Muon Isolation Optimisation Studies for Run-3 in ATLAS

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Qualification Task Overview

Title: Muon Isolation Optimisation with the Run-3 dataset

- Qualification task performed within the **ATLAS Muon Combined Performance (MCP)** group.
- Main topic of this project:
  - optimisation of **muon isolation working points (WPs)**
  - study of efficiency and rejection performance in **Run-3**
- Focus on the dependence of isolation on:
  - muon transverse momentum p_T and angular distance to the closest jet, $\Delta R(\mu, \text{jet})$

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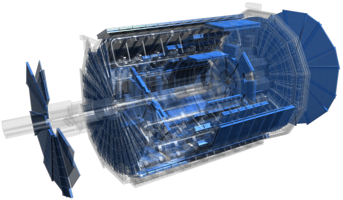
OTP task ID: 532774 **sub-task ID:** 556633

Motivation

- Muon isolation is a key tool in ATLAS analyses.
- It helps distinguish:
  - **prompt muons** from electroweak processes
  - **non-prompt / fake muons** from heavy-flavour decays or jets
- Well-optimised isolation WPs are essential for:
  - precision measurements
  - Standard Model analyses
  - searches for new physics
- In Run-3 conditions, a refined optimisation is needed due to:
  - updated detector and reconstruction conditions
  - higher pile-up
  - more challenging event topologies



Why Study Isolation vs Nearby Jets?

- Standard isolation definitions are mainly parametrised as a function of muon momentum.
- However, the performance also depends strongly on the local event environment.
- A particularly relevant variable is the distance between the muon and the closest jet:

$$\Delta R(\mu, \text{jet}) = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

- Small $\Delta R(\mu, \text{jet})$ can indicate:
  - heavy-flavour origin
  - nearby hadronic activity
  - higher probability of failing isolation
- This makes $\Delta R(\mu, \text{jet})$ a natural variable for WP optimisation.

Main idea

Study isolation efficiency and rejection power as a function of both p_T and $\Delta R(\mu, \text{jet})$.

Main Objectives of the Project

1. Study the behaviour of current muon isolation working points in Run-3 Monte Carlo samples.
2. Evaluate isolation efficiencies for:
   - prompt muons
   - non-prompt / heavy-flavour muons
3. Investigate the dependence of isolation performance on:
   - p_T
   - $\Delta R(\mu, \mathrm{jet})$
4. Assess possible:
   - process dependence
   - MC generator dependence
   - topology dependence
5. Provide inputs toward improved or optimised isolation WP recommendations for Run-3.

Physics Strategy

- Prompt muons are typically selected from:
  - $Z \to \mu\mu$ events
- Non-prompt / heavy-flavour muons are studied using:
  - $t\bar{t}$ events
- The comparison between these two topologies allows us to evaluate:
  - isolation efficiency for genuine signal-like muons
  - rejection of muons from heavy-flavour sources

Prompt sample: $Z \to \mu\mu$

Non-prompt sample: $t\bar{t}$

Baseline idea: good isolation WP should keep high efficiency for prompt muons while suppressing heavy-flavour and fake muons.

Samples and Data-taking Configurations

- The first studies are based on Run-3 Monte Carlo samples.
- Main categories used in the analysis:
  - $Z \rightarrow \mu\mu$ samples for prompt muons
  - $t\bar{t}$ samples for heavy-flavour muons
- The project is intended to cover the last two years of Run-3 data-taking.
- Different MC configurations can be compared to test generator and topology dependence.

Examples of targeted studies

- 2022-like and 2023-like MC setups
- comparison among MC23a, MC23d, MC23e where relevant
- stability of efficiencies across periods and processes

Analysis Workflow

1. Read Run-3 xAOD / DAOD inputs.
2. Reconstruct and select muons with standard quality requirements.
3. Apply baseline identification and TTVA selections.
4. Evaluate isolation working points.
5. Match muons to truth information whenever relevant.
6. Classify muons into prompt and heavy-flavour categories.
7. Build efficiency plots as a function of:
   - p_T
   - η
   - $\Delta R(\mu, \text{jet})$
8. Compare performance across processes and MC setups.

Tools Used in the Study

- **Standard ATLAS software environment.**
- **Simplified analysis tools:** `fastMuonChecker`.
- **Standard muon tools:** muon selection – calibration – isolation evaluation – scale factors – trigger matching.
- **ROOT used for:** ntuple inspection – histogram production – efficiency plots – comparison between samples.

> The work is expected to rely on standard tools used by the MCP and Isolation/Fake Forum groups, with improvements made available to the collaboration.

Muon Isolation Working Points

- Isolation working points are designed to quantify the activity around a muon.
- The goal is to select muons consistent with isolated prompt production.
- Typical working points include:
  - **Loose**
  - **Tight**
- Their performance is usually expressed through:
  - efficiency for prompt muons
  - rejection of heavy-flavour and fake muons

Optimisation principle

A good WP should maximise prompt-muon efficiency while maintaining strong rejection against non-prompt backgrounds.

Key Observables for This Study

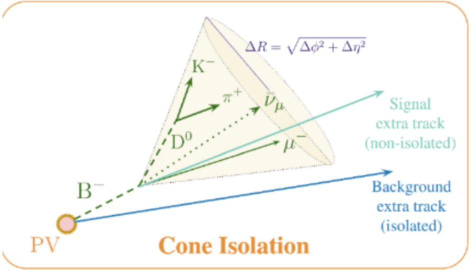
- **Muon transverse momentum:** p_T^μ
- **Muon pseudorapidity:** η^μ
- **Distance to closest jet:**

$$\Delta R(\mu, \text{jet})$$

- **Isolation efficiency:**

$$\epsilon_{\text{iso}} = \frac{N(\text{muons passing isolation})}{N(\text{selected muons})}$$

- Comparison between:
  - prompt resonance muons
  - heavy-flavour muons



Samples Used for the First Validation

- The first validation studies were performed using Monte Carlo samples processed with the `fastMuonChecker` workflow.
- The main samples used so far are:
  - **Pythia** $Z \to \mu\mu$
  - **Sherpa** $Z \to \mu\mu$
- These samples were used to compare the main reconstructed kinematic distributions:
  - invariant mass $m_{\mu\mu}$
  - muon pseudorapidity η^{μ}
  - muon transverse momentum p_T^{μ}
  - distance to the closest jet $\Delta R(\mu, \text{jet})$
- This corresponds to the first step of the qualification task: validating the analysis chain and checking the agreement of basic observables.

At this stage, the goal is not yet a full optimisation, but rather a first validation of the workflow and of the distributions obtained from the available MC samples.

Samples Targeted in the Qualification Task

- The full qualification task is intended to study muon isolation performance using Run-3 Monte Carlo samples.
- The target comparison includes several MC generators, in particular:
  - **Pythia**
  - **Herwig**
  - **Sherpa**
- The purpose is to evaluate possible generator dependence in the isolation-related observables and efficiencies.
- These studies will be extended to the samples and configurations relevant for the official task.

Main idea

The current results are a first step toward the generator comparison required for the qualification project.

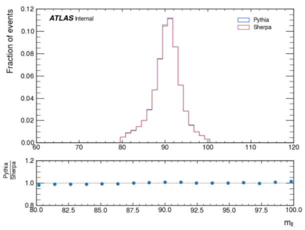
Small Technical Adjustments in `fastMuonChecker`

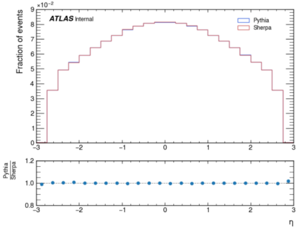
- A few light modifications were introduced in `fastMuonChecker.py` for these first studies.
- In particular, the workflow was adapted to:
  - inspect the selected muon content more easily
  - produce the variables needed for the first validation plots
  - facilitate the comparison between different MC samples
- These changes were technical and limited in scope.
- The overall goal remained the same: to validate the analysis chain before moving to the full isolation study.

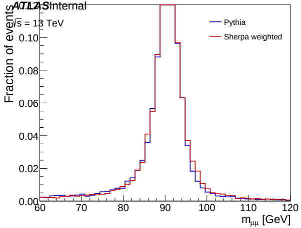
> Only small practical adjustments were made for the first checks; no major change in the physics strategy was introduced at this stage.

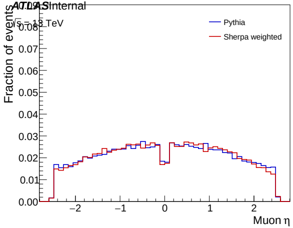
Comparison with ATLAS Note: $m_{\mu\mu}$ and η

NB: Upper plots: ATLAS note — Lower plots: My work.



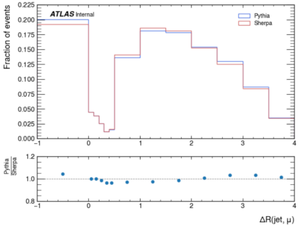


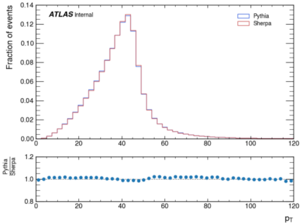


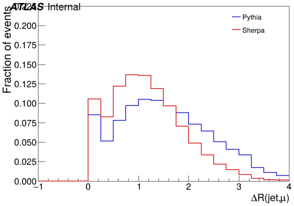


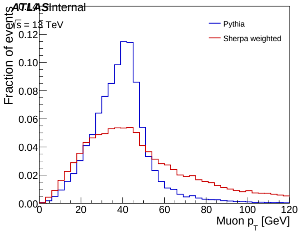
Comparison with ATLAS Note: $\Delta R(\mu, \text{jet})$ and p_T^{μ}

NB: Upper plots: ATLAS note — Lower plots: My work.



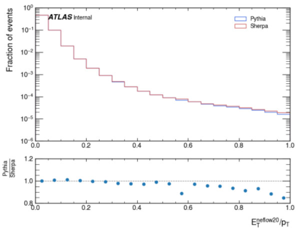


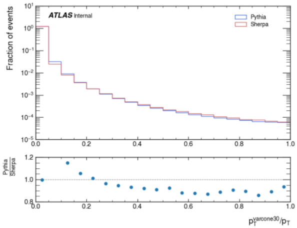


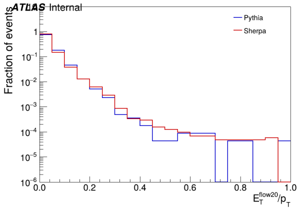


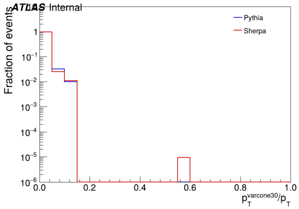
Comparison with ATLAS Note: $E_T^{\text{cone20}} / p_T$ and $p_T^{\text{varcone30}} / p_T$

NB: Upper plots: ATLAS note — Lower plots: My work.









Ongoing Work and Next Step

- I am still looking for the appropriate Run-3 samples for the:
  - **Pythia**
  - **Herwig**
  - **Sherpa**

  generators.
- These samples are needed in order to reproduce and extend the comparison plots in a way fully aligned with the qualification task.
- The next step is to use these Run-3 samples to produce the corresponding plots and continue the generator comparison.
- After that, the study will be extended toward the isolation-related observables and efficiencies.

Current status: first validation completed with available samples; Run-3 generator-specific samples are still being collected for the next stage of the study.

What We Expect to Learn

- How efficient the current isolation WPs are for prompt muons in Run-3.
- How strongly heavy-flavour muons are rejected.
- Whether the WP performance changes significantly when a jet is close to the muon.
- Whether different MC generators or event topologies modify the conclusions.
- Which phase-space regions are most relevant for future optimisation.

Long-term goal: contribute to the derivation of MCP recommendations for muon isolation in the full Run-3 dataset.

Organisation of the Qualification Task

- The work is expected to be carried out within:
  - the **Isolation and Fake Forum subgroup**
  - with feedback from the **Efficiency subgroup**
- Regular updates and presentations are expected at:
  - subgroup meetings
  - MCP plenary meetings
- Results, methods, and improvements are expected to be documented for the collaboration.

Tagged coordinators

Matteo Bauce as IFF coordinator for muons
Luca Martinelli for MCP

Expected Deliverables

- Validation plots for current isolation working points.
- Efficiency and rejection studies versus:
  - p_T
  - η
  - $\Delta R(\mu, \mathrm{jet})$
- Comparisons across processes and MC generators.
- Recommendations for possible WP optimisation.
- Internal documentation and supporting notes.
- Presentations to the ATLAS MCP community.

Planned Work Schedule

1. Familiarisation with existing isolation definitions and MCP tools.
2. Production of baseline performance plots in standard samples.
3. Study of the dependence on nearby jet activity.
4. Comparison across topologies and MC generators.
5. Development of optimisation ideas.
6. Validation and discussion within the subgroup.
7. Documentation and final recommendations.

Proposed beginning of qualification: 01/02/2026

Conclusion

- Muon isolation is a central ingredient in ATLAS physics analyses.
- Run-3 motivates a renewed study of isolation performance under updated detector and event conditions.
- This qualification project focuses on the optimisation of isolation WPs as a function of:
  - muon momentum
  - proximity to jets
- The expected outcome is a better understanding of current WP limitations and possible improvements toward future MCP recommendations.

Thank you for your attention!

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