Forward Detectors in ATLAS: ALFA, ZDC and LUCID

Laura Fabbri on behalf of ATLAS Collaboration and Forward Detectors Working Group
Outline

- Physics and luminosity:
  - Absolute and relative luminosity
- Techniques for luminosity measurement
- The Forward Detectors in ATLAS:
  - LUCID
  - ZDC
  - ALFA
- Conclusions
Physics Interest in L

- Absolute Luminosity:
  - measure cross sections for standard physics
  - measure Higgs production cross section
  - observe deviations from SM and New Physics

- Requirements:
  - ultimate precision at the 2-3% level
    - different methods needed for cross check
    - minimize systematics

Relative luminosity:
- beam stability
- beam degradation (efficient use of trigger)
- evaluate trigger & DAQ dead-times
- determine beam background
- Luminosity Block spread

Systematic error due to luminosity (ATLAS TDR)

COMBINED EFFORT FROM DIFFERENT DETECTORS, TRIGGER, DAQ.
Luminosity from LHC parameters

\[
L = \frac{f \sum_{i=1}^{k_b} N_{1i} N_{2i}}{4\pi \sigma_x^* \sigma_y^*} = \frac{f k_b N^2}{4\pi \varepsilon_N \frac{\beta^*}{\gamma}}
\]

\(N_{xi}\) = number of protons in bunch \(i\) of beam \(x\); \(f\)=revolution frequency; \(\sigma_x, \sigma_y\)=transverse beam dimensions at the IP; \(k_b\) = number of bunches; \(\beta^*\)=\(\beta\) function at IP; \(\varepsilon_N=\sigma_x^* \sigma_y^*/\beta^*\) normalized emittance; \(\gamma=E/m_p\) (~7460)

Accuracy limited by

- Extrapolation of \(\sigma_x \sigma_y\) from measurement point to IP
- Precision in measurement of bunch currents
- Beam-beam effects at IP, beam crossing angle, ...

Maximum precision obtainable from machine 5-10%
ATLAS Strategy

Goal precision on L ~ 2-3%

- Elastic scattering in Coulomb-Nuclear Interference region to get L and $\sigma_{\text{tot}}$ at L ~ $10^{27}$ cm$^{-2}$s$^{-1}$
- Optical theorem as a back-up solution
  ALFA detector in Roman Pots

- Luminosity monitor calibrated at low lumi but working up to L ~ $10^{34}$ cm$^{-2}$s$^{-1}$
  LUCID

- Absolute L from QED (pp → ppµµ) and QCD (W→lν, Z→ll) processes (need to control PDF)

- Improve Luminosity from machine with ZDC

- Further luminosity/beam monitoring with BCM, MBTS...

\[ \sigma_{\text{tot}} = \frac{16\pi}{1 + \rho^2} \times \frac{(dN / dt)|_{t=0}}{N_{el} + N_{inel}} \]

\[ R_X = \sigma_X \cdot L \]

\[ \sigma_X \sigma_Y \text{ from Van der Meer Scan} \]
ATLAS Forward Detectors

- ALFA at 240 m
- ZDC at 140 m
- LUCID at 17 m

Absolute Luminosity for ATLAS
Zero Degree Calorimeter
Luminosity Čerenkov Integrating Detector

2010
2009
2008

04/28/2009
DIS 2009 - L. Fabbri
LUCID: Luminosity Monitor

LUCID: “LUminosity measurement using Čerenkov Integrating Detector

- is made of 2 modules located at 17 m from the interaction point on each side
- is sensitive to charged particles pointing to the primary pp collisions
- is designed to measure luminosity up to $L \sim 4 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

Pseudo-rapidity coverage $5.6 < |\eta| < 5.9$

Beam pipe

20 x 1.5 m polished Al tubes ($\phi = 1.5 \text{ cm}$)

Radiator $C_4F_{10}$
**LUCID: Pointing Gas Čerenkov Counters**

- **Monitor instant. L:**
  - Bunch-to-Bunch structure
  - beam degradation
  - indep. of LVL1 trigger
  - indep. of TDAQ

- **Requirements:**
  - relative L sufficient
  - fast response (single bunch crossing)
  - online monitoring

- **Measure absolute L:**
  - Needed for phys. analysis

- **Requirements:**
  - calibration needed
  - final precision ~ 2-3%

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<table>
<thead>
<tr>
<th>Main parameters per module</th>
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<tbody>
<tr>
<td>η coverage</td>
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<td>N. Tubes</td>
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<tr>
<td>Material</td>
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<td>&lt;N. reflections&gt;</td>
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<td>Ch. threshold</td>
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<td>Signal duration</td>
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<td>Read-out</td>
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<td>Expected dose</td>
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Main assumption: number of collisions at Impact Point follows Poisson statistic

Zero Counting: Count bunch crossing with no interactions:
- Measurement is done for each bunch crossing (BCid)
- Working range 0.0001<μ<5
  - Zero starvation region starts at μ>5 (P(0, μ>5)<1%)
- Sensitive to beam gas interaction ⇒ Coincidence of the two modules can be required
  - Working range increased to μ<10

Hit Counting: Count the number of tubes with signal above threshold (hit):
- Measurement is done for each bunch crossing (BCid)
- Working at large luminosity
- Sensitive to noise on single PMT

Track Counting: Evaluate the number of primaries from the LUCID occupancy
- Measurement is done for each bunch crossing (BCid)
- It works up to μ=30

Hit Multiplicity:
Compare the hit multiplicity in the detector with the expected value obtained by single interaction
- No bunch by bunch luminosity measurement

Methods to measure luminosity with LUCID

The rate of the pp interaction (R_{pp}) seen by LUCID is proportional to the luminosity (L):

\[ R_{pp} = \mu_{LUCID} \cdot f_{BX} = \sigma_{pp} \cdot \varepsilon_{LUCID} \cdot L \]

Bunch crossing rate = filled BX/total BX x 40 MHz

 Efficiency (and acceptance) of LUCID to detect a pp interaction

# of pp interactions per bunch crossing (BX) as measured by LUCID.

\[ \mu_{LUCID} = - \ln \left( \frac{N_{BCid}^{Zero}}{N_{BCid}^{Turns}} \right) \]

\[ \mu_{LUCID} = - \frac{N_{BCid}^{Hit}}{ \langle N_{Hit}^{pp} \rangle_{PP} \cdot N_{Turns} } \]

mean number of hits per single interaction

\[ \mu_{Track} = - \ln \left( 1 - \text{Occ}^{BCid} \right) \]

\[ \text{Occ}^{BCid} = \frac{N_{Hit}^{BCid}}{N_{Tube} \cdot N_{Turns}} = 1 - P(0, \mu_{Track}) = 1 - e^{-\mu_{Track}} \]

\[ \# \text{ of pp interactions per bunch crossing} \]
LUCID: Luminosity Monitoring and Calibration

A detector able to count the number \( \mu \) of interactions per bunch crossing (BX)

\[
\mu = \sigma_{pp} \times L
\]

by measuring \( <M> = \text{mean number of charged particles per BX} \).

Calibrated at low luminosity where the average number of particles per detected interaction \( <N> \) is measured (small probability of more than 1 interaction per BX)

If \( \epsilon \) is the efficiency to detect one interaction:

\[
\mu = \frac{<M>}{<N> \cdot \epsilon} = \sigma_{pp} \times L \quad \Rightarrow \quad L = \frac{<M>}{<N> \cdot \epsilon \cdot \sigma_{pp}}
\]

“Luminosity independent” calibration constant (determined in dedicated runs \( \rightarrow \) absolute L measured simultaneously)

Needed dynamic range in \( \mu \) (bunch by bunch L) @ LHC: \( 2.5 \times 10^{-6} - 25 \)

(S. Ask - ATL-LUM-PUB-2006-001)
LUCID: Systematics and Calibration

- Working range (union of all the methods):
  - (Zero counting) $0.0001 < \mu < 30$ (track counting)
  - Inside this range statistics will never be a problem
- Notable overlap regions
  - systematics
- Several redundancies
  - checks on systematics
- Main systematics: inhomogeneities, migration, non-linearities, beam background *(is being studied).*
- Method calibrations by means of:
  - Monte Carlo (poor, sys unknown)
  - Machine information (5-10%)
  - Dedicated low luminosity runs / ALFA (2-4%)
  - Selected physics processes (after some months - 5%)
  - Other ATLAS detectors (after some months)
The Zero Degree Calorimeter

The ZDC will measure production of neutral particles in the forward direction.

The ZDC sits in a TAN in the crotch of the two beams and looks at neutral particles produced at zero degrees. The TAN is a shielding box that is 140m from the IP. Three types of modules compose the ZDC detector.
Study both Heavy Ions and pp physics
- measure neutral particles at 0° \( (n, \gamma, \pi^0) \) \( (\eta>8.3) \);
  - both EM and HAD sections

Beam monitoring and tuning
- crossing angle
- IP position
- luminosity monitor at the single bunch crossing level
- tune LHC parameters in first times
- radiation hard
  - Surviving at most 3 years in pp at \( L=10^{33}\text{cm}^{-2}\text{s}^{-1} \)

Three modules installed in each of 1-2 and 8-1 TAN locations.
The ALFA Roman Pots

- Measure elastic pp-scattering down to very small angles ($\theta_{\text{min}} \sim \mu\text{rad}$) → Coulomb-Nuclear Interference region ($f_C \approx f_N$) → $-t \sim 6.5 \times 10^{-4} \text{ GeV}^2$;

- Need special (High $\beta^*$) optics
  - Low luminosity special runs ($L = 10^{27} \text{ cm}^2 \text{ s}^{-1}$)
  - Parallel-to-point focusing

- Operate tracking detectors very close to the beam, $10 \sigma = 1.2 \text{ mm}$ (position accuracy $\sim 10 \mu\text{m}$)

- Detector resolution $\sigma_d = 30 \mu\text{m}$ (t-resolution dominated by beam divergence)

- Radiation tolerance 100 Gy/yr (dominated by beam halo)

- Rate capability $O(1 \text{ MHz})$ and time resolution $O(5 \text{ ns})$
ALFA performance

Systematics on L

- beam divergence and optics
- detector acceptance, resolution & alignment
- background from halo (beam-gas, off-momentum, betatron oscillations)
- Background from non-elastic interactions

Fit to simulated dN/dt data corresponding to ~ 1 week (10M events) of running at L = 10^{27} cm^{-2} s^{-1}

\[ -t = \left( p\theta^* \right)^2 = p^2 \left( \frac{\bar{\theta}^2}{L_{eff,x}} + \frac{\bar{\theta}^2}{L_{eff,y}} \right) \]

Fit Range

(H. Stenzel ATL-LUM-PUB-2007-001)

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<th>fit</th>
<th>Stat. error</th>
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<tr>
<td>L</td>
<td>8.10 10^{26}</td>
<td>8.151 10^{26}</td>
<td>1.77 %</td>
</tr>
<tr>
<td>\sigma_{tot}</td>
<td>101.5 mb</td>
<td>101.14 mb</td>
<td>0.9 %</td>
</tr>
<tr>
<td>\rho</td>
<td>18 Gev^{-2}</td>
<td>17.93 Gev^{-2}</td>
<td>0.3 %</td>
</tr>
<tr>
<td>\rho</td>
<td>0.15</td>
<td>0.143</td>
<td>4.3 %</td>
</tr>
</tbody>
</table>

\[ \Delta L/L \sim 3\% - \text{after 2010} \]
Conclusions

- Three detectors dedicated to luminosity measurement in the forward region:
  - LUCID (at 17 m): dedicated luminosity monitor
    - Ready from the first day
    - Monitor online bunch-by-bunch luminosity
    - Absolute luminosity after calibration
  - ZDC (at 140m): LHC parameter calibration/beam monitor
    - Useful to tune machine parameters in the early days
    - Study both heavy ions and pp physics
  - ALFA in Roman Pots (at 240m): absolute luminosity from elastic scattering
    - $L, \sigma_{\text{tot}}, \rho, b$
    - Ready in 2010
Physics Interest in L

Relates the cross section $\sigma$ of a given process to its event rate $N=\sigma L \rightarrow$ overall normalization of physics analysis; monitor of LHC performances

Higgs coupling

Systematic error dominated by luminosity (ATLAS TDR)

$\Delta L/L = 10\%$

$\Delta L/L = 5\%$

Higgs coupling

$H \rightarrow \gamma\gamma$

$ttH (H \rightarrow bb)$

$H \rightarrow ZZ^{\ell\ell} \rightarrow 4l$

$\tan\beta$ measurement

$L dt = 300 \text{ fb}^{-1}$

$m_A = 150 \text{ GeV}$

$H/A \rightarrow \tau\tau$

$H/A \rightarrow \mu\mu$

$\Delta L/L = 10\%$
Elastic Scattering

\[ \sqrt{s} = 14 \text{ TeV prediction of BSW model} \]

\[ d\sigma/dt \ (\text{mb/GeV}^2) \]

\[ L, \sigma_{\text{tot}}, b, \text{ and } \rho \text{ from FIT in Coulomb-Nuclear Interference region (CNI)} \]

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

CNI region: \( |f_C| \sim |f_N| \to \) @ LHC: \(-t\sim 6.5 \times 10^{-4} \ \text{GeV}^2; \ \theta_{\text{min}} \sim 3.4 \ \mu\text{rad}\)

\( (\theta_{\text{min}} \sim 120 \ \mu\text{rad} @ \text{SPS}) \)
**Total Cross-Section**

Luminosity-independent measurement via optical-theorem → simultaneous evaluation of forward elastic and inelastic rate

- elastic rate down to $|t|=10^{-3}$ GeV$^2$ to keep extrapolation error small (1-2%)

\[
\sigma_{tot} = \frac{16\pi}{1 + \rho^2} \times \frac{(dN / dt)|_{t=0}}{N_{el} + N_{inel}}
\]

\[
L\sigma_{tot}^2 = \frac{16\pi}{1 + \rho^2} \times \frac{dN}{dt} \bigg|_{t=0}
\]

Inversely:

\[
\sigma_{tot} \propto (\log s)^\gamma < \sigma_{tot}(LHC) \sim 110 \text{ mb (}\gamma=2; \text{ best-fit)}
\]

\[
\sigma_{tot}(LHC) \sim 95 \text{ mb (}\gamma=1)
\]

\[
(L + dN/dt|_{t=0}) \quad (\Delta L/L > \sim 2 \Delta \sigma_{tot}/\sigma_{tot})
\]

\[
(\sigma_{tot} + dN/dt|_{t=0}) \quad (\Delta \sigma_{tot}/\sigma_{tot} > \sim \frac{1}{2} \Delta L/L)
\]
The Optical theorem can be used in several ways for luminosity determination.

**Method 1**
Extrapolate elastic scattering to $t=0$ (the optical point) and in addition measure the total rate.

**Method 2**
Extrapolate elastic scattering to $t=0$ and use a measurement of $\sigma_{\text{total}}$ from another experiment.

**Method 3**
Measure elastic scattering as such small angles that the cross section is also sensitive to the Coulomb part.

Elastic scattering has traditionally provided a handle on luminosity at colliders.

The basis for this is the Optical Theorem which relates the total cross-section to the forward elastic scattering amplitude

$$\sigma_{\text{tot}} = 4\pi \text{Im} \ f_{\text{el}}(0)$$
From detector to luminosity

- Two main paths:
  - a detector provide signals each BX
  - Signals can be used to count empty events (Zero counting methods) or to sum the signal amplitudes in the detector (hit/track counting, energy flow, transverse energy, PMT currents…)
  - Acceptance, efficiency and/or calibration will be used to convert these in mean number of interactions at IP (µ)
  - Now luminosity measurement is easy

\[ \mathcal{L}_i = \frac{\mu_i f_{BX}}{\sigma_{pp}^{inel}} , \quad \mathcal{L} = \sum_{i=1}^{3564} \mathcal{L}_i \]
LUCID: Luminosity algorithms

- **Algorithms (5)**
  - Zero counting method \((\text{Zero AND})\)
  - Zero OR counting method
  - Hit counting method
  - Hit Coincidence counting method
  - Hit multiplicity distribution

- **Applied on two logical independent detectors (2)**
  - LUCID Tube+PMT signals
  - LUCID Tube+fibers+MaPMT signals

- **Type of evaluations (4:2x2):**
  - Integral methods (one value per lumi block)
  - Differential methods (3564 values per lumi block)
  - Delivered lumi (LHC) or Atlas LIVE lumi
    - (i.e. corrected for L1 dead time and/or L1 busy conditions)

Three out of five Available for each BCid