Precision measurement of the luminosity in ATLAS

ATLAS

LUCID

ZDC

MBTS

16 Plastic Scintillators

WLS fibers

ALFA

TileCal

Inner detector

BCM
ATLAS measures the luminosity for each individual pair of colliding LHC bunches:

$$\mathcal{L}_{BC} = f_{LHC} \frac{\mu}{\sigma_{\text{inel}}} = f_{LHC} \frac{\mu_{\text{vis}}}{\sigma_{\text{vis}}}$$

$$\mu_{\text{vis}} = \varepsilon \mu$$  Measured from detector rates  

$$\sigma_{\text{vis}} = \varepsilon \sigma_{\text{inel}}$$  Measured in beam separation scans

11245.5 Hz (LHC revolution frequency)

$$\mu$$ is the average number of pp-interactions

How can one measure $$\sigma_{\text{vis}}$$?
Measuring the luminosity

ATLAS measures the luminosity for each individual pair of colliding LHC bunches:

\[ \mathcal{L}_{BC} = f_{LHC} \frac{\mu}{\sigma_{\text{inel}}} = f_{LHC} \frac{\mu_{\text{vis}}}{\sigma_{\text{vis}}} \]

\[ \mu_{\text{vis}} = \varepsilon \mu \quad \text{Measured from detector rates} \]

\[ \sigma_{\text{vis}} = \varepsilon \sigma_{\text{inel}} \quad \text{Measured in beam separation scans} \]

efficiency & acceptance

\[ \mu \] is the average number of pp-interactions

Number of protons peak

Bunch 1

\[ n_{p1} \]

Number of protons

Bunch 2

\[ n_{p2} \]

The sigma of scan curves

\[ \mathcal{L}_{BC} = f_{LHC} n_{p1} n_{p2} \int \rho_1(x,y) \rho_2(x,y) \, dx \, dy = f_{LHC} n_{p1} n_{p2} \frac{1}{2 \pi \sum_x \sum_y} \]

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Beam separation scans

Lumi. from scan: \[ \mathcal{L}_{\text{BC}}^{\text{peak}} = f_{\text{LHC}} \frac{n_{p1} n_{p2}}{2\pi \sum_x \sum_y} \]

Lumi. from counting events: \[ \mathcal{L}_{\text{BC}}^{\text{peak}} = f_{\text{LHC}} \frac{\mu_{\text{vis}} \Delta \mu_{\text{vis}}}{\sigma_{\text{vis}}} \]

Calibration constant: \[ \sigma_{\text{vis}} = 2\pi \frac{\mu_{\text{vis}} \Delta \mu_{\text{vis}}}{\sum_x \sum_y} \left( \frac{n_{p1} n_{p2}}{n_{\text{vis}}} \right) \]

Scan profile

Scan width from fit

ATLAS Preliminary

Data

Double Gaussian fit

Scan curves

Current measurements

ATLAS Preliminary

Scan IV LUCID_Event OR

Scan IV LUCID_Event AND

Oct. 2010

Specific interaction rate \( \mu_{\text{vis}} / \eta_{n2} \times 10^{-22} \) protons

Colliding Bunch Number

Oct. 2010

0.6%

Same detector but different algorithms
Specific luminosity:

\[
L_{\text{spec}}^{\text{peak}} = \frac{f_{\text{LHC}}}{2\pi} \frac{1}{\sum_x \sum_y}
\]

What is the systematic error on \( \mu_{\text{vis}}^{\text{peak}} \sum_x \sum_y \)?
Beam separation scans

Specific luminosity:

\[ L_{\text{spec}}^{\text{peak}} = \frac{f_{\text{LHC}}}{2\pi} \frac{1}{\Sigma x \Sigma y} \]

Specific luminosity:

\[ L_{\text{spec}}^{\text{peak}} = \frac{f_{\text{LHC}}}{2\pi} \frac{1}{\Sigma x \Sigma y} \]

Scan VIII BCMEventOR
Scan VIII LUCIDEventOR

May 2011

ATLAS Preliminary

Syst. error on \( \mu_{\text{vis}}^{\text{peak}} \Sigma x \Sigma y \) (in 2010)

\[ \rho(x, y) = \rho(x) \rho(y) \quad - 0.9\% \]

Emittance growth - 0.5%
The rest (beam centering, beam position jitter, length scale & fit model) have all \( \leq 0.3\% \) each.

Measurement of \( \mu_{\text{vis}} \) - 0.5%

Total error: 1.3%
Current measurements

**DCCT: DC Current Transformer**
Measures the total current

**FBCT: Fast Beam Current Transformer**
Measures the fraction of the current in each bunch.

\[ \eta_{pj} = ( \alpha N_{DCCT} - N_{baseline} - N_{ghostcharge} ) \frac{N_{FBCT,j}}{\sum_j N_{FBCT,j}} \]

What is the systematic error?
Current measurements

DCCT: DC Current Transformer
Measures the total current

FBCT: Fast Beam Current Transformer
Measures the fraction of the current in each bunch.

\[ \eta_{pj} = \left( \alpha N^{DCCT} - N_{baseline} - N_{ghostcharge} \right) \frac{N_{FBCT}}{\sum_j N^{FBCT}} \]

Number of protons in bunch j
Calibrated scale factor

Syst. error on \( \eta_{p1} \eta_{p2} \):
- 2.7%
- <0.1%
- negligible

Total calibration error = Error scan + Error current = 1.3% + 3.1% = 3.4%
Comparison of the μ- (or μ_{vis}) value obtained from different methods and detectors provide the systematic errors in the determination of μ.
Long-term detector stability

Comparisons of average $\mu$-values from different methods and detectors as a function of time give information about the long-term stability.

**2010 data**
- LUCID_EventAND
- BCM_EventOR

**2011 data**
- Tile
- BCMV_EventOR
- Lucid_EventOR
- FCal

Long-term detector stability by comparing average $\mu$-values from different methods and detectors as a function of time.
Summary

2010

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

- LHC Delivered
- ATLAS Recorded

Total Delivered: 48.1 \( \text{pb}^{-1} \)
Total Recorded: 45.0 \( \text{pb}^{-1} \)

Calibration error: \( \pm 3.4\% \)
\( \mu \) determination: \( \pm 0.5\% \)
Detector stability: \( \pm 0.5\% \)
Background subtraction: \( \pm 0\% \)
Total error: \( \pm 3.4\% \)

2011 (preliminary)

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

- LHC Delivered
- ATLAS Recorded

Total Delivered: 1.30 \( \text{fb}^{-1} \)
Total Recorded: 1.25 \( \text{fb}^{-1} \)

Calibration error: \( \pm 3.4\% \)
\( \mu \) determination: \( \pm 1.0\% \)
Detector stability: \( \pm 1.0\% \)
Background subtraction: \( \pm 0.2\% \)
Total error: \( \pm 3.7\% \)
Back-up slides
Ways of measuring luminosity

Machine parameters:

\[ \rho_1(x,y) \quad \rho_2(x,y) \]

Number of protons in bunch 1 and 2

\[ \mathcal{L}_{BC} = f_{LHC} n_{p1} n_{p2} \int \rho_1(x,y) \rho_2(x,y) dx dy \]

11245.5 Hz (LHC revolution frequency)

Counting events:

\[ \int \mathcal{L} = \frac{N_{\text{events}}}{\varepsilon \sigma} \]

Measured number of $W,Z$ or inelastic events

Cross section from theory

Efficiency and acceptance from simulation

Elastic scattering:

\[ \frac{dN}{dt} = \pi \mathcal{L} \left( -\frac{2\alpha}{|t|} + \frac{\sigma^{\text{tot}}}{4\pi} (i+\rho) e^{-b|t|/2} \right)^2 \]

Ratio of real to imaginary part of the elastic scattering amplitude

Slope parameter

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Luminosity triggers

“OR” Trigger
Signals in at least one detector

“AND” Trigger
Signals in both detectors

In this example there is 3 “hits” and 4 “particles”
Ways of measuring luminosity

\[ \mathcal{L}_{BC} = f_{LHC} \frac{\mu(f)}{\sigma_{\text{inel}}} = f_{LHC} \frac{\mu_{\text{vis}}(f)}{\sigma_{\text{vis}}} \]

"visible \( \mu \)" is the \( \mu \)-value obtained from a measurement of a fraction \( (f) \) of events, hits or particles.

The "visible cross section" is a calibration constant.

**OR-event-counting:**

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

**AND-event-counting:**

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

where \( R = \sigma_{\text{vis}}^{\text{OR}} / \sigma_{\text{vis}}^{\text{AND}} \)

**Hit-counting:**

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

**Particle-counting:**

\[ f_{\text{part}} = \frac{N_{\text{part.}}}{N_{\text{BC}} N_{\text{ch}}} = \mu_{\text{vis}} \]
Beam separation scans

Transverse proton density functions

\[ \rho_1(x, y) \quad \text{Bunch 1} \quad \rho_2(x, y) \quad \text{Bunch 2} \]

Number of protons

\[ n_{p1} \quad n_{p2} \]

If both beams are Gaussian and circular with width = \( \sigma \).

Basic idea:

Move the beam(s).

Measure a rate proportional to luminosity.

The \( \Sigma \) from the scan curves and \( n_p \) gives peak luminosity which calibrates peak rate.
Circular Gaussian beam:
\[ \mathcal{L}_{BC}^{\text{peak}} = f_{\text{LHC}} \frac{n_1 n_2}{2\pi \sigma_x^2} \]

Elliptical Gaussian beam:
\[ \mathcal{L}_{BC}^{\text{peak}} = f_{\text{LHC}} \frac{n_1 n_2}{2\pi \sigma_x \sigma_y} \]

Beam of any shape:
\[ \mathcal{L}_{BC}^{\text{peak}} = f_{\text{LHC}} \frac{n_1 n_2}{2\pi} \frac{\mu_{\text{vis}}(x_0)}{\int \mu_{\text{vis}}(\Delta x) d\Delta x} \frac{\mu_{\text{vis}}(y_0)}{\int \mu_{\text{vis}}(\Delta y) d\Delta y} \]
Background

$L_{BC}$: Luminosity for each pair of bunches in the LHC

### Graph

- **$L$ in filled bunch-pairs**
- **$L$ in empty bunch-pairs**

- **ATLAS Preliminary**

- **LHC Fill 1875, 17/06/11**
  - Lucid_EventOR Collisions
  - BCMH_EventOR Collisions
  - Lucid_EventOR Afterglow
  - BCMH_EventOR Afterglow

- Stable Avg Lumi [$10^{30}$ cm$^{-2}$s$^{-1}$]

- Bunch Crossing Number

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