

# Luminosity measurements and systematic uncertainties

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## Abstract

This talk will briefly outline the main methods to measure the luminosity and to calibrate the luminosity detectors in the LHC experiments. It will discuss the size of the systematic uncertainties on the measured luminosity at the online and offline level. In addition it will include a discussion on any possible imbalance between the luminosities delivered to ATLAS and CMS during the 2017 run.

## INTRODUCTION

Measuring the delivered and recorded luminosity is a critical aspect for the LHC experiments. The measurements are needed for physics measurements (for example measuring cross sections), where the precision of the luminosity measurement can be the leading uncertainty. In addition the measurements are needed for running the experiment, for example for trigger pre-scales, pileup corrections, optimizing the collisions, and for input for machine studies. The timescale and precision of the luminosity values is different for these cases, but it is vital that the luminosity is measured in real time, per bunch, and independently of the main DAQ of the experiments. Since ATLAS/CMS are (mostly) colliding head-on, the luminosity measurements for these experiments can be directly related to beam parameters, whereas for ALICE/LHCb which are levelled with beam separation this is not the case. For this reason the discussion below concentrates on ATLAS/CMS, although many aspects are also relevant for the other experiments.

## METHODOLOGY FOR LUMINOSITY MEASUREMENTS

The luminosity measurements during high luminosity running, are derived from the rate of events with certain characteristics observed in dedicated luminosity detectors. For example this can be the rate of events with a certain number of hits or an absence of hits in these detectors. The rate is calibrated to give a luminosity value in a dedicated van der Meer (vdM) scan, which allows the absolute luminosity to be calculated from the beam parameters. The calibration then needs to be transferred from the vdM scan to the high luminosity regime.

### Absolute calibration

The absolute calibration is done during the vdM scan, which is carried with a specialized machine setup, optimized to minimize the luminosity uncertainty. For these scans the  $\beta^*$  in IP1/5 is 19m which gives a large luminous region and low pileup ( $\mu \approx 0.5$ ). Usually there is one vdM

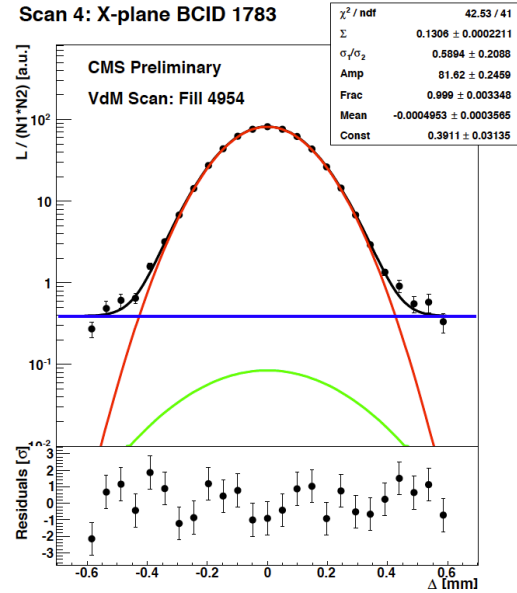


Figure 1: An example scan curve from the 2016 vdM scan in CMS. This figure is taken from [1].

scan scheduled per year, which along with commissioning, and validation takes about two days from the physics time. The basic idea is to scan the beams through each other to measure the size of the transverse overlap between the beams, which along with the bunch current normalization which is measured very precisely using LHC BI instruments, can give a precise measurement of the luminosity. An example scan curve, showing the luminosity algorithm rate, as a function of the beam separation for the 2016 vdM scan in CMS can be seen in Figure 1. A number of complications needs to be taken into account to give a precise calibration:

- Non-factorizable beams: the method assumes that the beam is factorizable in  $x/y$ , which may not be the case. This is studied by doing offset scans (for example, where the beam is scanned in  $x$ , while already displaced in  $y$ ) but this still leads to an uncertainty. The injected beam is attempted to be as factorizable as possible.
- Orbit-drifts: drifts in the orbit during the vdM scan effect the measured scan curve. This is monitored using the precise DOROS BPMs during the scans, and the orbit feedback is turned off during the scans.
- Beam-beam deflections and dynamic  $\beta^*$  effects: These are minimized by using filling schemes with

isolated bunches (no bunch trains), and by tuning the beam brightness, the effects and corrections are then be calculated.

- Ghost and satellite charge: This is measured precisely by LHCb using their SMOG beam-gas system.
- Length scale uncertainties: The beam deflection from the scan corrector magnets operating with a given current are calibrated in dedicated length-scale calibration scans. In these scans both beams are deflected and the position of the luminous region is precisely measured using the experiments tracking detectors. This allows the deflections used in the vdM scans to be accurately calibrated.

### Calibration transfer

The luminosity calibrations are derived in the vdM scan with a pileup of 0.5, and are then applied in physics fills with a pileup of up to 60 (in 2017 running), bunch trains, and which can take many months after the vdM scan. A number of effects can change the calibration between these regimes, and need to be corrected for when applying the calibrations. For example these can be related to pileup dependence (non-linearity) of the algorithm used, the effect of out-of-time pileup and activation (from bunch trains), detector ageing, and long term drifts in the calibration/efficiency of the detectors. These effects are carefully studied by comparing luminosity measurements taken using different detectors, which are effected differently from these effects. CMS also use emittance scans in order to control these effects, as discussed later. As an example, Figure 2 shows the ratio of luminosities between different algorithms with respect to a reference algorithm (based on track counting) as a function of time during the 2016 run, from ATLAS. This plot is after a number of corrections have been applied and shows that there are differences between the algorithms of up to 4% for the first few weeks of the run, but after this they agree within  $\approx 1\%$ .

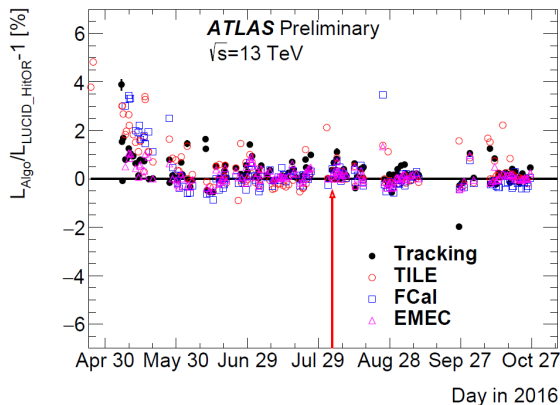


Figure 2: Long term stability of the ATLAS luminosity algorithm, across the 2016 data taking period. This figure is taken from [2].

## PRECISION AND TIMESCALE

Based on the experience of the last few years of LHC running, the final and most precise luminosity numbers for a year usually come out about one year after the data has been taken. This typically has an uncertainty of 2.5% for ATLAS/CMS. During the year the best estimate of the calibrations are used, and these usually have a precision of 5-10%, and the luminosity values shown on page-1 have this level of precision (on the absolute scale, relative changes should be more precise)<sup>1</sup>. Shortly after a fill the luminosity numbers are uploaded into Massi files, these usually have the same values as shown on page-1, but in some cases the values can be corrected before being published in the Massi files. The Massi files are sometimes updated when new calibrations become available, and versioning information in these files allows this to be followed.

## ADDITIONAL HANDLES

Additional information that can help understand the luminosity measurements in the experiments are discussed below.

### Emittance scans

At the beginning and end of nearly all physics fills CMS carries out emittance scans. These are fast beam separation scans in regular high luminosity physics running. During these scans 7 separations are used within  $\pm 2\sigma$  which takes about 4 minutes. The scans allow to check the luminosity detector/algorithm calibrations in real physics conditions (with high pileup, and bunch trains), and to monitor the long term stability of the calibrations. There are additional complications when interpreting the calibration results in these scans, compared to the vdM scan, particularly coming from long range beam-beam effects (due to running with bunch trains), and non-factorization of the beam (which can change from fill-to-fill). But they give a very nice cross-check and monitoring of the luminosity calibrations. More details about the CMS emittance scans can be seen in Ref. [3]. In addition with some assumptions these can be used to give the convoluted beam1/2 emittances in regular physics fills, and therefore also provide valuable information for machine studies. In 2018 ATLAS also plans to carry out such scans in regular physics fills, although the technical details (how many scans, how long they will take etc..) are still under discussion.

### Luminous region information

The size of the luminous region reconstructed by the experiments tracking detectors, can also provide useful input to the machine. The transverse sizes are related to the beam1/2 convoluted emittances, although the measurement resolution is larger than the size, and has to be unfolded. This is done by both experiments, and closure tests on simulation demonstrate that this works correctly. There are

<sup>1</sup>Note that for special runs, such as Pb-Pb or p-Pb collisions the uncertainties can be significantly larger.

however still a number of complications with precise measurements of the transverse beam-spot size, related to possible biases from pileup and trigger effects, as well as possible systematic effects from detector alignment. The size of the luminous region is included in the Massi files, and is therefore available for machine studies. With a few assumptions it can be shown that the ratio of the longitudinal length of the luminous regions in IP1/5 is equal to the ratio of the geometric factors in the luminosity formula, and therefore for the same  $\beta^*$  should be the same as the ratio of the luminosities. This gives an additional handle for monitoring any luminosity imbalance between ATLAS/CMS due to non-roundness of the beams.

### *Z-counting*

An important cross check of the delivered luminosity to the experiments is comparing the number of produced Z bosons in the experiments (after correcting for the efficiency of the selection). LPC has been coordinating an effort in 2016 and 2017 to measure the number of Z bosons decaying into muons in a well defined fiducial volume in the two experiments. The precision of the results are limited by the systematic uncertainty on the selection efficiency (and its pileup dependence) which are conservatively set to 5% per experiment at the moment, giving a precision of 7% on the ratio. Work is ongoing to improve the precision of this method. With this large uncertainty it is hard to make strong statements about the size of any imbalance in luminosity between the experiments, although the uncertainty is very correlated from fill-to-fill, so trends observed across the year are more precisely constrained. For 2018 running and beyond, ATLAS and CMS hope to provide the efficiency corrected Z boson yields in a fast way, to allow such information to be available for analysis about 1 week after the data is taken.

## LUMINOSITY IMBALANCE

In 2016 a significant imbalance between the delivered luminosity to IP1/5 was observed when comparing the final luminosity numbers, with the difference in the integrated luminosity across the year about 6%. This was studied in detail and for most of the year it seemed to be consistent with different H/V emittances, which coupled with the different crossing planes in IP1/5, leads to an imbalance in the luminosity. Studies of the test fill when the crossing angle was reduced to zero, also showed that the imbalance disappeared with no crossing angle [4]. However for the last period of the year the BSRT emittance measurement showed that the beams became round, but the measured luminosity showed the same level of imbalance between IP1/5 [5]. This part is not understood. In 2017 luminosity measurements by the experiments (with the current calibrations) do not show any imbalance (the integrated delivered luminosities over the year differ by less than 1%), and indeed measurements of the emittance show rounder beams than in most of 2016 running [6].

## SUMMARY

Precisely measuring the luminosity is critical for the LHC experiments physics programme, as well as for operations. The luminosity is calibrated in dedicated vdM scans, optimized to give the most precise calibration. The level of precision is 5-10% during running, with a final precision of  $\approx 2.5\%$  available about a year after the run. Additional information from emittance scans, the measured luminous region size, and Z-counting provides useful cross checks of the luminosity. In 2016 a significant imbalance in the luminosity delivered to IP1/5 was observed, but in 2017 this is not seen.

## ACKNOWLEDGMENT

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