ATLAS Electron Performance Results

efficiency measurements in Run2 data at LHC

Lorenzo Varriale (IFIC, CSIC-UV)

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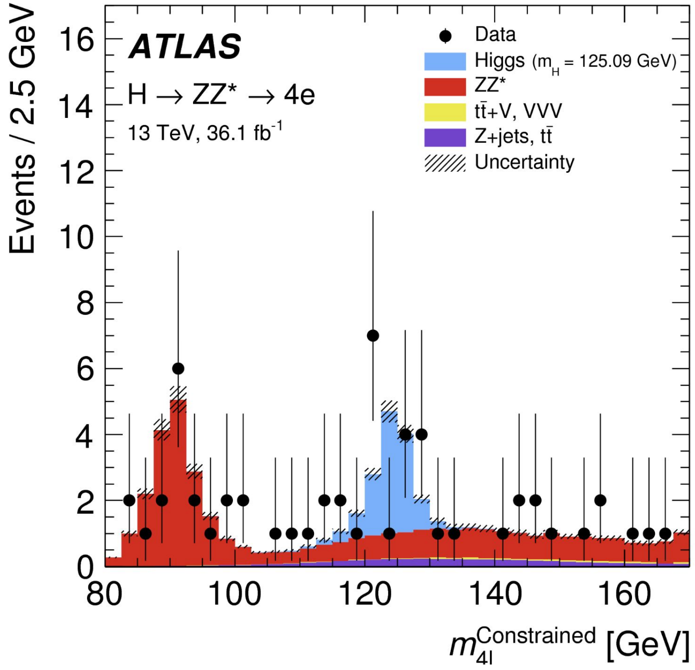
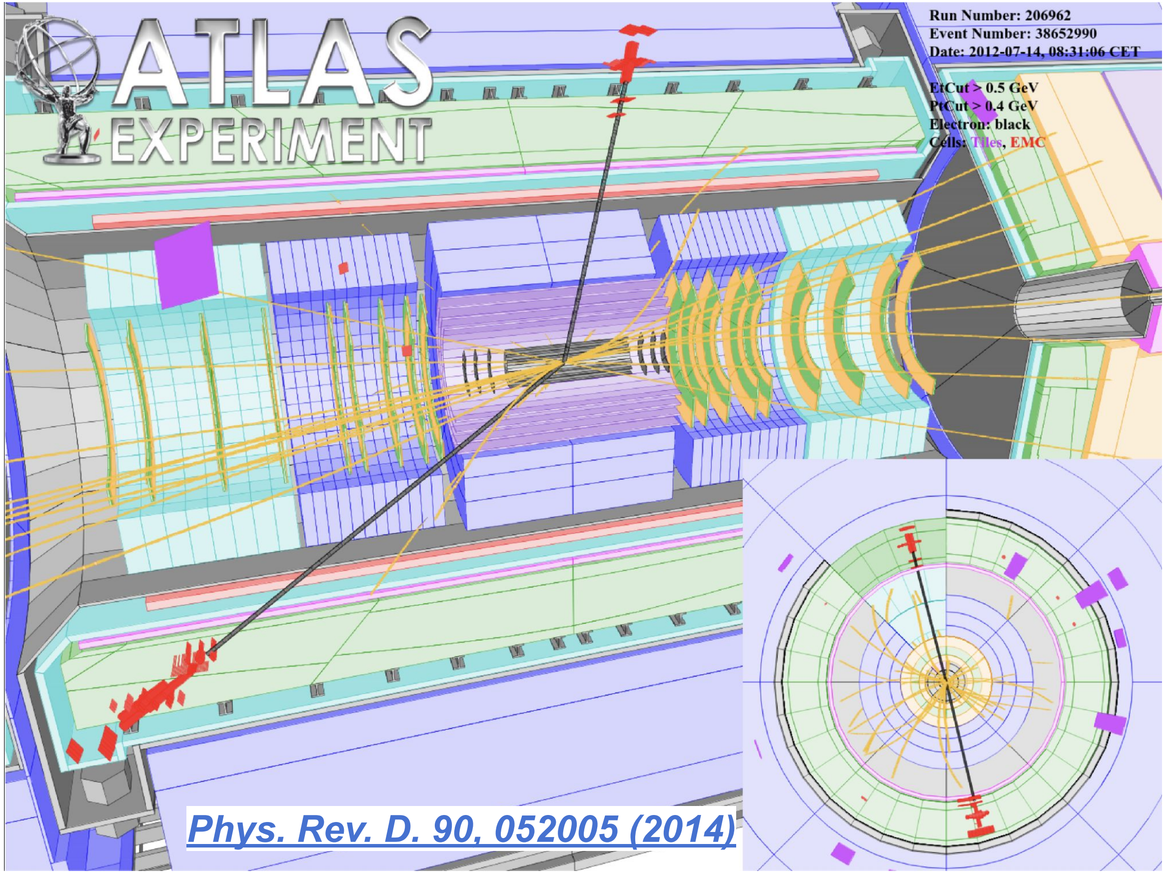
Why is electron performance so important?

- Electrons are excellent probes for studying physics at the LHC
- Signature of weak decays: W and Z bosons
- Discovery of the Higgs boson in the $H \rightarrow WW^*$ and $H \rightarrow ZZ^*$ decay channels
- Indispensable tool for ATLAS precision electroweak measurements
- BSM searches (additional gauge bosons, supersymmetric partners to the Higgs and electroweak bosons, and numerous other BSM particles) have signatures that include electrons
- Analyses (SM, Higgs and even BSM) need to pay great attention to electron performance!



JHEP 03 (2018) 095

Why is electron performance so important?

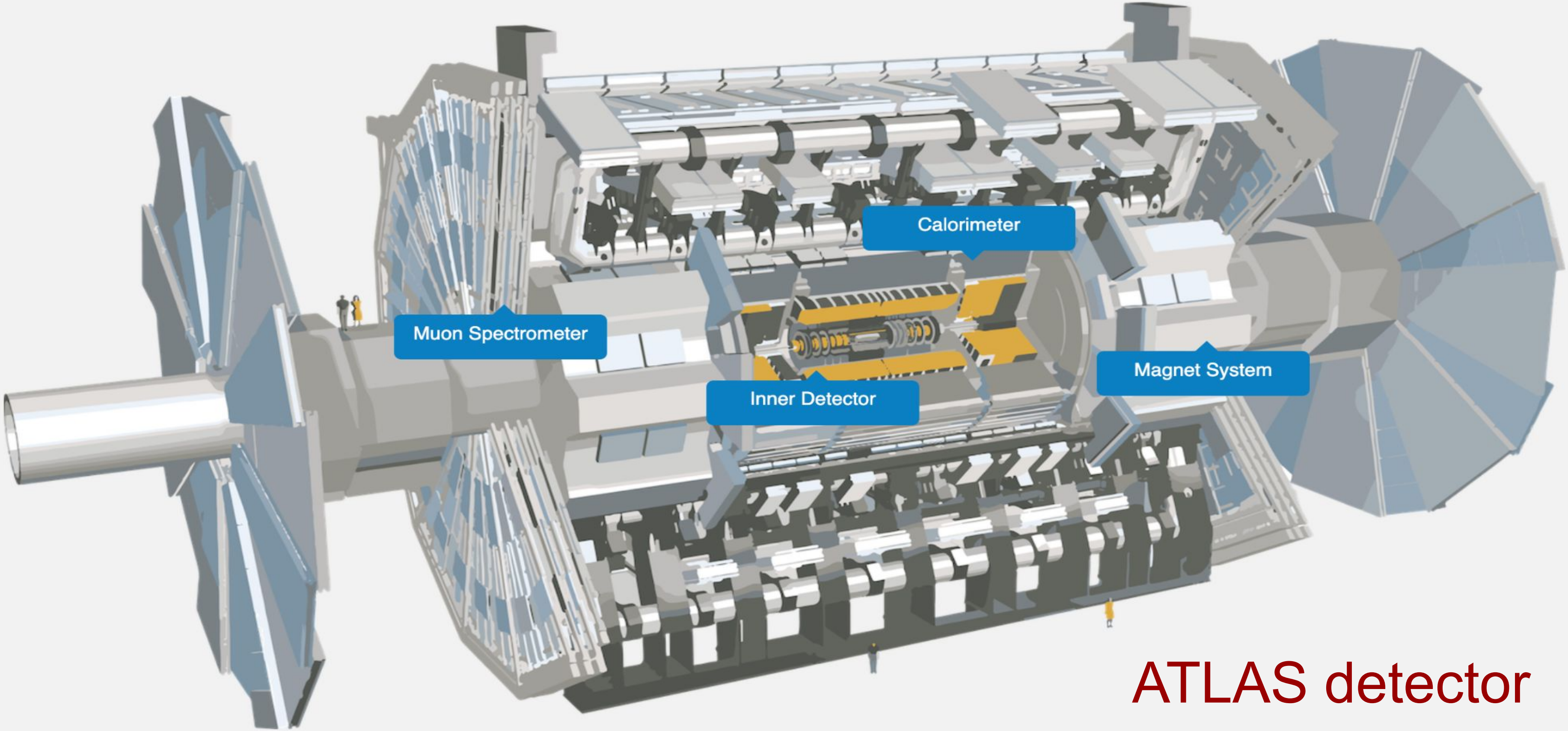


[Phys. Rev. D. 90, 052005 (2014)](https://doi.org/10.1103/PhysRevD.90.052005)

- This talk: summary of the ATLAS Run-2 Legacy electron performance results and efficiency measurements
- Run 2 electron performance paper https://arxiv.org/abs/2308.13362

Display of a very high invariant mass dielectron event

How do we detect electrons?



ATLAS detector

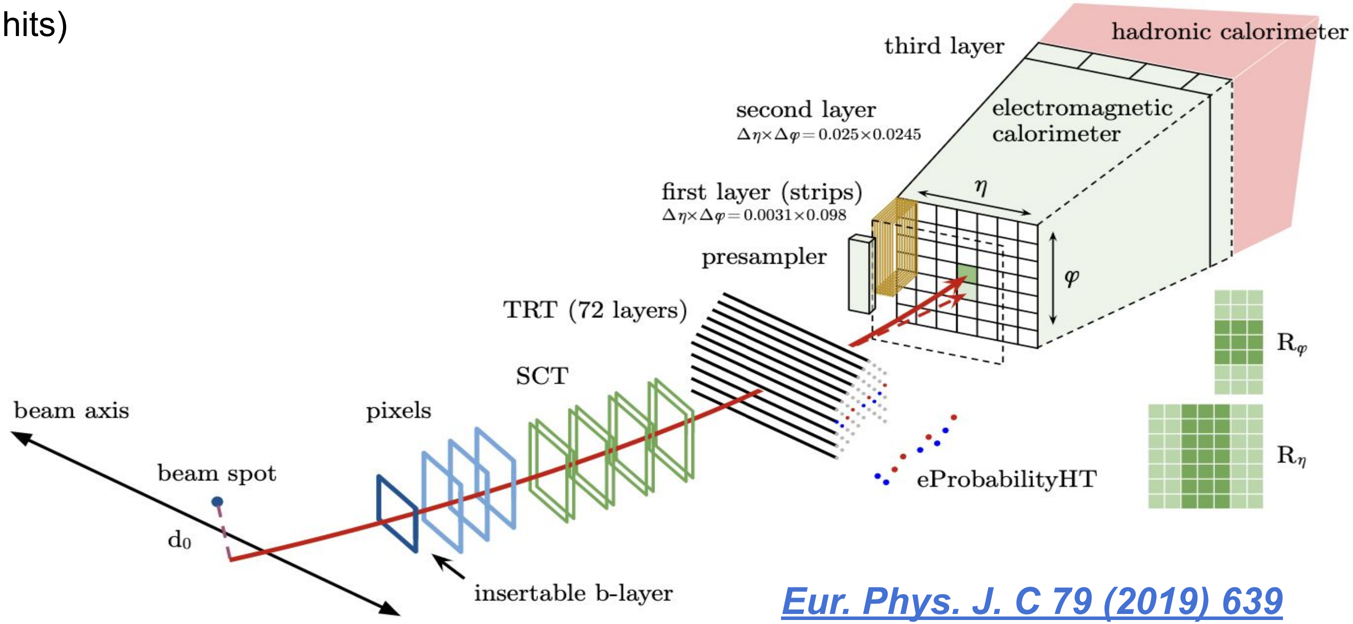
A typical journey of an electron

An electron traveling through the inner detector hits:

- 3 pixel layers (+ insertable b-layer)
- 4 double-sided silicon strips (8 hits)
- ~30 straw hits in the TRT (several high-threshold hits)

Then deposits its energy in four successive EM calorimeter layers:

- presampler (energy loss)
- high-granularity η strips layer
- second layer (collecting most of the energy)
- backplane layer (leakage correction)



Only small amounts of the electron's energy reach the hadronic calorimeter

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How do we reconstruct electron objects?

3 fundamental components for electron signatures:

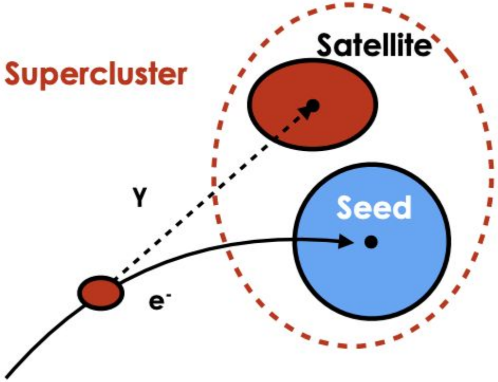
- charged-particle tracks identified in the inner detector
- localised clusters of energy deposits → search for small-radius energy deposits
- close matching in ηxϕ space of the tracks to the clusters → initial electron candidate

Final EM clusters:

- starting from the highest-energy electromagnetic (EM) cluster, nearby clusters within a $\Delta\eta \times \Delta\phi = 0.075 \times 0.0125$ of their respective barycentres are merged with the initial cluster to form the **superclusters**

Superclusters:

- Energy loss due to bremsstrahlung
- Dynamic, variable-sized topological clusters → recover low energy photons and connect them to their associated electron



How do we identify electron candidates?

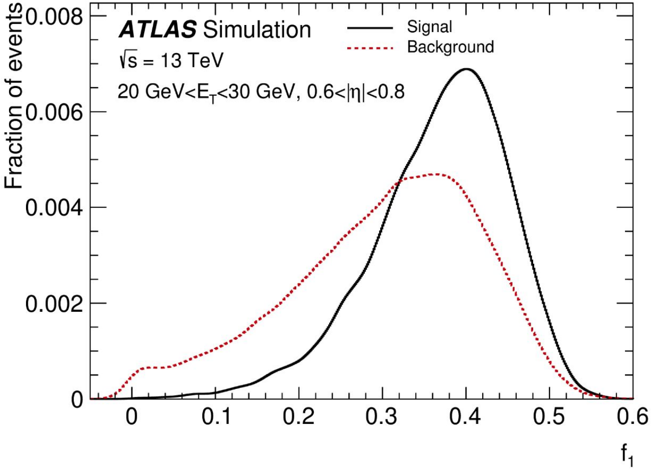
- Likelihood (LH) discriminant to separate prompt electrons from background objects
- LH built using variables (PDFs) related to:
    - properties of the track
    - shower development
    - track-cluster matching

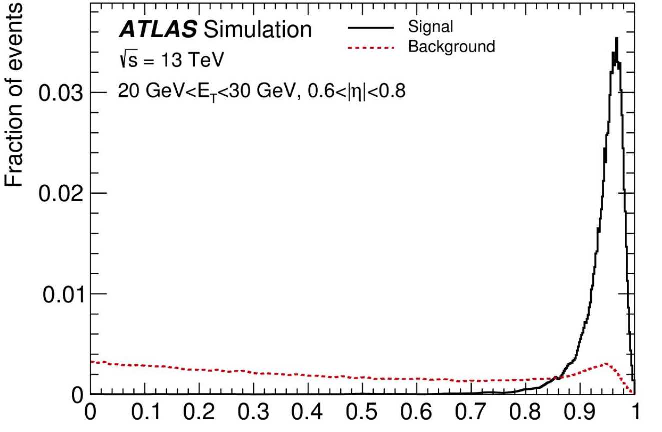
$$L_{\mathrm{S(B)}}(\mathbf{x}) = \prod_i P_{\mathrm{S(B)},i}(x_i)$$

$$d_{\mathrm{L}} = \frac{L_{\mathrm{S}}}{L_{\mathrm{S}} + L_{\mathrm{B}}}$$

- Better background rejection than a cut based algorithm (criteria on each variable)
- Identification selection requirements are applied as a function of $|\eta|$ and E_{T}

Calorimeter (ratio)	f_1, f_3, E_{ratio}, R_{had}, R_{had1}
Calorimeter (energy width)	w_{stot}, $w_{\eta 2}$, R_η, R_ϕ
Tracking	$n_{\text{B-layer}}$, n_{Pixel}, n_{Si}, d_0, $\lvert d_0/\sigma(d_0)\rvert$, $\Delta p/p$, eProbabilityHT
Track-cluster matching	$\Delta\eta_1$, $\Delta\phi_{\mathrm{res}}$, E/p





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Efficiency measurements

probability to reconstruct an EM-cluster given a true electron

number of (reconstructed, identified, and isolated) electron candidates passing the trigger requirements divided by N_{iso}

$$\varepsilon_{\text{total}} = \boxed{\varepsilon_{\text{EMclus}}} \times \boxed{\varepsilon_{\text{reco}} \times \varepsilon_{\text{id}} \times \varepsilon_{\text{iso}}} \times \boxed{\varepsilon_{\text{trigger}}}$$

reconstruction, identification and isolation efficiencies

Efficiencies estimated directly from data using tag-and-probe methods:

- select unbiased samples of prompt electrons from well known decays ($Z \to e^+e^-$ or $J/\psi \to e^+e^-$)
- one of the electrons must satisfy strict selection requirements (**tag**), the other very loose ones (**probe**)
- efficiency computed by applying selections on the probe sample in data (after subtracting any remaining background)

Followed by **Scale Factors** (SFs) measurements:

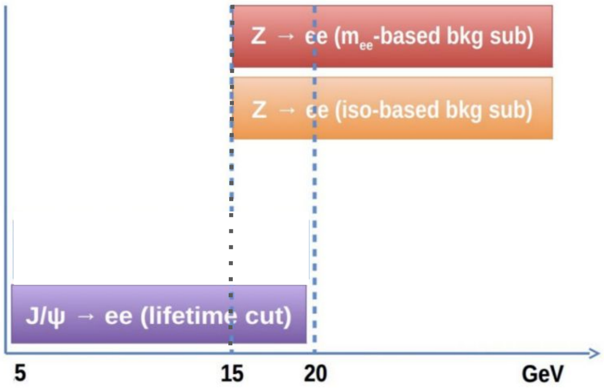
- MC simulation is corrected to reproduce the efficiencies measured in data
- it is defined as the ratio of the efficiency measured in data to the one determined in MC events
- universally applicable for any physics process
- generally close to unity

Identification efficiency measurements

$$\varepsilon_{\mathrm{ID}} = \frac{N_{\text{probes pass ID}} - N_{\text{bkg}}}{N_{\text{all probes}} - N_{\text{bkg}}}$$

- Development of electron identification (ID) algorithms: several sets of electron ID criteria called “menus”
  - Tight, Medium and Loose menus, also called Working Points (WPs)
- Efficiency of any of the several identification menus

- For electrons with E_T between 4.5 and 20 GeV it is measured using $J/\psi \rightarrow e^+e^-$ events
- For E_T > 15 GeV $Z \rightarrow e^+e^-$ events are used
  - single-electron triggers, tight identification for the tag, track isolation requirements
- Biggest challenge is the estimation of probes coming from background rather than signal processes
  - various data-based background estimation/subtraction methods
  - for $Z \rightarrow e^+e^-$: Z-mass and Z-iso method



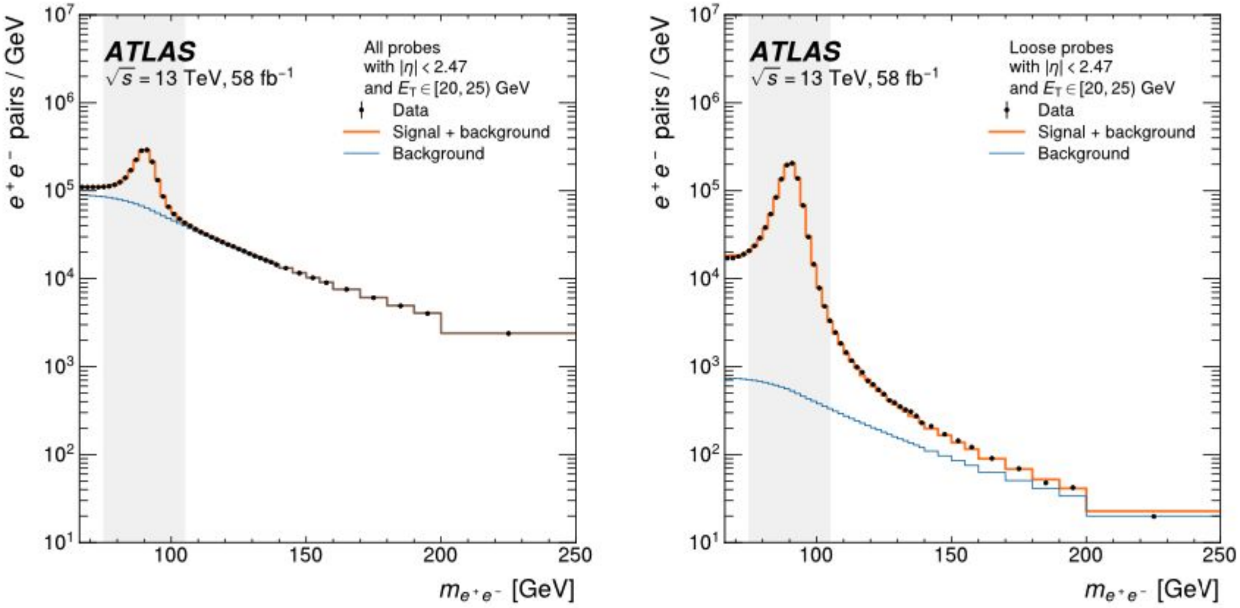
Identification efficiency measurements: Z-mass method

Z-mass method:

- uses reference invariant mass distributions of the opposite sign electron pair for signal and background (templates)
- estimation of background under the Z boson peak

New background subtraction procedure:

- template definition: background control region where probe electron has to fail a relaxed Loose LH ID
- template cleaning: subtract a $Z \to e^+e^-$ template obtained from MC
- extract background normalisation from pure background and MC signal template fit to data in the signal region
- scaled background template is then subtracted from the data

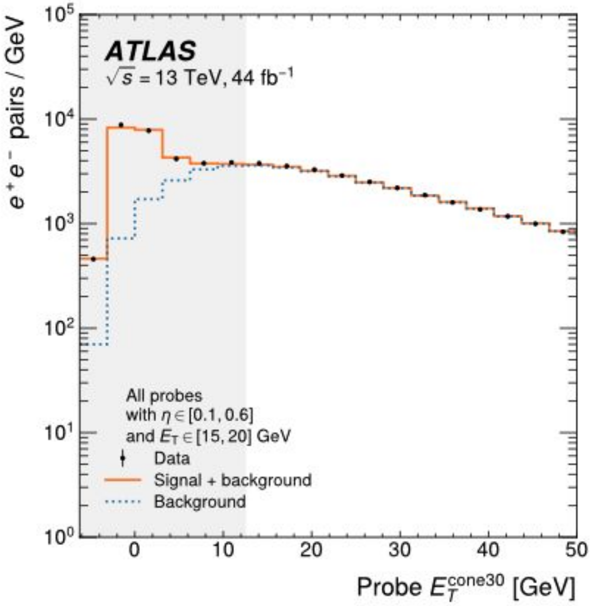


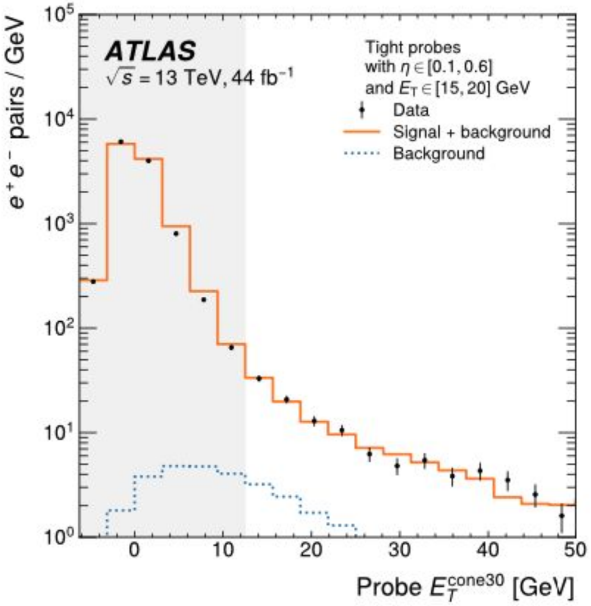
arXiv:2308.13362

Identification efficiency measurements: Z-iso method

Z-iso method:

- amount of transverse energy in a cone of radius ΔR (= 0.3) around the probe electron
- background templates are defined in data in a bkg-enriched region where the charges of the tag and probe are required to be same-sign and the probes must fail cuts on various ID variables
- signal contamination is subtracted from the background templates using MC simulation





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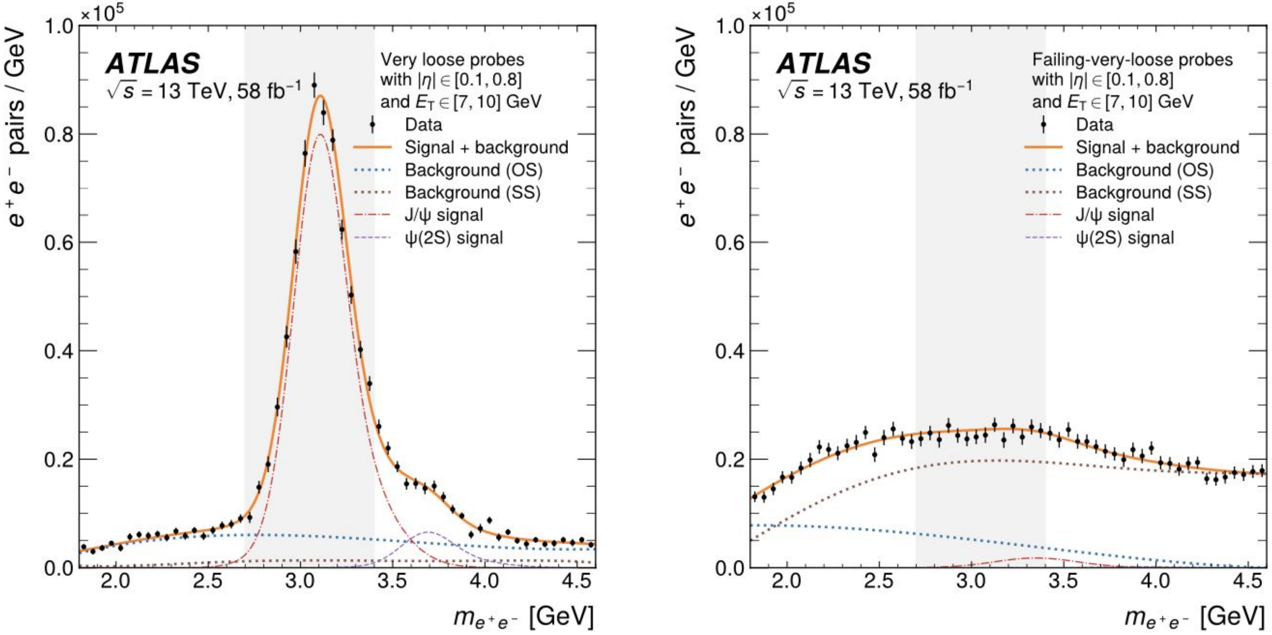
Identification efficiency measurements: $J/\psi \rightarrow e+e-$

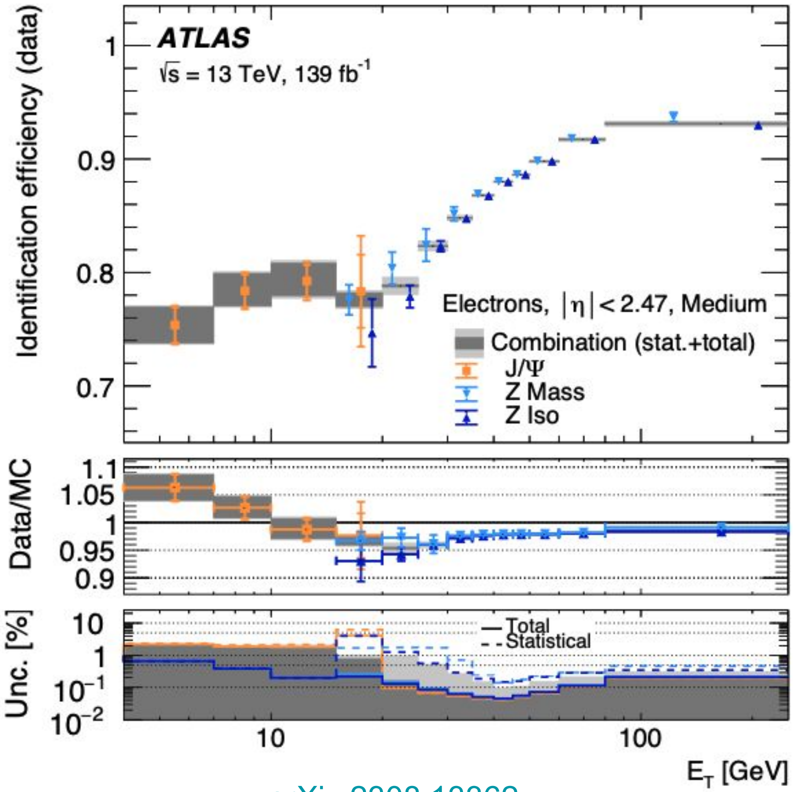
- Fitting invariant mass distributions of the two elecrons with functions to extract 3 contributions:
  - J/ψ, ψ(2S) and background events from hadronic jets, heavy flavour decays and electron from conversions
- $J/\psi \rightarrow e+e-$ events mixture of prompt and non-prompt J/ψ production (via b-meson decays)
  - requirements on pseudo-proper lifetime t_0 to suppress background

arXiv:2308.13362

- Signal (left) and bkg (right) fits to m_{e+e-} distributions to determine denominator efficiency (2018 data)
  - shaded bands: mass range used for efficiency extraction
- Clear J/ψ peak around 3.1 GeV in signal
- Very small signal contamination in background



Identification efficiency measurements: combination



arXiv:2308.13362

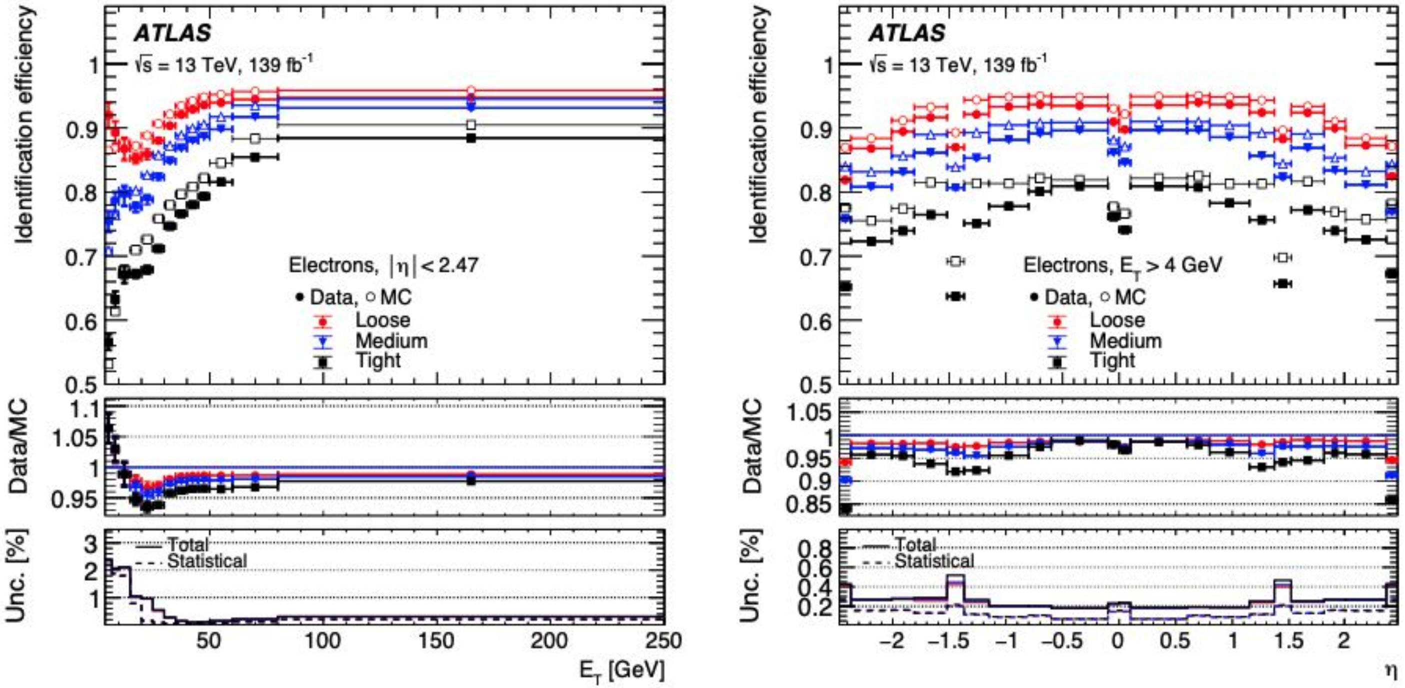
- Data efficiencies for medium ID WP for the individual methods and their combination

- Zmass+Ziso:
    - correction factors are combined by averaging them weighted by their uncertainties in each E_T - η bin
    - uncertainties coming from the modelling of the backgrounds are treated as uncorrelated
    - statistical uncertainties are treated as fully correlated

- Z correction factors combined with J/ψ in the overlapping E_T range

- Significant improvements in Run 2 in terms of systematic uncertainties and better agreement between Zmass and Ziso

Identification efficiency measurements: results



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- Measured ID efficiencies in data and MC (top panel) in function of E_T (left) and pseudorapidity η (right) for all ID WPs
- Efficiency way below the % level
- Measured electron ID SFs (middle panel) are close to unity (~5%)
- Statistical and total uncertainties in the data/MC ratio (bottom panel)

Isolation efficiency measurements

- A characteristic signature is little activity in an area of $\Delta\eta \times \Delta\phi$ around the object
- 2 different types of variables are constructed to quantify this activity: calorimeter-based and track-based isolation
  - usually performed by summing the transverse energies of clusters in the calorimeter or the transverse momenta of tracks in a cone around the direction of the electron candidate

- Calculated from **energy deposits in the calorimeter clusters** and corrected by removing the energy of the electron candidate, pile-up and underlying event contributions

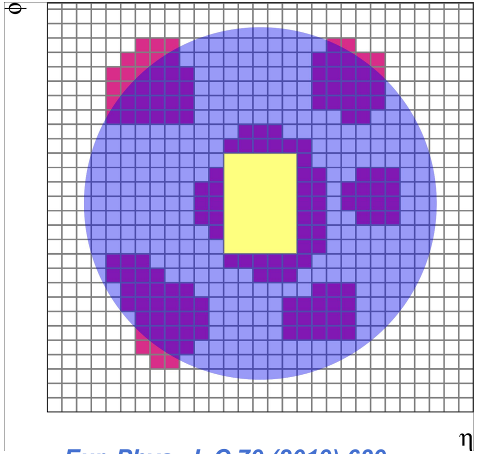
$$E_{\mathrm{T}}^{\mathrm{coneXX}} = \boxed{E_{\mathrm{T,raw}}^{\mathrm{isolXX}}} - \boxed{E_{\mathrm{T,core}}} - \boxed{E_{\mathrm{T,leakage}}(E_{\mathrm{T}}, \eta, XX)} - E_{\mathrm{T,pile\text{-}up}}(\eta, XX).$$

(XX is the size of the isolation cone)

energy of the EM calorimeter cells contained in a cluster $\Delta\eta \times \Delta\varphi$ = 5 × 7 cells; it's a measure of the electron candidate transverse energy

it doesn't subtract all the electron energy, so a leakage correction is needed; parametrised as a function of E_T and |η| of the electron using MC samples of single electrons without pile-up

pile-up and underlying event contributions to the isolation cone, estimated event per event and optimised using a $Z \to e^+e^-$ data sample



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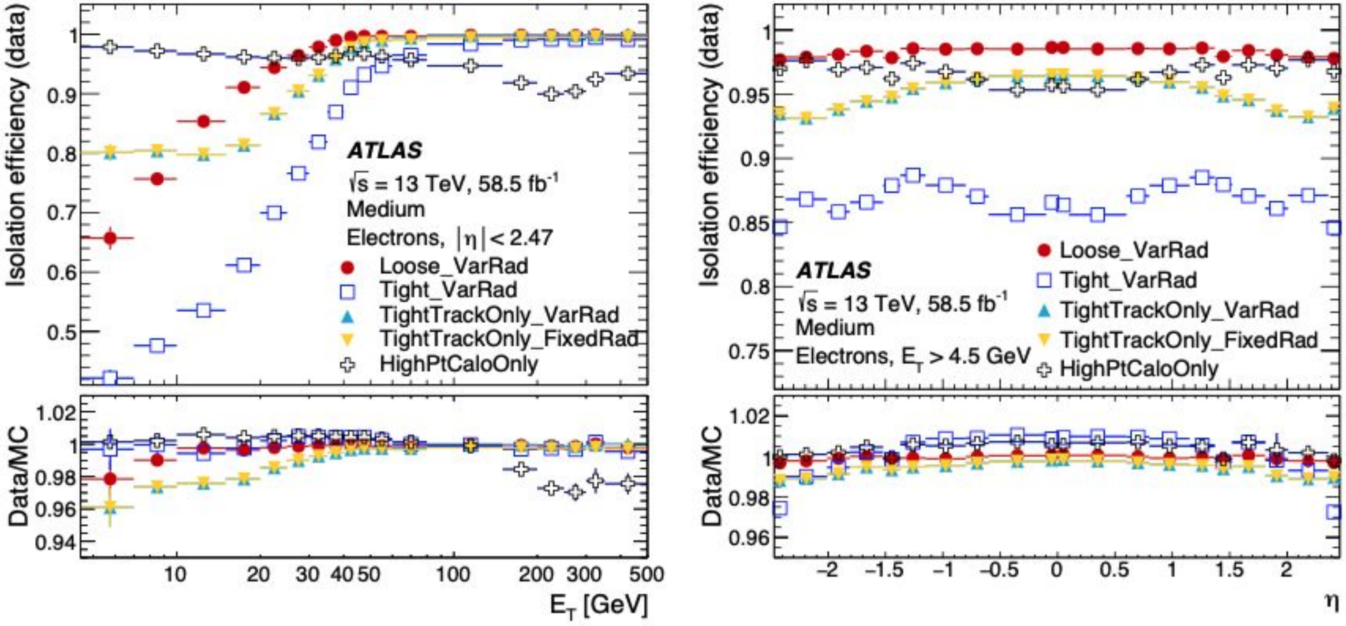
Isolation efficiency measurements: results

- Measured electron isolation efficiency for all isolation WPs from inclusive 2018 data $Z \rightarrow e^+e^-$ events (top panel) as a function of E_T (left) and pseudorapidity η (right)
- The denominator probe electrons are required to pass a Medium ID selection



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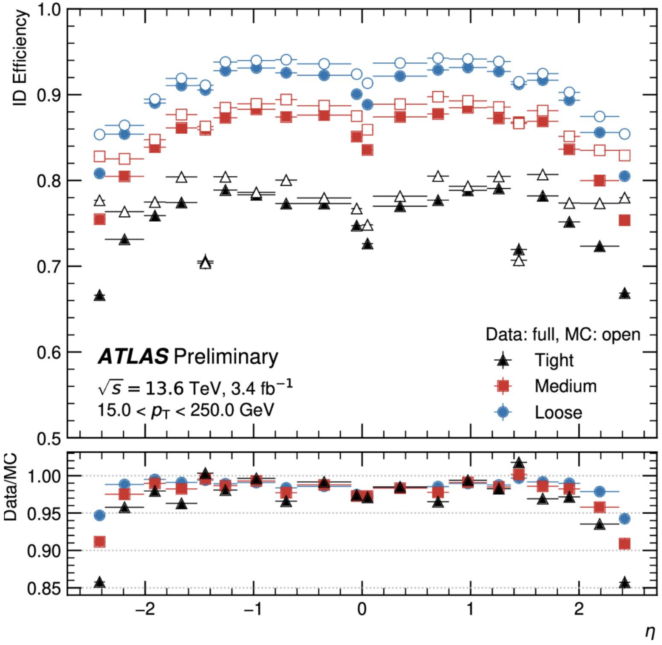
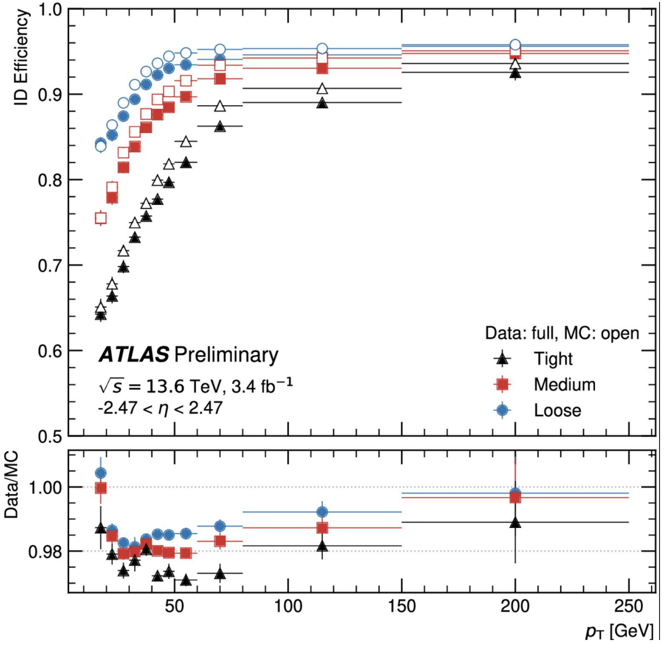
Early Run 3 results: identification efficiencies





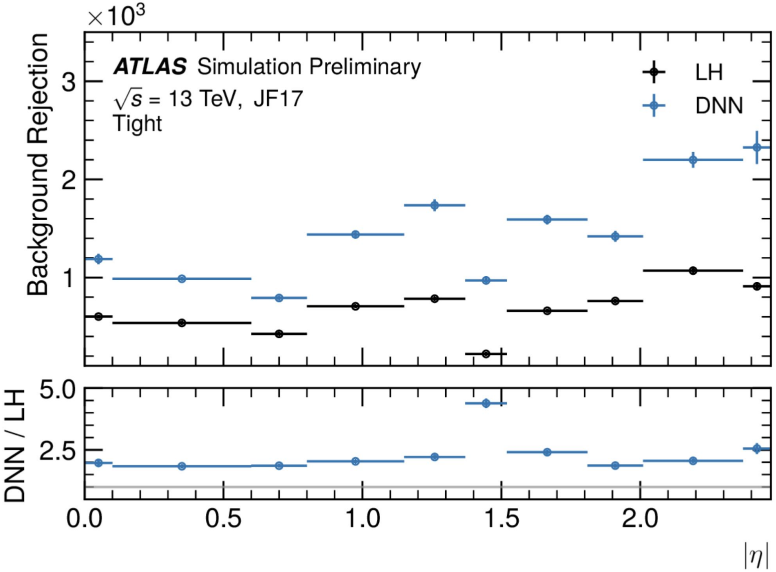
- Data recorded in 2022 at a $\sqrt{S}$ = 13.6 TeV and corresponding to an integrated luminosity of 3.4 fb^{-1}
- Efficiencies in data are obtained using the Z-mass method
- Same methods as in Run 2

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/EGAM-2022-04/

Machine learning techniques for electron ID

- LH: has been the default ID method for Run 2
- **DNN**: uses same input variables as the LH, exploit their correlations, recently introduced in Run 3
- **CNN**: high-level variables, additional track variables, and calorimeter images

ATL-PHYS-PUB-2022-022



DNN:

- Background rejection improved with respect to LH by factors of 1.7 to 5.5
- Multinominal classification: flexibility to define final discriminants that target specific background rejection

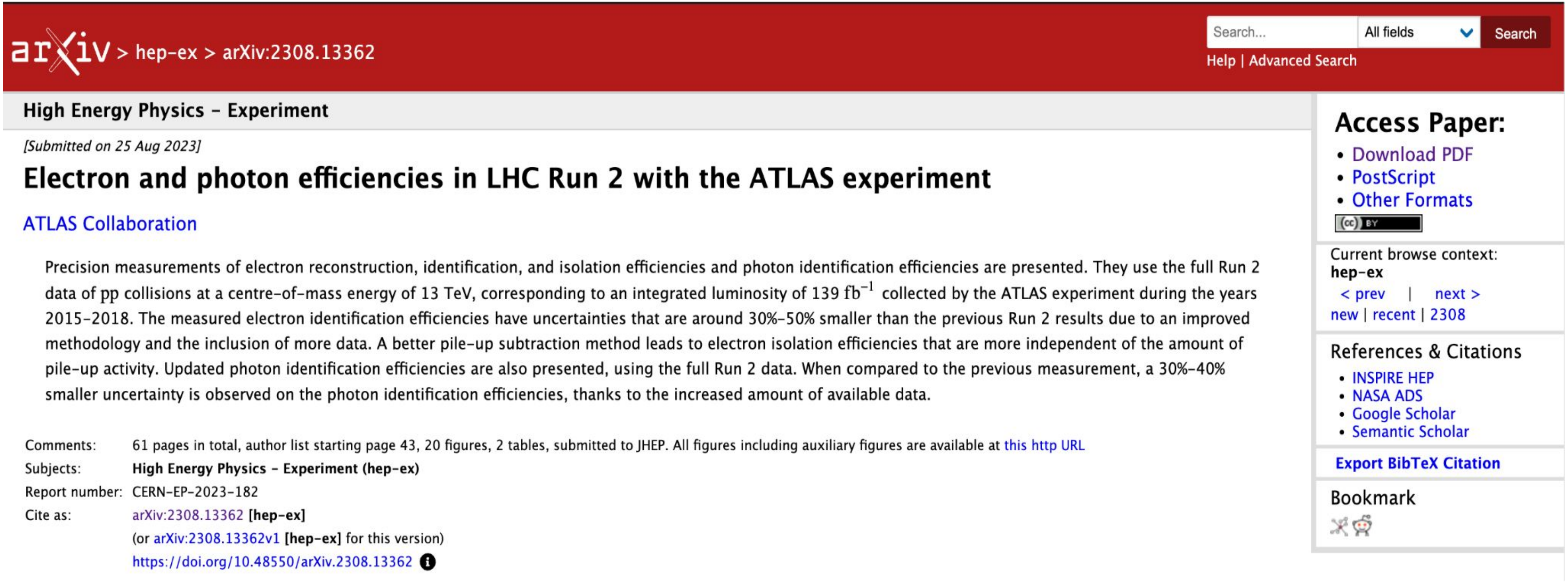
CNN:

- Large improvement achieved by factors of ~2 to 10 with respect to LH depending on regions and signal efficiency

Summary and Conclusions

- Importance of electron performance studies
- How to detect, reconstruct and identify electrons
- Efficiency measurements and tag-probe methods:
    - Z-mass and Z-iso methods
    - J/ψ
    - combination
- Efficiency precision measurements with full Run 2 data (139 fb^{-1}): identification
    - from “Electron and photon efficiencies in LHC Run 2 with the ATLAS experiment” paper (https://arxiv.org/abs/2308.13362)
    - 70% more data wrt previous results (81 fb^{-1})
    - electron identification uncertainties around 30%-50% smaller than the previous results
- Efficiency precision measurements with full Run 2 data (139 fb^{-1}): isolation
- Early Run3 results: a look at the first electron identification efficencies
- Developing new menus for identification based on machine learning techniques: DNN and CNN

BACKUP



High Energy Physics – Experiment

[Submitted on 25 Aug 2023]

Electron and photon efficiencies in LHC Run 2 with the ATLAS experiment

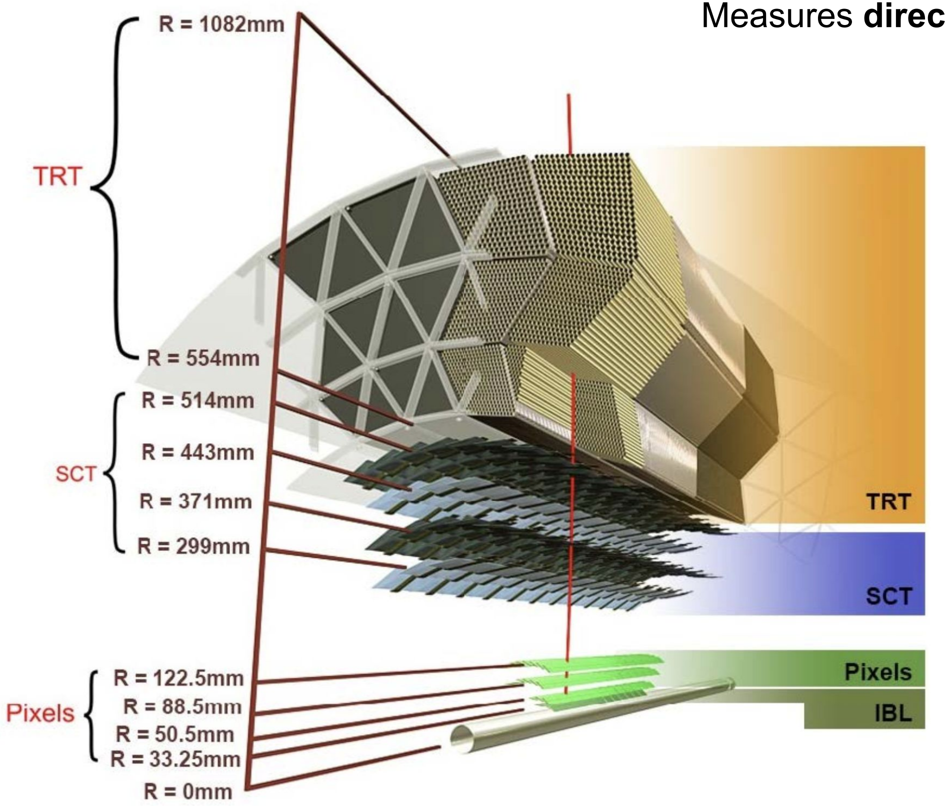
ATLAS Collaboration

Precision measurements of electron reconstruction, identification, and isolation efficiencies and photon identification efficiencies are presented. They use the full Run 2 data of pp collisions at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 139 fb^{-1} collected by the ATLAS experiment during the years 2015–2018. The measured electron identification efficiencies have uncertainties that are around 30%–50% smaller than the previous Run 2 results due to an improved methodology and the inclusion of more data. A better pile-up subtraction method leads to electron isolation efficiencies that are more independent of the amount of pile-up activity. Updated photon identification efficiencies are also presented, using the full Run 2 data. When compared to the previous measurement, a 30%–40% smaller uncertainty is observed on the photon identification efficiencies, thanks to the increased amount of available data.

Comments:	61 pages in total, author list starting page 43, 20 figures, 2 tables, submitted to JHEP. All figures including auxiliary figures are available at this http URL
Subjects:	**High Energy Physics – Experiment (hep-ex)**
Report number:	CERN-EP-2023-182
Cite as:	arXiv:2308.13362 **[hep-ex]** (or arXiv:2308.13362v1 **[hep-ex]** for this version) https://doi.org/10.48550/arXiv.2308.13362

https://arxiv.org/abs/2308.13362

The Inner Detector



Measures **direction, momentum** and **charge** of charged particles

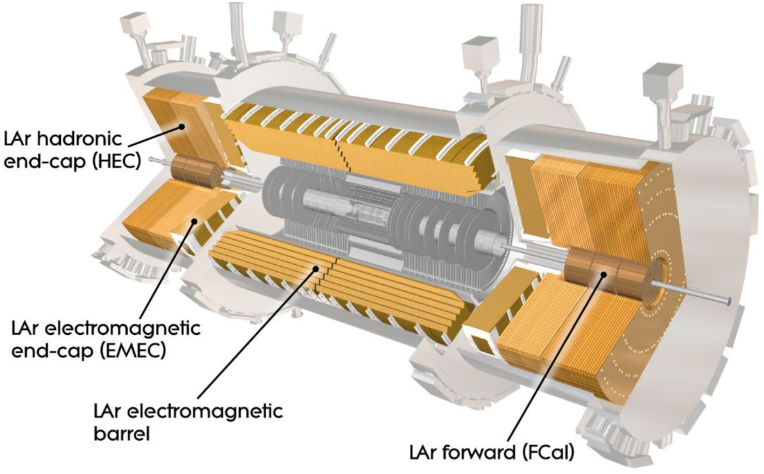
Main components:

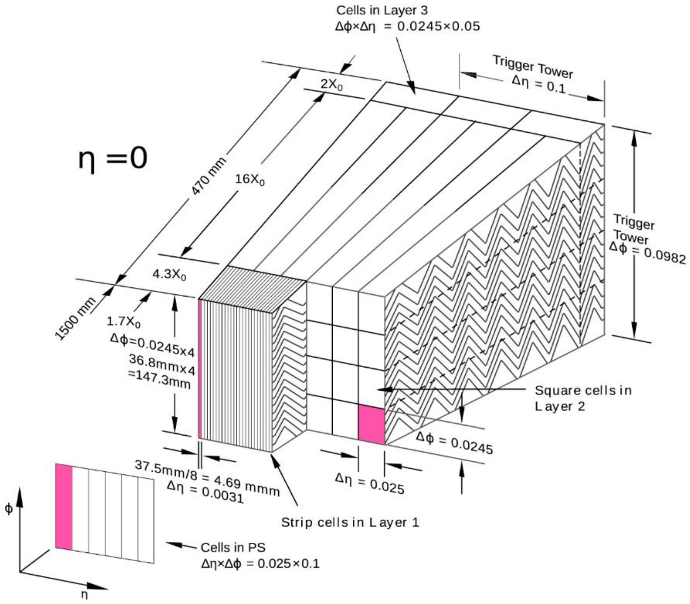
Pixel Detector, **Semiconductor Tracker** (SCT), and **Transition Radiation Tracker** (TRT)

- **Pixel Detector**:
  - silicon pixel sensors
  - measures origin and momentum of the particle
- **SCT**:
  - **6 million "micro-strips" of silicon sensors**
  - each particle crosses ~4 layers of silicon **precision of up to 25 μm**
- **TRT** reconstructs tracks and **provides information on the particle type**
  - **300,000** drift tubes or "**straws**"

The EM calorimeter: LAr

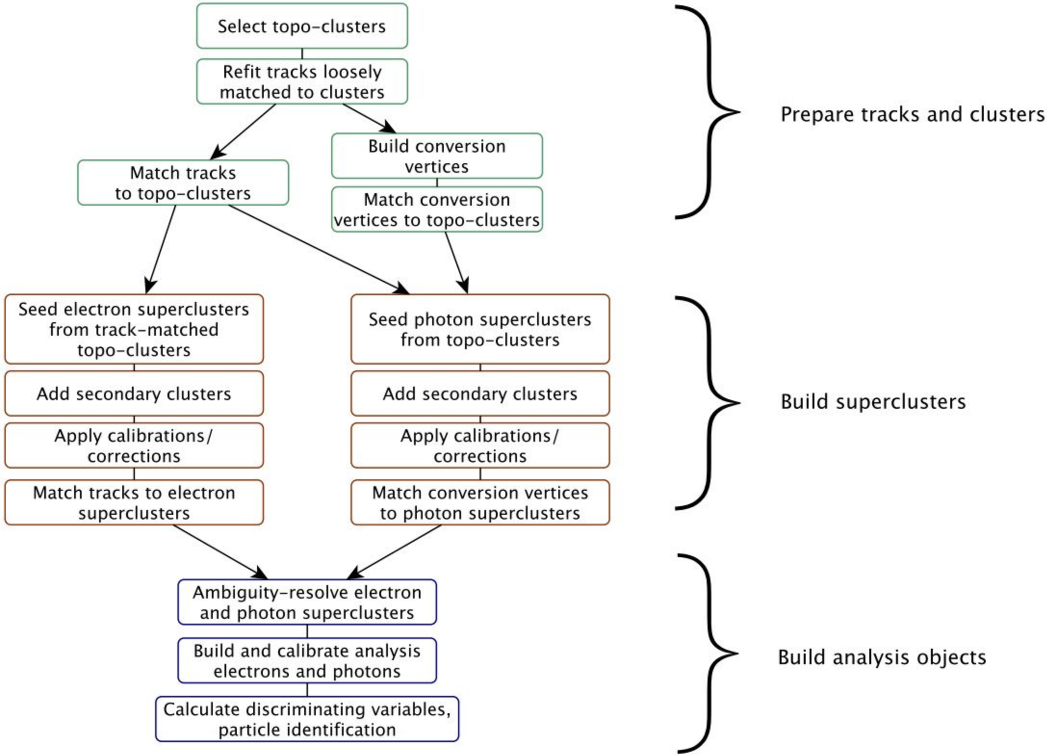
- Measures the energy of electrons, photons and hadrons
- Layers of metal (either tungsten, copper or lead) that absorb the energy of incoming particles
- Ionisation of liquid argon sandwiched between the layers, produces an electric current that is measured





- Energy of the original particle that hit the detector from combination of all of the detected currents
- Segmented in 3 layers (+ presampler):
  - finely-segmented η layer (“strips”)
  - squared cells layer of 16 radiation lenghts
  - backplane layer (used mostly to reject hadrons)

Algorithm for electron reconstruction



Select topo-clusters

Refit tracks loosely matched to clusters

Match tracks to topo-clusters

Build conversion vertices

Match conversion vertices to topo-clusters

Prepare tracks and clusters

Seed electron superclusters from track-matched topo-clusters

Add secondary clusters

Apply calibrations/ corrections

Match tracks to electron superclusters

Seed photon superclusters from topo-clusters

Add secondary clusters

Apply calibrations/ corrections

Match conversion vertices to photon superclusters

Build superclusters

Ambiguity-resolve electron and photon superclusters

Build and calibrate analysis electrons and photons

Calculate discriminating variables, particle identification

Build analysis objects

Identification efficiency measurements: LH ID WPs

- Identification efficiency of signal electrons as determined in MC simulation as a function of background rejection
- Shown for each of the electron categories
- For typical electroweak processes they are, on average, 93%, 88% and 80% for the Loose, Medium, and Tight operating points and gradually increase from low to high E_T
- The reduced efficiency of the Medium and Tight operating points is accompanied by an improved rejection of background processes