ATLAS Muon Spectrometer

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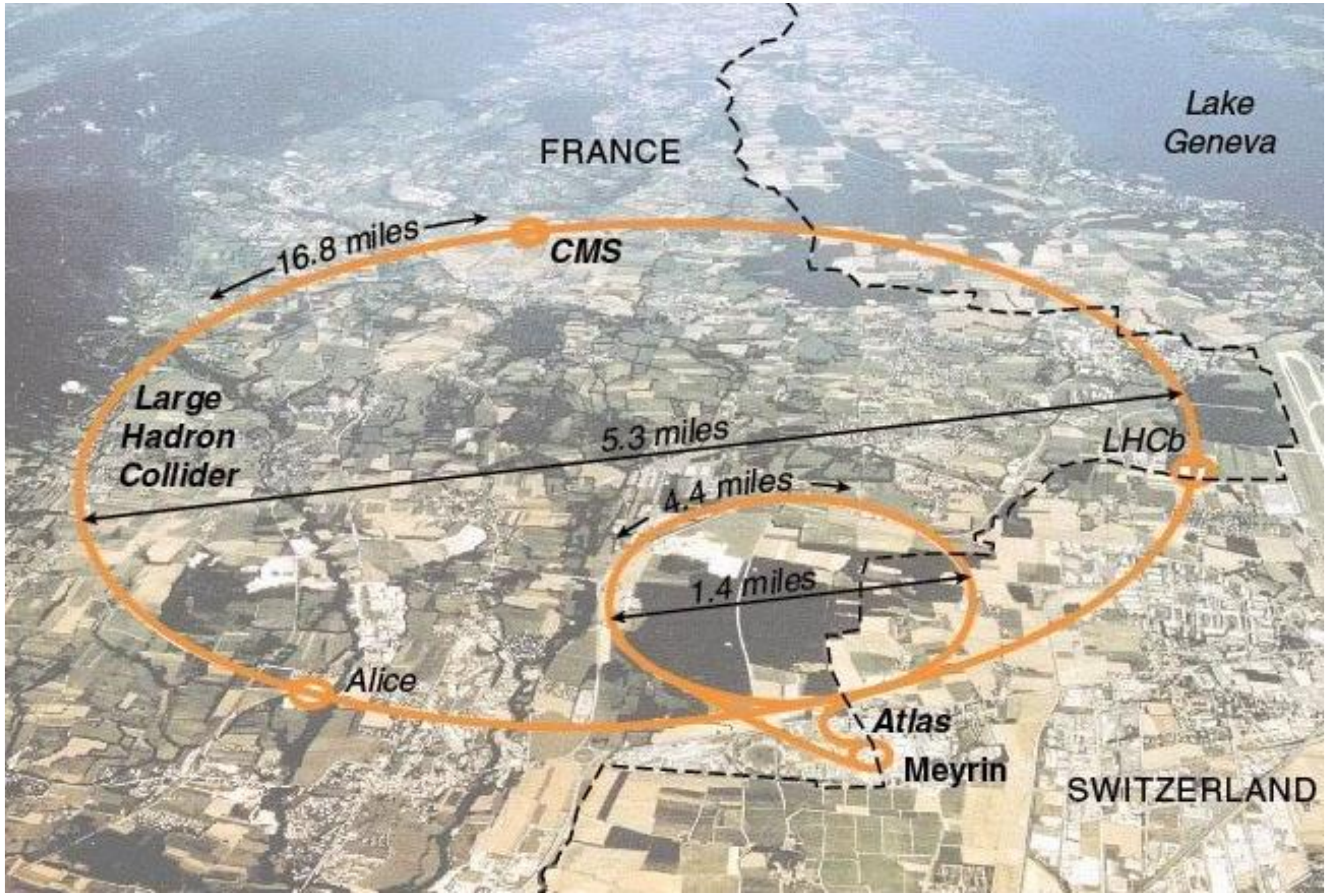
ATLAS – A Toroidal LHC ApparatuS



- Largest General-Purpose Detector at LHC
- One of the two LHC experiments involved in the discovery of the Higgs boson in July 2012
- ATLAS measures:
  - masses;
  - channels of production, decay and mean lifetimes;
  - interaction mechanisms and coupling constants for electroweak and strong interactions.

ATLAS Structure

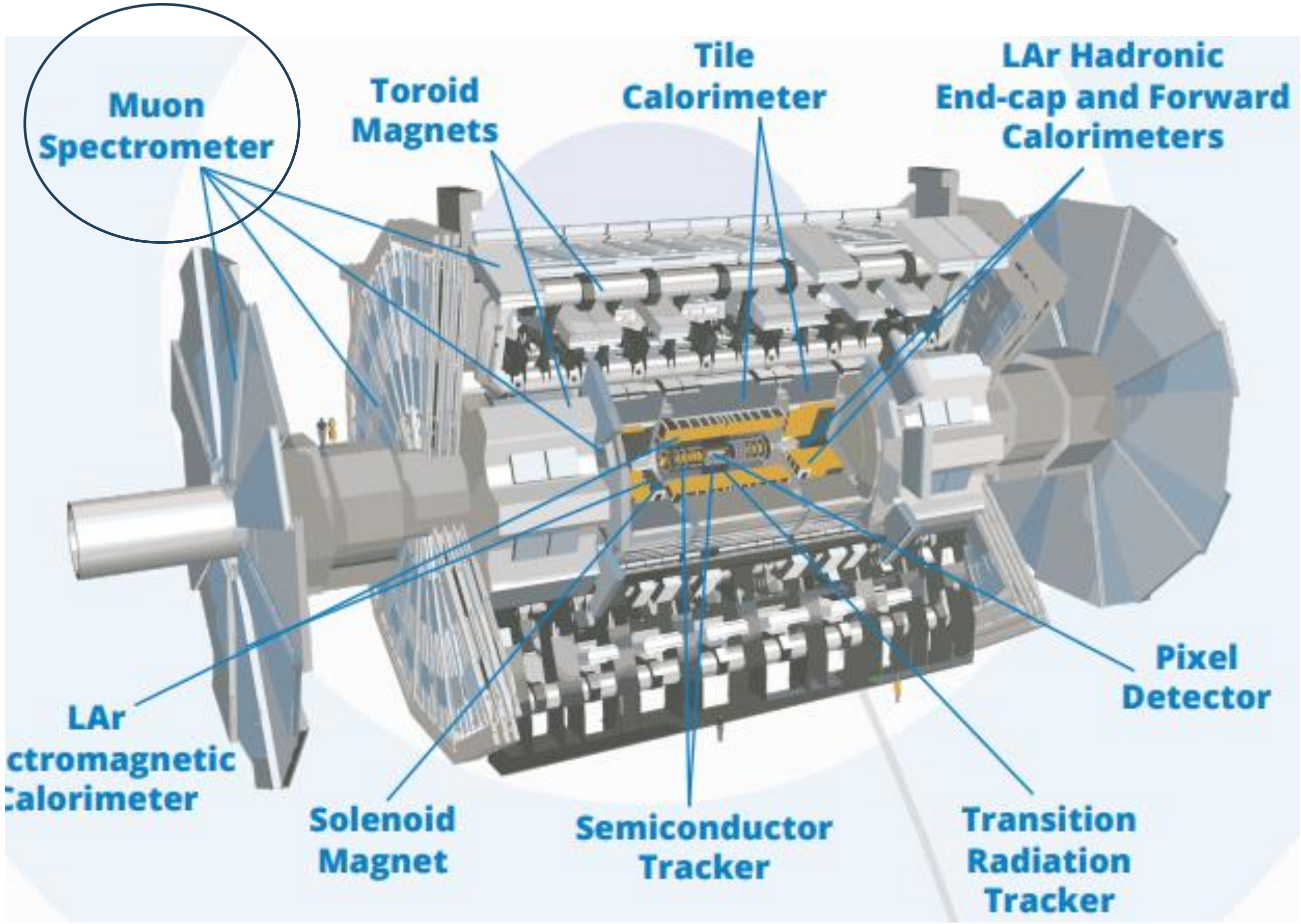
General Purpose

designed in layers of different types of detectors.

Concentric cylinders around the interaction point where the proton beams from the LHC collide.

MS consists of three parts:

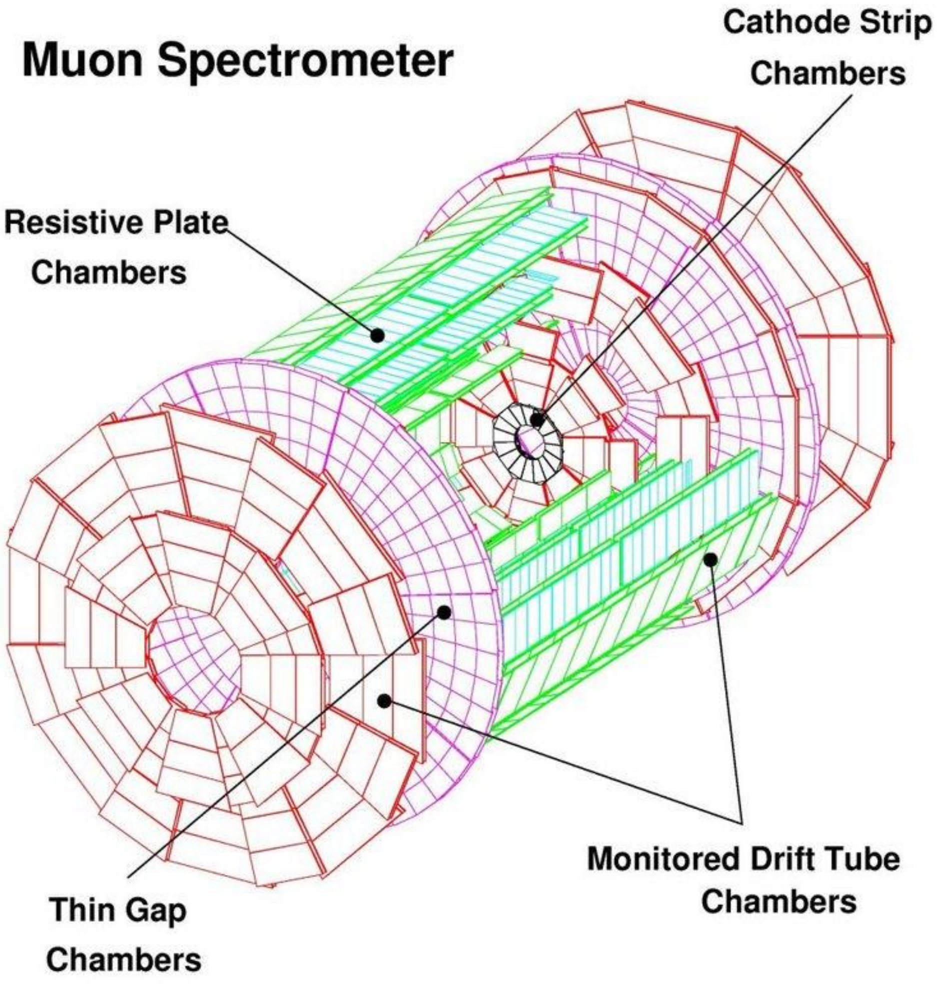
1. Magnetic field
2. A set of Track chambers measuring
3. A set of Triggering chambers with accurate time-resolution.



Why do we care to measure Muons?

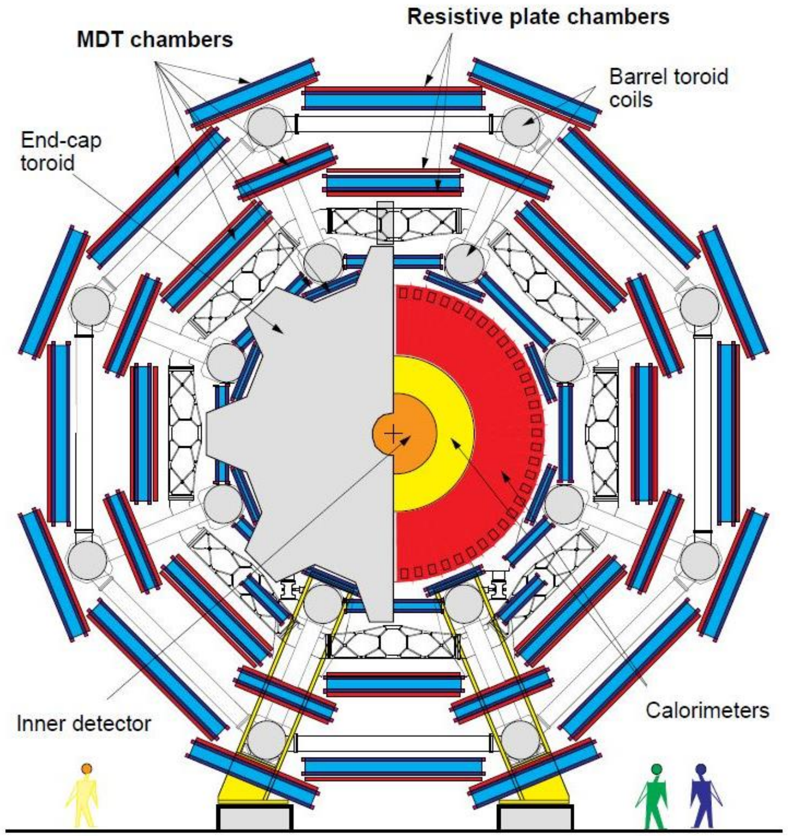
- because
  - Muons are the only (charged primary) collision products traversing the calorimeters. → Clean signature of muonic final states.
  - Many interesting physical processes can only be observed if one or more muons are detected (H → ZZ∗ → μμ, A → μμ, Z_0 → μμ.)
  - The total energy of particles in an event could not be measured if the muons were ignored.

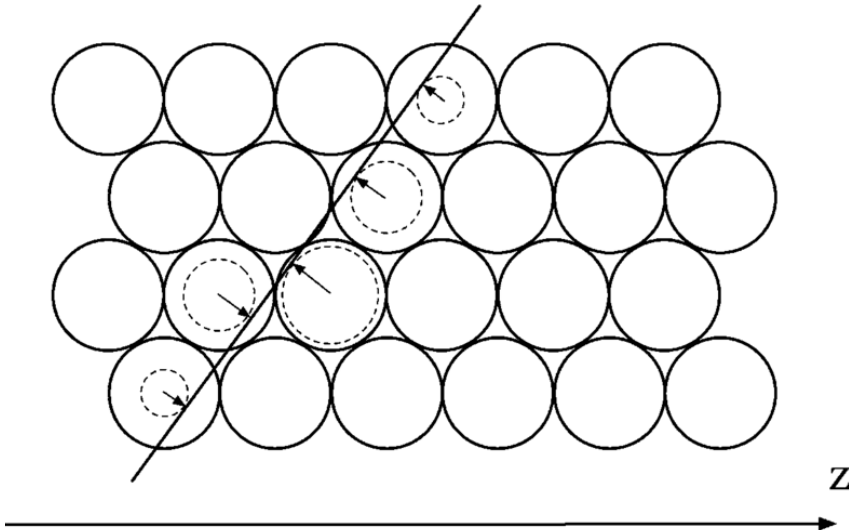
ATLAS Muon Spectrometer



Precision Detectors

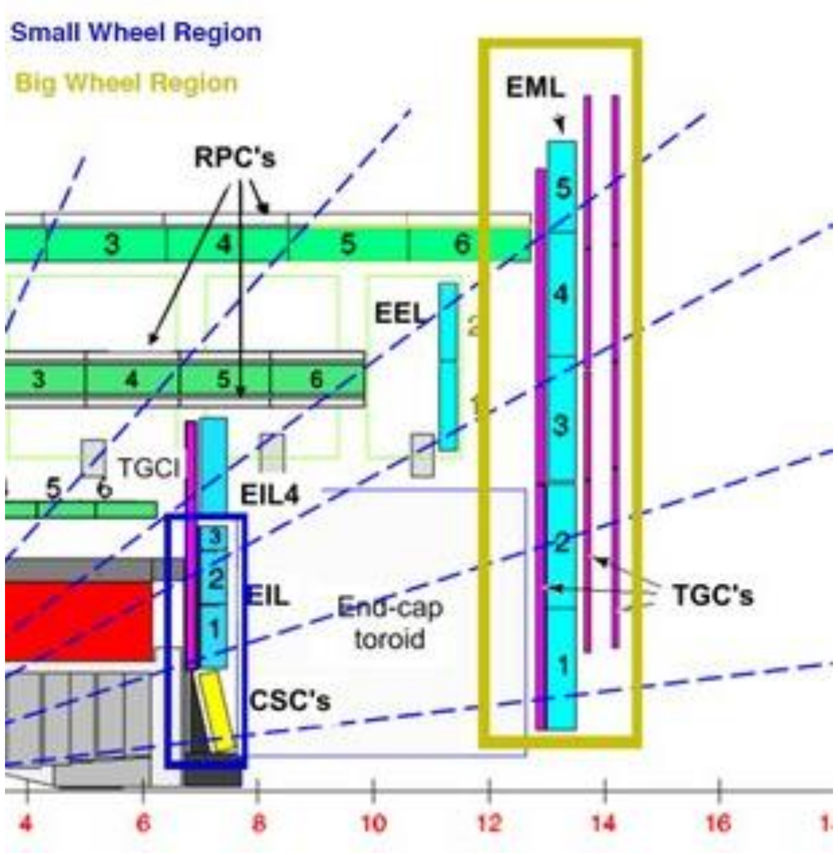
- Use: To determine the position of a muon,
- Accuracy: **less than a 10th of a millimetre**!
- How? Monitored Drift Tube (MDTs) detectors are
    - 3 cm wide aluminium tubes filled with a gas mixture. Argon and CO2
    - Muons pass through the tubes, ionize the gas.
    - Electrons drift to a wire at the center of the tube == signal!!!
    - Over **380,000 aluminium tubes** are stacked up in several layers in order to precisely trace the trajectory of each muon.
- https://www.youtube.com/watch?v=A8L2RtvEKok





Fast-Response Detectors

- Qickly select interesting collision
- They **make this decision within 2.5 µs** (400,000th of a second!!).
- The **Resistive Plate Chambers (RPCs)** surround the **central region** of ATLAS
  - pairs of parallel plastic plates at an electric potential difference, separated by a gas volume.
- **Thin Gap Chambers (TGCs)** are at the **ends** of ATLAS
  - **parallel 30 µm wires in a gas mixture**.
- Both chambers detect muons when they ionise the gas mixture and generate a signal.
- **Micromegas and Small-Strip Thin-Gap Chambers (sTGCs)** two additional detector technologies specially designed for **high-intensity LHC collisions**.
  - These detectors can track muons in high-density areas on either side of the experiment close to the LHC beam pipe, both quickly and with high precision.
- The combined data gives a rough measurement of a muon's momentum, allowing ATLAS to choose whether to keep or discard a collision event.



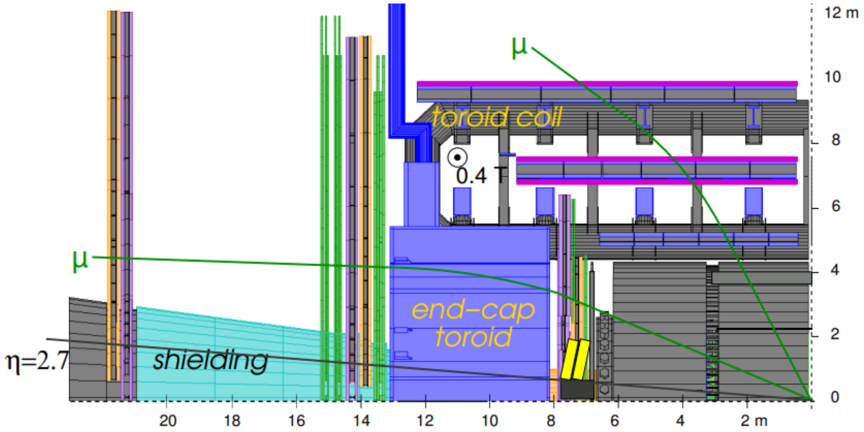
How is Muon Momentum Studied

As for other charged particles, muon momenta are determined from their deflection in a magnetic field (recall tracking and vertexing lecture)

1. What is providing the deflection?

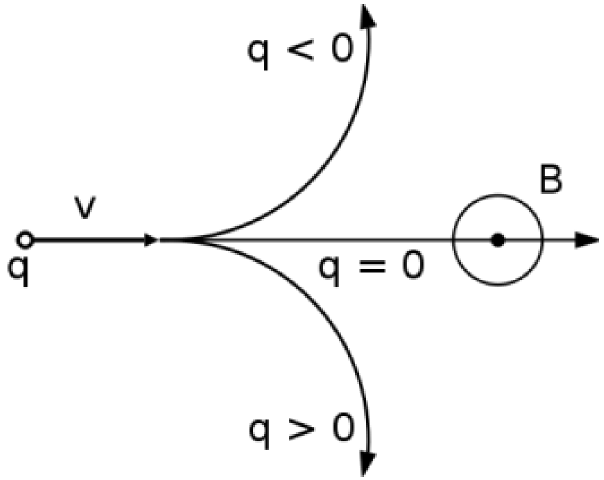
2. How does the bending of muon trajectory help us determine it's momentum

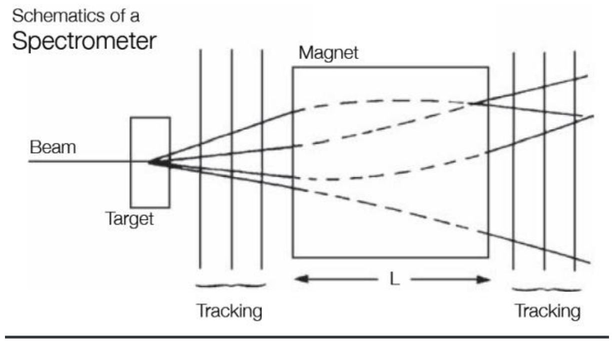
3. Why do we even care to find the muon's momentum?



Momentum Measurement

- 1. Deflection from Toroidal Magnetic Field (non uniform, 2-6 Tm)
- 2. Think of Charge and Magenetic field (and which very famous formula connects them)
- 3 We want to measure the momentum of the muon such that we can reconstruct its path back to where it originated from (interaction point)





$$\vec{F} = q\vec{v} \times \vec{B}$$

Lorentz force: is the force on a point charge due to electromagnetic fields

$$\frac{mv^2}{r} = qvB$$

… for a particle in motion perpendicular to a constant B field

Momentum Resolution

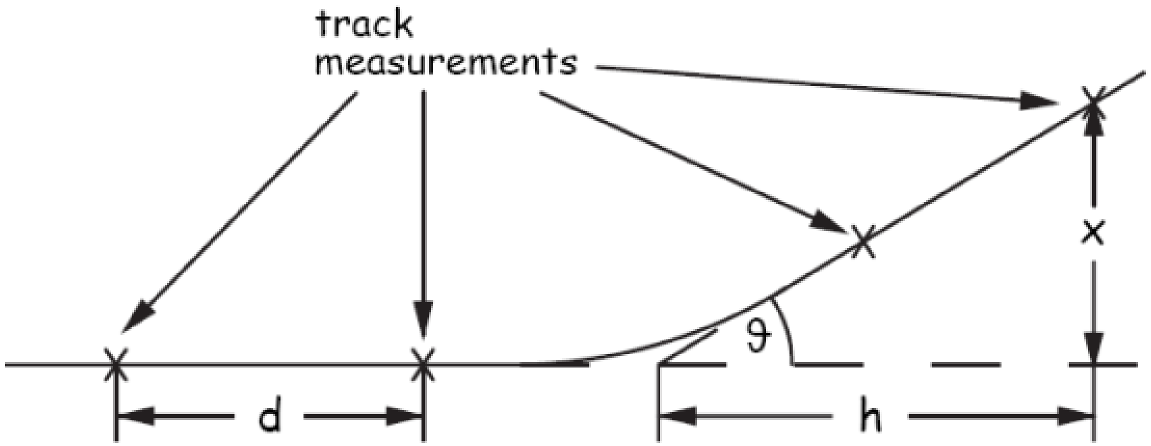
- Ability of a Particle Detector to accurately measure the momentum of a charged particle through it
- Mathematically:

$$\frac{\sigma_p}{p} = \frac{\sigma_\vartheta}{\vartheta}$$

with

$$\sigma_\vartheta \sim \sigma_x$$

- Recall, the magnetic field due to the torroid is not uniform



Determination of σ_p/p:

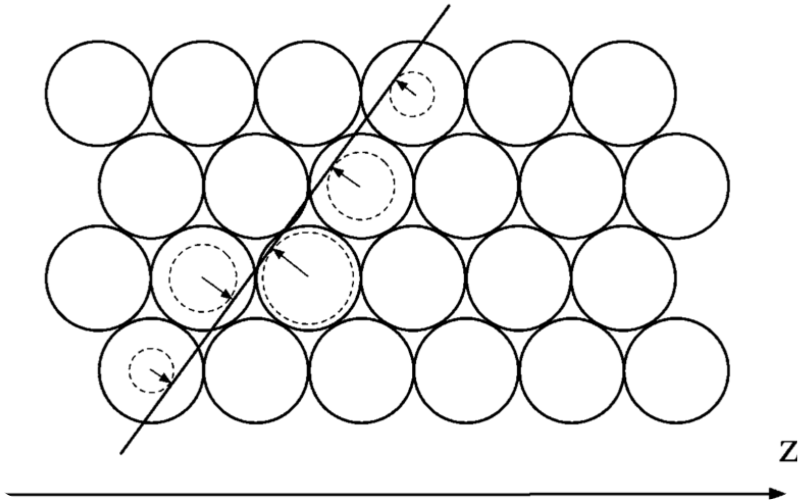
$$\vartheta = \frac{x}{h} \qquad \sigma_\vartheta = \frac{\sigma_x}{h}$$

$$\frac{\sigma_p}{p} = \frac{\sigma_\vartheta}{\vartheta} = \frac{\sigma_x}{h} \cdot \frac{p}{eBL}$$

Long lever arm improves momentum resolution ...

Momentum Resolution MDT

- Recall tracking and vertexing lecture
  - Momentum resolution scales with sagitta resolution



momentum component perpendicular to the B-field
transverse momentum p_t

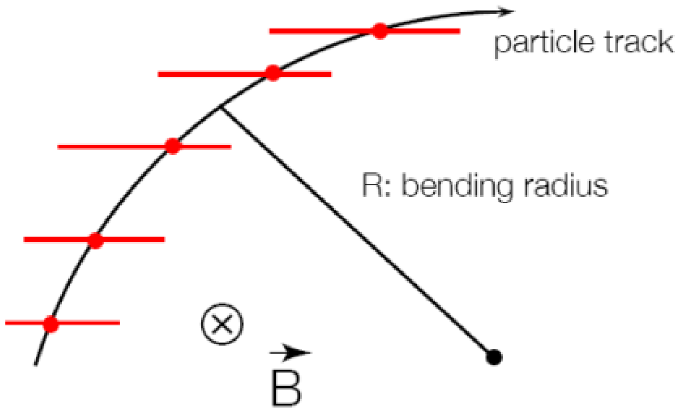
For Sagitta s:

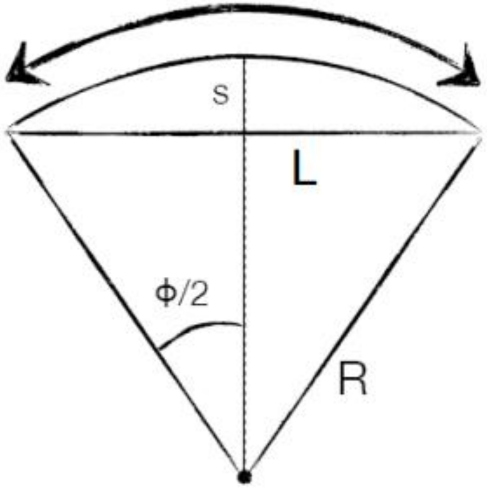
$$s = R - R\cos\frac{\phi}{2} \approx R\frac{\phi^2}{8} \qquad \text{with } \phi = \frac{L}{R}$$

$$s = R\frac{L^2}{8R^2} = \frac{L^2}{8R} \quad \text{and} \quad R = \frac{L^2}{8s}$$

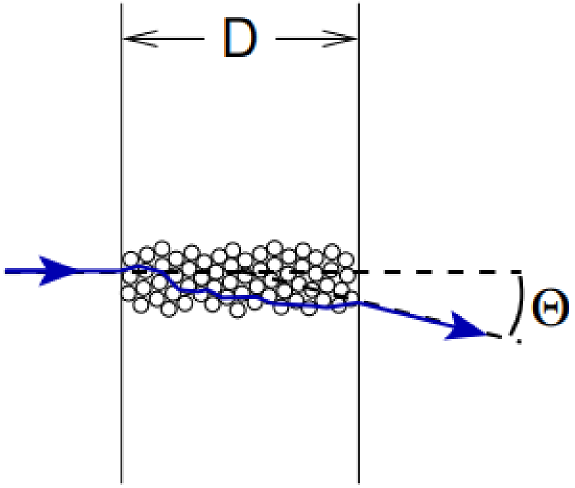
$$\rightarrow \frac{\Delta p}{p} = \frac{\Delta R}{R} = \frac{L^2}{8Rs} \cdot \frac{\Delta s}{s}$$

➔ radius is obtained by a circle fit through measurement points along the track with point resolution $\sigma_{r\phi}$





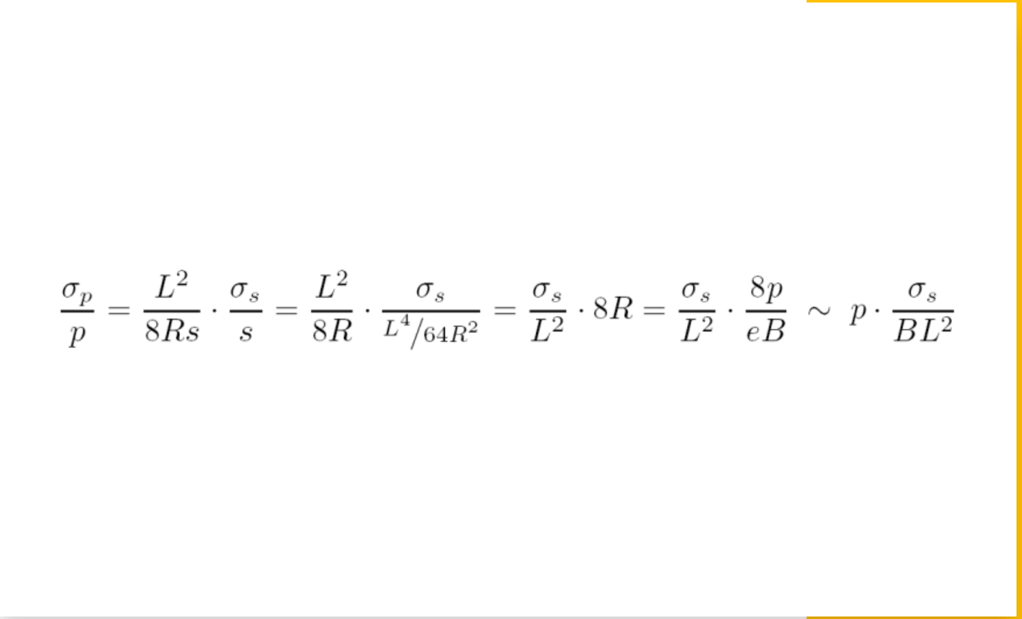
Multiple Scattering



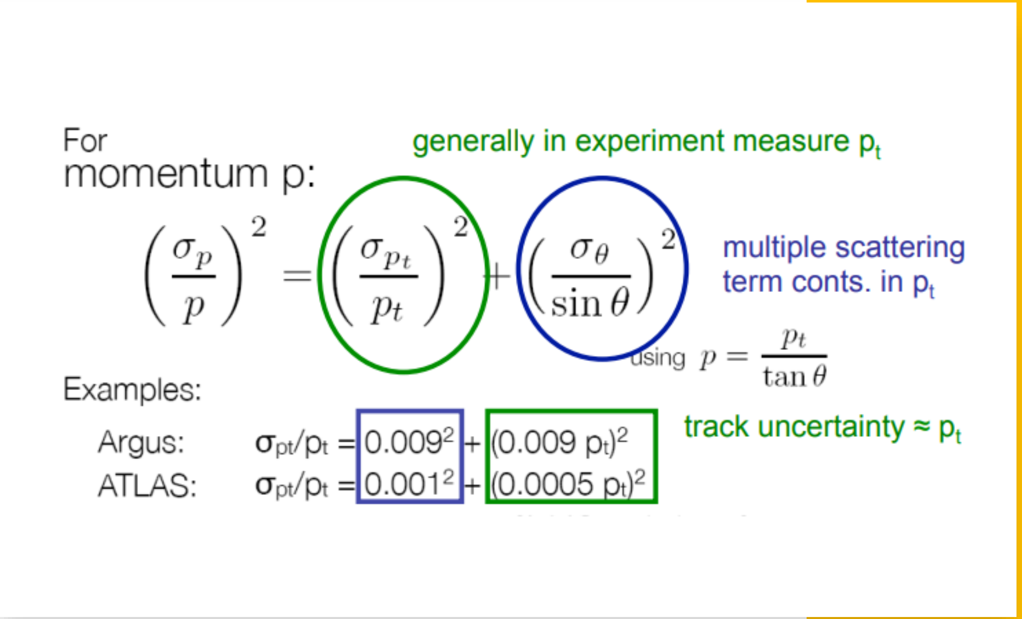
- However, one more thing to keep in mind when considering momentum resolution in MS
- Muons can “interact” with the Detector Material –> Multiple Scattering
  - additional uncertainty in momentum measurement
- Mathematically: $\left.\frac{\delta\left(\frac{q}{p}\right)}{\frac{q}{p}}\right|_{mult.scatt.} = \frac{\sigma_\Theta}{\int_{\mathcal{P}} B, dl}\cdot\frac{p}{q} = \frac{13.6\ \mathrm{MeV/c}}{\int_{\mathcal{P}} B\, dl}\sqrt{\frac{D}{X_0}}q,$ independent of p!
- Here X_0 is radiation length of the material
  - mean length (in cm) to reduce the energy of an electron by the factor 1/e.

Overall Momentum Resolution

- A good momentum resolution can be achieved by
  - Large path length L
  - Large Magnetic field B
  - Good Sagitta measurement



$$\frac{\sigma_p}{p} = \frac{L^2}{8Rs}\cdot\frac{\sigma_s}{s} = \frac{L^2}{8R}\cdot\frac{\sigma_s}{L^4/64R^2} = \frac{\sigma_s}{L^2}\cdot 8R = \frac{\sigma_s}{L^2}\cdot\frac{8p}{eB} \sim p\cdot\frac{\sigma_s}{BL^2}$$



For momentum p:

generally in experiment measure p_t

$$\left(\frac{\sigma_p}{p}\right)^2 = \left(\frac{\sigma_{p_t}}{p_t}\right)^2 + \left(\frac{\sigma_\theta}{\sin\theta}\right)^2$$

multiple scattering term conts. in p_t

using $p = \frac{p_t}{\tan\theta}$

Examples:

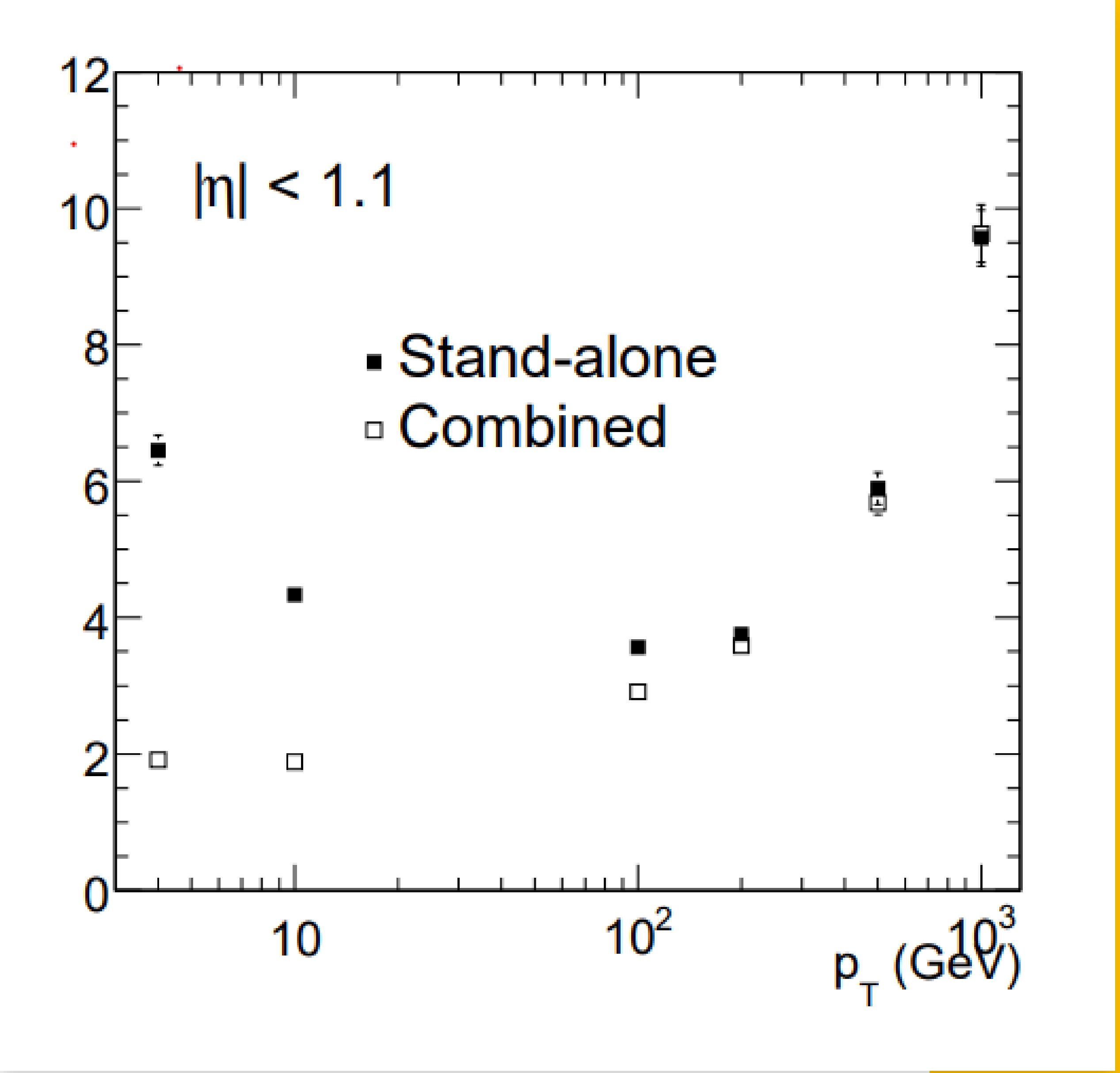
Argus: $\sigma_{pt}/p_t = \boxed{0.009^2} + \boxed{(0.009\ p_t)^2}$

ATLAS: $\sigma_{pt}/p_t = \boxed{0.001^2} + \boxed{(0.0005\ p_t)^2}$

track uncertainty ≈ p_t

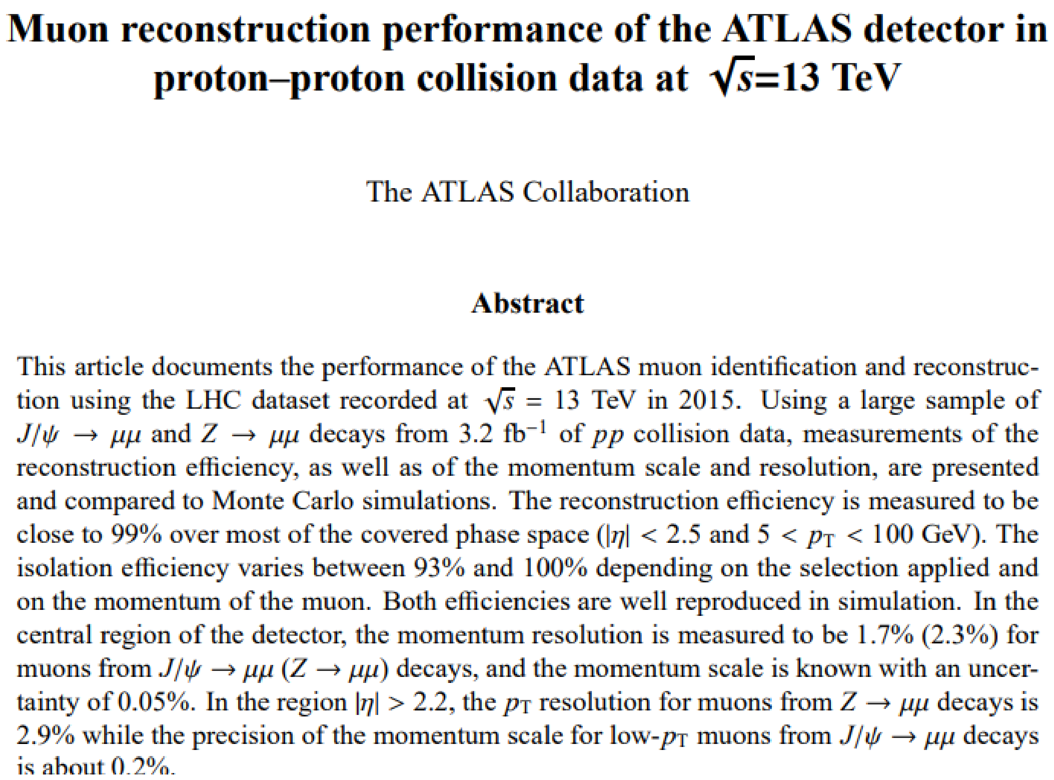
Need for MS

- Combining the measurements of the inner detector and muon spectrometer gives us a better momentum resolution
  - pT < 100 GeV Significant improvement of the resolution by the inner detector.
  - pT > 100 GeV Momentum resolution dominated by the muon spectrometer.
- Muon spectrometer crucial for good momentum resolution at large pT!!



Back to ATLAS –LHC Run 2

- Momentum Resolution: 2.3% - 2.9% (at endcaps)
  - using the LHC dataset recorded at $\sqrt{s}$ = 13 TeV in 2015
- Efficiency: $\epsilon = N\text{detected}/N\text{generated}$
  - 99% over most of the covered phase space (|η| < 2.5 and 5 < pT < 100 GeV). The isolation efficiency varies between 93% and 100% depending on the selection applied and on the momentum of the muon.



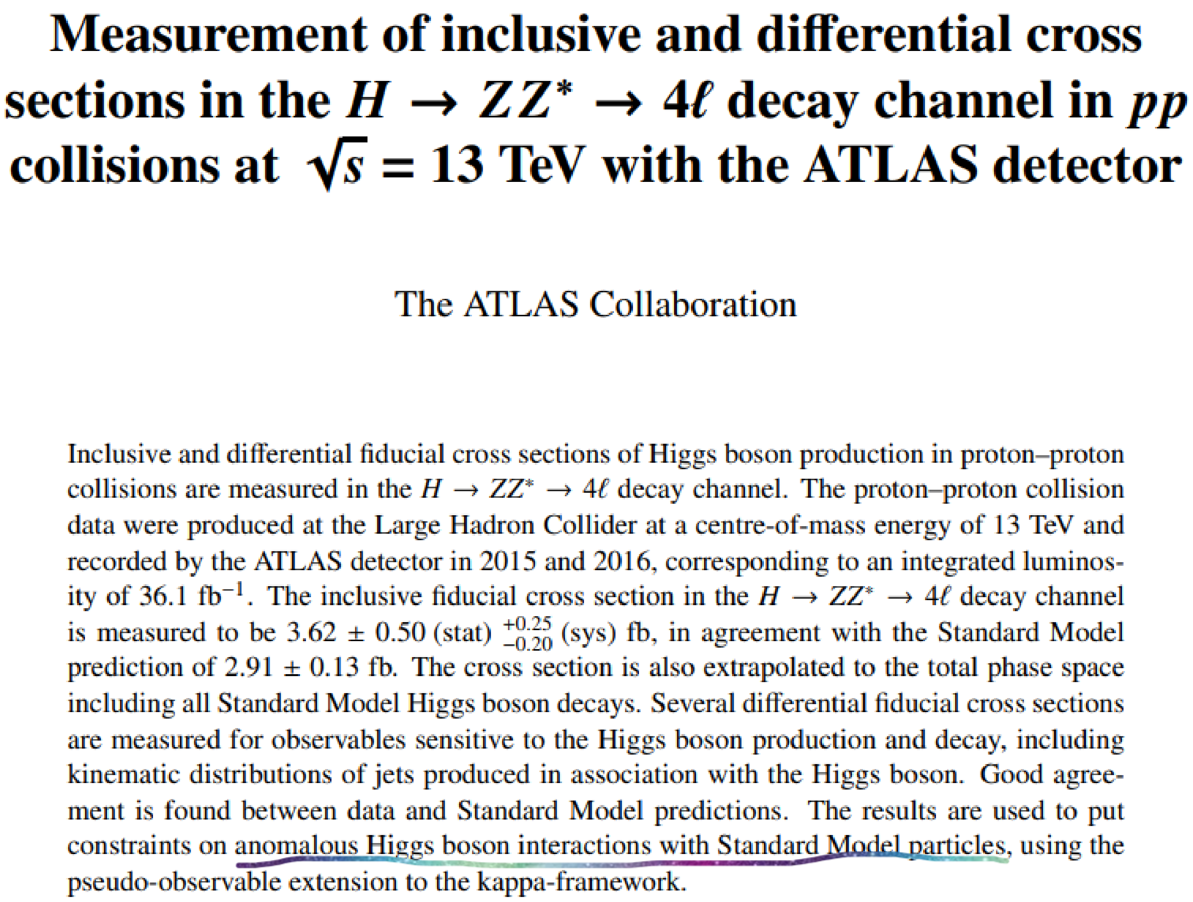
Muon reconstruction performance of the ATLAS detector in proton–proton collision data at $\sqrt{s}$=13 TeV

The ATLAS Collaboration

Abstract

This article documents the performance of the ATLAS muon identification and reconstruction using the LHC dataset recorded at $\sqrt{s}$ = 13 TeV in 2015. Using a large sample of $J/\psi \to \mu\mu$ and $Z \to \mu\mu$ decays from 3.2 fb^{-1} of pp collision data, measurements of the reconstruction efficiency, as well as of the momentum scale and resolution, are presented and compared to Monte Carlo simulations. The reconstruction efficiency is measured to be close to 99% over most of the covered phase space ($|\eta| < 2.5$ and $5 < p_T < 100$ GeV). The isolation efficiency varies between 93% and 100% depending on the selection applied and on the momentum of the muon. Both efficiencies are well reproduced in simulation. In the central region of the detector, the momentum resolution is measured to be 1.7% (2.3%) for muons from $J/\psi \to \mu\mu$ ($Z \to \mu\mu$) decays, and the momentum scale is known with an uncertainty of 0.05%. In the region $|\eta| > 2.2$, the p_T resolution for muons from $Z \to \mu\mu$ decays is 2.9% while the precision of the momentum scale for low-p_T muons from $J/\psi \to \mu\mu$ decays is about 0.2%.

Recent Study (2018)



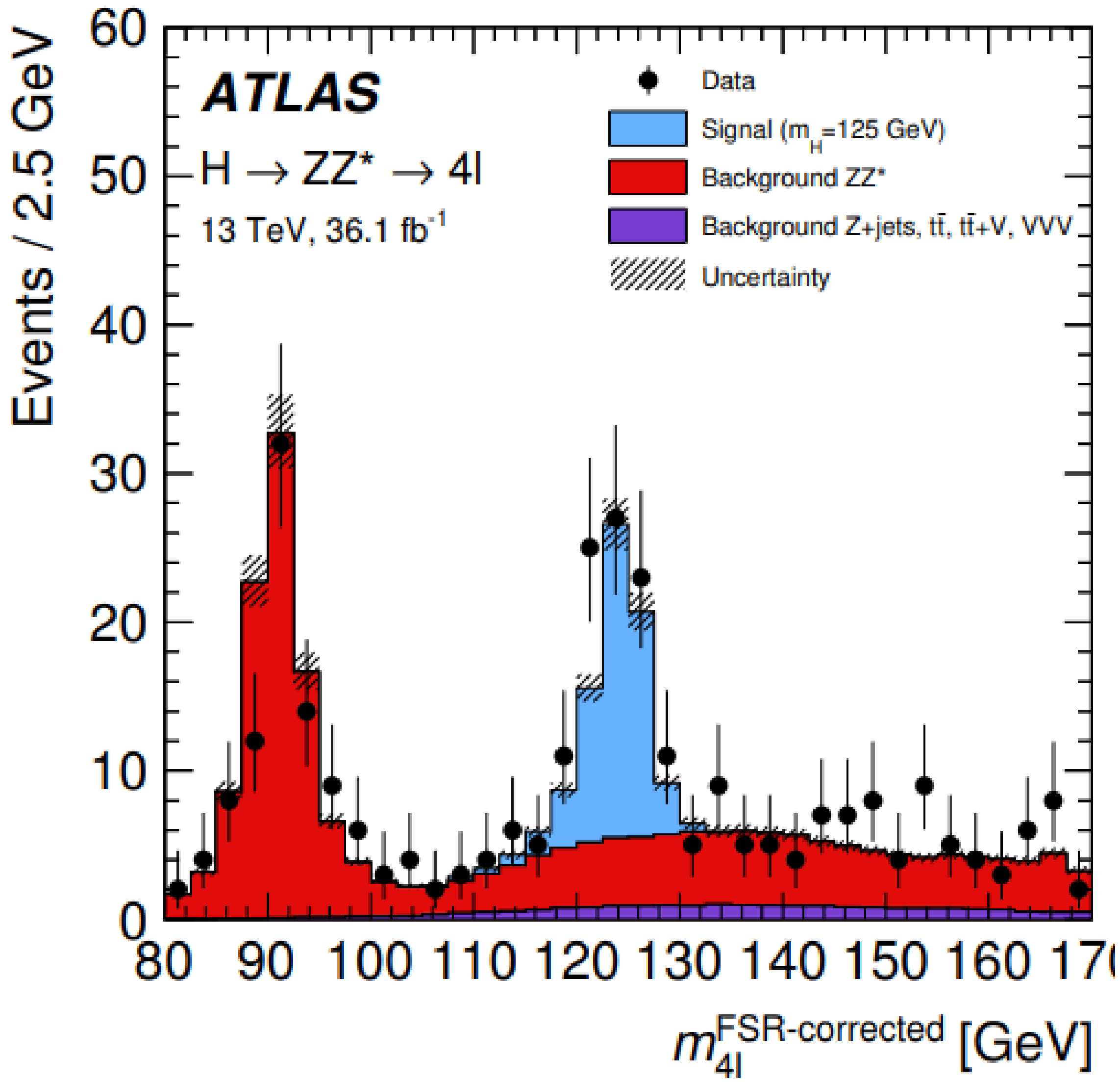
Measurement of inclusive and differential cross sections in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

Inclusive and differential fiducial cross sections of Higgs boson production in proton–proton collisions are measured in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel. The proton–proton collision data were produced at the Large Hadron Collider at a centre-of-mass energy of 13 TeV and recorded by the ATLAS detector in 2015 and 2016, corresponding to an integrated luminosity of $36.1\ \text{fb}^{-1}$. The inclusive fiducial cross section in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel is measured to be 3.62 ± 0.50 (stat) $^{+0.25}_{-0.20}$ (sys) fb, in agreement with the Standard Model prediction of 2.91 ± 0.13 fb. The cross section is also extrapolated to the total phase space including all Standard Model Higgs boson decays. Several differential fiducial cross sections are measured for observables sensitive to the Higgs boson production and decay, including kinematic distributions of jets produced in association with the Higgs boson. Good agreement is found between data and Standard Model predictions. The results are used to put constraints on anomalous Higgs boson interactions with Standard Model particles, using the pseudo-observable extension to the kappa-framework.

Event Selection

- Only events with a four-lepton invariant mass in the range 115−130 GeV are used in the extraction of the signal.
- “The acceptance of the fiducial selection is 42% for a SM Higgs boson with mH = 125 GeV. The ratio of the number of events passing the detector-level event selection to those passing the particle-level selection is 53%. Due to resolution effects, about 2% of the events which pass the detector-level selection fail the particle-level selection.”
- How many Higgs Boson are lost?



Conclusions

Fiducial cross section is in agreement with SM prediction (yay)

Fiducial cross section is also extended to the total phase space which includes all Standard Model Higgs boson decays

Extracted cross-section distributions are used to constrain anomalous Higgs boson interactions with Standard Model particle

Sources:

- https://indico.cern.ch/event/34087/contributions/802938/attachments/669254/919922/kortner.pdf
- https://www.desy.de/~garutti/LECTURES/ParticleDetectorSS12/L9_Tracking.pdf
- https://atlas.cern/Discover/Detector/Muon-Spectrometer