The Pixel Luminosity Telescope: a silicon sensor detector for luminosity measurement at CMS

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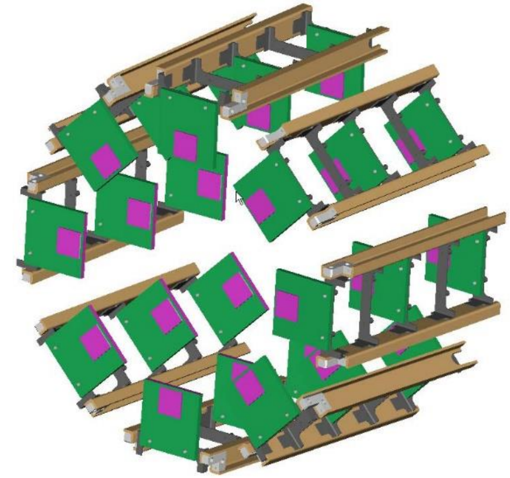
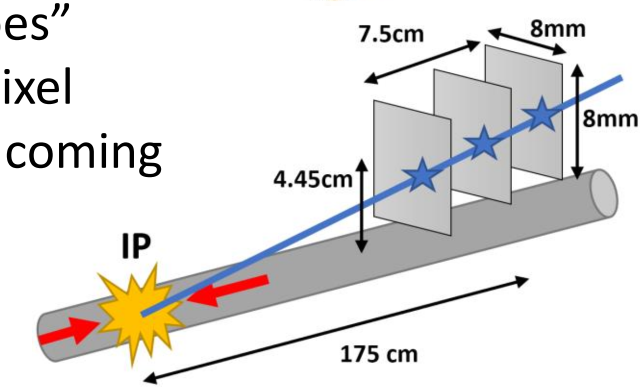
PLT overview



- Dedicated instrument for measuring luminosity installed in 2015 at beginning of Run 2 of the LHC
- 48 pixelated silicon sensor planes (~200k pixels total) arranged into 16 “telescopes” (8 on either side of CMS) outside the pixel endcap (|η|~ 4.2), such that a particle coming from the interaction point will pass through all three planes in a telescope



- Two readout modes:
  - “Fast-or” mode can read out whether a plane was hit at the full 40 MHz bunch crossing rate, using triple coincidences to provide online bunch-by-bunch measurements to LHC and CMS with 1% precision every 1.5s
  - Full pixel data read out at ~3 kHz for more detailed studies using track reconstruction and pulse heights
- Uses same sensors and readout chips (ROCs) developed for CMS phase-0 pixel detector

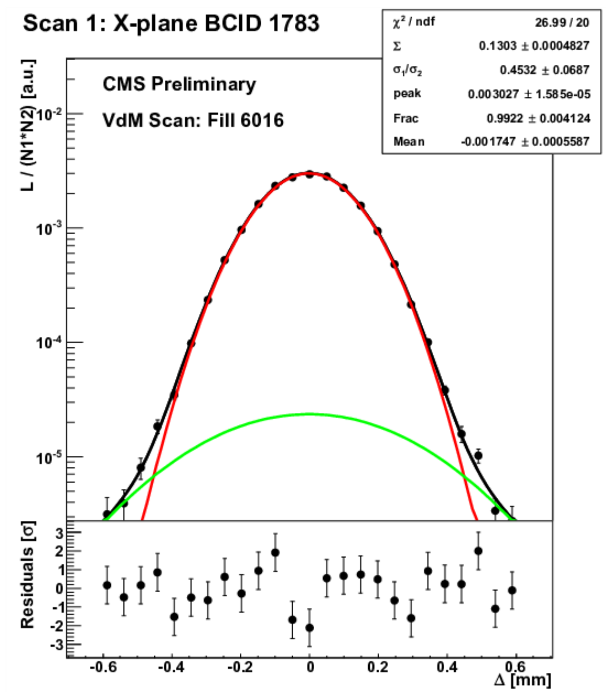
PLT calibration

- Basic principle: rate of measured triple coincidences is proportional to the luminosity, related by the "visible cross section" σ_{vis} ($R = \sigma_{vis} L$)
- To determine this calibration constant, use Van der Meer scans
- In a VdM scan, the beam separation is gradually varied and the resulting luminosity fit to determine the beam size. The absolute luminosity can then be determined:

luminosity per bunch *effective beam sizes*

$$L^i = N_1 N_2 \nu_{orb} / 2\pi\sigma_x\sigma_y$$

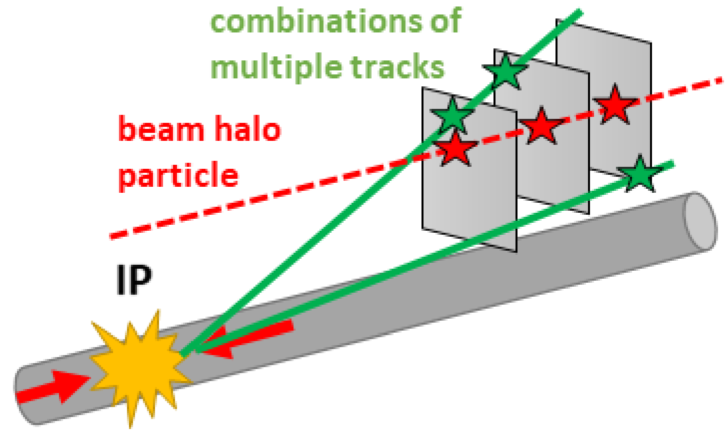
beam intensities *orbit frequency*



At right, we see an example fit for a single bunch in a single VdM scan from 2017. The resulting luminosity curve is fit with a double Gaussian (green and red) after background is subtracted. The effective width is extracted and used to find the overall calibration constant.

Challenges in the luminosity measurement

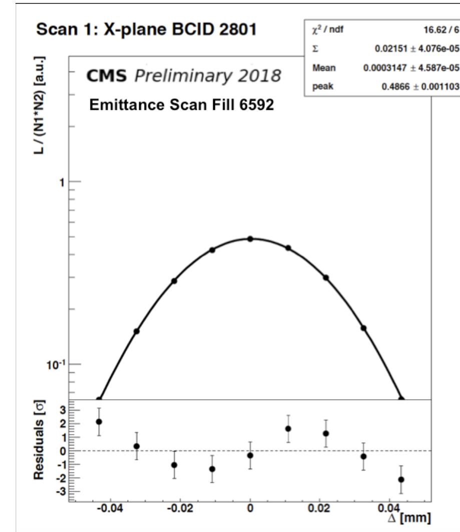
- Two main cases where the basic relation $R = \sigma_{vis} L$ is not necessarily perfect:
  - **Nonlinearity** of the rate with respect to luminosity, for example from "accidentals"
  - **Change in calibration over time**, principally due to radiation damage resulting in decreased efficiency

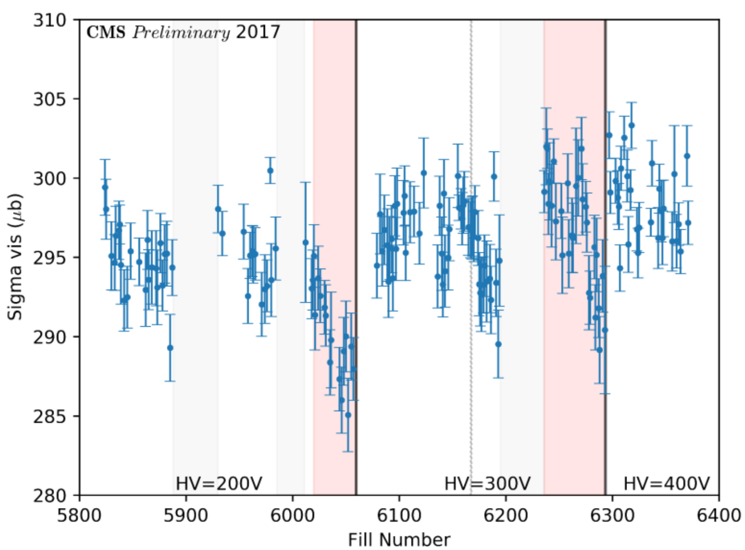


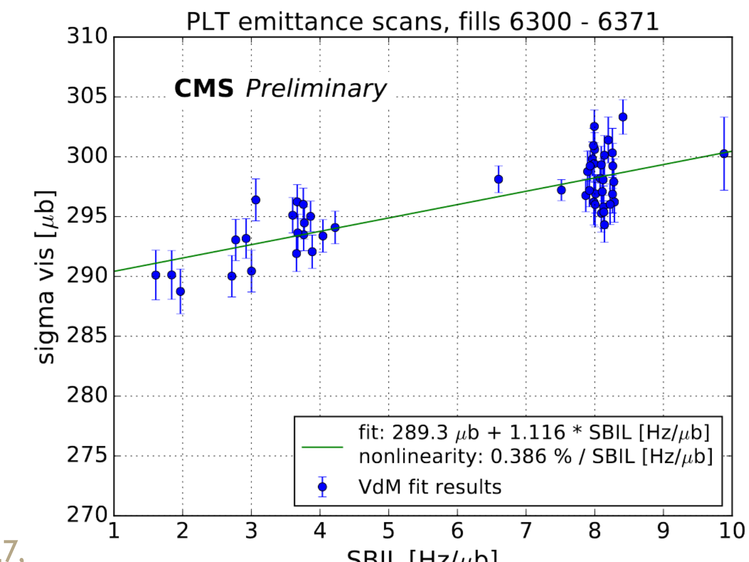
- Multiple tools to measure and correct for these effects:
  - **Emittance scans** in 2017-2018 to measure nonlinearity and change in σ_{vis} over time
  - **Track data** to identify triple coincidences from accidentals
  - **Pulse heights** to see decreased signal efficiency over time

Emittance scans

- Emittance scans are short scans taken by the LHC at the beginning and end of all fills
- Similar scan procedure to VdM scan but much shorter (fewer points, less time: ~couple of minutes)
- In 2017 CMS started using this data to measure detector performance over time and linearity
  - Left: Measured σ_{vis} from emittance scans in 2017, showing loss of efficiency over time recovered by increasing high voltage applied to sensors
  - Right: Measured σ_{vis} as a function of single-bunch instantaneous luminosity (SBIL) for some 2017 fills, showing slight nonlinear response

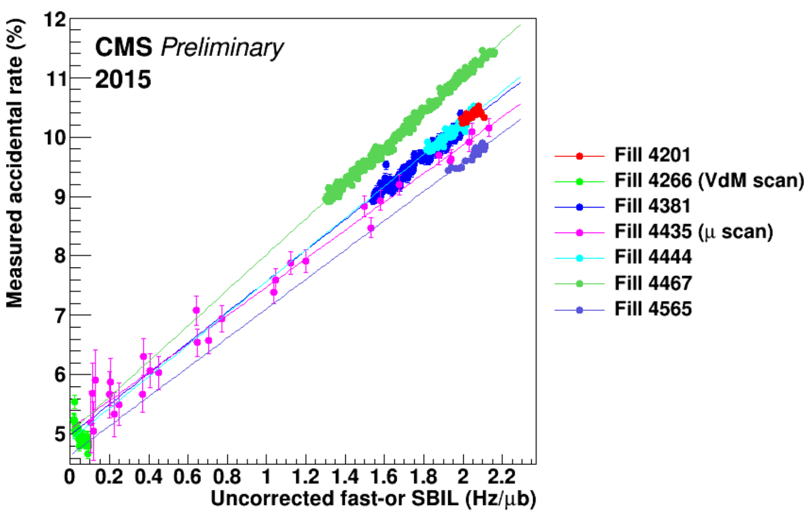


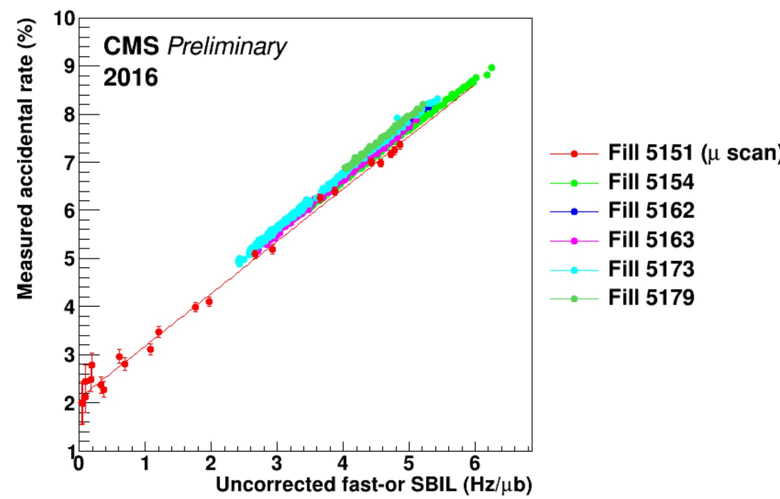




Track reconstruction and accidentals

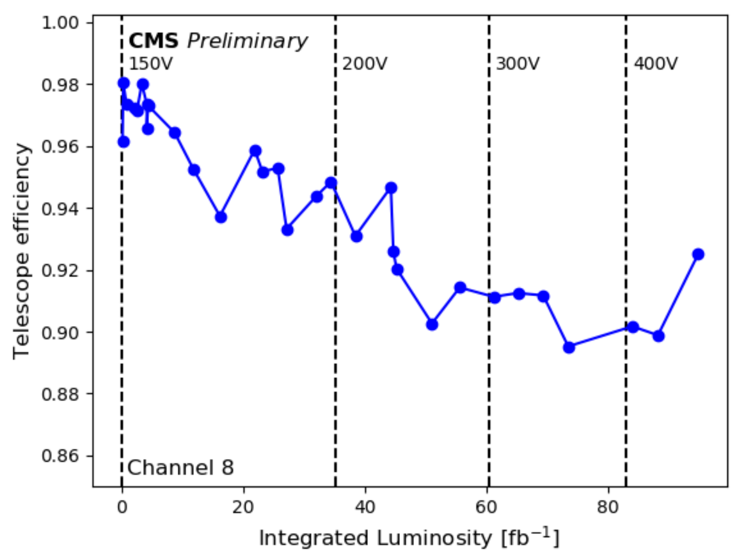
- Using the full pixel data, tracks can be reconstructed for further analysis
- Reconstructed tracks can be used to estimate the fraction of triple coincidences from accidentals
  - Look at slope and residual distributions and reject any track where these values are more than 5σ away from the mean
  - Resulting accidental rate is generally proportional to instantaneous luminosity but with some systematic variation
  - Active area of sensors reduced in 2016 to keep accidental rate reasonable



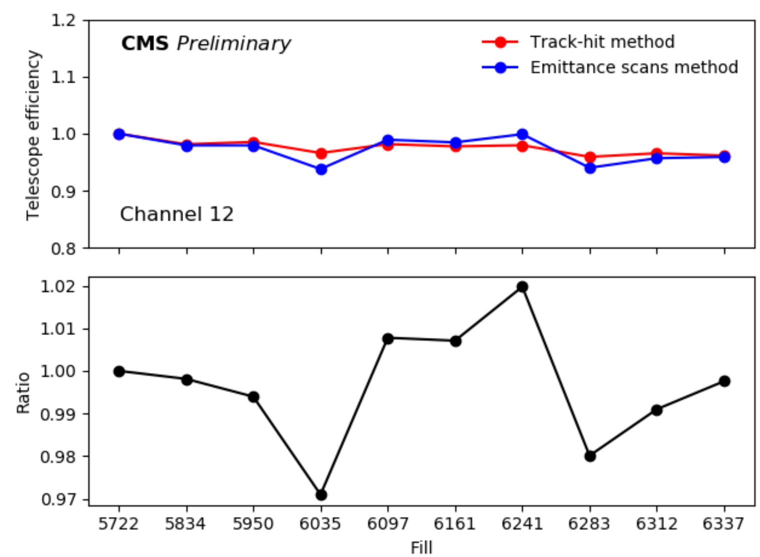


Efficiency using track reconstruction

- Reconstructed tracks can also be used to estimate efficiency loss by looking for events with two hits in two planes, extrapolating to the third plane, and seeing if the hit is found
- We can use this to derive efficiency measurements for all years. In 2017 the results agree well with the emittance scan results.



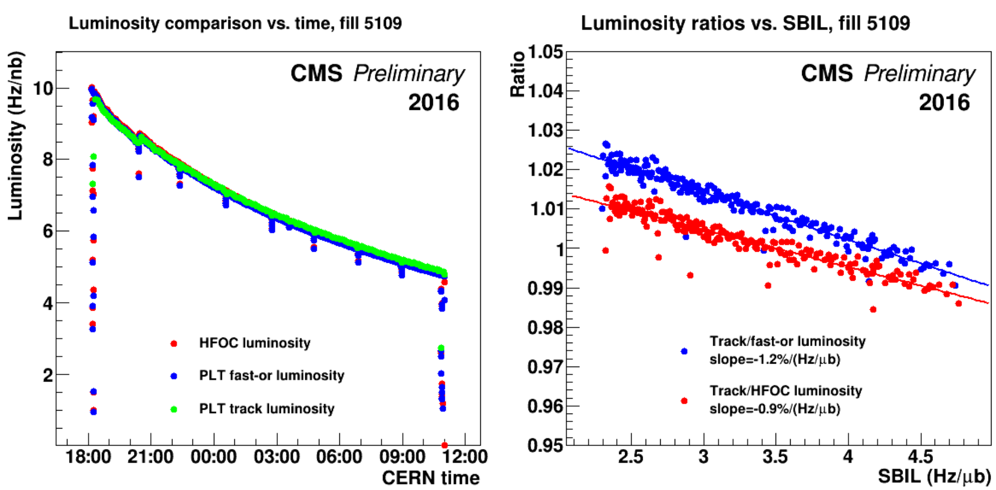
Efficiency for a single PLT telescope over 2017 using track reconstruction



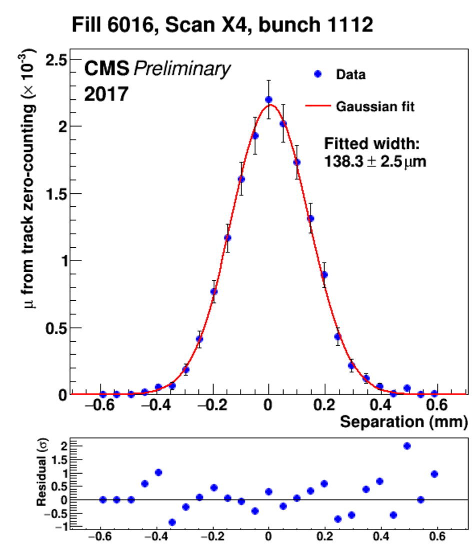
Comparison of efficiency from track reconstruction and emittance scans

Track luminosity

- The reconstructed tracks can also be used for a luminosity measurement
  - Less rate, so less precise than the triple-coincidence measurement
  - But active accidental rejection means a more linear measurement
- Use track data in 5-minute intervals
- Good agreement with other luminometers, although some nonlinearity remains
- Can even do VdM analysis using tracks; results are consistent with triple coincidence measurement



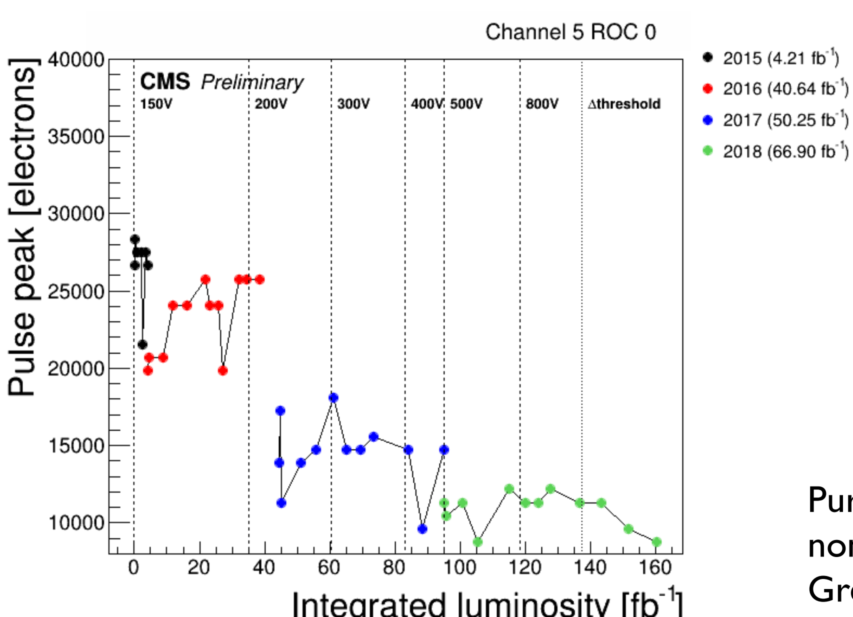
Measured luminosity with tracks (green) vs. other luminometers (left) and ratios with other luminometers over a fill (right)



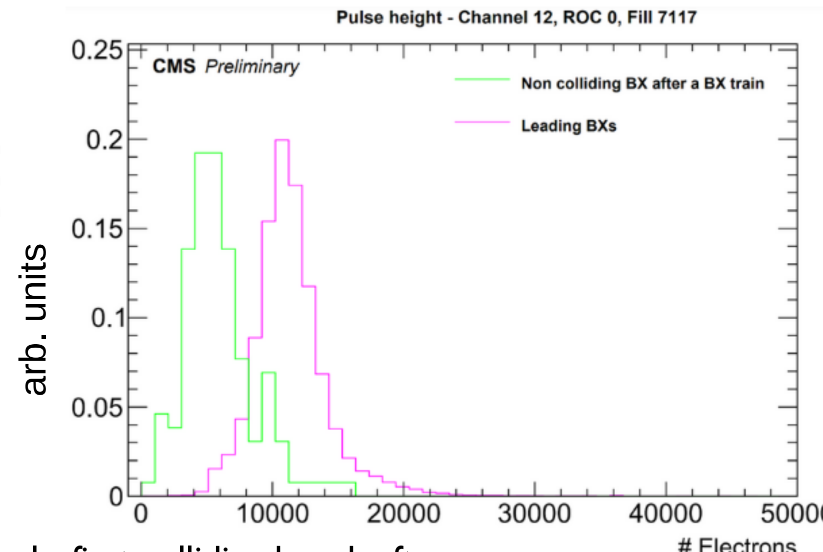
VdM scan curve for one bunch

Charge collection

- When reading out the full pixel data, the readout chip includes an analog measure of the charge collected
- This can also be used to monitor the effect of radiation damage as a function of time
- We also observe timewalk effects, where a signal from one bunch crossing spills over into the next 25ns interval – the charge collected can be used to identify these



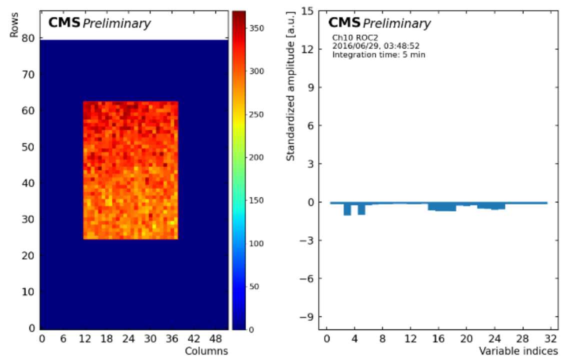
Most probable charge collected over time, 2015-2018



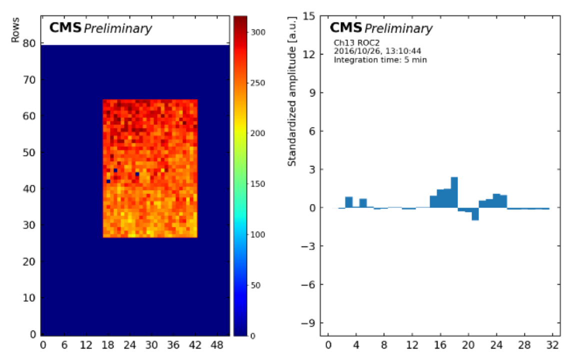
Purple: first colliding bunch after noncolliding bunches, should be free of timewalk events
Green: first noncolliding bunch after colliding bunches, should be ***only*** timewalk events
Data from late 2018, both histograms normalized to 1

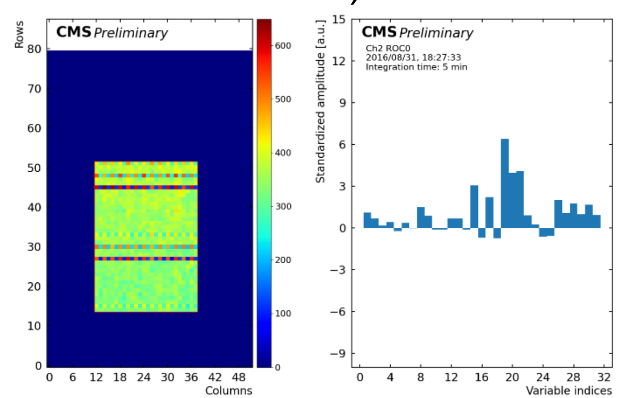
Data quality with machine learning

- Problems with the triple-coincidence readout can be spotted immediately, but issues with the pixel data can be more subtle
- Using occupancy maps, develop set of 31 features (e.g. standard deviations in rows/column) and apply unsupervised learning using k-means clustering to separate good maps from problematic ones
- Promising approach to online monitoring in Run 3



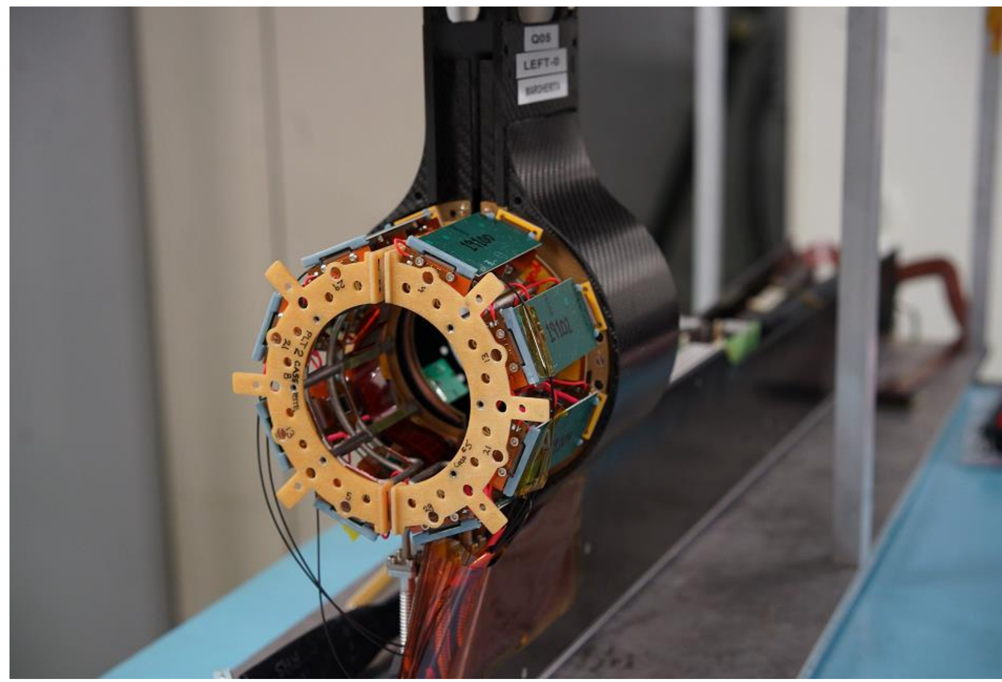
Top left: good data
Bottom left: some dead pixels
Bottom right: data decoding issues
The right panel shows the distributions of the different features used (each feature is given an index number)





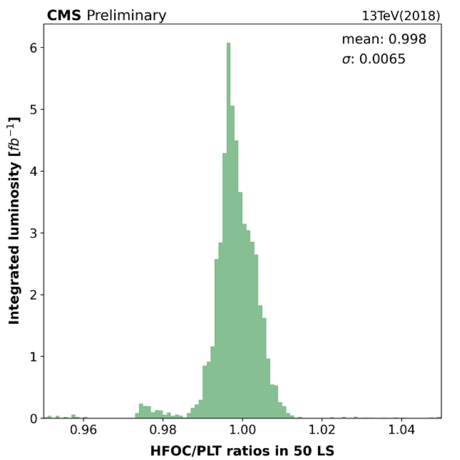
Run 3 plans

- For Run 3, two full new copies of the PLT will be used:
  - One has already been completed and installed at the beginning of July and is ready for start of operations
  - The other is foreseen to be installed when radiation damage significantly affects PLT operations, subject to availability of access opportunities
- Improved monitoring will be key to Run 3 operations, based on Run 2 experience and developments
  - Quick detection of operational issues
  - Prompt feedback on radiation damage
  - Consistent program of checking and adjusting HV and threshold settings for good operation

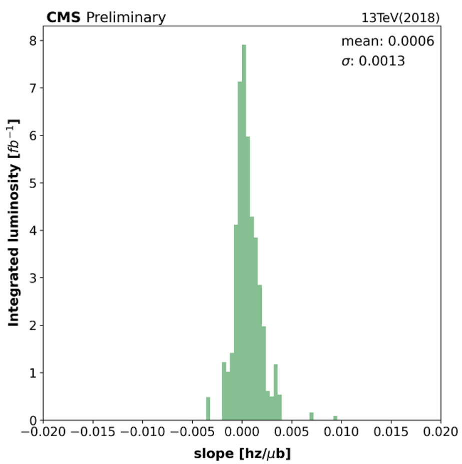


Conclusions

- PLT operated well over the course of Run 2 to provide both online and offline luminosity with high uptime and precision.
- Principal challenges from nonlinearity and efficiency changes; a variety of methods to measure and correct for these.
- Radiation damage in particular is expected to be a major issue in Run 3.
- Improved monitoring and calibration will be key to keep good performance.



Final 2018 comparison: PLT agrees well in overall value (top) and slope (bottom) with other luminometers.

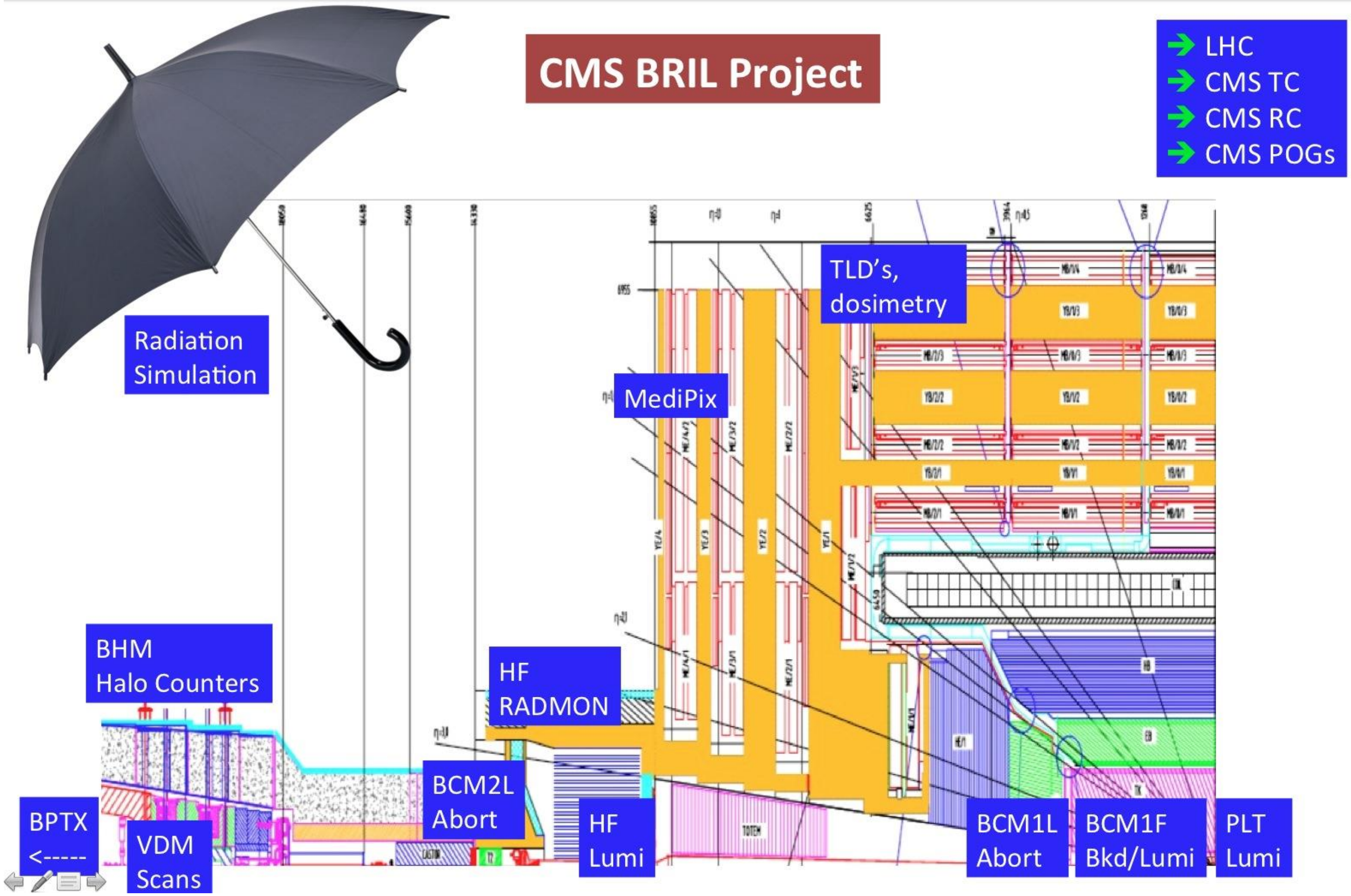


PLT performance paper in preparation (CMS DN-21-008), to be submitted to *Eur. Phys. J. C*

Backup slides

The CMS BRIL group

- BRIL (Beam Radiation, Instrumentation, and Luminosity) group oversees luminosity measurements, beam condition monitoring, radiation monitoring and simulation, etc. The systems included for Run 2 are shown.



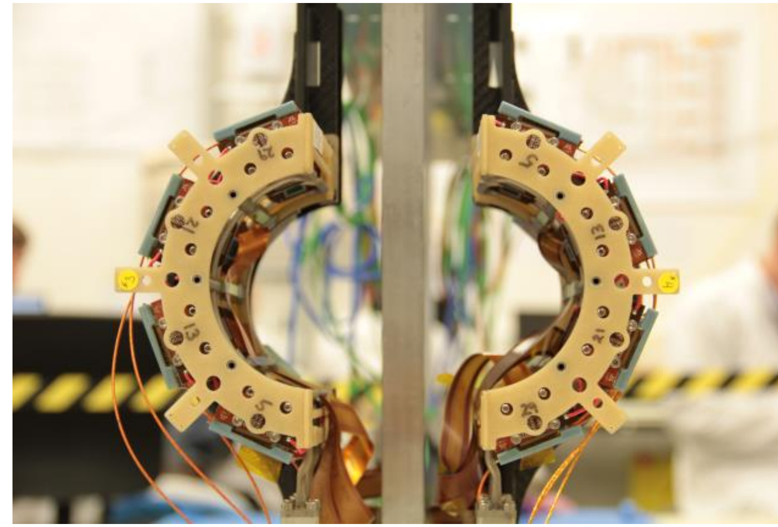
PLT contributing institutes

- CERN
- PSI
- Princeton University
- Rutgers University
- University of Tennessee
- University of Wisconsin
- University of Kansas
- Northwestern University
- Vanderbilt University
- DESY
- Vienna Institute for High Energy Physics
- Karlsruhe Institute of Technology
- University of Canterbury
- Universidad de Sonora
- National Technical University of Athens
- Eötvös Loránd University

Pixel Luminosity Telescope

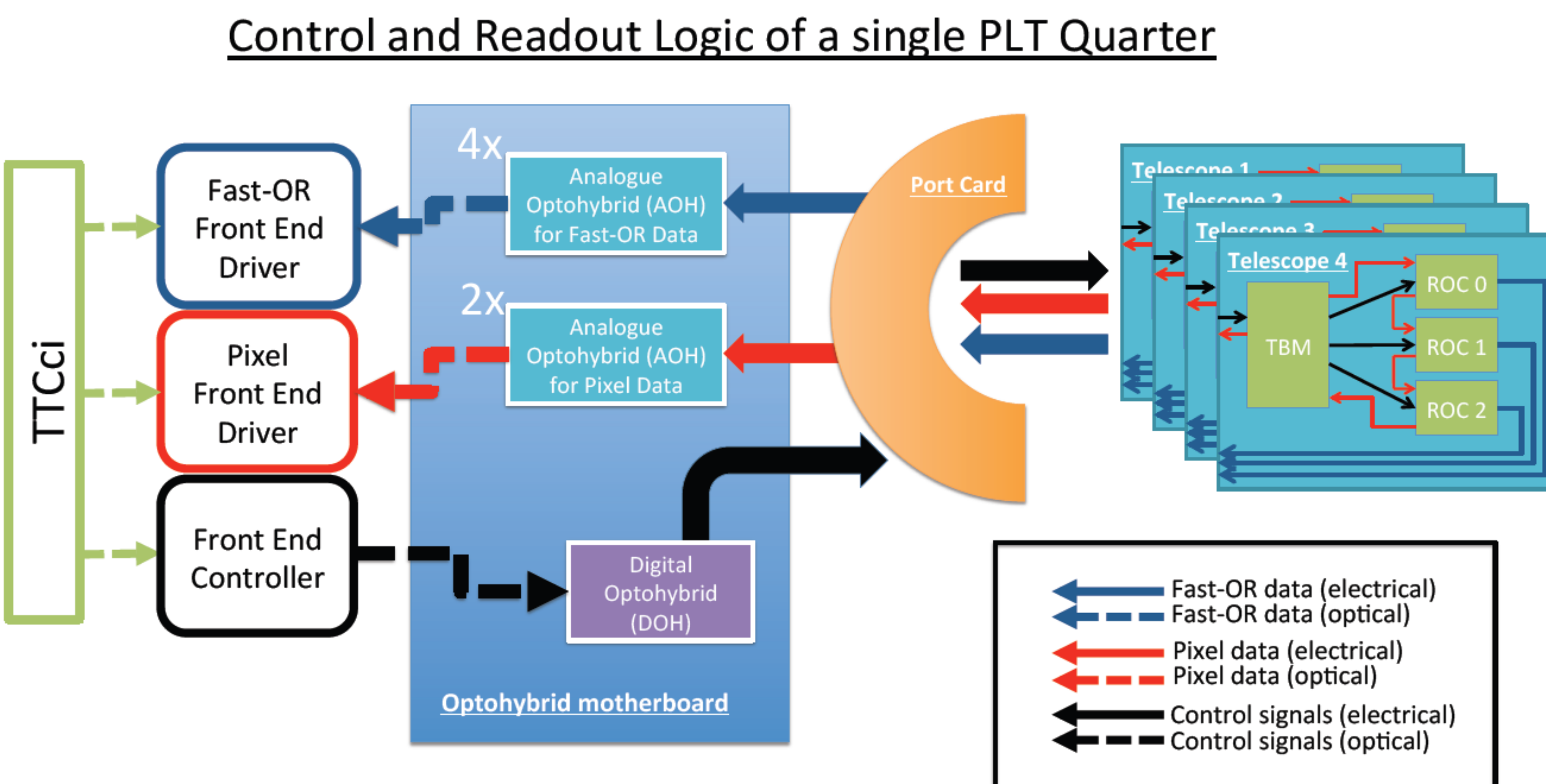
PLT readout

- PLT uses same sensors and PSI46v2 readout chips (ROCs) developed for the phase-0 pixel detector
  - Benefit from reusing proven hardware and software
  - Make use of a readout mode in the PSI46v2 chips not employed in the CMS pixel detector: the “fast-or” readout, which reads out a signal if any pixels on the sensor were hit, operating at the full BX rate of 40 MHz
  - Also read out full pixel data with a dedicated trigger at rate of ~3 kHz for additional studies



PLT front-end electronics

- Each 4-telescope quadrant is read by a port card, which is then connected to an opto-motherboard to convert to optical signals for readout.

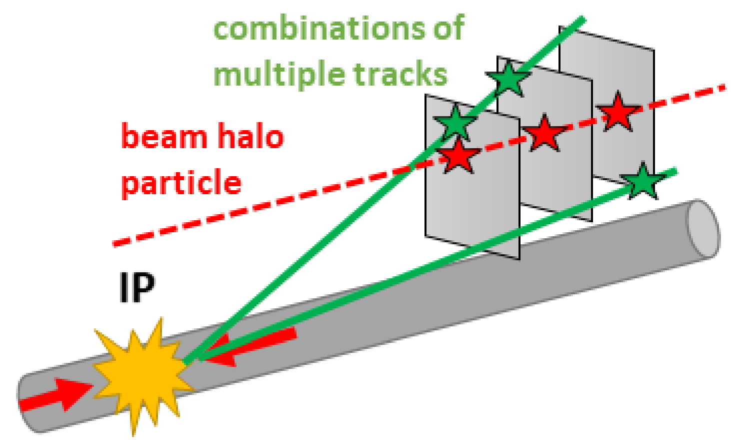


Zero-counting method

- Let μ the average number of tracks observed in the PLT. We assume that the luminosity is proportional to μ.
- The number of tracks observed per event is given by a Poisson distribution with a mean of μ.
- P(event with 0 tracks) = $e^{-\mu} \rightarrow \mu = -\ln f_0$
- Thus, the luminosity is proportional to $-\ln f_0$; we just need to determine the constant of proportionality

PLT calibration

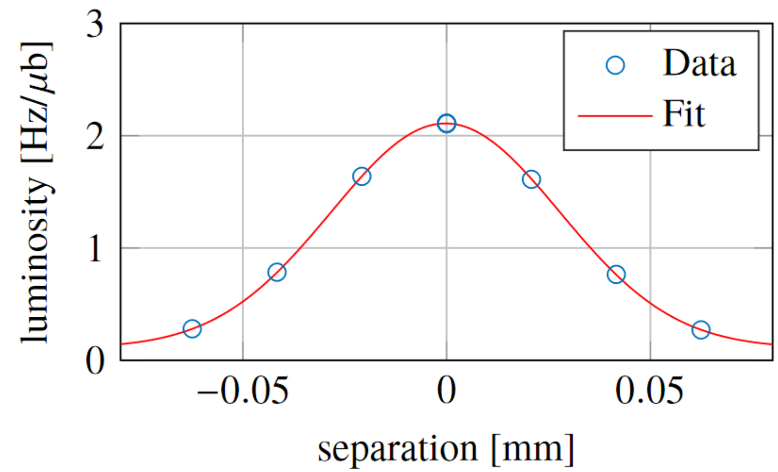
- Use rate of “triple coincidences” to measure luminosity
- To minimize systematic effects, use “zero-counting” method: count fraction of events where no triple coincidence is found and then use L ~ -ln $\langle f_0 \rangle$
- Correct measured data for “accidentals”: events where a triple coincidence is not from a real track from the IP (beam halo, combinatorics, etc.)



- Calibrate overall luminosity with a Van der Meer scan using special beam conditions

Emittance scans

- In 2017 and 2018, we also had a program of regular "emittance scans" – a reduced scan with 7 or 9 scan points and 10 sec/point
- Because these are quick (<2 mins. total) we can conduct them regularly without a large impact on beam time



M. Hostettler et al., IPAC2017

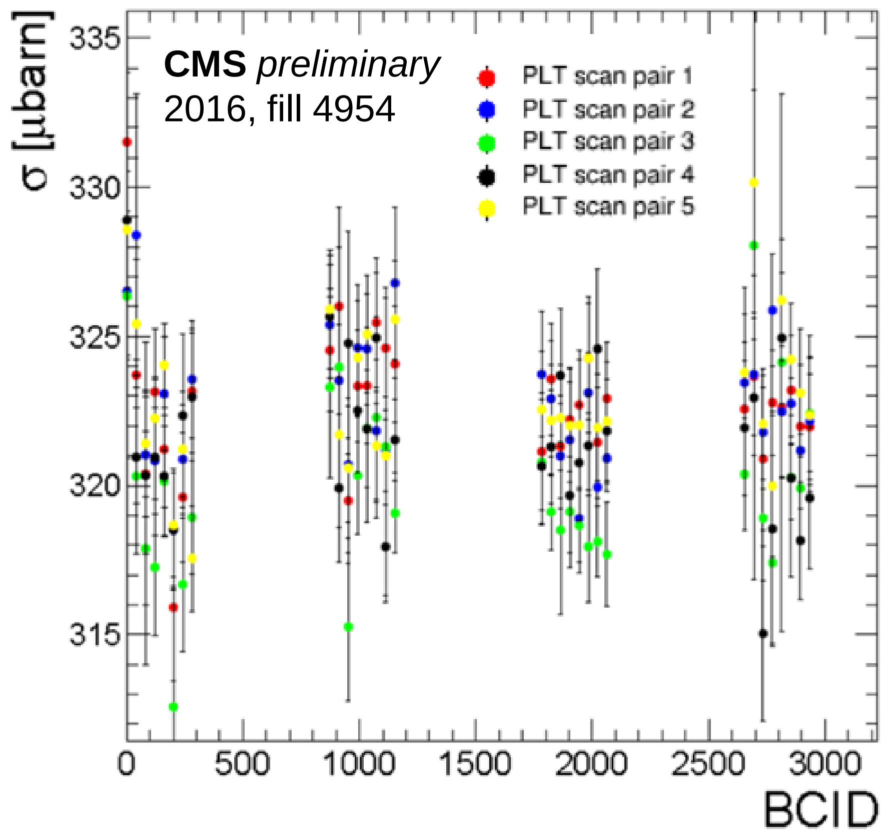
- Thanks to the high publication frequency of the PLT and other BRIL luminometers, these provide enough data to measure the beam size
- Special framework was developed in 2017 to automatically analyze these scans to provide real-time feedback

PLT operational history

- In 2015, two telescopes were lost due to failure of the LCDS chip on the port card.
- These were replaced during the 2016-2017 EYETS and were fully functional through the rest of Run 2.
- In 2016, two telescopes also suffered a failure in which the pixel readout stopped working, although the fast-or readout was still fully functional.
- These were not repairable within the EYETS timescale. For the rest of Run 2, we still took luminosity measurements with these telescopes, but they were excluded from the overall PLT luminosity measurement, since we could not monitor and calibrate these telescopes well.

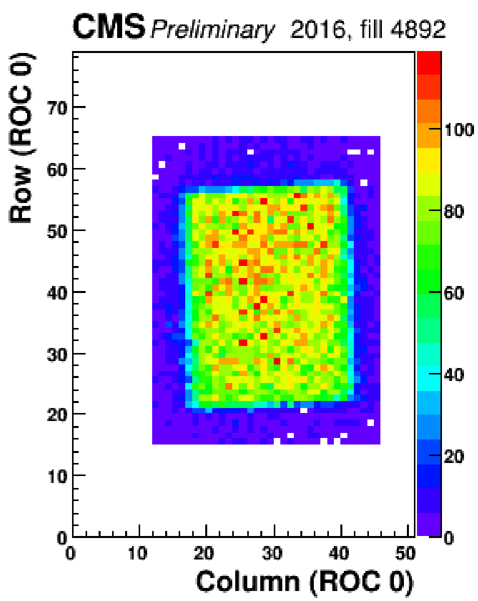
VdM scan stability

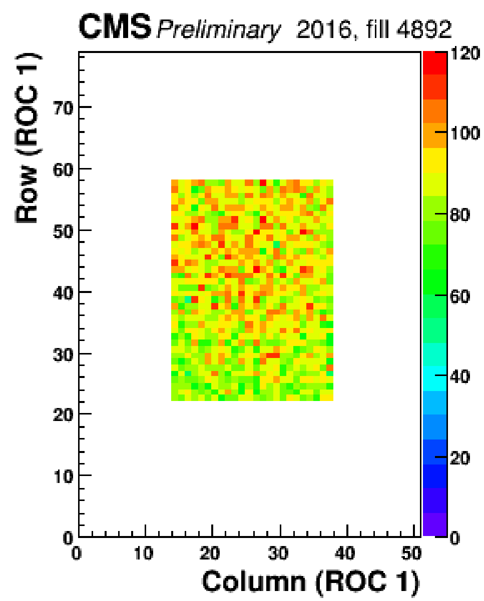
- The full VdM scan program in 2016 covered a total of five scan pairs and 32 colliding bunches. We see consistent results across all bunches and scans in the PLT.

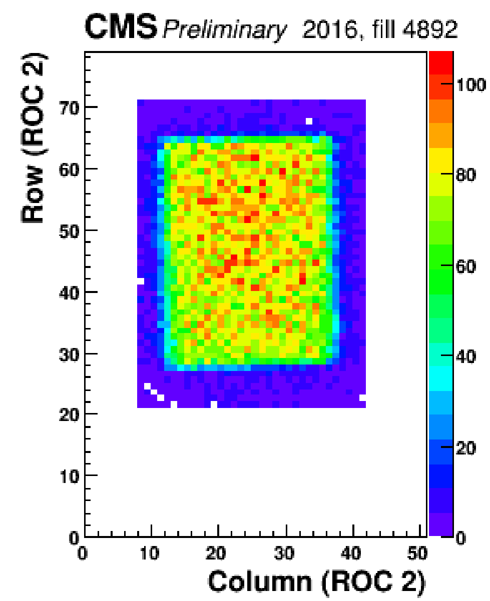


PLT tracks and occupancy

- Using the full pixel readout, we can look at events in a single telescope, and select only hits which can be reconstructed as a single track.
- The center plane has an active area of 3.6x3.6mm; outer planes slightly larger to allow for alignment and accidental effects.
- We can clearly see the effects of imperfect alignment and develop corrections.

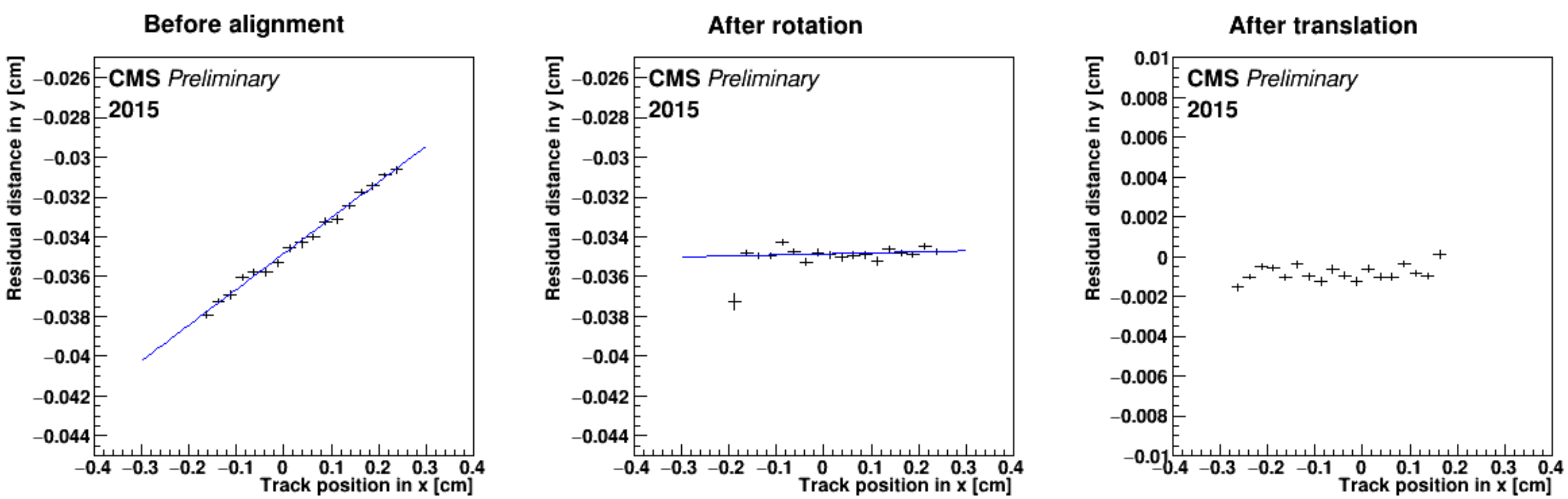






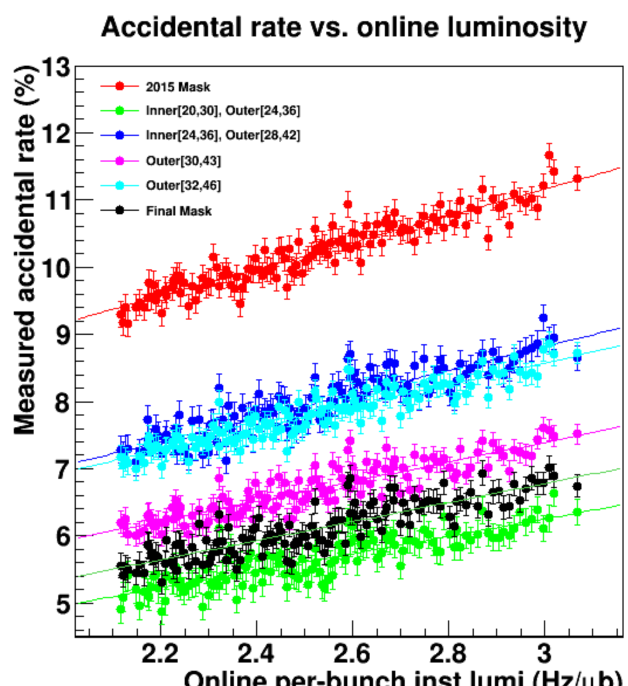
Alignment

- The alignment procedure uses the track residuals to derive the alignment in two steps: first a rotation to produce a constant residual, and then a translation to move the residuals to 0



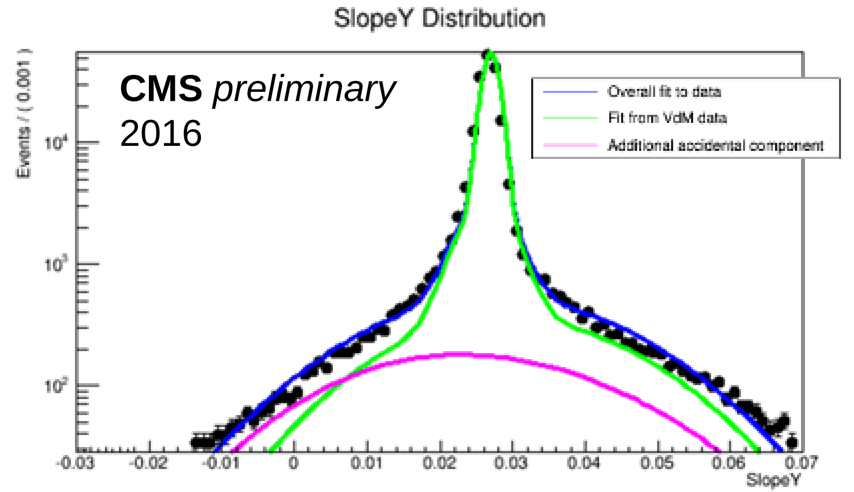
Accidental optimization

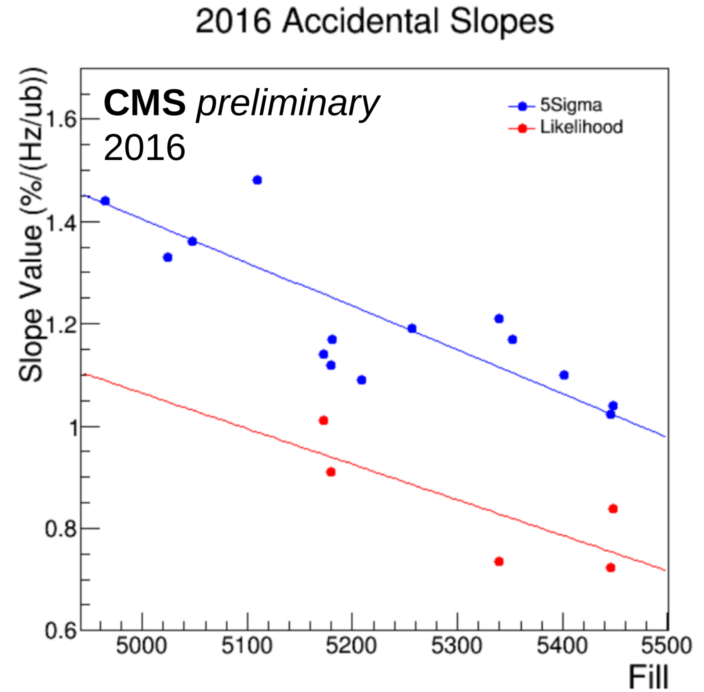
- Selecting the optimal active area involves a tradeoff between accidental rate (higher for larger areas) and statistical precision of the luminosity measurement.
- In 2016, we studied a variety of areas to see what would give a good accidental rate while still retaining good statistical precision. The red points show the 2015 active area, while the black is the final selection for 2016.



Accidental likelihood fit

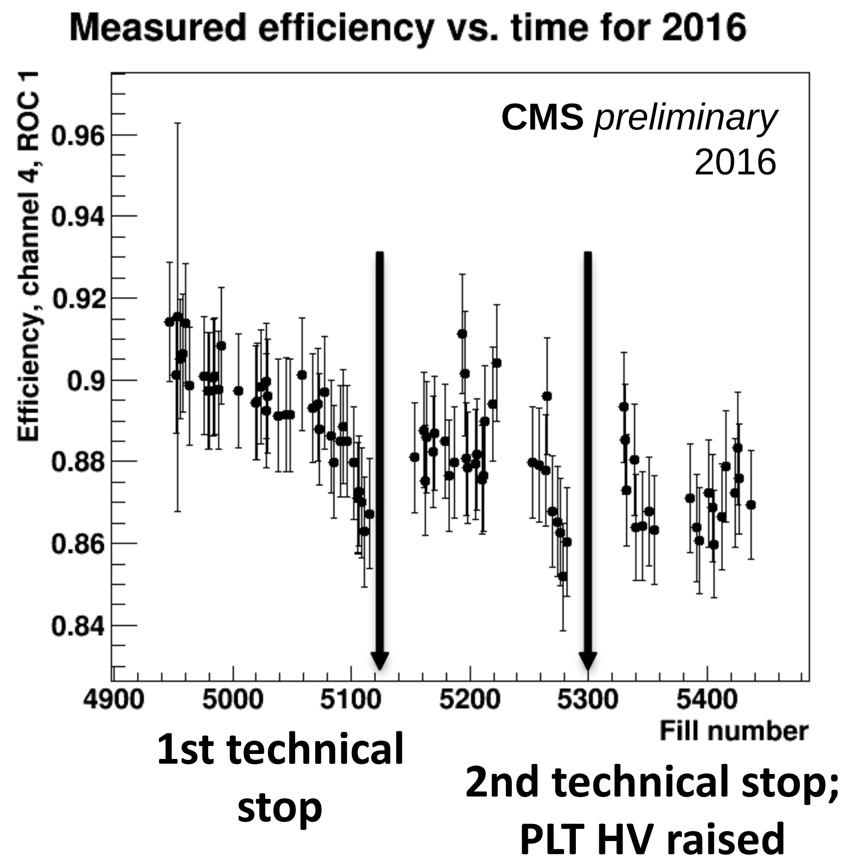
In 2016, a new method for measuring accidentals was devised, in which the slope distribution is fit using a maximum likelihood fit (top). The blue line shows the overall fit to data, with the green line showing the fit representing the slope distribution at VdM luminosity and the purple line showing the additional accidental component at higher luminosity. The results show a similar trend to that using the 5 sigma method (bottom).





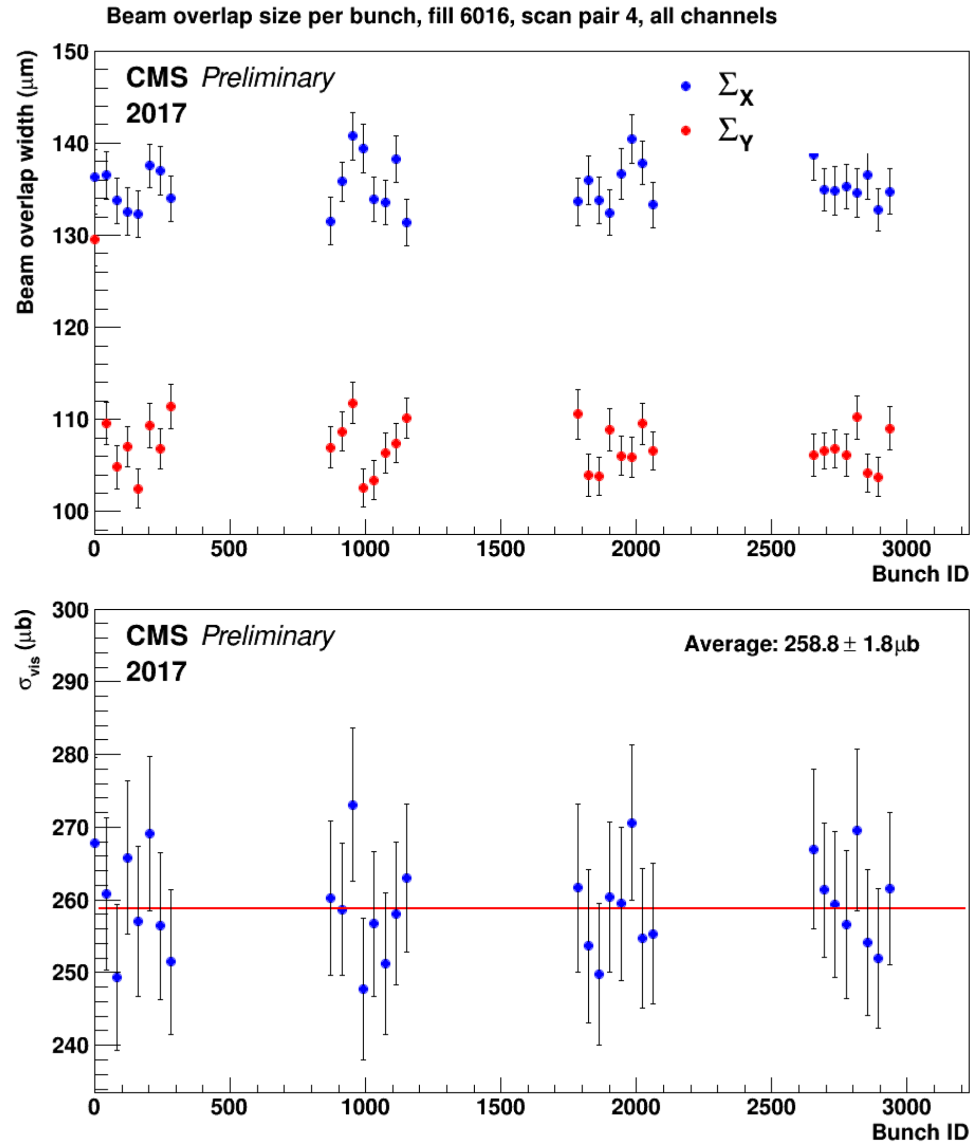
Efficiency corrections in 2016

- To correct for this, we needed to measure efficiency within the PLT.
- This was done by looking for events with two hits in two planes consistent with a track, and seeing how often the expected hit in the third plane was found.
- Derive corrections for the PLT efficiency loss over the course of 2016.
- After this correction is applied, the resulting RMS in the PLT/DT ratio is decreased from 1.8% to 1.2%.



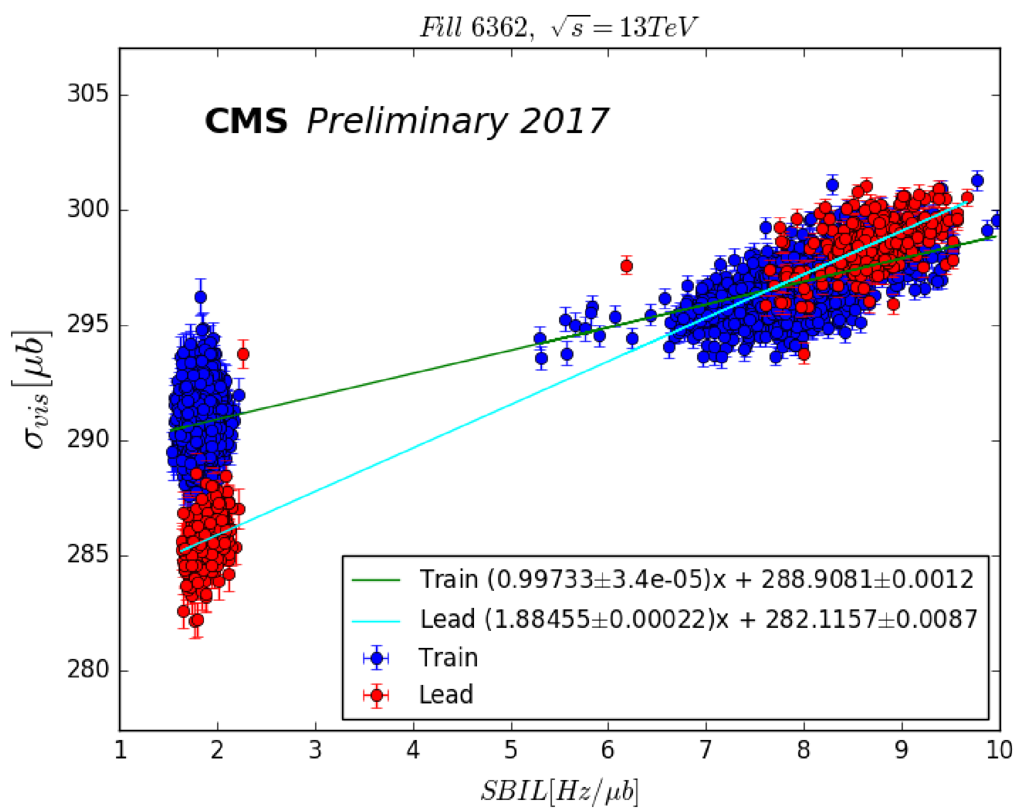
Track luminosity in VdM scan

- Overall results for measured beam overlap width consistent with triple coincidence method, and resulting σ_{vis} consistent across bunches



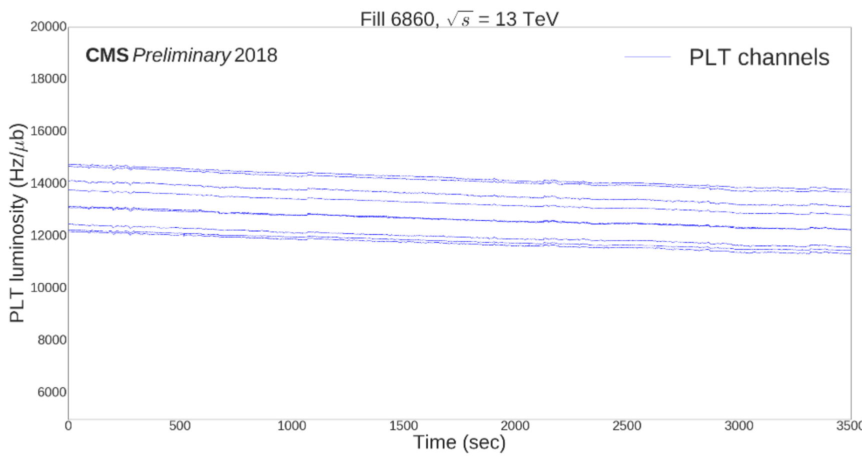
Train bunch effects

- Because the emittance scans can probe all bunches in the LHC fill, this provides a large number of data points.
- We can observe differences between leading and nonleading bunches in bunch trains and correct separately for them.

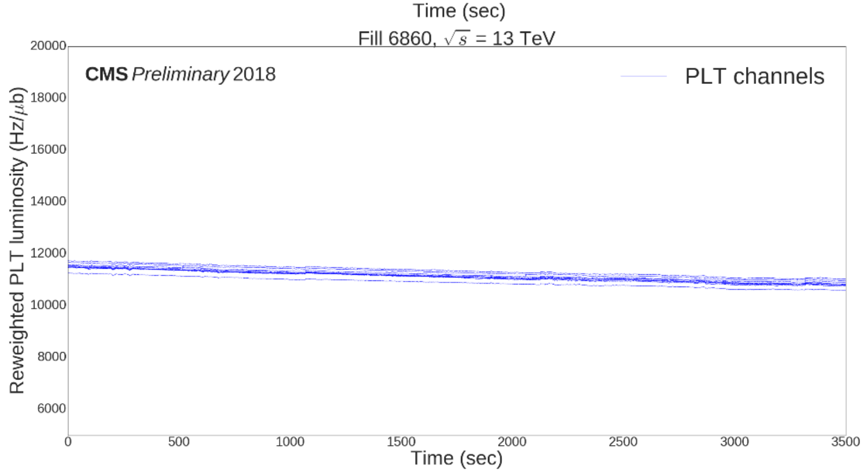


Per-channel corrections

- Over the course of Run 2 we observe that radiation damage affects the channels unequally.
- By developing per-channel corrections we can restore equal response across all channels.



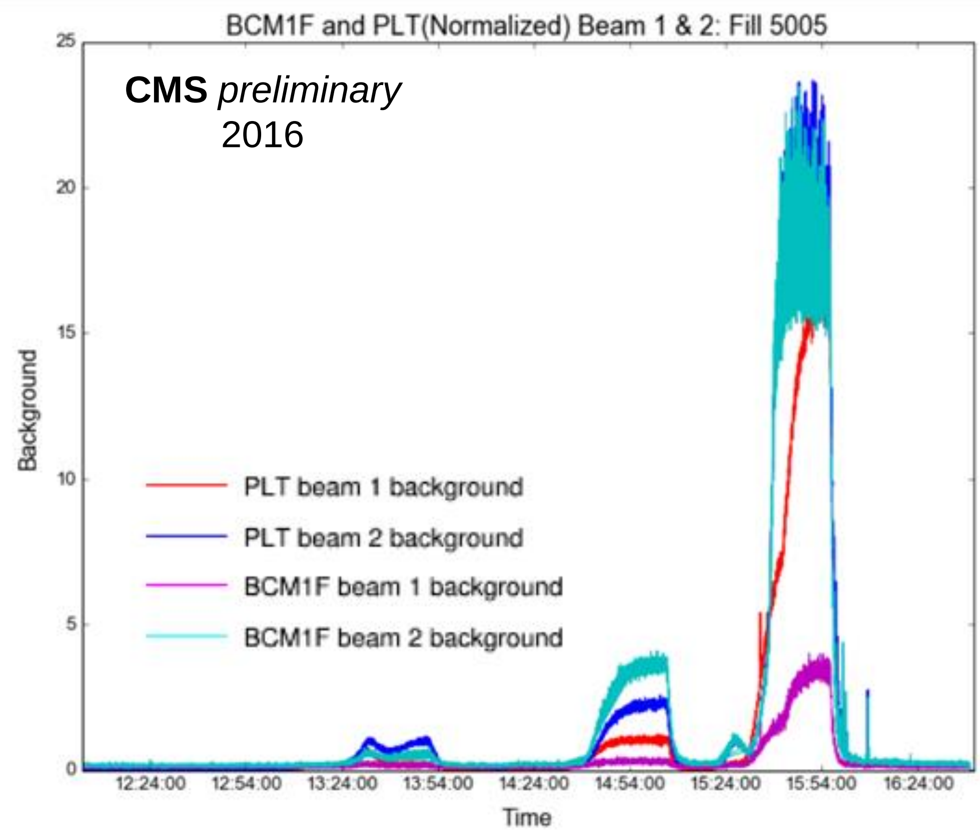
Top: luminosity per channel, as a function of time, before per-channel corrections.



Bottom: luminosity per channel after per-channel corrections are applied.

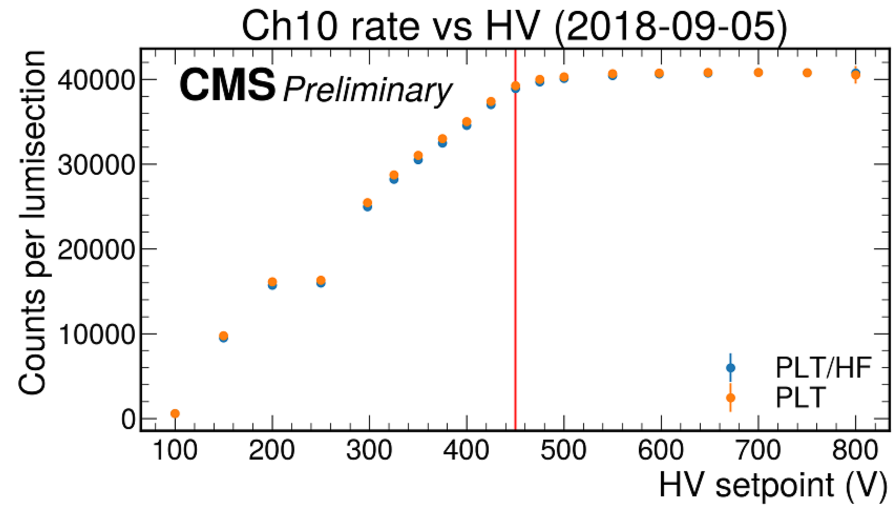
Background measurement in PLT

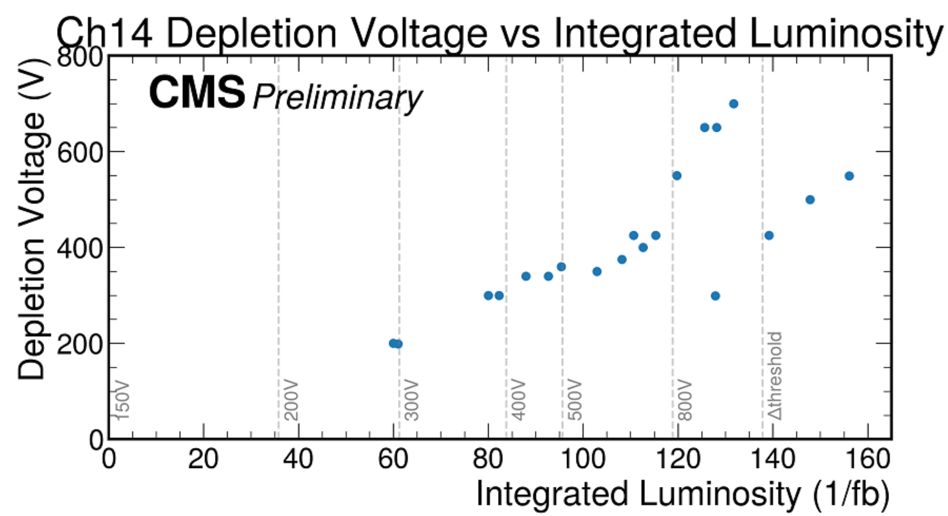
- To serve as a backup for the BCM1F, the main detector for measuring beam background, we used measurements of the PLT rate in non-colliding bunches.
- The right shows the rates using the PLT measurement compared to BCM1F in a special fill where gas was injected into the beampipe to induce beam background.



Depletion voltage

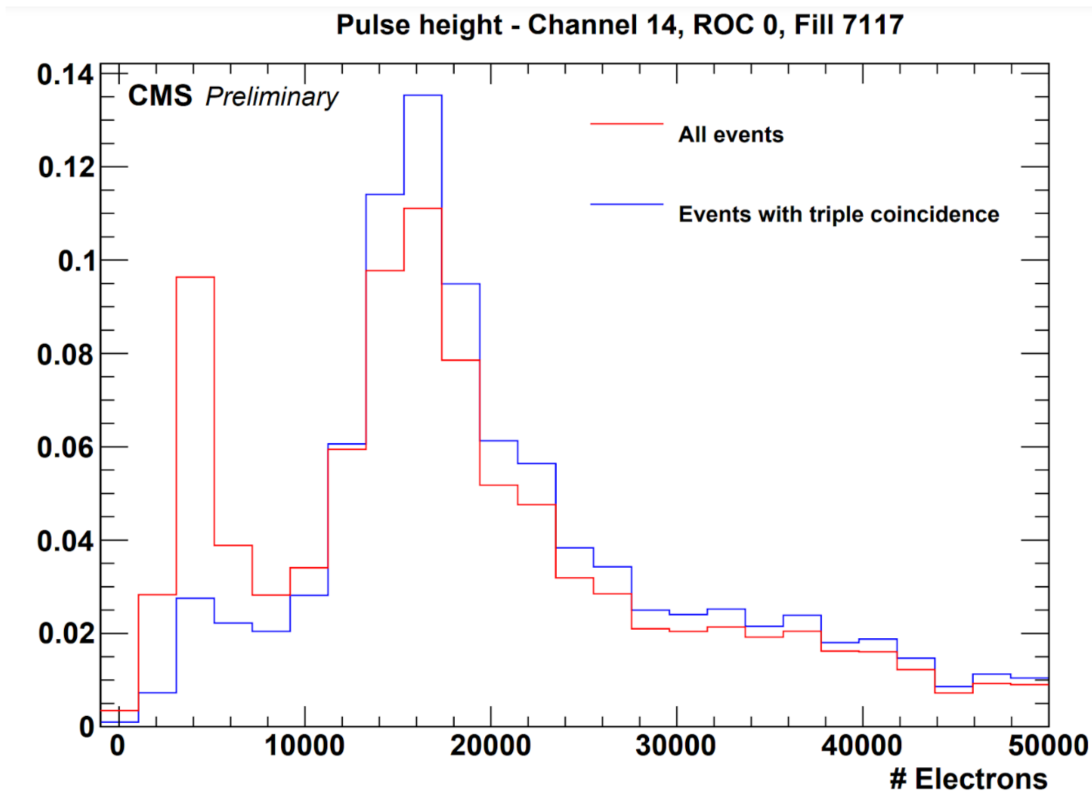
- High voltage scans can be used to find the necessary voltage to ensure the sensor is depleted
- This also serves as another monitor of radiation damage to the sensors



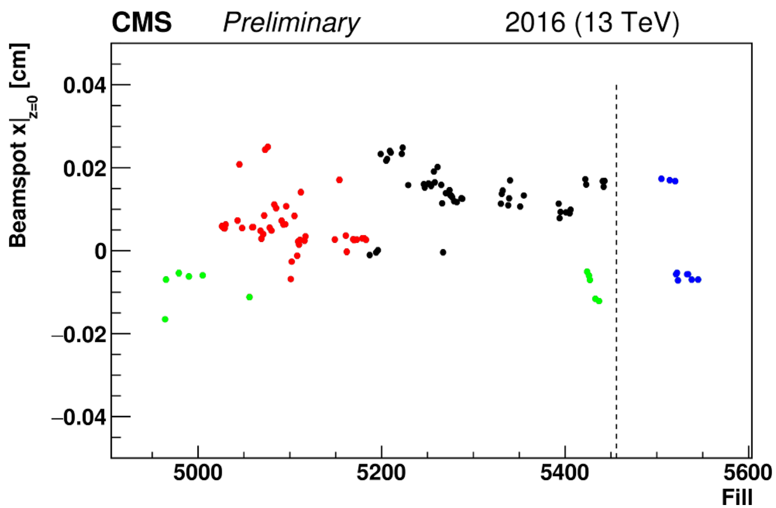


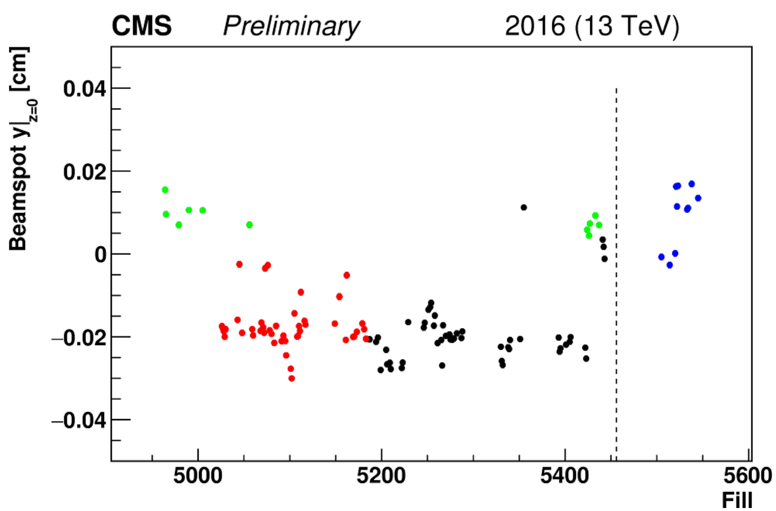
Charge collection with triple coincidences

- Requiring triple coincidences in the charge collection measurement significantly reduces the secondary peak, suggesting that a large component of these timewalk events is from noncollision sources

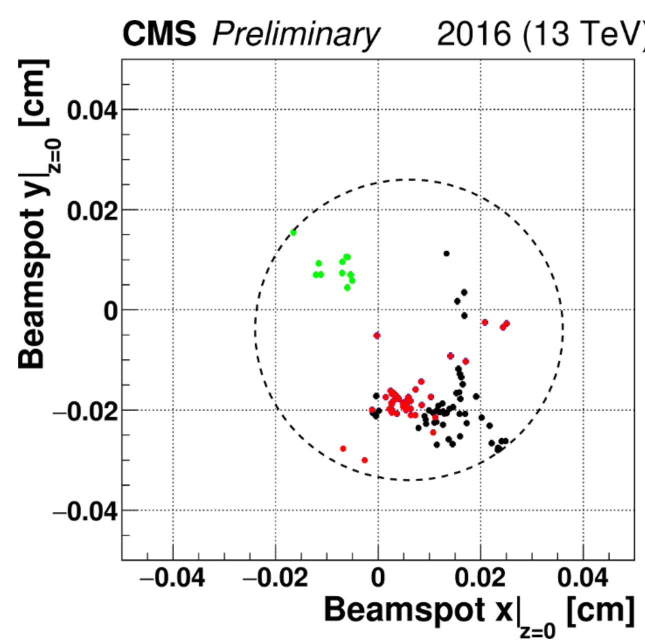


Beamspot reconstruction



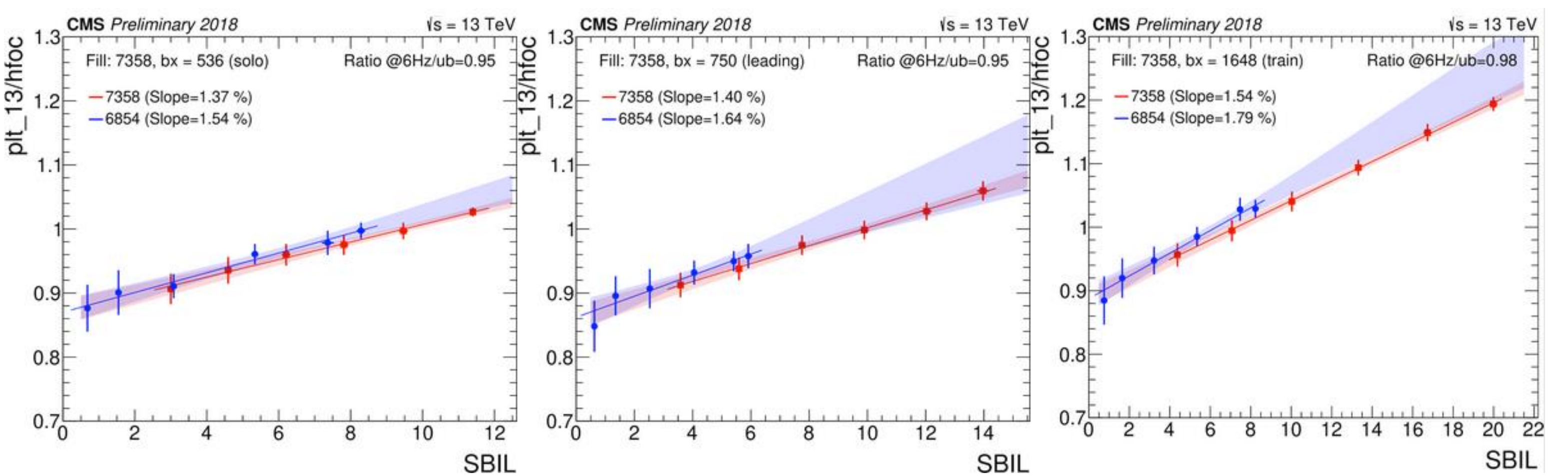


- By projecting the tracks back to the origin, the evolution of the beamspot over time can be monitored
- Left: beamspot position in x (top) and y (bottom) over time. Colors represent periods of stable beamspot position.
- Right: 2D beamspot position.



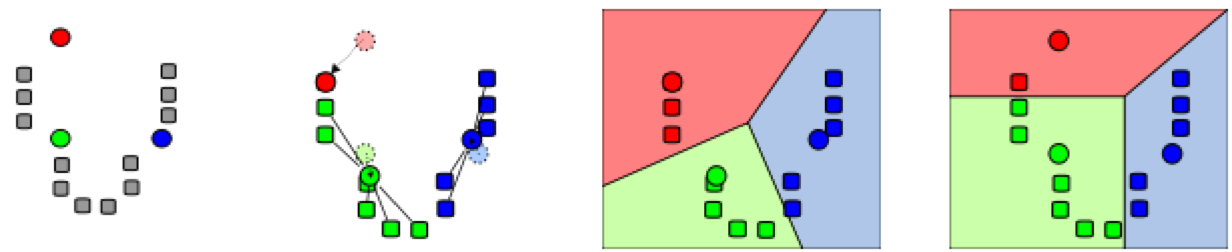
High-pileup fills

- Some special LHC fills for machine development have much higher pileup than normal, which can be used to probe the PLT linearity over a wider range.
- The nonlinearity observed is consistent with regular physics conditions.



Machine learning: k-means clustering

- Data is preprocessed by removing constant baseline and normalizing all features to mean of 0 and standard deviation of 1
- k-means clustering identifies a number (k) of centroid points, assigns points to centroids, and then iteratively adjusts the centroid positions until the sum of squares of distances is minimized



Initial centroids (color) are randomly generated

Clusters are generated by association with nearest centroid

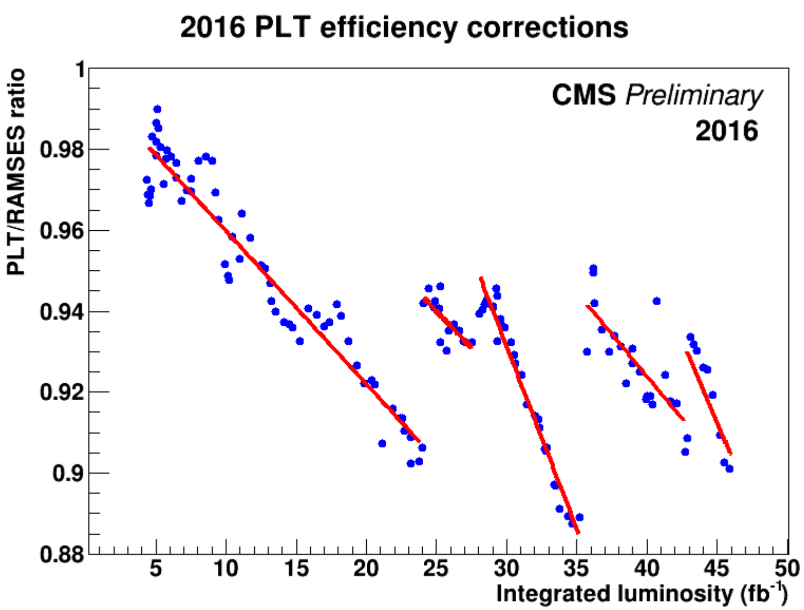
Each centroid is moved to the mean of the resulting cluster

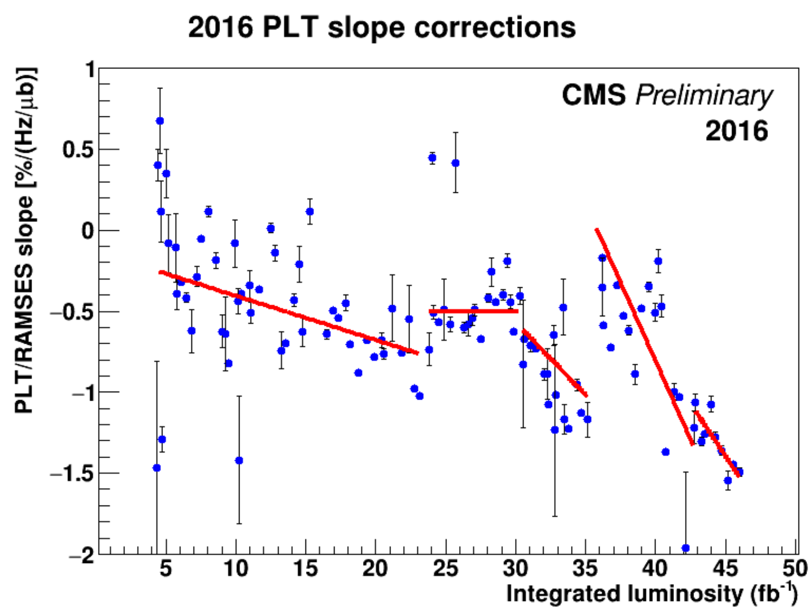
Procedure is iterated until convergence

- The largest resulting cluster comes from good occupancy maps, and the other clusters indicate occupancy maps with different types of problems (dead pixels, incorrect data decoding, etc.)

2016 corrections

- In 2016, since emittance scan data not available, linearity and efficiency corrections were derived by comparison to another luminometer (RAMSES)
- The year is divided into five periods, corresponding to different operating conditions, and a linear fit used for each





Statistical and systematic uncertainty

- Statistical uncertainty = 1% per bunch for smallest integration period (0.36 seconds)
- Overall systematic uncertainties are good and expected to improve with upcoming reanalysis of 2017 and 2018 luminosity

Systematic	Uncertainty (%)			
	2015	2016	2017	2018
Total normalization uncertainty	1.3	1.0	1.5	2.1
Cross-detector stability	3.0	0.9	1.3	1.0
Cross-detector linearity	1.8	0.8	1.4	1.5
CMS deadtime	0.5	< 0.1	0.5	< 0.1
Total integration uncertainty	3.6	1.2	2.0	1.8
Total uncertainty	3.8	1.6	2.4	2.8