# Elastic Scattering, Total Cross-Section and Luminosity Measurements at ATLAS

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**Abstract**
The ATLAS strategy to monitor and measure the absolute value of the LHC luminosity at the ATLAS Interaction Point is reviewed. The absolute luminosity will be extracted from the measurement of the $t$-distribution of the elastic $pp$-scattering in the Coulomb–Nuclear interference region, as performed during dedicated low luminosity runs using specific beam optics. A luminosity monitor, LUCID, to be precisely calibrated during the elastic scattering parametrization, will also be working in standard physics conditions to provide luminosity values both for bunch by bunch beam monitoring and data analysis. The design, installation plans and expected performances of luminosity–dedicated detectors are presented as well.

## 1 Introduction

A precise determination of the luminosity $L$ will be a crucial experimental issue at the LHC, as it is necessary to relate the cross section of any physical process to its event rate. Previous experiences at hadron colliders suggest that a 5–10% precision on $L$ may be reached from the measurement of the machine parameters:

$$L = \frac{f \sum_{i=1}^{k_b} N_{1i} N_{2i}}{4\pi \sigma_x^* \sigma_y^*} \tag{1}$$

where $f$ is the revolution frequency, $k_b$ is the number of bunches, $N_{ji}$ is the number of protons in bunch $i$ of beam $j$ and $\sigma_x^*$ and $\sigma_y^*$ are the transverse beam dimentions at the Interaction Point (IP). However, at the LHC such a precision would already dominate the systematic error on the determination of fundamental quantities, like the Higgs-boson coupling and the $\tan\beta$ parameter of the MSSM [1].

Besides the machine parameters, the luminosity can also be obtained by measuring the rate of a clean and well–known process. In case of non–negligible background contamination, the background cross–section must be known as well. Both QED and QCD processes will be available at LHC for this task, namely $pp \to pp\mu^+\mu^-$ and $W^\pm \to \ell^\pm\nu$, $Z \to \ell^+\ell^-$. The former will be limited in recorded statistics, whereas the latter requires a good control of the proton PDF, which makes it unclear if the achievable precision on $L$ through this event counting will exceed the level of 5% [2].

Elastic $pp$-scattering at very small angles together with the total $pp$ cross–section provide a further handle on the determination of the luminosity. In fact, by measuring the total interaction rate

($R_{tot}$) and the elastic rate in the forward direction ($dR_{el}/dt|_{t=0}$) both the luminosity and the total cross section ($\sigma_{tot}$) can be determined [3]:

$$L = \frac{1}{16\pi}\frac{R^2_{tot}(1+\rho^2)}{dR_{el}/dt|_{t=0}} \quad (2)$$

$$\sigma_{tot} = \frac{16\pi}{(1+\rho^2)}\frac{dR_{el}/dt|_{t=0}}{R^2_{tot}} \quad (3)$$

where $\rho$ represents the real–to–imaginary part ratio of the elastic amplitude in the forward direction. In order to keep extrapolation errors small, this method requires the measurement of very small proton scattering angles (down to about $10\mu$rad at LHC) or, equivalently, very small momentum trasfer $|t| \simeq (p\theta)^2$, where $p$ represents the proton momentum and $\theta$ its scattering angle ($t_{min} \simeq 10^{-3}$ GeV$^2$ at LHC). Dedicated detectors close to the beam–line and specific beam optics are therefore needed for this measurement togheter with a precise determination of the inelastic rate, in turn requiring a good coverage in pseudorapidity. The ATLAS coverage in $\eta$ is somewhat limited in this context.

A further approach is to measure the elastic $pp$ scattering down to even smaller angles so as to reach the Coulomb region where the interference between the nuclear ($f_N$) and the Coulomb ($f_C$) scattering amplitudes is maximum. In particular, both the luminosity and the total cross section can be extracted from the elastic rate dependence on the momentum transfer $t$ in the Coulomb–Nuclear Interference (CNI) region without the need of any inelastic detector [3]. In addition, fundamental soft physics parameters like the nuclear slope and $\rho$ can be measured. This technique was used in the past by the UA4 experiment at the CERN SPS [4], although with a somewhat simplified theoretical description of the elastic cross section. In any case, to implement it at the LHC, proton scattering angles of few $\mu$rad ($t_{min} \simeq 6.5 \times 10^{-4}$ GeV$^2$) need to be detected. As a comparison, the instrinsic LHC beam divergence in high–luminosity runs will be larger than $30\mu$rad, which makes this measurement impossible during standard physics running.

## 2 ATLAS strategy

The strategy chosen by ATLAS will fulfil two complementary goals: to measure the absolute value of $L$ at the ATLAS IP with $2-3\%$ precision on the one hand, and to monitor the istantaneous luminosity bunch by bunch in physics running conditions on the other hand, so as to provide online–luminosity information useful for fast control and efficient use of the beams as well as data analysis.

The program will be accomplished in various steps: the first estimate of the absolute luminosity will certainly come from the machine parameters, although with limited accuracy, and will be used to first–calibrate the ATLAS dedicated luminosity monitor, the LUCID Cherenkov counter, that will also be operational from the first beams. Then, on a longer time scale, we aim at extracting the absolute luminosity from the $t$-distribution of the elastic $pp$–scattering in the CNI region. This will be measured by another dedicated detector, the ALFA scintillating–fiber tracker, housed in Roman Pots [5] at 240 m on both sides of the ATLAS IP. Dedicated runs with specific beam optics will be needed to perform this measurement. Should not the CNI region be reached, the measurement of the forward elastic rate will still provide a measurement of the absolute Luminosity with twice the precision on the measurement of $\sigma_{tot}$, once complemented with the total cross section as measured by the TOTEM experiment [6]. In addition, the rate of events from well known processes will be measured and used to cross–check the calibration of the luminosity monitor. In any case, the best available estimate of the absolute luminosity will be used for the calibration of LUCID, which was designed to be operational over a wide dynamic range and in different beam optics conditions.

### 2.1 Experimetal aspects of absolute $L$ measurement

In order to measure the $t$ distribution of the elastic *pp*–scattering in the CNI region various ingredients are needed:

- *Large $\beta^*$ optics*: a beam with an intrinsic divergence at the ATLAS IP smaller than the minimum scattering angle to be measured is mandatory. This traslates into a large $\beta^*$ optics, in turn implying large transverse dimensions of the beams at the ATLAS IP, and thus low luminosity. A solution has been found ($\beta^* = 2625$ m, $L \simeq 10^{27}$ cm$^{-2}$s$^{-1}$) that is compatible with the one prepared by the TOTEM collaboration for the measurement of the total cross section [6], so as to allow TOTEM and ATLAS to run high–$\beta$ optics at the same time.
- *Parallel–to–point focusing*: due to the non–negligible beam size implied by the aforementioned large $\beta^*$ optics ($\sigma^* \simeq 600\mu$m) the measurement of the momentum transfer $|t|$ needs to be independent of the actual vertex position. This is realized by a $90^o$ betatron phase advance in the vertical plane between the IP and the detector, which makes the detector–level vertical displacement of the scattered proton to depend only on its scattering angle.
- *Edgeless detector in Roman Pots*: the ALFA tracking detector (scintillating–fiber based) will approach the circulating beams at $10 - 15\sigma$ (i.e. 1–2 mm) inside Roman Pots placed at 240 m on both sides of the IP. This will allow to measure $t$ with the needed acceptance and precision. The goal spatial resolution is $30\mu$m. Two test beam campagnes have shown that both the detector concept and the readout electronics design are valid. A further test beam is scheduled in October 2007 to test the full system, including Roman Pots. Then, eight vertical Roman Pots housed in four stations will be installed and instrumented during the 2008-2009 shutdown and become fully operational. Meanwhile, based on previous test beam results, the performance of the system has been estimated [7] by reconstructing and analysing 10M of simulated data corresponding to about one week of running at $L \simeq 10^{27}$ cm$^{-2}$s$^{-1}$. The measured $t$ distribution has been used to extract both $L$ and $\sigma_{tot}$, as well as $\rho$ and the nuclear slope parameter $B$. Although the standard West–Yennie $pp$ elastic cross–section formula was used (where $\rho$ is independent of $t$), this study indicates that a measurement of $L$ with about $3\%$ precision is reachable, including systematics from both the beams and the background, as well as the detector acceptance, resolution and alignment. The statistical precision on $\sigma_{tot}$ is expected to be better than $1\%$. Further details on the detectors and their associated electronics can be found in [3], and results of prototype–detectors can be consulted in [8].

### 2.2 Experimetal aspects of relative $L$ measurement

Any detector able to count the number $\mu$ of interactions occurring in a bunch crossing (BX) can be used as a luminosity monitor, since $\mu = \sigma \cdot L$ by definition. The LUCID Cherenkov counter will monitor $\mu$ by counting the mean number of charged particles produced in each BX within its acceptance. In order to estimate the absolute value of $\mu$, and thus the luminosity, a proper calibration is needed. The idea is to perform it while measuring the absolute luminosity $L$ in large $\beta^*$ runs, when the probability to have more than one interaction per BX is negligible and a number $\langle N \rangle$ of charged particles is counted per interaction. Then, if $\epsilon$ is the efficiency to detect one interaction and $\langle M \rangle$ is the average number of particles counted by the LUCID at any time:

$$\mu = \frac{\langle M \rangle}{\langle N \rangle \cdot \epsilon} = L \cdot \sigma \tag{4}$$

from which

$$L = \frac{\langle M \rangle}{\langle N \rangle \cdot \sigma \cdot \epsilon} \tag{5}$$

where the product $\sigma \cdot \epsilon$ is a "luminosity independent" calibration constant obtained by comparison to the measured value of $L$ and known with the same precision as $L$ [9].

The LUCID detector consists of two arrays of aluminum tubes filled with C4F10 Cherenkov radiator at about 1.2 bar pressure. The arrays will be placed around the beam pipe at 17 m of the ATLAS IP, on both sides. The Cherenkov light is emitted at about $3^o$ with respect to the impinging charged track direction and is collected at each tube end by either a PMT or an optical fiber–bundle leading to a PMT, after few reflections on the tube internal surface. The key characteristics of the detector are:

- *the Cherenkov threshold*, amounting to 10 MeV for electrons and 2.8 GeV for pions, to limit the background;
- *the pointing geometry* allowing particles coming from the IP to produce more light than background particles coming from the LUCID sides;
- *the aluminum reflectivity*, at the level of 80 to 95% in the 320–700 nm wavelength range after mechanical polishing, as measured in dedicated bench tests;
- *the radiation hardness* needed to survive in a high radiation environment.

In addition, the lack of Landau fluctuations in the number of Cherenkov photons makes the particle counting robust, while a good time resolution (2–3 ns) allows bunch by bunch measurements. Two test beam campagnes in 2006 showed that 80 p.e. are produced on average per aluminum tube traversed by a high momentum collinear track, out of wich 60 are produced in the gas and 20 in the PMT quartz window. Subsequent simulation studies including the background expected in the LUCID area in physics run conditions showed that the single PMT signal can be safely separated from the background by requiring a threshold of 50 p.e. at both low and medium luminosity ($L \leq 10^{33}$ cm$^{-2}$s$^{-1}$). Furthermore, radiation hardness tests for the PMTs with both gammas and neutrons proved that these devices are suitable for the first years of LHC running.

The LUCID implementation will therefore be performed in two phases: at low–to–medium luminosity, e.g. up to $L \simeq 10^{33}$ cm$^{-2}$s$^{-1}$, 16 tubes with direct PMT readout plus 4 tubes with optical fibers will be installed on each side, corresponding to a pseudorapidity coverage $5.6 \leq |\eta| \leq 6.0$. At higher luminosity, when the PMTs might not survive the intense radiation, 168 tubes coupled to far–away PMTs by optical fibers should replace the previous 20 on each side, covering the pseudorapidity range $5.4 \leq |\eta| \leq 6.1$.

Various methods for particle counting exist, each having both *pro* and *cons*. They range from

the counting of BX with no interactions (*zero counting*), statistically unfit at high luminosity, to *hit–counting*, subject to saturation at high luminosity when more than one charged particle is likely to hit the same tube, and *particle counting*, which is an intrinsically linear method but is sensitive to PMT gain fluctuations. Monte Carlo studies have shown that *hit–counting* is a good option for LUCID phase I, although all methods will be investigated. In particular, no saturation effects and subsequent loss of linearity are expected when the number of interactions per BX is up to 7. Should the background level be substantially worse than expected, side coincidence will be required.
A detailed study of the systematics is currently under study. The one due to differences in optics conditions between calibration and physics has been estimated to be below 1%. Based on the experience of the CDF collaboration with the CLC luminometer [10], conceptually very similar to the LUCID, we hope to keep the systematics at the level of 2%, the ones related to uncertainties in acceptance and inelastic cross–section being included in the error on the calibration constant.

## 3 The Zero Degree Calorimeters

A letter of Intent [11] has been presented last January to complement the ATLAS detector with Zero Degree Calorimeters (ZDC) to be inserted in the transverse aperture of the ATLAS neutral particle absorbers, at about 140 m from the IP on each side. They consists of Tungsten-quartz fiber calorimeters suited to study both heavy ions and $pp$ physics. In particular, ZDC have shown to be very effective devices for $pp$ beam tuning, and therefore for luminosity monitoring: at RHIC the ZDC coincidence rate versus the relative beam position has been used during Van der Meer scans to measure both the beam crossing angle and the longitudinal position of the IP. ZDC are thus expected to be useful tools to tune the accelerator parameters in the early LHC days. The installation of the hadronic module of the ATLAS ZDC is scheduled for the fall of 2007. Due to the high radiation environment, the devices are expected to survive at most three years in $pp$ collisions at $L \simeq 10^{33}$ cm$^{-2}$s$^{-1}$.

## 4 Conclusions

In the last years new ideas and concerns on the matter of luminosity measurements at the LHC have led to proposals to complement the ATLAS detector with new devices in the forward region. In particular, a luminosity monitor (LUCID) will be installed around the beam pipe at about 17 m from the IP in the 2007–2008 winter, together with a pair of Zero Degree Calorimeters at about 140 m from the IP. Then, in the 2008–2009 shutdown, Roman Pot stations equipped with scintillating fiber trackers (ALFA) will be installed at 240 m from the ATLAS IP to provide elastic scattering and absolute luminosity measurements, the latter with a precision of 2–3%. The luminosity monitor will be calibrated with 5–10% accuracy at the LHC startup based on information from the accelerator. Then, a 5% accuracy on the LUCID calibration is expected at mid–term based on the rate of QED and QCD processes, to reach the goal accuracy of few percent after 2009.

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