Luminosity Measurements and Systematics

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Acknowledgements to the luminosity groups of the experiments and in particular Witold Kozanecki and David Stickland

Evian workshop
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Overview

- The main focus of this talk is to recall the luminosity measurements from the experiments, as these are used to validate the luminosity model of the LHC
- For this ATLAS/CMS are the relevant luminosities when they are not levelled
  - link between emittance and luminosity not easy with separated beams
- Will also recap on the luminosity ratio of IP1/5

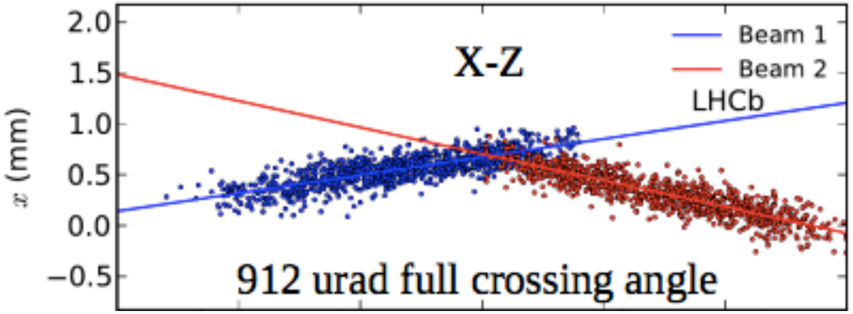
Motivations for precise luminosity measurements

- Two main uses
  - Physics
    - Precise measurements of cross section of physics processes to compare with theory
      - e.g. W production, Z production, top pair production and Higgs production!
  - Operations
    - Fast measurement of luminosity needed for
      - Trigger prescale settings
      - Pileup corrections (online and offline)
      - Optimize the delivered luminosity from LHC
      - Help to understand machine setup (luminosity model, emittance etc..)
- Different timescales and levels of precision for these two use cases
- Requirements:
  - Luminosity needs to be measured in real time and per bunch
  - Measurements required to be deadtime-less
    - Independent of main experiment DAQ system which is based on triggered events

Methodology

- Dedicated luminosity detectors used to count events with certain characteristics
  - hits or lack of hits in certain channels
- Rate (R) of such events proportional to luminosity
  - $R = \sigma_{eff} . L$
- Calibrate absolute luminosity scale using beam separation (Van der Meer) scans and various measured beam parameters
- Need to transfer calibration for VdM regime to physics regime
  - low pileup, no bunch trains -> high pileup with trains
- Try to use multiple detectors and algorithms in order to have redundancy, cross-checks and to minimize systematic uncertainties

In addition to the VdM scan LHCb uses the ‘Beam Gas Imaging’ method for the calibration, relying on their excellent vertex resolution. Measuring the single beam profiles using beam-gas events (gas deliberately injected into beam pipe).



https://doi.org/10.1016/j.ppnp.2014.11.002

BGI also gives measurement of ghost charge used by other experiments in their lumi measurements

VdM scans

$$\boxed{\mathcal{L}} = \boxed{\frac{R}{\ }}\!\!\!\!\sigma = \frac{\boxed{\mu\, n_b\, f_r}}{\sigma_{inel}} = \frac{\boxed{\epsilon\mu}\, n_b\, f_r}{\boxed{\epsilon}\sigma_{inel}} = \frac{\boxed{\mu_{eff}}\, n_b\, f_r}{\boxed{\sigma_{eff}}}$$

μ = number of inelastic pp collisions per bunch crossing

n_b = number of colliding bunch pairs

f_r = LHC revolution frequency (11245 Hz)

σ_{inel} = total inelastic pp cross-section (~80 mb at 13 TeV)

ε = acceptance x efficiency of luminosity detector

μ_{eff} = # visible (= detected) collisions per bunch crossing

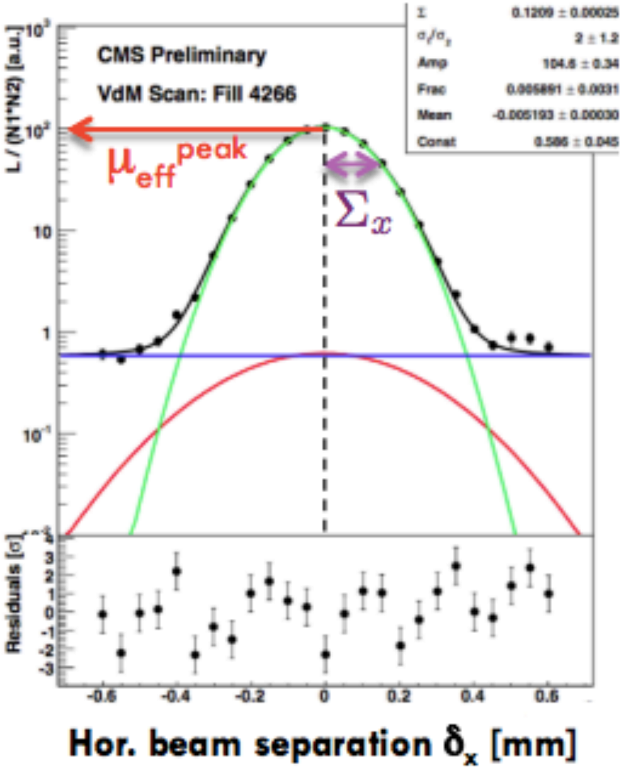
σ_{eff} = effective cross-section = luminosity calibration constant

VdM scans

- Measure visible interaction rate μ_{eff} as a function of beam separation δ
- The measured reference luminosity is given by

$$\mathscr{L} = \frac{n_b f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y}$$

with $\Sigma_{x,y}$ = integral under the scan curve / peak



- This allows a direct calibration of the effective cross section σ_{vis} for each luminosity detector/algorithm

effective cross-section

$$\boxed{\sigma_{\text{eff}}} = \boxed{\mu_{\text{eff}}^{\text{peak}}} \frac{2\pi \boxed{\Sigma_x \Sigma_y}}{\boxed{n_1 n_2}}$$

scan widths

bunch populations

peak rate

- Key assumption: factorization of luminosity profile

$$\mathscr{L}(\delta_x, \delta_y) = f_x(\delta_x)\, f_y(\delta_y)$$

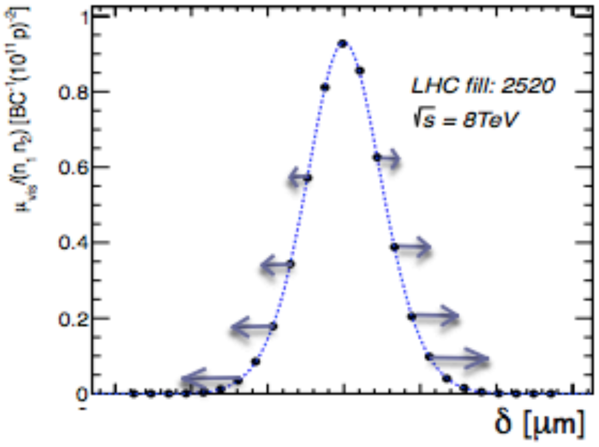
VdM scan fill specifics

- After a number of years the machine setup for VdM fills has been optimized to give the most precise calibration
- Complications are:
  - non-factorizable beams
  - orbit-drifts
  - beam-beam deflections and dynamic-β*
  - Ghost and satellite charge
- Fills details:
  - no bunch trains / long-range encounters
    - minimize beam-beam effects
  - no crossing angle
  - large β*
    - 19m in IP1/2/5
      - Allows to resolve luminous region with tracking information from detectors
    - 24m in IP8 (and large crossing angle)
      - Allows LHCb BGI data to be used to measure single beam profiles
  - Tailored intensity and emittance
    - optimize to minimize beam-beam effects, while preserving sufficient rate (pileup ~0.5)
  - Gaussian shaped and x/y factorizable beams
    - Injector gymnastics – but how factorizable the beam is seems somewhat random
  - Dedicated off-centre scans to assess the non-factorization (does Σ_x depend on separation in y?)
- Dedicated length scale calibration to calibrate beam separation bump using tracking detector information

Relies on high precision measurements from LHC BI devices e.g. bunch currents, and orbit

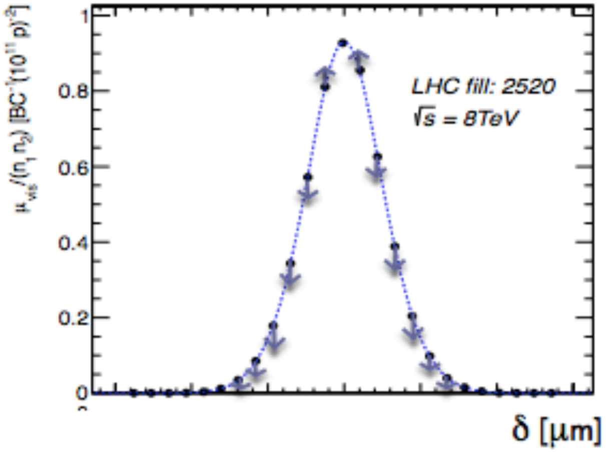
VdM scan fill specifics

Beam-beam deflection



True beam separation larger than nominal separation δ

Dynamic-β

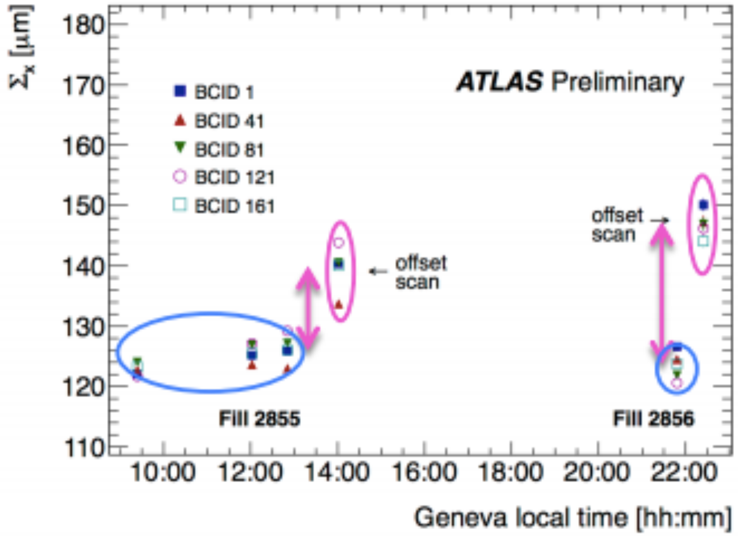


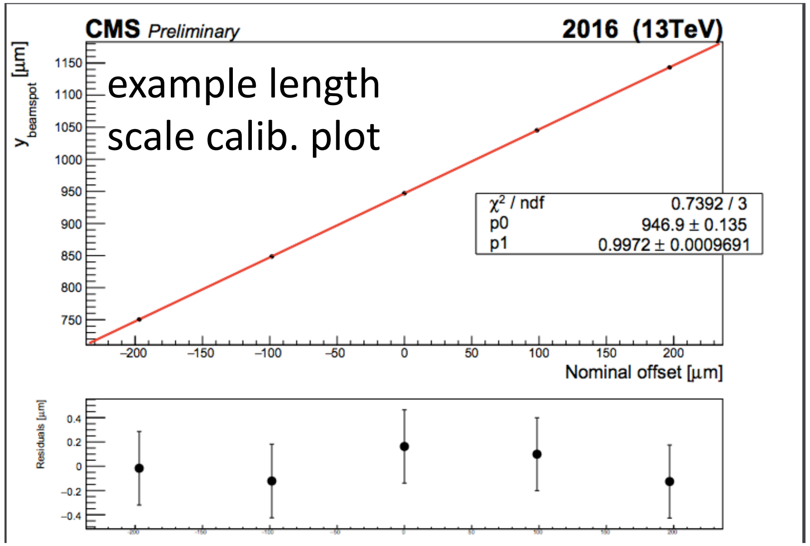
Beams focus/defocus each other by an amount that is a function of separation

(Size of effects exaggerated for demonstration)

non-factorization effect.

~20% difference in Σx between offset and centered scans

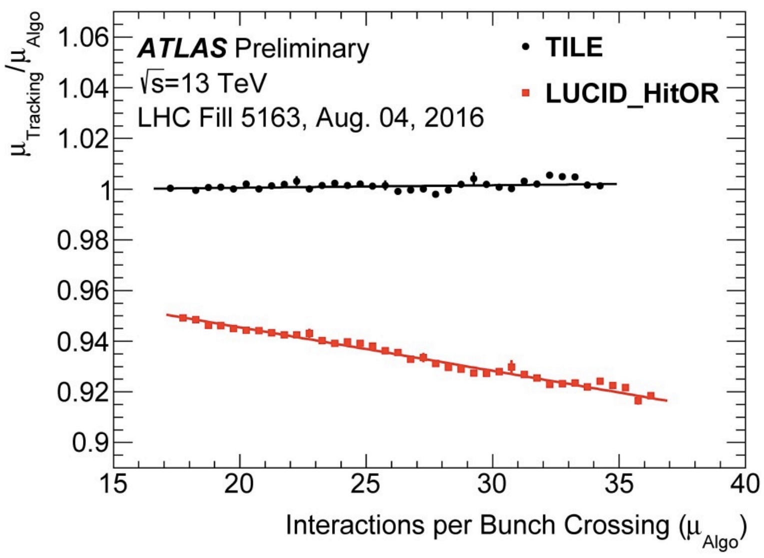


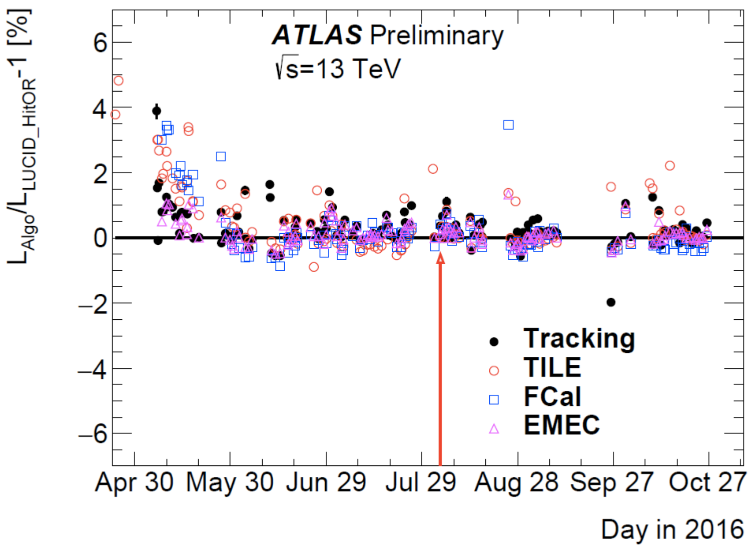


example length scale calib. plot

Applying the calibration at high lumi

- The VdM calibration is derived at μ~0.5, need to apply this in high luminosity running with μ~60 at the start of fill
- Important to understand and correct for
  - Non-linearities from pileup and/or bunch trains
  - Change in detector efficiencies (and therefore σ_{eff}) from ageing, radiation dose (with different timescales) etc…
- Large work to monitor performance and derive corrections
- Important to have multiple detectors/algorithms to give confidence that these effects are understood





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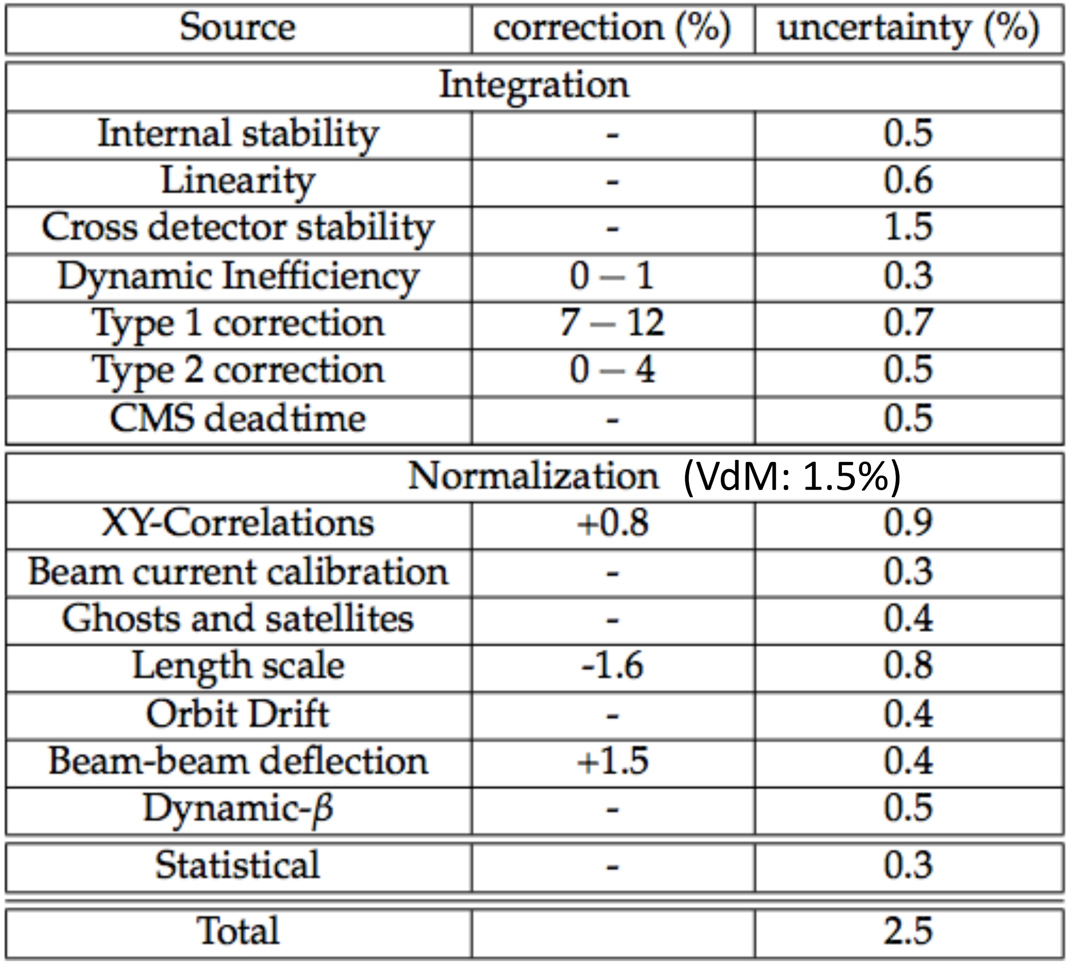
Timescales & precision

- Usually to get the most precise calibration from VdM scans takes ~1 year of analysis giving a precision of ~2.5%
- During running the best estimate of the calibration is used (either based on previous year, or a fast partial analysis of the VdM) this gives a precision of ~5-10%
- The lumi values shown on page-1 have this level of precision
  - Worse precision for special runs, ions, p-Pb, 2.5 TeV etc…
- Shortly after a fill values are put into Massi files, usually these are very similar to what was on page-1 and have a similar precision, although in some cases mistakes going to page-1 can be corrected for at this stage
- The final luminosity numbers are usually released for a big physics conference ~1 year after the VdM is taken
  - so after the years physics run is finished
  - Massi files can be updated at this stage if useful
  - Massi files now have versioning information in them, to allow updates to be easily tracked

Year	ALICE	ATLAS	CMS	LHCb
2015	3.4%	2.1%	2.7%	3.9%
2016	similar to 2015	2.2%	2.5%	3.9% (better later)

Final precision (for 2016)

CMS:



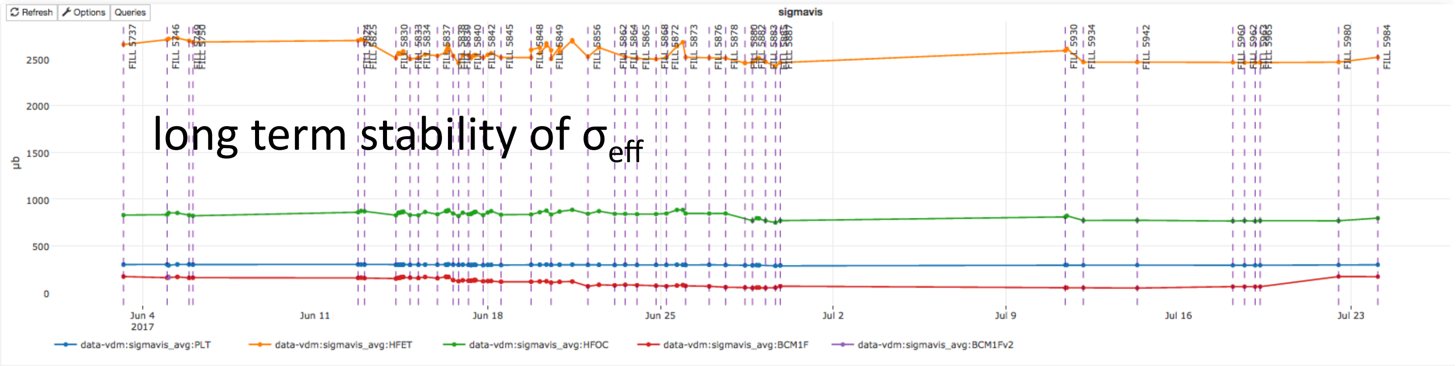
Source	correction (%)	uncertainty (%)
Integration		
Internal stability	-	0.5
Linearity	-	0.6
Cross detector stability	-	1.5
Dynamic Inefficiency	0 – 1	0.3
Type 1 correction	7 – 12	0.7
Type 2 correction	0 – 4	0.5
CMS deadtime	-	0.5
Normalization (VdM: 1.5%)		
XY-Correlations	+0.8	0.9
Beam current calibration	-	0.3
Ghosts and satellites	-	0.4
Length scale	-1.6	0.8
Orbit Drift	-	0.4
Beam-beam deflection	+1.5	0.4
Dynamic-β	-	0.5
Statistical	-	0.3
Total		2.5

ATLAS:

Main systematic uncertainties	2016 luminosity uncertainty (%)
vdM calibration	1.2 %
Calibration transfer	1.6 %
Tracking efficiency	0.6 %
Long-term consistency	0.7%
Total	**2.2 %**

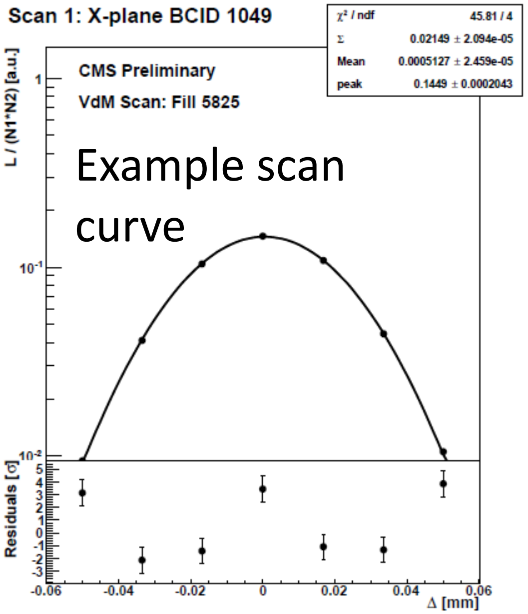
Emittance scans

- CMS have been taking fast beam-separation scans during high luminosity running
  - 7 separations in +/-2σ [later: 9 points +-3.5σ] (takes ~4mins)
  - Taken in all physics fill at start/end of fill
- Allows measuring σ_{eff} in real physics conditions
  - Some complications (LRBB effects, non-factorization)
  - Nicely allows to track stability over time throughout the year
  - Allows to check if machine changes affect σ_{eff}
    - Examples
      - crossing-angle changes during a fill
      - 50 ns vs 25 ns running
- In addition gives measurement of beam size (and emittance with some caveats) during physics running
- Clearly a very useful tool for experiment and machine
- For 2018 ATLAS will also take such scans
  - frequency/parameters to be determined

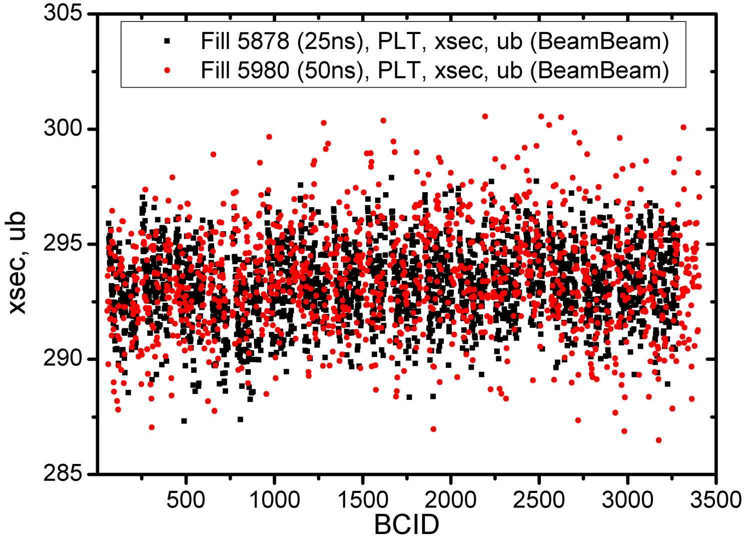


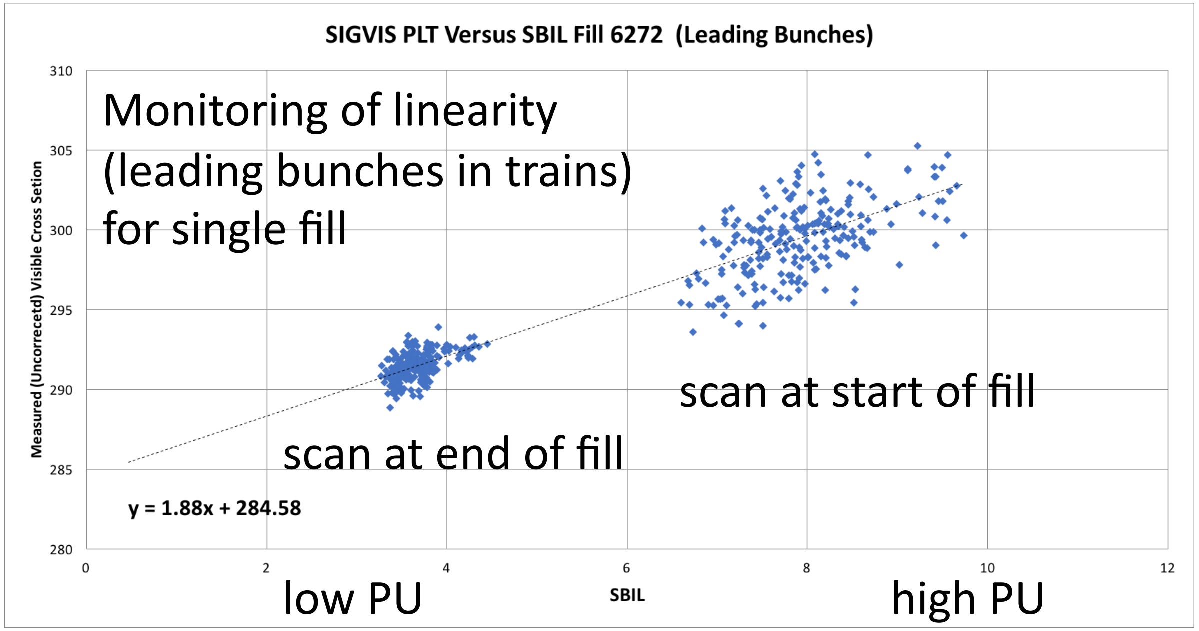
long term stability of σ_{eff}

Emittance scans – plots…



Example scan curve





Monitoring of linearity (leading bunches in trains) for single fill

scan at start of fill

scan at end of fill

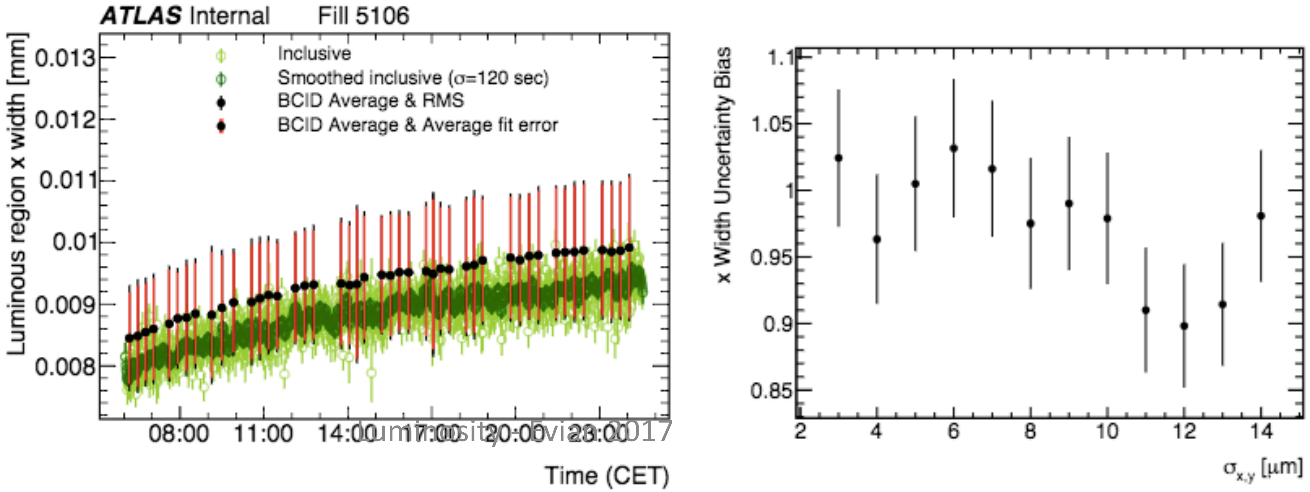
low PU

high PU

Luminous Region data

- Not directly related to luminosity measurements but additional information for emittance understanding
  - e.g. see slides from Mike at LPC meeting at start of year
- ATLAS and CMS can measure the x,y and z size of the luminous region using tracking information
- With some assumptions this can give the B1,B2 convoluted emittance per plane
- In principle difficult measurements, resolution bigger than transverse lumi-region size, fit for resolution scale factor
- Uncertainties related to tracker alignment, choice of trigger used (try to avoid biases due to vertex merging)
- ATLAS closure tests with realistic beam spot in simulation shows only very small biases
- Bunch integrated lumi-region data in Massi files, although no CMS data available for 2017 yet – will come after reprocessing
  - Per bunch data in principle can be produced for a few fills, but significant work (computing and person power)

Example ATLAS plots
(A. Morley)



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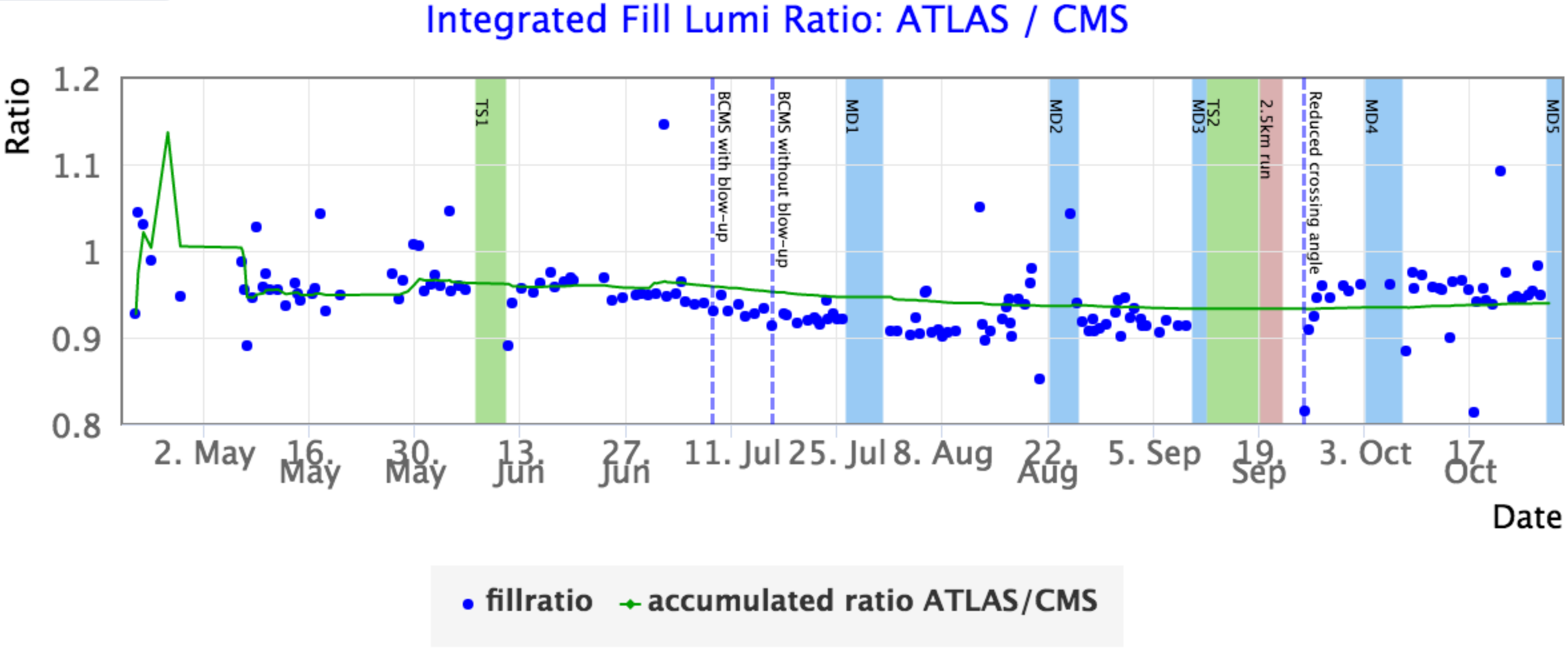
ATLAS/CMS luminosity imbalance 2016



With final luminosity calibrations, ATLAS/CMS measure delivered luminosity imbalance of ~6%* over 2016. Lots of discussion on this and thought to be (at least partially) due to the different crossing-planes in IP1/5 and different H/V emittances. Some evidence of this from zero crossing angle test, but last set of fills of 2016 do not agree with observed imbalance taking BSRT emittances. Not fully understood.

(* - for much of the year this was thought to be ~10% but was reduced to 6% after a CMS re-calibration)

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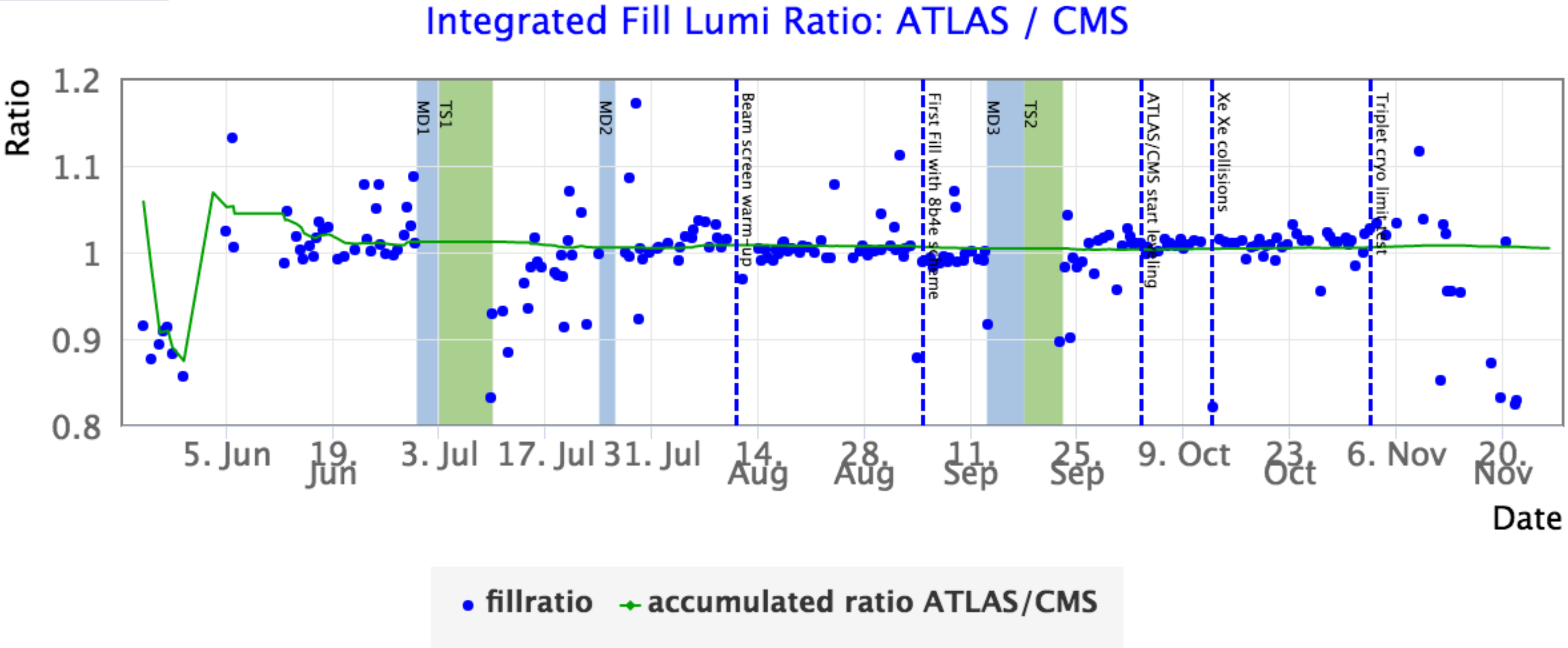
ATLAS/CMS luminosity imbalance 2017

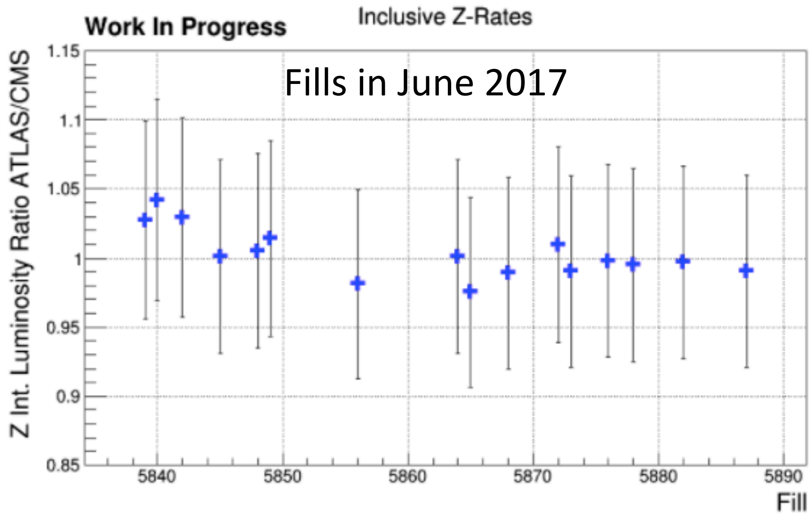


With current luminosity calibrations, ATLAS/CMS measure the same delivered luminosity to within 1% - very impressive. Situation could change with final calibrations but would be surprising if this is more than a ~5% effect.

Slightly different regime than in 2016, as significant data collected when levelled using the measured luminosity values.

Z counting

- A complementary measurement of the luminosity (or IP1/5 ratio) can be made by counting produced Z bosons
  - Completely independent to VdM approach
- Systematic uncertainty on correction from number of observed Z-bosons, to number produced ~3-5% per experiment, so doesn't give a very precise comparison (4-7%)
- Z counting comparison effort pushed last year to give more information on observed lumi imbalance
  - Information for full set of 2016 fills provided
- In 2017 unfortunately less focus on this (various other priorities)
- Should have first comparisons for full 2017 dataset in before end of year
- Hope this can be done faster and more automatically in the future



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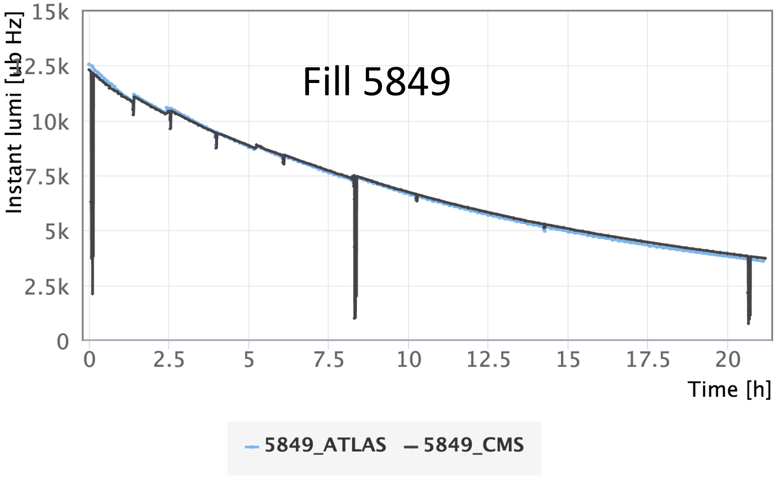
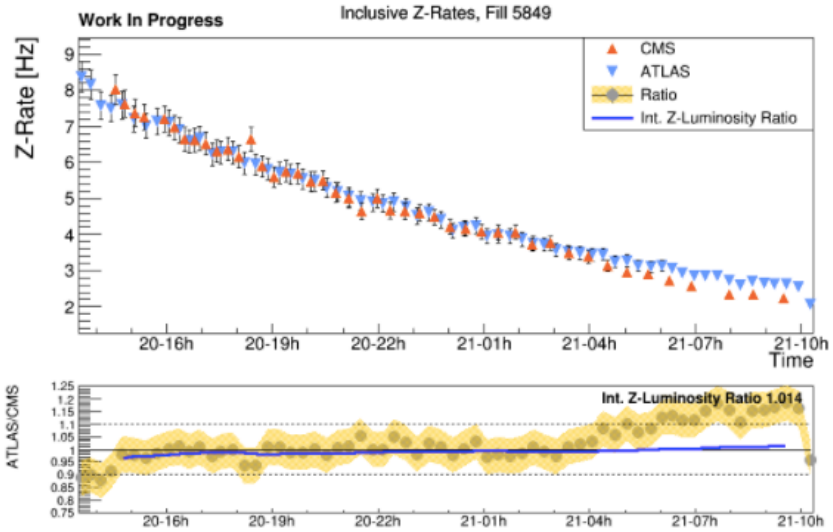
Instantaneous Fill Lumi





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Conclusions

- ATLAS/CMS luminosity measurement precision ~5% before final analysis (~1 year after VdM) reduced to ~2.5% final uncertainty
- Emittance scans by CMS a useful tool for tracking drifts in lumi detector response, ATLAS will also do this in 2018
- ~6% luminosity imbalance in 2016, with current calibrations <1% difference in 2017
- Z counting a useful independent cross check of luminosity ratios
- Luminous region measurements can also be useful for luminosity and emittance understanding