Luminosity Measurement and Monitoring in ATLAS

LHC Machine-Experiments Workshop
On behalf of ATLAS Collaboration
Laura Fabbri
OUTLINE

• Motivations for Luminosity measurements
• ATLAS’ forward detectors
• Techniques for Luminosity measurements
• Open Problems/ Conclusion
Motivation I

- Analysis of all the data samples and acquisition time frame
  - Cross section measure of “well known” processes
    - ttbar
    - W/Z
    - …
  - New Physic evidence
    - Deviation from SM prediction
  - Higgs production study
    - Cross section
    - tanβ in MSSM Higgs, …

Luminosity dominating errors for many studies

Goal ~ 2-3% accuracy

[ATLAS-TDR-15, May 1999]

\[ \sigma_H \times BR \]
Motivation II

• Fast control of running conditions
  • Determine beam background
  • Prevent beam loss

• Efficiently use of beam and optimize yield
  • Trigger optimization (pre-scaler)

• Provide online luminosity measurement for LHC

• Study beam deterioration
• Monitor luminosity bunch-by-bunch
Forward Detectors @ ATLAS

Beam condition Monitor $L \approx 10^{27}-10^{34}$
Minimum Bias Trigger Scintillators $L \approx 10^{33}$, $L \approx \text{comm.}$
Forward Calorimeter $L \approx 10^{27}$
LUCID $L \approx 10^{27}-10^{34}$

High voltage current $L \approx 10^{27}$

Integrated anode current $L > 10^{28}$
\( \eta \) coverage

\[
p_T^{\text{max}} \sim \sqrt{s} \exp(-\eta)
\]

Pythia v6.319

Inelastic

\[ \text{Charged particle density} \]

\[
\frac{dN}{d\eta} \quad \text{TILE} \quad \text{MBTS} \quad \text{BCM} \quad \text{LUCID} \quad \text{RP}
\]

\[ -15 \quad -10 \quad -5 \quad 0 \quad 5 \quad 10 \quad 15 \]

\[ \eta \]

\[ \mu\text{-chambers} \quad \text{Barrel} \quad \text{EndCap} \quad \text{Tracking} \quad \text{FCAL} \quad \text{LUCID} \quad \text{TAS} \quad \text{RP} \quad \text{ZDC/TAN} \]

MBTS
LUCID: luminosity monitor

LUCID: “LUminosity measurement using Cerenkov Integrating Detector

- 2 symmetric arrays of 20 x 1.5 m polished Aluminum tubes (Ø=1.5cm), filled with C$_4$F$_{10}$, surrounding the beam pipe and pointing the IP (Z~17 m)
- It can fit in available space & has low mass (< 25 kg/end)
- Charged particles emit Cherenkov light at ~3 degrees (P=1 bar)
- Photons propagate along the tube with multiple reflections (~2.6) and read out by a PMT (Radiation hard)
The signal amplitude are used to measure the event track multiplicity ($\propto \mu \propto L$)

The PMT time resolution of few ns could be used to measure bunch-by-bunch luminosity

4 out of 20 tubes are readout by MaPMTs via fiber bundles (Test new detector design for high luminosity)
The LUCID Data Flow

The LUCID information will be available:
1. in the global ATLAS triggered event
2. in the online monitor
3. to possibly trigger interaction events or reject high multiplicity events
LUCID Performances

1 interaction per event

- Sensitive to IP-pointing tracks above threshold
- Much shorter paths for non pointing secondaries

Cherenkov photons from PMT quartz window

Cherenkov photons from gas + PMT

- The response of the detector is linear with both PMT and fiber read-out
- Detector occupancy with fiber read-out is lower → more suitable at high luminosity
Beam Condition Monitor

- 4 diamond sensors:
  - 1x1 cm$^2$
  - 500 μm thick
- Radiation hard (50 Mrad, $10^{15} \pi$/cm$^2$)
- 5 cm radius from the beam
- 1.8 m from the IP on each side
- Pseudo-rapidity coverage $3.9 < |\eta| < 4.1$
BCM

• The BCM is foreseen to provide monitor information about anomalous beam conditions (beam-gas and beam-collimator interaction events, beam loss)
• Designed to work for the full luminosity range of LHC
• Designed with a sufficient time resolution to identify individual bunch crossings (Rise-time ~ 1 ns, Width ~ 3 ns, Restoration ~ 10 ns)

• Distinguish interactions from background via time of flight (interactions in time, background out of time on one side)

• The amplitude of the signal can be used to determine the number of particles transverse the detector
• Possibility for luminosity measurement is under study
Minimum Bias Trigger Scintillator Counters (MBTS)

- Wedge-shape plastic scintillators installed on the front face of LAr end-cap cryostat (Z=±3.6 m)
- Each scintillator cover $\Delta \phi = 2\pi/8$ and consist of two separated sections $(2.1< \eta_{\text{inn}} < 2.8, 2.8< \eta_{\text{out}}<3.8)$
- Material: Polystyrene doped with fluorescing agent
- Light emitted is collected by wavelength-shifter optical fibers embedded in grooves in the scintillator
- These fibers are connected to the PMTs and readout electronics designed for the calorimeter

$R_{\text{max}} = 88 \text{ cm}$

$R_{\text{min}} = 14 \text{ cm}$
MBTS

- MBTS goal is trigger on physics and veto halo events during the commissioning phase (L< 5 x 10^{32} cm^{-2}s^{-1})
- It will work from the first beam till 3-4 months and will be dismounted during the first shut down
- It is able to detect 1 minimum ionizing particle
- It provides LVL1 trigger information and data to the ROS for triggered events
- Can be used to determine luminosity by counting the minimum bias trigger rate
- The precision of the measurement is limited by expected significant radiation damage
Calorimeters

TileCal
Minimum bias monitor via integrated anode current of the PMTs (high luminosity)

LAr
Minimum bias monitor via integrated high voltage current

Relative luminosity information will be provided from the local monitor systems outside the event stream
Two RP stations with top and bottom vertical pots, separated by 4 m, at each side 240 m from IP1
ATLAS’ Roman Pots

- Measure elastic pp-scattering down to very small angles (~3 \( \mu \) rad) \( \Rightarrow \) Coulomb region \( f_C \approx f_N \)
- operate tracking detectors very close to the beam, \( 10 \sigma = 1.2 \) mm (position accuracy \( \sim 10 \mu \)m)
- detector resolution \( \sigma_d = 30 \mu \)m (t-resolution dominated by beam divergence)
- radiation tolerance 100 Gy/yr (dominated by beam halo)
- rate capability \( O(1 \) MHz\) and time resolution \( O(5 \) ns\)

\[
\frac{dN}{dt}\bigg|_{t=0} = L \pi \left| f_C + f_N \right|^2 \approx L \pi \left( \frac{2 \alpha_{EM}}{t} \right) + \frac{\sigma_{tot}}{4 \pi} (i + \rho) e^{-b|t/2|^2}
\]

- 15 \( \sigma \) scintillator plate for triggering
- y-measurement detector
- x-measurement detector

\[
t = \left( p \theta^* \right)^2 = p^2 \left( \overline{\theta_x}^2 + \overline{\theta_y}^2 \right) = p^2 \left( \frac{\overline{\chi}}{L_{eff,x}} \right)^2 + \left( \frac{\overline{\psi}}{L_{eff,y}} \right)^2
\]

10-15 \( \sigma \) or \( \geq 1.5 \) mm
Techniques for Luminosity measurements

- **Use a relatively well known, copious, process:**
  - Inclusive inelastic pp cross-section
    - large acceptance at small angles
  \[ \mu \cdot f_{BC} = \sigma_{in} \cdot L \]
  - \( \mu \) = avg. # of interactions/b.c.
  - \( f \) = frequency of bunch crossings
  - \( \sigma_{in} \) = tot inelastic cross-section
  - \( L \) = inst. luminosity

- **Use dedicated detector:**
  \[ \tilde{\mu} \cdot f_{BC} = \sigma_{in} \cdot \varepsilon_{\alpha} \cdot L \]

- **Use a good estimator**
  - Measure the fraction of crossings with pp interactions
    - Use: \( P_0(\mu) = e^{-\mu} \) prob. of no int.
  - Direct counting # of pp interactions
    - Counting particles
    - Counting hits

- **Cross-calibrate**
  - Machine information
  - Roman Pots
  - Rarer, clean, better understood physic processes
Monitor Calibration Strategy

Run LUCID in parallel with calibration measurement

LUCID with 200 tubes (No Secondaries)

\[ \langle M \rangle = \langle C \rangle \cdot A \cdot L \]

Given by calibration method

Calibration Constant:
\[ A = \varepsilon_{pp} \times \sigma_{inel} \]

Calculated \( \varepsilon \) and measured \( \sigma_{tot} \) used for consistency cross checks

Advantage of “Parallel” Calibration

\[ A = \sigma_{tot} \cdot \varepsilon \]

Calculated:
Acceptance shown at the Tevatron to be difficult to calculate in forward region

Measured:
Not easy at high precision, e.g. CDF vs E811 discrepancy

Measured by LUCID

(at low luminosity \( \mu < 1 \))

Measured by LUCID

Run LUCID in parallel with calibration measurement
Whole Calibration Methods

• Initially,
  LHC Machine Parameters
  (Precision: ~10%)

• Medium term
  Physics processes, W/Z & $\mu\mu/ee$
  (Precision: ~5-10%)

• Late 2009 – Early 2010
  Roman Pot (ALFA) measurement
  (Precision: ~2-3%)

Including estimated latency for data-taking and analysis
Conclusions

• A big effort is made by the ATLAS collaboration to provide as many methods as possible to monitor luminosity
• Different detectors based on different working techniques are studied and ready for installation
• Monitors’ information are available both in the ATLAS TDAQ than outside the event stream
• Luminosity will be monitored bunch-by-bunch and synchronized with LBs
• Absolute calibration against Machine Luminosity and Roman Pots. Calculated $\epsilon$ and measured $\sigma_{\text{tot}}$ only used for consistency cross checks
Luminosity with Collision (zero) counting method

Measure the average of the Poisson distribution by measuring the 0 bin.

\[ \mu = \sigma_{inel} \cdot \langle L_B \rangle = \text{Mean \# interactions per (any) BC} \]

\[ \frac{n_{pp}}{n_{BC}} = \text{Collision Rate} \]

\[ 1 - \frac{n_{pp}}{n_{BC}} = \text{“Zero” Rate} \]

- Advantages:
  - Less sensitive to ADC calibration
  - Formula is correct at every L

- Disadvantages
  - Not linear at higher luminosity (\( \mu \geq 1 \))
  - Statistically limited at very high L (\( P_0(\mu=25) \approx 10^{-8} \))

\[ P_0(\mu) = e^{-\mu} \]
Particle Counting
(Baseline Method)

Estimated to be Linear even in Pile-Up Region

\[ \langle M \rangle = \langle C \rangle \cdot \epsilon_{pp} \cdot \mu \]

Mean # Particles per Detected Interaction
(measured at low lum. where the prob. For >1 int./BC is very small)

Detector Requirements:
- Acceptance coverage sensitive to min. bias event rate
- Time resolution to make measurement for individual BCs
- **Capable of counting particles**
- Calibrated by efficiency (acceptance) and inelastic cross section from calibration measurement or calculations
\[ p_T - \eta \text{ ATLAS' Coverage} \]

\[ p_T^{\text{max}} \sim \sqrt{s} \exp(-\eta) \]
Commissioning and Start-up phases

LHC 40 MHz Beam:
→ 3564 possible bunch crossings (BC)
→ Only 2808 BC will be filled due to injection etc. (e.g. 89um long-gap)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Comm</th>
<th>Nominal</th>
<th>Unit</th>
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</thead>
<tbody>
<tr>
<td>Energy</td>
<td>0.9</td>
<td>7</td>
<td>TeV</td>
</tr>
<tr>
<td># of Bunches</td>
<td>2808</td>
<td>2808</td>
<td></td>
</tr>
<tr>
<td># of particles per bunch</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>$10^{27} - 10^{32}$</td>
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</tr>
<tr>
<td>$\beta^*$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;$#&gt;$ of interactions/ev</td>
<td></td>
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</tbody>
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Observables:
→ Time structure of luminosity reflects BC structure of beam
→ Instantaneous luminosity corresponds to average rate from a set of BCs
→ The BC will in practice imply discrete luminosity quanta
→ Bunch Luminosity = Integrated luminosity of one specific BC

Calibration can be carried from elastic scattering data over the full dynamic range
Physic Processes

QED: small $\sigma_{QED}$
- $pp \rightarrow (p+\gamma^*)+(p+\gamma^*) \rightarrow p+(\mu^+\mu^-)+p$
- Low rate ($<< 1$ Hz) still at $L=10^{34}$ cm$^{-2}$ s$^{-1}$
- Process calculated with $\sim 1\%$ accuracy

EW: $W/Z \rightarrow$ leptons
- Theoretically well understood processes (calculated till NNLO)
- High rate: $\sim 6$Hz for $Z \rightarrow \mu^+\mu^-$, $\sim 60$Hz for $W \rightarrow \mu^+$ at $L=10^{34}$ cm$^{-2}$ s$^{-1}$
  - Online monitor at high luminosity
    $(\Delta L/L)_{\text{syst}} \sim 4-6\%$ *; $(\Delta L/L)_{\text{stat}} \sim 1-5\%$ *

QCD: $\sigma_{tot} \sim 100$ mb
- Roman Pots at dedicated luminosity ($L \approx 10^{27}$ cm$^{-2}$ s$^{-1}$) and optic
  - Absolute Luminosity $L$
  - Counting of the number of bunch crossings with/without interaction
    - Online monitor $\Rightarrow$ Relative Luminosity $L$

* Small statistical error ($<1\%$) $\rightarrow$ homogeneous samples with at least 10K-100K ev