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Luminosity determination for the measurement of the total proton-proton cross section and the ρ-parameter at 13 TeV with the ATLAS experiment at the LHC

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The ATLAS experiment has measured the total proton-proton cross section during the LHC Run-1 at $\sqrt{s}$ = 7 and 8 TeV and in Run-2 at $\sqrt{s}$ = 13 TeV using a luminosity dependent approach. This measurement requires special data-taking conditions with high-β^* which represent a challenge for the luminosity determination. The systematic uncertainty associated to the luminosity value represents one of the dominant components of the overall uncertainty on σ_{pp}^{tot} and the ρ-parameter. Thanks to the excellent performance and sensitivity of the main ATLAS luminometer, LUCID-2, and of the ancillary measurement based on track-counting algorithms used to estimate the systematic uncertainty, a precision on the luminosity determination of 1.0% (2.15%) was obtained in 2018 (2016) data taking at β^* = 90 m (2.5 km).

In this work, a description of the luminosity measurement in the Run-2 data taking at $\sqrt{s}$ = 13 TeV aimed to measure σ_{pp}^{tot} and ρ is given, with emphasis on the ATLAS approach, based on the redundancy of the luminosity information provided by different detectors and methods with different sensitivity to the LHC optic conditions, backgrounds and systematic effects.

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1. Luminosity for σ_{pp}^{tot} and ρ parameter measurements with the ATLAS detector

The total hadronic cross section (σ_{pp}^{tot}) is a fundamental parameter of strong interactions. Perturbation theory is not applicable in its calculation and the experimental approach is the only handle to precisely determine it. The Optical Theorem connects the hadronic component of the total cross-section to the imaginary part of the scattering amplitude in the forward direction ($f_{\mathrm{el}}(t \to 0)$): $\sigma_{pp}^{tot} = 4\pi \mathrm{Im}[f_{\mathrm{el}}(t \to 0)]$, where t is the four-momentum transfer. ATLAS [1] uses the luminosity-dependent method which requires a high-precision measurement of the luminosity, needed to normalise the elastic cross section. An important quantity is also the ρ-parameter, defined as the ratio of the real to the imaginary part of f_{el}, in the limit $t \to 0$. This parameter is sensitive not only to the high-energy evolution of the total hadronic cross section, but also to the fundamental structure of the elastic-scattering amplitude. ATLAS has measured elastic scattering in dedicated low-luminosity, high-β^* data-taking sessions, the so-called *ALFA runs*, performed at 7 [2] and 8 TeV [3] using the ALFA detector, which is situated in Roman Pot cavities [2]. The measurement of the ρ-parameter was performed with data from 13 TeV ALFA runs with $\beta^* = 2.5$ km [4], during which very small $|t|$-values could be reached. A β^* value of 90 m was chosen for another set of 13 TeV runs. This allows to access a region in the t-spectrum where the interference of diffractive amplitudes generates a local minimum, called the *dip*. The following study discusses the luminosity determination that feeds into the mentioned measurements based on the 13 TeV ALFA datasets.

2. The LUCID-2 detector

LUCID-2 (LUminosity Cerenkov Integrating Detector), shown in Figure 1 (Left), is the main ATLAS luminosity monitor. It can provide bunch-by-bunch luminosity information, both online and offline, for any beam condition and luminosity range. Over the years it has undergone several upgrades [1, 5], but its detection principle has generally remained unchanged. LUCID-2 [5] is made of two identical modules placed at a distance of 17 m from the interaction point, each one composed of a ring of 16 PMTs around the beam pipe. The Cherenkov light produced by charged particles in the PMT quartz window is detected and used to evaluate the average number of interactions per bunch crossing, μ, and consequently the luminosity. Single PMTs can act as independent detectors or can be combined in global algorithms, like Bi2EventOR A, which consists in a logic OR among the PMTs placed on the Side-A[1] and belonging to the PMT subgroup called Bi2. For a further description of LUCID algorithms see Ref. [6]. On the PMTs windows a ^{207}Bi source is deposited. Its decays emit $\sim$ 1 MeV electrons and it can so be used as gain monitoring system. ^{207}Bi and the background from nuclear de-excitation after collisions, so-called *afterglow*, constitute the main sources of background for LUCID-2.

3. Luminosity measurement for high-β^* LHC runs

The analysis technique employed for low-luminosity runs resembles the one used for physics data-taking [6]. Various independent LUCID algorithms are calibrated employing the so-called van der Meer (vdM) method [6, 8]. The total collected luminosity of the high-β^* LHC runs is then obtained using one LUCID algorithm as reference, chosen based on its performance over all considered runs. The run conditions, listed in Table 1, require a specific approach for some aspects of the analysis, especially for background evaluation (bismuth activity and afterglow).

[1] ATLAS labels the two sides with respect to the Interaction Point as "A" and "C".

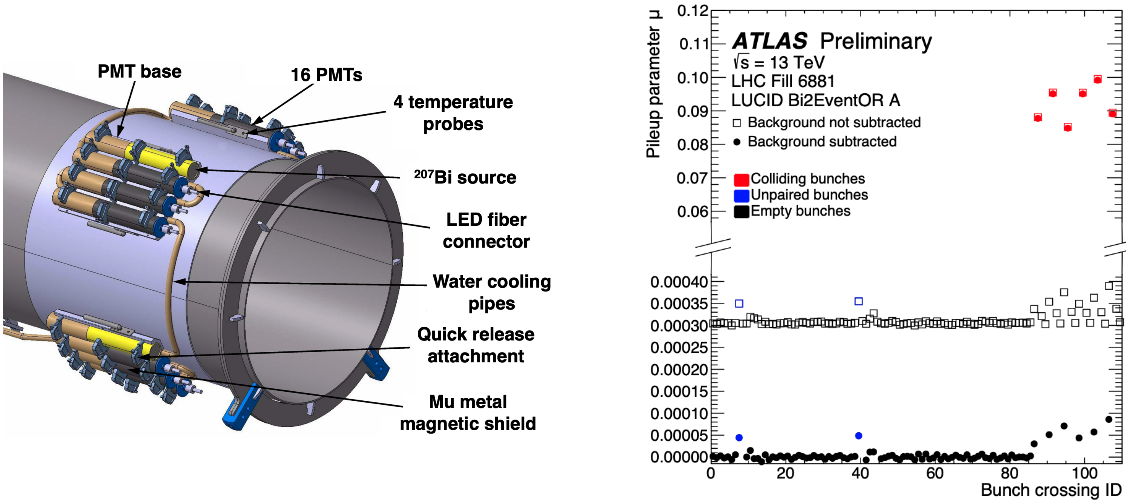

Figure 1: *Left*: Drawing of the LUCID-2 detector [5]. *Right*: Run averaged pileup parameter μ as a function of the bunch-crossing identifier (BCID) as measured by the LUCID Bi2EventOR A algorithm. The empty squares (full circles) refer to the data before (after) ^{207}Bi background subtraction. The red markers refer to the colliding bunch slots, the blue ones to unpaired-bunch slots, and the black ones to nominally empty slots [7].

Background subtraction is done by subtracting from the μ value measured in each bunch slot, the μ value registered in the preceding bunch, as shown in Figure 1 (Right). Different background-subtracted calibrated LUCID algorithms are then compared to independent luminometers, like Track Counting from the Inner Detector or Beam Condition Monitor (BCM). Consistency over the larger data-taking period is determined by evaluating the percentage difference in run-integrated luminosity between the aforementioned systems and the chosen reference algorithm, as shown in Figure 2. The main source of systematic uncertainty often arises from the vdM-based absolute calibration.

Further systematics account for the compatibility among the detectors and the different algorithms, as described above. This allows to consider the long-term stability, any background subtraction uncertainty and the effects introduced by the luminosity scale difference between the vdM run and the complete dataset.

Parameters	2018 high-β* runs	2018 vdM scan	2016 high-β* runs	2016 vdM scan	High-lumi runs
Number of colliding bunches	~ 80 – 700	124	4 – 5	32	2544
Average pile-up parameter μ	0.1 – 0.2	0.35	0.002 – 0.006	0.5	~ 55
Instantaneous lumi (10^{30} cm^{-2}s^{-1})	~ 2.4 – 10	~ 6	~ $(1.4 - 4) \cdot 10^{-3}$	2.6	$19 \cdot 10^{3}$
β* (m)	90	19	2500	19	0.3 – 0.25

Table 1: Main parameters for high β^* and van der Meer runs in 2018 and 2016. The high-luminosity parameters refer to 2018 runs [6].

4. Results

The luminosity results for the ALFA runs in both LHC Run-1 and Run-2 are summarised in Table 2. For 2016 data (β^* = 2.5 km), the selected reference algorithm was LUCID BiEventOR C due to its stability over time and low sensitivity to background. The systematic uncertainty was

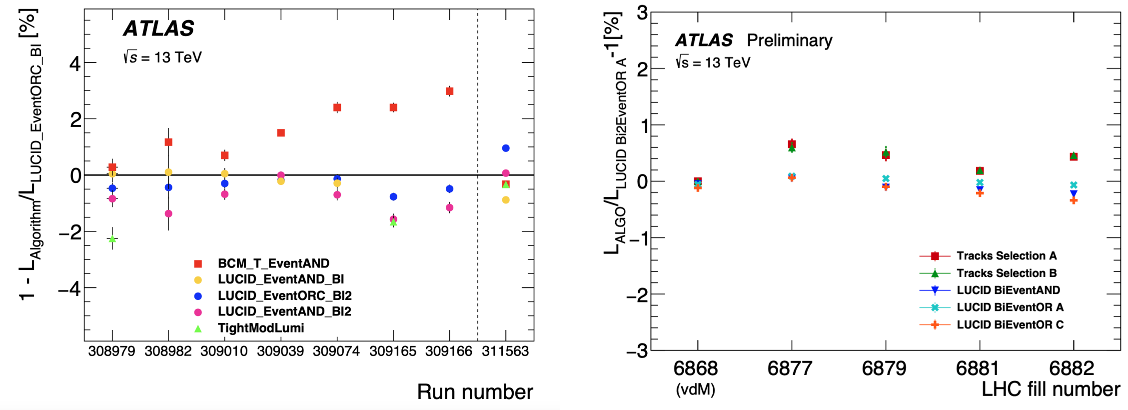

Figure 2: *Left*: percentage difference in run-integrated luminosity among different LUCID and track-counting algorithms for 2016 data with $\beta^* = 2.5$ km [4]. *Right*: same quantity for 2018 data with $\beta^* = 90$ m [7]. The track selections considered are defined in Ref. [6].

evaluated as the quadratic sum of the contributions from the vdM calibration uncertainty (1.1%) and the consistency of the available independent luminosity measurements [4]. The highest discrepancy for the total integrated luminosity value was used as upper limit for the latter uncertainty, which in 2016 was 1.85%, from the comparison to Track Counting. The total precision on the integrated luminosity measurement for the 2016 ALFA dataset was therefore 2.15%. For 2018 data, the reference algorithm was LUCID Bi2EventOR A, chosen mainly to exclude bad-behaving Side-C PMTs. Background from single-beam interactions with residual gas in the beam pipes was evaluated looking at the discrepancy with respect to LUCID BiEventAND data, insensitive to it. Thanks also to the small uncertainty on the vdM calibration (< 1%), the preliminary value of the total systematic uncertainty on the integrated luminosity is determined to be 1%.

Energy [TeV]	Data-taking period	β^* [m]	L_{tot} $[\mu b^{-1}]$	Precision on L_{tot}	Status
7	2011 (LHC Run-1)	90	$78.7 \pm 0.1_{stat.} \pm 1.9_{syst.}$	2.3%	Published [2]
8	2012 (LHC Run-1)	90	$496.3 \pm 0.3_{stat.} \pm 7.3_{syst.}$	1.5%	Published [3]
13	2016 (LHC Run-2)	2500	$339.9 \pm 0.1_{stat.} \pm 7.3_{syst.}$	2.15%	Published [4]
13	2018 (LHC Run-2)	90	$(664 \pm 7_{stat.+syst.}) \times 10^3$	1.0%	Preliminary

Table 2: Summary of the luminosity results for the ATLAS *ALFA run* campaigns for LHC Run-1 and Run-2. The result in the last row is first presented in this work.

5. Conclusions

The precise evaluation of the total hadronic cross section in proton-proton interactions (σ_{pp}^{tot}) and the ρ-parameter require a dedicated dataset, the so-called *ALFA runs*, as well as an associated precise luminosity measurement. The LUCID detector has proven its ability to achieve excellent precision in the extremely challenging data-taking conditions offered by these runs, given their low μ. This allowed the most precise measurement of σ_{pp}^{tot} and ρ released so far by the ATLAS Collaboration using the 13 TeV runs with $\beta^* = 2.5$ km [4], with a total luminosity uncertainty of 2.5%. The latest luminosity measurement for 13 TeV runs with $\beta^* = 90$ m has been obtained with a preliminary 1% total uncertainty, here presented for the first time.

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