Performance of electrons and photons at CMS and recent developments

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on behalf of the CMS Collaboration

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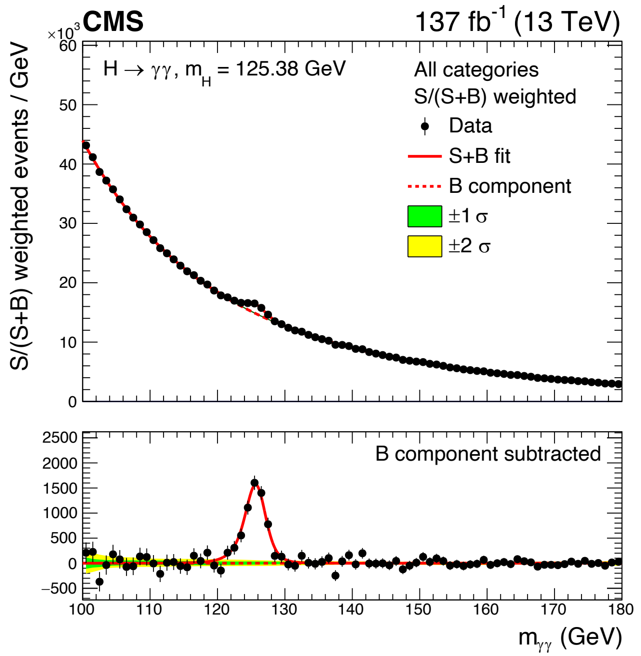
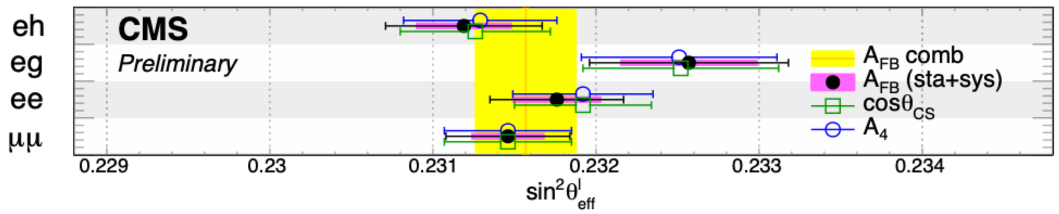
Electrons and photons at CMS

Critical for the success of the CMS physics program, both in terms of standard model measurements and searches

Run2 $H \to \gamma\gamma$ production cross section and couplings



Effective leptonic weak mixing angle

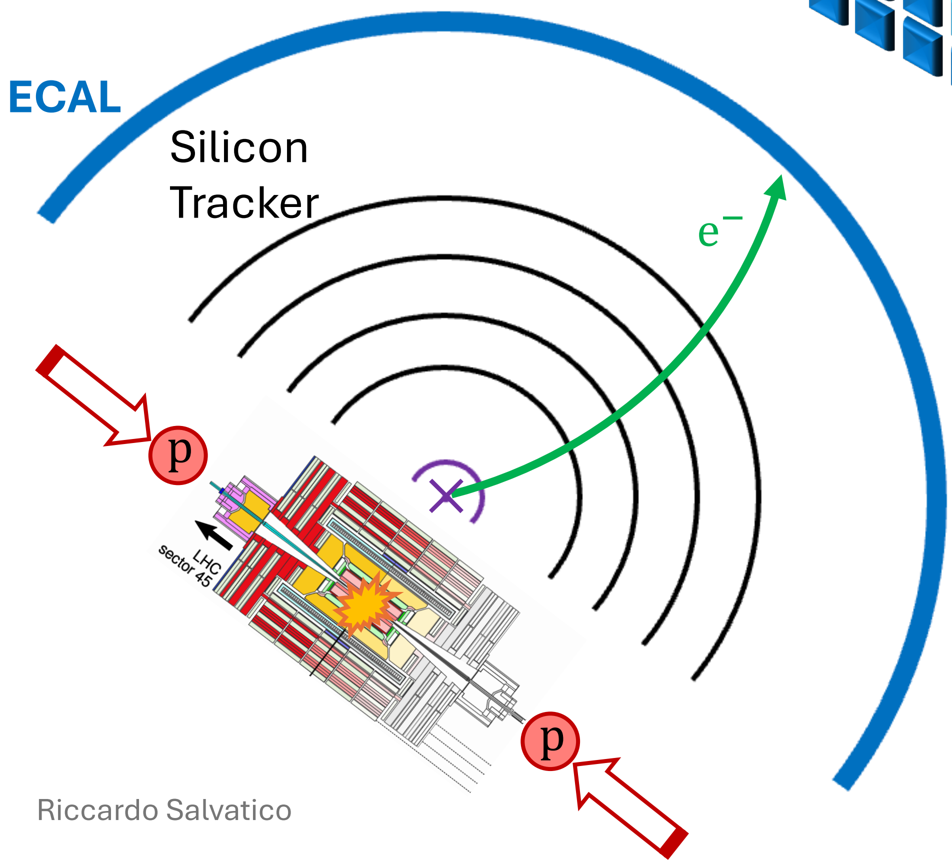


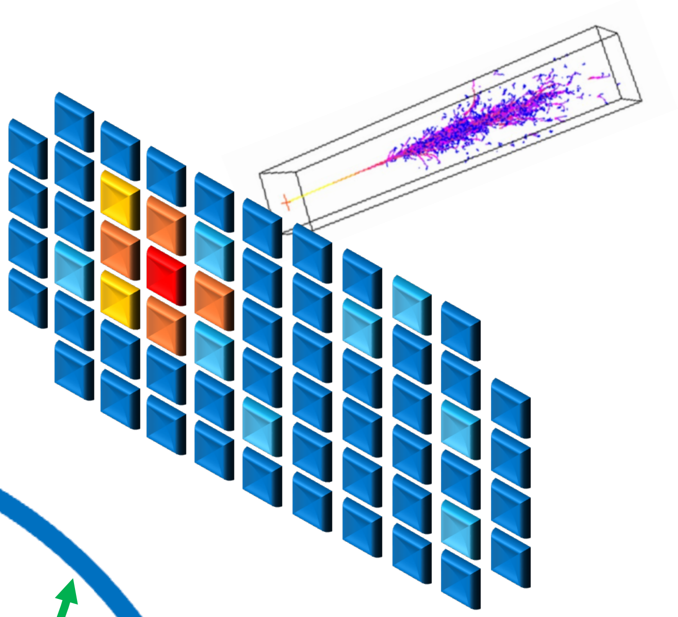
At ICHEP 2024:

- $H \to \gamma\gamma$ and $H \to 4\ell$ cross sections and couplings in Run3 (see Jan Lukas' talk)
- H boson mass and width (see Badder's talk)
- Several searches with photons in the final state (see Rocco's talk for SM, Jyoti's talk for BSM)
- Compressed SUSY with electrons in the final state (see Margaret's talk)
- etc.

Electrons and photons at CMS – how to

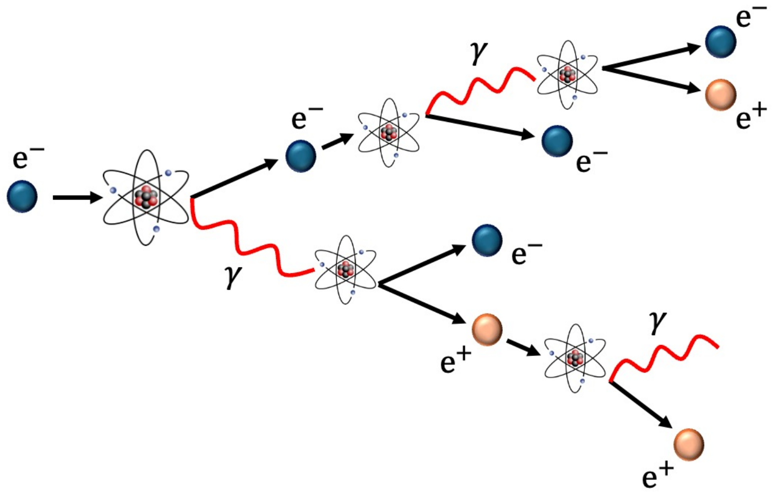
IDEAL



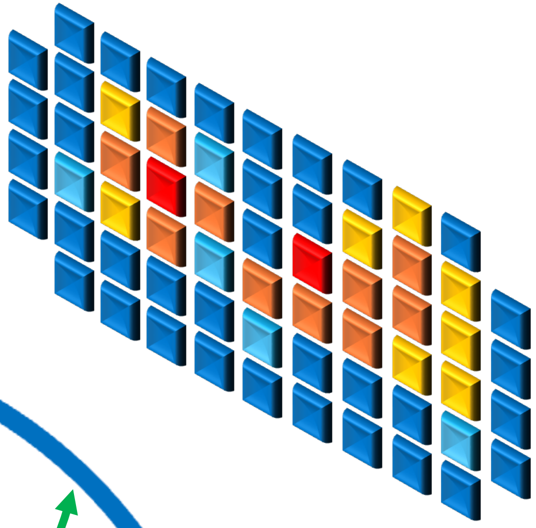


A hit in the ECAL

→ an EM shower in a small **cluster** of $PbWO_4$ crystals

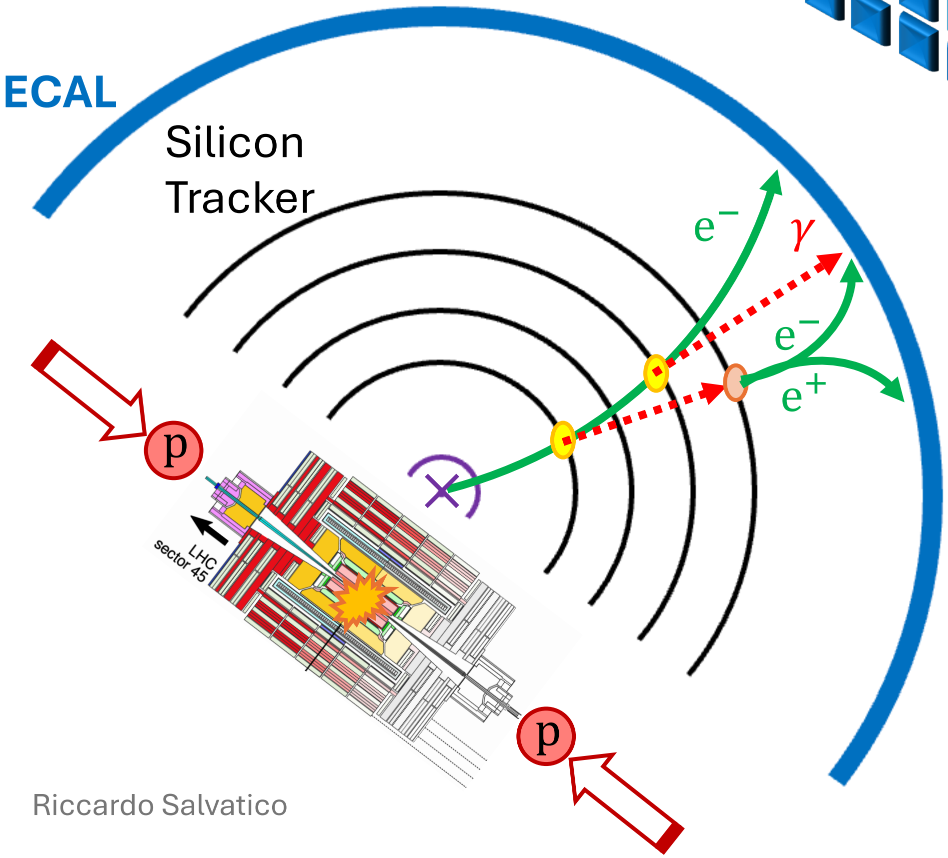


REAL



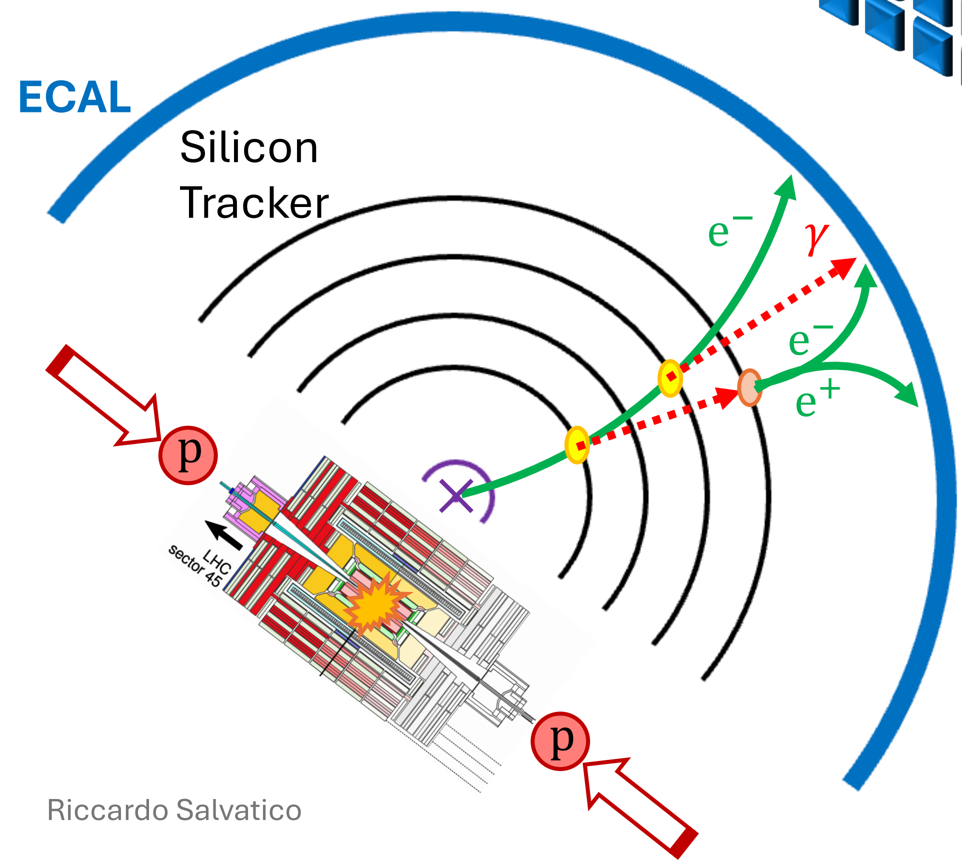
Bremsstrahlung and photon conversions need to be associated to the same initial particle

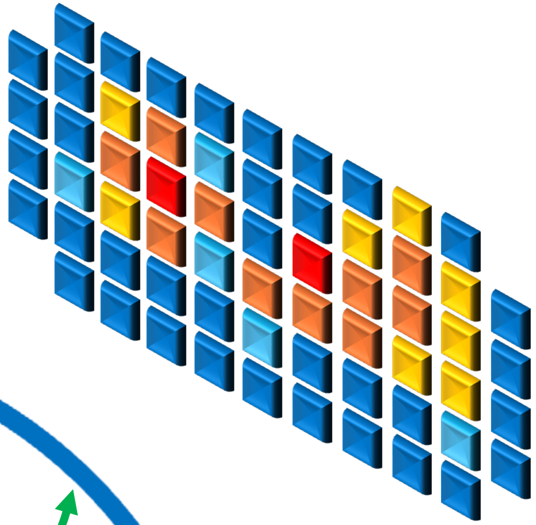
→ **Supercluster**



Electrons and photons at CMS – how to

REAL





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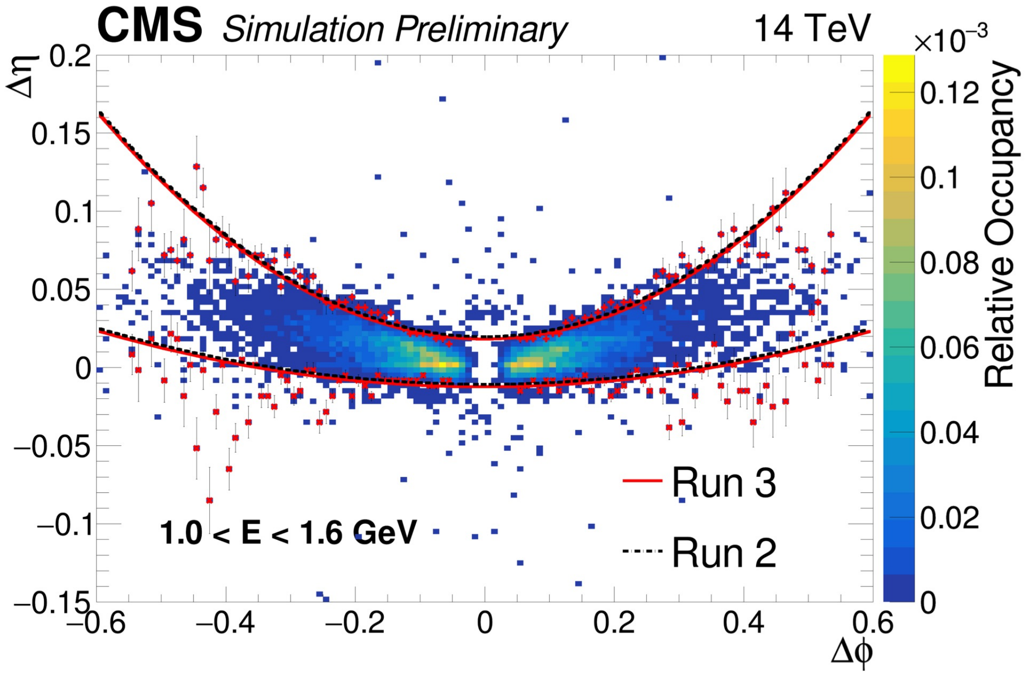
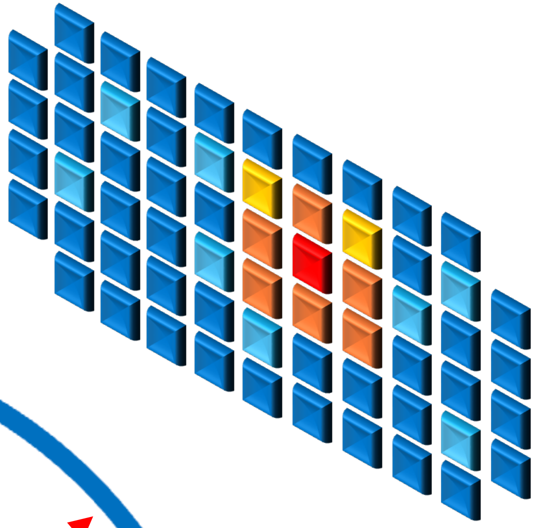
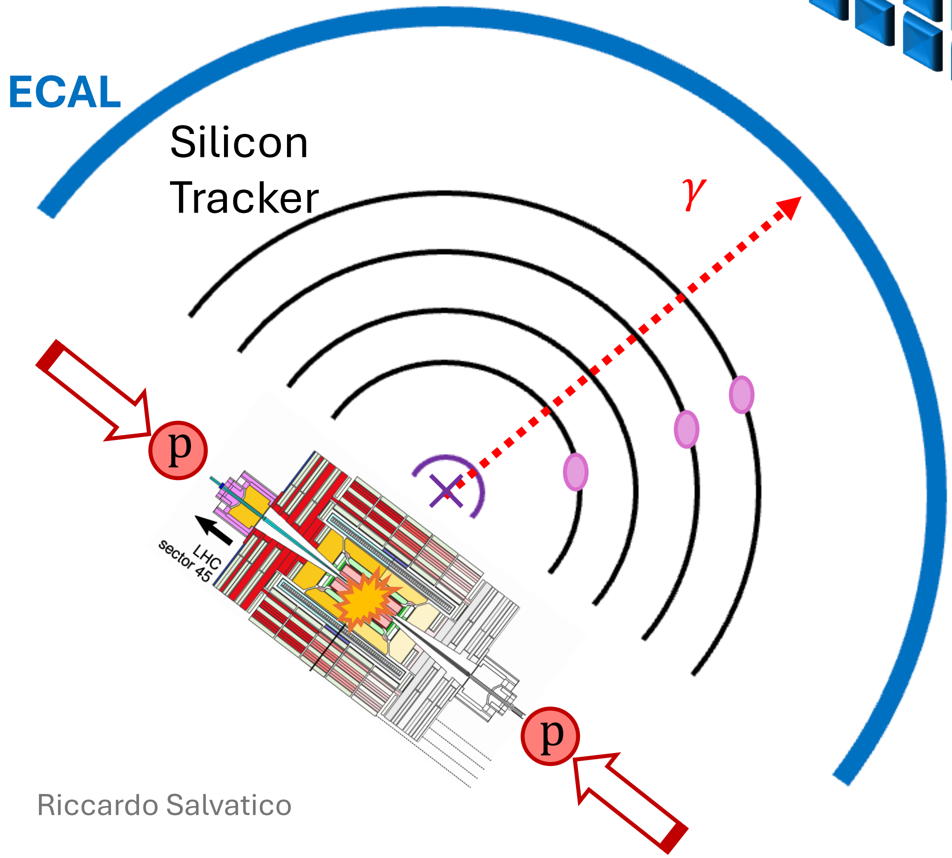


Geometrical procedure that considers the slight bending in η of the low-p_{T} constituents of EM showers → ***moustache***. The moustache was retuned for Run3 to reduce the noise.

Photons at CMS – how to

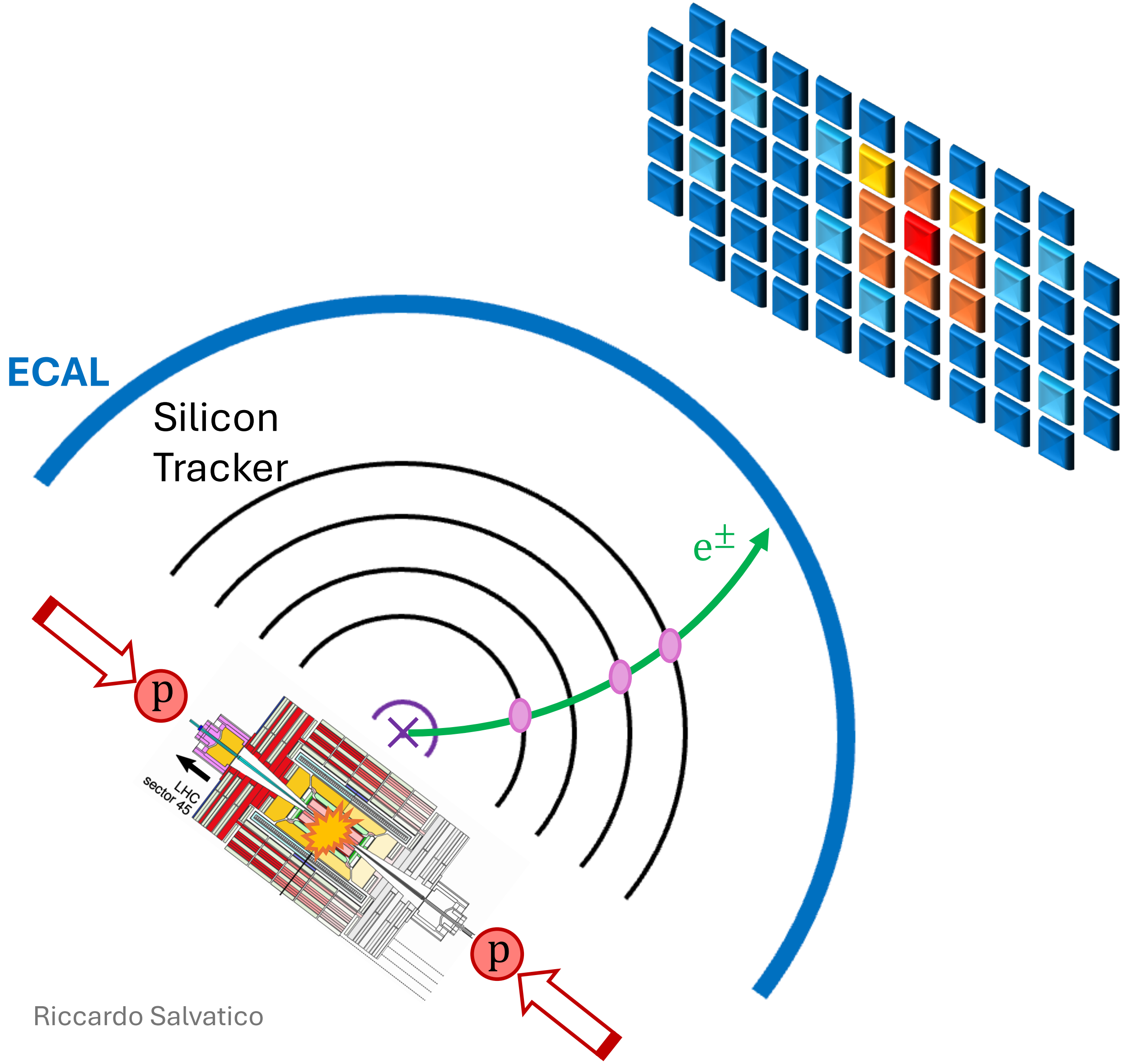




Energy deposit in the ECAL

→ **photon**

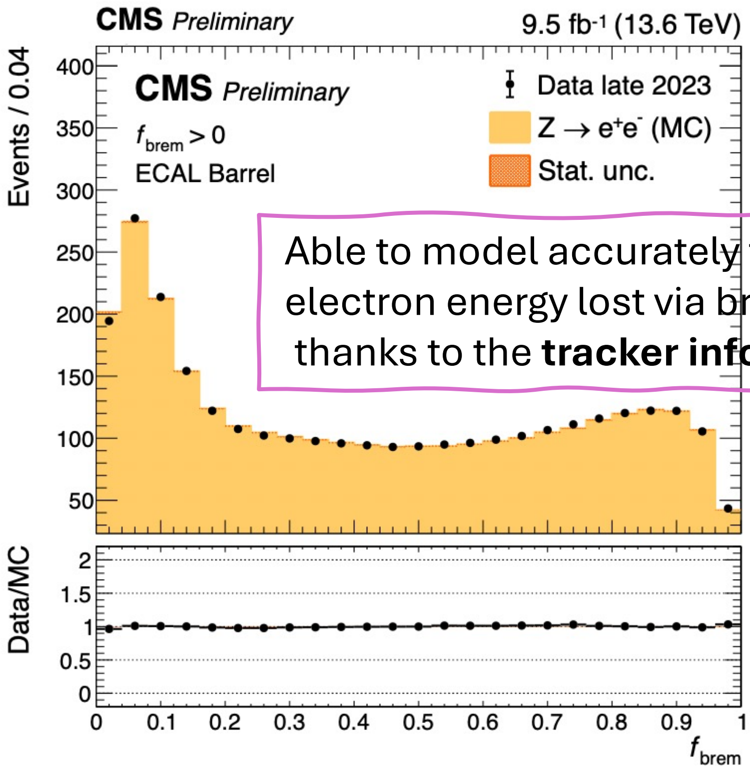
Electrons at CMS – how to



Energy deposit in the ECAL + track association

→ **electron/positron**

Using **special track reconstruction algorithm** (Gaussian-sum filter) to consider energy losses via photon radiation. CMS Note 2005/001



Able to model accurately the fraction of electron energy lost via bremsstrahlung thanks to the **tracker information** too.

Online reconstruction performance

[CMS-DP-23/015](#)
[CMS-DP-24/041](#)

[CMS-DP-23/008](#)
[CMS-DP-23/055](#)

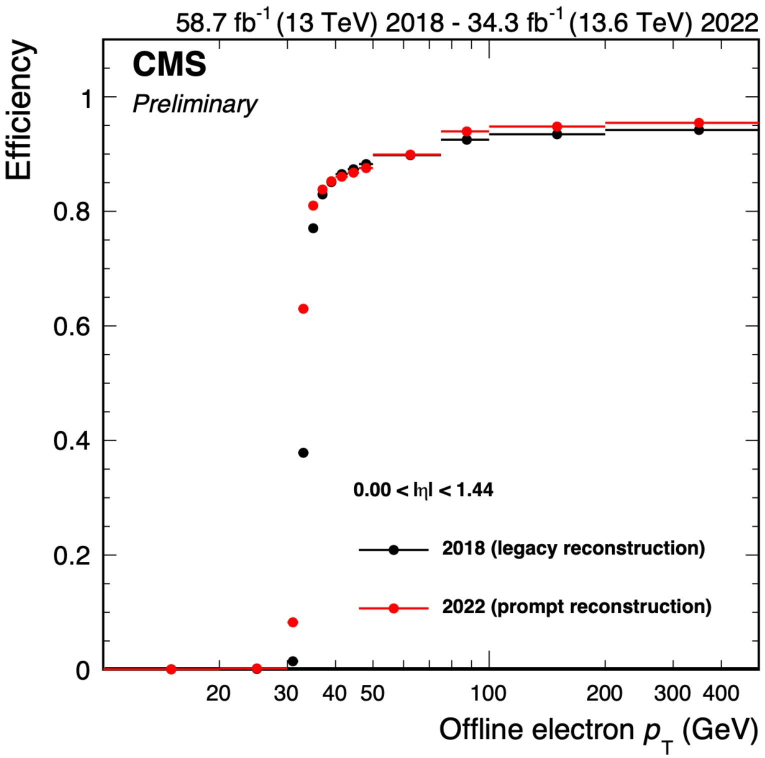
The CMS trigger system selects the collision events to save for further analysis. It is two-tiered:

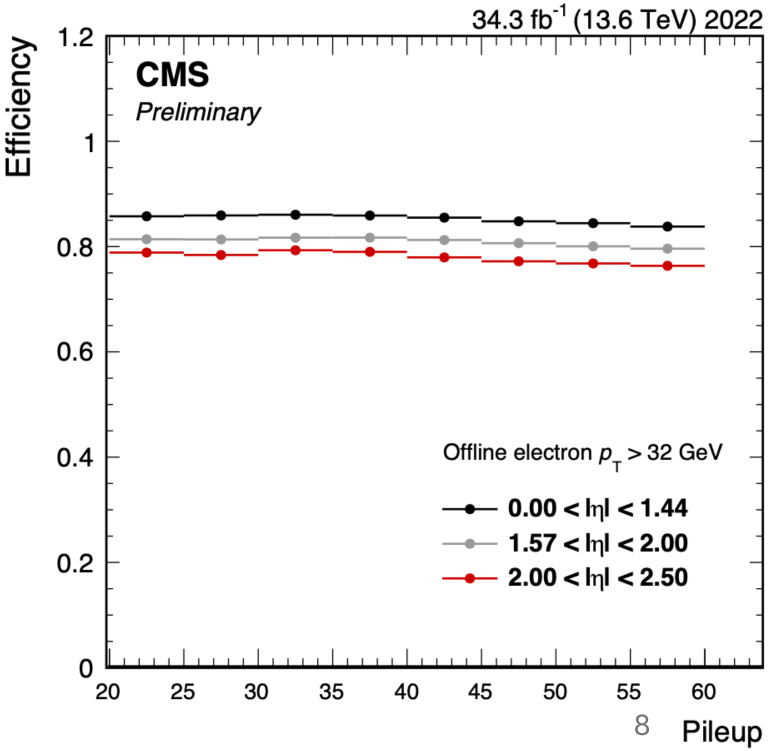
L1: hardware-based, using on-detector electronics. Saves $\sim$**110 kHz**.

HLT: software. Runs a simpler (→ *faster*) version of the offline reconstruction, allowing us to access data quality and physics content “online”, during collisions. Saves $\sim$**1.5 kHz**.

High-purity single electron trigger

- Excellent HLT performance in Run3
- Great stability vs pileup





Online reconstruction performance

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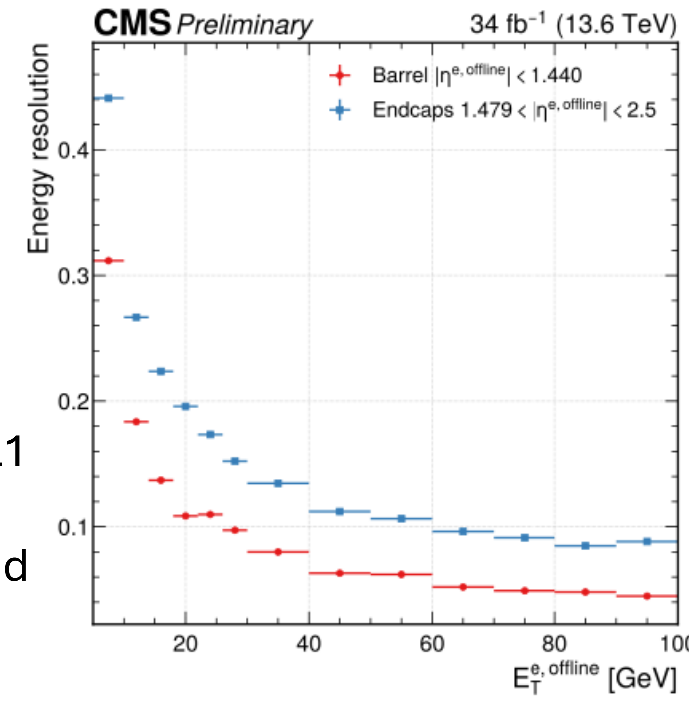
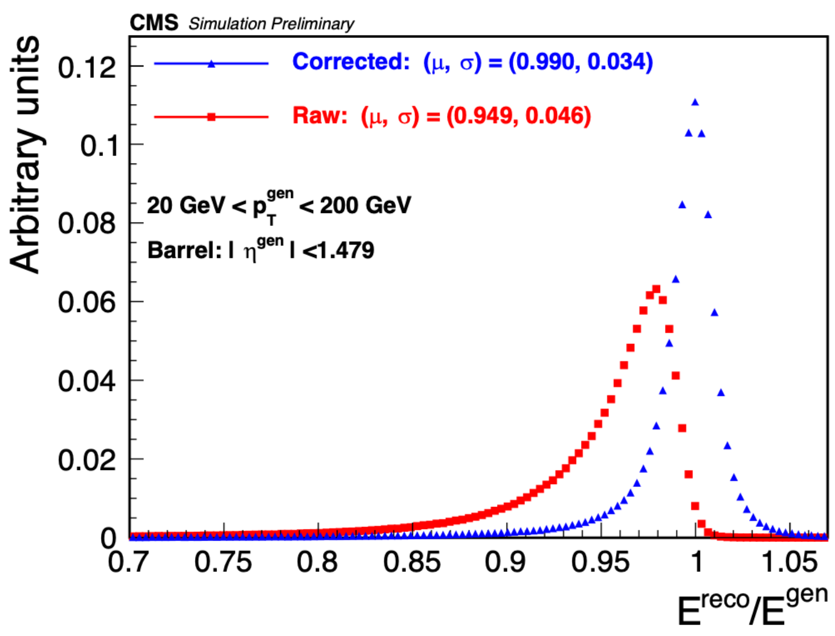
High-purity single electron trigger

- Excellent HLT performance in Run3
- Great stability vs pileup
- Backed by good e/γ energy resolution at L1
- Supercluster energy response corrected using a BDT-based regression

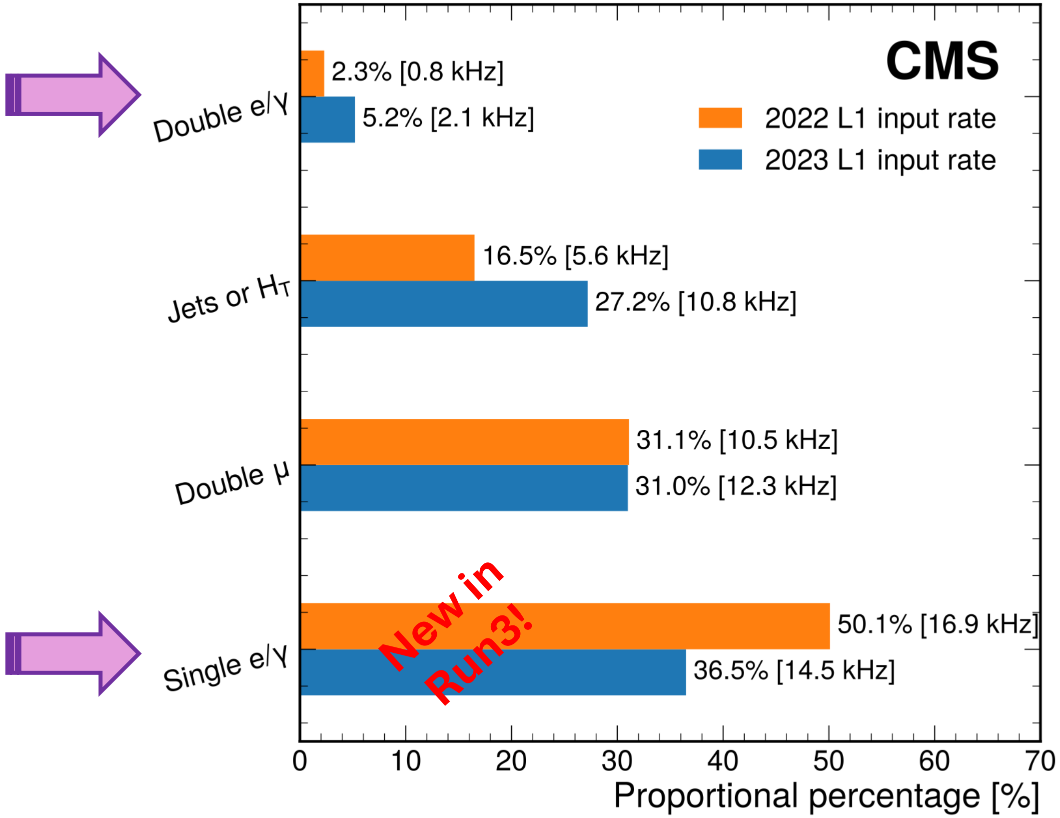




Scouting electrons and photons

HLT scouting: allow larger rate at low-p_{T} at the price of giving up the offline reconstruction.

(Can we produce competitive physics results using objects reconstructed online only and with limited event content information? Run2 answer)



- Large fraction of L1 rate in input to the scouting streams dedicated to single and double e/γ.
- Minimal HLT selection (on supercluster) and thresholds:
  - **30 GeV** for single e/γ → **~ 9.0 kHz HLT** (2023)
  - **12 GeV** for double e/γ → **~ 0.5 kHz HLT** (2023)

Scouting electrons and photons

arXiv:2403.16134

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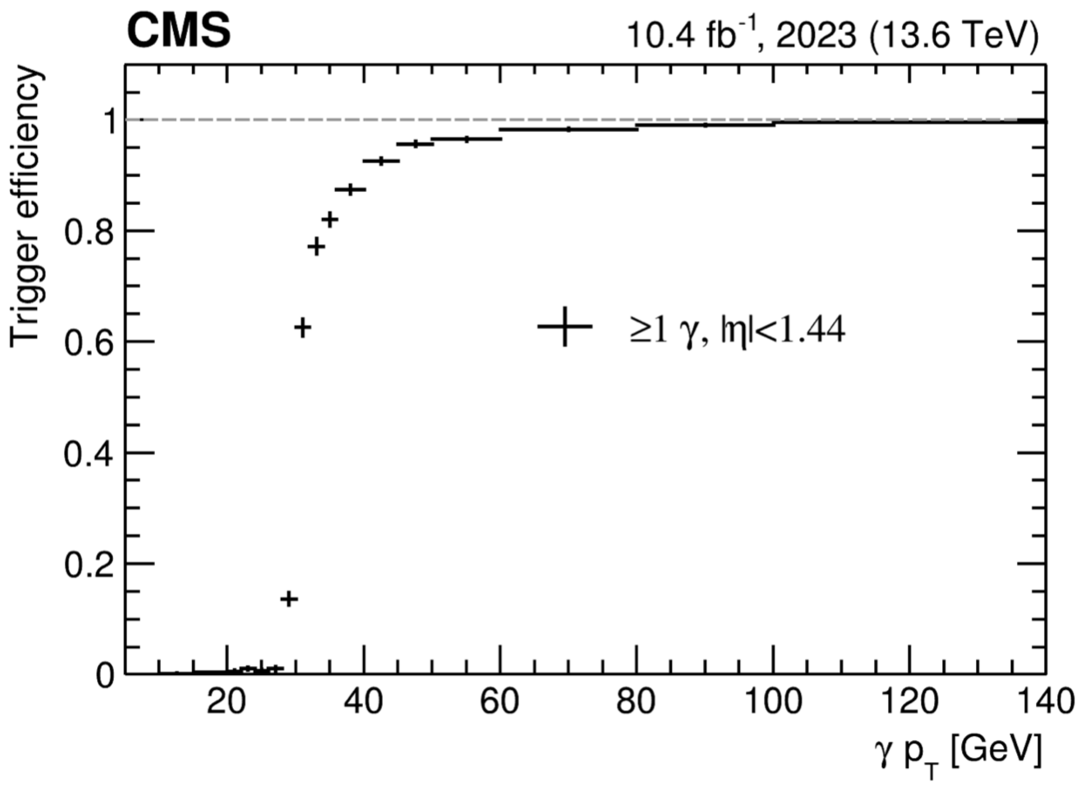

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- Considerably reduce p_T thresholds wrt standard HLT, especially for single photon (200 GeV in 2022 and 2023).

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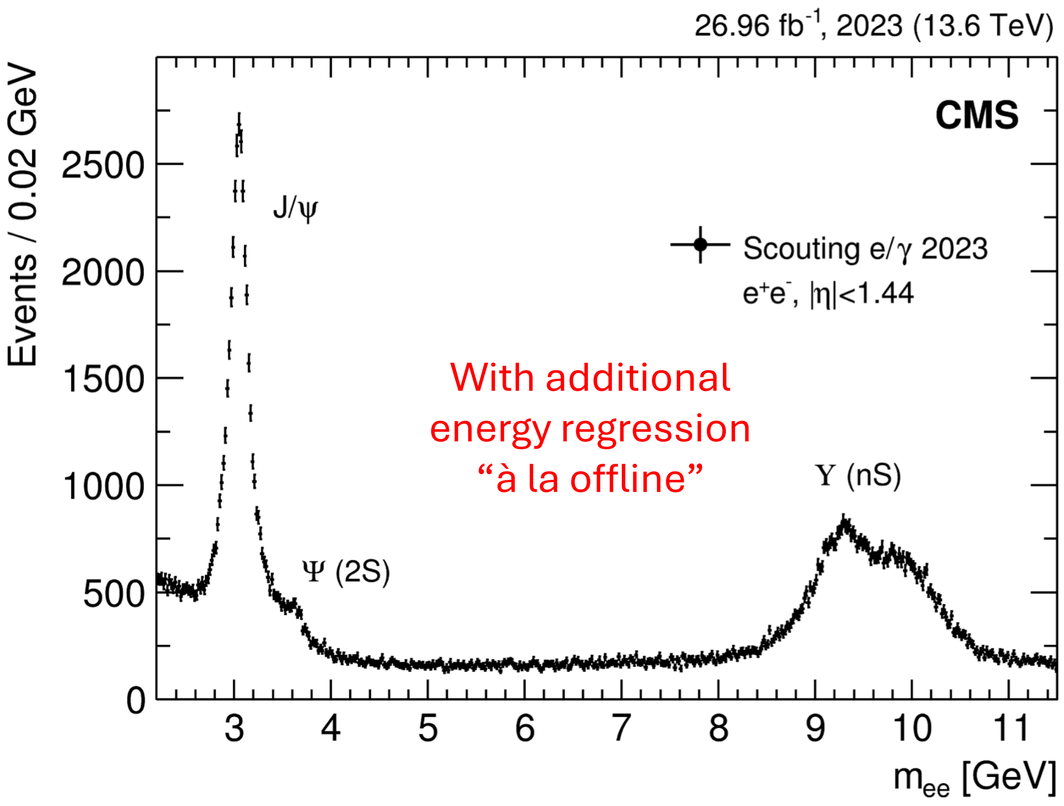

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- Considerably reduce p_{T} thresholds wrt standard HLT, especially for single photon (200 GeV in 2022 and 2023).
- Additional low p_{T} electrons and photons saved in events recorded using triggers seeded by L1 muons, jets or H_{T}.

Offline reconstruction

The **offline reconstruction** is more refined than the online one and allows for further data reprocessing with improved corrections and detector calibration.

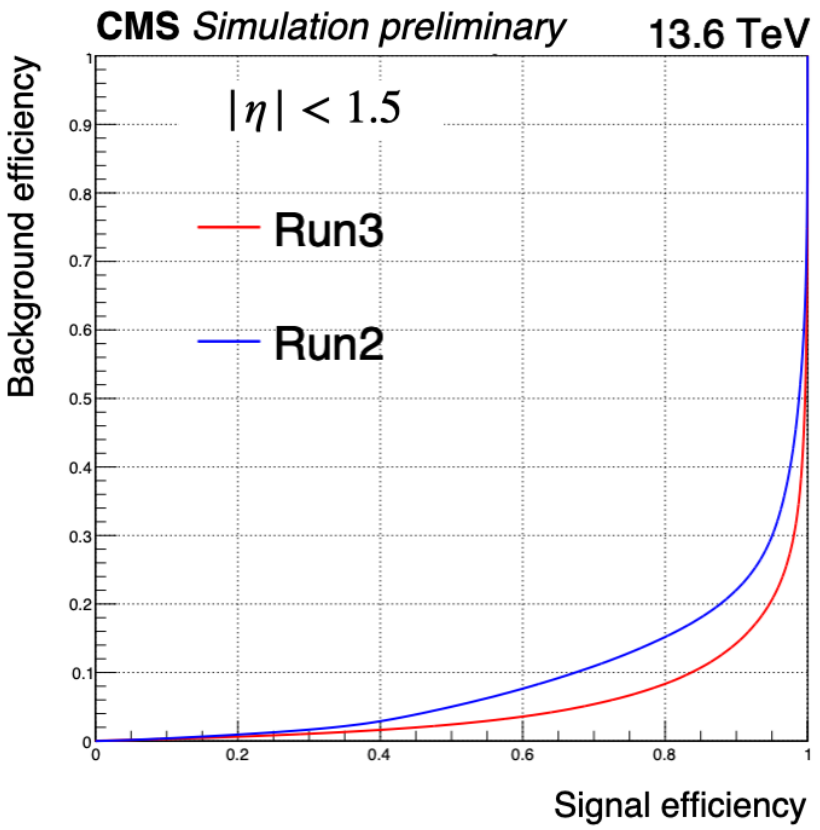
For electrons and photons, this means:

- More "layers" of energy corrections (and potentially more complex models → timing is not a concern)
  - Notably, combination of ECAL energy and tracker momentum measurements to determine the final electron energy, which does not happen at HLT
- More sophisticated IDs
  - Cut-based
    - Flexible – easy to remove unwanted cutoffs at analysis level (e.g., isolation)
  - MVA-based (BDT or DNN)
    - *Generally* stronger signal/background discrimination

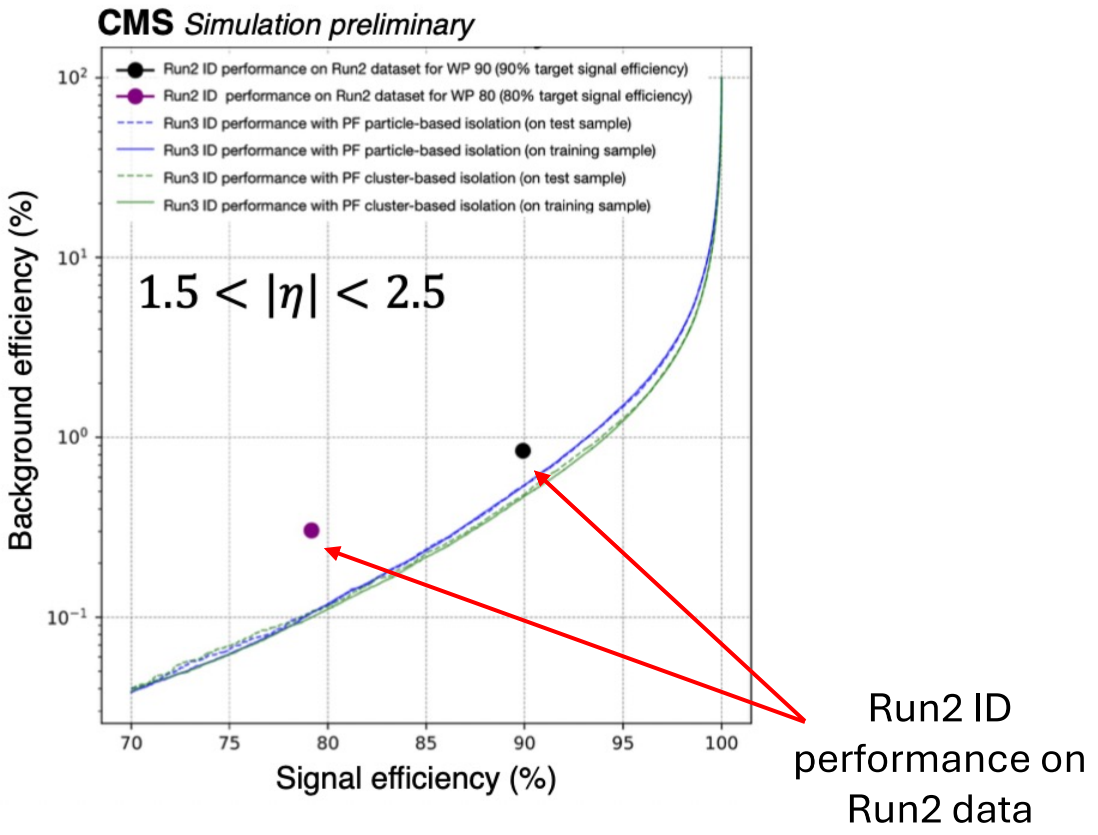
Run3 IDs

In Run3, the cut-based and MVA-based electron and photon IDs were tuned or retrained to ensure a better performance than the Run2 ones within the Run3 data-taking and detector conditions.

MVA-based photon IDs

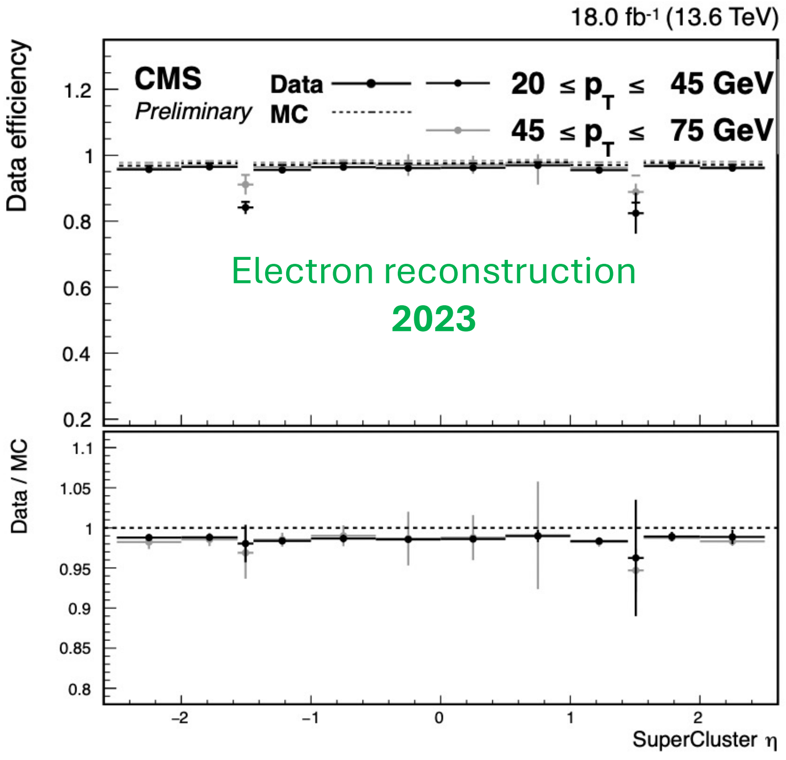


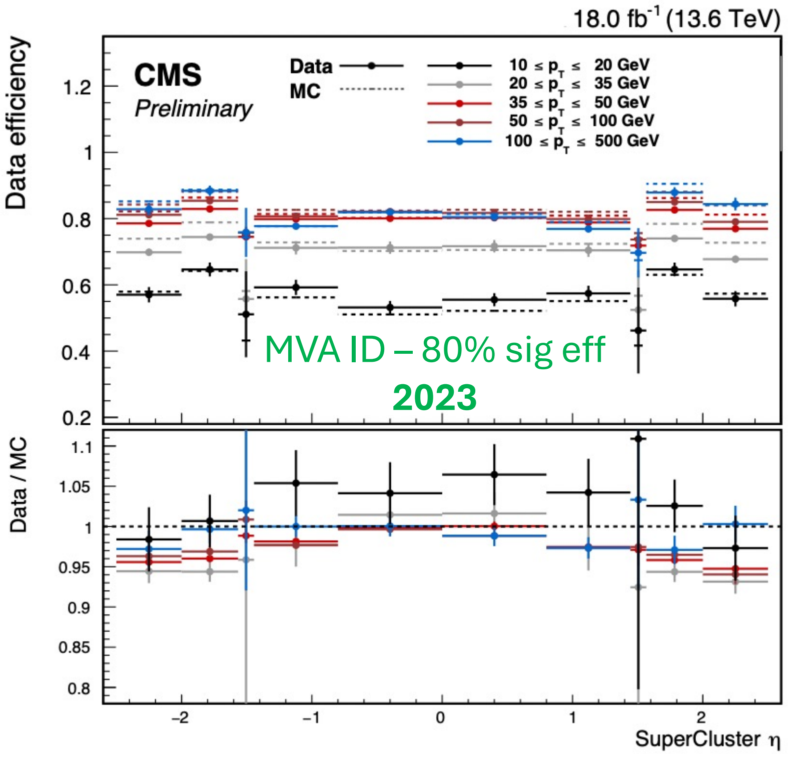
MVA-based electron IDs

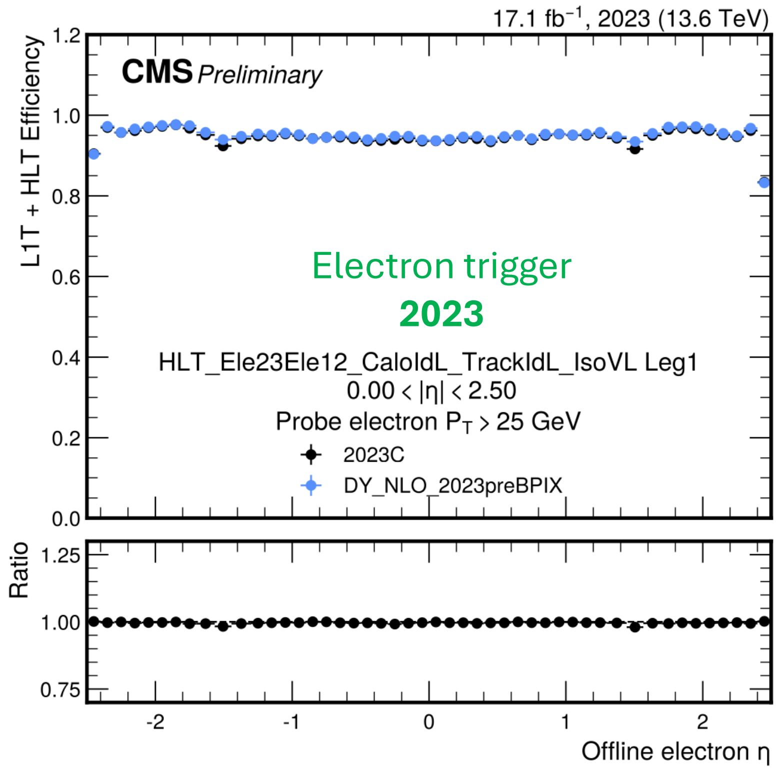


Run3 offline performance and corrections

The reconstruction, identification, and trigger performance for electrons and photons is studied in collision data and simulation, and we correct them for discrepancies.







Efficiency to match a supercluster with a track in the tracker

Efficiency to satisfy a set of identification criteria

Efficiency for offline-reconstructed objects to pass a certain trigger

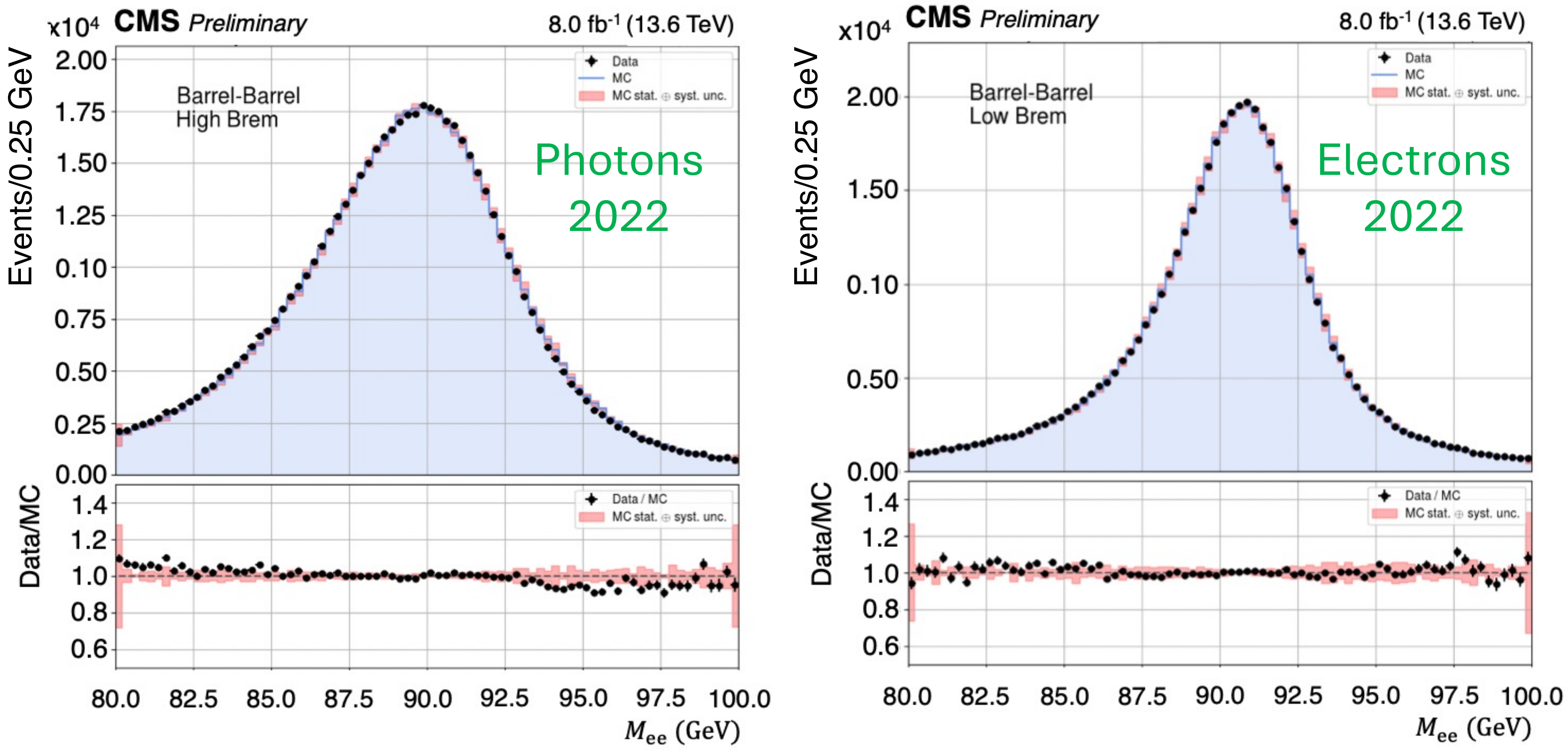
Run3 offline performance and corrections

CMS-DP-24/052

The reconstruction, identification, and trigger performance for electrons and photons is studied in collision data and simulation, and we correct them for discrepancies.

Scale and resolution corrections

- Derived using electrons from $Z \rightarrow ee$ for different:
  - particle's p_T or ECAL amplifier gains
  - detector regions
  - data acquisition runs
  - bremsstrahlung emission
- Scale e/γ energy in collision data
- Spread e/γ energy in simulation

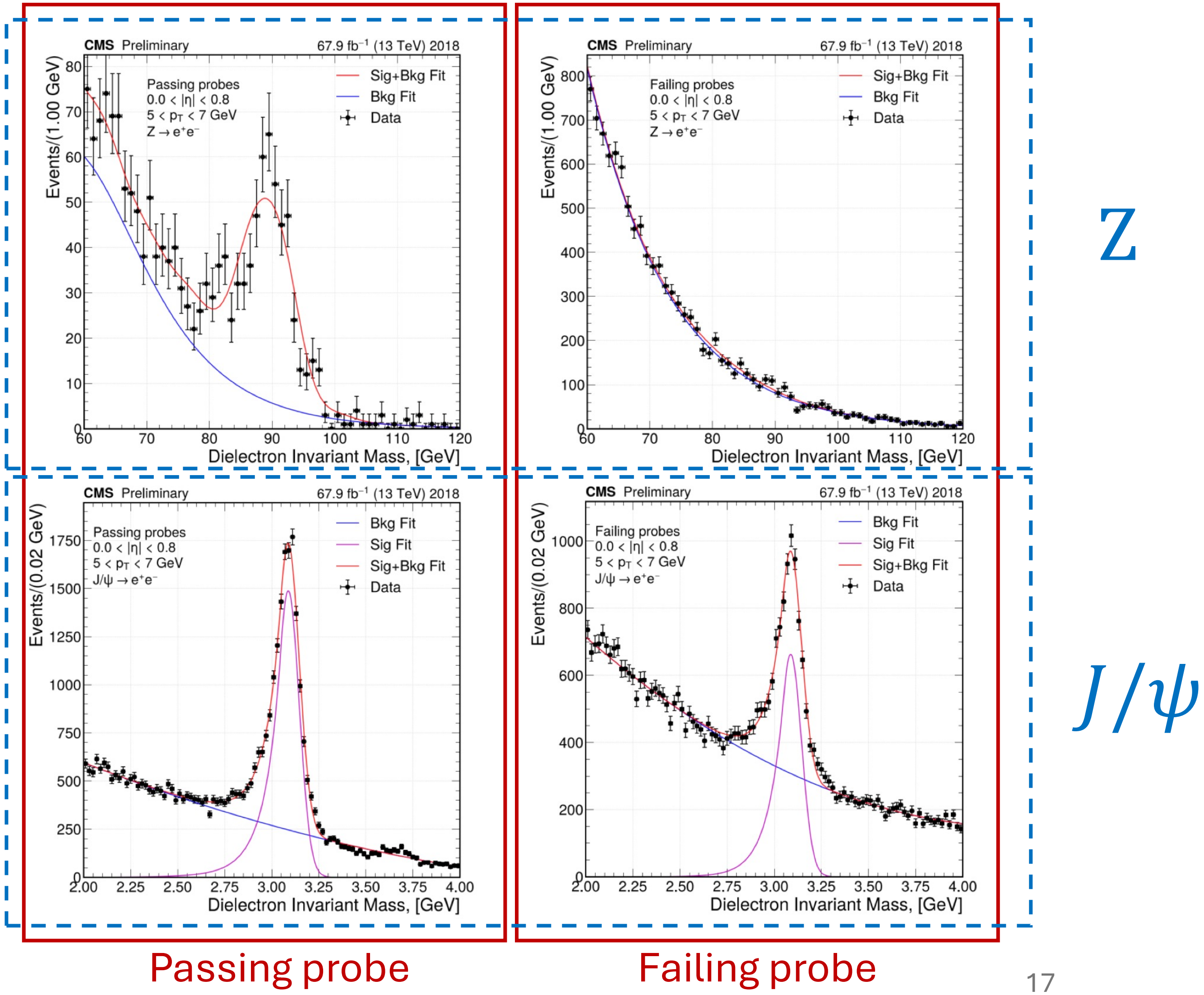


Measuring efficiencies at low pT

An accurate efficiency measurement for low p_T (< 20 GeV) e/γ requires a standard candle different from the Z resonance

J/ψ **decays** provide significantly higher statistics and make the measurement possible even below 10 GeV

- *Tag & Probe*: signal peaks clearly visible in both passing and failing probe $m(\mathrm{ee})$ distributions.



Measuring efficiencies at low pT

CMS DP-2023/081

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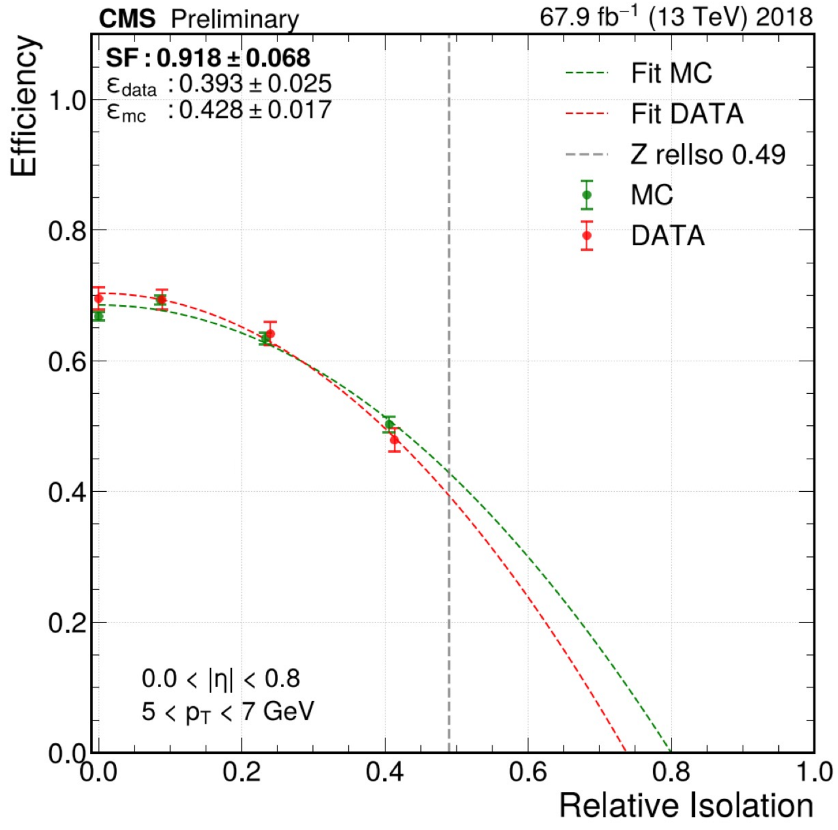
- *Tag & Probe*: signal peaks clearly visible in both passing and failing probe $m(\text{ee})$ distributions.

J/ψs electrons tend to be less isolated than Z electrons

- Extrapolate efficiency at the Z relative isolation value from a fit to the trend of the $J/\psi \rightarrow \text{ee}$ efficiency for different relative isolation bins.



ONGOING STUDY

Redesigning the supercluster

Supercluster

- Base component in the reconstruction of photons and electrons
- Essential for the ECAL energy response calibration
- One of the inputs to the Particle Flow global event reconstruction

Moustache

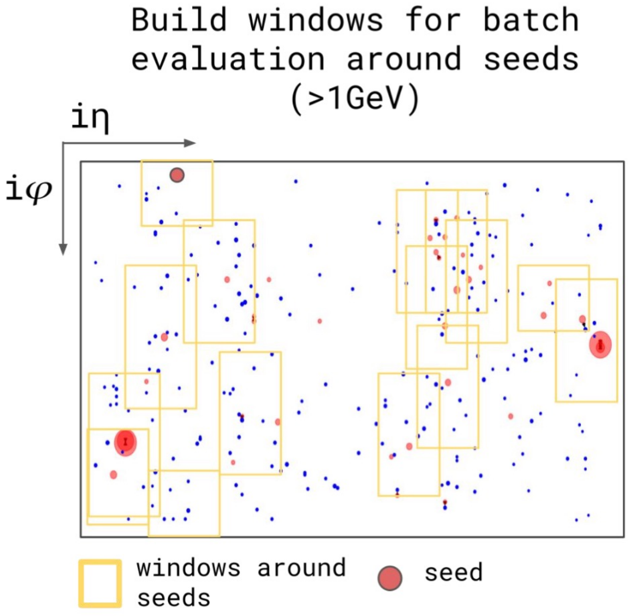
- selects clusters defining a parabolic $\eta - \phi$ region parametrized by the seed position and the cluster transverse energy
- very efficient but subject to PU/noise contamination – resolution degrades with PU

GNN supercluster → "DeepSC"

- uses small clusters and single crystal hits in a window around the seed
- filters noise/PU *on a cluster-by-cluster basis*, improving the "raw" resolution

The DeepSC

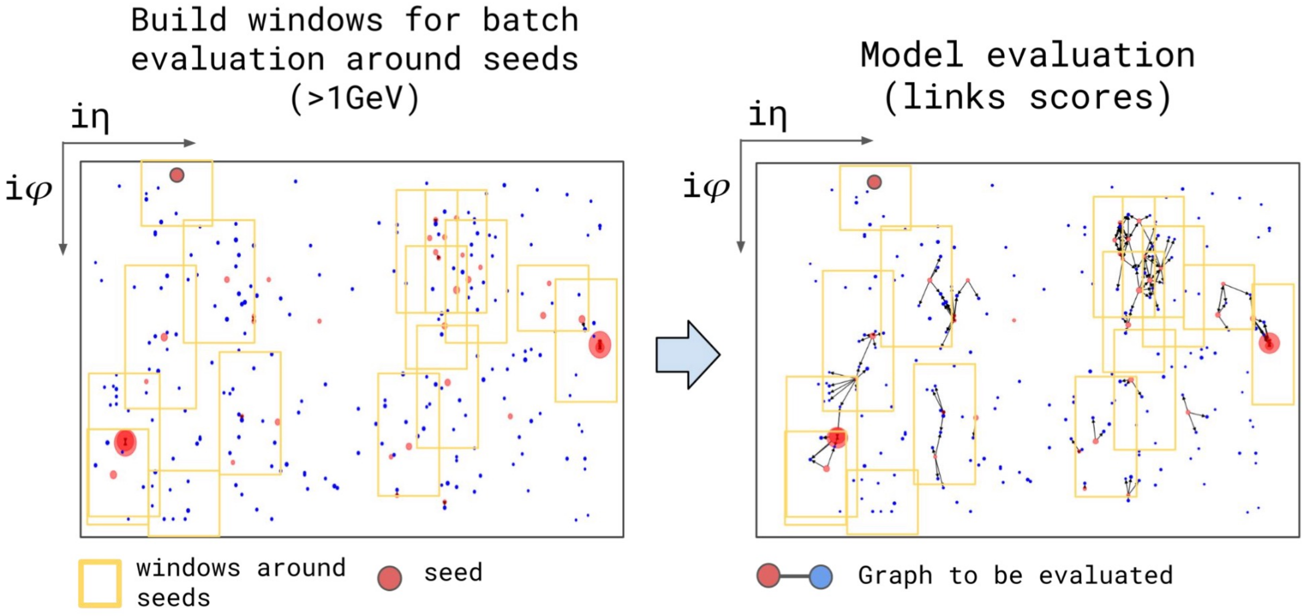
- Build detector windows around each cluster with $p_T > 1$ GeV (**seed**).



The DeepSC

CMS-DP-22/032
CMS-DP-22/058

- Build detector windows around each cluster with $p_T > 1$ GeV (**seed**).
- Connect the seed to all the clusters in each window to form a graph. Use basic cluster properties to evaluate a TensorFlow model on groups of detector windows: the output is the **probability** of each edge between the seed and the nearby clusters.



ONGOING STUDY

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CMS-DP-22/032
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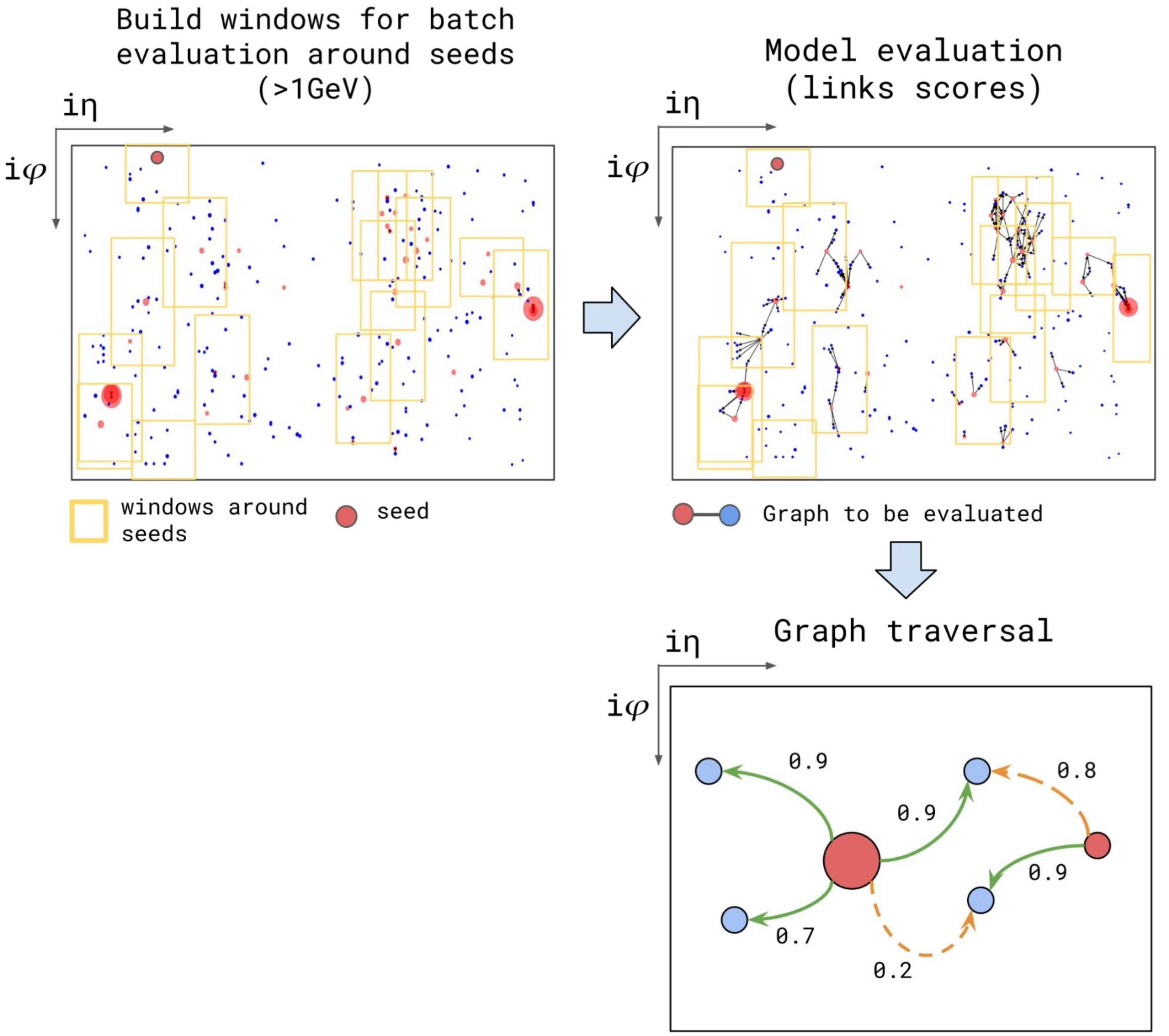
- Traverse the graph starting from the highest energy seed to choose how to **assign clusters** that can potentially belong to several superclusters.



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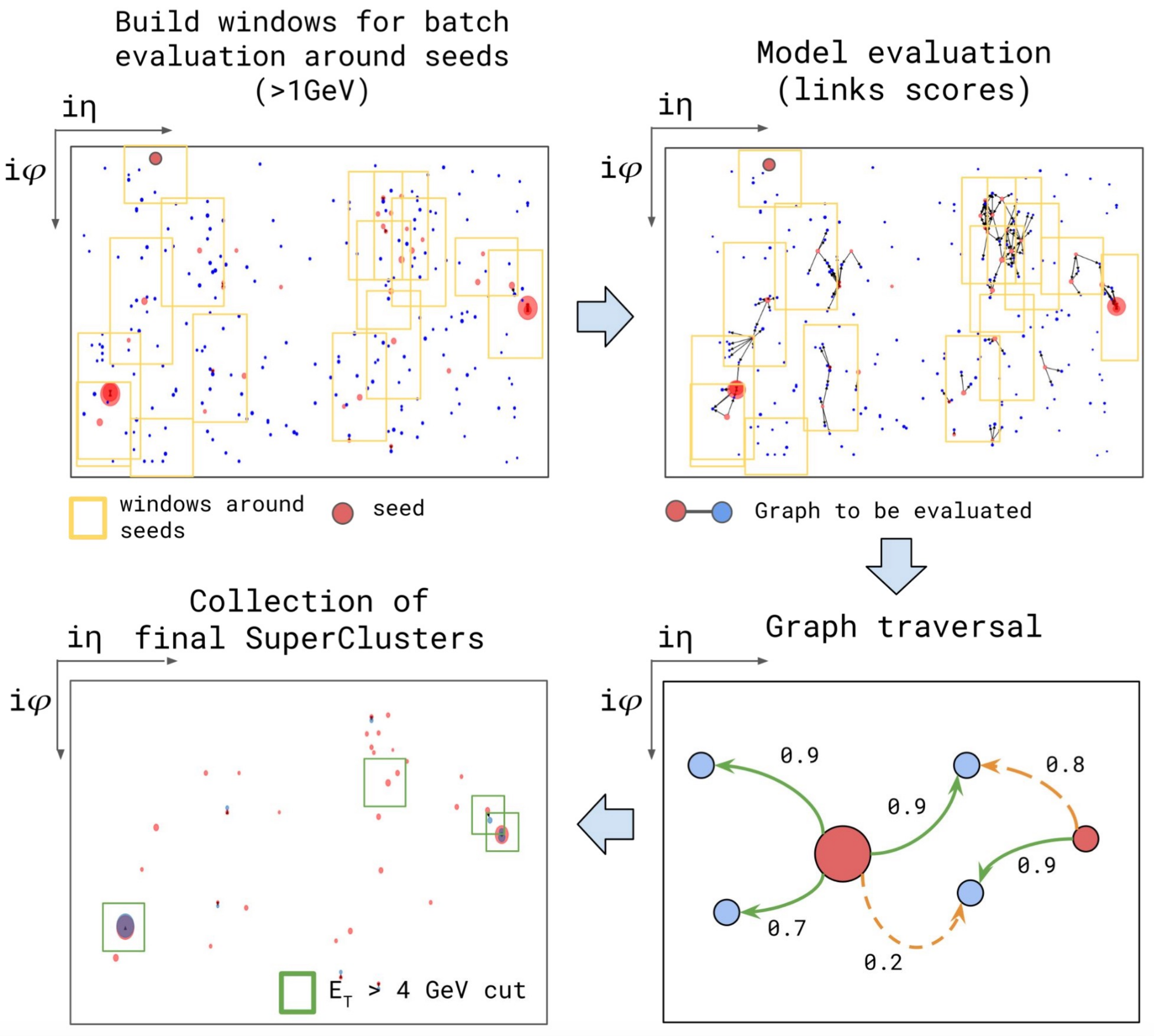
- Traverse the graph starting from the highest energy seed to choose how to **assign clusters** that can potentially belong to several superclusters.
- **Apply a cut** of $p_T > 4$ GeV to remove supercluster formed mainly by detector noise and very low energy pileup.

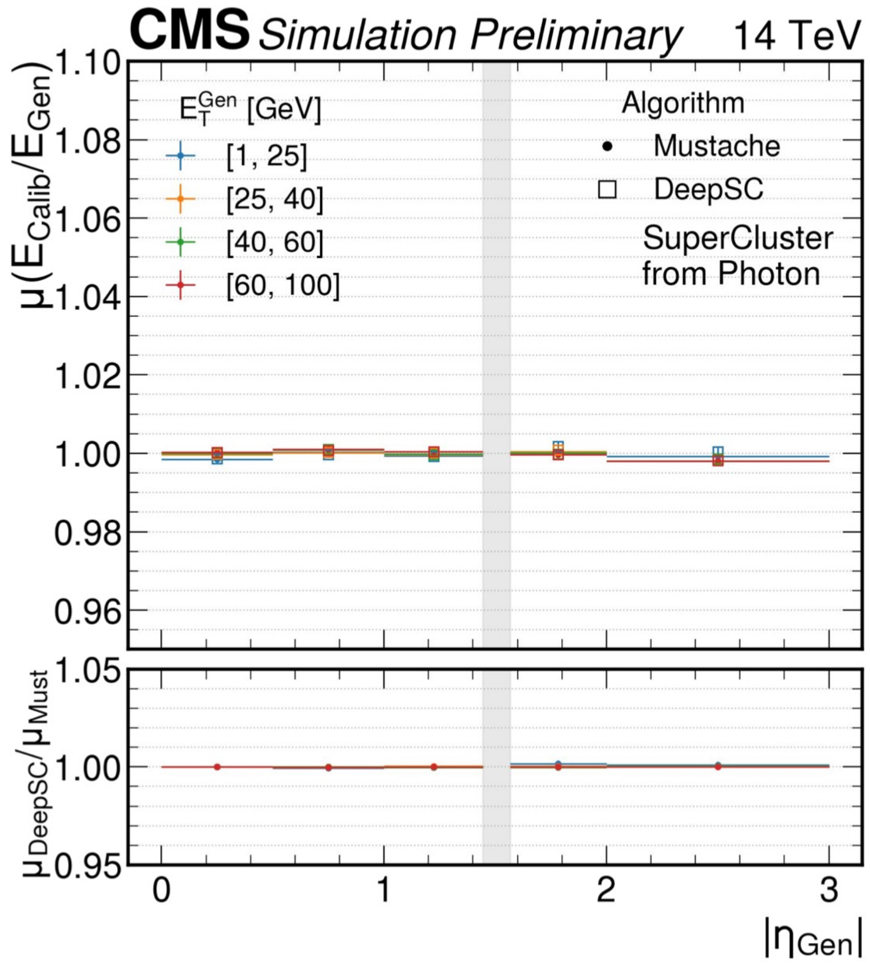


A promising way forward

CMS-DP-22/032
CMS-DP-22/058

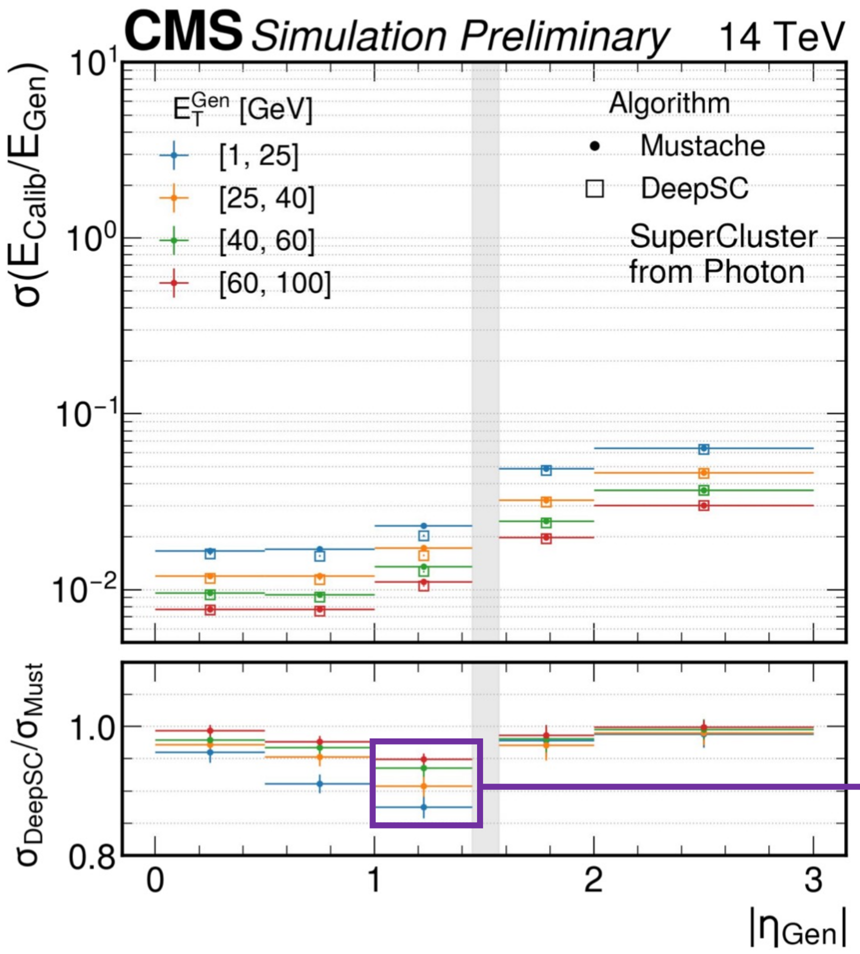
Energy scale

comparable to the moustache



Energy resolution

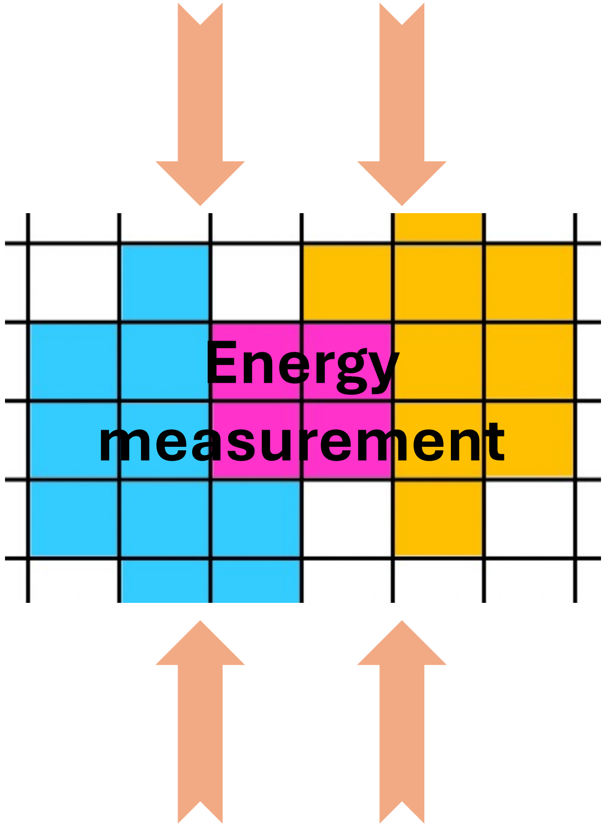
improvements observed across the detector, in particular in the most challenging regions



Region with the largest tracker material budget in front of the ECAL
→ **largest secondary emissions**

Supercluster, electron and photon energy corrections

Energy loss in the tracker
Leakage into the HCAL



Clustering inefficiency
Finite noise thresholds

Supercluster, electron and photon energy corrections

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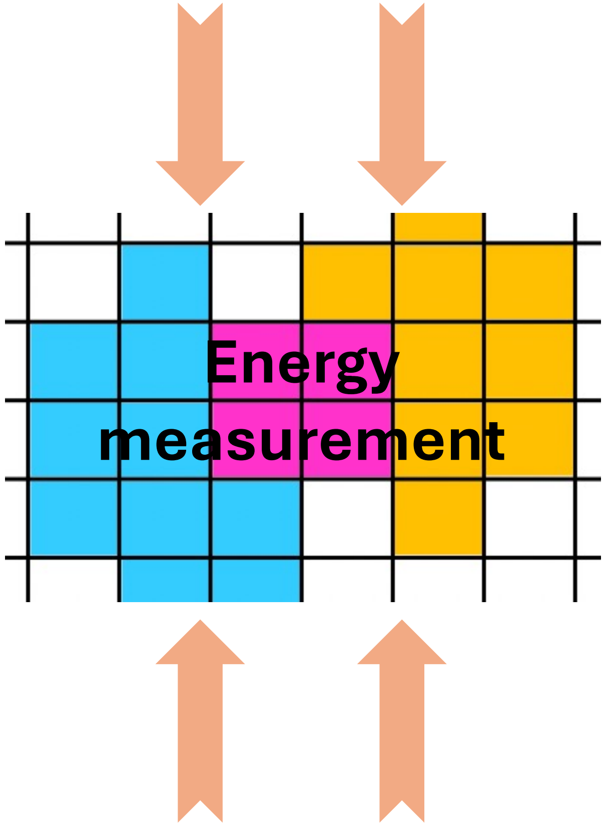
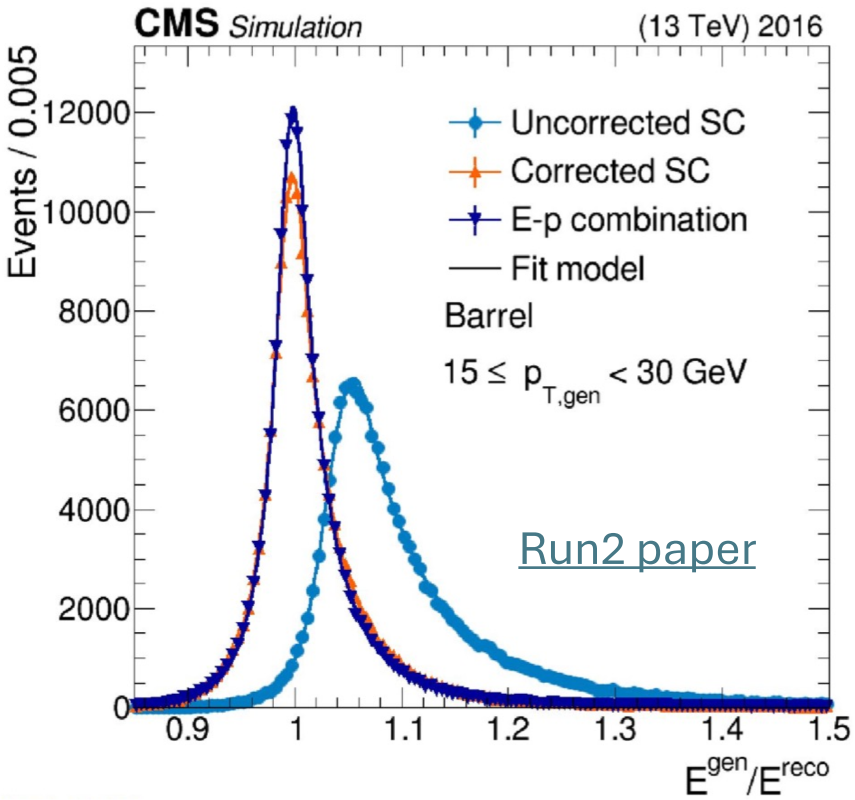


Clustering inefficiency
Finite noise thresholds

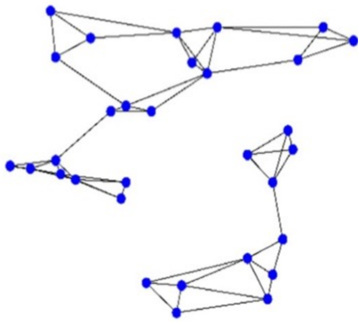
BDT-based **semi-parametric regression** using ~30 high-level input variables

Provide per-object correction (supercluster, electron, photon)



Run2 paper

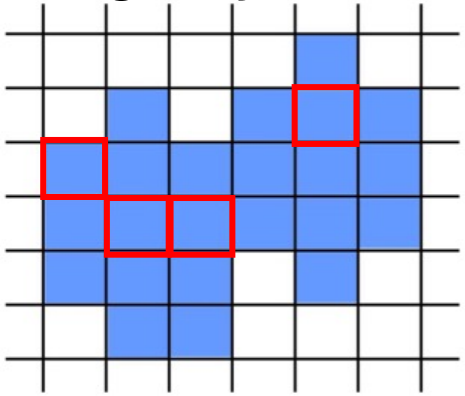
DRN energy regression



Dynamic Reduction Network (GNN)

- Allows for variable size input
- Can deal with unordered inputs
- Can handle complicated geometries
- Can handle representation in 4D (x, y, z, energy)

Single-crystal hits



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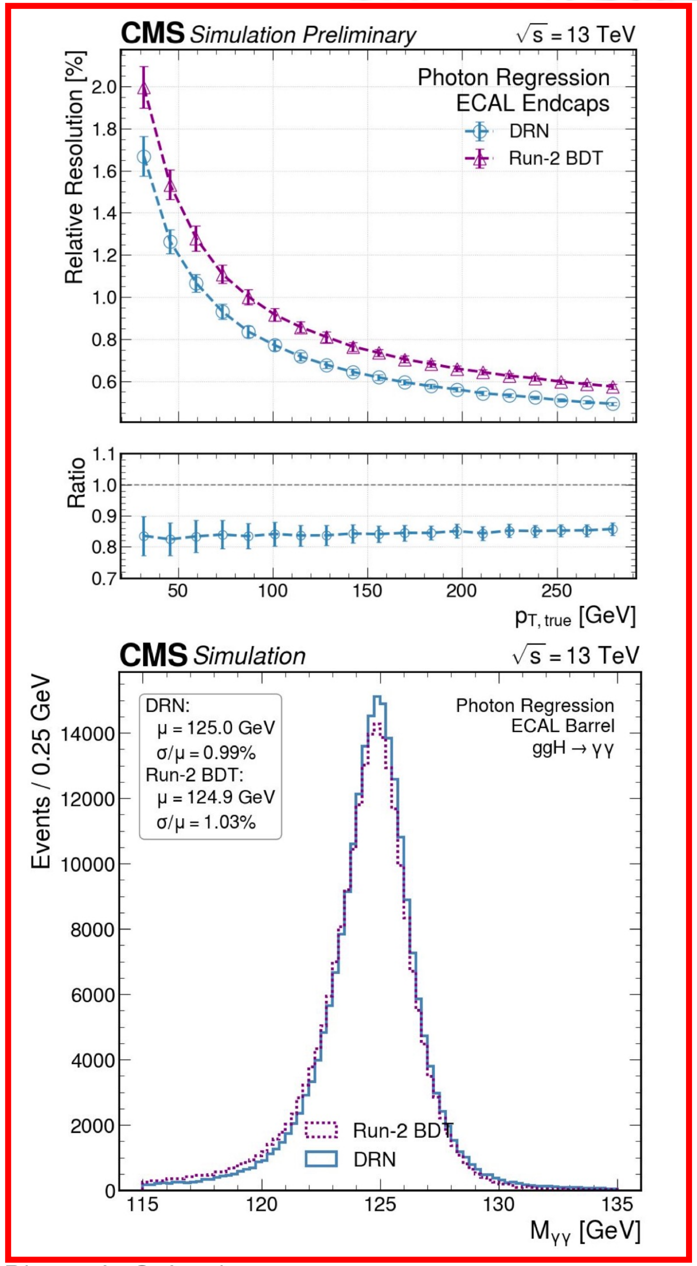
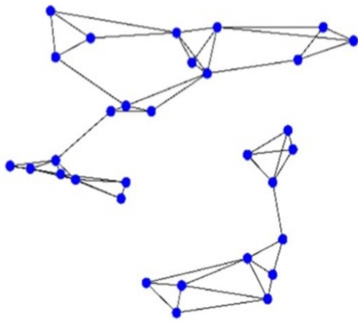
a few higher-level variables (median energy density, H/E)

ONGOING STUDY

DRN energy regression

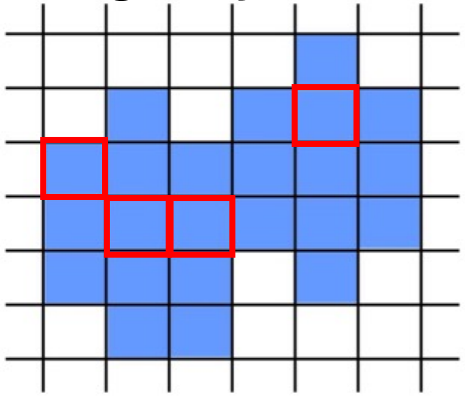
CMS-DP-22/019





1. Hits are mapped to a multidimensional space
2. GNN learns high-level characteristics from the hits by grouping them based on their similarities
3. The new object is passed through a further NN which maps the learned features to the regression target

Single-crystal hits



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a few higher-level variables (median energy density, H/E)

~5% improvement in the $M_{\gamma\gamma}$ resolution in the barrel region!

Summary

- Excellent electron and photon reconstruction performance in Run3 – offline and online
  - ✓ Online, the "scouting" trigger extends the reach to lower momentum phase spaces wrt the standard trigger
    - ✓ Can be an asset for several statistically limited searches
- Electron and photon IDs were tuned or fully retrained in Run3
  - ✓ Comparable or better identification performance than in Run2
- Several types of calibrations and corrections are adopted to ensure the best precision
  - ✓ New methods have been studied that can improve the effectiveness of such corrections, or make the performance measurements more robust or even possible in certain phase spaces (e.g., at low p_{T})
- Several ongoing studies using novel techniques are paving the way to more efficient electron and photon reconstruction and more robust energy measurements

ADDITIONAL MATERIAL

The "scale & smearing" corrections

The goal of the scale and smearing corrections is to reduce the residual differences in the electron and photon energy scale and resolution between collision data and simulation. They are derived using electrons from $\mathrm{Z} \rightarrow \mathrm{e}^{+}\mathrm{e}^{-}$ and they:

- scale the electron energy in data: $M_{\mathrm{ee}}^{\mathrm{scaled}} = M_{\mathrm{ee}}\sqrt{(1+\Delta P_{\mathrm{e1}})(1+\Delta P_{\mathrm{e2}})}$, where ΔP_{ei} is the scale shift with respect to MC for electron "i";
- smear the electron energy in the simulation: $M_{\mathrm{ee}}^{\mathrm{smeared}} = M_{\mathrm{ee}}\sqrt{\mathrm{Gaus}(1,\Delta C_{\mathrm{e1}})\mathrm{Gaus}(1,\Delta C_{\mathrm{e2}})}$, where ΔC_{ei} is the additional smearing for electron "i".

The variables ΔP_{ei} and ΔC_{ei} are determined by minimizing a global binned negative log-likelihood of the invariant mass for each di-electron category. The categories are defined by subdividing events according to the data acquisition run number, the ECAL amplifier gain, and the electron η, p_{T}, and R_9.

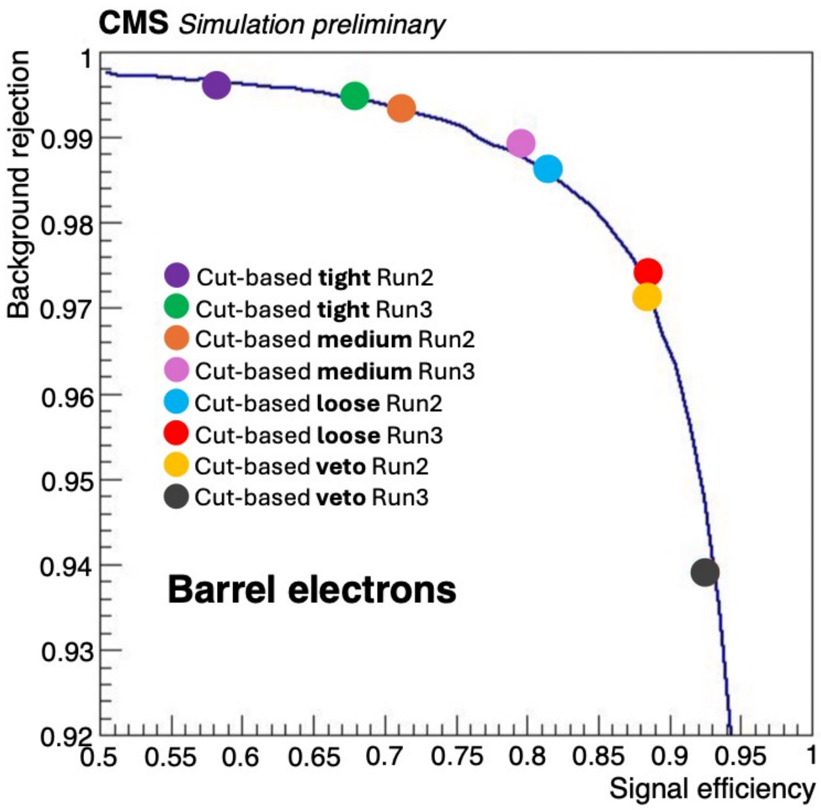
The derivation of scale and smearing corrections for photons uses electrons from Z boson decay reconstructed as photons by the CMS software, and to which the photon energy regression was applied.

Choice of new regression architecture

Can it (easily) handle…	BDT	MLP	CNN	RNN	GNN
Variable-size input	❌	❌	✅	✅	✅
Complicated geometries	✅	✅	❌	✅	✅
4D inputs	✅	✅	❌	✅	✅
Unordered inputs	❌	❌	✅	❌	✅

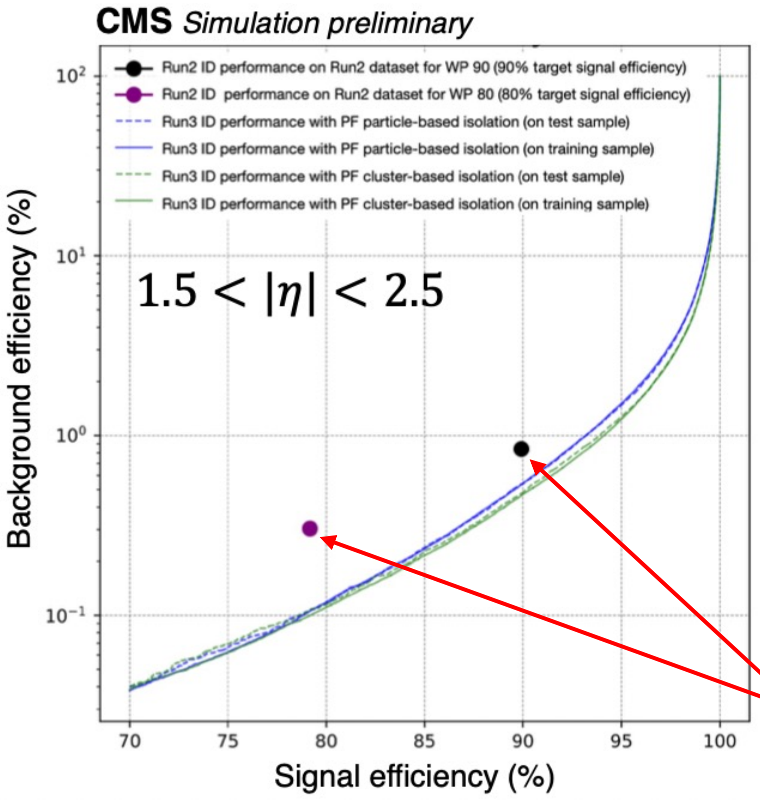
Run3 IDs

In Run3, the cut-based and MVA-based electron and photon IDs were tuned or retrained to ensure a better performance than the Run2 ones within the Run3 data-taking and detector conditions.

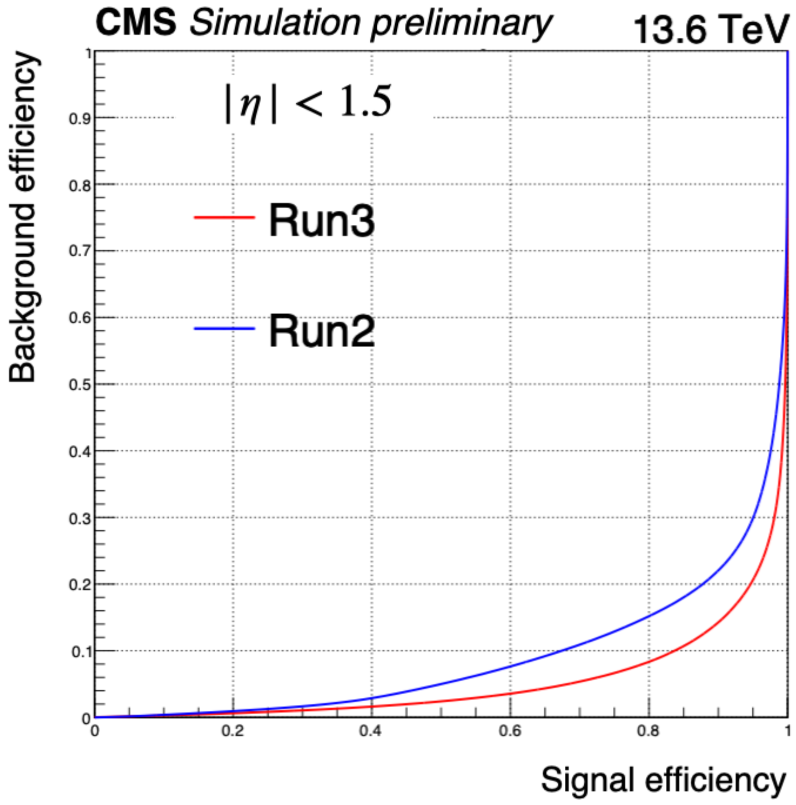


Cut-based electron IDs

MVA-based electron IDs



Run2 ID performance on Run2 data



MVA-based photon IDs

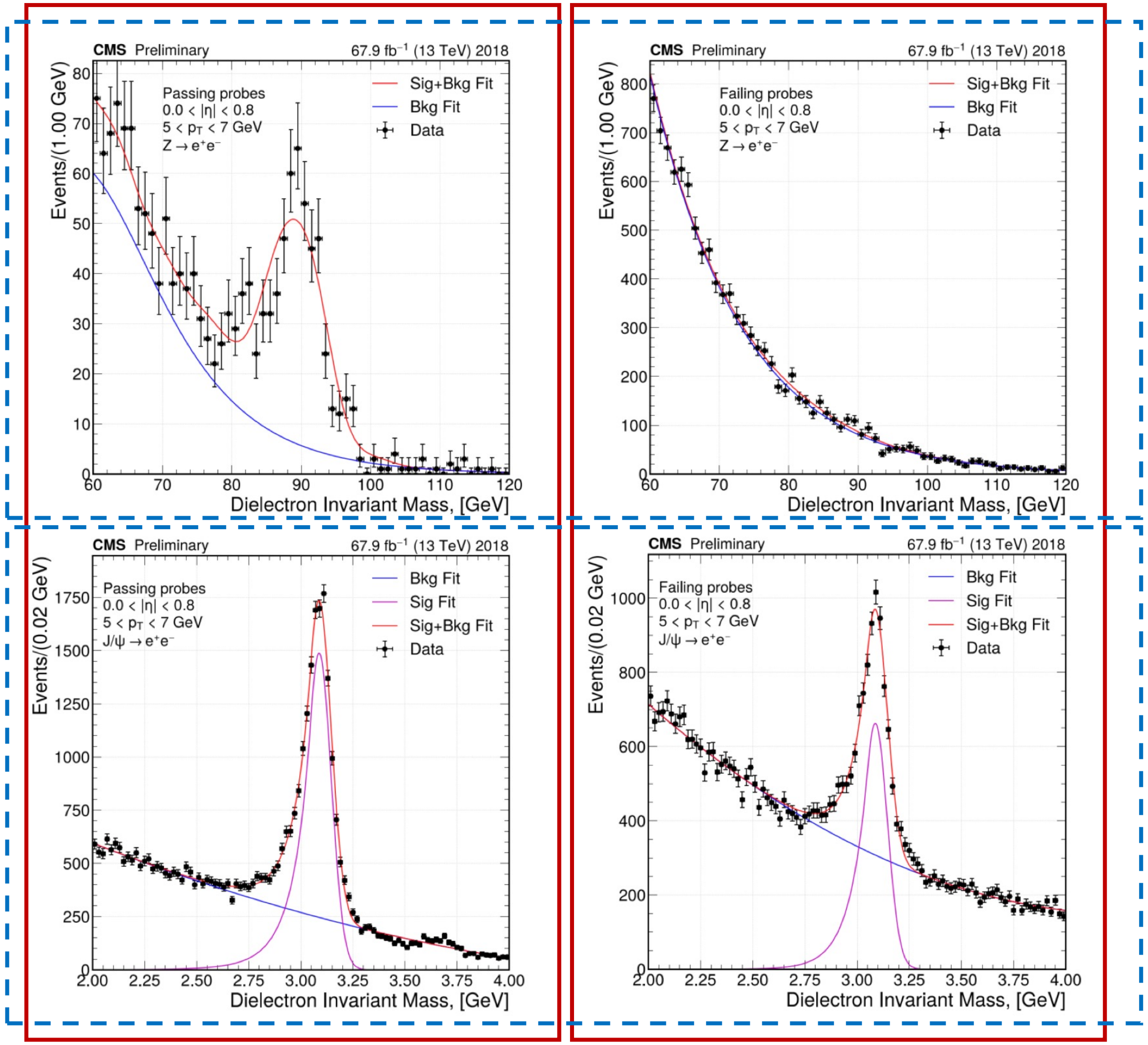
Measuring efficiencies at low pT

CMS DP-2023/081

An accurate efficiency measurement for low p_{T} (< 20 GeV) e/γ requires a standard candle different from the Z resonance

J/ψ **decays** provide significantly higher statistics and make the measurement possible even below 10 GeV

- Tag & Probe: signal peaks clearly visible in both passing and failing probe $m(\mathrm{ee})$ distributions.



Z

J/ψ

Passing probe

Failing probe

Measuring efficiencies at low pT

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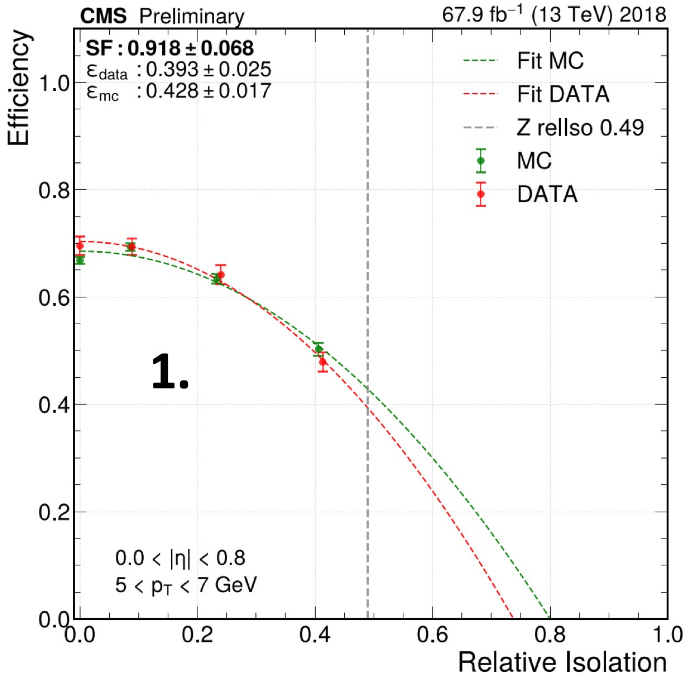
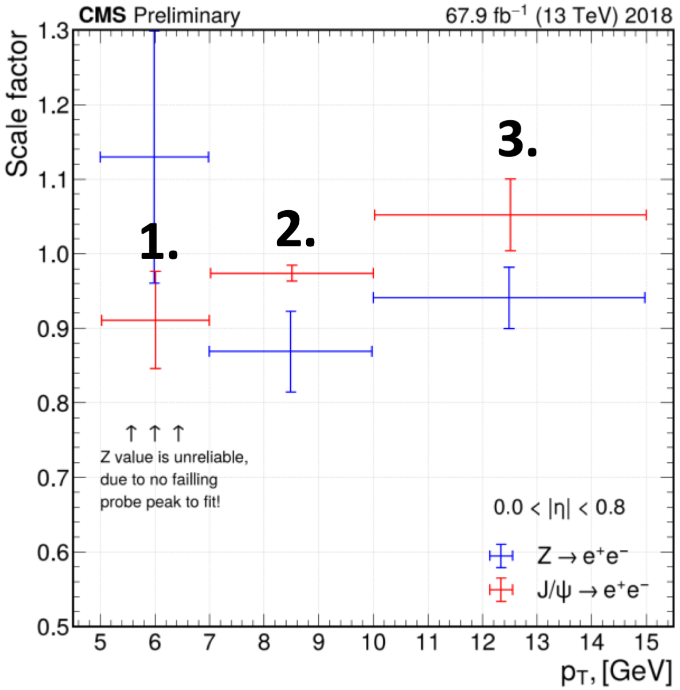
J/ψs electrons tend to be less isolated than Z electrons

- Studied a method to make reliable measurements of ID efficiencies when the IDs contain isolation requirements





I. Measure the electron ID efficiencies from J/ψ events in different (p_T, η, ***relative isolation***) bins.
II. Fit the trend of efficiency measured in step **I.** vs relative isolation for each (p_T, η) bin.
III. Take the efficiency value obtained by interpolating the measurements done in step **I.** with the fit done in step **II.** at the average Z MC relative isolation value in that particular (p_T, η) bin.