Muonic final states will provide clean signatures for many physics processes at the LHC. The two LHC experiments ATLAS and CMS will be able to identify muons with a high reconstruction efficiency above 96% and a high transverse momentum resolution better than 2% for transverse momenta below 400 GeV/c and about 10% at 1 TeV/c. The two experiments follow complementary concepts of muon detection. ATLAS has an instrumented air-toroid magnetic system serving as a stand-alone muon spectrometer. CMS relies on high bending power and momentum resolution in the inner detector, and uses an iron yoke to increase its magnetic field. The iron yoke is instrumented with chambers used for muon identification. Therefore, muon momenta can only be reconstructed with high precision by combining inner-detector information with the data from the muon chambers.

Keywords: ATLAS, CMS, LHC, muon, muon identification

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INTRODUCTION

The large hadron collider (LHC) will be the next hadron collider which will go into operation. From the year 2008 on, it will collide protons at a centre-of-mass energy of 14 TeV with a luminosity between $10^{33} \text{cm}^{-2}\text{s}^{-1}$ and $10^{34} \text{cm}^{-2}\text{s}^{-1}$ [?]. Many physics processes which are currently out of reach at the existing colliders will become accessible by the LHC. These processes range from the production of the Higgs and new gauge bosons to the production of superpartners of the known fundamental particles. All of them, however, are highly obscured by QCD reactions. The QCD reactions are usually accompanied by multiple jets in the final state and leptons of low transverse momenta. Therefore many of the interesting non-QCD processes can be detected in final states with leptons of high transverse momenta. Since muons lose very little energy on their passage through matter and are therefore the only highly energetic charged particles traversing the entire detector, muonic final states provide the cleanest signatures for the detection of new physics processes.

![Figure 1](image-url)  
**Figure 1.** Transverse momentum distribution for muons from $H$, $Z$, $A$, and $Z'$ decays as predicted by Pythia [?].
bosons with a mass of 2 TeV/c^2. As the masses of the resonances cover a range from 90 GeV/c^2 to 2 TeV/c^2, the decay muons have transverse momenta from a few GeV/c to 1 TeV/c. As a consequence, the detectors at the LHC must be able to detect and identify muons over this large transverse momentum range.

Yet the main source of muons are mesons as can be concluded from the inclusive muon cross sections in Figure 2. The cross sections presented there depend on the hermicity and density of the calorimeters of the detector; the detectors under discussion in this article have similar cross sections. Most of the muons with transverse momenta \( p_T < 10 \) GeV/c are from the decays of charged pions and kaons in the final state of the initial proton-proton collision. At \( p_T \approx 10 \) GeV/c, decays of \( b \) and \( c \) mesons become the dominant source of muons. The inclusive cross sections for muons from \( W \) and \( Z \) decays are only comparable to the inclusive cross sections for muons from \( b \) and \( c \) meson decays in the region around 50 GeV/c. Muons from \( t \) quark decays are much rarer than from \( b \) and \( c \) decays. Charged pions are not only produced in the primary proton-proton collision but also during the absorption of the final state hadrons in the calorimeters. The pions in hadron showers, however, have lower transverse momenta than the primarily produced pions. Hence the shower muons, i.e. the muons from the decays of pions in hadron showers, are very soft so that most of them cannot escape the calorimeter and remain undetected. At the LHC, shower muons are insignificant as compared to muons from the decay of pions and kaons before their interaction in the detectors. Although the muons of all the different sources can be detected as muons by the particle detectors at the LHC, it has become common practice in muon identification to identify only those muons as muons which do not emerge from pion and kaon days or hadron showers.

Two omnipurpose experiments will be operated at the LHC: ATLAS (a toroidal LHC apparatus) and CMS (the compact muon solenoid). Both experiments have a high muon detection and identification capability as will be explained in the present article.

**THE ATLAS AND CMS MUON SYSTEMS**

In the ATLAS and CMS detectors, muons are identified as those charged particles which leave a trace in the inner tracker which matches a charged track in tracking chambers mounted outside the calorimeters. Muons lose about 3 GeV of their energy on average during their passage through the calorimeters. The energy loss of muons is dominated by ionization up to muon energies of 100 GeV. As the energy lost in a single ionization is small, the overall energy loss has a small spread about its mean value. Above 100 GeV, direct \( e^+e^- \) pair production, bremsstrahlung, and nuclear losses contribute significantly to the energy loss of muons [?]. The latter two processes may relatively often lead to a single "catastrophic" energy loss comparable to the total muon energy. This causes a low-energy tail in the measured muon energy. Its spectrum still exhibits a peak with a \( \sigma \) of about 20% for \( E_\mu = 1 \) TeV. The measured muon energies
in the tail of the distribution can be recovered by means of the energy detected along the muon trajectory in the calorimeter.

The energy of a muon at the exit of the calorimeters is therefore equal to the energy of the muon plus its well calculable energy loss in the calorimeters with a relative accuracy of about 1% for muon energies above 10 GeV.

**FIGURE 3.** Sketch of the ATLAS detector on the left and the CMS detector on the right.

Both ATLAS and CMS have the capability of measuring the energies of the muons in the muon systems. They differ, however, as in the accuracy of the designs of the detectors follow different strategies. Sketches of the ATLAS and CMS detectors are shown in Figure 3. Both detectors have the typical structure of collider detectors: an inner tracking detector in a solenoidal magnetic field surrounded by electromagnetic and hadron calorimeters which are themselves enclosed in a muons system.

The muon system of ATLAS is designed to be able to measure muon momenta with high accuracy independently of the inner detector. It uses a system of eight superconducting air-core toroid coils, which produces a toroidal magnetic field of 0.4 T on average in the muon system. The air-core structure was used to minimize the amount of material the muons have to traverse in the muon spectrometer, hence to minimize multiple scattering of muons in the muon spectrometer. The deflections of the muons in the barrel part of the spectrometer are measured by three layers of tracking chambers with 2.5 m interspace. The inner and outer layers are attached to the toroid coils, the middle layer is mounted in the middle of the coils. The endcap part of the muon chambers consists of three disks of tracking chambers at 6 m interspace with the two inner disks enclosing the endcap toroid system (see Figure 3). The sagittae of curved muon trajectories in the spectrometer are of the order of \( \sigma = 0.5 \times 10^{-3} \) m, thus 0.5 mm for \( p = 1 \text{ TeV} / c \). In order to measure the sagitta of 0.5 mm for 1 TeV muons with an accuracy of 10%, ATLAS uses monitored drift-tube chambers which have a spatial resolution better than 0.040 mm. An optical alignment system is used to monitor the geometry of the muon spectrometer with 30 \( \mu \text{m} \) accuracy. Since the monitored drift-tube chambers have a maximum response time of 700 ns and are therefore slow compared to the 25 ns bunch-crossing frequency of the LHC, resistive-plate chambers in the barrel part and thin-gap chambers in the endcap part of the muon spectrometer are used for triggering. The trigger chambers have a response time below 10 ns and are therefore capable of assigning the measured muons to the correct bunch crossing. The muon spectrometer is capable of detecting muons up to pseudorapidities of 2.7.

In the design of the CMS detector great emphasis is given on a very high momentum resolution of the inner detector. The momentum resolution is inversely proportional to the bending power inside the inner detector. A magnetic field strength of 4 T in the inner detector is achieved by amplifying the magnetic field with a large iron yoke embedding the superconducting solenoid coil. For comparison: as ATLAS abstains from an iron yoke, the magnetic field in the inner detector of ATLAS is only 2 T. The return yoke of the CMS solenoid is instrumented with four layers of muon chambers. As the momentum resolution of the CMS muon system is dominated by multiple scattering of the muons in the iron yoke, tracking chambers with a lower spatial resolution (\( \approx 70 \mu \text{m} \)) than in ATLAS can be used. Drift-tube chambers with 400 ns response time are used in the barrel part of the CMS muon system, cathode strip chambers with 50 ns response time in the endcaps. Like in ATLAS, fast trigger chambers are needed to identify the detected muons with the right bunch crossing of the LHC. Resistive-plate chambers are used throughout the whole CMS muon system for triggering. The CMS muon system has a pseudorapidity coverage of 2.4.

The muon momentum resolutions which can be achieved in stand-alone mode of the ATLAS and CMS barrel muon systems are shown in Figure 4. The ATLAS muon spectrometer has a high transverse momentum resolution between 2 and 4% for transverse muon momenta \( p_T^\mu \leq 300 \text{ GeV} / c \). The \( p_T^\mu \) resolution reaches 12% for \( p_T^\mu = 1 \text{ TeV} / c \). Energy loss fluctuations only influence the momentum resolution at very low \( p_T^\mu \). The resolution has a lower limit of 2%.
caused by multiple scattering in the muon spectrometer. For $p_\mu^T > 300 \text{ GeV}/c$ the curvatures of the muon trajectories in the muon spectrometer are so small that the intrinsic spatial resolution of the chambers and the limited accuracy of the chamber alignment dominate the momentum resolution of the spectrometer. In the CMS muon system, the transverse momentum resolution is limited by the chambers resolution for high values of $p_\mu^T$, but multiple scattering of the muons in the iron yoke is the dominant contribution to its transverse momentum resolution up to $p_\mu^T = 400 \text{ GeV}/c$. The transverse momentum resolution is proportional to the amount of multiple scattering and inversely proportional to the bending power of the magnetic field in the muon system. The amount of multiple scattering is about 14 times larger in CMS than in ATLAS, but the bending power of the magnetic field is 5 times larger in CMS than in ATLAS such that, overall, the stand-alone transverse momentum resolution is only 3 times worse than in ATLAS.

FIGURE 5. Momentum resolution of the ATLAS and CMS detector after combining the momentum measurements of the inner detectors and the muon systems [19][20]. Left: Momentum resolution for muons in the barrel region. Right: Momentum resolution for muons in the endcap region.
The situation improves significantly after the combination of the momentum measured by the muon system with the momentum measured by the inner detector (see Figure 5). CMS achieves an overall $p_T^\mu$ resolution between 0.5 and 2% for $p_T^\mu \leq 300$ GeV/c due to the high bending power and the high resolution of the inner detector system. The bending power in the ATLAS inner detector is about half as big as in CMS and the combined muon momentum resolution is about twice poorer than in CMS. The bending power of the CMS magnet is much smaller in the endcaps than in the barrel part of the muon system which makes the stand-alone muon momentum resolution worse. The measurement of the momentum of muon flying into an endcap is totally determined by the inner detector. ATLAS profits from its high stand-alone performance and achieves a better combined momentum resolution than CMS for high $p_T^\mu$ muons in the endcaps.

MUON TRACK-RECONSTRUCTION AND IDENTIFICATION

All high momentum tracks which are recorded by the muon system of ATLAS and CMS are muon tracks. Both experiments follow the same track reconstruction strategy.

Figure 6 illustrates the track reconstruction steps in case of a muon with $p_T^\mu > 10$ GeV/C in the barrel part of the ATLAS muon spectrometer. As the trigger chambers have a much lower granularity and simpler geometry than the precision chambers, their hits can easily be used to define a so-called "region of activity" through which the muon must have passed. In the second step of the track reconstruction, straight segments are reconstructed in the precision chambers within the region of activity. The local straight segments of the region of activity are then combined to a curved candidate trajectory which is finally refined by a global refit of the hits lying on the candidate trajectory.

The combination of the trajectory found in the muon system with a matching trajectory in the inner detector serves two goals: (1) the improvement of the momentum resolution, especially in case of CMS where the stand-alone muon momentum resolution is poor compared to the momentum resolution of the inner detector; (2) the rejection of muons from pion and kaon decays. The mother pions and kaons of the muons have decays lengths of a few metres. Thus most of them leave a long trace in the inner detector before they decay. Since considerable parts of the energies of the mother pions or kaons are carried away by neutrinos, the energies of the decay muons is significantly lower than the energies of their mothers and the momentum of the inner-detector track is in mismatch with the muon-spectrometer track. Therefore muons from pion or kaon decays can be rejected by requiring a good match of the corresponding inner-detector and muon-spectrometer trajectories.

FIGURE 6. Track reconstruction in the barrel of the ATLAS muon spectrometer.

The procedure described above cannot be applied to muons of $p_T^\mu < 10$ GeV/C because their trajectories do not extend to the outermost layers of the muon systems. In case of CMS, they are absorbed by the iron yoke before; in case of ATLAS, the magnetic field in the spectrometer is strong enough to bend them away from them. So the reconstruction starts with a low-momentum inner-detector track in the same solid angle as segments found in the muon system, extrapolates it to the muon system, and the segments lying on the extrapolation are selected. The number of these segments, their length and position must be compatible with the momentum of the inner-detector track. This requirement rejects muons from pion and kaon decays. Pions and kaon decaying in the calorimeters deposit much more energy in the calorimeters than muons which are minimum ionizing particles. One therefore also requires that
the energy deposited along the extrapolated inner detector trajectory in the calorimeters is compatible with the muon hypothesis. Monte-Carlo studies \cite{1}\cite{2} show that an efficiency $>80\%$ and a fake rate $<0.5\%$ can be achieved for muons of $p_T^\mu > 5 \text{ GeV/c}$ in both experiments.

Figure 7 summarizes the muon identification efficiency of ATLAS and CMS. The two experiments achieve the same track-reconstruction efficiency, namely about $90\%$ for $5 < p_T^\mu < 20 \text{ GeV/c}$ and $>96\%$ for $p_T^\mu > 20 \text{ GeV/c}$ at a fake rate $<0.5\%$.

![Figure 7](image)

**FIGURE 7.** Muon identification efficiency of ATLAS\cite{3} and CMS \cite{4}.

This result is particularly difficult to achieve in case of ATLAS. Simulations \cite{5}\cite{6} show that, different from CMS, a sizeable amount of low-energy neutrons leaks out of the calorimeters into the muon spectrometer. These neutrons excite nuclei in the entire experimental hall of ATLAS such that the muon spectrometer is operated in a huge neutron and $\gamma$ background. This background leads to occupancies of up to $20\%$ in the precision chambers, but less than $0.3\%$ in the trigger chambers due to their much shorter response time. The low occupancy of the trigger chambers is responsible for a reliable determination of the regions of activity in the track reconstruction in the muon spectrometer. Test-beam studies \cite{7}\cite{8} and Monte-Carlo simulations \cite{9} show that efficient track reconstruction in the precision chambers is possible under these circumstances.

**SUMMARY**

Leptonic and especially muonic final states are best suited for physics discoveries at the LHC. The two omnipurpose experiments ATLAS and CMS which will be operated at the LHC are capable of detecting and identifying muons with an efficiency $>90\%$ and a fake rate $<0.5\%$ over a wide muon momentum interval of $5 < p_T^\mu < 1 \text{ TeV/c}$. Both experiments achieve a $p_T^\mu$ resolution $<12\%$ over the whole momentum range.

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