Performance of Leptons and Photons at the LHC

LHCP 2023 Belgrade

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On behalf of CMS, ATLAS, ALICE, and LHCb

Leptons and Photons

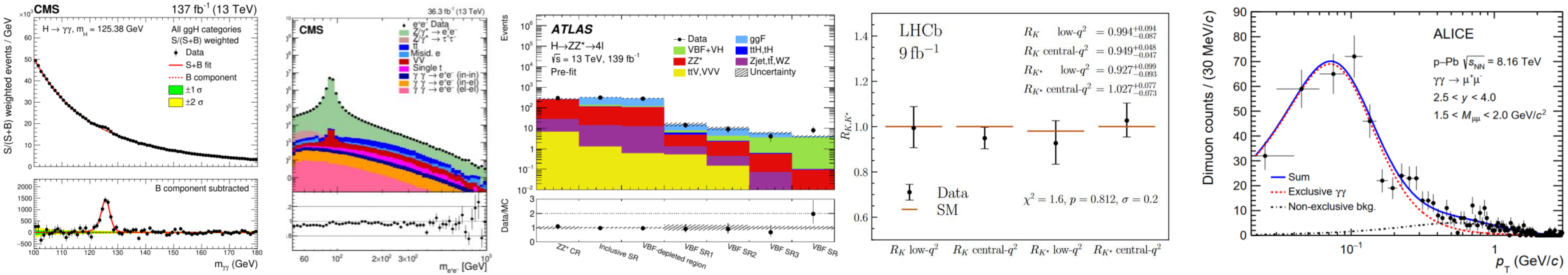
Muons

Electrons

Photons

Tau leptons

- Muons, electrons, photons, and tau leptons - are essential components of the LHC experiments' physics program.



- Without their accurate reconstruction and identification, it would be impossible to perform any measurement or search for new physics.
- Each experiment reconstructs these in not-so-different, yet characteristic ways.

The basic principle

Muons

Dedicated sub-detector to detect muons → Muon detector/spectrometer

Being charged, muons leave hits in the tracker → Tracker

Electrons

Being charged, electrons leave hits in the tracker → Tracker

Photons

Electrons & Photons deposit energy in EM calorimeter → Electromagnetic calorimeter

Tracker information is also be used for photons

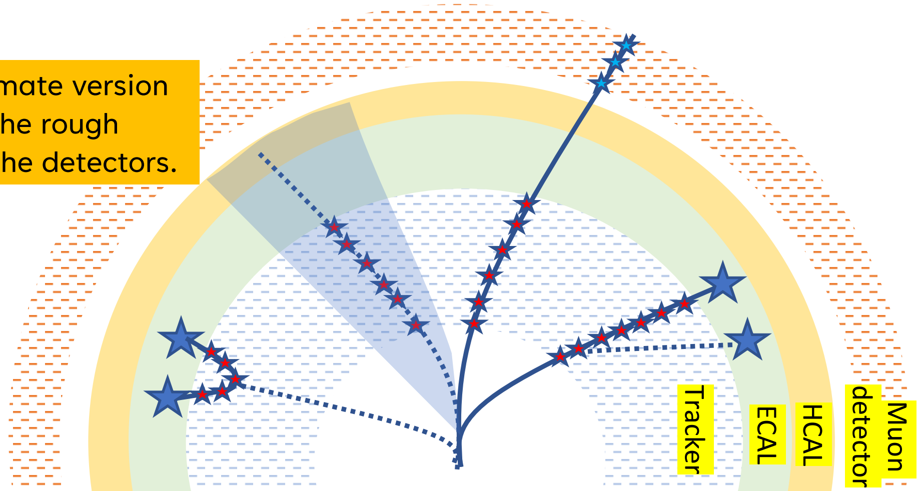
Muon detector/spectrometer | **Tracker** | **Electromagnetic calorimeter**

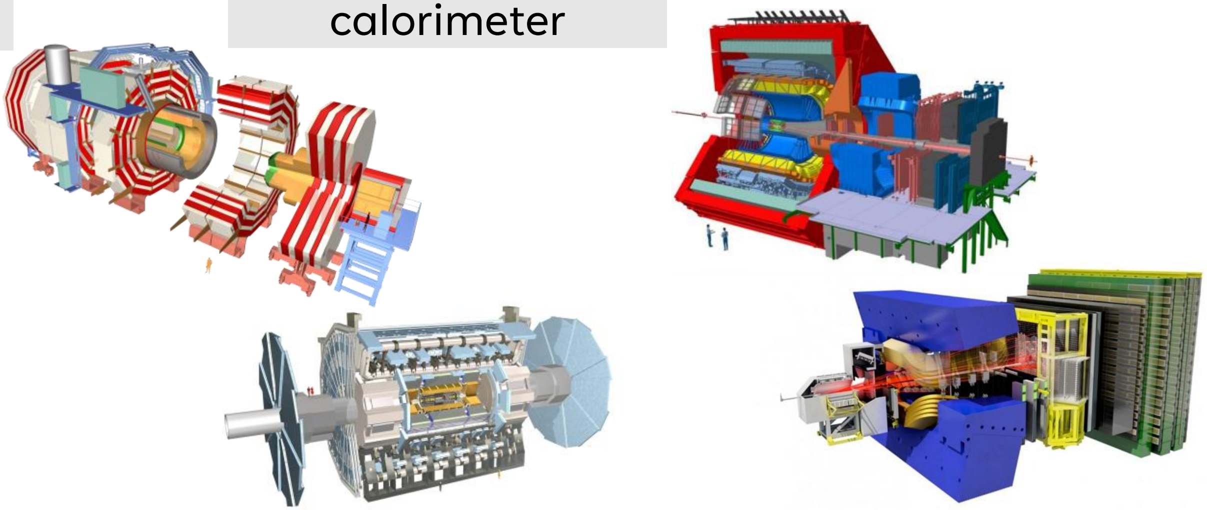
Tau leptons

Tau leptons can decay leptonically or hadronically.
(Will not be discussed in this talk)

Indirect information of other sub-detectors is also used for a full proper reconstruction.

A very approximate version of what is the rough principle of all the detectors.



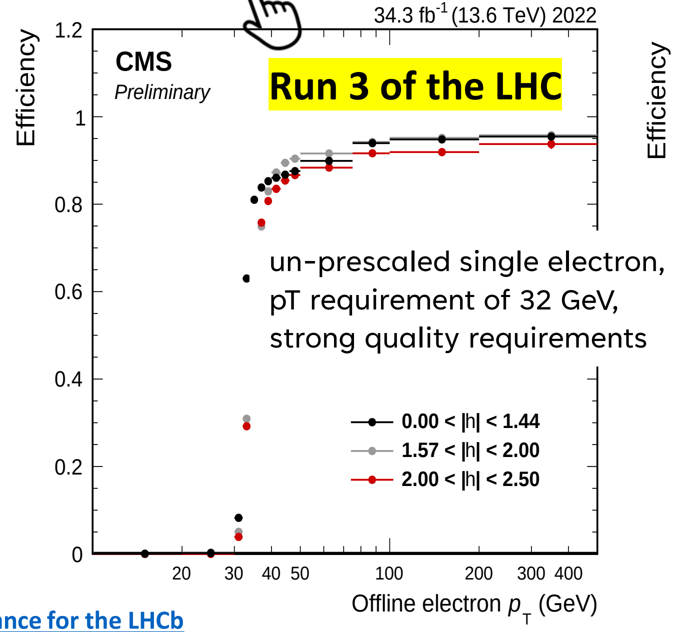


Triggering → Offline reconstruction → Identification

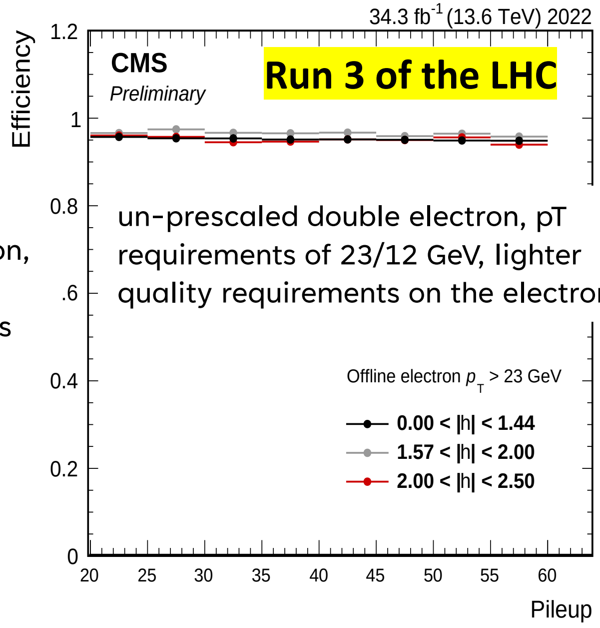
Triggering in Run 3

- The trigger system selects which collision events to record for further analysis.
- It is a somewhat toned down version of the full offline reconstruction, to quickly access data quality and physics content online at the time of collisions.
- Object requirement, machine learning, and particle ID are used to trigger the right kind of events and store them for further analysis downstream.

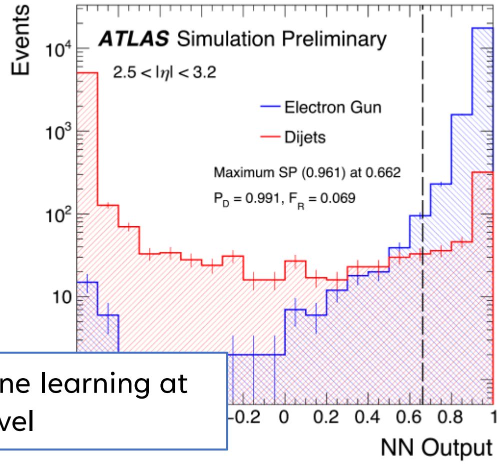
DP-2023/015



un-prescaled single electron, pT requirement of 32 GeV, strong quality requirements

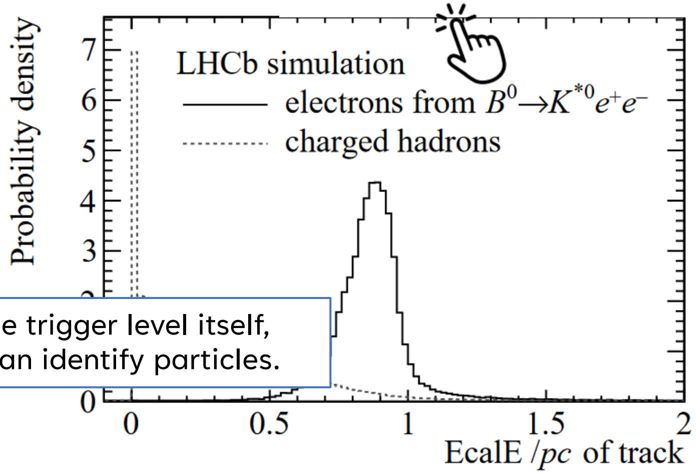


un-prescaled double electron, pT requirements of 23/12 GeV, lighter quality requirements on the electrons

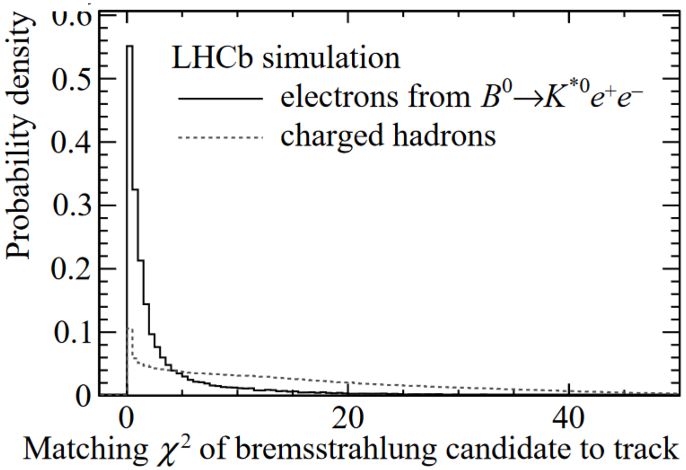


Use of machine learning at the trigger level

HLT2 reconstruction performance for the LHCb



At the trigger level itself, we can identify particles.



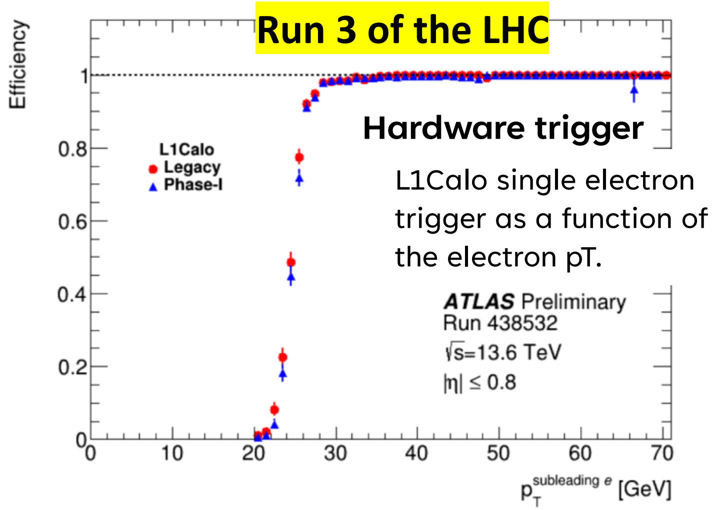
WATCH OUT!

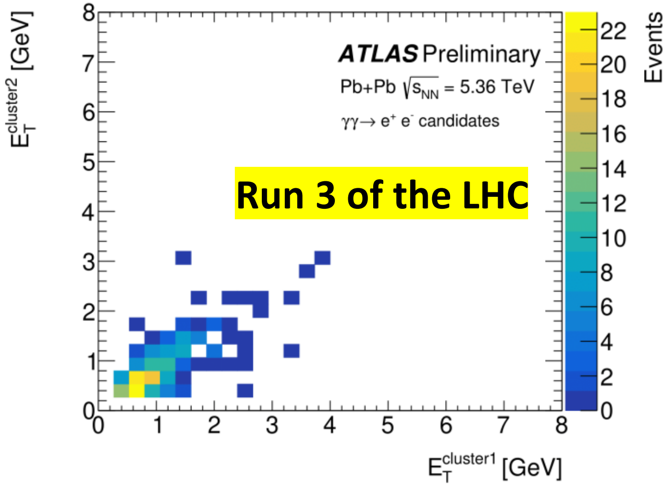
A dedicated Trigger talk by Marianna Fontana was on 23rd May: Link

Triggering in Run 3

- The trigger system selects which collision events to record for further analysis.

- Before online reconstruction of the event, information present at the hardware level can also be exploited
- These would usually require something like the presence of a certain amount of energy in the calorimeter, muon detector, etc.
- **Here you see ATLAS's electron reconstruction efficiency already at the hardware level and the correlation between the transverse energy of two calorimeter clusters corresponding to the γγ → e+e- process.**

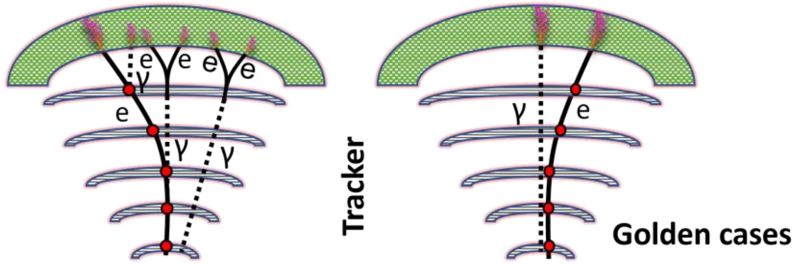




Hardware based Triggering

A dedicated Trigger talk by Marianna Fontana was on 23rd May: Link

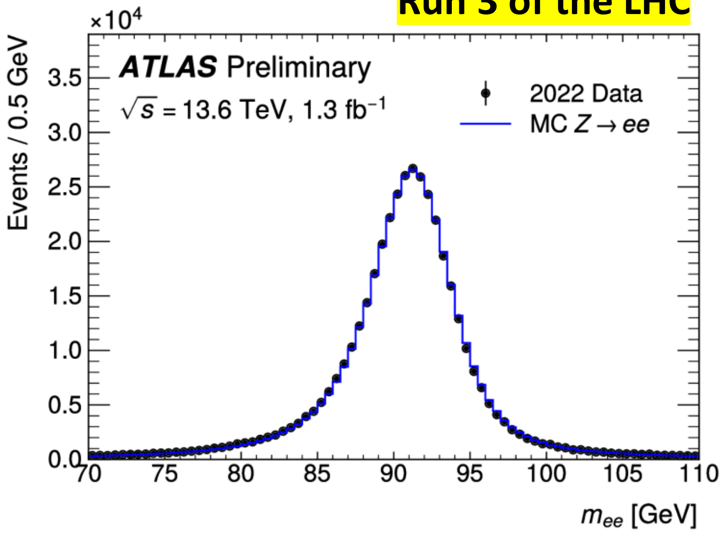
Offline reconstruction



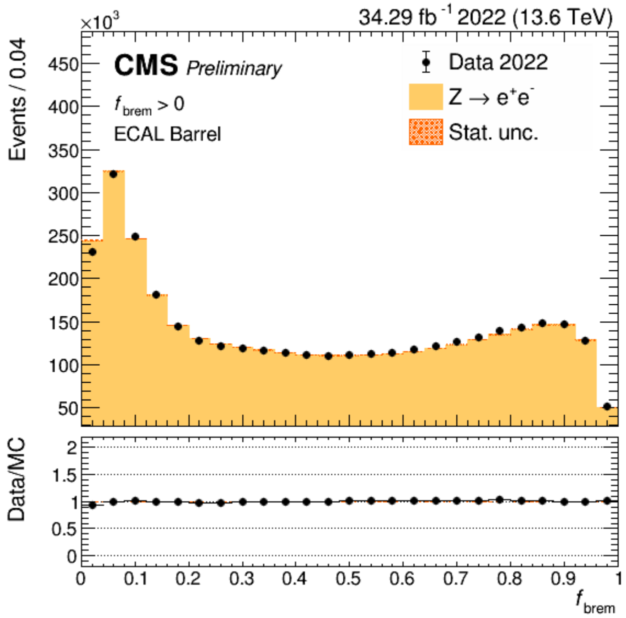
- Events that pass trigger requirements are subjected to full offline reconstruction.
- It is at this stage, analysis quality objects are reconstructed for most purposes (well mostly!)
- Leptons and Photons reconstructed at this stage

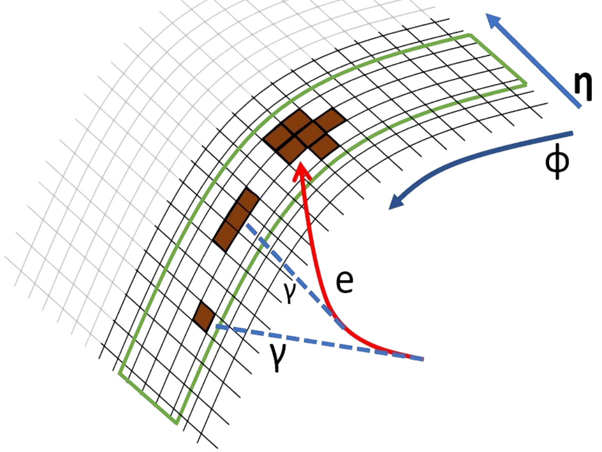
- Already after the startup of the machine, experiments at LHC have seen an excellent performance of the detectors and reconstruction algorithms in Run 3 at 13.6 TeV.
- **This is here demonstrated by the ability to reconstruct di-electron mass (shown for ATLAS) and to model momentum loss due to bremsstrahlung from electrons (shown for CMS) in Z→ee.**

Run 3 of the LHC



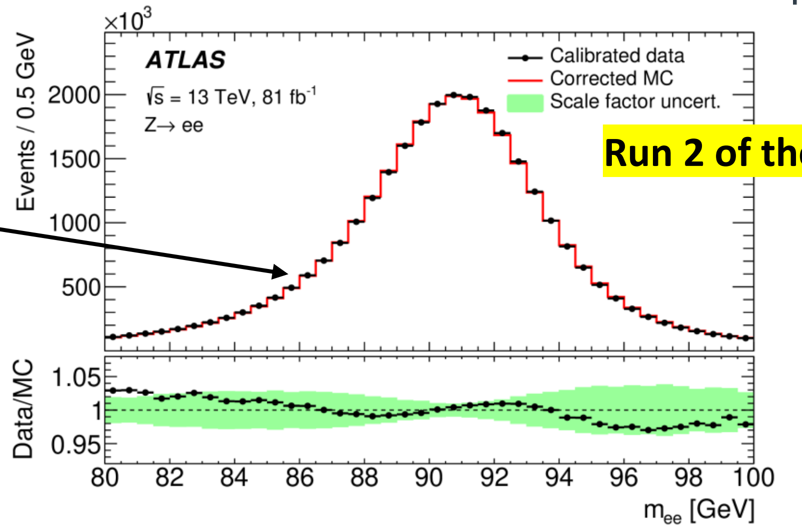
Run 3 of the LHC





Offline reconstruction

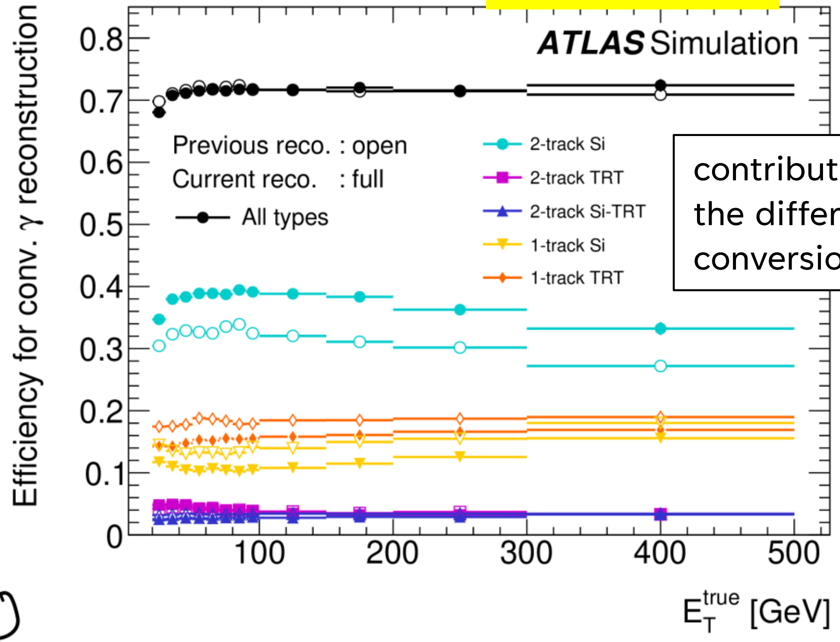
- **As the data is understood over time, it is better calibrated, and the simulation is correspondingly better corrected. Below is shown Z→ee performance of the final datasets from Run2. A similar performance can be expected for Run 3 as well.**



Run 2 of the LHC

- Photons convert due to interaction with material along its path.
- In ATLAS and CMS electrons and photons are reconstructed independently, so it may happen that the same electromagnetic cluster is used to reconstruct both an electron and a photon.
- Both CMS and ATLAS have dedicated logic to resolve the ambiguity between a photon and an electron.
- Converted photons and un-converted photons also have distinct signatures, thus allowing us to distinguish one from another.
- **Here you see the efficiency of the reconstruction of converted photons as a function of E_T^{true}**

Run 2 of the LHC



contributions of the different conversion types

JINST 14 (2019) P12006

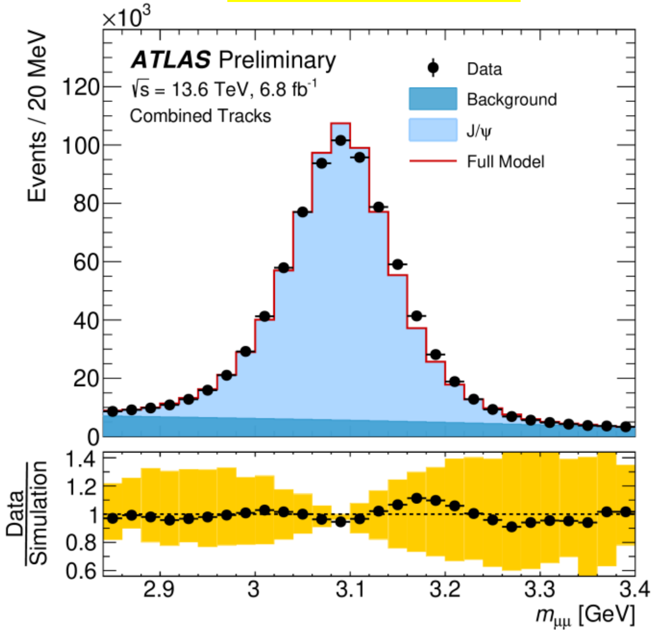
Offline reconstruction

- As the data is collected, experiments continuously monitor detector performance and commission payloads and algorithms.
- **Here you see early Run 3 muon reconstruction performance from ATLAS for low di-muon mass and high di-muon mass.**
- These were released right after data taking in 2022.

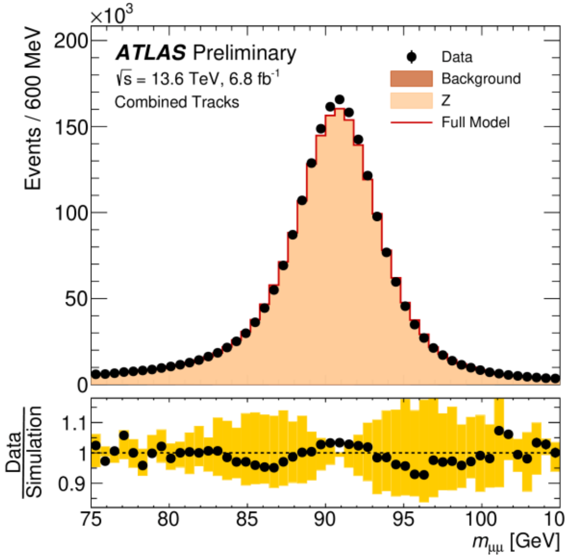
- **Due to excellent lepton/photon reconstruction, the experiments at LHC can also measure and study unique processes like Drell-Yan production in the μμγ final state.**

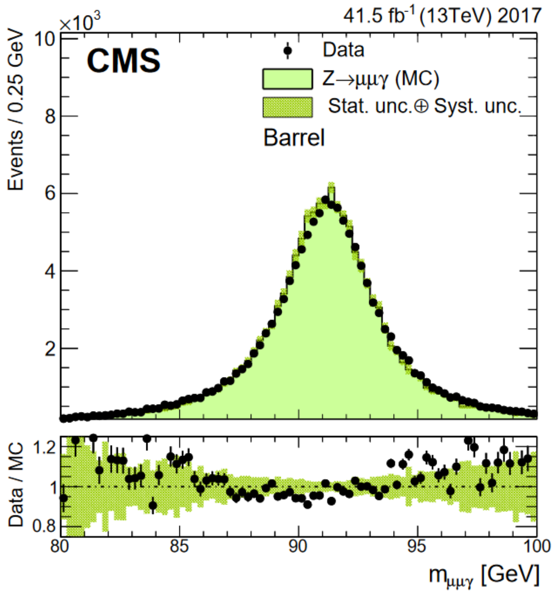
JINST **16** P05014

Run 3 of the LHC

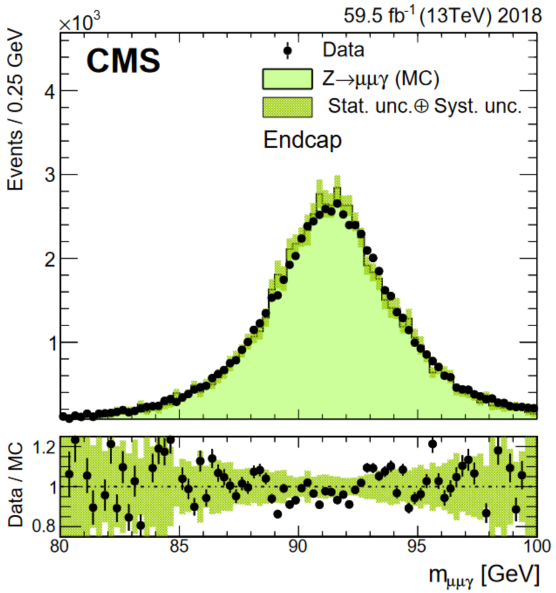


Run 3 of the LHC





Run 2 of the LHC



Early Run 3 muon reconstruction: ATLAS

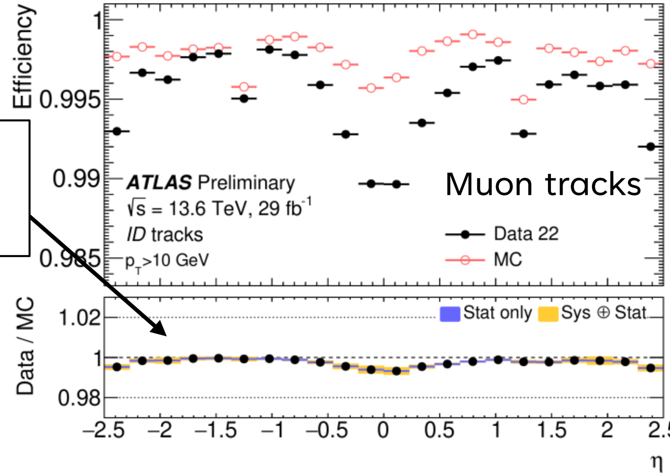
Offline reconstruction and Identification

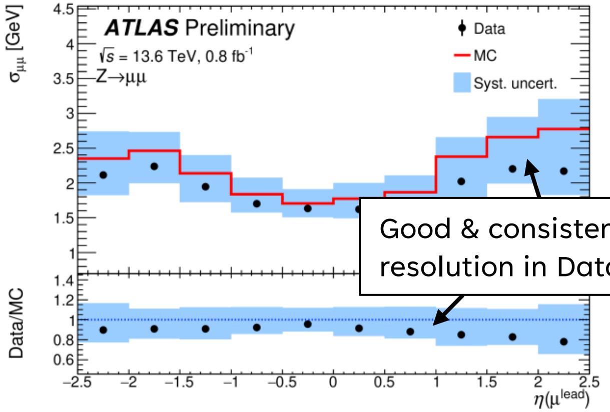
Muon reconstruction performance of the ATLAS detector in 2022

MUON-2022-01, MUON-2023-01

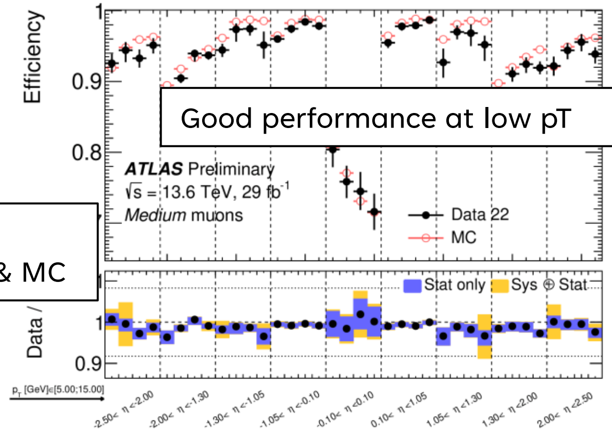
Run 3 of the LHC

Good agreement between data and MC already





Good & consistent resolution in Data& MC

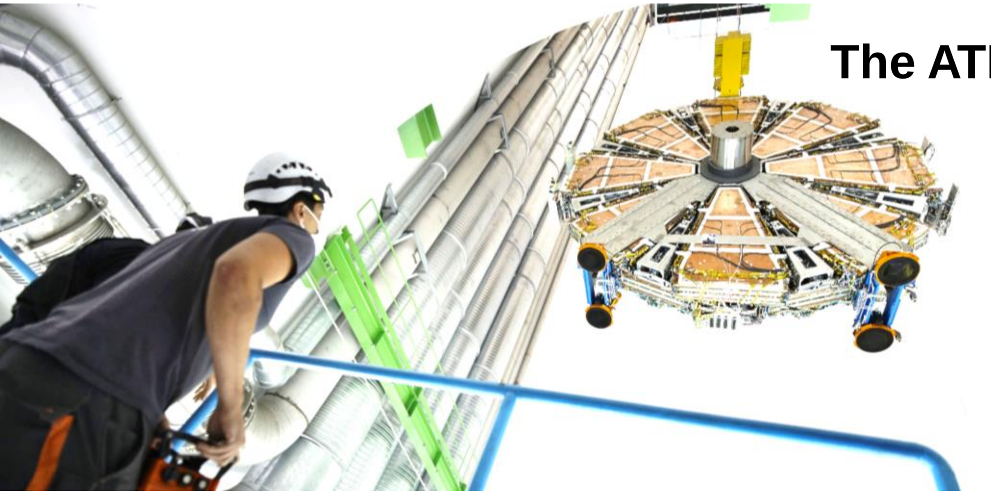


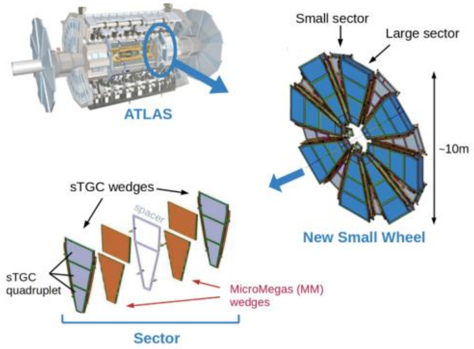
Good performance at low pT

Hardware also gets upgraded

The ATLAS New Small Wheel New Muon Stations Ready for LHC Run3

ATL-MUON-PROC-2022-003

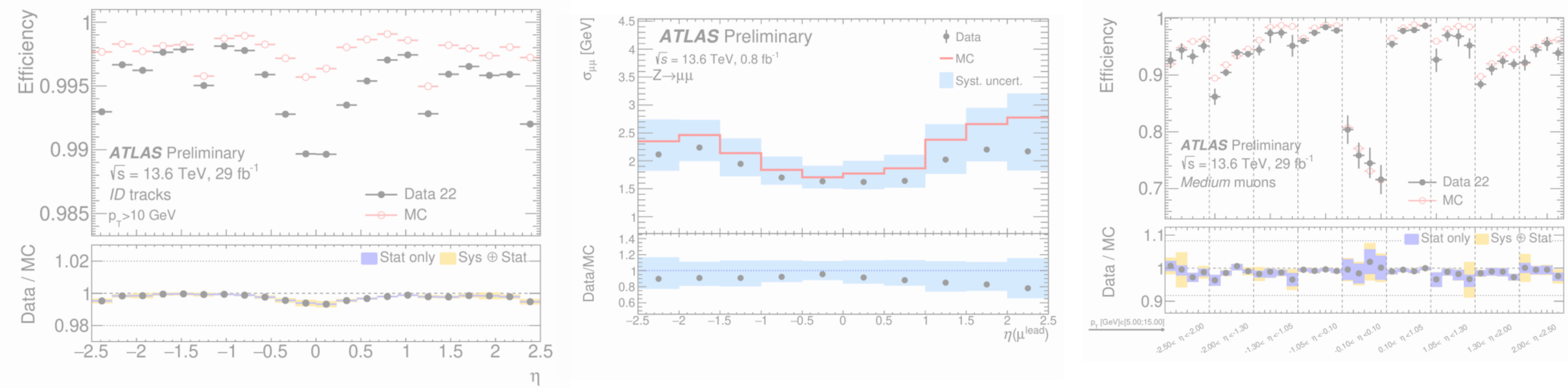




Offline reconstruction and Identification

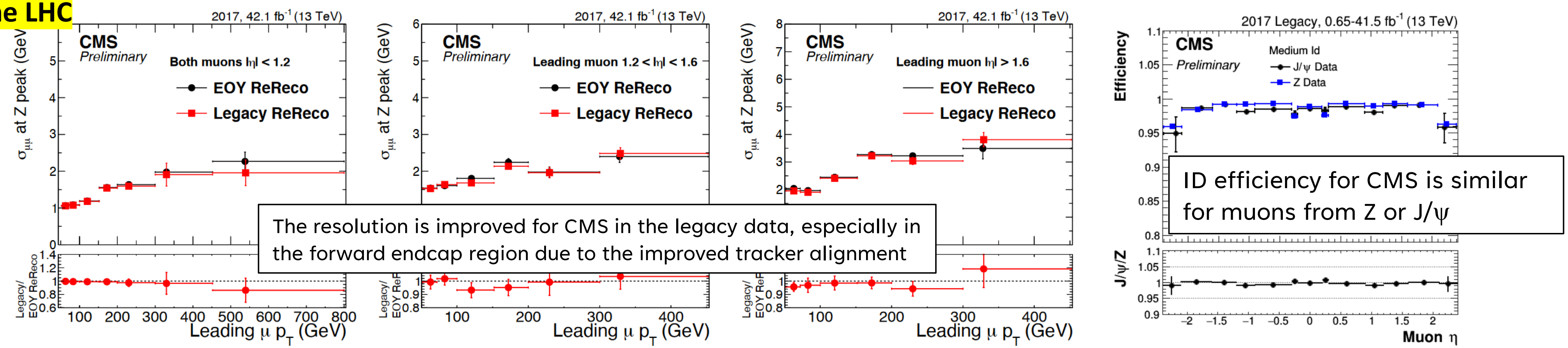
Muon reconstruction performance of the ATLAS detector in 2022 MUON-2022-01, MUON-2023-01

Run 3 of the LHC



Mass resolution usually improves as we understand the data better (from CMS in Run 2) CMS-DP-2020-040

Run 2 of the LHC



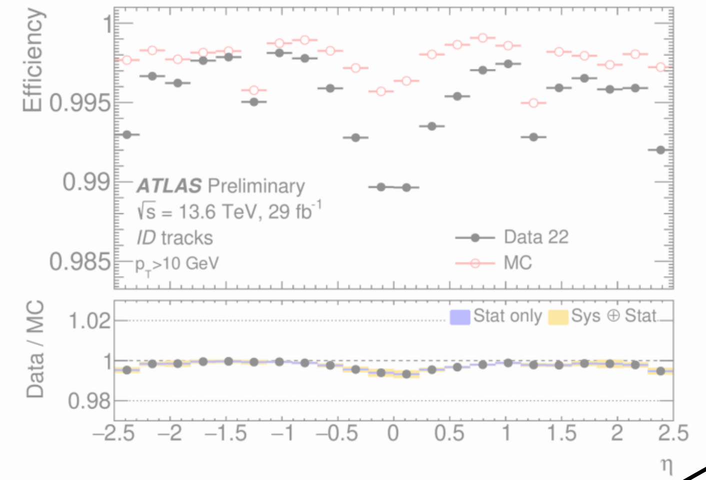
The resolution is improved for CMS in the legacy data, especially in the forward endcap region due to the improved tracker alignment

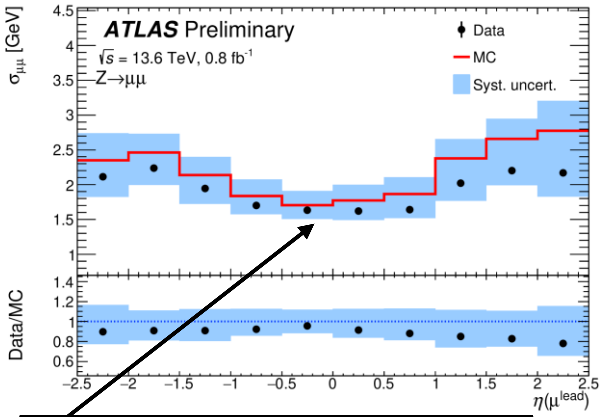
ID efficiency for CMS is similar for muons from Z or J/ψ

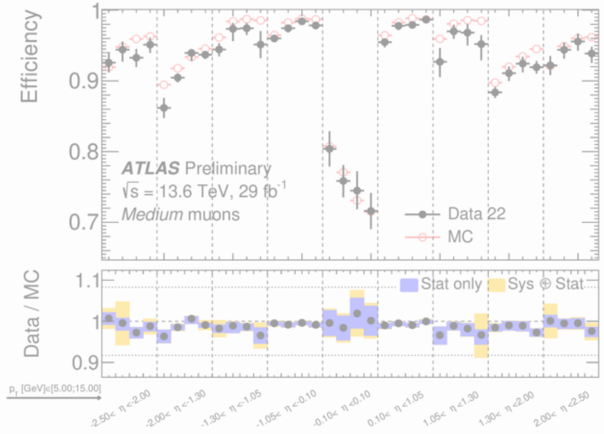
Offline reconstruction and Identification

Muon reconstruction performance of the ATLAS detector in 2022 MUON-2022-01, MUON-2023-01

Run 3 of the LHC



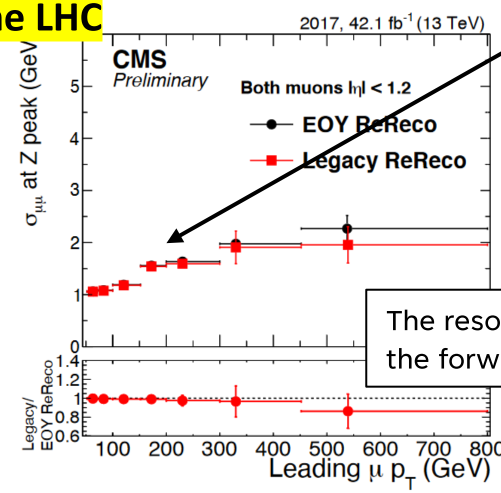


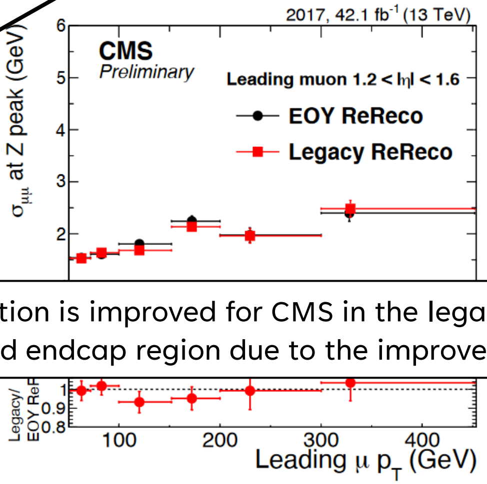


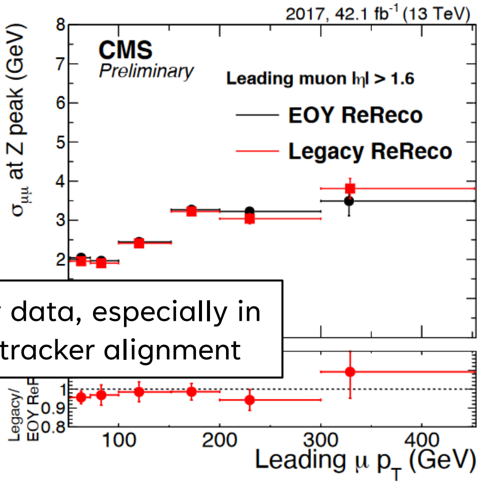
Overall resolution is very similar

Mass resolution usually improves as we understand the data better (from CMS in Run 2) CMS-DP-2020-040

Run 2 of the LHC







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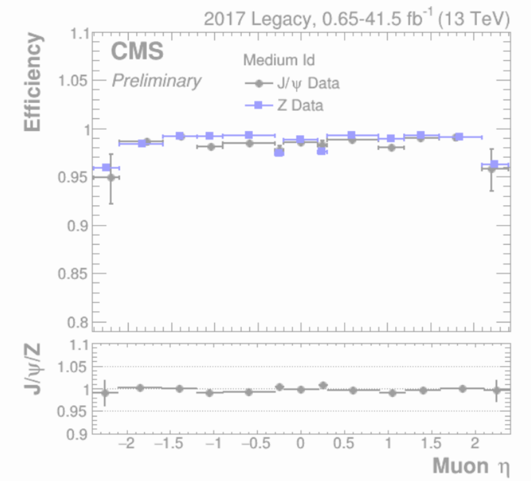
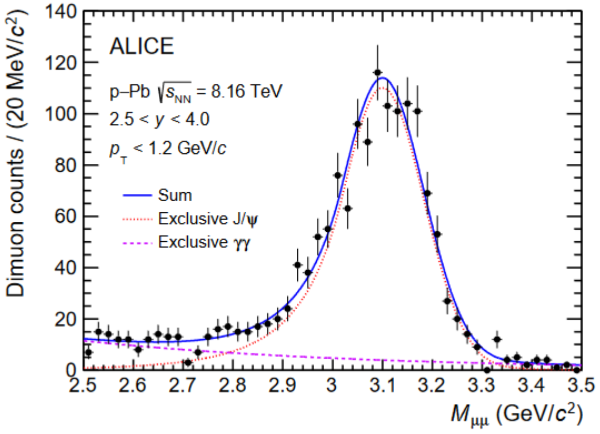
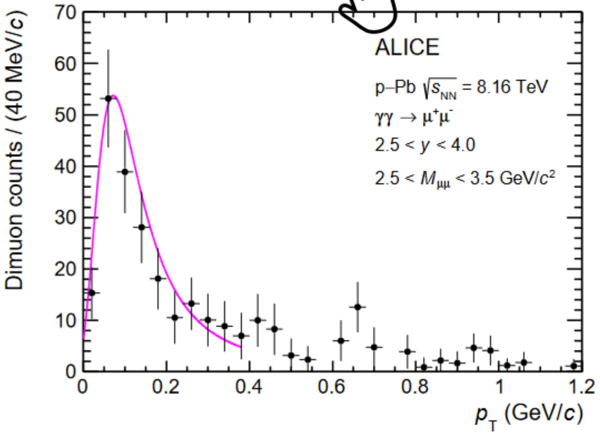


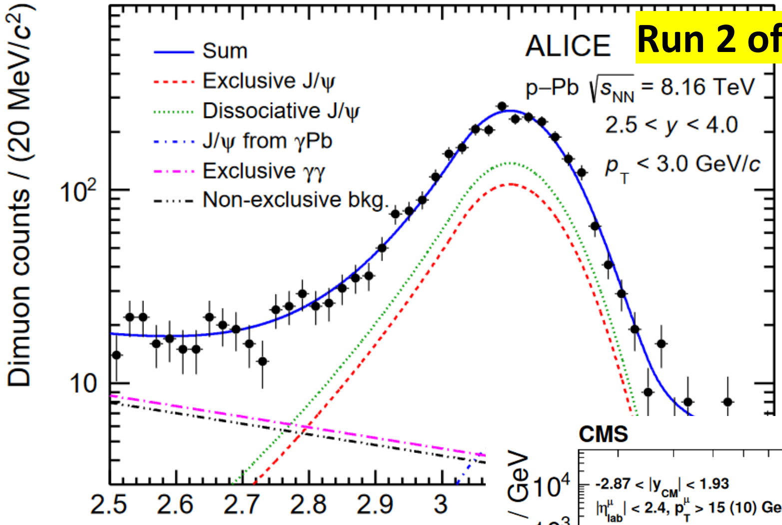
Physics with muons

- Due to excellent lepton/photon reconstruction, the experiments at LHC can also measure and study unique processes in proton-lead collisions; Drell-Yan (Shown for CMS) and J/ψ (Shown for ALICE) with dimuons.
- Both the measurements below also employ a single muon trigger to collect the right data, and thus rely not only on offline reconstruction but also proper trigger level identification of muons in a complex environment like proton-lead collisions.

CERN-EP-2023-059

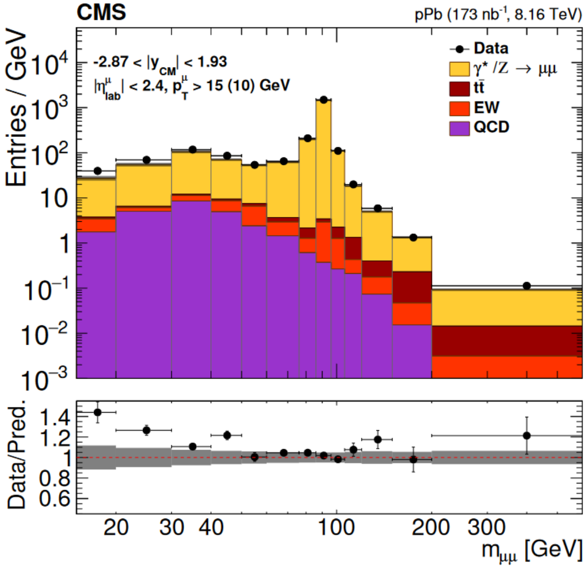






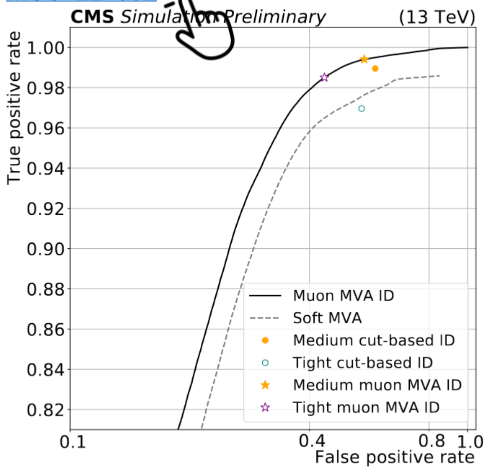
Run 2 of the LHC

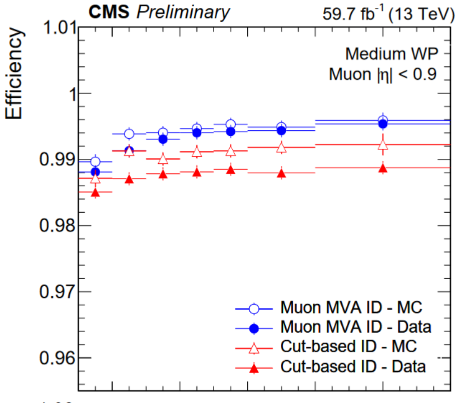
Run 2 of the LHC

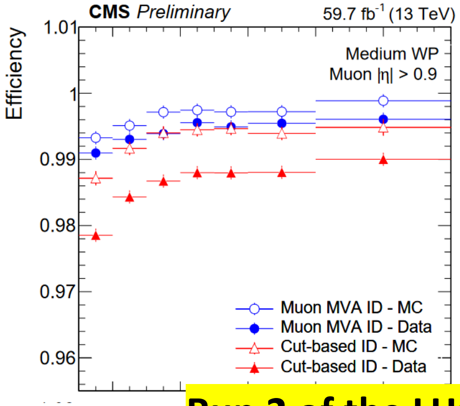


Identification of prompt and isolated muons using multivariate techniques

MUO-22-001







Run 2 of the LHC

JHEP 05 (2021) 182

New ways for Identification

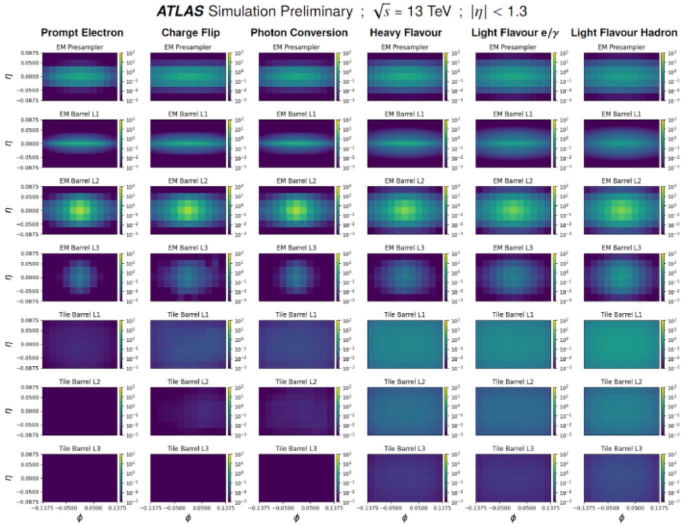
CMS Run 2 identification techniques for electrons and photons
[JINST 16 P05014]

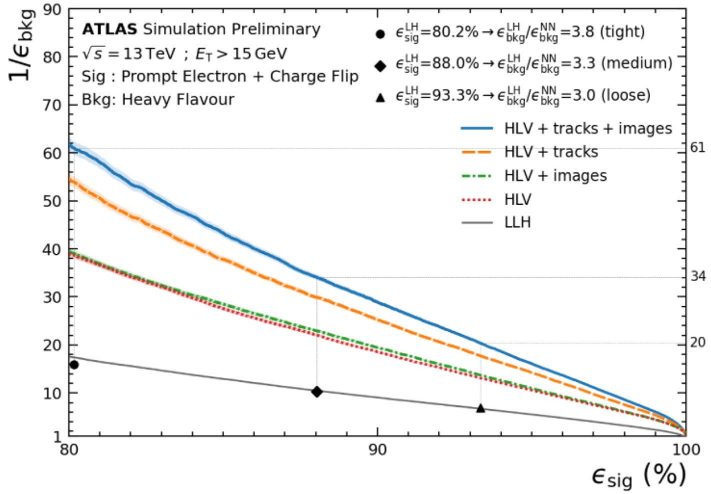
- Unintentional background can often be reconstructed wrongly as the particle of interest. It is thus crucial to properly identify the right particles.
- Experiments at the LHC rely on two main schemes for particle identification:

1) A cut-based approach, where selections are applied on the properties of reconstructed objects, and
2) Where machine learning methods are used to design discriminators and classifiers.

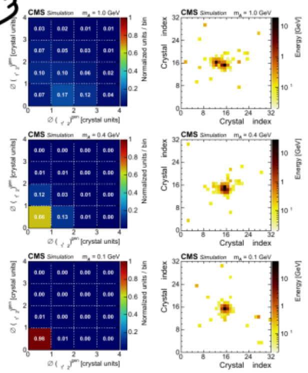
- While Run 3 criteria are still being tested and refined for analysis, a lot of work in Run 2 and Run 3 has happened in the investigation of advanced machine learning techniques to improve identification in scenarios where standard identification techniques don't work that well.

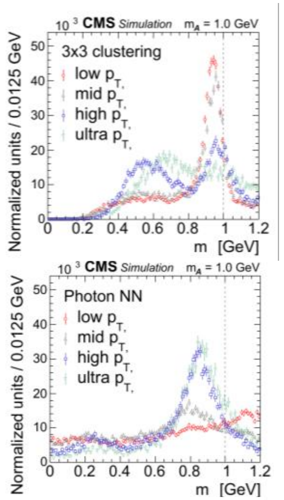
Electron Identification with a Convolutional Neural Network in the ATLAS Experiment
ATL-PHYS-PUB-2023-001

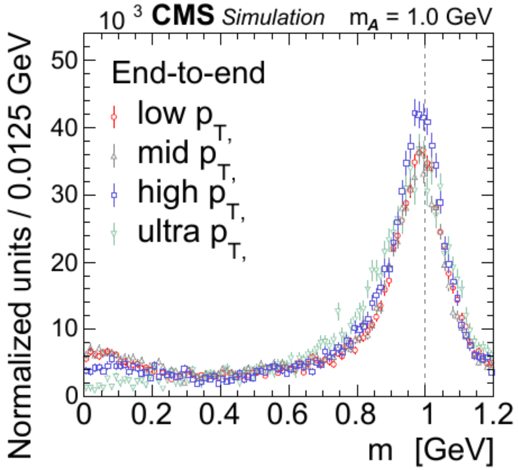




Applied to an actual search as well: Reconstruction of decays to merged photons using end-to-end deep learning
CERN-EP-2022-028



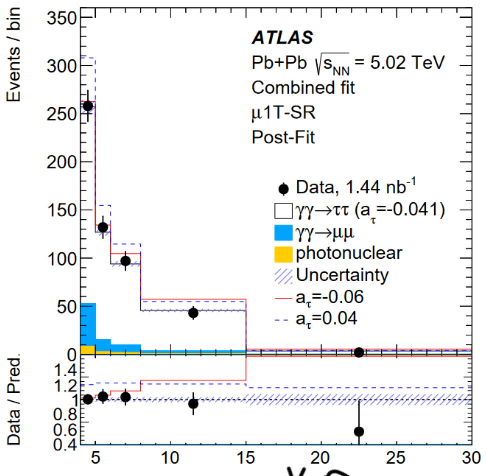




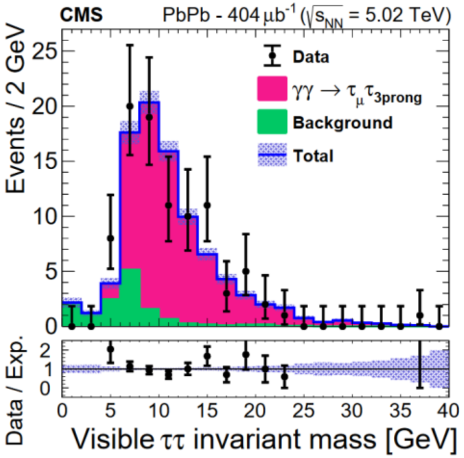
Follow Christian Sonnabend's talk today for **ALICE** and **LHCb** dedicated information
Link

Where muons and electrons meet tau leptons

- ATLAS and CMS experiments have recently measured the tau g-2 using heavy ion collisions using $\gamma\gamma \rightarrow \tau^{+}\tau^{-}$ process
- The accurate measurement of such a process, depends on the proper modeling of backgrounds from leptons such as $\gamma\gamma \rightarrow ee(\mu\mu)$.
- In fact for leptonic decays of tau leptons, the measurement directly depends on efficient lepton reconstruction



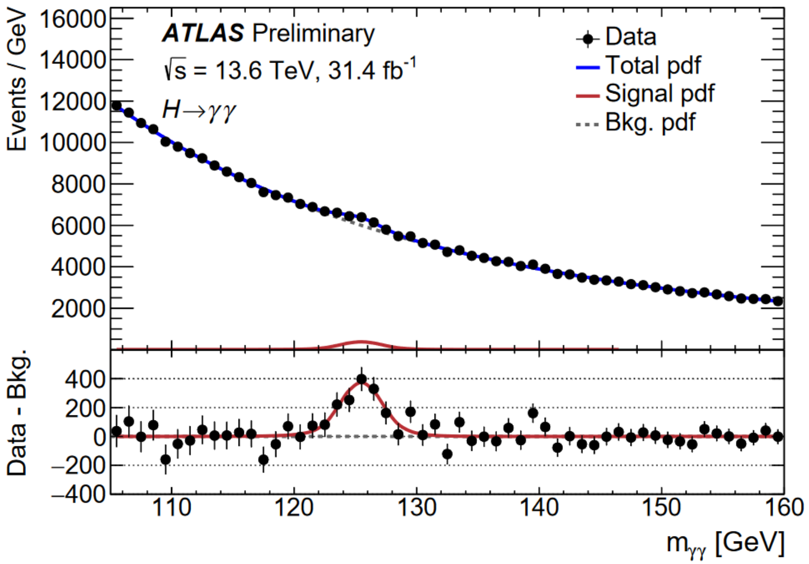
ATLAS g-2 paper



CMS g-2 paper

Early Run 3 $H \rightarrow \gamma\gamma$ fiducial cross-section measurement

ATLAS-CONF-2023-003



The value of the fiducial cross-section, extracted from the fit to this $m_{\gamma\gamma}$ spectrum, is measured to be

$$76^{+14}_{-13}\ \text{fb} = 76 \pm 11(\text{stat})\ ^{+9}_{-7}(\text{syst})\ \text{fb}$$

SM prediction = 67.5 ± 3.4 fb.

Conclusion

Performance of leptons and photons at LHC experiments

- Run 3 lepton and photon performance for triggers and offline reconstruction looks excellent for all the LHC experiments.
- After a successful Run 2 of the LHC, all the experiments are ready for Run 3 of the LHC.
- Several new developments in the area of triggers and offline reconstruction have resulted in improved performance of lepton and photon reconstruction.
- Advanced machine-learning techniques to reconstruct and identify leptons and photons have been developed and are ready to be (or are already being) deployed for Run 3 of the LHC.
- Exploiting excellent lepton and photon reconstruction, CMS, ATLAS, LHCb, and ALICE are preparing for their early publications with Run 3 of the LHC while continuing to analyze the large Run 2 dataset.
- Several interesting results could either not be presented or fully covered today:

Performance of electron energy calibration in the CMS ECAL using graph neural networks - CMS-DP-2022-009

Performance of photon energy corrections in the CMS ECAL using graph neural networks - CMS-DP-2022-019

ECAL SuperClustering with Machine Learning - CMS-DP-2021-032

ECAL trigger for Run 3: - CMS-DP-2022-016

ECAL Clustering for run 3 - CMS-DP-2022-015

ECAL DeepSC Particle ID - CMS-DP-2022-010

Performance of electron and photon triggers in ATLAS during LHC Run 2 -CERN-EP-2019-169

Electron and photon performance measurements with the ATLAS detector using the 2015-2017 LHC proton-proton collision data - CERN-EP-2019-145

Muon reconstruction performance of the ATLAS detector in 2022 -MUON-2023-01

Identification of electrons using a deep neural network in the ATLAS experiment - ATL-PHYS-PUB-2022-022

Graph Clustering: a graph-based clustering algorithm for the electromagnetic calorimeter in LHCb - LHCb-DP-2022-003

Selected HLT2 reconstruction performance for the LHCb upgrade - LHCb-FIGURE-2021-003

backup

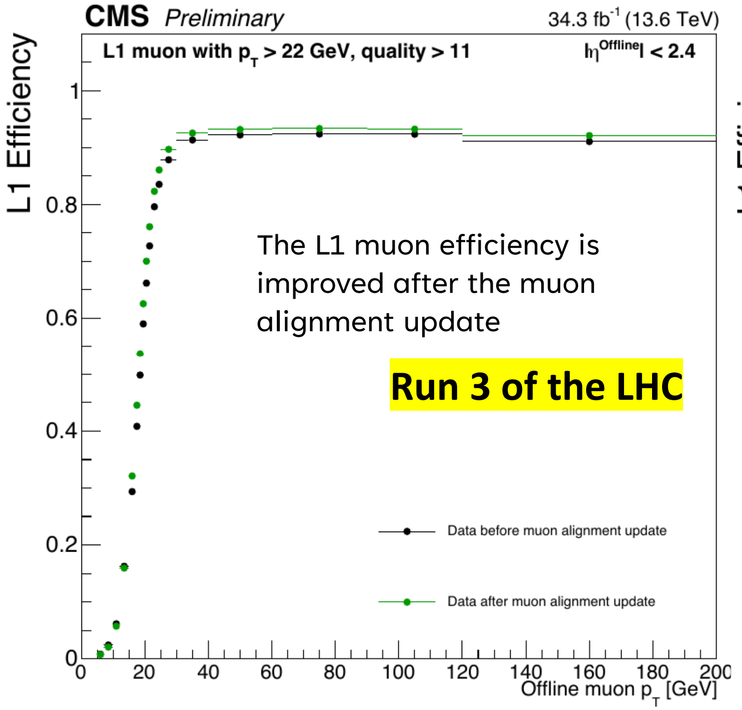
Run 2 and Run 3 at the LHC

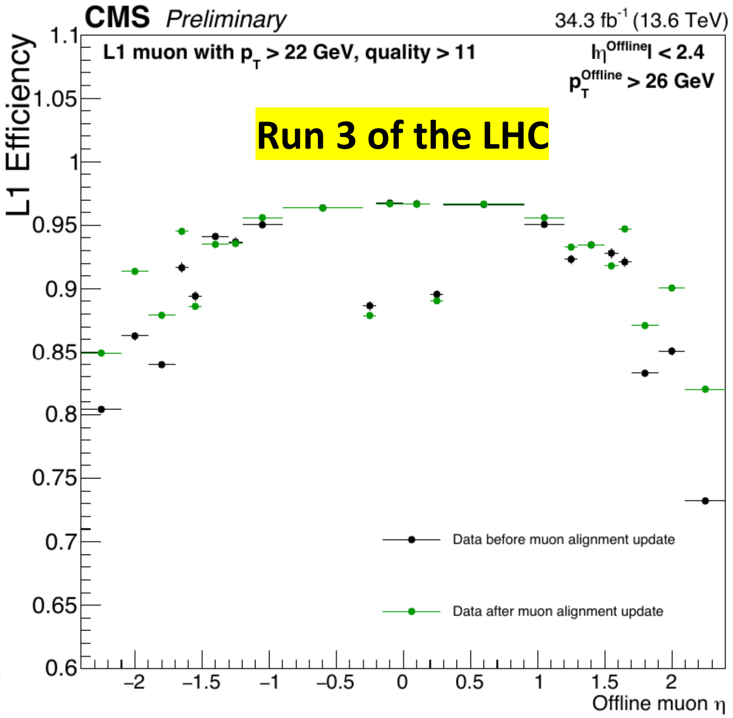
- The completion of Run 2 of the Large Hadron Collider (LHC) in 2018 marked a significant milestone in the field of particle physics.
- At that time, the LHC, along with its numerous experiments such as CMS, ATLAS, LHCb, and ALICE, temporarily ceased operation in order to undergo crucial upgrades.
- In 2022 LHC had a first run at 13.6 TeV. Thus reaffirming the LHC's unwavering commitment to exploring uncharted territories in the realm of particle physics.
- Comprehensive testing and validation of enhanced experimental setups and algorithms are being carried out within the unique operating conditions of the LHC.
- The analysis and interpretation of data rely heavily on the performance of leptons (such as electrons and muons) and photons. These elementary particles play a crucial role in understanding various phenomena and interactions that occur within the LHC experiments.
- Performance of leptons and photons will be shown in this talk, primarily focusing on Run 3 results from 2022 and shedding some light on the performance from Run 2.

Triggering of muons in Run 3

- As data is being collected, the different sub-detectors are properly aligned live.
- Any misalignment between sub-detectors can lead to erroneous measurements of particle energies, trajectories, and timing, which can negatively impact the trigger performance
- **Here you see the performance of the CMS Single Muon trigger before and after proper alignment of the detector.**
- Clearly, the trigger is more efficient once the detector is properly aligned.

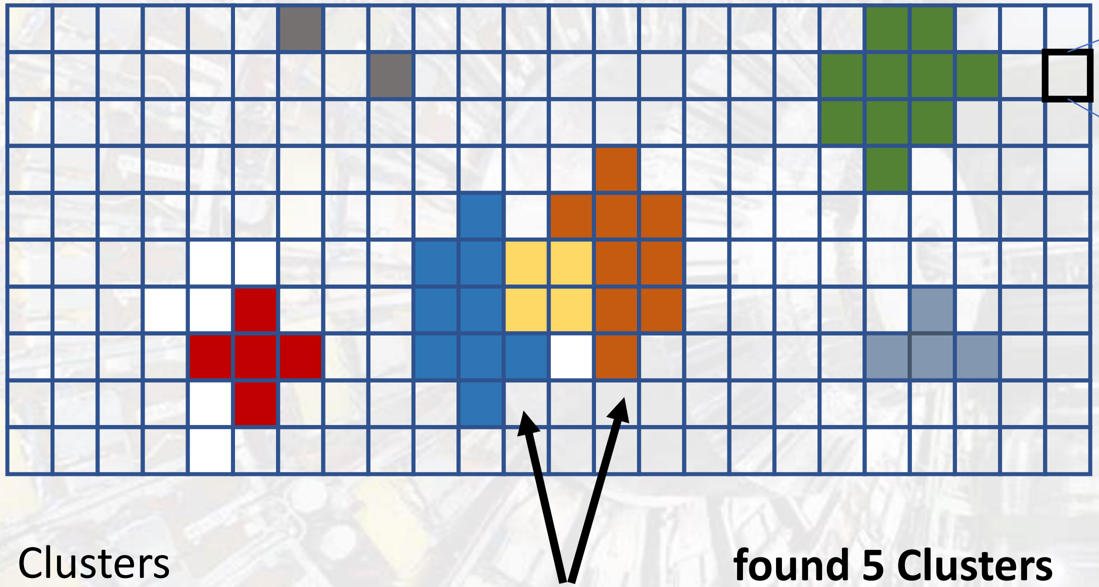
[Performance of Muon High-Level Trigger CMS-DP-2023-017](#)





Reconstruction

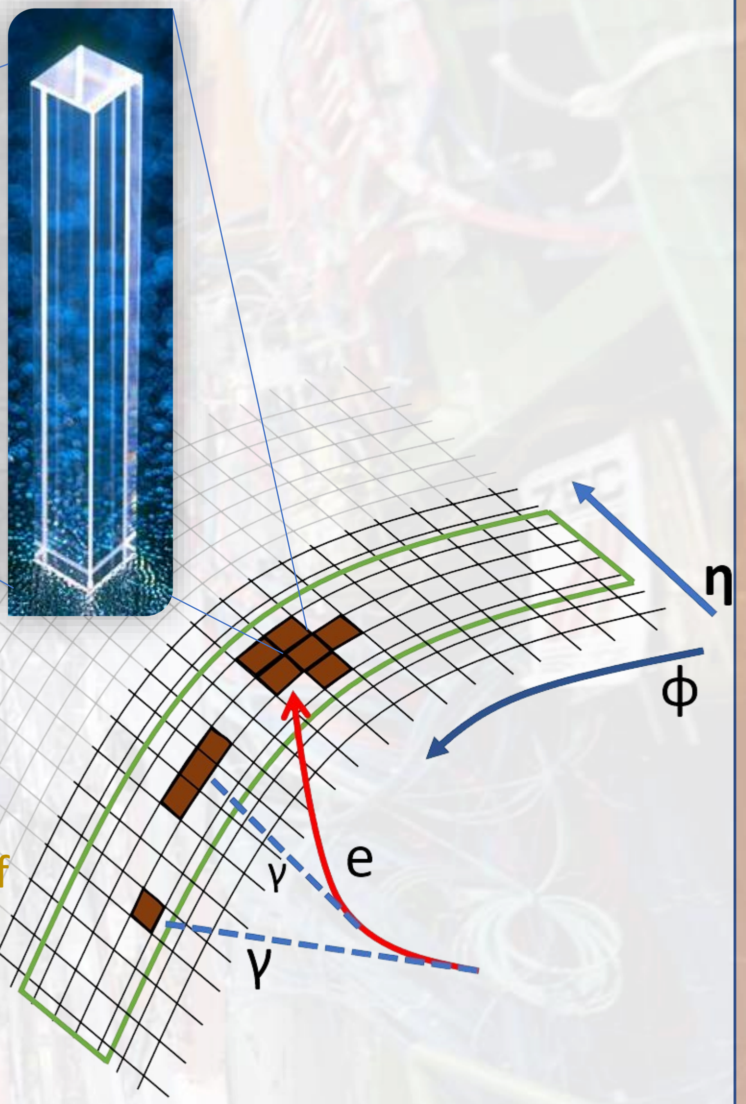
- Clustering of ECAL clusters



Clusters corresponding to electrons / photons

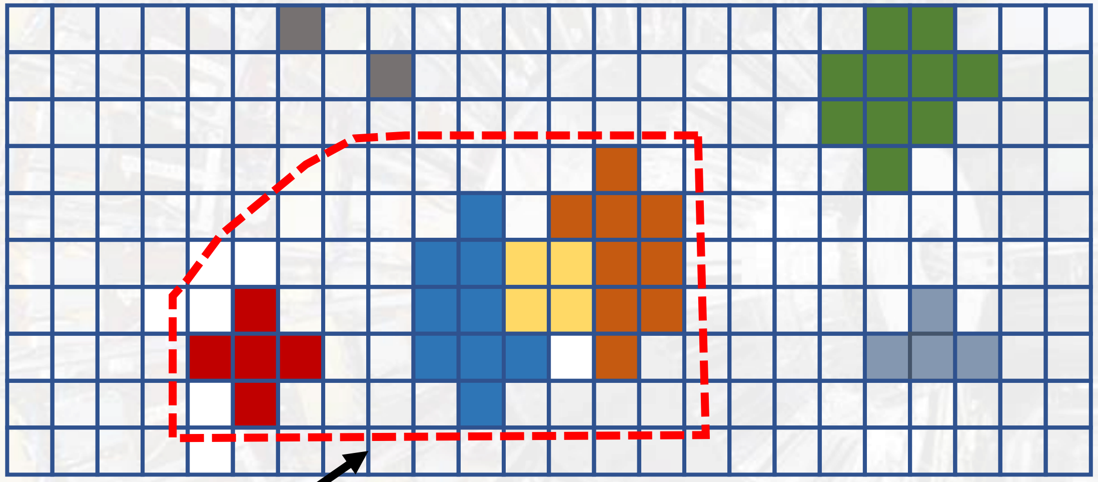
found 5 Clusters

these two clusters overlap, clustering algo shares energy of yellow rec-hits between the two clusters according to a Gaussian energy profile, each gets a fraction of the rec-hit energy



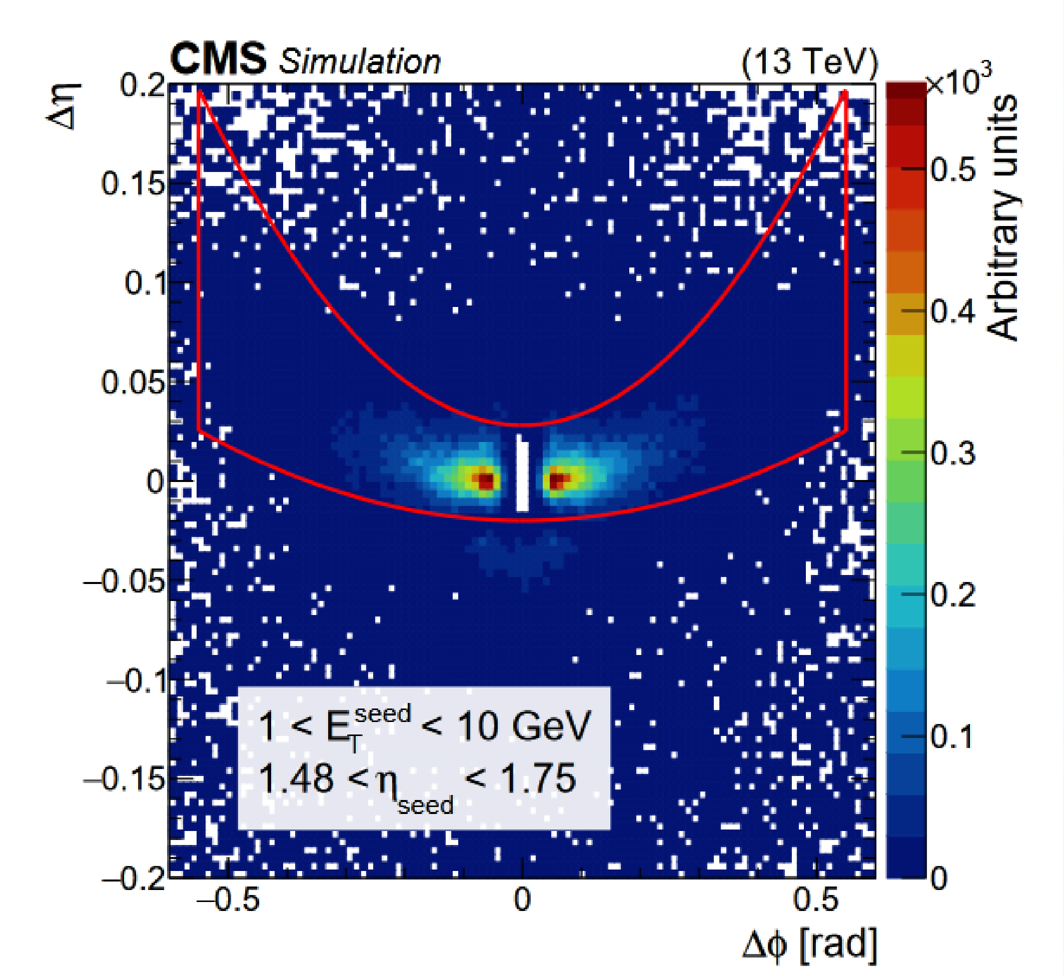
Reconstruction

- Clustering of ECAL clusters



Moustache supercluster
A cluster of clusters

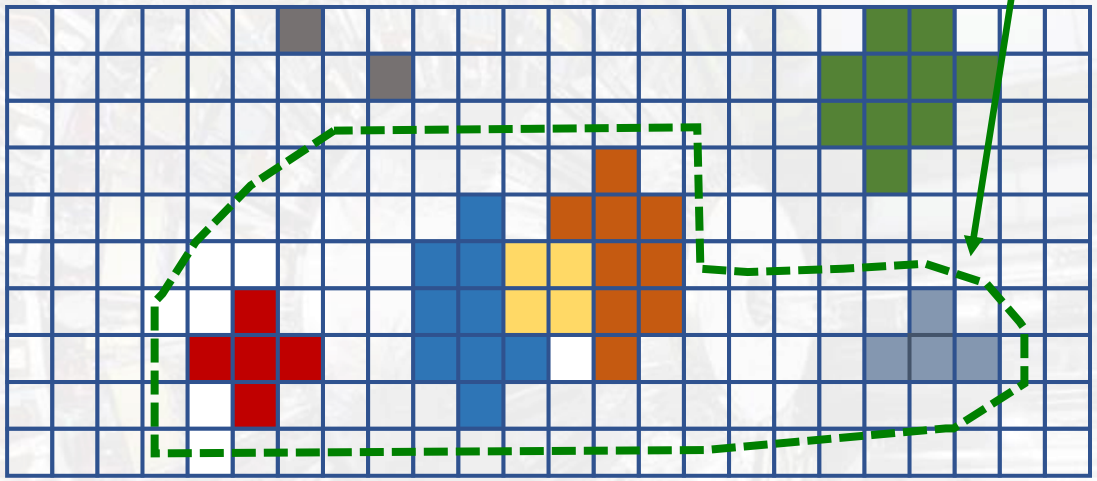
JINST **16** P05014



Reconstruction

- Clustering of ECAL clusters

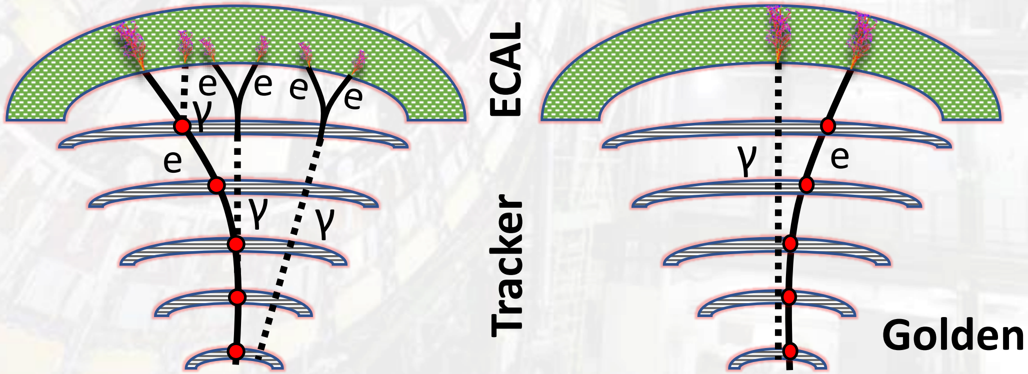
Refined Supercluster



Refined superclusters use the information from the tracker, to be able to link bremsstrahlung emissions to missed ECAL deposits

Information from clustering and tracking is used in tandem to achieve best resolution

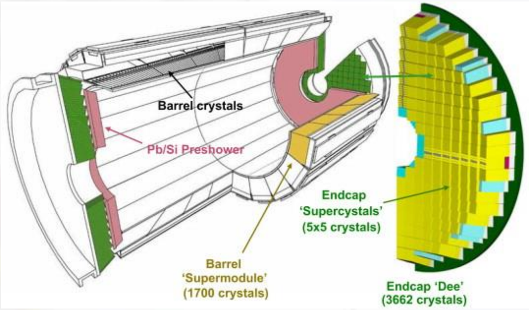
With bremsstrahlung and conversions



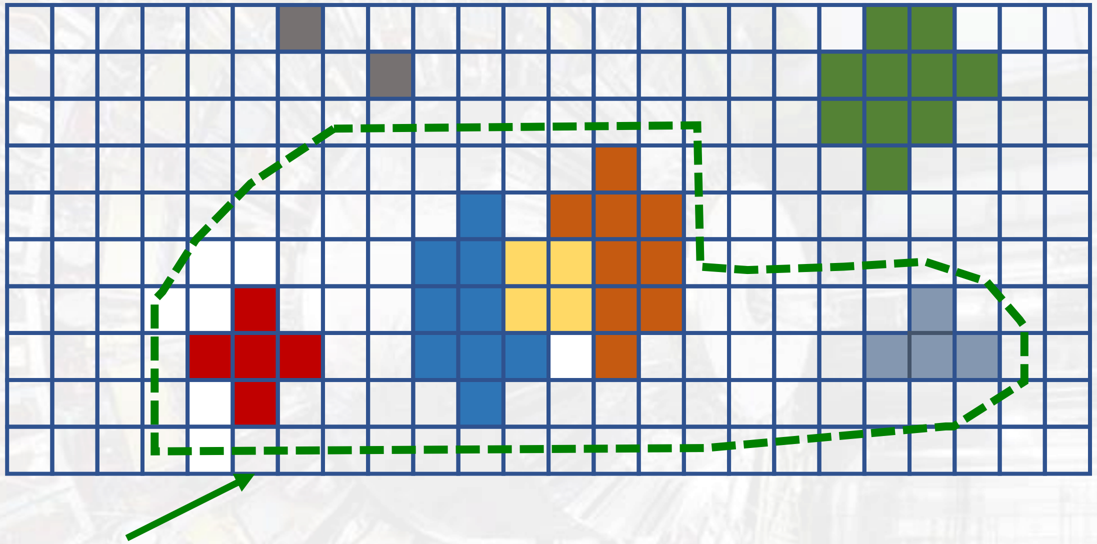
Golden cases

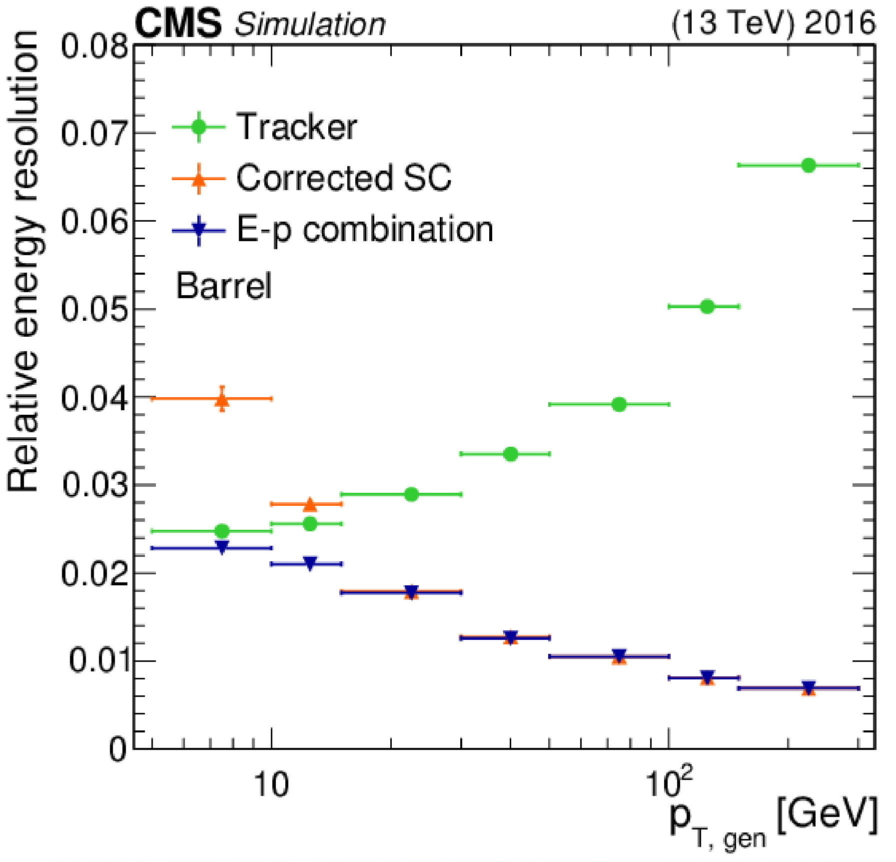
Reconstruction

- Clustering of ECAL clusters



[*JINST* **16** P05014](#)



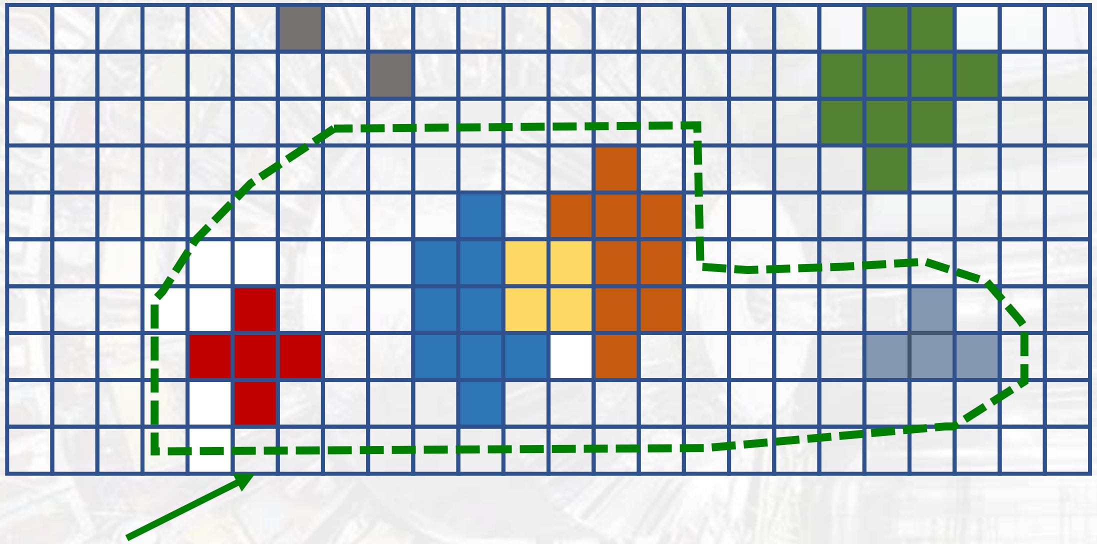


Refined superclusters use the information from the tracker, to be able to link bremsstrahlung emissions to missed ECAL deposits

There is also dedicated photon conversion recovery algorithm

Reconstruction

- Clustering of ECAL clusters



Refined superclusters use the information from the tracker, to be able to link bremsstrahlung emissions to missed ECAL deposits

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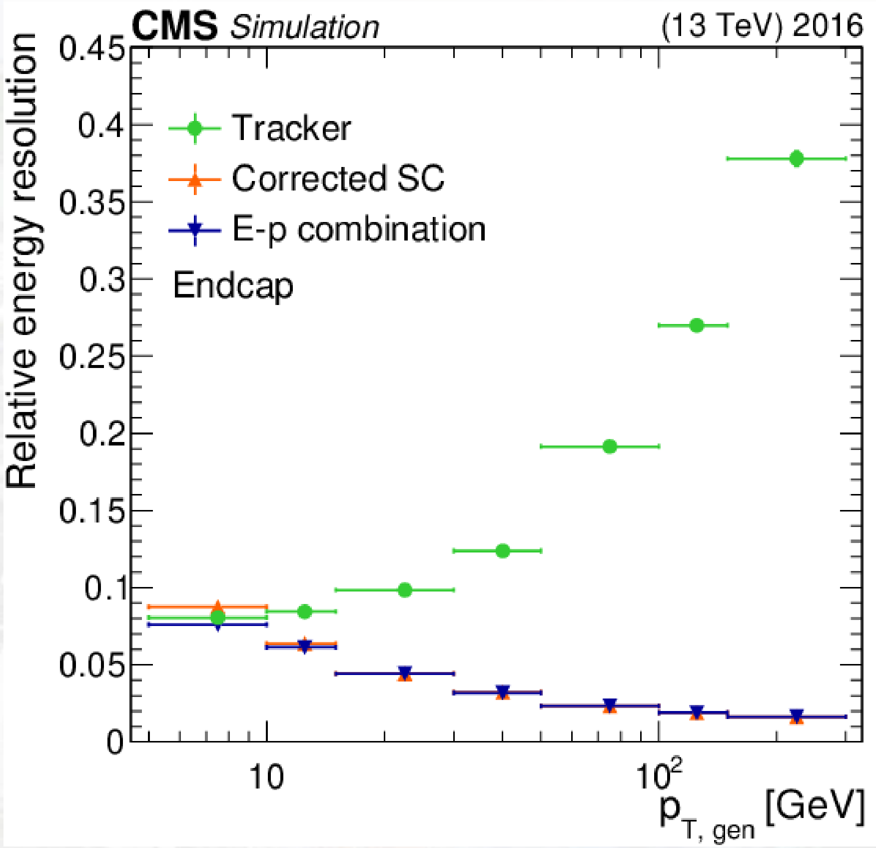
[JINST 16 P05014]



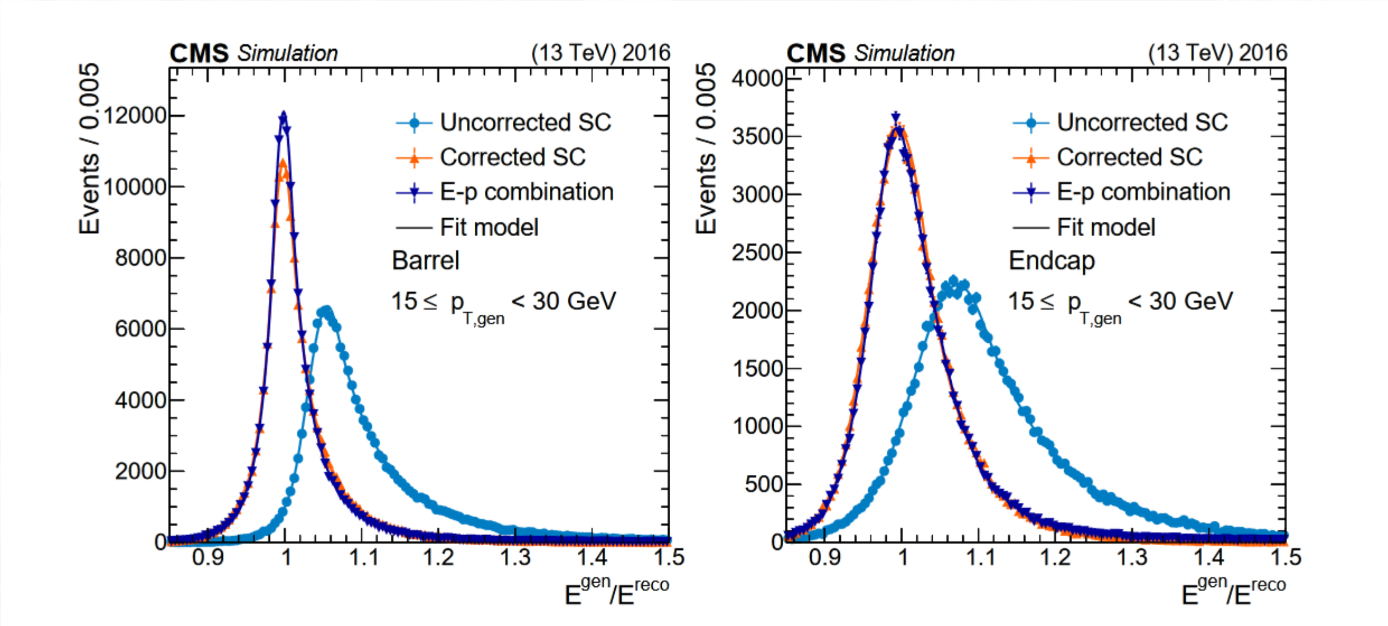
Energy corrections

- Several losses occur before electrons and photons deposit energy in the ECAL

➢ We calibrate the reconstructed energy back to expected original energy using correction procedures

➢ Employ machine learning in tandem with algorithmic approaches

➢ Tracker information used for E-p combination



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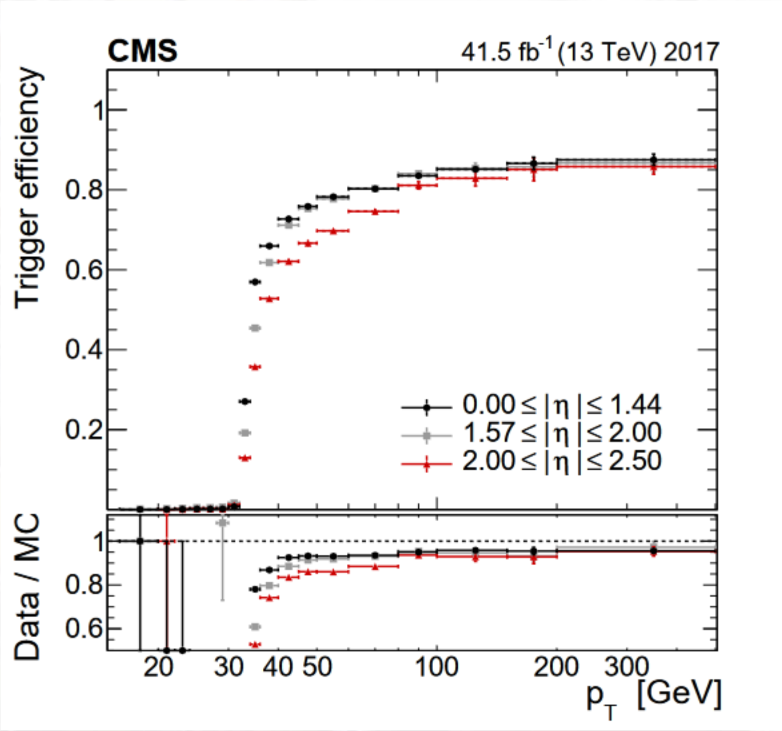
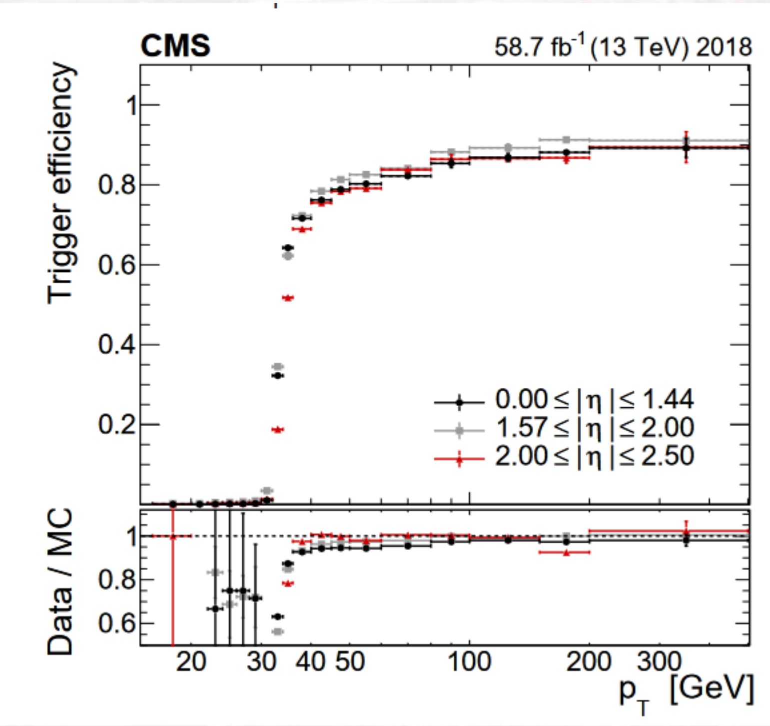
High level trigger performance

- We do not collect all collision data: we deploy triggers to collect interesting data
- Trigger could mean presence of single high energy electrons, two high energy electrons, high energy photons
- Excellent and stable performance of these triggers during all of Run 2



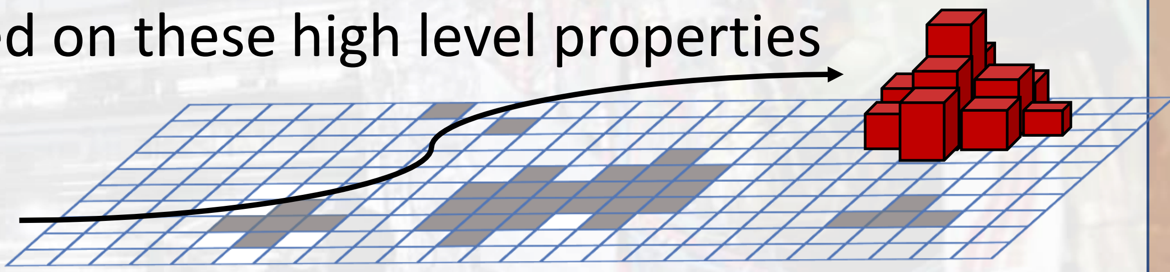


Identification

- **Two schemes are primarily used for identification:**

➢Via series of selections on various high-level properties

➢Via machine learning based classifiers trained on these high level properties



What are high level properties?

➢**Description of the electromagnetic shower**

(energy deposit pattern, lateral and longitudinal spread etc.)

➢**Tracking and clustering matching parameters**

(momentum trajectory extrapolated to ECAL considering the magnetic field etc.)

➢**Quantification of isolation of these objects**

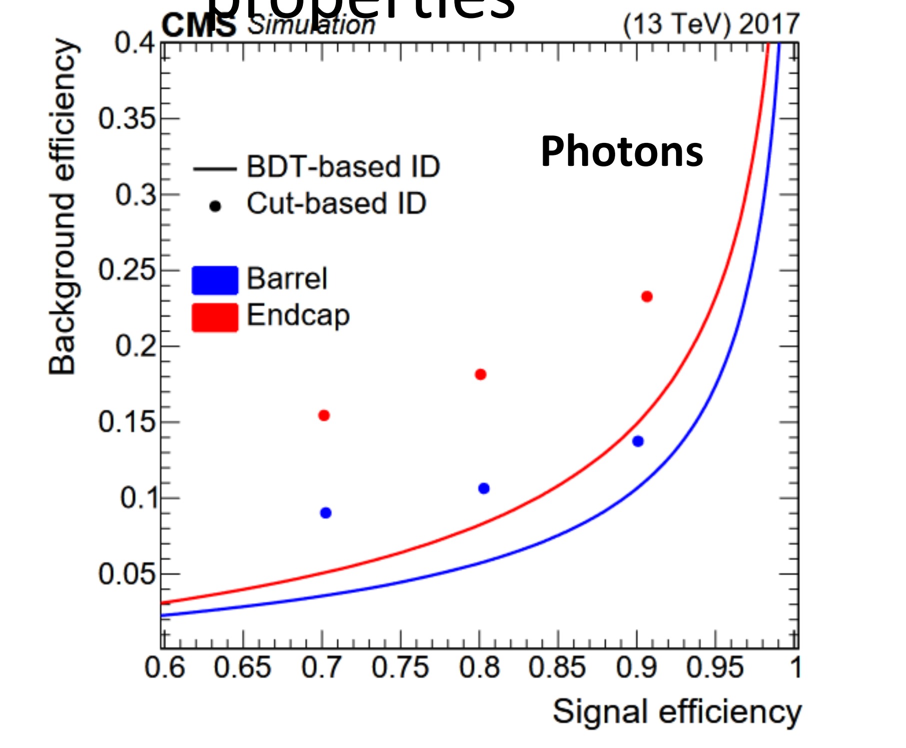
(Energy sums of crystals in ECAL in a defined area, leakage in HCAL etc.)

Identification

- **Two schemes are primarily used for identification:**

➢Via series of selections on various high-level properties

➢Via machine learning based classifiers trained on these high level properties



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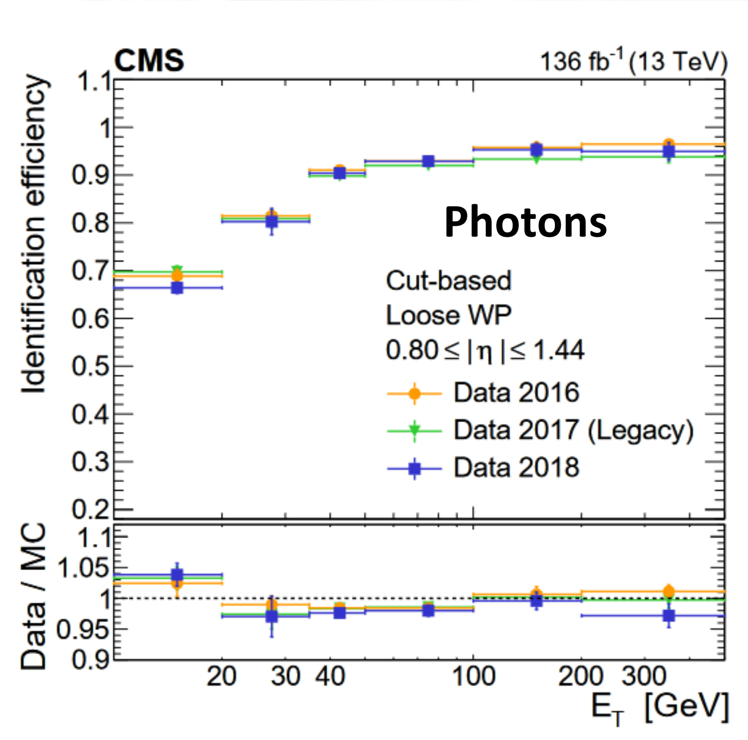
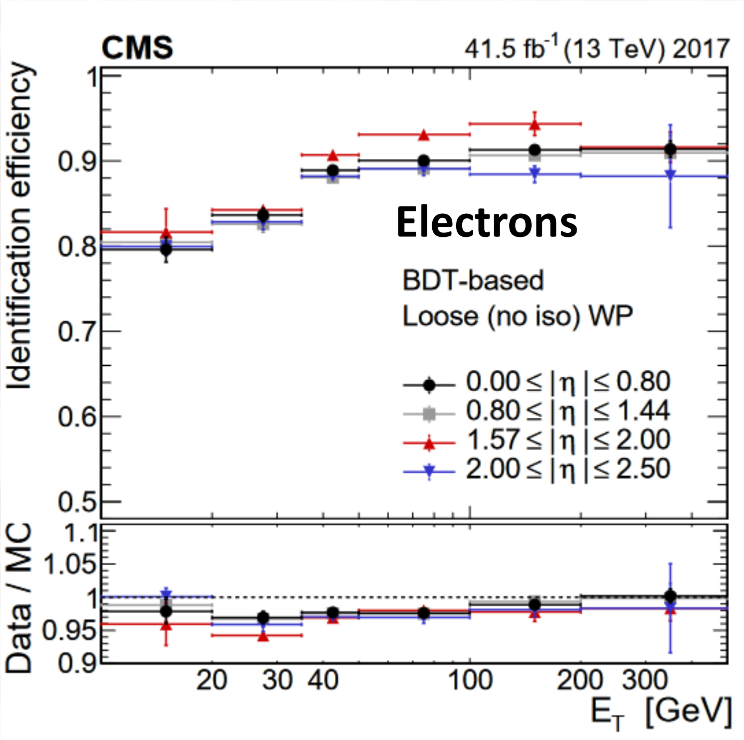
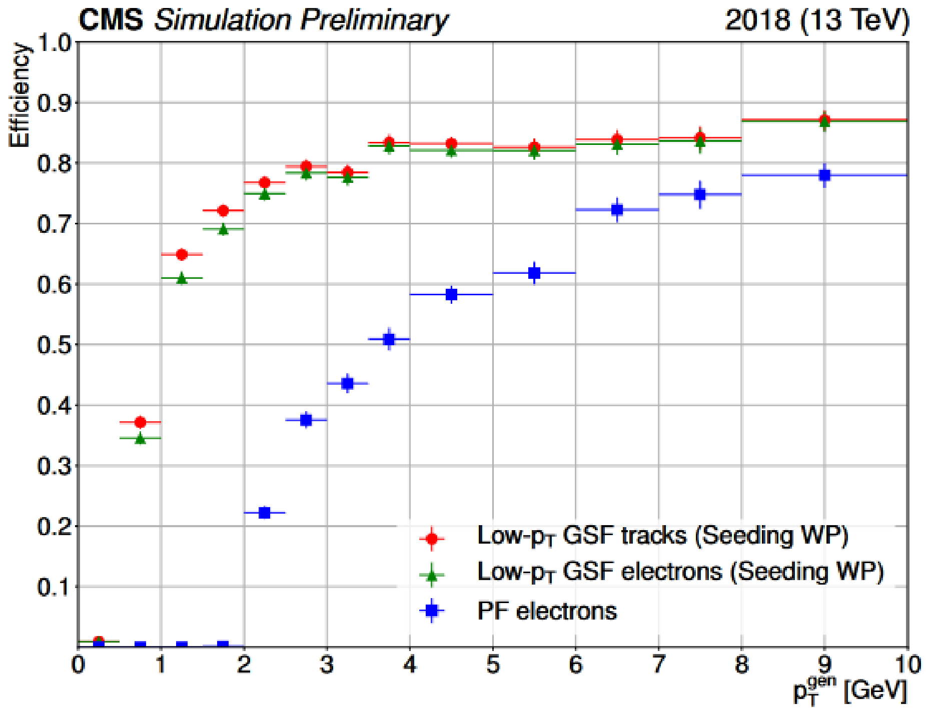


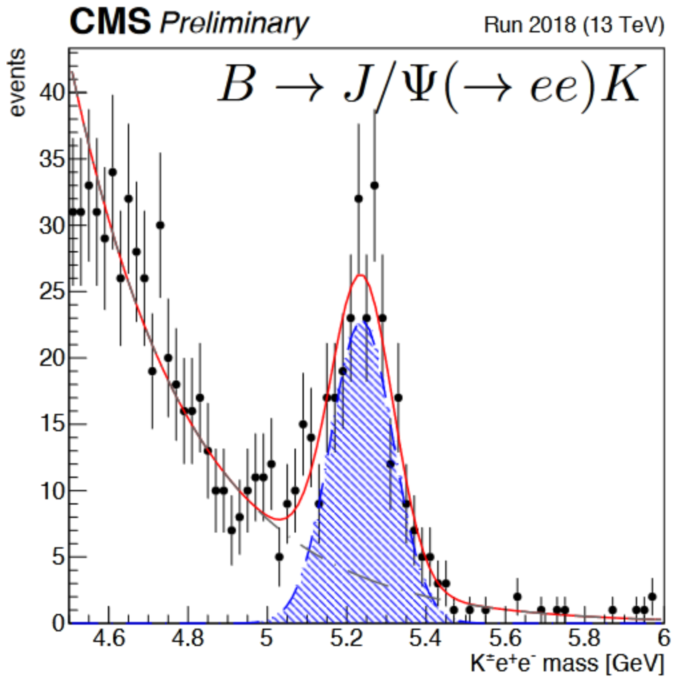


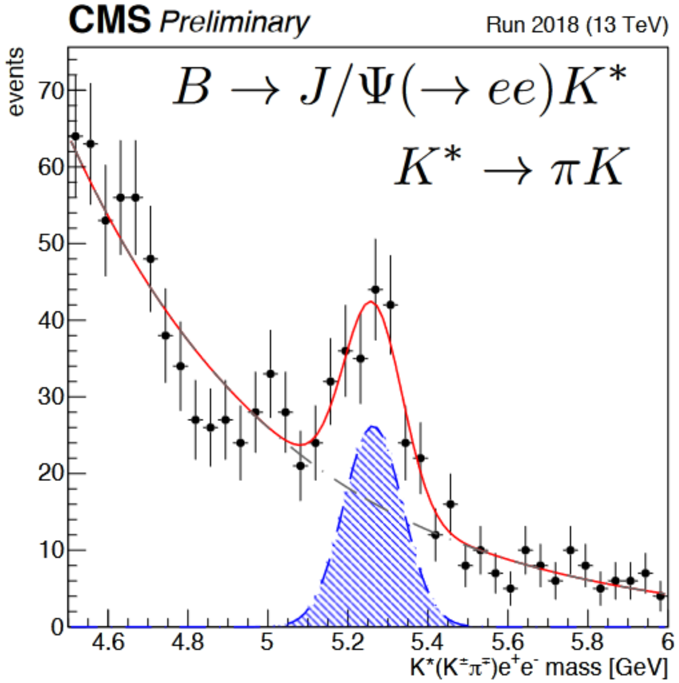
Reconstruction: efficiencies for low-p_T electrons

The figure shows the reconstruction efficiency for PF electrons (blue squares) as a function of the generator-level electron p_T. No identification criteria are applied to the PF electrons.

The figure also shows the efficiencies obtained for low-p_T GSF tracks (red circles) and electrons (green triangles) that are reconstructed from electron candidates of the seeding logic described in the previous slide, which uses a logical OR of the loose seeding working points (10% mistag rate) for the two BDTs. No identification criteria are applied to the low-p_T electrons.







$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}$$

Energy Resolution of EM Calorimeters

Intrinsic energy resolution:

$$E \propto N \Rightarrow \sigma(N) \propto \sqrt{N} \Rightarrow$$

$$\boxed{\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{E}}}$$

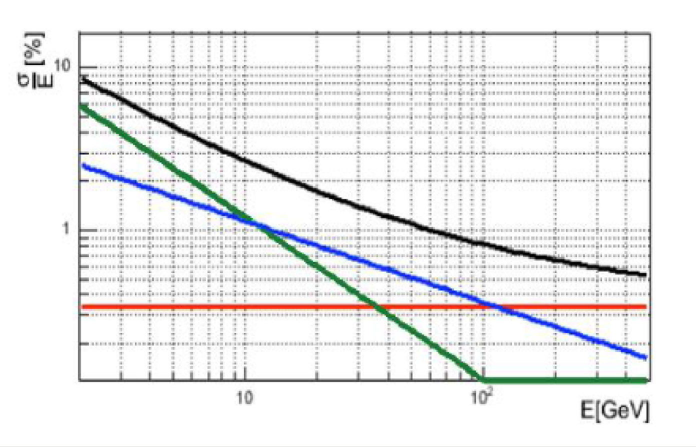
Energy resolution of real detectors

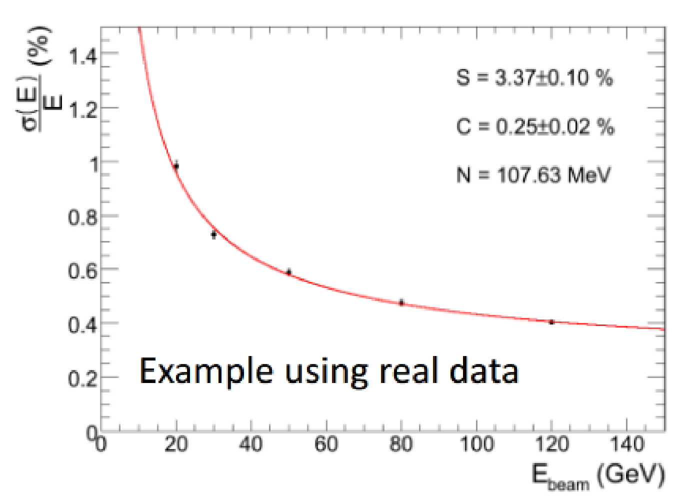
$$\boxed{\frac{\sigma(E)}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C}$$

S: stochastic term from Poisson-like fluctuations

N: noise term from electronics and pile-up

C: constant term



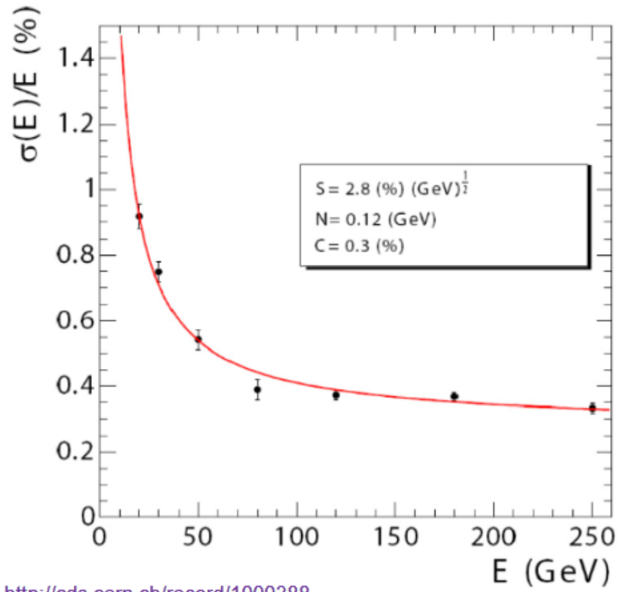


ECAL Energy Resolution

ECAL “standalone” **energy resolution** measured at the **test beam** (3x3 arrays of barrel crystals)

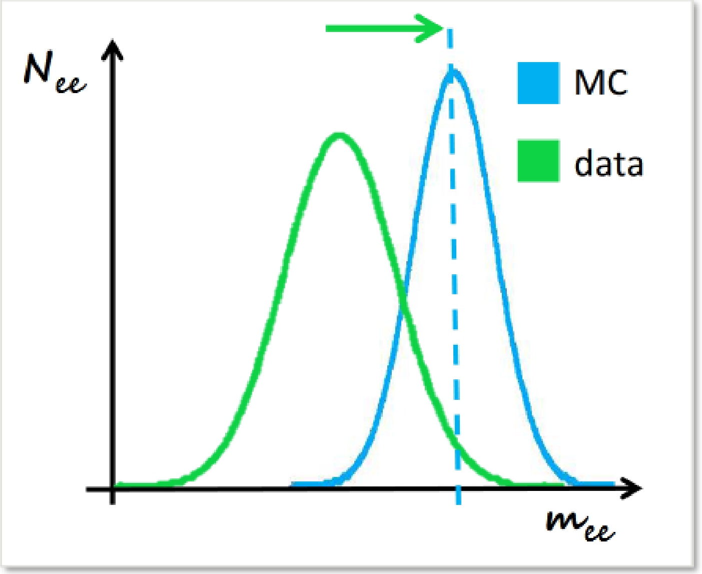
- No magnetic field
- No material in front of the ECAL
- Negligible inter-calibration contribution in the constant term

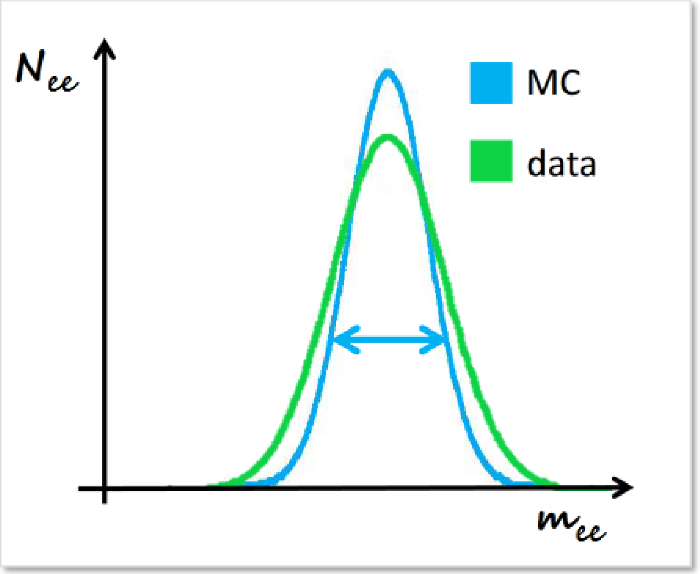
$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E(\text{GeV})}} \oplus \frac{12\%}{E(\text{GeV})} \oplus 0.3\%$$



http://cds.cern.ch/record/1000388

- Refined supercluster calibration is **MC-based**
- **Residual** data/MC **discrepancies** corrected using the Z mass and width, by comparing $Z \rightarrow ee$ events in data and MC
- Simultaneously adjust **energy scale** (data) and **resolution** (MC)





Electron and Photon Identification

- Several **variables** are developed to **separate electrons/photons from background** (jets, photon conversion, particles from secondary vertices)
- They exploit that electrons/photons are **single objects** which are almost fully **contained** in the **ECAL**
- **Many** different **types**:
  - **Shower-shape variables**
  - **Track matching variables**
  - **Conversion ID variables**
  - **Isolation variables**

Are the energy deposits in the calorimeters compatible with coming from a single electron/photon?

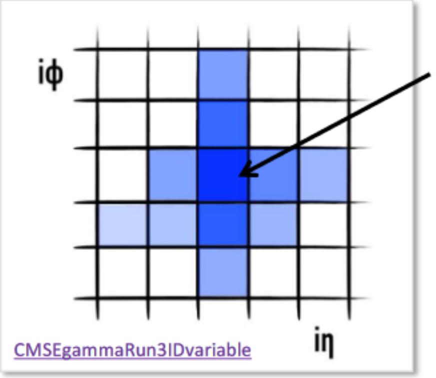
Does the ECAL deposit have a compatible track?

Are the tracks compatible with coming from the collision point? Or do they appear later on in the tracker?

Is there a large amount of other particles nearby the electron/photon?

Shower Shape Variables: $\sigma_{i\eta i\eta}$

- $\sigma_{i\eta i\eta}$ is one of the **most important** electron/photon **ID variables** in CMS
- It measures the **spread** of an electromagnetic shower **along η** direction
- A **5x5 array of crystals** is the area where an electron/photon is almost **fully contained**

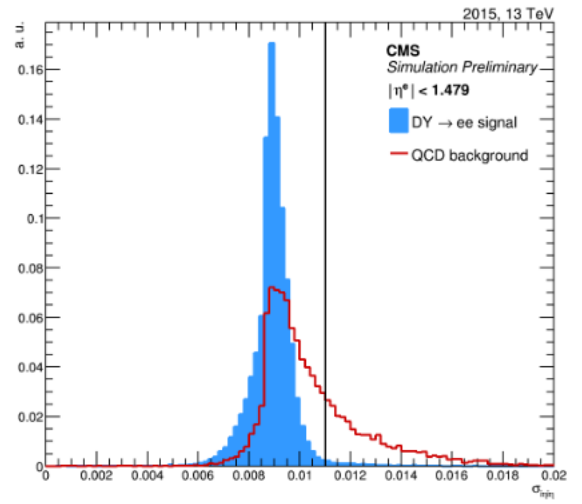


CMSEgammaRun3IDvariable

Most energetic crystal of 5x5 array

$$\sigma_{i\eta i\eta} = \sqrt{\left(\frac{\Sigma_i^{5\times5} w_i(\eta_i - \bar{\eta}_{5\times5})^2}{\Sigma_i^{5\times5} w_i}\right)}$$

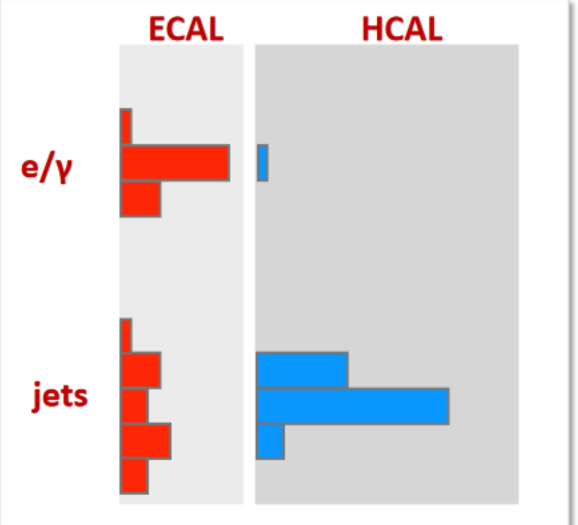
w_i non zero if $E_i > 0.9\%$ of E_{5x5}



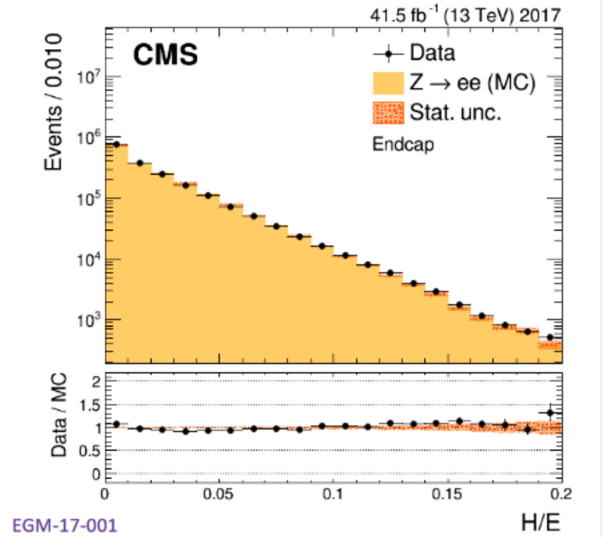
CHEP2015: Electron ID at the HLT

Shower Shape Variables: H/E

- **H/E** is the ratio of the **hadronic energy** to the **electromagnetic energy**
- **Excellent** ID **variable** used in electron and photon identification
- Very **well modelled** in simulation



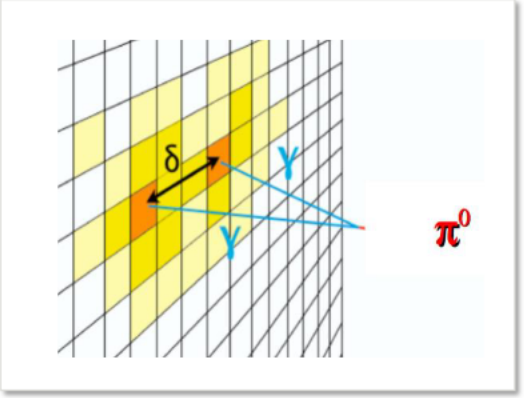
Courtesy of S. Mukherjee

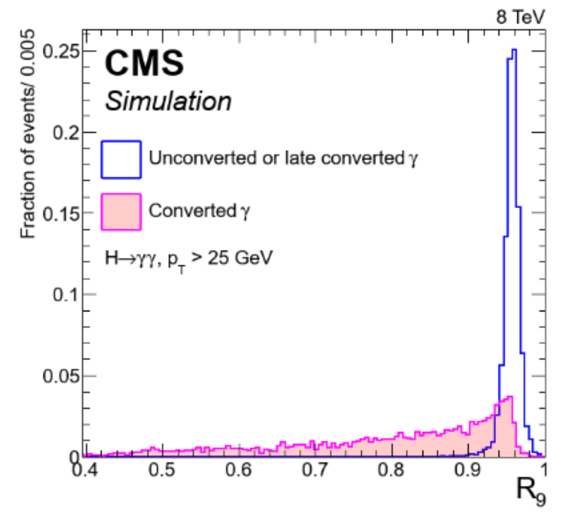


EGM-17-001

Conversion ID Variables: R_9

- **5x5 matrix** contains 96.5% (97.5%) of **unconverted photon energy** in EB (EE)
- **R_9** is the **energy sum** of the **3×3 crystals** centred on the most energetic crystal in the supercluster divided by the **energy** of the **supercluster**
- R_9 helps in **conversions identification** and to distinguish real photons from π_0

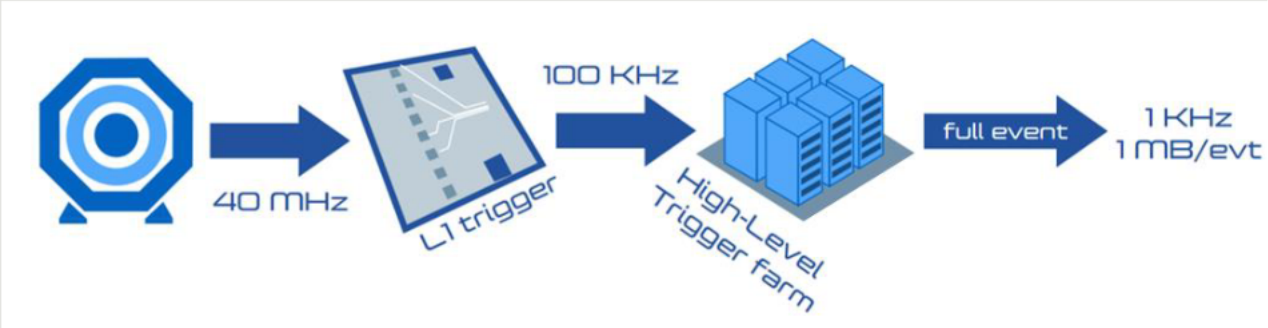




10.1088/1748-0221/10/08/P08010

Trigger Selection and Performance

- Single and double electromagnetic **objects** at **L1** (L1 seeds)
  - Information coming only from **calorimeter detectors**
  - **No distinction** between **electrons** and **photons**
- Single and double electron/photon **HLT selections**
  - Correspond to the **first selection step** of **most** offline **analyses** using electrons/photons
  - Must ensure a **large acceptance** for physics signals, while keeping the **CPU time** and **output rate** under control
  - Can be very **complex**



Time resolution measurement

- ECAL also provides a time of arrival for energy deposits
- This can help separate prompt electrons and photons from backgrounds

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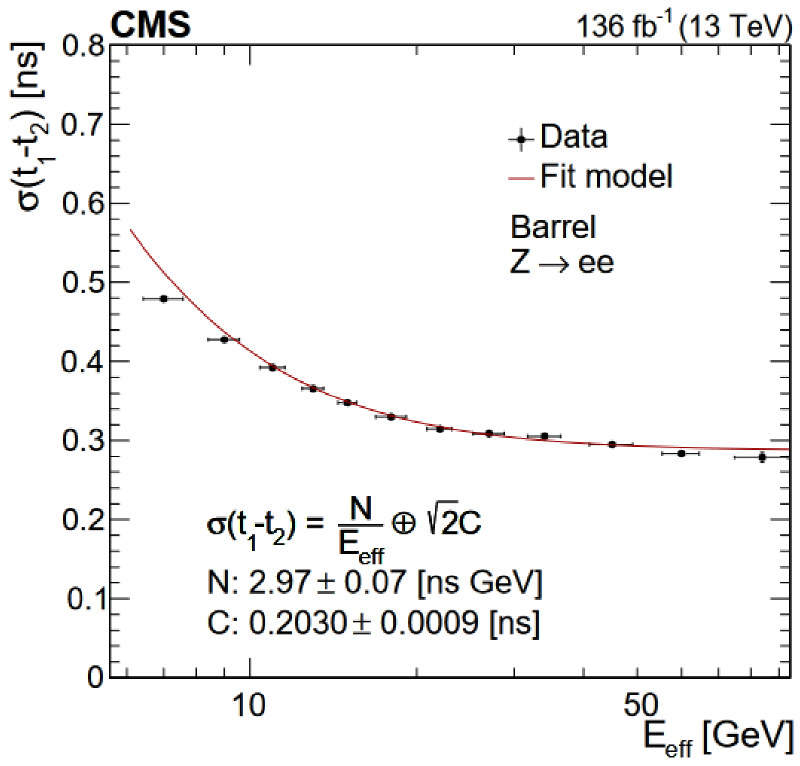
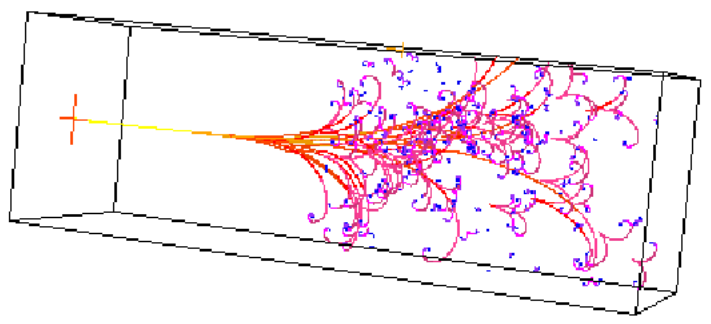


Definition of Calorimeter

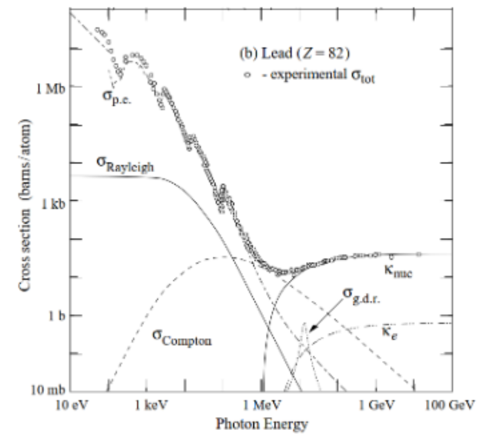
- In particle physics a **calorimeter** is a **detector measuring** the **energy** carried by an incoming particle
  - **Instrumented blocks of matter** in which the particle interacts and **deposits all its energy** in the form of a cascade of particles
- The **particle energy** is **measured** in **eV** (MeV-GeV-TeV 10^6, 10^9, 10^{12} eV)
  - **1 eV** = energy acquired by one **electron** accelerated by **1 V**
  - The **temperature effect** of a 100 GeV particle in 1 litre of water (at 20 °C) is $\Delta T = 3.8\times10^{-12}$ K



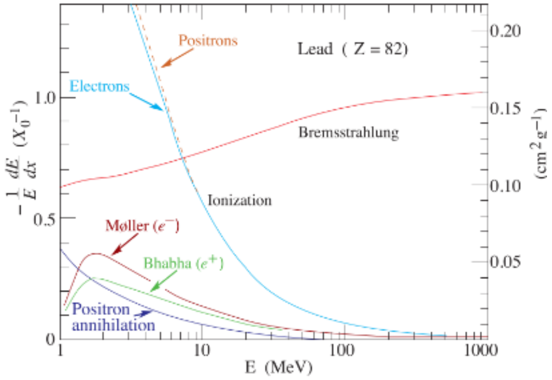
https://www.mpp.mpg.de/~menke/elss/home.shtml

Particle-Matter Interactions

- In matter **electrons** and **photons** loose energy **interacting** with nuclei and atomic electrons
- **Main photon interactions** with matter:
  - Photoelectric effect
  - Compton scattering
  - Pair production
- **Main electron interactions** with matter:
  - Ionization
  - Bremsstrahlung
  - Čerenkov radiation
  - Multiple scattering



PDG 2018



PDG 2018