Upgrade of the ATLAS MDT Readout and Trigger for the HL-LHC

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On behalf of the ATLAS Muon Collaboration
Concepts, Plans and Questions

- The HL-LHC challenge.
- How to find Muons?
- Good muons and bad muons.
- What do muons tell us?
- Scrutinizing the quality of the muon $p_T$.
- Fast trigger chambers helped by slow MDT?
- Detectors and instruments.
- The hard currency in triggering: latency.
- The construction program for the MDT Readout.
- The Muon Trigger in the ATLAS trigger community.
- Summary.
The HL-LHC Challenge

The total inelastic p-p cross section

<table>
<thead>
<tr>
<th>σ [barn]</th>
<th>evt. rate [kHz]</th>
<th>evts./crossing</th>
<th>evt. rate [kHz]</th>
<th>evts./crossing</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.088</td>
<td>880,000</td>
<td>22</td>
<td>6,600,000</td>
<td>165</td>
</tr>
</tbody>
</table>

NB: $10^{34}/(\text{cm}^2\cdot\text{s}) = 10^{10}/(\text{barn}\cdot\text{s})$

- At a luminosity of $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ we expect about $7 \times 10^9$ interactions/s = 170/BX
- Looking for muon related physics, we consider about 5 per million worth recording, i.e. ~ 35 kHz.
- How do we select them for the first level trigger?

A hopeless task?
Mother nature is helping!

The big majority is minimum bias, i.e. low $p_T$:

- Charged tracks curl inside the ID. $\Rightarrow$ Do not reach the Muon Spectrometer.
- Most of the $\gamma/e$ deposit little energy in the ECAL $\Rightarrow$ do not reach trigger threshold of 20 GeV.
- Physicewise of no interest.
- This discards the majority of all interactions.

- „Interesting physics“ mainly comes from heavy objects (Z, W, t...), decaying into energetic leptons with high transverse momentum ($p_T$), typically $> 20$ GeV
- The $\mu$‘s are particularly interesting:
  - authentic witnesses of the object’s decaying habits, flying nearly unperturbed across heavy detector components
  - very rare objects: only $\sim$ one muon in about 1000 beam crossings
- Lets give them a closer look!

$p_T$ distrib. in minimum bias events

charged tracks

5 GeV

neutrals

5 GeV
Frequent $\mu$-signatures at the LHC

Prompt $\mu$-pairs (a) and (b), **coming from the IP vertex**.

(a) **At least one muon** with $p_T > 20$ GeV („high-$p_T$“)
   → **Single Muon Trigger**

(b) **Two muons**, one of them with $p_T > 6$ GeV
   → **Di-muon Trigger**

   The 2 muons may come from decays of, e.g.:
   $Z$ ($92$ GeV), $J/\Psi$ ($3.10$ GeV), $Y$ ($9.46$ GeV)

(c) A muon pair with a **very small opening angle** → small invariant mass. May be rejected by the MUCTPi if outside a predefined mass window.

(d) This $\mu$ does not extrapolate to the IP vertex and is close to a jet, most likely coming from an in-flight decay of a $\pi$ or K in a jet → rejected by the Global Trigger.

(e) The **angular separation** of this high-$p_T$ muon from the jets is sufficiently large („isolation“) and it comes from the IP vertex. → retained in the Global Trigger

**NB**: Diagrams are schematic. Track curvatures are strongly exaggerated.
The plot shows the recorded rates of Φ, J/Ψ and Y as a function of the invariant μ⁺μ⁻ mass and of thresholds for the di-muon trigger.

→ Lowering the threshold from 11 to 6 and finally to 4 leads to a signal increase of about 3.

→ In this analysis the muons from the ~10⁷ J/Ψ and Z (not shown) are used for a fine-tuning of the p_T calibration in all η/φ regions of ATLAS.
The inclusive \( \mu \) spectrum and the trigger selectivity for single muon tracks

\[ p_T = 20 \text{ GeV} \]

\[ \sigma = 1.6 \times 10^3 \text{ cm}^{-2} \text{s}^{-1} \]

\[ \text{trg. rt. Ph-I [kHz]} = 160 \]

\[ \text{trg. rt. Ph-II [kHz]} = 1200 \]

\[ \text{NB:} \ 10^{34}/(\text{cm}^2\text{s}) = 10/(\text{nb}s) \]

Rate of single muon triggers depends on the \( p_T \) resolution of the trigger system. \( \Rightarrow \) Need high spatial resol. along the track to keep rates down.

<table>
<thead>
<tr>
<th>( p_T ) [GeV]</th>
<th>( \sigma ) [nb]</th>
<th>rate [kHz]</th>
<th>evts./BX</th>
<th>rate [kHz]</th>
<th>evts./BX</th>
<th>sagitta [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>8.8</td>
<td>9.3</td>
<td>0.0022</td>
<td>660</td>
<td>0.0165</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>0.93</td>
<td>0.0002</td>
<td>70</td>
<td>0.0017</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>20</td>
<td>0.04</td>
<td>0.4</td>
<td>1.00E-05</td>
<td>3.0</td>
<td>7.50E-05</td>
<td>30</td>
</tr>
</tbody>
</table>

\( \Rightarrow \) Need high spatial resol. along the track to keep rates down.

From ATLAS Trigger performance 1998 (CERN/LHCC98-15)
A quick look at the structure of the Muon Spectrometer  
*(Phase-I)*

- Chambers in the MS are arranged in 6 projective sectors along \( \eta \) and 16 along \( \Phi \).
- In each sector, 3 layers of precision MDT are matched to 3 layers of „fast“ trigger chambers, forming a trigger tower.
- Trigger signals are processed per sector in the Sector Logic.
- Trigger info from the 192 trigger sectors is collected in 2 processors, one for barrel and EC, the MuCTPi. From there, the trigger candidate is forwarded to the CTP.
- The Readout of the MDT follows a separate path. MDT and trigger data only meet at the L2 trigger.
The p_T resolution of in the single muon trigger in Run 1&2

(Example Muon Barrel)

The RPC trigger is blind for small deviations from a straight track due to insufficient spatial resolution. \( \Rightarrow \) Accepts many muons below 20 GeV. Actual rate goes from 3.7 to \( \sim \) 20 kHz.

- \( p_T \) resolution:
  - 10 GeV: \( \sigma \approx 48 \text{ mm} \), 890 nb, 30 kHz
  - 20 GeV: \( \sigma \approx 24 \text{ mm} \), 47 nb, 3.7 kHz
  - 40 GeV: \( \sigma \approx 12 \text{ mm} \), 3 nb, 0.3 kHz

Using the MDT hits for L1:
- much better spatial resolution
- increase of the track length due to the Inner MDT layer
- improved pointing accuracy to the IP due to the Inner layer
- smarter electronics (!) needed

MDT accuracy is \( \sigma \sim 0.1 \text{ mm} \)
How to combine RPC/TDC and MDT info?

Need to ask your friends from TDAQ:

a) to supply coordinates for trigger candidates from Sector Logic (RoIs)
b) to kindly wait until…
   • MDT drift is over
   • data have been read out
   • decision about track-to-RoI match is done
   • arrival of yes/no

3 Methods proposed for MDT track finding:

a) the histogramming approach
b) use of the Legendre Transformation
c) use of the Associative Memory technic
The histogramming method and results from simulation

The histogramming method
Projecting the hits along the direction, given by the RPCs. This yields the most likely trajectory.

Simulation
Taking into account inefficiencies due to
• inert material (MDT walls)
• corruption by $\delta$-rays
• masking of “good” hits by cavern background (10% occup. assumed)

The diagram shows the difference between generated and reconstructed slopes for 35 k events. Categories are good, medium and poor for $\Delta m < 3$, $< 9$ and $> 9$ mrad.

For most tracks, the MDT coordinates provide a substantial improvement of the slope measurement.
Finding a track in a MDT

(a) get the raw hit pattern from the MDT
(b) find track segments using RPC seeds
(c) link segments and determine $p_T$

From K. Ntekas, march, 20, 2018

Sept-4-2019      TWEPP19      Upgrade of the ATLAS MDT Readout&Trigger      R. Richter
The MDT R/O architecture in Phase-II

Phase-I: MDT & Trigg. chambers are read out independently
- MDT R/O only on L1 trigger, saving bandwidth
- Trigg. ch’s use hardware logic at the frontend to select trigger candidates

Phase-II: MDT data are used to sharpen the trigger decision w.r.t. the muon pT of the trigger candidate
- Find accurate pT using ROI seed from trigg. ch’s and confirm/reject trigger hypothesis
- All MDT hits are streamed to MDT processor → requires higher bandwidth

General concept of chamber readout: move decision making to the counting room: (a) can combine info from various trigger sources (b) no problems with TID (c) easy to service – BUT … (d) needs more bandwidth, processing power …

Sept-4-2019 TWEPP19 Upgrade of the ATLAS MDT Readout&Trigger R. Richter
Accumulation of Latency along the Muon Trigger Path

Input of trigger info to the MDT processor (waiting for MDT hits) $t = 1.7 \mu s$

MDT processor done $t = 3.6 \mu s$

Sector Logic done $t = 4.01 \mu s$

MUeCTPi done $t = 4.46 \mu s$

Global Trigger done $t = 5.86 \mu s$

CTP done $t = 6.69 \mu s$

FELIX done $\rightarrow$ broadcast Trigger to the frontends $t = 6.9 \mu s$

**Best estimate** for L0 trigger latency: $6.9 \mu s$

**Maximum estimated** latency value: $9.1 \mu s$

**Maximum allowed** latency: $10.0 \mu s$

Data from TDAQ TDR, table 5.5 (Dec. 2017)

Sept-4-2019 TWEPP19 Upgrade of the ATLAS MDT Readout&Trigger R. Richter
Zooming into the MDT Trigger Processor

MDT data from Barrel Middle and Inner

MDT data from Barrel Outer

SL of this Sector

Service module for Configuration & external Communication

For more details, see poster by Davide Cieri at this workshop.
2 Options for the CSM under study

CSM = Chamber Service Module

**The FPGA based CSM**

**PROs**
- Flexibility in FPGA firmware design
- Can easily handle migration from Ph-I to Ph-II

**CONs**
- Questions on FPGA SEU in Phase II
- Maintenance needed for firmware
- Difficult access

**The GBTx-based CSM**

**PROs**
- Radiation hard ASICs from CERN
- No firmware design/maintenance needed
- Low power consumption, low cost

**CONs**
- Functionality fixed by GBTx ASIC
- Small ASIC chip needed for JTAG distribution (Mezzanine Card control)

Prototypes exist for both concepts at Univ. of Michigan

From Xueye Hu, Univ. of Michigan, apr., 18th, 2018
### Implementation of h/w for the MDT trigger

<table>
<thead>
<tr>
<th>Component</th>
<th>Function</th>
<th># of devices</th>
<th>technology</th>
<th>Location</th>
<th>Performance Criteria</th>
<th>Status (aug. 2019)</th>
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</thead>
<tbody>
<tr>
<td>ASD</td>
<td>8-ch preamp</td>
<td>60 k</td>
<td>IBM/GF 130 nm</td>
<td>Frontend board</td>
<td>gain, thresh. matching, ENC, functionality</td>
<td>devices from engineering run under test</td>
</tr>
<tr>
<td>TDC</td>
<td>24-ch</td>
<td>20 k</td>
<td>TSMC 130 nm</td>
<td>Frontend board</td>
<td>bandwidth, latency, transmission rate</td>
<td>working prototype ASIC</td>
</tr>
<tr>
<td>CSM</td>
<td>serving 18 TDC</td>
<td>1.5 k</td>
<td>GBTx, FPGA</td>
<td>On-chamber</td>
<td>transmission rate, latency, data integrity</td>
<td>prototypes for 2 versions</td>
</tr>
<tr>
<td>L0 Muon Trigger</td>
<td>serving 3 MDT</td>
<td>1.5 k</td>
<td>GBTx, FPGA, Zync, ARM proc.</td>
<td>USA15</td>
<td>$p_T$ determ., latency, interface to SL, transm. speed</td>
<td>prototypes</td>
</tr>
</tbody>
</table>

**Production, test, prototyping of Hardware well advanced for Phase-II**
Step-by-step refinement of the L0Muon trigger

(a) The MDT Processor: Refinement of the $p_T$ measurement

(b) The MUCTPi sees data from all sectors
- suppress double-counting of tracks (MDT sector overlap!)
- define trigger candidates

(c) The Global Trigger sees Muon and Calo trigger objects. Can run „offline-like“ algorithms. E.g.: require
- invariant mass of $\mu\mu$ inside limits
- isolation btw. muon and jets

(d) The CTP: controls
- trigger menu
- performs prescaling
- takes final L0 trigger decision

Data from TDAQ TDR, table 5.5 (Dec. 2017)

NB: Matching of tracks from the Muon Spectrometer to the ITK will not be done for L0.
### Trigger Menu foreseen for 1 MHz L0 Rate

<table>
<thead>
<tr>
<th>Muon Spectrum</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
<th>Regional Tracking</th>
<th>Event Filter Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kHz</td>
<td>kHz</td>
<td>kHz</td>
<td>kHz</td>
<td>kHz</td>
<td>kHz</td>
</tr>
<tr>
<td>single (\mu)</td>
<td>9.3</td>
<td>15.5</td>
<td>15</td>
<td>38</td>
<td>38</td>
<td>1.5</td>
</tr>
<tr>
<td>di - (\mu)</td>
<td>1.9</td>
<td>5.2</td>
<td>4</td>
<td>10</td>
<td>5</td>
<td>0.2</td>
</tr>
<tr>
<td>single e</td>
<td>19</td>
<td>27</td>
<td>14</td>
<td>200</td>
<td>40</td>
<td>1.5</td>
</tr>
<tr>
<td>di - e</td>
<td>6.5</td>
<td>1.7</td>
<td>5</td>
<td>40</td>
<td>10</td>
<td>0.2</td>
</tr>
<tr>
<td>others</td>
<td>38.3</td>
<td>25.6</td>
<td>62</td>
<td>771</td>
<td>334</td>
<td>7.0</td>
</tr>
<tr>
<td>total</td>
<td>75</td>
<td>75</td>
<td>100</td>
<td>1059</td>
<td>334</td>
<td>10.4</td>
</tr>
</tbody>
</table>

Triggered at L0: ~ 1 MHz
Permanently stored by EF: ~ 10 kHz

Data extracted from TDAQ TDR, table 6.4 (Dec. 2017)

Sept-4-2019 TWEPP19 Upgrade of the ATLAS MDT Readout&Trigger R. Richter
Expected reduction of low-\(p_T\) fake triggers using the MDT

Relative efficiency of the MDT 3-station trigger with respect to the Phase-I first-level muon trigger vs. \(p_T\), measured in the offline reconstruction.

The \(\eta\) distributions of muon candidates selected with first-level \(p_T\) threshold of 20 GeV
- White distribution: before Phase-II
- Blue: Using the MDT info at L1
- Green: Full off-line analysis

Oliver Kortner, MPI
Substantial reduction of the L1 Muon trigger rate due to use of high precision MDT track co-ordinates.

Complete replacement of existing Readout Electronics required.

Development of new modules well under way in accordance with time schedule.

Some technical options still open, presently studied with fully functioning prototypes.

Not all power consumption / cooling issues completely defined/solved yet, but no show stopper in sight.
Bibliography

- TDR for the Phase-II Upgrade of the ATLAS Muon Spectrometer CERN-LHCC-2017-017
- Article: The ATLAS Experiment at the CERN Large Hadron Collider, JINST 3 (2008) S08003
  URL: http://cds.cern.ch/record/331068
The Muon Trigger path in Phase I and II

Phase-I Muon Trigger

Trigg. chambers deliver trigger candidates with raw $p_T$ from a local coincidence matrix. MDT are only read out on a L1 trigger (saving R/O bandwidth.)

Phase-II Muon Trigger

Trigg. chambers send raw to SL.

→ Trigger candidates selected by SL. position and slope of the muon candidates are sent to the MDT trigger processor.

All MDT data are streamed to the MDT trigger processor. Tracklet coordinates of muon candidates are seeds to find corresponding track segments in the MDT.

If MDT confirms $p_T$ above threshold, SL forwards candidate to MuCTPi and Global Trigger.

Global Trigger checks e.g. on isolation from jets, reports to CTP.
Muon trigger and readout scheme. The muon trigger decision is made in the endcap and barrel sector logic (SL) using data from the muon trigger chambers (TGCs and RPCs), from the Tile calorimeter, and from the MDT trigger processor. The trigger decisions of the SL's are collected by the MuCTPi. All muon hit data are read out through the Front-End Link Interface eXchange (FELIX) and passed to the HLT and the down-stream readout system.
The L1 selection in the endcap in Phase-II

- The NSW determines the track angle in the R/Z plane with ~1 mrad accuracy.
- To match this accuracy of the angular measurement with the one in the „Big Wheel“, the MDT precision info will be needed for L1.