CMS luminosity calibration results

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on behalf of the CMS collaboration

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Outline

- The offline CMS luminosity measurement
  - HF luminosity
  - Luminosity measurement from counting pixel clusters
    - Analysis
    - Absolute normalization
    - Afterglow correction
    - Systematic uncertainties
- Online luminosity: status and plans
- Van der Meer scan plans and requests

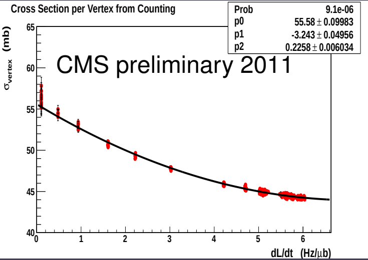
The offline CMS luminosity measurement

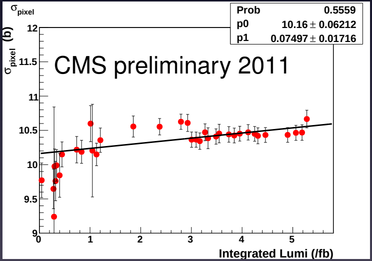
HF lumi

The CMS forward hadronic calorimeter (HF) was intended to be used as *the* CMS luminometer. As such it is the only CMS subdetector capable of recording data for each and every bunch crossing, for each and every orbit.

Over 2011, however, two major issues have been uncovered:

- Less linear vs. pileup than expected
- Significant calibration shift (≈ 4–6%), presumably due to radiation damage in the PMTs





HF lumi: corrections

Over 2011 CMS has resorted to using corrections based on the number of reconstructed primary vertices in zero-bias data to tame the HF results.

The most recent analysis is based on counting pixel clusters to determine the instantaneous luminosity.

The plan is to use this approach also in 2012 for offline luminosity analysis, while keeping the HF for the online luminosity measurement and to determine the relative per-crossing luminosities.

Pixel-based lumi: disclaimer

Please note that the following analysis is not yet fully approved by CMS. Results shown are preliminary and under scrutiny.

No physics analysis so far is using this.

So far no complications have been found, and work on final cross checks and full approval is in progress.

Pixel-based lumi: introduction

The pixel cluster cross section

Define the pixel cluster cross section σ_{clus} as the zero-bias cross section σ_{zb} multiplied by the average number of pixel clusters per zero-bias interaction $< N_{\mathrm{clus}} >$.

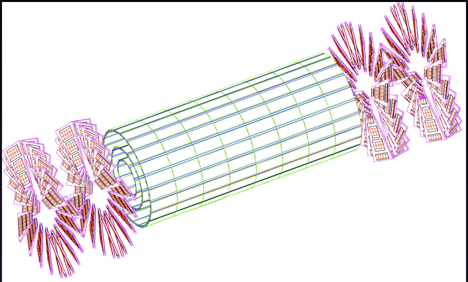
The luminosity L delivered in any lumi section is then given by:

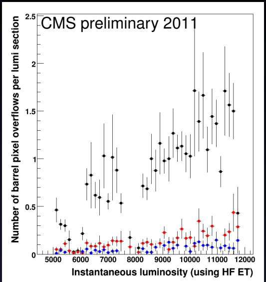
$$L = \frac{< N_{\mathrm{clus}} > n_{\mathrm{bx}} f_{\mathrm{orb}} \Delta t_{\mathrm{ls}}}{\sigma_{\mathrm{clus}}}$$

where:

- n_{bx} is the number of active bunch crossings in the current LHC filling scheme
- $f_{\mathrm{orb}} = 11246$ Hz is the LHC revolution frequency
- $\Delta t_{\mathrm{ls}} = 2^{18}\ \mathrm{orbits} \approx 23.31$ s is the duration of a single luminosity section

Pixel-based lumi: analysis details





The inner pixel barrel layer

Since it has been shown that in 2011 the innermost pixel barrel layer suffered from dynamic readout inefficiencies ($\approx 0.6\%$ at $\mathcal{L} \approx 3.5 \times 10^{33}$ s^{-1}m^{-2}), these modules were excluded from the pixel luminosity analysis. In the rest of the pixel detector these effects were limited to less than 0.4%, which was adopted as a systematic uncertainty.

Modules recovered during technical stops

Also excluded from the analysis were six modules that were not consistently part of the data taking over all of 2011.

Absolute normalization: Van der Meer scan

Van der Meer scan: σ_{clus}

- May 2011 Van der Meer scan; LHC fill 1783, CMS run 165100
- Only crossings 817 and 2752 enabled (neither was ‘private’ to CMS)
- Two pairs of scans done: x, y, x, y

$$\frac{dL}{dt} = \frac{I_1 I_2 f_{\mathrm{orb}}}{2\pi\sigma_{\mathrm{x}}\sigma_{\mathrm{y}}}$$

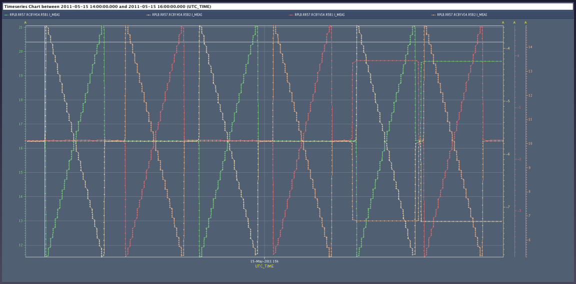
$$\mu f_{\mathrm{orb}} = \sigma_{\mathrm{clus}} \frac{dL}{dt}$$

$\longrightarrow$

$< N_{\mathrm{clus}} >$ @ peak from fit

$$\sigma_{\mathrm{clus}} = \frac{2\pi \boxed{\mu} \boxed{\sigma_{\mathrm{x}}\sigma_{\mathrm{y}}}}{\boxed{I_1 I_2}}$$

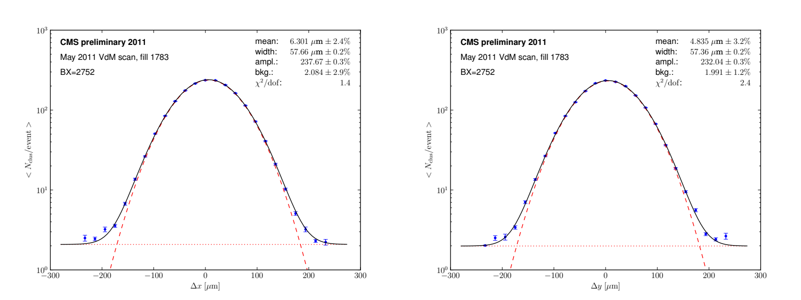
single-bx parameters



Van der Meer scan: fits

Van der Meer scan fits: μ and $\sigma_{\mathrm{x,y}}$

Left: bx 817, right: bx 2752



Fitted with a single Gaussian plus a flat background to take into account non-collision effects. Overall: good fits, some effects in the tails could use a better understanding.

Van der Meer scan: results

Scan	Direction	BX	Peak Rate	σ_x^{eff} (μm)	σ_y^{eff} (μm)	$I_1 I_2$ (10^{22} protons)	σ_{cluster} (mb)
1	x	817	240.5	57.70	56.75	0.7048	7.019
		2752	237.7	57.25	56.76	0.6852	7.082
	y	817	238.1	58.20	57.09	0.7018	7.083
		2752	232.0	57.69	56.90	0.6831	7.006
2	x	817	238.3	58.65	57.42	0.6989	7.213
		2752	235.4	58.09	57.04	0.6813	7.193
	y	817	235.2	59.11	57.74	0.6962	7.245
		2752	230.7	58.49	57.18	0.6793	7.137
						Average:	7.122 ± 0.084 $7.122 \pm 1.2\%$

- Very small variation ($\sigma \approx 0.5\%$) between cross sections within the same scan pair.
- Larger variation ($\sigma \approx 1.0\%$) between cross sections obtained from first and second scan pairs. Also present in the HF data and in the vertex-counting cross check ($\sigma \approx 1.4\%$).

Pixel-based lumi: afterglow correction

Two components:

- 'Ghost response' due to the tail of the pulse shape of the pixel readout. Effect: $\approx 10\%$ in the crossing following an active crossing $\rightarrow$ not relevant for 50 ns operations.
- A long tail resulting from activation, modeled as an exponential tail with mean lifetime (2.7 ± 0.1) µs. Small size, $(7 \pm 2) \times 10^{-4}$, but long range $\rightarrow O(3\%)$ effect.

Pixel-based lumi: afterglow correction

Correction

For each LHC filling scheme the single-bunch response is convolved with the filling pattern. An overall luminosity correction factor for this filling scheme is obtained from the ratio of the raw and convolved luminosities summed over all active crossings:

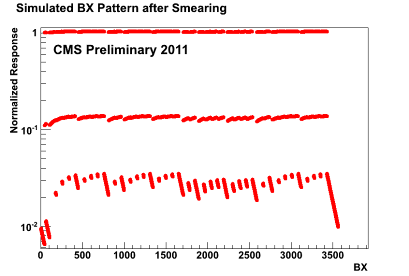
$$C = \frac{\sum_{n\ \mathrm{active}} L_n(\mathrm{raw})}{\sum_{n\ \mathrm{active}} L_n(\mathrm{convolved})}$$

Typical values for C:

$n_{\mathrm{active}} < 200$: $C > 0.990$

$n_{\mathrm{active}} = 214$: $C = 0.989$

$n_{\mathrm{active}} = 1331$: $C = 0.972$



Cross checks

Several cross checks were performed. Cross checks showing significant effects were adopted as systematic uncertainties.

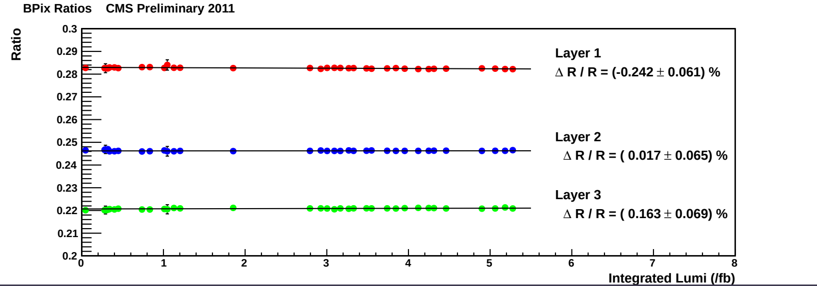
Notable cross checks that remained cross checks:

- It was verified that, as expected because of the large number of pixels, no saturation effects in the cluster count are observed.
- A comparison with the cluster count in the strip tracker shows that the pixel cluster count is only significantly affected by beam conditions under extreme conditions, e.g., the deteriorated vacuum during fill 2208. Since only a very minor fraction of the 2011 data was taken under such conditions, the effect on the overall luminosity is negligible.

Systematic uncertainties

Stability across pixel detector regions

The pixel detector naturally divides into different regions. Our choice: the three barrel layers and the inner and outer forward disks. The relative contributions from each of those regions over all of 2011 was stable to less than 0.3%.



Systematic uncertainties

Pixel gains and pedestals

Cluster reconstruction could potentially suffer from changes in pixel gains/pedestals. No such effect is visible in the aforementioned ratios, but since these are only sensitive to effects of $O(0.5\%)$, this was assigned as systematic uncertainty.

Afterglow correction uncertainty

The single-bunch response used for the afterglow correction was obtained using only the last bunch in each bunch train. This potentially biases the result due to bunch-to-bunch intensity variations, which are known to be of the order of 30%. Assuming that half this range represents a realistic estimate of the real spread in intensity, and using the maximum correction (2.8%), an uncertainty of 1% was assigned.
As a check, the afterglow corrections were derived on data from two different groups of runs with the same filling scheme. The resulting differences were approximately 0.5%. No additional uncertainty was attributed for this fact.

Systematic uncertainties

VdM scan contributions

Length-scale correction

As determined in a dedicated length-scale calibration, the beam widths as measured during the VdM scan are respectively 0.7% and 0.8% too small in the x and y plane. One-third of the corresponding effect on the cross section of 1.5% has been included as systematic uncertainty.

Beam width evolution

The full size of the beam width extrapolation over the duration of the VdM scans, 0.6%, has been included as systematic uncertainty.

Systematic uncertainties - overview

Preliminary and under scrutiny

Source	Uncertainty (%)
Stability across pixel detector regions	0.3
Pixel gains and pedestals	0.5
Dynamic inefficiencies	0.4
Length-scale correction	0.5
Beam width evolution	0.6
Beam shape	-
Beam intensity	3.1
Scan-to-scan variations	1.2
Afterglow	1.0
Total	**3.6**

Systematic uncertainties - overview

Preliminary and under scrutiny

Source	Uncertainty (%)
Stability across pixel detector regions	0.3
Pixel gains and pedestals	0.5
Dynamic inefficiencies	0.4
Length-scale correction	0.5
Beam width evolution	0.6
Beam shape	-
Beam intensity	3.1
Scan-to-scan variations	1.2
Afterglow	1.0
Total	$\mathbf{3.6}$

Preliminary 2011 integrated luminosity

Extrapolating from the pixel live-time to the total delivered luminosity in 2011 this comes to 6.1 fb$^{-1} \pm \approx 5\%$.

Systematic uncertainties - overview

Preliminary and under scrutiny

Source	Uncertainty (%)	2011 vs. 2012 7 TeV vs. 8 TeV
Stability across pixel detector regions	0.3	correlated
Pixel gains and pedestals	0.5	uncorrelated
Dynamic inefficiencies	0.4	uncorrelated
Length-scale correction	0.5	correlated
Beam width evolution	0.6	depends on beam phase space
Beam shape	-	depends on beam optics
Beam intensity	3.1	uncorrelated
Scan-to-scan variations	1.2	?
Afterglow	1.0	largely correlated
Total	**3.6**	

Systematic uncertainties - overview

Intentions/expectations for 2012

- The variation between results from subsequent scans is still escaping us. This will be one of our main focus points. Possible suspects include the beam width evolution and (maybe?) the beam shape.
- For the afterglow correction we expect to be able to
  - improve the afterglow correction, and
  - reduce the corresponding uncertainty by a factor two.

Online luminosity: status and plans

CMS luminometers

Our main online luminometer remains the HF

- Lookup tables converting ADC counts to energy have been updated.
- Online HF luminosity will be corrected based on the pixel cluster information.
- Will be watched by many sharp eyes this year.

BCM1F

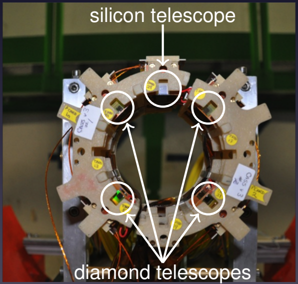
One of our Beam Condition Monitors has been equipped with gated counters. Work is in progress to include this (initially) as a ‘cross-check luminometer.’

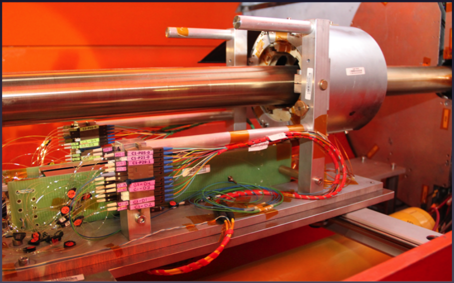
CMS luminometers

Pixel Luminosity Telescope

- Dedicated, stand-alone luminometer
- Just finished installation of 4 diamond-pixel and 1 silicon-pixel telescope
- First diamond tracker prototype in forward region!
- Full installation (8 telescopes on each side of CMS) in LS1
- Capable of reliably measuring the high instantaneous luminosities expected in 2015 and beyond
- Aim: per-crossing relative luminosities precise to 1% once per second

Finalizing DAQ software, planning to join the first Van der Meer scans!





Van der Meer scan plans and requests

Semi-regular 'low-cost' scans

Request: semi-regular small scans for IP5 only

- On-request, parasitic end-of-fill scans
- One scan in x, one in y
- Limited range: O(10) points over two σ_{beam}
- Limited duration: a few minutes per point

This would allow us to keep better track of our all our luminometers over time. No perfect fit needed every time, the aim is to collect a trend.

Early Van der Meer scans

From the CMS side there is no desire for a dedicated Van der Meer scan fill very early on. We would like, however, to have a relatively early opportunity to verify our luminometers.

- Can be with nominal optics ($\beta^* = 0.6$ m, nominal crossing angle, etc.)
- One scan in x, one in y, please
- One of these proposed hybrid filling patterns would be fine

The precision Van der Meer scan

CMS would like to postpone *the* precision Van der Meer scan till after the ICHEP data set has been frozen.

Wish-list

- $\beta^* = 11$ m
- Sparse filling scheme, low intensity, no trains
- No very strong feelings about the crossing angle

Heavy Ion Van der Meer scan

The CMS HI group would like to request a dedicated HI Van der Meer scan, if in any way possible, to verify the absolute calibration.

All in all

CMS:

- is finalizing a promising new approach to measuring the luminosity offline based on pixel cluster counting;
- will keep the HF, but corrected based on pixel cluster information, as our main online luminometer;
- is adding to their arsenal of luminometers with BCM1F and the PLT

Concerning Van der Meer scans in 2012 the main focus is on:

- watching possible trends in calibration;
- understanding and correcting the scan-to-scan calibration differences;
- improving the afterglow correction and reducing the corresponding uncertainty

Backup slides

Pixel-based lumi: VdM scan results

Pixel Fits

Scan	Direction	BX	Peak Rate	σ_x^{eff} (μm)	σ_y^{eff} (μm)	$I_1 I_2$ (10^{22} protons)	σ_{cluster} (mb)
1	x	817	240.5	57.70	56.75	0.7048	7.019
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						Average:	7.122 ± 0.084 $7.122 \pm 1.2\%$

Vertex Fits

Scan	Direction	BX	Peak Rate	σ_x^{eff} (μm)	σ_y^{eff} (μm)	$I_1 I_2$ (10^{22} protons)	σ_{cluster} (mb)
1	x	817	1.582	57.90	57.90	0.7033	46.50
	y		1.583				46.96
	x	2752	1.550	57.61	57.75	0.6842	46.50
	y		1.551				46.94
2	x	817	1.560	58.88	58.92	0.6976	47.88
	y		1.560				47.41
	x	2752	1.541	58.28	58.23	0.6803	48.29
	y		1.542				47.89
						Average:	47.30 ± 0.68 $47.30 \pm 1.4\%$

Pixel-based lumi: afterglow correction

Model

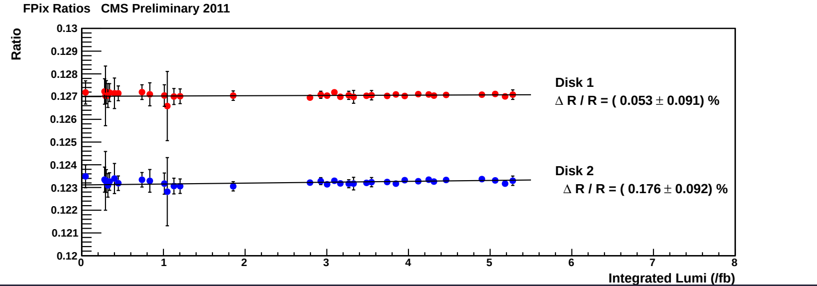
Starting from an active crossing n:

- afterglow fraction in crossing $n+1$: α_1
- afterglow fraction in crossing $n+2$: α_2
- afterglow fraction in crossing $n+3$ etc.: $\alpha_2\alpha_3^{n-2}$

Using random-trigger data a single-bunch response was derived and α_i were determined:

α_1	0.104
α_2	$(7 \pm 2) \times 10^{-4}$
α_3	0.9907 ± 0.0002

Systematic uncertainties



Systematic uncertainties

Dynamic inefficiencies