Measurement of Luminosity with LUCID in ATLAS

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On behalf of the ATLAS forward detectors luminosity group
Outline

• Concept of Luminosity
• LUCID detector
• LUCID simulation
• Luminosity measurement
  – Detector related effects
  – Coincidence effect
LHC: a pp collider

<table>
<thead>
<tr>
<th>LEP</th>
<th>Beams</th>
<th>Energy</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP</td>
<td>e+ e-</td>
<td>200 GeV</td>
<td>$10^{32}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>LHC</td>
<td>p p</td>
<td>14 TeV</td>
<td>$10^{24}$</td>
</tr>
<tr>
<td></td>
<td>Pb Pb</td>
<td>1312 TeV</td>
<td>$10^{27}$</td>
</tr>
</tbody>
</table>

Proton-Proton

- (2835 x 2835 bunches)
- Protons/bunch: $10^{11}$
- Beam energy: 7 TeV (7x$10^{22}$ eV)
- Luminosity: $10^{34}$ cm$^{-2}$ s$^{-1}$
- Crossing rate: 40 MHz
- Collisions: $10^7$ - $10^9$ Hz

1 bunch-crossing every 25 ns

Selection of 1 in $10,000,000,000,000$
Concept of Luminosity

- Luminosity relates physics process rates \( R \) to their cross sections \( \sigma \)
- To observe rare processes (Higgs), high luminosity needed (LHC: \( 10^{34} \text{ cm}^{-2}\text{s}^{-1} \))
- Luminosity is controlled by “beam parameters”

\[
L = \frac{R}{\sigma}
\]

\[
L = f_{\text{BX}} \frac{N_{\text{protons}/\text{BX}}^2}{4\pi \sigma_x \sigma_y}
\]

<table>
<thead>
<tr>
<th></th>
<th>Instantaneous luminosity</th>
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</thead>
<tbody>
<tr>
<td>( L )</td>
<td>Instantaneous luminosity</td>
</tr>
<tr>
<td>( f_{\text{BX}} )</td>
<td>Bunch crossing frequency</td>
</tr>
<tr>
<td>( N_{\text{protons}/\text{BX}} )</td>
<td>Number of colliding protons per bunch crossing</td>
</tr>
<tr>
<td>( \sigma_{x,y} )</td>
<td>Transversal beam size</td>
</tr>
</tbody>
</table>

The largest uncertainty comes from beam-size
Luminosity measurement in ATLAS

• In “special low luminosity runs” luminosity will be initially measured with “beam parameters” (20%) and, later on, it will be precisely (<3%) measured from elastic proton-proton collisions (using Roman Pot detectors)

• In “physics runs”, luminosity will be extrapolated with relative luminosity monitors, which are typically sensitive inelastic proton-proton collisions

The aim is to reach an accuracy of less than 5%
LUCID: the main ATLAS luminosity monitor

• LUCID is made of two modules located at 17 m from the interaction point

• LUCID is sensitive to charged particles pointing to the primary $pp$ collision

• LUCID is designed to measure the luminosity up to $L = 4 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

Technical challenge: locate the detector in a high radiation area
7 Mrad/year @ highest luminosity \((10^{34} \text{ cm}^{-2}\text{s}^{-1})\)
Array of mechanically polished Aluminum tubes filled with a Cherenkov gas ($C_4F_{10}$). $C_4F_{10}$ pressure at 1.1 bar (Leak <20 mbar/day/module).

$\eta$ coverage: [5.6, 5.9]
LUCID detector principle

- **Background suppression:**
  - Cherenkov threshold: 10 MeV for $e^-$ and 2.8 GeV for $\pi$, in the gas
  - Geometry: tubes are pointing to the $pp$ interaction region

- **The fast response (few ns) allows for single bunch crossing detection.**

- Photons are emitted at $3^\circ$
- Typically 3 reflections inside the tubes
- Photons are read-out by PMT
- Further photons radiated inside PMT
LUCID read-out scheme

2×16 tubes are directly coupled to Photo-Multiplier Tubes (PMT). PMT must be radiation hard.

2×4 tubes are coupled to multi-anode PMT via Winston Cones and optical fibers. Better for high luminosity runs (MAPMT not exposed to high radiation doses).
Simulation of LUCID response to inelastic pp interactions

- A hit is defined by a threshold (50 p.e.)
- Average hits per pp interaction: 1.21
- High luminosity $\rightarrow$ high occupancy
- Maximum number of hits: 32 (saturation)

![Graph showing hits distribution]
Measurement of Luminosity with LUCID

LUCID measurement is based on inelastic $pp$ collisions

\[ \frac{L}{f_{BX}} = L_{BX} = \frac{\mu_{BX}}{\sigma_{pp}^{inel}} \]

<table>
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<tr>
<th>$L_{BX}$ [cm$^{-2}$]</th>
<th>Average bunch luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{BX}$</td>
<td>Mean number of inelastic $pp$ interactions per bunch crossing</td>
</tr>
<tr>
<td>$\sigma_{pp}^{inel}$ [cm$^2$]</td>
<td>Inelastic proton-proton cross section (MB, SD, DD)</td>
</tr>
</tbody>
</table>

- $\sigma_{pp}^{inel} = 84.5$ mb (PHOJET1.12)
- $\mu_{BX} \sim 25$ at highest LHC luminosity ($L = 10^{34}$ cm$^{-2}$s$^{-1}$)
- LUCID is designed to measure luminosity up to $\mu_{BX} = 10$ ($L = 4 \times 10^{33}$ cm$^{-2}$s$^{-1}$)

The question is how to measure $\mu_{BX}$
Measurement of $\mu_{BX}$

**Hit counting method:** the number of particles is estimated with the number of detector hits

\[
\mu_{BX} = \frac{\langle N \text{ particles/BX} \rangle}{\langle N \text{ particles/pp} \rangle} = \frac{\langle N \text{ hits/BX} \rangle}{\epsilon_{pp} \times \langle N \text{ hits/pp detected} \rangle}
\]

<table>
<thead>
<tr>
<th>$\langle N \text{ hits/BX} \rangle$</th>
<th>Mean number of LUCID hits per bunch crossing</th>
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<td>$\epsilon_{pp}$</td>
<td>LUCID efficiency to “detect a pp interaction”</td>
</tr>
<tr>
<td>$\langle N \text{ hits/pp detected} \rangle$</td>
<td>Mean number of LUCID hits per “detected pp interaction”</td>
</tr>
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</table>

The question is how to define a “detected pp interaction”
Definition of detected interaction

- **Single side mode**: at least 1 hit in a module
- **Coincidence mode**: at least one hit in both modules

The presence of hits in the detector might be due to particles crossing the detector and “not directly related” to the primary *pp* collisions.

The advantage of a coincidence method is to suppress “accelerator background”
Simulation of LUCID performance

Calibration scenario

• Calibration is performed at low luminosity
• At maximum 1 interaction per event is expected
• Single interaction events are used to extract $\varepsilon_{pp}$ and $<N_{hits/pp detected}>$

Measurement scenario

• Measurements are performed at high luminosity
• High luminosity events are simulated by mixing single interaction events ($\mu_{true} = 0.01, 0.05, 0.1, 1, 2, 5, 10, 15, 20, 25$)
• The measured number of $pp$ interaction ($\mu_{measured}$) is extracted

$$
\mu_{measured} = \frac{\langle N_{hits/BX} \rangle}{\varepsilon_{pp} \times \langle N_{hits/pp \ detected} \rangle}
$$
Measurement in Single Side mode

- Relation between $\mu_{\text{meas}}$ and $\mu_{\text{true}}$ is not linear in the full luminosity range
- Deviation from linearity: 8% @ $\mu = 10$, when the threshold is 50 p.e.
- Underestimate of $\mu$ is due to “saturation effect”
- Overestimate of $\mu$ at intermediate values is due to “migration effect”

A fit (based on MC) can be performed to provide the relation between $\mu_{\text{meas}}$ and $\mu_{\text{true}}$
Overestimate of $\mu$: Migration effect

- The spectrum get flattened when $\mu$ increases (>1 particle through the same tube)
- This effect is called “migration” of secondaries above threshold
Measurement in Coincidence mode

- In addition to migration and saturation, coincidence mode suffers of non-linear effects due to combinatorial and Poisson statistics, which can be calculated (solid line)
- Deviation from prediction: 9% @ $\mu = 10$, when threshold is 50 p.e.

A fit (based on MC) can be performed to provide the relation between $\mu_{\text{meas}}$ and $\mu_{\text{true}}$
Conclusions

• The measurement of luminosity with LUCID in ATLAS is possible

• “Accelerator related background” can be suppressed requiring coincidences of hits in the two detector modules

• At high luminosity, “detector related” effects (migration and saturation) are under control

• Global fits based on Monte Carlo simulations, can be performed to increase the accuracy of the measurement in the non-linear region (at higher luminosity)

Other measurement methods are currently under study to improve LUCID performance in the non-linear region (fully based on data)
Back-up slides
LUCID calibration

\[ L_{BX} = \frac{\mu_{BX}}{\sigma_{pp}^{inel}} = \frac{\langle N_{hits}/BX \rangle}{\sigma_{pp}^{inel} \times \varepsilon_{pp} \times \langle N_{hits}/pp^{detected} \rangle} = k_{LUCID} \times \langle N_{hits}/BX \rangle \]

\[ k_{LUCID} = \frac{1}{\sigma_{pp}^{inel} \times \varepsilon_{pp} \times \langle N_{hits}/pp^{detected} \rangle} \]

Calibration with Monte Carlo
- \( \sigma_{pp} \) from theory
- \( \varepsilon_{pp} \) and \( \langle N_{hits/pp \, detected} \rangle \) from MC (1 pp/event)

Calibration with Data at low luminosity (\( \mu_{BX} \ll 1 \))
- \( \langle N_{hits/BX} \rangle \) is measured by LUCID
- \( L_{BX} \) is measured by LHC or ALFA

\( \langle N_{hits/pp \, detected} \rangle \) can be measured at low luminosity (1 pp/BX) and compared with MC
Radiation hardness test

\[ ^{60}\text{Co}, \ E = 1.22 \text{ MeV} \]
\[ \text{Dose} = 20 \pm 1 \text{ Mrad} \]
\[ 30 \text{ years of LHC in phase I} \]

\[ n: \text{ENEA-Casaccia reactor} \]
\[ E = 100 \text{ KeV} \]
\[ \text{Dose} = 10 \text{ years of LHC in phase I} \]

No visible damage to metal and quartz.
Glass opacity increased.

No visible damage to metal, glass and quartz.
Radiation hardness

\[ \gamma: \text{^{60}Co}, E = 1.22 \text{ MeV} \]
\[ \text{Dose} = 20 \pm 1 \text{ Mrad} \]
\[ 30 \text{ years of LHC in phase I} \]

\[ \alpha = 7.12 \pm 0.10 \]
\[ \alpha = 7.15 \pm 0.10 \]

No relevant effects for phase I
Radiation hardness

Gain

$\alpha = 6.34 \pm 0.29$
$\alpha = 6.63 \pm 0.30$

No relevant effects for phase I

n: ENEA-Casaccia reactor
$E = 100$ KeV
Dose = 10 years of LHC in phase I

Spectral Response

Anodic current (mA)

0  0.1  0.2  0.3  0.4  0.5  0.6

Wavelength (nm)

0  200  300  400  500  600  700  800

Scan on wl for PMT/n before and after irradiation

No relevant effects for phase I