ATLAS measurements of minimum bias and soft QCD

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Abstract. The first measurements of charged particle production in proton-proton collisions at center-of-mass energy $\sqrt{s} = 900$ GeV and 7 TeV recorded with the ATLAS detector at the LHC are presented. Minimum bias distributions are measured for events with at least one charged particle in the kinematic range $|\eta| < 2.5$ and $p_T > 500$ MeV and compared with the predictions from various Monte Carlo models. Activity in the underlying event was measured with respect to the highest p_T track in the event. Both the minimum bias and underlying event measurements are fully corrected for detector effects to obtain distributions at the hadron level.

A new PYTHIA6 Monte Carlo tune, *ATLAS Minimum Bias Tune 1*, was produced using ATLAS minimum bias distributions measured in a diffractive limited phase-space in combination with measurements from previous hadron collider experiments. The new tune is shown to significantly improve the predictions for minimum bias distributions measured in the diffractive limited phase-space.

Keywords: Non-perturbative QCD, Minimum Bias, Underlying event

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INTRODUCTION

These proceedings report on measurements of primary charged particle multiplicity distributions and underlying event activity using the first data recorded by the ATLAS experiment [1], corresponding to $\sim 8 \mu\text{b}^{-1}$ at 7 TeV and $\sim 7 \mu\text{b}^{-1}$ at 900 GeV.

Proton-proton interactions are composed of non-diffractive and diffractive processes that predominantly involve low momenta transfers which are not calculable within perturbative QCD and are only described by phenomenological models implemented in Monte Carlo (MC) event generators. ATLAS measurements were made in a specific phase-space region, by requiring events with at least one primary charged particle with pseudo-rapidity $|\eta| < 2.5$ and transverse momentum $p_T > 500$ MeV. To avoid model dependency in the measurement, no removal of the single-diffractive component was applied. The ATLAS measurements are fully corrected for detector effects to obtain distributions at the hadron level.

Inclusive charged-particle distributions have been measured in pp and $p\bar{p}$ collisions in previous hadron collider experiments and have been used to constrain phenomenological models of soft-hadronic interactions, which provide a basis of comparison for the ATLAS measurements.

MEASUREMENT STRATEGY

The event and track selection match the kinematic range of charged particles chosen for the ATLAS measurements. Events were required to have:

- at least one hit in the Minimum Bias Trigger Scintillators (MBTS) at $2.09 < |\eta| < 3.84$,
- a reconstructed primary vertex composed of 2 or more tracks,
- no further primary vertex composed of 4 or more tracks (to veto pile-up events),
- at least one good track.

It was found that the primary vertex requirement in combination with the pile-up veto reduced the measured contribution from back-background and pile-up events to a negligible level [2].

A good track is defined as one that satisfies

- $p_T > 500$ MeV and $|\eta| < 2.5$,
- a minimum of one Pixel and six Semiconductor Central Tracker (SCT) hits,
- transverse and longitudinal impact parameters calculated with respect to the event primary vertex $|d_0| < 1.5$ mm and $|z_0| \cdot \sin \theta < 1.5$ mm, respectively.

In order to obtain the distributions at particle-level for events with at least one primary charged particle ($n_{\text{ch}} \geq 1$) within the chosen kinematic range, knowledge of trigger, vertex and tracking efficiency is required as is described in the next sections.

Selection efficiency

The ATLAS minimum bias trigger efficiency was measured with respect to a control trigger. The control trigger consisted of a random trigger coincident with colliding bunches and required events to have at least 4 hits in the pixel detector and another 4 space-points¹ in the SCT detector.

The primary reconstruction efficiency was determined from the ratio of events with a reconstructed primary vertex compared to all triggered events.

The track reconstruction efficiency was determined from a large sample of simulated non-diffractive events. The uncertainty on the tracking efficiency was determined from the level of agreement between data and simulation for various track reconstruction parameters as well as from the reconstructed K_s^0 mass. The largest uncertainty on the tracking efficiency was found to come from the material description of the tracking detector. Data/simulation comparison resulted in a conservative estimate of 10% uncertainty on material, which gives a 3% uncertainty in the tracking reconstruction efficiency.

¹ A space-point is constructed from hits detected in two overlapping silicon strips.

Correction procedure

Corrections for detector effects to obtain particle-level distributions in the chosen phase-space were done in the following steps:

First, the effect of events lost due to the trigger and vertex requirements was corrected using an event-by-event weight:

$$w_{\text{ev}}(n_{\text{sel}}^{\text{BS}}) = \frac{1}{\varepsilon_{\text{trig}}(n_{\text{sel}}^{\text{BS}})} \cdot \frac{1}{\varepsilon_{\text{vtx}}(n_{\text{sel}}^{\text{BS}})},$$

where $\varepsilon_{\text{trig}}(n_{\text{sel}}^{\text{BS}})$ and $\varepsilon_{\text{vtx}}(n_{\text{sel}}^{\text{BS}})$ are the trigger efficiency and vertex reconstruction efficiency as function of $n_{\text{sel}}^{\text{BS}}$, the number of selected tracks with respect to the beam-spot².

Second, track distributions were corrected using a track-by-track weight as a function of p_{T} and η :

$$w_{\text{trk}}(p_{\text{T}}, \eta) = \frac{1}{\varepsilon_{\text{trk}}(p_{\text{T}}, \eta)} \cdot (1 - f_{\text{nonp}}(p_{\text{T}}, \eta)) \cdot (1 - f_{\text{okr}}(p_{\text{T}}, \eta)),$$

where ε_{trk} is the track reconstruction efficiency, f_{nonp} is the fraction of non-primary tracks passing the track selection cuts and f_{okr} is the fraction of selected tracks for which the corresponding primary particle was outside the kinematic range.

An unfolding matrix $M_{n_{\text{ch}}, n_{\text{sel}}}$ was defined to express the probability that a given number of selected tracks n_{sel} was due to a certain number primary particles n_{ch} . This matrix was populated using simulated data (generated with PYTHIA6 with the ATLAS MC09 tune) and applied to data to obtain the n_{ch} distribution. The resulting distribution was then used to re-populate the matrix and the correction was re-applied until it converges after four iterations.

CHARGED PARTICLE DISTRIBUTIONS IN MINIMUM BIAS EVENTS

Figure 1 shows the measured charged particle multiplicity $1/N_{\text{ev}} \cdot dN_{\text{ch}}/d\eta$ as a function of pseudo-rapidity η and transverse momentum p_{T} of the primary charged particle for $\sqrt{s} = 7$ TeV, compared to the predictions of several Monte Carlo models [2]. The uncertainty on the measurements is dominated by the systematic uncertainty from the tracking efficiency and is represented by the green bands in the plots.

It can be seen that the η distribution is best described by the PYTHIA6 tune ATLAS MC09c [3], though the predictions are still 5% below the measured values. For $p_{\text{T}} > 4$ GeV, ATLAS MC09c predicts a significantly harder spectrum than what was measured.

Figure 2 shows the charged particle multiplicity versus number of charged particles in the event and the average transverse momentum versus number of charged particles. The

² The trigger and vertex efficiency were determined without the vertex requirement and so could only cut on the impact parameter of tracks with respect to the beam-spot.

charged particle multiplicity versus n_{ch} is best predicted by PYTHIA ATLAS MC09c, but at low n_{ch} the contribution from diffractive processes dominates and the model predictions are seen to exceed those measured in data.

The average transverse momentum $\langle p_T \rangle$ is best predicted by PHOJET for values of $n_{\text{ch}} < 60$, but for values of $n_{\text{ch}} > 60$ PHOJET shows a rise not seen in the data.

FIGURE 1. The measured charged particle multiplicity versus pseudo-rapidity (left) and distribution of the transverse momentum (right) compared to Monte Carlo predictions [2].

FIGURE 2. The multiplicity distribution of charged particles in the event (left) and the average transverse momentum versus number of charged particles (right) compared to Monte Carlo predictions [2].

The distributions shown in figures 1 and 2 were also measured for $\sqrt{s} = 900$ GeV [4]. Figure 3 shows the measurement results for $1/N_{\text{ev}} \cdot dN_{\text{ch}}/d\eta$ at $\eta = 0$ as function of center-of-mass energy of the proton-proton collisions. The measured energy dependence of the multiplicity is described within 5% by PYTHIA ATLAS MC09 [3].

FIGURE 3. The measured average charged particle multiplicity for $\eta = 0$ as a function of the center-of-mass energy, compared to Monte Carlo predictions [2].

TRACK-BASED UNDERLYING EVENT MEASUREMENTS

The activity accompanying the hard scattering process, the *underlying event*, was measured by looking at charged particle density and angular distribution with respect to the highest p_T track (=leading track) in the event [5]. The transverse region with respect to the leading track is assumed to be principally filled by the underlying event. Tracks are defined to be in the transverse region when their azimuthal angle with respect to the leading track is within $60^\circ < |\Delta\phi| < 120^\circ$.

Figure 4 illustrates the measured charged particle number density for particles with $p_T > 500$ MeV and $|\eta| < 2.5$ as a function of the transverse momentum of the leading track p_T^{lead} , showing both the result at $\sqrt{s} = 7$ TeV compared with Monte Carlo predictions and the comparison of the results at the different center-of-mass energies. It can be seen that for $p_T^{\text{lead}} > 5$ GeV the activity in the underlying event reaches a plateau. The number density is higher than predicted by any of the Monte Carlo models.

The underlying activity increases by approximately a factor of two between 900 GeV and 7 TeV data, the ratio of the increase between these energies is roughly consistent with the increase predicted by the Monte Carlo models. It can also be noted that the charged particle density in the plateau region of the underlying event distributions is about a factor of two larger as the one measured in minimum bias events. This is expected as the high p_T track requirement for the leading tracks results in higher momentum exchange and a lack of diffractive contributions compared to the minimum bias events.

FIGURE 4. Measured charged particle number density in the transverse region as a function of p_T^{lead} , showing (left) the comparison with predictions from different Monte Carlo models at $\sqrt{s} = 7$ TeV and (right) the comparison of the results at different center-of-mass energies [5].

THE ATLAS MINIMUM BIAS TUNE 1

The predictions from the PYTHIA6 tune ATLAS MC09 showed a reasonable agreement with the ATLAS measurements of minimum bias and underlying event distributions, compared to the various other models, but still showed significant discrepancies with respect to data. The ATLAS Minimum Bias Tune 1 (ATLAS MBT1) is a new PYTHIA6 tune based on ATLAS MC09 in which several model parameters were re-tuned to improve the description of the non-diffractive component of the measured distributions.

In order to remove (most of the) contribution from diffractive processes, the minimum bias distributions in ATLAS were measured in a diffractive limited phase-space by requiring at least 6 primary charged particles with $p_T > 500$ MeV and $|\eta| < 2.5$ per event ($n_{ch} \geq 6$). CDF data was included in the tuning procedure so that the predictions would remain consistent with measurements from previous experiments. More detail on the tuning procedure and new parameter values of ATLAS MBT1 can be found here [6].

Figure 5 illustrates how the ATLAS MBT1 tune improves the prediction of the minimum bias distributions in the diffractive-limited phase-space. The ATLAS MBT1 prediction of charged particle multiplicity as a function of p_T is shown to reduce the deviations at high p_T with respect to ATLAS MC09c. Also the distribution of $\langle p_T \rangle$ as function of n_{ch} is predicted significantly better by ATLAS MBT1 than any of the other models, and shows a large improvement with respect to ATLAS MC09c.

CONCLUSION

The first ATLAS measurements of minimum bias and underlying event in proton-proton collision at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV have been presented. ATLAS measurements were made in a specific phase-space, with no removal of the single diffractive component, to make model-independent measurements.

Minimum bias distributions were measured in events with at least one primary

FIGURE 5. The measured minimum bias distributions for $n_{\text{ch}} \geq 6$ at $\sqrt{s} = 7$ TeV compared to Monte Carlo predictions, including ATLAS MBT1, showing the charged particle multiplicity versus transverse momentum (left) and the average transverse momentum versus number of charges particles (right) [6].

charged particle with a kinematic range of charged particle of $p_T > 500$ MeV and $|\eta| < 2.5$. Both the average charged particle multiplicity in minimum bias events and the activity in the underlying event were measured to be significantly above the predictions of any of the Monte Carlo models.

A new PYTHIA6 tune, ATLAS Minimum Bias Tune 1, was made in order to improve the description of the non-diffractive component of the minimum bias distributions by using ATLAS measurements in a diffractive limited phase-space. The ATLAS MBT1 tune was shown to significantly improve the prediction for ATLAS minimum bias measurements in the non-diffractive phase-space.

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