PROCEEDINGS OF SCIENCE

Luminosity determination in proton-proton collisions at $\sqrt{s}$ = 13.6 TeV with the ATLAS detector

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A precise measurement of the luminosity is a crucial input for many ATLAS physics analyses, and represents the leading uncertainty for W, Z and top cross-section measurements. The first ATLAS luminosity determination in Run-3 of the LHC, for the dataset recorded in 2022, at a center-of-mass energy of 13.6 TeV follows the procedure developed in Run-2 of the LHC. It is based on van der Meer scans during dedicated running periods each year to set the absolute scale, and an extrapolation to physics running conditions using complementary measurements from the ATLAS tracker and calorimeter subsystems. The presentation discusses the procedure of the ATLAS luminosity measurement, as well as the results obtained for the 2022 proton-proton dataset.

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[*] Speaker

1. Introduction

In physics analyses at the LHC, physicists are interested to know how often processes happen in order to measure their cross-sections. A cross-section (σ) of a process can be expressed as

$$\sigma = \frac{N}{L} \tag{1}$$

where L is the integrated luminosity and N is the number of events in the corresponding process. Any uncertainty on the luminosity is directly translated into an uncertainty on the cross-section, as can be seen in Equation 1. Thus, to measure physics processes more precisely and potentially find physics beyond the Standard Model, the luminosity needs to be determined as accurately as possible.

In ATLAS, luminosity is measured by three main methods: LUCID, track-counting and calorimeter luminosity measurements.

The luminosity determination can be divided into three major steps:

1. **Absolute luminosity calibration**: van der Meer (vdM) scans analysis in special beam conditions
2. **Calibration transfer**: calibration transfer from vdM beam conditions to physics beam conditions
3. **Long term stability**: stability of the luminosity determination over time

In Run 3 the same methodology as in Run 2 is applied for the luminosity determination. A detailed description can be found in Reference [1].

1.1 Luminometers in ATLAS

LUCID The **LU**minosity **C**herenkov **I**ntegrating **D**etector (LUCID) [2], is situated in the forward region of the ATLAS detector, around 17 m away from the IP. Very close to the beam pipe, 16 photomultipliers (PMTs) are situated on each side. The PMTs have a quartz window that generates Cherenkov radiation by passing charged particles. LUCID can deliver a measurement at every bunch-crossing.

Track-counting Track-counting is based on silicon trackers, the semiconductor tracker (SCT) and pixel detectors including the insertable B-Layer (IBL) [3, 4]. It measures the average number of tracks per bunch-crossing, averaged over a discrete time interval usually close to 60 seconds, called luminosity block (LB). The per bunch resolution of track-counting is statistically limited in the low-μ region, meaning that track-counting has measurements only for some of the nominally filled bunch slots but not for all of them.

Calorimeter The calorimeter measurement is obtained from the endcap electromagnetic calorimeter, forward calorimeters and the scintillating-tile hadronic calorimeter [3]. The endcap and forward calorimeters measure luminosity through the gap currents in the liquid argon, while the scintillating-tile hadronic calorimeter uses the signal produced by the plastic scintillator. The measured currents are proportional to the number of particles traversing the corresponding calorimeter and thus to the luminosity. Unfortunately, calorimeters can only provide bunch-integrated luminosity measurements, i.e. the sum over all the bunch slots.

2. Absolute luminosity calibration

The per bunch luminosity can be expressed as

$$L = \frac{\mu f_r}{\sigma} \tag{2}$$

where L is the instantaneous luminosity, f_r is the LHC revolution frequency, μ is the average multiplicity of a process and σ the corresponding cross-section [1].

In the case of the LHC, protons are being collided, and the process considered is the inelastic proton-proton scattering. The luminosity detectors see a part of the inelastic cross-section called the visible cross-section (σ_{vis}). The luminosity for a detector can be written as

$$L = \frac{\mu_{vis} f_r}{\sigma_{vis}} \tag{3}$$

where μ_{vis} can be measured with LUCID, f_r is well known, the only quantity that is unknown is σ_{vis}: this is the absolute calibration constant. Once it is found, the luminosity at any point in time can be obtained by simply measuring μ_{vis}.

The absolute calibration constant can be measured from van der Meer scans as

$$L = \frac{n_1 n_2 f_r}{2\pi \Sigma_x \Sigma_y} \tag{4}$$

where n_1 and n_2 are the bunch populations of the colliding bunches of respectively beam 1 and beam 2. These bunch populations are measured with LHC instrumentation. Σ_x and Σ_y are the convolved beam widths. When doing a beam-beam separation scan in k plane, the width of the resulting luminosity distribution profile is Σ_k, with $k = x, y$. It is important to remark at this stage that Equation 4 is obtained by assuming that the beams have factorisable beam profiles in x and y planes by assuming in the derivation that the densities of the beams are factorisable as $\rho(x, y) = \rho_x(x)\rho_y(y)$. By combining Equations 3 and 4, the calibration constant can be found as

$$\sigma_{vis} = \frac{2\pi \Sigma_x \Sigma_y \mu_{vis}}{n_1 n_2 f_r} \tag{5}$$

A van der Meer scan pair, is a transverse scan of the beams through each other, first in one plane and then in the other plane during a special fill. The rate measured by LUCID versus the beam-beam separation results in Gaussian like scan curves.Through a fit to these two scan curves, the convolved beam widths (Σ_x, Σ_y) and the rate at the peak (μ_{vis}) can be extracted. Consequently, by using Equation 5, the visible cross-section (σ_{vis}) can be obtained.

In practice, it is more complicated since several effects that impact this calibration need to be taken into account and corrected for. A list of the corrections ordered from the largest to the smallest in size in 2022 is given here:

- Non-factorisation correction
- Length scale calibration correction
- Beam-beam corrections
- Ghost and satellite charge corrections

- Background subtraction
- Orbit drift correction
- Emittance change correction
- Bunch current offset

The non-factorisation correction corrects for any bias in the calibration due to the factorisation assumption used. The length scale calibration correction, corrects the beam-beam separation scale set to the real separation the beams have. The beam-beam effects originate from the beams interacting electromagnetically with each other and changing their separation and size, the beam-beam corrections correct for this effect. Ghost and satellite charges are charges in a bucket outside the filled slot or outside the filled bucket in the same slot. They need to be subtracted from the total beam currents to get the exact bunch populations n_1 and n_2. Backgrounds including for example instrumental noise and beam gas interactions are subtracted from the signal at each data point before fitting the scan curves. The orbit drift correction corrects for any drift in the beams when they should be still. This has multiple origins, including the Earth's tides and quadrupole movements due to temperature variations. The beams' emittance varies over time, leading to a bias in the calibration due to the x and y scan being taken at different points in time. The bunch current offset correction corrects for any residual dependency of the calibration constant on the bunch currents.
In 2022, the non-factorisation correction has the largest size. A first hint of the bias in the calibration due to the factorisable assumption can be obtained by comparing the off-axis convolved beam widths with the on-axis ones. An off-axis scan has a non-zero beam-beam separation in the non-scanning plane, compared to a zero beam-beam separation in the case of an on-axis scan. If the beams are factorisable the convolved beam widths do not depend on the separation in the non-scanning plane. A strong proof of non-factorisation effects in 2022 can be seen in Figure 1. In comparison, in 2018 these effects were negligible.

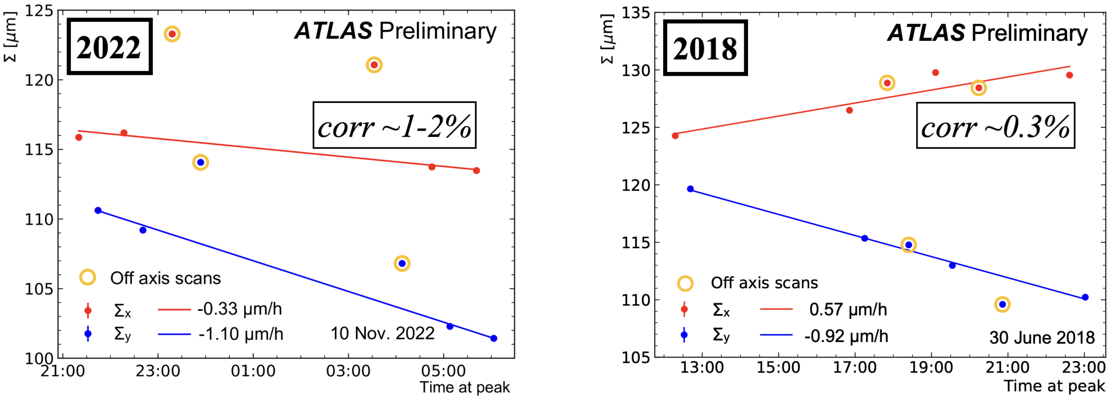

Figure 1: Time evolution of convolved beam widths for all scans: left in 2022, right in 2018. The yellow circled points are the off-axis scans while the non-cricled points are the on-axis scans [5].

The systematic uncertainties for the absolute luminosity calibration part are summarized in table 1. These include the comparison to alternative technologies, algorithms and methods in the correction estimation. It can be seen that the non-factorisation effect is also the dominant systematic uncertainty in this calibration.

Non-factorisation effect	1.1%
Bunch-by-bunch consistency	0.5%
Differences between algorithms	0.4%
Other contributions <0.4%	0.7%
Subtotal vdM calibration	1.5%

Table 1: Summary of systematic uncertainties for the vdM calibration part [5].

3. Calibration transfer

As briefly mentioned, the vdM scans are taken in a special fill, that means special beam conditions. These vdM scan conditions have isolated low intensity bunches (low pileup and low number of bunches) and no crossing angle between beams. However, data are taken in physics conditions, which have trains of high intensity bunches (high pileup and high number of bunches) and with the usual crossing angle between beams. To use the absolute luminosity calibration done in special conditions in the data taking conditions, a calibration transfer needs to be performed. This is done by using track-counting luminosity, which is normalised to LUCID luminosity in the quiet vdM periods. It is assumed that track-counting behaves linearly as a function of pileup. A long physics run with luminosity decay is used to get access to a large variety of pileup conditions. These data are used to measure the ratio of track-counting to LUCID luminosity as a function of pileup. A linear dependence is fit to this distribution to extract a correction to the LUCID measurement for higher pileup conditions.

The uncertainty on the calibration transfer is estimated by cross-checking the linearity assumption of track-counting as a function of pileup. For this, calorimeter luminosity is compared to track-counting for runs with different conditions (high pileup, low pileup). Calorimeter luminosity is well known to behave linearly with pileup. After normalising it to track-counting, the biggest difference between the various runs is taken as the uncertainty on calibration transfer. This amounts to 1.5% in the preliminary luminosity calibration for 2022. This uncertainty is considered very conservative and should reduce in future.

4. Long term stability

The last part in the luminosity determination consists in evaluating the stability of the luminosity determination over the different runs in the year. To evaluate this, the different luminosity measurements are compared to the preferred LUCID algorithm. The largest mean deviation over all independent luminometers gives the long term stability uncertainty of the preliminary 2022 luminosity determination and amounts to 0.41%

5. Conclusion and outlook

For many physics analyses a precise luminosity determination is crucial, in particular for W, Z and top cross-section measurements where this uncertainty is the dominant one. Using 2022 data, the ATLAS collaboration has performed a preliminary luminosity determination using several luminometers. The preliminary total uncertainty on the luminosity determination can be added together and is found to be 2.2%, as shown in table 2.

Subtotal vdM calibration	1.5%
Calibration transfer	1.5%
Calibration anchoring	0.5%
Long term stability	0.4%
Total uncertainty	2.2%

Table 2: Summary of systematic uncertainties [5].

In 2022 the first 2D van der Meer scan in ATLAS, shown in Figure 2, was taken. It is hoped that this will help improve the non-factorisation correction and its uncertainty.

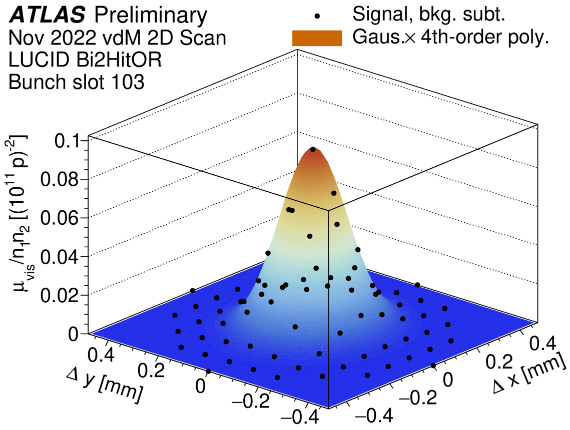

Figure 2: First 2D van der Meer scan in ATLAS. The visible cross-section rate μ_{vis} per bunch population $n_1 n_2$ is given as a function of beam-beam separation for BCID 103 and LUCID Bi2HitOR algorithm. The data are shown in black while the fitted function in colours [5].

References

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