High Precision Electron and Muon Reconstruction Performance with ATLAS at LHC Run-2

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On behalf of the ATLAS Collaboration

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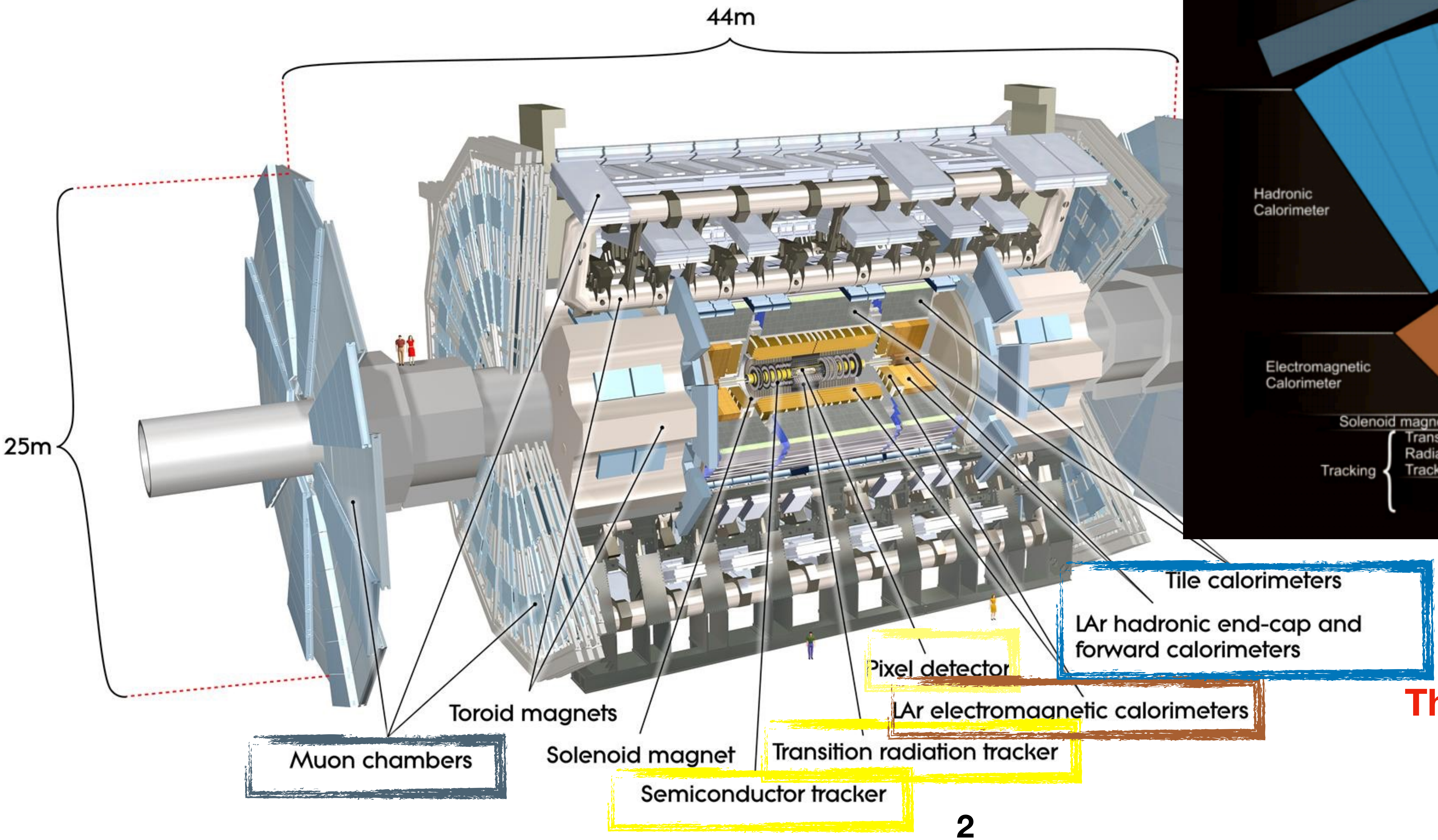
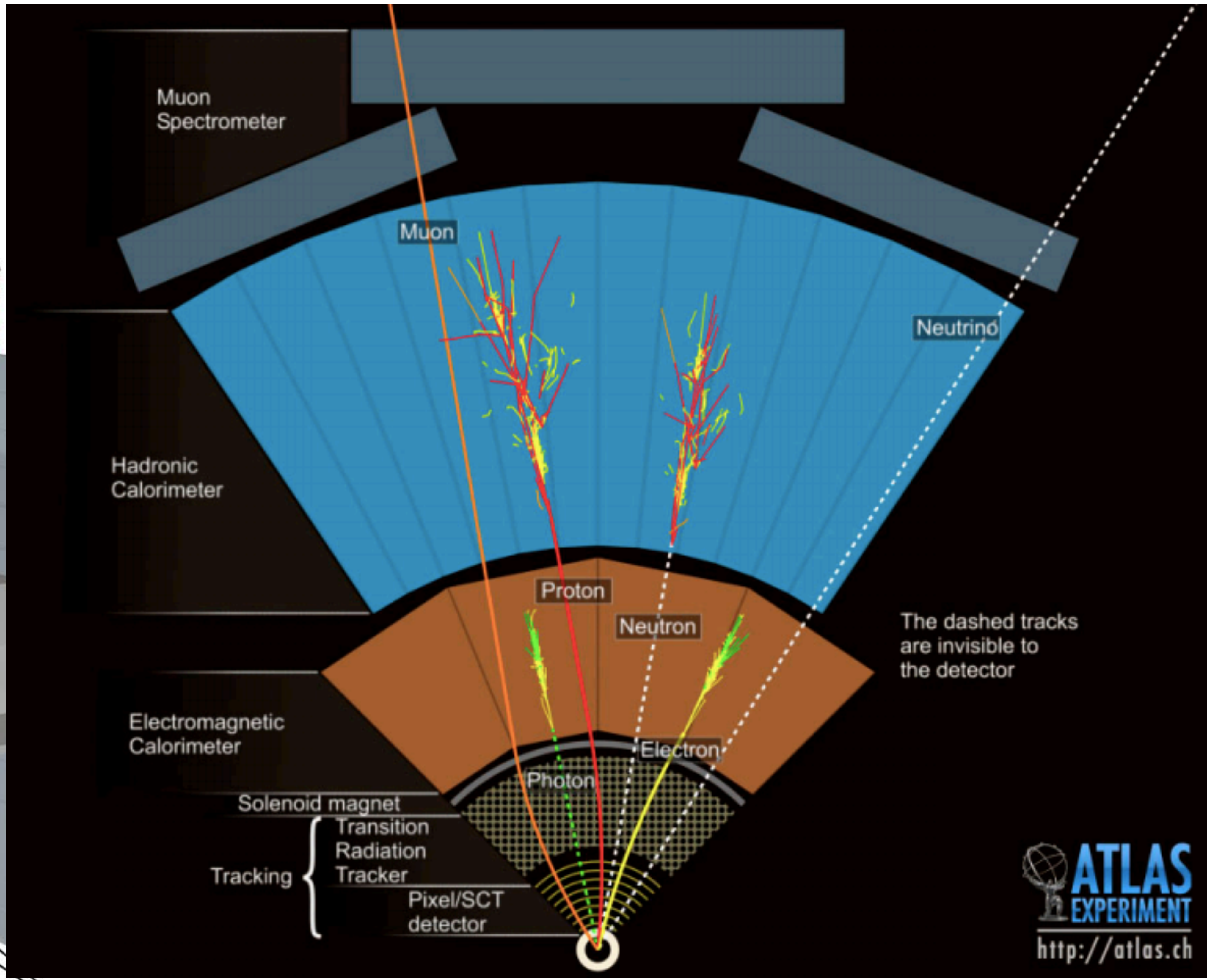
The ATLAS Experiment

Multi-purpose detector: 44x25x25 m^3





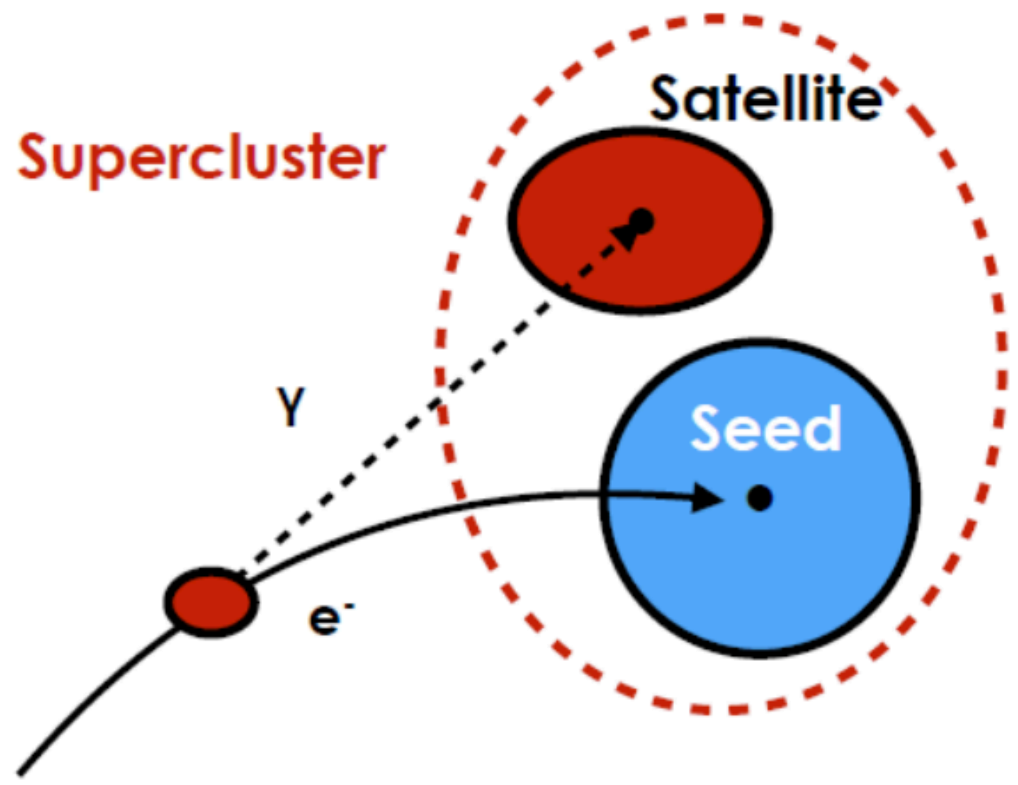
This slides will present results on pp collision at 13 TeV

Electron reconstruction, calibration and identification

Electron reconstruction work-flow

- **Run1 workflow:** Eur. Phys. J. C 76 (2016) 666.
  1. Select **fixed-size electromagnetic(EM) clusters** and tracks
     - Clusters are reconstructed using sliding windows (**SW**) algorithm

changed to use **dynamic**, **variable-size clusters**

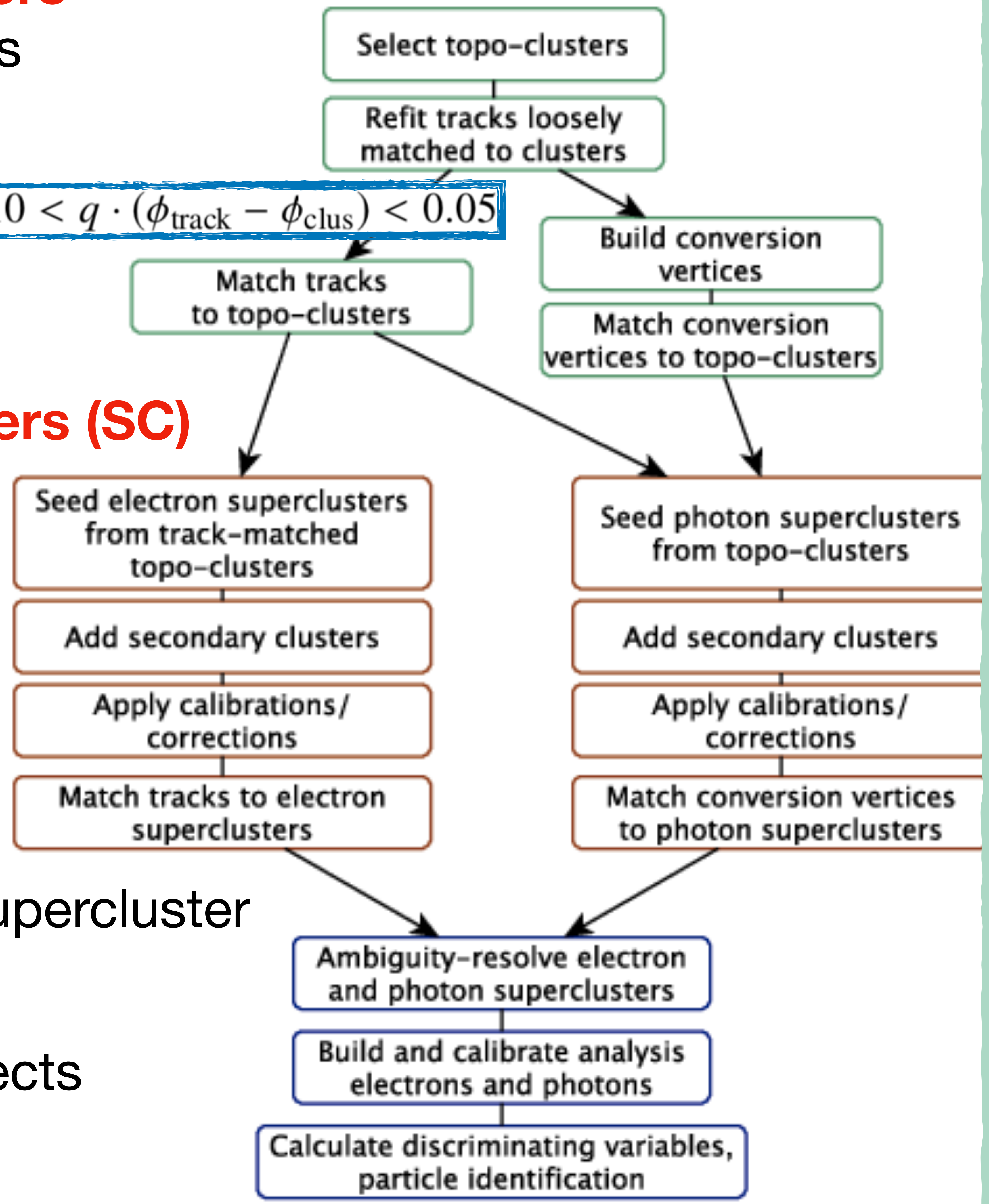


Recover low E photons from bremsstrahlung

  2. Match tracks clusters
  3. Build analysis objects

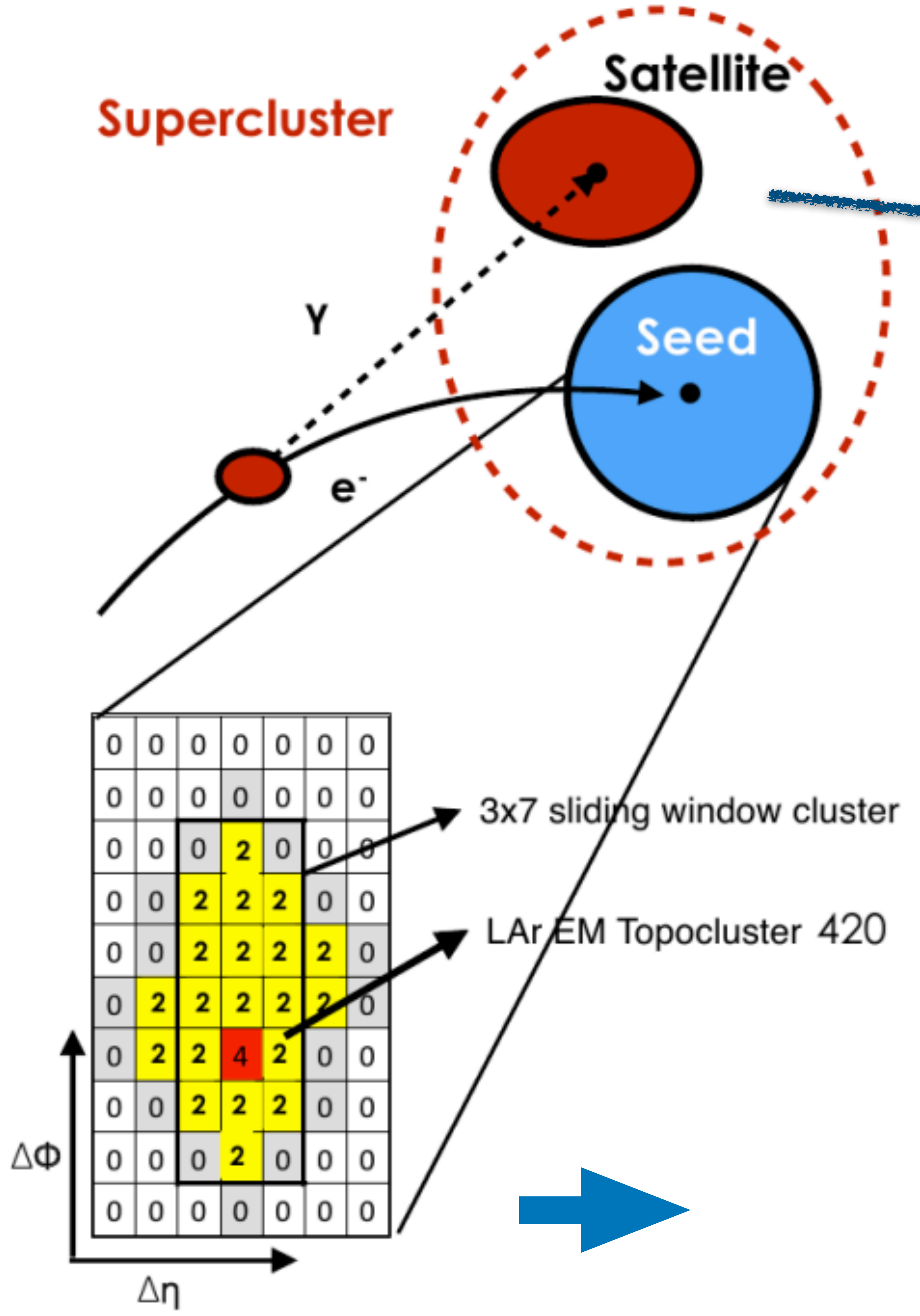
- **Run2 work-flow**: CERN-EP-2019-145
  1. Build **topo-clusters** and prepare tracks
  2. **Build superclusters (SC)**
  3. Match tracks to supercluster
  4. Build analysis objects

$|\Delta\eta| < 0.05$ and $-0.10 < q \cdot (\phi_{\rm track} - \phi_{\rm clus}) < 0.05$



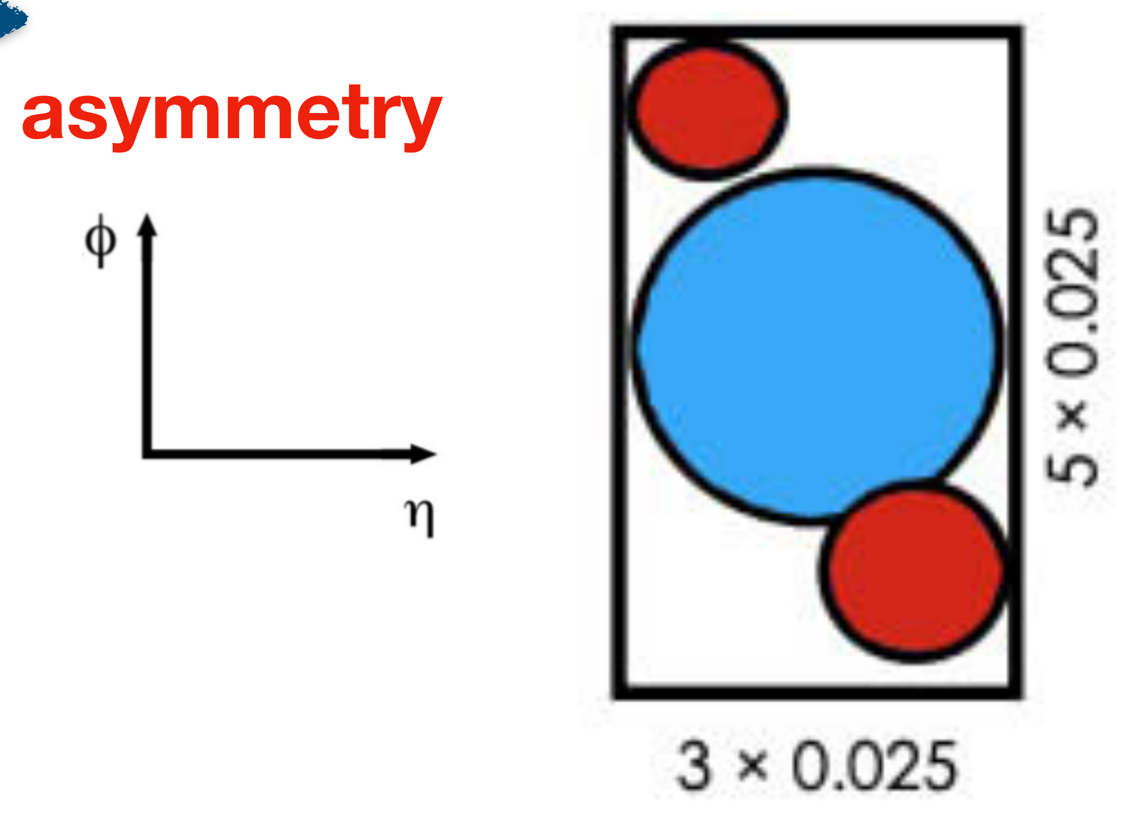
Build Supercluster

Main goal: Include radiative losses from bremsstrahlung into cluster to **improve energy measurement**

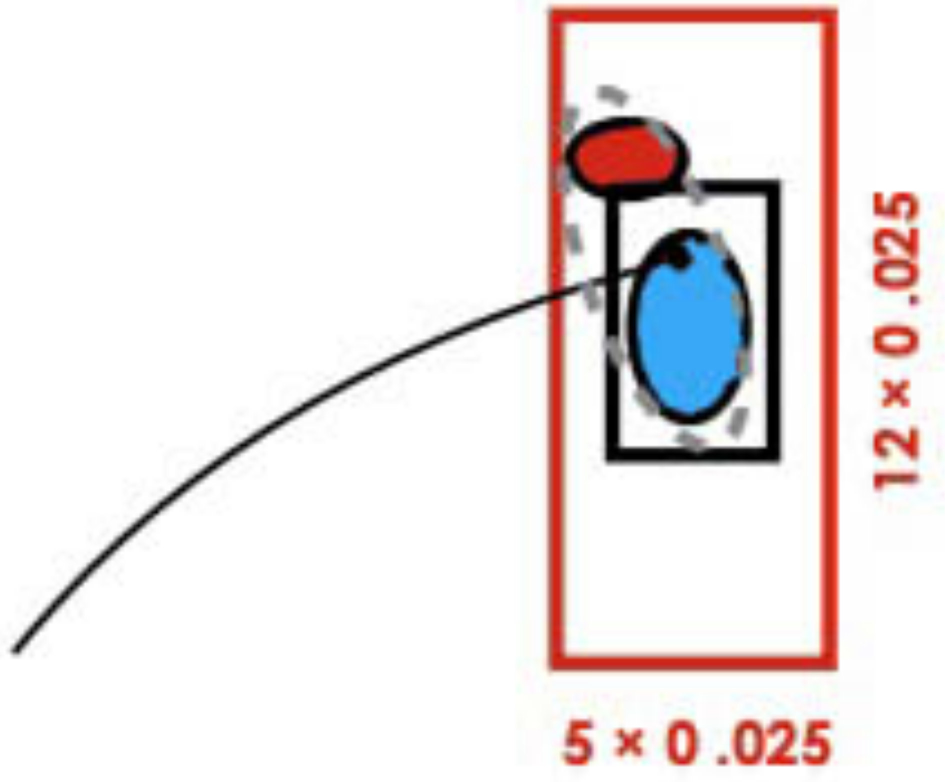


2. Find satellite clusters

Add all clusters within 3 × 5 window around seed cluster



Seed, secondary cluster **match the same track**



1. Select seed cluster

- Electron reconstruction starts from the **topo-clusters**
  - Initial seeds are found when cell energy > 4*sigma of noise.
  - Cluster grows as touching cells have energy > 2*sigma.
  - Final layer added with cluster energy > 0*sigma.
- $E_T > 1$ GeV and is matched to a track with >= 4 hits.

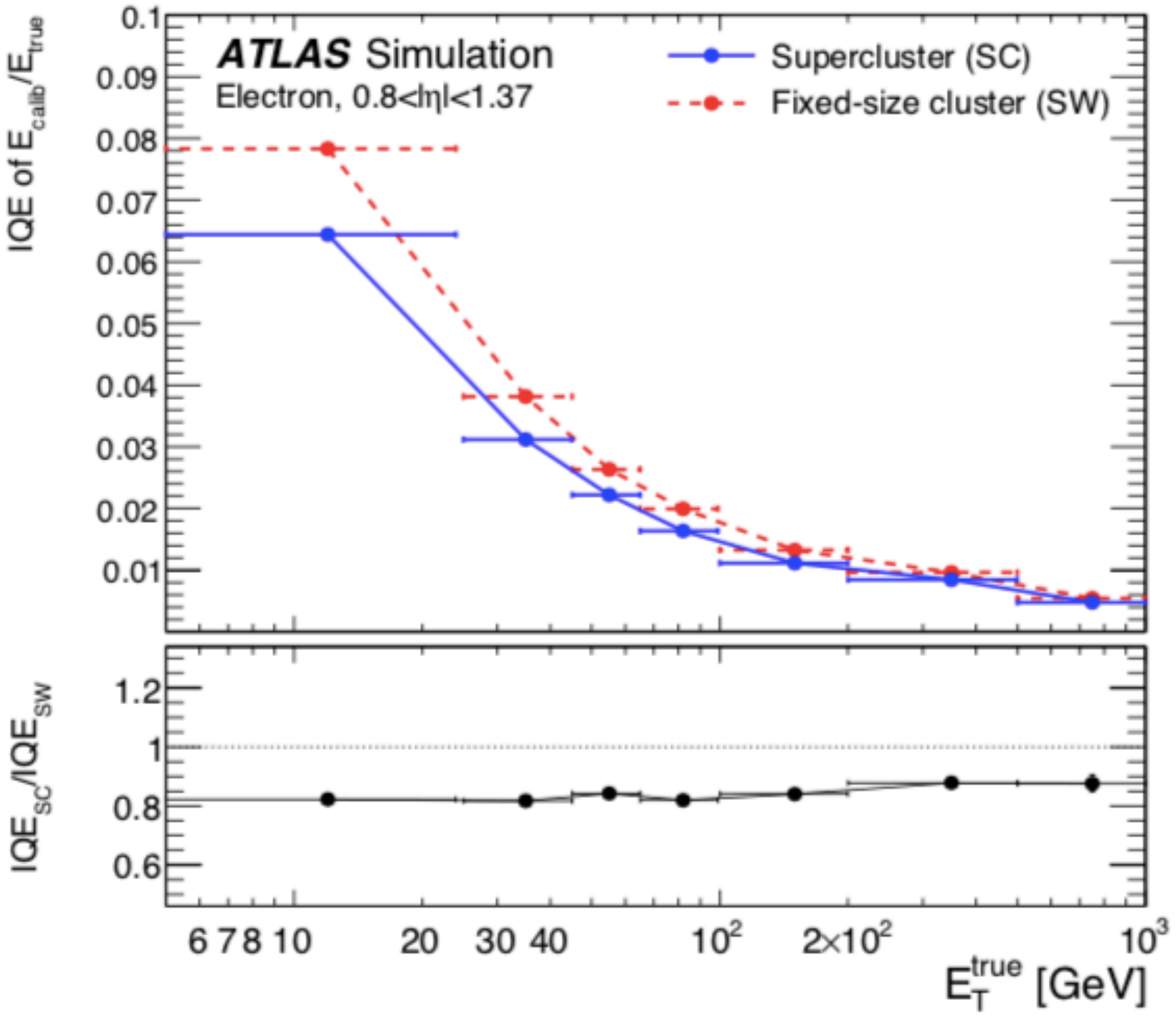
Supercluster Performance

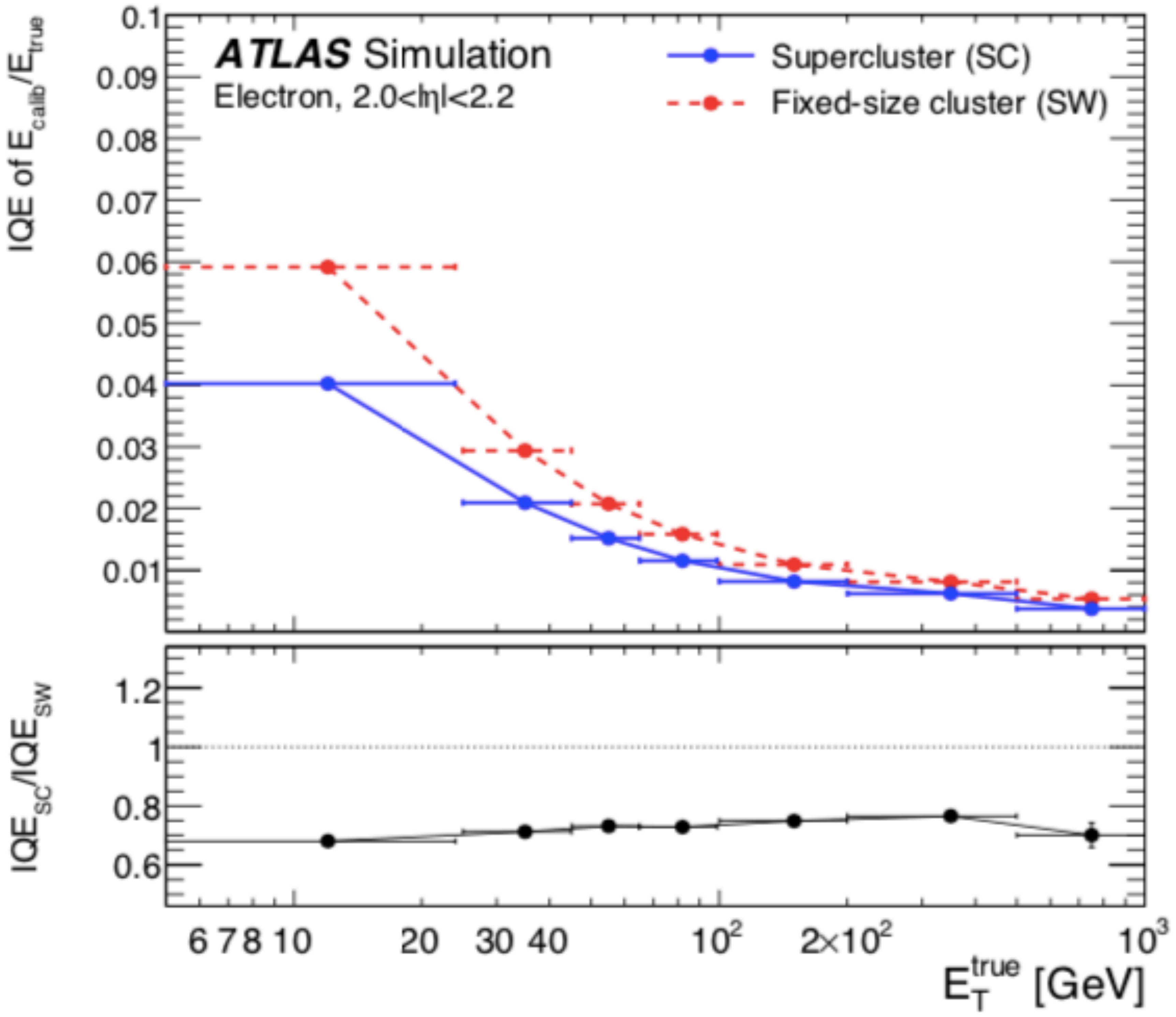
- **The energy resolution of the electron or photon is optimized using a multivariate regression algorithm based on the prop of the shower development in the EM calorimeter:** CERN-EP-2019-145
  - **Recover** energy loss out of cluster and in passive material
  - Input samples: simulated e and converted & unconverted γ
    Target: E_{true}/E_{reco}

$$\mathrm{IQE} = \frac{Q_3 - Q_1}{1.349}$$

Q_1, Q_3 are the first and third quartiles of the distribution of E_{calib}/E_{true}

supercluster algorithm improves E resolution by up to 30%





Electron energy calibration using $Z \rightarrow ee$ events

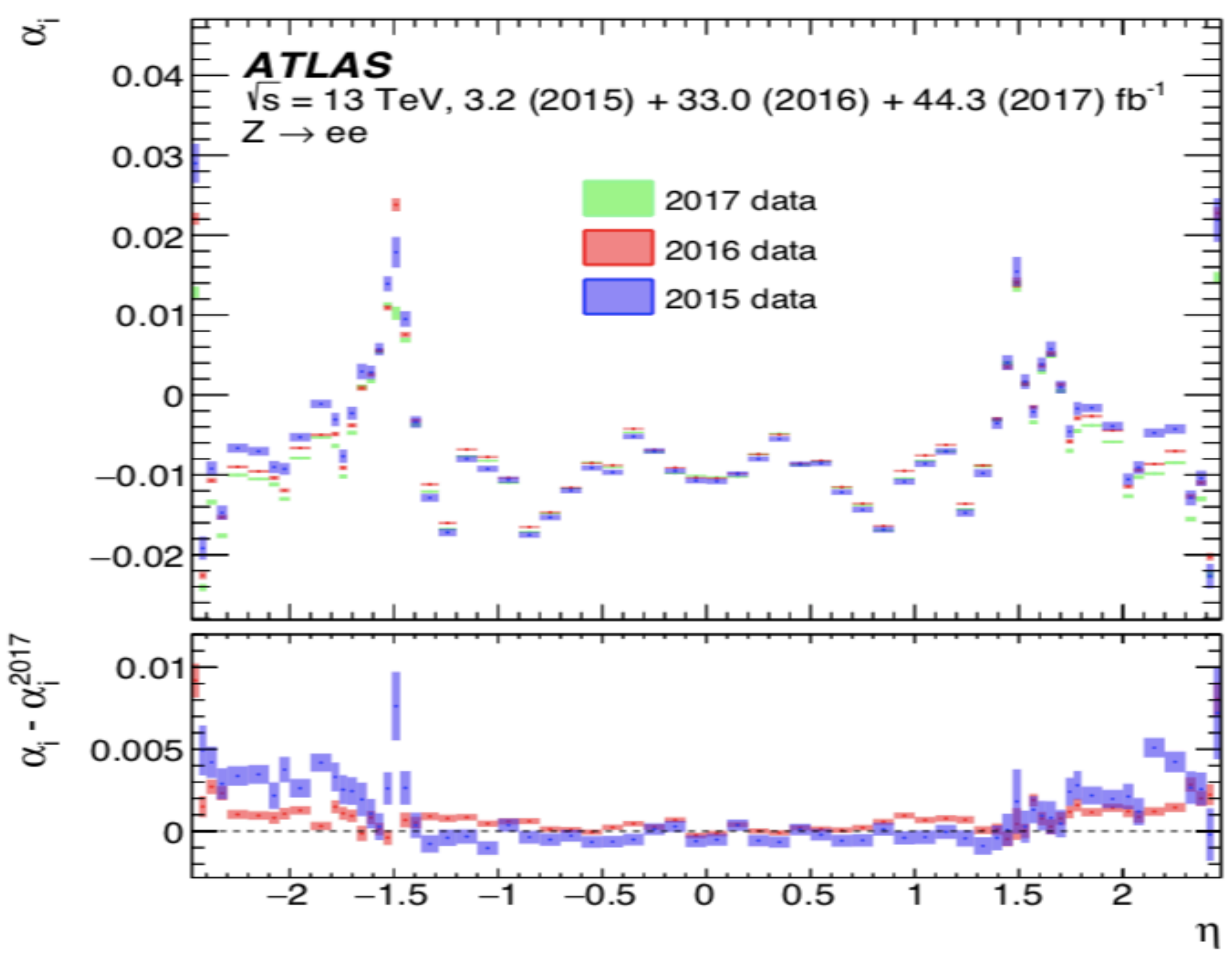
- CERN-EP-2019-145

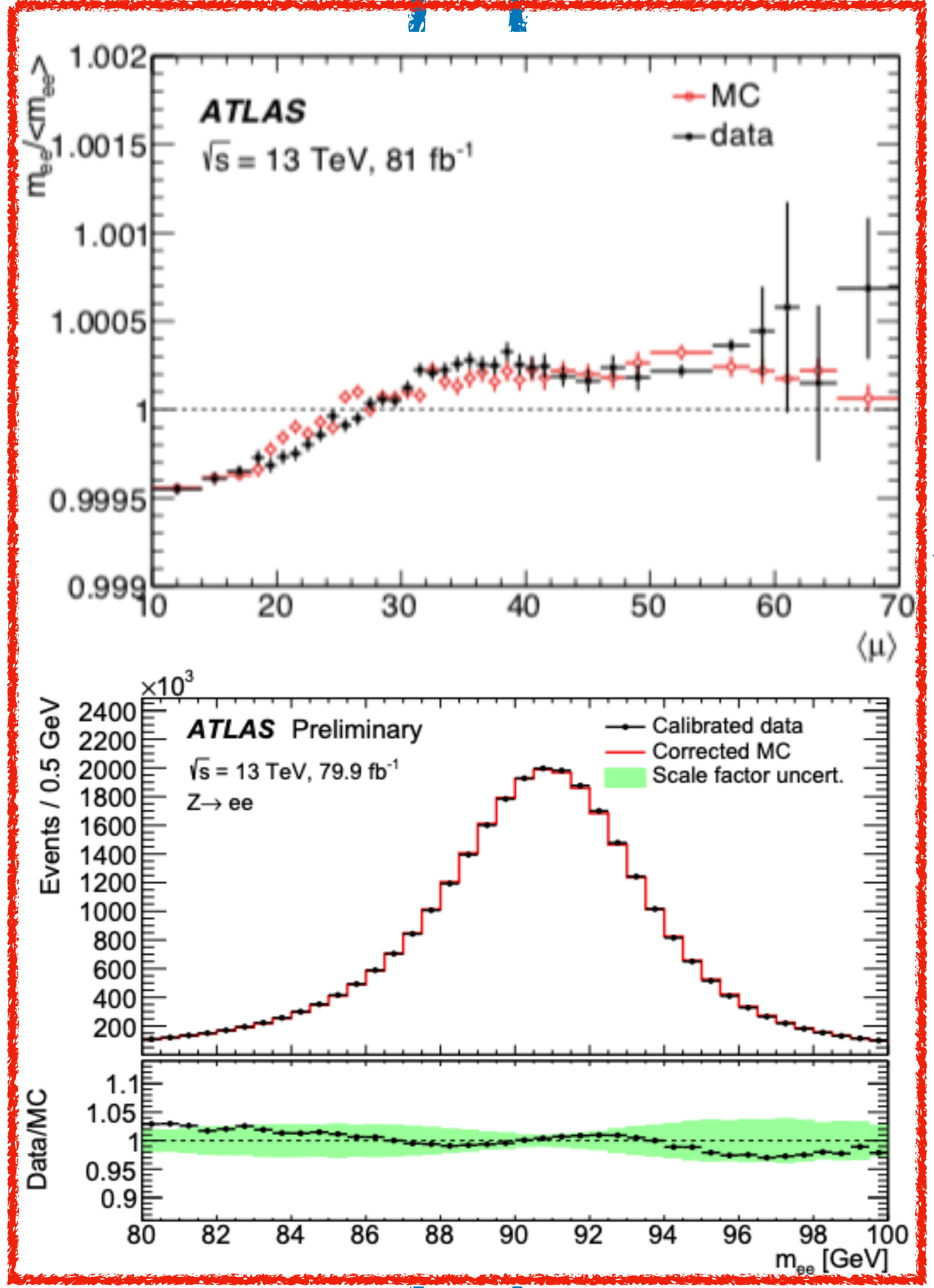
Energy scale

$$E_i^{Data} = E_i^{MC}(1 + \alpha_i),\ i \rightarrow \eta\ bins$$

- Difference in a_i between the different years mainly due to:
  - The LAr temperature change
  - Increase of the luminosity

Applied on data



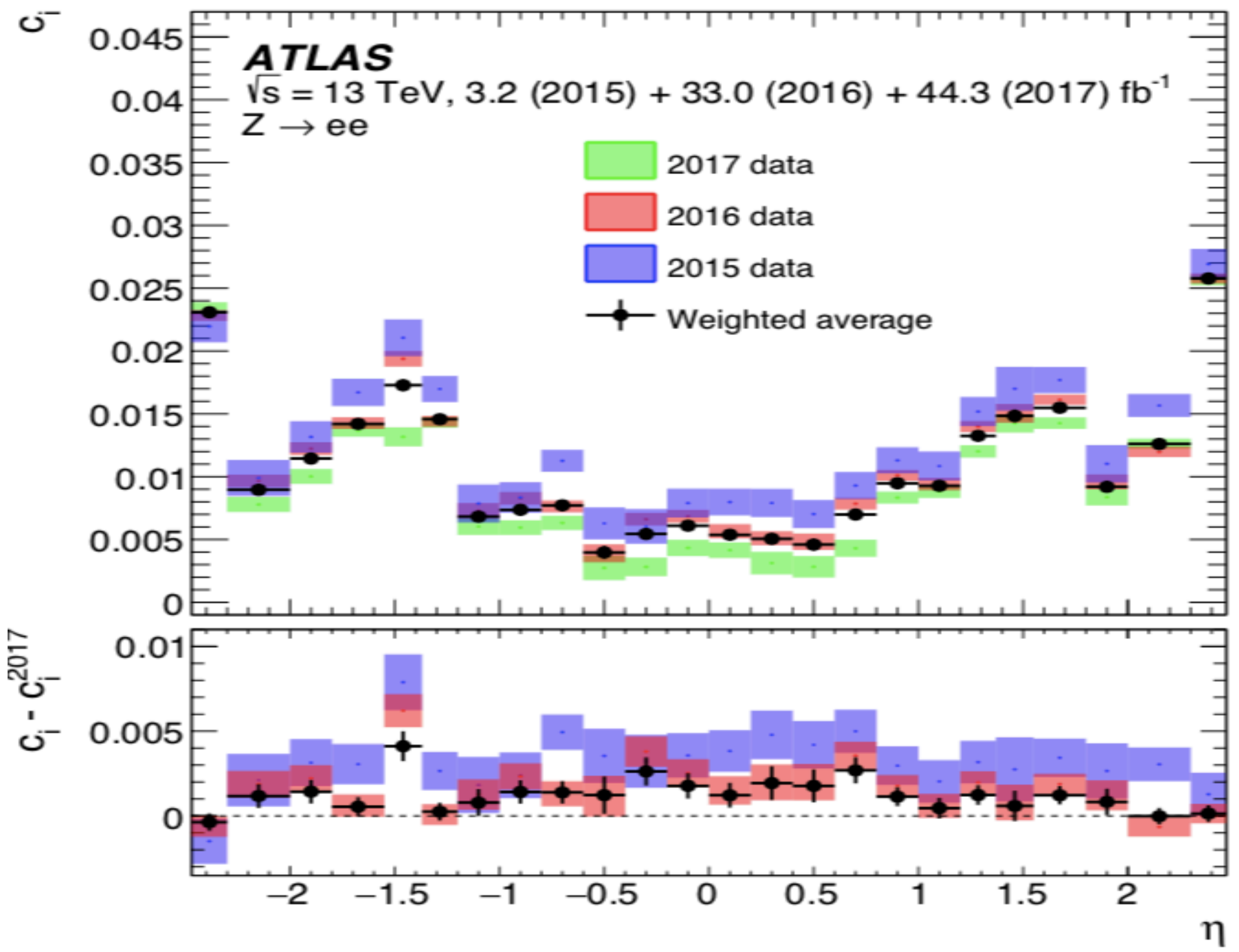


Energy resolution

$$\left(\frac{\sigma_E}{E}\right)^{Data} = \left(\frac{\sigma_E}{E}\right)^{MC} \oplus c_i,\ i \rightarrow \eta\ bins$$

- c_i is an eta-dependent constant term
- Symbol $\oplus$ denotes a sum in quadrature

Applied on simulation



Electron identification

Electron identification(ID) relies on a **likelihood (LLH) discriminant** constructed from quantities measured in the inner detector and calorimeter

- Discriminate **prompt electrons** from:
  - E deposits from **hadronic jets** and **conv γ**
  - Non-prompt electrons produced in **heavy flavour hadrons** decays

- The likelihood discriminant d_L

$$d_L = \frac{L_S}{L_S + L_B}, \qquad L_{S(B)}(\boldsymbol{x}) = \prod_{i=1}^{n} P_{s(b),i}(x_i),$$

- x_i is the vector of discriminating variables
- $P_{s(b)}, i(x_i)$ is the value of the pdfs of the signal or background

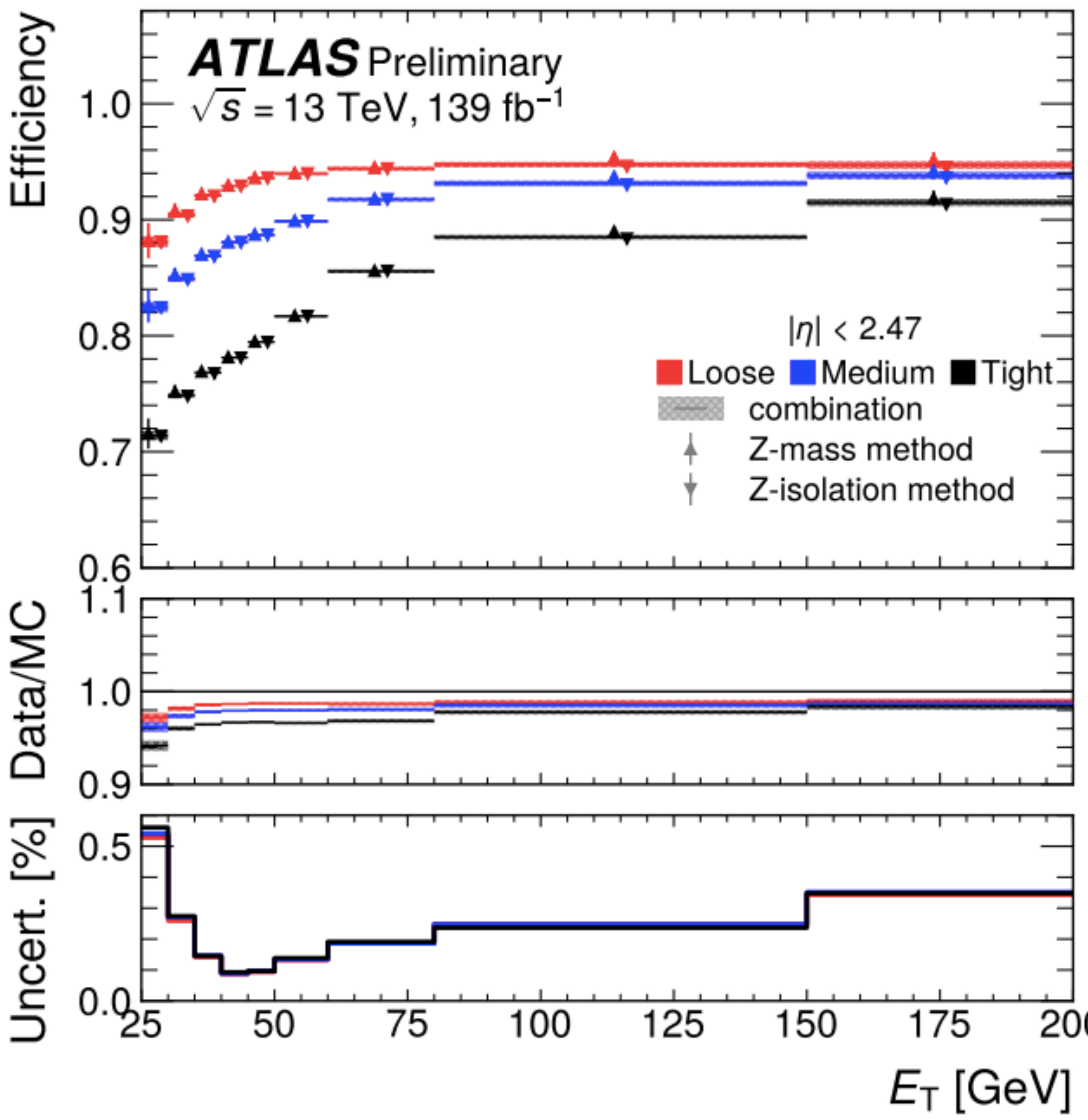
→

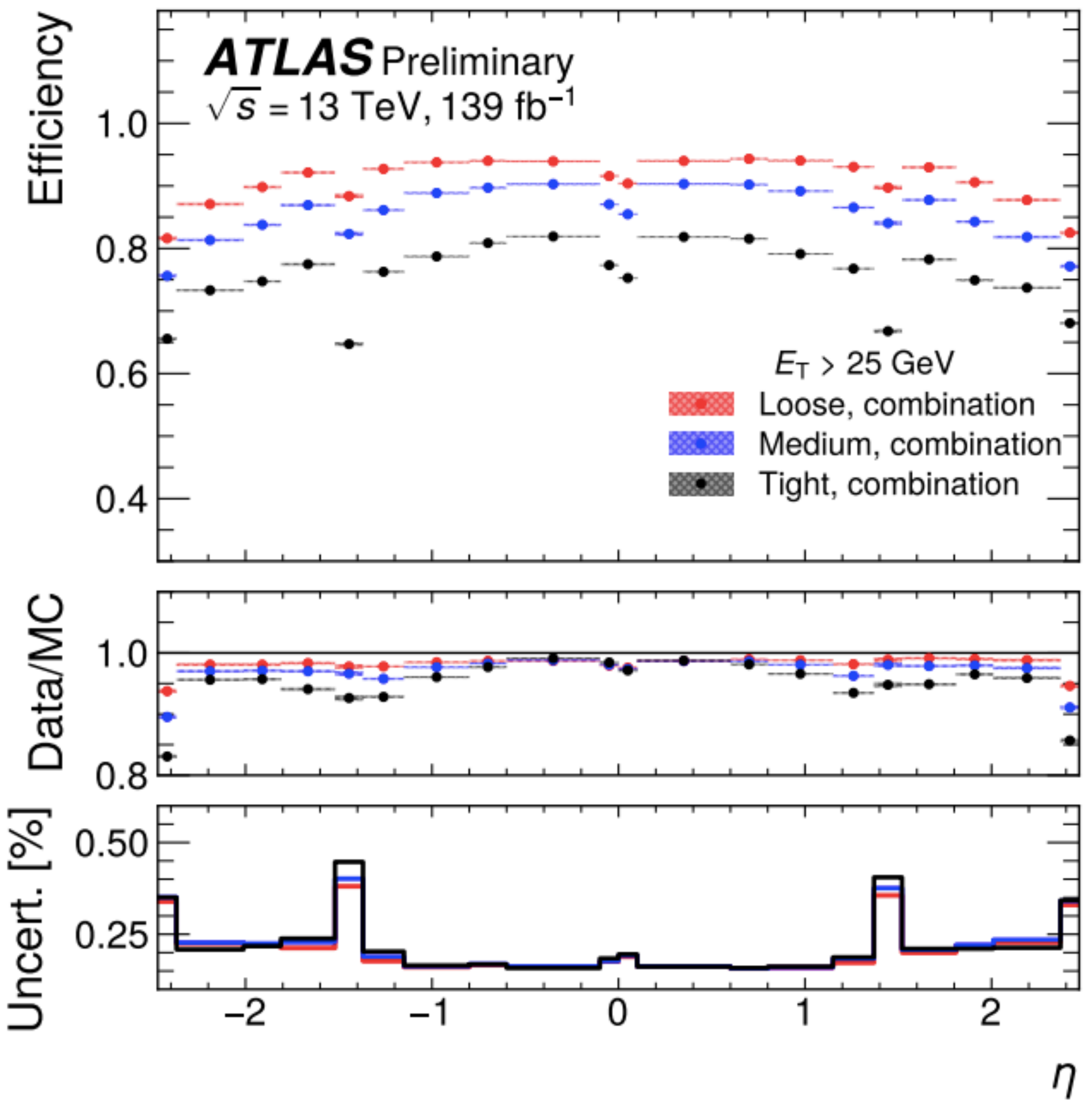
- **electron track** qualities
- **shower shapes** in EM calorimeter
- **track-cluster matching** properties

Electron identification efficiency

Three electron ID WPs defined: **Loose**, **Medium** and **Tight**

- Their optimization is done in bins of η and pT with MC simulations.

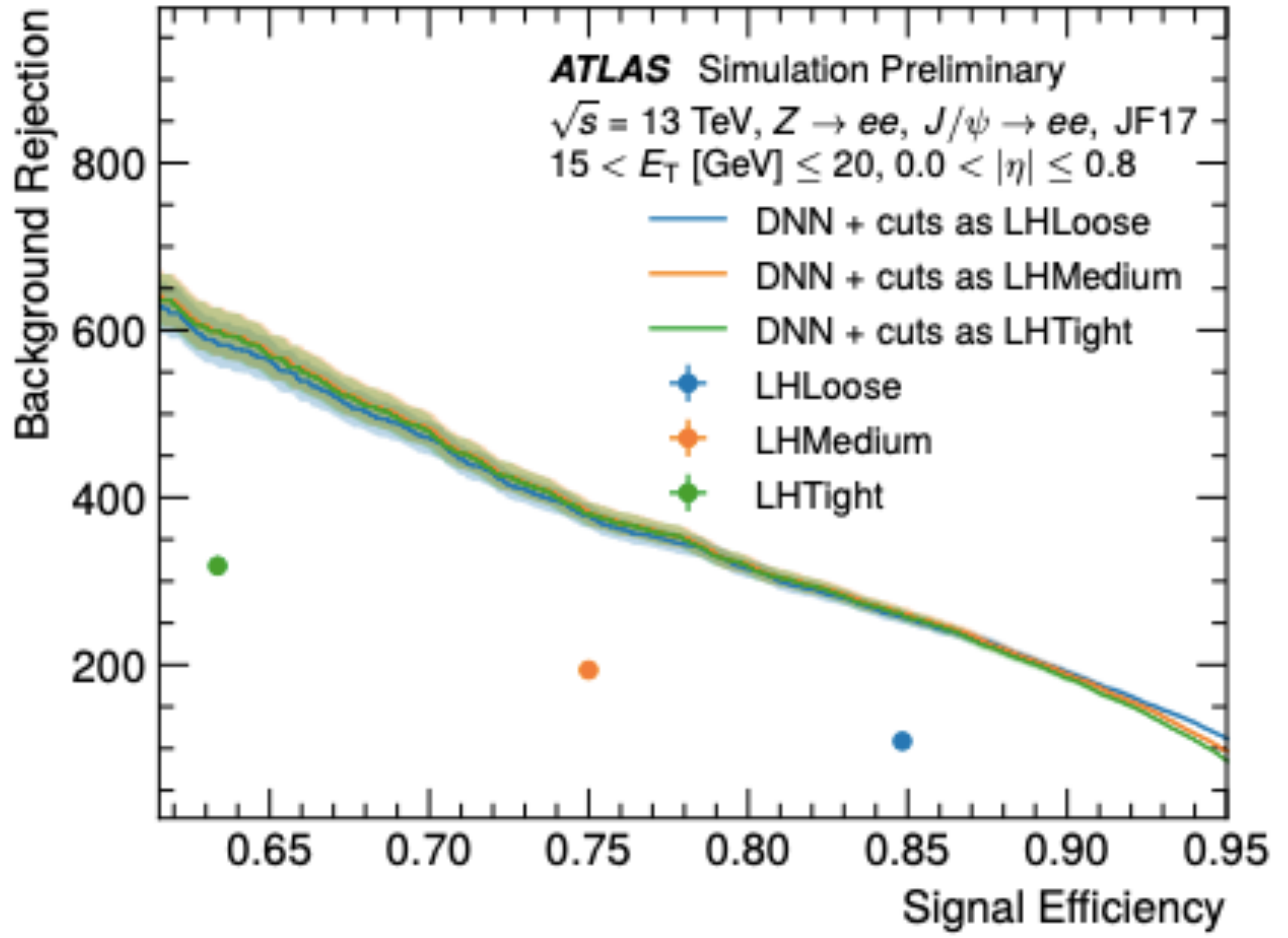




- The ID efficiency for electrons from typical electroweak processes(**on average**):
  - 93%, 88% and 80% for the **Loose**, **Medium**, and **Tight** WPs and gradually increase from low to high ET.

New Identification techniques for Run3:
Deep neural network based ID

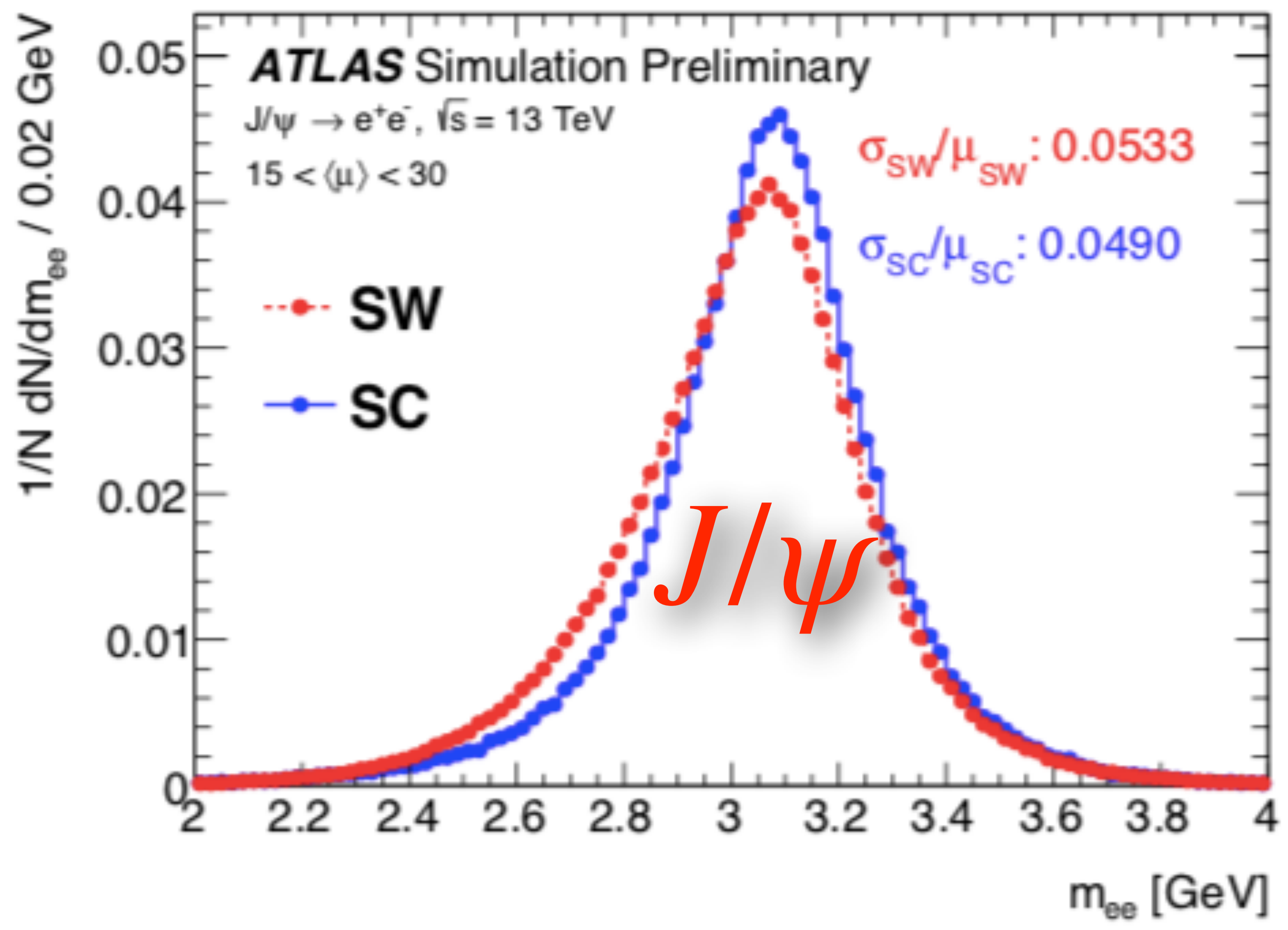
ATL-PHYS-PUB-2022-022



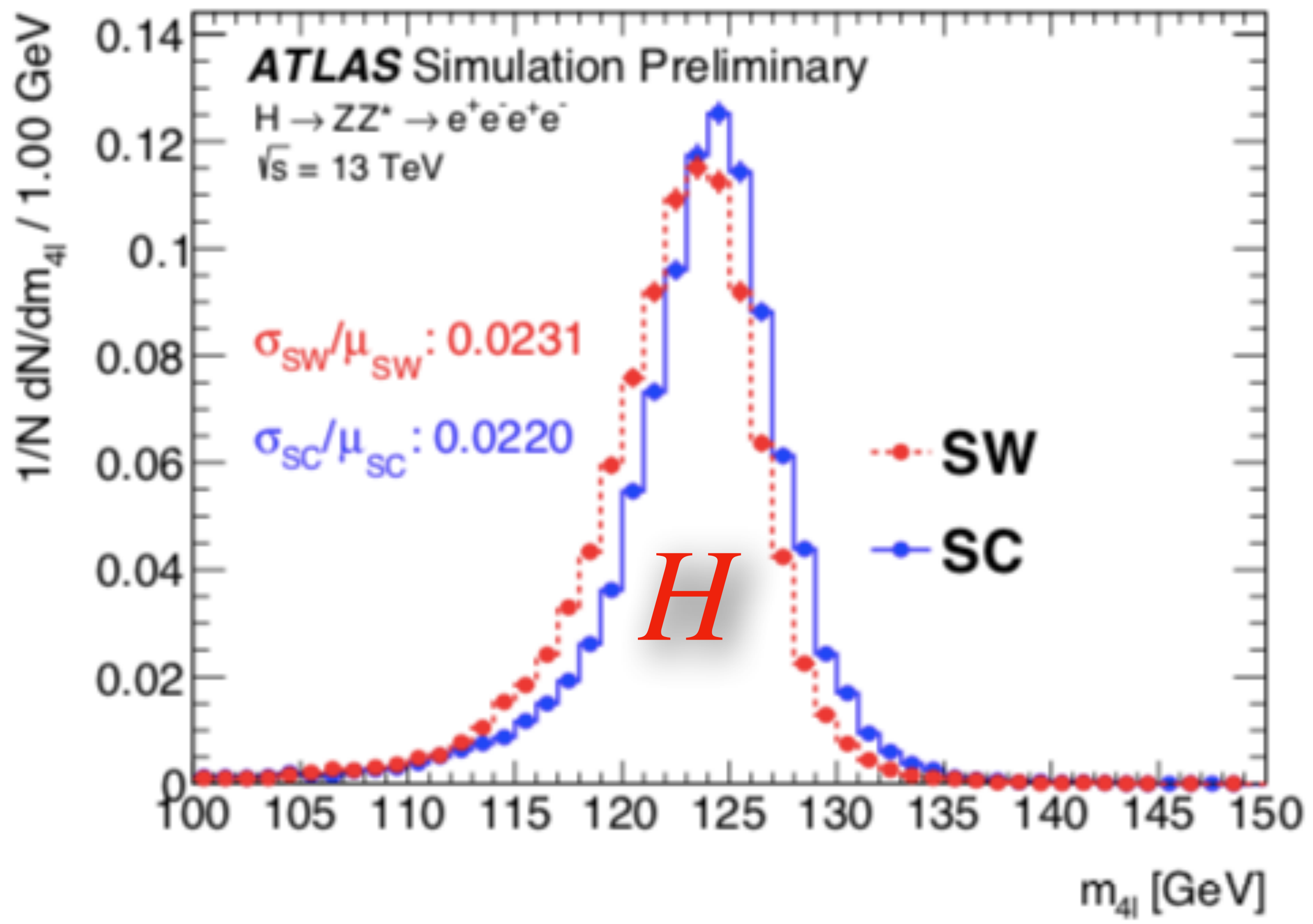
- DNN can deal with correlated features
- Increase in background rejection by 1.7~5.5 at the same signal efficiency

Electron supercluster performance

Perform on simulations



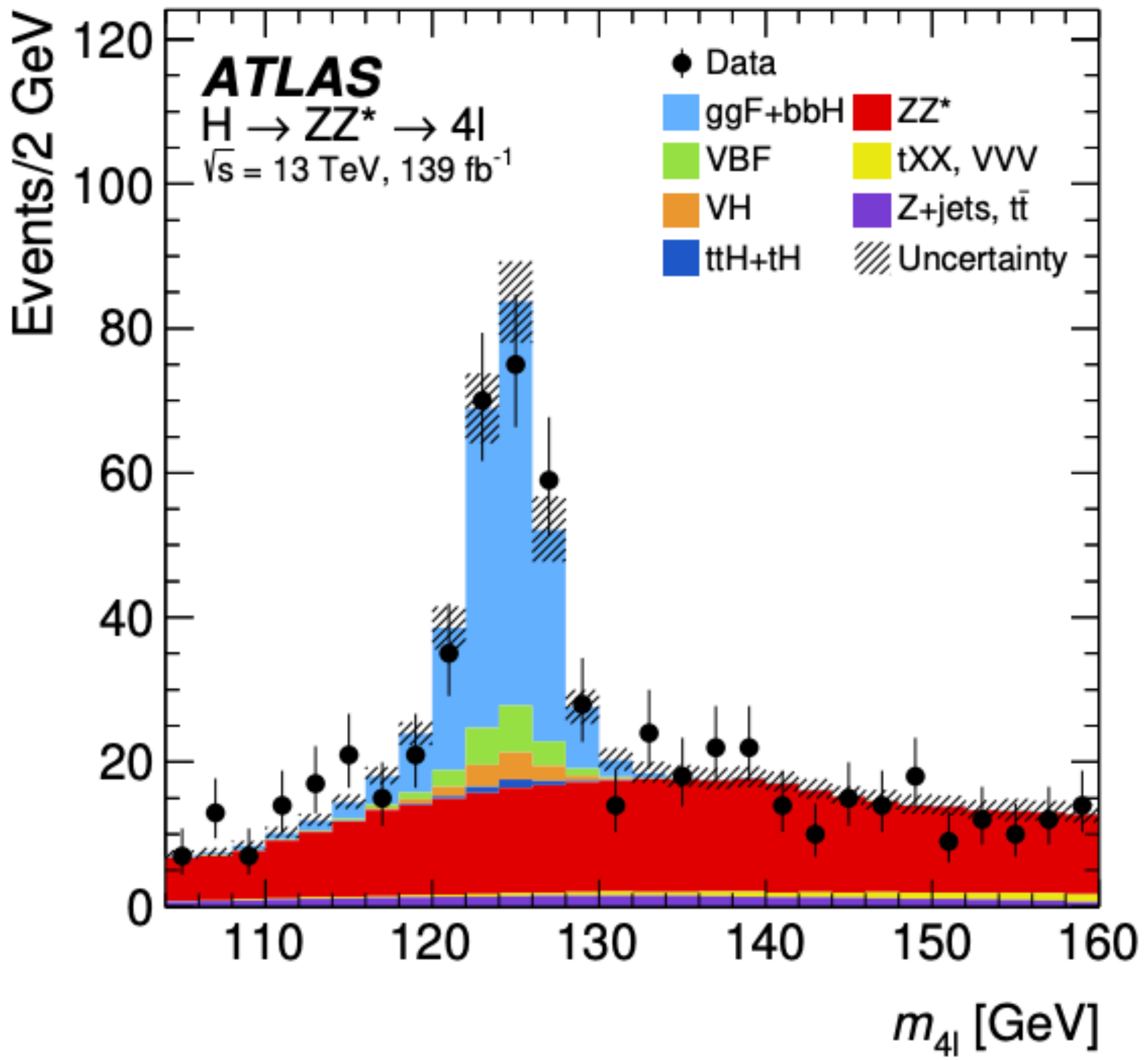
- Gaussian fit,
- Improvement of resolution ~8%
- Shift towards the best-know J/ψ mass: 3.096GeV



- Double Crystal Ball fit
- 4e channel shows 5% improvement in resolution

Higgs production cross-section measurements

CERN-EP-2020-034



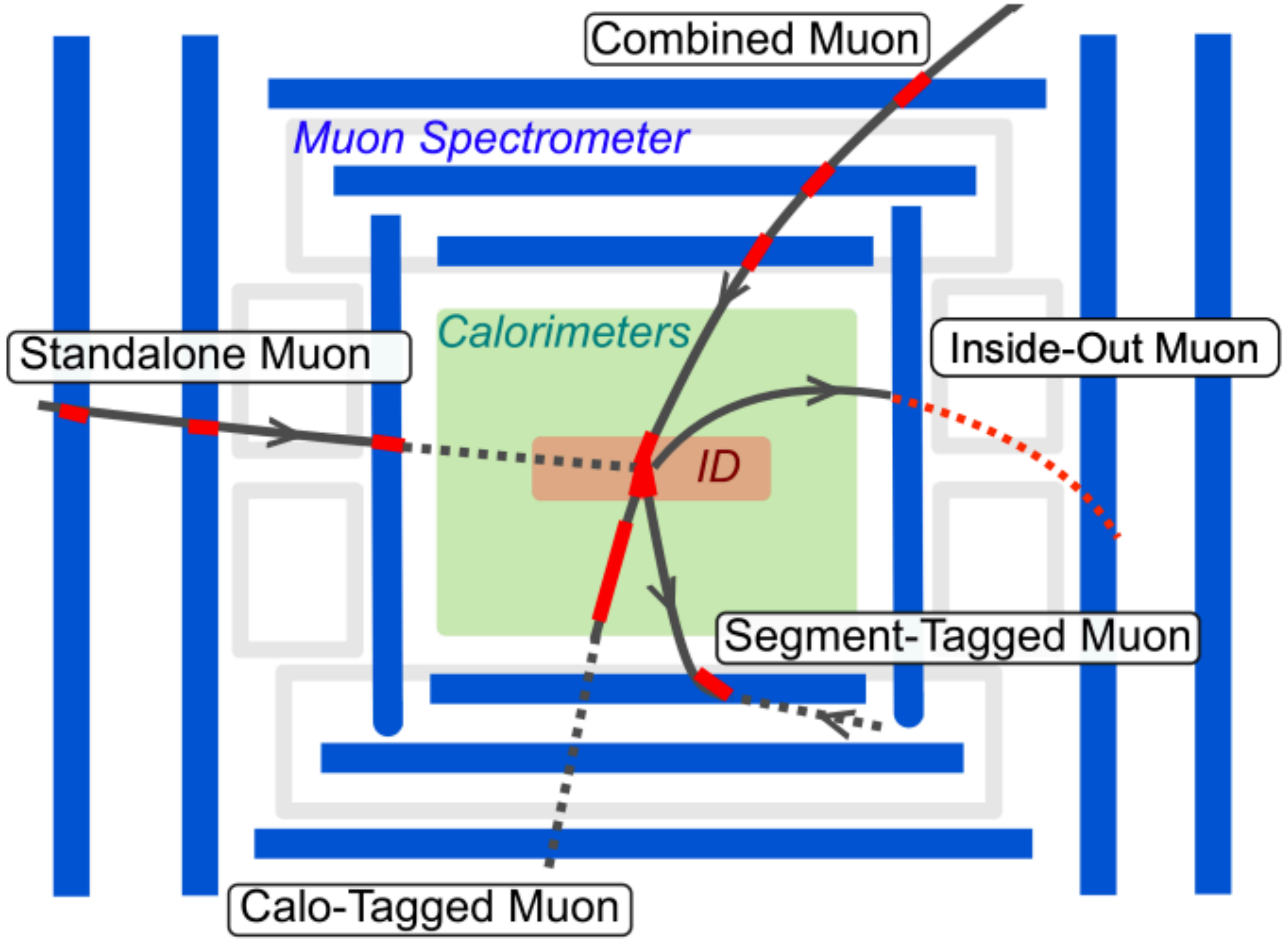
- 2015-2018 data
- Data and MC are in a good agreement.
- Uncertainties from **electron identification** and **reconstruction** are 1~2%

Muon reconstruction, identification, isolation and efficiency measurements

Muon reconstruction

The main signature exploited for muon reconstruction is that of a **minimum-ionizing particle**: CERN-EP-2020-199

- Presence of a track in the Muon Spectrometer (MS)
- Characteristic energy deposits in the calorimeters



Reconstruction strategies

- **Combined(CB) muon:** re-fit the **ID- & MS-track** into one single track
- **Inside-Out(IO) muon**: re-fit the ID track and MS hits(>2) pattern
- **Segment-Tagged(ST) muon**: ID tracks combined with single segments of the MS (at low energies)

Final analysis container merge all these types

- **Muon-spectrometer Extrapolated(ME) muon**: Only MS track, extrapolated to the beam-line (beyond the coverage of ID, $|\eta|>2.5$)
- **Calo-Tagged(CT) muon**: ID tracks with additional small energy in the calorimeter(at $\eta \approx 0$)

Muon identification

Several muon ID working points(WP) targeted the **rejection of light hadrons** are defined:

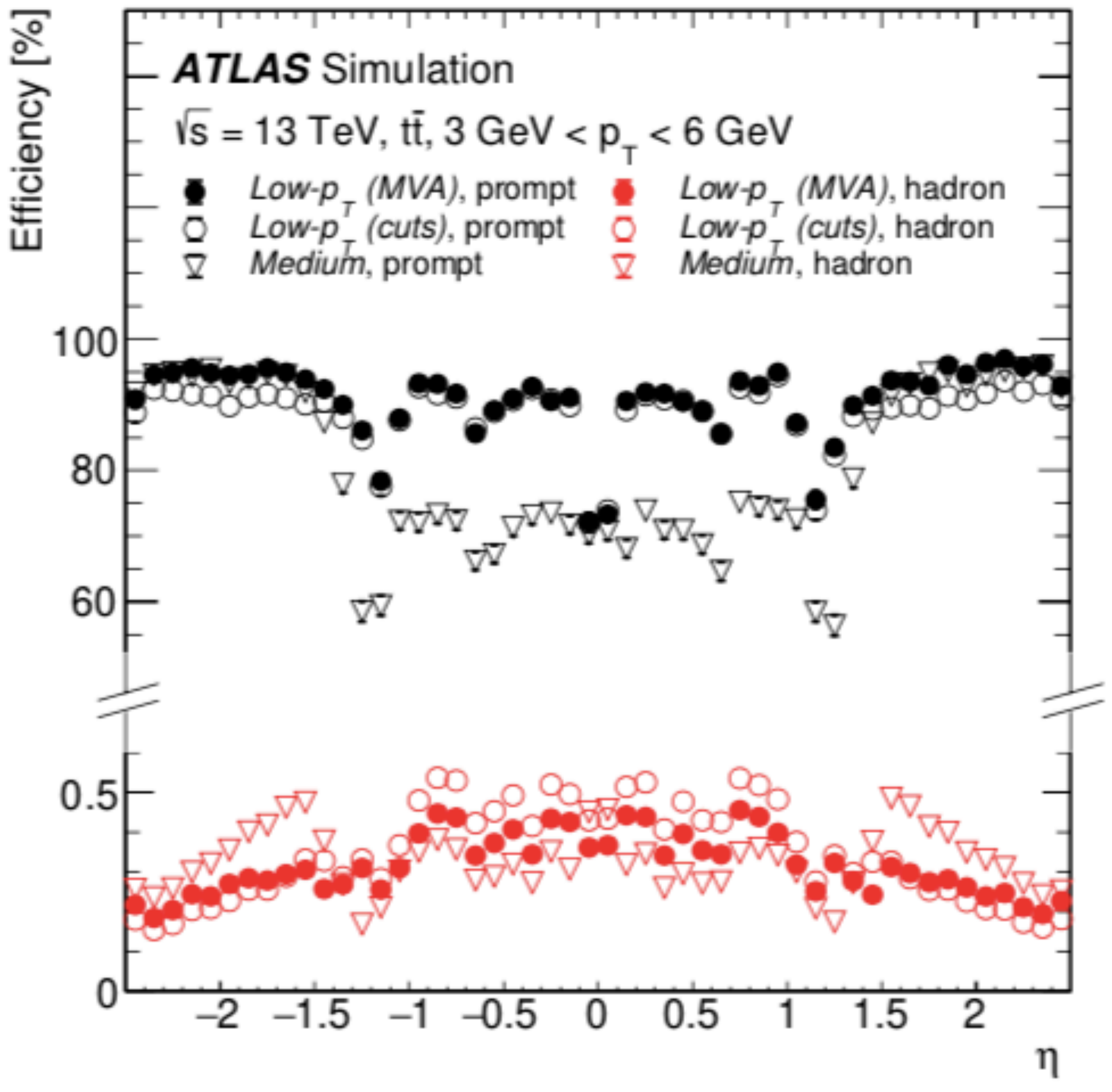
Features:

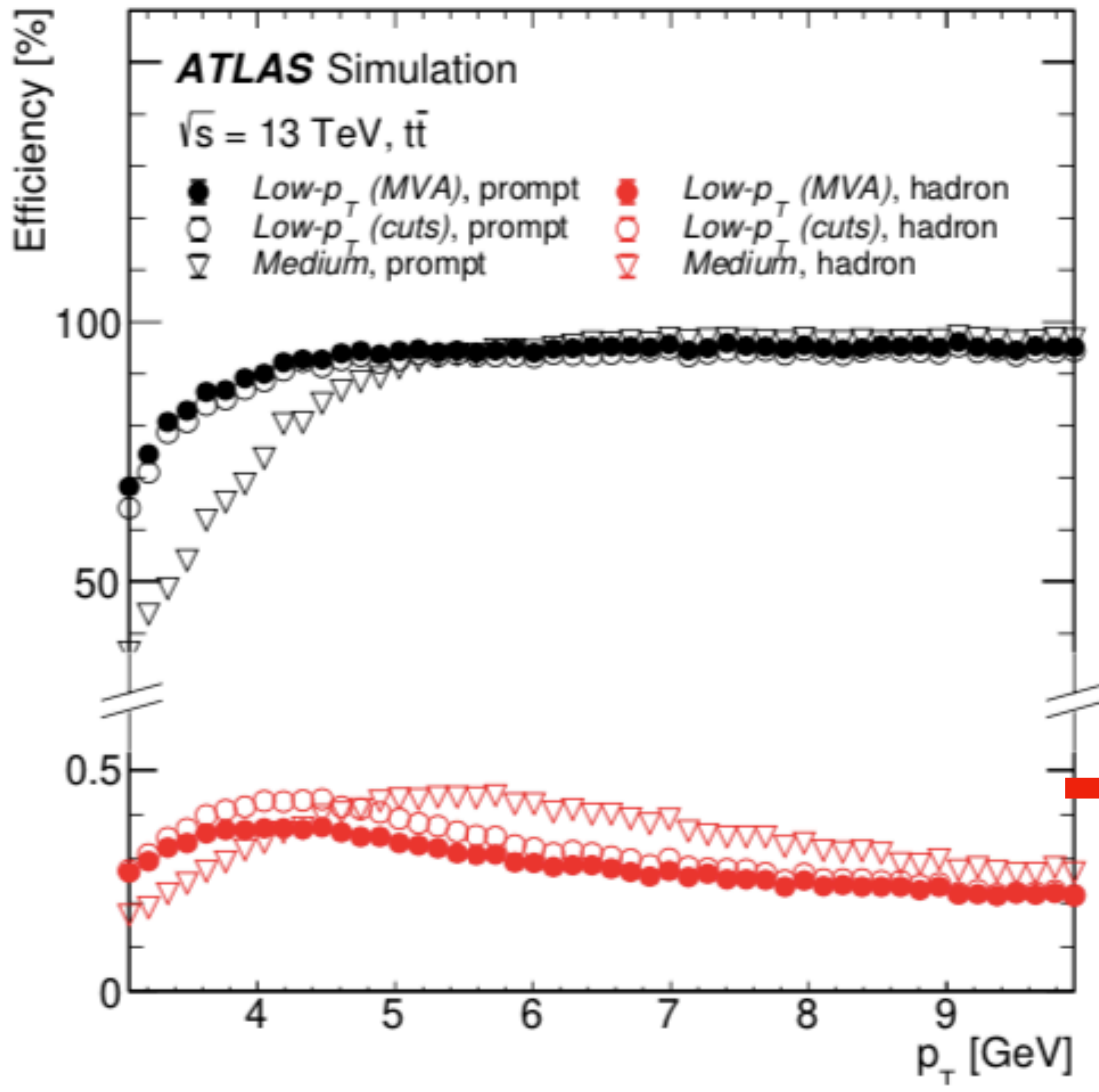
- N hits in the ID sub-detectors or MS stations
- Track fit properties
- compatibility of the measurement in the two detector systems.

Cut base/MVA

- **Loose**(e.g. H→ 4l): maximal efficiency
- **Medium**(default):minimize systematics
- **Tight**(e.g. W+c): maximize hadron rejection
- **Low-pT, High-pT**: extremes of pT spectrum

(Low-PT MVA WP: first MVA-based muon ID WP)



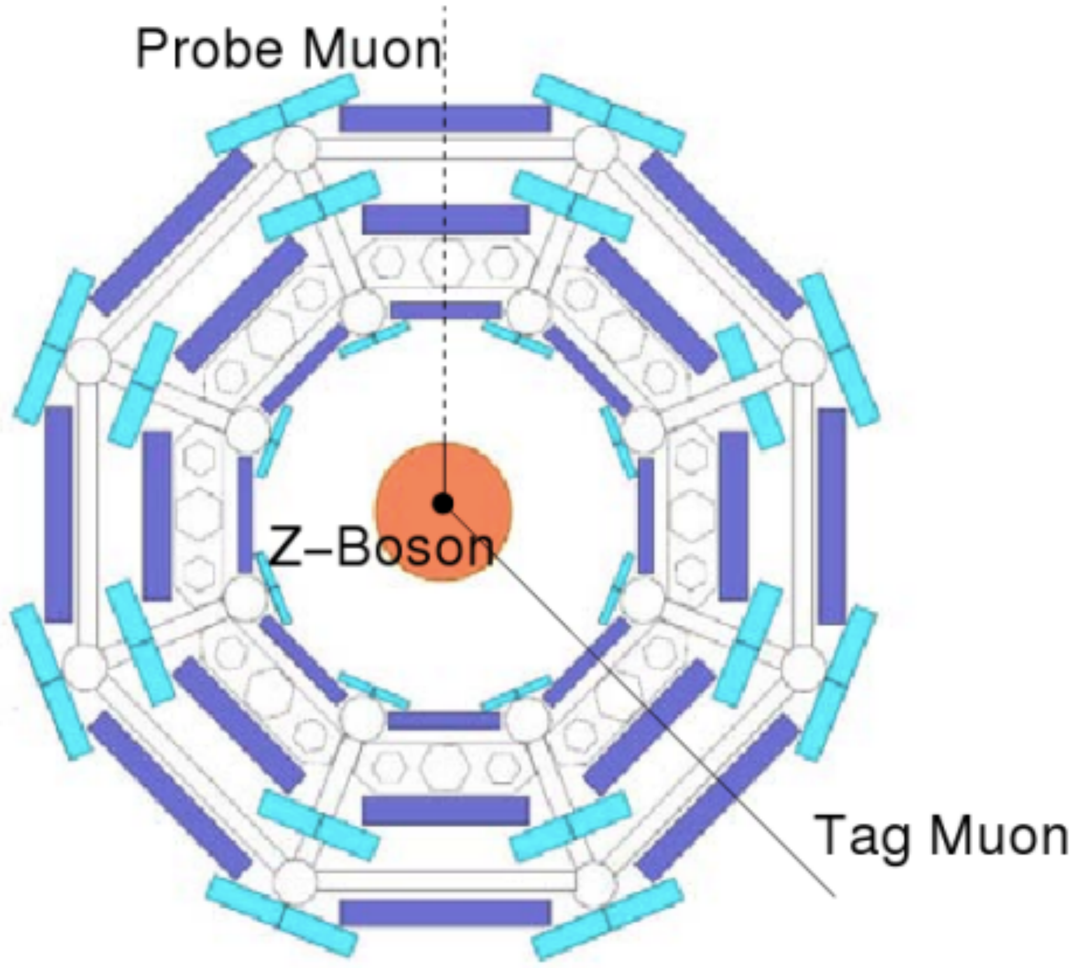


Efficiencies of muon ID WP in simulated $t\bar{t}$ events.

Background muon

Muon efficiency measurements

[CERN-EP-2020-199]



Tag & Probe method:

Select sample containing di-muon pairs

- Tag muon:
  fires trigger; passes stringent identification and isolation criteria;

- Probe muon:
  loosely reconstructed muons

$Z \rightarrow \mu\mu$

2015 paper: $\epsilon(X) = \epsilon(X|\mathrm{ID}) \times \epsilon(\mathrm{ID}) \simeq \epsilon(X|\mathrm{CT}) \times \epsilon(\mathrm{ID}|\mathrm{MS})$

muons with MS track — *muons without MS track*

Current method: $\epsilon(X) \simeq \epsilon(X|\mathrm{ID} \wedge \mathrm{MS}) \times \epsilon(\mathrm{MS}|\mathrm{CT}) \times \epsilon(\mathrm{ID}|\mathrm{MS}) + \epsilon(X \wedge \neg\mathrm{MS}|\mathrm{ID}) \times \epsilon(\mathrm{ID}|\mathrm{CT})$

X eff. (e.g. Medium) — *MS eff.* — *ID eff.* — *X eff.* — *ID eff.*

$J/\psi \rightarrow \mu\mu$

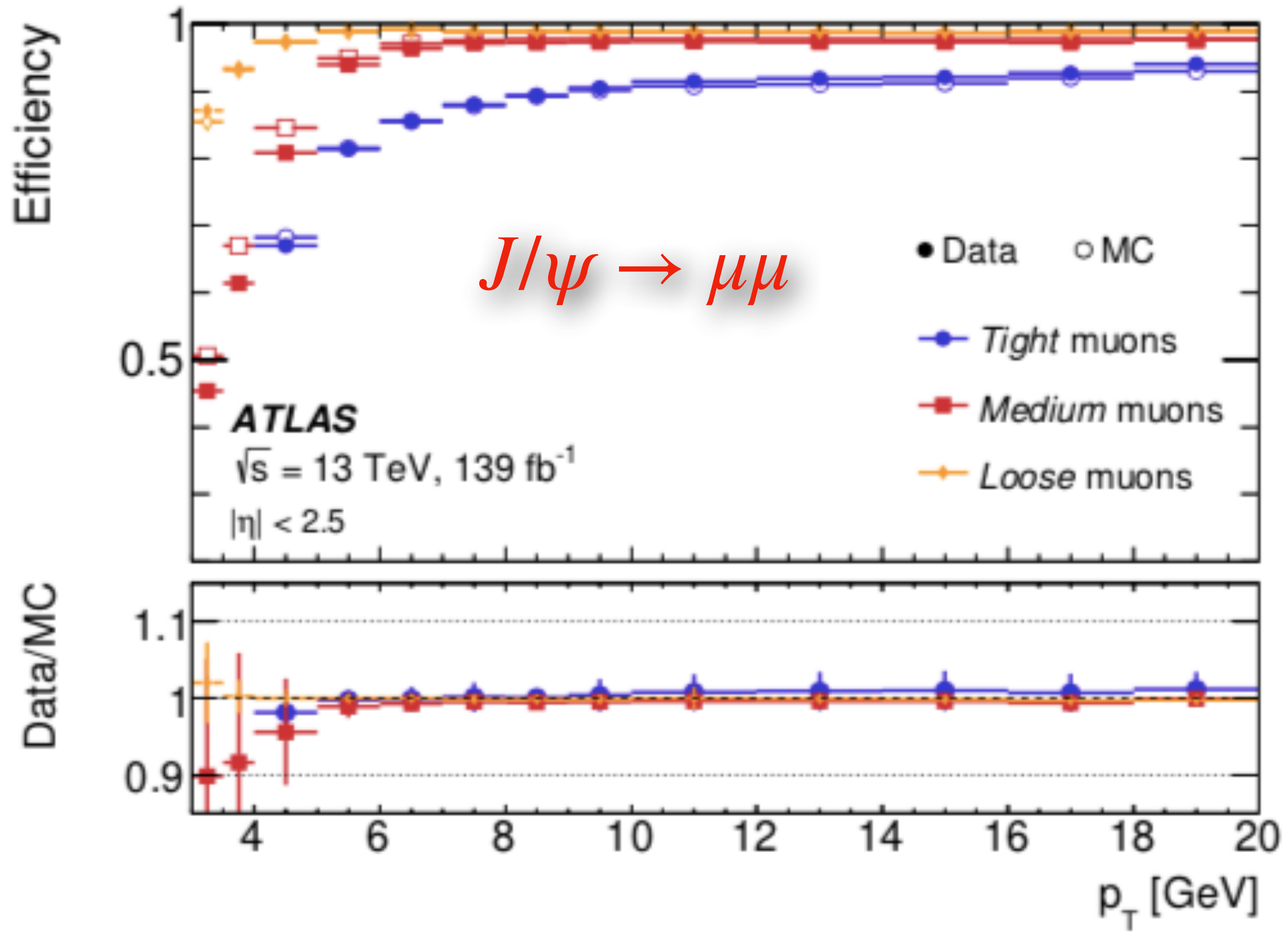
X eff. given ST — *ST eff. given CT or ID* — **ID eff.**

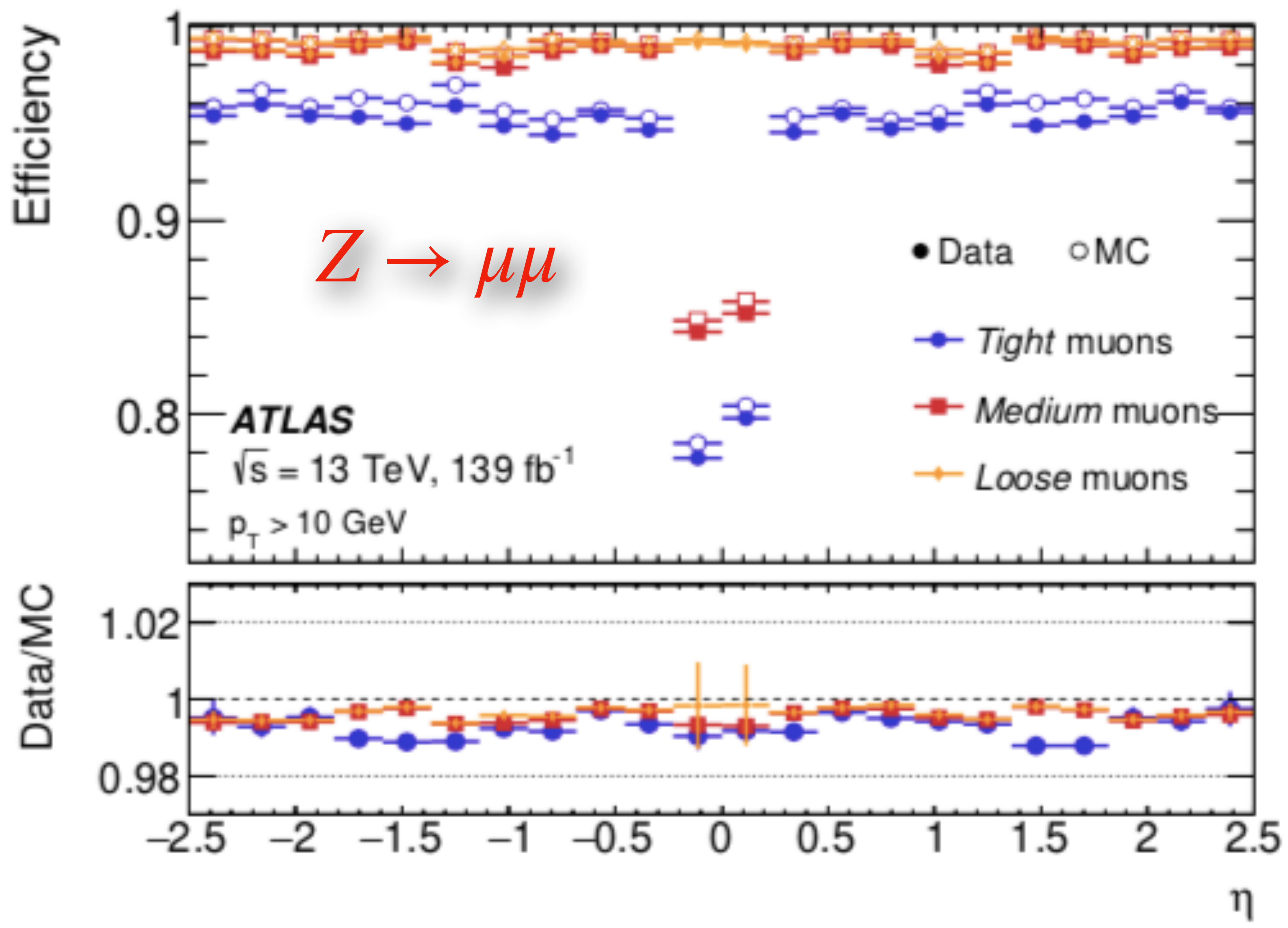
$\epsilon(X) \simeq \epsilon(X|\mathrm{ST}) \times \epsilon(\mathrm{ST}|\mathrm{ID} \vee \mathrm{CT} \text{ if } p_{\mathrm{T}} > 5\,\mathrm{GeV}) \times \epsilon(\mathrm{ID}|\mathrm{MS})$

CT: ID + calorimeter; ST: ID + MS segment **X = *Loose, Medium, …***

Muon reconstruction & identification efficiencies

CERN-EP-2020-199





- pT < 5 GeV, efficiencies drop significantly:
  - Muons are too soft to cross the calorimeters and reach the second station of precision MS chambers.
- ***Loose*** WP allows for recovering efficiency in the regions with limited MS acceptance

Muon isolation requirements

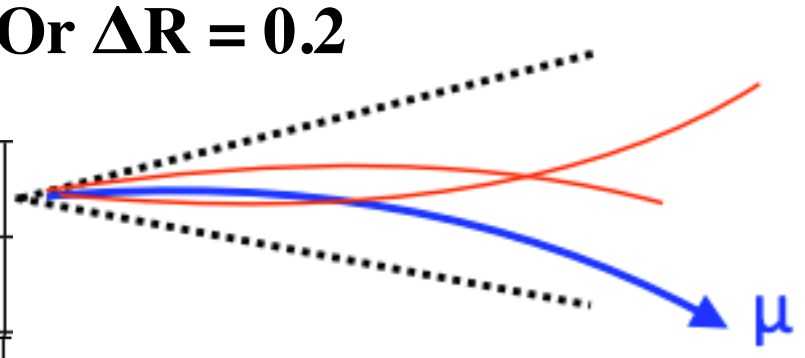
- Transverse energy reconstructed around the muon can be used to define **isolation.**
- **Isolation** criteria can reject most **non-prompt muons** from hadron decays.

Track based iso

Particle-flow based iso

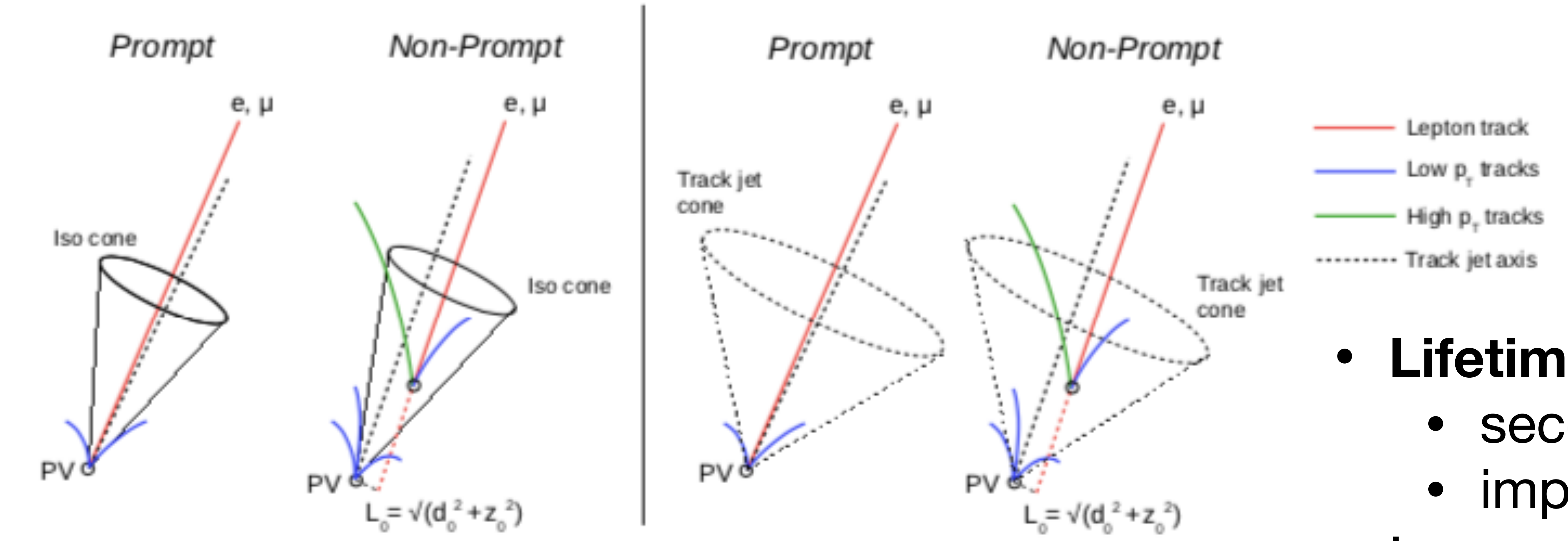
$\Delta R = \min(0.3, 10\ \text{GeV} / p_T)$

Or $\Delta R = 0.2$

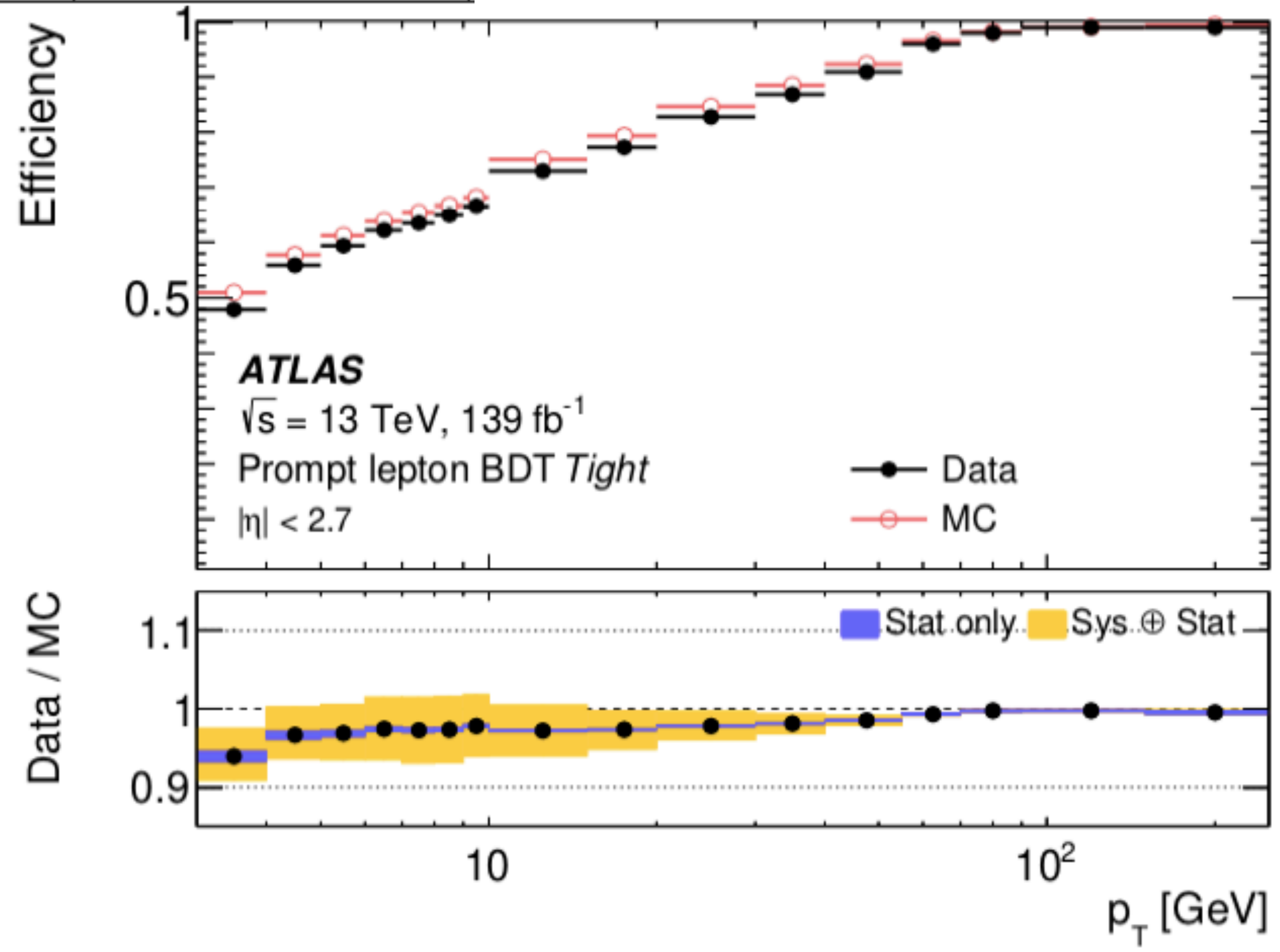


Isolation WP	Definition	Track p_T requirement	$20 < p_T$ [GeV] < 100: ϵ_μ [%]	ϵ_{HF} [%]
*PflowLoose**	$(p_T^{varcone30} + 0.4 \cdot E_T^{neflow20}) < 0.16 \cdot p_T^\mu$	$p_T > 500$ MeV	97	5.0
*PflowTight**	$(p_T^{varcone30} + 0.4 \cdot E_T^{neflow20}) < 0.045 \cdot p_T^\mu$	$p_T > 500$ MeV	87	0.9
PLBDTLoose (*PLBDTTight*)	$p_T^{varcone30} < \max(1.8\ \text{GeV}, 0.15 \cdot p_T^\mu)$ BDT cut to mimic *TightTrackOnly* (*Tight*) efficiency	$p_T > 1$ GeV	93	1.3
			87	0.5

Use BDT combine **isolation** and **lifetime** features to maximise the rejection for non-prompt muons/electrons



MVA method



- **Lifetime features** are extracted from:
  - secondary vertex
  - impact parameters of the ID tracks around the muon
- Improves rejection of non-prompt muons by **1.8** than PflowTight WP in $t\bar{t}$ MC

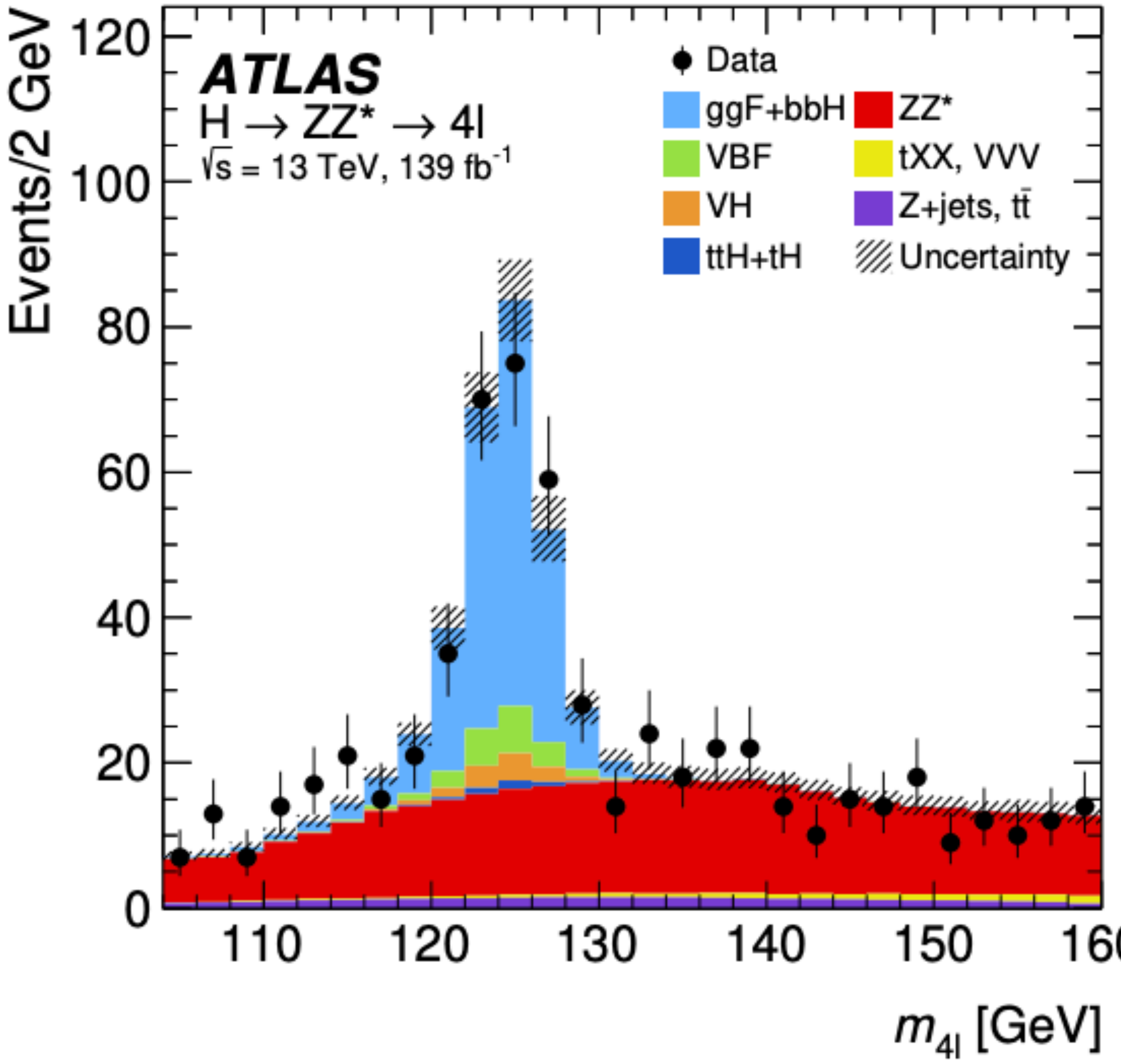
Summary

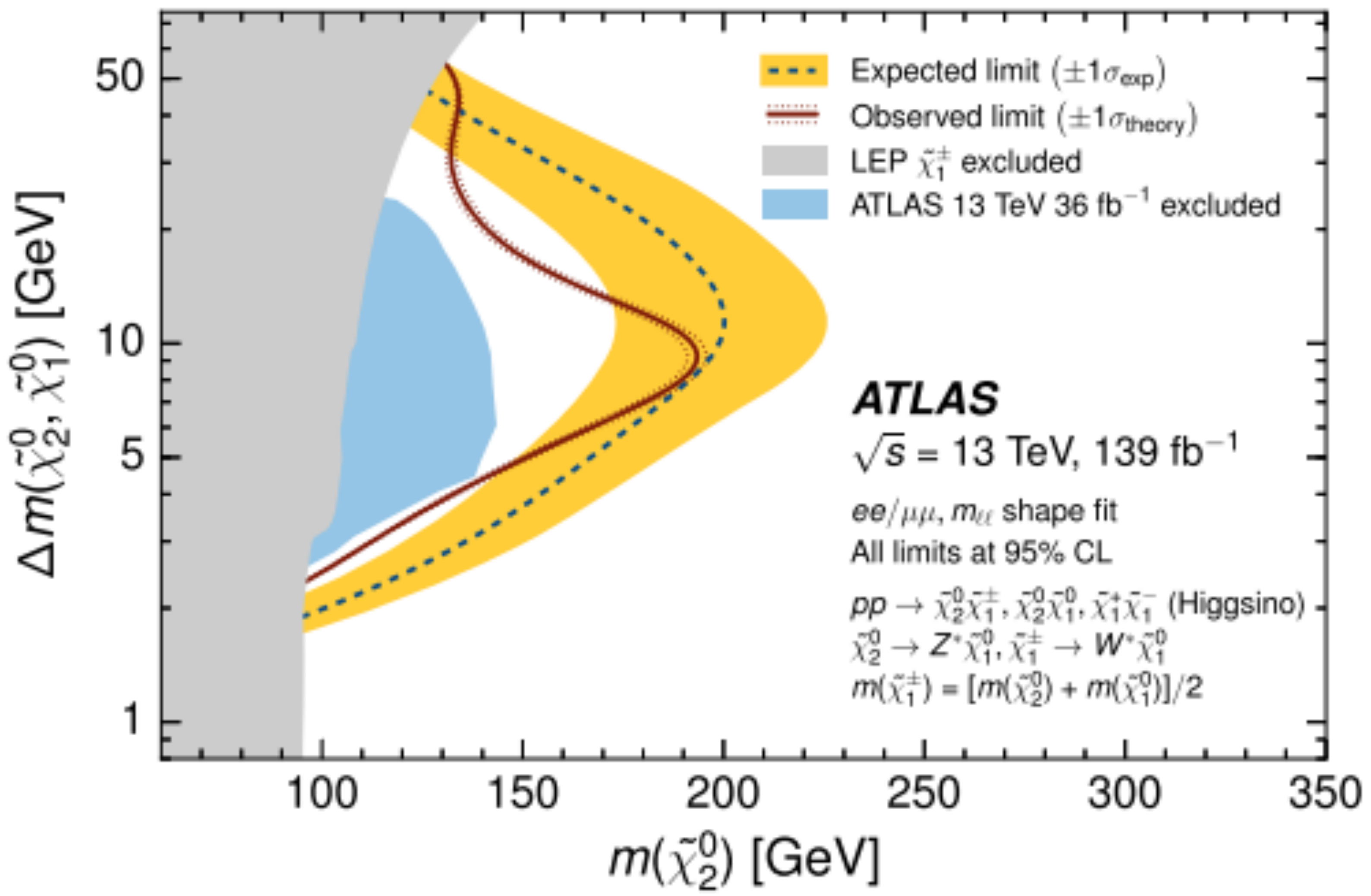
Electron:

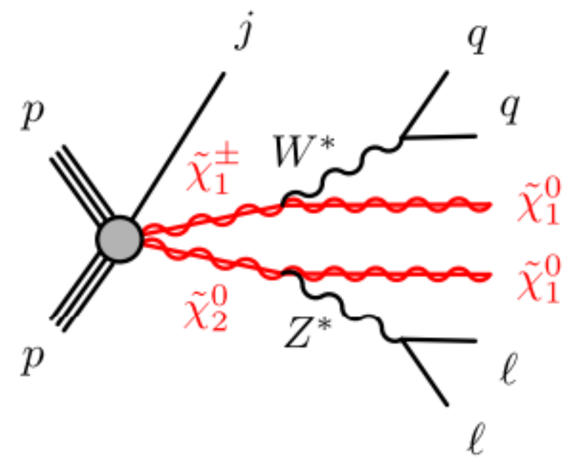
- Supercluster method is introduced in the electron reconstruction and improves the **energy resolution** by up to **30%, mass resolution** (J/ψ, H) improves by **5~8%**
- The identification of electrons and photons has been revisited to match the improved cell clustering procedure.

Muon:

- Re-optimized the reconstruction & identification with ~40 times more data w.r.t. the 2015 result.
- Improves the efficiency measurement down to pT = 3 GeV and covering |η| < 2.7







SUSY

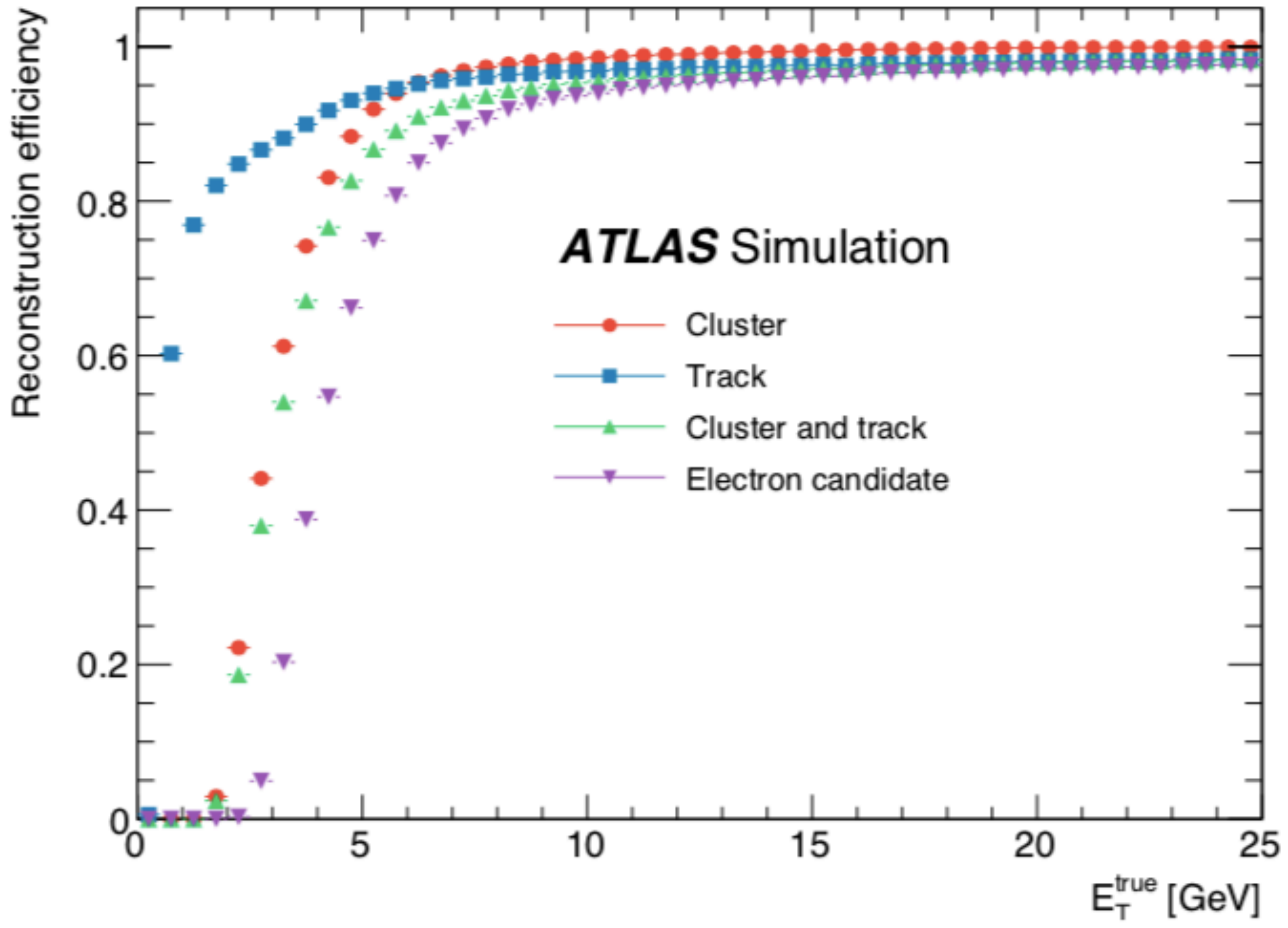
CERN-EP-2019-242

- Low-pT ID used for the muon;
- Recovers approximately 20% ID eff. at 3 < pT < 6GeV |η| < 1.2 region

Backup

Electron reconstruction efficiency

Electron reco efficiency reaches the track efficiency at high pT (as expected)

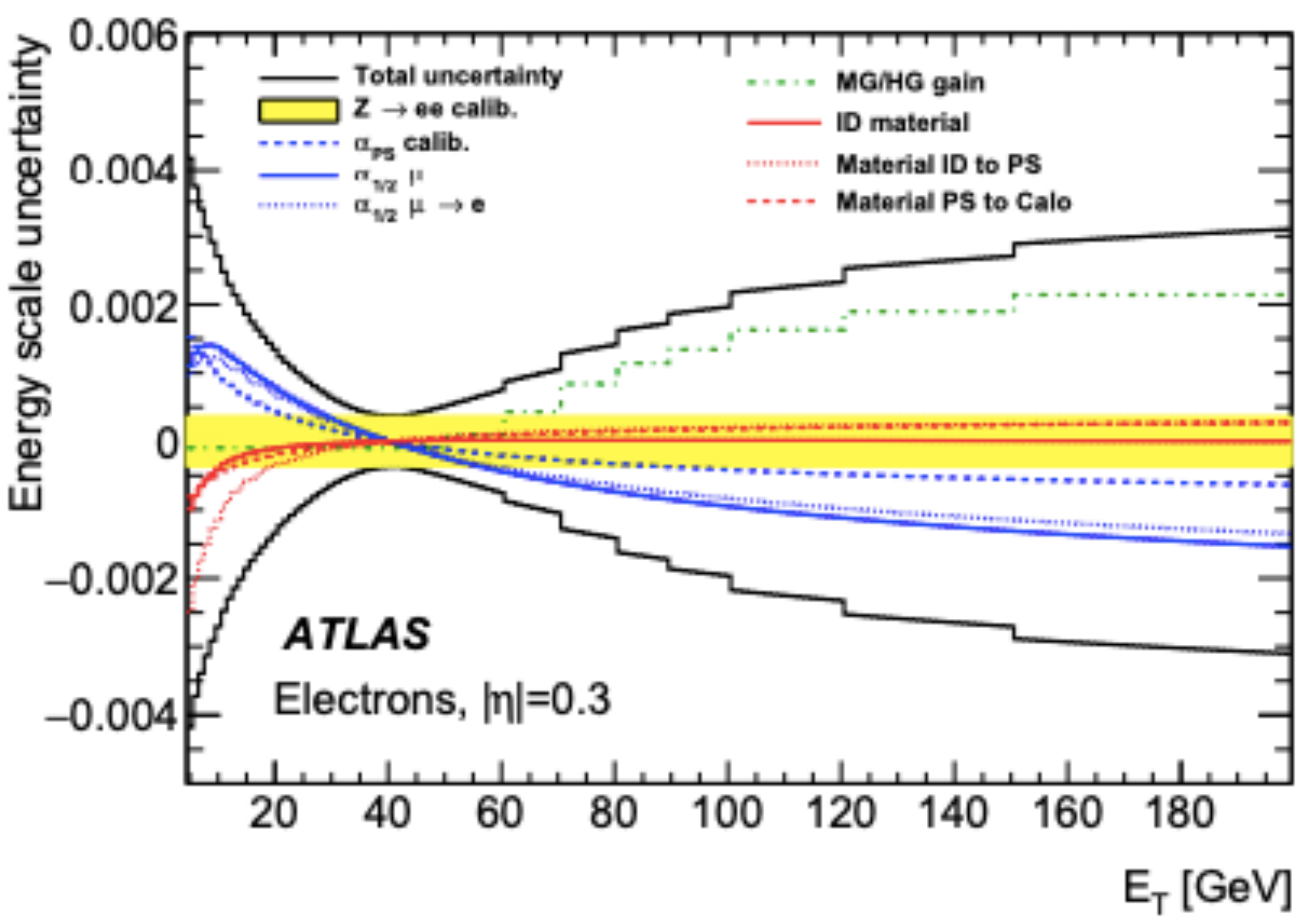


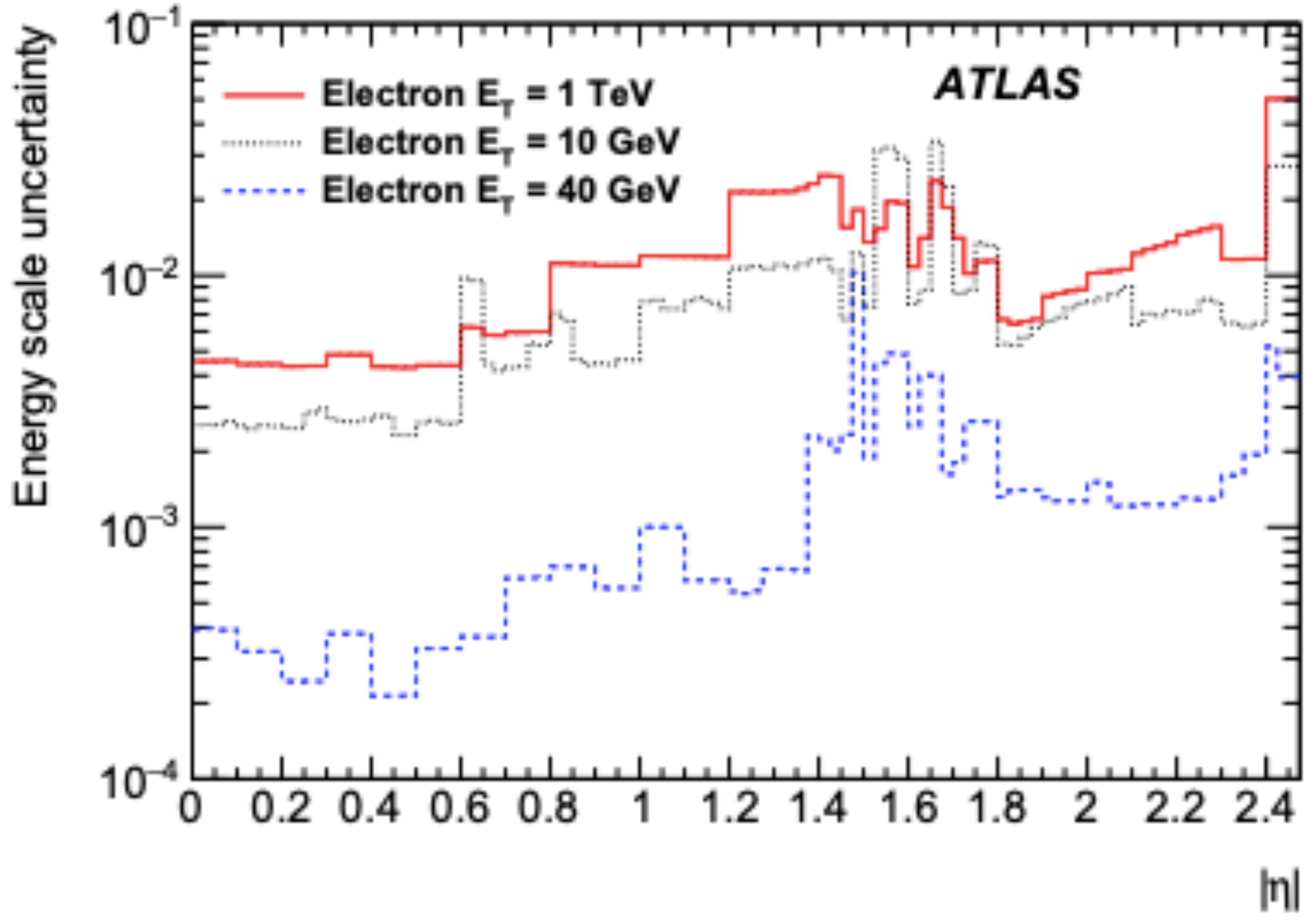
Electron energy scale and resolution uncertainty

CERN-EP-2018-296

Based on 2015-2016 proton–proton collision data

Energy scale





Energy resolution