Performance of the Pixel Luminosity Telescope for Luminosity Measurement at CMS during Run 2

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The CMS BRIL Group

- BRIL (Beam Radiation, Instrumentation, and Luminosity) group oversees luminosity measurements, beam condition monitoring, radiation monitoring and simulation, etc.
The Pixel Luminosity Telescope

- Dedicated instrument for measuring luminosity installed in 2015 at beginning of Run 2
- 48 silicon sensor planes arranged in 16 “telescopes” (8 on either side of CMS) outside the pixel endcap ($|\eta| \sim 4.2$)
- Look for events where all three planes in a telescope register a hit (“threelfold coincidence”) to measure luminosity
- Provide online bunch-by-bunch measurements to LHC and CMS with a statistical precision of 1% every 1.5s to allow for fast feedback (e.g., for beam optimizations)
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 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 $L \sim -\ln <f_0>$.
- 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.
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:

\[ L = N_1 N_2 \nu_{\text{orb}} N_b / 2\pi\sigma_x \sigma_y \]

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

- In 2016, the data was corrected for accidentals by looking at the distribution of tracks in reconstructed slopes, measuring the mean slope, and rejecting any track more than $5\sigma$ away from the mean.
- This accidental rate was measured over a variety of fills and luminosities and showed consistent behavior.
- A new technique was developed for 2017 using a maximum likelihood fit on the slope distributions, providing consistent results.
Efficiency Loss in 2016

- Over the course of 2016, we observed two periods where the PLT luminosity decreased by several percent compared to other luminometers.
- This appears to be due to higher-than-expected efficiency loss due to radiation damage during high-luminosity periods of LHC running.
- PLT sensor HV was raised to 200 V in October which worked to alleviate further efficiency loss.

![Luminosity ratio at single-bunch instantaneous luminosity of 4 Hz/μb](image)
Efficiency Corrections

- 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%.
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.
Conclusions

- PLT has been operating successfully in 2015 and 2016 to provide both online and offline luminosity with high uptime and precision.
- Some issues in 2016 due to efficiency loss. These have now been corrected.
- In 2017, better monitoring has been deployed to more quickly look at PLT performance and speedily fix issues if they arise.
- Looking forward to an excellent year of running!
Backup Slides
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.

Control and Readout Logic of a single PLT Quarter
Emittance Scans

- In 2016 and 2017 we also have a program of regular “emittance scans” – a reduced scan with 7 scan points and 10 seconds/point
- Because these are quick (<2 mins. total) we can conduct them regularly without a large impact on beam time
- Thanks to the high publication frequency of the PLT and other BRIL luminometers, these provide enough data to measure the beam size
- In 2017, we can do regular analysis of these scans to monitor our detector performance
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 are now fully functional.

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 now we still take luminosity measurements with these telescopes but they are excluded from the overall PLT luminosity measurement, since we cannot monitor and calibrate these telescopes as well.
Zero-Counting Method

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

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