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The ATLAS Forward Physics Program

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After a brief review of the approved ATLAS forward detector system we describe the main ATLAS forward physics program. This program currently includes such topics as soft and hard diffraction, double pomeron exchange[a], central exclusive production, rapidity gap survival, two photon physics, the determination of the total cross-section and the determination of the absolute luminosity A possible high luminosity upgrade program involving new forward proton detectors is also briefly reviewed. This program opens up a new vista of forward physics for ATLAS that includes SM/MSSM/NMSSM Higgs boson studies, W pair production, slepton production and gluino pair production, etc.

1 The ATLAS Forward Detector System

The central ATLAS detector consists of an inner tracking detector ($|\eta| < 2.5$), electromagnetic (EM) and hadronic calorimeters (($|\eta| < 4.9$)and a muon spectrometer ($|\eta| < 2.7$). In addition, there are a number of sub-detectors that measure far-forward particle production at ATLAS. They are, in order of distance from the ATLAS IP, the LUCID [1], ZDC [2] and ALFA [3] detectors. The LUCID detectors [1] are located ±17 m from the interaction point, and provide a coverage $5.5 < |\eta| < 6.0$ for charged particles. Each LUCID detector is a symmetric array of polished aluminium tubes that surround the beam-pipe and point toward the ATLAS IP. Each tube is 15mm in diameter and filled with C4F10 gas, which results in a maximum of Cerenkov emission from charged particles from the IP which traverse the full length of the tube. The Cerenkov light is read out by photo-multiplier tubes. A high luminosity scenario upgrade strategy for LUCID, that enhances its efficacy in the forward physics program, is being explored.

The Zero Degree Calorimeters (ZDCs) provide coverage of the region $|\eta| > 8.3$ for neutral particles. They reside in a slot in the TAN (Target Absorber Neutral) absorber, which would otherwise contain copper shielding. The TAN is located at ± 140m from the interaction point, at the place where the straight-section of the beam-pipe divides into two independent beam-pipes. The ZDC consists of one EM and three hadronic tungsten/quartz calorimeters. Vertical quartz strips provide the energy measurements and horizontal quartz rods are used for coordinate readout. At LHC startup, when the luminosity is low, the ZDC EM calorimeter is not installed and the space it would occupy is filled by the LHCf experiment. After initial running, LHCf is removed and the full ZDC installed.

The ALFA (Absolute Luminosity For ATLAS) Roman Pot (RP) spectrometers are located ± 240 m from the interaction point [3]. The RP spectrometers are not fixed relative to the beam. At injection, the ALFA detectors are moved away from the beam. After the beam has stabilized, the detectors are moved back to within 1.5 mm of the beam. Elastic and diffractive protons which are not in the beam pass through arrays of scintillating fibre

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[a]The lowest order prototype of the Pomeron (IP) is, in perturbative QCD, a colour neutral system of two gluons

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 β^* beam optics in combination with reduced emittance.

2 Determination of the Absolute Luminosity and Total Cross-section

The number of interactions per beam-crossing must be known in order to determine luminosity. LUCID is based on the principle that the number of interactions in a bunch-crossing is proportional to the number of particles detected. This holds true even when most of the detected particles originate from secondary interactions. The relative luminosity at ATLAS is determined using the LUCID detector. By observing the change in the mean number of hits in LUCID one can determine the change in luminosity during each LHC store. The good timing resolution, of order nano-seconds, allows the relative luminosity of each bunch crossing to be determined.

For LUCID to provide the actual luminosity during a store, rather than the relative luminosity, it must be calibrated using a known absolute luminosity. Initially, this can be achieved, using machine parameters, to an accuracy of 10-20%. After this initial period W/Z-boson counting can be used to calibrate LUCID, as the production cross sections are reasonably well known. This provides an absolute luminosity calibration to 5-8% accuracy. The final calibration of the absolute luminosity will be determined to an accuracy of a few percent using elastic proton-proton scattering detected by the ALFA detectors.

During the special LHC runs with high β^* 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. Protons scattered through a specific angle θ, are focussed by the quadrupole magnets to a specific point at 240m - 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 rate of elastic scattering is linked to the total interaction rate through the optical theorem, which states that the total cross section is directly proportional to the imaginary part of the forward elastic scattering amplitude extrapolated to zero momentum transfer squared $-t$ (at small values of $-t$): $\sigma_{tot} = 4\pi . Im[f_{el}(0)]$

The baseline ATLAS approach to the determination of the total cross-section and the absolute luminosity is to measure elastic scattering down to such small t-values that the cross section becomes sensitive to the electromagnetic amplitude via the Coulomb interference term. If the Coulomb region can be reached, an additional constraint is available from the well-known electromagnetic amplitude, as can be seen from the simplified equation below, that describes elastic scattering at small t values:

$$\frac{dn}{dt} = L\pi(f_C + f_N)^2 \approx L\pi \left(-\frac{2\alpha_{EM}}{|t|} + \frac{\sigma_{tot}}{4\pi}(i+\rho)e^{-b|t|/2} \right)^2 \tag{1}$$

where the first term corresponds to the Coulomb and the second to the strong interaction amplitude.

Using this additional constraint together with the optical theorem allows the determination of both luminosity and the total cross section without a measurement of the inelastic rate. In practice, one would fit the measured rate to the above expression: L will be determined from the fit as well as the other parameters ρ (the ratio of the real and imaginary parts of the forward scattering amplitudes) the total cross-section (σ_{tot}) and the slope parameter b. This method can be used to determine the luminosity, L and σ_{tot}, to a few percent.

3 Forward Physics With Initial Data

3.1 Single Diffractive di-jet Production

SD processes can also be tagged by identifying a rapidity gap, for example, by requiring that the forward detector system register little hadronic activity. The ATLAS forward calorimeter (FCAL), LUCID and the ZDC can be utilized as part of a rapidity gap requirement for a diffractive analysis. Di-jet production by SD should be measurable with $\sim$100 pb^{-1} of data, corresponding to around 1.5 years of data acquisition at L = 10^{31} cm^{-2} s^{-1}.

The cross section for SD di-jet production is predicted by the POMWIG event generator [4] to be 3.6 (0.2) μb for ξ <0.1 for jet transverse energy (E_t) greater than 20 (40) GeV, where ξ is the fractional momentum lost by the proton during the interaction. The expected ATLAS trigger pre-scale at ATLAS will be approximately 6000 (100) at L = 10^{31} cm^{-2} s^{-1} for jets with E_t > 18 (42) GeV and one would expect of the order of 10K SD events to be available in each final sample. However, the rapidity gap requirement is envisaged to reduce this number by a factor of $\sim$10 to a few thousand events, with a rapidity gap region defined by the FCAL, LUCID and ZDC. The event rate increases by as much as an order of magnitude if only LUCID and ZDC are required to define the rapidity gap. In fact, the single diffractive di-jet study will probably use LUCID veto at L1.

SD di-jet production permits a study of factorization breaking in diffractive events. Additional soft interactions and multiple parton-parton scattering during the proton-proton interaction reduce the observed cross section for diffractive processes at hadron colliders, with respect to the predicted cross section obtained from diffractive parton distribution functions measured at HERA. These additional soft interactions break up the diffractive proton producing particles which fill the rapidity gap. By studying the ratio of SD (rapidity gap) events to inclusive events, one can measure the "soft survival factor", which accounts for these additional interactions.

3.2 Central Exclusive Di-jet production

Central Exclusive Production (CEP) is defined as the process $pp \to p\phi\bar{p}$, where all of the energy lost by the protons goes into the production of a hard central system, ϕ. Thus the final state consists 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 which results from CDF at the Tevatron have already started to constrain [6][12].

The di-jet cross section is predicted by the ExHuME event generator [5] to be approximately 8 nb for a minimum jet transverse energy of 20 GeV. It should be noted that the current measurements of CEP by the CDF collaboration [6] are in good agreement with the theoretical predictions that form the physics basis of the ExHuME generator. Given the large pre-scale on low E_T jets, one would expect approximately 100 events in 100 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. One might be able to do this by exploiting the clean nature of the exclusive event by requiring a rapidity gap in the L1 trigger (using LUCID, ZDC, FCAL), in conjunction with a triggered jet.

The current CEP di-jet search foresees to use an MBTS veto on one side to select the events (this is now in the menu). Initial results indicate that this can run un-prescaled at a luminosity of 10^{31} cm^{-2}s^{-1} luminosity. The LUCID/ZDC gaps would be used to help identify the event.

3.3 Soft Single Diffraction Studies Utilizing ALFA

Single diffraction (SD) is characterized by a centrally produced system separated by a rapidity gap, or lack of hadronic activity, from an outgoing proton. The cross section is typically presented in terms of ξ, and the momentum transfer, t. In SD exchange the outgoing proton can be tagged and measured during special LHC runs by the ALFA detectors [3]. However, the low luminosity means that only soft-SD can be studied - in particular the forward proton spectrum at low ξ. The acceptance is $\sim$ 50% for $\xi \sim 0.01$, falling to 10% for $\xi \sim 0.1$. It is expected that at a luminosity of 10^{27} cm^{-2} s^{-1} there would be 1.2$\rightarrow$1.8 million events recorded in 100 hours of data acquisition. The ξ measurement resolution of the measurement is approximately 8% for $\xi = 0.01$, falling to 2% for $\xi = 0.1$.

3.4 Rapidity Gaps Between Jets

Rapidity gaps between jets arise from 2$\rightarrow$2 scatters via a colour singlet exchange. This process has previously been measured at HERA and the Tevatron [7]. A possible candidate for the colour singlet exchange is the BFKL pomeron [8]. 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. 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 [9] that the rapidly falling PDFs at high x tempered the expected rise and meant that a large enough sample of events with large jet separations could not be obtained, since $\Delta\eta = ln(\hat{s}/|t|)$. 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 $\Delta\eta \sim 9 \rightarrow$ 9.5. The gaps-between-jets trigger will be 2FJ18 (one jet in each forward calorimeter with $(|eta|$¿3.2). This trigger will only require a low prescale value.

4 Forward Physics at High Luminosity

At high luminosity, the rapidity gap method cannot be used to select diffractive events since particles from pile-up events will fill in the gaps. However, a forward physics program can be continued by installing new very forward proton detectors at ± 220 m and ± 420 m on each side of the interaction point (IP). It is envisaged that the pile-up background can be handled by using ultra precise ToF detectors to differentiate the vertex of interest from the vertices of the pile-up events. The use of forward proton taggers opens up the possibility of searching for new physics in CEP, such as Higgs boson production in the Standard Model, MSSM and NMSSM. When both protons are tagged and measured the mass of the centrally produced system can be calculated using the equation $M^2 = \xi_1 \xi_2 s$, 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 photoproduction and photon-photon induced processes, such as W-pair production via the anomalous quartic gauge coupling $\gamma\gamma$WW, [10] [11]. The possibility of installing forward detectors at 420 m from the IP has been extensively studied by the FP420 R&D collaboration [11]. The physics program offered by the detectors at 420 m is enhanced by detectors at ±220 m which increase the acceptance of higher mass events. Furthermore, detectors at ±220 m can be included in the level-1 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 in time.

5 Conclusion and Summary

The luminosity monitor LUCID, calibrated by the ALFA detector, will allow the luminosity delivered to ATLAS to be determined to better than 5% accuracy. The ZDC will measure forward spectators for heavy ion collisions and provide trigger and centrality measurements. It will also provide a luminosity measurement and, measure forward particle production for MC tuning. Low luminosity forward physics topics include: elastic scattering and σ_{tot} determination at the few percent percent level, using ALFA; SD forward proton spectrum (ALFA); single diffractive di-jet and W production; di-jets from Double Pomeron Exchange (DPE) and CEP (with rapidity gap veto in FCAL, LUCID, ZDC); and, gaps between jets as a probe of colour singlet exchange.

At high luminosities the ATLAS Forward Physics (AFP) project aims to deploy proton taggers at ∼220m and ±420m in order to obtain access to a rich new vein of CEP physics, that includes SM/MSSM/NMSSM Higgs boson studies, W pair production, slepton production and gluino pair production, etc. As evidenced by recent results from the CDF Collaboration [6][12] the LHC is not only a $p-p$ collider, but also a $IP-IP$, $\gamma-IP$ and a $\gamma-\gamma$ collider.

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