Development of a New First-Level Trigger for Isolated Muons at the ATLAS Experiment

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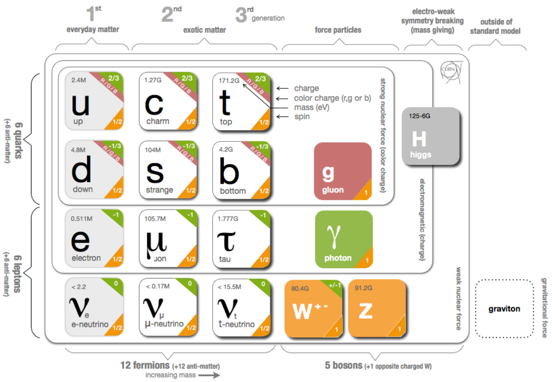
Introduction & Motivation

- The LHC collides high-energy protons at high rates.
- The ATLAS detector records many relevant variables from these collisions.
- Huge data volume generated requires a Trigger System to select interesting events.
- Moreover, HL-LHC upgrade will increase data significantly $\rightarrow$ Trigger must keep improving
- This thesis aims to optimize the Level-1 Trigger to better identify prompt muons.

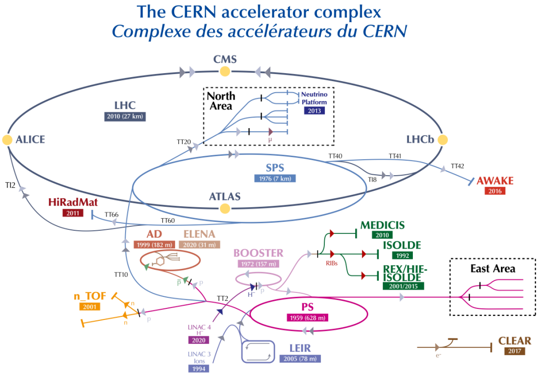
Theoretical Background

- **Elementary particles** interact with each other via **fundamental interactions** mediated by the exchange of **force carriers**



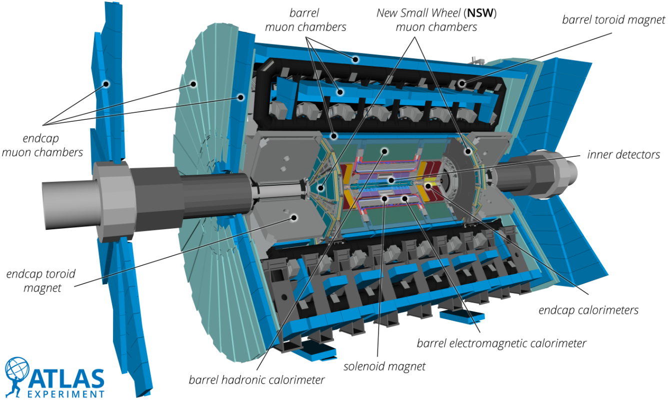
The LHC Accelerator

- Protons are **pre-accelerated** in smaller accelerators.
- Two beams circulate in **opposite directions** inside a 26.7 km ring.
- Beams are guided and focused using **superconducting magnets**.
- Collisions up to **13.6 TeV** center-of-mass energy at 4 interaction points (e.g., **ATLAS** detector).



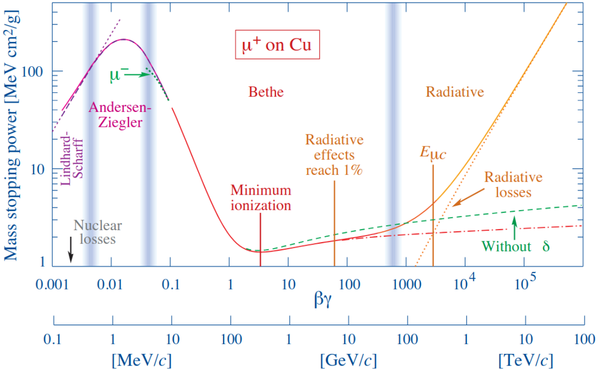
The ATLAS Detector I

- Reconstructs particle **energy, momentum, charge, and trajectories**.
- **Main subsystems**: Inner Detector, Calorimeter & Muon Spectrometer



The ATLAS Detector II

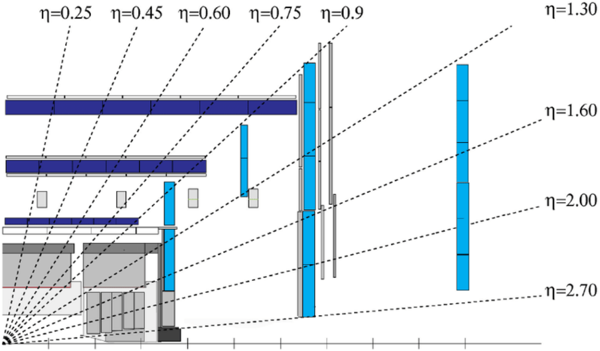
- **Inner Detector:** Tracks charged particles inside a magnetic field. Measures momentum from trajectory curvature.
- **Calorimeters:** Absorbs particles to measure energy.
- **Muon Spectrometer:** Detects muons after they pass through other subsystems. Uses gas chambers and magnetic fields for precise tracking.



Coordinate System & Kinematic Variables I

- Coordinates:
  - Cylindrical **z** and **azimuth angle** ϕ
  - **Pseudorapidity** (η): preferred over θ, approximately Lorentz-invariant:

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



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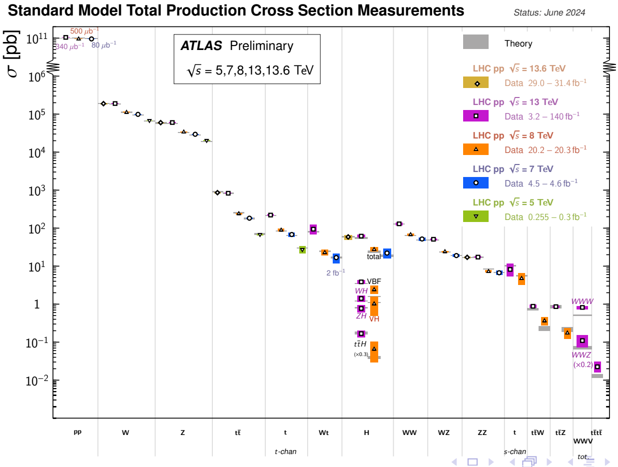
Coordinate system & Kinematic Variables II

Other variables

- **Transverse momentum (p_T)**: pp collisions involve **partons** with **unknown momentum along** z**, but known** p_T.
- **Angular distance:** $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$

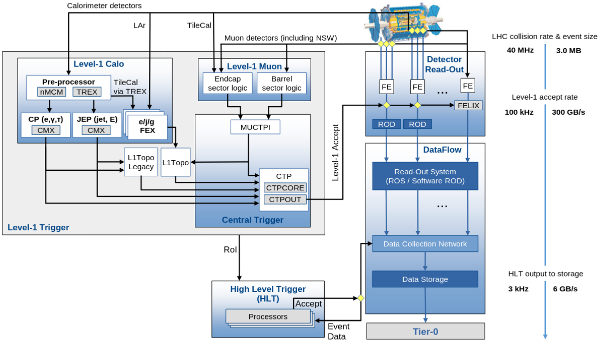
ATLAS Trigger System I

- ATLAS observes **40 million collisions per second**, corresponding to **more than 60 TB/s** of data.
- Most events are common and already well-studied.



ATLAS Trigger System II

- The ATLAS Trigger System **reduces the data rate to 3 kHz**, by selecting only *interesting* events.
- Two main parts:
    - **Level-1 Trigger**: Hardware-based, decision in $< 2.5\,\mu\text{s}$.
    - **High-Level Trigger (HLT)**: Software-based, slower full event reconstruction.



ATLAS Trigger System III

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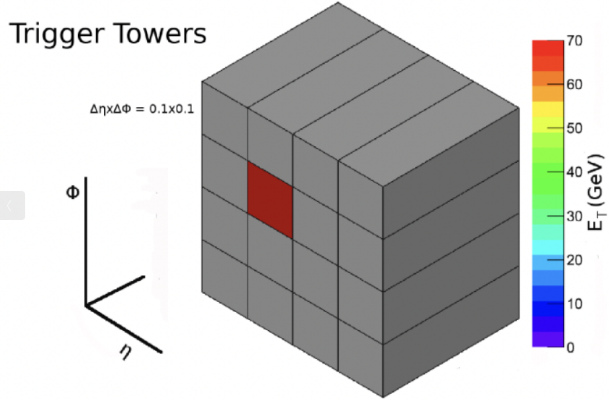
ATLAS Trigger System IV

- **L1Calo**: Detects high-energy jets, electrons and taus via calorimeter data.
  - **jFEX module**: Real-time jet detection and energy sums (7680 calorimeter towers, or *pixels*).



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ATLAS Trigger System V

- Muons penetrate through inner detectors and calorimeters.
- **L1Muon**: Detects muons via hits in spectrometer chambers. It checks for sequences of hits in multiple spectrometer layers.
- **Coincidence windows** used to determine p_T thresholds.

CTP: Combines all L1 info to make final decision.

Methodology & Results

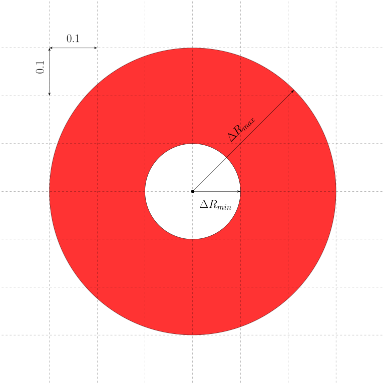
Goal: Improve Level-1 Muon Trigger

Goal and strategy

- Distinguish **prompt muons** (from the primary $p-p$ interaction) from **non-prompt muons** (produced in-flight by hadron decays).
- How? Comparing calorimeter-based **isolation energies** from promp and non-prompt muons.
- Why? **Jets surrounding non-prompt muons** may help to discriminate

Muon Isolation

- Construct a **hollow cone** around the muon impact point
- **Sum the energies** of all calorimeter towers whose centers lie **inside the cone**.
- Result = *isolation energy* (E_{iso}).



$$\Delta\eta \times \Delta\phi = 0.1 \times 0.1$$

Dataset Overview

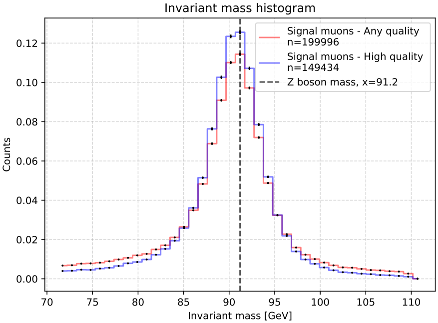
- **Data source:** ATLAS Run 3 (offline+online objects).
  - *Online objects*: reconstructed in **real time** by the trigger.
  - *Offline objects*: reconstructed **after** data-taking → used to **mimic Run 4** trigger performance
- **Samples:**
  1. $Z \to \mu^- \mu^+$: predominantly **prompt muons**.
  2. **ZeroBias**: enriched in **non-prompt muons**
- **Pre-selections** must be applied

Pre-selections on $Z \to \mu\mu$ events I

- **To fire the Trigger**
  - **Kinematics**
    - Leading muon $p_T \geq 25\,\mathrm{GeV}$
    - Sub-leading muon $p_T \geq 20\,\mathrm{GeV}$
  - **Isolation**: both muons satisfy a track-based isolation cut.
  - **Invariant-mass window**: $70 < m_{\mu\mu} < 110\,\mathrm{GeV}$ (close to Z mass).

Pre-selections on $Z \to \mu\mu$ events II

- **Z mass selection**
  - For events with > 2 muons, compute $m_{\mu\mu}$ for every possible pair.
  - Keep the pair closest to 91.2 GeV.
- Only muons with `Quality = 0` (highest reconstruction standards)

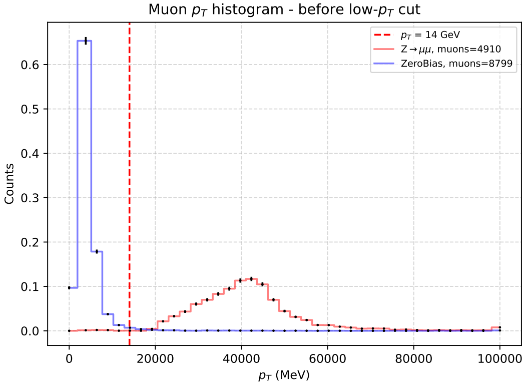


Pre-selections on ZeroBias events I

- **ZeroBias trigger**
  - Random events (no physics-specific selection).
  - Dominated by **non-prompt muons**, ideal for background studies.

Pre-selections on ZeroBias events II

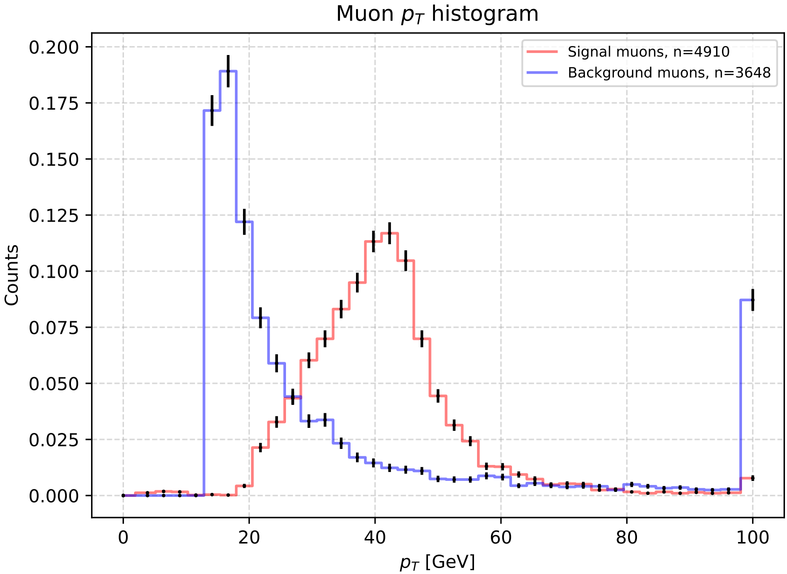
- **Online–Offline matching**: Offline muons are kept only if they are close to an online muon ($\Delta R < 0.4$).
- **Low-p_T cut**: Discard ZeroBias muons with $p_T < 14\,\text{GeV}$, to make the background p_T spectrum comparable to the $Z \to \mu\mu$ sample.



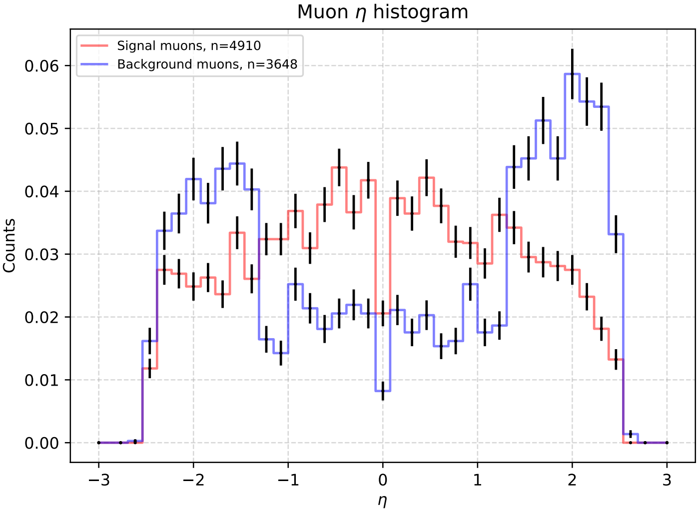
Samples after pre-selections I

- **Signal sample**
  - Derived from the original $Z \rightarrow \mu^- \mu^+$ dataset.
  - Expected to contain a high fraction of **prompt muons**.
- **Background sample**
  - Obtained from the original ZeroBias dataset.
  - Dominated by **non-prompt muons**.

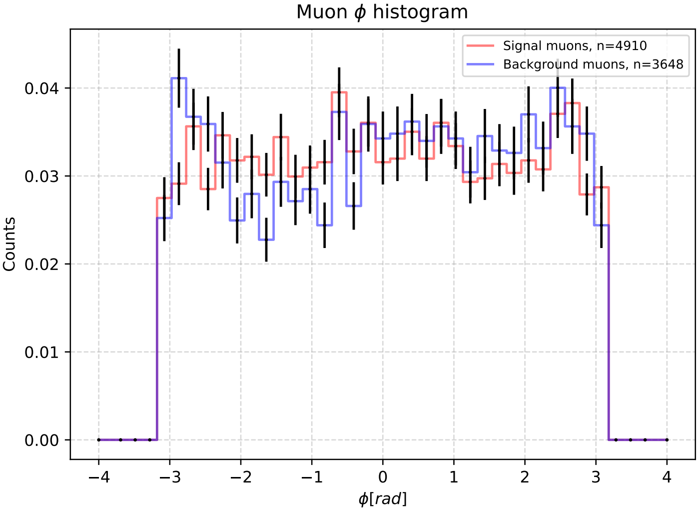
Samples after pre-selections II



Samples after pre-selections III



Samples after pre-selections IV



Calorimeter noise cuts I

Noise sources

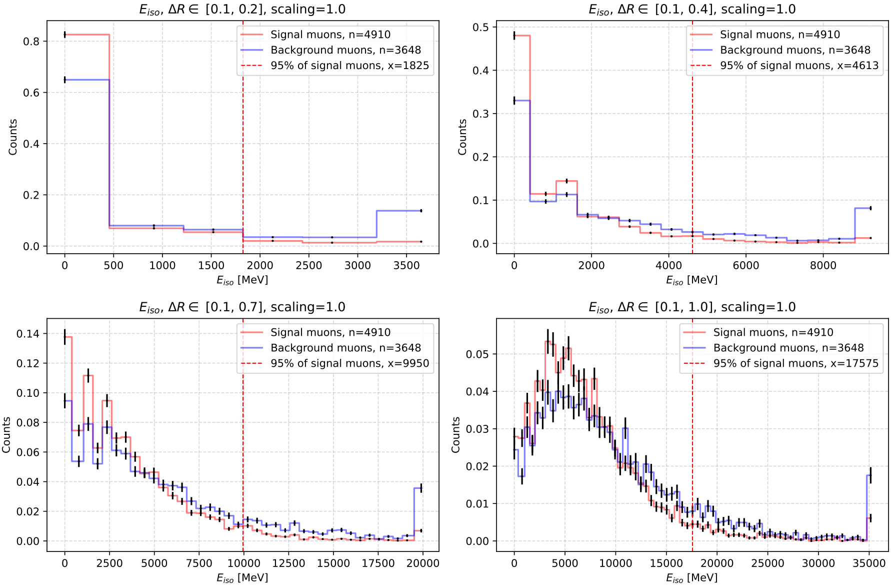
- **Detector noise**: fluctuations in electronic read-out / sensor imperfections
- **Pile-up**: simultaneous interactions may overlap in the detector.

- **Strategy**
  - Apply a *minimum-energy threshold* to each calorimeter tower.
  - Thresholds depend on tower type and η position
  - Towers with energy below the threshold are set to zero (treated as noise).

Calorimeter noise cuts II

η Interval	EM Noise Cuts [MeV]	HAD Noise Cuts [MeV]
(0, 0.1]	1150	0
[0.1, 0.2]	1150	0
[0.2, 0.3]	1200	0
[0.3, 0.4]	1150	0
[0.4, 0.5]	1100	0
[0.5, 0.6]	1100	0
[0.6, 0.7]	1050	0
[0.7, 0.8]	1050	0
[0.8, 0.9]	1000	0
[0.9, 1.0]	1000	0
[1.0, 1.1]	950	0
[1.1, 1.2]	950	0
[1.2, 1.3]	900	0
[1.3, 1.4]	850	0
[1.4, 1.5]	1300	500
[1.5, 1.6]	1150	950
[1.6, 1.7]	1050	850
[1.7, 1.8]	1000	700
[1.8, 1.9]	1050	750
[1.9, 2.0]	950	700
[2.0, 2.1]	950	650
[2.1, 2.2]	900	650
[2.2, 2.3]	850	600
[2.3, 2.4]	900	550
[2.4, 2.5]	800	1300
[2.5, 2.7]	2150	1250
[2.7, 2.9]	2000	1150
[2.9, 3.1]	1800	350
[3.1, ∞)	1100	0

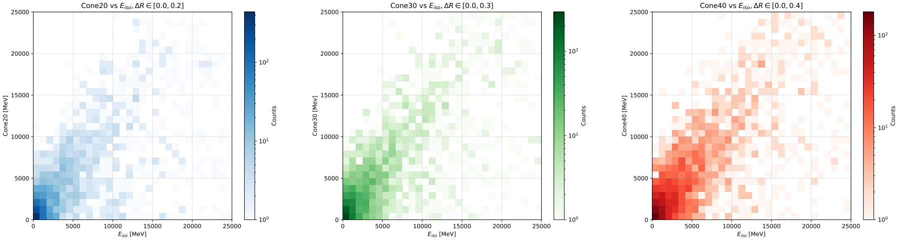
Isolation energy vs. ΔR cone I



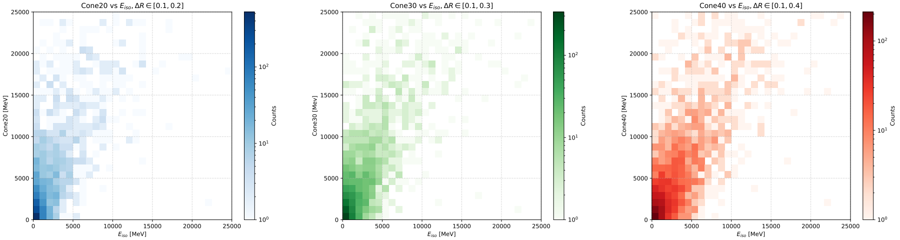
Isolation energy vs. ΔR cone II

- *TopoEtCones* are fancier isolation quantities used in ATLAS reconstruction.
- **Impossible to compute** them in real time.
- We employ an isolation that acts as an **approximation** of the TopoEtCones.
- As a sanity check we compare the two.

Isolation energy vs. ΔR cone III



Isolation energy vs. ΔR cone IV



ROC curves I

ROC curve

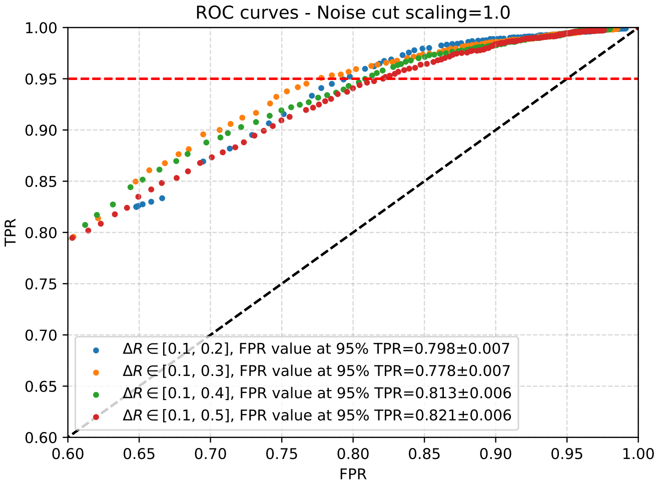
A **ROC curve** visualizes the trade-off between **signal efficiency** and **background contamination**.

- **x-axis**: FPR: fraction of background muons that pass the selection (trigger rate).
- **y-axis**: TPR: fraction prompt muons correctly identified (trigger efficiency).

ROC curves II

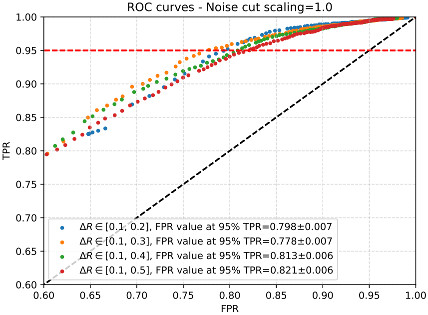
Goal

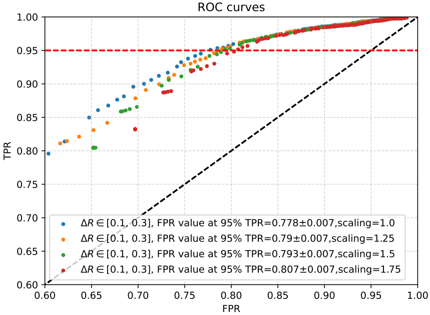
Find the ΔR cone that yields the lowest FPR value at $\text{TPR} = 0.95$



Two-variable optimization I

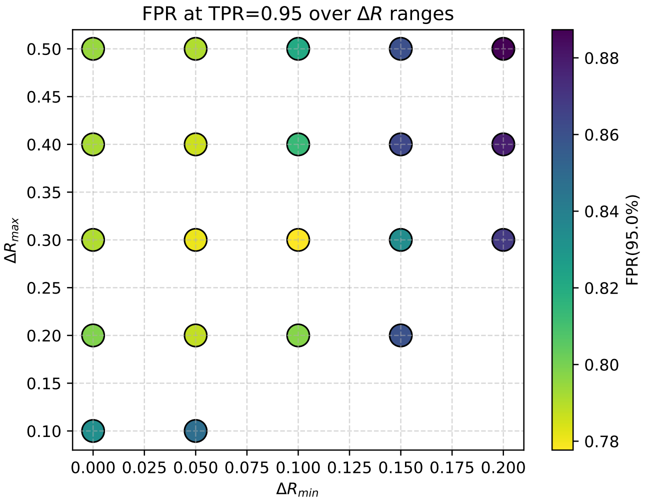
- FPR(95%)depends on two parameters: ΔR_{min} and $\Delta R_{\max}$
- Hard to tell which is best





Two-variable optimization II

- Solution: use a grid displaying FPR at TPR=0.95 values



Two-variable optimization III

1. **Hollow cones are superior.**
   - Best region clusters around $\Delta R_{\text{min}} \approx 0.1$
2. **Too large ΔR_{min} is bad.**
   - Potentially excludes part of the jet surrounding a non-prompt muon, which locates around the center
3. **Optimal outer radius.**
   - With $\Delta R_{\text{min}} \approx 0.1$, the minimum FPR(95%) occurs near $\Delta R_{\text{max}} \approx 0.3$.
   - Extending the cone beyond 0.3 incorporates additional noise without capturing extra jet activity.

Summary & Conclusions

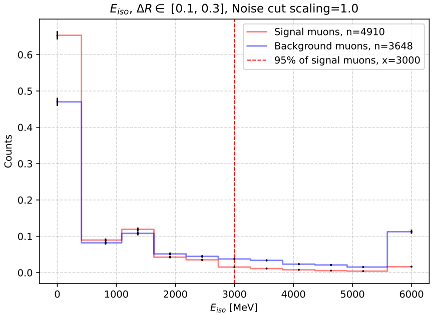
Summary & Conclusions I

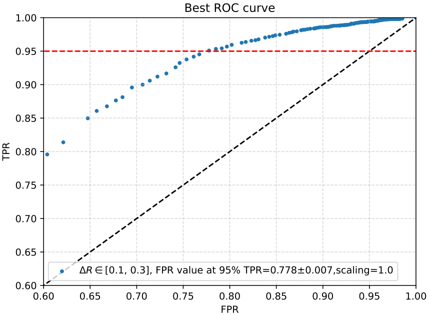
- ATLAS records events at $\mathcal{O}(40\text{MHz})$; the trigger must decide within a few µs.
- Muons are excellent signatures of rare processes (e.g. $Z \to \mu^+\mu^-$, $W \to \mu\nu$).
- Goal: improve prompt-muon vs. non-prompt-muon.

Key result

- Optimal isolation cone: $\Delta R \in [0.1,\, 0.3]$.
- Achieved $\text{FPR}(95\%) = 0.778 \pm 0.07$, i.e. a $\sim 22\%$ reduction in trigger rate for only a 5% loss in efficiency.

Summary & Conlcusions II





Future work & improvements

1. **Integration into the real Muon Trigger**
   This was just a proof-of-concept, not tested in the real world
2. **Low-p_T muon regime**
   Extend the study to $p_T < 20\,\mathrm{GeV}$ muons; evaluate whether the same ΔR window remains optimal.
3. **Other physics processes**
   Test the method on other muon-producing decays, such as $W \rightarrow \mu\nu$.

References I

Figures without reference are properly referenced in the *Bibliography* section of my thesis.

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- Alessandra Betti, https://www.mdpi.com/2410-390X/6/3/37

Thanks

Thank you!