Non factorisation in ATLAS and ALICE vdM scans: experience in Run 2, impact on luminosity calibration

M. Dyndal (CERN), on behalf of the ATLAS and ALICE Collaborations

Abstract

The original vdM formalism for calibrating luminosity measurements at hadron colliders assumes that the particle densities in each bunch can be factorised into independent horizontal and vertical components. The effect of violations of this assumption (non-factorisation) is quantified by performing dedicated measurements during LHC Run 2 vdM scan sessions of the ATLAS and the ALICE detectors. In both experiments, this is done by observing and modelling the evolution of various beamspot phenomena during the scans.

INTRODUCTION

The luminosity measurement in both the ATLAS [1] and ALICE [2] experiments is based on an absolute calibration of the luminosity-sensitive detectors in low-luminosity runs with specially-tailored LHC conditions using the van der Meer (vdM) method [3]. The vdM method assumes that the transverse profile of the beam overlap region factorises into the product of two one-dimensional profiles along the two scan directions (x and y). If this factorisation assumption is violated, the vdM estimate of the beam overlap integral becomes inaccurate.

Evidence for non-factorisation was clearly seen at the LHC during Run 1 [4, 5, 6, 7], especially when dedicated beam-tailoring in the LHC injectors was not used. This results in up to 4% bias of the beam overlap integral when using the factorised vdM formalism. In Run 2, special care was taken in the LHC injector chain to produce beams with Gaussian-like transverse profiles in x and y to minimise non-factorisation effects in the scans.

THE METHOD

The non-factorisation coefficient R is defined as the following ratio:

$$R = \frac{\displaystyle\int \rho_1(x,y)\rho_2(x,y)dxdy}{\displaystyle\int \rho_{1x}(x)\rho_{2x}(x)dx \int \rho_{1y}(y)\rho_{2y}(y)dy}\ , \quad (1)$$

where $\rho_j(x,y)$ ($j = 1,2$) denotes transverse beam densities. This ratio can be then used to correct the visible cross-section from the standard factorisable analysis: $\sigma_{\text{corr}} = \sigma/R$.

Following Run 1 analyses, non-factorisation corrections in ATLAS and ALICE were evaluated individually for each Run 2 vdM scan session. The nominal method used in both experiments relies on a combined fit to the beam-separation dependence of the luminometer rate and of the position, orientation and shape of the luminous region, characterised by the three-dimensional spatial distribution of the primary collision vertices formed from tracks reconstructed in the detectors. The luminous-region parameters (collectively referred to as the *beamspot* information) are extracted from an unbinned maximum likelihood fit to the measured spatial distribution of reconstructed collision vertices, using as a fit model a 3D single Gaussian corrected for the vertex-position resolution.

Additionally, vdM scans with non-zero separation (offset) in the non-scanned direction were performed by both ATLAS and ALICE, in order to study the beam profiles in the tails to better constrain non-factorisation effects. The offset typically amounts to about 2–4σ_{beam}.

For comparison, the CMS experiment uses the so-called beam-imaging method to evaluate the size of the factorisation bias [8]. This method uses fits to reconstructed primary-interaction vertex data.

In the nominal ATLAS analysis, the proton density in each beam j is parameterised by a triple Gaussian function in 3D:

$$\begin{aligned} g_j(x,y,z) = w_j\, G_{j,a}(x,y,z) + (1-w_j)[w_{b,j}\, G_{j,b}(x,y,z) \\ +(1-w_{b,j})\, G_{j,c}(x,y,z)]\ , \end{aligned} \quad (2)$$

where w_j and $w_{b,j}$ represent the fraction of the distribution in each 3D Gaussian function, $G_{j,v}$ ($j = 1,2$ and $v = a,b,c$), defined as:

$$G_{j,v}(x,y,z) = \frac{1}{(2\pi)^{3/2}|S_{j,v}|^{1/2}}\ \exp\left(-\frac{1}{2}\,\boldsymbol{x} S_{j,v}^{-1}\boldsymbol{x}\right)\ , \quad (3)$$

$$S_{j,v} = \begin{pmatrix} \sigma^2_{x,j,v} + \theta^2_{xz}\,\sigma^2_{z,j,v} & \kappa_{j,v}\,\sigma_{x,j,v}\,\sigma_{y,j,v} - \theta_{xz}\,\theta_{yz}\,\sigma^2_{z,j,v} & \theta_{xz}\,\sigma^2_{z,j,v} \\ \kappa_{j,v}\,\sigma_{x,j,v}\,\sigma_{y,j,v} - \theta_{xz}\,\theta_{yz}\,\sigma^2_{z,j,v} & \sigma^2_{y,j,v} + \theta^2_{yz}\,\sigma^2_{z,j,v} & -\theta_{yz}\,\sigma^2_{z,j,v} \\ \theta_{xz}\,\sigma^2_{z,j,v} & -\theta_{yz}\,\sigma^2_{z,j,v} & \sigma^2_{z,j,v} \end{pmatrix}\ , \quad (4)$$

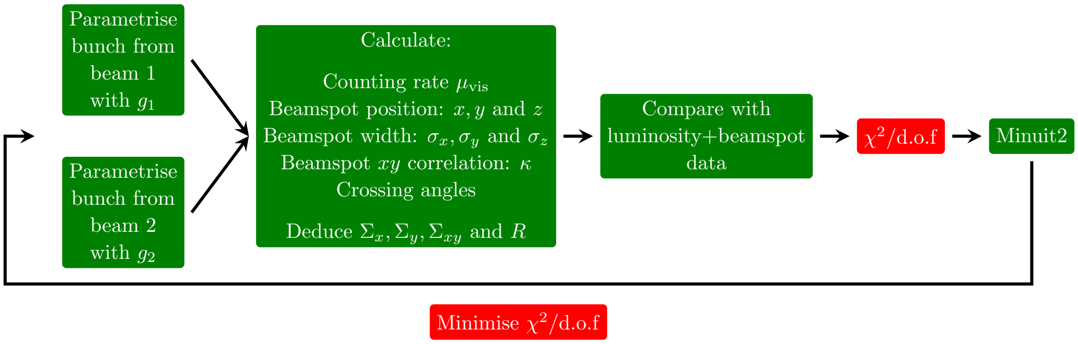

Figure 1: Scheme of the process for the non-factorisation correction factor (R) measurement in the nominal method used in ATLAS and ALICE.

where:

- $S_{j,v}$ is the matrix associated with $G_{j,v}$,
- $\sigma_{x,j,v}$, $\sigma_{y,j,v}$ and $\sigma_{z,j,v}$ are the widths in the x, y and z direction of $G_{j,v}$,
- θ_{xz} and θ_{yz} are the crossing angles,
- $\kappa_{j,v}$ are the xy correlation coefficients.

ALICE uses a double Gaussian parameterisation of proton densities, defined in an analogous way. Moreover, by keeping the longitudinal beam characteristics in the fit, it is possible to indirectly measure the beam crossing angles θ_{xz} and θ_{yz} (if applicable).

The fitting process is schematically shown in Figure 1. The simulated 3D luminosity distribution, and the resulting evolution of the luminous-region parameters, are computed numerically, at each step of the scan, from the time-overlap integral of the simulated proton-density distributions of the colliding bunches. The full procedure is repeated multiple times in the χ^2 minimisation process.

Examples of best-fit curves for a representative set of luminous-region parameters and vdM scan sessions for ATLAS and ALICE are shown in Figure 2. At each step of the scans, the specific visible interaction rate is measured using the LUCID (ATLAS) or T0 (ALICE) luminosity detectors. The proton density is modelled, for each bunch separately, by a 3D triple-Gaussian (double-Gaussian) for ATLAS (ALICE), the parameters of which are fitted to the evolution, during the scan, of the measured interaction rate and luminous-region parameters. The red lines show the result of these fits, which provide fair description of the data.

ALTERNATIVE METHOD

In ATLAS, an alternative method for the R measurement is developed, which uses only information from the beam-separation dependence of the luminometer rate. One can show that:

$$R = \frac{\Sigma_x \Sigma_y}{\Sigma_{xy}} \, , \tag{5}$$

$$\Sigma_x = \frac{1}{\sqrt{2\pi}} \int f_x(\Delta x, 0) \, d\Delta x \, , \tag{6}$$

$$\Sigma_y = \frac{1}{\sqrt{2\pi}} \int f_y(0, \Delta y) \, d\Delta y \, , \tag{7}$$

$$\Sigma_{xy} = \frac{1}{2\pi} \int f_{xy}(\Delta x, \Delta y) \, d\Delta x \, d\Delta y \, , \tag{8}$$

where Σ_x and Σ_y are the so-called convolved beam widths and functions $f_u(\Delta u)$ (where $u = x,\ y$) describe the evolution of the luminometer counting rate as a function of the transverse beam separation Δu.

The functions f_x, f_y and f_{xy} can be defined in the form of a double-Gaussian parameterisation

$$f_u(\Delta u) = w_u \, e^{-\frac{1}{2}(\Delta u/\sigma_{u,1})^2} + (1 - w_u) \, e^{-\frac{1}{2}(\Delta u/\sigma_{u,2})^2} \, , \tag{9}$$

$$\begin{aligned} f_{xy}(\Delta x, \Delta y) &= w_{xy} \, e^{-\frac{1}{2}(\Delta x/\sigma_{x,1})^2} e^{-\frac{1}{2}(\Delta y/\sigma_{y,1})^2} \\ &+ (1 - w_{xy}) \, e^{-\frac{1}{2}(\Delta x/\sigma_{x,2})^2} e^{-\frac{1}{2}(\Delta y/\sigma_{y,2})^2} \, , \end{aligned} \tag{10}$$

while R takes the analytic form:

$$R = \frac{[w_x \sigma_{x,1} + (1 - w_x)\sigma_{x,2}] \, [w_y \sigma_{y,1} + (1 - w_y)\sigma_{y,2}]}{[w_{xy} \sigma_{x,1}\sigma_{y,1} + (1 - w_{xy})\sigma_{x,2}\sigma_{y,2}]} \, . \tag{11}$$

The functions f_x, f_y and f_{xy} can be also parameterised using Gaussian times sixth-order polynomial form:

$$f_u(\Delta u) = e^{-\frac{1}{2}(\Delta u/\sigma_u)^2} \left[1 + \sum_{\boldsymbol{n=2}}^{6} c_{u,n} \left(\frac{\Delta u}{\sigma_u} \right)^n \right] \, , \tag{12}$$

$$\begin{aligned} f_{xy}(\Delta x, \Delta y) &= e^{-\frac{1}{2}(\Delta x/\sigma_x)^2} e^{-\frac{1}{2}(\Delta y/\sigma_y)^2} \\ &\times \left[1 + \sum_{\boldsymbol{n=2}}^{6} c_{x,n} \left(\frac{\Delta x}{\sigma_x} \right)^n + c_{y,n} \left(\frac{\Delta y}{\sigma_y} \right)^n \right] \, . \end{aligned} \tag{13}$$

One should note that for this parameterisation, the values of polynomial coefficients associated to odd powers of

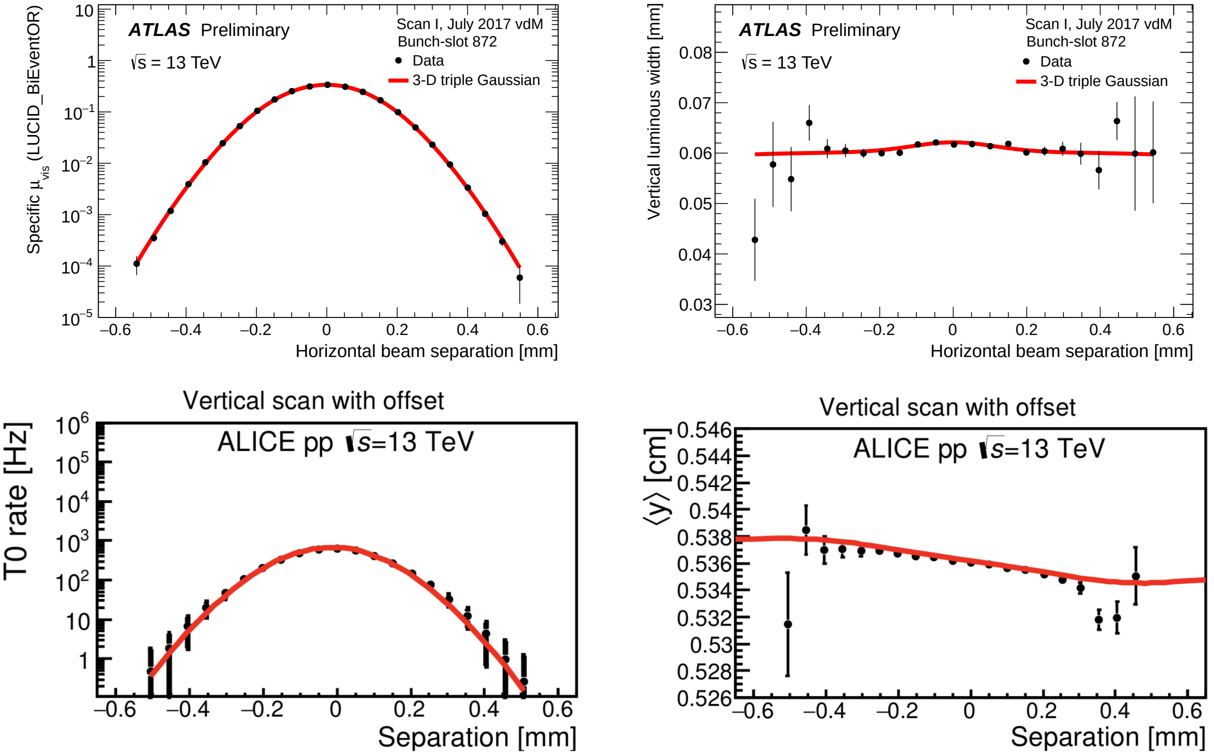

Figure 2: (Top) Beam-separation dependence of the specific visible interaction rate (left) and the vertical luminous width (right) during a horizontal vdM scan in ATLAS taken in 2017 [9]. (Bottom) Beam-separation dependence of the specific visible interaction rate (left) and the vertical position of the luminous centroid (right) during a vertical vdM scan (with an extra offset in horizontal direction) in ALICE taken in 2015 [10]. The uncertainties shown are statistical only.

$\Delta x/\sigma_x$ and $\Delta y/\sigma_y$ are expected to be zero. This choice is related to the assumption that the measured specific rate values should be symmetric with respect to "zero" beam separation. In this case R is given by:

$$R = \frac{(1 + c_{x,2} + 3c_{x,4} + 15c_{x,6})(1 + c_{y,2} + 3c_{y,4} + 15c_{y,6})}{(1 + c_{x,2} + 3c_{x,4} + 15c_{x,6} + c_{y,2} + 3c_{y,4} + 15c_{y,6})}, \quad (14)$$

where $c_{u,2}$, $c_{u,4}$ and $c_{u,6}$ are the appropriate polynomial coefficients.

The disadvantage of this method is that it is less precise (statistically) compared to the nominal fits that are constrained using both measured interaction rate and measured luminous-region parameters. On the other hand, the nominal procedure requires a large number of reconstructed vertices per scan step; therefore it was typically carried out for only a handful of colliding bunch pairs, for which the tracking information was read out at sufficiently enhanced rate.

RESULTS

Figure 3 presents the non-factorisation correction factor for several colliding-bunch pairs and scan sets extracted in ATLAS for 2017 and 2018 pp data at 13 TeV. The R value is extracted from fits to the beam-separation dependence of the luminosity as well as the position, shape and orientation of the luminous ellipsoid, as reflected by the spatial distribution of reconstructed pp-collision vertices (nominal method), or of only the luminosity - using a 2D Gaussian function multiplied by a sixth-order polynomial (alternative method). The results use either on-axis scans or combined fits to on- and off-axis scans. No large dependence on colliding-bunch pair is observed and therefore the results are averaged and the uncertainties are assigned based on the spread of the measured R values for individual colliding-bunch pairs. The averaged R values are $R = 0.998 \pm 0.002$ for 2017 and $R = 1.003 \pm 0.005$ for 2018 when using the nominal method. The alternative method gives consistent results, although with worse statistical precision (see Fig. 3 top left).

Table 1 shows the bunch-averaged non-factorisation correction factor values for individual datasets in ATLAS and ALICE. In general, the R values are not more than 1% from unity and the uncertainties are typically well below 1%. One should mention that the size of the uncertainty is estimated differently in both experiments: ATLAS uses full spread of R values for individual colliding-bunch pairs as a measure of systematic uncertainty, whereas in ALICE the deviation of R from unity is taken to assign the relevant uncertainty.

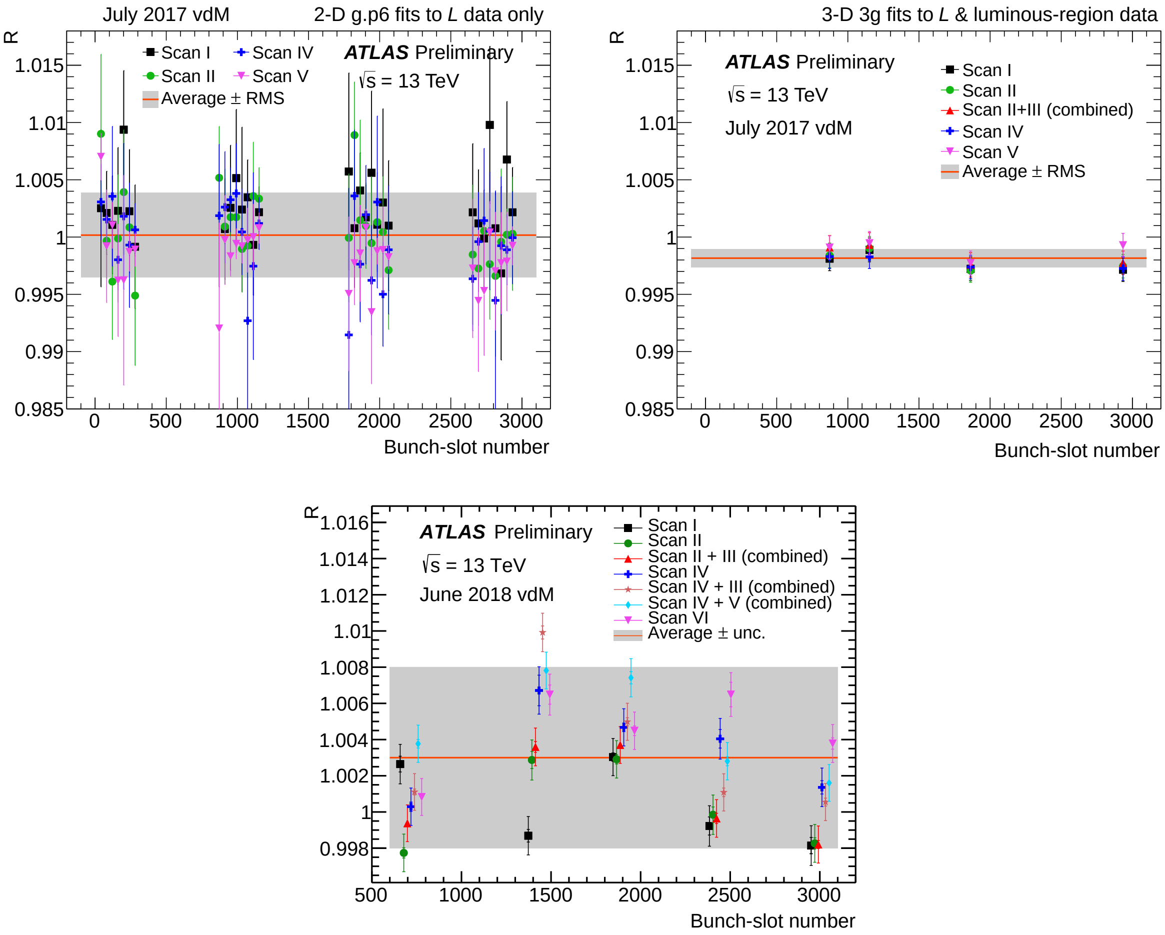

Figure 3: Non-factorisation correction factor R for several colliding-bunch pairs and scan sets extracted during 2017 (top) and 2018 (bottom) vdM scans in ATLAS at 13 TeV [9, 11]. For the 2017 analysis, the R values extracted from fits to the beam-separation dependence of only the luminosity (left) or of the luminosity as well as the position, shape and orientation of the luminous ellipsoid, as reflected by the spatial distribution of reconstructed pp-collision vertices (right), are shown. For 2018, only the results from nominal method are shown. The red lines represent the error-weighted mean corrections, and the grey bands the uncertainties assigned from the spread of the measured R values.

Table 1: Summary of R values for individual datasets in ATLAS and ALICE. The values are taken from Refs [10, 11, 12, 13]

Dataset	R
ATLAS 2015 *pp* 13 TeV	1.01 ± 0.01
ATLAS 2016 *pp* 13 TeV	1.006 ± 0.004
ATLAS 2017 *pp* 13 TeV	0.998 ± 0.002
ATLAS 2017 *pp* 5 TeV	0.999 ± 0.003
ATLAS 2018 *pp* 13 TeV	1.003 ± 0.005
ALICE 2015 *pp* 13 TeV	1.009 ± 0.009
ALICE 2015 *pp* 5 TeV	1.01 ± 0.01
ALICE 2017 *pp* 5 TeV	1.000 ± 0.001
ALICE 2016 *p*Pb 8.16 TeV	1.006 ± 0.006
ALICE 2016 Pb*p* 8.16 TeV	1.009 ± 0.009

SUMMARY

The methods used in the ATLAS and ALICE experiments to evaluate the factorisation bias of the vdM luminosity calibration are presented. The results show that the non-factorisation correction factor is typically close to unity in Run 2, which confirms the expectations: for vdM scan sessions the LHC injector chain usually produces beams with clean, Gaussian-like transverse profiles. The uncertainty on the non-factorisation coefficient R is typically less than 1% for all analyses.

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