Analysing Muons using the ATLAS software

ATLAS software tutorial

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on behalf of the Muon Combined Performance (MCP) group

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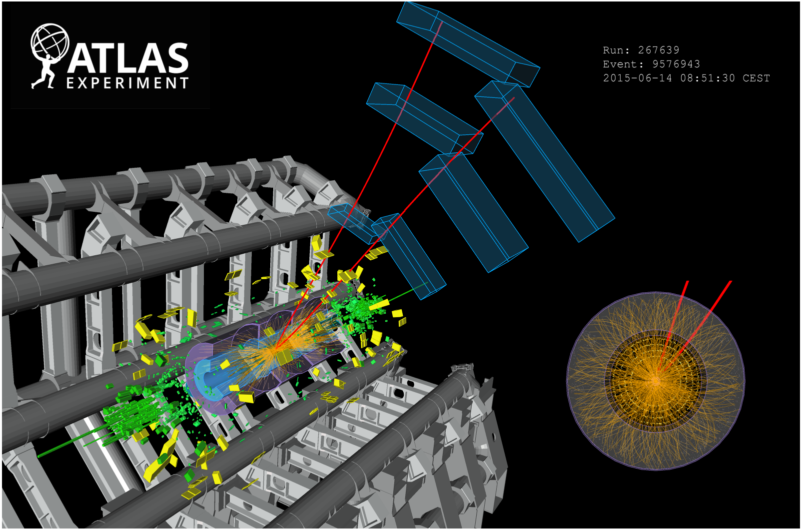
Muons in ATLAS

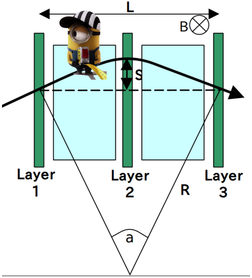


Muon reconstruction in ATLAS

Muons deposit only little energy in the calorimeters (minimal ionizing particle)

→ They cannot be stopped in ATLAS

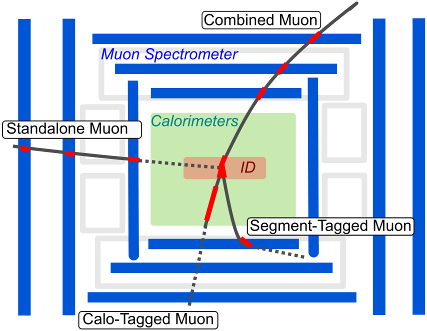
- Muon trajectory bent by the Solenoid & Toroid magnets
- Inner Detector (ID) & Muon Spectrometer (MS) record their hits



→ Momentum estimated from the sagitta of their path $p_T \propto \frac{L^2 \cdot B}{s}$

- Information from the calorimeter corrects for energy loss & allows for additional tagging
- I'll show you today...
  - ... the basics of the `xAOD::Muon` EDM in ATLAS
  - ... how to calibrate & select muons
  - ... how to retrieve (reconstruction) efficiencies

The four muon types



Reconstruction with the ID

- Combined muons : Fit the ID- & MS-track into one single track
- Calorimeter-Tagged muons: ID tracks with additional small energy deposits in the calorimeter (at $|\eta| \approx 0$)
- Segment-Tagged muons: ID tracks combined with single segments of the MS (at low energies)

The ATLAS-MS can reconstruct the muon independently of the ID

- Standalone muons: Used only at high $|\eta|$ (> 2.5) beyond the coverage of the ID

xAOD::Muon - your stairway to...

xAOD::Muon (← link) is the class handling all information concerned muons

Associated particles

```
/// @brief Returns a pointer (which can be NULL) to the  TrackParti
const TrackParticle* trackParticle( TrackParticleType type) const;
///This is determined in the following order:
///  1. CombinedTrackParticle
///  2. InnerDetectorTrackParticle
///  3. ExtrapolatedMuonSpectrometerTrackParticle
///  4. MSOnlyExtrapolatedMuonSpectrometerTrackParticle
///  5. MuonSpectrometerTrackParticle
const TrackParticle* primaryTrackParticle() const;
/// Retrieve the associated cluster with a bare pointer
const CaloCluster* cluster() const;
/// @brief Number of MuonSegments linked to by this Muon.
size_t nMuonSegments() const;
/// @brief Returns a pointer to the specified MuonSegment.
/// @param i Index of the MuonSegment requested. If i is n
const MuonSegment* muonSegment( size_t i ) const;
```

Kinematics

```
/// The transverse momentum (\f$p_T\f$) of th
virtual double          pt() const;
/// The pseudorapidity (\f$\eta\f$) of the pa
virtual double          eta() const;
/// The azimuthal angle (\f$\phi\f$) of the p
virtual double          phi() const;
/// The invariant mass of the particle..
virtual double          m() const;
/// The total energy of the particle.
virtual double          e() const;
/// The true rapidity (y) of the particle.
virtual double          rapidity() const;
```

Muon quality

```
enum Quality {Tight, ///
              Medium, ///
              Loose, ///
              VeryLoose};
Quality quality() const;
```

Many more methods to access all information

Prerequisites to use muons in your analysis

- Which lines do you need to put where to compile your code?
- Needed dependencies in your `CMakeLists.txt` file:

  ```
  Event/xAOD/xAODMuon
  PhysicsAnalysis/Interfaces/MuonAnalysisInterfaces
  ```

- Add the include statements to the header of your analysis class

```
// General information about the event.
#include <xAODEvent/EventInfo.h>
// Access the Particle & vertex containers
#include <xAODMuon/MuonContainer.h>
#include <xAODTracking/VertexContainer.h>
#include <xAODTracking/TrackParticleContainer.h>
// Helper functions to calculate the
// closest approach to the primary vertex
#include <xAODTracking/TrackParticlexAODHelpers.h>
```

Retrieve the MuonContainer

- At the very beginning of each event you first need to retrieve the Containers

→ Add therefore in your event execution method

```
// Retrieve the muons from the event
const xAOD::MuonContainer* muons= nullptr;
ATH_CHECK(evtStore()->retrieve(muons, "Muons"));
// Retrieve the event info
const xAOD::EventInfo* ev_info = nullptr;
ATH_CHECK(evtStore()->retrieve(ev_info, "EventInfo"));
// We also need the primary vertex. Please consider the track-tutorial
// how to carry this out properly
const xAOD::Vertex* pv = nullptr;
```

First simple analysis

- Print out some information of the muon and its track

```
float primvertex_z = pv ? pv->z() : 0;
// Loop over the container and print some basic properties
for ( auto mu : *muons) {
    // retrieve the primary track
    const xAOD::TrackParticle* mu_trk = mu->primaryTrackParticle();
    float d0(-1), z0_sintheta(0), d0sig(0);
    // Calculate the impact parameters
    if (mu_trk){
        z0 = (mu_trk->z0() + mu_trk->vz() - primvertex_z);
        d0 = mu_trk->d0();
        d0sig = xAOD::TrackingHelpers::d0significance( mu_trk ,
                                                ev_info->beamPosSigmaX(),
                                                ev_info->beamPosSigmaY(),
                                                ev_info->beamPosSigmaXY());
    } else {continue;}
    ATH_MSG_INFO("Found muon with pt: "<< mu->pt()/1.e3
                            <<" eta: " << mu->eta()
                            <<" phi: "<<mu->phi()
                            <<" d0: "<<d0<<" rel d0sig: "<<d0sig /d0
                            <<" z0: "<<z0);
}
```

Calibrate the muon momenta

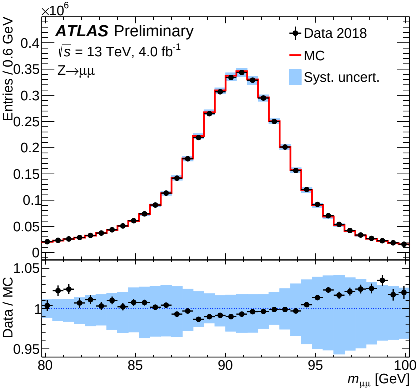
Δs_0: Energy loss inside ATLAS
Δs_1: Magnetic field integral & distortions

$$p_T \rightarrow \frac{\Delta s_0 + (1 + \Delta s_1) p_T}{\mathcal{G}\left(\mu=1, \sigma=\sqrt{\left(\frac{\Delta r_0}{p_T}\right)^2 + \Delta r_1{}^2 + (\Delta r_2\ p_T)^2}\right)}$$

Δr_0: Energy loss fluctuations
Δr_1: Multiple scattering & local distortions
Δr_2: Intrinsic resolution & misalignment

- Muon momentum needs to be adjusted between data and simulation
- Correction of small residual discrepancies
- Calibration parameters from $(Z\ /\ J/\psi) \rightarrow \mu\mu$ decays
- ID & MS track separately calibrated

  Muon momentum scale known to $\sim 0.05\%$!
- Calibration procedure provided by `IMuonCalibrationAndSmearingTool`



The MuonCalibrationAndSmearingTool

- Recommendations how to calibrate muon momenta are summarized here
- Add these statements to the top of your header file

```
// Interface methods for MuonCalibration
#include <MuonAnalysisInterfaces/IMuonCalibrationAndSmearingTool.h>
// Takes care to create instances of the analysis tools
#include <AsgTools/AnaToolHandle.h>
```

- Add this line to your class declaration

```
asg::AnaToolHandle<CP::IMuonCalibrationAndSmearingTool> m_muonCalibTool;
```

- Finally setup the Tool inside your initialize section

```
// the MuonCalibrationPeriodTool is already preconfigured
// according to latest MCP recommendations
muonCalibTool.setTypeAndName(
    "CP::MuonCalibrationPeriodTool/MuonCalibTool");
// create the tool and retrieve it
ATH_CHECK(muonCalibTool.retrieve());
```

- Have a look at this TWiki page to learn about pile-up reweighting

The MuonCalibrationAndSmearingTool

- Since calibration changes the p_T of your muons, need to create a so-called `shallowCopyContainer` to store them (cf. `xAOD` EDM tutorial)

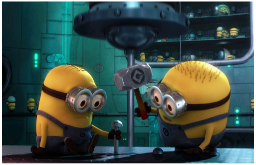
```
// The muons container is locked. I. e. you cannot change any property
// of the muons. For the calibration we need to have a writeable
// container let's create it first. I'm using a ShallowCopy here
std::pair<xAOD::MuonContainer*,
    xAOD::ShallowAuxContainer*> shallowcopy =
            xAOD::shallowCopyContainer(*muons);
// Use the EvtStore to take care of cleaning up the container
// if it is no longer needed. Define foreach container a unique_name
ATH_CHECK(evtStore()->record(shallowcopy.first, "CalibratedMuons"));
ATH_CHECK(evtStore()->record(shallowcopy.second,"CalibratedMuonsAux."));

xAOD::MuonContainer calibrated_muons = shallowcopy.first;
if (!xAOD::setOriginalObjectLink(*muons, *calibrated_muons)) {
    ATH_MSG_ERROR("Failed to set original object links for muons");
    // Bail out of the loop
}
```

The MuonCalibrationAndSmearingTool

- To calibrate the muon, call the `MuonCalibrationAndSmearingTool` and it changes the p_T of the muon you pass to it (cannot be the original `const` muon)

```
// Now we can calibrate the muons by calling the tool
for (auto mu : *calibrated_muons) {
    // Remember that auto mu -> xAOD::Muon* mu
    // The tool requires the reference to the object -> *mu
    if (m_muonCalibTool->applyCorrection(*mu) ==
                                        CP::CorrectionCode::Error){
        ATH_MSG_ERROR("Something went wrong");
        // Bail out
    }
}
```

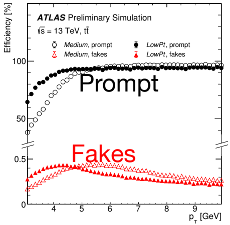


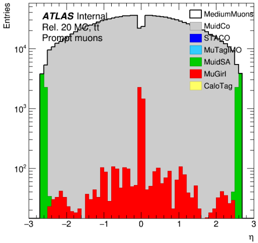
Pick the good muons in the event

- Most of the muons not from primary process or poorly measured

$\rightarrow$ Apply muon selection based on hits & fit quality

- MCP provides 5 dedicated working points (c.f. Twiki):
  `Loose`, `Medium`, `Tight`, `LowPt`, `HighPt`





- The `IMuonSelectionTool` is the recommended tool for muon selection
- Requirements on $z_0 \sin\theta < 0.5$ mm & $\sigma(d_0)/d_0 < 5$ (TTVA cuts) reject muons from secondary processes

A short word about isolation

- Electrons & muons from a primary *W*, *Z* or SUSY decay (real) expected to fly through ATLAS without a particle appearing in the close vicinity
- Leptons from a *b* or π-decay originate from a QCD-jet (fake) expected to have many accompanied particles close-by

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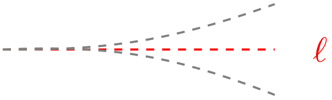

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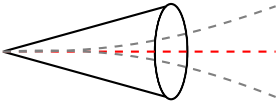


$\rightarrow$ The concept of isolation helps to efficiently suppress secondary leptons by defining $p_{\mathrm{T}}^{\mathrm{(Var)Cone}\mathcal{X}}$ & $E_{\mathrm{T}}^{\mathrm{Cone}\mathcal{X}}$

1. The sum of the p_{T} of all ID-tracks close by tracks within $\Delta R < \min\left(\frac{p_{\mathrm{T}}(\ell)}{10\ \mathrm{GeV}}, \frac{\mathcal{X}}{100}\right)$
2. The sum of the E_{T} of all calorimeter within $\Delta R < \frac{\mathcal{X}}{100}$

- The `IsolationSelectionTool` provides many working points based on the ratio of the isolation variables to the lepton-p_{T}

Selecting muons and checking isolation

- Needed includes to use the both tools

```
#include <MuonAnalysisInterfaces/IMuonSelectionTool.h>
#include <IsolationSelection/IIsolationSelectionTool.h>
```

- Declare the member variables in your analysis class

```
asg::AnaToolHandle<CP::IMuonSelectionTool> m_muonSelTool;
asg::AnaToolHandle<CP::IIsolationSelectionTool> m_iso_tool;
```

- Create the instance of the MuonSelectionTool

```
muonSelTool.setTypeAndName(
    "CP::MuonSelectionTool/MuonSelectionTool");
ATH_CHECK(muonSelTool.retrieve());
```

- And finally also the IsolationSelectionTool

```
m_iso_tool.setTypeAndName(
    "CP::IsolationSelectionTool/IsolationSelectionTool");
// since this is a common tool also for electrons/photons
// set also other "Working Points"
ATH_CHECK(m_iso_tool.setPropery("ElectronWP", "FCLoose"));
ATH_CHECK(m_iso_tool.setPropery("MuonWP", "FCTight"));
ATH_CHECK(m_iso_tool.retrieve());
```

Apply reconstruction and isolation criteria...

- Select Medium muons with $p_T > 5$ GeV and $|\eta| < 2.7$

```
// create VIEW_ELEMENTS container for Medium muons
xAOD::MuonContainer medium_muons(SG::VIEW_ELEMENTS);
// loop on the calibrated muons and select only the Medium ones
// with pt > 5GeV and |eta|<2.7
for (auto mu : *calibrated_muons) {
    if (std::fabs(mu->eta())>2.7 || mu->pt()<5000) continue;
    if (m_muonSelTool->getQuality(*mu) <= xAOD::MuonMedium) {
        medium_muons.push_back(mu);
    }
}
```

- Check that muons also pass isolation criteria

```
// only check this for the Medium muons
for (auto mu : medium_muons) {
    if (m_iso_tool->accept(mu)) {
        ATH_MSG_INFO("Found isolated muon");
    }
}
```

Muon efficiencies - fine-tune your Monte Carlo

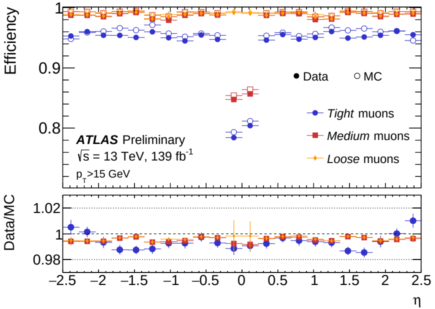
- Simulation might not exactly reflect the detector behavior during data taking

$\longrightarrow$ Tiny deviations in muon modeling $\rightarrow$ tiny differences in efficiencies

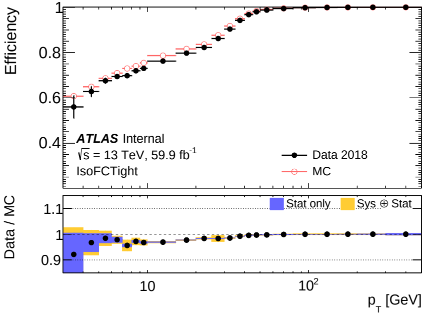
$\longrightarrow$ The efficiency of the muon reconstruction, TTVA & isolation selection measured in Data & Monte Carlo using $(Z\,/\,J/\psi) \rightarrow \mu\mu$-decays

- Efficiency Scale Factors (SFs) applied on simulation to match Data

Reconstruction & Identification



Isolation



IMuonEfficiencyScaleFactors

- Latest prescriptions of the SF measurements summarized here
- `IMuonEfficiencyScaleFactors` provides framework to apply *reconstruction*, *isolation* & *TTVA* SFs
- Needed include:

```
#include <MuonAnalysisInterfaces/IMuonEfficiencyScaleFactors.h>
```

- Declare member variables, one for each measurement:

```
asg::AnaToolHandle<CP::IMuonEfficiencyScaleFactors.h> m_reco_medium_sf;
asg::AnaToolHandle<CP::IMuonEfficiencyScaleFactors.h> m_reco_ttva_sf;
asg::AnaToolHandle<CP::IMuonEfficiencyScaleFactors.h> m_reco_iso_sf;
```

- Initialize the tools (e.g. for reconstruction SFs):

```
m_reco_medium_sf.setTypeAndName(
    "CP::MuonEfficiencyScaleFactors/Medium_SF");
// the "WorkingPoint" property already encodes whether
// the tool is for reconstruction/isolation/ttva...
ATH_CHECK(m_reco_medium_sf.setProperty("WorkingPoint", "Medium"));
ATH_CHECK(m_reco_medium_sf.retrieve());
```

Calculate the muon scale-factor

```
// retrieve the muon reconstruction efficiency scale factor per event
// only take the 'good' selected muons to calculate it
float tot_sf = 1;
for (auto mu : good_muons) {
    float mu_sf = 1;
    if (m_reco_medium_sf->getEfficiencyScaleFactor(*mu, mu_sf, ev_info)
        != CP::CorrectionCode::Ok) {
        // printout warning, that something went wrong with
        // retrieving the scale factor
    }
    tot_sf *= mu_sf;
}
```

Concluding remarks

- MCP Twiki contains all relevant information about handling of muons
- Make yourself comfortable with the `xAOD::Muon` EDM
- There is still much to learn about:
  - Dealing with systematic variations
  - Muon trigger selection & efficiencies
  - ...

Request developer access!

$\longrightarrow$ At some point, you will need an analysis *framework* (such as XAMPP, ...)

- Join MCP (or Muon Software) if you want to work in an awesome CP group

Thanks & enjoy your time in ATLAS!