MEASUREMENT OF CMS LUMINOSITY

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Adam Hunt for the CMS Collaboration

Overview

- Methods for luminosity measurement at CMS:
  - Online - HF
  - Offline - HF & Vertex
- Performance and comparison of methods
- Absolute calibration using Van der Meer Scans:
  - Introduction to the method
  - Scans & Results at CMS
  - Systematic Uncertainties
- Results & Conclusion

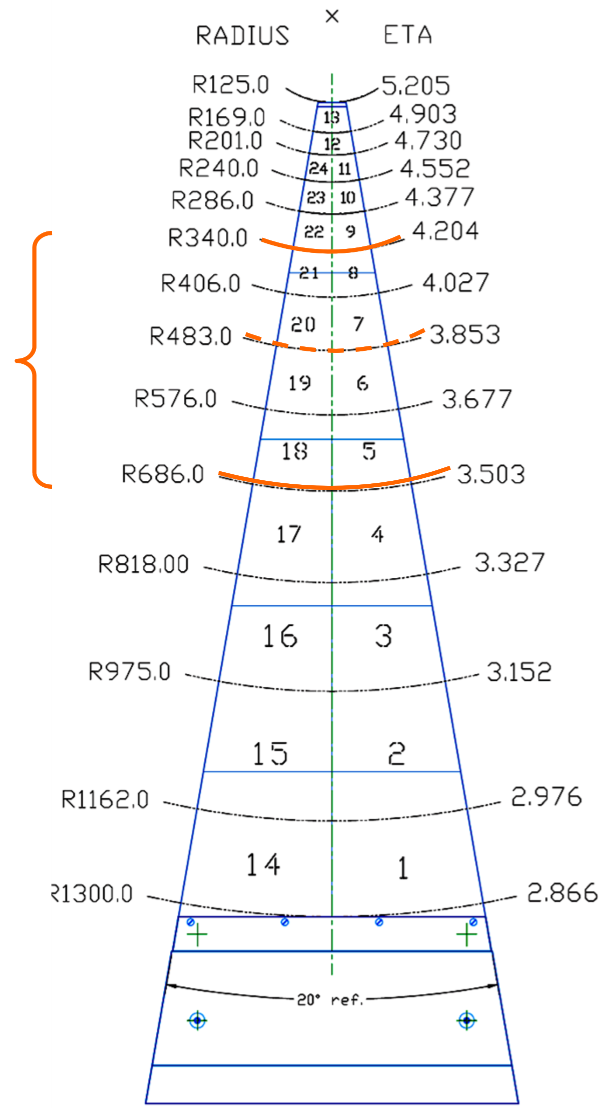
Measuring Luminosity

$$R = \sigma L$$

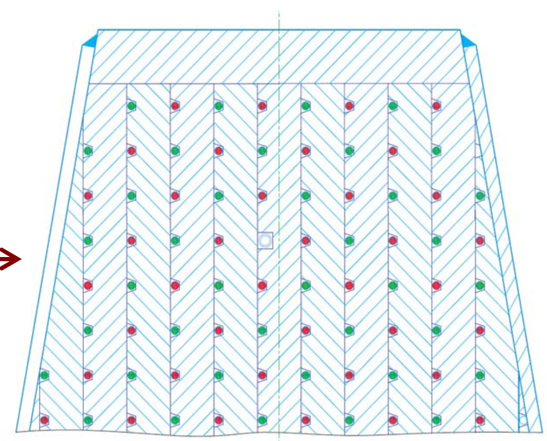
- Why do we measure luminosity?
  - Measure absolute cross sections.
  - Determine accelerator performance.
- http://cms-physics.web.cern.ch/cms-physics/public/EWK-10-004-pas.pdf

Luminosity Measurement: Online - HF

- CMS Luminosity is continuously measured using the forward hadronic calorimeters (HF), which cover the pseudorapidity range $3 < |\eta| < 5$, in two ways:
  1. Tower occupancy measurement (2×2 η rings)
  2. Total E_T measurement (4 η rings)



Single HF Tower (13) with alternating long (L) and short (S) fibers.



Luminosity Measurement: Online – Tower Occupancy

- We start from formula relating luminosity to number of interactions, where μ = mean number of interactions per bunch crossing, σ = pp cross-section, L = instantaneous luminosity and f = bunch crossing frequency.

$$\mu = \frac{\sigma L}{f}$$

No. of interactions is Poisson with mean μ

- For a noiseless calorimeter system, with ***p*** being the **probability that a tower is not hit in a single bunch crossing**, it is easy to show the average fraction of empty towers, $<f_0>$, is:

$$\langle f_0 \rangle = e^{-(1-p)\mu}$$

- Accounting for noise is a non-trivial exercise that adds non-linear corrections. These are small (ε<<1) under certain conditions that our system meets. The final expression for the log of the empty tower fraction is linear with μ.

$$-\ln\langle f_0 \rangle = (1-p)(1-\varepsilon)\mu + N$$

Slope correction
Non-linear, but small

Noise offset

Luminosity Measurement: Online – E_T Sum

- The average transverse energy sum per bunch crossing is also linear with the number of interactions:
- There is no inherent non-linearity in the method. However, if truncation is used, as occurs in the HF Look-up Table (LUT), extra non-linear terms are introduced.
- The effect of this truncation is less than 2% over a very large range of luminosities, $10^{28} – 10^{34}$ cm^{-2}s^{-1}.

Noise offset.

$$\langle E_T \rangle = \nu_s (1-p)\mu + N$$

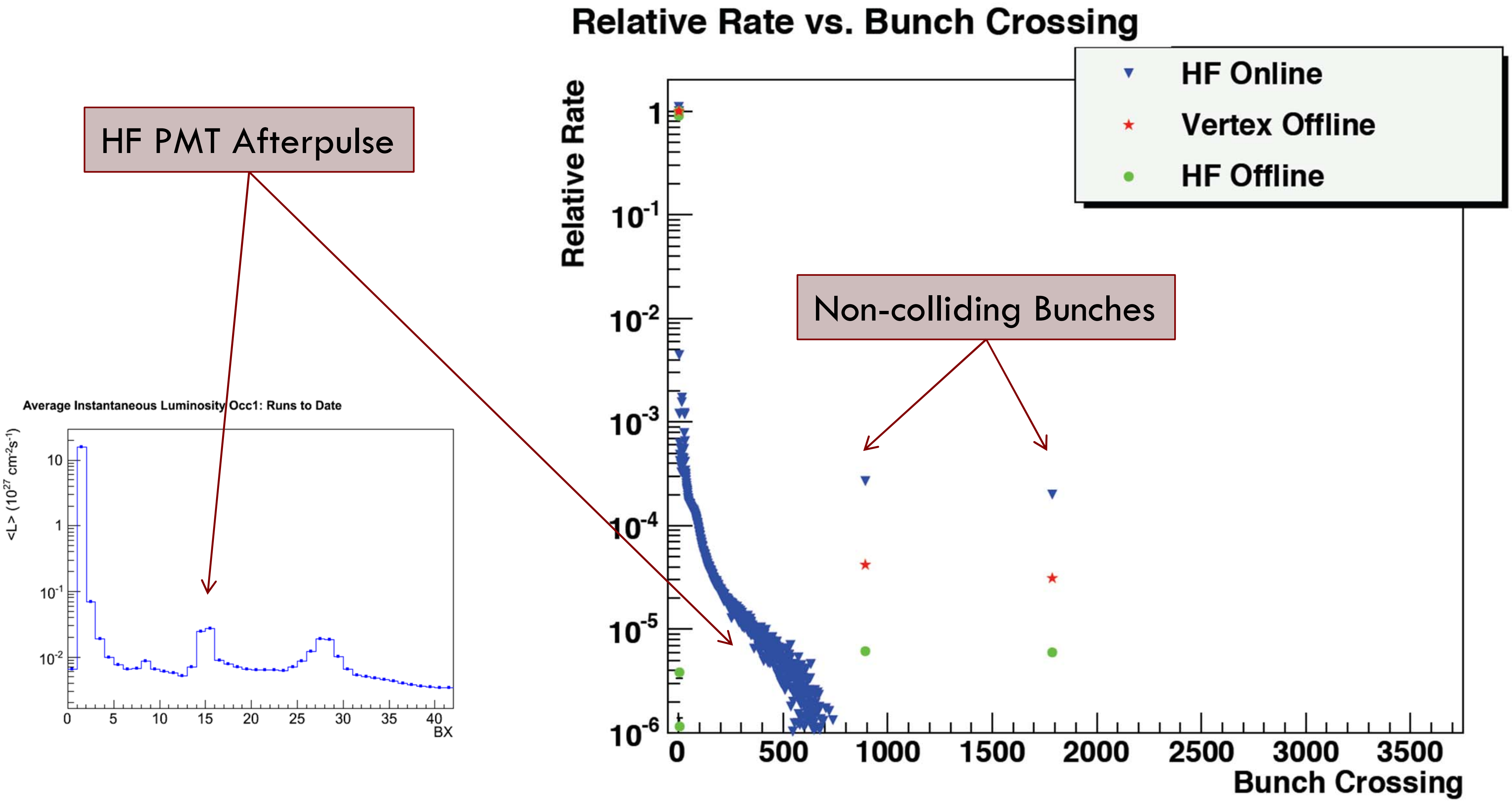
ν_s gives the average energy of a single bunch crossing.

Luminosity Measurement: Offline – HF & Vertex

- HF Offline
  - Require $\Sigma E_T > 1$GeV in both HF+ and HF-
  - Require $|t| < 8$ns in both HF+ and HF-
- Vertex Counting Offline
  - Require ≥ 1 vertex with $|z| < 15$cm
- Monte Carlo Efficiency Estimate

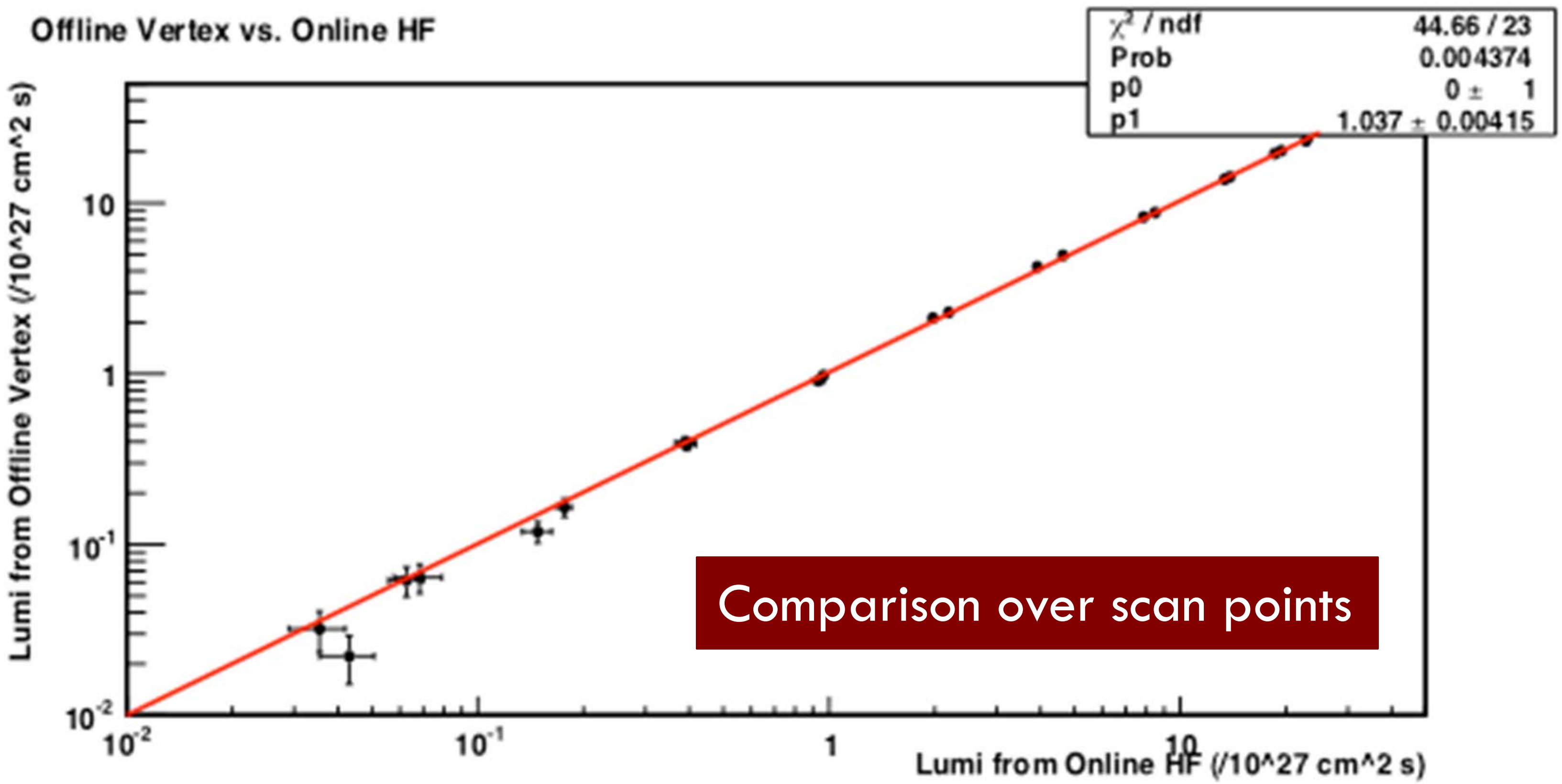
$\sigma_{Minbias}$ = 73.1 mb		
Method	Efficiency	Eff. Cross-Section
HF	63.4 %	45.2 mb
Vertex	73.4 %	52.3 mb

Performance Comparison

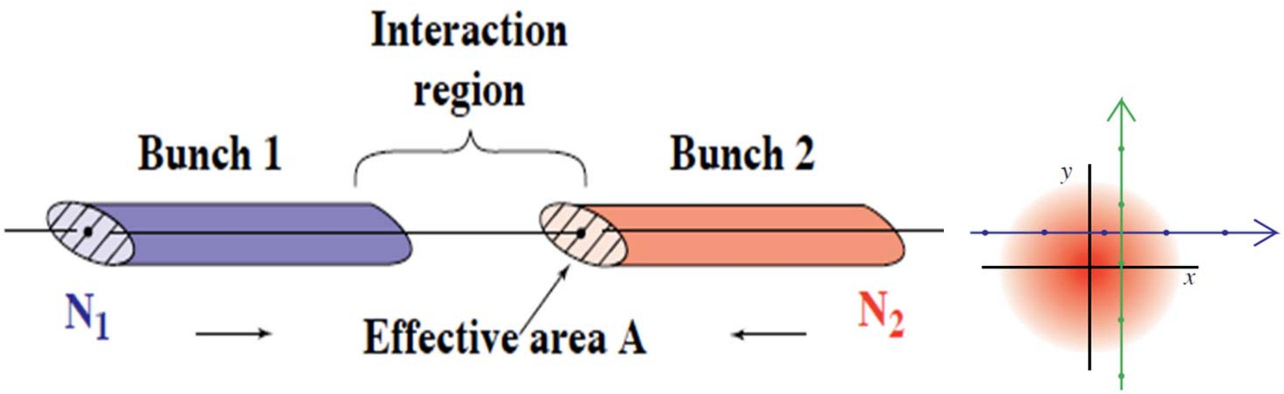


Online - Offline Comparison

	$<\mathcal{L}>$	Online	HF Offline		Vtx Offline	
Fill	$(\mathrm{cm}^{-2}\mathrm{s}^{-1})$	L ($\mu\mathrm{b}^{-1}$)	L ($\mu\mathrm{b}^{-1}$)	Ratio	L ($\mu\mathrm{b}^{-1}$)	Ratio
1058	6.1×10^{27}	71.1	71.3 ± 1.2	1.004	74.4 ± 1.2	1.047
1089	2.0×10^{28}	230	234 ± 2	1.016	240 ± 2	1.041
1104	6.9×10^{28}	461	473 ± 4	1.026	485 ± 4	1.052



Absolute Calibration Method



$$L = N_1 N_2 F n_b \int \rho_1(x,y)\rho_2(x,y)dxdy$$

$$L = \frac{N_1 N_2 f n_b}{A_{eff}}$$

$$A_{eff} = 2\pi\sigma_x\sigma_y$$

Luminosity can be accurately measured by scanning the beams across each other (separation scan method) and measuring the size and shape of the interaction region. [Method pioneered by S. Van Der Meer at ISR.] Note: method is in principal independent of the beam profile shape.

N_1 = Number of protons in beam 1
N_2 = Number of protons in beam 2
f = Orbit frequency
n_b = number of colliding bunch pairs
$\rho_{1,2}(x,y)$ = proton density
$\sigma_{x.y}$ =Width of the convolution of two beams with Gaussian density

Absolute Calibration at CMS

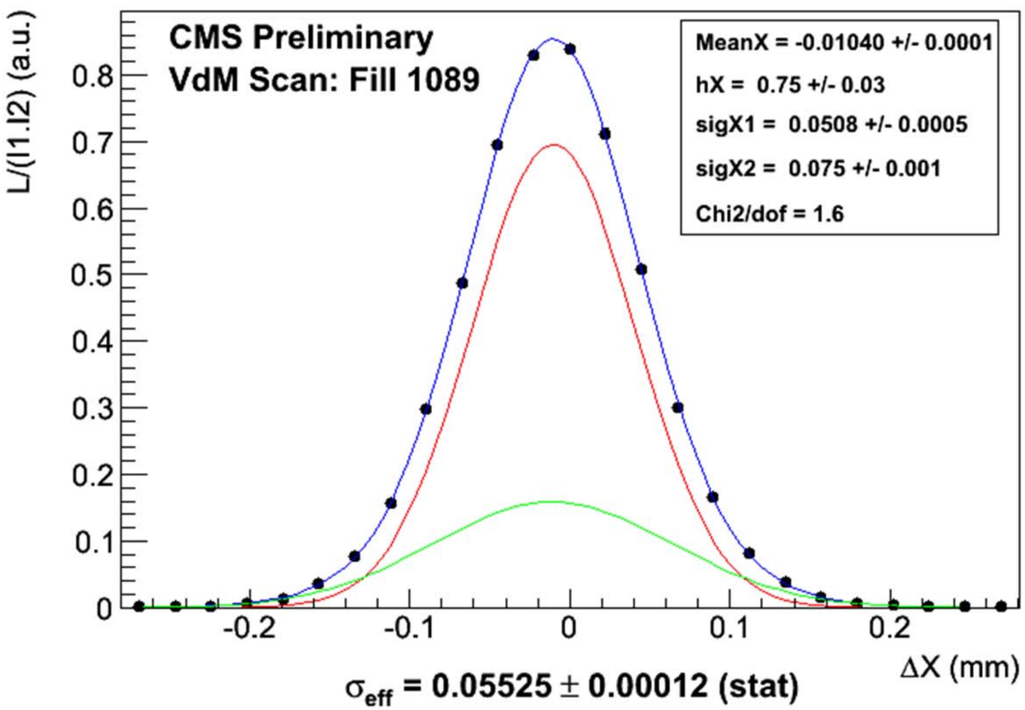
- The separation scan method is used for absolute calibration at CMS. We had 25 different beams separations per scan with a maximum separation of 4.5σ (±~280μm).
- A double-Gaussian beam profile is needed to fit the beams observed in CMS.
- Luminosity with beam separation *d* is given by

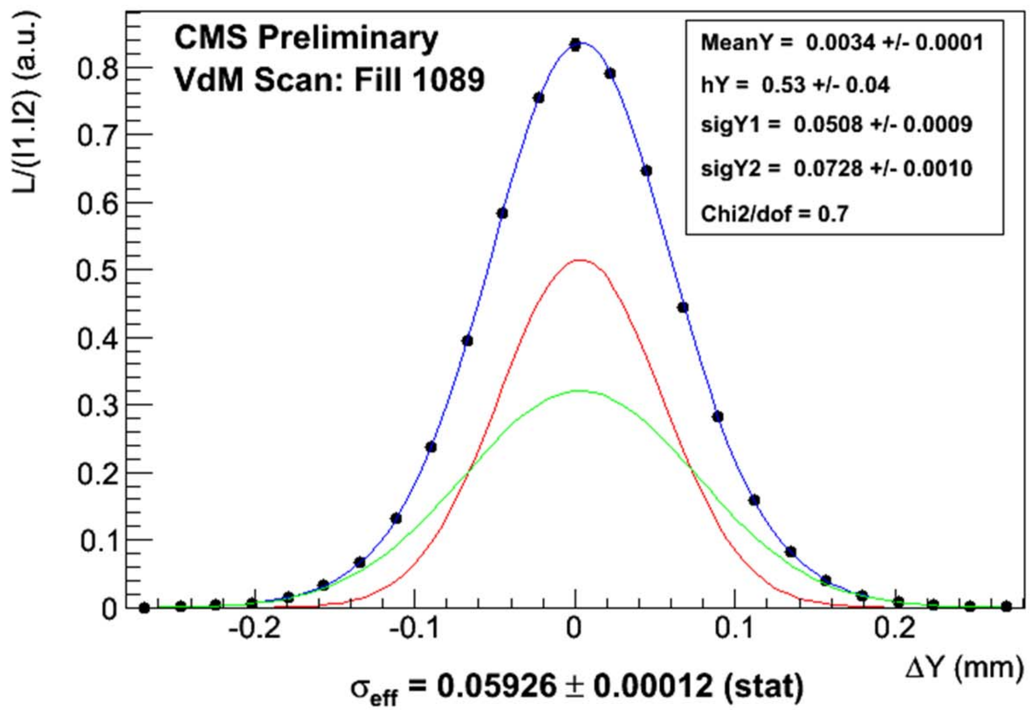
$$L = \frac{N_1 N_2 f n_b}{2\pi\sigma_{eff}(x)\sigma_{eff}(y)}$$

$$\sigma_{eff}(i) = \frac{\sigma_{1i}\sigma_{2i}}{h_i\sigma_{2i} + (1-h_i)\sigma_{1i}}$$

$$L(d) = L_0\left(\frac{h_i}{\sqrt{2\pi}\sigma_{1i}}\exp\frac{-d^2}{2\sigma_{1i}^2} + \frac{(1-h_i)}{\sqrt{2\pi}\sigma_{2i}}\exp\frac{-d^2}{2\sigma_{2i}^2}\right)$$

Online Scan Results

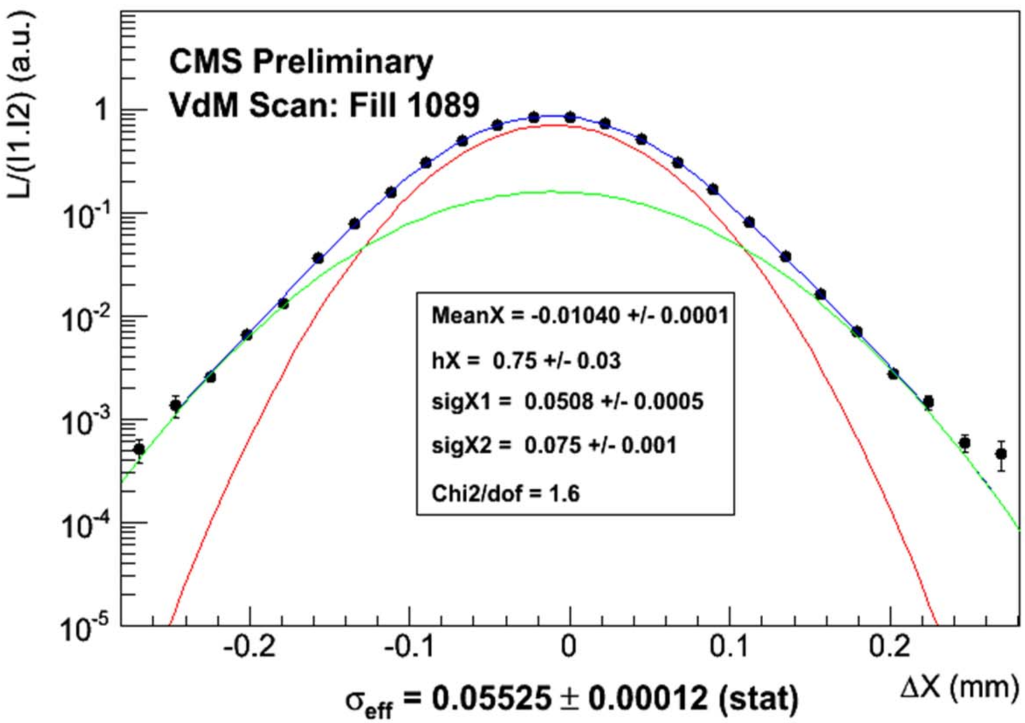


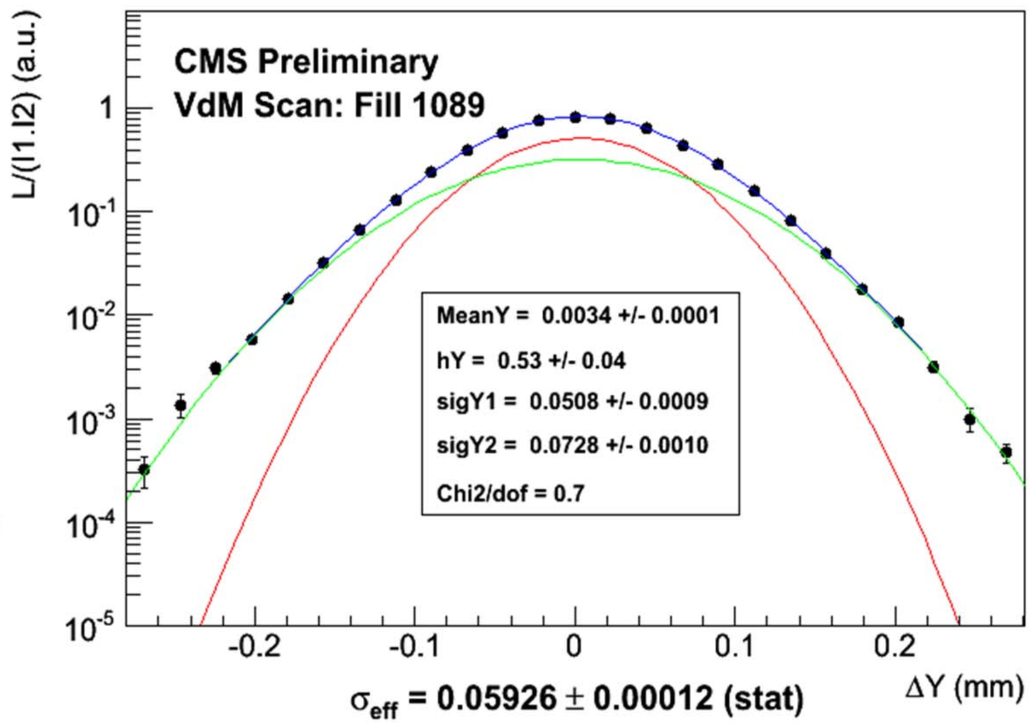


X Backward

Y Forward

Online Scan Results





X Backward

Y Forward

Fit Results Summary

Fill	Scan	σ_{eff} (i) HF Offline	σ_{eff} (i) Vtx Offline	σ_{eff} (i) HF Online
1089	X forward	0.05513	0.05534	0.05503±0.00012
	X backward	0.05531	0.05534	0.05525±0.00012
	Y forward	0.05906	0.05940	0.05926±0.00012
	Y backward	0.06001	0.06007	0.05985±0.00010

- Generally excellent agreement on the widths between the different fit results.

Systematic Uncertainties

Beam Background

This accounts for any contribution of non-pp collision backgrounds to the luminosities used for the fit. It is evaluated by taking the difference between the nominal fit, and a fit with the total apparent luminosity from the two non-colliding bunches subtracted. The difference is < 0.1%.

Fit Systematics

To evaluate the systematic error associated with the fitting procedure, we look at the differences in the beam widths from the three independent methods. Conservatively this gives an error of 0.5% per plane, and allowing for possible correlations we take an error of 1%.

Beam Shape

To allow for the fact that we don't know the true beam shape and estimate it with a double-Gaussian, we recalculate the beam widths using cubic spline fits. For fill 1089 the error is ~ 0.5%. For fill 1058 the errors are 1.9% and 2.8%. We take the larger errors, and use a total of ~3%.

Beam Current Measurement

The RMS measurement errors on the beam currents are 5% per beam. At least some of the contributions to the error are correlated, we conservatively assume full correlation and add the current errors linearly to give a total error of 10%. This is the dominant systematic uncertainty.

Systematic Uncertainties: Summary

Error	Value [%]
Beam Background	0.1
Fit Systematic	1
Beam Shape	3
Length Scale Calibration	2
Zero Point Uncertainty	2
Total:	4

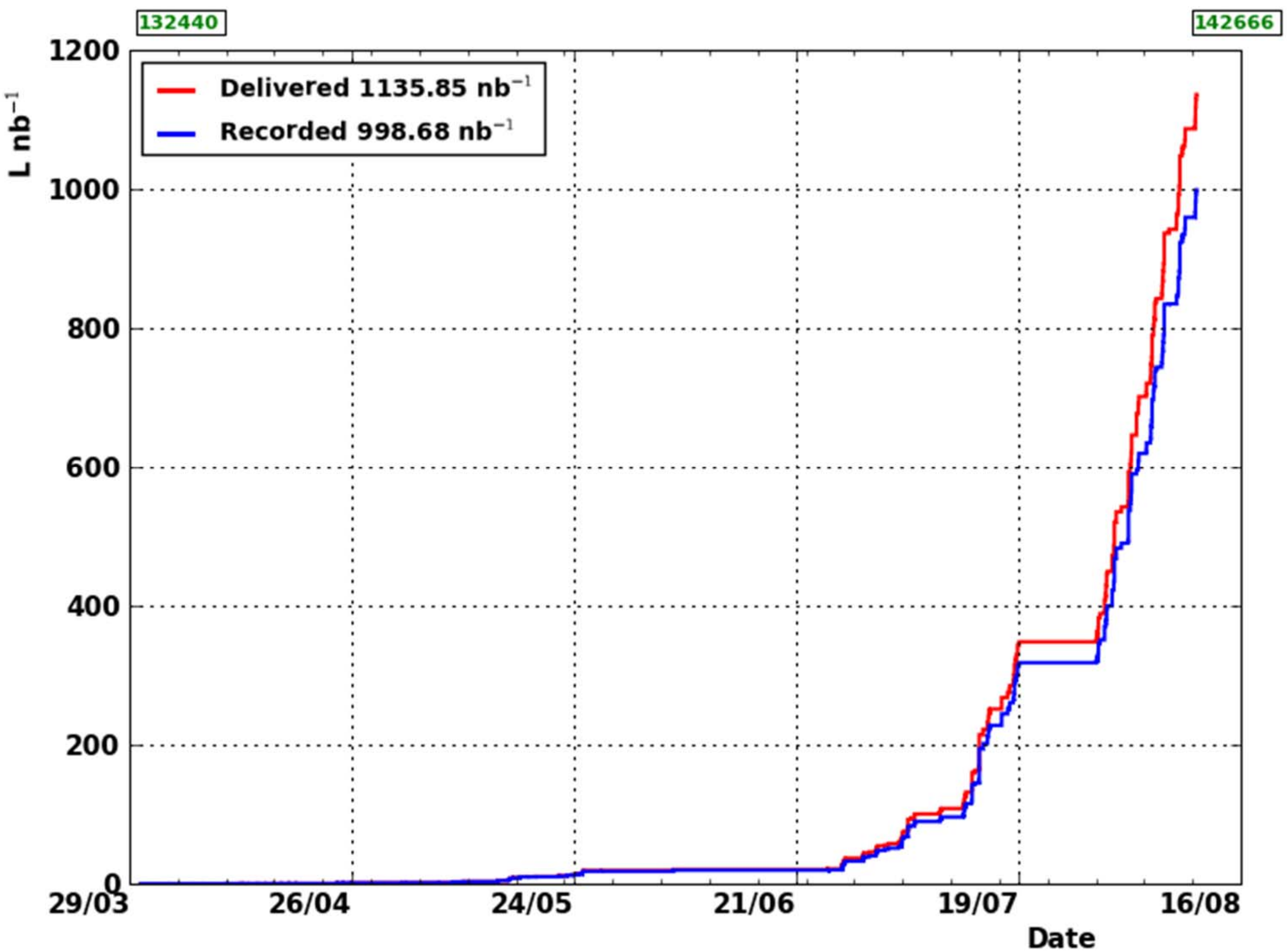
Error	Value [%]
Previous total	4
Beam Current Normalization	10
Total:	11

With the HF systematic uncertainty, the total uncertainty is still 11%.

Improvements on the Uncertainty

- Beam Current uncertainty: As we move to higher beam currents, the beam normalization uncertainty will decrease.
- Once the beam current normalization is completely understood, the relative importance of the other uncertainties will increase. We expect to make modest improvements in these areas also.

Integrated Luminosity



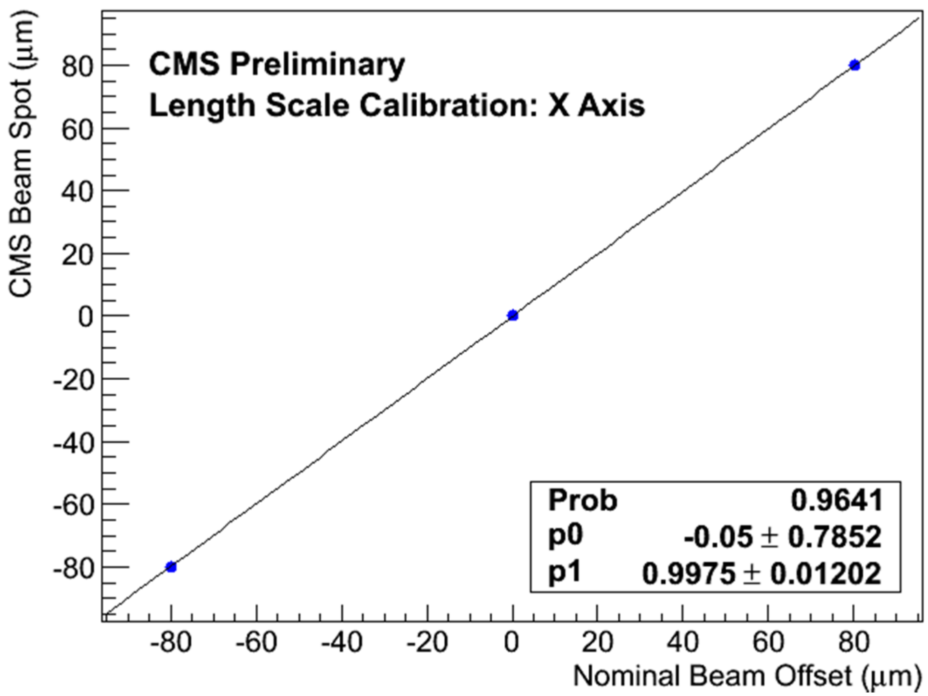
Conclusion

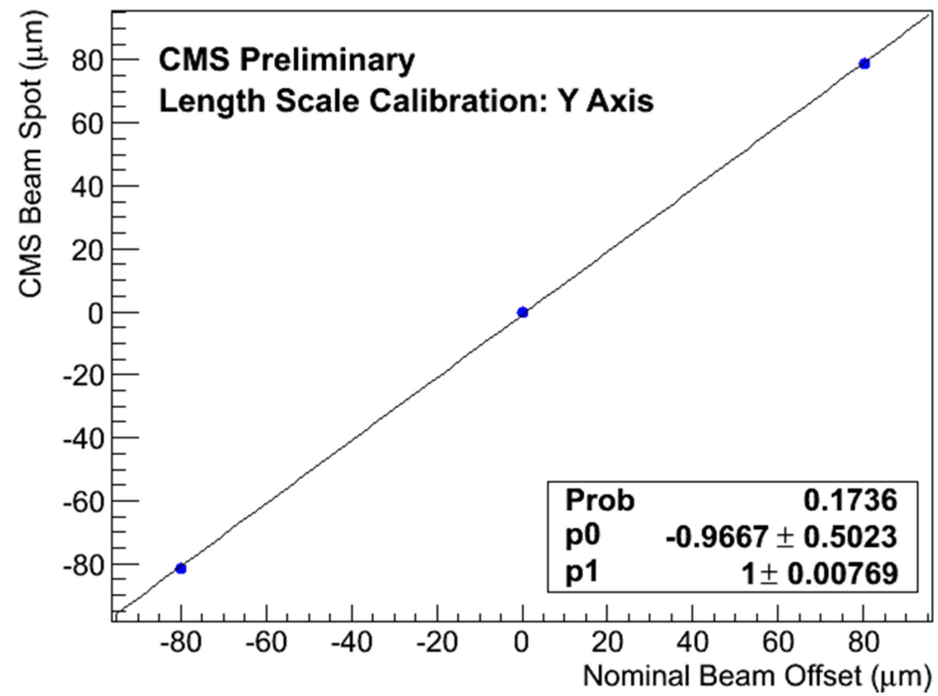
- Comparisons between the online HF measurement and the offline HF and vertex methods demonstrate very good consistency and linearity over a large range of luminosities.
- Analysis of the Van der Meer scan data has been used to arrive at an absolute normalization for the luminosity measurement. We give the result relative to the Monte Carlo derived normalization:

$$R_{scan/MC} = 1.007 \pm 0.003 \pm 0.110\ (\text{syst})$$

Backup Slides

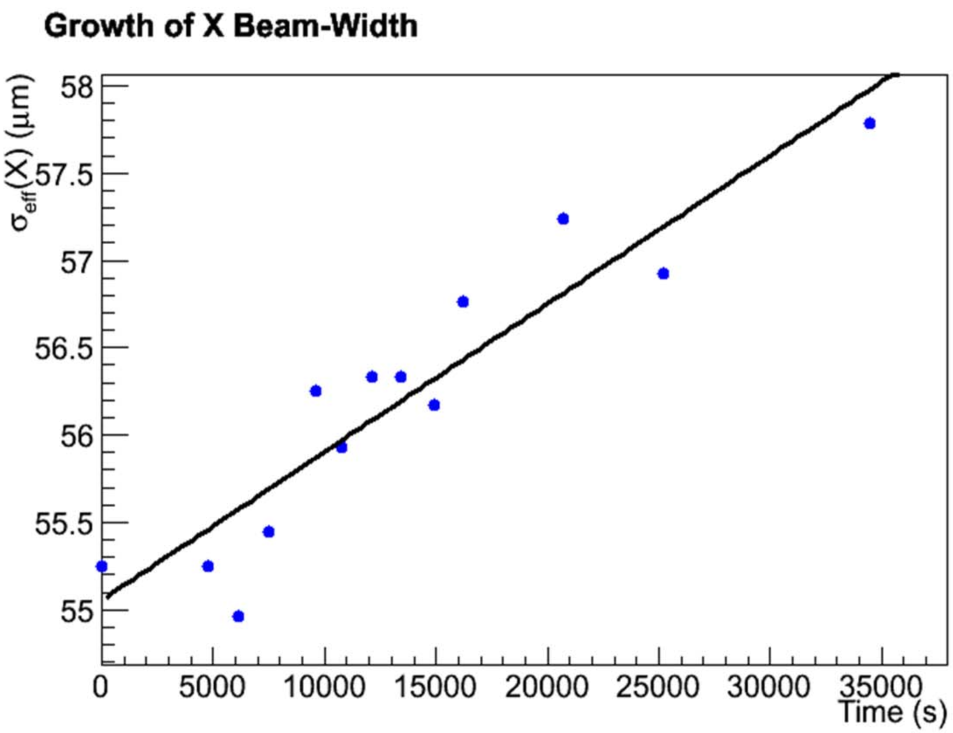
Systematic Uncertainties: Length Scale Calibration

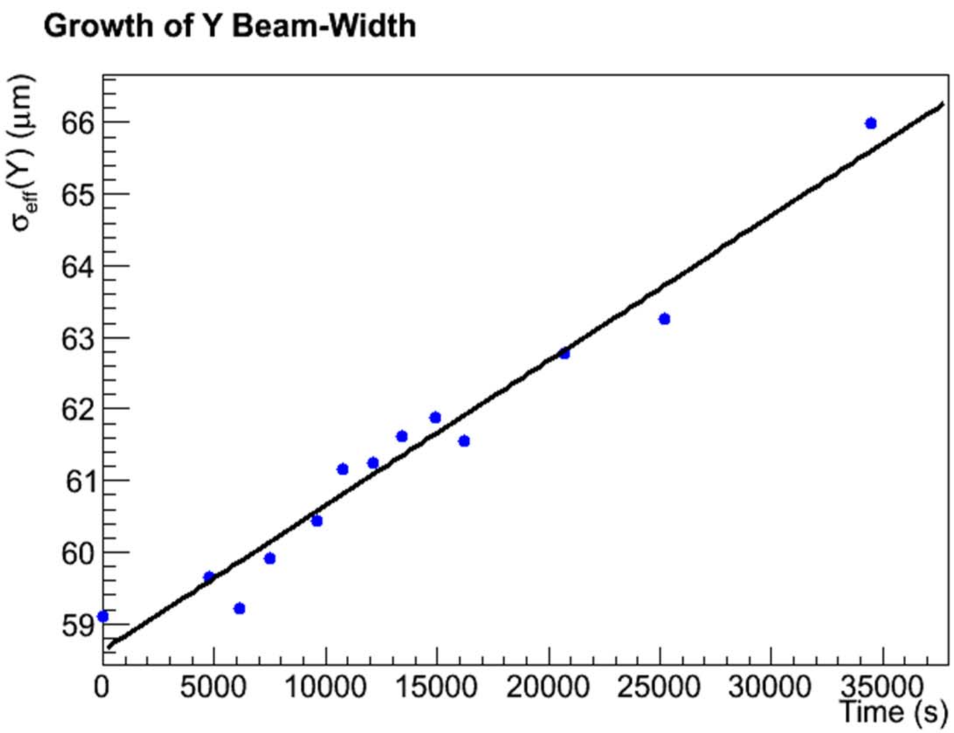




The length scale calibration for the relative offsets of the scans points is made via a "bump" calibration. Both beams are moved together to a nominal displacement (±80μm in each plane), and the position is calculated from the vertex position measured by the CMS tracker. The error on the scale is taken to be the error on the slope from the fits. Adding linearly (assuming correlated errors) for the two planes yields a total of ~2%.

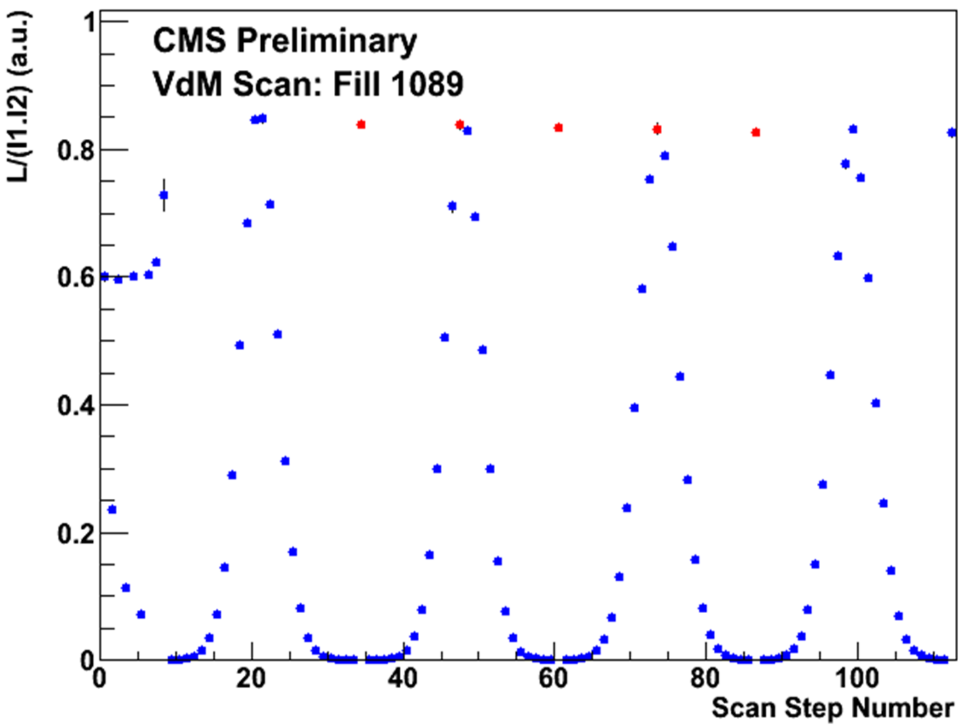
Systematic Uncertainties: Emittance Correction

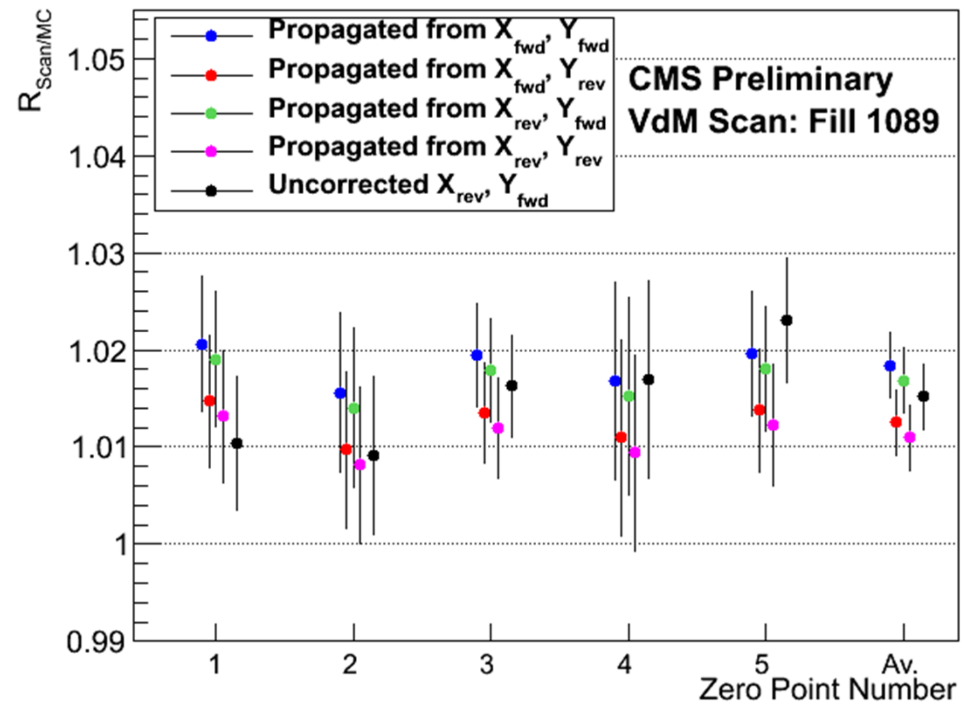




Beam width growth as calculated from the measured emittances during fill 1089. The slopes from the lines can be used to correctly extrapolate the measured widths to their corresponding values at the zero points of the scan.

Calibration & Absolute Luminosity Results





To calibrate we use the five central peak luminosity or "zero" points (depicted in red) with the two central scan widths. The measured beam widths are corrected for emittance blow-up. Effects of the emittance corrections can be seen by comparing green and black points on the right hand plot.