHC.

As the LHC beams act also as a source of high-energy photons a rich program of photon-photon and photon-proton physics can be pursued. The LHC will open up a new kinematic regime for the photoproduction of jets, providing information on the low-x and low-Q^2 structure of the proton. Top-quark pairs will also be produced in this mode. In photon-photon collisions, one may expect lepton pairs (theoretically very well-known: this kind of process is a candidate for the luminosity measurement) as well as W-pairs.

3 Acceptance

In general, the position of a proton hit in detectors at 220 or 420 m depends (for a given beam optics) on the energy and the scattering angle of the outgoing proton and the z-vertex position of the collision. The energy and scattering angle are directly related to the kinematic variables ξ and $-t$. Fig.1 shows the acceptance in the (x, y) plane for the 220 m and 420 m detectors for beam 1 and beam 2, respectively, around IP1 (ATLAS). The scattered protons were tracked with the MAD-X package [14] with LHC optics version 6.5. The distribution of diffractively scattered protons explains why only horizontal stations are needed for both, the FP420 and RP220 projects. The two projects however differ in where these stations are necessary to be put: as protons in the 220 m region are deflected away from the ring, they can be detected by pots approaching the beam from outside the ring. In contrast to that, protons in the 420 m region are deflected inward the ring and this poses greater demands on the engineering work related to the adaptation of the connection cryostat as described in Section 6.

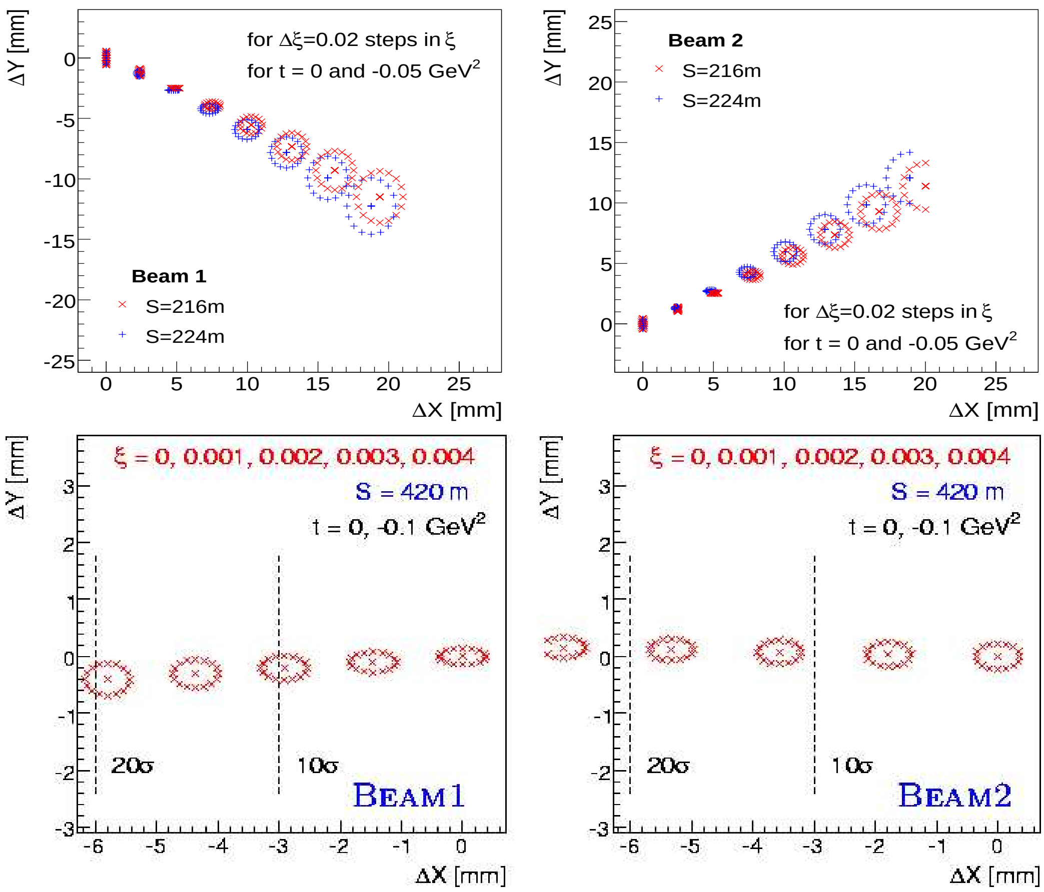

Fig. 1: The acceptance for diffractively scattered protons in the (x, y) plane determined by MAD-X at 220 m for beam 1 (upper left), beam 2 (upper right) and at 420 m for beam 1 (lower left) and beam 2 (lower right).

The low-ξ (and therefore low mass) acceptance depends critically on the distance of approach of the active area of the sensitive detectors from the beam. This is shown in Fig.2 on left hand plot. While the acceptance for the 420+420 configuration in the 120 GeV range is not too sensitive to the distance of approach (not shown), the acceptance of the 220+420 configuration is quite sensitive. This is because the 220 m detectors have acceptance only for relatively high ξ forcing the proton detected at 420 m to have lower ξ and therefore to be closer to the beam. The final distance of approach will depend on the beam conditions, machine-induced backgrounds and collimator positions, and the RF impact of the detector on the beams. For FP420, the nominal operating position is assumed to be between 5 and 7.5 mm, depending on the beam conditions, for RP220, it is between 1.5 and 2 mm. For masses above about 120 GeV, the 220 m detector adds to the acceptance with power increasing as mass increases. While the difference between the IP1 and IP5 acceptances and beam 1 and 2, for the 420 detectors is negligible, the situation is more complicated at 220 m where the crossing angle is in the vertical plane for IP1 and the horizontal plane for IP5. This results in a significantly higher acceptance at IP1 (ATLAS) than IP5 (CMS) for 420+220 configuration, as shown in Fig.2 on right [11].

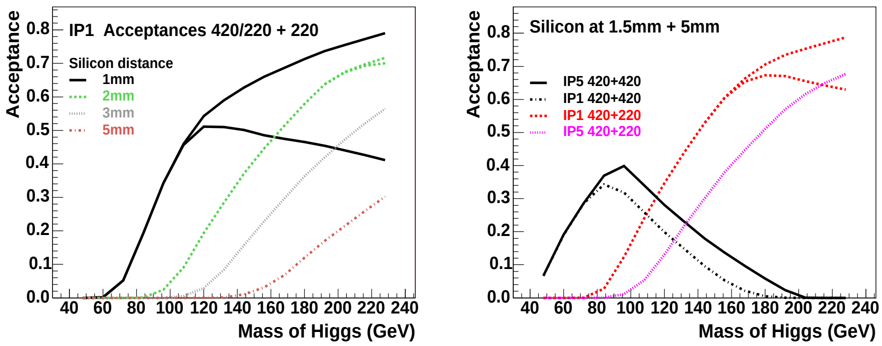

Fig. 2: Mass acceptance for various detector configurations. Left: 420+220 configuration for various combinations of distance of approach to the beam (with 5 mm as the nominal value for the 420 detector). Right: 420+420 and 420+220 configurations for one combination of the distance of approach to the beam (5 mm for 420 m and 1.5 mm for 220 m detectors) for IP1 and IP5. In the case of splitted curves, the lower one corresponds to the 420+220 configuration, while the higher one to the sum of acceptances for the 420+220 and 220+220 configurations.

4 Timing detectors

The necessity of equipping the forward detectors operating at the highest luminosities by timing detectors emerged from studies estimating the effect of pile-up background on diffractive processes at LHC [15]. At an instantaneous luminosity of $2 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, the average number is 7 events per bunch crossing, at $1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, it is 35. Of these pile-up events, 3% (1%) contain a proton within the acceptance of forward detector at 220 m (420 m). If we consider e.g. the case of CEP of Higgs boson with 120 GeV mass that decays into a pair of b-jets, an overlay of three events, namely two single diffractive ones each with a proton within the acceptance of forward detectors on opposite sides and one hard-scale dijet event, mimics the signal almost perfectly. Given the much larger cross section of inclusive dijet events compared to the signal, this is the most important source of background. This background can be reduced by exploiting the correlations between quantities measured in the central detector and those measured by the forward detectors. One possibility is to compare ξ or pseudorapidity, η, another possibility is to use fast timing detectors placed close to the forward detectors. Fast timing detectors with an expected sub-10 ps time resolution corresponding to a vertex resolution of better than 2.1 mm should be able to assign a vertex to the proton detected in the forward detector and as preliminary studies indicate, to reject about 97% of cases that appear to be CEP events but where the protons in reality originated from coincidences with pile-up events. Currently the development of fast timing detectors proceeds on several fronts, the interest comes also from other fields of physics as well as from medical applications. Presently two detector options are studied, namely Quartz and Gas Cerenkov which may be read out with a Constant Fraction Discriminator which allows the time resolution to be significantly improved compared to usual electronics.

5 Trigger

The detectors at 420 m are far away from the central detectors to be included in the L1 trigger in normal running conditions. The events with protons detected in the 420 m detectors can however be retained by other means. In the case of no pile-up, it is possible to lower the L1 trigger jet thresholds by a sufficient value to retain the Higgs boson events by vetoing on energy in the forward region at L1 [16]. Another way is to collect the events with protons tagged by a 420 m detector on one side and by a 220 m detector on the other side (this point is elaborated below). A further 10% of b-jet events can be saved irrespective of pile-up conditions by triggering on muons from B-hadron decays in the jets [15].

A big advantage of Roman Pots at 220 m is that they can be directly included in the L1 trigger. Various strategies to trigger on diffractive physics have been studied in [15]. As anticipated in Section 1 and 4, the big issue for any diffractive channel at high LHC luminosities is the fact that diffractive protons from pile-up events may fake the signal diffractive protons. For example, at the highest luminosity the rate of fake pile-up protons per bunch crossing seen in both Roman Pots at 220 m on CMS side is about 50%. The rates for the 420+420 and 420+220 configurations are 10% and about 60%, respectively [15]. The numbers for the ATLAS case are similar. These rates are of course enormous and need to be brought down to an acceptable L1 level. The trigger strategy depends on the mass of the diffractively produced object. Triggering on heavy mass objects (e.g. masses above 200 GeV) should not be a problem since the expected L1 rate of two jet trigger with $E_T > 100$ GeV is about 6 kHz at the highest luminosity and it can be reduced to about 2 kHz if we require in addition the double proton tag at 220 m. Triggering on low mass objects is more difficult but in principle feasible as documented in the detailed study [17] where a diffractive L1 trigger for 120 GeV Higgs boson decaying in two b-jets has been proposed. The trigger consists of the following conditions:

- 2 jets with $E_T > 40$ GeV (an expected L1 trigger rate is 2.6 kHz and 260 kHz at $\mathcal{L} = 10^{32}\text{cm}^{-2}\text{s}^{-1}$ and $\mathcal{L} = 10^{34}\text{cm}^{-2}\text{s}^{-1}$, respectively)
- Requirement of exclusiveness, $(E_{T1} + E_{T2})/H_T > 0.9$ where H_T is the scalar sum of all L1 jet transverse momenta, reduces by a factor of 2 independently of luminosity

- One proton detected in the detector at 220 m on at least one side from the IP.
- Momentum conservation along the beam axis, $(\eta_1+\eta_2)\cdot\eta_{220} > 0$ where $\eta_{1,2}$ are pseudorapidities of two L1 jets and η_{220} is the pseudorapidity of the proton detected in the detector at 220 m, reduces by a factor of 2
- Requirement of $\xi_{1(2)} < 0.05$ following from the missing mass formula

The output rate of this trigger was estimated to be within 1 kHz up to luminosities of $\mathcal{L} = 2 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ corresponding to 7 pile-up events per bunch crossing. Other reductions might be achieved from the knowledge of the precise Higgs boson mass after it has been measured and from a possible use of timing detectors at L1. The single-sided 220 m condition opens up space for the protons caught in detectors at 420 m thereby enabling to collect also asymmetric 220+420 and partly even 420+420 configurations. This enlarges the missing mass spectrum towards lower values. On top of that, a hit in 420 m detector may help to reduce the output rate of high level triggers - similarly to comparing pseudorapidities or masses of the central object calculated from the dijet system and from both protons seen in detectors on opposite sides from the IP.

A natural proposal for another diffractive L1 trigger would be based on a double-sided proton presence in 220 m detectors. This trigger would only enable us to retain events with higher mass objects (masses above roughly 160 GeV) by requiring in addition standard L1 triggers such as high mass Higgs boson decaying into WW or ZZ, inclusive high p_T dijets and inclusive high p_T jets (or low p_T jets highly prescaled).

6 FP420

The FP420 R&D collaboration, with members from ATLAS, CMS and LHC aims at installing high precision tracking and timing detectors close to the beam at 420 m from the IP. At LHC start-up, the beam pipes in the 420 m region are contained in a 15 m long interconnection cryostat that connects the superconducting arcs and dispersion suppressor regions of the LHC. The cryostat provides continuity not only of cold (2 K) beam pipes, but also of the insulation vacuum, electrical power, cryogenics circuits and thermal and radiation shielding. The engineering challenge of integrating detectors operated at room temperatures into the cryogenic section has been solved by replacing the existing interconnection cryostat with a warm beam-pipe section and a cryogenic bypass. A new connection cryostat with approximately 8 m of room temperature beam pipes has been designed using a modified Arc Termination Module (which includes cold to warm transitions for the beam-pipes) at each end. A solution has also been found for a mechanism which would bring the detectors close to the beam. It is a movable beam-pipe section to which the detector stations would be attached. Detection of the protons will be achieved by two 3D silicon detector stations at each end of the FP420 region. This novel technique use electrodes processed inside the silicon bulk instead of being implanted on its surface which makes it very radiation-resistive and which may provide the insensitive area as small as 5 μm close to the beam. The current prototypes utilize radiation-hard ATLAS pixel readout chip and were tested in several beam tests. With a silicon detector electrode pitch of 50 μm a resolution in the two spatial dimensions of about 15 μm can be reached. Monte Carlo studies indicate that for CEP of a Higgs boson with mass between 120 and 200 GeV this translates into a mass resolution of around 1.5 GeV, when the two protons are detected at 420 m on opposite sides.

7 RP220

The RP220 project is aiming at installing Roman Pots at 216 and 224 m on both sides of the ATLAS detector. In a natural way, it follows up the ALFA project which is to measure the total cross section of proton-proton interaction, by concentrating on measurements of hard diffractive physics accessible at high luminosities.

The Roman Pot design closely follows that used by the Totem collaboration and by the ALFA project in ATLAS. As discussed in Section 3, a sensitive detector of a 2×2 cm^2 size placed in a horizontal pot approaching the beam from outside should be sufficient to detect all diffractive protons.

There will be two kind of detectors to be put inside the pots, one for precise position measurements, the other one for precise time measurements. For both cases, the experience of FP420 with their development is closely followed. There are two options for the position detectors: either five layers of silicon strips of 50 μm and two additional layers for triggering purposes, or 3D silicon design as chosen for the FP420 project. In both cases, the precision of the position measurement is foreseen to be 10–15 μm which translates in a mass resolution of the order of 3% over a wide range of masses. The dead zone up to the active edge will be of the order of 50 μm for the strip detector, while it is of the order of 5 μm for the 3D option. Assuming a thin window of 200 μm and the distance of approach to the beam 10σ (15σ), the minimum value of ξ is about 0.01 for beam 1 and 0.012 for beam 2 (0.014 and 0.016), respectively. The detectors will be read out by standard ABCNext chip being developed for the silicon detectors in ATLAS. The latency time of this chip is of the order of 3.5 μs, time long enough to send back the local L1 decision from pots to ATLAS and to receive the L1 decision from ATLAS Central DAQ.

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