Upgrade of the ATLAS Muon System for the HL-LHC

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for the ATLAS Experiment

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High-Luminosity LHC

- **HL-LHC** upgrade of the LHC: increase *instantaneous luminosity* to $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (ultimate: $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$), total *integrated luminosity* of 3000 fb$^{-1}$ (ultimate: 4000 fb$^{-1}$)

- **ATLAS Phase-I upgrade** in Long Shutdown 2 (LS2, 2 years duration, planned for 2019/20), followed by LHC Run 3

- **ATLAS Phase-II upgrade** in LS3 (2.5 years, presently scheduled for 2024-26), followed by (HL-) LHC Runs 4,5,6,...
- **ATLAS muon spectrometer**: muon chambers (blue) embedded in air-core **toroid magnets** (orange)
  - Monitored Drift Tube (MDT) chambers and Cathode Strip Chambers (CSC) for precision tracking
  - Resistive Plate Chambers (RPC) and Thin Gap Chambers (TGC) for triggering
**Muon Spectrometer**

- **8 Large (L) sectors** in-between barrel toroid coils (14°)
- **8 Small (S) sectors** overlapping with toroid coils (8.5°)
- Most tracks traverse either **only L** or **only S** chambers
- Toroid magnets (0.5 T) **bend tracks in η** (ID solenoid: in φ), $\Delta p_T/p_T = 4\%$ over large range in $p_T$, increasing to 11% at 1 TeV

**Muon spectrometer trivia:**
- **B**=Barrel ($|\eta|<1.0$), **E**=Endcap ($1.0<|\eta|<2.7$)
- **I**=Inner, **M**=Middle, **O**=Outer, **E**=Extra
- **1..6 position in Z/R**
- Most tracks traverse **BI/BM/BO** or **EI/EM/EO**

![R-Z view of a large sector](image)

![X-Y view](image)
ATLAS Phase-II Upgrade

- No upgrade → lepton trigger thresholds would have to be increased to ~50 GeV → unacceptable impact on physics
- Need more selective trigger algorithms
- Need higher sustainable trigger rates
- Detectors can cope with pile-up as high as $\mu = 200$ (including cavern background) without major problems
- Phase-II trigger upgrade:
  - L0 trigger at 1 MHz, 10 $\mu$s latency (present: L1 at 100 kHz, 2.5 $\mu$s latency)
  - High-Level Trigger (HLT) PC farm, max output rate 10 kHz (present: 1.5 kHz)
- Option to evolve to an L0/L1 scheme max 4 MHz/800 kHz 10/35 $\mu$s
Muon System Upgrade

- **Chambers:**
  - BI upgrade: add BIL+BIS RPC chambers, replace BIS MDT by sMDT chambers
  - **New Small Wheels (NSW):** replace CSC and MDT in EI region by Micromegas and sTGC chambers
  - EIL4 TGC chambers: replace TGC doublets by triplets
  - Option: High-η tagger to identify muons at 2.7<|η|<4.0

- **Electronics:**
  - Replace the entire MDT electronics chain
  - Replace most of the RPC/TGC electronics chain

Address weaknesses of the present detector, increase robustness in a more challenging environment

NSW is a Phase-I upgrade
Skip in this talk
Skip, not yet approved
Enable more sophisticated trigger algorithms, ensure compatibility with new trigger/DAQ scheme
Rate Limitations

- **No general rate or longevity issues** for ATLAS MDT and TGC

- **Present ATLAS RPC**: GIF++ tests indicate there is a current limit, equivalent to a maximum long-term sustainable rate ("safe operating mode") of **100 Hz/cm²** at nominal HV

- **Expected rates** at HL-LHC: up to **300 Hz/cm²**

- **Solution**: reduce gas gain (HV) in regions with high rates in order to reduce currents

- **Price**: reduced hit efficiency, worst case: 65% around |\( \eta \)|=1

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### RPC rates (Hz/cm²) at HL-LHC vs \( \eta \) and \( \phi \) (incl. safety factor 2)

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<th>RPC unit id. along Z direction</th>
<th>Average</th>
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<tr>
<td>0.16</td>
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BI Upgrade: RPC

- Present RPC trigger ("high-\(p_T\)") uses 3/3 coincidence of 3 RPC doublet layers (2 in BM=middle, 1 in BO=outer)
- Not viable if RPC hit efficiency too low due to reduced HV
- To maintain high trigger efficiency, loosen coincidence requirements on BM and BO chambers
- To maintain high trigger selectivity, need to add more chambers to the coincidence → new layer of RPC: BI RPC project

Present (high/low \(p_T\)) trigger scheme

high/low \(p_T\): trigger thresholds above/below 10 GeV

All single-muon triggers use high \(p_T\)

BIS78 here

New BI RPC

Position of new BI RPCs (X-Y view)
BI Upgrade: RPC+sMDT

- Install **new RPC triplets** in innermost barrel layer (BI)
- 1 mm gap instead of 2 mm, 5400 V instead of 9600 V, high-sensitivity front-end elx, rate capability = tens of kHz/cm²
- BIS78 Phase-I **pilot project**: chambers = close to final BI RPC design, electronics = prototypes
- Problem: **insufficient space** in small sectors → replace present BIS MDT by sMDT → lower profile → gain space for RPC
- sMDT: 15 mm tube diameter instead of 30 mm, 2730 V instead of 3080 V (same field)
- **Bonus**: 8x higher rate capability (not really needed)
Barrel Trigger Performance

- Depending on coincidence requirements, **geometrical acceptance of trigger** increases from 78% to up to 96%
- Even for severely degraded hit efficiency in BM/BO: very good **trigger efficiency \times acceptance**

Trigger efficiency \times acceptance assuming hit efficiency in BM and BO degraded down to 65% (worst-case scenario)

**ATLAS Simulation**

\[ L_0 \text{ efficiency wrt offline} \]

*Present RPC*

ATLAS Simulation

3/3 chambers

3/4 chambers + BIBO

3/4 chambers

3/3 chambers

**ATLAS Simulation**

BI-RPC upgrade

3/4 chambers + BI-BO

Trigger geometrical acceptance vs \( \eta \) and \( \phi \)

Requiring hits in 3/4 of BI+BM1+BM2+BO or in BI and BO only
New Small Wheels

- **Region of highest rates**: endcap CSC and MDT closest to the IP (EI region, a.k.a. "Small Wheels")

- **Efficiency and resolution degrade** above $2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ in this region, and **90% of trigger rate** due to particles not coming from the IP

- **New Small Wheels (NSW)**: replace CSC and MDT in EI by Micromegas (MM) and sTGC

- **8+8 layers**, for both **triggering** (coincidence with EM, a.k.a. “Big Wheels”) and **precision measurements**, fully redundant

- **Challenge**: **Phase-I** project, but front-end, trigger and readout electronics **Phase-II compliant**
EIL4 TGC Chambers

- **EIL4 TGC chambers** at $1.0 < \eta < 1.3$: doublet chambers, originally not foreseen to be used in trigger, but included to reduce rate of endcap triggers from non-IP tracks (same motivation as for NSW and BIS78)

- To maintain high trigger efficiency, doublets can only be used in a **1/2 coincidence**; this, and too large coincidence windows, would result at HL-LHC in **9 MHz trigger rate from cavern background**

- Replace doublets by triplets, with smaller coincidence windows → enable a more robust **2/3 coincidence**, much less sensitive to background
High-\(\eta\) Tagger (Option)

- New **Inner Tracker (ITk)** will cover up to \(|\eta|<4.0\) – present muon spectrometer **coverage** ends at \(|\eta|<2.7\)

- Studying the option to install a **muon tagger** on innermost part of NSW shielding disk – to **identify** (tag) ITk tracks as muons (measurement of momentum solely by ITk)

- **Less advanced** than the remainder of the muon Phase-II program, R&D focusing on choice of **detector technology**
Front-End Electronics

- **ATLAS electronics** were **qualified for doses** corresponding to at least 1000 fb\(^{-1}\), including large **safety factors**

- After first years of LHC operation, simulations were found to agree well with data: **updated (reduced) safety factors** compensate for most of 1000 fb\(^{-1}\) → 3000/4000 fb\(^{-1}\)

- **Replace electronics only** if no longer adequate for purpose – not for radiation considerations

- **Front-end electronics** for signal amplification, shaping, discrimination **do not need modification** for HL-LHC running

- **Replace digital electronics** that implements e.g. buffers of fixed size, assumptions about trigger scheme and rates, etc.
MDT Trigger

- Presently, MDT information used only in High-Level Trigger (HLT), not in L1
- **pT resolution** limited by position resolution and alignment of RPC and TGC
- Phase-II upgrade: use MDT information in L0 trigger to sharpen the pT threshold
- **Trigger rate** reduced by >50%
- Optionally, gain in efficiency by accepting loose RPC/TGC coincidences if confirmed by MDT (e.g. BI-BO)
- Challenges: computing-intensive, maximum L0 trigger latency → need hit information available for trigger decision **fast**
MDT Trigger and Readout

- Present **triggered MDT readout**: on L1 trigger accept signal, all hits inside a time window are retrieved from TDC buffer and sent to counting room
  - Saves **bandwidth** at low trigger rates – but not at high (Phase-II) rates
  - **Waiting** for trigger signal – costs time
  - At Phase-II trigger rates, the same hit may even be sent **multiple times**
  - Replace by **trigger-less MDT readout**: send out every hit to counting room **immediately**
• In present scheme, RPC and TGC on-detector trigger and readout electronics implements the L1 trigger (coincidence matrices) and sends a trigger signal to the counting room.

• In Phase-II scheme, send out all the hits from the detectors, make the L0 trigger decision in counting room.

• “Intelligent” on-detector trigger and readout electronics replaced by “stupid” data multiplexers and high bandwidth.
Trigger and DAQ

- Can use **commercial** (non radiation-hard) FPGAs or CPUs instead of hard-wired rad-hard coincidence logic → enable more **sophisticated** trigger algorithms

- MDT trigger **seeded** by RPC/TGC trigger candidates, to reduce required computing power

- On L0 trigger accept: all hit data are already available in counting room → direct transfer to DAQ system
Power System

- **HV/LV power distribution system** (CAEN EASY 3000 family) has been designed in 2000-05, qualified for radiation corresponding to 1500 fb⁻¹ (after safety factors update)

- **Aging + irradiation + obsolescence of components** (→ no more maintenance/repairs): very unlikely the system will survive until 2035-40

- Planning for **gradual replacement**, operating old+new components together for ~5 years (2025-30)

- Requires the new design to be as **backward-compatible** as reasonably achievable

### Inventory of the present muon power system

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<tr>
<th>CAEN module</th>
<th>Function</th>
<th>MDT</th>
<th>RPC</th>
<th>TGC</th>
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Total: 493 531 444 54 1522

Ch. Amelung

Upgrade of the ATLAS Muon System

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Installation

- Replacement of on-detector **trigger and readout electronics**: $O(1,000)$ components (CSM, Pad/Splitter, PS board) for each of MDT, RPC, TGC, *reasonably good access*

- Much more difficult is replacement of **MDT mezzanine cards**: $O(15,000)$ electronics cards

- Need 15–30 min per card, with **access** conditions ranging from **challenging** to **extremely demanding**

- Given "short" duration of LS3, most or all mezzanine cards have to be **replaced in situ**, without moving or removing chambers
Installation

Where are they???

Toroid coil

Mezzanine card covers

BIL
Summary

- For HL-LHC running, the **ATLAS muon system** needs to be **upgraded** in LS3
- Installation of new **RPCs**, including the **MDT in the trigger**, and replacement of some **TGCs** will improve the robustness and selectivity of the trigger
- All on- and off-detector **trigger and readout electronics** will be replaced, as well as all the MDT **mezzanine cards**
- The **power system** will be replaced
- This completes the upgrade program of the muon system that starts with the **New Small Wheels** upgrade in LS2

http://cds.cern.ch/record/2285580
Summary

- **ATLAS posters related to Muon Phase-I/II upgrades:**
  - **BIS78:**
    - Design and Construction of Integrated Small Diameter Drift Tube Chambers and Thin-Gap Resistive Plate Chambers for the Phase-I Upgrade of the ATLAS Muon Spectrometer – *H. Kroha*
  - **NSW:**
    - Small-Strip Thin Gap Chambers for the Muon Spectrometer Upgrade of the ATLAS Experiment – *R. Rojas*
    - Studies of the MicroMegas performances using INFN SM1 prototype with data recorded at the LNF cosmic ray test – *G. Mancini*
    - High Voltage Stability and Cleaning of 2 m² Resistive Strip Micromegas Detectors – *P. Massarotti*
    - Performance and Calibration of 2 m² Micromegas Detectors for the ATLAS Muon Spectrometer Upgrade – *G. Maniatis*
### Phase-II Trigger Menu

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<td>25,25</td>
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<td>65(2-tags)</td>
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<td>1066</td>
<td>338</td>
<td>10.4</td>
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† In Run 2, the 4-jet $b$-tag trigger operates below the efficiency plateau of the Level-1 trigger.

†† This is a place-holder for selections to be defined.

††† Assumes additional analysis specific requires at the Event Filter level.
Small Sector
Performance of New RPC

ABS 3.3 ≈ 10 kHz/cm²
RPC Trigger and Readout Scheme

ON-DETECTOR

BO RPC

DCT

BM RPC

DCT

BI RPC

DCT

TILE CALORIMETER

OFF-DETECTOR

FELIX

Barrel Sector Logic

MDT TRIGGER PROCESSOR

MuCTPi
TGC Trigger and Readout Scheme
Installation

- Detailed study of **in-situ** access to mezzanine cards (without moving chambers)

- **BIL** are most problematic, developed two scenarios:
  - Temporarily remove BIL chambers to **surface**
    Many other chambers need to be disconnected and moved out of the way → risk of damage
  - **In-situ** access to BIL, moving chambers ~80 cm along rails
    Physically challenging working conditions → risk of damage

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**BIS**: will be replaced by sMDT, are easier to move out

**"Easily" accessible**
- Requires temporary scaffolding or platform
- Doable but needs dedicated engineering study
- No idea how to access without moving chamber
Scenario 1: Temporarily Remove BIL

For removal of BIL chambers from the detector:
- Move EES sectors in azimuth to make space for BML
- Move BML 5,6 along beam line to make space for EIL4
- Move EIL4 radially and rotate to make space for BIL
Scenario 2: In-situ Access to BIL

- Even if BIL remain in the detector, it is necessary to slide BILs along rails to disconnect BIS services.
- To move BIL, all BIL services need to be disconnected.
- Some BIL mezzanine card (covers) are at least easily visible (top right picture), others are very difficult to get to (bottom right). Need to foresee modification of platforms, removal of some services: boxes, cables, pipes.

Tests have shown that in principle the space is marginally sufficient for the removal of old cards and replacement by new ones.
BIL RPC Installation

**Scenario 1:**
The same frame as for MDT installation can be adapted for the RPC

**Scenario 2:**
Space between EIL4 and BIL6 can be used for the insertion of the RPCs. Procedure of manipulations is complicated, access very difficult. We need to consider special tools to be ordered/designed/produced. One example of a similar tool shown in the picture.

Schematic view of the tool functions for the RPC installation in scenario 2.