Muon identification and performance in the ATLAS experiment

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Muon Identification in ATLAS

- Two systems
- Inner Detector ID Tracker
  - Solenoidal B field (bends in phi, xy)
- Muon System MS
  - Toroidal B field (bends in theta, rz)

- Muons can be identified combining detectors
  - ID track – Calorimeter deposits
  - MS track
  - These two are fully independent

- ATLAS exploits different strategies – detector combinations - for muon identification.
Muon Identification

- Muon Spectrometer reconstruction
  - Segments (straight line track in MS station)
  - Standalone MS track (fitting segments)

- Standalone muons based on MS

- Tagged muons based on ID track “inside-out”
  - Matched with MS segment
  - Matched with Calorimeter deposits

- Combined Muons i.e. MS & ID
  - Fit ID track with MS track
  - Inside-out ID track – MS hits – MS segments – fit ID & MS hits
Physics with muons: working points

- **Loose**: Maximize reconstruction efficiency; uses all muon types
- **Medium**: Default selection for ATLAS; uses CB & MS muons
- **Tight**: Maximize purity; uses only CB & MS muons
- **Low-pT**: Maximize efficiency and fake-rejection for \( p_T < 5 \) GeV
- **High-pT**: Maximize momentum resolution for \( p_T > 100 \) GeV

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**Loose**

**Higgs \( \rightarrow 4\ell \)**

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**High-pT**

**Z’ \( \rightarrow \mu\mu \) search**

arXiv 1903.06248v2

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Efficiencies for muons: Z tag and probe

Use high-statistics samples of $Z \rightarrow \mu\mu$

- Tag: Medium muon that fires the trigger
- Probe: e.g Calo-Tagged muon; mass $Z$
- Check Probe side if Loose, Medium, Tight, low-pT, high-pT muon (not Calo-Tagged) is found
- This gives efficiency $\varepsilon(\muon|\ID)$

- The ID tracking efficiency $\varepsilon(\ID)$ can also be measured using MS probes
- The full $\varepsilon(\muon)$ equals $\varepsilon(\ID) \varepsilon(\muon|\ID)$
Muon efficiencies: Z tag and probe

- Efficiency > 98% for medium \(|\eta|>0.1\) data/MC within 1-2%
- Calorimeter muons recover \(|\eta|<0.1\) systematics < 0.5%

**Graph 1:**
- Data 2018 • MC
- Tight muons
- Medium muons
- Loose muons

**Graph 2:**
- Data 2018
- MC
- ATLAS Preliminary
- \(\sqrt{s} = 13\) TeV, 59.9 fb\(^{-1}\)
- \(p_T>10\) GeV
- \(0.1<|\eta|<2.5\)

**Graph 3:**
- Data 2018
- MC
- ATLAS Preliminary
- \(\sqrt{s} = 13\) TeV, 59.9 fb\(^{-1}\)
- Medium muons
- 0.1<|\eta|<2.5

**Graph 4:**
- Data 2018
- MC
- ATLAS Preliminary
- \(\sqrt{s} = 13\) TeV, 59.9 fb\(^{-1}\)
- \(\eta\) systematics < 0.5%

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Muon momentum scale and resolution

- **Scale:**  
  \[ p_T' - p_T = \Delta s_0 + \Delta s_1 p_T \]
  - \( \Delta s_0 \): Energy loss in Calorimeter and Muon system
  - \( \Delta s_1 \): B field and radial distortions

- **Resolution:**  
  \[ \sigma'^2 - \sigma^2 = \left( \frac{\Delta p_0}{p_T} \right)^2 + \Delta p_1^2 + (\Delta p_2 p_T)^2 \]
  - \( \Delta p_0 \): Energy loss fluctuations
  - \( \Delta p_1 \): multiple scattering (B field and radial distortions)
  - \( \Delta p_2 \): detector resolution and misalignments

Use Z and J/ψ samples to measure scale and resolution in the Inner detector and Muon system

- **Z:**  
  \( p_T \) 10-200 GeV
- **J/ψ:**  
  \( p_T \) 3-25 GeV
- **Y:**  
  \( p_T \) 5-50 GeV
Muon momentum scale and efficiencies

- scale systematics: 0.1-0.2%
- resolution data/MC 5-10%
- Validation of the results on the Upsilon (2019)

Muon isolation efficiencies and pile up

- The efficiency of different muon isolation algorithms can be measured by Z tag and probe
  - FixedCut: $\Sigma E$ calorimeter or $\Sigma p$ track in a cone
  - FixedCutPflow: $\Sigma E$ particle flow in a cone
  - FixedCutHighMu: combines all

- The efficiency can be kept reasonably constant at high $\mu$
  - Loose isolation 0.5-1% and Tight 2-10%

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*ATLAS Preliminary*

$\sqrt{s} = 13$ TeV, 43.8 fb$^{-1}$

Data 2017

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*ATLAS Preliminary*

$\sqrt{s} = 13$ TeV, 43.8 fb$^{-1}$

Data 2017
Energy loss modeling in the track fit

- The expected energy loss is modeled using a tracking geometry description of the material $X_0$ in the tracker, calorimeters and muon system based on PDG formula’s.
  - Ionization: Landau distribution with a $E_{\text{MOP}}$ and $\sigma_L$
  - Radiation: Exponential with $E_{\text{rad}}$
- The energy loss is also measured $E_{\text{meas}}$ in the calorimeters with $\sigma_{\text{meas}}$
- Two regimes are defined $E_{\text{cut}} = 2.5 \sigma_{\text{meas}}$ IEEE (2007) 54 5
  - $E_{\text{meas}} - E_{\text{MOP}} - E_{\text{rad}} < E_{\text{cut}}$ use expected $E_{\text{MOP}} + E_{\text{rad}}$
  - $E_{\text{meas}} - E_{\text{MOP}} - E_{\text{rad}} > E_{\text{cut}}$ use measured $E_{\text{meas}}$
- Finally, from the $E_{\text{meas}}$, $\sigma_{\text{meas}}$, and $E_{\text{MOP}}$, an Energy constraint was calculated with asymmetric errors. The constraint is used in the track fit.
- The technique was implemented in 2017 and the tracking geometry description of the simulated muon energy loss was scrutinized. This resulted in an improved momentum resolution and a smaller $E$ loss momentum correction term $\Delta s_0$. 

PDG 2018
Alignment uncertainties in the track fit

- **AlignmentEffectOnTrack** AEOT has position and angle uncertainties on a group of hits (e.g. chamber)
- Typical sagitta (sys) uncertainty is 30-80 µm (RUN2) put in Middle Chamber
- Can also treat Barrel-Endcap alignment systematics (1 mm)
- Track fit performed using gaussian constraint on groups of hits with alignment uncertainties
- Implemented for the global $\chi^2$ fitter

- Improves the track parameters e.g. momentum resolution by about 10%; uncertainties are more realistic
Conclusions

- Muon Identification in ATLAS
  - complementary ways to identify a muon
- Physics with muons
  - working points for a wide physics range
- Efficiencies for muons: Z tag and probe
  - data/MC within 1-2% and systematics < 0.5%
- Muon momentum scale and resolution
  - scale systematics: 0.1-0.2%
  - resolution data/MC 5-10%
- Muon isolation efficiencies and pile up
  - Efficiencies stable: Loose at 0.5-1% and Tight 2-10%
- Energy loss modeling in the track fit
- Alignment uncertainties in the track fit