Minimum Bias Physics at the LHC with the ATLAS Detector

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Abstract
This paper presents the status of Minimum Bias physics analysis with the ATLAS detector [1]. The current uncertainties in modelling soft p-p inelastic collisions at LHC energies are discussed in the context of primary charged track measurements. The selection and reconstruction of inelastic p-p interactions with the ATLAS detector at the LHC is discussed. The charged track reconstruction performance is explored using a GEANT4 [2] simulation of the ATLAS detector.

1 Introduction

The properties of inelastic proton-proton and proton anti-proton interactions have previously been studied over a wide range of energies [3–12]. Previous analyses have selected events with minimal bias and illustrated their behaviour through $dN_{Ch}/d\eta$, dN_{Ch}/dp_T, KNO scaling [13], and $\langle p_T \rangle$ vs N_{Ch} distributions. These distributions are typically produced from a selection of non-single-diffractive events, defined as a sample of inelastic events, where the trigger acceptance for single diffractive events is very low. Previous results from CERN and Fermilab experiments have been used to tune [14] the PYTHIA [15] event generator such that the generator properly describes previous measurements. In particular figure 1 illustrates the measured and predicted charged particle density for non-single diffractive events as a function of the centre of mass energy. There are clear differences in the predicted multiplicities of PYTHIA(ATLAS and CDF tune-A [16]) and PHOJET [17, 18] at the Large Hadron Collider (LHC) centre of mass energies of $\sqrt{s} = 10$ TeV and $\sqrt{s} = 14$ TeV.

The first physics run of the Large Hadron Collider (LHC) is expected to take place in late 2009. The LHC is expected to run first at a centre of mass energy $\sqrt{s} = 10$ TeV during 2009-2010, and then at $\sqrt{s} = 14$ TeV following a shutdown. Data collected from the first physics run at the LHC will allow models of soft QCD processes to be constrained. These studies are vital to understand QCD within the LHC energy regime and to model additional proton-proton interactions, which will be abundant at higher instantaneous luminosities.

2 Predicted Properties

The total p-p cross section can be expressed as a sum of the components parts,

$$\sigma_{tot} = \sigma_{elas} + \sigma_{sd} + \sigma_{dd} + \sigma_{nd}$$

where these cross-sections are elastic (σ_{elas}), single diffractive (σ_{sd}), double diffractive (σ_{dd}) and non-diffractive (σ_{nd}), respectively. In this approximation the small central diffractive component of the cross section is ignored. Predictions for the cross sections at 14 TeV are given

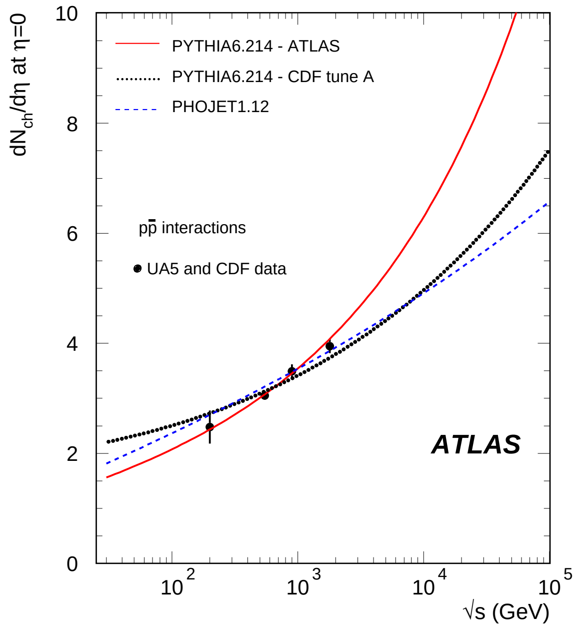


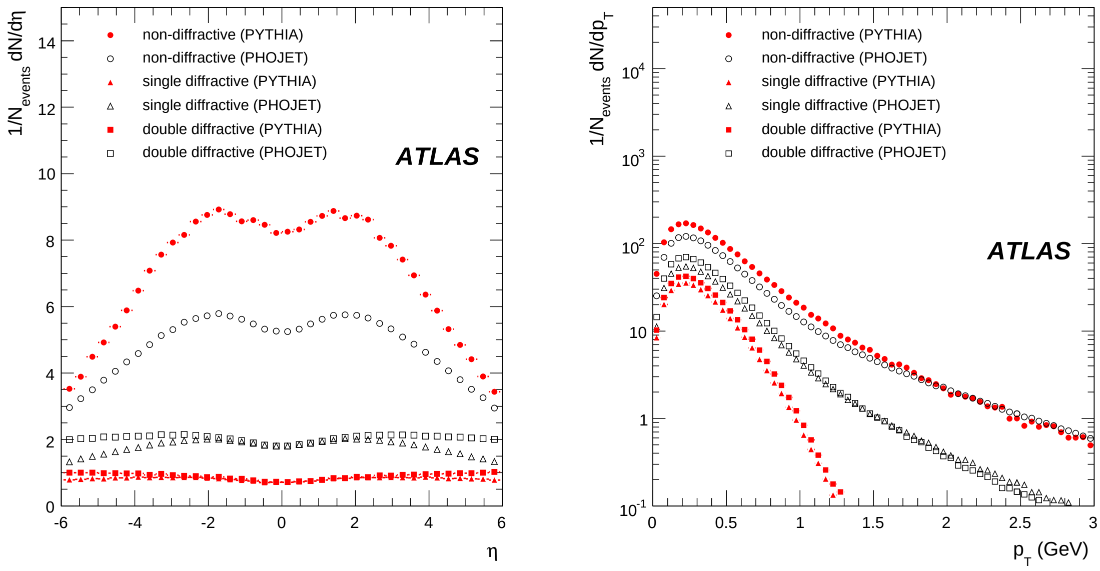
Fig. 1: Central charged particle density for non-single diffractive inelastic p-$\bar{p}$ collisions.

elsewhere [19]. 10 TeV cross sections are expected to be of the order of 10% lower. Using the PYTHIA and PHOJET event generators the predicted properties of the $dN_{Ch}/d\eta$ and dN_{Ch}/dp_T distributions are illustrated in figure 2. This paper focuses on the $dN_{Ch}/d\eta$ and dN_{Ch}/dp_T distributions, and the very first results expected from the ATLAS detector.

3 Event Selection

The LHC is expected to run with a range of different operating parameters, providing different mean numbers of interactions per p-p bunch crossing. During initial running it is expected that the mean number of inelastic interactions per p-p bunch crossing will be much less than one. Within this operating regime it is necessary to select the rare events containing inelastic interactions over those where the beams do not produce such an interaction and only detector noise is recorded. Once the mean number of interactions approaches, or exceeds unity the majority of inelastic interactions will be selected by simply requiring the presence of two crossing proton bunches.

The ATLAS detector [1] is a multi-purpose detector designed to study all areas of physics at the LHC. The key components for early Minimum Bias physics measurements are the Inner Detector (ID) and sections of the trigger system dedicated to the selection of inelastic interactions with minimal bias. The ID covers radii of 50.5 mm to 1066 mm and is composed of a silicon pixel system, a silicon micro-strip tracker (SCT), and a gas-based transition radiation detector (TRT). The ID is housed inside a solenoid magnet which produces a 2 Tesla axial magnetic field. A summary of the active ID acceptance is given in table 1, where the silicon tracking detectors



(a) (b)

Fig. 2: Pseudorapidity (a) and transverse momentum (b) distributions of stable charged particles from simulated 14 TeV p-p inelastic collisions generated using the PYTHIA and PHOJET event generators

and the TRT cover $|\eta| < 2.5$ and $|\eta| < 2.0$ respectively.

		Radius (mm)	Length (mm)
Pixel	Barrel (3 layers)	$50.5 < R < 122.5$	$0 < |z| < 400.5$
	End-cap (2x3 disks)	$88.8 < R < 149.6$	$495 < |z| < 650.0$
SCT	Barrel (4 layers)	$299 < R < 514$	$0 < |z| < 749$
	End-cap (2x9 layers)	$275 < R < 560$	$839 < |z| < 2735$
TRT	Barrel (73 straw planes)	$563 < R < 1066$	$0 < |z| < 712$
	End-cap (160 straw planes)	$644 < R < 1004$	$848 < |z| < 2710$

Table 1: A summary table of the ATLAS ID acceptance.

During initial low luminosity running, events will be selected with the Minimum Bias trigger. For initial measurements based on charged tracks reconstructed in the ID, inelastic collisions will be selected with either the Minimum Bias ID trigger or the Minimum Bias Trigger Scintillators (MBTS). The primary Minimum Bias ID trigger uses Pixel clusters and SCT space point information and covers $|\eta| < 2.5$. The MBTS are situated at $z = \pm 3560$ mm and are segmented into eight units in azimuth and two units ($2.82 < |\eta| < 3.84$, $2.09 < |\eta| < 2.82$) in pseudo-rapidity.

The ATLAS detector has a three stage trigger to select events: Level 1, Level 2 and the Event Filter (EF). Inelastic events are selected if they satisfy one of the Minimum Bias Level 1 triggers. Most of the events containing tracks within the ID acceptance will be selected by either the level 1 MBTS trigger or the random filled bunch trigger (L1_RDO_FILLED). Events passing the random filled bunch trigger will be filtered at Level 2 by using ID information.

A Level 1 MBTS trigger is formed by requiring a given number of MBTS counters above threshold. For the selection of inelastic interactions with minimal bias it is necessary to require a minimum number of MBTS counters. A requirement of just one counter is sensitive to the electronic noise level, and therefore two counters are preferred. For minimum trigger selection bias the number of MBTS counters above threshold from the two sides are summed. If this sum is greater than or equal to 2 the primary physics trigger L1_MBTS_2 fires.

L1_RDO_FILLED simply requires the presence of two proton bunches and a random clock cycle. During the initial running period the luminosity is expected to be too low for L1_RDO_FILLED to be used without filtering at Level 2. At Level 2, events selected with L1_RDO_FILLED are passed to the Minimum Bias ID trigger, where the total number of Pixel clusters and SCT space points are used to select p-p bunch crossings containing an inelastic interaction. The SCT modules are made from pairs of silicon sensors mounted in small angle stereo with each other. A space point is formed from a strip hit coincidence of the pair of sensors, reducing the sensitivity to noise. Pixel clusters are formed from a cluster of pixels above a time-over-threshold constraint. While the Pixel clusters only include one sensor plane the noise occupancy is expected to be low enough [20, 21] for the total number of pixel clusters to be used within the Minimum Bias ID trigger. Thresholds for the multiplicity constraints on Pixel and SCT detectors were set by studying the simulated performance of these detectors, where the noise model contained random electronic noise occupancies taken from detector measurements. Events which pass the Pixel cluster and SCT space point requirements are further filtered at the EF by requiring a number of reconstructed tracks. For the EF selection of an event two tracks were required to have $p_T > 200$ MeV and a nominal $|Z_0| < 200.0$ mm, minimally biasing the selection, but rejecting some beam background.

Inelastic single diffractive, double diffractive and non-diffractive events were generated with the PYTHIA event generator at $\sqrt{s} = 14$ TeV. These events were then passed through a GEANT4 simulation and overlaid with simulated detector noise. In addition to the physics samples, beam-gas was simulated with the HIJING event generator [22] and events containing no p-p interactions were also studied. The resulting Minimum Bias trigger efficiencies are illustrated in figure 3, where the Pixel and SCT efficiencies were calculated with the other multiplicity requirement set to zero, the track trigger efficiency includes the prior selection of Pixel and SCT at Level 2, and the simulated noise in the MBTS is artificially high within the beam-gas sample.

Using a nominal MBTS signal threshold of 40 mV from previous cosmic studies, and SCT and Pixel thresholds defined by the requirement of a maximum detector noise trigger efficiency of 5×10^{-4}, the trigger efficiencies were calculated and are listed in table 2.

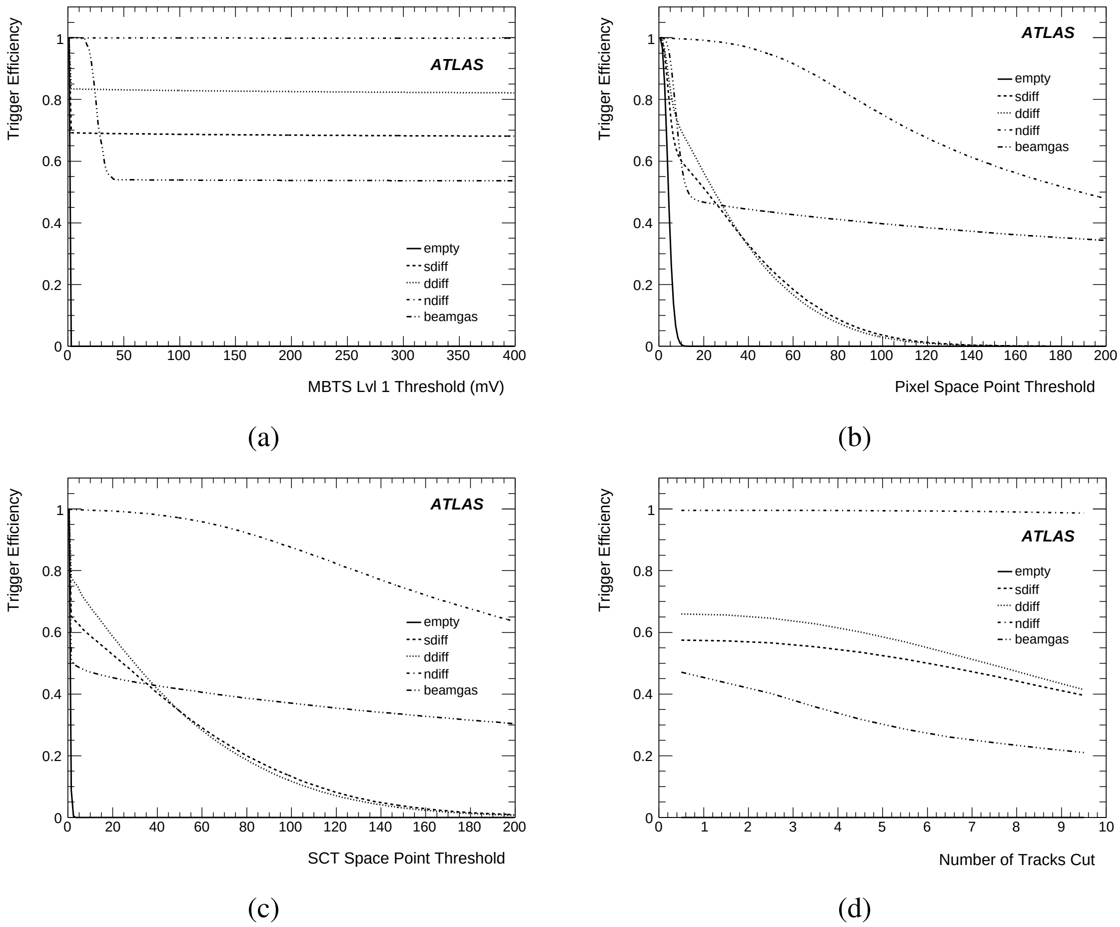


Fig. 3: The trigger efficiency for: MBTS_2 as a function of the counter threshold (a), Pixel space point as a function of the number of Pixel space points required (b), SCT space point as a function of the number of SCT space points required (c), and track trigger as a function of the required number of reconstructed tracks (d).

	MBTS_1_1	MBTS_2	SP	SP & 2 Tracks
Non-diffractive	99%	100%	100%	100%
Double-diffractive	54%	83%	66%	65%
Single-diffractive	45%	69%	57%	57%
Beam-gas	40%	54%	47%	40%

Table 2: A table of trigger efficiencies for: an MBTS threshold of 40 mV, requirements of $\geqq 12$ Pixel and $\geqq 3$ SCT space points (SP), and the requirement of two tracks with nominal $Z_0 < 200$ mm and $p_T > 200$ MeV after the SP requirement.

4 Event Reconstruction

Initial Minimum Bias physics measurements involve the reconstruction of charged particle multiplicity distributions. Figure 2 clearly illustrates the predicted event properties, where the most probable particle p_T is expected to be around 220 MeV. In high multiplicity environments, such as expected in high energy hard scatter processes or higher luminosity running at the LHC, it is necessary to normally require a p_T cut-off of 500 MeV or higher within the track reconstruction software. This cut-off is required to reduce the number of combinations of track candidates and improve the performance of the track reconstruction algorithms. For Minimum Bias events a second low p_T track reconstruction step has been introduced.

The ATLAS track reconstruction software [23] is run over the silicon hits twice: finding tracks with p_T above 500 MeV and then reconstructing the remaining tracks down to a minimum p_T of 100 MeV. Hits that are attached to tracks reconstructed during the first tracking pass are tagged such that they are not used during the second pass. Then the second reconstruction pass runs with a wider azimuthal road size and looser track reconstruction constraints. During both the first and second pass of the track reconstruction the silicon tracks are projected into the TRT, finding track extensions where present. The combined tracking performance was studied from inelastic non-diffractive p-p events generated using PYTHIA at $\sqrt{s} = 14$ TeV which were passed through the ATLAS GEANT4 detector simulation.

Following previous tracking performance studies [24], the track reconstruction efficiency was defined as the ratio of reconstructed tracks matched to Monte Carlo particles, divided by all stable charged primary Monte Carlo particles. The fake rate was defined as the ratio of all primary reconstructed tracks not matched to a Monte Carlo particle divided by all primary reconstructed tracks. For the measurement of tracking efficiency and fake rate, primary Monte Carlo particles and primary reconstructed tracks were selected by requiring:

- ID Acceptance ($|\eta| < 2.5$)
- Primary Particle
  - Not generated from the GEANT4 simulation.
  - $|d_0| < 2$ mm with respect to the generated primary vertex.
- Stable charged particle PDG id.
- $p_T > 100$ MeV

and

- ID Acceptance ($|\eta| < 2.5$)
- N$^{o.}$ Silicon Hits $\geqq 5$, from 11 planes of silicon.
- Primary Track
  - $|d_0| < 2$ mm with respect to the generated primary vertex.
  - $|Z_0 sin(\theta)| < 10$ mm
- $p_T > 100$ MeV

respectively. The resultant tracking performance is illustrated in figure 4.

5 Conclusion

The ATLAS Collaboration expects to record the first p-p inelastic collisions later this year. A trigger system to select inelastic events with minimal bias within the tracking acceptance has been developed. The trigger performance given in table 2 indicates good acceptance of inelastic events suitable for minimum bias physics studies. Reconstruction of inelastic non-diffractive

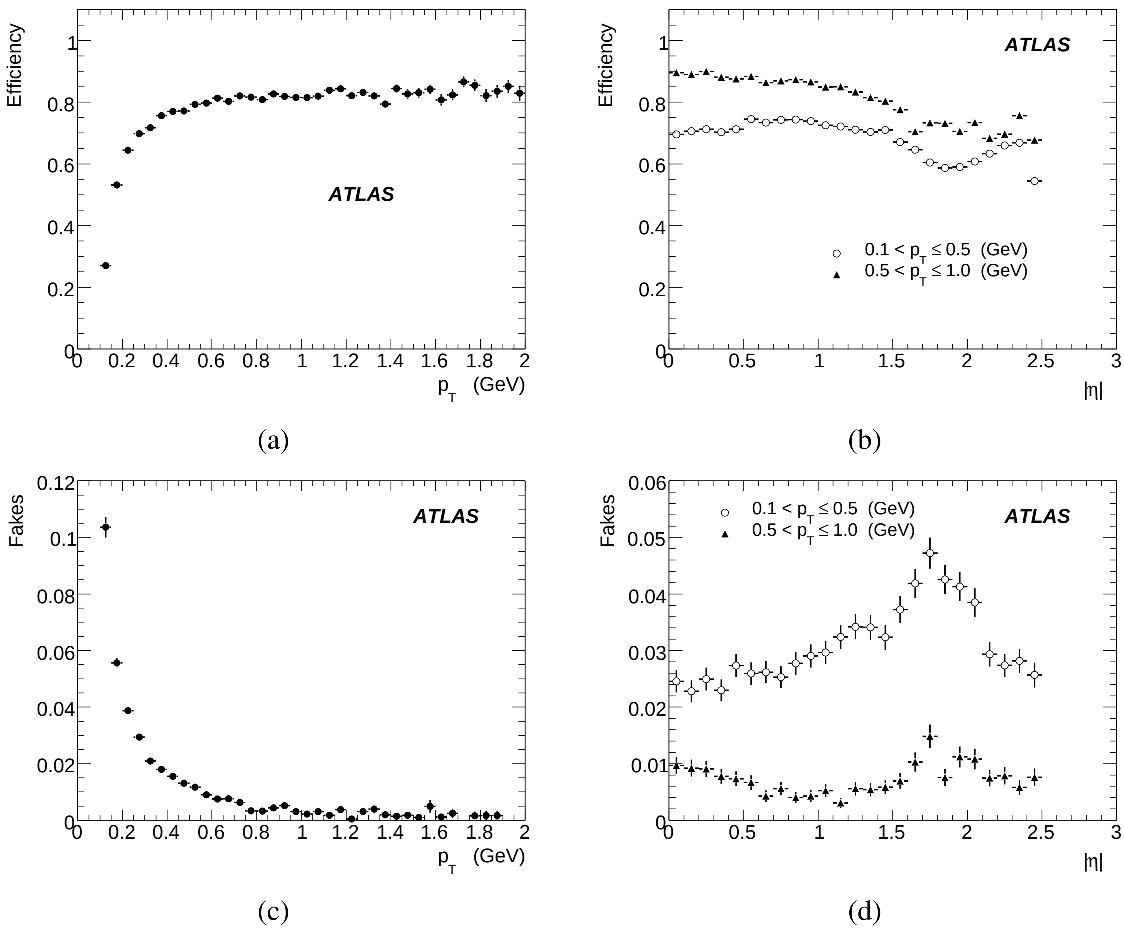


Fig. 4: Tracking performance: efficiency as a function of p_T (a) and pseudo-rapidity (b), normalised track fakes as a function of p_T (c) and pseudo-rapidity (d).

events has been explored with low momentum track reconstruction algorithms. The performance of these low momentum track reconstruction algorithms is illustrated in figure 4, and clearly demonstrates track reconstruction below the nominal 500 MeV cut-off. Further improvements in the track reconstruction efficiency and reduction of the associated fake rates are expected following additional algorithm tuning. Previous studies [19] have found the systematic uncertainty on an expected $dN/d\eta$ measurement to be of the order of 8% for a non-single-diffractive measurement, sufficient to distinguish between different theoretical models. The ATLAS Collaboration therefore looks forward to the first LHC beam and the first physics results.

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track reconstruction software, and detector noise measurements. The author therefore thanks all of those involved in these areas of research.

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