ATLAS Run2 Higgs→γγ mass and e/γ energy calibration

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IRN Terascale @ Marseille
26th October 2023

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

ATLAS EXPERIMENT

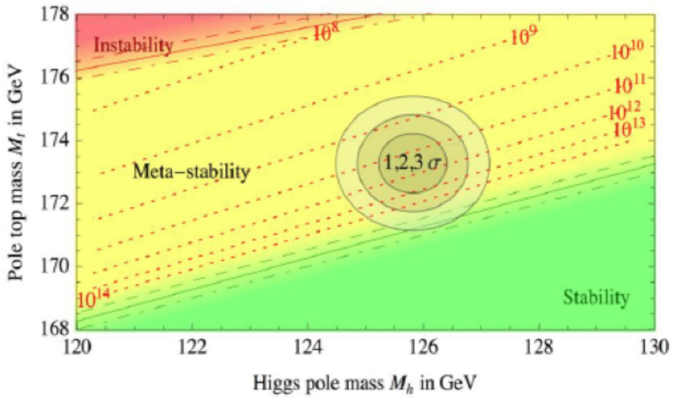
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

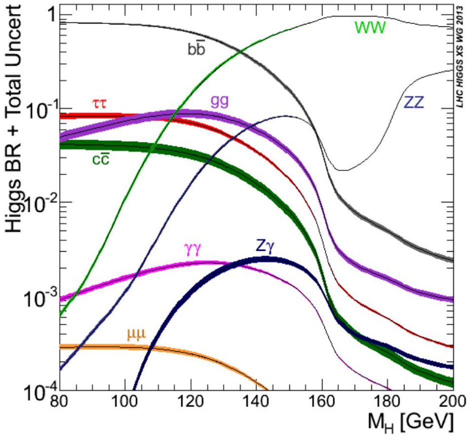
DESY.

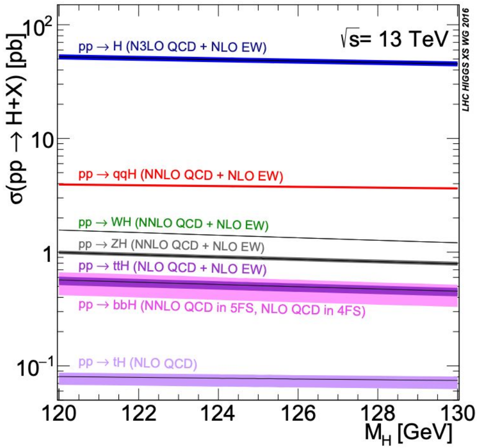
Introduction

Why Higgs boson mass is important?

- govers **coupling** between Higgs and other SM particles
- key input for **global electroweak fit**
- electroweak **vacuum stability**
- **free parameter in SM (experiemental)**







At LHC, m_H is measured with H→γγ and H→4l decays thanks to their excellent mass resolution and S/B ratio

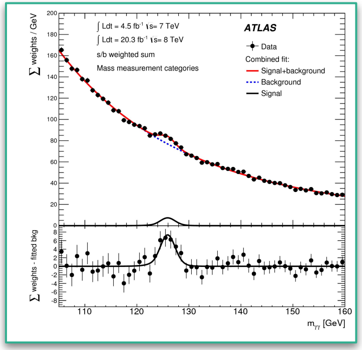
This talk will present the full run 2 ATLAS H→γγ mass measurement with 140 fb^{-1} data (paper link)

Roadmap of ATLAS H→γγ mass

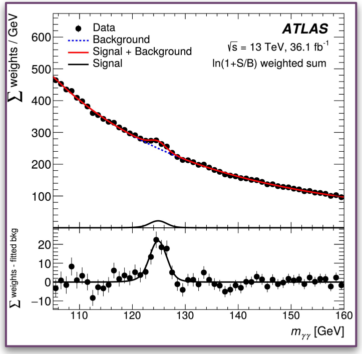
From Run 1 to Run 2

01 Run1: 25 fb^{-1}

$$m_H = 125.98 \pm 0.42(\text{stat}) \pm 0.28(\text{syst})\,\text{GeV}$$
$$= 125.98 \pm 0.50\,\text{GeV}$$



02 Partial Run2: 36 fb^{-1}



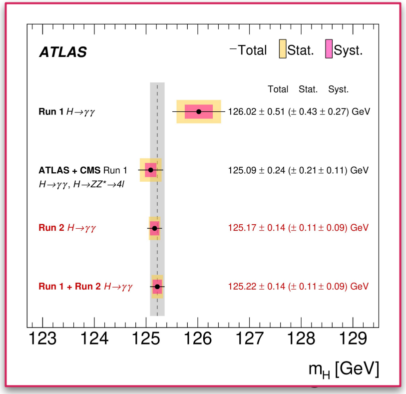
$$m_H = 124.93 \pm 0.21(\text{stat}) \pm 0.34(\text{syst})\,\text{GeV}$$
$$= 125.93 \pm 0.40\,\text{GeV}$$

NEW results with unprecedented 0.1% precision shown in LP2023 and EPS-HEP 2023

$$m_H = 125.17 \pm 0.11(\text{stat}) \pm 0.09(\text{syst})\,\text{GeV}$$
$$= 125.17 \pm 0.14\,\text{GeV}$$

03 Full Run2: 140 fb^{-1}

- **topic of this presentation**
- current best γ channel result
- was the best single channel just ~ **1 month ago** before CMS-4l **0.12 GeV** precision paper



For a good m_H measurement with photons

"just think about what are at least needed🙂"

Major requirements:

- Good photon selection against the jet fakes photon
- Vetex algorithm for trackless process (e.g. $gg\rightarrow\gamma\gamma$)
- Minimize m_H uncertainty:
  - good S/B ratio
  - statistical uncertainty ~ $m_{\gamma\gamma}$ resolution (γ energy, vertex resolution, etc)
  - systematic uncertainty ~ photon energy scale
  - Splitting into categories often helps

Other important ones:

- Accurate modelling of signal and background
- Interference between $gg/gq\rightarrow H\rightarrow\gamma\gamma$ and $gg/gq\rightarrow\gamma\gamma$ affects the Higgs mass peak

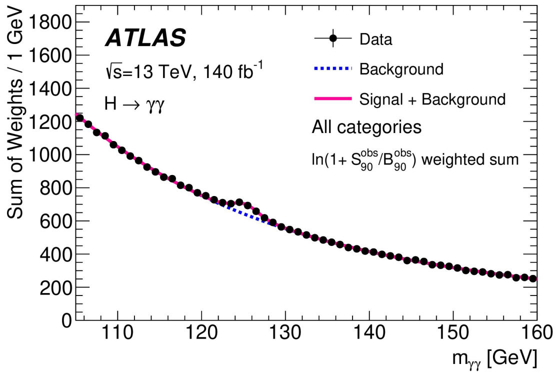
How m_H is measured with photons

All events

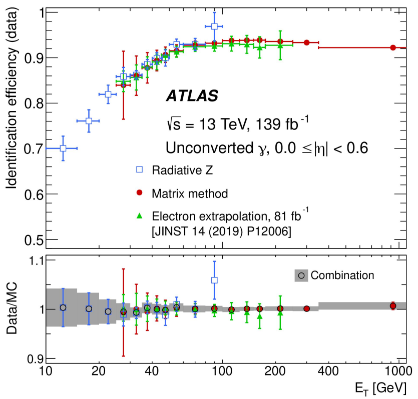
Di-photon cut

- **2 identified&isolated** unconverted or converted ($\gamma \rightarrow ee$ before calorimter) photons
- **Neural Network** based vertex reco (trackless)
- $p_T^{\gamma}/m_{\gamma\gamma}$ > 0.35 (0.25)

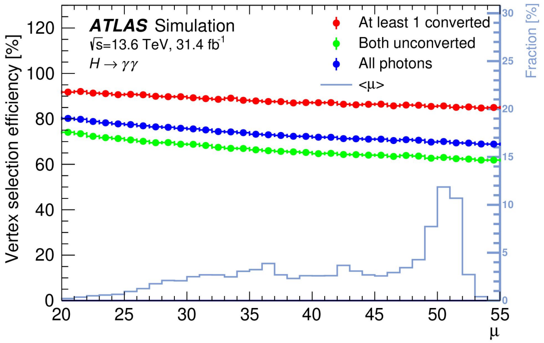
inclusive $m_{\gamma\gamma}$



- ATLAS has powful **photon identification** criteria and **isolation selection**
- Calorimeter pointing information trained in **vertex NN** improve $m_{\gamma\gamma}$ resolution by up to 8%



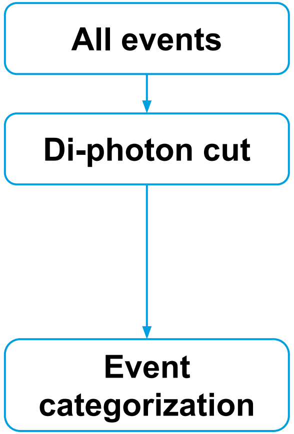
90% efficiency Iso&ID for unconverted photon EGAM-2021-01

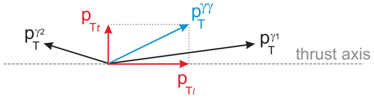


diphotn vertex efficiency > 70%

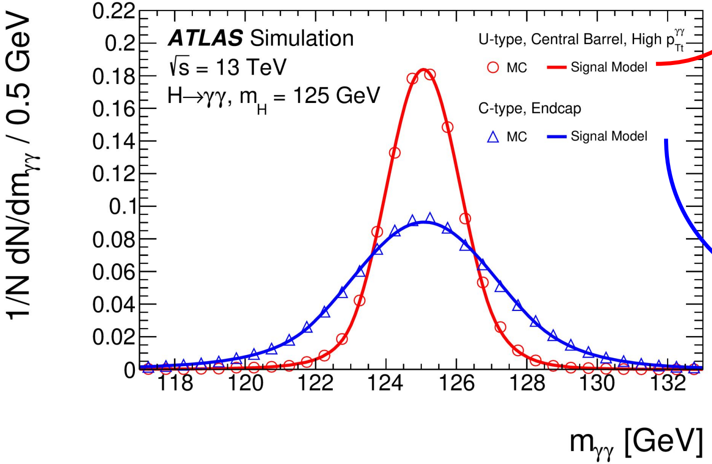
(plot taken from Run 3 H→γγ cross section)

How m_H is measured with photons





$m_{\gamma\gamma}$ resolution in different regions and for different **γ**-type

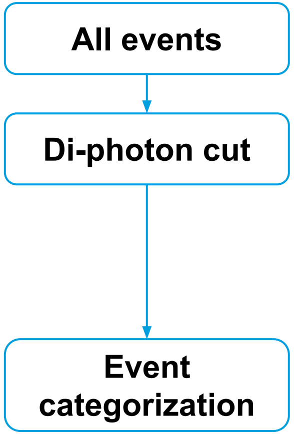


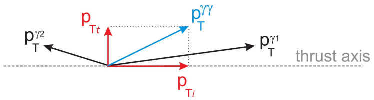
Category	$\sigma_{68}^{\gamma\gamma}$ [GeV]
U, Central-barrel, high $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.10
U, Central-barrel, medium $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.38
U, Central-barrel, low $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.47
U, Outer-barrel, high $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.24
U, Outer-barrel, medium $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.52
U, Outer-barrel, low $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.75
U, Endcap	1.90
C, Central-barrel, high $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.17
C, Central-barrel, medium $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.51
C, Central-barrel, low $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.68
C, Outer-barrel, high $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.44
C, Outer-barrel, medium $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.82
C, Outer-barrel, low $p_{\mathrm{Tt}}^{\gamma\gamma}$	2.10
C, Endcap	2.23
Inclusive	1.82

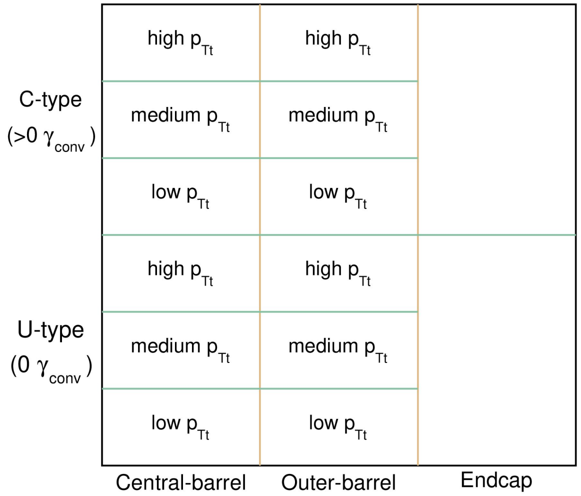
Events are further classified into categories characterised by different:

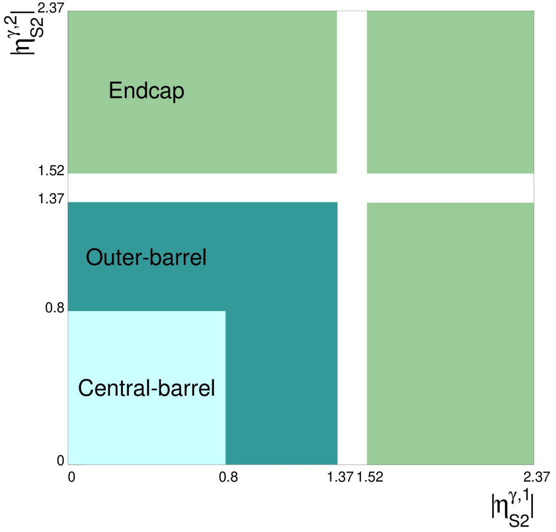
- $m_{\gamma\gamma}$ resolution (✅ low η, unconv)
- S/B ratio (✅ high p_{Tt})
- γ energy syst. (✅ low η, unconv)

How m_H is measured with photons









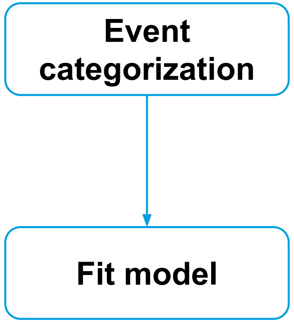
14 categories definition based on:

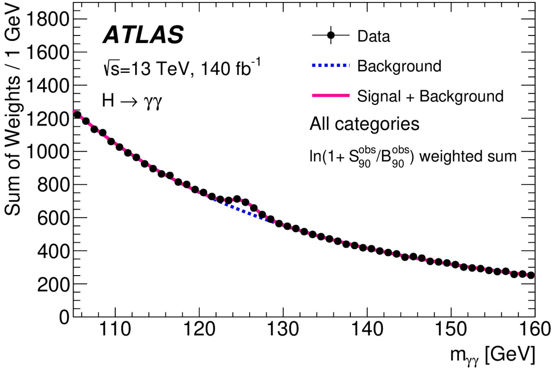
- number of converted photon
- photon pseudo-rapidity
- diphoton transverse thrust p_T

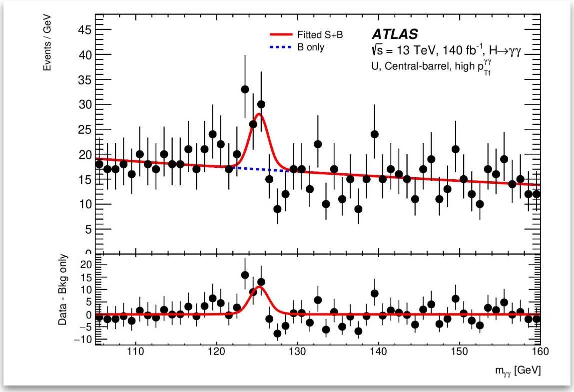
Categories optimized to reduce the total mass uncertainty by 17% compared with an inclusive measurement

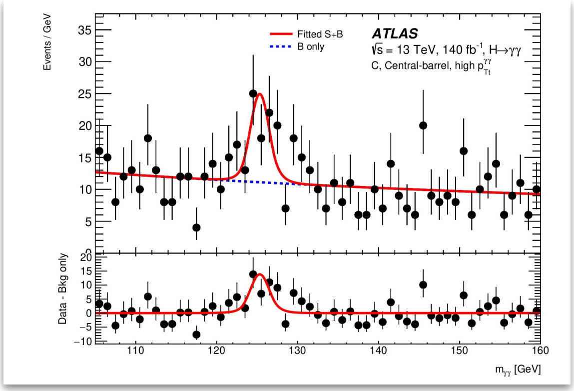
How m_H is measured with photons

Fitted $m_{\gamma\gamma}$ for unconverted and converted categories in central-barrel and high p_{Tt} regions





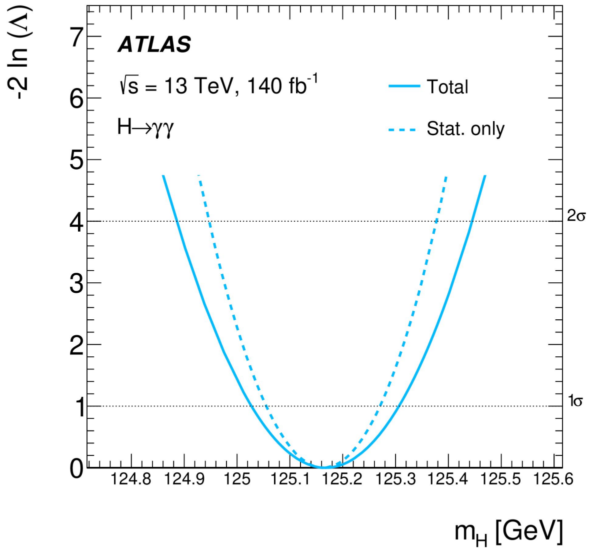


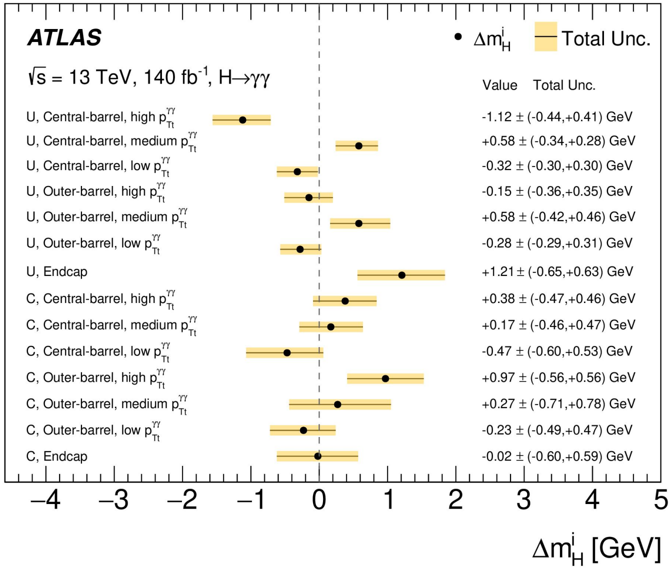


m_H is obtained by a maximum unbinned likelihood fit on $m_{\gamma\gamma}$, simultaneously in all the 14 categories:

- **signal** modelled by a double-sided crystal function depending on hypothesis m_H, i.e. pdf($m_{\gamma\gamma}|m_H$)
- **bkg** modelled by exponential, power law or exponentiated polynomia

Run 2 H→γγ mass results





m_H = 125.17 ± 0.11 (stat.) ± 0.09 (syst.) = 125.17 ± 0.14 GeV

- A **total 0.11% precision** achieved, with **0.09% (0.07%)** relative **statistical (systematic)** uncertainty
- The best fits of m_H per category are consistent with a p-value of 8%
- **~ a factor 4 improvement** on **systematic** uncertainty w.r.t. previous (36.1 fb^{-1})

$$\text{Previous } (36.1\ \text{fb}^{-1}) : \ m_H = 124.93 \pm 0.21(\text{stat}) \pm 0.34(\text{syst})\ \text{GeV} = 125.98 \pm 0.40\ \text{GeV}$$

Run 2 H→γγ mass results

m_H systematic breakdown

Final Run2 (140 fb^{-1})

Source	Impact [MeV]
Photon energy scale	83
$Z \to e^+e^-$ calibration	59
E_T-dependent electron energy scale	44
$e^\pm \to \gamma$ extrapolation	30
Conversion modelling	24
Signal–background interference	26
Resolution	15
Background model	14
Selection of the diphoton production vertex	5
Signal model	1
Total	90

Paritual Run2 (36.1 fb^{-1})

Source	Systematic uncertainty on $m_H^{\gamma\gamma}$ [MeV]
EM calorimeter cell non-linearity	±180
EM calorimeter layer calibration	±170
Non-ID material	±120
ID material	±110
Lateral shower shape	±110
$Z \to ee$ calibration	±80
Conversion reconstruction	±50
Background model	±50
Selection of the diphoton production vertex	±40
Resolution	±20
Signal model	±20

How was the systematics reduced from 340 MeV to 90 MeV:

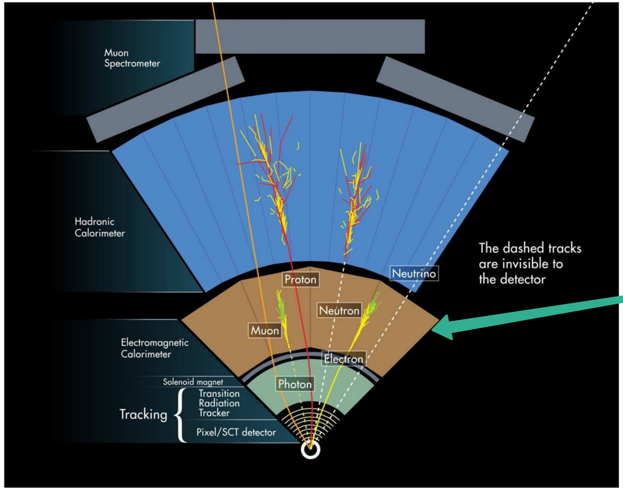
- Benefit from the extensive works that **refine the photon energy calibration** and **associated uncertainties (factor 2)**
- E_T-dependent electron energy scale uncertainties are **constrained** by **data-to-MC energy scale difference measured in E_T bins with Z→ee events (factor 2)**

Effect on mass peak due to **interference** between H→γγ and γγ+jets is currently included as systematic. Better simulation will help to include the interference as a correction to the future analysis

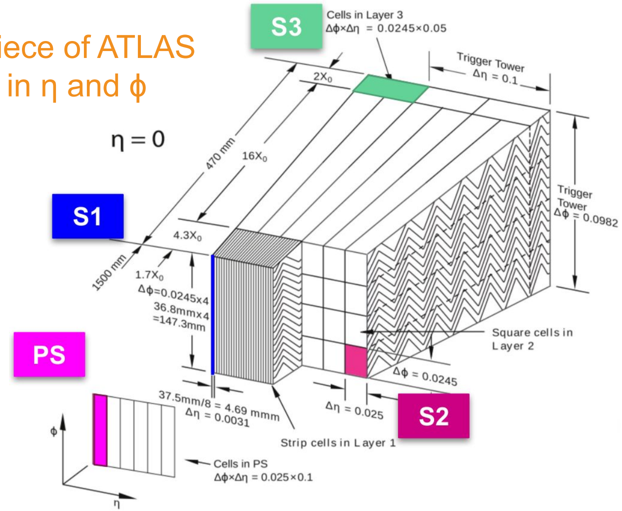
In the following, I will discuss about the ATLAS electromagnetic calorimeter energy calibration

Previous (36.1 fb^{-1}) : $m_H = 124.93 \pm 0.21(\text{stat}) \pm 0.34(\text{syst})\,\text{GeV} = 125.93 \pm 0.40\,\text{GeV}$

ATLAS ECAL and energy calibration



A small piece of ATLAS ECAL in η and ϕ



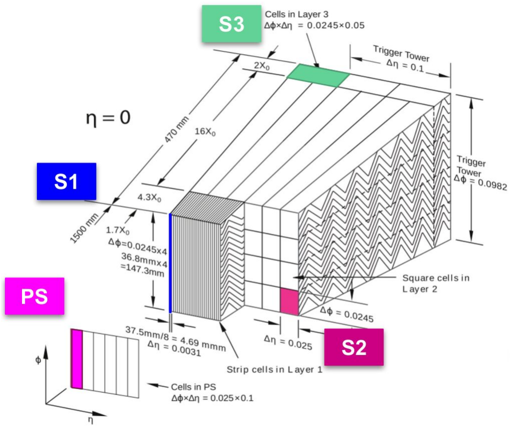
- **Sampling calorimeter** with lead (liquid argon) as dense (active) material
- **4-layer structure** to record the **longitudinal shower** information
  - Layer 0: presampler used to estimate energy loss due to material before ECAL
  - Layer 1: fine η granularity to distinguish e^+e^- pair from neutral pion and photon conversion
  - Layer 2: main deposition of EM shower
  - Layer 3: estimate leakage to hadronic calorimeter

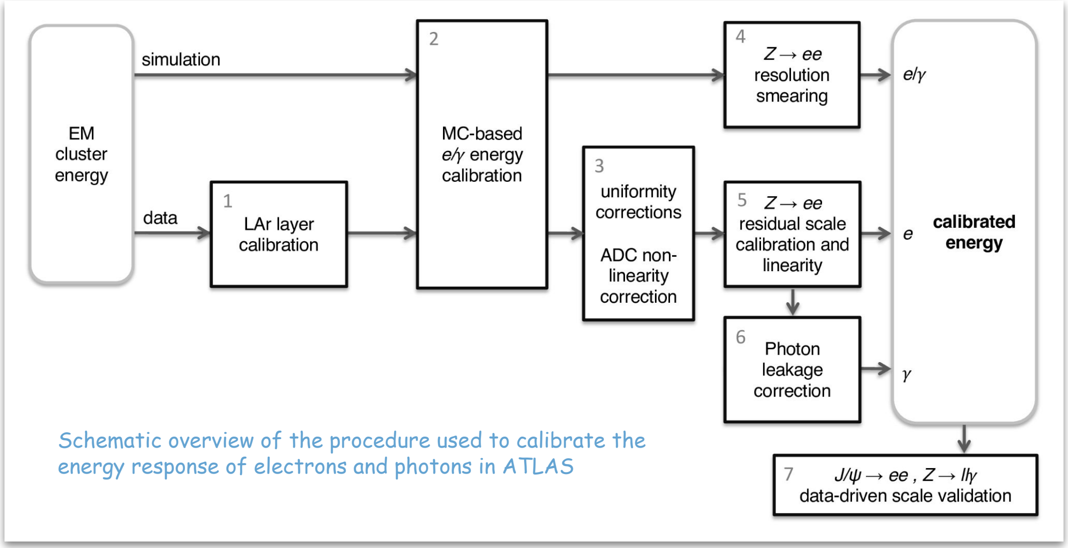
For precise energy response (in particular **energy linearity**), the **various layers** should be properly calibrated and intercalibrated

ATLAS ECAL and energy calibration

Final run 2 egamma calibration paper

was out last month





Schematic overview of the procedure used to calibrate the energy response of electrons and photons in ATLAS

Extensive efforts made, such as improved material description upstream the ECAL, new clustering algorithm, improved electronics calibration, detector uniformity, etc. I will **focus 3 parts** of the entire calibration:

- **Layer 1 and layer 2 intercalibration**
- **Photon leakage correction**
- **Systematic constraints with data-to-MC energy scale difference measured in E_T bins with Z→ee events (energy non-linearity)**

ATLAS ECAL and energy calibration

Layer 1 and layer 2 intercalibration

Rebalance of relative energy between **layer 1** and **layer 2** between data and MC, using both **muons** and **electrons**:

$$\alpha_{1/2} = \frac{E_1^{data}/E_2^{data}}{E_1^{MC}/E_2^{MC}}$$

Muon

Pros:

- minimum ionized particle → blind to upstream material
- compact shower in 1-2 cells → easy energy reconstruction

Cons:

- affected by pileup and electronic noises
- muon longitudinal "shower" different to electron

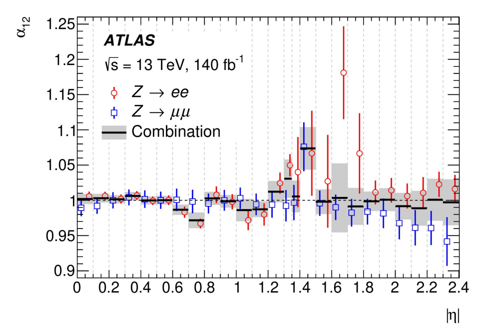
Electron

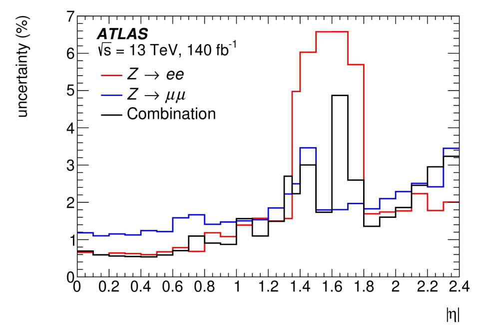
Pros:

- less affected by noises
- real shower from electron

Cons:

- bremsstrahlung → sensitive to upstream material





- layer1/2 calibration is an important systematic for $m_H(\gamma\gamma)$, with **impact>100 MeV**

- Previous: muon-based
- New: combination of both muon and electron results.

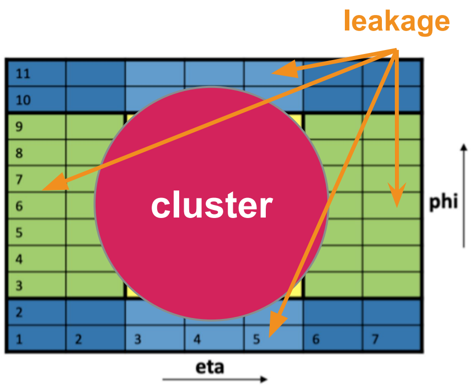
Uncertainty improved by ~ 2 in central ECAL

ATLAS ECAL and energy calibration

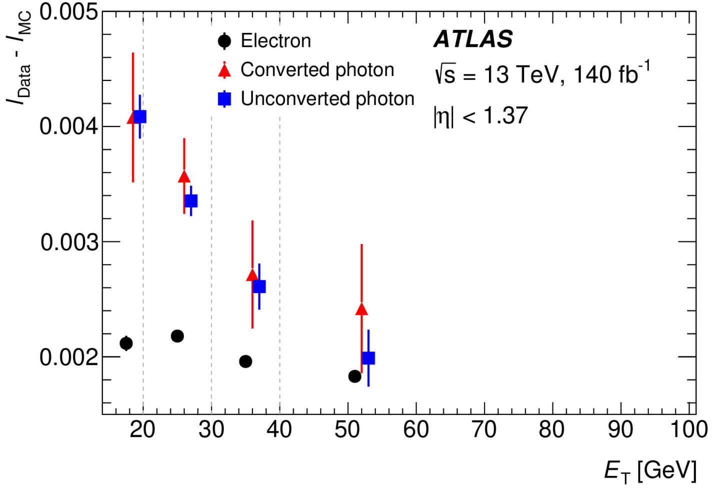
Photon leakage correction

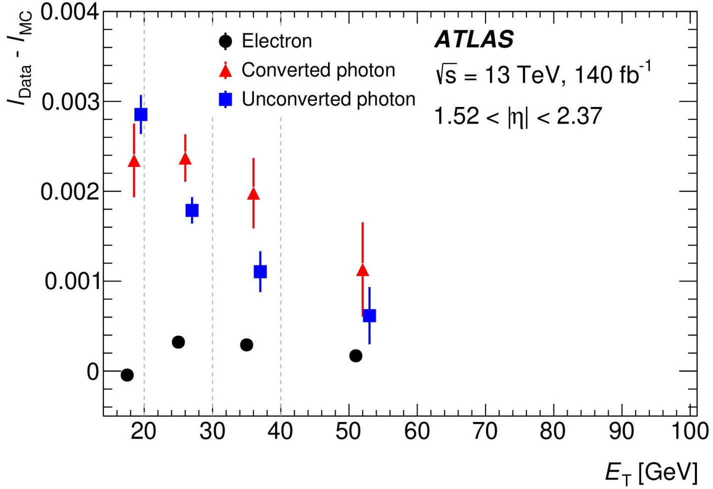
Leakage: **"seepage" of EM shower** exterior of the reconstruction cluster

- **γ vs e** residual difference not covered in previous calibration
- **~100 MeV contribution to previous γγ mass uncertainty**
- **Effect corrected in the new mass result**



An illustration of barrel region





ATLAS ECAL and energy calibration

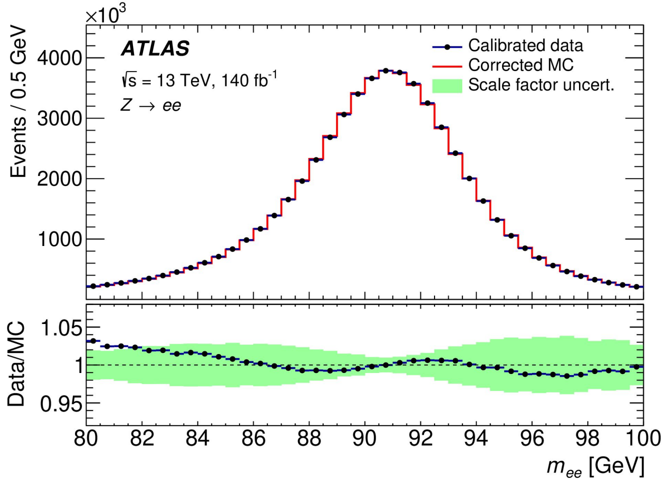
E_T-dependent energy scale uncertainties constraints (energy non-linearity)

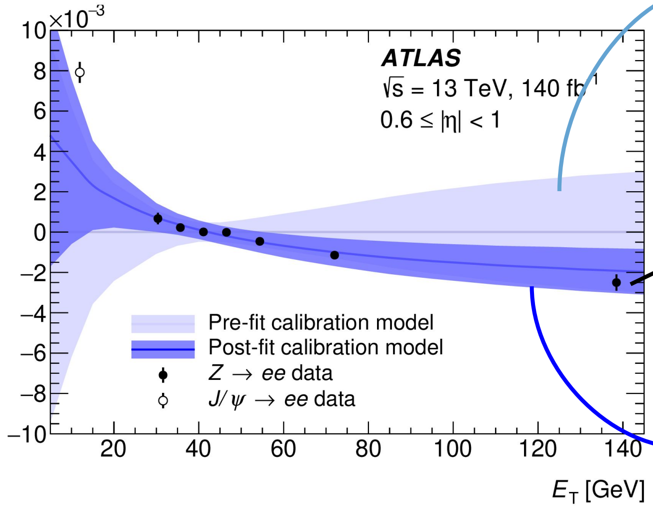
Z→ee mass peak used to calculate **e/γ data-to-MC energy scale factor $E_{data}=E_{MC}(1+\alpha(\eta))$**

- **α(η)** → E_T**-dependent energy scale uncertainties** to cover energy non-linearity away from $\langle E_T^{Zee} \rangle$ ~40 GeV
- New auxiliary measuremnt of **Z→ee residual energy non-linearity α'(η, E_T)**

↪ **constrain** the **E_T-dependent energy scale uncertainties**

↪ ~ factor 2 (4) reduction for 60 (140) GeV electron





E_T-dependent energy scale uncertainties

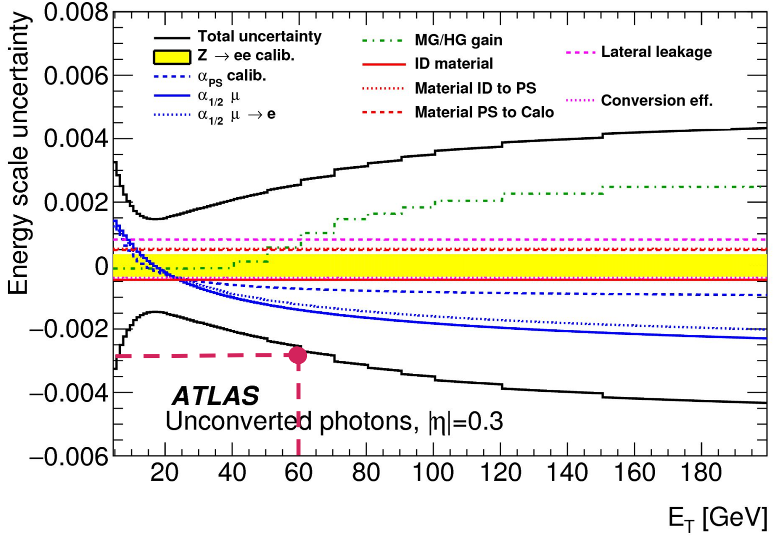
residual non-linearity α'(η, E_T)

constrained E_T-dependent energy scale uncertainties

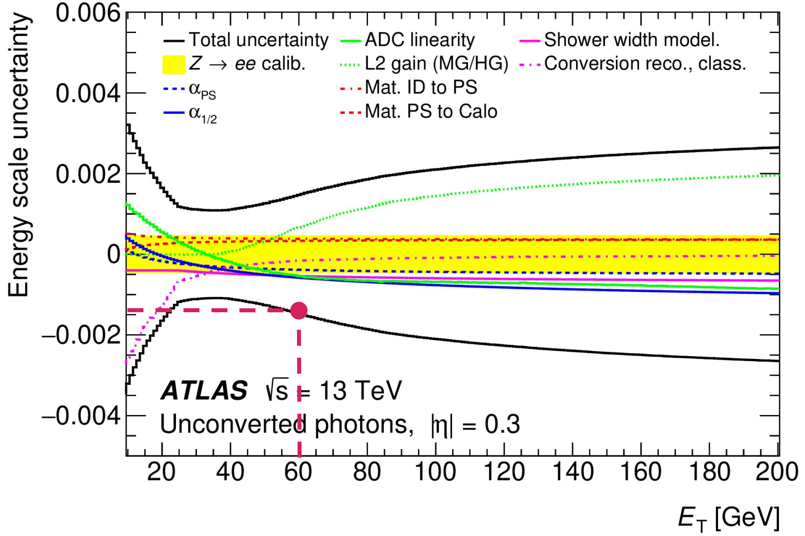
Photon energy scale systematic

Improvement before applying linearity constraint

2015-2016



Full Run 2

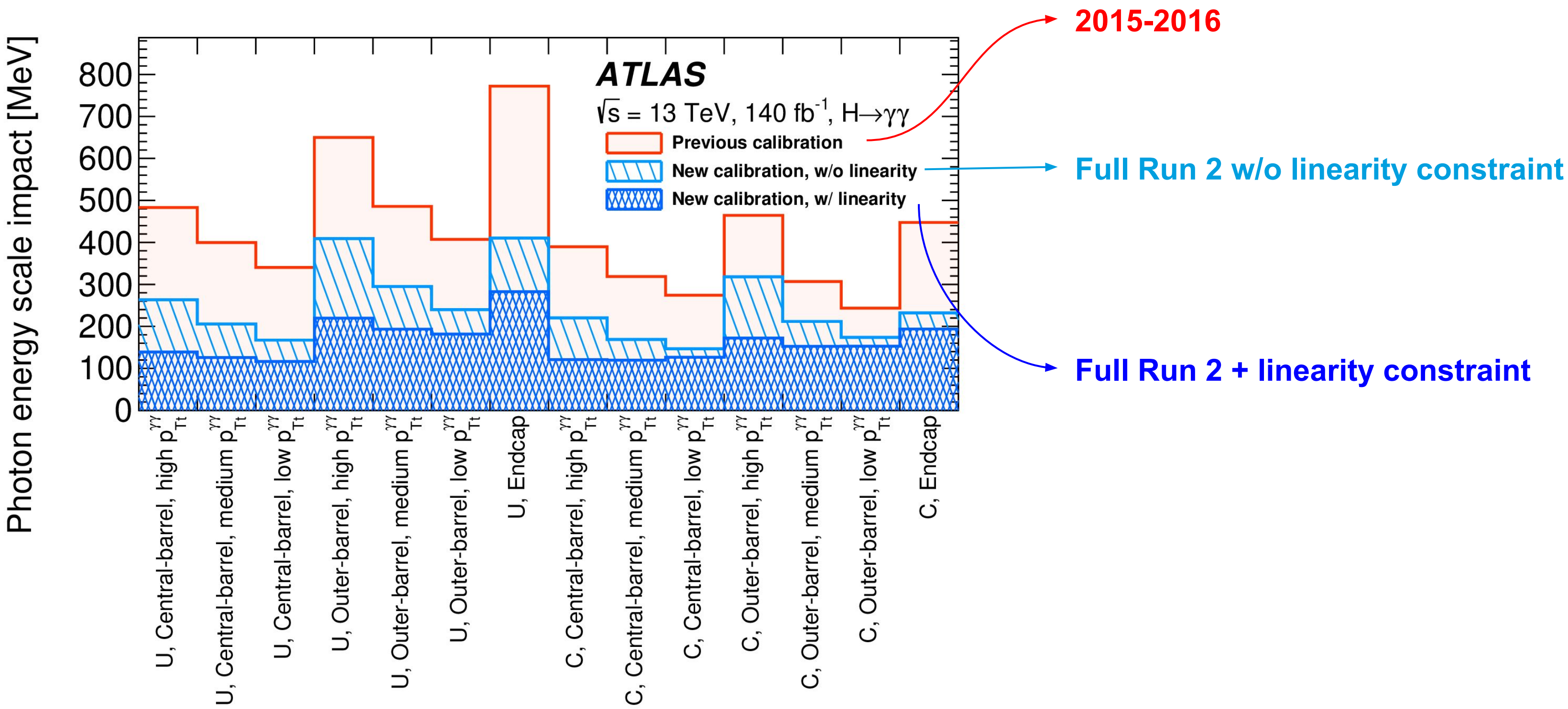


For **central unconverted photon with p_T=60 GeV** (~m_H/2), uncertainty improved

from 0.3% to 0.15%

Photon energy scale systematic improvement

Another factor 2 reduction benefitting from Z→ee linearity constraints

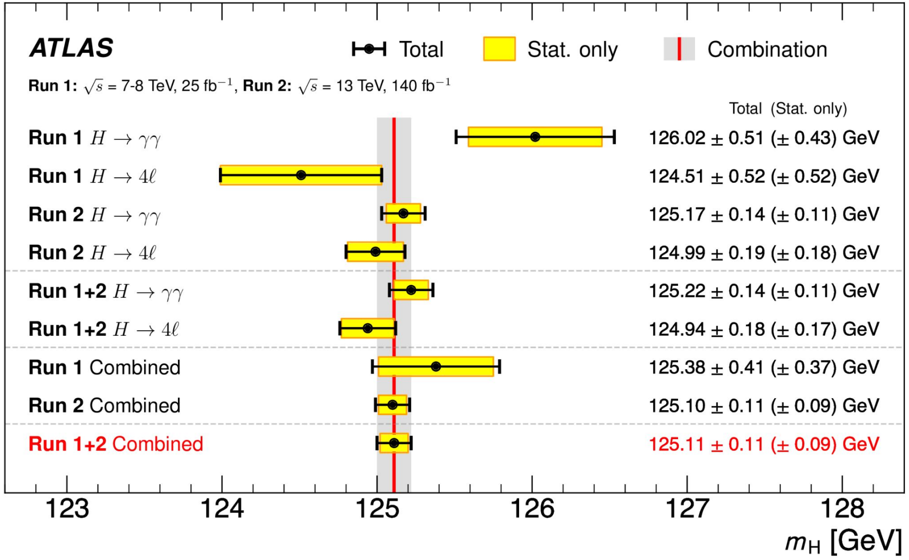


Conclusion

Full Run 2 γγ: **m_H = 125.17 ± 0.11 (stat.) ± 0.09 (syst.) = 125.17 ± 0.14 GeV**

+ Run 1 γγ: **m_H = 125.22 ± 0.11 (stat.) ± 0.09 (syst.) = 125.22 ± 0.14 GeV**

+ 4-lepton: **m_H = 125.11 ± 0.09 (stat.) ± 0.06 (syst.) = 125.11 ± 0.11 GeV**



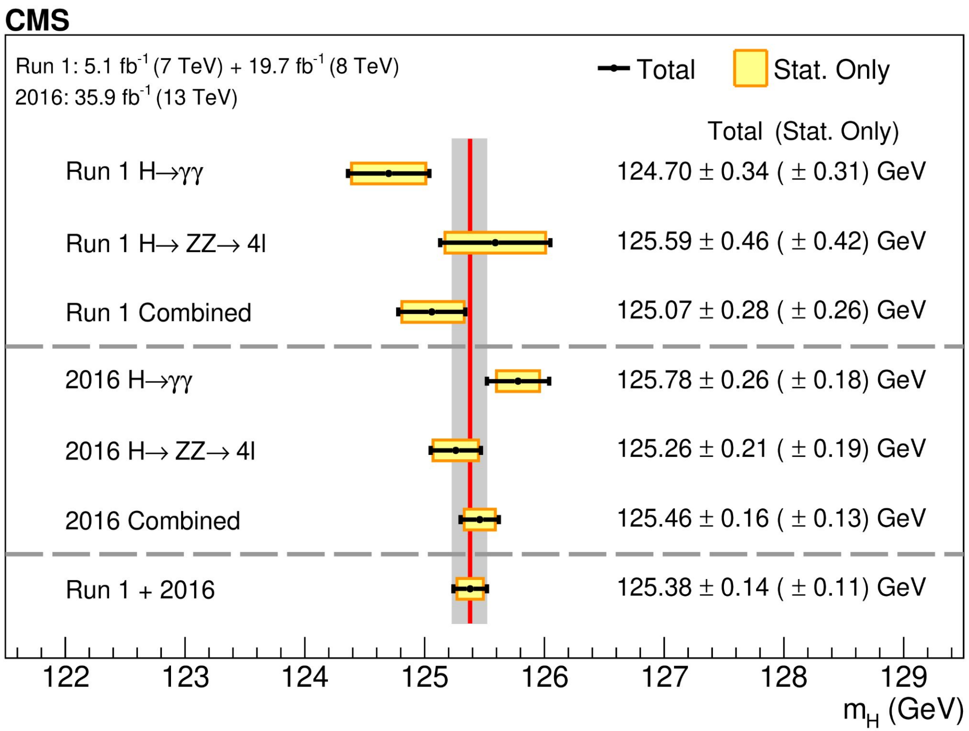
The full combined result is still the **most precise**

Very excited to look forward to combination with nice results from CMS

Backup

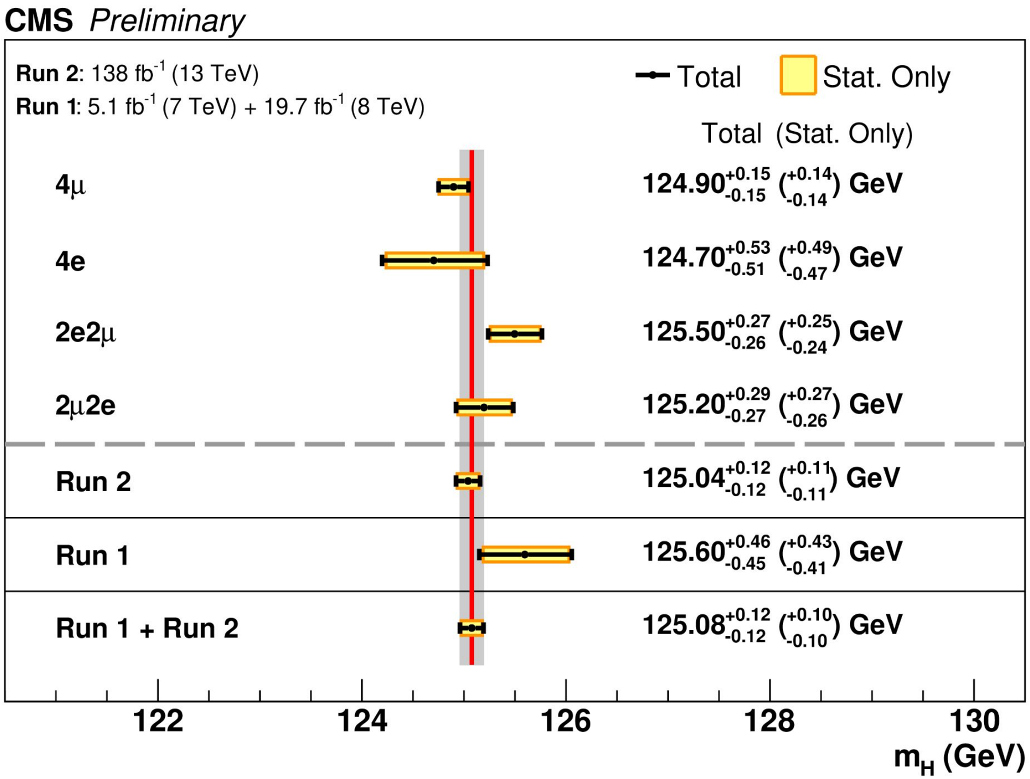
CMS diphoton m_H

Phys. Lett. B 805 (2020) 135425



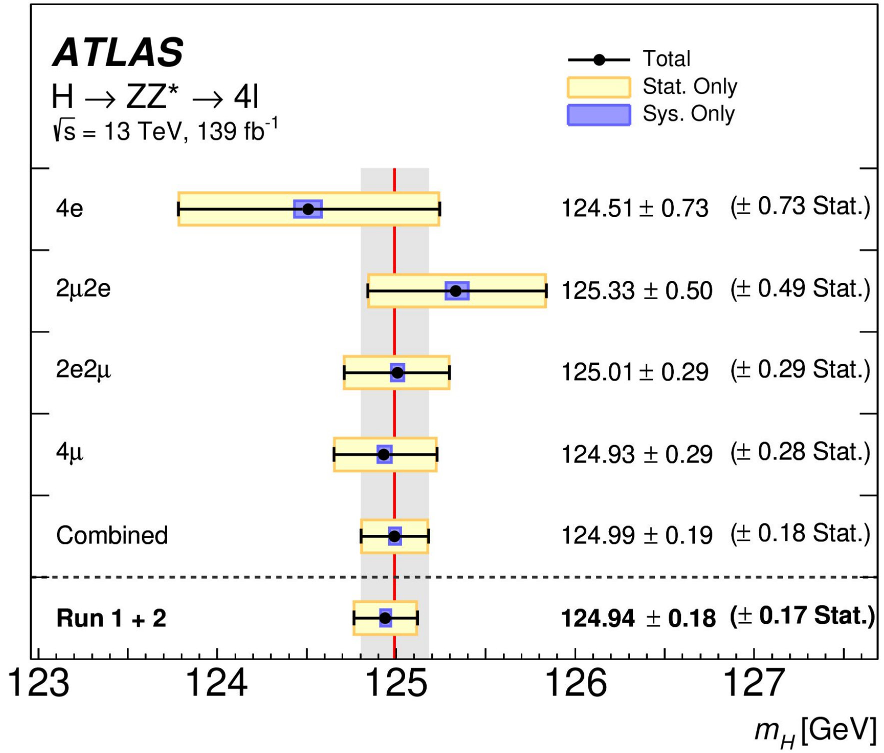
CMS 4-lepton m_H

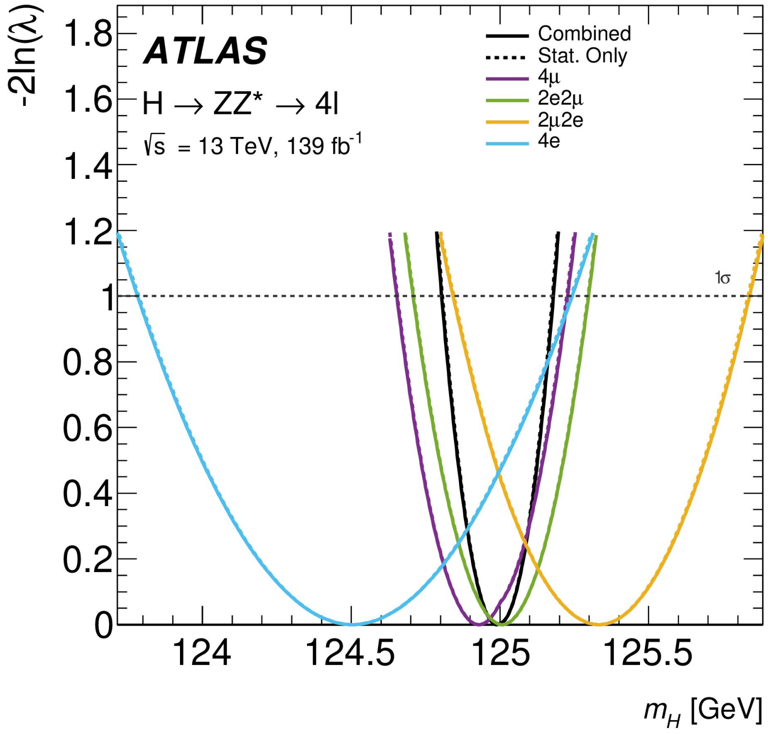
CMS HIG-21-019



ATLAS 4-lepton m_H

Phys. Lett. B 843 (2023) 137880





ATLAS Run 2 γγ m_H

$m_{\gamma\gamma}$ resolution, S and B per category

Category	$\sigma_{90}^{\gamma\gamma}$ [GeV]	S_{90}	B_{90}	f_{90} [%]	Z_{90}
U, Central-barrel, high $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.88	42	65	39.1	4.7
U, Central-barrel, medium $p_{\mathrm{Tt}}^{\gamma\gamma}$	2.34	102	559	15.4	4.2
U, Central-barrel, low $p_{\mathrm{Tt}}^{\gamma\gamma}$	2.63	837	13 226	6.0	7.2
U, Outer-barrel, high $p_{\mathrm{Tt}}^{\gamma\gamma}$	2.16	31	83	27.4	3.3
U, Outer-barrel, medium $p_{\mathrm{Tt}}^{\gamma\gamma}$	2.63	108	981	9.9	3.4
U, Outer-barrel, low $p_{\mathrm{Tt}}^{\gamma\gamma}$	3.00	869	22 919	3.7	5.7
U, Endcap	3.33	759	29 383	2.5	4.4
C, Central-barrel, high $p_{\mathrm{Tt}}^{\gamma\gamma}$	2.10	26	44	37.3	3.6
C, Central-barrel, medium $p_{\mathrm{Tt}}^{\gamma\gamma}$	2.62	62	389	13.8	3.1
C, Central-barrel, low $p_{\mathrm{Tt}}^{\gamma\gamma}$	3.00	508	9 726	5.0	5.1
C, Outer-barrel, high $p_{\mathrm{Tt}}^{\gamma\gamma}$	2.56	34	103	25.0	3.2
C, Outer-barrel, medium $p_{\mathrm{Tt}}^{\gamma\gamma}$	3.20	114	1 353	7.8	3.1
C, Outer-barrel, low $p_{\mathrm{Tt}}^{\gamma\gamma}$	3.71	914	30 121	2.9	5.2
C, Endcap	4.04	1 249	52 160	2.3	5.5
Inclusive	3.32	5 653	128 774	4.2	15.6

ATLAS Run 2 $\gamma\gamma$ m_H

Secondary systematics

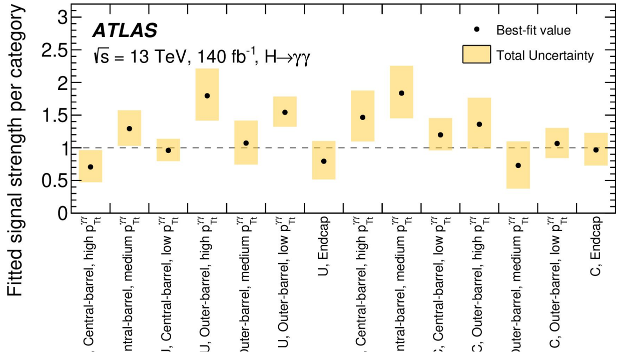
Copied from Laura Nasella

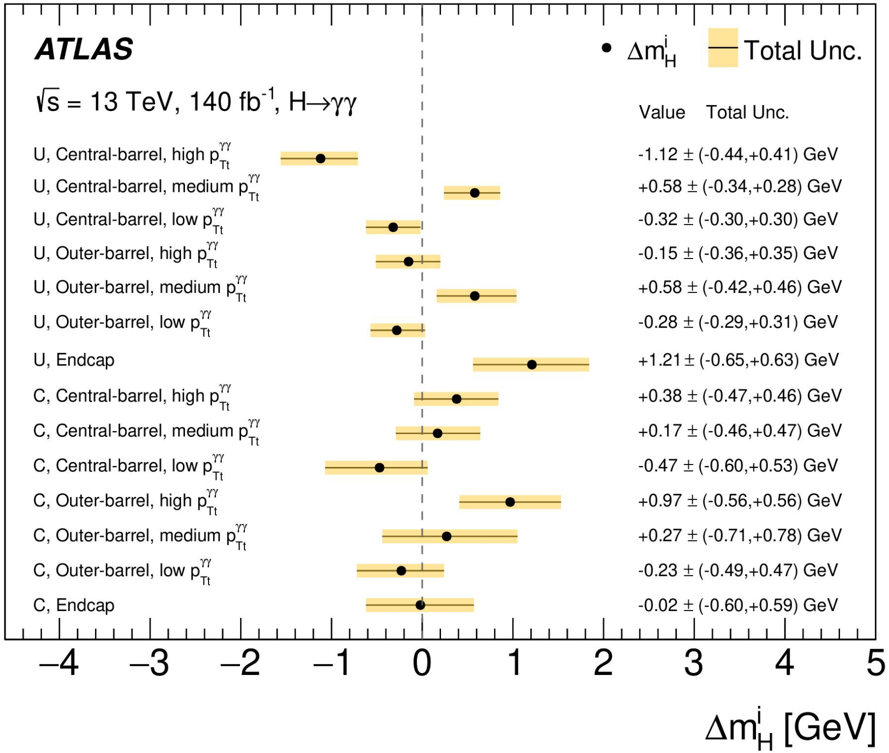
Additional and secondary systematic uncertainties are included in the likelihood model

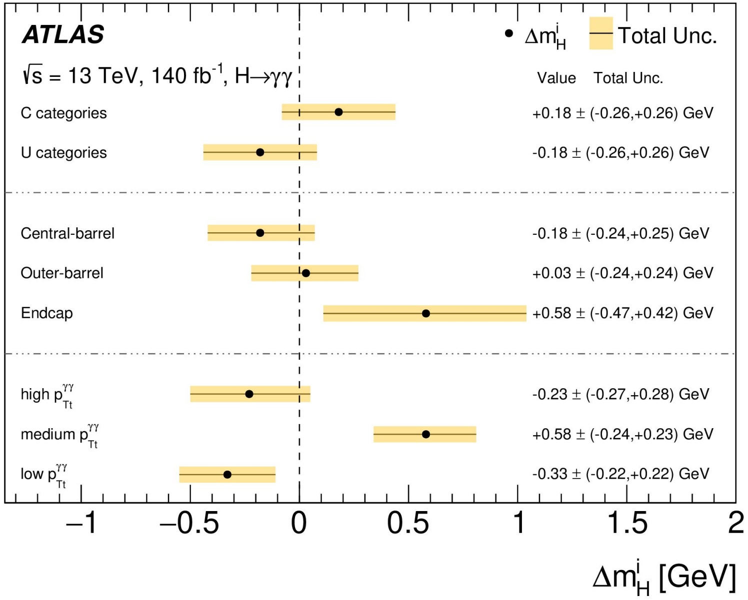
- **Signal and background modelling**: an inaccurate model can cause a bias in the m_H measurement
  - Evaluated by injecting sig (bkg) MC sample over a bkg (sig) Asimov ∀ category, then refit with S+B model and compute m_H shift
  - Effect uncorrelated among categories, impact of **5 (18) MeV** for signal (background)
- **Interference** between $gg \to \gamma\gamma$ and $gg \to H \to \gamma\gamma$ processes causes a shift of the m_H
  - Evaluated by injecting interference MC sample over a S+B Asimov ∀ category, then refit with S+B model and compute m_H shift
  - Effect correlated among categories, expected **26 MeV** impact
- Photon energy **resolution** (PER): evaluated as interquartile difference of $m_{\gamma\gamma}$ distribution per category, applied on width of DSCB
- Photon **conversion reconstruction** affecting category migrations
  - Estimated with data/MC comparison in $Z \to ll\gamma$ events, correlated to corresponding scale effect
- **NN vertex selection** effect on m_H (5 MeV)
  - Estimated with data/MC comparison in $Z \to ee$ events where *e* are treated as unconverted photons
- Luminosity / BR $\gamma\gamma$ / QCD scale / PDF + α_s / Parton shower / Spurious signal / Yield
  - All included and with $\sim$ null impact on m_H

ATLAS Run 2 γγ m_H

category compatibility

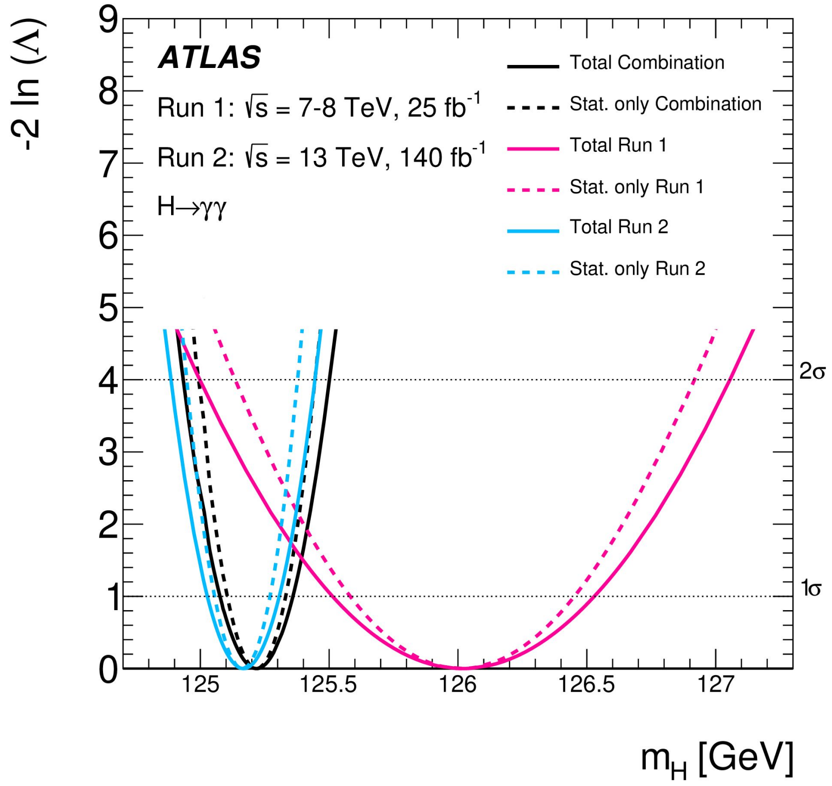


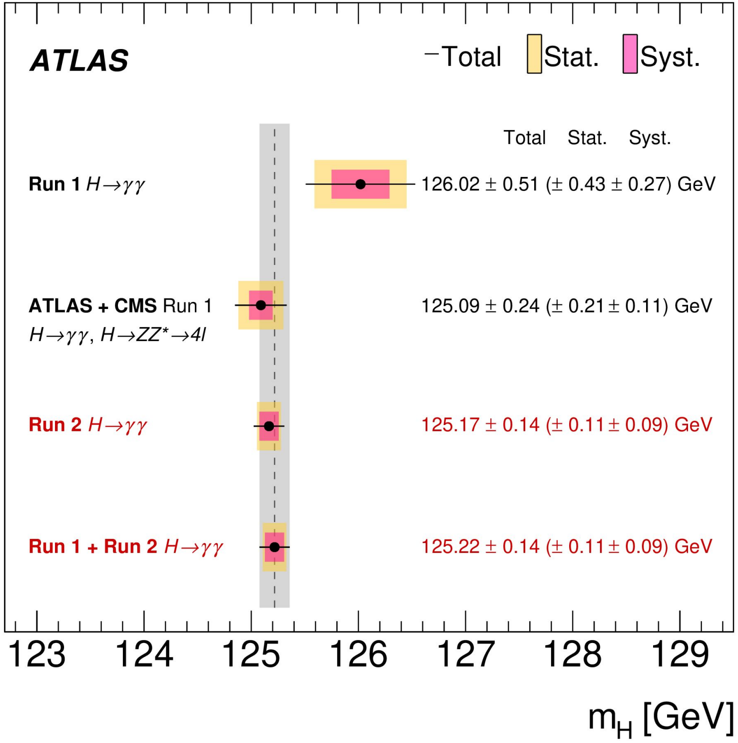




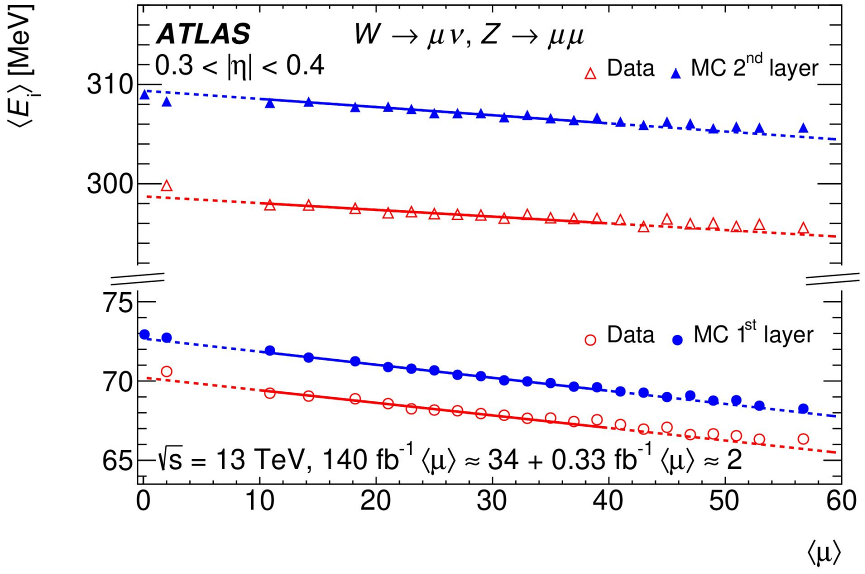
ATLAS Run 2 γγ m_H

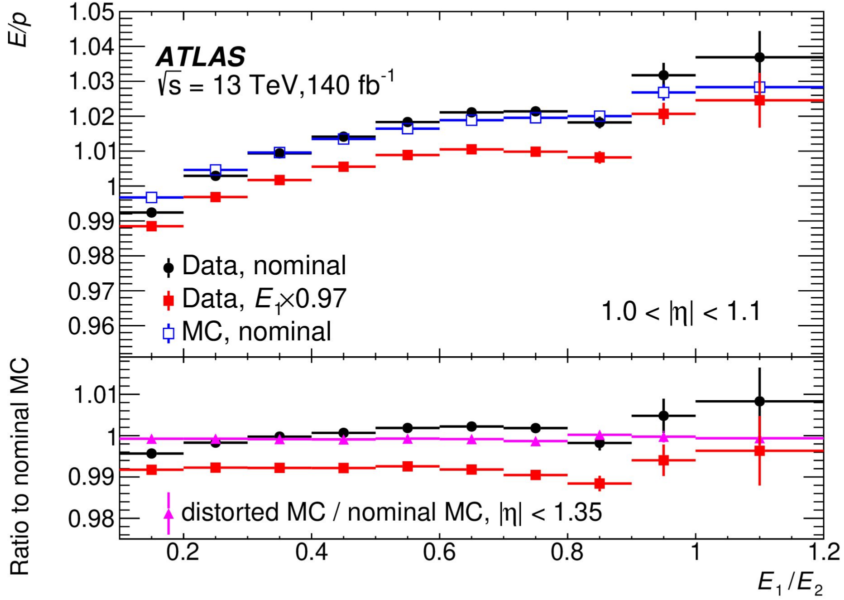
Run1+Run2 combination



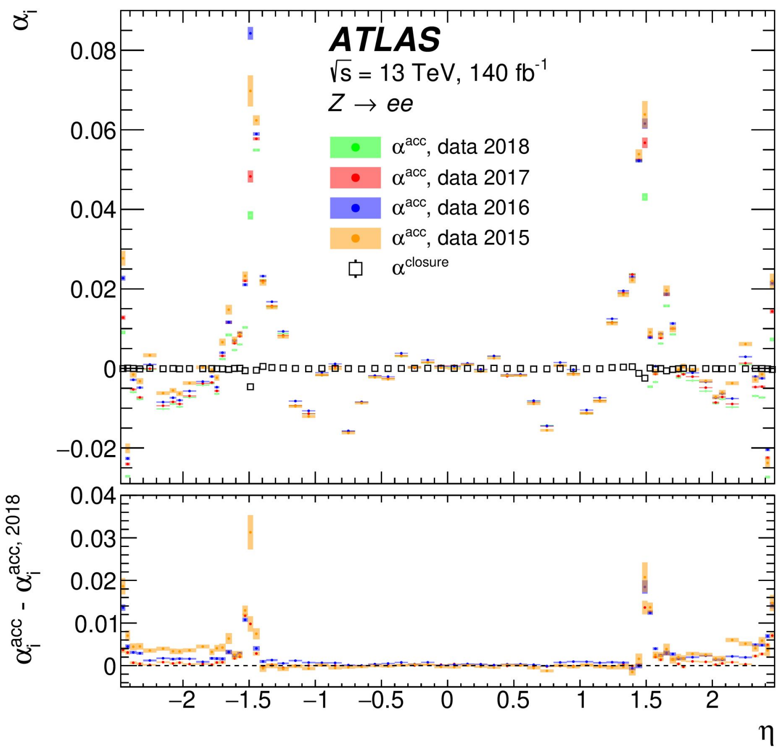


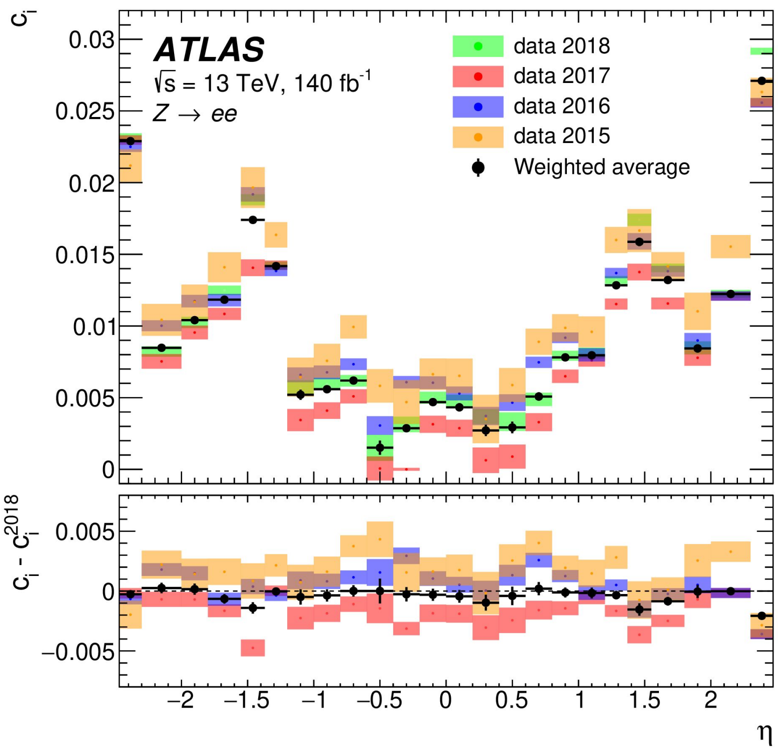
ATLAS layer intercalibration





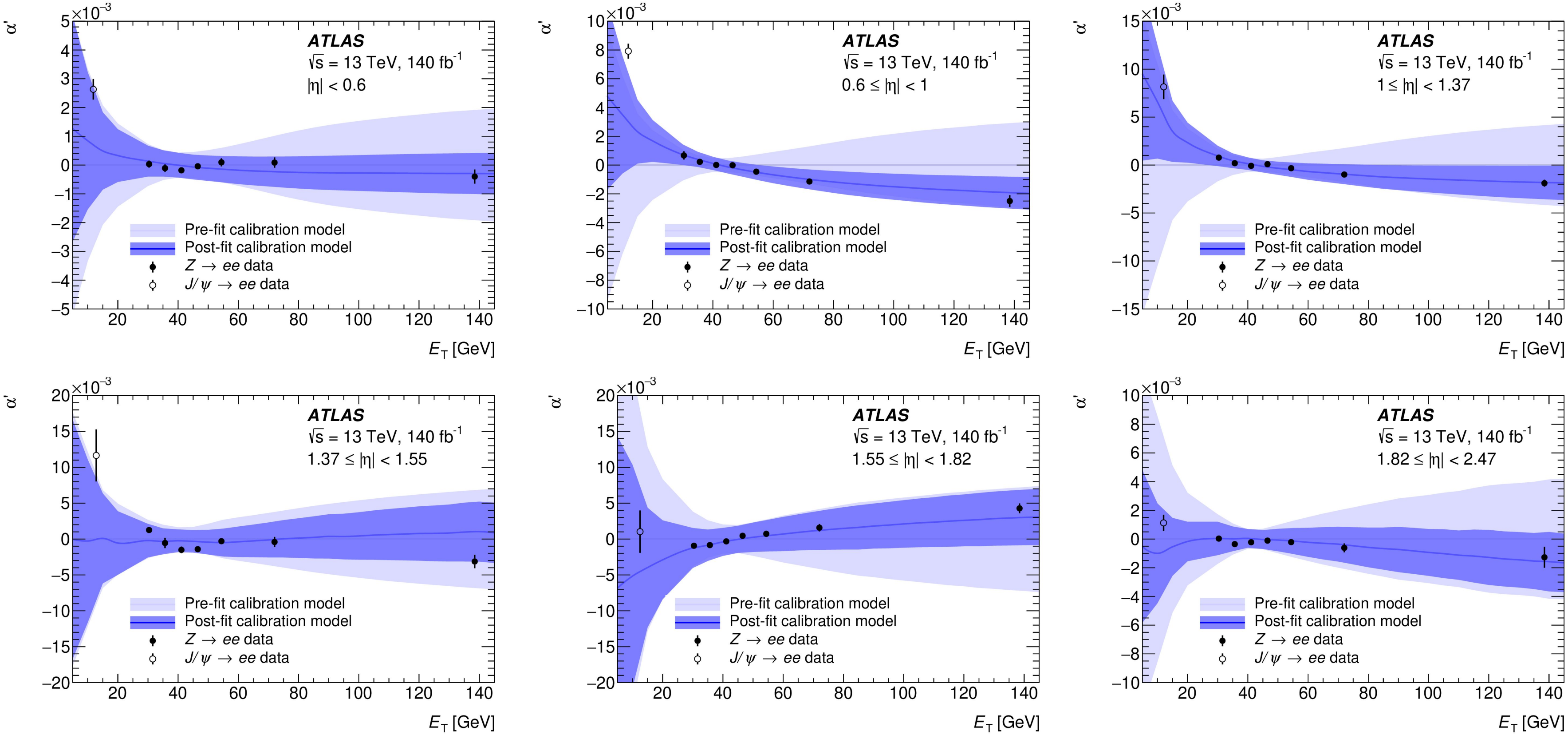
ATLAS in-situ calibration





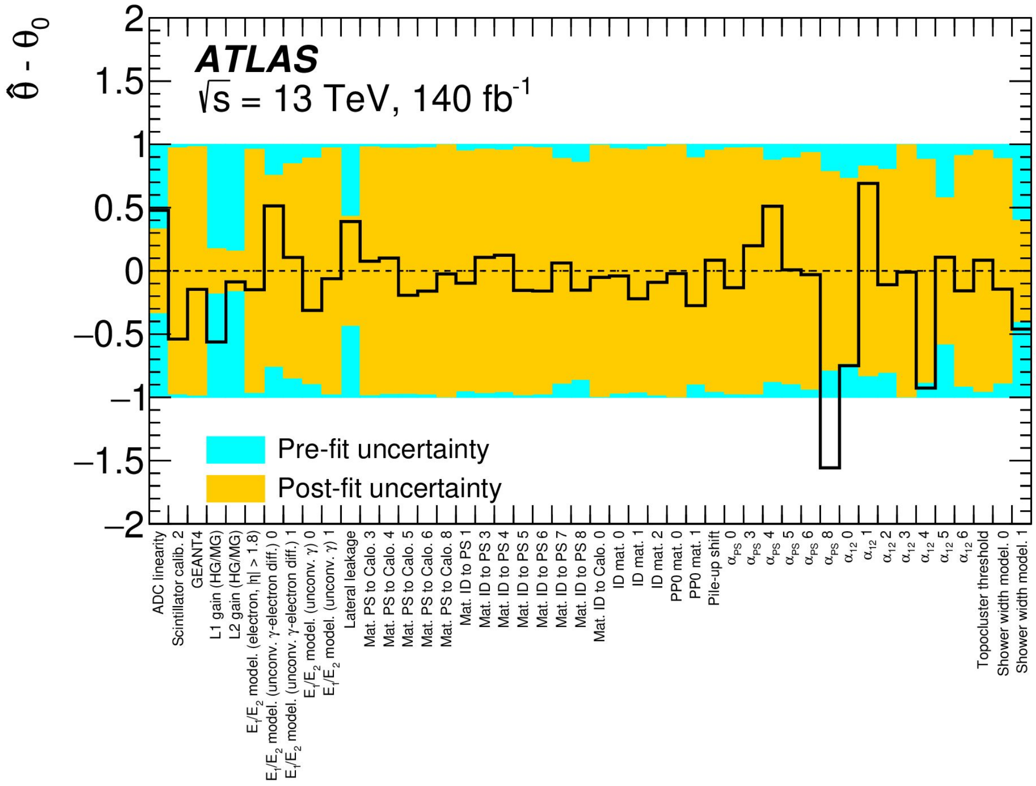
ATLAS ECAL and energy calibration

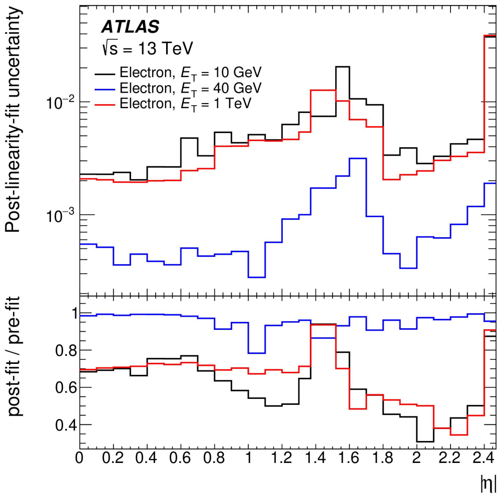
E_T-dependent energy scale uncertainties constraints

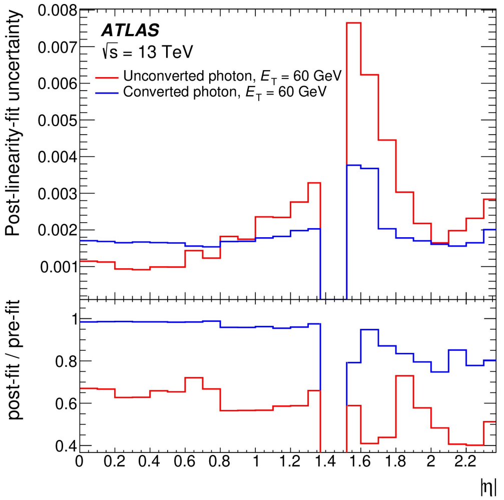


ATLAS ECAL and energy calibration

E_T-dependent energy scale uncertainties constraints

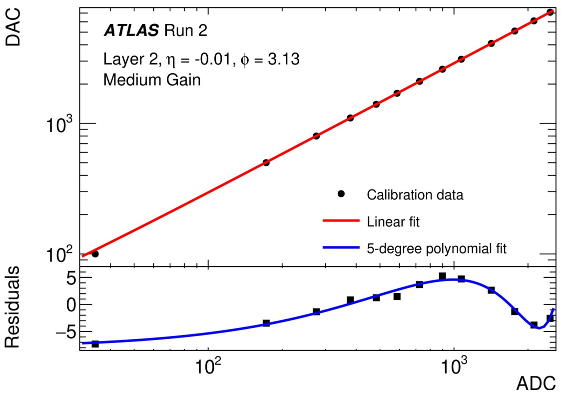






ATLAS electronics calibration

ADC



HG/MG