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Luminosity measurements of the LHC experiments

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The determination of the luminosity is a key element in the measurement of cross sections at the LHC. The uncertainty in this determination has a major impact on the accuracy of measured physics quantities. The definition of luminosity and the main strategy of its estimation by ALICE, ATLAS, CMS and LHCb experiments are presented. The van der Meer technique and associated corrections are discussed. Finally, a summary of the current results is presented.

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1. Introduction

Physics experiments at the LHC are designed to study selected processes of interest by detecting and counting their occurrence. Due to the specific acceptance of detectors the resulting numbers are generally experiment dependent. If we want to compare results from different experiments, we need to transfer the findings into experiment-independent quantities, like the cross section. At circular particle accelerators, a parameter called luminosity is introduced for this purpose.

The instantaneous (or relative) luminosity [1, 2] is defined as

$$\mathcal{L}_{\mathrm{inst}} = \frac{R_{\mathrm{evts}}}{\sigma_{\mathrm{proc}}}, \tag{1}$$

where σ_{proc} is the cross section of the process and R_{evts} is the event rate for the chosen process. Integrating $\mathcal{L}_{\mathrm{inst}}$ over time [3] one can obtain the integrated luminosity $\mathcal{L}_{\mathrm{int}}$, which is a fundamental measure for the amount of sampled data at the LHC experiments.

The absolute accuracy of the luminosity calculation is important for the all the experiments, ALICE, ATLAS, CMS and LHCb, and in some cases dominates the systematic uncertainty of cross section measurements. Accuracy estimation is a challenging task with many sources of systematic uncertainties. The work on this topic, performed for Run 2 data, is documented in Refs. [4–23].

2. Luminosity measurement via visible cross section

The luminosity of two head-on colliding bunches is defined as

$$\mathcal{L} = \nu_{\mathrm{rev}} N_1 N_2 \int \rho_1(x,y)\rho_2(x,y)\mathrm{d}x\mathrm{d}y, \tag{2}$$

where ν_{rev} is the revolution frequency, N_i is the colliding bunch intensity, defined as the number of particles in a bunch, and ρ_i is the colliding bunch density distribution in the (x,y) plane. Integrating out the bunch density distributions, the luminosity can be expressed in terms of the effective widths of the bunch overlap region in the two transverse directions Σ_x, Σ_y and (2) rewritten to

$$\int \rho_1(x,y)\rho_2(x,y)\mathrm{d}x\mathrm{d}y = \frac{1}{2\pi\Sigma_x\Sigma_y} \quad \rightarrow \quad \mathcal{L} = \nu_{\mathrm{rev}} \frac{N_1 N_2}{2\pi\Sigma_x\Sigma_y}. \tag{3}$$

The luminosity can be estimated in several ways which differ in the achieved accuracy. Choosing the approach with the best achievable accuracy is a key ingredient for a precise physics analysis. Therefore in physics data-taking, the luminosity is measured indirectly using a suitable reference process for which the cross section is known with good accuracy. The reference cross section can be taken either from a known physics process (i.e. Z-boson decay [24]) or by measuring a visible cross section σ_{vis}. A series of modifications of (1) and (3) give

$$\mathcal{L} = \nu_{\mathrm{rev}} \frac{N_1 N_2}{2\pi\Sigma_x\Sigma_y} = \frac{\mu_{\mathrm{vis}}\nu_{\mathrm{rev}}}{\sigma_{\mathrm{vis}}} \quad \rightarrow \quad \sigma_{\mathrm{vis}} = \frac{2\pi\mu_{\mathrm{vis}}\Sigma_x\Sigma_y}{N_1 N_2}, \tag{4}$$

where μ_{vis} is the average number of visible interactions per bunch crossing. Equation (4) tells us that we need a data-taking settings where we can measure μ_{vis}, N_i and Σ_i simultaneously.

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The most common calibration session used at the LHC experiments to obtain the visible cross section is the van der Meer scan (vdM) [25, 26]. In this session, the contra-heading beams are being displaced independently in x- and y-direction and μ_{vis} is measured as a function of the beam separation. An example of such a measurement with description of Σ_i calculation is in Fig. 1. The bunch intensitites N_i are provided by LHC via DC Current Transformers and Fast Beam Current Transformers [27] and are further corrected for ghost [1] and satellite charge [2] [28].

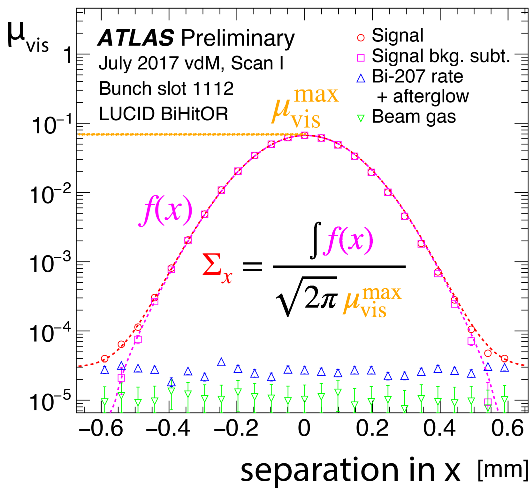

Figure 1: Dependence of the average number of visible interactions μ_{vis} on the size of beam separation x. The curve $f(x)$ is fitted with a double-Gaussian model [4, 10]. The integral of this curve is used to calculate the effective width of the bunch overlap region Σ_x. Taken from Ref. [11] (modified).

Several corrections related to the beam measurement quality and which impact the luminosity determination precision have to be made. One of them is a so-called length-scale calibration. This correction responds to the difference between the nominal beam displacement and the actual beam displacement during vdM scans. Vertex positions for different fixed beam displacements are measured and compared to the nominal displacements. The slope of the linear fit to the found dependency is the correction factor and is usually of the order of a few percent.

In the derivation of (3) a factorisation assumption, $\rho(x, y) = \rho(x)\rho(y)$ was used. This is not completely true and it changes from bunch to bunch and in time. The effect is estimated from simultaneously fitting the dependency from Fig. 1 for all vdM scans, and the rates and luminous-region parameters (positions, sizes, transverse tilt) [4, 11], or with Beam-Gas Imagine method [23]. Thanks to beam tailoring in the LHC injection chain this effect is tamed under 2% in Run 2 analyses.

The orbit and the shape of colliding bunches are distorted by mutual electromagnetic interactions [29]. While the beam-beam deflection (the change in beam separation) can be estimated analytically, the optical distortion (the change in beam profile) has to be simulated and hence the full effect is properly simulated [30]. In total, this effect is estimated to be below 1%.

At each end of the interaction points the positions of the beam are measured with Beam Position Monitors and a difference between expected and measured beam positions was found. Dedicated

[1]The charge circulating outside of the nominally filled slots.

[2]The charge circulating within a nominally filled slot but not captured in the central bucket.

Table 1: A summary of known total relative uncertainties of the measurement of luminosities for each LHC experiment in pp collisions at different energies of Run 2 periods. The corresponding references are in the table. Numbers without reference are from personal communication. Low-μ corresponds to periods with low pile-up with respect to standard physics data taking.

	$\sigma_{\mathcal{L}}/\mathcal{L}$[%] for pp at 13 TeV					$\sigma_{\mathcal{L}}/\mathcal{L}$[%] for pp at 5 TeV	
	2015	2016	2017	2018	Run 2	2015	2017
ALICE	3.4 [4]	1.9 [8]	2.7 [8]	2.1 [8]	1.6 [8]	2.3 [5]	2.1 [7]
ATLAS	2.1 [11]		2.4 [11]	2.0 [11]	1.7 [11]	1.5 [13]	
ATLAS low-μ			1.5 [13]				
CMS	1.6 [23]	1.2 [23]	2.3 [18]	2.5 [20]	1.6	2.3 [16]	1.9 [21]
CMS low-μ			1.7 [18]				
LHCb	2.0					2.0	

Table 2: A summary of known total relative uncertainties of the measurement of luminosities for each LHC experiment in heavy-ion collisions of Run 2 periods. The corresponding references are in the table. Numbers without reference are from personal communication.

	$\sigma_{\mathcal{L}}/\mathcal{L}$[%] for p–Pb/Pb–p at 8 TeV	$\sigma_{\mathcal{L}}/\mathcal{L}$[%] for Pb–Pb at 5 TeV	
	2016	2015	2018
ALICE	1.9/2.0 [6]	2.3 [9]	
ATLAS	2.4 [12]	1.5 [14]	1.9 [15]
CMS	3.7/3.2 [17]		1.5 [19]
LHCb	2.6/2.5 [31]	13	4.2

tests [32] point to a non-linear behaviour (hysteresis) of the steering magnets. This effect impacts the vdM calibration precision in order of several permille and is currently assessed.

The vdM calibration is a special session, in which conditions do not exactly corresponds to the ones of the physics data-taking periods. In comparison to proton-proton physics collisions, the vdM is taken at low pile-up and with isolated bunches. This is a crucial difference mainly for data-taking at the ATLAS and CMS experiments. The ATLAS vdM calibration transfer to physics conditions is based on track-count luminosity [11] while CMS calibration transfer is based on emittance scans (short vdM in physics conditions) [22]. This effect is of the order of 10%.

All experiments have to also cope with the luminosity measurement stability and reproducibility over time. The common strategy across experiments is to use different luminometers to cross-check [9, 11, 33]. The ATLAS Collaboration also also studied the difference between the luminosities determined via visible cross section and the decay of the Z boson [24].

3. Summary of achieved accuracy at the LHC

Summaries of uncertainties of all available luminosity determinations of Run 2 data from ALICE, ATLAS, CMS and LHCb collaborations are shown in Tab. 1 and Tab. 2 for proton-proton and heavy-ion collisions respectively. Overall, the accuracy has been improved over Run 2 and currently the uncertainty is being held below 2%.

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