Luminosity measurements and forward physics in ATLAS

- forward detectors
- luminosity calibration and monitoring
- forward physics beyond luminosity

Hasko Stenzel on behalf of the ATLAS Luminosity & forward physics WG
ATLAS proposes a two-stage program:

1: Luminosity calibration with Roman Pot detectors from elastic scattering in the Coulomb region using special beam optics with high $\beta^*$. Relative luminosity monitoring by an integrated Cerenkov detector LUCID up to highest luminosity.

2: Hard diffractive physics, exclusive central diffraction, double-Pomeron exchange, requiring proton tagging and momentum-loss measurements at collision optics.

Studies for radhard RP detectors at 220m are ongoing, complementing FP420 studies.
The ATLAS detector

Barrel Toroid
Inner Detector
Hadronic Calorimeters
Muon Detectors
Solenoid
Forward Calorimeters
End Cap Toroid

Charged particle density

Pythia v6.319
inelastic

μ-chambers

Barrel
EndCap
Tracking
FCAL

Diffraction/Proton Tagging Region

LUCID
TAS
RP
ZDC/TAN
Motivation for a precise Luminosity determination

Determination of Standard Model cross sections
- heavy quark production
- W/Z production
- QCD jet cross sections

Background for searches, constraints of PDFs

Theoretical predictions at the level of 5% with prospect for improvements (NNLO).

New physics manifesting in deviation of \( \sigma \times \text{BR} \) relative to the Standard Model predictions

Important precision measurements
- Higgs production \( \sigma \times \text{BR} \)
- \( \tan \beta \) measurement for MSSM Higgs

\[
\sigma_{\text{exp}} = \frac{N_{\text{obs}} - N_{\text{bgd}}}{A \cdot \varepsilon \cdot L_{pp}}
\]

Relative precision on the measurement of \( \sigma_{H} \times \text{BR} \) for various channels, as function of \( m_{H} \), at \( \int L \, dt = 300 \) fb\(^{-1}\). The dominant uncertainty is from Luminosity: 10% (open symbols), 5% (solid symbols).

(ATLAS-TDR-15, May 1999)
Methods of Luminosity measurements

Absolute luminosity

- from the parameters of the LHC machine
- rate of $pp \rightarrow Z^0/W^\pm \rightarrow l^+ l^- l^+ l^-$
- rate of $pp \rightarrow \gamma\gamma \rightarrow \mu^+ \mu^-$
- Optical theorem: forward elastic + total inelastic rate, extrapolation $t \rightarrow 0$ (but limited $|\eta|$ coverage in ATLAS)
- cross-check with ZDC in heavy ion runs
- from elastic scattering in the Coulomb region
- combinations of all above

Relative luminosity

- LUCID Cerenkov monitor, large dynamic range, excellent linearity

ATLAS aims for 2-3% accuracy in $L$
Luminosity from elastic scattering

Measure elastic pp-scattering down to very small angles (~3 μrad)

- operate tracking detectors very close to the beam, 10 σ = 1.2 mm
- high β* optics parallel-to-point focusing
- reconstruct the t-spectrum
- fit L to the t-spectrum

\[
\frac{dN}{dt}\bigg|_{t=0} = L\pi|F_C + F_N|^2 \approx L\pi \left( \frac{2a_{EM}}{\sqrt{|t|}} + \frac{\sigma_{tot}(i+\rho)e^{-\sqrt{|t|}}}{4\pi} \right)^2
\]

Coulomb region: \( F_C \approx F_N \)

\[-t_{\min} \leq \frac{8\pi a_{EM}}{\sigma_{tot}} \approx 6 \times 10^{-4} \text{ GeV}^2 \Rightarrow \theta_{\min} \leq 3.5 \mu\text{rad} \]
Detector requirements

Physics & operation requirements

• detector resolution $\sigma_d = 30\, \mu m$, beam spot size =120 $\mu m$ at RP
  (t-resolution dominated by beam divergence)
• detector sensitivity up to the edge towards the beam
  (‘edgeless detector’, insensitive region $d_0 \leq 100\,\mu m$ at the edge)
• position accuracy $\sim 10\,\mu m$ relative between top and bottom detector
  (stringent survey and metrology requirements)
• radiation tolerance 100 Gy/yr (dominated by beam halo)
• rate capability $O(1\,MHz)$ and time resolution $O(5\,ns)$
• insensitive to EM pulse from the bunched beam

Integration & construction constraints

• integration in the readout/DAQ/trigger scheme of ATLAS
• LHC safety, control and interlock requirements
• limited resources and tight schedule
Roman Pots for ATLAS

Two RP stations with top and bottom vertical pots, separated by 4 m, at each side 240 from IP1
Roman Pot detectors

- MAPMTs
- FE electronics & shield
- PMT baseplate
- Optical connectors
- Scintillating fibre detectors
- Overlap & trigger

Roman Pot mechanics (TOTEM design)
The Roman Pot (modified TOTEM design)

- Top flange with helicoflex joint
- Rectangular body out of center
- Pumping hole
- Overlap extrusions brazed on bottom
- Brazing of beam windows
detector principle

key features:

- square scintillating fibres 0.5x0.5 mm²
- U/V geometry 45° stereo layers
- 64 fibres per module plane
- 10 double sided modules per pot
- staggering of modules by \( n \sqrt{2} \times 0.5\text{mm}/10 \)
- trigger scintillator in the crossing area
- overlap detectors for relative vertical alignment
- overlap triggers in the beam halo

Fiber detector:
10 plates of 2x64 fibers

Overlap detector:
3 plates of 2x30 fibers

Trigger for detector:
1 plastic scintillator 3mm thick

Trigger for overlap detector:
2 plastic scintillator 3mm thick
**detector prototypes**

**Principle**
- 0.5mm spacers
- 0.17mm Al₂O₃ ceramic substrate
- reference edge

**Prototype: 20 Planes u and v of 6 fibres**

HERA-LHC workshop  ATLAS luminosity and forward physics
Purpose of the testbeam:
- photoelectric yield
- efficiency
- cross talk
- edge sensitivity
- track resolution

proof of principle

At DESY22, 6 GeV e⁻
October/November 2005
testbeam results: photoelectric yield and cross talk

OPERA readout (900 V)

$<\text{Npe}>/\text{MIP}=4-4.5$

total optical cross talk = 4%
testbeam results: efficiency

single fibre efficiency 90-94% (depends on cut)

insensitive area at the edge < 30 μm (limited by resolution)
**testbeam results**

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_x$ [µm]</th>
<th>$\sigma_y$ [µm]</th>
<th>$\epsilon$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si telescope</td>
<td>29.9</td>
<td>29.5</td>
<td>?</td>
</tr>
<tr>
<td>ALFA</td>
<td>36.00</td>
<td>36.56</td>
<td>98.99</td>
</tr>
</tbody>
</table>

- resolution scales like 1/E
- large multiple scattering contribution
- expect $\sigma_{x,y} \approx 20$ µm from MC at LHC
Transversal displacement of particles in the ring away from the IP:

Special optics with high $\beta^*$ and parallel-to-point focusing:

$y = \sqrt{\frac{\beta}{\beta^*}} (\cos \Psi + \alpha^* \sin \Psi) y^* + \sqrt{\beta \beta^*} \sin \Psi \theta_y^*$

$\beta^* = 2625 \text{ m}$
$\beta_y = 119 \text{ m}$
$\alpha^* \approx 0$
$\Psi \approx 90^\circ$
$L \approx 10^{27} \text{ cm}^{-2} \text{s}^{-1}$

$\sigma_d = 0.12 \text{ mm}$
$\theta_{\text{min}} = 2.7 \mu\text{rad}$
$\theta_{\text{max}} = 44.7 \mu\text{rad}$
$t_{\text{min}} = 0.0004 \text{GeV}^2$
$t_{\text{max}} = 0.098 \text{GeV}^2$

properties at the roman pot (240m)
Simulation of elastic scattering

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

\[ t = -0.0007 \]

\[ t = -0.001 \]
**L from a fit to the t-spectrum**

\[
\frac{dN}{dt} = L \pi |F_C + F_N|^2
\]

\[
= L \left( \frac{4\pi^2 (\hbar c)^2}{|t|^2} - \frac{\alpha \rho \sigma_{tot} e^{-B|t|/2}}{|t|} + \frac{\sigma_{tot}^2 (1 + \rho^2) e^{-B|t|}}{16\pi (\hbar c)^2} \right)
\]

Simulating 10 M events, running 100 hrs
fit range 0.00055-0.03

<table>
<thead>
<tr>
<th></th>
<th>input</th>
<th>fit</th>
<th>error</th>
<th>correlation</th>
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<tbody>
<tr>
<td>$L$</td>
<td>$8.124 \times 10^{26}$</td>
<td>$8.162 \times 10^{26}$</td>
<td>1.5%</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{tot}$</td>
<td>100 mb</td>
<td>101.1 mb</td>
<td>0.74%</td>
<td>-99%</td>
</tr>
<tr>
<td>$B$</td>
<td>18 GeV$^{-2}$</td>
<td>17.95 GeV$^{-2}$</td>
<td>0.59%</td>
<td>64%</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.15</td>
<td>0.1502</td>
<td>4.24%</td>
<td>92%</td>
</tr>
</tbody>
</table>

large stat.correlation between $L$ and other parameters
Currently under re-evaluation

- beam divergence $\sigma' = 0.23 \mu$rad
- detector resolution
- detector alignment
- background from
  - Halo
  - beam-gas
  - beam-wall
  - non-elastic
- beam optics uncertainties

$\Delta_{\text{exp}} \approx 2-3\%$
LUCID: Luminosity measurement using Cerenkov integrating detector

Front face of LUCID end is ~17m from the IP - covering $5.4 < |\eta| < 6.1$

LUCID region 6→7 Mrad/year at $10^{34}$ cm$^{-2}$s$^{-1}$

from J. Pinfold
Two detectors x 168 Al tubes filled with $\text{C}_4\text{F}_{10}$ or Isobutane at 1 or 2 Bar pressure

Winston cones at the end of the tubes bring the Cerenkov light onto quartz fibers.

LUCID Cross-section

[Diagram of LUCID detector with Winston cones and fibers]

Concentrator Outlet Fibers 1 mm
4 layers x 42 tubes x 7 fibers = 1176 fibers

Layer 1 Layer 2 Layer 3 Layer 4
**LUCID test beam performance**

- \( \langle N_{pe} \rangle \) / Cerenkov tube = 5.3, a bit lower than anticipated from simulation
- Triggered design improvements for tubes/winston cones/fibre coupling
Sensitive to primaries – projective geometry – smaller signals for secondaries & soft particles:
- shorter paths length for secondaries
- Cerenkov thresholds

No Landau fluctuations in Cerenkov emission counting multiple tracks/tube – no saturation

Excellent time resolution
- ~140ps @ CDF
- Luminosity bunch-by-bunch

Linear relationship between lumi & track counting

Segmentation in tubes gives position sensitivity

Radiation hard – light – compact

Calibration using
- elastic scattering data
  At $10^{27}$ cm$^{-2}$s$^{-2}$

Overall Calibration

Calibration using
- single W/Z production at Lumi > $10^{30}$ cm$^{-2}$s$^{-2}$
- $\gamma \rightarrow \mu\mu$ data
  At Lumi > $10^{30}$ cm$^{-2}$s$^{-2}$

Response Correlation

Linear response

Response Amplitude Distribution

No Saturation
Forward physics beyond luminosity

From the luminosity run and elastic scattering we get:

- the total cross section $\sigma_{\text{tot}}$
- the nuclear slope $B$
- the $\rho$-parameter

... to some accuracy
A new study for RP detectors at ~220 m for DPE at high luminosity has started.
acceptance study

- Place two horizontal RP stations around 220m
- Run at high luminosity with collision optics
- Si strip / micromegas detectors studied
- Cerenkov counters for timing considered
- Extension of the luminosity program, complementary to FP420

Beam spot calculated with MADX in the RP region
acceptance for $t$ and $\xi$

acceptance for $\xi$
from $\sim0.01$ to $\sim0.16$
ATLAS luminosity program

- with roman pot detectors from elastic scattering for absolute calibration
- complemented by W/Z counting and $\gamma\gamma$-processes
- and machine parameters
- with LUCID for luminosity monitoring
- gaining experience in operation close to the beam
- 2006: testbeams for ALFA and LUCID, final design

Upgrade options

- RP220 under study to explore hard diffraction & DPE
- complementing/extending FP420
- time scale 2008-2009