

FP420 : An R&D Proposal to Investigate the Feasibility of Installing Proton Tagging Detectors in the 420m Region at LHC

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1. Executive Summary

The physics potential of forward proton tagging in the 420m region at the LHC has only been fully appreciated within the last few years. By detecting protons that have lost less than 1.5% of their longitudinal momentum, a rich electroweak, Higgs, beyond the Standard Model and QCD program becomes accessible, with the potential to make measurements which are unique at LHC, and difficult even at a future linear collider.

By tagging both outgoing protons in the process $pp \rightarrow p + X + p$, the LHC is effectively turned into a glue-gluon collider. Initially, this will open up a rich, high-rate diffractive and QCD physics menu, allowing the study of the off-diagonal un-integrated gluon densities of the proton, rapidity gap survival (and therefore underlying event), and providing a source of almost pure gluon jets. In the few-fb⁻¹ luminosity range, a new field of high-energy photon physics opens up, giving access to precision studies of the quartic gauge couplings, anomalous W or Z pair production and, at higher luminosities, supersymmetric particle pair production in an extremely clean environment. As the delivered luminosity reaches tens of fb⁻¹, the double-tagged 'central exclusive' production process becomes a tool to search for new physics, delivering signal to background ratios greater than unity for Standard Model (SM) Higgs production and more than an order of magnitude larger for certain supersymmetric (MSSM) scenarios. It can provide a clear determination of the Higgs quantum numbers and excellent mass resolution, which may be necessary to resolve a nearly degenerate Higgs sector. It also offers a unique probe (at least until a linear collider) of the CP structure of the Higgs sector, through azimuthal asymmetry measurements of the tagged protons or detailed analysis of the missing mass lineshape. In addition to Higgs physics, 420m proton tagging provides an opportunity to investigate the entire strong interaction sector of physics within and beyond the Standard Model, from the production of heavy hadron resonances to gluonia and radions.

The 15m drift spaces around 420m from the ATLAS and CMS interaction points offer a physics opportunity that is not exploited in the current LHC physics programme. Protons that lose between $\sim 10^{-3}$ and 10^{-2} of their initial momenta emerge from the beams in these regions, which we propose to instrument in the FP420 project. In doing so, we will access the central mass range from 30 GeV to 200 GeV which is required for Higgs and discovery physics. This region is at present enclosed in a 'connection cryostat' which maintains a series of superconducting bus-bars, and the beam pipes themselves, at a temperature of 1.7K. The FP420 detector will replace the 420m interconnection cryostat.

Our intention is to perform a complete R&D study of the FP420 project. The UK will lead this study in collaboration with our international partners. Details of the international collaboration are given in section 5. The key deliverable will be a fully costed and approved (by CERN) design that will form the basis of Technical Design Reports from either or both of ATLAS and CMS. The first opportunity for installation is the planned LHC shutdown in autumn 2008. In order to meet this goal, we must complete this R&D study within 12 months. By the end of the 12 month period the decision to build FP420 at ATLAS and /or CMS will have been taken, and the means by which collaboration can

continue on construction and installation within the ATLAS and CMS collaboration frameworks will have been established. It is worth emphasising that the FP420 detectors will be sub-detectors of either ATLAS and / or CMS. The common R&D route is unusual, but the only feasible approach given the limited time-scale and manpower available.

2. The Physics Case for FP420

The 420m detectors would cover the region of fractional proton momentum loss $0.002 < \xi < 0.015$, giving access to central systems in the mass range $30 < M < 200$ GeV. This complements and extends the reach of the proposed 220m detectors at ATLAS and CMS / TOTEM, which have no acceptance for central systems below 200 GeV with two proton tags (one on each side) in normal high-luminosity LHC running.

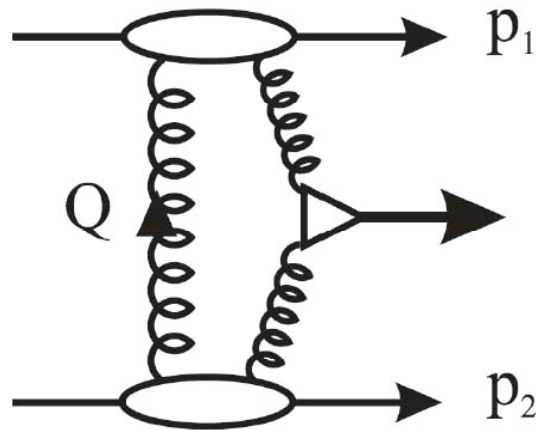


Figure 2.1 The central exclusive production process.

The potential of forward proton tagging to increase the discovery potential of the LHC rests on two main production processes: central exclusive production (i.e. gluon initiated) and two-photon production. By central exclusive production, we refer to the gluonic production process $pp \rightarrow p \oplus \phi \oplus p$, where \oplus denotes the absence of hadronic activity ('gap') between the outgoing protons and the decay products of the central system ϕ (see figure 2.1). There are three primary reasons why this process is attractive. Firstly, if the outgoing protons remain intact and scatter through small angles, then, under some general assumptions, the central system ϕ is produced in the $J_z=0$, C and P even state. An absolute determination of the quantum numbers of any produced resonance is possible by measurements of the correlations between outgoing proton momenta. Secondly, the mass of the central system can be determined very accurately from a measurement of the transverse and longitudinal momentum components of the outgoing protons alone. This means an accurate determination of the mass irrespective of the decay mode of the centrally produced particle. Thirdly, the process delivers excellent signal to background ratios, due to the combination of the $J_z=0$ selection rules, the mass resolution, and the cleanness of the event in the central detectors. An additional attractive property of central exclusive production is its sensitivity to CP violating effects in the couplings of the object

ϕ to gluons. The cross sections for a variety of new physics scenarios have been calculated, and will be briefly reviewed in section 2.1.

The di-photon production process (which has the same final state) will give access to precision studies of the quartic gauge couplings, anomalous W or Z pair production and, at higher luminosities, supersymmetric particle pair production in an extremely clean environment. These processes will be discussed in section 2.2. Finally, at lower luminosities, a wide-ranging program of QCD physics will provide a valuable tool for understanding the detectors, as well as an interesting and valuable physics program in its own right. This program will be reviewed in section 2.3.

2.1 Discovery Physics Using Central Exclusive Production

The ‘benchmark’ central exclusive production process for new physics searches is Standard Model (SM) Higgs production. The cross section for $pp \rightarrow p \oplus H \oplus p$ was calculated in [1,2] to be 3 fb for $M_H = 120$ GeV, falling to ~ 1 fb at $M_H = 200$ GeV. The simplest channel to observe the SM Higgs from an experimental perspective is the WW decay channel. A recent study [2] found that, for $M_H = 140$ GeV 19 exclusive $H \rightarrow WW$ events would be expected to have double proton tags for an LHC luminosity of 30 fb^{-1} . This rises to 25 at 160 GeV. Of these, approximately 25% will be taken by the standard ATLAS and CMS level 1 leptonic triggers, although we expect that with further optimisation of the trigger thresholds this efficiency should rise to close to 50% [2]. In the gold plated semi-leptonic channels, the signal to background ratio will be in excess of unity, and observation of SM Higgs in this channel will cleanly establish its quantum numbers with 30 fb^{-1} of delivered luminosity.

More challenging from a trigger perspective is the b-jet decay channel. That this channel is possible to observe at all is a consequence of the $J_z=0$ selection rules for central exclusive production [3], which heavily suppresses exclusive b-jet production; in conventional channels this signal is swamped by the copious QCD background. For $M_H = 120$ GeV, we expect 60 exclusive $H \rightarrow bb$ events to have double proton tags. A recent study [4] found that, after taking into account losses due to b-tagging efficiencies and kinematic cuts to reduce backgrounds, and the likely achievable mass resolution of the proton tagging detectors, 11 signal events remain with a signal to background ratio of order unity for a luminosity of 30 fb^{-1} . We discuss triggering in more detail in section 4.

The b-jet channel becomes extremely important in the so-called ‘intense coupling regime’ of the MSSM. This is a region of MSSM parameter space in which the couplings of the Higgs to the electroweak gauge bosons are strongly suppressed, making discovery challenging at the LHC by conventional means [5]. The rates for central exclusive production of the two scalar MSSM Higgs bosons are enhanced by an order of magnitude in these models, however. We expect close to 1000 exclusively produced double-tagged h and H bosons in 30 fb^{-1} of delivered luminosity, for $M_{h,H} \sim 125$ GeV and $\tan \beta = 50$ [6]. Under the same assumptions as for the SM Higgs, approximately 100 would survive the experimental cuts, with a signal to background ratio of order 10. For such regions of the

MSSM, therefore, central exclusive production is likely to be the discovery channel, and the scalar Higgs Bosons could be observed with only a few fb^{-1} of delivered luminosity. It is also worth noting that the pseudo-scalar Higgs (A) is practically not produced in the central exclusive channel. Since its mass is very close to that of the scalar Higgs Bosons in most regions of parameter space, FP420 allows for a clean separation of the scalar Higgs bosons which is impossible in conventional channels.

There are extensions to the MSSM in which central exclusive production becomes in all likelihood the only method at the LHC of isolating the underlying physics. One example, recently studied by Ellis et al. [7], is the case where there are non-vanishing CP phases in the gaugino masses and squark couplings. In such models, the neutral Higgs bosons are naturally nearly degenerate for large values of $\tan \beta$ and charged Higgs masses around 150 GeV. The authors conclude that observing the missing mass spectrum using forward proton tagging may well be the only way to explore such a Higgs sector at the LHC. It was also noted in [8] that explicit CP-violation in the Higgs sector can show up as a sizeable asymmetry in the azimuthal distributions of the tagged protons – again a measurement which is unique at the LHC.

As well as the specific models discussed above, central exclusive production is an extremely attractive way of searching for any new particles that couple strongly to glue. An example studied in [1] is the scenario in which the gluino is the lightest supersymmetric particle. In such models, there should exist a spectrum of gluino – gluino bound states which can be produced in the central exclusive channel.

During the recent HERA – LHC workshop, there was a large amount of work carried out on assessing the uncertainties in the central exclusive cross sections quoted above. The consensus view is that the primary uncertainty comes from the errors on the knowledge of the off-diagonal un-integrated gluon distributions of the proton (for example see [9]), leading to an uncertainty of a factor of 2 – 3 in the rate. Both the CDF and D0 Collaborations are in the process of searching for related central exclusive production signals at the Tevatron, including exclusive di-jet, $\gamma\gamma$ and χ_C production. Preliminary exclusive $\gamma\gamma$ production results from CDF were shown at the Manchester Forward Physics meeting in December 2005 [9] and are in line with the calculations of [1,3]. A recent analysis of the published CDF diffractive dijet data from Run I [10] shows that the results are compatible with the presence of an exclusive component at the level predicted in [1,3], and that the Run II data will be sensitive to an exclusive component if such a component is present. In summary, therefore, there is now growing evidence that the exclusive process is present in the data at the level expected from the calculations of [1,3].

2.2 High Energy Photon Physics with FP420

As well as the new physics discovery potential delivered by the central exclusive process, the 420m region makes possible a unique and exciting program of high-energy photon interactions physics at the LHC [11]. Using events when two forward protons are detected, photon-photon interactions can be selected at energies well above the

electroweak scale. The two-photon production of W pairs will allow studies of the quartic gauge couplings $\gamma\gamma WW$. The production cross section is 110 fb with average $M_{\gamma\gamma} > 300$ GeV, leading to approximately 1000 events in the semi and fully leptonic decay channels in 30 fb^{-1} . This would deliver sensitivity to anomalous quartic couplings a factor of 10,000 times better than the current LEP2 limits. There is no other way at the LHC to approach this level of sensitivity. There is similarly high sensitivity to the anomalous production of Z pairs in the process $\gamma\gamma \rightarrow ZZ$. The photoproduction of supersymmetric charged pairs, such as charginos and sleptons, or indeed any central systems which have large couplings to photons, is also a possibility [12].

Tagging a single proton at 420m opens up a rich field of high-energy photon-proton interactions at the LHC. High-rate processes of interest include W boson production at high transverse momentum and top pair production via photon-gluon fusion.

2.3 QCD and Diffractive Physics

Proton-proton interactions with large rapidity gaps are a rich source of information about the fundamental properties of QCD. The addition of detectors at 420 m will extend the ξ acceptance of the roman pot detectors installed at 220 m by an order of magnitude to 0.002 for nominal LHC luminosity optics. Access to such low ξ values in pp collisions is unprecedented, significantly better than that achievable at the Tevatron, and overlapping with the HERA diffractive DIS range. This will allow precise, high statistics studies of, for example, the gluon content of the proton at low- x and gap survival probabilities in the HERA kinematic range, which in turn will provide valuable insight into the contribution of multi-parton interactions to the underlying event. The latter will be very important for the whole LHC physics program. The low ξ reach of the 420m detectors will also allow the diffractive structure functions of the proton to be probed at low values of β and high values of Q^2 beyond the HERA range. Single diffractive production of W , Z and Y will be interesting in their own right, probing different kinematic regions of the diffractive structure functions, as well as being valuable processes for the detector calibration.

The cross section for the central exclusive production of di-jets is predicted to be ~ 1 nb for 2 jets with $E_T > 20$ GeV, $|\eta| < 1$ and invariant mass $M_{jj} > 50$ GeV, falling to ~ 0.5 pb for $E_T > 50$ GeV, $M_{jj} > 200$ GeV. The high rate will allow for a precise determination of the off-diagonal un-integrated gluon densities of the proton and the gap survival probability at 14 TeV. Whilst of interest in its own right, this measurement will allow the uncertainties in the predictions for the central exclusive production cross sections of Higgs bosons and other exotic particles to be reduced to the 1% level, which will in turn allow the observed rates for the production of exotic objects to be compared with theoretical expectations, and any anomalies investigated. The off-diagonal un-integrated gluon densities themselves will be measured in a region that may be sensitive to saturation or colour glass condensate effects.

3. An Overview of FP420

FP420 is a magnetic spectrometer. The LHC magnets between the ATLAS and CMS interaction points and the 420m regions bend protons that have lost a small fraction of their initial momentum out of the beam envelope. The FP420 detector is a moveable silicon tracking detector system, which measures the spatial position relative to the LHC beams and the arrival time of the outgoing protons at several points in a 15m region around 420m. A measurement of the displacement (and angle) of the outgoing protons relative to the beam allows the momentum loss and transverse momentum of the scattered protons to be reconstructed. This in turn allows the mass of the centrally produced system to be reconstructed to an accuracy of better than 2 GeV (see below). The detector position relative to the beam can be measured using either beam position monitors fixed at a known distance from the silicon detectors, or by making use of a high-rate physics process which produces protons of a known momentum loss (from a central detector measurement of the central system) in the FP420 acceptance range. This second method has the advantage that the magnetic field between the central detectors and FP420 does not have to be precisely known a-priori. A measurement of the time of arrival of the protons at FP420 in the 10 pico-second range allows for matching of the detected protons with a central vertex. This is desirable to reject non-physics backgrounds and overlap events at high luminosities.

3.1 The acceptance and resolution of FP420

The acceptance of the FP420 detectors as a function of the invariant mass of the central system (in this case taken to be a Standard Model Higgs boson) is shown in figure 3.1. These curves were generated using LHC optics v6.4. The acceptance is governed primarily by the dispersion of the LHC at 420m and the distance of the FP420 silicon detectors from the beam. It may be possible to increase the dispersion at 420m by optimising the LHC optics. This will be studied in work package 2. For the studies shown here, we use the standard high-luminosity-running LHC optics. The closest possible safe distance of approach to the beam, assuming ideal beam conditions, is 3mm (10σ). We show the acceptance for the silicon detectors positioned at 3mm, 5mm and 7.5mm from the beam. The acceptance for a 120 GeV central system is approximately 28%, and insensitive to the distance of approach of the detectors to the beams (up to 7.5 mm), for events with proton tags in the FP420 detectors at each side of the interaction point ('double tagged events'). This is easily understood, since protons of the smallest detectable momentum loss (~ 20 GeV) emerge closest to the beam. Positioning the detectors further from the beam therefore only affects the acceptance at lower masses. All indications are that 7.5mm is an extremely conservative estimate of the FP420 running position. Also shown are the acceptances when one proton is detected in a 420m detector, and one proton is detected in a 220m detectors at ATLAS (labelled IP5) and CMS (labelled IP1). Such detectors are envisaged at both ATLAS and CMS at or near LHC start-up, and should be available in 2009. These detectors only contribute to the acceptance in the 120 GeV mass range if the FP420 silicon can approach the beam to a distance of 3mm, and in this case only at ATLAS. This is because protons must lose at

least 100 GeV to be detectable at 220m, forcing the proton at 420m to lose less than 20 GeV for a 120 GeV central system. Protons with such small momentum losses emerge very close to the beam. The difference between ATLAS and CMS is due to the difference in the plane of the crossing angle of the beams at IP1 and IP5. The effect of this difference persists up to 220m, but is washed out by 420m. With no tuning of the LHC optics, therefore, the 220m detectors contribute to the FP420 acceptance only at high masses, or in excellent beam conditions when a close approach to the beams at 420m is possible. A summary of the acceptance for 420m – 420m tags as a function of the distance of approach of the silicon detectors is shown in figure 3.2 (a).

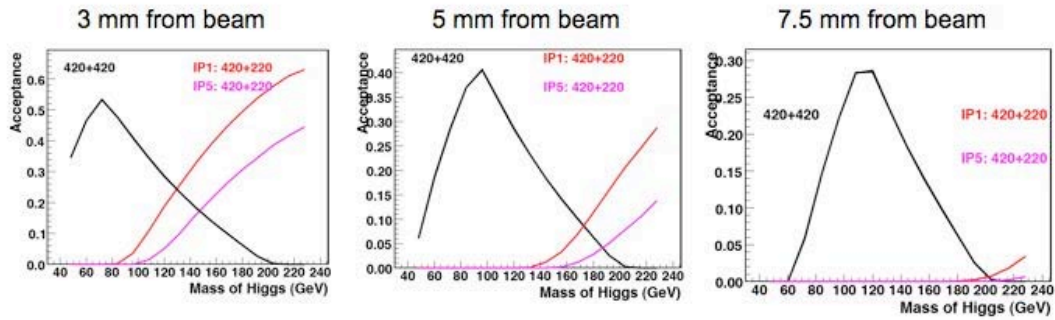


Figure 3.1. The acceptance as a function of Higgs boson mass for the detection of both protons at 420m (black line) and one proton at 420m and one proton at 220m at ATLAS (IP1) (red line) or CMS (IP5) (purple line).

Figure 3.2 (b) shows the mass resolution on the central system of FP420 as a function of the mass of the standard model Higgs boson, for 420m – 420m and 220m – 420m proton tags. The dominant effect on the mass resolution of FP420 comes from the incoming beam momentum spread of $\sigma_0 = 0.77$ GeV. The achievable resolution is better than 1.5 GeV if both protons are detected at 420m. If one proton is detected at 220m, the resolution is ~ 3 GeV for a 120 GeV central system at ATLAS, and ~ 3.5 GeV at CMS.

In summary, therefore, FP420 can achieve the best mass resolution and maximum robustness to poor beam conditions when both outgoing protons are detected at 420m. If, however, beam conditions are good and a 3mm approach is possible, detecting one of the outgoing protons in a 220m detector can double the acceptance for 120 GeV central systems at ATLAS, and the acceptance for higher masses is significantly increased at both interaction points.

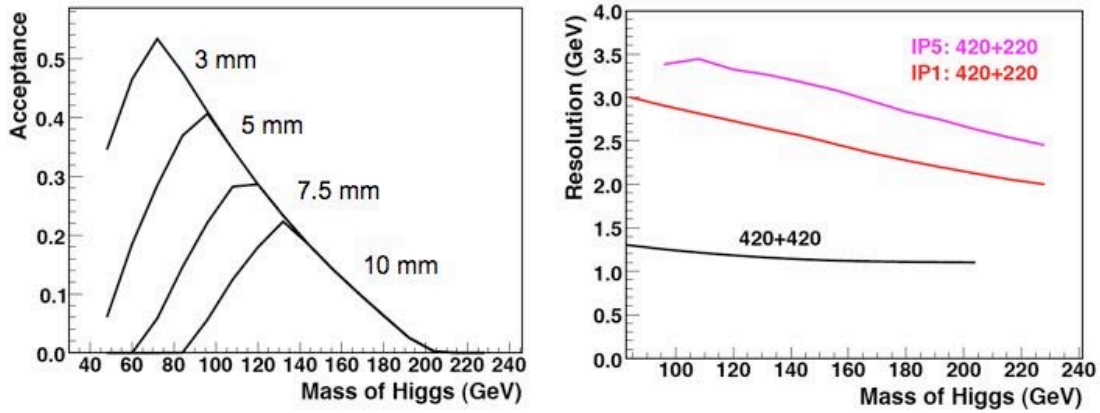


Figure 3.2. The acceptance as a function of Higgs boson mass for the detection of both protons at 420m at varying distances from the beam (Left hand plot). The right hand plot shows the mass resolution as a function of Higgs boson mass for the case where both protons are detected at 420m (black line), one proton is detected at 420m and one at 220m at ATLAS (IP1) (red line) or CMS (IP5) (purple line).

3.2 Trigger

It is not possible for the 420m detectors to be included in the level 1 (L1) trigger of ATLAS or CMS in normal running mode because the signal travel time from 420m exceeds the L1 trigger latency. FP420 events must therefore be kept at L1 using the central detectors alone. For semi-leptonic WW and $\tau\tau$ decay channels of the central system (or indeed any final states with high- p_T leptons, missing E_T or other standard new physics signatures) this is not a problem, since these will be kept at L1 routinely by both ATLAS and CMS. The most challenging case is the b-decay channel of a 120 GeV Higgs boson with both protons detected in the 420m detectors. This produces 2 b-jets of transverse momenta ~ 60 GeV. This channel is of little interest to ATLAS and CMS without proton tags because of the copious QCD backgrounds. As discussed above, however, the channel is expected to be observable using FP420, and therefore it would be highly desirable to keep such events at L1 (FP420 can be incorporated into the higher-level trigger system). A study of this channel has been carried out by Arneodo et al. for the CMS detector as part of the HERA-LHC workshop [14]. The L1 trigger rate for 2-jet events at CMS is 1 KHz. At luminosity of $1 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ the 2-jet rate for jets with $E_T > 40$ GeV is 2 KHz. This can be reduced to below 1 KHz by requiring a rapidity gap (i.e. no energy) in the forward detectors of CMS (T1 and T2) or ATLAS (LUCID). This technique is always possible in the absence of pile-up (multiple pp interactions per bunch crossing), and has an efficiency of $> 90\%$. At luminosities of $1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ there are on average 3.5 events / bunch crossing, and the rapidity gap veto technique becomes inefficient. At this luminosity, the 2-jet rate for jets with $E_T > 40$ GeV is 26 KHz. This can

be reduced by a factor of ~ 2 by making an ‘exclusivity’ requirement using the scalar sum (H_T) of all the level 1 jet E_T values, and requiring that $(E_{T,1} + E_{T,2})/H_T > 0.9$. A further factor of ~ 2 can be achieved by making rapidity requirements on the central jets. Beyond the study presented in [14], it is expected that further reductions may be possible by requiring the invariant mass of the 2-jet system to be within the acceptance of the 420m detectors (or some suitably defined mass window within this acceptance). It is therefore possible that, at least for luminosities up to $1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, that an acceptable trigger strategy can be found. Further studies are in progress at both ATLAS and CMS at the time of writing. For the case in which 1 proton is detected in a 220m detector (which can be included in the L1 trigger), the rate can be kept below 1 Khz up to luminosities of $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, although these asymmetric events have poorer mass resolution and depend on good beam conditions, as discussed in section 3.1. For the high-rate MSSM scenarios discussed in section 2.1, a discovery can be made with luminosities at or below $1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. At higher luminosities, triggering on muons from the b-decays will allow $\sim 10\%$ of events in the b-decay channel to be kept, allowing samples of higher rate processes to be taken irrespective of pile-up conditions.

FP420 have initiated a study at ATLAS to determine whether it may be possible to incorporate the 420m detectors into L1 for special runs. The standard ATLAS L1 trigger latency is $2.5 \mu\text{s}$, and the limit with the current hardware is $3.2 \mu\text{s}$. Counting from the time of the collision it will take $3 \mu\text{s}$ for signals from FP420 to reach the ATLAS L1 Central Trigger Processor (CTP), using $0.93c$ cables. The full L1 latency includes the propagation time from the CTP to the detector frontends, which will add about $0.5 \mu\text{s}$. While some ATLAS sub-detectors will not be able to exceed a latency of $3.2 \mu\text{s}$ without major hardware changes, a large part may be able to cope with latencies long enough to allow the FP420 into the L1 trigger in special running modes. The practical implications of these special setups and their impact on the physics potential of FP420 are currently under study, and will continue as part of Work Package 6. The infrastructure requirements of the FP420 readout and trigger electronics have been inserted into the ATLAS planning and rack space has been reserved near the L1 Central Trigger to facilitate the use of FP420 signals in the trigger.

In summary, any new physics processes with leptons in the final state or other standard new physics signatures will be triggered routinely by the central detectors, and will not be a problem for FP420. The only scenario in which special attention will have to be paid to level 1 triggering is the b-decay channel of light Higgs Bosons. In this case, for luminosities of $1 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, it is possible to keep candidate events with a high efficiency. Up to luminosities of $1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, it may be possible to keep a reasonable fraction of events. At high luminosity, $\sim 10\%$ can always be kept by triggering on muons from the b-decays. It may be possible to integrate the FP420 detectors into the L1 trigger at ATLAS for special physics runs, and FP420 will be designed such that this option is open at both ATLAS and CMS.

3.3 Alignment and Calibration

Experience at HERA has shown that the most reliable and accurate way to calibrate forward proton detectors is to find a high-rate physics process which produces protons of known outgoing momentum determined from a measurement made using the central detectors alone. For FP420, the cleanest process is $\gamma\gamma \rightarrow \mu\mu$, shown in figure 3.3. In this process, the momentum loss of BOTH protons is fully constrained by the measurement of the two central muons (or electrons) alone, under the assumption that the photons have zero transverse momentum (a very good approximation). This means that for calibration purposes only one of the two outgoing protons needs to be detected by FP420. A detailed study using a full simulation of the CMS detector (including the standard L1 trigger) has been carried out by the Louvain group [16]. The resolution on the fractional proton momentum loss x is shown in figure 3.3. This is better than the theoretical limit on the resolution of FP420 which comes from the uncertainty in the incoming beam energy of the LHC, $\sigma_0 = 0.77$ GeV, corresponding to a best-possible x resolution of $\sim 10^{-4}$. The cross section for this process is well known and has a very small uncertainty due to hadronic corrections [17]. In the acceptance range of FP420, at a luminosity of 1×10^{33} $\text{cm}^{-2} \text{s}^{-1}$ we expect over a hundred events per fill using the standard L1 trigger thresholds, allowing for an accurate offline run by run calibration. If the L1 trigger thresholds can be lowered (for example by using a rapidity gap veto at low luminosities as described in section 3.2), calibration could be further improved by using central upsilon production.

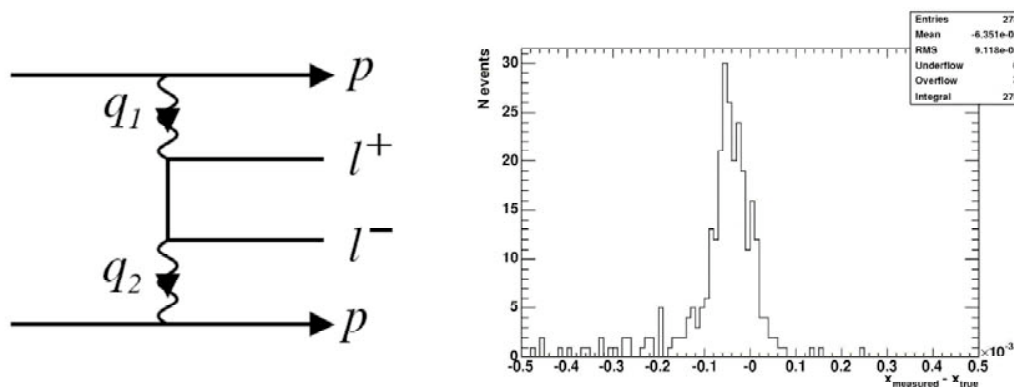


Figure 3.3. The calibration process $pp \rightarrow p \gamma\gamma p \rightarrow p \mu\mu p$ (left hand plot) and the resolution on the fractional proton momentum loss x using a full simulation of the CMS detector (right hand plot) [16].

An independent on-line (i.e. real-time) calibration will be possible by using the beam position monitors to measure the relative position of the silicon detectors (and therefore the proton tracks) to the beam. It is expected that this distance can be measured to a few 10s of microns using carefully calibrated standard LHC BPMs. Such a measurement must be available on-line in order to move FP420 safely into it's working position. If the LHC beam simulation program is sufficiently accurate for off-momentum protons, then the position measurement of the off-momentum proton tracks relative to the beam centre is

sufficient to determine the energy loss of the proton. The intrinsic energy spread of the beam corresponds to a 50 μm position uncertainty at 420m. FP420 must therefore be aligned internally and relative to the beam to an accuracy of a few 10s of microns, which is certainly achievable. The main uncertainty with this procedure is in the knowledge of the LHC magnetic field for off-momentum protons over the 420m path from the interaction point to the FP420 detectors. Investigation of this will form part of work package 2.

3.4 Backgrounds

The machine induced background processes at the LHC interaction regions include [18]:

1. *Inelastic beam-gas interactions* - beam-proton interactions with the nuclei of the residual gas in the arc cells, dispersion suppressors and straight sections.
2. *Elastic beam-gas interactions* – elastic, single diffractive and central diffractive proton-nucleus collisions, producing leading small angle protons
3. *Cleaning inefficiency* – proton out-scattering from the collimators followed by a lack of absorption in the collimators or in other elements of the beam cleaning system. Protons are in this case lost downstream of the cleaning system.
4. *Collisions in the interaction point* – proton-proton collisions, mainly elastic or single diffractive in the high luminosity interaction points producing energetic protons that are transported and lost in the next interaction region.

Beam halo, which consists mainly of protons from processes 2 and 3 above, is hard to calculate reliably prior to hands-on experience of running the LHC. The complete calculations of the magnitude of the backgrounds are still in progress. Preliminary results for IP5 [18] indicate that at full luminosity the rate of halo protons after cleaning is ~ 1 kHz in a $3 \times 1 \text{ cm}^2$ sensor. Background due to proton-proton (process 4) collisions from IP5 will dominate with a rate of the order of 1 MHz.

The dominant physics background comes from two overlapping single-diffractive events (i.e. one proton in each of the FP420 detectors) with a interesting hard central event (e.g. Higgs production). Approximately 1% of interactions have a diffractive proton in the acceptance of FP420, which implies an extra proton in the detector in $\sim 30\%$ of events at a luminosity of $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, where there will be an average of 7 pile-up events per bunch crossing. In most cases, requiring the missing mass measurement from the tagged protons to match the mass of the central system will remove these events. Using QUARTIC [19] it will be possible to reject these double-overlap events with a $\sim 95\%$ probability. Further investigation of physics background suppression and the use of QUARTIC are in progress within the US, Canadian and Helsinki groups at the time of writing.

4. An overview of the FP420 Hardware

The start-up LHC design has a 15m-long ‘interconnection cryostat’ at 420m that connects the superconducting arcs of the accelerator with the warmer interaction regions (see figure 4.1). This cryostat provides continuity not only of the beams, but also of the insulation vacuum, electrical power, cryogenic circuits and thermal and radiation shielding of the accelerator. An FP420 module is essentially a 15m long tracking detector which replaces this interconnection cryostat. Design of this detector is the primary responsibility of the UK, and comprises work package 1.



Figure 4.1. The 420m interconnection cryostat at LHC start-up

Figure 4.2 shows a cross section through the interconnection cryostat at LHC start-up. The protons of interest emerge between the two beam pipes V1 and V2. V2 is the outgoing beam pipe, which is closest to the wall of the LHC tunnel. FP420 must be able to reconstruct the tracks of outgoing protons that are a few millimetres away from the circulating beam in V2. In order to do this, at least two silicon pixel detector clusters (one at each end, although there are likely to be more to increase the number of spatial points available for track reconstruction and provide redundancy) must be moved into position as close as possible to the beam when the LHC running conditions become stable after injection and acceleration to 7 TeV. The development of the 3D edgeless silicon detectors

and the associated mechanical mountings, cooling and electronics are a UK responsibility, and will be described in detail in work packages 3 and 4 respectively.

The three bus bars, labelled M1, M2 and M3, must be continuous and maintained at 1.9K. These carry the currents for the LHC magnets. The heat exchanger, labelled X contains 2-phase liquid helium and must remain parallel to the floor throughout the region. Notice also that in the present interconnection cryostat, the beam pipes are within the cold volume at 1.9K. Running detectors and electronics at this temperature is difficult and undesirable, so a design choice has already been made in collaboration with CERN to raise the beam pipes to room temperature in this region. The end pieces of FP420 must match exactly the cross section of the present interconnection cryostat, and must return the beam pipes to 1.9K for re-connection into the LHC.

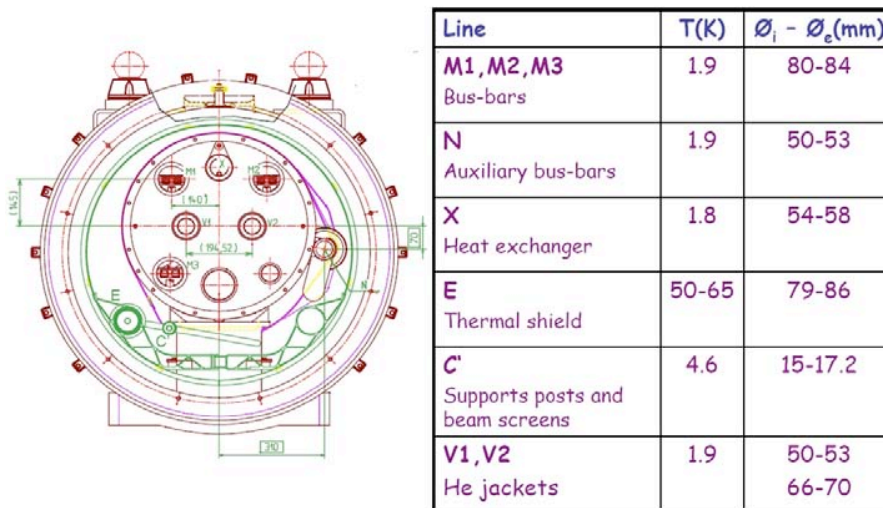


Figure 4.3 The 420m connection cryostat at LHC start-up. Protons from central elastic production can be detected by positioning suitable detectors between the beam pipes.

During beam injection, the FP420 detectors must be kept out of the standard beam-pipe aperture. When stable running conditions are achieved, the detectors must be able to move from the left of V2 to a working position approximately 3mm from the beam. The dominant limiting effect on the momentum resolution of FP420 is set by momentum uncertainty of the incoming beams, leading to a precision of ~ 1.5 GeV on the mass of the central system. This corresponds to a position uncertainty in FP420 of ~ 50 microns. It must therefore be possible to align FP420 internally, and relative to the beam in V2, to better than 50 micron precision. The distance of the silicon detectors from the beam can be measured in real time to an accuracy of a few 10's of microns with standard (but carefully calibrated and aligned) LHC beam position monitors (BPMs). High-accuracy off-line calibration of this alignment will be possible using the high-rate $\gamma\gamma \rightarrow \mu\mu$ / ee processes that allow the momentum loss of detected protons to be accurately determined from the central detectors alone.

In addition to the silicon detectors, a fast timing detector with 10 ps resolution will allow matching of the detected protons with a central detector vertex with a resolution of ~ 3 mm. Development of these detectors (known as 'QUARTIC') will be carried out by the US and Canadian FP420 groups (for a summary of the international collaborators on FP420, see section 5). QUARTIC will be segmented to allow for the separation of the arrival times of multiple protons of different momentum losses, allowing for additional background suppression at high luminosities (see section 3.4)

One solution for the movement mechanism under study is the so-called 'Hamburg Pipe', shown schematically in figure 4.4. Here, the entire length of the FP420 beam pipe is moveable, and connected by bellows at each end to the standard pipe. The silicon detectors, timing detectors and beam position monitors are fixed to the pipe in an 'optical bench' arrangement, allowing internal alignment to better than 1 micron using capacitive coupler technology developed at CERN for CLIC. The movement mechanism for the Hamburg Pipe will be designed, tested and constructed in Belgium by the Louvain group.

Another solution under investigation is the 'LongPot' design from the Helsinki group. In this solution, each silicon detector and timing detector has an individual movement mechanism similar to a traditional Roman Pot design. This design has the advantage of redundancy, in that a failure of one unit does not compromise FP420 operations. Access to the detectors is also potentially easier through the secondary vacuum arrangement as shown in figure 4.5. Alignment is more difficult than the Hamburg Pipe solution, however, since each detector station will move independently.

It is anticipated that a decision on the movement mechanism concept will be made during Summer 2006. Once this decision is made, the competing groups will join to design, construct and test the chosen design.

The Cockcroft institute will undertake the design of the beam pipe itself, since it requires extensive accelerator science expertise. In particular, the electromagnetic effects of a variable geometry structure close to the LHC beam must be accurately modelled, and the FP420 beam pipe designed accordingly. The beam pipe must also incorporate detector windows to allow the protons to pass through and into the detectors. The thickness, material and shape of these windows will also contribute to the electromagnetic impact of FP420 on the LHC beam (as well as defining the acceptance and background conditions in the silicon detectors). The design and RF modelling of the new beam pipe forms part of Work Package 2.

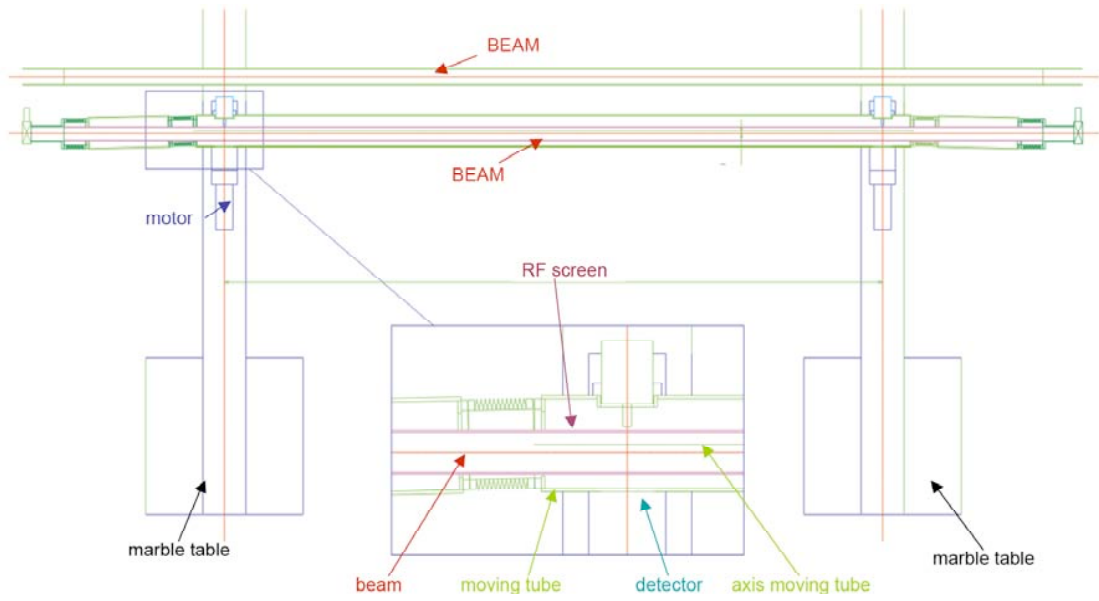


Figure 4.4 The 'Hamburg Pipe' design of FP420

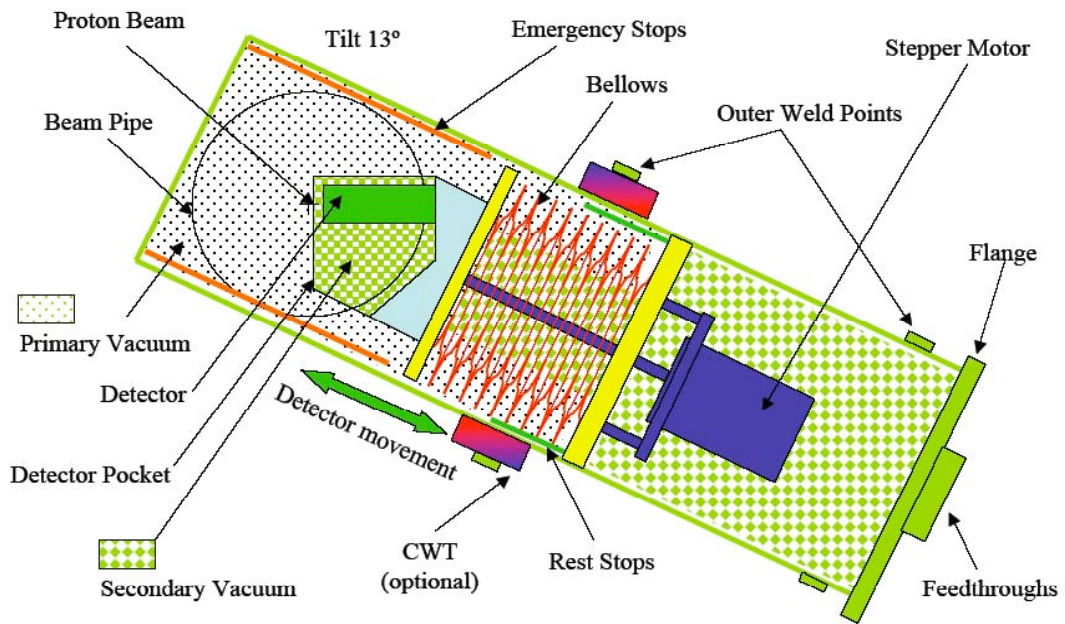


Figure 4.5 The 'Helsinki LongPot' design

5. International Collaboration and FP420 Collaboration Management Structure

The FP420 Letter of Intent to the LHCC [15] was signed by 58 physicists from 29 institutes in 11 countries. The Collaboration is chaired by Brian Cox (ATLAS / Manchester) and Albert DeRoeck (CMS / CERN / Durham). Cinzia DaVia (Brunel) is the technical co-ordinator. The management board is made up of the above, plus Mike Albrow (FNAL), Michele Arneodo (University of Eastern Piedmont, Novara and INFN-Turin), Andrew Brandt (University of Texas at Arlington), Krzysztof Piotrkowski (UC Louvain and Risto Orava (Helsinki Institute of Physics).

This bid is concerned with the UK R&D responsibilities. Here, we summarize the areas of FP420 development.

The mechanical design of the FP420 module itself, and its interface with the LHC machine is a UK responsibility, detailed in work package 1. The movement mechanism is the responsibility of the Louvain and Helsinki groups and collaborators. The design of the movement mechanism will of course affect the design of the detector housing itself. Work Package 1 will therefore be carried out in close collaboration with these groups.

The QUARTIC fast timing detectors will be developed in the US and Canada, led by The University of Alberta and The University of Texas at Arlington. QUARTIC will be a relatively small quartz detector, and is not expected to have a major impact on the design work in WP1.

The integration of FP420 into LHC operation and the optimisation of the machine parameters for FP420 will be led by the Cockcroft Institute, in collaboration with CERN. This is work package 2.

The silicon detector development is led by Brunel, and forms work package 4.

The detector hybrid cards and on-detector electronics are the responsibility of Manchester, in collaboration with MSSL, and form work package 3.

The off-detector electronics, power supplies and services will be developed by the Italian groups led by Torino. Torino and Antwerp will also lead the Geant simulation of the FP420 region in collaboration with CERN.

The interface to the ATLAS experiment, including data acquisition and trigger, will be led by UCL and Cambridge. Responsibility for the interface to CMS will be taken by Antwerp.