Overview of ATLAS Run-2 luminosity determination

Richard Hawkings, on behalf of the ATLAS luminosity WG
LHC Lumi Days, 4/6/2019

- Overview of the ATLAS luminosity calibration and uncertainties
  - Luminosity-sensitive detectors in ATLAS
  - The run-2 dataset
  - Brief reminder of vdM formalism, and dedicated LHC setup
  - vdM scan analysis and uncertainties
  - Calibration transfer to physics regime (high-\(\mu\), bunch trains)
  - (Long-term stability throughout the year – see talk of V. Lang)
  - Final uncertainties and how we might improve

  - Further details in dedicated talks at this workshop from M. Dyndal, W. Kozanecki and V. Lang (and RH again)
ATLAS luminosity detectors: LUCID & BCM

- Primary Run 2 bunch-by-bunch (b-b-b) measurement from LUCID

- Secondary b-b-b measurements from Beam Conditions Monitor (BCM)
  - 4 diamond sensors in inner detector volume (z=±1.8m) each side of IP
  - Do not work well with 25ns bunch trains – in Run 2 mainly used in vdM scans

- Cherenkov light from quartz windows of 2x16 PMTs at z=±17m from IP
  - b-b-b measurements for every bunch crossing, integrated over ‘luminosity blocks’ of typically 60 seconds
  - PMT windows coated with Bismuth calibration source
    - Gain adjusted run-by-run
  - Several ‘algorithms’ to combine PMTs
    - ‘HitOR’ combination of 2x4 PMTs
    - Many channels had problems in 2018
    - … used single best PMT (C12) offline instead of OR of surviving 7 PMTs
Other luminosity measurements

- **Track-counting**
  - Reconstruct tracks in SCT+pixels in randomly-sampled filled bunch-crossings
  - Data read-out in dedicated event-building stream and reconstructed offline
    - Readout rate 200 Hz in physics running, >10 kHz in vdM and other dedicated runs
  - Number of tracks/crossing proportional to \(<\mu>\), intrinsically very linear
    - Several track-selection ‘working points’ used with different sensitivities to pileup
  - Can resolve individual bunches, but statistically limited

- **Calorimeter algorithms (similar to run-1)**
  - LAr calorimeter high-voltage gap currents (EMEC and FCal)
  - Tile calorimeter scintillator PMT currents
    - D5 and D6 cells for long-term monitoring
    - E1-E4 ‘gap’ scintillators sensitive at very low luminosity
  - Calorimeter measurements are ‘slow’, cannot resolve individual bunch-crossings

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ATLAS luminosity calibration in a nutshell

1. van der Meer scan run (once per year)
   - Absolute luminosity calibration (of LUCID) in controlled conditions, low-µ isolated bunches
   - Reference luminosity from beam parameters
     - Need luminous region $\Sigma_x$, $\Sigma_y$ and currents $n_1$, $n_2$

   $$L_b = \frac{f_l n_1 n_2}{2\pi \Sigma_x \Sigma_y}$$

2. Calibration transfer (~once per year)
   - Transfer lumi. scale to physics (high-µ, trains)
   - LUCID over-estimates by $O(10\%)$ at $\mu=40$
     - Correct with track-counting – much more linear
   - Cross-check track-counting with Tile calorimeter scintillators E1-E4

3. Run-to-run stability throughout the year
   - Is LUCID stable wrt tracks, EMEC, Tile, FCAL, TPX, Z-counting …?

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Run-2 13 TeV pp datasets

- Total of $L_{\text{int}} \approx 156 \text{ fb}^{-1}$ delivered at Run 2
  - 139 fb$^{-1}$ (89%) recorded by ATLAS with sufficient data quality for physics analysis
  - <3% of $L_{\text{int}}$ in 2015, then 3 progressively better production years in 2016-18
    - Instantaneous luminosity improvements from reduction in $\beta^*$ and beam emittance
    - Resulting in maximum $<\mu>$ above 60 in 2017 (during 8b4e running period)
      - Luminosity levelling used for part of 2017 8b4e dataset
Absolute luminosity calibration – the vdM method

- Basic outline of (factorisable) vdM formalism

\[ \mathcal{L}_b = f_r n_1 n_2 \int \hat{\rho}_1(x, y) \hat{\rho}_2(x, y) \, dx \, dy \]

Per-bunch \( L_b \) from revolution frequency \( f_r \), bunch populations \( n_1 \) and \( n_2 \), beam profiles \( \rho_{1,2}(x,y) \) in transverse plane

- Overlap-int. from convolved beam sizes \( \Sigma_x \Sigma_y \)

Measured in vdM scan of one beam vs other

\[ \Sigma_x = \frac{1}{\sqrt{2\pi}} \frac{\int R(\Delta x) \, d\Delta x}{R(0)} \]

\[ \mathcal{L}_b = \frac{f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y} \]

Calibration constant \( \sigma_{\text{vis}} \):

\[ \sigma_{\text{vis}} = \mu_{\text{vis}}^{\text{max}} \frac{2\pi \Sigma_x \Sigma_y}{n_1 n_2} \]

\( \mu_{\text{vis}} \) is visible count rate in at the peak of scan curve

- Need b-b-b analysis: LUCID and BCM only

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LHC setup for vdM scans

- vdM scans in dedicated low-luminosity running with special LHC setup
  - $\beta^*=19.2\text{m}$ (c.f. 0.25-0.8m in physics), larger beam emittances 3-4 $\mu\text{m}\cdot\text{rad}$
    - Resulting in large transverse beam sizes of $\sim 90\,\mu\text{m}$, c.f. $\sim 15\,\mu\text{m}$ in physics
    - Beam profiles are large wrt. primary vertex resolution in ATLAS inner detector
  - 30-140 isolated bunches – avoid long-range encounters, better beam quality
  - Reduced bunch currents of $\sim 0.8\times10^{11}$ p/bunch, minimise beam-beam effects
  - ... All resulting in $\mu\approx0.5$ at peak of scans
- Scans of 2x20 minutes (x+y), several x+y pairs + off-axis scans in a session
  - vdM fills lasting up to 24 hours with alternating ATLAS and CMS scans sets
vdM scan curve fit

- Typical scan curve from 2017
  - Fitted with Gaussian\(^n\) polynomial function after background subtr
  - Backgrounds determined from preceding empty bunch crossings and unpaired collisions
  - Try several fit functions
    - G\(\ast\)P4, double-G, super-G
    - Difference gives systematic
  - Bunch populations of \(n_1\) and \(n_2\):
    - Current per bunch from FBCT, normalised to DCCT
    - Corrections of O(0.1\%) for ghost and satellite charges
      - Determined from LHC LDM and LHCb beam-gas event rates
      - Systematics <= 0.05%
vdM analysis details

- Various corrections must be taken into account (additional systematics)
  - Orbit drifts during scans, measured using LHC arc and triplet (DOROS) BPMs
    - See dedicated discussion in talk of W. Kozanecki
  - Beam position jitter (beam movement within one scan step)
    - BPMs constrain possible movement within a scan step, input to simulated vdM scans
  - Beam-beam effects (scan curve distortion, dynamic $\beta$)
    - Depends on beam energy, transverse beam size, bunch currents, actual $\beta^*$ and tune
    - Calculated using MADX simulation, as in Run 1
    - Significant (positive) corrections of 1.3-1.7% on $\sigma_{\text{vis}}$
    - Systematics from variation of $\pm 20\%$ on assumed $\beta^*$, $\pm 0.01$ on tune ($0.2-0.3\%$ on $\sigma_{\text{vis}}$)
  - Emittance growth (uncertainty carried over from run 1 analysis)
    - Only if horizontal and vertical emittances grow at different rates (which they do)
  - Non-factorisation effects: $\Sigma_x \Sigma_y$ does not fully represent the 2D overlap integral
    - Dedicated studies and off-axis scans – see talk of M. Dyndal
Length scale calibration

- Relation between nominal (i.e. requested) and actual beam displacement at IP
  - Displace both beams in **same** direction
  - Reconstruct luminous centroid position using vertices reconstructed in ATLAS inner detector
    - Perform a mini-scan in beam-2 x-pos around fixed beam-1 x-pos to find peak position
  - Fit linear relation between bump amplitude and luminous centroid to find calibration
    - Typically within ~1-2% of unity
  - Repeat for B1y, B2x, B2y
    - From Nov 2017: use same directions of movement as in vdM scan, to get same hysteresis effect
  - Uncertainties of 0.3-0.4%, dominated by orbit drift corrections (see talk of W. Kozanecki)

- Additional systematics from ID alignment
  - Assessed by considering ‘realistic’ misalignment scenarios, giving ~0.1% uncertainty
vdM scan consistency - I

- Should get same $\sigma_{\text{vis}}$ for different bunch pairs and scan sets

- Spread of values for different bunches within same scan gives bunch-by-bunch consistency uncertainty, after subtracting expected spread from statistical errors
- Maximum difference between extreme scans (for any algorithm) gives scan-to-scan consistency error which is then symmetrised
  - Gives 1.2% in 2017, only half that in other years
vdM scan consistency – II

- Do not expect same $\sigma_{\text{vis}}$ for all the different LUCID and BCM algorithms
  - But should get same $\Sigma_{x,y}$ values
- Quantify this with specific luminosity $L_{\text{spec}}$
  - Compare $L_{\text{spec}}$ for different algorithms by plotting ratios for each bunch-pair
  - Largest deviation of mean from unity gives ‘reference specific luminosity’ error
    - Largest (0.4%) in 2018

- Total uncertainty on $\sigma_{\text{vis}}$: 1.1 - 1.5%
  - Largest in 2017, due to poor scan-to-scan consistency
Calibration transfer correction

- LUCID over-estimates luminosity at high-$\mu$
  - By ~10% compared to tracks, EMEC, TILE
- LUCID calib. from vdM needs corr$n$ at high-$\mu$
  - From linear fit to $L_{\text{track}}/L_{\text{LUCID}}$ ratio vs. $\mu$ in a long high-lumi physics fill, giving $p_0$ (offset) and $p_1$ (slope) parameters
    \[ \mu_{\text{corr}} = p_0 \mu_{\text{uncorr}} + p_1 \mu_{\text{uncorr}}^2 \]
  - Track-counting first normalised to LUCID in head-on period of vdM fill
    - $p_0 \neq 1$: bunch train and crossing angle effects
- Correction determined ~once per year
  - $p_0$ and $p_1$ can be determined from any long physics fill – monitor stability throughout year
    - In 2017, two corrections were needed
  - Origin of the LUCID non-linearity not fully understood
    - But varies according to the bunch train pattern

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LUCID response in bunch trains

- Special LHC fill 6194 in 2017 with 2x25ns and 2x8b4e trains in same fill
  - $\mu$-scan allows track-counting / LUCID ratio to be studied vs. $\mu$ in a controlled way
  - Fit the $p_0$ and $p_1$ parameters for each bunch in the train separately

- Slope becomes larger (i.e. $p_1$ more negative) for bunches deeper into the train
  - For long 25ns trains, saturates after $\sim$10 bunches, partial ‘recovery’ in 8b4e gaps
  - Standard correction procedure uses an average correction applied to all bunches

\[
R = p_0 + p_1 \mu
\]

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Systematics on calibration transfer - I

- LUCID $\mu$-correction implicitly assumes track-counting has no $\mu$-dependence going from the vdM regime ($\mu=0.5$) up to $\mu\approx50$ – need to verify this
  - Only other detector with sensitivity in both ranges is Tile gap scintillators (E-cells)
- Compare Tile/track ratios in vdM fill and closely-following physics fill
  - Ratio normalised to 1 in vdM, deviations in physics fill imply relative non-linearity

Complications
- Low S/B for Tile in vdM fill
  - Delicate pedestal subtraction
  - Residual activation ($\tau\sim1$ day) from any high-lumi running just before vdM fill can swamp signal
- E-cells age rapidly at high lumi.
  - Visible drop in response through physics fill 6024
- Inconsistency between E3 and E4
  - 1.3% systematic assigned in 2017
  - Assume non-linearity is in tracks

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Systematics on calibration transfer - II

- Another example, from 2016 – two vdM fills each followed by high-lumi

- Complications visible:
  - E-cells ageing also affects Tile/tracks ratio in 1\textsuperscript{st} vs 2\textsuperscript{nd} vdM fills
  - Imperfect pedestal subtraction in 2\textsuperscript{nd} vdM fill (residual activation)
  - 1.6% systematic assigned in 2016
    - Average of high-lumi/vdM shifts for the two fill pairs, using both E4 and E3 cells

- In 2018, LSC+vdM fills done directly after intensity ramp-up (CMS request)
  - Strong activation effects in vdM fill
    - Instead, had a 140b ‘vdM-like’ fill with $\mu=0.5$ in ATLAS at start of intensity ramp-up, followed by 600, 1200, 2400b fills: should allow us to study Tile/Tracks evolution
      - We are still analysing this data; use 1.3% from 2017 for preliminary 2018 uncertainty

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Long-term stability throughout the year

- Compare per-fill LUCID integrated-lumi with other detectors throughout year
  - After normalising them all to agree in a reference run (red arrow)

- Long-term stability uncertainty from ‘stability band’ enclosing bulk of points
  - Assigned ±1.0%, ±0.7%, ±1.3% and ±0.8% for the four years 2015-18
  - More details in talk of V. Lang – also including Z-counting and emittance scans
Uncertainties and combination

- Per-year uncertainty summary
  - Treating 2015+16 as one dataset
  - Absolute vdM calibration subtotal
  - Contributions to physics lumi.
  - Total uncertainties for individual years are 2.0-2.4%
    - Largest single uncertainty from calibration transfer

- Combination of years
  - Taking correlations into account
  - */+=fully/partially correlated
    - See talk of R. Hawkings tomorrow

- Total run 2 lumi: 139.0±2.4 fb⁻¹
  - Uncertainty 1.7%, dominated by calibration transfer and then long-term stability

### Data sample

<table>
<thead>
<tr>
<th></th>
<th>2015+16</th>
<th>2017</th>
<th>2018</th>
<th>Comb.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated lumi (fb⁻¹)</td>
<td>36.2</td>
<td>44.3</td>
<td>58.5</td>
<td>139.0</td>
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<tr>
<td>Total uncertainty (fb⁻¹)</td>
<td>0.8</td>
<td>1.0</td>
<td>1.2</td>
<td>2.4</td>
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### Uncertainty contributions (%):

<table>
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<tr>
<th></th>
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<tr>
<td>DCCT calibration†</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
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<td>FBCT bunch-by-bunch fractions</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
<td>Ghost-charge correction*</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>Satellite correction†</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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<td>Scan curve fit model†</td>
<td>0.5</td>
<td>0.4</td>
<td>0.5</td>
<td>0.4</td>
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<tr>
<td>Background subtraction</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
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<tr>
<td>Orbit-drift correction</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
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<td>Beam position jitter†</td>
<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
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<tr>
<td>Beam-beam effects*</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Emittance growth correction*</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
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<tr>
<td>Non-factorization effects*</td>
<td>0.4</td>
<td>0.2</td>
<td>0.5</td>
<td>0.4</td>
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<tr>
<td>Length-scale calibration</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>ID length scale*</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
<td>Bunch-by-bunch $\sigma_{vis}$ consistency</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
<td>0.2</td>
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<tr>
<td>Scan-to-scan reproducibility</td>
<td>0.5</td>
<td>1.2</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>Reference specific luminosity</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
<td>0.2</td>
</tr>
</tbody>
</table>

- Subtotal for absolute vdM calibration | 1.1     | 1.5   | 1.2   | -      |
- Calibration transfer†                | 1.6     | 1.3   | 1.3   | 1.3    |
- Afterglow and beam-halo subtraction* | 0.1     | 0.1   | 0.1   | 0.1    |
- Long-term stability                  | 0.7     | 1.3   | 0.8   | 0.6    |
- Tracking efficiency time-dependence  | 0.6     | 0.0   | 0.0   | 0.2    |

Total uncertainty (%) | 2.1     | 2.4   | 2.0   | 1.7    |
Speculation – where can we improve further?

- Leading uncertainty is from calibration transfer, correlated between years
  - 1.3-1.6%, based on delicate Tile vs tracks comparisons
    - Inconsistencies in these comparisons assigned as a systematic on track-counting, but possibly telling us more about Tile response 😐?
  - More to learn from 2018 post-TS1 intensity ramp-up, μ-scans in 2017+2018, and ‘internal’ studies of track-counting systematics (e.g. varying track selections)

- Can the vdM calibration uncertainties be improved?
  - Total uncertainty on vdM is 1.1-1.5% for individual years, partially correlated
  - Largest effects coming from non-factorisation, and scan-to-scan & bunch-to-bunch consistency tests
    - Some element of ‘chance’ – some scan sessions are better than others – why?
    - We are also evaluating these uncertainties rather conservatively – ‘maximum deviation seen’ makes less sense when you have lots of bunches/ scans / algorithms
  - Fit model uncertainties are also significant – better choice of fit functions?
  - 1.7% now, could we get to 1.5% for the final run-2 uncertainty?
Conclusion

- Described the luminosity calibration for complete run 2 13 TeV high-$\mu$ dataset
  - Absolute calibration of LUCID (and BCM) from vdM scans in each year
  - Extrapolated to physics regime using complementary measurements from other detectors
- Preliminary calibration has uncertainties of 2.0-2.4% per year, and 1.7% for the combined run 2 dataset
  - A great success – thanks to everyone involved!
  - Largest uncertainty from calibration transfer from vdM to physics regime

- Calibration applicable to full run 2 high-$\mu$ dataset (or subsets)
  - Not applicable to special runs with low pileup recorded for W/Z physics ($\mu=2$) or in high $\beta^*$ very low-$\mu$ running for ALFA
  - These require special treatment – mainly for calibration transfer to low-$\mu$ bunch train running

4th June 2019

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Additional slides
ATLAS luminosity detectors
LHC parameters in physics running

- Values typical of LHC peak performance in the different years
  - Both 25ns long-train and 8b4e values given for 2017 running

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum number of colliding bunch pairs ( (n_b) )</td>
<td>2232</td>
<td>2208</td>
<td>2544/1909</td>
<td>2544</td>
</tr>
<tr>
<td>Bunch spacing (ns)</td>
<td>25</td>
<td>25</td>
<td>25/8b4e</td>
<td>25</td>
</tr>
<tr>
<td>Typical bunch population ( (10^{11} ) protons)</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1/1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>( \beta^* ) (m)</td>
<td>0.8</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3–0.25</td>
</tr>
<tr>
<td>Peak luminosity ( \mathcal{L}_{\text{peak}} ) ( (10^{33} \text{ cm}^{-2} \text{s}^{-1}) )</td>
<td>5</td>
<td>13</td>
<td>16</td>
<td>19</td>
</tr>
<tr>
<td>Peak number of inelastic interactions/crossing ( \langle \mu \rangle )</td>
<td>~16</td>
<td>~41</td>
<td>~45/60</td>
<td>~55</td>
</tr>
<tr>
<td>Luminosity-weighted mean inelastic interactions/crossing</td>
<td>13</td>
<td>25</td>
<td>38</td>
<td>36</td>
</tr>
<tr>
<td>Total delivered integrated luminosity ( (\text{fb}^{-1}) )</td>
<td>4.0</td>
<td>38.5</td>
<td>50.2</td>
<td>63.4</td>
</tr>
</tbody>
</table>