Performance and Calibration of 2 m²-size 4-layered Micromegas Detectors for the ATLAS Upgrade

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LHC Upgrade Status

LHC / HL-LHC Plan

- 2011: 30 fb⁻¹
- 2013: 150 fb⁻¹
- 2024: 3000 fb⁻¹

- 2011: 7 TeV
- 2012: 8 TeV
- 2014: 13-14 TeV
- 2016: 2x \( \mathcal{L}_0 \)
- 2018: 5x \( \mathcal{L}_0 \)
- 2019: Injector upgrade
- 2021: LS2 14 TeV
- 2022: LS3 14 TeV
- 2024: HL-LHC installation

- Muon Detectors
- Tile Calorimeter
- Liquid Argon Calorimeter
- Toroid Magnets
- Solenoid Magnet
- SCT Tracker
- Pixel Detector
- TRT Tracker

Monitored Drift Tubes

- 30 mm Ø tubes:
  - Single tube
  - Chamber (2x4)

ATLAS NSW TDR
LHC / HL-LHC Plan

- Run 1: 7 TeV, 2011-2012, 30 fb⁻¹
- Run 2: 8 TeV, 2013-2014, 150 fb⁻¹
- Run 3: 13-14 TeV, 2015-2018, 2x L₀
- LS1: splice consolidation, button collimators, RIEE project
- LS2: EYETS, injector upgrade, cryo Point 4, Civil Eng., P1-P9
- LS3: cryogenic interaction regions, HL-LHC installation, 5 to 7 x nominal luminosity
- Run 4-5: >5 x L₀, 2021-2037, 3000 fb⁻¹

LHC Upgrade Status

- 2 m² & 4-layered Micromegas for ATLAS

M. Herrmann (LMU Munich)
Upgrade of the Muon Small Wheels

replacement of the current end caps of the muon spectrometer by small-strip Thin Gap Chambers (sTGC) and Micromegas quadruplets

New Small Wheel Sectors

Micromegas quadruplets
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New Small Wheel Sectors

Micromegas quadruplets
Micromegas Quadruplets for track reconstruction in the NSW

MICROMEGAS - MICROMEesh GAseous Structure

\[ \text{centroid} = \frac{\sum_{\text{strips}} \text{strip} \cdot q_{\text{strip}}}{\sum_{\text{strips}} q_{\text{strip}}} \]

\[ t_{\text{drift}} = f(\text{strip}) \]

⇒ position = centroid × pitch

⇒ incident angle reconstruction

4 active layers of Micromegas

⇒ 2 × back-to-back
Design of Readout Anodes

- **eta planes** for precision reconstruction in pseudorapidity direction perpendicular to anode strips
- **stereo planes** for additional coarse position information along the anode strips

**SM2 anode**

- Misalignment (exaggerated)
  - < 100 μm
  - 1.35 m

**Technical limitations**
- Micropattern readout anode: width ≤ 50 cm
  - ⇒ 3(/5) printed circuit boards (PCB) per active layer
  - ⇒ reconstruction and calibration of alignment errors (during production) required
SM2 Prototype - M0

Measurement Campaign

- Cosmic Ray Facility in Munich
- testbeam at H8 beamline at the SPS
Cosmic Ray Facility LMU Munich

**Micromegas**

- Upper trigger hodoscope
- Upper reference detector
  - $\sigma = 40 \, \mu m$
  - Reference track 1
- Lower reference detector
  - Reference track 2
  - $\sigma = 40 \, \mu m$
- Lower trigger hodoscope

**Track Prediction Accuracy Given by Multiple Scattering**

- Track reconstruction
- Trigger: 2 × Monitored Drift Tube chambers (MDTs)
- Active area: 2.2 m × 4 m
- Angular acceptance: $\pm \, 30^\circ$
- Readout: 12288 channels
  - $\rightarrow$ 96 APVs (frontend electronics)
  - $\rightarrow$ 6 FECs (scalable readout system)
- Readout rate: 130 Hz (full muon rate)
- Measurement period: 17.10. - 06.12. 2017
M0: Full Area Pulse Height

- $U_{\text{amp}} = 600 \text{ V}$
- $U_{\text{drift}} = -300 \text{ V}$
- Ar:CO$_2$ 93:7 vol%

- for each bin (54.4 mm × 100 mm):
  - cluster charge distribution fitted with Landau
  - Most Probable Value (MPV)

- differences between readout boards clearly visible
  - higher amplification for central board
  - homogeneity spoiled by prototype PCB quality

- smaller features due to trigger acceptance

- exponential rise as function of the amplification voltage (Townsend)

- differences between readout layers due to variation in prototype PCB quality
M0 : Full Area Efficiency

- $U_{\text{amp}} = 600 \, \text{V}$
- $U_{\text{drift}} = -300 \, \text{V}$
- Ar:CO$_2$ 93:7 vol%

- 5 mm efficiency:
  number of cluster found within ± 5 mm to reference track
divided by
number all tracks going through partition
⇒ calculated for each bin separately

- higher amplification of central board
  leads to higher efficiency

- efficiency at boarders spoiled due to tapered edges (rectangular partitions)

- efficiency turn on curve reaches more than 90% at 590 V for all layer

- differences between layer due to problematic prototype PCB material

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2 m$^2$ & 4-layered Micromegas for ATLAS
Alignment using Reference Tracks

Concept:

- Reference track detector
- Detector under study
- Perpendicular track
- Assumed position
- Measured position
- Residual

Implementation:

- Residual = pos_{measured} - pos_{reference}

⇒ Residual vs. slope (reference track)

⇒ Linear fit

\[ \text{shift}_{\text{horizontal}} = \text{intercept}_{\text{fit}} \]

\[ \text{shift}_{\text{vertical}} = \text{slope}_{\text{fit}} \]
Reconstruction of the Gravitational Sag of M0

eta in plane

⇒ all layers show gravitational sag
⇒ irrelevant for ATLAS, as detectors will be used vertically in NSW
position = centroid \times pitch

\text{pitch deviation}

\begin{align*}
\text{pitch} &= 425 \ \mu m \\
\text{pitch}_{\text{cor}} &= 425.12 \ \mu m
\end{align*}

\text{corrected pitch}

\begin{align*}
\text{pitch}_{\text{cor}} &= \text{pitch} \times (1 - \text{relative pitch deviation})
\end{align*}

construction equipment optimized
⇒ avoid shifts

humidity control of readout boards
⇒ avoid pitch deviation
H8 Testbeam for SM2 M0 in August 2017

**Beam eta out
eta in
stereo out
stereo in
\( \sigma_{\text{track}} = 65 \mu m \)

**Beam either muons or pions

**Trigger scintillators

**Tracking telescope:

- \( 3 \times 2D \text{ GEM} \)
- \( 2 \times 2D \text{ TMM} \)

**Track accuracy:** 65 \( \mu m \) (extrapolated at module)

**Channels:**
- \( 4 \times 1024 \)
- 2976

**Readout:**
- 32 APVs \( \rightarrow \) 2 FECs module
- 24 APVs \( \rightarrow \) 2 FECs telescope

**Trigger rate:** \( \sim 1 \text{ kHz (muons)} \)

**Readout rate:** 220 Hz

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M0 : Behavior of Pulse Height and Efficiency

- pulse height:
  exponential rise as function of the amplification voltage (Townsend)
- differences between layers due to variation in prototype PCB quality
- efficiency plateau starting at 590 V
- lower efficiency due to unconnected strips in measurement region (e.g. eta out plane)
M0 : Results for Charge Weighted Position Reconstruction

- residual distribution (difference of measured position and track prediction) fitted with double Gaussian

\[ \Rightarrow \text{weighted sigma:} \]
\[ \sigma_w = \frac{l_{\text{narrow}} \cdot \sigma_{\text{narrow}} + l_{\text{broad}} \cdot \sigma_{\text{broad}}}{l_{\text{narrow}} + l_{\text{broad}}} \]

\[ \Rightarrow \text{consider track uncertainty:} \]
\[ \sigma_{\text{res}} = \sqrt{\sigma_w^2 - \sigma_{\text{Track}}^2} \]

- resolution for perpendicular incident for both eta layers similar

\[ \Rightarrow 80 \ \mu m \]

- resolution independent of amplification and drift voltage
- Drift time measurement enables reconstruction of inclined tracks: time-projection-chamber like
- Inhomogeneous ionization leads to a timing dependence of the residual
- Degradation of resolution for inclined incident using charge weighted reconstruction only
  ⇒ Similar behavior as small size chambers
- Charge weighted timing correction improves resolution considerably
  ⇒ Almost constant for angles \( \leq 30^\circ \)
- Resolution limited by signal to noise ratio of APV readout
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charge weighted timing correction improves resolution considerably

⇒ almost constant for angles ≤ 30°

resolution limited by signal to noise ratio of APV readout
Summary

- Upgrade of the ATLAS muon spectrometer inner end cap
  - sTGC and Micromegas quadruplets (16 active layers in total)
  - Threepart (/fivepart) readout structure
    ⇒ reconstruction and calibration is required after construction

- Investigation of the SM2 Prototype (M0) at the Cosmic Ray Facility in Munich
  - Full active area responsive, despite problematic prototype PCB quality
  - Calibration of the full active area of SM2 demonstrated

- Measurement at H8 Beamline of the SPS with the SM2 M0
  - Reasonable pulse height and efficiency behavior
  - Charge weighted position reconstruction for perpendicular tracks
    ⇒ 80 µm resolution
    ⇒ Same for both eta layers
    ⇒ Independent of drift and amplification voltage
  - Drift time measurement for tracks with ≤ 30° inclination
    ⇒ Similar resolution
    ⇒ Limitation by signal to noise ratio of APV electronics
      (final electronics currently under test with first series SM2 module at H8)
Backup
Time Evolution of the Signal on a Single Strip

Beginning of the signal: fit by an inverse Fermi function

\[ f_{\text{Fermi}} = \frac{p_0}{1 + \exp[(p_1 - x)/p_2]} + p_3 \]

- \( p_0 \): maximal pulse height \( \Rightarrow \) charge of signal
- \( p_1 \): time of 50% maximal pulse height
- \( p_2 \): \( \propto \) rise time
- \( p_3 \): pedestal

\( \Rightarrow \) 3 values of \( f_{\text{Fermi}} \) at 10%, 50% and 90% define start time of signal by extrapolation
Position and Track Reconstruction

- **centroid method**
  \[ x_{\text{centroid}} = \frac{\sum x_{\text{strip}} \cdot q_{\text{strip}}}{\sum q_{\text{strip}}} \]

- **TPC-like method**
  angle reconstruction by drift time measurement
  \[ \alpha = \arctan \left( \frac{\text{pitch}}{\text{slope}_{\text{fit}} \cdot v_{\text{drift}}} \right) \]
Position Reconstruction Using Charge Weighted Clustertime

- charge weighted timing:
  \[ t_q = \frac{\sum t_{\text{strip}} q_{\text{strip}}}{\sum q_{\text{strip}}} \]
  \[ \Rightarrow \text{vertical position in drift gap} \]

- for inclined incident:
  centroid residual
  VS charge weighted timing
  \[ \Rightarrow \text{linear dependence} \]

- slope given by
  drift time and incident angle
  \[ \Rightarrow \text{drift time is given by gas mixture, cathode voltage and drift gap} \]
  \[ \Rightarrow \text{for NSW Micromegas incident angle is almost fixed} \]
  (direction to interaction point)

- new position is given by:
  \[ x = x_{\text{cen}} + \Delta t \cdot v_{\text{drift}} \cdot \tan \theta \]
  with:
  \[ x_{\text{cen}} \] centroid position
  \[ \Delta t \] \[ t_q - t_{\text{mean}} \]
  \[ v_{\text{drift}} \] drift velocity
  \[ \theta \] incident angle
SM2-M0 at H8 Testbeam August 2017 Measurement Overview

- for second configuration the order of layers was inverted
- at Points 12 and 13 module was tilted for inclined measurements
- several amplification scans made at different Points
expected time jitter of signal due to 40 MHz sampling of APVs

- record time difference of trigger signal and FEC cards (connected to APVs) via TDC
- merge at DAQ PC
  ⇒ offline offset correction and zerosuppression