Luminosity Determination in pp Collisions using the ATLAS Detector at the LHC

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Luminosity Overview

ATLAS Online Luminosity \( \sqrt{s} = 7 \text{ TeV} \)

- LHC Delivered
- ATLAS Recorded

Total Delivered: 5.61 fb\(^{-1}\)
Total Recorded: 5.25 fb\(^{-1}\)

2011 Delivered Luminosity: \( \int L dt = 5.61 \pm 0.10 \) fb\(^{-1}\)

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResults
Reference Reaction: inelastic pp scattering

- **LUCID**
  - Dedicated Luminosity Monitor
  - Gas Cherenkov Tubes, 5.6 < $|\eta|$ < 6.0

- **Beam Conditions Monitor (BCM)**
  - Designed for beam abort system
  - Diamond Sensors, $|\eta|$ ~ 4.2

- **Primary Vertex Counting**
  - Limited trigger bandwidth
  - Special conditions only

- **Calorimeter currents**
  - TileCal PMT currents
  - FCal LAr HV currents
  - Total luminosity only

Redundancy key for evaluating systematic uncertainties
Luminosity from Rates

\[ L = \mu \ n_b \ f_r / \sigma_{\text{inel}} = \mu_{\text{vis}} \ n_b \ f_r / \sigma_{\text{vis}} \]

Inelastic Interactions per Beam Crossing

\( n_b \) - Bunch pairs colliding  
\( f_r \) - Revolution Frequency

Event counting: \( f = N_{\text{evt}}/N_{\text{BC}} \)

\( \mu_{\text{vis}} \) from observable rates

\[ f_{\text{OR}} = \frac{N_{\text{OR}}}{N_{\text{BC}}} = 1 - e^{-\mu_{\text{vis}}} \]

\[ f_{\text{AND}} = \frac{N_{\text{AND}}}{N_{\text{BC}}} = 1 - 2e^{-(1+R)\mu_{\text{vis}}/2} + e^{-R\mu_{\text{vis}}} \]

\[ R = \sigma_{\text{vis}}^{\text{OR}} / \sigma_{\text{vis}}^{\text{AND}} \]

\[ f_{\text{hits}} = \frac{N_{\text{hits}}}{N_{\text{BC}} N_{\text{Ch}}} = 1 - e^{-\mu_{\text{vis}}} \]

\[ f_{\text{part}} = \frac{N_{\text{part}}}{N_{\text{BC}} N_{\text{Ch}}} = \mu_{\text{vis}} \]

Measured quantity

\( \varepsilon \times \sigma_{\text{inel}} \)  
To be calibrated

Algorithm Specific
Beam separation scans provide absolute luminosity calibration

\[ \mathcal{L}_{\text{peak}} = \int \int \rho_1(x, y) \rho_2(x, y) \, dx \, dy \]

\[ = \int \int \frac{1}{2\pi \Sigma_x \Sigma_y} \]

\[ \Sigma_x, \Sigma_y \text{ - convolved beam widths} \]

\[ n_1 \, n_2 \text{ - bunch population product} \]

S. van der Meer, CERN-ISR-PO-68-31 (1968)
• Separate beams and measure specific interaction rate
• Directly calibrate $\sigma_{vis}$ for each algorithm

$$\sigma_{vis} = \frac{\mu_{vis}^{MAX} \pi \sum x \sum y}{n_1 n_2}$$

Peak Rate

Scan Widths

Bunch Population

• Specific rate $\mu_{vis} / (n_1 \ n_2)$ removes current dependence
• Requires careful control of machine parameters (beam time)
  - Low numbers of bunches (14 in 2011)
  - Modest peak $\mu$ (~2.5 in 2011)
  - Multiple scan consistency used to assess systematics (2 in 2011)
\[ L_{\text{spec}} = \frac{L}{n_b n_1 n_2} = \frac{f_r}{2\pi \Sigma_x \Sigma_y} \]

- All algorithms/detectors should measure the same \( L_{\text{spec}} \)
- Spec. Luminosity varies per colliding bunch pair (BCID) by up to \( \sim 10\% \)
- Varies between scans by \( \sim 2\% \) (due to emittance growth)
- Good consistency between algorithms/detectors
- Residual variation taken as systematic uncertainty

\( \pm 0.3\% \) uncertainty on \( \sigma_{\text{vis}} \)
Variations seen by BCID and by scan (similar across detectors)

- Band is (RMS variation over BCIDs) $\oplus$ (variation between scans)
- Uncertainty taken from data-driven consistency check

$\pm 0.9\%$ uncertainty on $\sigma_{vis}$
Bunch Population Product

DCCT - DC Current Transformer
accurate, but measures everything

\[ n_i = (\alpha \ S_{DCCT}^{DCCT} - S_{Baseline} - S_{ghost}) \ S_{FBCT}^{FBCT} / \sum S_{FBCT}^{FBCT} \]

FBCT - Fast Beam Current Transformer
bunch-by-bunch measurements

Uncertainty needed on \( n_1 n_2 \)
(from BCNWG)
DCCT: CERN-ATS-Note-2012-026
FBCT: CERN-ATS-Note-2012-028
G/S: CERN-ATS-Note-2012-029

±0.54% uncertainty on \( \sigma_{vis} \)

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCCT Baseline</td>
<td>0.1%</td>
<td>0.10%</td>
</tr>
<tr>
<td>DCCT Scale ( \alpha )</td>
<td>2.7%</td>
<td>0.21%</td>
</tr>
<tr>
<td>( S_{FBCT}^{FBCT} / \sum S_{FBCT}^{FBCT} )</td>
<td>1.6%</td>
<td>0.20%</td>
</tr>
<tr>
<td>Ghost Charge/Satellites</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Uncertainty</td>
<td>3.1%</td>
<td>0.54%</td>
</tr>
</tbody>
</table>
### 2011 vdM Scan Uncertainty

#### Uncertainty on $\sigma_{\text{vis}}$ from vdM calibration

**2011:** 1.5%  
**2010:** 3.4%

Main improvement from $(n_1 \cdot n_2)$

More complete determination of other uncertainties

Largest observed deviation typically sets uncertainty

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scan Number</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scan Number</td>
<td>VI–VII</td>
<td></td>
</tr>
<tr>
<td>Fill Number</td>
<td>1783</td>
<td></td>
</tr>
<tr>
<td>Beam centering</td>
<td>0.10%</td>
<td>Uncorrelated</td>
</tr>
<tr>
<td>Beam-position jitter</td>
<td>0.30%</td>
<td>Uncorrelated</td>
</tr>
<tr>
<td>Emittance growth and other non-reproducibility</td>
<td>0.67%</td>
<td>Uncorrelated</td>
</tr>
<tr>
<td>Bunch-to-bunch $\sigma_{\text{vis}}$ consistency</td>
<td>0.55%</td>
<td>Uncorrelated</td>
</tr>
<tr>
<td>Fit model</td>
<td>0.28%</td>
<td>Partially Correlated</td>
</tr>
<tr>
<td>Background subtraction</td>
<td>0.31%</td>
<td>Partially Correlated</td>
</tr>
<tr>
<td>Specific Luminosity</td>
<td>0.29%</td>
<td>Partially Correlated</td>
</tr>
<tr>
<td>Length scale calibration</td>
<td>0.30%</td>
<td>Partially Correlated</td>
</tr>
<tr>
<td>Absolute ID length scale</td>
<td>0.30%</td>
<td>Partially Correlated</td>
</tr>
<tr>
<td>Beam-beam effects</td>
<td>0.50%</td>
<td>Partially Correlated</td>
</tr>
<tr>
<td>Transverse correlations</td>
<td>0.50%</td>
<td>Partially Correlated</td>
</tr>
<tr>
<td>$\mu$ dependence</td>
<td>0.50%</td>
<td>Partially Correlated</td>
</tr>
<tr>
<td>Scan subtotal</td>
<td>1.43%</td>
<td>Correlated</td>
</tr>
<tr>
<td>Bunch population product</td>
<td>0.54%</td>
<td>Partially Correlated</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.53%</strong></td>
<td></td>
</tr>
</tbody>
</table>
Luminosity Extrapolation

- Must apply vdM calibration over entire 2011 data period
  - time stability
  - different bunch structure (50 ns bunch trains)
  - linearity to highest interaction rates (μ)
- One algorithm provides central value (BCMV_EventOR in 2011)
- Consistency between all methods determines uncertainty

Data-driven uncertainties determined from redundant measurements
 BCM drifts

- BCM is CVD diamond sensor with separate H/V readout pairs
- BCM response ‘drifts’ after each technical stop (no beam)
- Seen separately in all 4 BCM sensors

- Asymptotically stable value after exposure of about \(\int Ldt \sim 5 \times 10^{36} \text{ cm}^{-2}\)

- Unfortunately, May 2011 vdM scan taken just after technical stop...
- BCMH \(\sigma_{\text{vis}}\) calibration corrected by observed drift
- No net drift observed in BCMV

\[ \pm 0.25\% \text{ unc. on Lumi} \]
Figure 7.: Fractional deviation in the mean interaction rate obtained using different algorithms with respect to the BCMV EventOR value as a function of time in 2011. Each point shows the mean deviation for a single run compared to a reference run taken in the middle of September. Statistical uncertainties per point are negligible. The figure shows the relative variation of this ratio over time compared to a single fill in September which is used to provide a reference point. The fill used to normalize this ratio for the figure is the same fill where the LUCID3TileCal cross calibration is performed, and comes approximately four months after the vdM scan in May. The variation seen on the left-hand side of this plot indicates the level of long-term stability from the vdM scan until this time in mid-September.

The various BCM algorithms are very stable with respect to each other, with agreement at the level of a few tenths of a percent over the entire 2011 run. The first few fills with low numbers of colliding bunches after each technical stop are not shown in this figure. This demonstrates the reproducibility of the BCM luminosity scale after each technical stop as discussed in Section (4.4). The LUCID data is shown only for the period of operation without gas from July onwards. Some variation at the level of $\pm 0.7\%$ can be seen for the LUCID Event algorithms, with somewhat larger variations observed for LUCID HitOR. These variations are observed to be correlated with drifts in the PMT gains inferred from measurements of single-photon pulse-height distributions in the LUCID data.

The FCal luminosity is observed to vary by about $-0.7\%$ with respect to BCMV EventOR from early to late 2011. Studies have shown that this variation is actually the result of a residual non-linearity in the FCal luminosity response. Since the average luminosity increased considerably from early to late 2011 due to the increase in the number of colliding bunches, this non-linearity with total luminosity manifests itself as an apparent drift on the time stability plot. The TileCal luminosity is observed to undergo a slow drift with respect to BCMV EventOR at the level of $0.7\%$ over the course of 2011. In contrast to the FCal, this variation has been shown not to be dependent on luminosity, but rather is likely due to residual PMT gain variations which are not corrected by the TileCal laser calibration system.

Based on the observed variation with time between the various algorithms shown in Figure 7, a systematic uncertainty on long-term stability, which includes any effects related to dependence on the

$\pm 0.7\%$ on Lumi
**Single Run $\mu$ dependence**

**ATLAS** Preliminary

Data 2011  
LHC Fill 2208 - Oct 12, 2011  
$\sqrt{s} = 7$ TeV  
Reference LHC Fill 2105 - Sep 13, 2011

$\left< \mu \right>_{\text{algorithm}} / \left< \mu \right>_{\text{BCMV EventOR}} - 1 \%$

Offsets due to long-term stability variation

Algorithms linear to better than $\pm 0.5\%$ over this high-$\mu$ range

Extrapolation to $\mu \sim 2$ dominates uncertainty: $\pm 0.5\%$ on Lumi
### Final Luminosity Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty Source</th>
<th>( \delta L / L )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2010</td>
</tr>
<tr>
<td>Bunch Population Product</td>
<td>3.1%</td>
</tr>
<tr>
<td>Other ( v_dM )</td>
<td></td>
</tr>
<tr>
<td>Calibration Uncertainties</td>
<td>1.3%</td>
</tr>
<tr>
<td>Afterglow Correction</td>
<td>0.2%</td>
</tr>
<tr>
<td>BCM Stability</td>
<td>0.2%</td>
</tr>
<tr>
<td>Long-Term Consistency</td>
<td>0.5%</td>
</tr>
<tr>
<td>( \mu ) Dependence</td>
<td>0.5%</td>
</tr>
<tr>
<td>Total</td>
<td>3.4%</td>
</tr>
</tbody>
</table>

Bunch population product significantly reduced
Other uncertainties remain largely similar to 2010
even with significantly larger pileup, bunch trains

Preliminary, but nearly final: ATLAS-CONF-2012-080
2012 Outlook

New year, new challenges...

2012 luminosity has exceeded 2011
Average interaction rate doubled

Will continue to rely on redundancy
to demonstrate reliability of
ATLAS luminosity scale

Lumi analysis for 2012 ongoing

First vdM scan taken in April
Second scan planned for mid-July

Initial (preliminary) analysis for ICHEP `12: $\delta L/L = \pm 3.6\%$
Additional Material
Afterglow creates a luminosity background in bunch trains
- Relatively small effect (~0.8% for LUCID_OR, ~0.4% for BCM_OR)
- Simple correction by subtracting effective lumi in BCID-I
- More correct (but slow) ‘template’ analysis gives same results
2011 $\mu$ dependence

Same data as time history
Tile variation from time dependence

±0.5% on Lumi
Pileup Scan Data

ATLAS Preliminary
Data 2011 - $\sqrt{s} = 7$ TeV
LHC Fill 2086 - Pile-up Scan

- BCMV_EventAND
- BCMH_EventOR
- BCMH_EventAND
- LUCID_EventOR
- LUCID_EventAND
- FCal
- Tile
- Vertex

End-of-fill data taken by separating beams
Very-low $\mu$ behavior dominated by background issues (bunch trains)
vdM Scan $\mu$ dependence

Good linearity at low $\mu$ seen in vdM scan (no bunch trains)