CMS emittance scans for luminosity calibration in 2017

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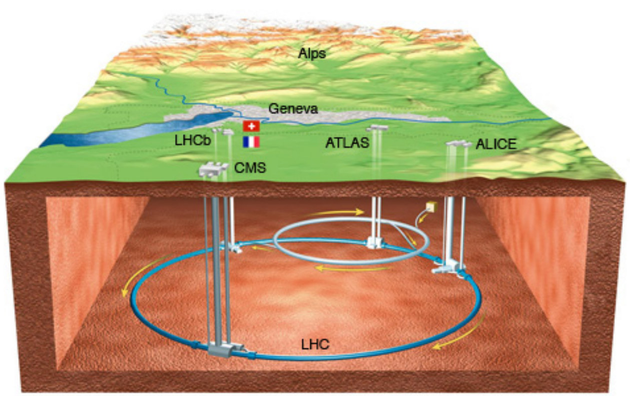
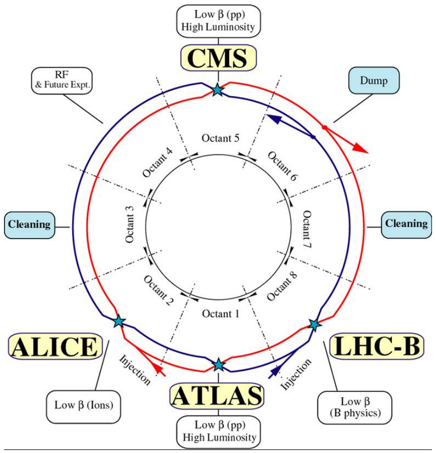
Outline

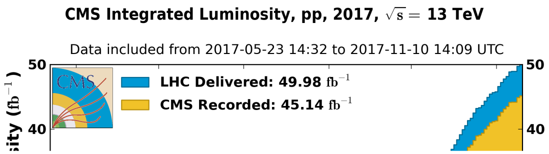
- Luminosity measurement and calibration
- Luminometers of the CMS experiment
- Van der Meer scan and emittance scans
  - Nonlinearity and stability of the luminometers
- Bunch by bunch online emittance calculation
  - Web monitoring plots

Luminosity

- ***Luminosity (L)*** is a key quantity of any collider, which is used for physics cross section calculation.
- The uncertainty of the cross section measurement cannot be better than the uncertainty of the luminosity measurement.
- Luminosity is obtained from the observed ***rate in a detector (R)*** and calibration constant, called ***visible cross section*** (σ_{vis}): $L = R / \sigma_{vis}$.

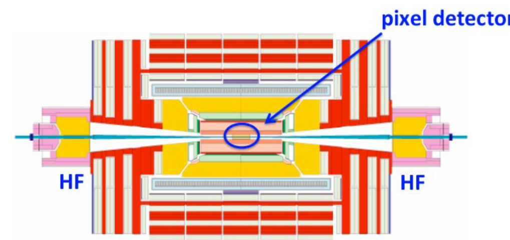


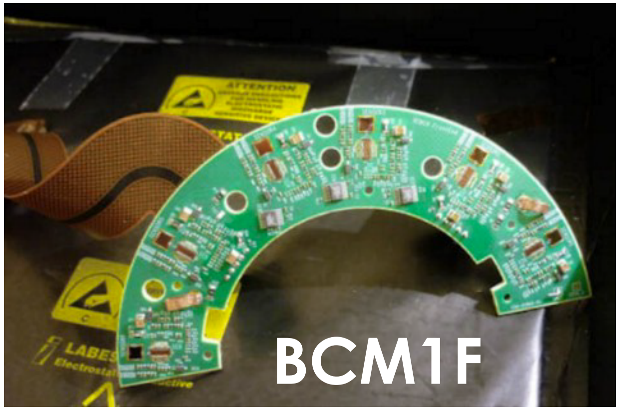


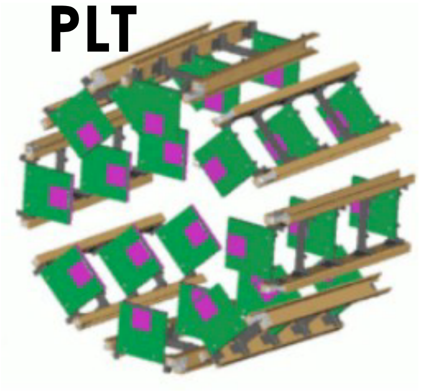


Luminosity measurement

- **Any detector, which can provide particles hit rates can be used as a luminometer.**
- **A luminometer with a linear response produces a signal that is proportional to the instantaneous luminosity.**
- In CMS the following luminometers are used:
  - *- Pixel Detector*
  - *- Forward calorimeter (HF)*
  - *- Fast Beam Conditions Monitor (BCM1F)*
  - *- Pixel Luminosity Telescope (PLT)*

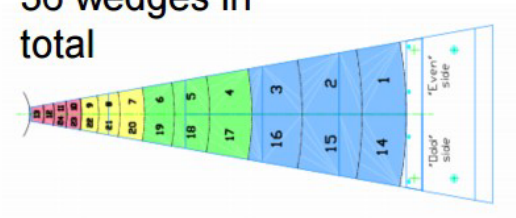






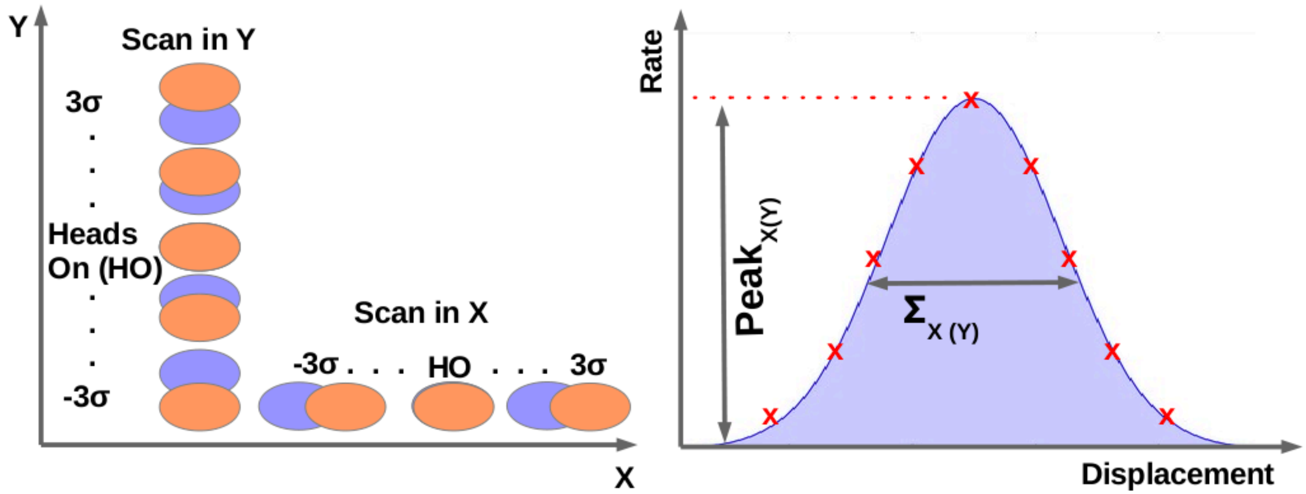
HF wedge

36 wedges in total

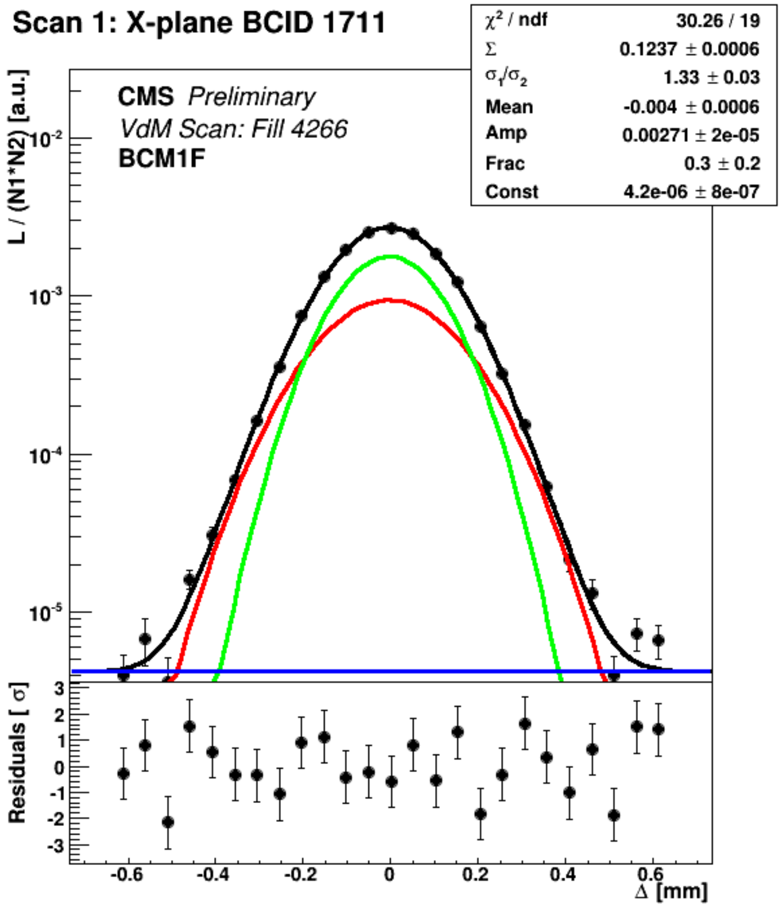


Luminosity calibration

- ***The Van der Meer scan method is used for LHC luminosity calibration.***
  - The proton beams are scanned through each other to determine the effective overlap of the beams at their point of collision and the visible cross section of the device.
  - *For reproducibility and detailed study of the systematic effects there is a special series of VdM scans **once per year.***



Visible cross section measurement



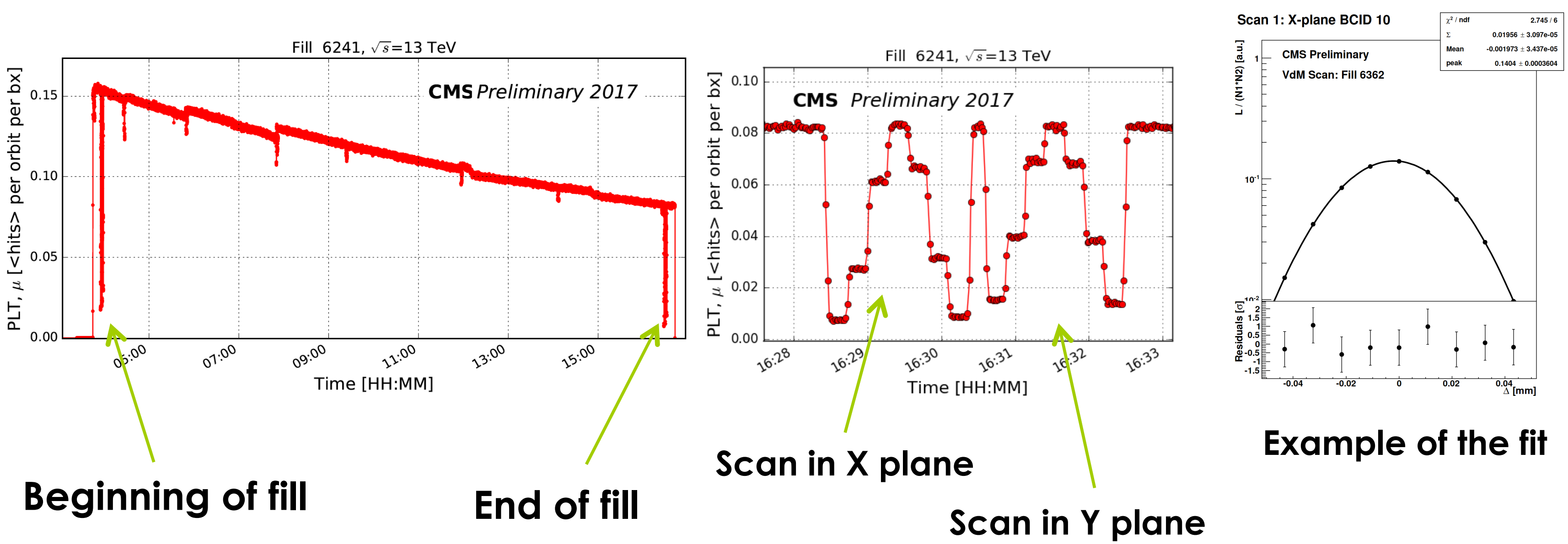
Analysis framework is used to fit beam overlap and to calculate $\sigma_{vis.}$ – the effective cross section seen by the luminometer:

$$\sigma_{vis} = \frac{2\pi\Sigma_x\Sigma_y}{N_1 \cdot N_2 \cdot f \cdot n_b} \cdot R_{peak}$$

where $\Sigma_X \Sigma_Y$ – the beam overlap widths obtained from the fit, N_1, N_2 - number of protons in beams 1 and 2, f - LHC orbit frequency, n_b - number of colliding bunches, R_{peak} - average rate at the peak in X and Y scans.

Emittance scan difference from VdM scan

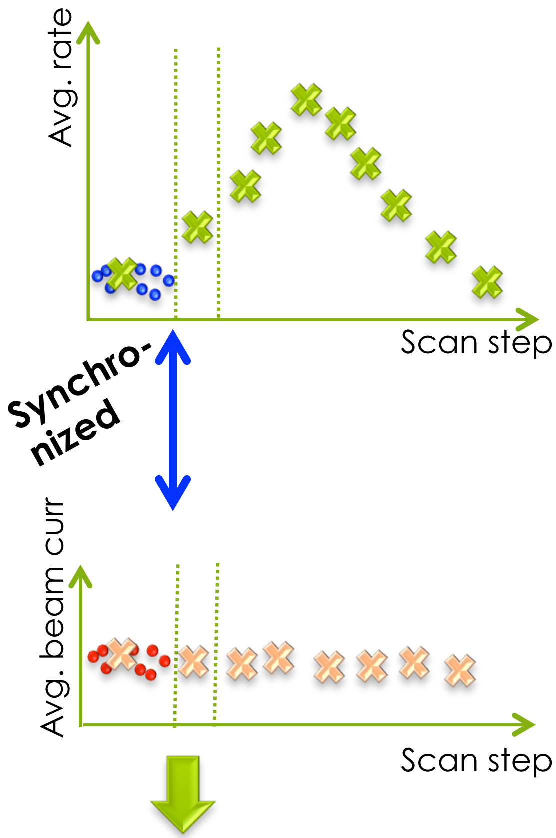
- **Emittance scans** are short Van der Meer type scans performed at the beginning and at the end of LHC fills.
  - Beams are scanned in 7 displacement steps (19-25 steps in VdM);
  - 10 s per step (30 s per step in VdM);
  - The same beams as in physics data taking (in VdM fill special beam optics is used);
  - Filling scheme with 25 ns separated bunches, “bunch trains” (well separated bunches in VdM);
  - Single Gaussian fit is used to fit the emittance scan shape and to extract Peak and beam overlap in X and Y.



Data analyses

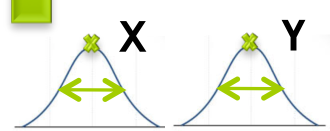
CMS XDAQ-based online application

Per bunch online analyses



Rates normarized by beam currents, fit

$Peak_X$ and Σ_X measured



$\sigma_{vis.}$ per bunch calculation

Python-based offline application

VdM files saved to disk

Analyses launched at the end of fill automatically

Results published to Web page with 15 min latency.

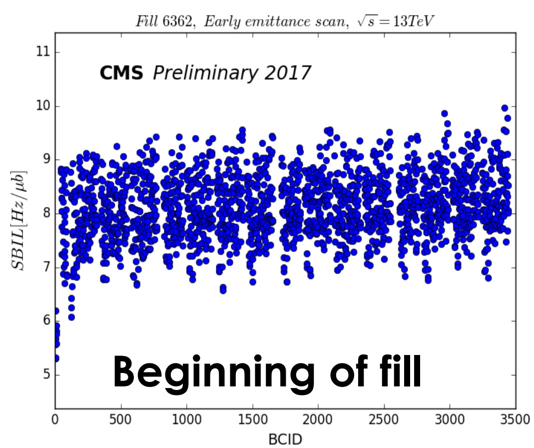
Online analyses is fast, but offline framework has advantage of multiple analyses and different fitting.

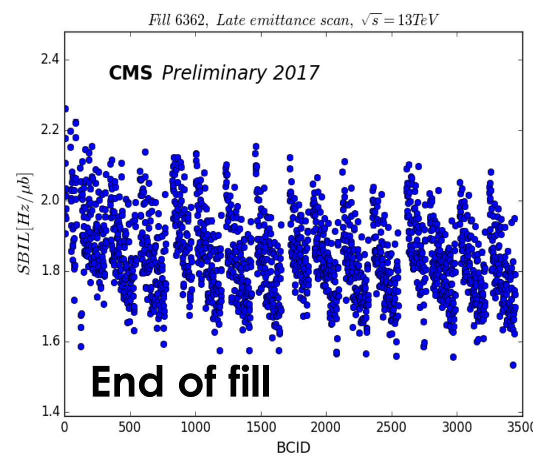
Emittance scans for nonlinearity measurement

- Due to spread of emittances in the bunch train and natural beam intensity drop towards the end of the fill wide **range of single bunch instantaneous luminosity (SBIL)** is covered in one fill.
- Difference in the SBIL allows nonlinearity study for each luminometer on a per fill bases.

Each 10th RF bucket is filled → 25 ns

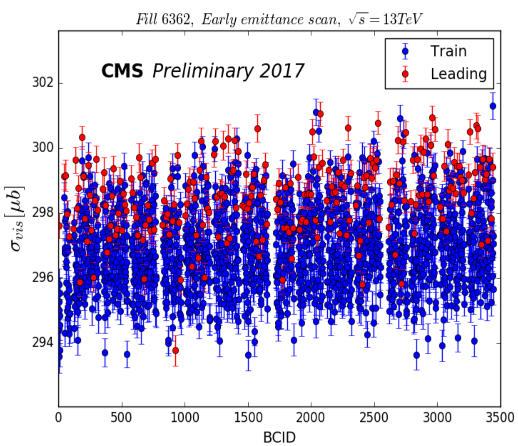
25 ns bunches are grouped in bunch trains

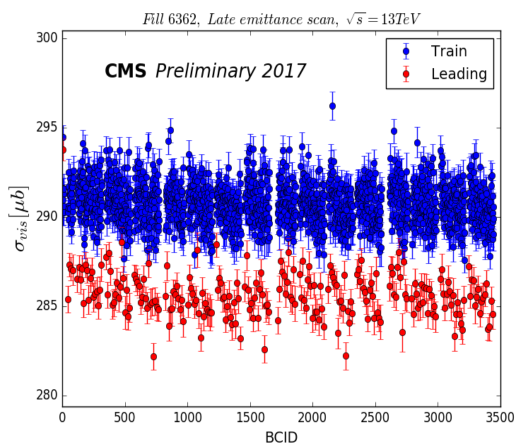


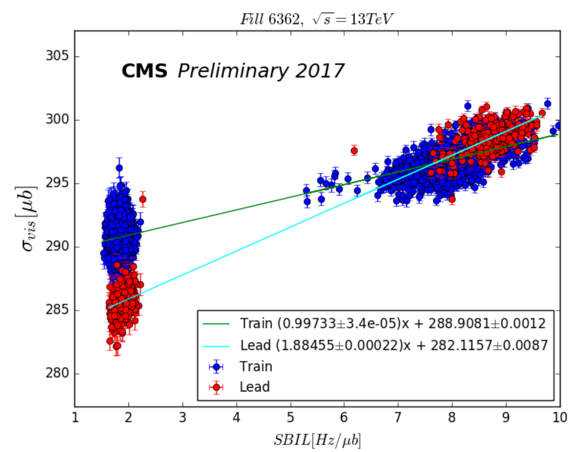


Emittance scans for nonlinearity measurement

- The nonlinearity is different for leading and train bunches.
- For the measurement of the nonlinearity emittance scans at the beginning and at the end of the fill are used.
- Nonlinearity correction is applied per fill per detector for final luminosity measurement.



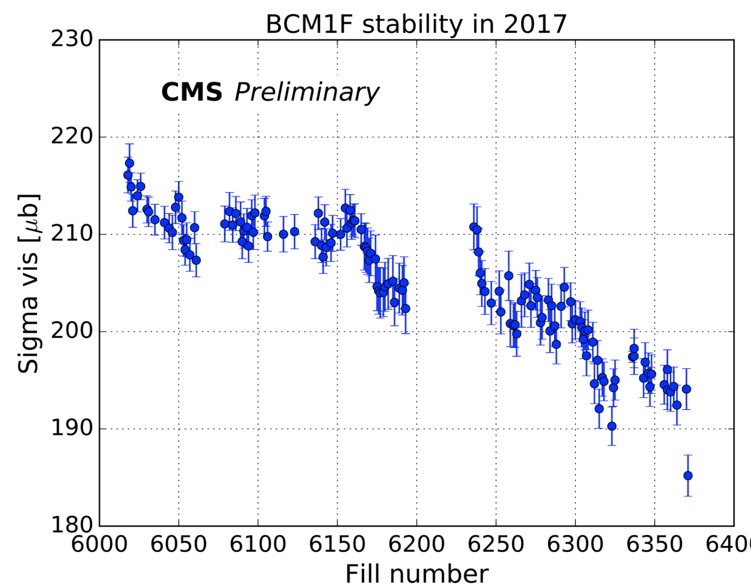




Emittance scans for stability measurement

- As emittance scans are performed regularly they became a powerful tool used to track the relative changes in the VdM calibration.
- Any changes in σ_{vis} reflect changes of the detector state (e.g. nonefficiency) and therefore can be used to monitor detector stability.

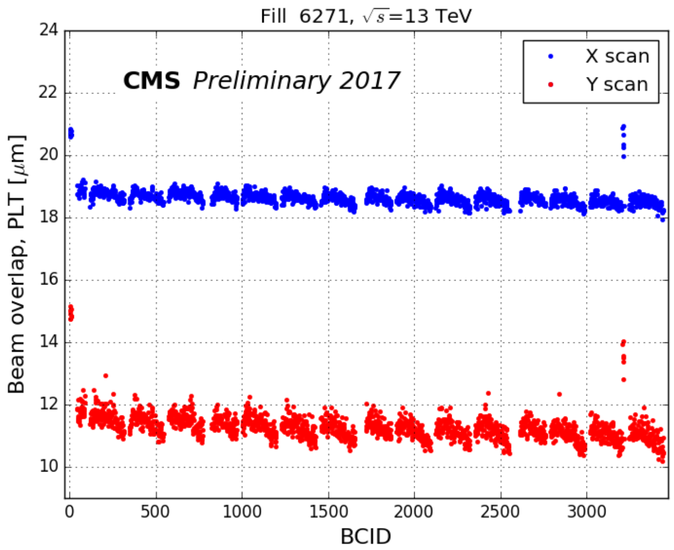
PLT stability in 2017

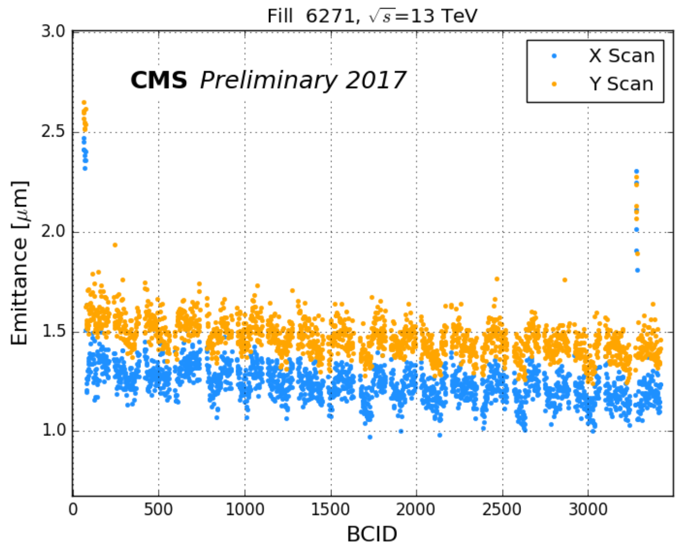


Per bunch emittance calculation

- Bunches are colliding with a crossing angle between 110 μ rad and 140 μ rad at the interaction point of CMS.
- Using beam overlap regions measured by CMS from emittance scans emittance values are calculated as:
  - $\varepsilon_X = [\Sigma_X^2 \gamma - 2\gamma \sigma_Z^2 \sin^2(\alpha/2)] / [2\beta^* \cos^2(\alpha/2)]$,
  - $\varepsilon_Y = \Sigma_Y^2 \gamma / 2\beta^*$,

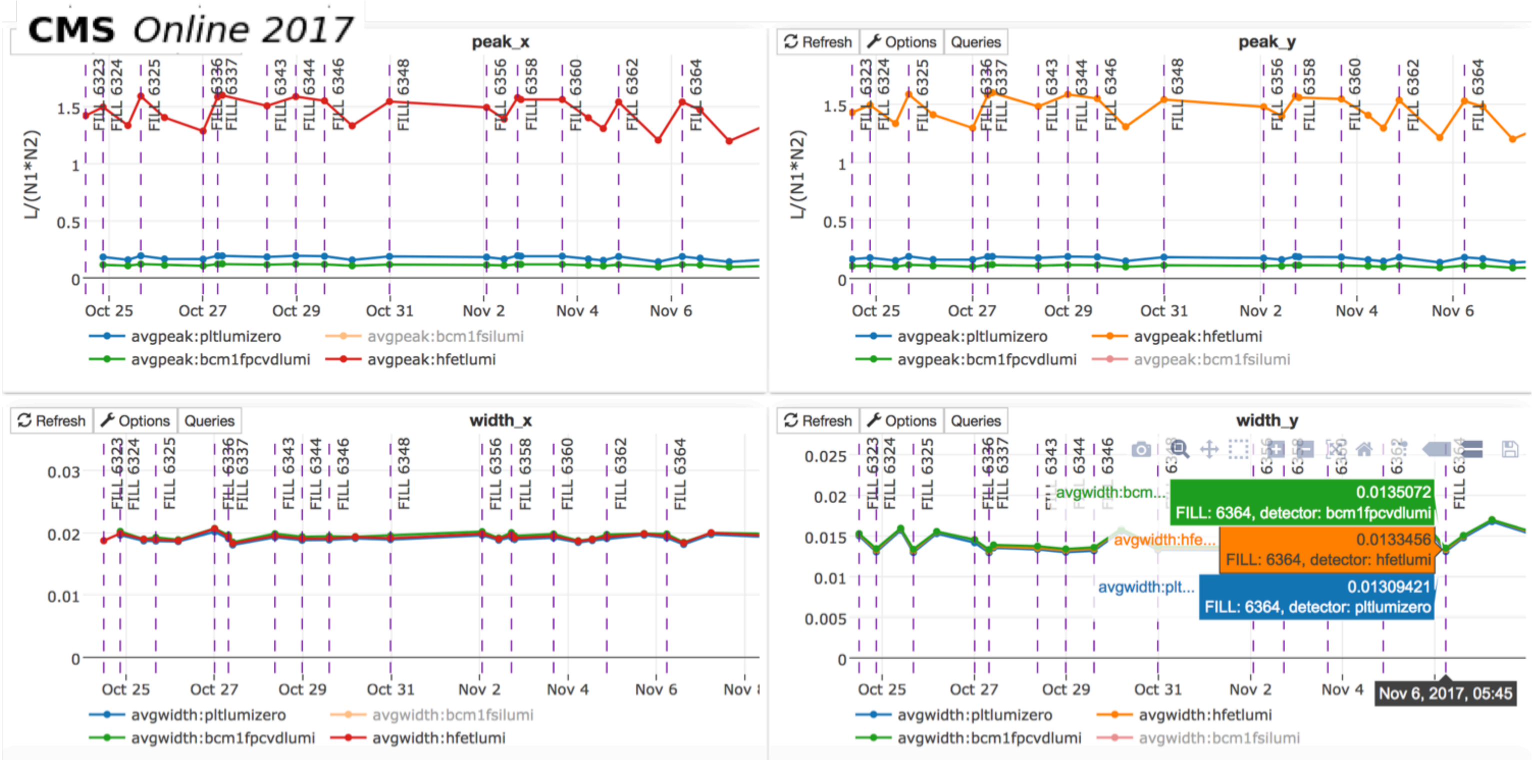
  where $(\alpha/2)$ crossing angle, γ relativistic factor, β^* related to beam optics parameter (0.3 m in operation and 19 m in the VdM fill), σ_Z bunch length.





Web monitoring

- The emittance scans analyses is an important feedback to the LHC.
- Online monitoring pages are used for fast access and monitoring of emittance scans results.
- Effective beam overlap, σ_{vis} per detector, single bunch instantaneous luminosity, pileup, per bunch emittances are published in online regime for CMS and LHC.



Conclusion

- **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 and became a powerful tool for **luminosity calibration, stability and nonlinearity monitoring**.
- Bunch by bunch beam overlap and emittance measurement are important feedback to LHC.
- Two independent applications are used for analyzing emittance scans. They show a ~0.2% agreement and allow fast and easy access to analyzed data.