

# The ATLAS Forward Physics Program

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The ATLAS forward detector system is presented. Luminosity determination using the LUCID and ALFA detectors is discussed in addition to diffractive measurements that should be possible with early data. A possible high luminosity upgrade strategy involving new forward proton detectors is also briefly reviewed.

## 1 The ATLAS forward detector system

The central ATLAS detector consists of an inner tracking detector ( $|\eta| < 2.5$ ), electromagnetic and hadronic calorimeters ( $|\eta| < 4.9$ ) and the muon spectrometer ( $|\eta| < 2.7$ ). In addition to these, there are a number of sub-detectors that measure far-forward particle production at ATLAS. These are the LUCID, ZDC and ALFA detectors.

The LUCID detectors [2] are located 17 m from the interaction point, one on each side of ATLAS, and provide coverage of  $5.6 < |\eta| < 6.0$  for charged particles. Each LUCID detector is a symmetric array of polished aluminium tubes that surround the beam-pipe. Each tube is 15mm in diameter and filled with  $C_4F_{10}$  gas, which results in Cerenkov emission from charged particles crossing the tube. The Cerenkov light is read out by photo-multiplier tubes. An upgrade strategy for LUCID is to provide full azimuthal coverage, which is incomplete at installation and for early data taking.

The Zero Degree Calorimeter (ZDC) [3] is located 140 m from the interaction point in the TAN region (target absorber for neutrals), which is the point where the single beam-pipe splits into two, and provides coverage of  $|\eta| > 8.3$  for neutral particles. The ZDC consists of one electromagnetic and 3 hadronic tungsten/quartz calorimeters. Vertical quartz strips provide the energy measurements and horizontal quartz rods are used for coordinate readout. At LHC startup, when there are few bunches in the beam, the electromagnetic calorimeter is not installed and the space it would occupy is used by the LHCf experiment. After initial running, LHCf is removed and the full ZDC installed.

The ALFA roman pot (RP) spectrometers are located 240 m from the interaction point [4]. Unlike other detectors, the RP spectrometers are not fixed relative to the beam. At injection, the ALFA detectors are in a withdrawn position far from the beam. After the beam has stabilized, the detectors are moved to within 1.5 mm of the beam. Elastic and diffractive protons which are not in the beam pass through arrays of scintillating fibre trackers (20×64 fibres in each array), which measure the distance of the proton to the beam. ALFA is used during special LHC runs at low luminosities with high  $\beta^*$  optics.

## 2 Luminosity determination

The relative luminosity at ATLAS is determined using the LUCID detector. The mean number of hits per tube per event is directly proportional to the luminosity. By observing the change in the mean number of hits per tube, LUCID can determine the change in

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luminosity during each LHC store. LUCID also provides the relative luminosity of each bunch-bunch crossing because a specific bunch in one LHC beam always interacts with the same bunch in the other beam. LUCID achieves this due to good timing resolution, of order nano-seconds.

For LUCID to provide the actual luminosity during a store, rather than the change in luminosity, it must be calibrated using a known absolute luminosity. Initially, with special effort, this can be achieved using machine parameters to an accuracy of 10-20%. In addition,  $Z$ -boson events can be used as a *standard candle* as the production cross section is well known. This provides an absolute luminosity calibration to 5-8% accuracy. The final calibration of the absolute luminosity will be determined using elastic proton-proton scattering detected by the ALFA detectors.

During the the special LHC runs with high  $\beta^*$  optics, the protons in each LHC beam are quasi-parallel at the interaction point. For elastic scattering, the protons leave the interaction point at an angle with respect to the beam and the protons. Protons scattered through a specific angle,  $\theta$ , are focussed by the quadrupole magnets to a specific point at 240 m – this is known as parallel-to-point focussing. Thus the position of the proton with respect to the beam, which is measured by ALFA, is used to directly measure the angle of outgoing protons. For small angle scattering, the momentum transfer of the proton can be determined by  $t \sim -p^2\theta^2$ , where  $p$  is the proton momentum of the beam.

The elastic  $t$  distribution has both strong and electromagnetic components due to pomeron and photon exchange respectively. The electromagnetic component falls off much more quickly as  $|t|$  increases. The absolute luminosity, the total cross section and the elastic slope,  $b$ , can be determined from a fit to the  $t$ -distribution. More details can be found in [4]. It is expected that the absolute luminosity will be determined to  $\sim 2$ -3% accuracy.

### 3 Diffractive measurements with early data

#### 3.1 Soft single diffraction using ALFA

Single diffraction (SD) is characterized by a centrally produced system separated by a large rapidity gap, or lack of hadronic activity, from an outgoing proton. The cross section is typically presented in terms of the fractional momentum lost by the proton during the interaction,  $\xi$ , and the momentum transfer,  $t$ . The outgoing proton in SD exchange can be tagged and measured during special LHC runs by the ALFA detectors [4], although the very low luminosity means that only soft-SD can be studied (in particular, the forward proton spectrum at low  $\xi$ ). The acceptance is approximately 50% for  $\xi \sim 0.01$ , falling to 10% for  $\xi \sim 0.1$ . It is expected that at a luminosity of  $10^{27} \text{ cm}^{-2} \text{ s}^{-1}$  there would be between 1.2 and 1.8 million events recorded in 100 hours of data acquisition. The resolution of the  $\xi$  measurement is approximately 8% for  $\xi = 0.01$ , falling to  $\sim 2\%$  for  $\xi = 0.1$ .

#### 3.2 Single diffractive di-jet production

Single diffractive processes can also be selected by identifying a rapidity gap, for example, by requiring that a forward detector register little hadronic activity. Both LUCID, the ZDC and the ATLAS forward calorimeter (FCAL) can be used as part of a rapidity gap requirement for a diffractive analysis.

Di-jet production by SD should be measurable with  $100 \text{ pb}^{-1}$  of data, which corresponds to  $\sim 1.5$  years of data acquisition at  $\mathcal{L} = 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ . The cross section for SD di-jet

production is predicted by the POMWIG event generator [5] to be 3.6 (0.2)  $\mu\text{b}$  for  $\xi < 0.1$  given a jet transverse energy greater than 20 (40) GeV. The trigger pre-scale at ATLAS is expected to be approximately 6000 (100) at  $\mathcal{L} = 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$  for jets with transverse energy greater than 18 (42) GeV and one would expect tens of thousands of SD events to be available in each final sample. However, the rapidity gap definition will reduce this number and one would expect a few thousand events if the rapidity region covered by the FCAL, LUCID and ZDC were required to be devoid of activity. The event rate increases by up to an order of magnitude if only LUCID and ZDC are required to define the rapidity gap.

Single diffractive di-jet production will allow a study of factorization breaking in diffractive events; the observed cross section for diffractive processes at hadron colliders is reduced with respect to the predicted cross section (obtained from diffractive parton distribution functions measured at HERA), due to additional soft interactions and multiple parton-parton scattering during the proton-proton interaction. These additional interactions break up the diffractive proton and produce particles which destroy the rapidity gap. By examining the ratio of SD (rapidity gap) events to inclusive events, one can measure the so-called soft survival factor, which accounts for these additional interactions.

### 3.3 Central exclusive di-jet production

Central exclusive production is defined as the process  $pp \rightarrow p + \phi + p$ . All of the energy lost by the protons goes into the production of a hard central system,  $\phi$ . Thus the final state consist of two outgoing protons, a hard (e.g. di-jet) central system and no other activity. There is a large amount of theoretical uncertainty on the CEP cross section<sup>a</sup> and measurements by ATLAS will help constrain the calculation.

The di-jet cross section is predicted by the ExHuME event generator [6] to be approximately 8 nb for a minimum jet transverse energy of 20 GeV. Given the large pre-scale on low  $E_T$  jets, one would expect approximately 100 events in 100  $\text{pb}^{-1}$  of data. To obtain a good measurement of the CEP cross section, it will be necessary to reduce the L1 pre-scale using the forward detectors. It may be possible to exploit the clean nature of the exclusive event by employing a rapidity gap definition in the L1 trigger (using LUCID, ZDC, FCAL) in conjunction with the triggered jet.

### 3.4 Gaps-between-jets

Gaps-between-jets arises from a  $2 \rightarrow 2$  scatter via a colour singlet exchange and has previously been measured at HERA and the Tevatron [8]. The process was observed to be a strong interaction and a possible candidate for the colour singlet exchange is the BFKL pomeron [9]. This however remains to be experimentally verified. A prediction of BFKL is that the fraction of events with little activity between the jets (the gap-fraction) should rise with the separation of the jets,  $\Delta\eta$ . The rise of the gap-fraction was not observed at the Tevatron, for example, because the centre-of-mass energy was too small; it was shown in [10] that the rapidly falling PDFs at high  $x$  tempered the rise and meant that a large enough sample of events with large jet separations could not be obtained (because  $\Delta\eta = \ln(\hat{s}/|t|)$ ). An improved measurement should be possible at the LHC due to the increased centre-of-mass energy. In principle, ATLAS should be able to measure the gap-fraction up to  $\Delta\eta \sim 9, 9.5$ .

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<sup>a</sup>It should be noted that the current measurements of CEP by the CDF collaboration are in good agreement with the theoretical predictions [7].

## 4 Forward physics upgrade at high luminosity

At high luminosity, the rapidity gap method cannot be used to select diffractive events because particles from pile-up will fill in the gaps. A diffractive physics program can be continued, however, by installing new forward proton detectors 220 m and 420 m either side of the interaction point (IP). This opens up the possibility of searching for new physics in CEP, such as Higgs boson production in the Standard Model, MSSM and NMSSM. The main benefit arises when both protons are tagged and measured because the mass of the centrally produced system can be calculated by  $M^2 = \xi_1 \xi_2 s$ , where  $\sqrt{s}$  is the centre-of-mass energy of the colliding protons. Thus, for exclusive resonance production, a mass measurement can be made regardless of the decay products of the produced particle. Furthermore, forward proton tagging allows measurement of photon induced processes, such as  $W$ -pair production via the anomalous quartic gauge coupling  $\gamma\gamma WW$ . We refer to [11, 12, 13] for more details.

The possibility of installing forward detectors at 420 m from the IP has been extensively studied by the FP420 R&D collaboration [13]. The physics program offered by the detectors at 420 m is enhanced by detectors at 220 m by increasing the acceptance of higher mass events. Furthermore, detectors at 220 m can be included in the L1 trigger decision, which is not the case for the detectors at 420 m as the signals from the detectors will not reach the central trigger processor within the 3.2  $\mu$ s latency.

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