# Emittance scans for CMS luminosity calibration

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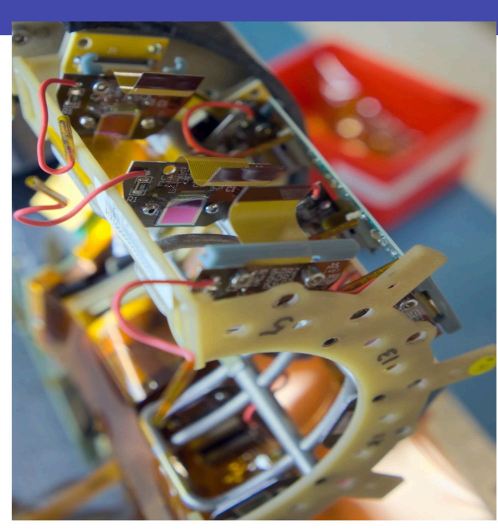
## Abstract

*Emittance scans are short van der Meer type scans performed at the beginning and at the end of LHC fills. The beams are scanned against each other in X and Y planes in 7 displacement steps. These scans are used for LHC diagnostics and since 2017 for a cross check of the CMS luminosity calibration. An XY pair of scans takes around 3 minutes. The BRIL project provides to LHC three independent online luminosity measurement from the Pixel Luminosity Telescope (PLT), the Fast Beam Condition Monitor (BCM1F) and the Forward calorimeter (HF). The excellent performance of the BRIL detector front-ends, fast back-end electronics and CMS XDAQ based data processing and publication allow the use of emittance scans for linearity and stability studies of the luminometers. Emittance scans became a powerful tool and dramatically improved the understanding of the luminosity measurement during the year. Since each luminometer is independently calibrated in every scan the measurements are independent and ratios of luminometers can directly be used as a final validation for 2017 data. Two independent analyses of emittance scans are launched: a Python-based offline framework and an online XDAQ-based application. Results are published on the monitoring web-pages in real-time for the XDAQ-based analysis and typically within 15 minutes for the Python-based framework, which has however the advantage of being rerunnable.*

## BRIL luminometers



**Pixel Luminosity Telescope (PLT).**
PLT telescopes on titanium alloy SLM cassette.

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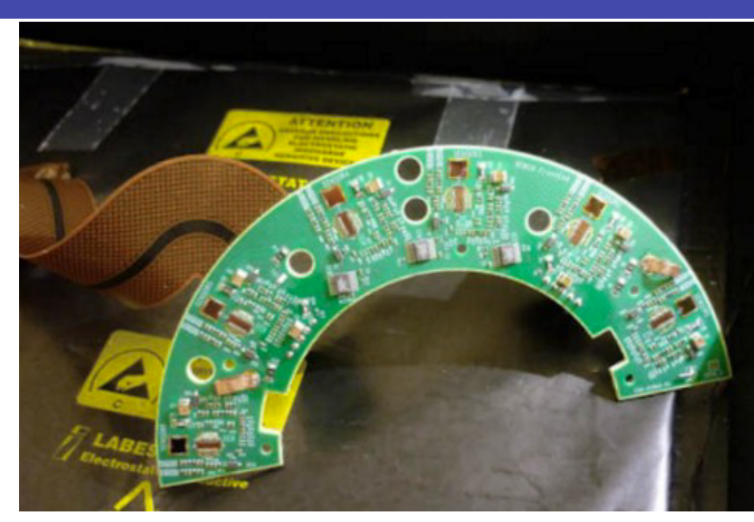

**Fast Beam condition monitor (BCM1F).**
6 BCM1F sensors and dedicated ASICs mounted on PCB.

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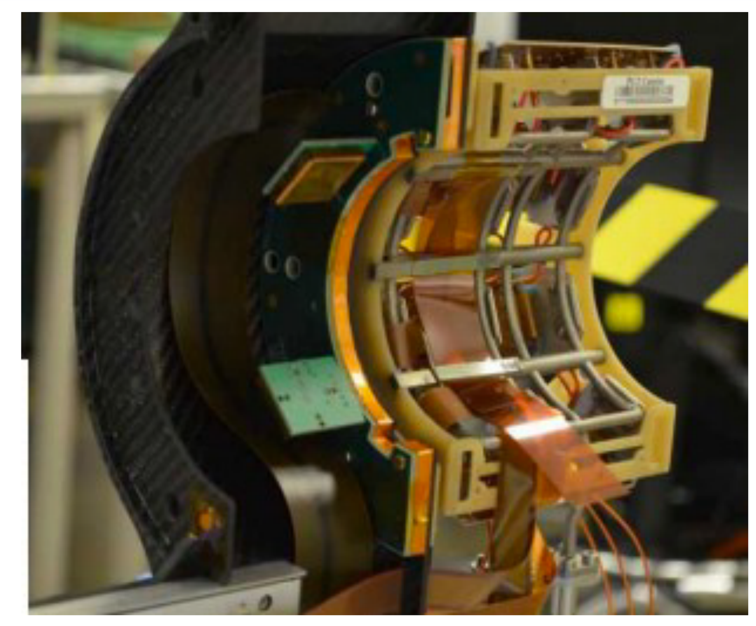
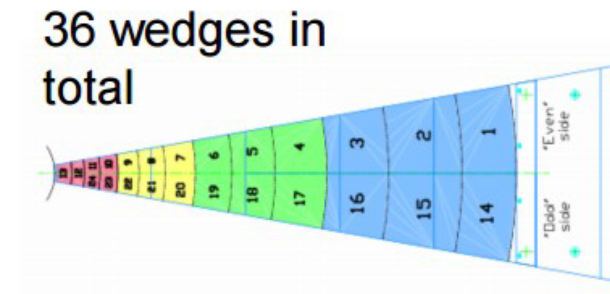


HF wedge

36 wedges in total



**Forward calorimeter (HF).**

Two algorithms are used for luminosity measurement:

- occupancy algorithm (HFOC), “zero counting”;

- based on transverse energy, $E_T$ (HFET).

## Introduction: emittance scans

The number of hits per bunch crossing (BX) follows a Poisson distribution. The probability of a certain number of hits is described by **p(n)**, and the probability of having no hit is **p(0)**. Since the occupancy per channel is low this **“zero counting”** method is used to determine the mean value of the number of hits per orbit per bunch crossing **μ** for luminosity calculation.

$$p(n) = \frac{\mu^n e^{-\mu}}{n!}$$

$$\mu = -ln[p(0)] = -ln[1 - p(\neq 0)]$$

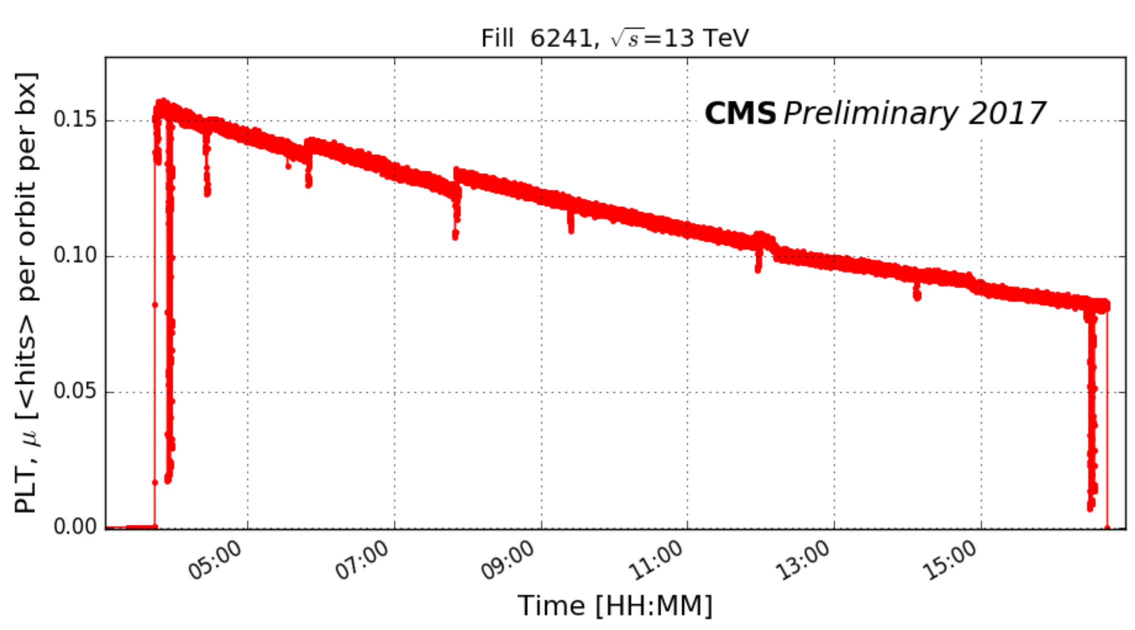



*Fig.1.* μ values for the PLT during the whole fill 6241.

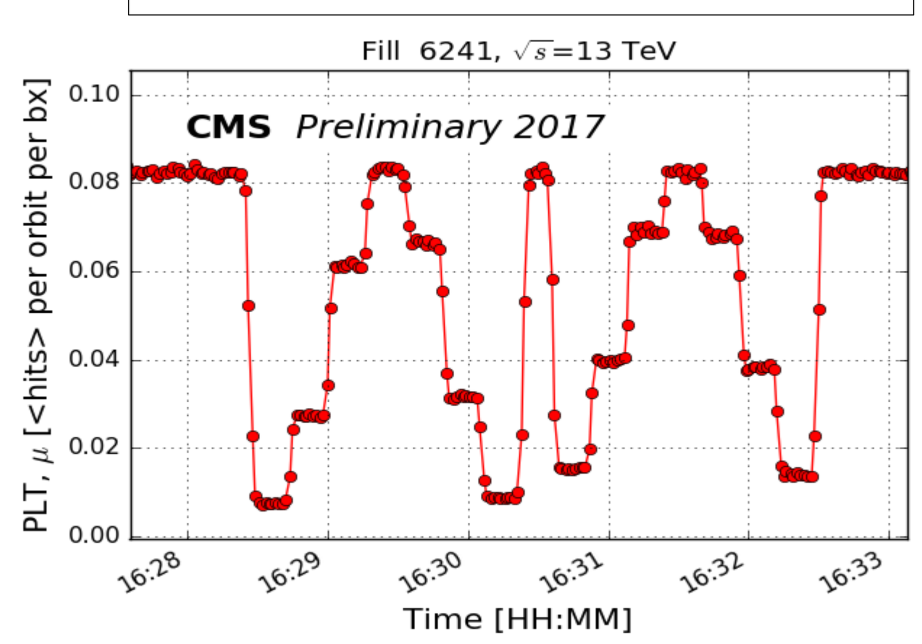



*Fig.2.* . μ values for the PLT during emittance scan.

Fig.1 illustrates **μ** values for the PLT during fill 6241. An almost 50% drop in luminosity is observed after 12 h of collisions. In 2017 so-called “emittance scans” were performed at the beginning and at the end of the fill for luminosity calibration purposes. In Fig.1 they are seen as two deep dips, one at the beginning (“early” emittance scan) and one at the end of the fill (“late” emittance scan). The smaller dips along the fill correspond to beam optimizations, which are performed to find the position where beams collide head-on or after a crossing angle change.

In Fig.2, a zoom into the “late” emittance scan is shown. Scans of the beam in the X and Y directions are performed with 7 steps each, staying 10 s on each separation step. After the scan in X the beams are brought to head-on position for approximately 5 s (step to the maximum rate between the scans) after which the scan in Y is performed.

## Luminosity calibration

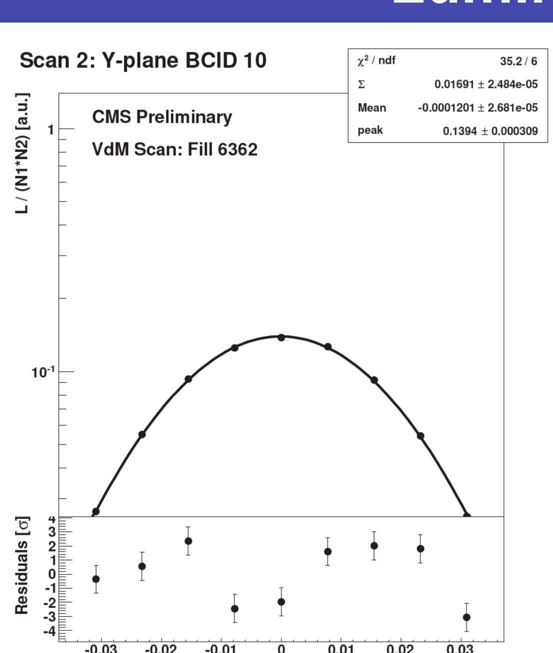



*Fig.3.* An example of Single Gaussian fit to emittance scan shape.

A single Gaussian function is used to fit the emittance scan shapes. The peak rate in X ($R_{max,\,x}$) and Y($R_{max,\,y}$), peak position, and beam overlap width in X ($\Sigma_x$) and Y ($\Sigma_y$) are obtained from the fit and used to calculate the visible cross-section also called sigma visible (SigmaVis, $\sigma_{vis}$).

$$\sigma_{vis} = \pi \Sigma_x \Sigma_y \left( R_{max,\,x} + R_{max,\,y} \right)$$

$$L = R / \sigma_{vis}$$

$\sigma_{vis}$ values are used for luminosity calibration and to monitor the stability and linearity of BRIL detectors.

## Per bunch crossing $\sigma_{vis}$ measurement

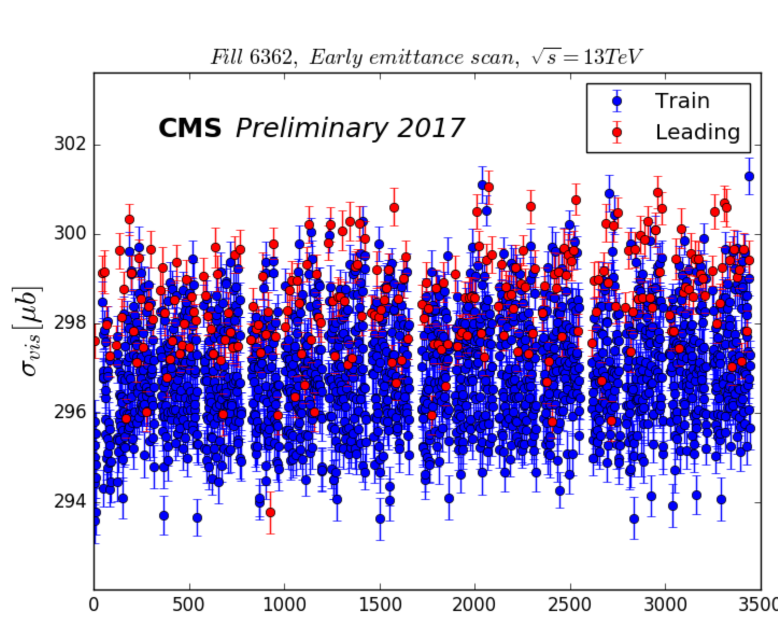



*Fig.4.* Visible cross-section as a function of bunch crossing (BCID) in Fill 6362 for PLT for leading and train bunches. Data from an early emittance scan is shown.

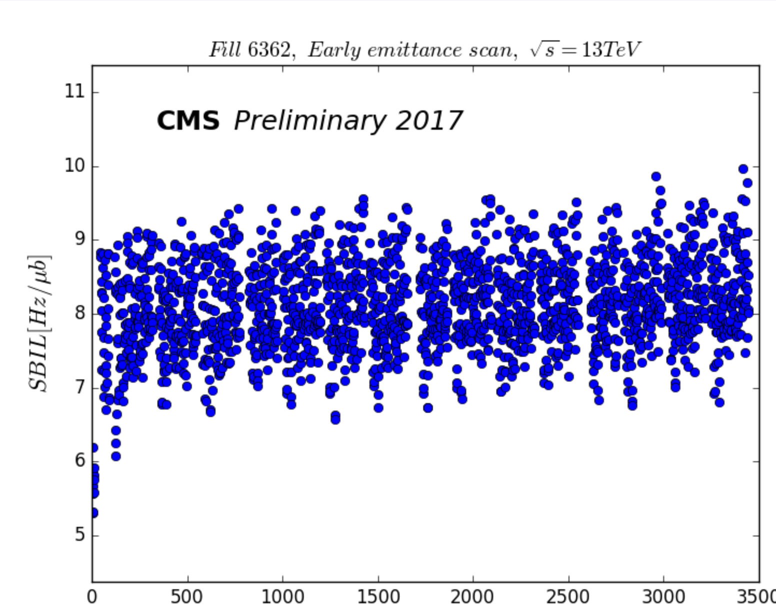



*Fig.5.* Single Bunch Instantaneous Luminosity (SBIL) as a function of Bunch Crossing (BCID). The usual range of the SBIL at the beginning of the fill is between 6 and 10 Hz/μb, while the SBIL range for the late scan strongly depends on the length of the fill.

An automated offline Python-based framework (FW), which provides results within 15 minutes after a scan is used to obtain per bunch crossing $\sigma_{vis}$ measurements, as shown in Fig.4 separately for leading and train bunches. The difference of $\sigma_{vis}$ between leading and train bunches increases towards the end of the fill due to nonlinearity.
A single LHC fill contains bunches of varying Single Bunch Instantaneous Luminosity (SBIL), as shown in Fig.5. The peak rate values obtained from FW fits are used to calculate SBIL for each of the luminosity detectors.

## Stability and nonlinearity monitoring

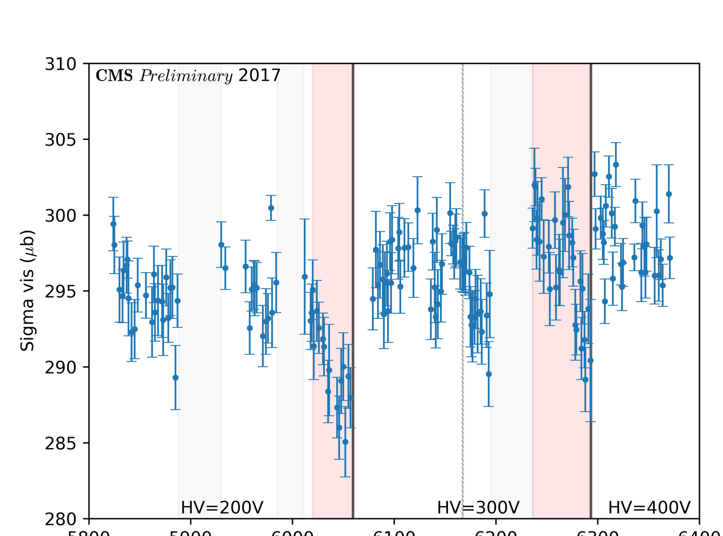



*Fig.6.* PLT $\sigma_{vis}$ as a function of fill number.

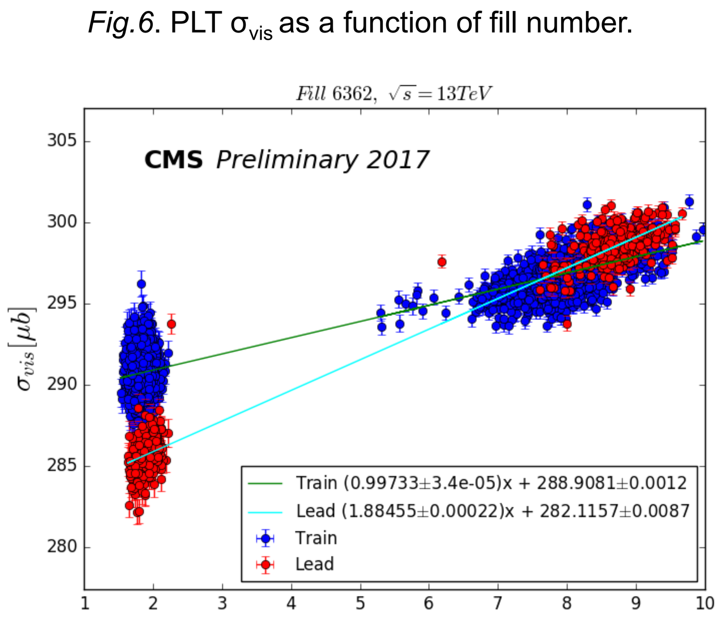



*Fig.7.* PLT $\sigma_{vis}$ as a function of SBIL used for nonlinearity monitoring for leading and train bunches.

$\sigma_{vis}$ obtained in all early emittance scans performed in 2017 operation, shown in Fig.6, were used to monitor the efficiency of the PLT detector. The downward trends highlighted in pink show decreases in efficiency which were mitigated by an increase of the operational high voltage (HV). Time of the HV change are indicated with black lines. Technical stops and machine development periods are highlighted in light green. The gray vertical line points to the time of the filling scheme change from long bunch trains to a “8 bunches filled 4 bunches empty” (8b4e) scheme.

As early and late scans cover wide range of SBIL, a nonlinearity measurement is done for every fill. An example of linear fits of the $\sigma_{vis}$ as a function of SBIL is shown in Fig. 7 for leading and train bunches in red and blue respectively. One point of the plot corresponds to one of 3564 bunch crossings (BCID) in an orbit. A nonlinearity correction is applied for leading and train bunches separately taking into account the fraction of each type in a particular fill.
In the (8b4e) filling scheme, the fraction of leading bunches is not negligible as it was for long bunch trains. Therefore emittance scans became a powerful tool to deliver nonlinearity corrections.

## Online VdM web-monitoring tool

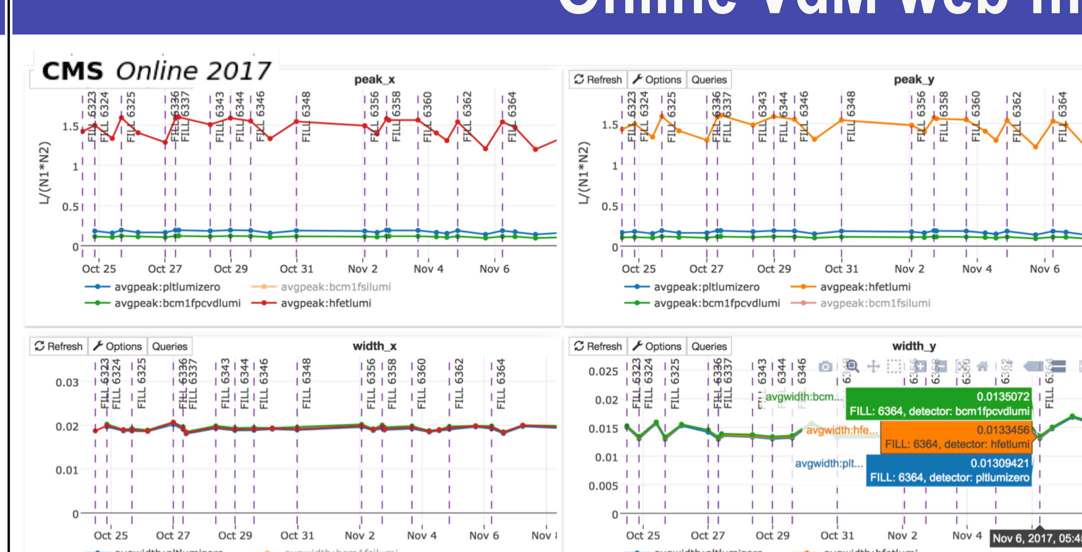



*Fig.8.* The screenshot of the online VdM-monitor.

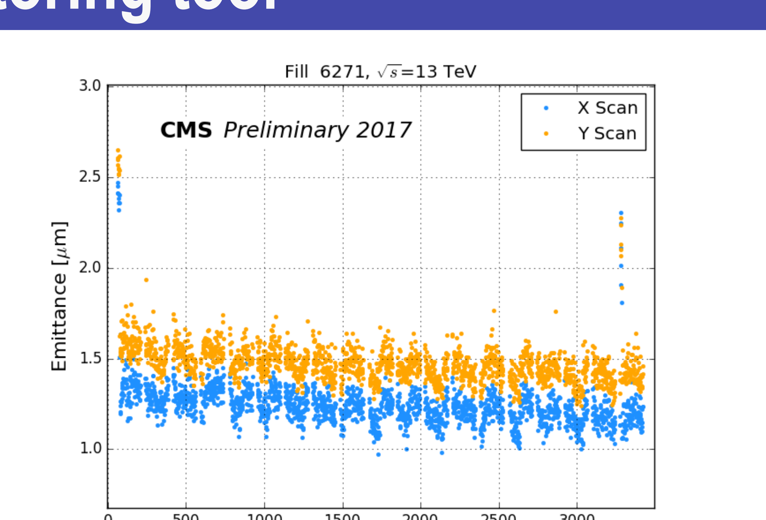



*Fig.9.* Emittance values calculated based on beam width in X and Y obtained from CMS emittance scans.

This monitoring plot (Fig.8) of the peak rate and beam overlap width measured in each emittance scan with the online CMS XDAQ-based application is displayed in the CMS control room and used to monitor stability of the luminometers and provide fast comparison of the performance. This application also provides the $\sigma_{vis}$ within seconds after the end of the scan and calculates the emittance values from the measured beam overlap width in X and Y (Fig.9). This is valuable feedback to the LHC and a DIP publication of the emittance measured by CMS was implemented since the end of 2017.

## Summary

CMS emittance scans were run on a regular basis in 2017 at the beginning and at the end of fills. These short scans completed in 3 min became a powerful tool for luminosity calibration, stability and nonlinearity monitoring.
Two independent applications are used for analyzing emittance scans. They show a ~0.2% agreement and allow fast and easy access to analyzed data.