Precise luminosity determination at CMS

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1st Annual Conference on Large Hadron Collider Physics (25–30 May 2020)

Abstract

Precise luminosity calibration at bunched-beam hadron colliders like the Large Hadron Collider (LHC) is critical to determine fundamental parameters of the standard model and to discover or constrain beyond-the-standard-model phenomena. This poster shows the results of luminosity determination at LHC interaction point 5 with the Compact Muon Solenoid (CMS) detector, using proton-proton collisions in 2018. The leading sources of systematic uncertainty in the integrated luminosity measurement are shown.

The van der Meer (vdM) method

The rate R recorded by a luminosity detector ("luminometer") is measured as a function of beam separation in horizontal and vertical planes, $x$ and $y$, in a fill with special beam conditions, and fitted with (typically) a Gaussian-like function to obtain the beam overlap widths $\Sigma_x$ and $\Sigma_y$ as well as $R_{\text{peak}}$ at zero separation. Assuming that the bunch proton density function is factorizable into independent $x$ and $y$ terms, the measured value of $\sigma_{xy}$ is used during physics fills to calculate the per bunch instantaneous luminosity $L(t)$:

$$L(t) = \frac{R(t)}{\sigma_{xy}}$$

$$\sigma_{xy} = 2\Sigma_x \Sigma_y N_1 N_2 f_n / R_{\text{peak}}$$

Bias from x-y factorization assumption

The assumption that the bunch proton density function is factorizable into independent $x$ and $y$ terms can lead to a biased estimate of the beam overlap integral. This effect is measured using two methods:

Constant separation scan: Beams are separated by 1.05 $\sigma_b$ (where $\sigma_b$ is the beam size) and moved together in steps of 0.3 $\sigma_b$ along the positive then negative directions in $x$ and $y$.

Variable separation scan: Each beam is moved from $-2.5\sigma_b$ to $+2.5\sigma_b$ in 5 steps along the positive horizontal and vertical directions. In each step, a 3-point miniscans is performed with the other beam at relative positions of $-2.5\sigma_b$, 0 and $+2.5\sigma_b$.

The CMS tracker is used to reconstruct the position of interaction vertices defining the luminous region and the resulting mean position is plotted against the nominal (orbit drift corrected) separation. The length scale correction is extracted by a linear fit.

Integration uncertainty: luminometer stability and linearity

During the course of the data-taking years, individual luminometers are affected by operational issues and radiation damage that can be monitored by short vdM-like ("emittance") scans in normal physics conditions, performed at the start and end of fills. They provide data with different single bunch instantaneous luminosity (SBIL), thus linearity response can also be measured and corrected for.

After corrections, the various luminometer measurements are compared to measure stability and residual nonlinearity. The luminosity ratio of luminometer pairs plotted as a function of SBIL and fitted by a linear function gives the relative nonlinearity.

Luminometer uncertainty

The total uncertainty in proton-proton collisions in 2018 is 2.5% (similar to previous years) and dominated by the uncertainty from x-y factorization and luminometer linearity. When the full Run 2 data set of 2015–2018 is combined, it is reduced to 1.8%.

To reach the target precision of 1% at the HL-LHC, all sources of uncertainties must be controlled at the subpercent level. Developments are thus ongoing both to improve the measurement techniques and the luminometer instrumentation.