1 Charged particle multiplicity in proton-lead collisions at
2 $\sqrt{s_{\text{NN}}} = 5.02$ TeV in the ATLAS experiment *

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8 This note describes ATLAS results on multiplicity of produced charged
9 particles in p +Pb collisions at the centre-of-mass energy of 5.02 TeV. The
10 charged particle density was measured in a wide pseudorapidity range as a
11 function of the collision centrality using 2.1 million events which were col-
12 lected during a "pilot run" in September 2012. Analysis methods, centrality
13 determination and the particle production dependence on the number of
14 nucleons participating in the collisions are presented.

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16 **1. Introduction**

17 Since 2010 the $p + p$, Pb+Pb and p +Pb collisions at the highest centre-
18 of-mass energies were delivered by the Large Hadron Collider (LHC) [1] and
19 measured using the ATLAS detector [2] giving a chance to observe new phe-
20 nomena. While analysis of $p + p$ collisions is focused predominantly on the
21 searches for the Higgs boson and signs of a new physics beyond the Standard
22 Model, the studies of Pb+Pb collisions are aimed at investigation of prop-
23 erties of the Quark-Gluon Plasma (QGP). The charged particle multiplicity
24 in heavy ion collisions is one of the most important global observables char-
25 acterizing properties of the matter created in nuclear collisions. It has been
26 studied at lower than LHC energies in many experiments using beams inter-
27 acting with a fixed target [3–5] or delivered in collider accelerators [6–8] for
28 various colliding systems. In the analysis of A+A collisions properties of the
29 QGP thermalization and collective evolution are obscured by purely nuclear
30 effects. These latter phenomena can be studied in p +A collisions [9], where

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31 formation of the QGP is not expected. The measurement of charge particle
 32 multiplicity as a function of centrality of collisions can show how multiple
 33 interactions of a proton in a heavy nucleus affect bulk particle production.
 34 Such measurements provide valuable tests of saturation models and nuclear
 35 parton distributions.

36 In September 2012 the LHC provided first p +Pb collisions at the centre-
 37 of-mass energy $\sqrt{s_{NN}} = 5.02$ TeV. Due to the difference between proton and
 38 lead beam energies, the collisions have a rapidity boost of -0.47 with respect
 39 to the ATLAS detector frame of reference. In this pilot run the beam with
 40 the lead nuclei had positive rapidity (Pb-going side) and the proton beam
 41 had negative rapidity (proton-going side)¹. During this short run ATLAS
 42 collected 2.1 million minimum-bias events corresponding to an estimated
 43 integrated luminosity of $1\mu\text{b}^{-1}$.

44 2. The Atlas detector and experimental setup

45 The Atlas detector [2] is the largest detector at the LHC accelerator [1].
 46 In its structure we can distinguish three main layers of subdetectors: track-
 47 ing system, calorimeters and muon chambers. For the presented here anal-
 48 ysis the innermost part of the ATLAS tracking system: silicon Pixel detec-
 49 tor [2] is the most important. It is placed very close to the beam pipe and
 50 consists of the "barrel" and "endcap" sections. In the barrel part, rectan-
 51 gular silicon modules are arranged in three layers with the first of them at
 52 50.5 mm from the beam axis. The two endcaps, located on both sides of the
 53 barrel, consist of silicon modules forming three rings. The Pixel detector
 54 covers over 5 pseudorapidity units in the central rapidity region.

55 In the centrality determination signals from the forward calorimeter
 56 (FCal) are used. This detector covers $3.1 < |\eta| < 4.9$ range, but only the
 57 part at positive η measuring Pb nucleus fragmentation is used in the cen-
 58 trality calculations. The trigger for minimum-bias p +Pb collisions is based
 59 on information from the Minimum-Bias Trigger Scintillators (MBTS) which
 60 consists of two rings with 16 scintillator modules each, placed at positive
 61 and negative z and covering $2.1 < |\eta| < 3.9$.

62 3. Event selection

63 The primary trigger requires effectively at least one signal on each side
 64 of the MBTS detector, with the time difference between them less than
 65 10 ns. The standard tracks reconstruction algorithm, optimized for $p + p$

¹ In the ATLAS coordinates frame z axis is along the beam direction, x axis is hori-
 zontal and points towards the centre of the LHC ring, and y axis is vertical.

66 minimum-bias events, was used to reconstruct tracks and find collision ver-
 67 tices [10]. The collision vertex range was restricted to $|z_{\text{vxt}}| < 175$ mm. The
 68 contribution from pileup was small and was further suppressed by reject-
 69 ing events with two or more reconstructed vertices that are separated in z
 70 by more than 15 mm, reducing the pileup fraction to about 10^{-4} [11]. In
 71 p +Pb collisions significant contributions from electromagnetic and diffrac-
 72 tive processes are expected. Some fraction of them is rejected by trigger
 73 requirements, but in addition a rapidity gap analysis was applied to remove
 74 the remaining events of these classes. In this analysis the detector is divided
 75 into slices of $\Delta\eta = 0.2$ and each slice containing at least one reconstructed
 76 track or a calorimeter cluster with $p_T > 200$ MeV was treated as occupied.
 77 The edge-gaps are calculated as a distance in pseudorapidity between the
 78 edge of the calorimeter (-4.9 or 4.9) and the nearest occupied slice. Events
 79 with large edge-gaps on positive η direction $\Delta\eta_{\text{gap}}^{\text{Pb}} > 2.0$ are excluded from
 80 the analysis, as they represent predominantly electromagnetic processes or
 81 diffractive excitations of the proton.

4. Centrality estimation

82
 83 To determinate centrality of p +Pb collisions the total transverse energy
 84 from forward calorimeter on the Pb-going side, ΣE_T^{Pb} , was used. The signals
 85 in the FCal were evaluated at the electromagnetic energy scale and have
 86 not been corrected for hadronic response. The transverse energy from FCal
 87 on the Pb-going side is more sensitive measure of the collision centrality
 88 (as expected to be associated with multiple interactions of the proton in
 89 the target nucleus) than the summed transverse energy from FCal on the
 90 proton-going side ΣE_T^{P} or the sum from both sides.

91 Figure 1 presents distribution of ΣE_T^{Pb} after applied events selection
 92 criteria. The alternating shaded and unshaded bands represent centrality
 93 intervals which are defined in terms of percentiles of the ΣE_T^{Pb} distribution
 94 after accounting for an estimated inefficiency of $2 \pm 2\%$ for p +Pb events.

95 The following centrality intervals are used in this analysis: $0 - 1\%$,
 96 $1 - 5\%$, $5 - 10\%$, $10 - 20\%$, $20 - 30\%$, $30 - 40\%$, $40 - 60\%$, $60 - 90\%$.
 97 The most peripheral collisions were excluded from the analysis due to un-
 98 certainties regarding event selection efficiency and remaining contributions
 99 of electromagnetic or diffractive events.

5. Measurement of charged particle multiplicity

100
 101 In the presented analysis, three different reconstruction methods, based
 102 on the information from the Pixel detector were used [11]. In the first
 103 two methods a tracklet reconstruction algorithm [12–14] is applied. The

Fig. 1. Distribution of the summed transverse energy deposited on the lead-going side, ΣE_T^{Pb} . The distribution is divided into nine intervals which correspond to centrality classes, from most central events (large ΣE_T^{Pb}) to peripheral collisions (small ΣE_T^{Pb}) [11].

104 two-point tracklet is defined by the reconstructed vertex and two clusters
 105 registered in two different layers of the Pixel detector. For each pair of
 106 clusters, the first from *layer* 0 closest to the beam pipe and second from
 107 more distant *layer* 1 (or *layer* 2) the difference in their positions in η and
 108 ϕ were calculated

$$\Delta\eta = \eta_1 - \eta_0, \Delta\phi = \phi_1 - \phi_0. \quad (1)$$

109 Using Monte Carlo simulations of events obtained from the HIJING
 110 generator [15] the optimal selection criteria reducing the false cluster com-
 111 binations were estimated. The minimal values of the differences $|\Delta\phi|$ and
 112 $|\Delta\eta|$ are 0.1 and 0.015 respectively.

113 Two variants of the tracklet method were used. Both of them require
 114 one cluster in the innermost layer but differ in the treatment of the second
 115 cluster. In the first approach, "Method 1", clusters from farther layer in the
 116 search region are treated as one hit. This way the number of fake tracklets
 117 is significantly reduced. In the second approach, "Method 2", all combi-
 118 nation of clusters in the search region are used to form tracklets. Later,
 119 the combinatoric background is removed by subtracting the distribution of
 120 tracklets obtained from modified events in which clusters from the outer
 121 layers are flipped in the azimuthal angle (in this case only fake tracklets are
 122 reconstructed). Both methods are schematically illustrated in Fig. 2.

123 In addition to the two tracklet methods, the third method based on pixel
 124 tracks was used. The pixel tracks are found by the standard ATLAS track

Fig. 2. Schematic picture of tracklet "Method 1" (left side) and "Method 2" (right side)

reconstruction algorithm, but restricted to the Pixel detector. The combinatoric background is in this case suppressed even more than in "Method 1", but the acceptance is smaller than in other two methods due to inactive areas in the pixel detector.

For each reconstruction method the corrections factors, C , were determined, as described below, and then applied to the data. The left panel of Fig. 3 shows the pseudorapidity distribution for the generated primary charged particles from HIJING [15] and reconstructed η distributions for tracklets and pixel tracks. Using these distributions, the correction factors are evaluated as:

$$C(O, z_{vtx}, \eta) \equiv \frac{N_{pr}(O, z_{vtx}, \eta)}{N_{rec}(O, z_{vtx}, \eta)}, \quad (2)$$

where N_{pr} is the number of generated primary charged particles and N_{rec} is the number of tracklets or tracks reconstructed with the considered methods. The correction factors are evaluated as a function of occupancy, O , position of the event vertex z_{vtx} and η in 8 intervals of detector occupancy and 7 intervals of vertex position. These corrections account for several effects such as inactive areas in the Pixel detector, reconstruction efficiency, contributions from fake tracklets or tracks and secondary particles, losses due to tracks or tracklets selection cuts etc. The final charged particle pseudorapidity density is calculated as:

$$\frac{dN_{ch}}{d\eta} = \frac{1}{N_{evt}} \sum_{z_{vtx}} \frac{\Delta N^{raw}(O, z_{vtx}, \eta) C(O, z_{vtx}, \eta)}{\Delta \eta} \quad (3)$$

where N_{evt} is the number of events, ΔN^{raw} indicates either the number of reconstructed tracklets or pixel tracks in the data. Right panel in Fig. 3 shows

146 experimental distributions from three methods, both the raw distributions of
tracklets or tracks and final results after applying corrections. The corrected

Fig. 3. Charged particle multiplicity in 0 – 10% most central events as a function of pseudorapidity obtained for generated primary charged particles (black histogram), from two tracklet methods (circles and squares) and from the pixel Track method (diamonds). In the left panel results obtained for Monte Carlo simulations (raw tracklets and tracks distributions) are shown, while in the right panel results obtained from experimental data: raw tracklets and tracks distributions and the final corrected particle density (full symbols) are included [11].

147 charged particle densities are in good agreement for all three methods, which
148 indicates that the correction procedure is well understood. In following, the
149 "Method 1" is used for the measurement of $dN_{ch}/d\eta$. "Method 2" is used
150 for estimation of systematic uncertainties and the pixel track method serves
151 as a cross check.

152 The total systematic uncertainties are largest for peripheral events, where
153 they reach 5.76 % in the barrel and 7.53 % in the endcaps, while for central
154 collisions they are 3 % in the barrel and 5.44 % in the endcaps.
155

156 6. Results

157 The $dN_{ch}/d\eta$ measurement is presented in Fig. 4, where the charged
158 particle density measured in pseudorapidity range from -2.7 to 2.7 for eight
159 centrality classes is shown. The charged particle density increases with cen-
160 trality, and in more central collisions we observe asymmetric distributions
161 due to enhanced particle production in the lead-going side. In the most pe-
162 ripheral events the charged particle density becomes similar to the charged
163 particle density in $p + p$ collisions [10, 16].

164 In order to study the centrality evolution of particle production, the
165 distributions of the charged particle density measured in different centrality
166 classes are divided by the charged particle density for the most peripheral

Fig. 4. Charged particle density in $p + Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV as a function of pseudorapidity obtained for eight centrality classes. Shaded bands represent systematic uncertainties [11].

167 event class (60-90%). The ratios are shown in Fig. 5. The original double
 168 peak structure disappears, the ratios increase approximately linearly with
 169 pseudorapidity with the slope of this dependence growing with centrality.
 170 For the most central collisions this ratio at $\eta = 2.7$ is almost two times
 171 higher than for $\eta = -2.7$. The ratios in Fig. 5 are fitted with a second order
 172 polynomial and parameters of this function are presented in Table 1.

Centrality ratio	a	b	c
0 – 1%/60 – 90%	-0.033 ± 0.006	0.77 ± 0.05	6.78 ± 0.28
1 – 5%/60 – 90%	-0.030 ± 0.005	0.515 ± 0.031	5.35 ± 0.22
5 – 10%/60 – 90%	-0.0218 ± 0.0035	0.377 ± 0.021	4.49 ± 0.18
10 – 20%/60 – 90%	-0.0169 ± 0.0025	0.269 ± 0.014	3.77 ± 0.14
20 – 30%/60 – 90%	-0.0113 ± 0.0020	0.182 ± 0.010	3.11 ± 0.11
30 – 40%/60 – 90%	-0.0076 ± 0.0016	0.122 ± 0.006	2.61 ± 0.08
40 – 60%/60 – 90%	-0.0037 ± 0.0011	0.0595 ± 0.0031	1.95 ± 0.06

Table 1. Parameters of second order polynomial fits ($a\eta^2 + b\eta + c$) to ratios of $dN_{ch}/d\eta$ distributions in different centrality classes divided by the $dN_{ch}/d\eta$ distribution for the most peripheral collisions (60-90%) [11].

173 An important characteristics of the particle production is the multiplic-

Fig. 5. Charged particle density for seven centrality intervals divided by the charged particle density for the most peripheral events. Red lines represent second order polynomials fitted to the ratios [11].

ity of charged particles per a pair of nucleons participating in the collision,
 N_{part} . The estimate of $\langle N_{\text{part}} \rangle$ requires modelling of the interactions of nu-
 cleons in the nuclei, which is commonly provided by the Glauber model.
 In this analysis, the number of participants is obtained from three differ-
 ent versions of Glauber model. In Fig. 6 the charged particle multiplicity
 divided by the mean number of participant pairs, in several pseudorapidity
 intervals, is shown as a function of the number of participants N_{part} . For
 the standard Glauber model [17] in the top panel we observe an increase of
 the normalized charged particle density starting from $N_{\text{part}}=10$. This be-
 haviour wasn't expected and it may mean that the standard Glauber method
 does not work well at LHC energies. Plots below present the same depen-
 dence but for N_{part} calculated using two versions of the Glauber-Gribov
 model [18,19] with different values of the Ω parameter, which represents
 the width of the assumed fluctuations of the nucleon-nucleon cross section,
 σ_{NN} . In these cases we observe different behaviours indicating sensitivity to
 the initial-state modelling.

Fig. 6. Charged particle density divided by the number of pairs of participants as a function of $\langle N_{\text{part}} \rangle$ for three implementations of the Glauber model and in several η intervals. Standard Glauber model implementation is shown in the top panel. In the middle and in the bottom panel the Glauber-Gribov implementations with $\Omega = 0.55$ and $\Omega = 1.01$ respectively are presented. The shaded boxes represent the total systematic uncertainty [11].

7. Conclusions

The charged particle density in p +Pb collisions was measured by the ATLAS experiment. The measurement was done in $|\eta| < 2.7$ range and for the 90% most central collisions. Centrality of collisions was estimated using information from the forward calorimeter on Pb-going side. The average number of participants $\langle N_{\text{part}} \rangle$ was obtained with the Monte Carlo Glauber, and Glauber-Gribov models for each centrality interval. The shape of $dN_{\text{ch}}/d\eta$ distribution changes with centrality. In the most peripheral collisions this shape is approximately symmetric but with growing centrality of collisions it becomes increasingly asymmetric. On the other hand the

ratio of $dN_{\text{ch}}/d\eta$ divided by $dN_{\text{ch}}/d\eta$ in the most peripheral collisions (60-90%) is approximately linear in η . The slope of this ratio strongly depends on centrality. Charged particle density is sensitive to the modelling of the initial-state, especially in the most central collisions.

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REFERENCES

- [1] L. Evans, P. Bryant (Eds.), LHC Machine, JINST 3 (2008) S08001.
- [2] ATLAS Collaboration, JINST 3 (2008) S08003.
- [3] W.Busza and R.Ledoux, Ann. Rev. Nucl. Part. Sci. 38 (1988) 119-159.
- [4] J.Elis, W.Busza, C.Halliwell, D.Luckey, P.Swartz, et al., Phys. Rev. D 22(1980) 13.
- [5] Bari-Cracow-Liverpool-Munich-Nijmegen Collaboration, C.De Marzo et al., Phys.Rev.D 26 (1982) 1019.
- [6] PHOBOS Collaboration, Phys. Rev. Lett. 93 (2004) 082301.
- [7] ALICE Collaboration, Phys. Rev.Lett. 110 (2013) 082302.
- [8] ATLAS Collaboration, Phys.Lett. B710 (2012) 363.
- [9] L.P.Cserani, J.Kapusta and L.D.McLerran, Phys. Rev.Lett.97 (2006) 152303.
- [10] ATLAS Collaboration, New J.Phys. 13 (2011) 053033.
- [11] ATLAS Collaboration, ATLAS-CONF-2013-096.
<http://cds.cern.ch/record/1599773>
- [12] ATLAS Collaboration, Phys. Lett. B710 (2012) 363-382.
- [13] PHENIX Collaboration, Phys.Rev.Lett. 86 (2015) 3500-3505.
- [14] PHOBOS Collaboration, Phys. Rev. C83 (2011) 024913.
- [15] X.-N. Wang and M. Gyulassy, Phys. Rev. D44 (1991) 35013516.
- [16] ATLAS Collaboration, Phys. Lett. B688 (2010) 21-42.
- [17] M.L.Miller, K. Reygers, S.J.Sanders and P.Steinberg, Ann. Rev. Nucl. Part. Sci. 57 (2007) 205-243.
- [18] V.Guzeya and M. Strikman, Phys. Lett. B633 (2006) 245-252.
- [19] M.Avioli and M. Strikman, Phys. Lett. B722 (2013) 347-354.