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CMS electron and photon performance at Run 2 and prospects for Run 3

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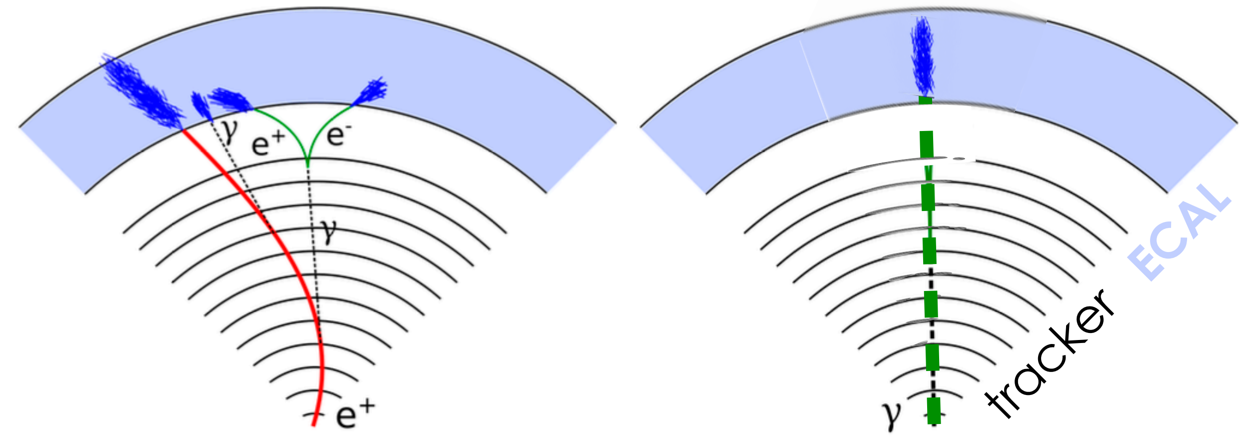
Overview

- **Electrons and photons** reconstructed and identified with **high precision and purity at CMS**

  - Interplay between **calorimeters and tracker**
  - **High level tools** to maintain excellent performance in the harsh LHC environment

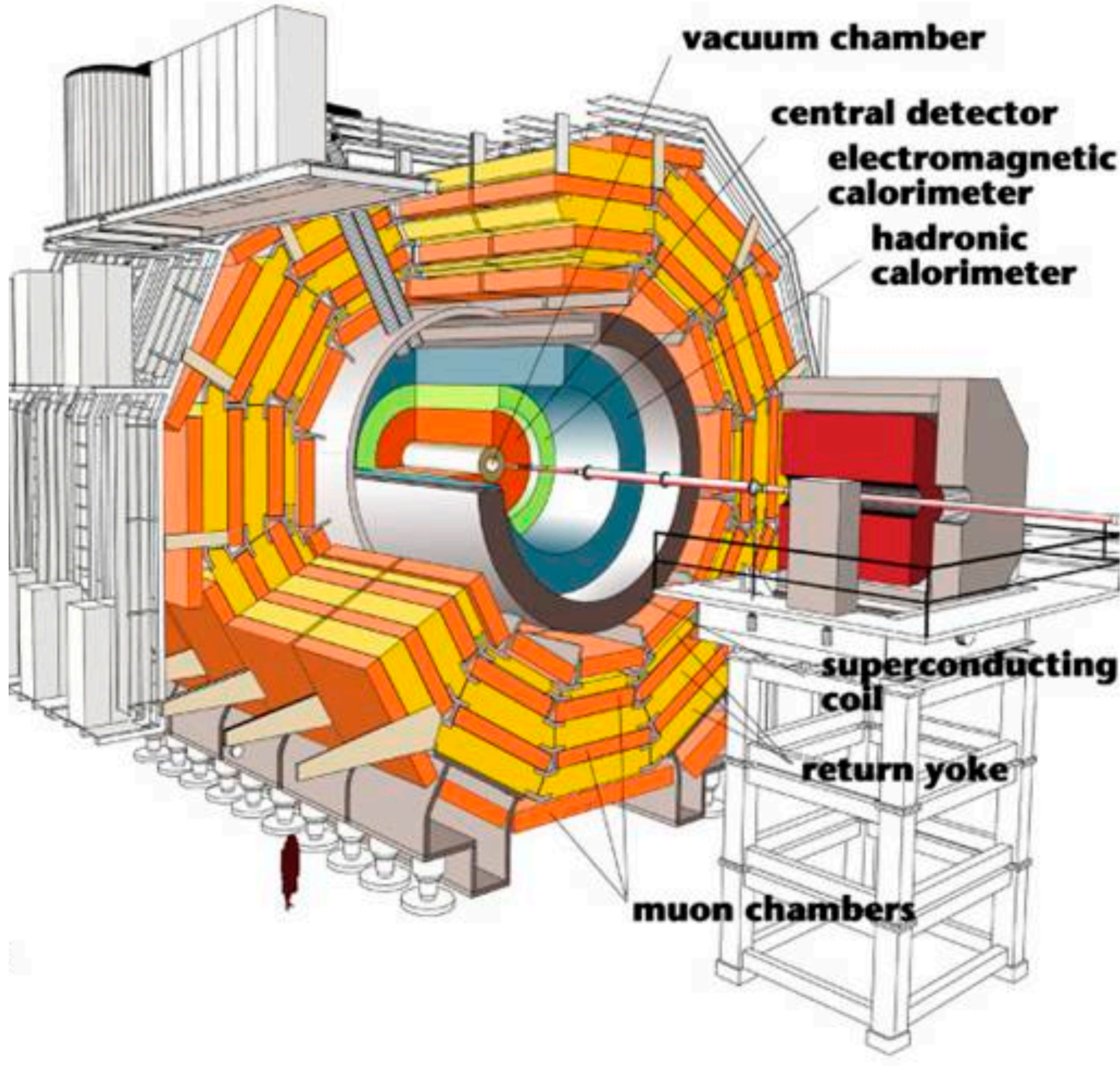


- Results shown here include [full Run 2 data]() collected in **2016, 2017 and 2018 years**

  - **Reprocessed 2017 data ("Legacy")** with improved calibration and more precise description of data conditions in simulation
  - Improvement in resolution and data/MC agreement
  - **Similar** performance expected for **Legacy 2016 and 2018**

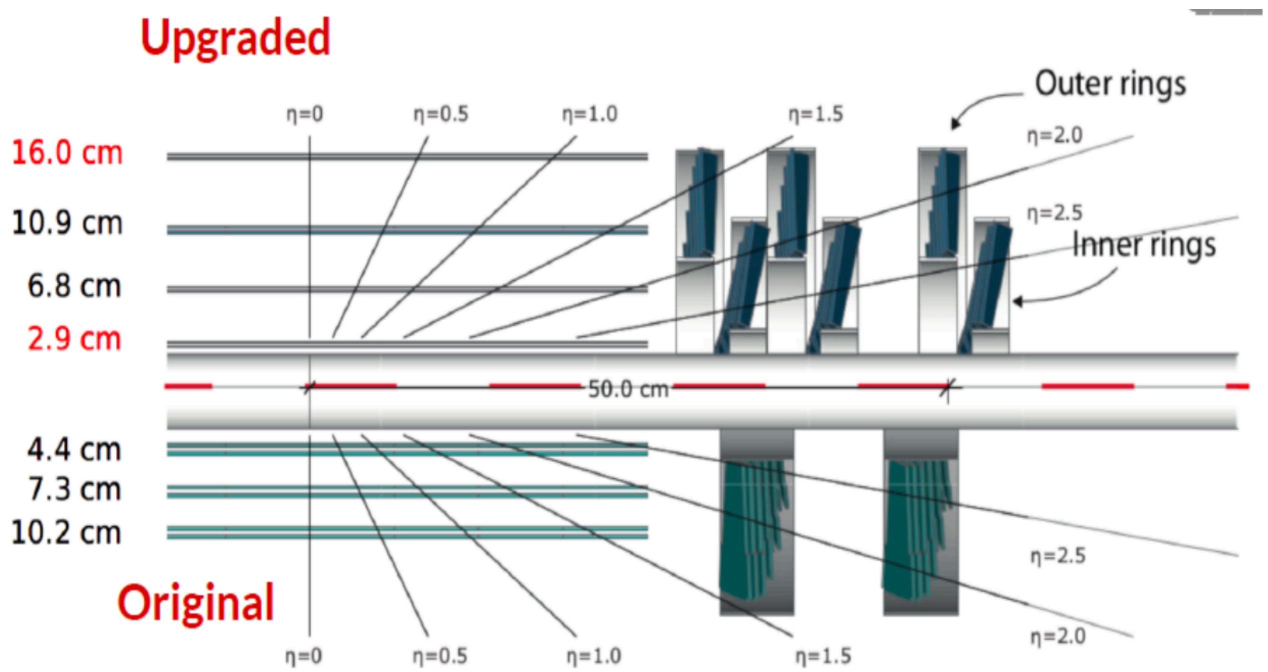
- Performance of **Run 3** algorithms will be shown for the fist time

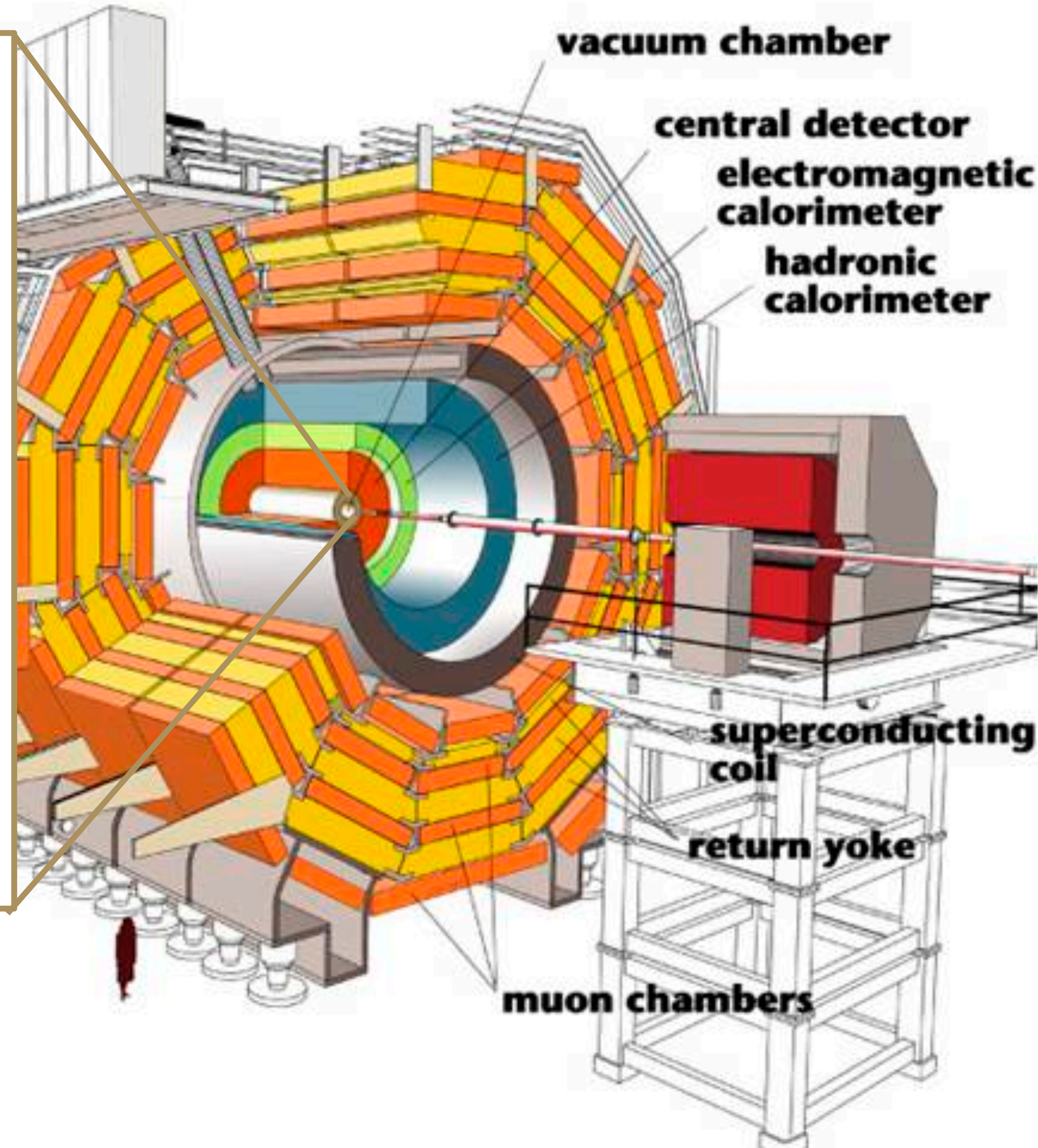
The CMS Run 2 Detector



The CMS Run 2 Detector

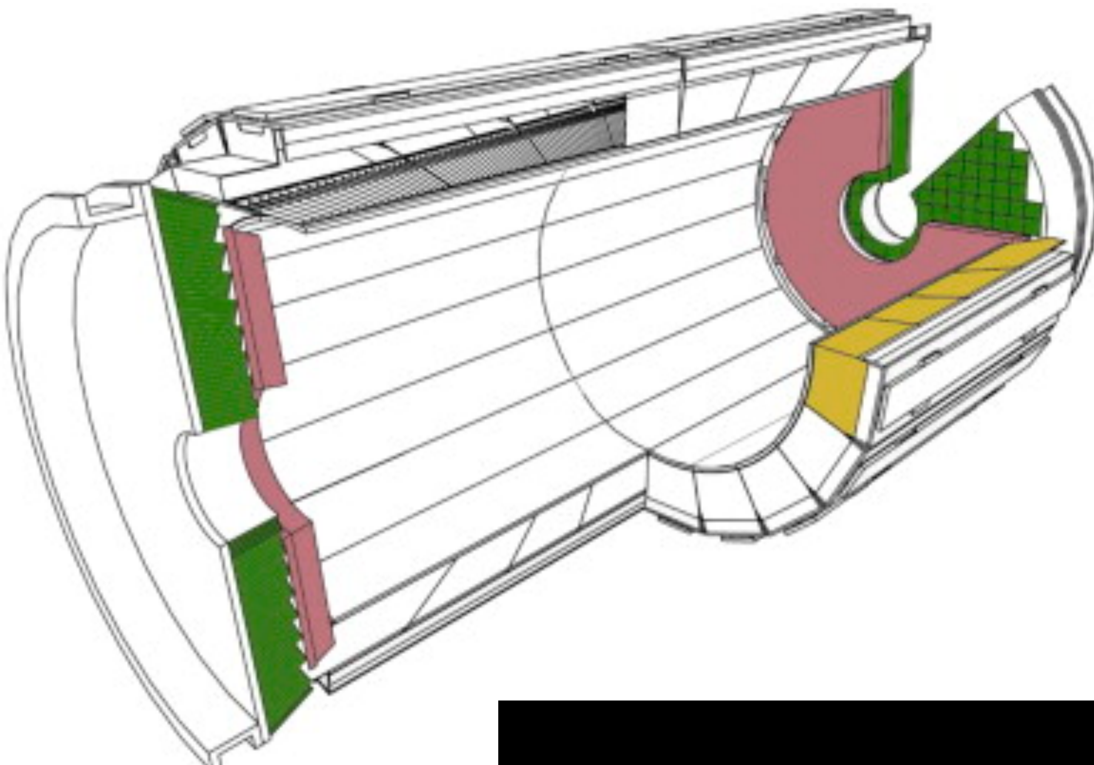
- One additional pixel layer in barrel and one in endcap: **reduce fake rate, improve track resolution and efficiency**



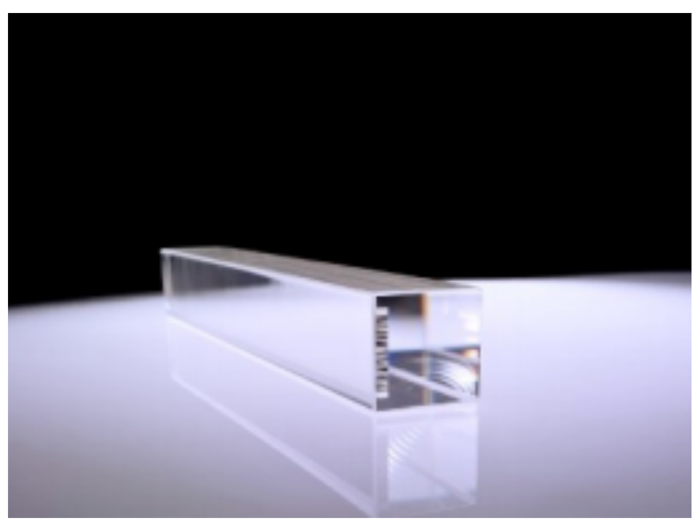


The CMS Run 2 Detector

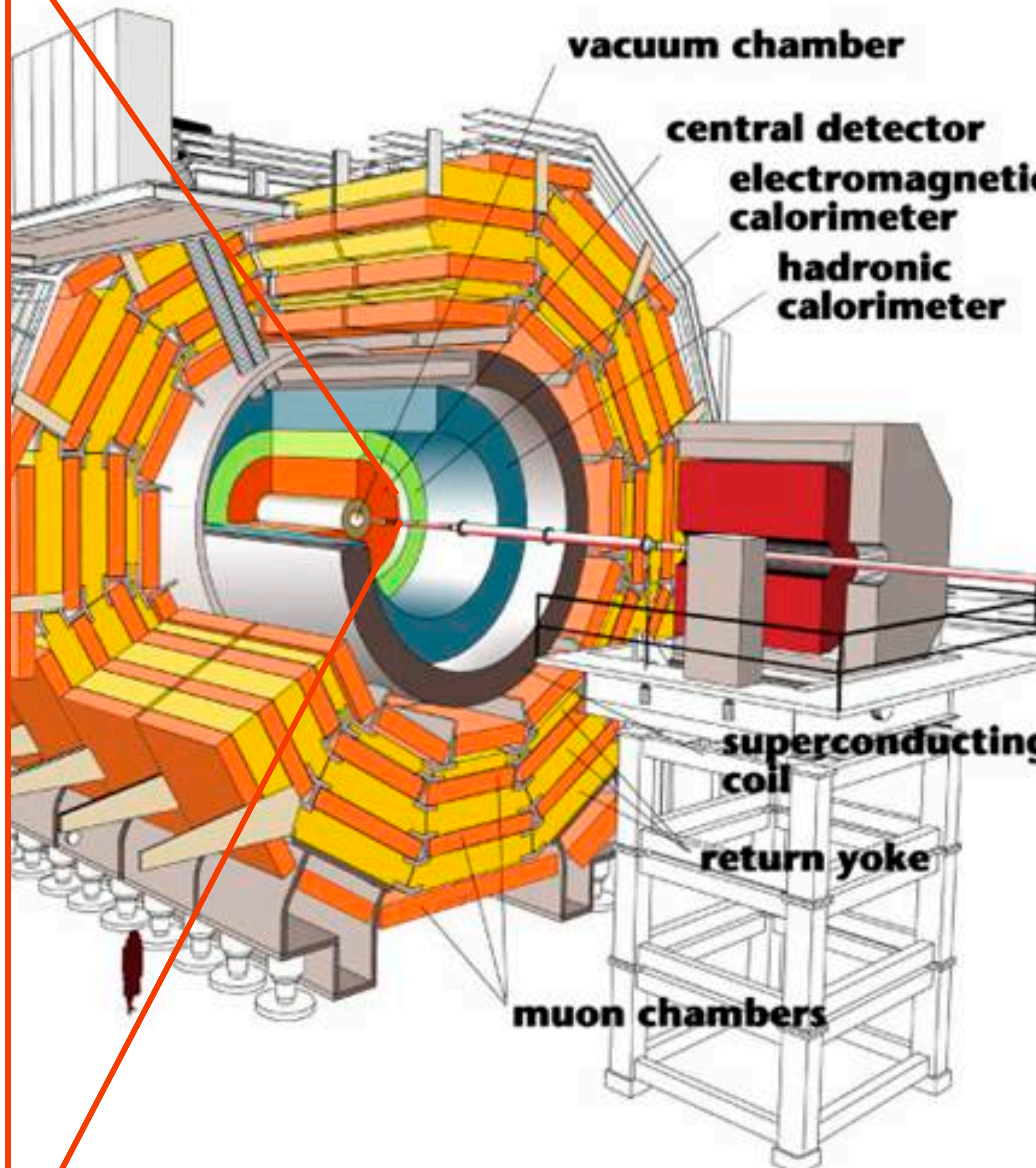
- Hermetic **Barrel** & **Endcap** (75848 crystals) + Lead/Si **preshower**



Lead Tungstate (PbWO4) crystal



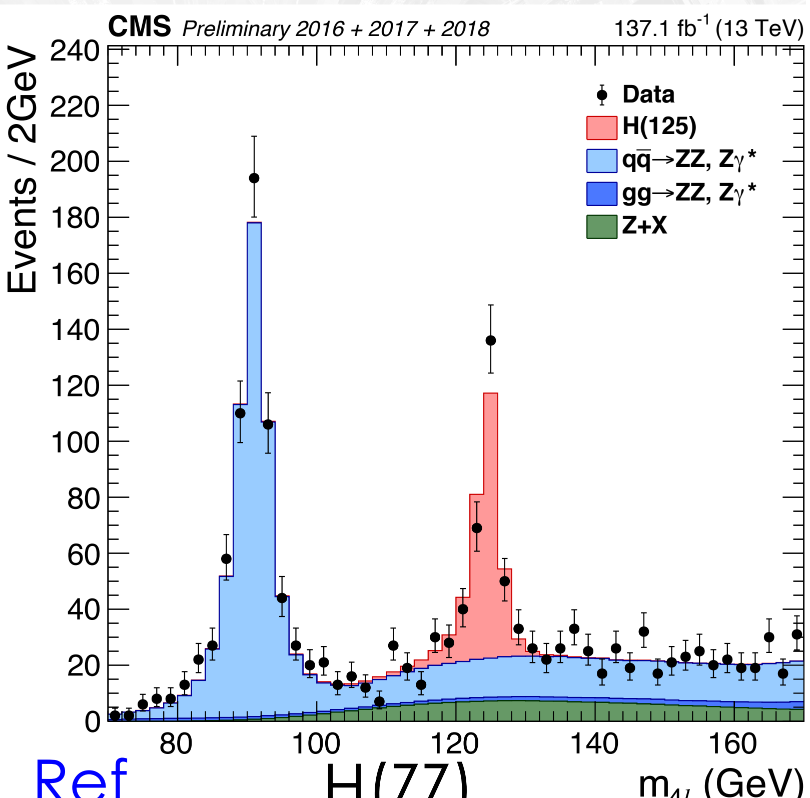
[More on D. Soldi's talk and D. Kostantinov's poster]



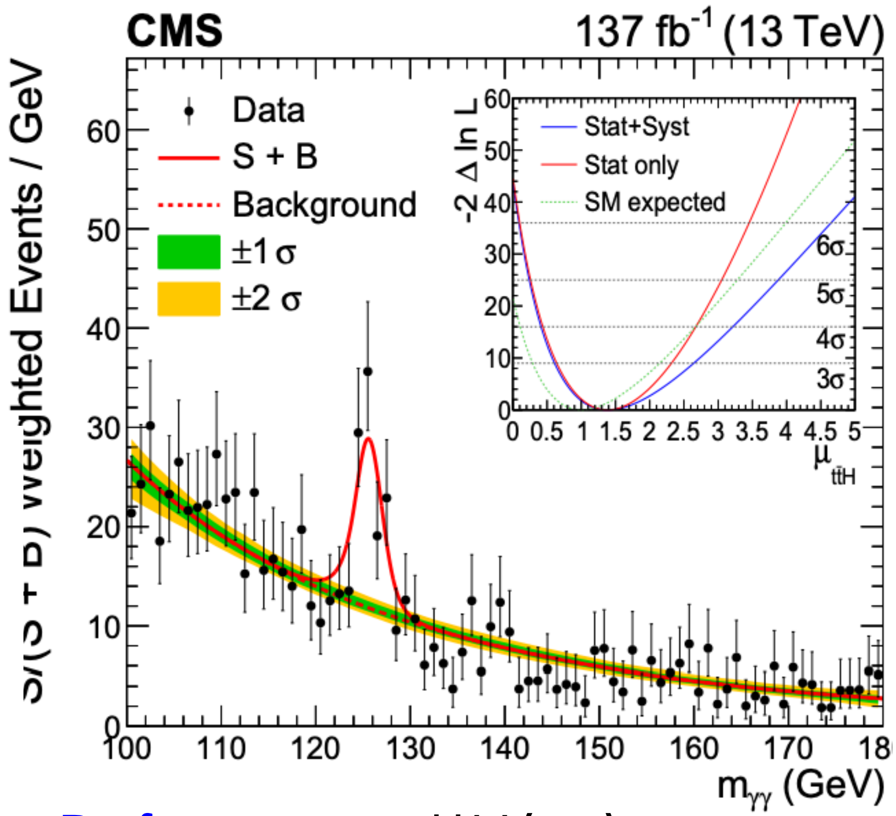
Role of e/γ in Physics Analyses

See H. Mei's talk

See M. Bonanomi's talk

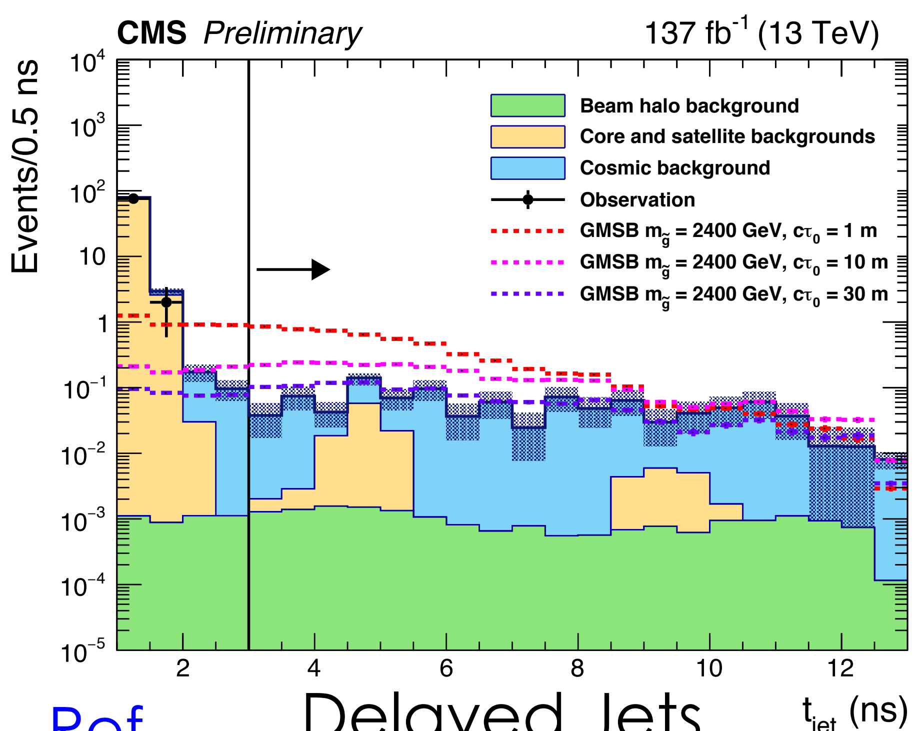


Ref H(ZZ)



Ref ttH($\gamma\gamma$)

See C. Herrera's talk

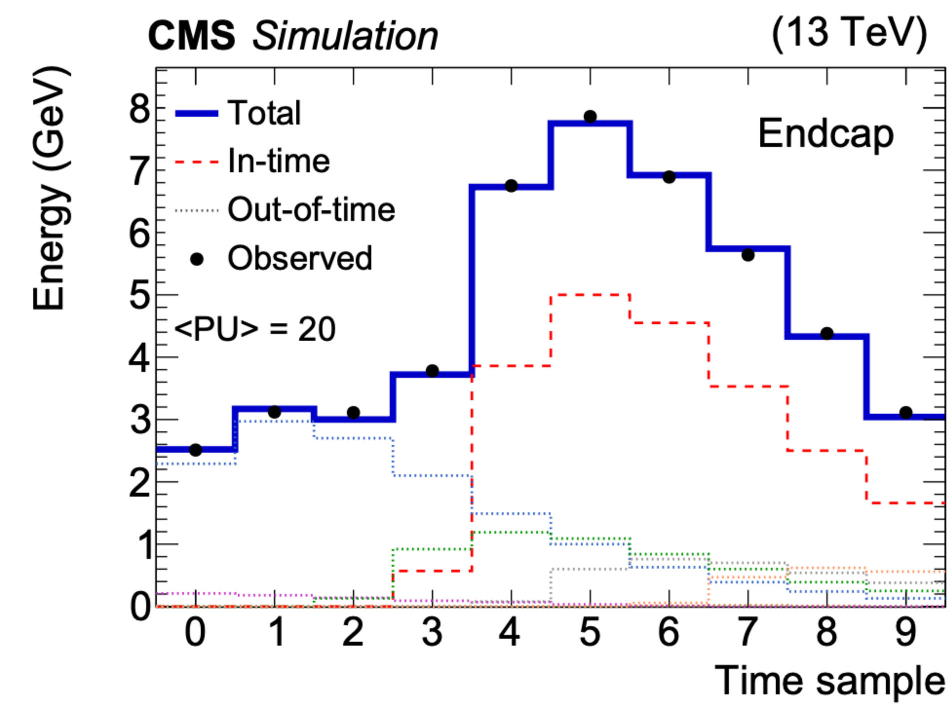


Ref Delayed Jets

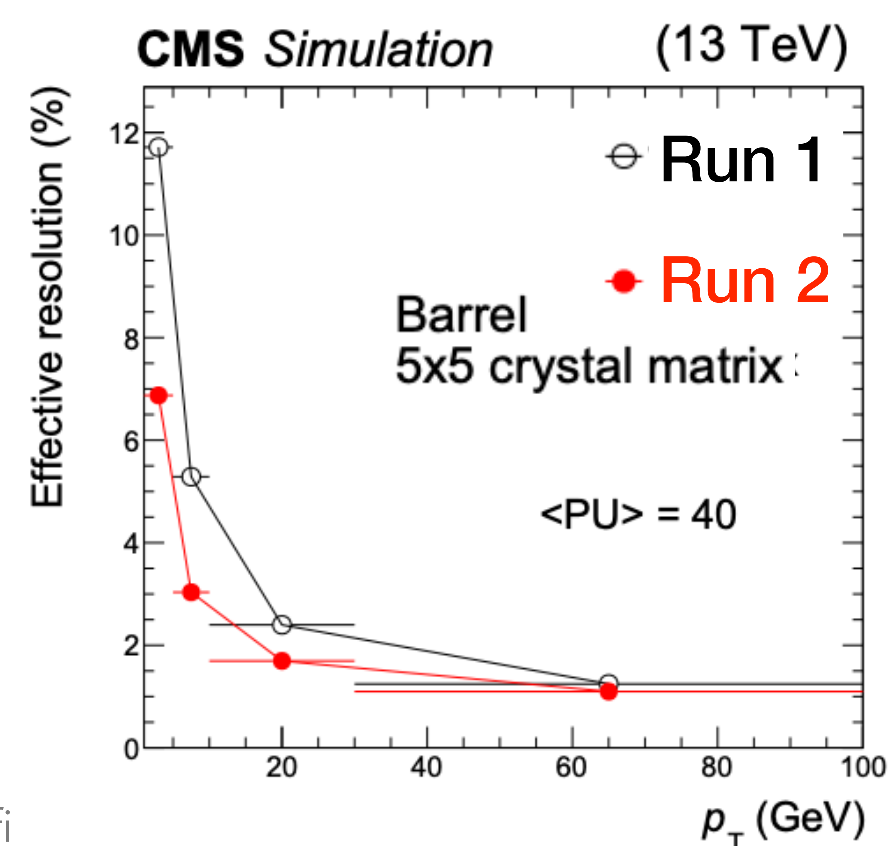
- **Excellent energy resolution ([1.5-4]%)** and electron/photon ID crucial in discovery and characterization of the **125 GeV Higgs Boson**
- **Good timing resolution (~200 ps)** key ingredient in searches for **non conventional signatures**

ECAL Amplitude Reconstruction

- Run 1 ECAL amplitude reconstruction optimized for suppression of electronics noise in low out-of-time (OOT) pileup



- Run 2 algorithm (used since 2015) to cope with much larger OOT and <PU> ~40 and new 25 ns bunch crossing scheme
  - Submitted to JINST **New**
  - **Template fit** with fixed pulse shape w/ multiple pulses for different bunch crossings
  - Binned templates **derived from collisions data** for each crystals averaging over many hits

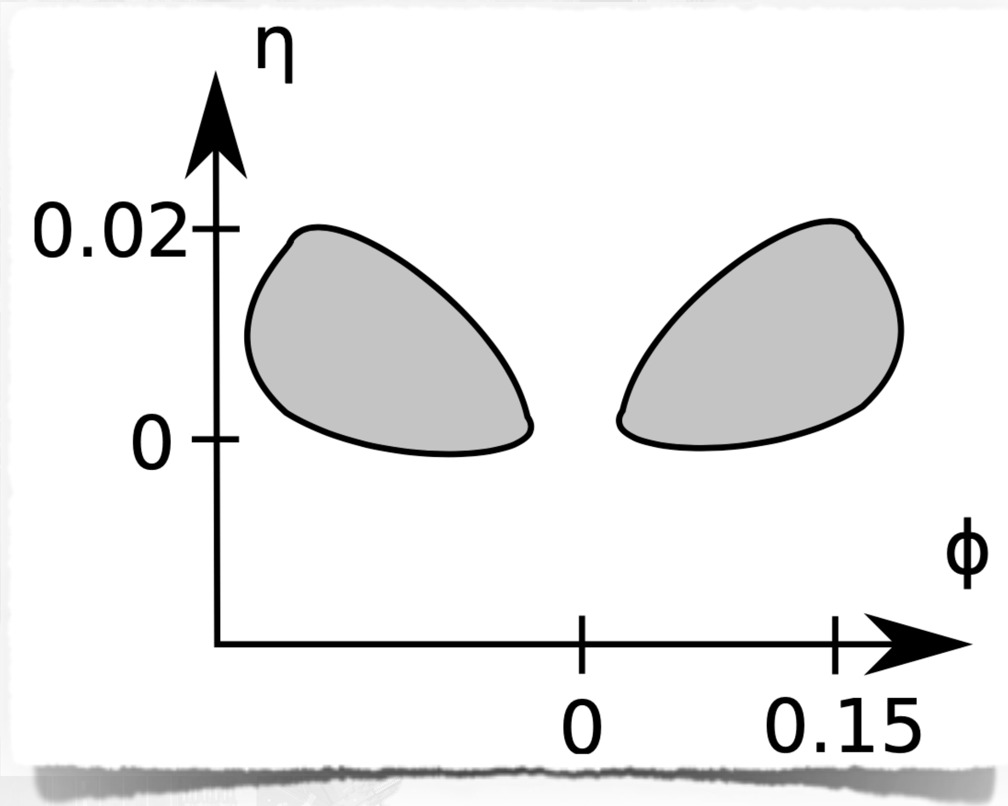


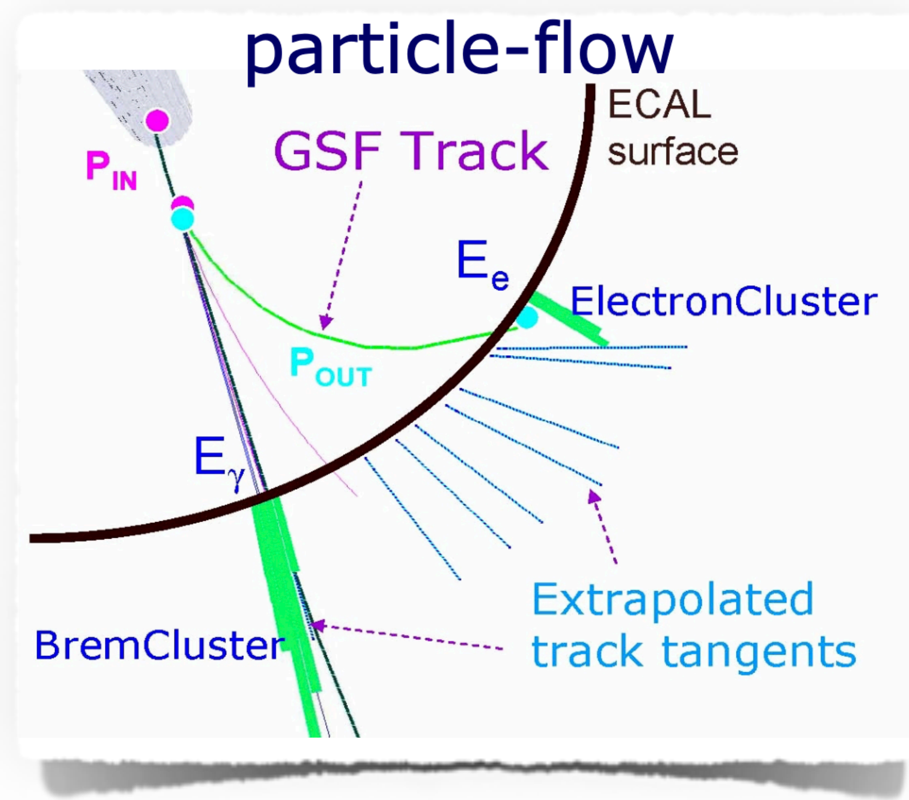
e/γ Reconstruction

- Strong interplay between **clustering** and **tracking** to achieve best resolution

- Collect single particle-like clusters to form clusters that look like e/γ: **"Mustache"** pattern due to magnetic field.

- Large radiative losses, which bend track in ϕ, recovered with a GSF (**Gaussian Sum Filter**) instead of Kalman Filter



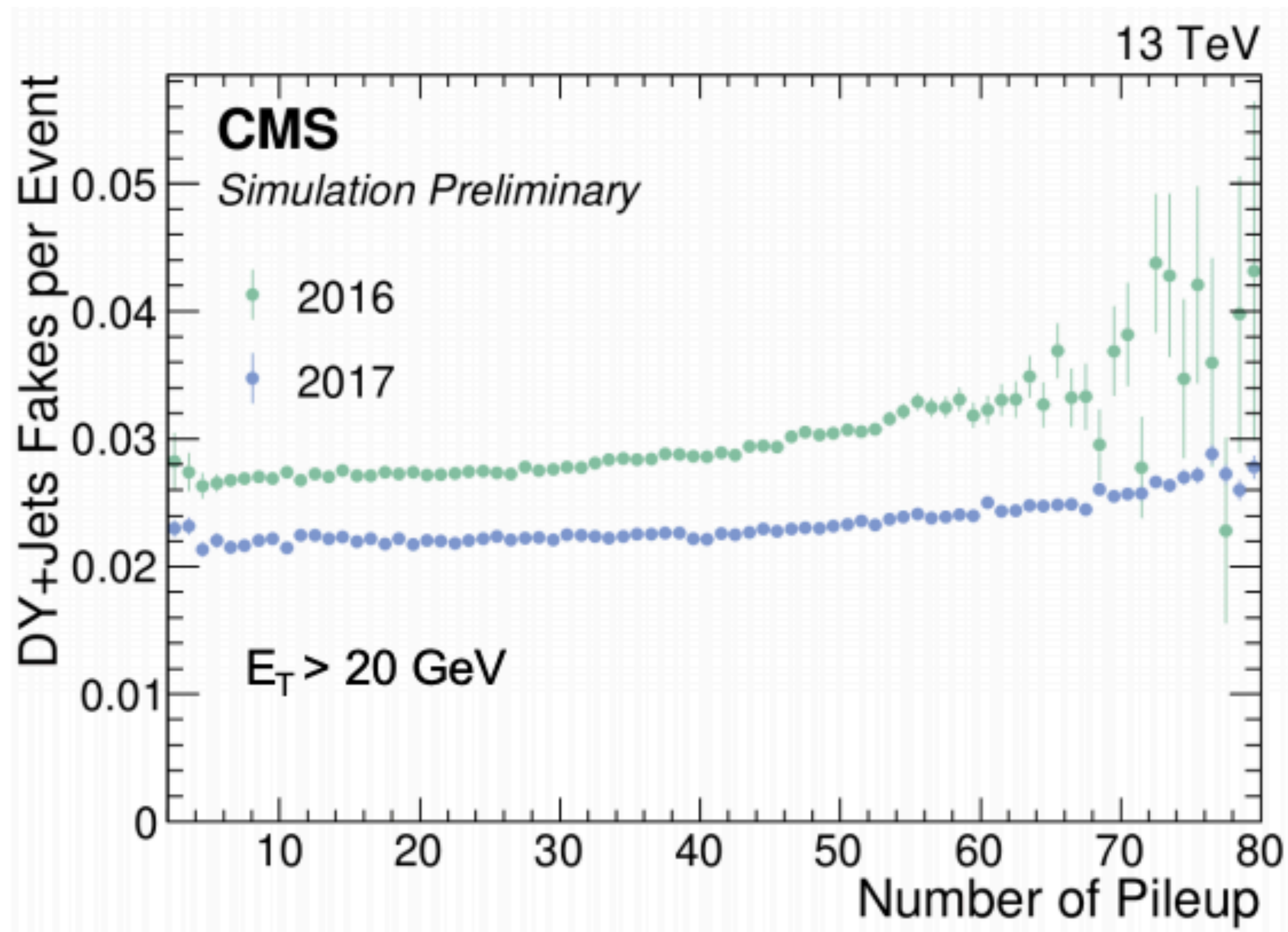


- High Level Trigger (HLT) and offline reconstruction following similar path
- Dedicated brem and photon conversion recovery algorithms

e/γ Reconstruction Performance

- Fake rate and reconstruction efficiency measured in data and simulation

- In 2017 and 2018, **fake rate lowered due to the new pixel detector by 30%**, additional reduction after the Identification step

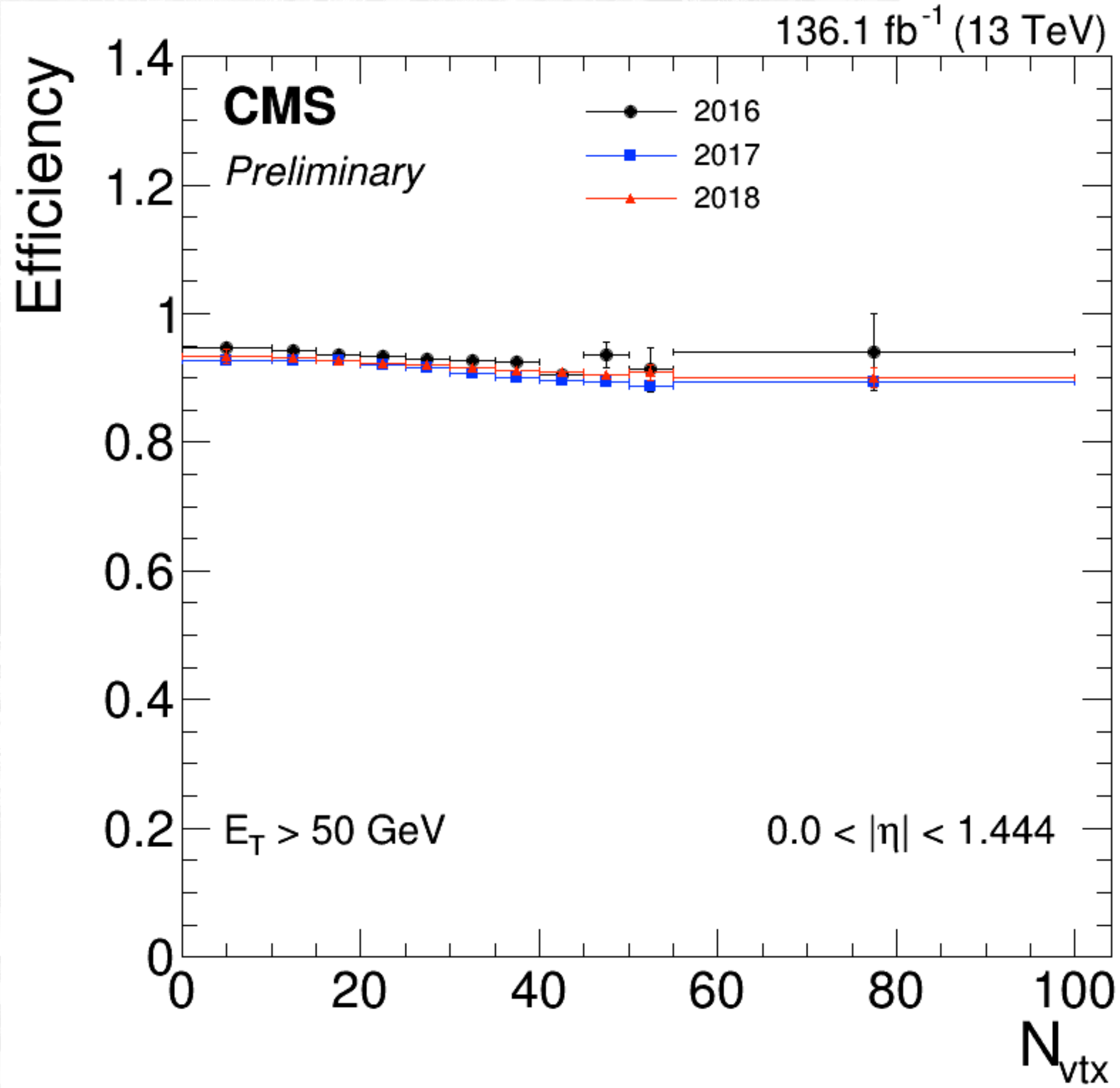


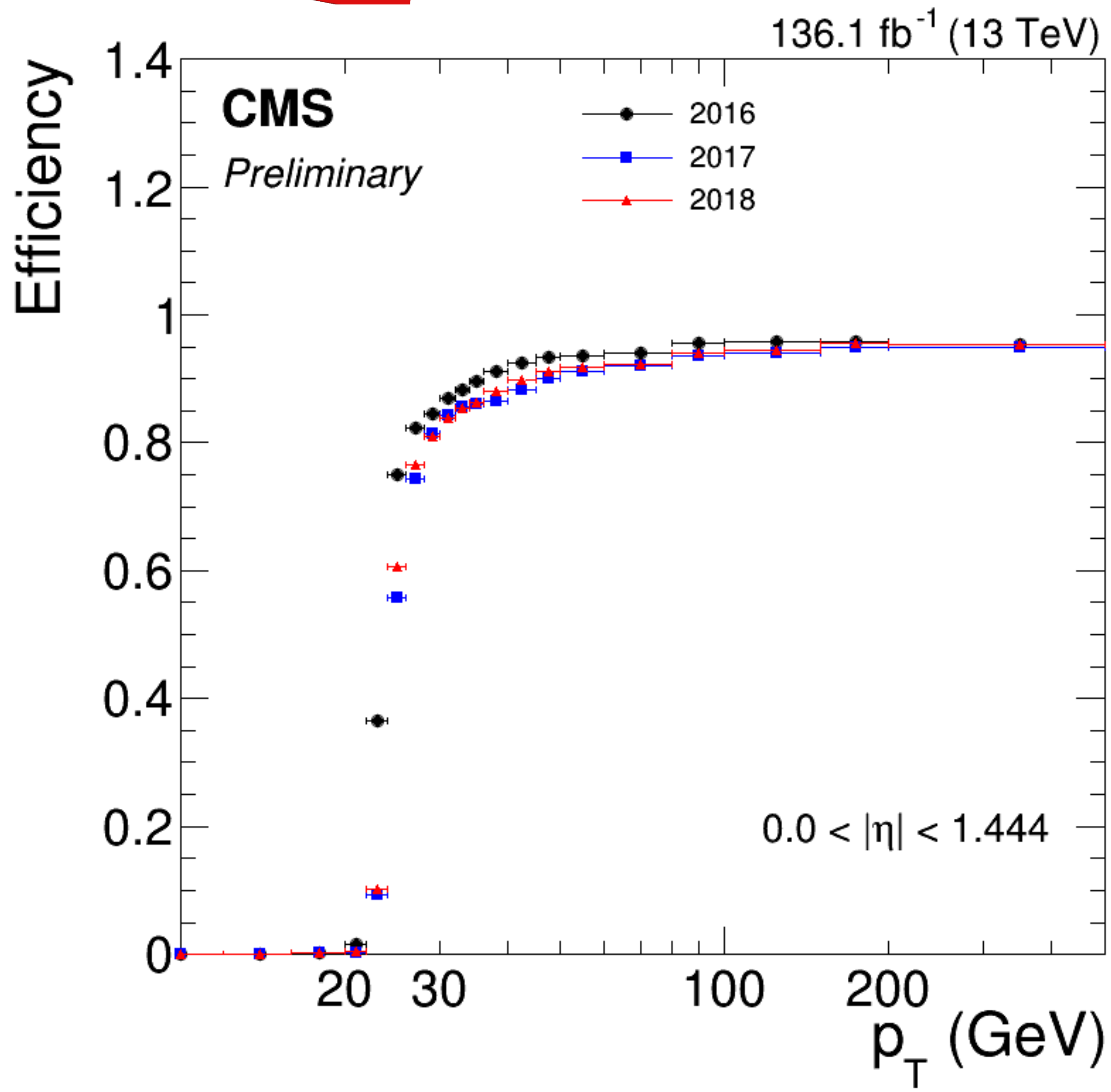
- Electron reconstruction efficiency measured with tag-and-probe method **better than 96% over the full E_T/η spectrum**

- **2-4% improvements with Legacy** calibration

e/γ HLT Performance

- Trigger efficiency measured with tag-and-probe method on Z→ee
- Maintain high efficiencies at Run 2 w/o increasing rates thanks to new pixel detector
- [Full Run 2 results](#) stable vs PU and detector aging





Double isolated electrons p_T>23/12 GeV, loose ID and isolation requirements

e/γ Energy Corrections

Multi step procedure to prevent from energy resolution degradation

- Advanced Machine Learning technique to derive **correction** to systematic variations of **energy deposited in ECAL**

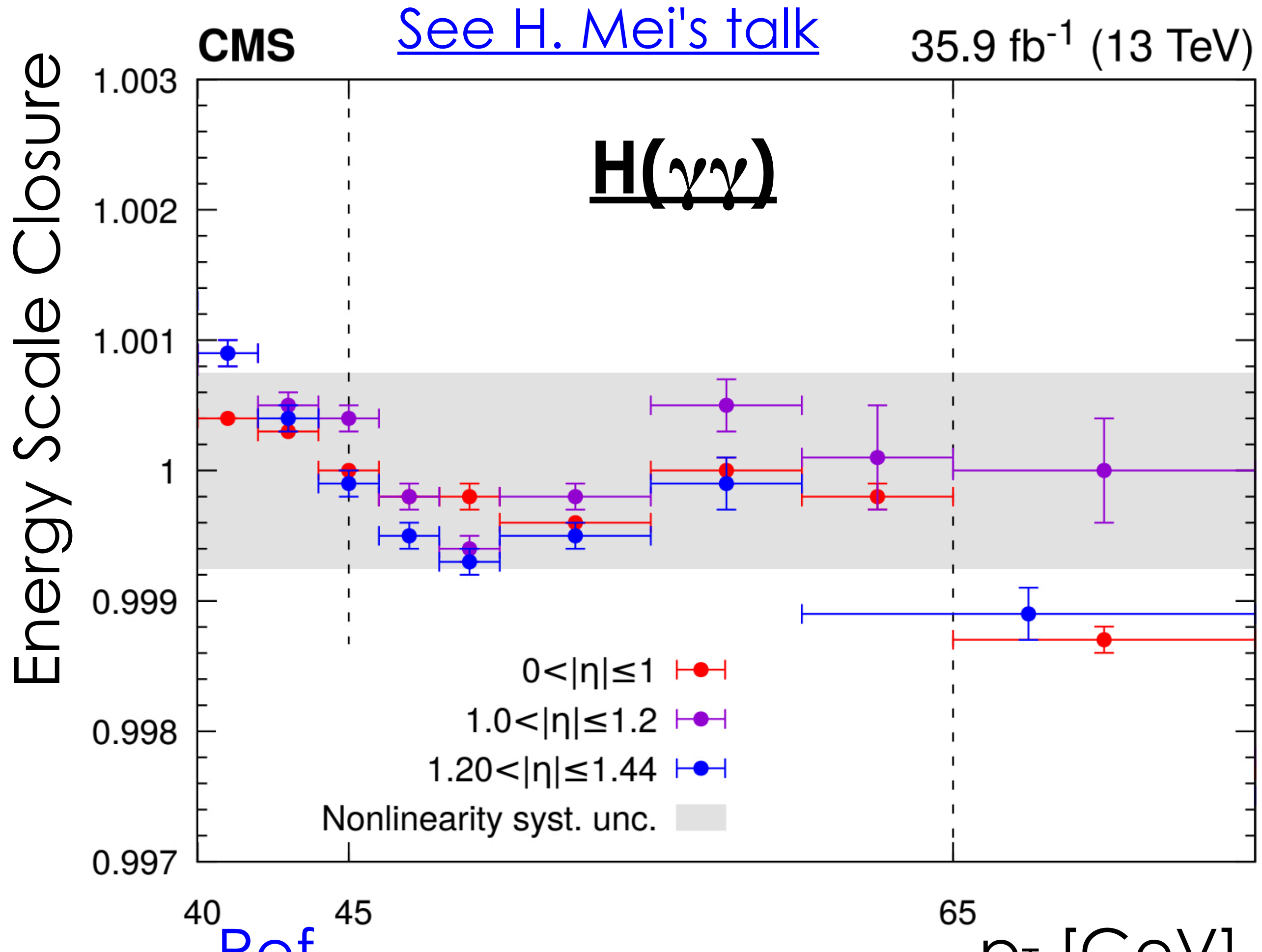
- **Residual corrections** applied to bring the energy scale and resolution in agreement in data and MC **using Z boson mass**

  - Significant **improvement in granularity and precision w.r.t. Run 1**

  - Dedicated **p_T dependent scale corrections for precision analysis**

New

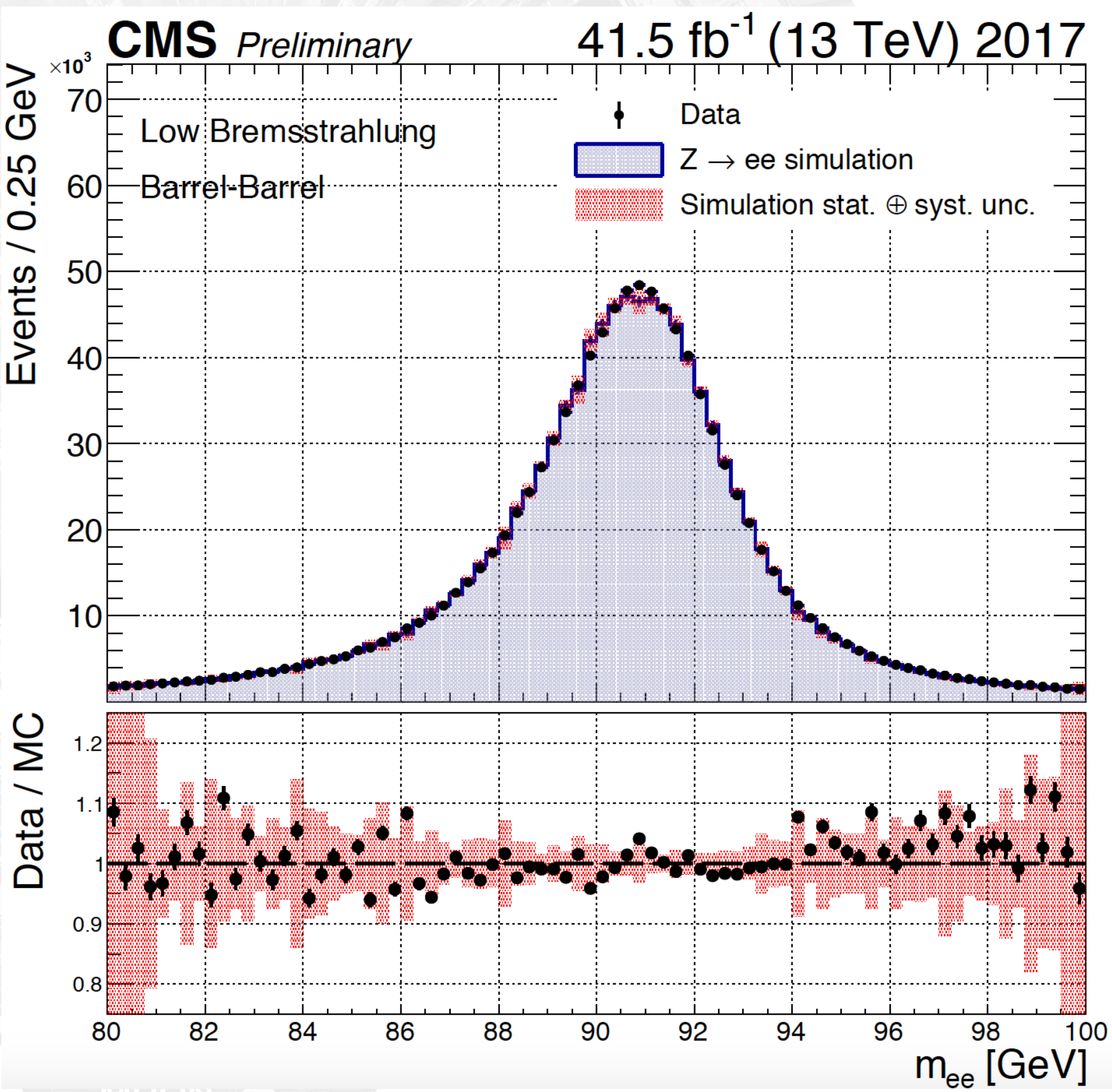
Main **systematic uncertainty in diphoton Higgs mass measurement**

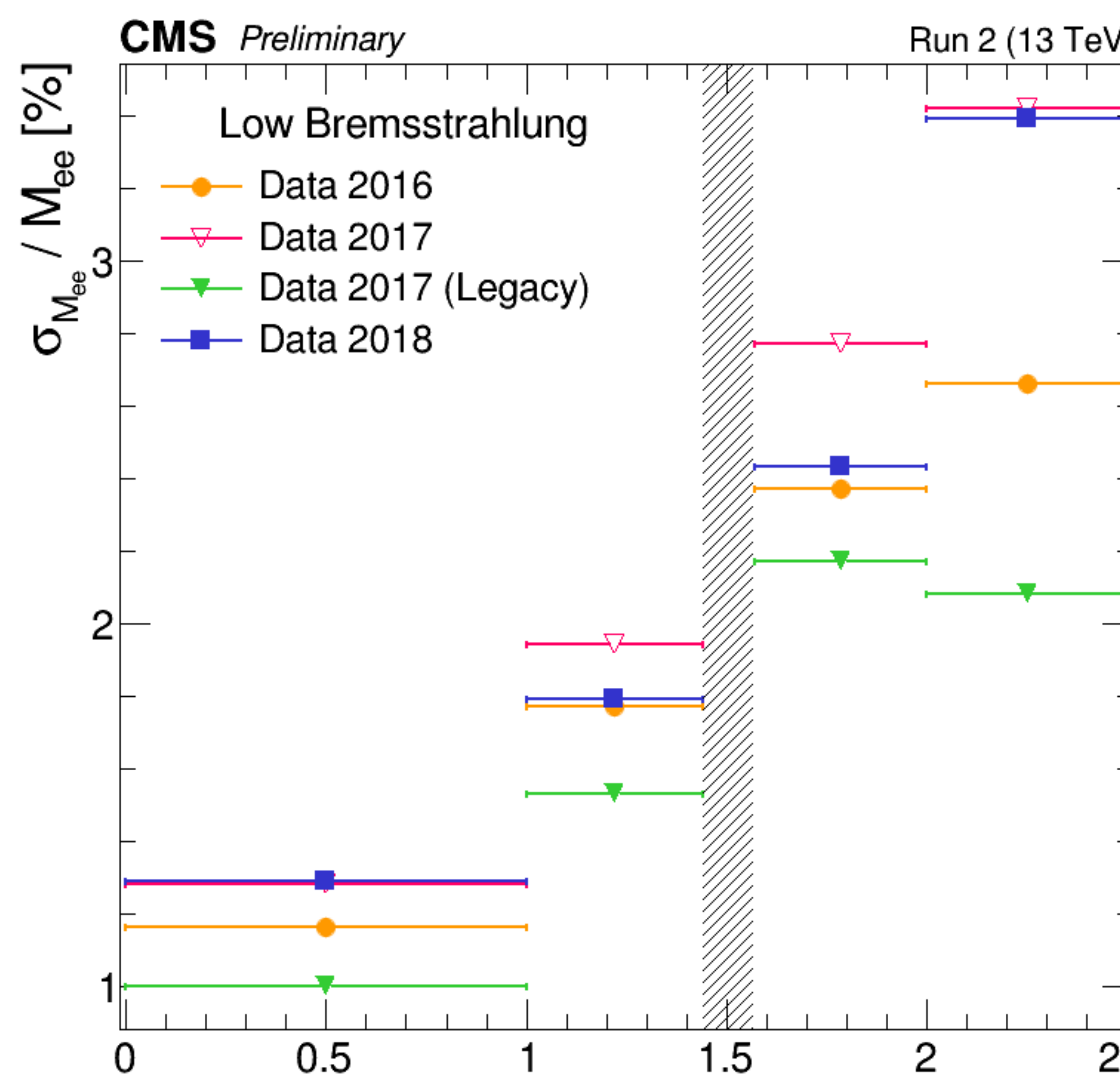


Ref

Ultimate Energy Resolution at Run 2

- Excellent data/MC agreement, after application of residual scales to data and smearings to simulated events
- Energy **resolution measured in 2017 significantly better** b/c of **Legacy calibration**
- Overall the energy resolution through **Run 2 between 1% and 3.4%**

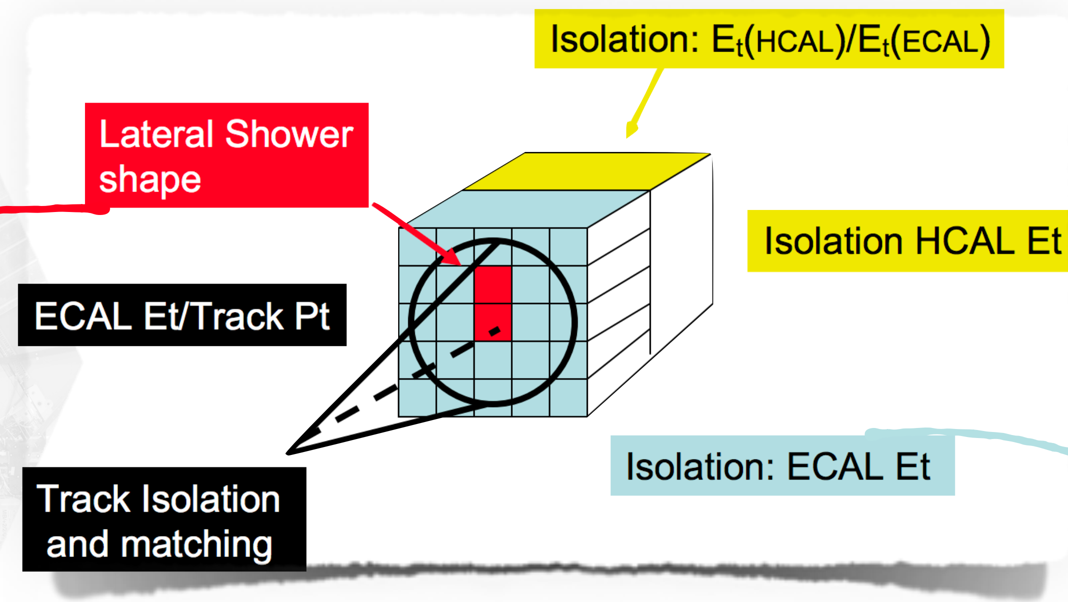




Ref. New

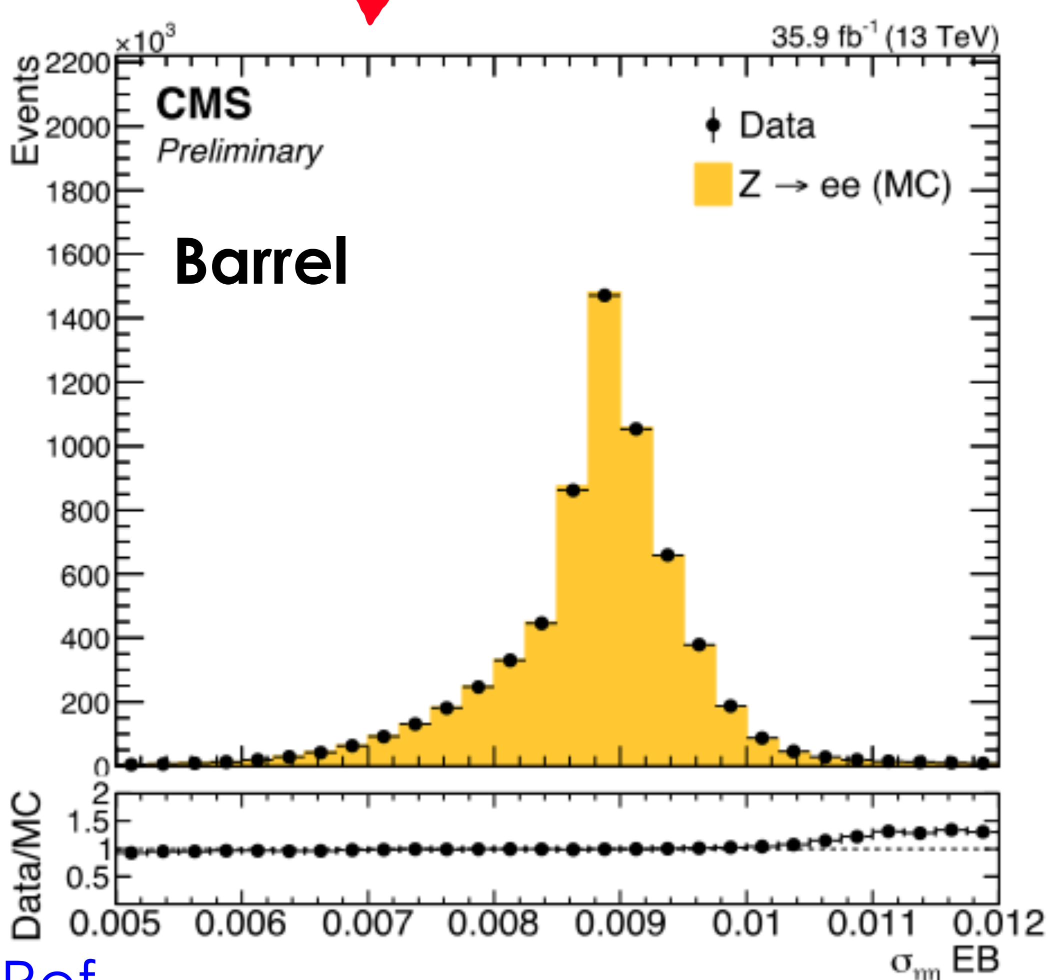
e/γ Identification Strategies

- Ele/γ **identification variables** to separate from backgrounds (jets, conversion, non-prompt particles)



Energy deposit shape

Isolations



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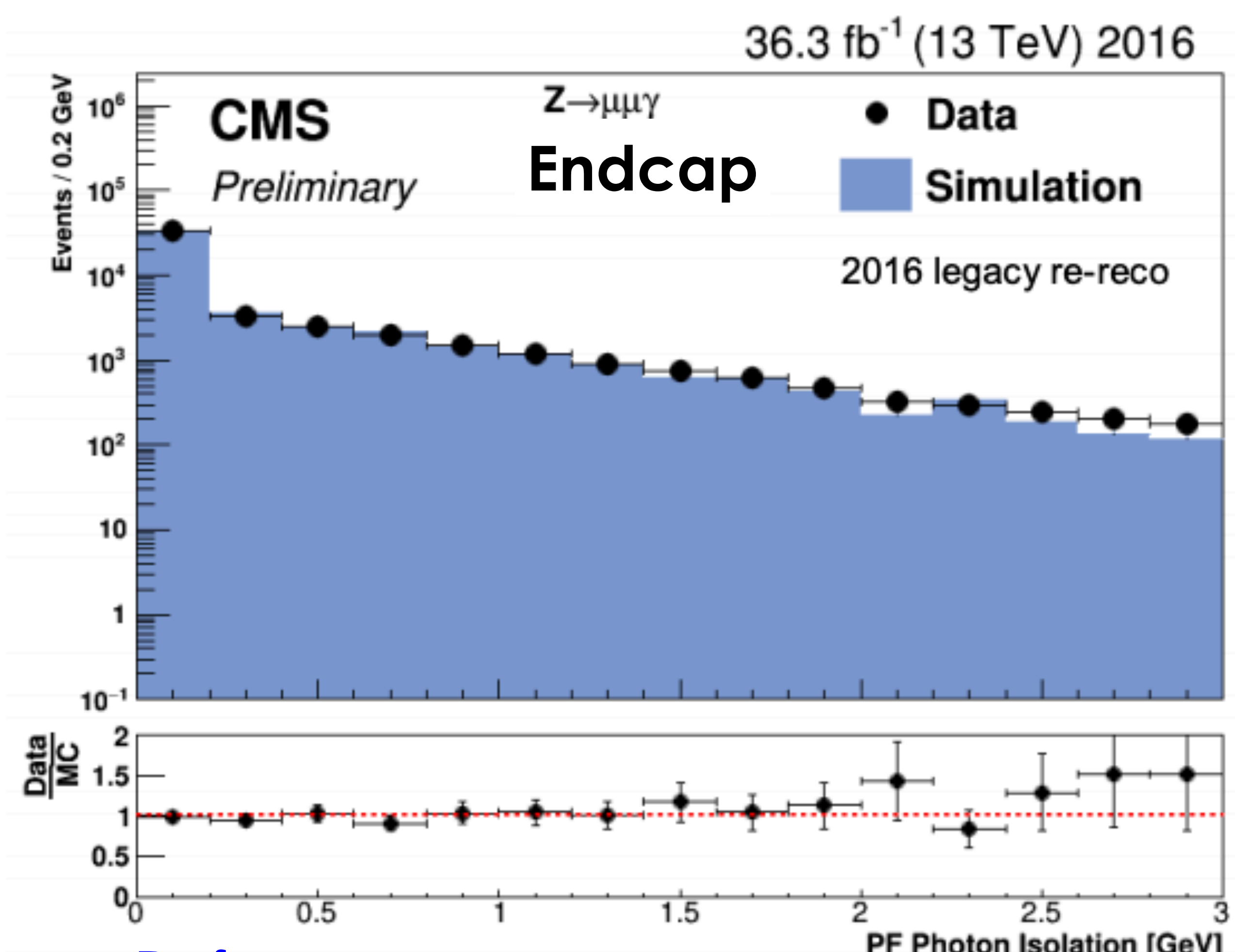


[Ref]

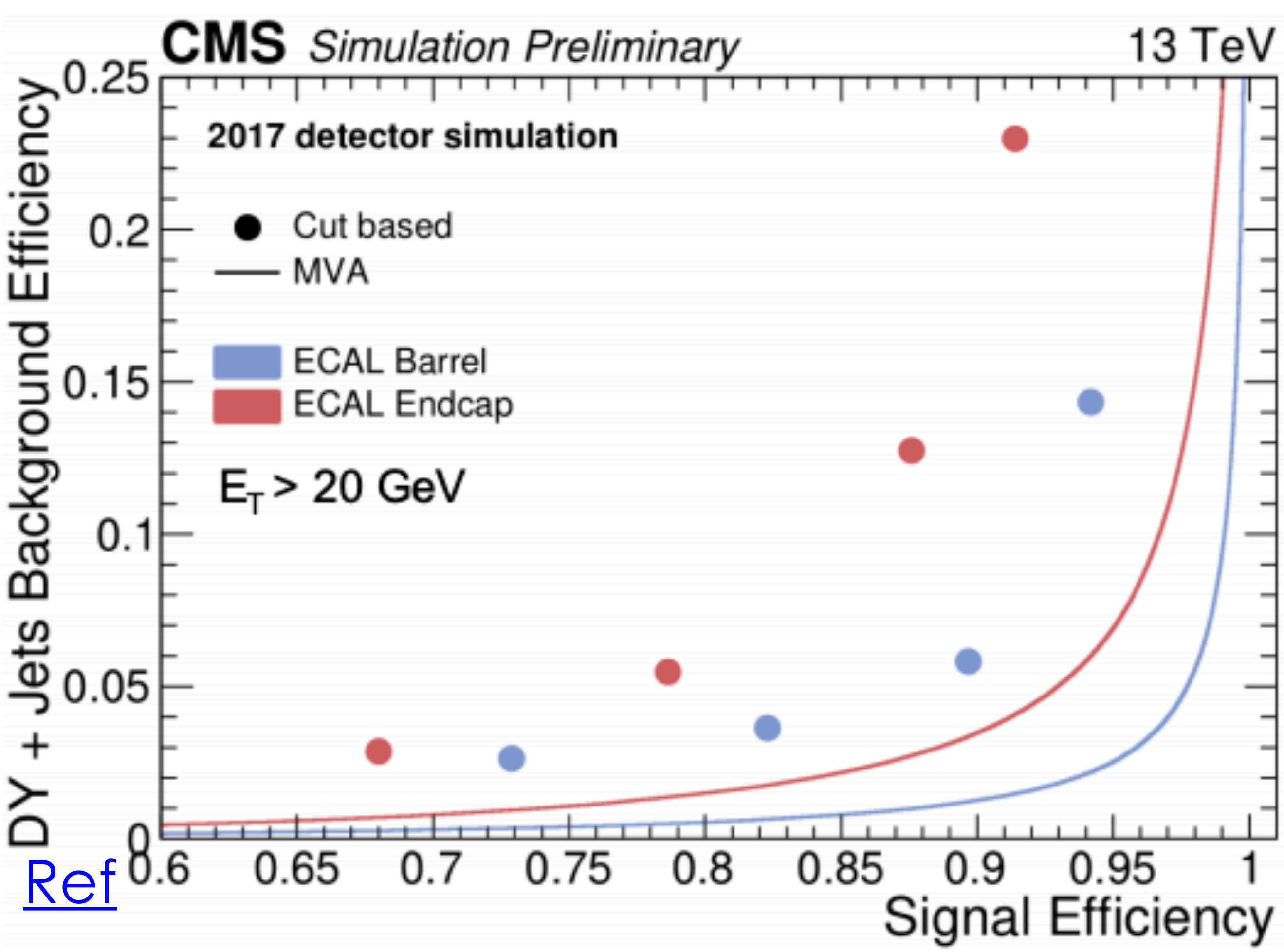
e/γ Identification Efficiencies

- **Several selections** are derived depending on the analysis, based on these variables (**MVA** and **cut-based** approaches)

relevant for **exotic searches** (less variables, control regions in data)

  - Several **working points**
  - Different selections **EB/EE**

Electrons



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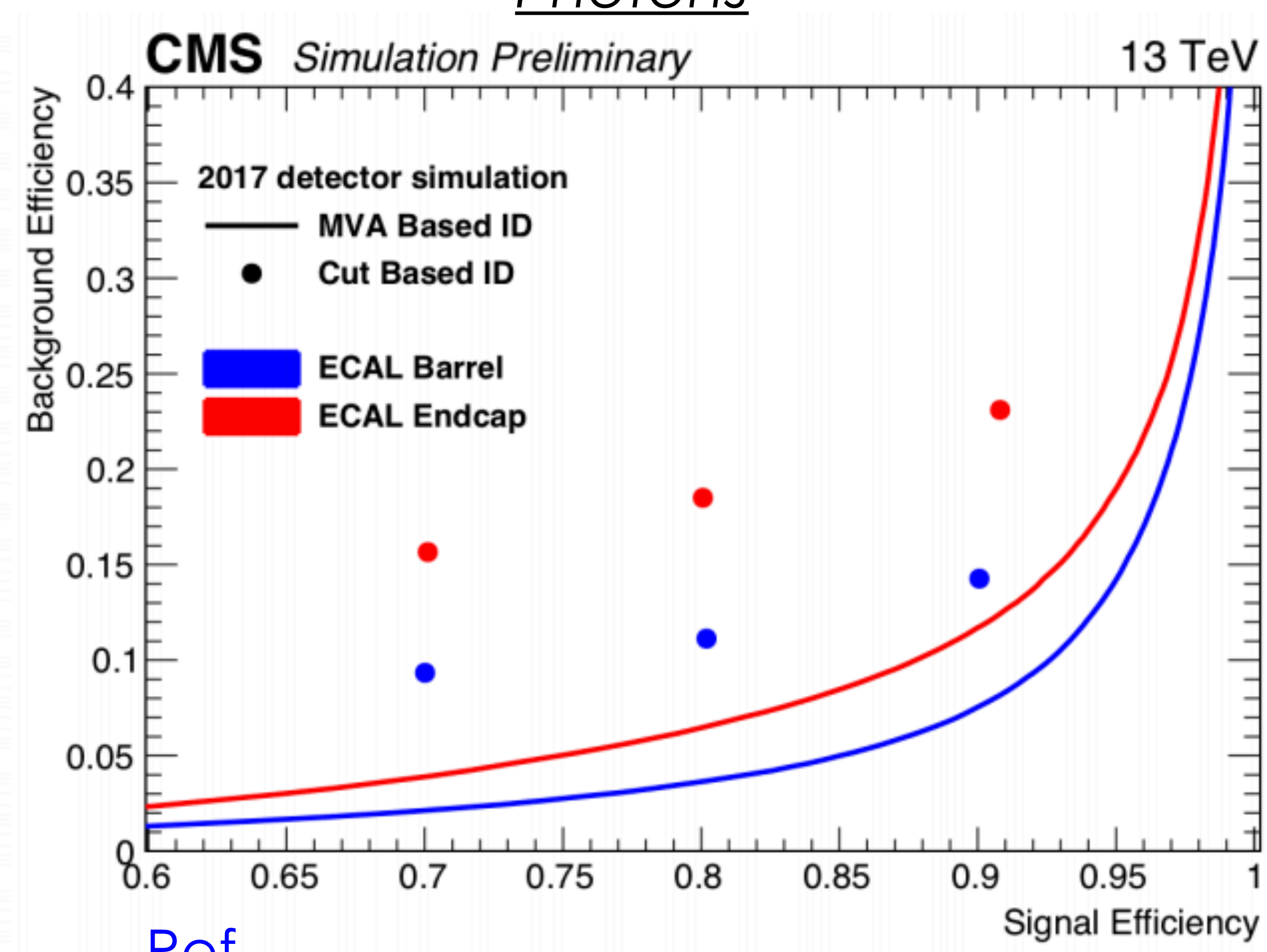
Photons

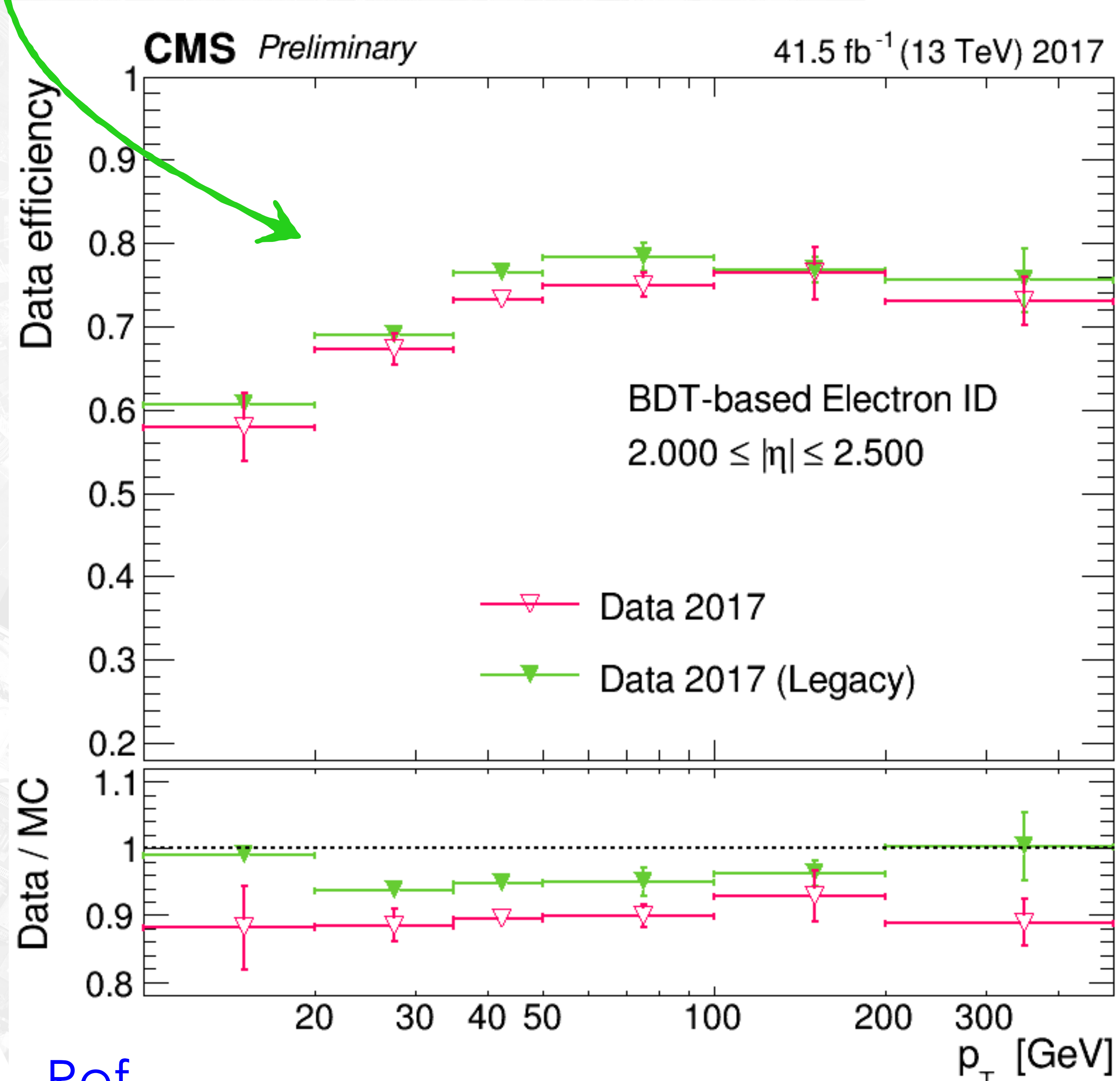


Ref

- + **dedicated IDs for high energy e/γ**

e/γ Identification Performance

- **Data/MC correction factors** derived for each selection using tag-and-probe
  - Data/MC agreement improved from ~88% to 95% when using **Legacy calibration in 2017** New
  - Correction factors **stable within 3% over the full Run 2** New



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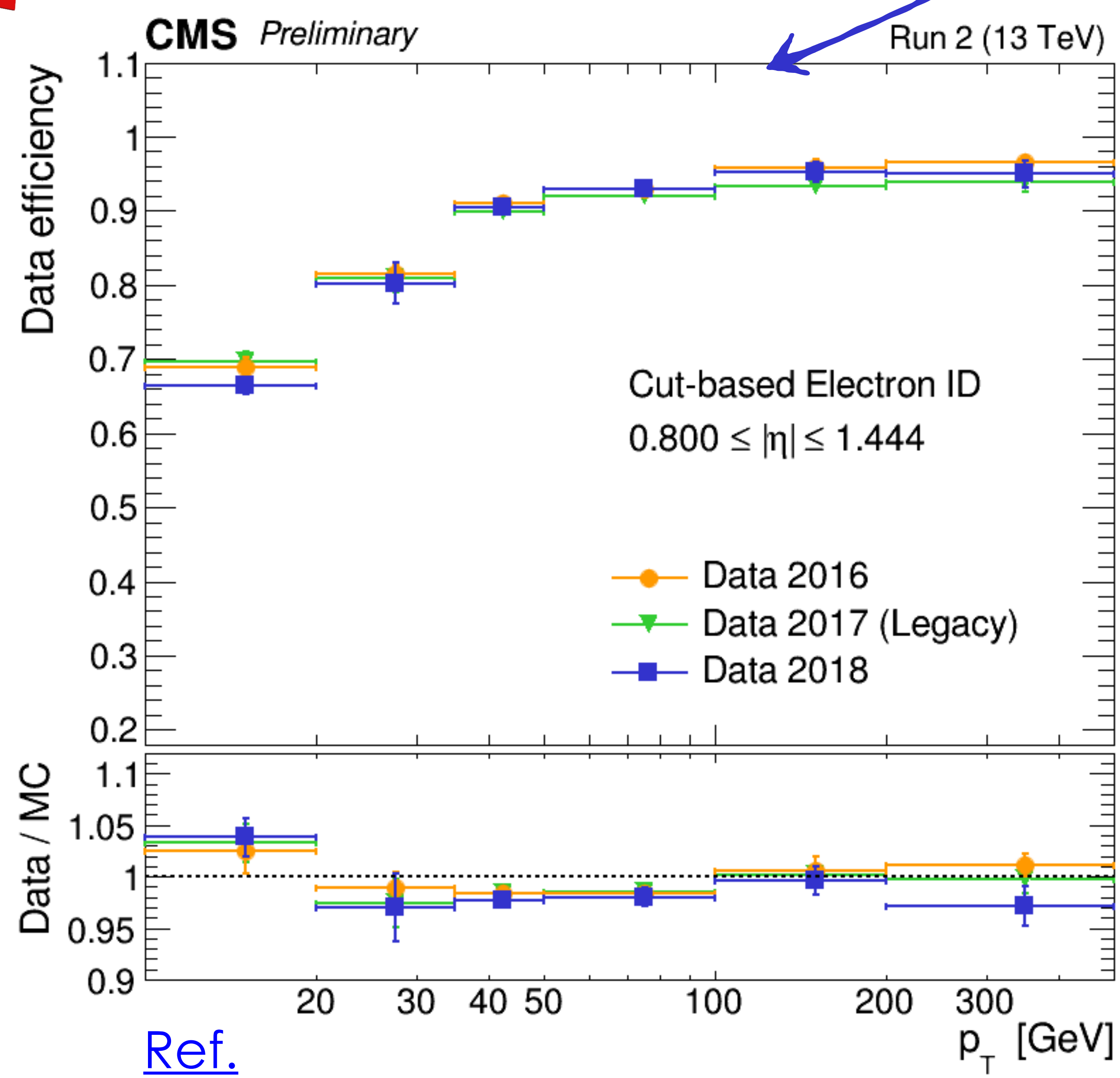

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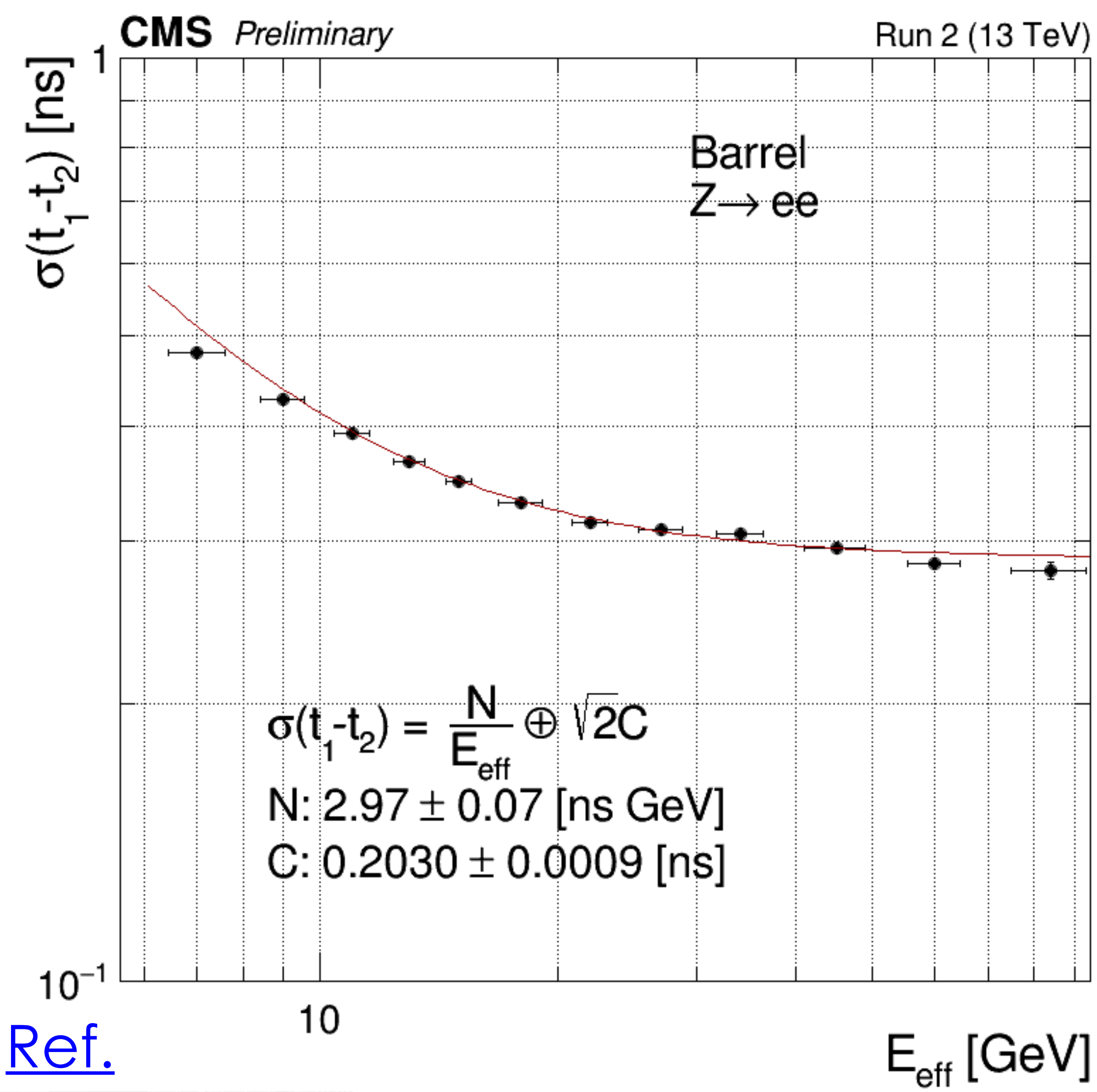
e/γ Timing Performance

- Global **ECAL time resolution** measured from the time difference between electrons from Z using full **Run 2 data** New
- The time of the electron corresponds to the **time of the cluster seed crystal**



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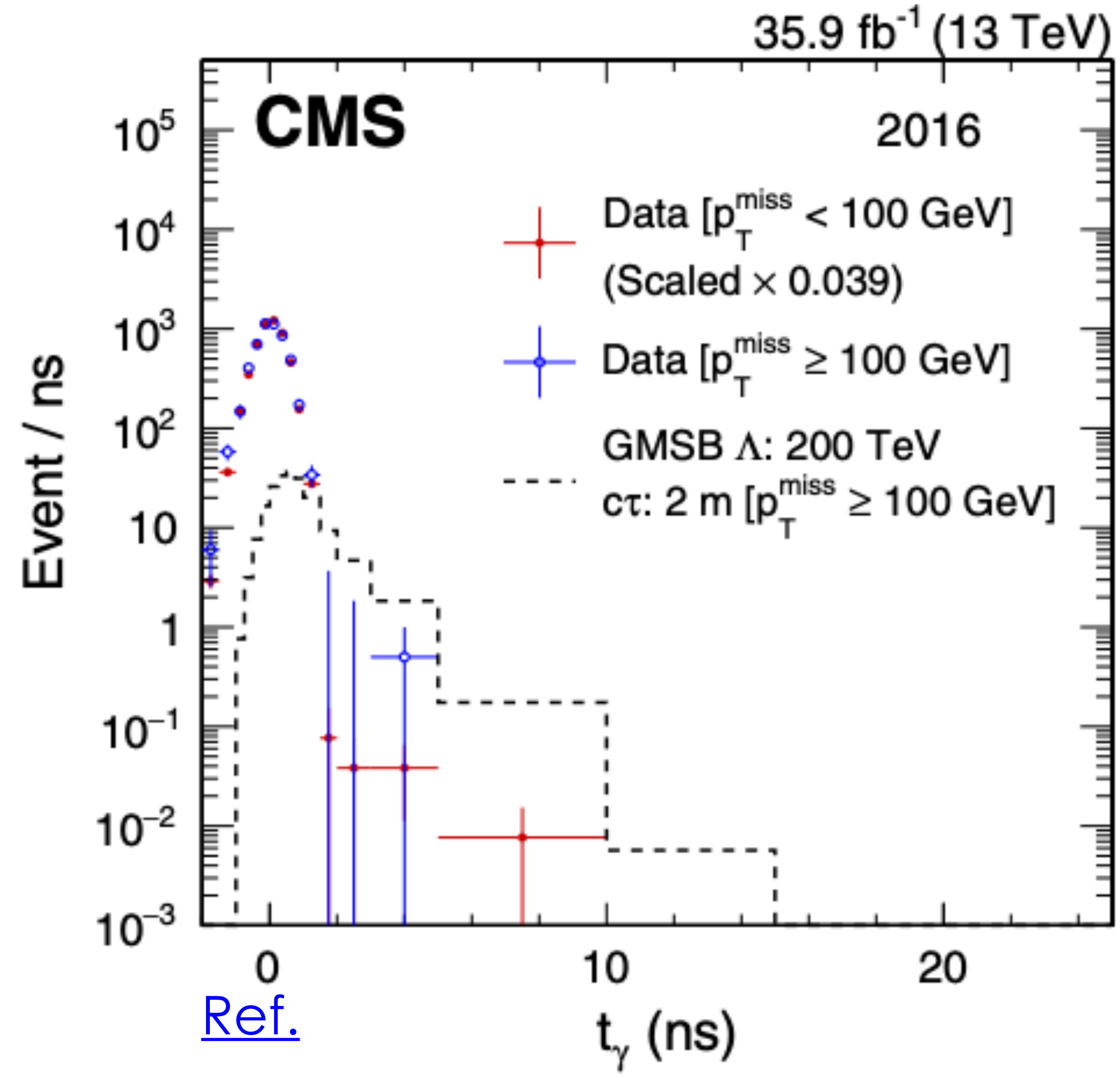
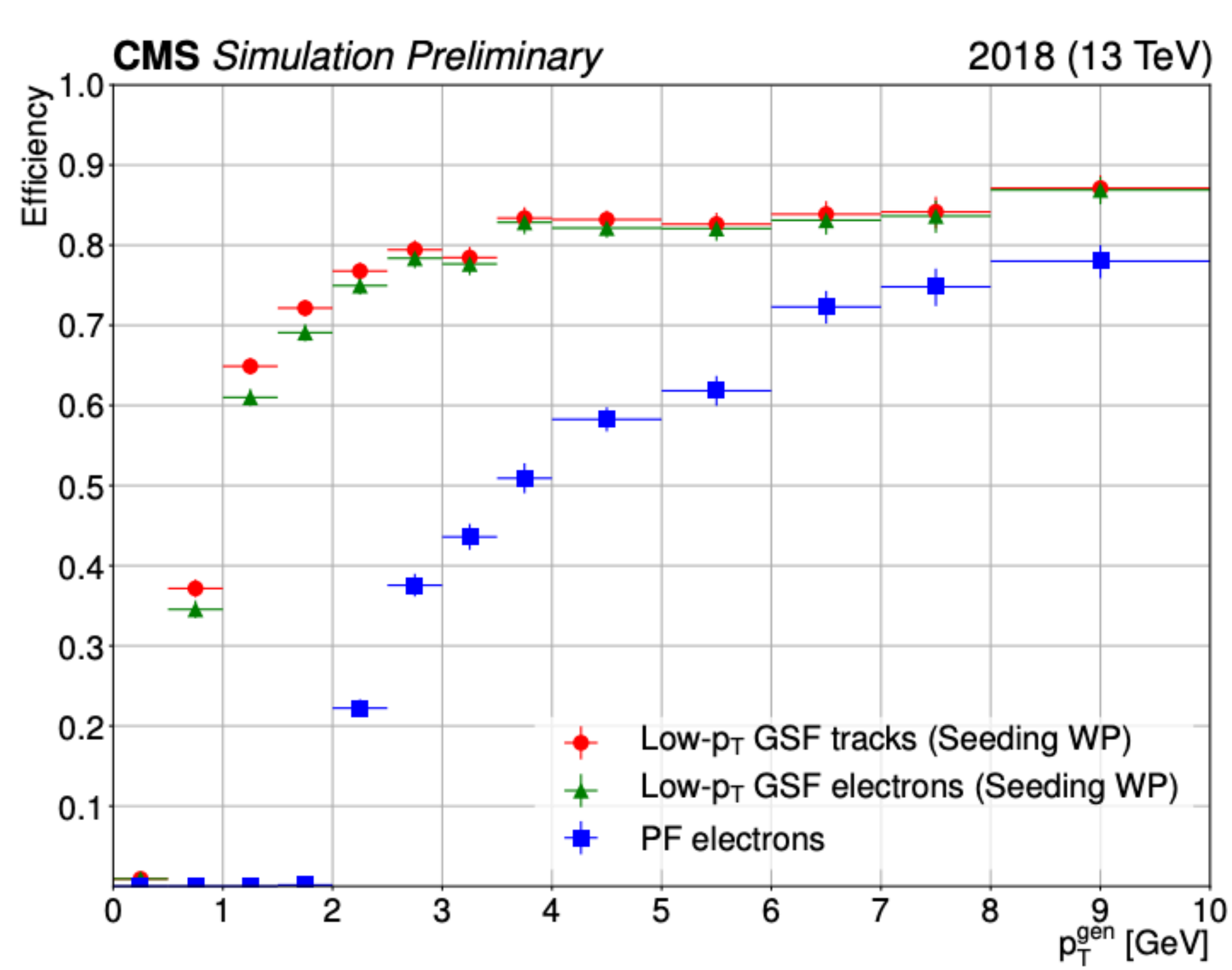


Ref.

- **Long lived particles** searches performed using **photon or jet time of arrival in ECAL**

Dedicated Reconstruction for low p_T e

- Custom low-pT electron reconstruction developed for the B Parking data set.
- GSF tracking seeding replaced by a **more computationally efficient logic that identifies low-p_T electron candidates**
- **10% mistag rate** while providing a factor **~2 gain in efficiency**
- However, we require a **sophisticated ID to control purity**



e/γ Run 3 Challenges

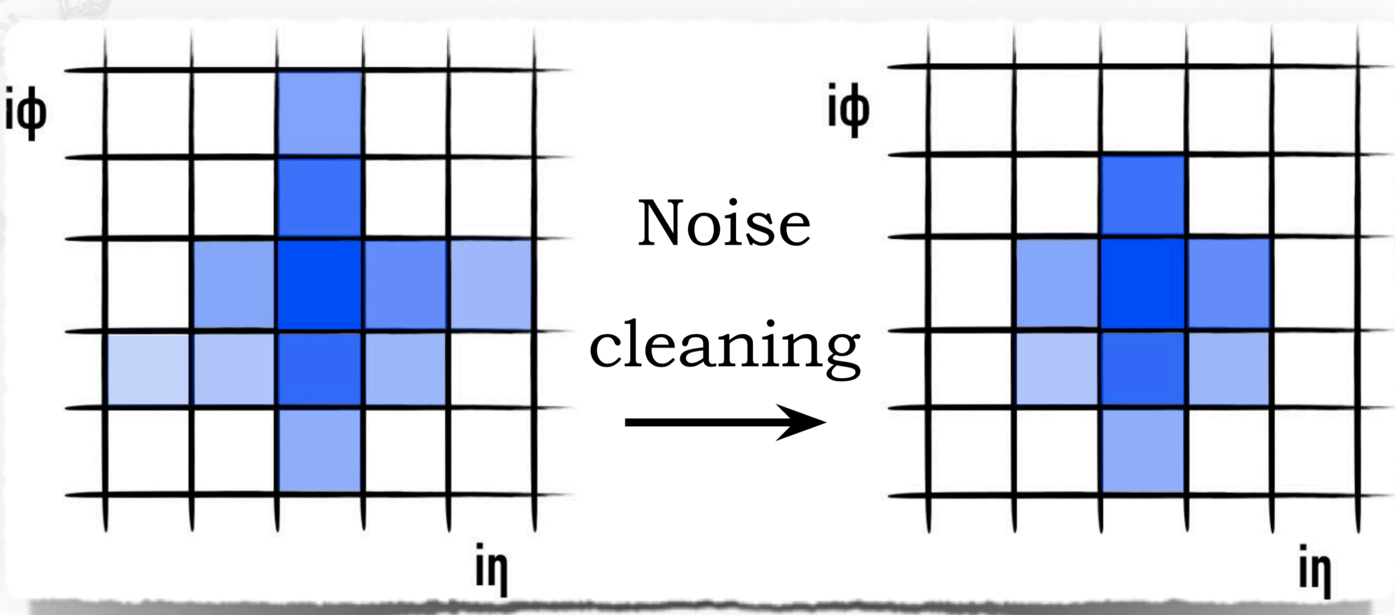
- Run-3 brings **harsher environment** for electromagnetic object reconstruction and identification compared to Run-2:
  - **Pile-up** interactions increase
  - **Noise in the ECAL** increases especially in the endcaps by a factor 1.8, 3 and 4 at $|\eta|$=1.5, 2.5 and 3

Noise

\# **rechits mistakenly assigned** to supercluster

e/γ reconstruction and identificaiton **performance**

- **New superclustering strategy** currently being designed w/ **DNN based algorithm**



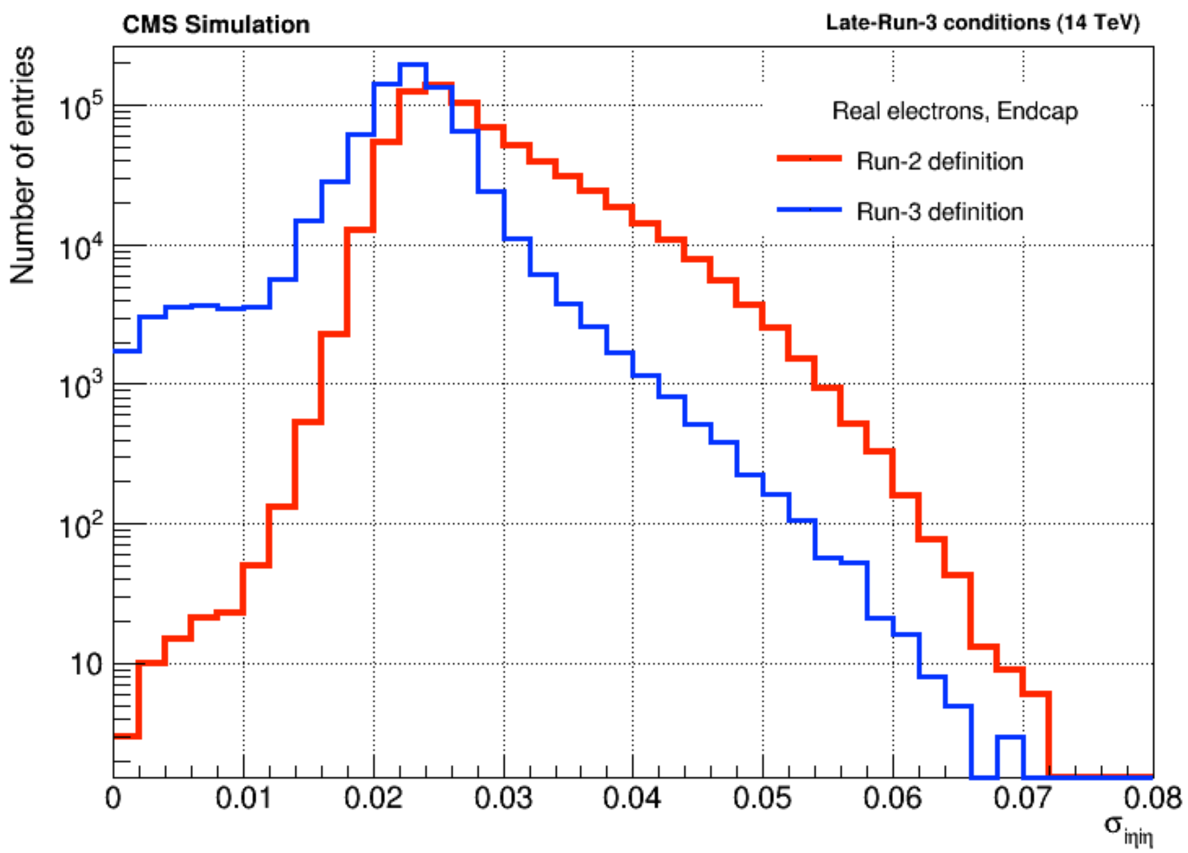
Redefinition of e/γ identification variables for Run-3

- Redefinition of **ID $\sigma_{i\eta i\eta}$ variable sensitive to ECAL noise** New

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

$$w_i \propto E_i$$

- **Absolute cut on E_i** above noise threshold to **remove spurious rechits**



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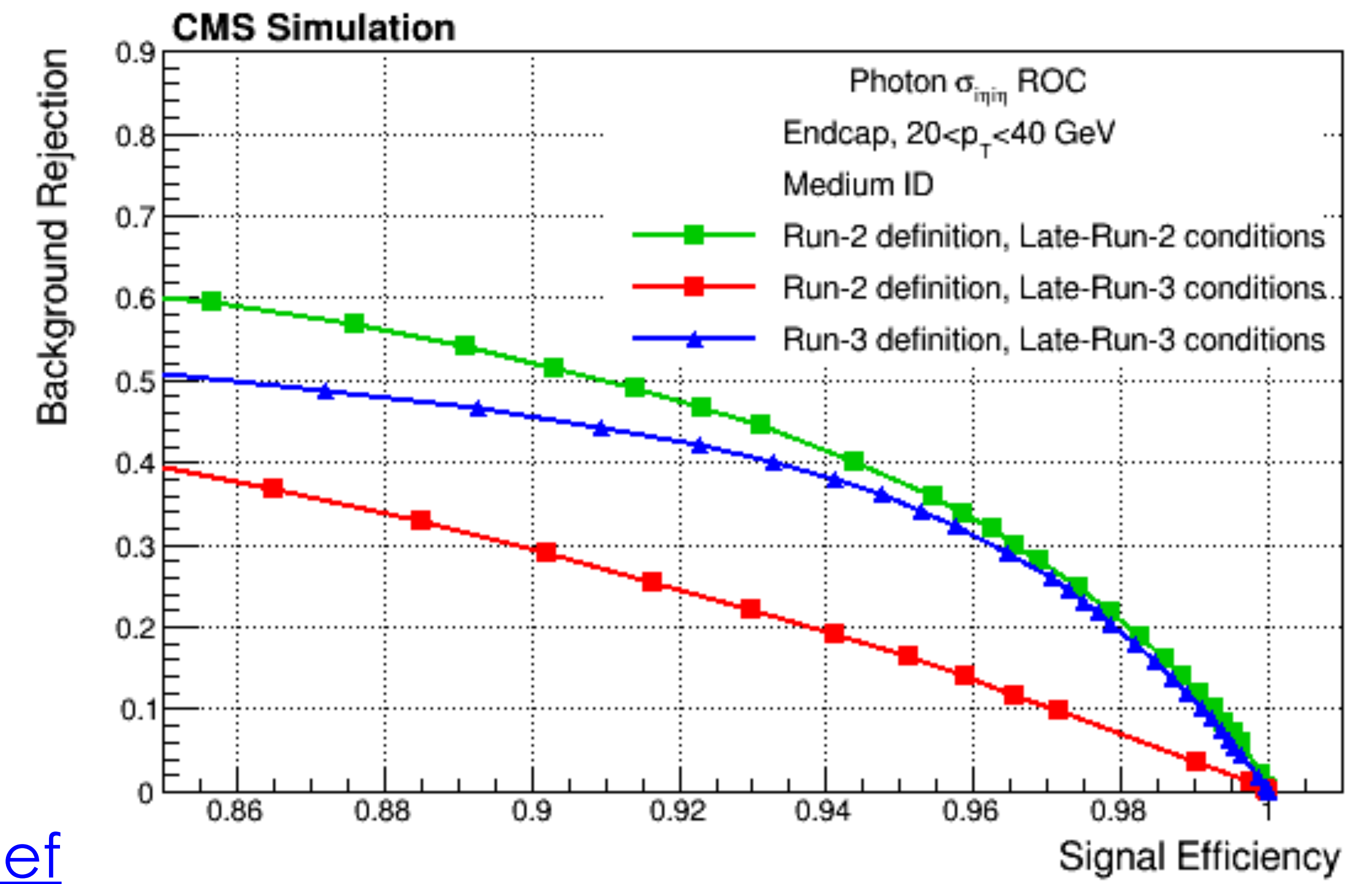
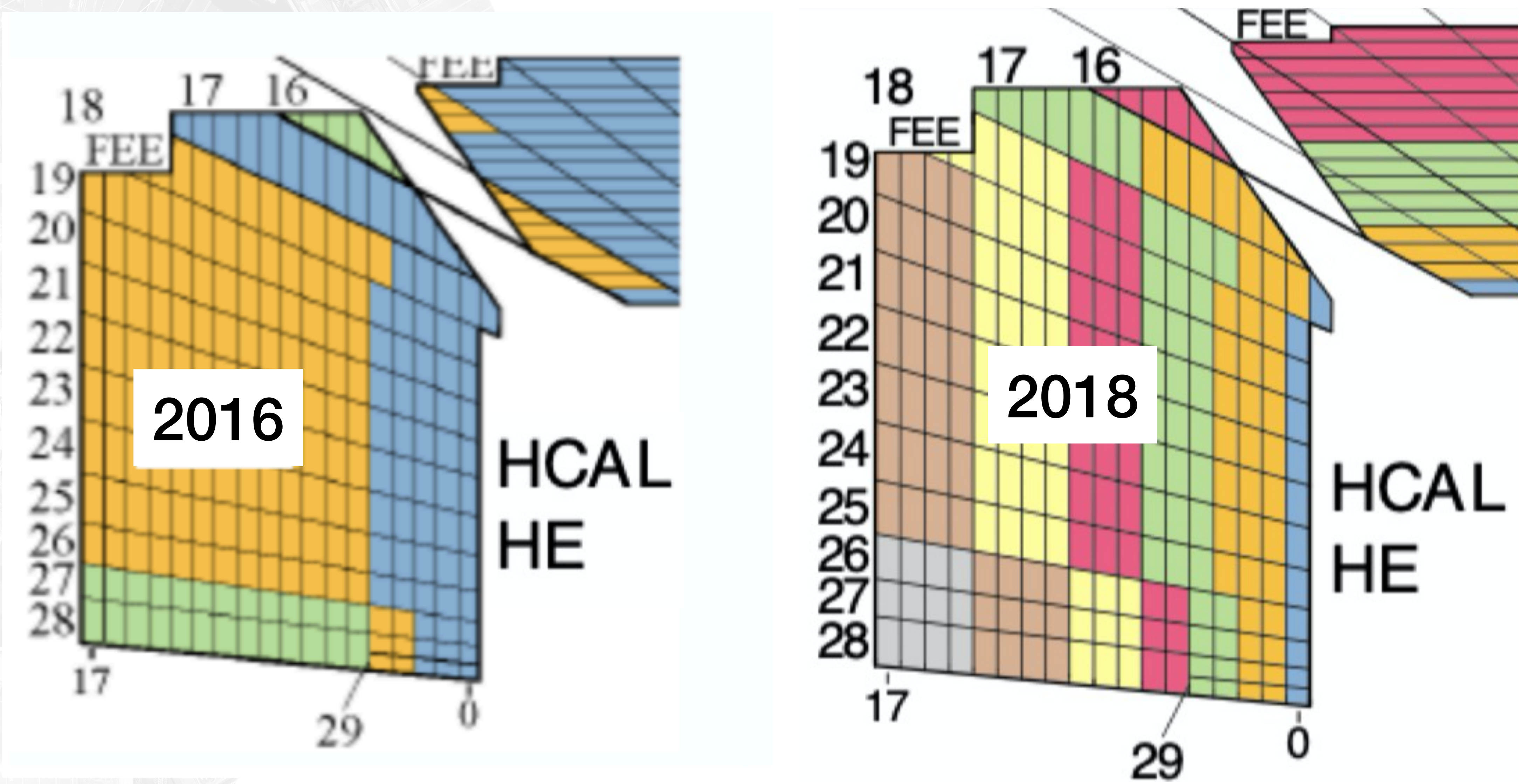


- Applied to **both electrons and photons.** More effective in endcap

e/γ Identification w/ New HCAL Detector

- New design of **HCAL detector** with replacement of readout electronics allows **depth segmentation**

New



- Combine information of **energy deposited in different HCAL layers**

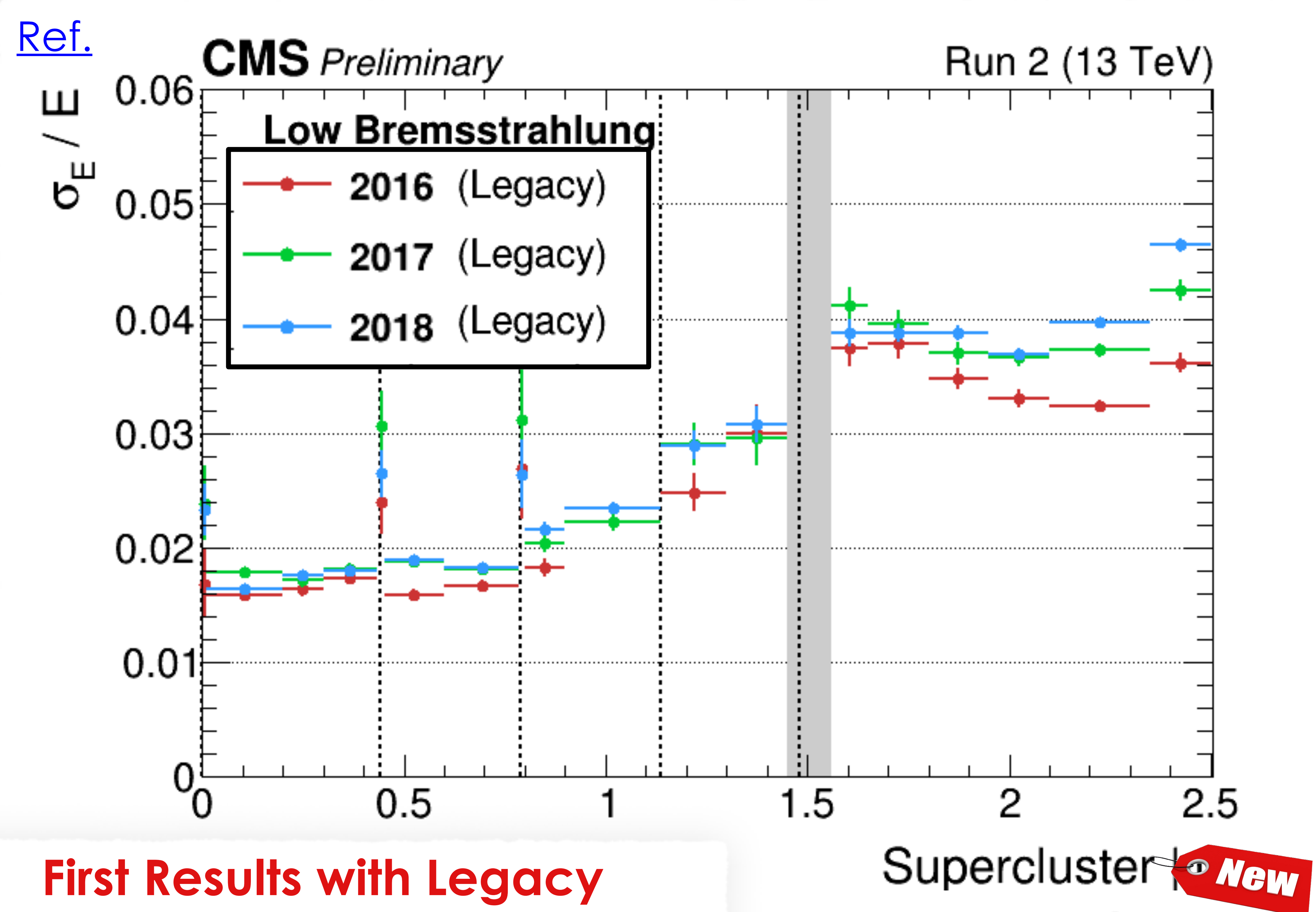
- Better **shower-development measurement** and **background rejection for e/γ**

Conclusions and Outlook

- **Very successful CMS ECAL for e/γ** reconstruction and identification in **LHC Run2**
  - Out-of-time **pileup mitigation**
  - **Reprocessing** of Run 2 data on-going
  - Improved calibration **gain up to 20%** in energy resolution and up to 10% in data/MC agreement
  - Excellent **energy resolution ([1.5-4]%)** and **timing resolution (< 200 ps)** as key ingredients of CMS physics program

Conclusions and Outlook

- **Very su** [Ref.](#) **un2**
  - Out-o
  - **Repro**
  - Impro data/
  - Excell ingred /



First Results with Legacy calibration of full Run 2!

Conclusions and Outlook

- **Very su** Ref. **un2**
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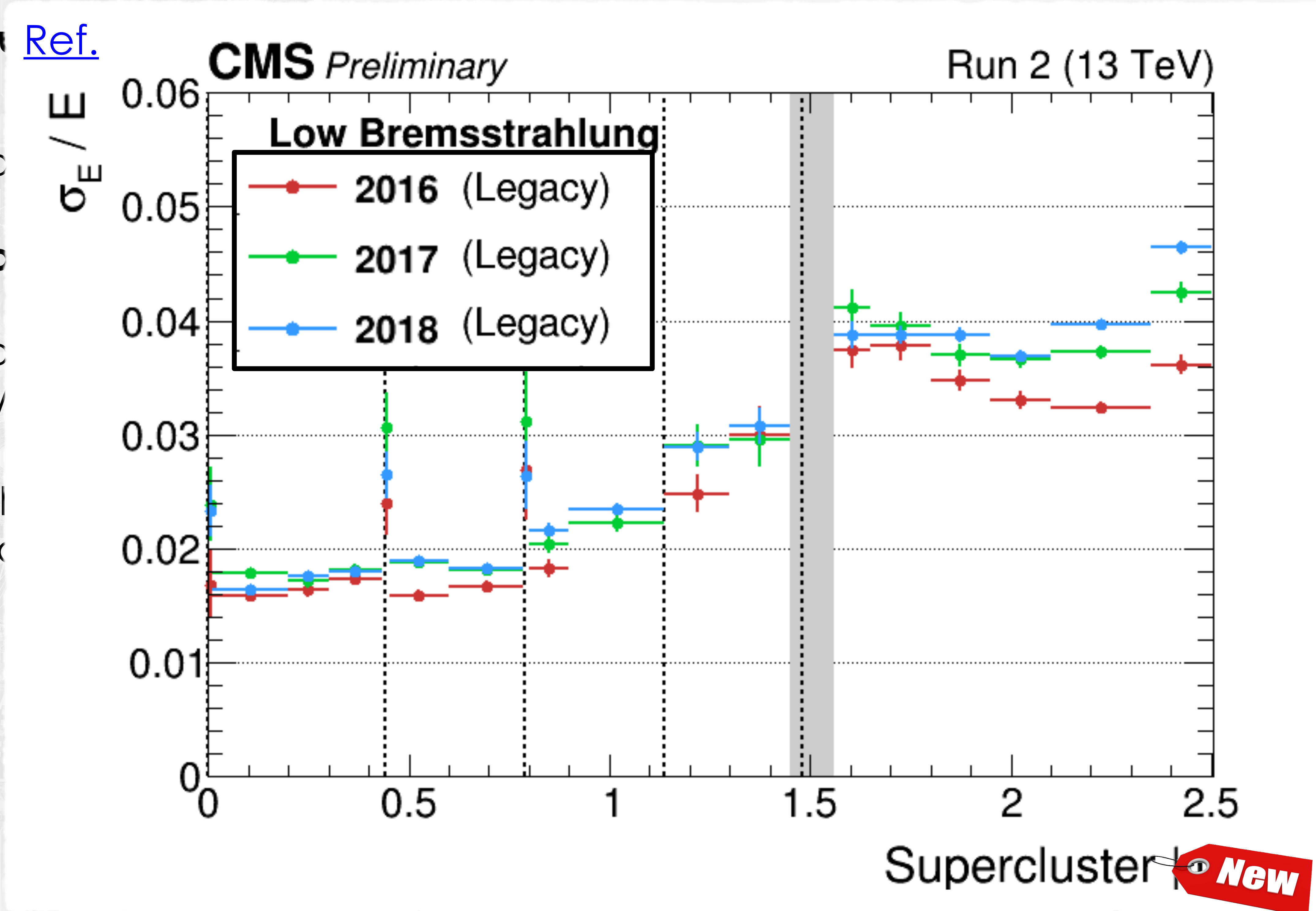
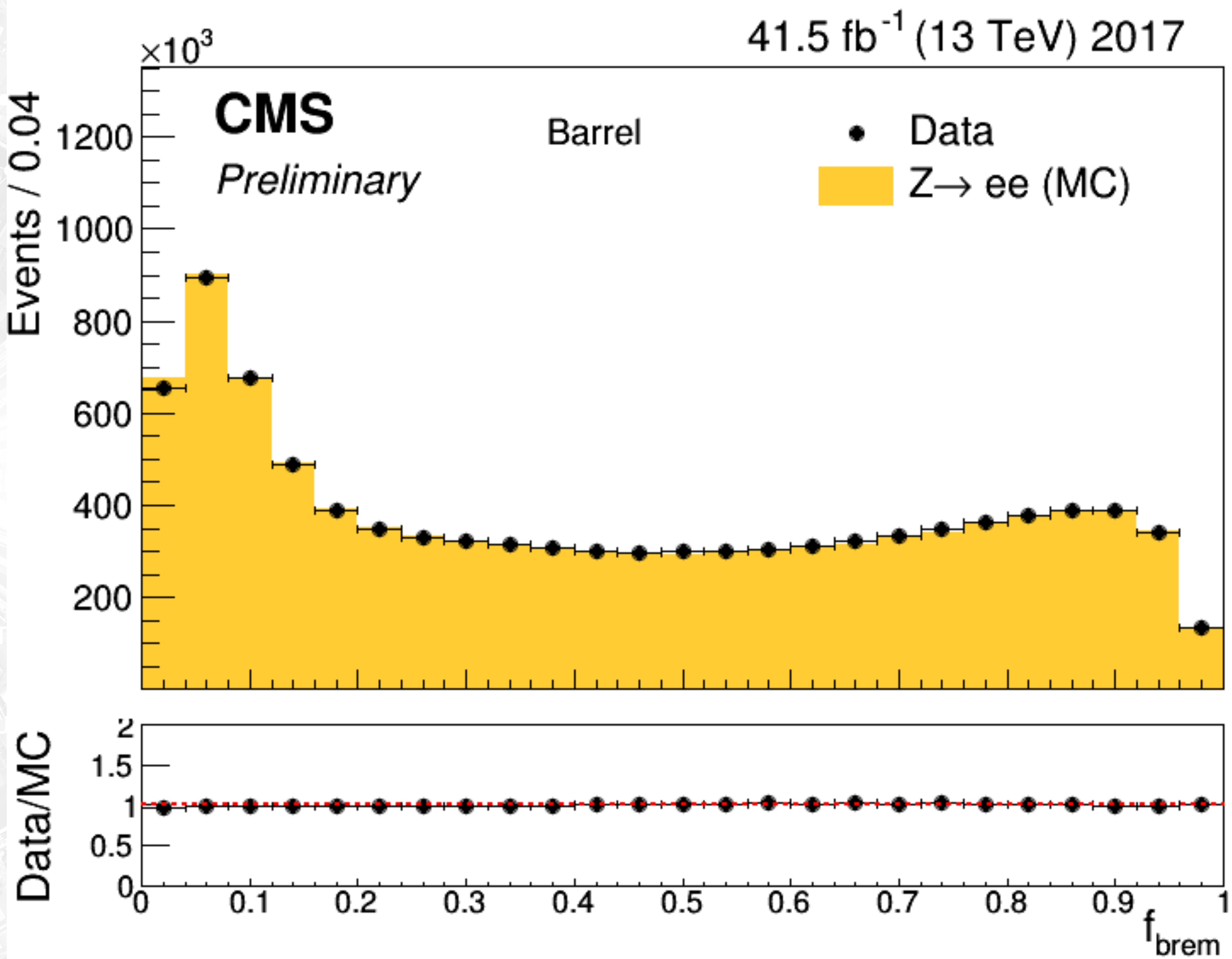


- Run 3 improvements will **boost significantly e/γ analyses sensitivity**

- **Full Run 2 performance paper** will be released in summer 2020 New

BACKUP

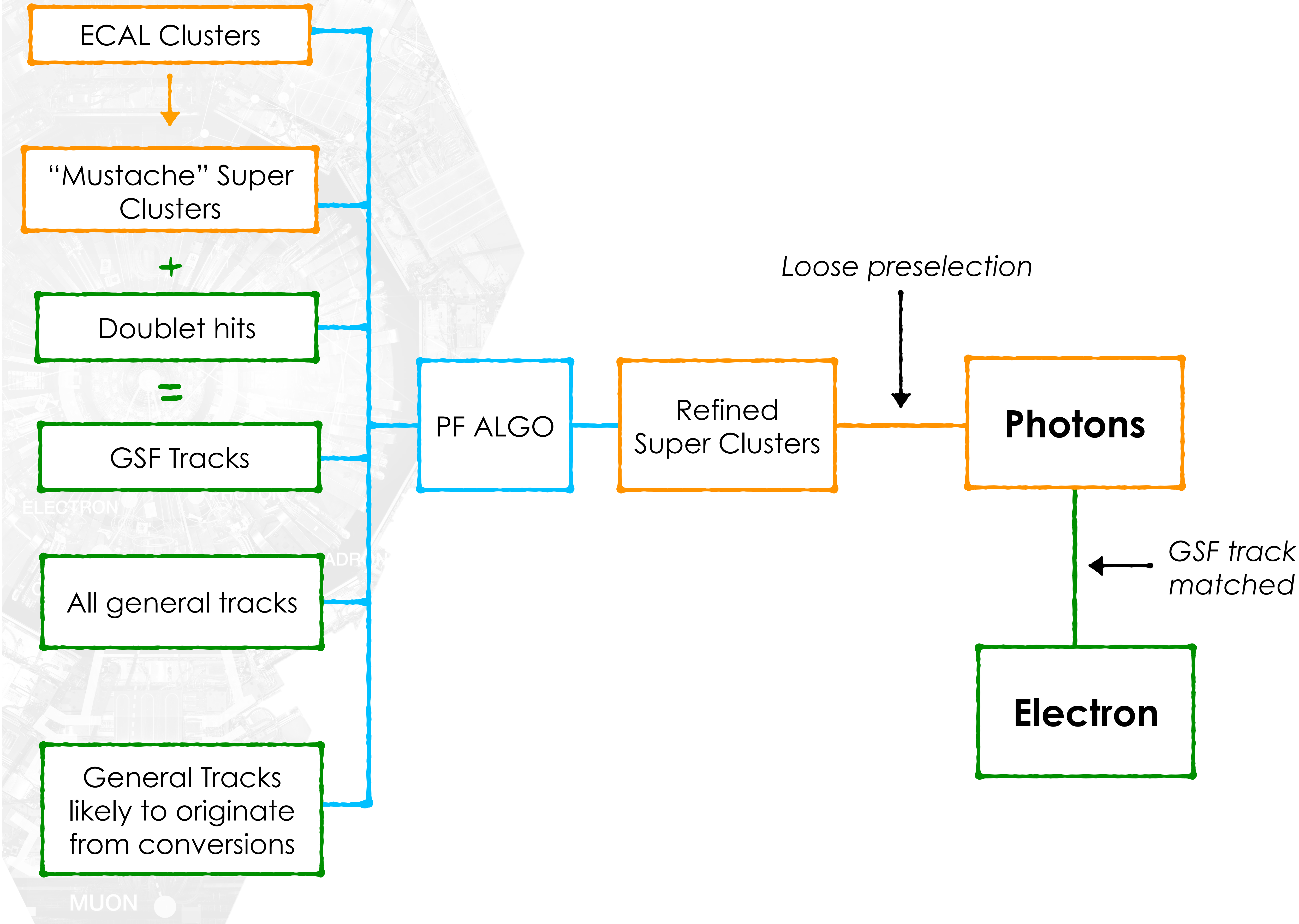
F Brem Variable



- fBrem = $(p_{in} - p_{out})/ p_{in}$ - tells the fraction of momentum lost to bremsstrahlung in the tracker

https://cds.cern.ch/record/2718815/files/DP2020_024.pdf

Ele/Pho Reconstruction Overview



ECAL Clustering

- By the time the particle reaches the ECAL original object may consist of several electrons and/or photons due to **bremsstrahlung and pair production**

- Clustering step looks for local maxima above a given energy threshold

- Clusters are linked using the **“mustache” algorithm**:

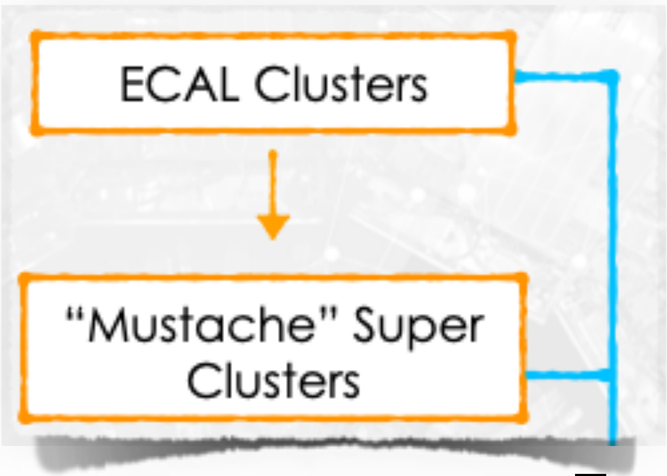
  - uses information only from the **ECAL and the preshower**

  - predefined **E_T dependent $\Delta\eta$ and $\Delta\phi$ threshold** to include any cluster found within this window

  - distribution of $\Delta\eta$(seed-cluster, cluster) versus $\Delta\phi$(seed-cluster, cluster) has a slight bend in $\Delta\eta$ because of bending charged particles in B

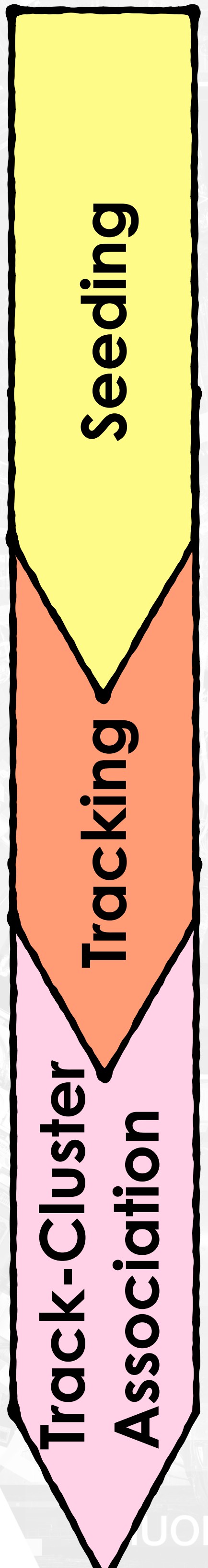
  - Region dependent on E_T

Major Difference w.r.t. Run 1



Electron Track Reconstruction

- GSF algo CPU intensive: run only on something which is likely to be an electron



"ECAL-driven"

- works better for high p_T
- tracker seeds from doublets ihits matched in dPhi and dZ window

"tracker-driven"

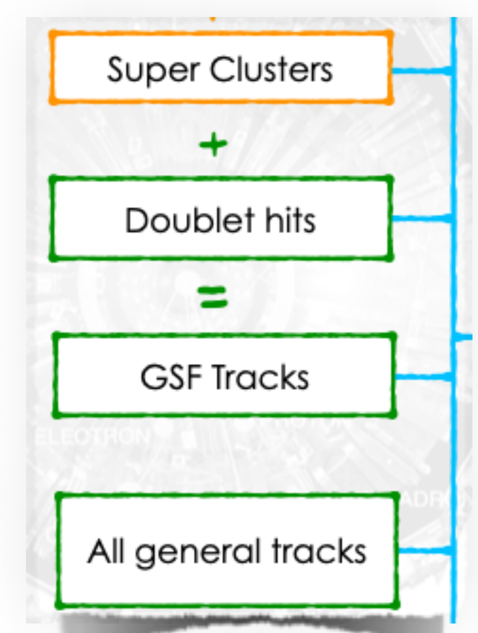
- recover efficiency for low p_T in PU and non-isolated
- compatibility check w/ track quality and track-cluster matching variables.

- final collection of the selected electron seeds used for reconstructing tracks

- **Standard KF algorithm** not optimal for electron track reconstruction. Make use of GSF, w/ bremsstrahlung modeled w/ mixture of Gaussians

- GSF tracks extrapolated to ECAL for track-cluster association

- **BDT** combines track kinematics and quality, PF cluster, and association



ECAL Supercluster Refinement

- Mustache SC improved w/ **tracker info** to recover conversions and brem while being able to reject clusters with a high probability of not being electron or photon

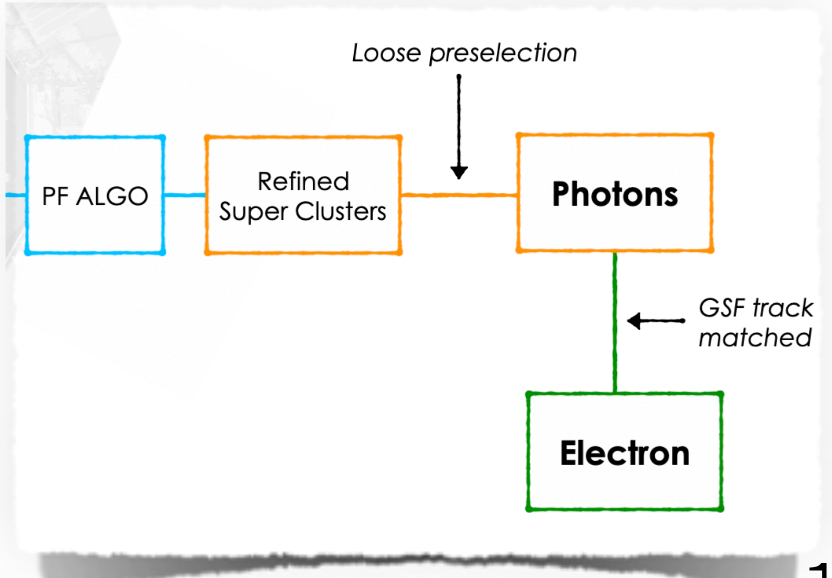
- **Mustache SC, ECAL clusters, general tracks, GSF tracks, and conversion flagged tracks** passed to GED algorithm to link into a single “PF block” from which ele/pho objects are built.

- Resulting SC are known as the **“refined” SC** and are used for all ECAL based quantities for electrons and photons.

- A given ECAL cluster can belong to only a single SC and as such the **same SC is used for both electron and photon reconstruction.**

    - **These are electrons and photons used by physics analyses**

- GED filters them and uses them to build **PFCandidates used by Jet/MET**



Energy Corrections Overview

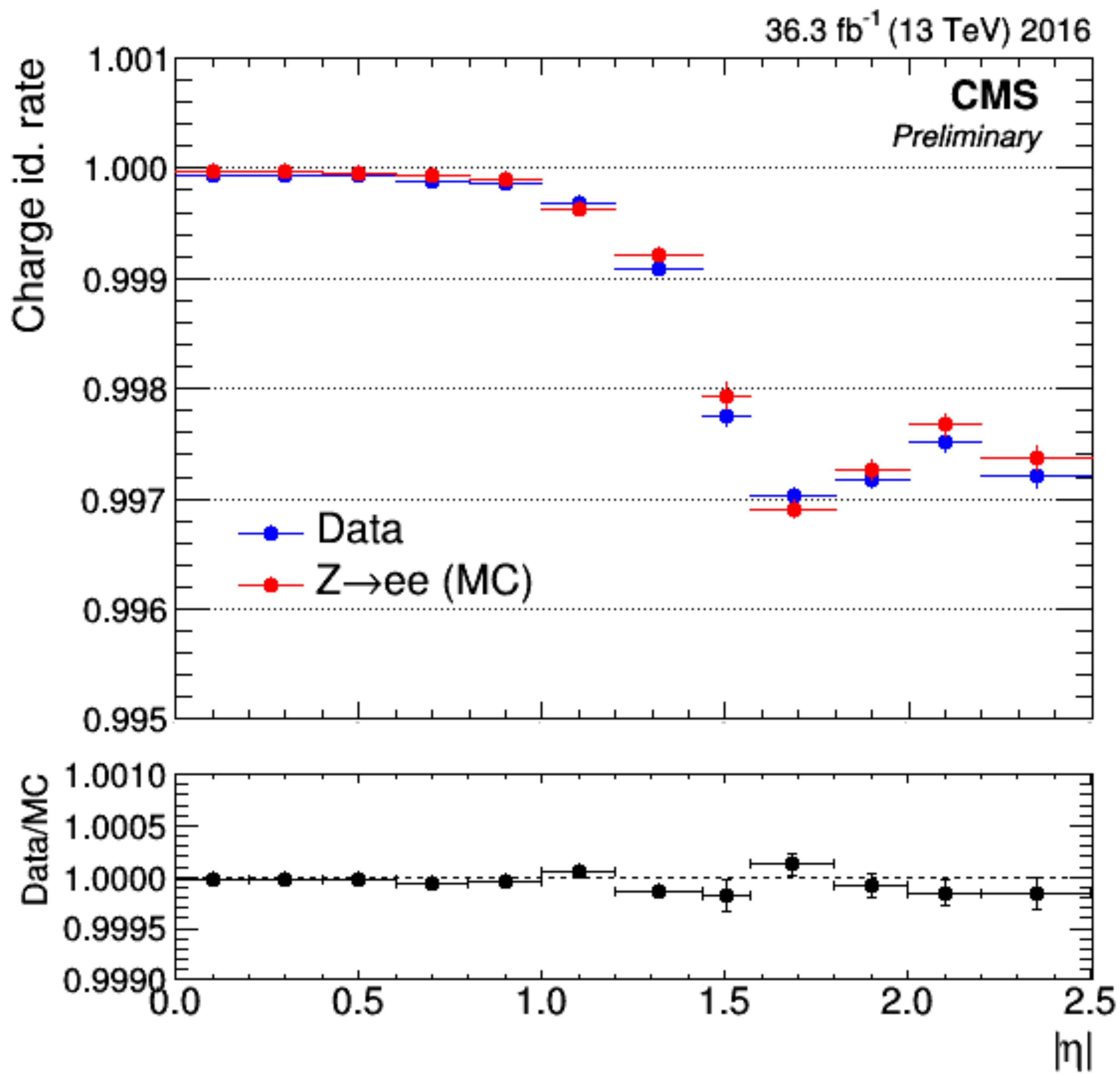
- TRegression's prediction is **correction factor** to be applied to the measured energy
- Input variables include **object's and event parameters**
- Implemented as **Gradient Boosted Decision Trees** w/ a semi-parametric likelihood

- Energy correction estimates sub-optimal for the data.
  - underestimation of material budget
  - underestimation of uncertainty in ECAL crystal intercalibration
  - residual differences between tECAL geometry and one simulated

- First step: correction of energy scale in **data vs time** (~ LHC fill)and **η regions**, owing to the different levels of radiation damage and upstream material budget using fit method (<1.5%)

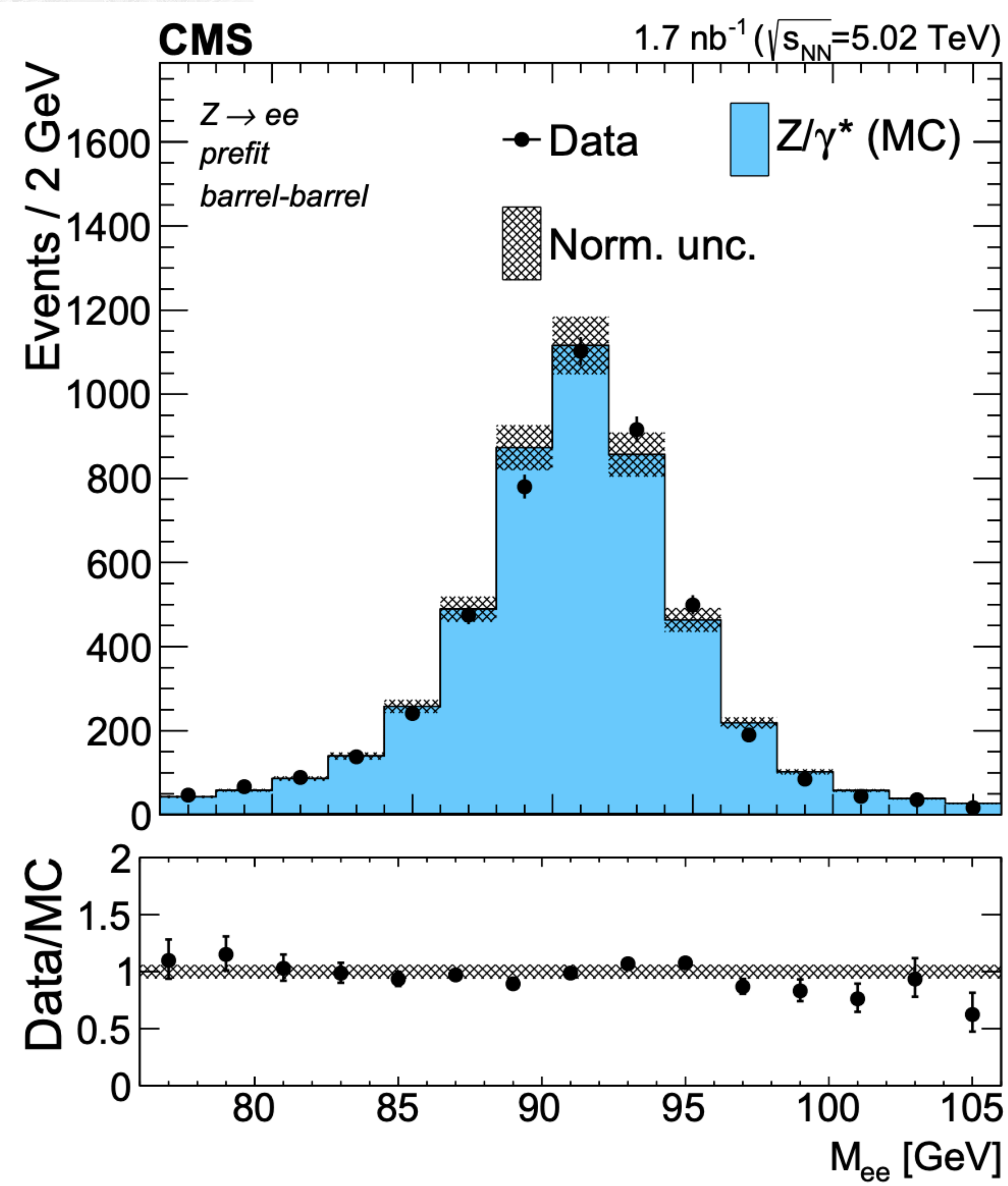
Charge Measurement

- Rate of correct charge identification for Z electrons as a function of pseudorapidity. All (selective method) electrons on the left (right).



Performance in PbPb Collisions

- Dedicated reconstruction, identification, and energy correction algorithms optimized to perform in the extreme conditions of central PbPb collisions

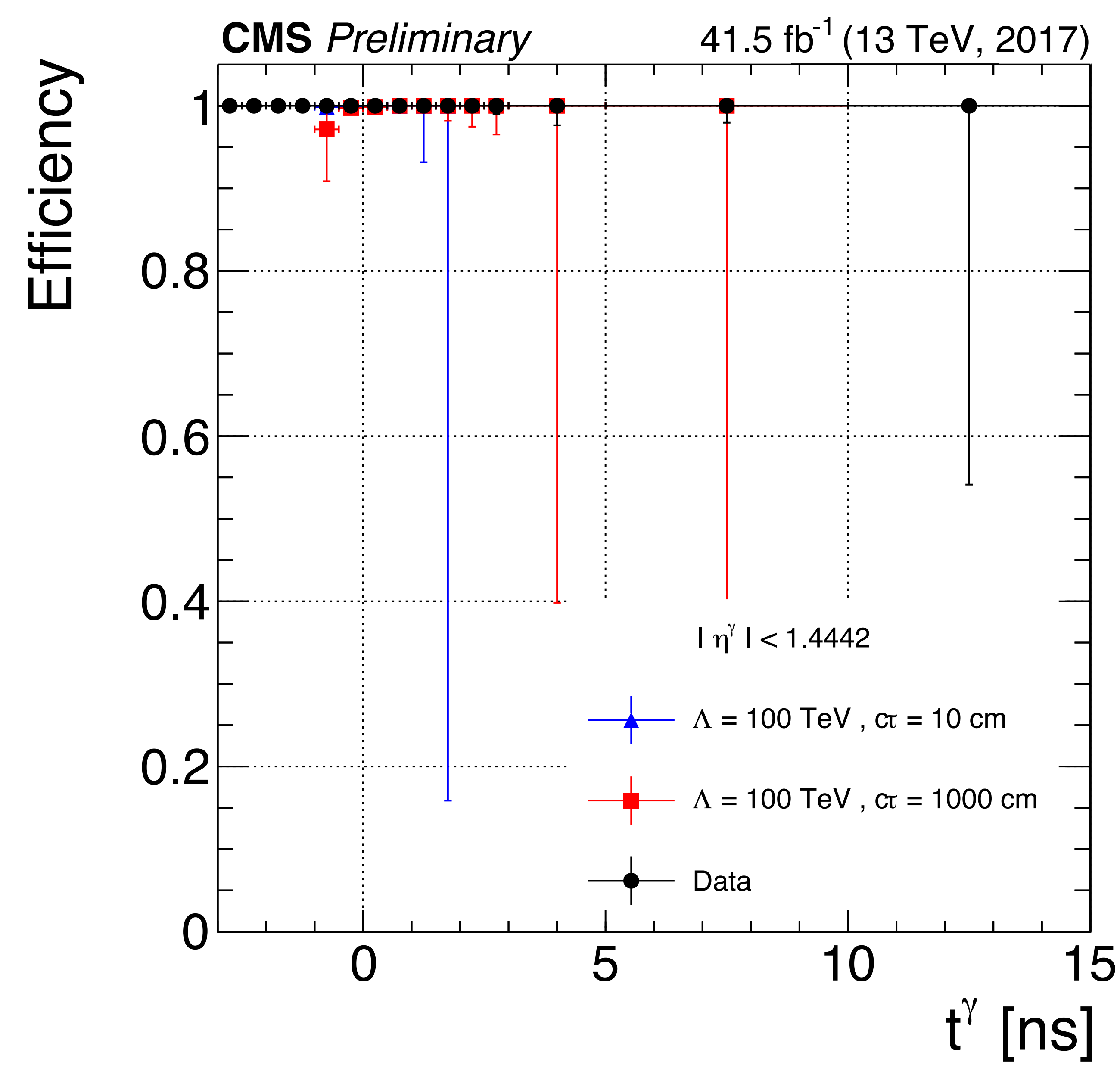


Timing

- Uses **dedicated displaced photon trigger**:must be **efficient for both prompt and late in time photons** to facilitate background estimation techniques

- **GMSB used as benchmark model**: upper limits given on cross-section as a function of breaking scale and neutralino proper lifetime

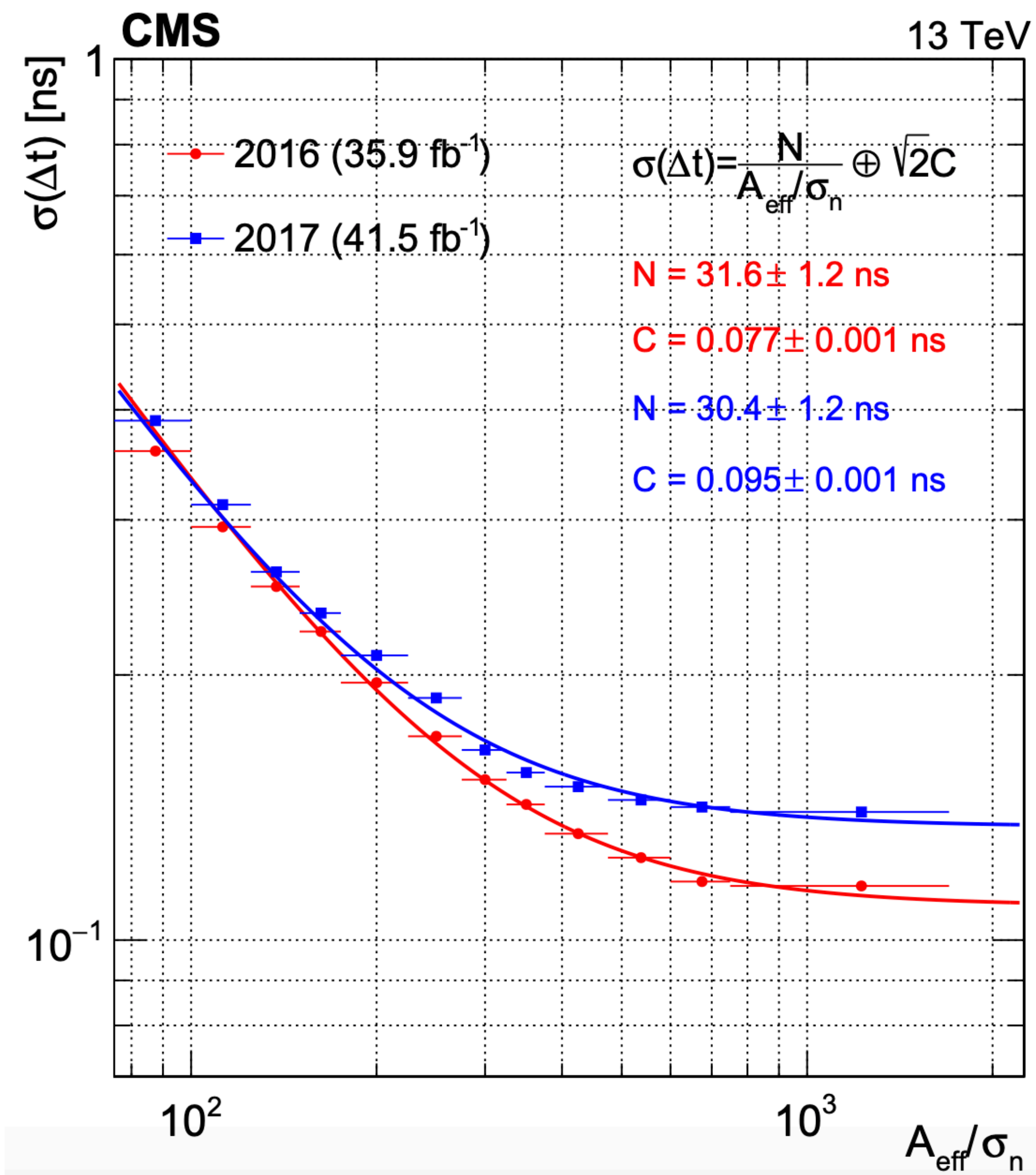
  - While at **a dedicated offline reconstruction for out of time photons above 3 ns is needed**, by default the **HLT does not apply any cut on the time of ECAL rechits** within a bunch crossing to retain sensitivity to out of time objects



$$E_{eff} = \frac{E_1 E_2}{\sqrt{E_1^2 + E_2^2}}$$

Timing Performance

- Excellent time resolution in measuring the time of arrival of photons and electrons in ECAL
- Rejection of background with a broad time distribution: cosmic rays, beam halo muons, electronic noise, and out-of-time proton-proton
- Identify particles predicted by different models beyond the Standard Model
- Timing resolution as a function of the pulse amplitude



$$A_{eff} = \frac{A_1 A_2}{\sqrt{A_1^2 + A_2^2}}$$

The CMS Detector at LHC

High sensitivity to a wide spectrum of final states

Silicon Tracker

Pixel (100 x 150 μm) - 66M channels

MicroStrips (80 x 180 μm) - 9.6M channels

- ✓ P_T resolution ~ 1.5% @100 GeV
- ✓ dE/dx measurement

Electromagnetic CALorimeter

76K PbWO4 crystals

- ✓ Designed energy resolution ~0.5% for E(γ) > 100 GeV
- ✓ Fast scintillation scale: > 80% of the light emitted in ~ 25 ns

Brass/Scintillator Hadron Calorimeter

Muon Chambers

Drift Tube - Cathode Strips Chambers - Resistive Plate Chambers

- ✓ Single-point resolution ~ 200 μm
- ✓ σ_{DT} ~ 3ns
- ✓ σ_{CSC} ~ 7ns