Performance of electrons and photons with the CMS detector at $\sqrt{s} = 13$ TeV

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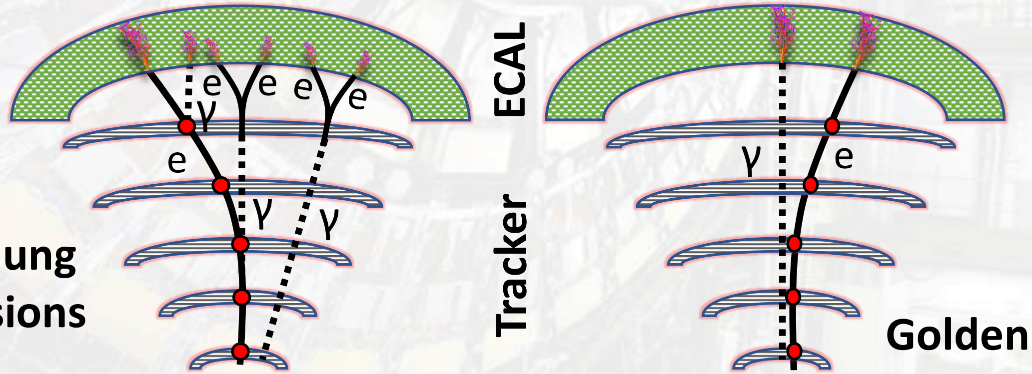
on behalf of the CMS Collaboration

ICHEP, Bologna 2022

Overview

- **Electrons** (e) **and photons** (γ) are critical to the experimental high energy physics program at the LHC
- e **&** γ appear in several new physics signatures
- Also critical to standard model measurements
- At CMS, **Reconstruction** & **Identification** of e **&** γ is done primarily using information from silicon tracker & electromagnetic calorimeter (ECAL)

With bremsstrahlung and conversions



Golden cases

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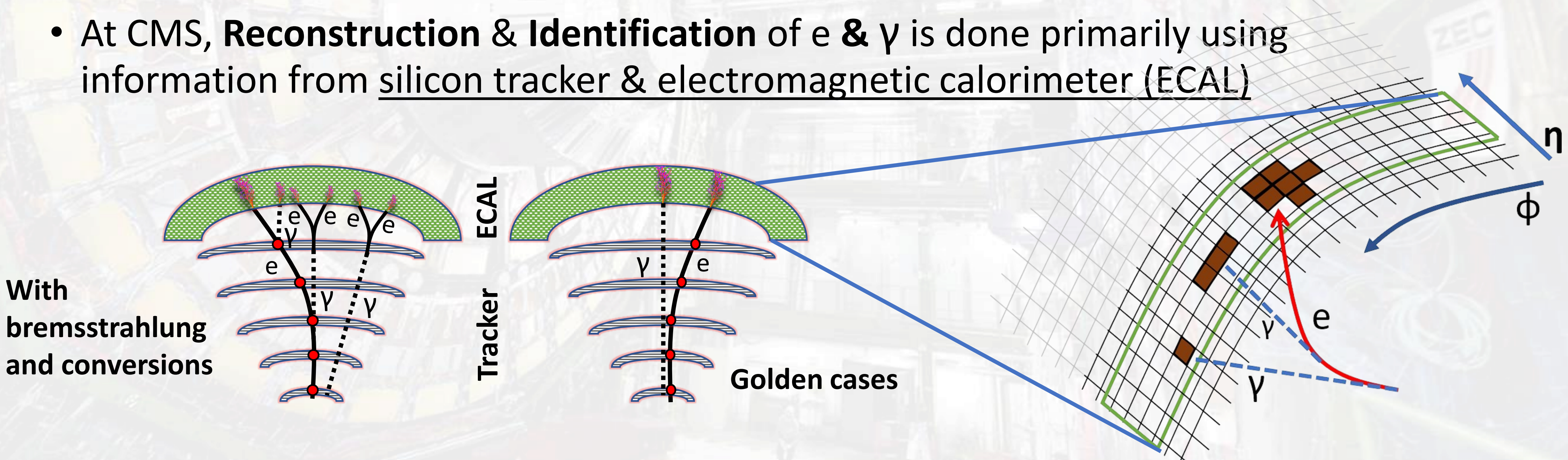
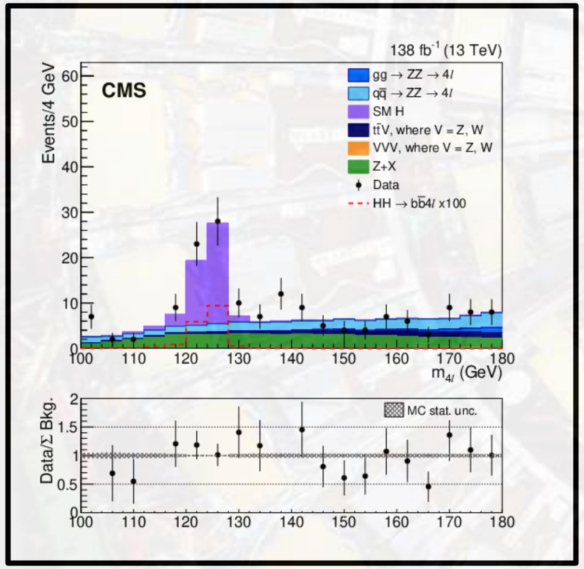
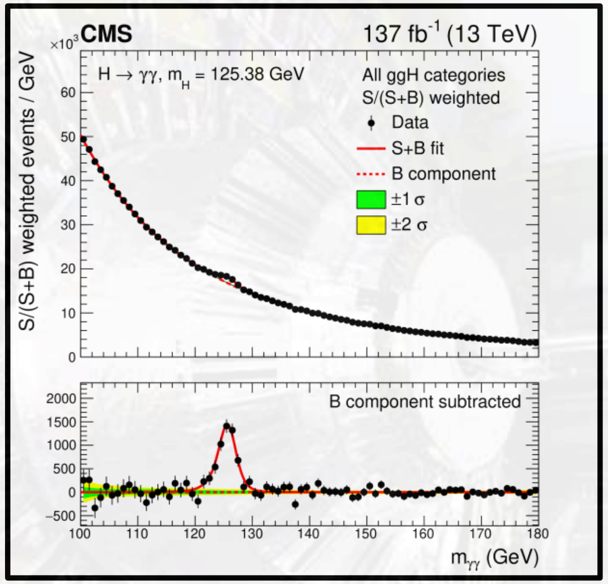


Physics searches/measurements with e & γ

Search for non-resonant Higgs boson pair production in the four leptons plus two b jets final state

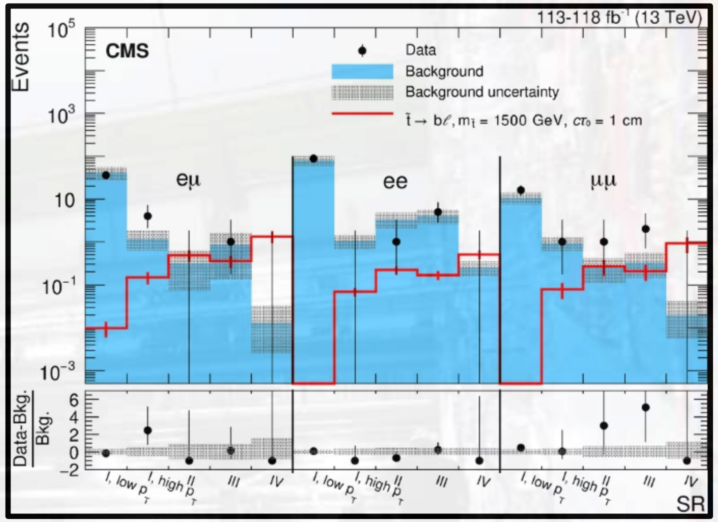


[CERN-EP-2022-114](#)
Submitted to the JHEP



[JHEP 07 (2021) 027](#)

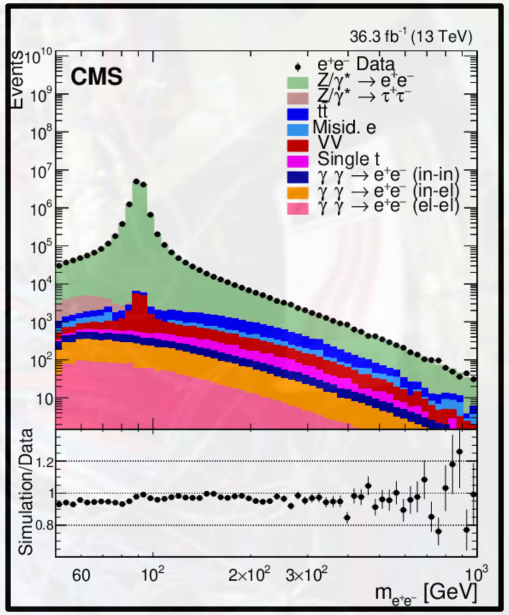
Measurements of Higgs boson production cross sections and couplings in the diphoton decay channel



[Eur.Phys.J.C 82(2022)1537](#)

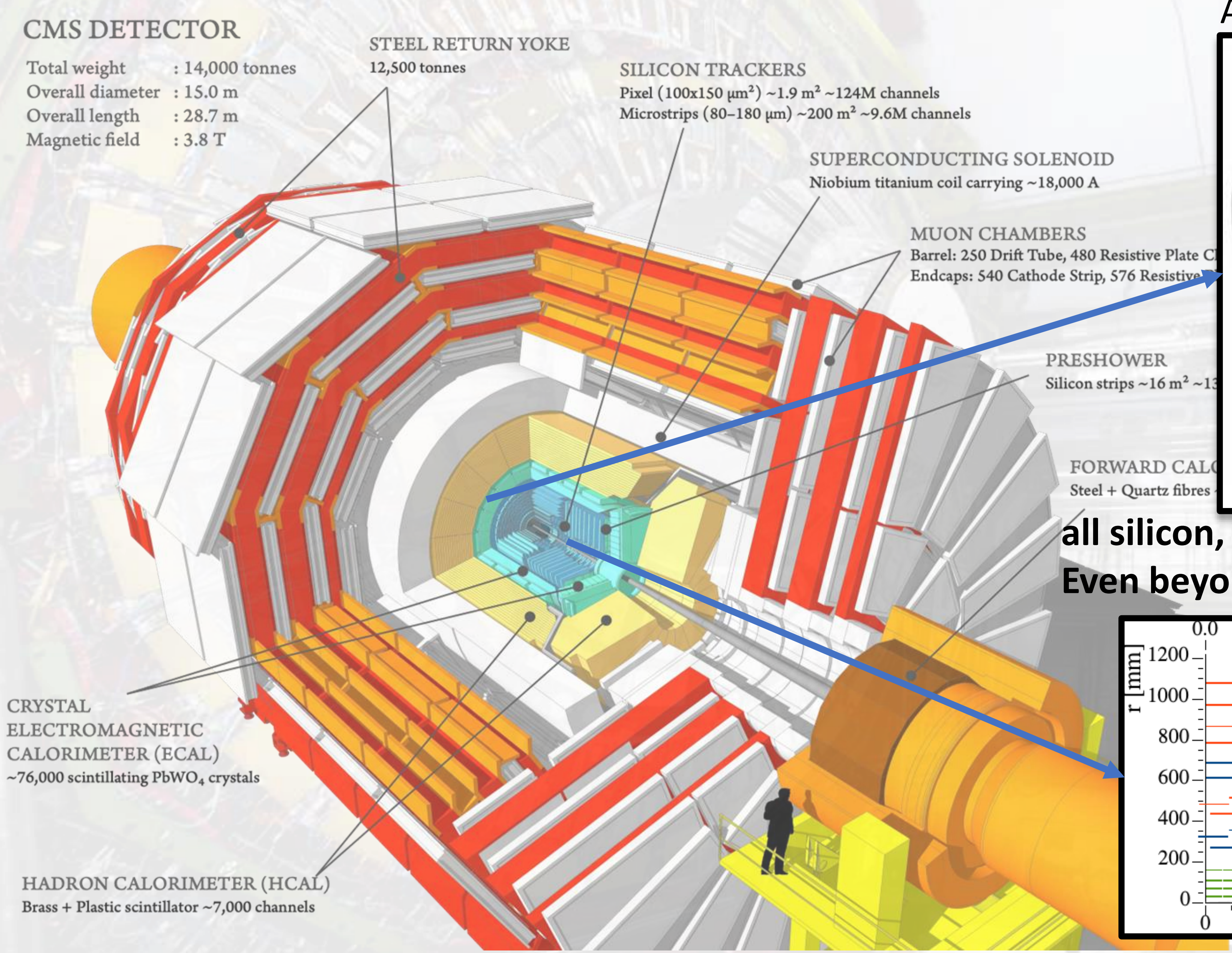
Search for long-lived particles decaying to displaced leptons

[CERN-EP-2022-053](#)
Submitted to the EPJ-C



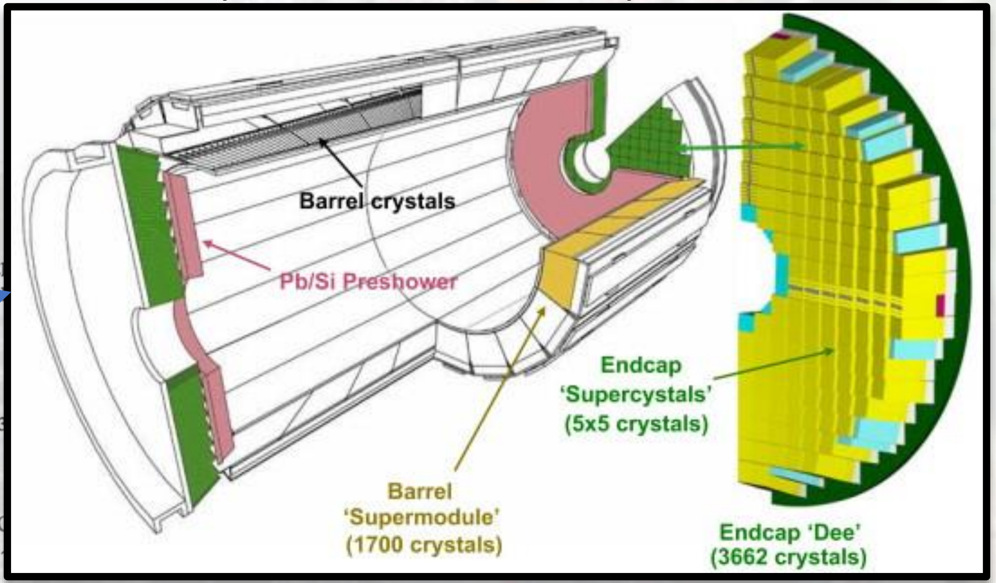
Measurement of the mass dependence of the transverse momentum of lepton pairs in Drell-Yan

The CMS Run 2 detector



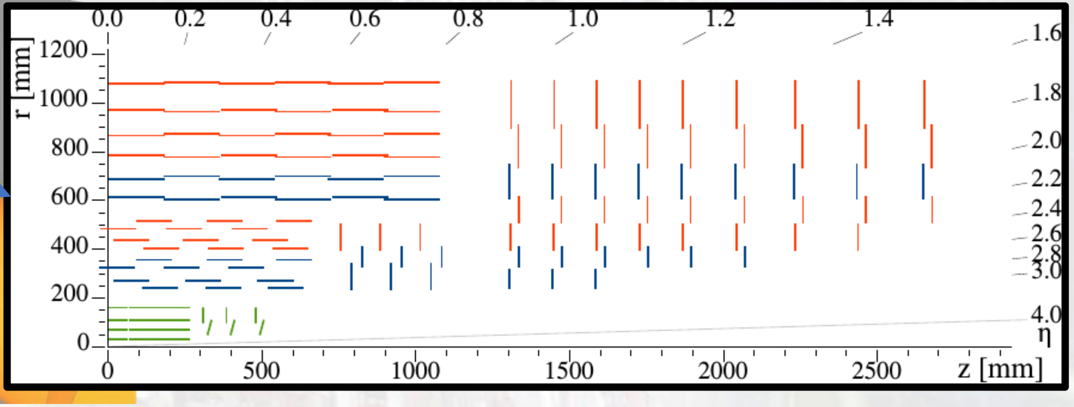
PbWO4 crystals **<u>Hermetic Barrel & Endcap</u>**

Additional preshower for endcap

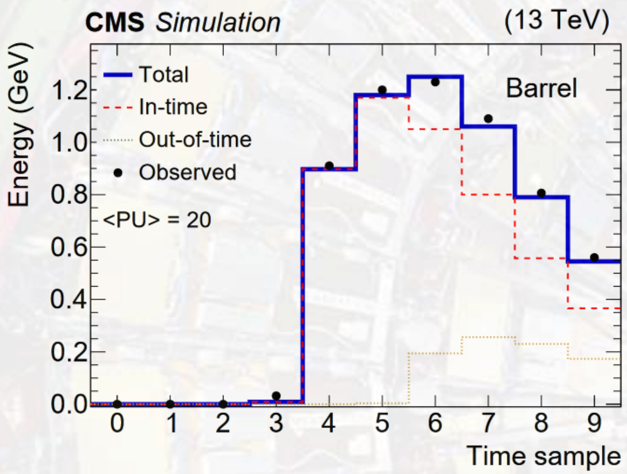


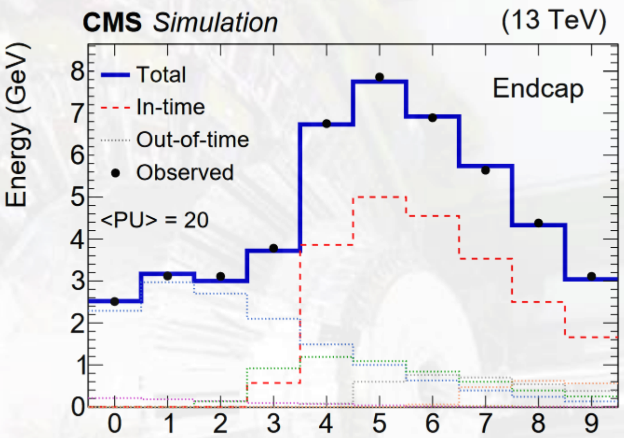
all silicon, full coverage |η|<2.6

Even beyond, |η|>2.6, some coverage from the pixel detector



ECAL energy reconstruction and performance





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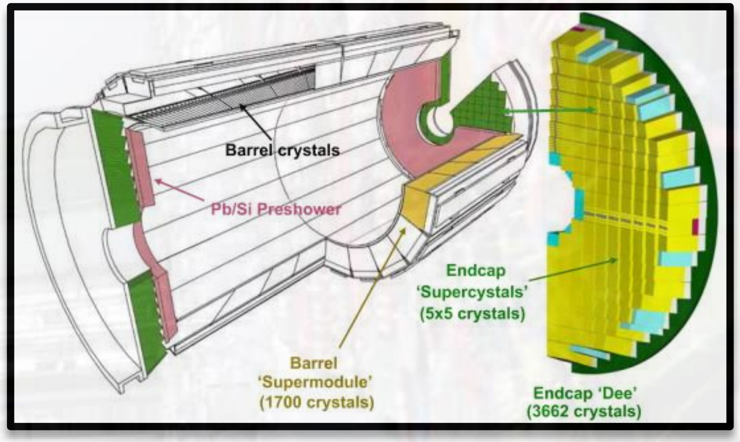
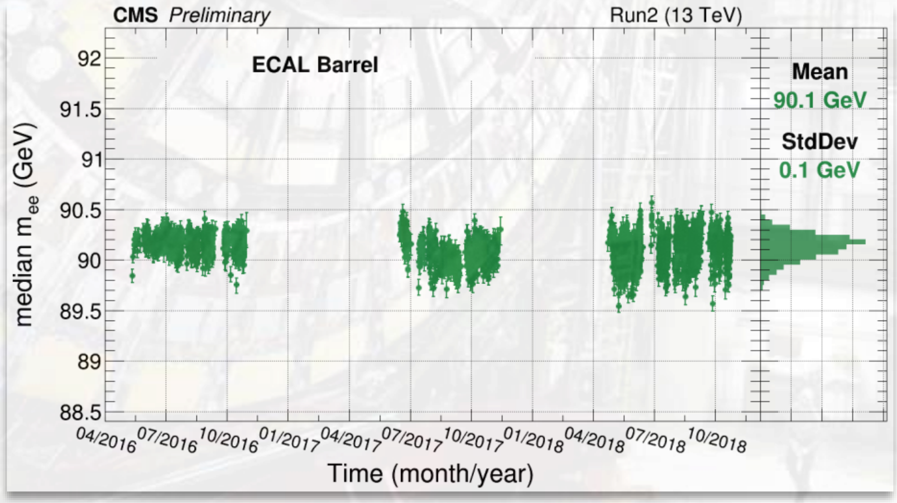
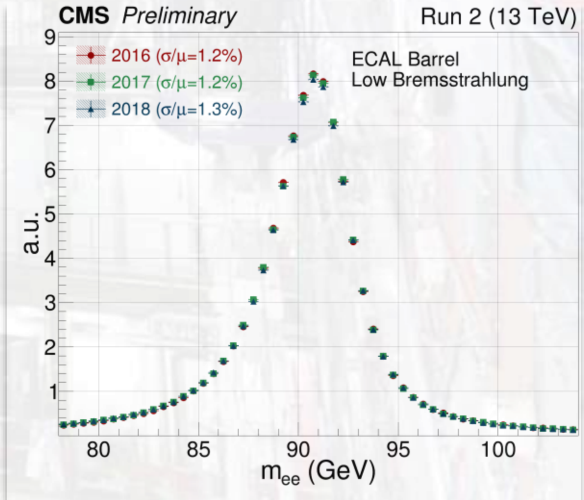


A multi template fit with multiple pulses for different bunch crossings

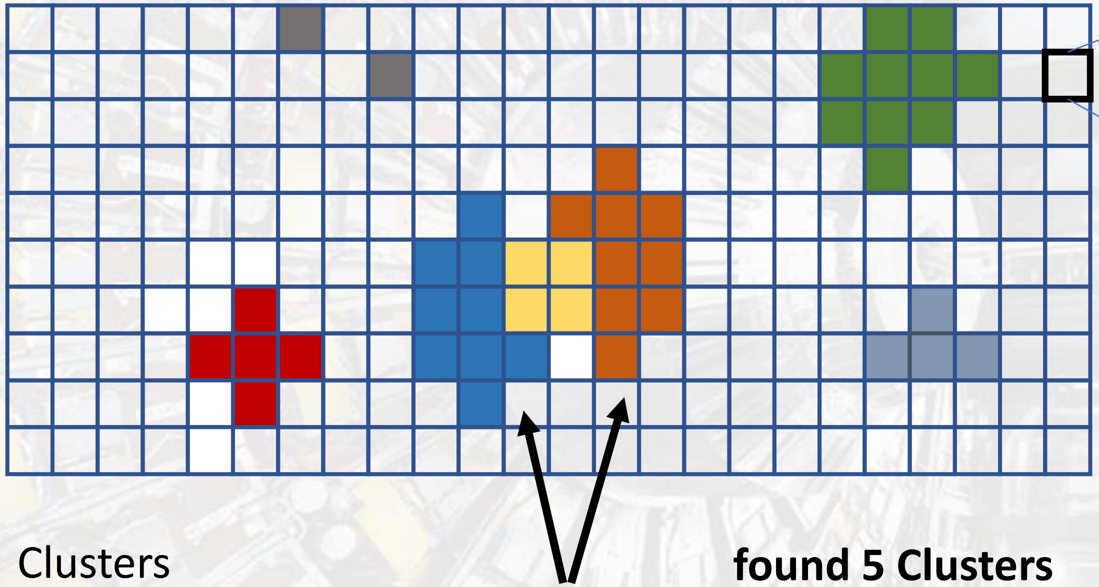
The "multifit" method uses templates derived from collision data





Reconstruction

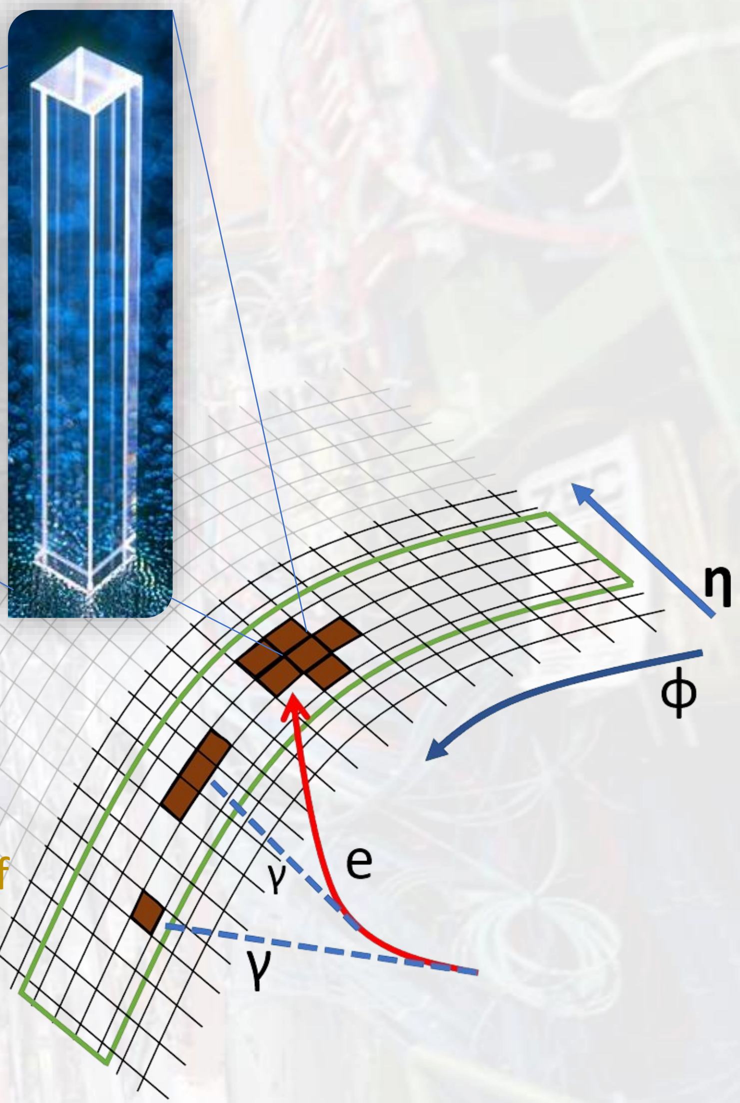
- Clustering of ECAL clusters



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



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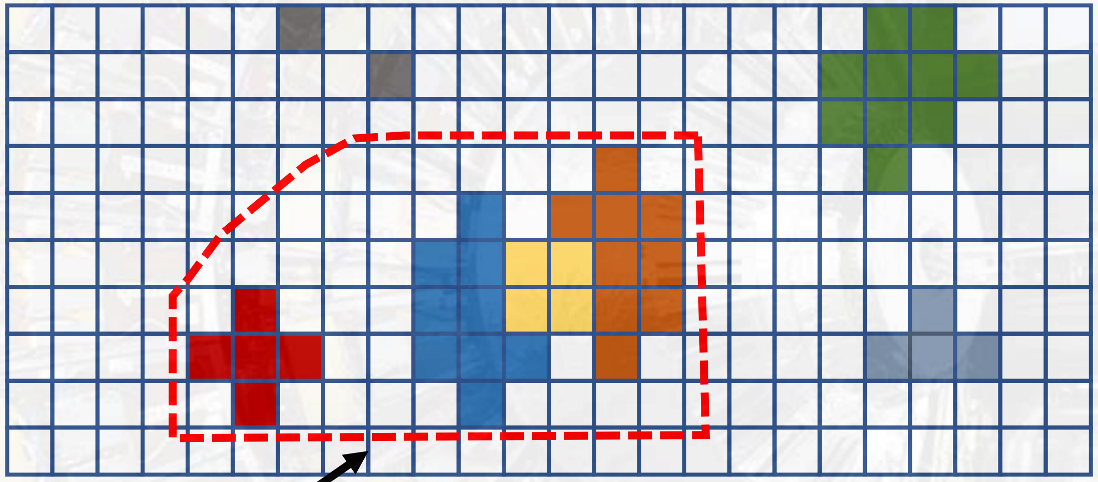

Moustache supercluster
A cluster of clusters

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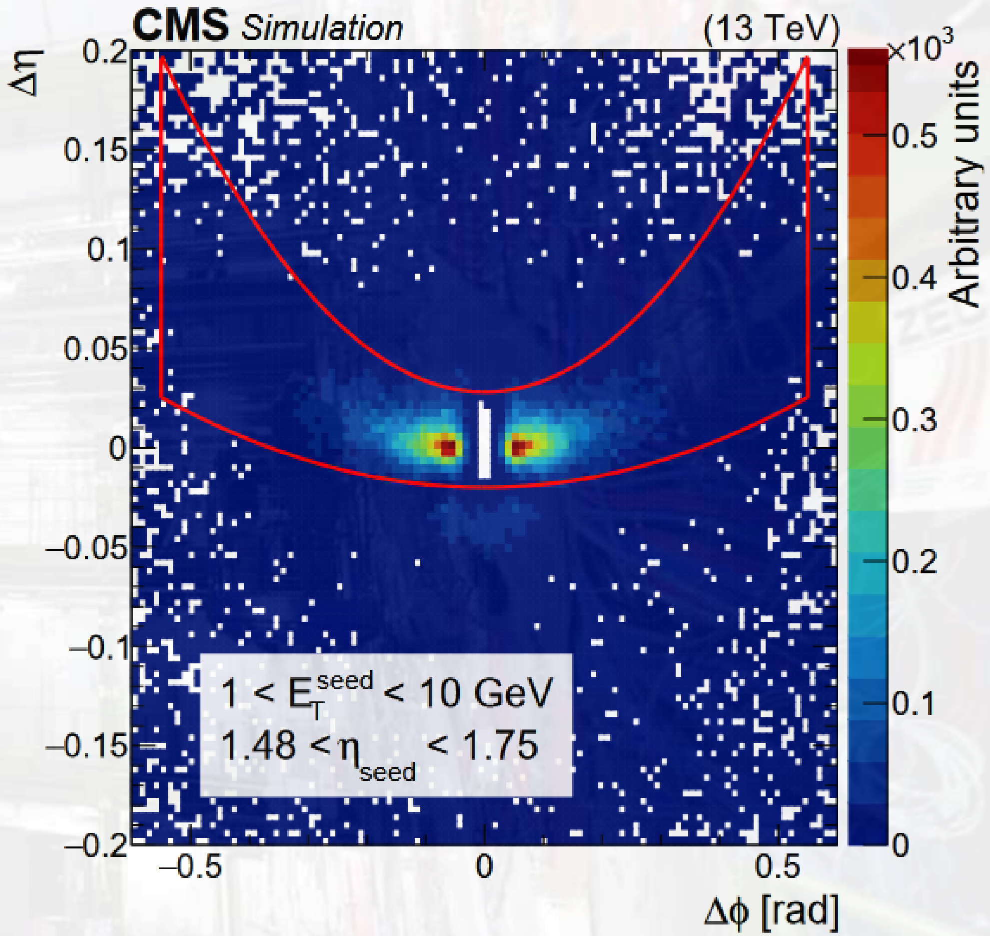

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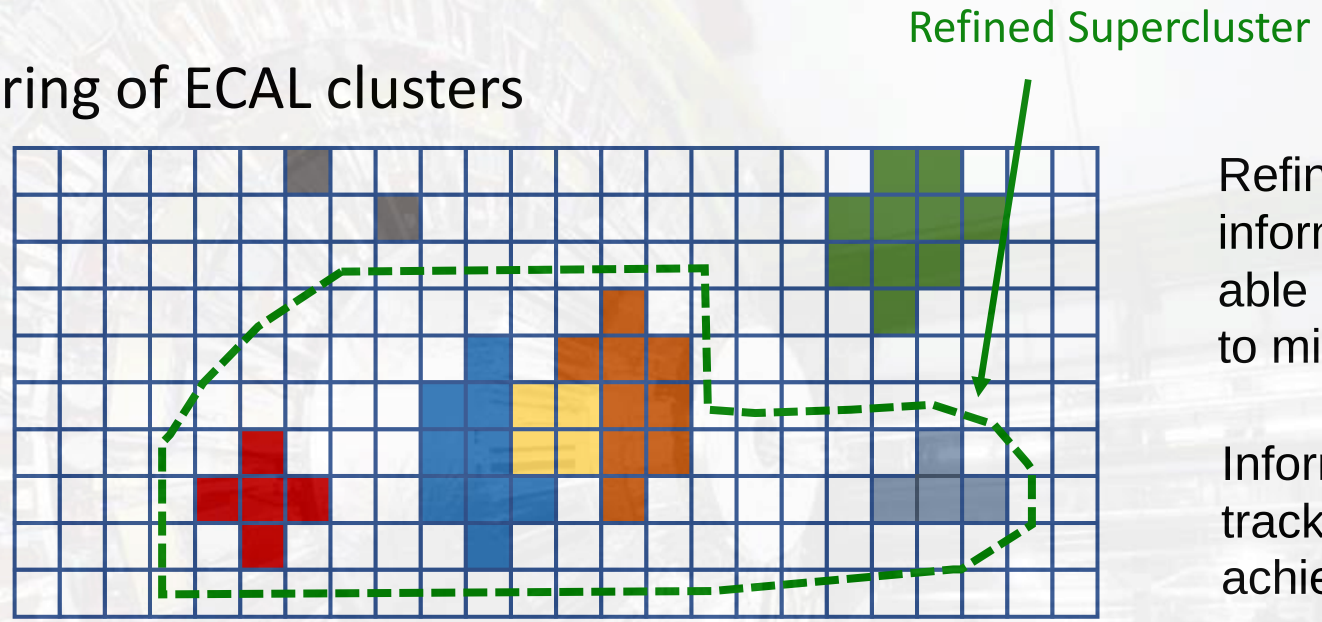
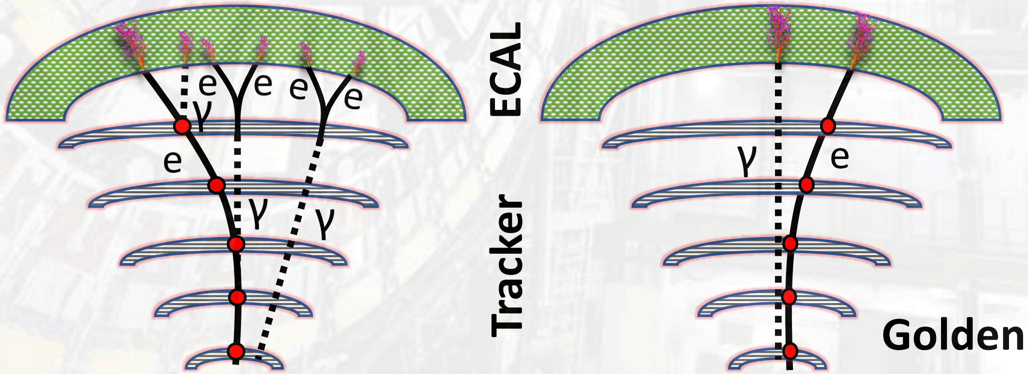


Refined superclusters use the information from the tracker, to be able to link bremsstrahlung emissions to missed ECAL deposits

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

With bremsstrahlung and conversions



Golden cases

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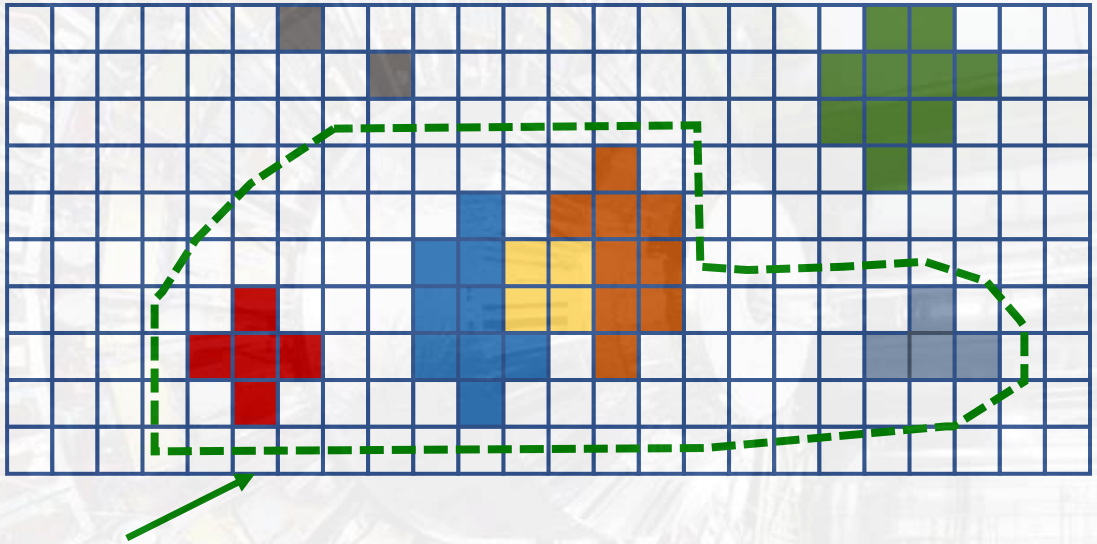

Refined superclusters use the information from the tracker, to be able to link bremsstrahlung emissions to missed ECAL deposits

There is also dedicated photon conversion recovery algorithm

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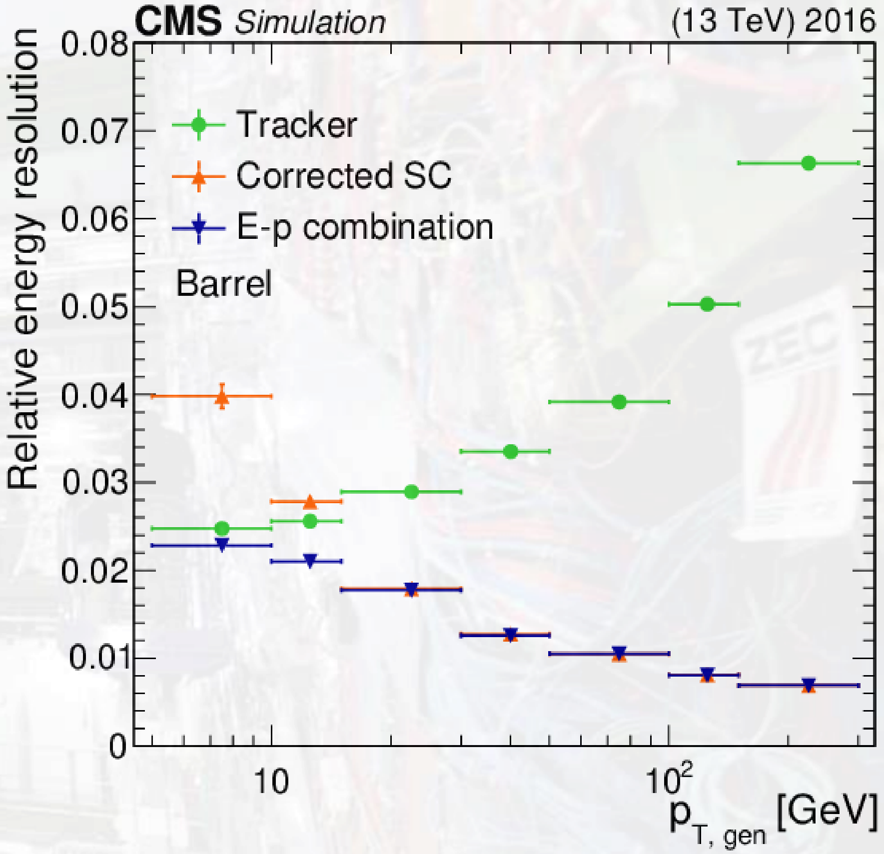

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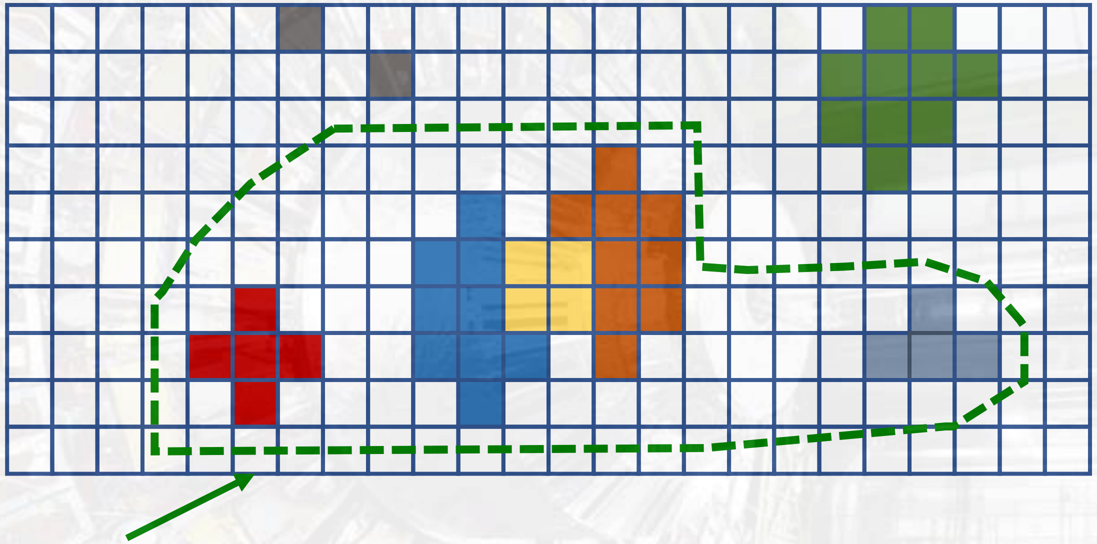

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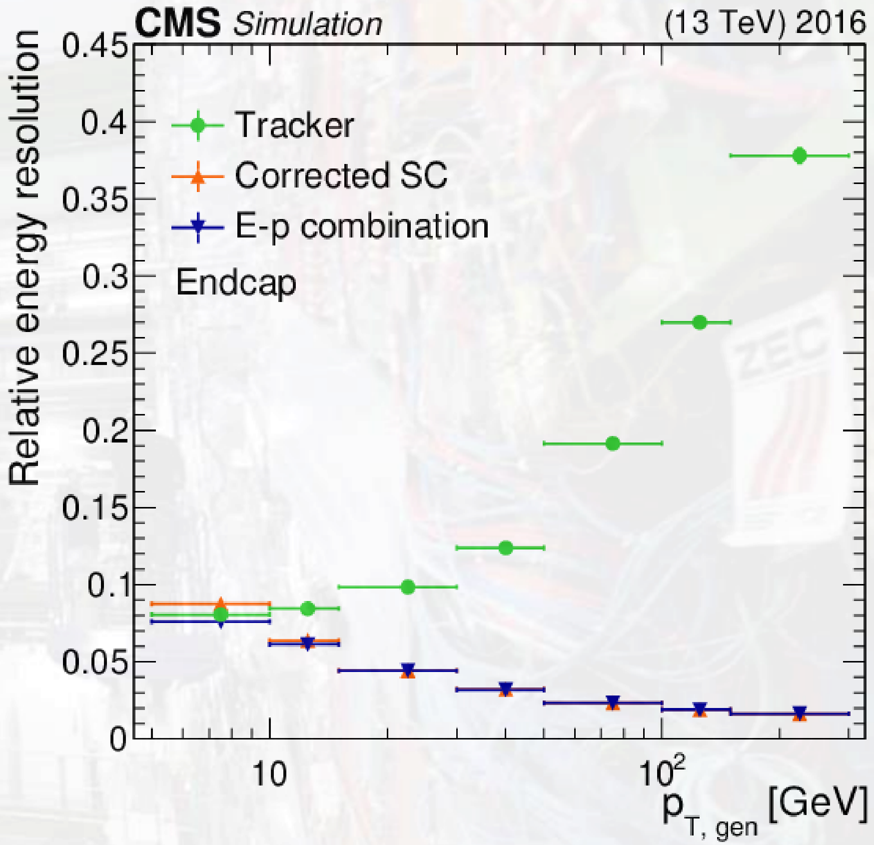
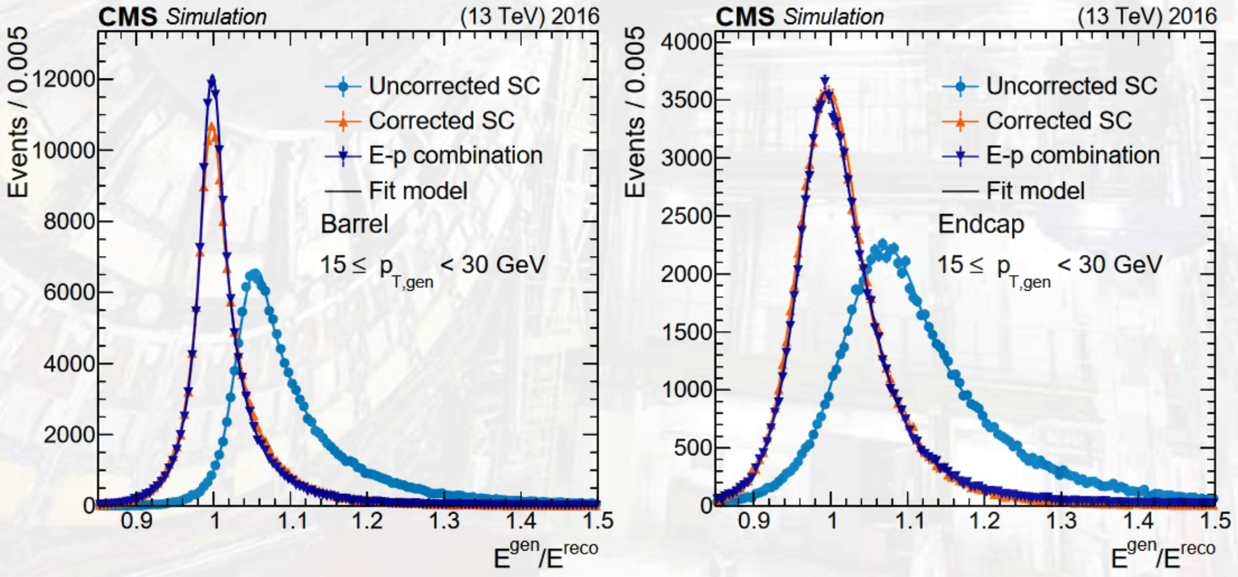


Energy corrections

- 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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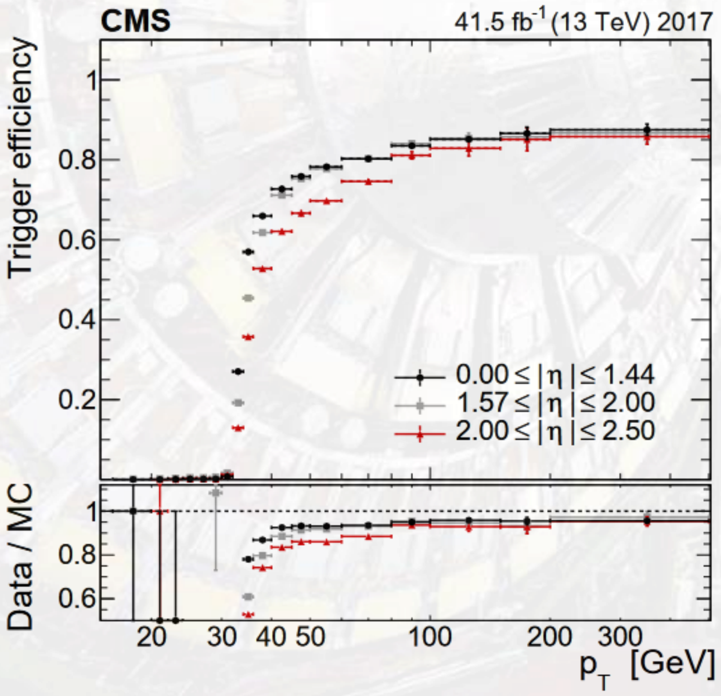
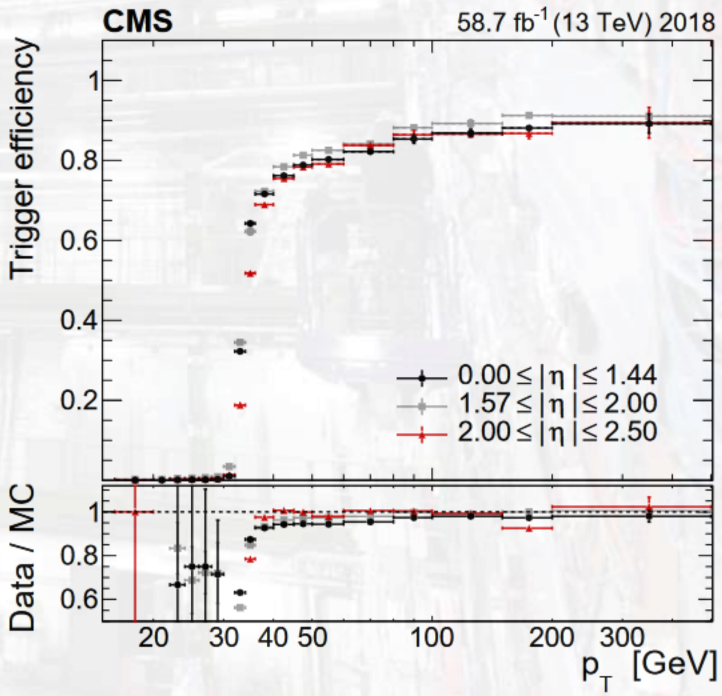
High level trigger performance

- 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

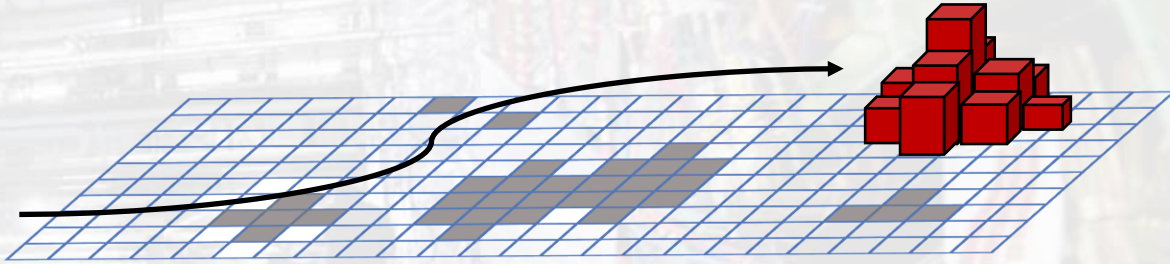
- **Two schemes are primarily used for identification:**

➢ 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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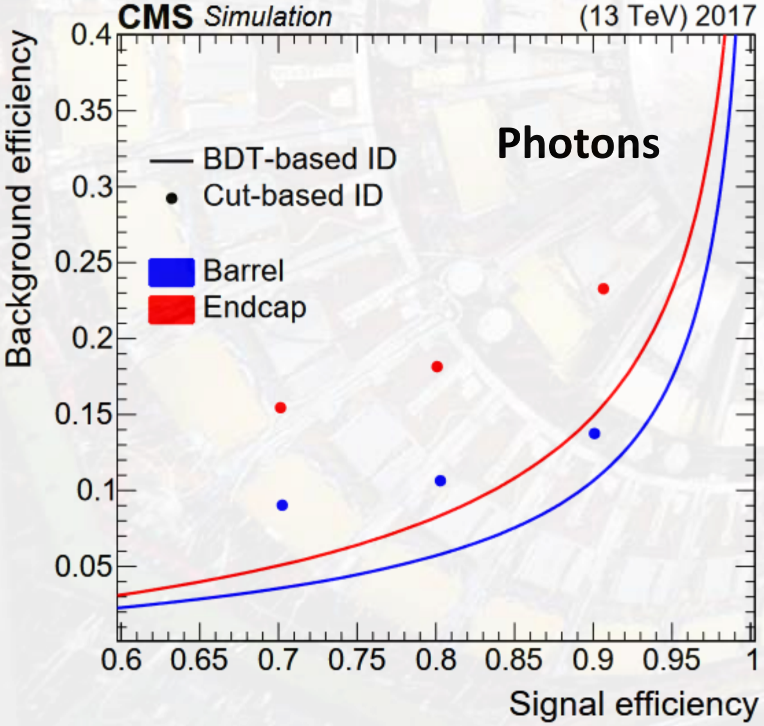
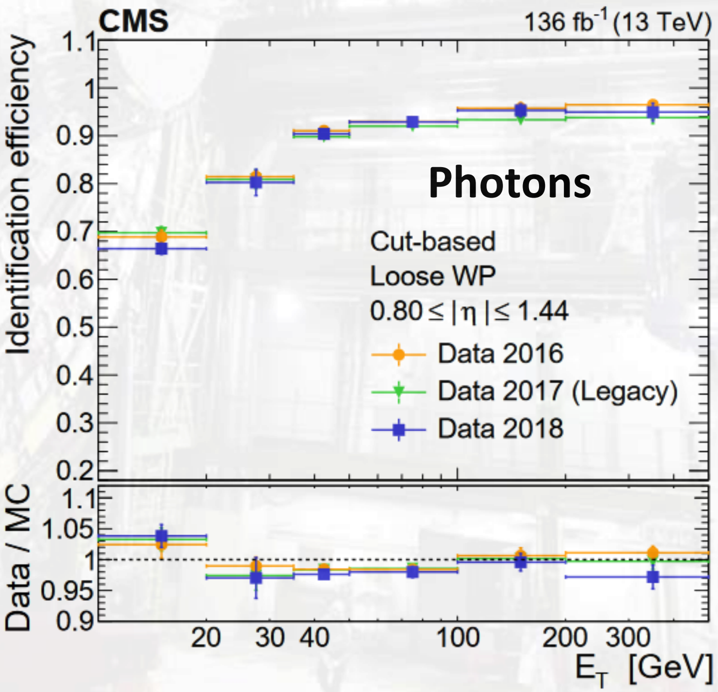
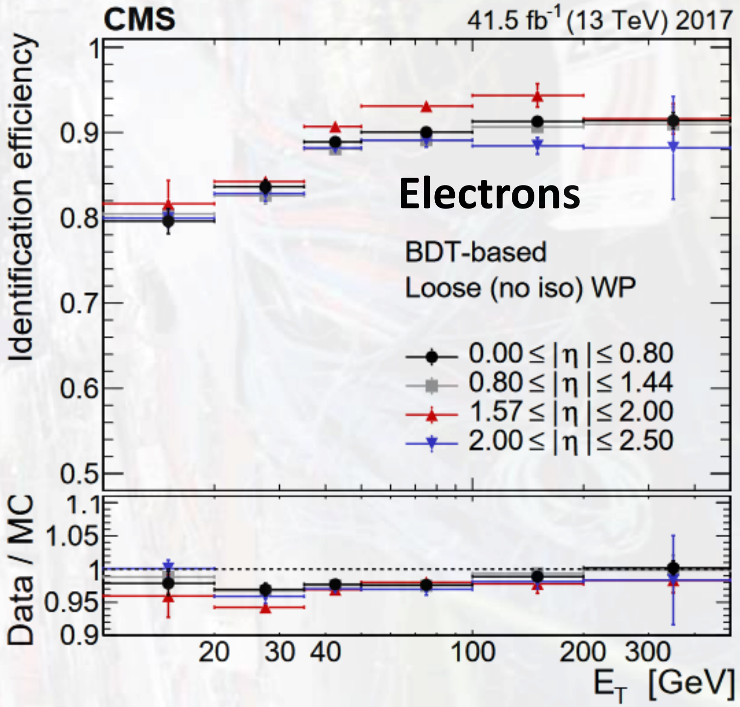






Looking forward to Run 3

- **Run 3 going on as we speak** (First collisions seen on the 5th of July)
- It will come with several challenges

➢ **Higher pileup Interactions**

➢ **Noise in ECAL will increase**

Several new developments to tackle the challenges:

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

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 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

Dedicated talks/posters for many of these at ICHEP 2022

Conclusions

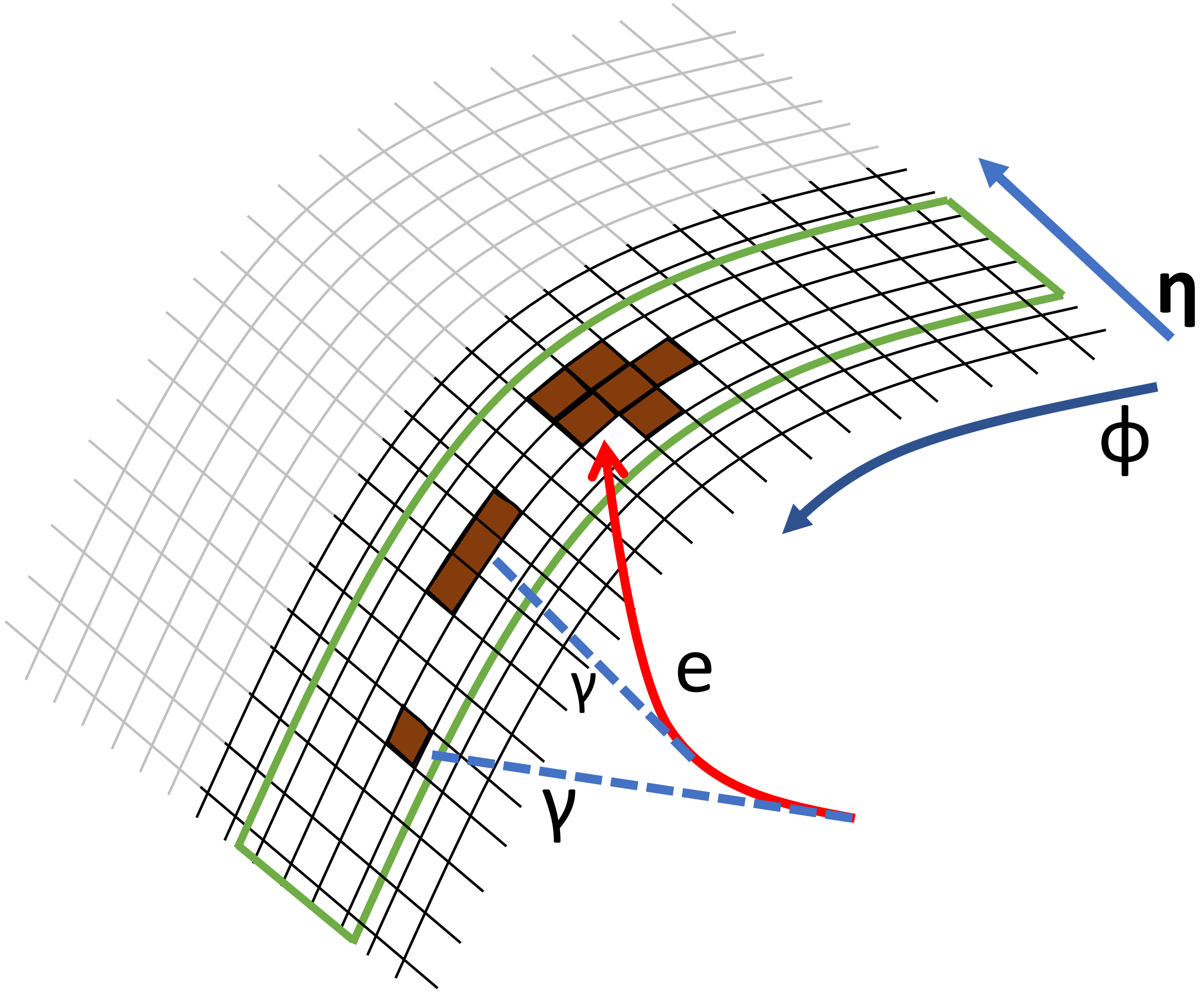
- The CMS detector gave excellent performance for reconstruction and identification of electrons and photons in Run2 of the LHC
- We had stable energy resolution and identification efficiencies for the full Run 2 data-taking period
- Several high quality physics results published by CMS using electrons and photons in Run 2
- We are looking forward to see the performance of electrons and photons in the challenging Run 3 collisions
- Several related talks/posters on electrons and photons in ICHEP 2022

Some other performance and development

The ultimate CMS ECAL calibration and performance for the legacy reprocessing of LHC Run 2 data **- Raffaella Tramontano**
Deep learning techniques for energy clustering in the CMS electromagnetic calorimeter **- Badder Marzocchi**
The CMS ECAL upgrade for precision timing measurements at the High-Luminosity LHC **- Stefano Argiro**
Calorimetry with Graph Neural Networks in CMS **- Simon Rothman**

Dedicated talks/posters at ICHEP 2022

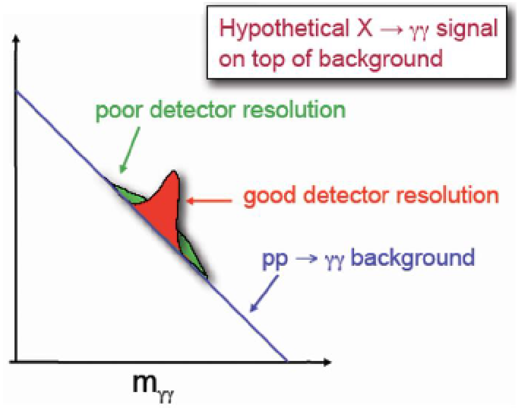
BACKUP



η
ϕ
e
γ
γ

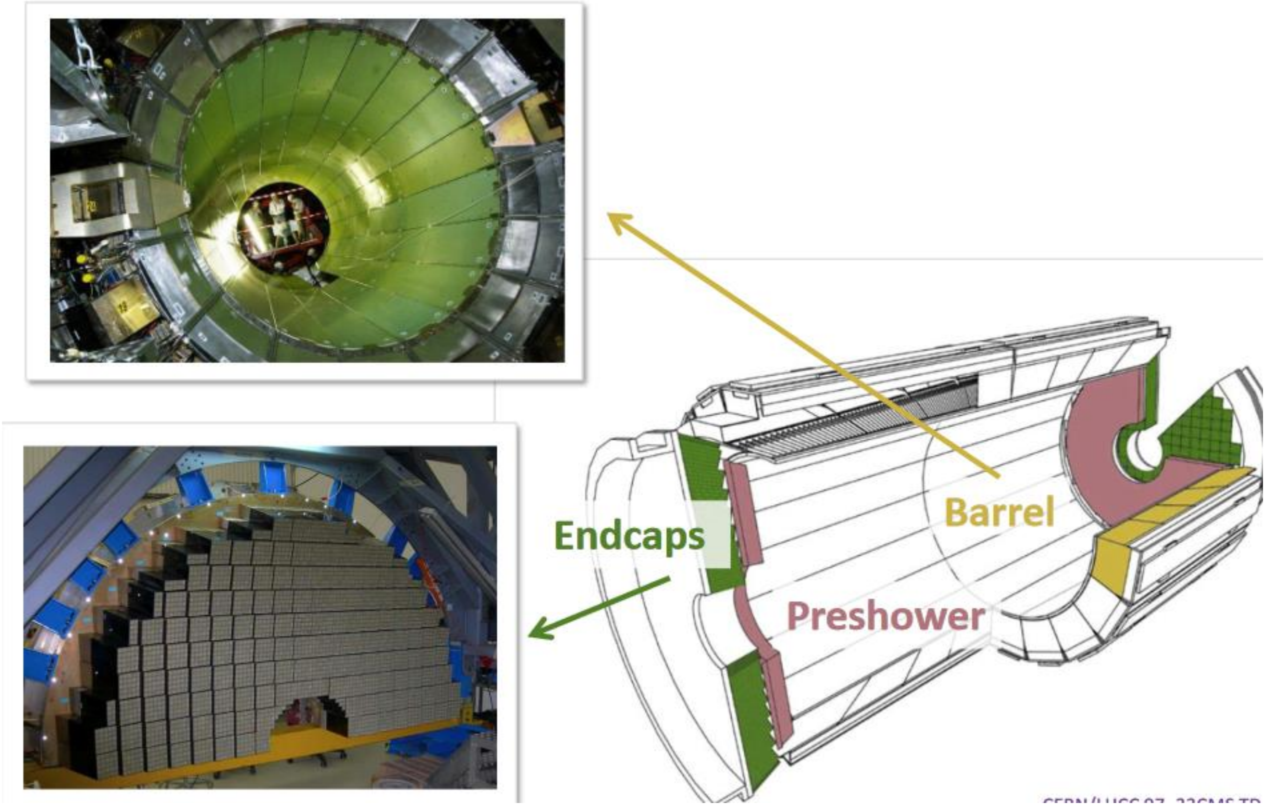
LHC Requirements for Calorimeters

- **Fast response** (25 ns or faster) and **high granularity**, to reduce pile-up induced noise
- **Radiation-hard** detectors and electronics
- **Hermetic** and **cover** the full azimuthal angle and rapidity range, to tag very forward jets and well measure the missing energy
- **Excellent** electromagnetic **energy resolution**
  - To detect the two photon decay of an intermediate mass Higgs (golden channel together with H→ZZ →4l)
    - $m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\theta)}$
    - Uncertainty on $m_{\gamma\gamma}$ determined by uncertainty on photon energy and direction



Courtesy of C. Mariotti

CMS Electromagnetic Calorimeter

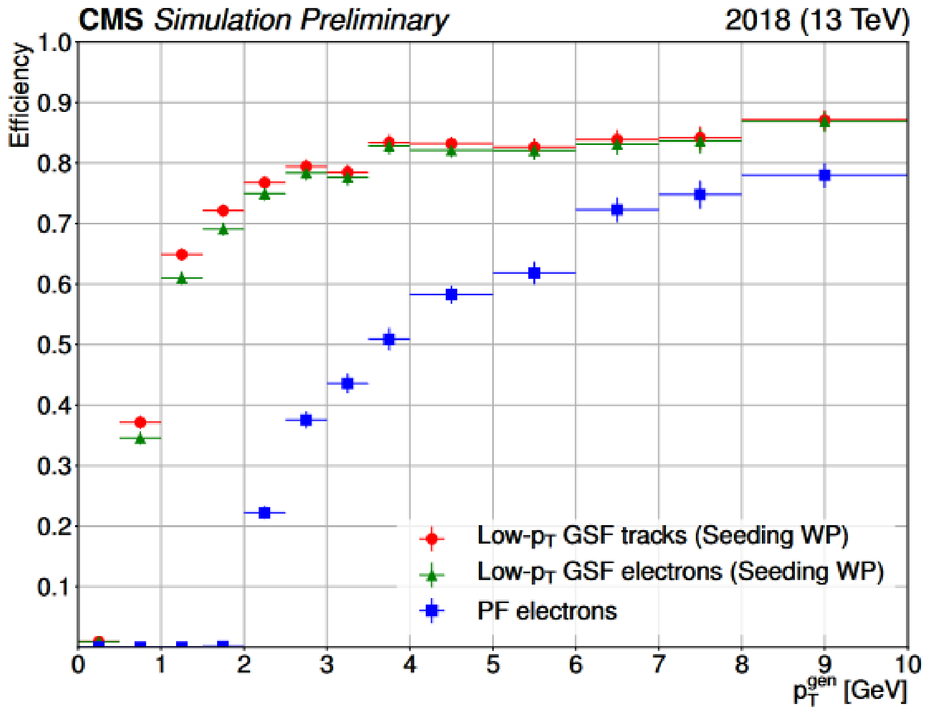


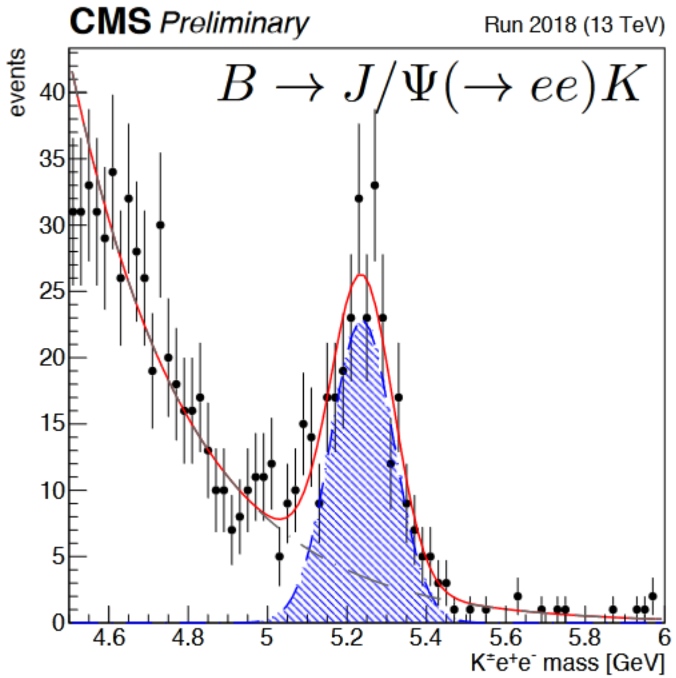
CMS DP -2019/043

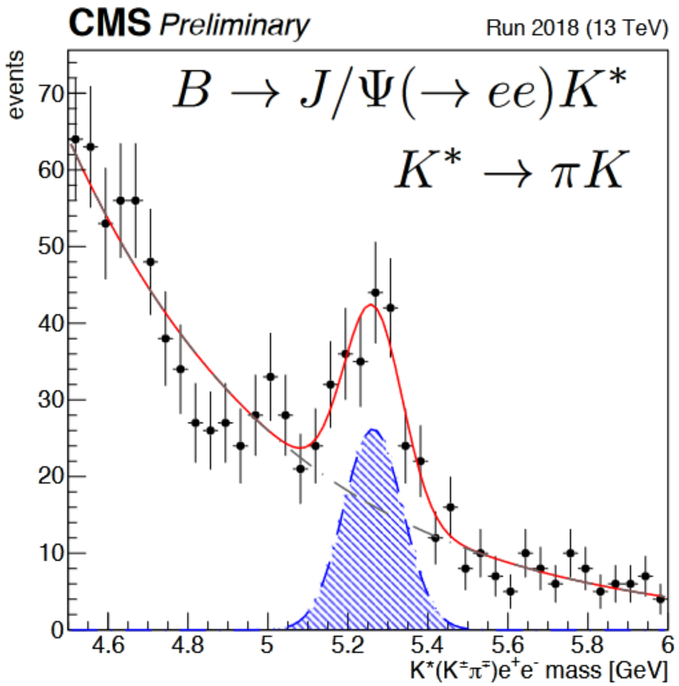
Reconstruction: efficiencies for low-p_T electrons

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:

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

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

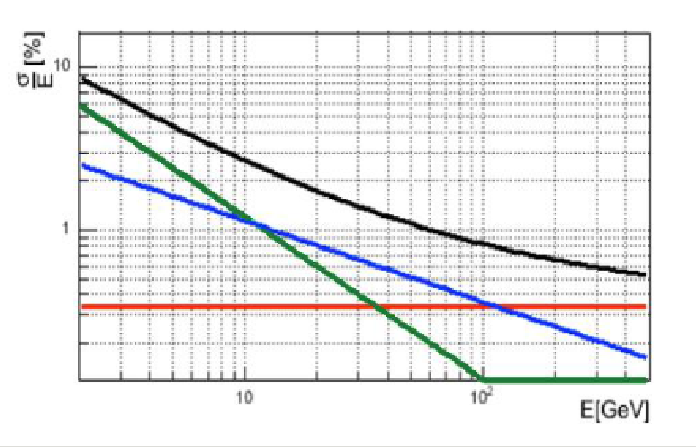
Energy resolution of real detectors

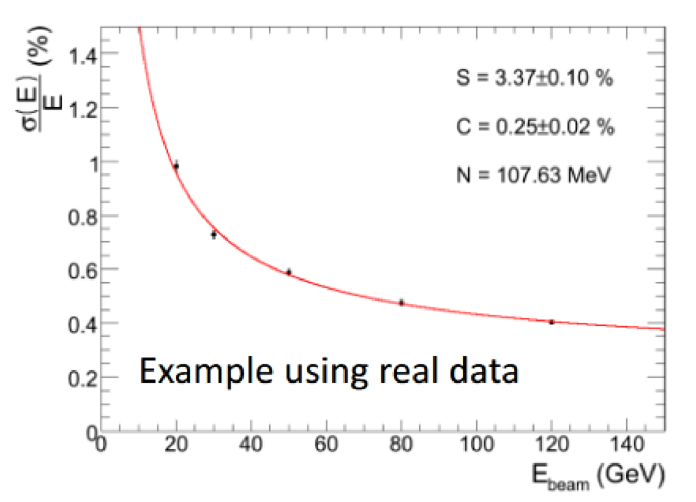
$$\boxed{\frac{\sigma(E)}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C}$$

S: stochastic term from Poisson-like fluctuations

N: noise term from electronics and pile-up

C: constant term



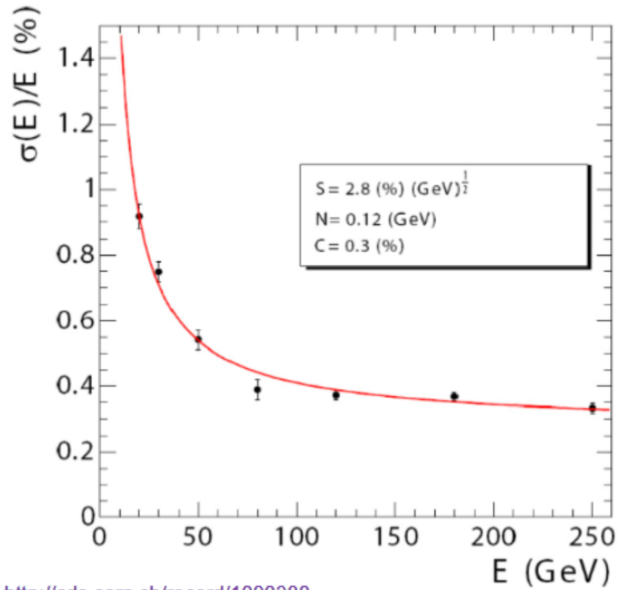


ECAL Energy Resolution

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

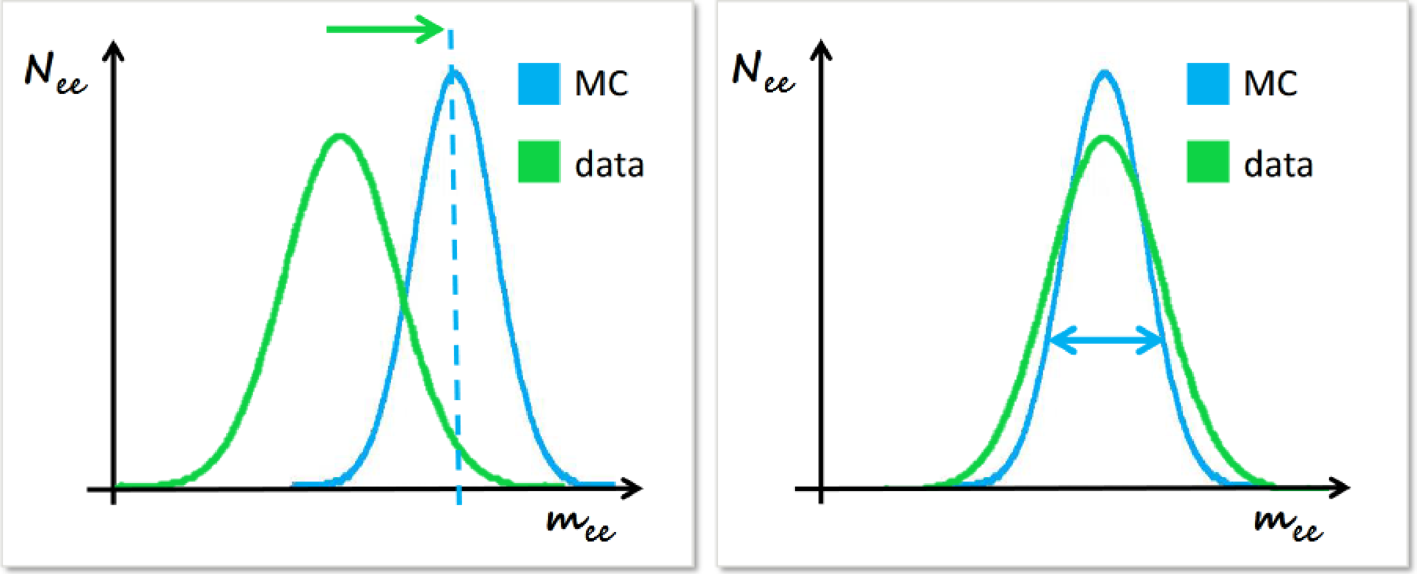
- No magnetic field
- No material in front of the ECAL
- Negligible inter-calibration contribution in the constant term

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



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)

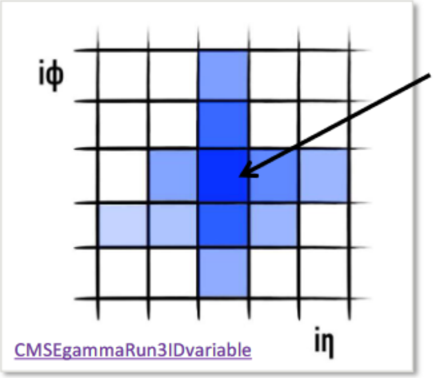


Electron and Photon Identification

- 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** → Are the energy deposits in the calorimeters compatible with coming from a single electron/photon?
  - **Track matching variables** → Does the ECAL deposit have a compatible track?
  - **Conversion ID variables** → Are the tracks compatible with coming from the collision point? Or do they appear later on in the tracker?
  - **Isolation variables** → Is there a large amount of other particles nearby the electron/photon?

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

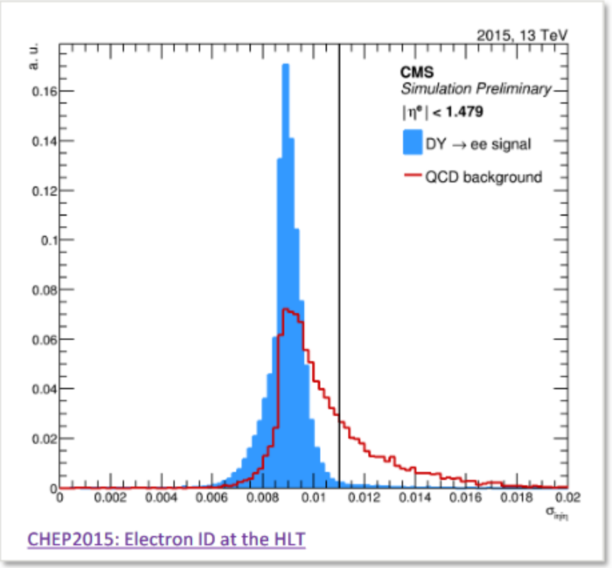
- **$\sigma_{i\eta i\eta}$** is one of the **most important** electron/photon **ID variables** in CMS
- It measures the **spread** of an electromagnetic shower **along η** direction
- A **5x5 array of crystals** is the area where an electron/photon is almost **fully contained**



Most energetic crystal of 5x5 array

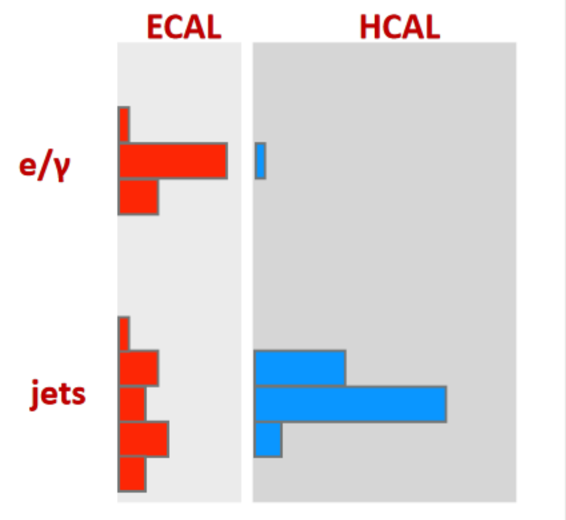
$$\sigma_{i\eta i\eta} = \sqrt{\left(\frac{\Sigma_i^{5\times5} w_i(\eta_i - \bar{\eta}_{5\times5})^2}{\Sigma_i^{5\times5} w_i}\right)}$$

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

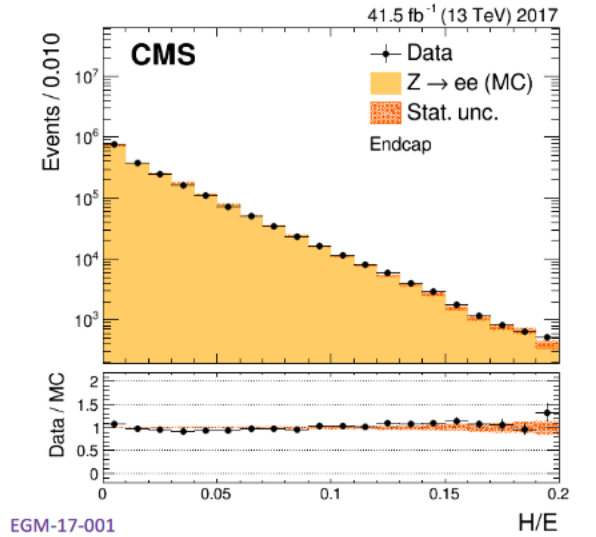


Shower Shape Variables: H/E

- **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



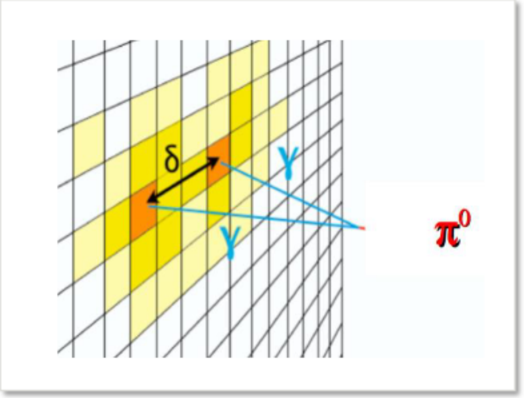
Courtesy of S. Mukherjee

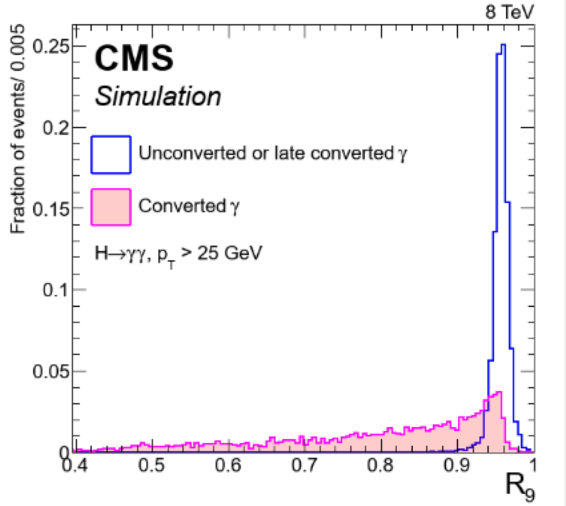


EGM-17-001

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

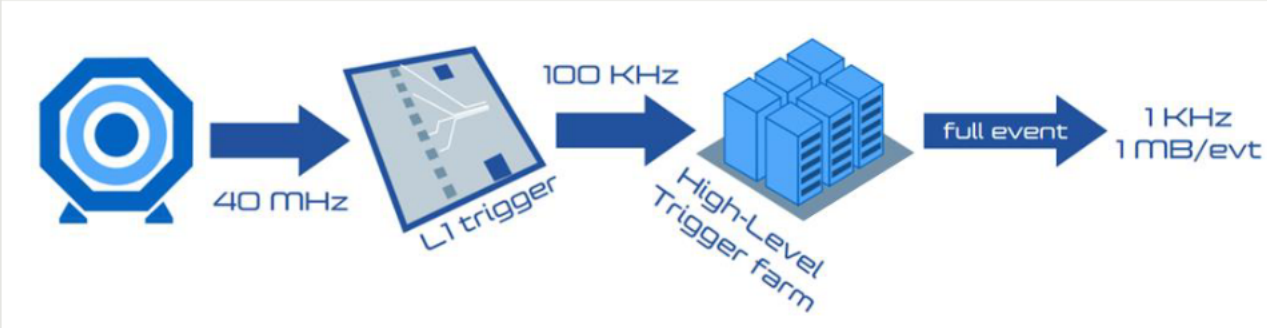




10.1088/1748-0221/10/08/P08010

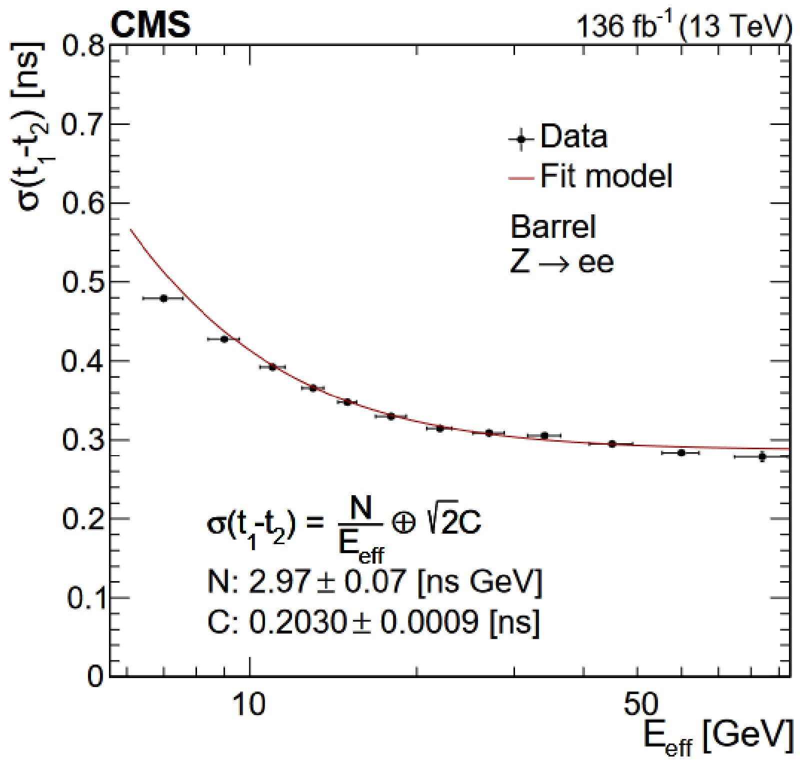
Trigger Selection and Performance

- 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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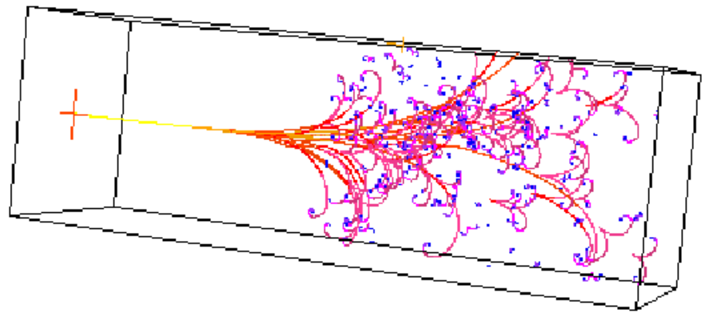
Definition of Calorimeter

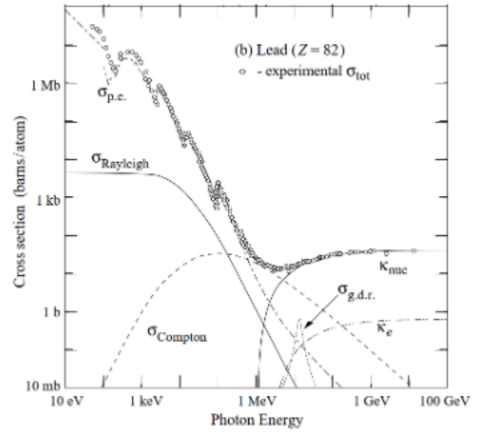
- In particle physics a **calorimeter** is a **detector measuring** the **energy** carried by an incoming particle
  - **Instrumented blocks of matter** in which the particle interacts and **deposits all its energy** in the form of a cascade of particles
- The **particle energy** is **measured** in **eV** (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



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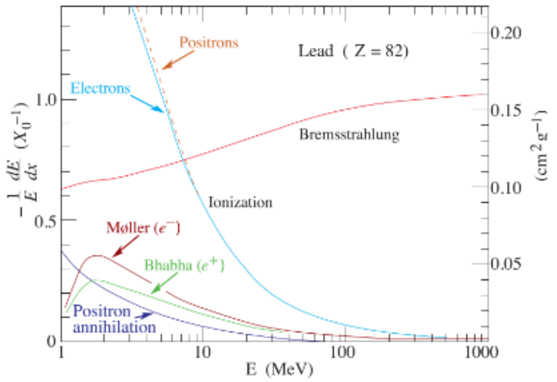

PDG 2018