Luminosity measurement at CMS

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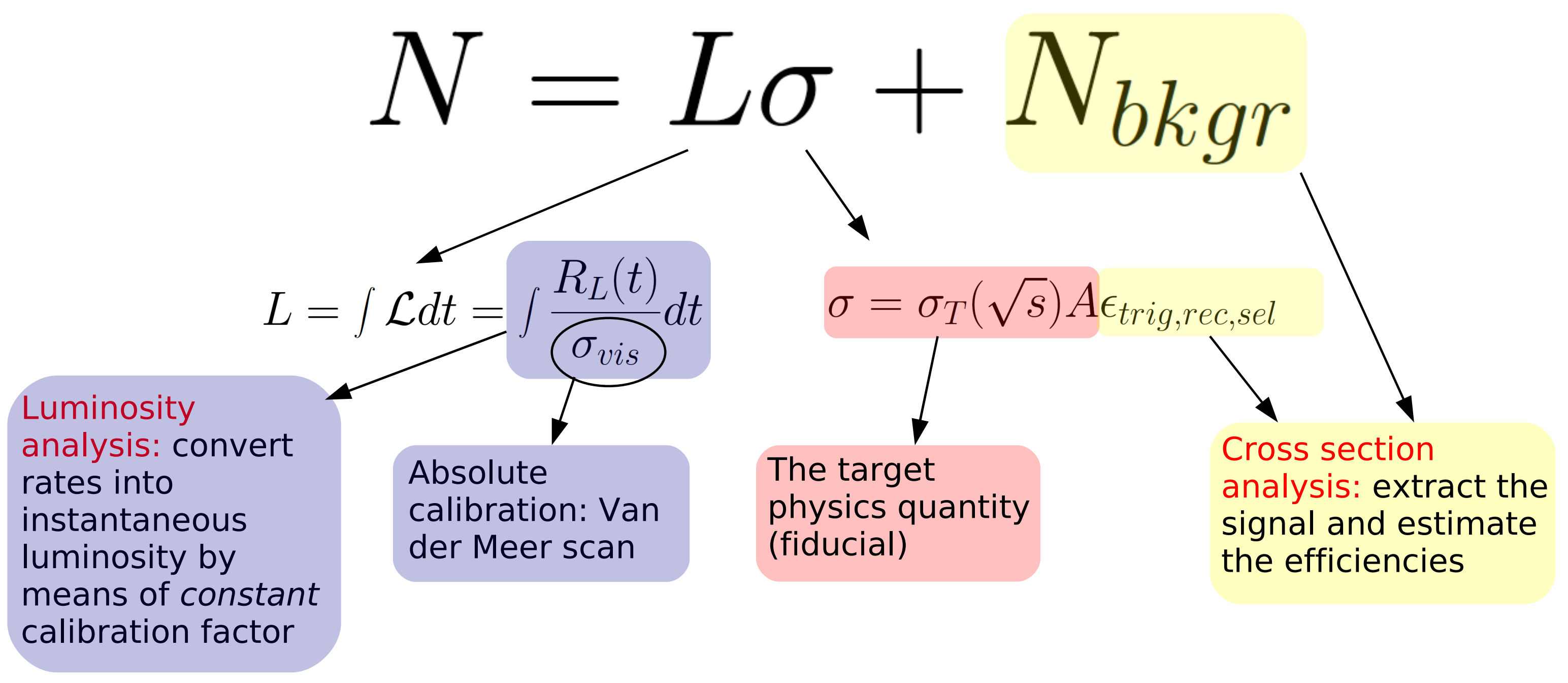
On behalf of the CMS Collaboration

Luminosity at CMS overview



$$N = L\sigma + N_{bkgr}$$

$$L = \int \mathcal{L}dt = \int \frac{R_L(t)}{\sigma_{vis}} dt$$

$$\sigma = \sigma_T(\sqrt{s}) A \epsilon_{trig,rec,sel}$$

Luminosity analysis: convert rates into instantaneous luminosity by means of *constant* calibration factor

Absolute calibration: Van der Meer scan

The target physics quantity (fiducial)

Cross section analysis: extract the signal and estimate the efficiencies

In a given physics analysis, the number of events recorded is equal to the total luminosity of the data taken multiplied by the cross section of the physics process, plus the number of background events that also pass the signal selection. Luminosity is an integral part of this equation, and as such, should be precisely determined.

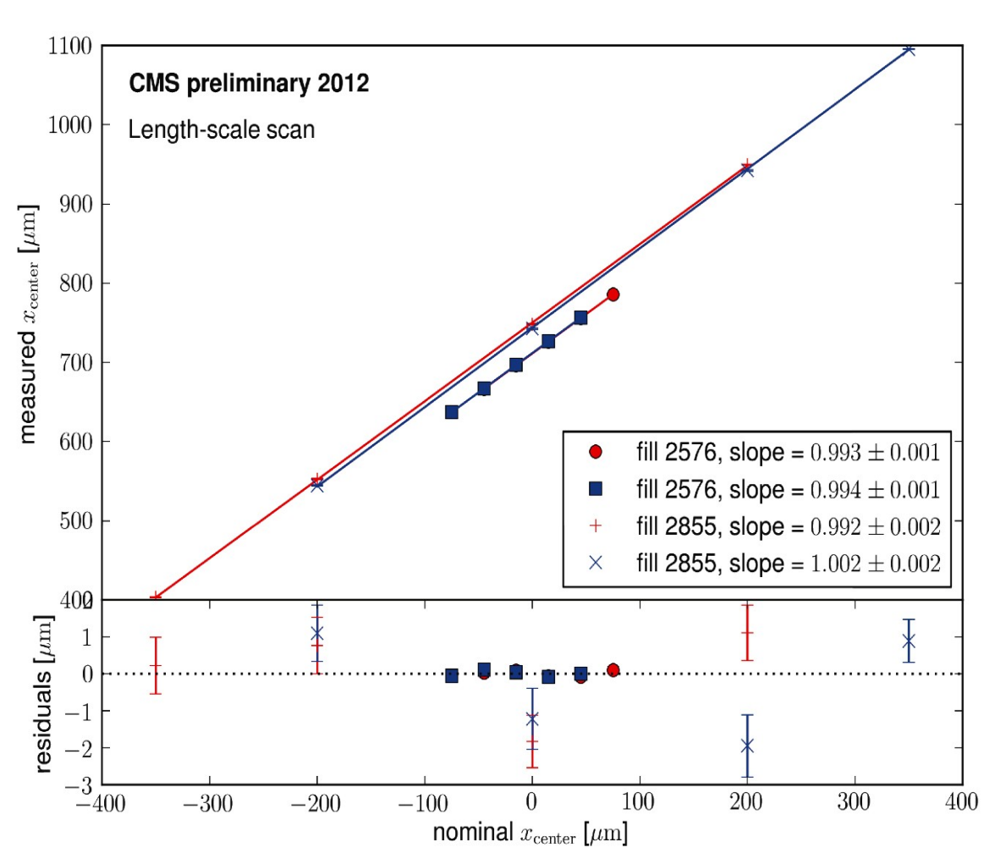
The luminosity measurement system at CMS consists of several steps. The luminosity integration is done via subsystems (luminometers) that measure a given quantity, linear with luminosity, in real time. The luminometers must additionally be calibrated to absolute values.

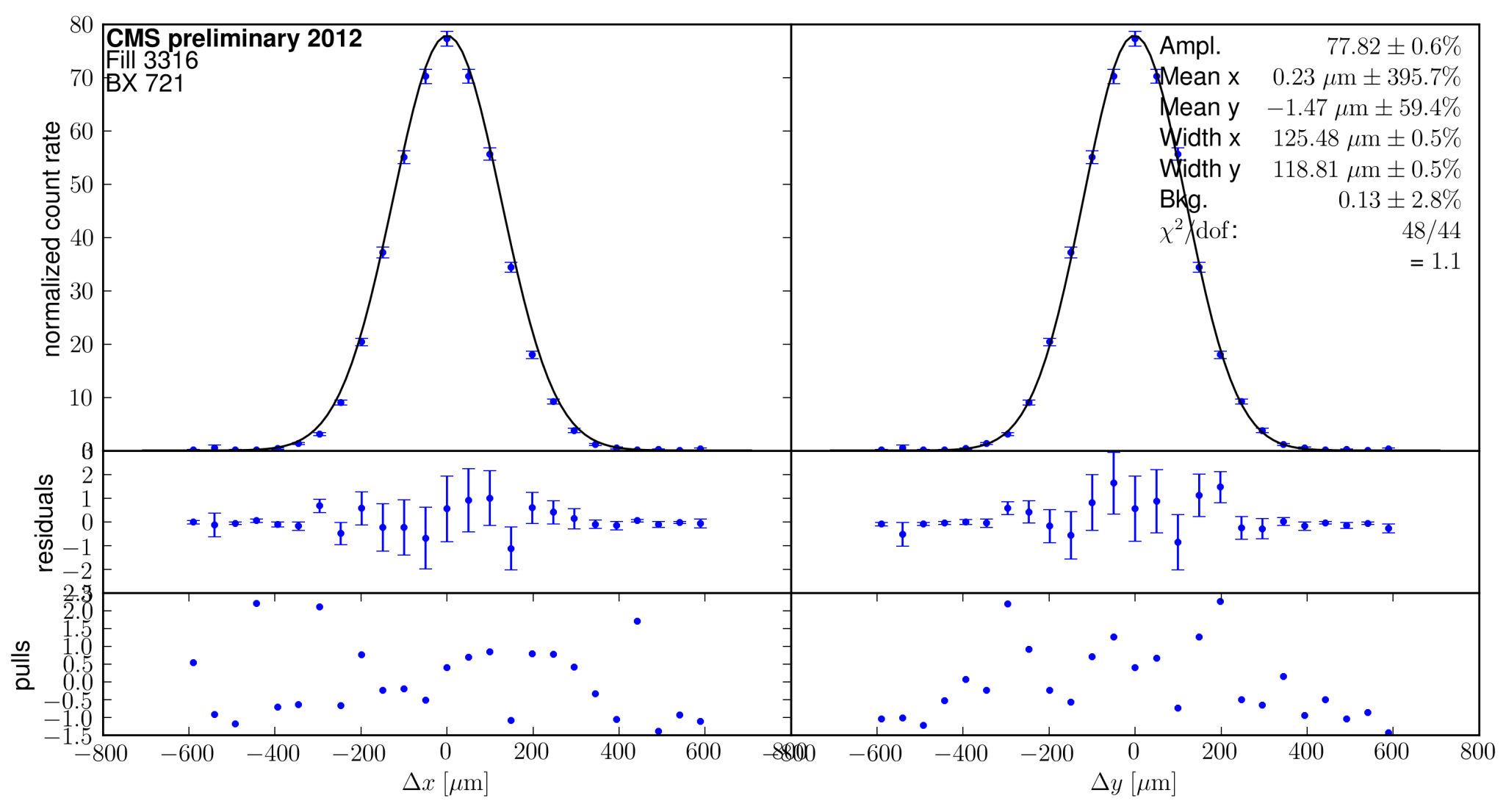
Luminosity calibration

The goal of the luminosity calibration is to determine the luminosity as a function of beam parameters. From this, the calibration constant σ_{vis} can be calculated. Luminosity calibration at CMS is done via a Van der Meer scan, during which the LHC beams are scanned across each other. The effective area of the beams can be determined from the rate as a function of beam separation. The beam current is measured by dedicated instrumentation (Fast Beam Current Transformer and DC Beam Current Transformer).

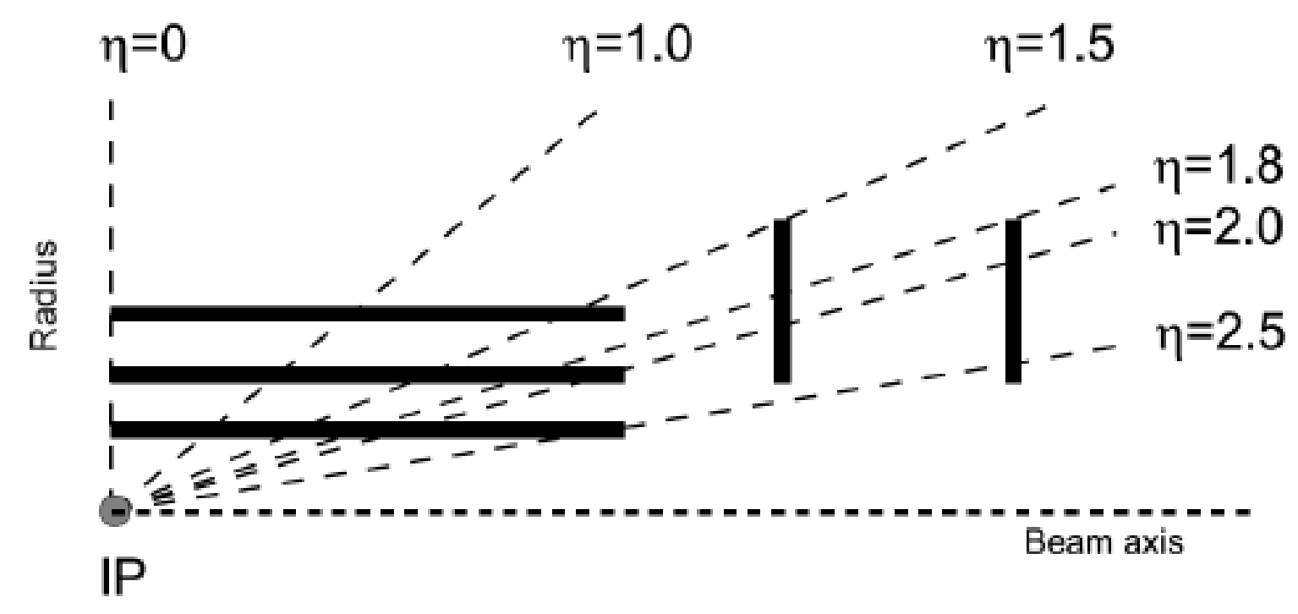
Several effects must be corrected for during the Van der Meer scan analysis. The beam separation distance is determined from the current in the corrector magnets. This must be compared with the measured luminous region using the CMS tracker. In addition, the beams can grow in size during the 30 minutes of the scan. However, this effect can be measured during the scan and corrected for easily if the growth is linear. The beams can also drift in the x-y plane during the scan, and the beam position may be affected by beam-beam repulsive effects. These can also be measured and corrected for.

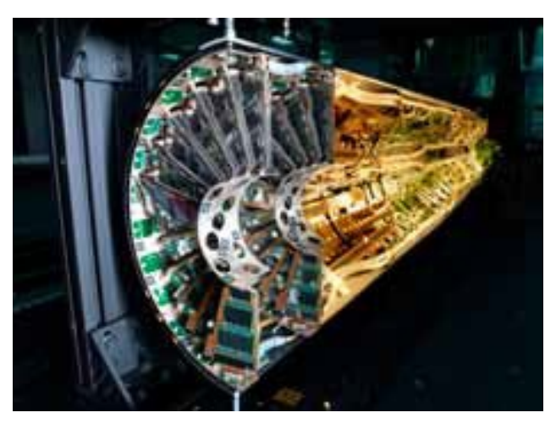
It is convenient to assume that the beams have a Gaussian shape and that the shape is independent in the x and y directions. The LHC setup during the Van der Meer scan is optimized to fulfill these conditions as much as possible. However, the exact functional form of the beam shape is unknown, and these assumptions currently contribute the largest component of the uncertainty to the luminosity measurement. (See section *Offline luminosity measurement: pixel cluster counting* for a summary of the uncertainties on the offline measurement.)





Offline luminosity measurement: pixel cluster counting





CMS silicon pixel detector
- 3 barrel layers, 2 endcap disks per side
- 100 x 150 µm sensors
- 66 million channels, 96.3% always alive
- <0.1% occupancy at 10^{34} $cm^{-2}s^{-1}$
- Max readout rate 100kHz

The pixel detector is especially suited to luminosity measurement because of its high fraction of always-alive channels, minimizing variation in detector acceptance, and its very low occupancy at high luminosity, which means count rates are linear with luminosity. It can only operate during stable running conditions, which means it must only be used as an offline luminometer. However, the system is stable and precise and, as such, is the reference luminometer for CMS.

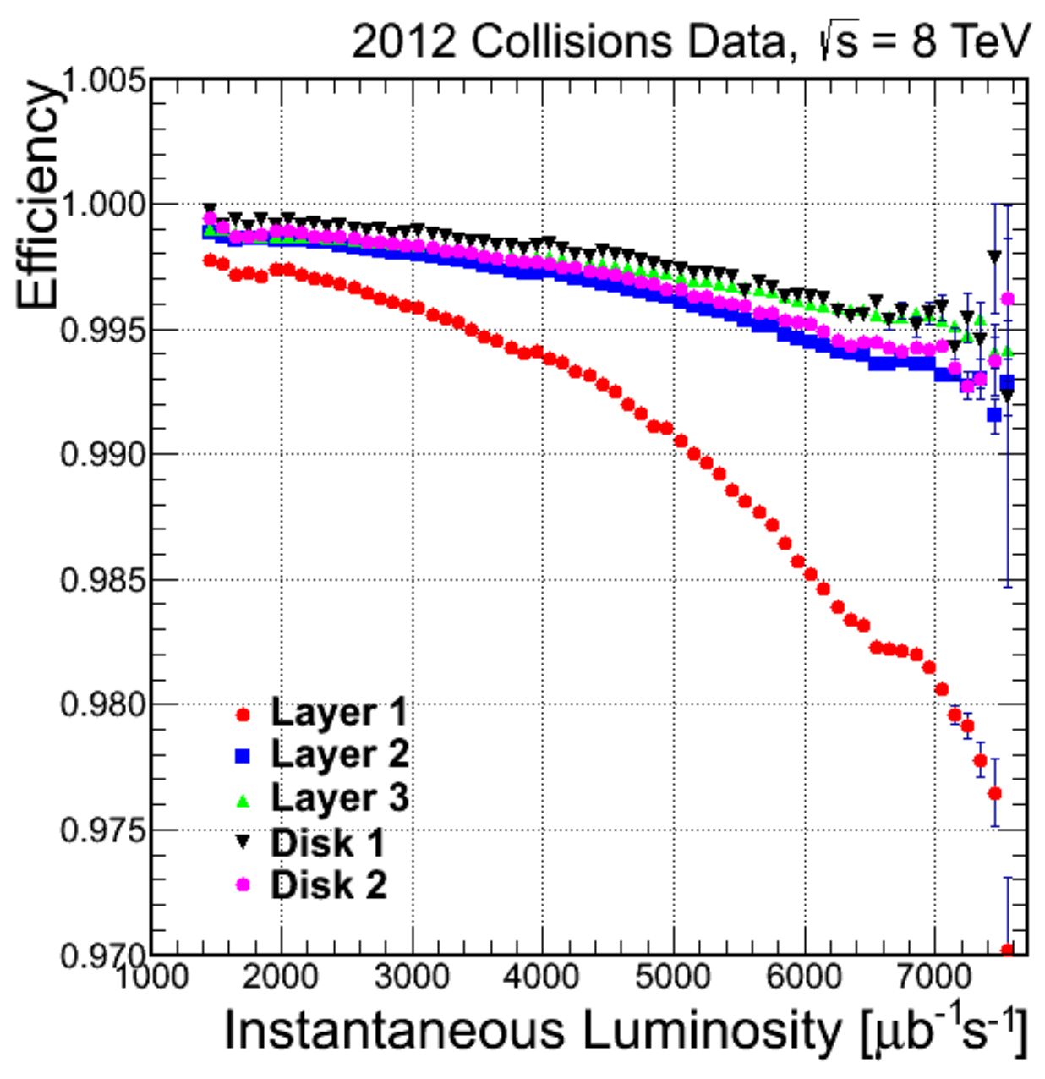
Several effects need to be accounted for during the analysis.

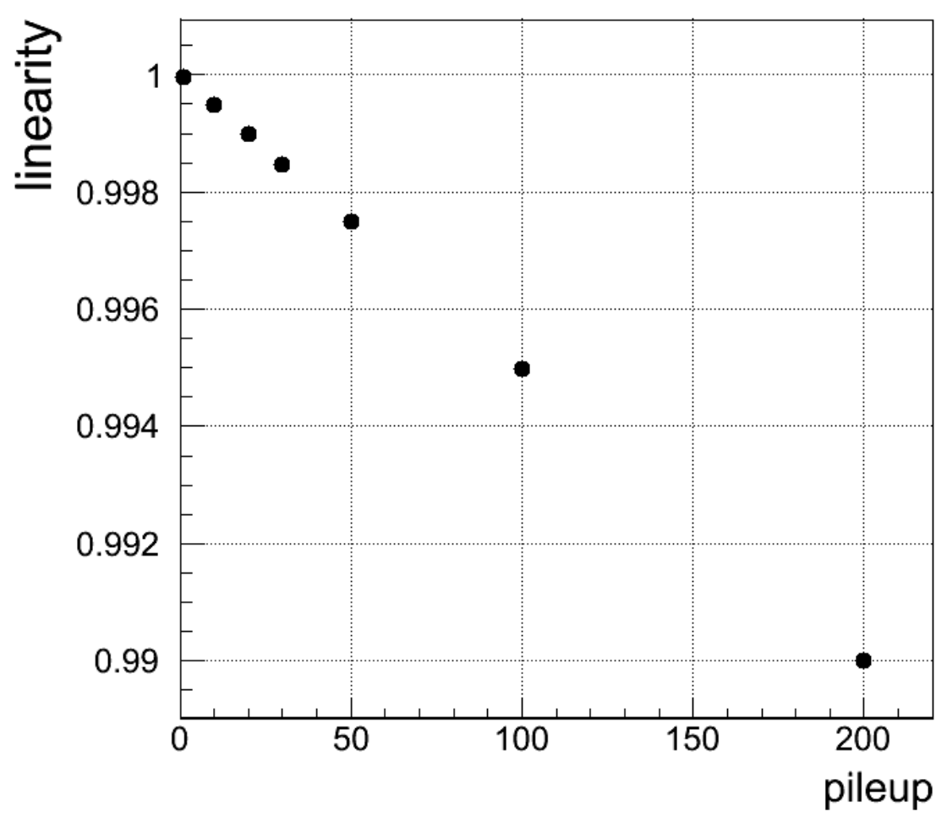
The relationship between number of pixel clusters and luminosity can become nonlinear when pixel clusters belong to more than one track. However, the loss of linearity was determined to be very small, only 1% at a pileup value of 200 (below).

The detector can also be affected by "dynamic inefficiencies" when the data rate becomes very high, causing the data acquisition system to become busy and preventing data taking. This effect is in general quite small, less than 0.5% overall (upper right).

"Afterglow" due to detector material activation can cause out-of-time response in the pixel cluster count. The afterglow effect was modeled assuming an exponential decay, and the effect was determined to be ~2%.

In general, the uncertainty of the luminosity integration is low, contributing a total of 1.2% on the overall uncertainty, which is 2.5%.



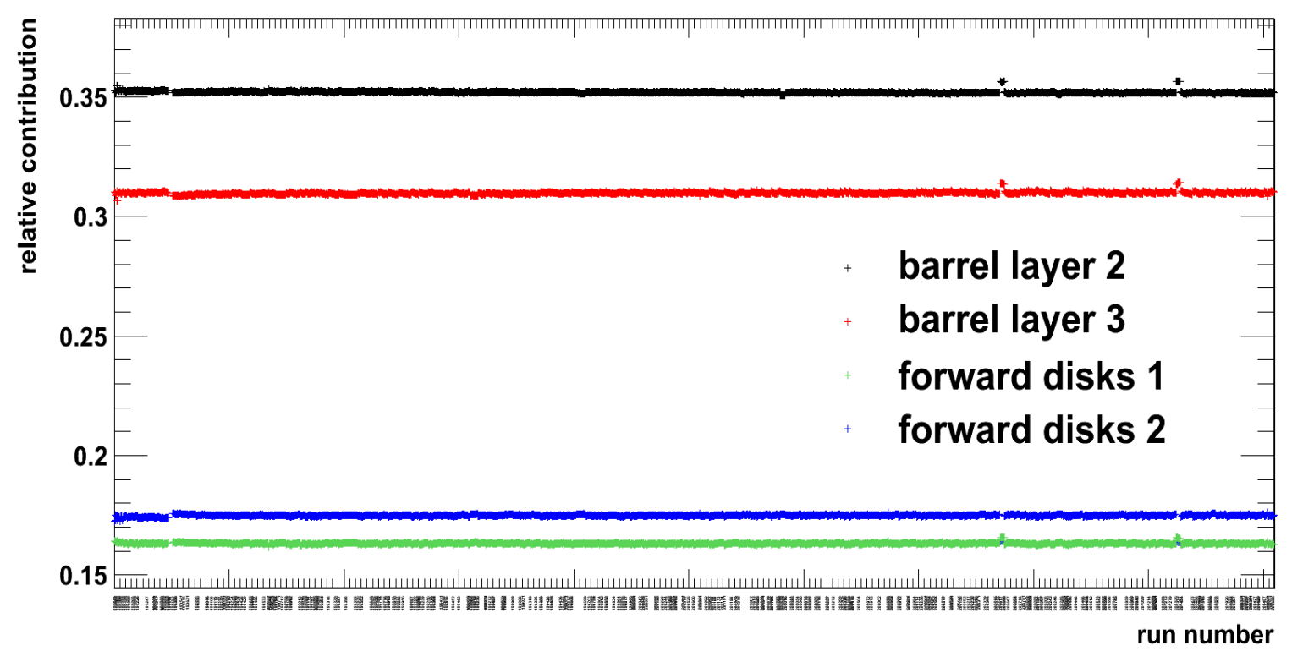


	Systematic	correction (%)	uncertainty (%)
Integration	Stability	-	1
	Dynamic inefficiencies	-	0.5
	Afterglow	~ 2	0.5
Normalization	Fit model	-	2
	Beam current calibration	-	0.3
	Ghosts and satellites	-0.4	0.2
	Length scale	-0.9	0.5
	Emittance growth	-0.1	0.2
	Orbit Drift	0.2	0.1
	Beam-beam	1.5	0.5
	Dynamic-β	-	0.5
	Total		2.5

Stability of measurement

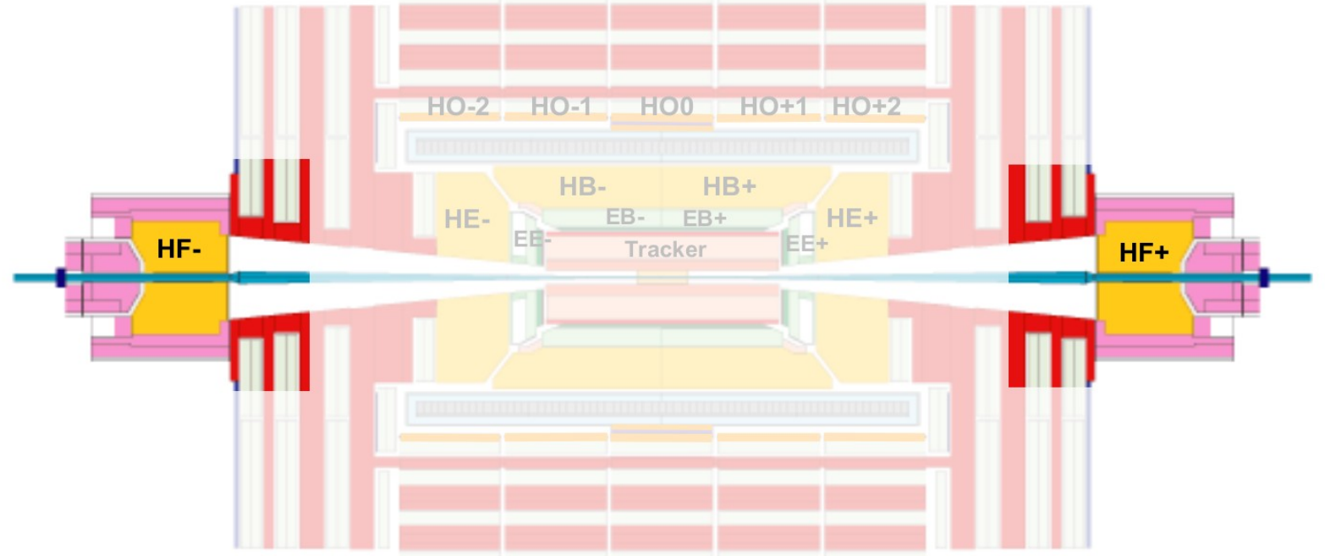
The luminosity calibration constant, σ_{vis}, should remain constant in time, but this is only true of an ideal luminometer. Since it depends on the acceptance and efficiency of the luminometer, it may need to be corrected according to the measured acceptance and efficiencies. Using only channels that have been active for the full run mitigates this need to a certain extent, but there are many other effects that can play a role.

One method of ensuring σ_{vis} remains constant is to check the pixel layers against each other. This gives excellent results, as shown in the figure below. The relative comparisons show stability at the 0.5% level.



Another stability check is a comparison with the Z->µµ cross section. By definition the true Z->µµ cross section is constant with time and constant beam energy. Therefore, if a different cross section is measured with time, it can be corrected and the corrections also applied to the luminosity measurement. This study is in progress.

Online luminosity measurement: forward hadronic calorimeter

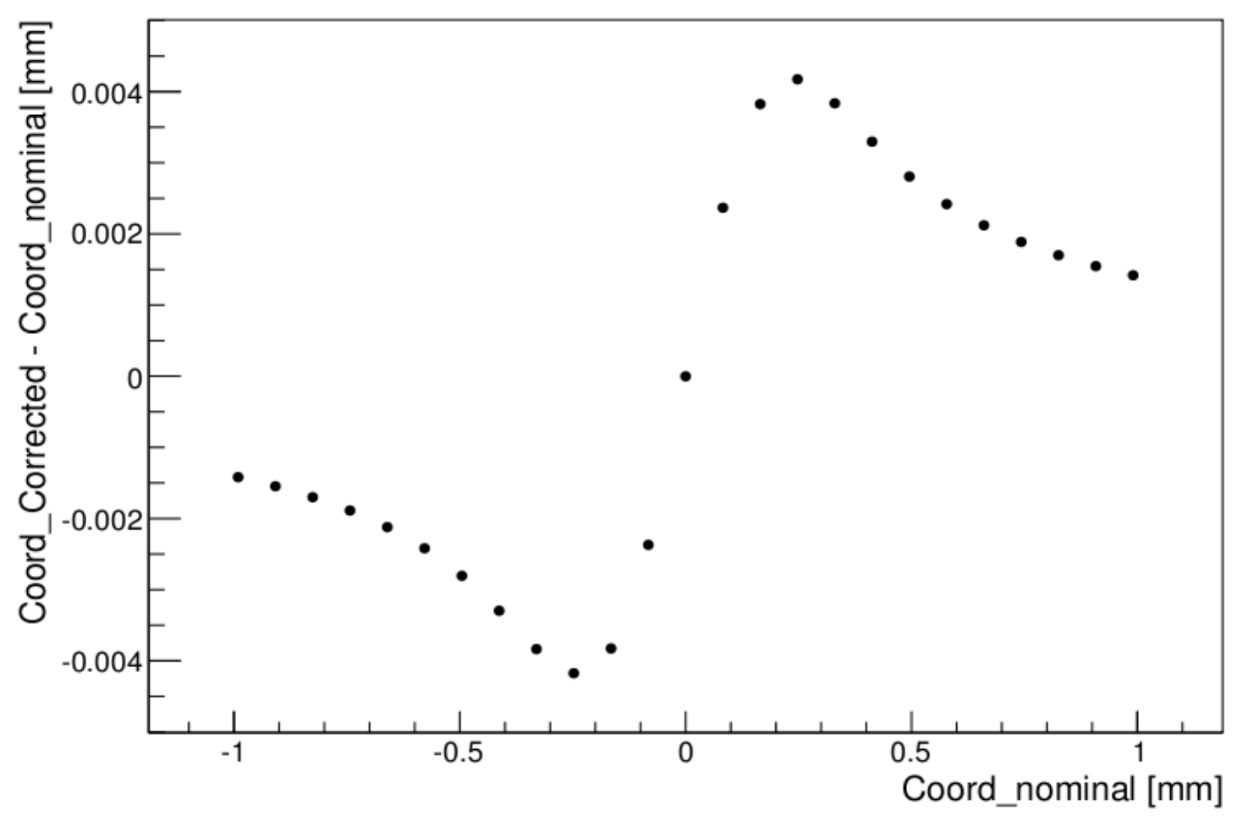


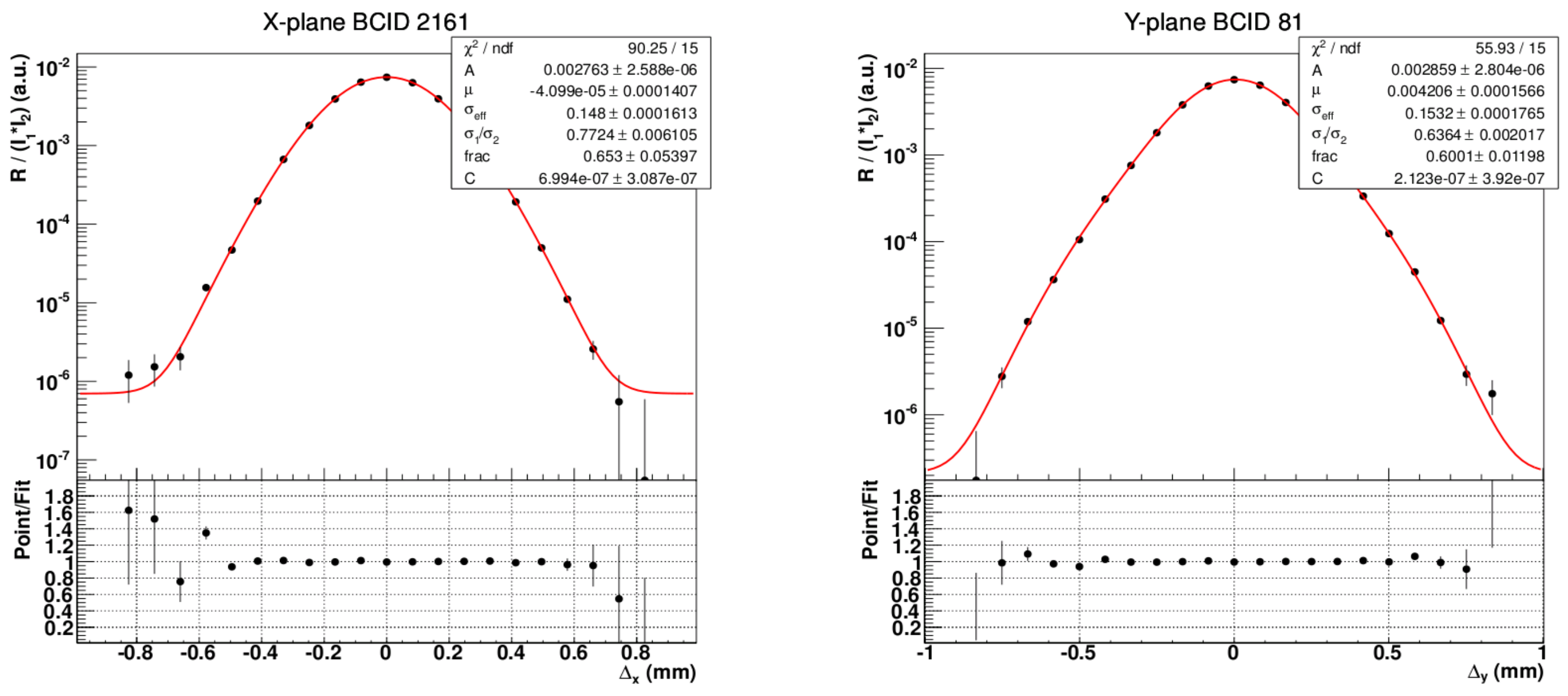
CMS forward hadronic calorimeter
- Extension of endcap hadronic calorimeter, 3 < |η| < 5
- 36 segments in ϕ, 12 in η
- Quartz fibers embedded in iron absorber
- Fast (~10 ns) collection of Cherenkov radiation

The hadronic forward calorimeter HF was used for the online luminosity measurement during Run I, providing bunch-by-bunch luminosity values in real time. The measurement is less precise than that of the pixel detector, but the HF does not require stable beam and can therefore operate under all beam conditions.

The HF luminosity measurement uses the zero-counting technique. The number of bunch crossings with zero hits is counted. The negative logarithm of this quantity is proportional to the number of interactions in the same time period, due to the Poissonian behavior of the hit rate. When the fraction of zero hits is very high, the relationship between luminosity and the measured quantity is linear.

HF also participated in Van der Meer scans for absolute luminosity calibration. In the examples shown below, the rate vs beam separation curves for individual bunches were fitted with a double-Gaussian plus a constant. The plot to the right shows the impact of beam-beam deflection effect on the beam position. Overall, the result of the most recent Van der Meer scan (Jan/Feb 2013) was an absolute calibration with an uncertainty of 3.7%.





Upgrades to online luminometers

After the upgrade, the online luminosity measurement system will include several more subsystems. This will introduce redundancy into the system, ensuring continuous performance in case one subsystem drops out. In addition, having multiple measurements provides confirmation of the measured luminosity value.

The Fast Beam Condition Monitor (BCM1F) will consist of 24 single-crystal diamonds situated in two parallel planes on either side of the interaction point. The Pixel Luminosity Telescope (PLT) will consist of 16 3-layer silicon telescopes, situated just outside BCM1F in the z-direction. The subsystems will each provide their raw data to the LumiDAQ software system, which will combine it for publishing, processing, and storage. The LumiDAQ system will also serve to synchronize the subsystems, providing identical timing and control signals to each, as well as counters to ensure proper resynchronization in case one system joins the run on-the-fly.