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Lepton and photon reconstruction and identification performances in ATLAS and CMS in Run II

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Leptons and photons are not only important for precision physics analyses (e.g. $H \rightarrow \gamma\gamma$), but also are very important handles for a vast number of beyond the Standard Model (BSM) searches. It is important to have a good understanding about their reconstruction, identification and energy scale and resolution. This proceeding summarises the lepton and photon performance results from the two multi-purpose experiments at the Large Hadron Collider (LHC), *viz.*, ATLAS and CMS, using the full Run 2 dataset. In addition, CMS has recently performed the re-calibration of the full Run 2 dataset (referred to as the "Legacy ReReco") with improved detector description in the simulation and updated calibration, alignment etc., in data. Results on electron and photon performances from the Legacy ReReco dataset are shown for the year 2017 and compared with the last available dataset of 2017 (referred to as the "End Of the Year (EOY) ReReco"). In this report, only the results are presented. Detailed description can be found in the references therein.

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1. The ATLAS and CMS experiments

The ATLAS and the CMS detectors are two multi-purpose apparatuses at the Large Hadron Collider (LHC) with a very broad physics program ranging from precision physics analyses to BSM searches. There are differences in the way the two detectors are constructed but the general layout is the same. The main differences between the two detectors are the following:

- The inner tracking system of ATLAS is silicon + transition radiation tubes. Whereas, for CMS, it is an entirely silicon-based system.
- The electromagnetic calorimeter (ECAL) of ATLAS is longitudinally segmented and is made of liquid Argon. For CMS, the ECAL is homogeneous and is made entirely of lead tungstate crystals ($PBWO_4$).
- In ATLAS, a 2 T superconducting solenoid surrounds the tracking system. In CMS, a 3.8 T superconducting solenoid surrounds the tracking as well as the calorimeter (electromagnetic and hadronic) system. In addition, ATLAS uses a toroid magnetic field as a part of the muon spectrometer.

2. Legacy ReReco of 2017 dataset of CMS

CMS recently re-calibrated the full Run 2 dataset. As a result of this, the ECAL resolution has improved considerably leading to an improvement by $\sim 43\%$ for $|\eta| > 2$ as shown in Figure 1 on the left, which shows the comparison between the resolutions of Legacy ReReco dataset and EOY dataset for 2017. Also, the simulation now describes the data well. Figure 1 on the right shows the agreement between data and simulation for the Legacy ReReco of 2017 dataset, of the variable f_{brem} which is the fraction of momentum lost in the tracker as a result of crossing various tracker layers [1].

3. Electron and photon performance

In both the ATLAS and CMS detectors, information from the ECAL and tracker are used to reconstruct electrons and photons. In ATLAS, the reconstruction of electrons is done by matching the tracks from the inner detector (tracker) with the topologically connected clusters in the ECAL [2]. In CMS, electron reconstruction starts by first forming small clusters of ECAL hits and then collecting these small clusters into the so called "superclusters" which take into account the energy spread due to bremsstrahlung and pair production [1]. In both the experiments, converted photons are reconstructed by dedicated algorithms [3]. Different physics analyses with final states of electrons and/or photons may have different physics needs. Some analyses would benefit with a loose criteria on the identification (ID) variables and others with a tighter ID. Keeping this in mind, both the experiments usually have 3 working points (WP) for electrons and photons: Loose, Medium and Tight ID. In ATLAS, for electrons, these WPs are optimised using a likelihood-based method combining the information from ECAL and the tracker [4]. Whereas for photons, the WPs are optimizd using cut based approach. In CMS, the WPs for electrons and photons are optimised

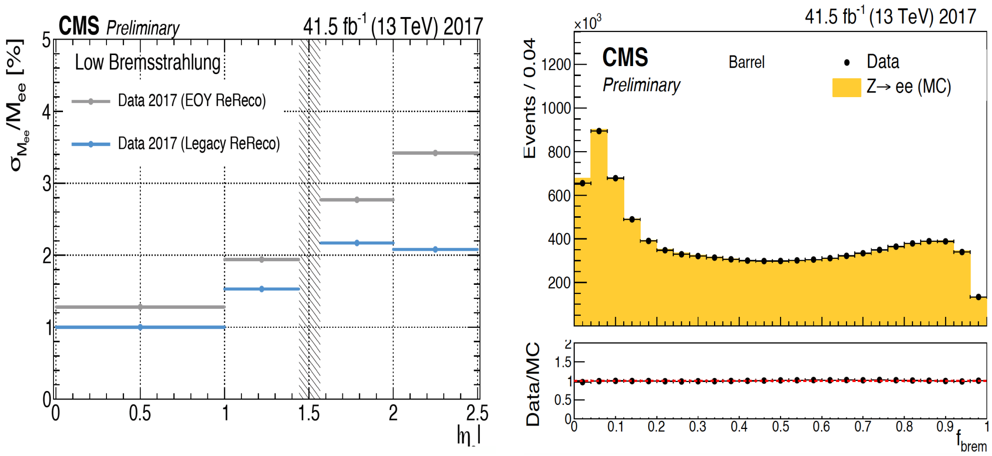

Figure 1: Comparison of di-electron mass resolution from "Legacy ReReco" to that in the "EOY ReReco" is shown on the left. There is more than 40% improvement in the resolution in the highest η bin. Distribution of the fraction of the momentum lost by bremsstrahlung between the inner and outer parts of the tracker for electrons from Z-boson decays in the ECAL barrel in the "Legacy ReReco" dataset is shown on the right.

using cut-based approaches. In addition to the cut-based approaches, multivariate analyses (MVA) approaches are also used to form MVA based ID WPs.

Figure 2 shows on the top (bottom), the electron MVA ID (photon loose ID WP) efficiency in data, for a WP of 90% signal efficiency and the related data/simulation scale factors (SFs) in CMS comparing the EOY ReReco with the Legacy ReReco. As can be seen, the SFs in the Legacy ReReco become much closer to 1. The efficiencies in data are estimated using the tag and probe method with $Z \to ee$ electrons with $p_T > 20$ GeV.

In ATLAS, the efficiencies are separated into identification and isolation efficiencies. For electrons, the tag and probe method is used to determine the efficiency and the SFs using $Z \to ee$ electrons for $p_T > 15$ GeV and J/ψ for $p_T < 15$ GeV. In the case of photons, the following three methods are used to determine the efficiencies in data: inclusive photons, photons radiated in $Z \to \ell\ell\gamma$ and $Z \to ee$ electrons, and a method that transforms the electron shower shapes to resemble the photon shower shapes [4]. Figure 3 shows the electron (photon) ID efficiency (left) and isolation efficiency (right) on the top (bottom) for various WPs for electrons (photons). SFs are mostly within 5%. The discontinuity in electron ID efficiencies for $p_T < 15$ GeV is due to a known mismodeling of the variables used in the likelihood discriminant [4].

3.1 Electron and photon energy calibration performance

Various corrections are derived in simulation and applied to data to account for the energy losses in the tracker material and gaps within the calorimeter. The corrected energy still has disagreement between data and simulation. Consequently, the energy scale in data $Z \to ee$ events is adjusted to match that in the simulation, whereas, the resolution in simulation is smeared to match that in data. Figure 4 shows the comparison of invariant mass of the di-electron system in simulation with that in the data for both ATLAS (left) and CMS (right). For CMS, it is shown for the Legacy ReReco dataset. The scale uncertainties in ATLAS and CMS range from 0.04% to 0.2% [5, 6]. CMS

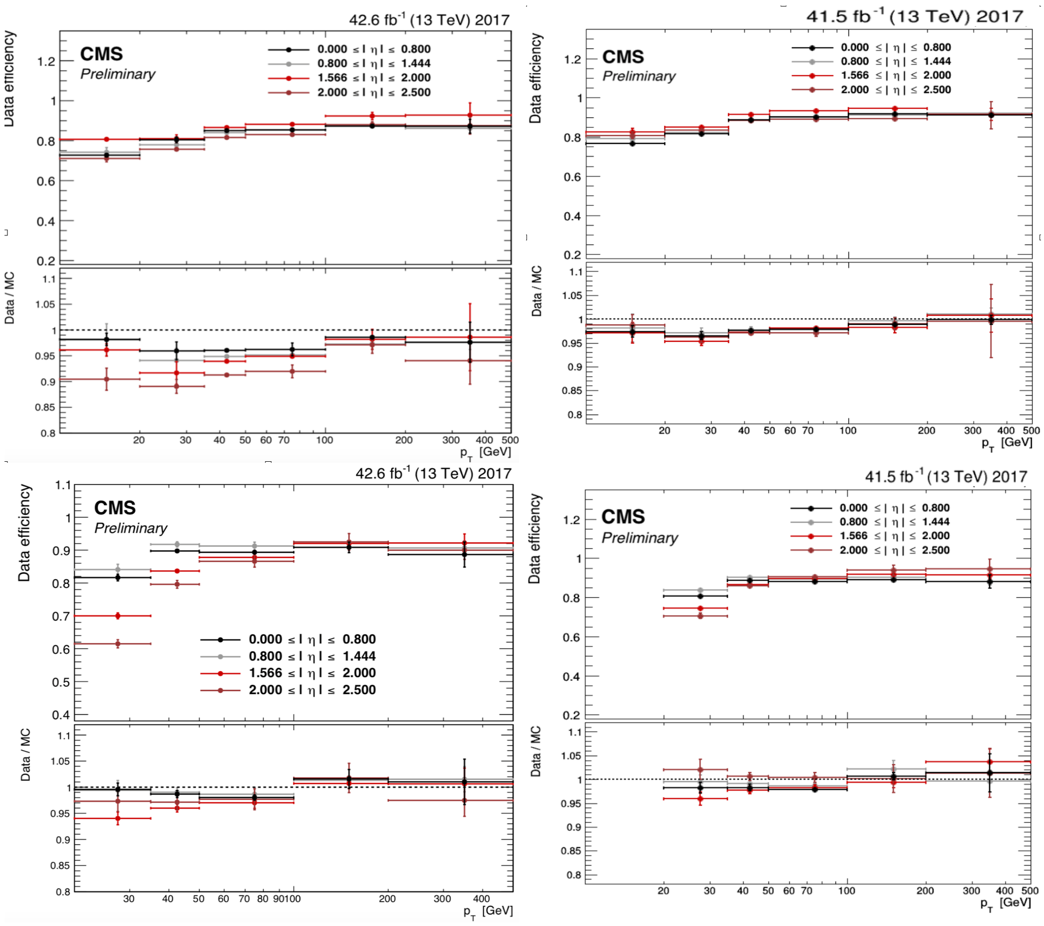

Figure 2: Electron ID efficiency for MVA ID with WP of 90% on the top and photon loose ID efficiency on the bottom. Left plot is for the EOY ReReco, right plot is for the Legacy ReReco for CMS. Top panel of the plots shows the efficiency in data, whereas, bottom panel shows the estimated data/simulation scale factors. It can be seen that the SFs are much closer to 1 in the Legacy ReReco dataset. The uncertainties include quadrature sum of statistical and systematic uncertainties.

additionally has dedicated p_T dependent scale corrections for precision analyses (e.g. $H \rightarrow \gamma\gamma$). With these fine-binned corrections, the precision is better than 0.2%.

4. Muon performance

In ATLAS and CMS, the muon reconstruction is performed independently in the tracker and the muon system. This information is then combined to form combined muon tracks [7, 8]. ATLAS additionally has calorimeter tagged muons, based on calorimeter energy deposit matched with the tracks in the inner detector. CMS also has standalone-muons built using only the standalone muon system and tracker muons which are built by propagating the tracker tracks to the muon system with loose matching to segments in the muon system.

ATLAS has also recently developed low p_T muon reconstruction down to 3 GeV, whereas CMS has developed high p_T muon reconstruction (typically above $p_T > 200$ GeV).

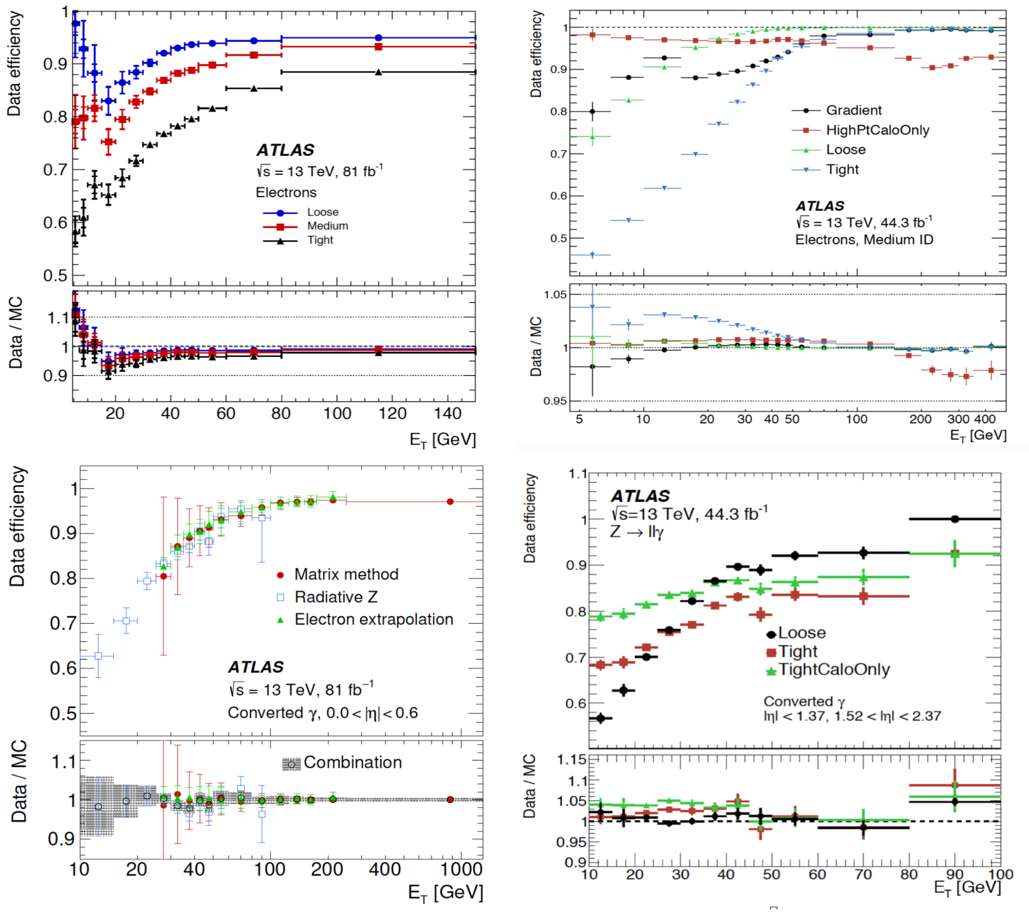

Figure 3: ID efficiency on the left and isolation efficiency on the right for various WPs in ATLAS. Top plots are for electrons and bottom for photons. Top panel of the plots show the efficiency in data, whereas, bottom panel shows the estimated data/simulation scale factors. The uncertainties include quadrature sum of statistical and systematic uncertainties.

4.1 Low p_T muon reconstruction in ATLAS

A sizeable amount of energy is lost in the calorimeters for muons with p_T <5 GeV. For such muons, track segments from inner detector are matched only to a single muon station. This ID is developed with loose requirements and a $\sim$ 20% gain in [9] efficiency is observed in $J/\psi \rightarrow \mu\mu$ events w.r.t. the medium WP, as can be seen in the Figure 5 (left). A decent agreement is seen in data and simulation as can be seen in Figure 5 (right).

4.2 High p_T muon reconstruction in CMS

High p_T muons are important for exotic searches but reconstruction can be challenging especially because showers are created at such high p_T giving rise to extra hits in the muon chambers. Thus, dedicated track-fit algorithms have been developed to exclude the hit segments produced in the muon stations where the shower happens [10]. Figure 6 (left) shows the width of the q/p_T relative residuals in cosmic ray muon data and simulation showing good agreement even at high

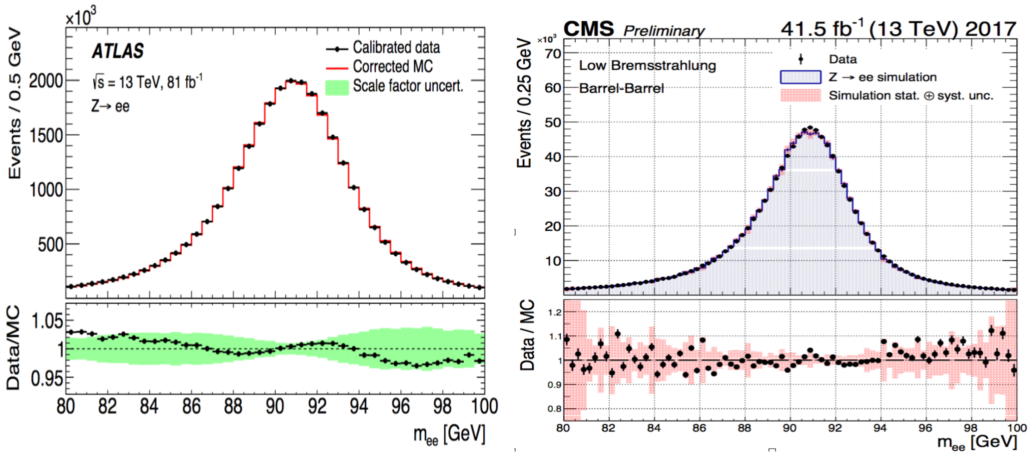

Figure 4: Invariant mass distribution of M_{ee} after the scale corrections in data and smearing corrections in simulation. Left is for ATLAS and right is for CMS.

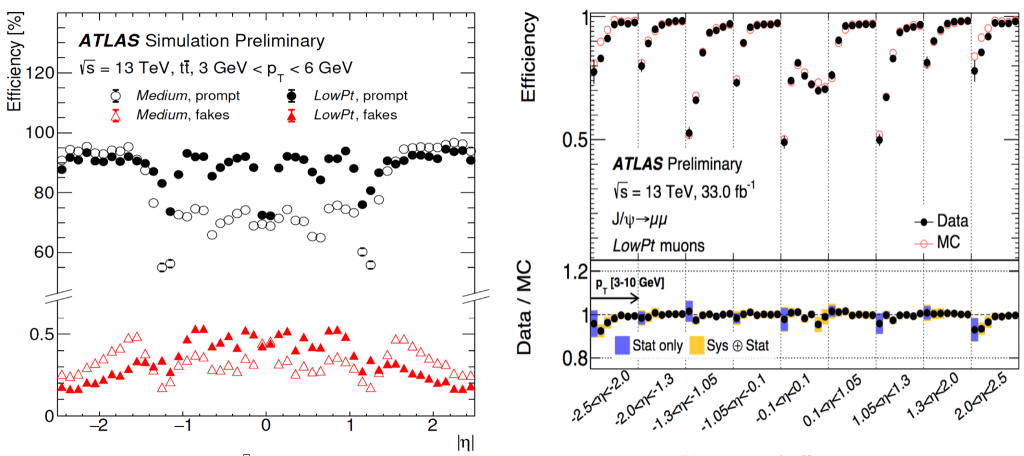

Figure 5: Left plot shows the low p_T muon ID efficiency in simulation showing a gain in efficiency for low p_T muons especially in the barrel. The efficiency is close to 90% whereas the mis-identification rate is below 0.5%. Right plot shows the estimated efficiency in data as a function of p_T in various η bins. It can be seen that the SFs are very close to 1. These plots are for the ATLAS detector.

p_T. The same figure on the right shows the ID efficiency for high p_T muons using high p_T $Z \to \mu\mu$ events. The decrease in efficiency seen in run I for $p_T > 400$ GeV is absent from run 2 high p_T muon ID. Also, the data-to-simulation SFs are quite close to 1.

5. Conclusions

The performance of lepton and photon identification algorithms for the ATLAS and CMS experiments were discussed using the full LHC Run 2 data. Latest results for the reconstruction, identification and energy scale corrections were presented comparing data with the simulation. In addition, CMS recently recalibrated the full Run 2 dataset. Results for this recalibrated dataset

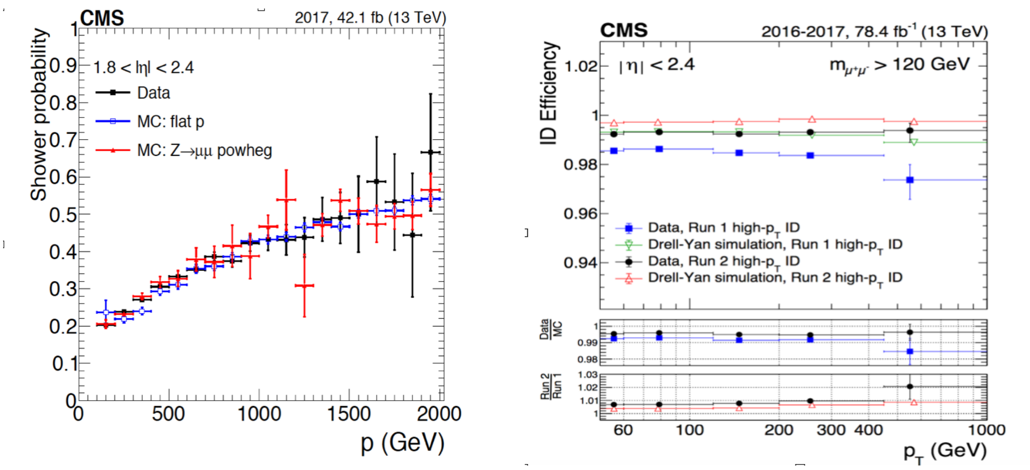

Figure 6: Left plot shows the width of the q/p_T relative residuals in cosmic ray muon data and simulation for high p_T muons in CMS. It can be seen that the right plot shows the ID efficiency for high p_T muons using high p_T $Z \rightarrow \mu\mu$ events.

(Legacy ReReco) for the year 2017 were presented and compared with the EOY ReReco dataset. In both the experiments, overall good agreement between data and simulation has been seen. Also, ATLAS recently developed low p_T muon reconstruction and identification which allows for about 90% of signal efficiency for p_T < 5 GeV muons. In addition, CMS has also improved the high p_T muon reconstruction and identification in Run 2 which gives reasonable agreement between data and simulation up to as high as 1 TeV muons.

6. Acknowledgements

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