Measurement of the Higgs Boson Mass

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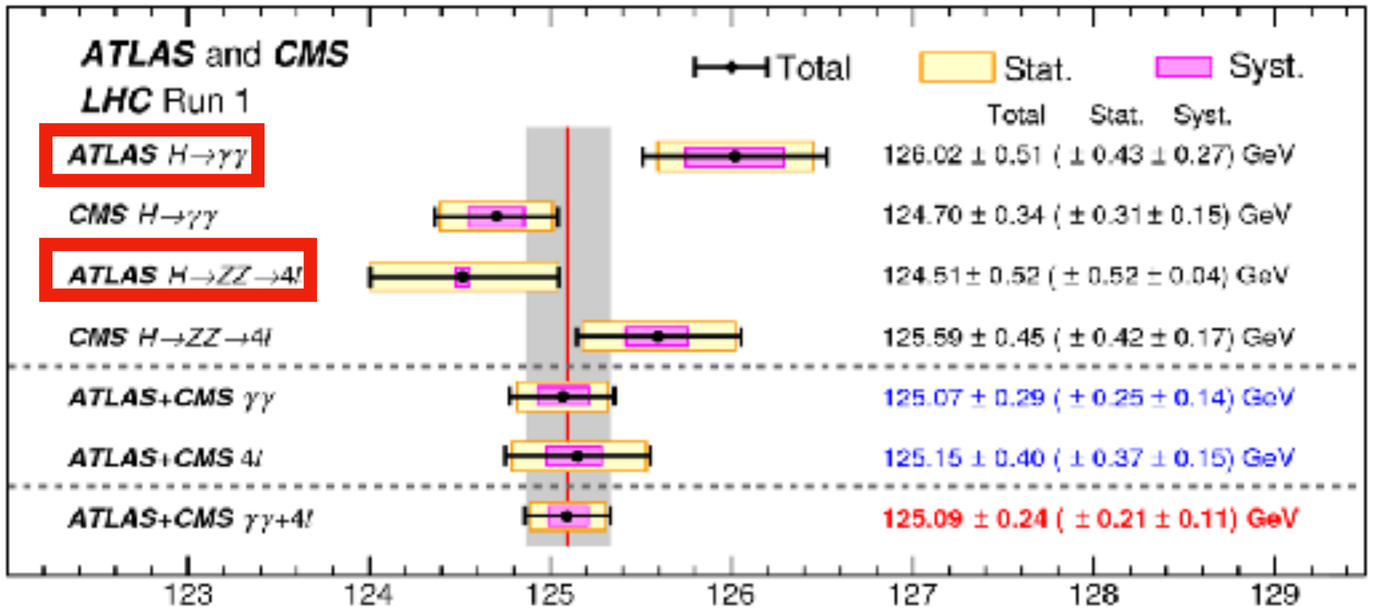
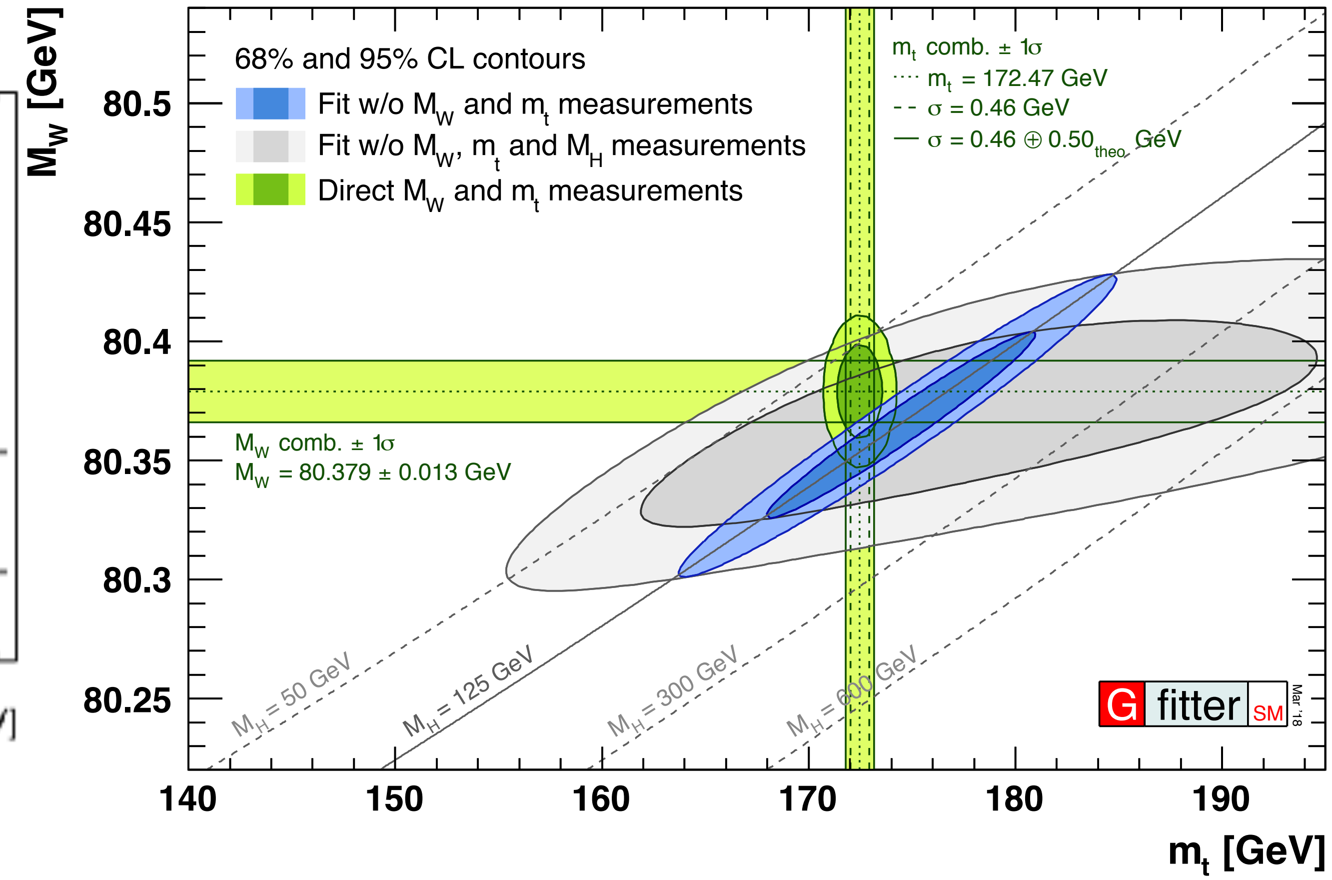
The Higgs Boson Mass

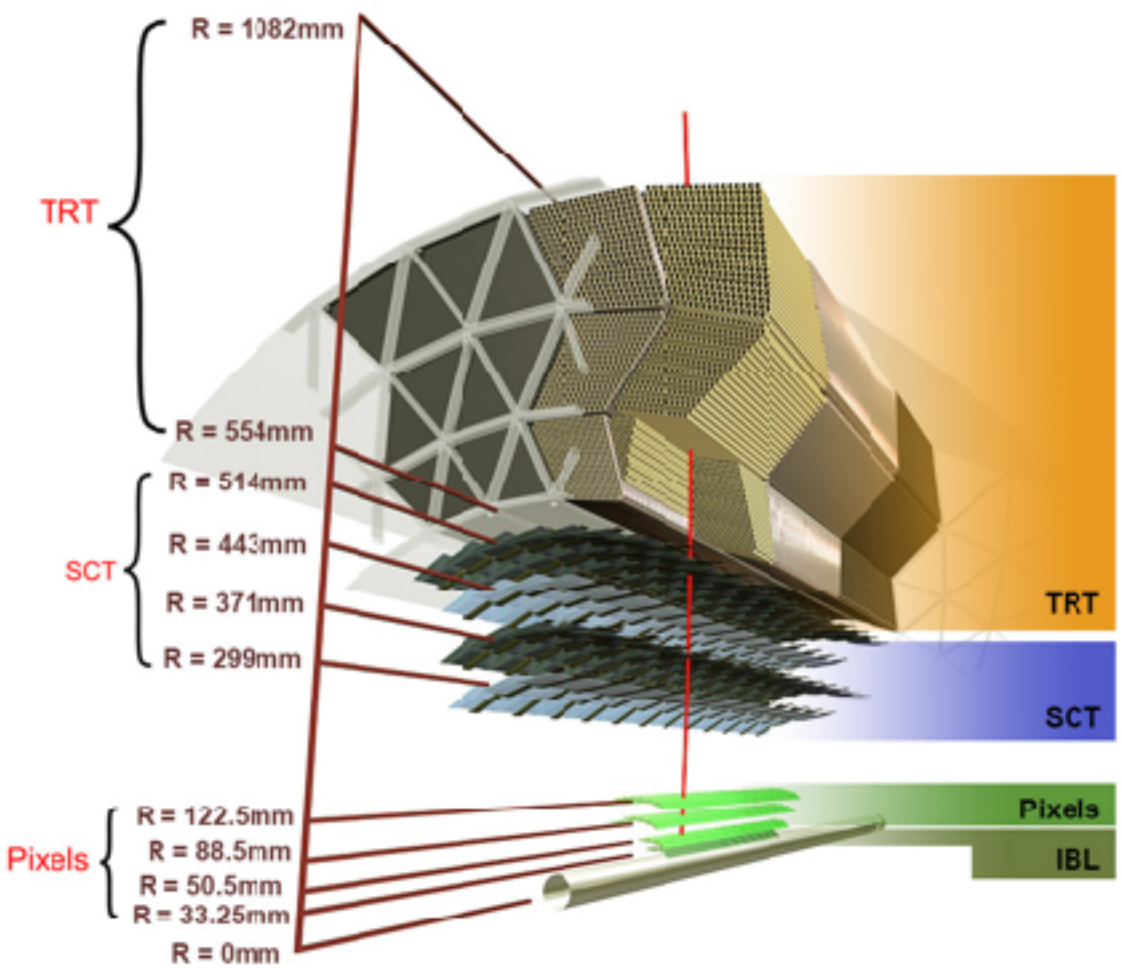


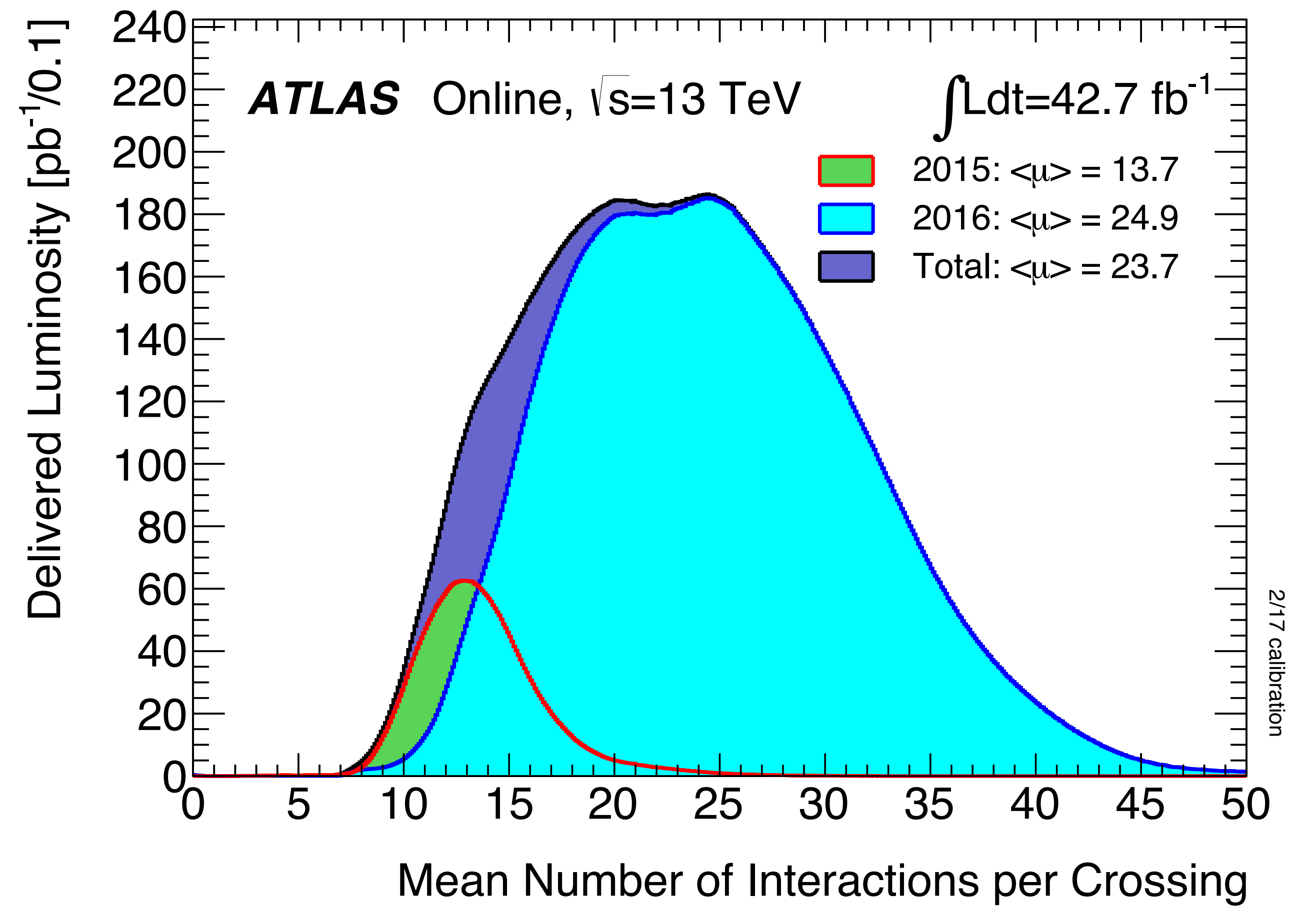
Phys. Rev. Lett. 114 (2015) 191803



- Free parameter of the SM
- Important ingredient in SM (and BSM) predictions
  - Not a test for new physics, but needed for such tests
  - Previously measured by ATLAS to precision of 0.33%
- Analysis results shown here from arXiv:1806.00242 [hep-ex] (submitted to PLB) except where noted

ATLAS in Run-2

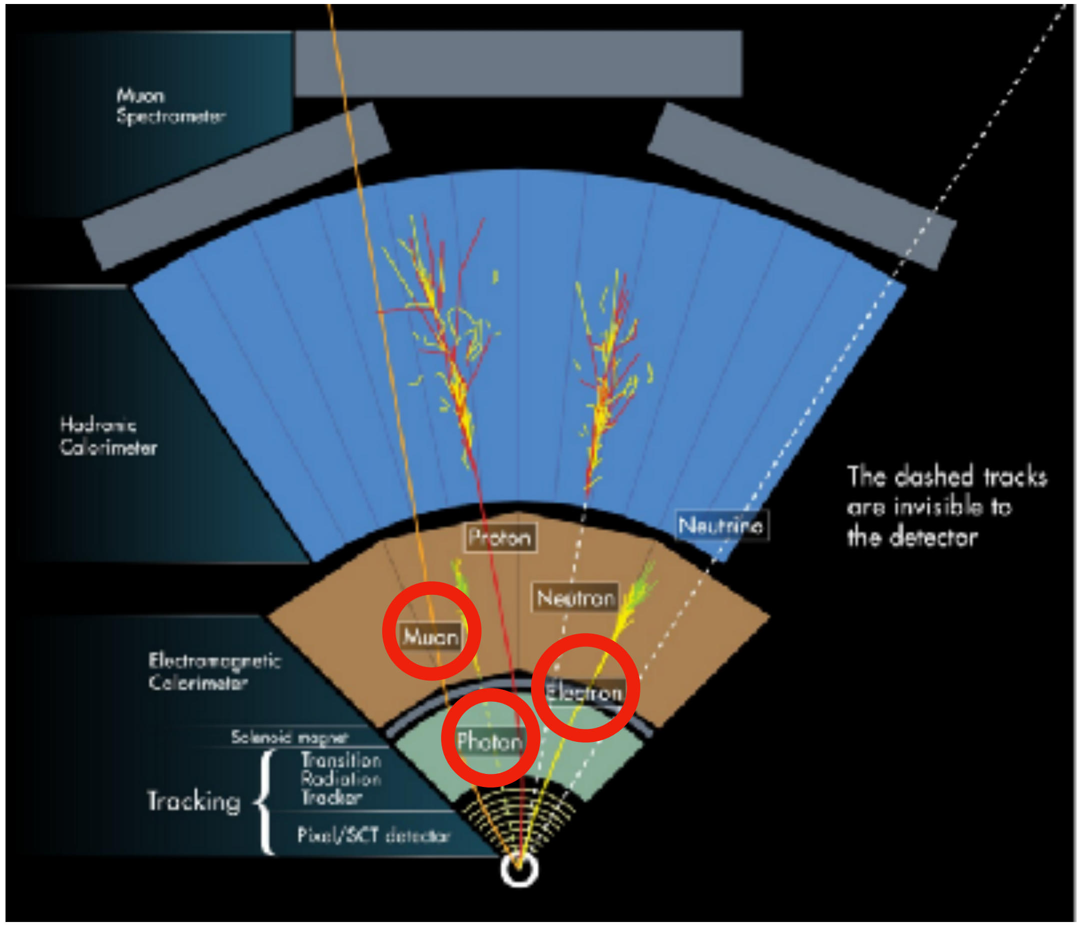


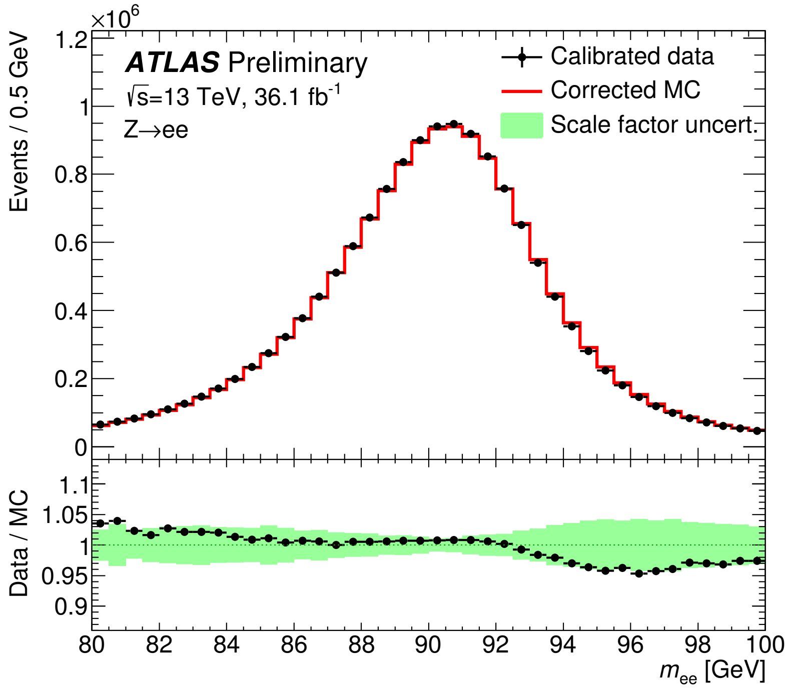


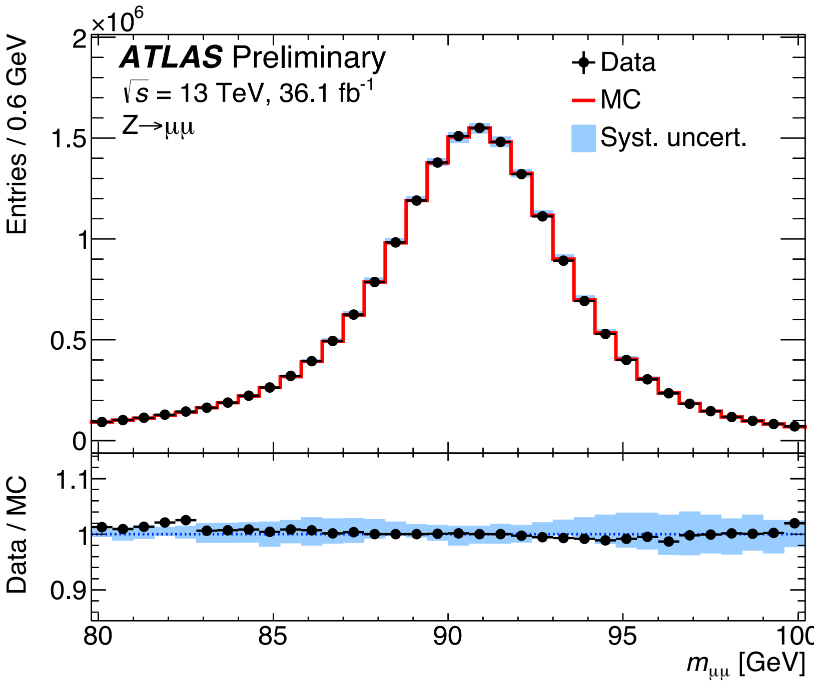
- Results shown use 36.1 fb^{-1} of $\sqrt{s}$=13 TeV data collected by ATLAS in 2015 and 2016
- ATLAS is improved compared to Run-1
    - New pixel layer close to beamline improves rejection of electron backgrounds
    - Improved MS coverage for better muon reconstruction efficiency

Precision Mass Measurement

- Measurement involves fitting m_H-dependent model to data
  - Model developed from simulation
- Requires precise understanding of particle response in the detector
  - Simulation must accurately reflect data
  - Mass resolution limited by resolution of Higgs boson decay products

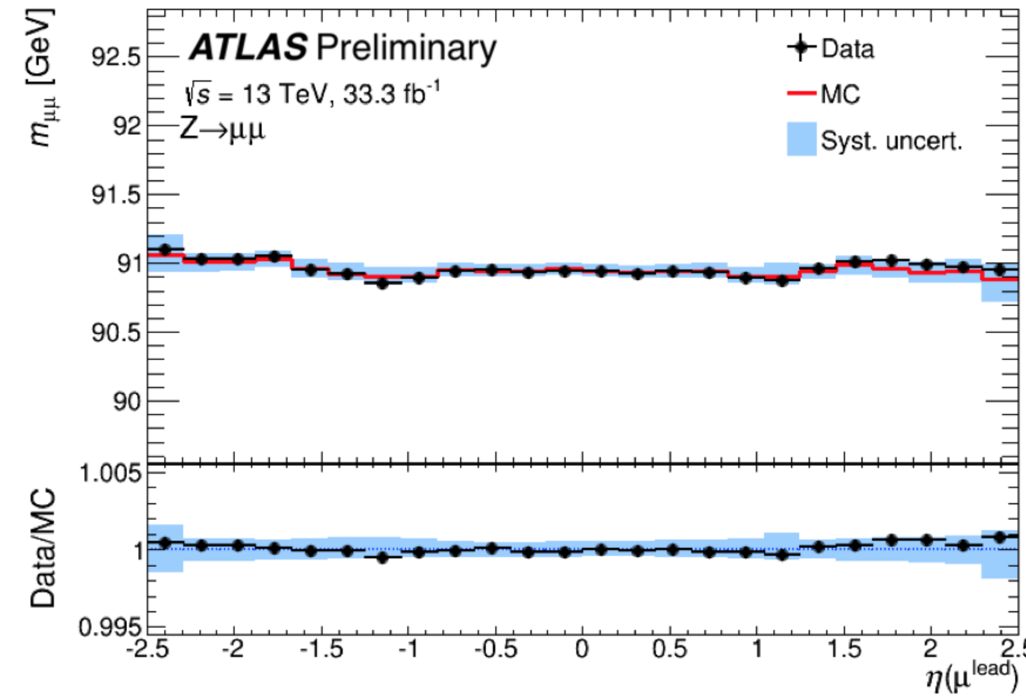


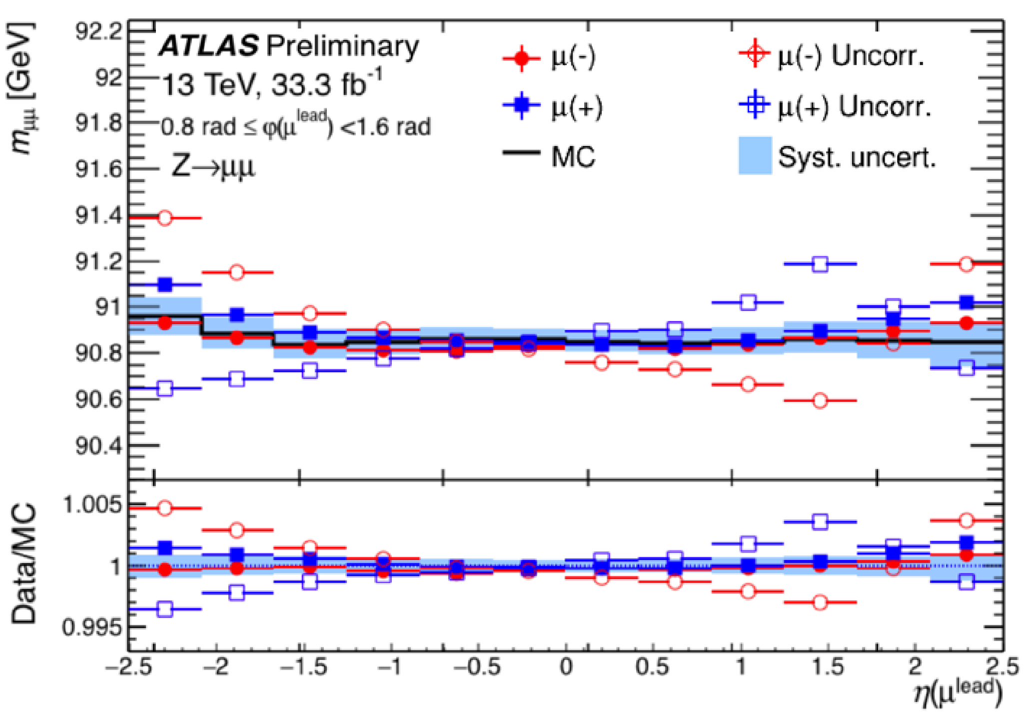


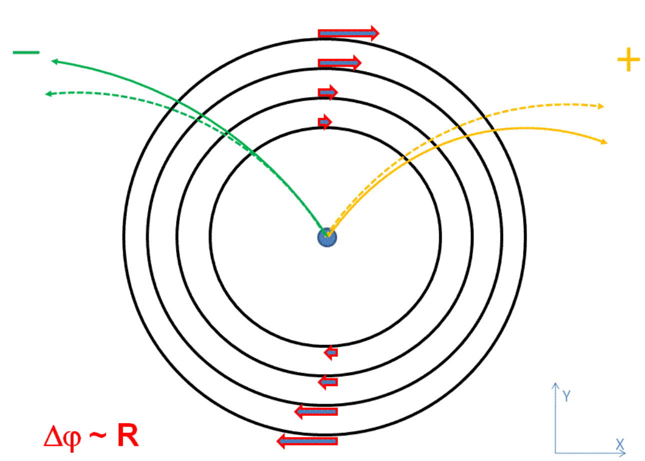


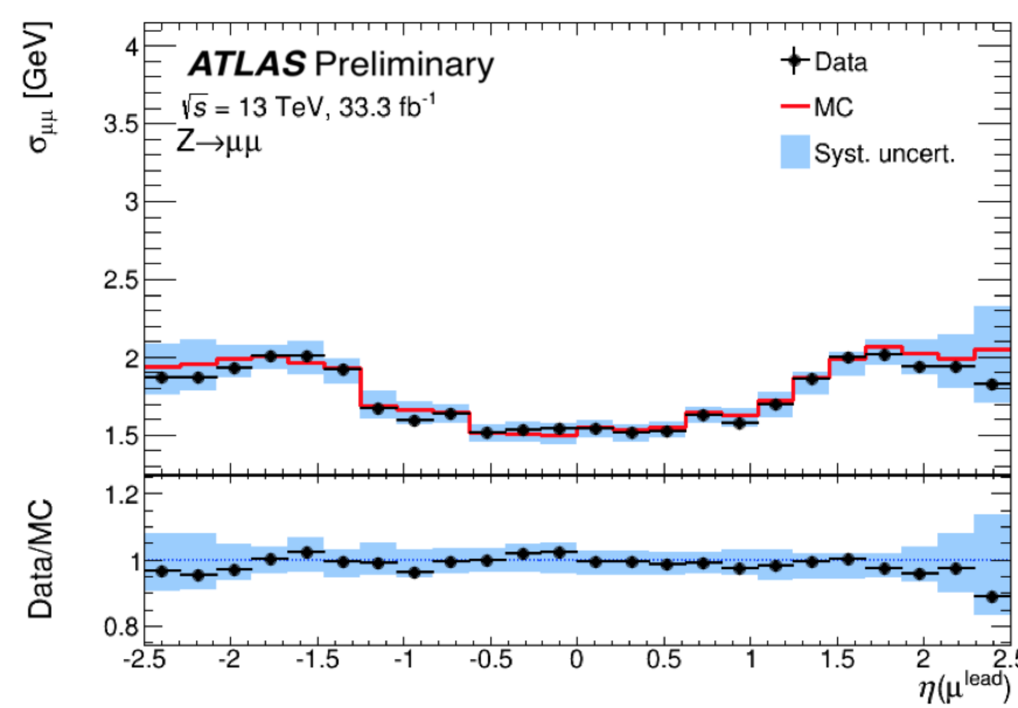
Measuring Muon Momenta

- Muon tracks are measured separately in MS and ID
  - Then combined fit w/all hits + calo information
- Resolution and p_T scale measured in Z, J/ψ decays
  - Simulated momenta corrected and smeared to match data
  - Uncertainties on scale <0.05% in barrel, <0.2% in endcap
    - Energy loss, material, radial distortions, B-field
  - Uncertainties on resolution 1-2% in barrel, up to 10% in endcap
- Additional η-ϕ dependent correction for residual ID misalignment improves Z→μμ resolution by 1-5%





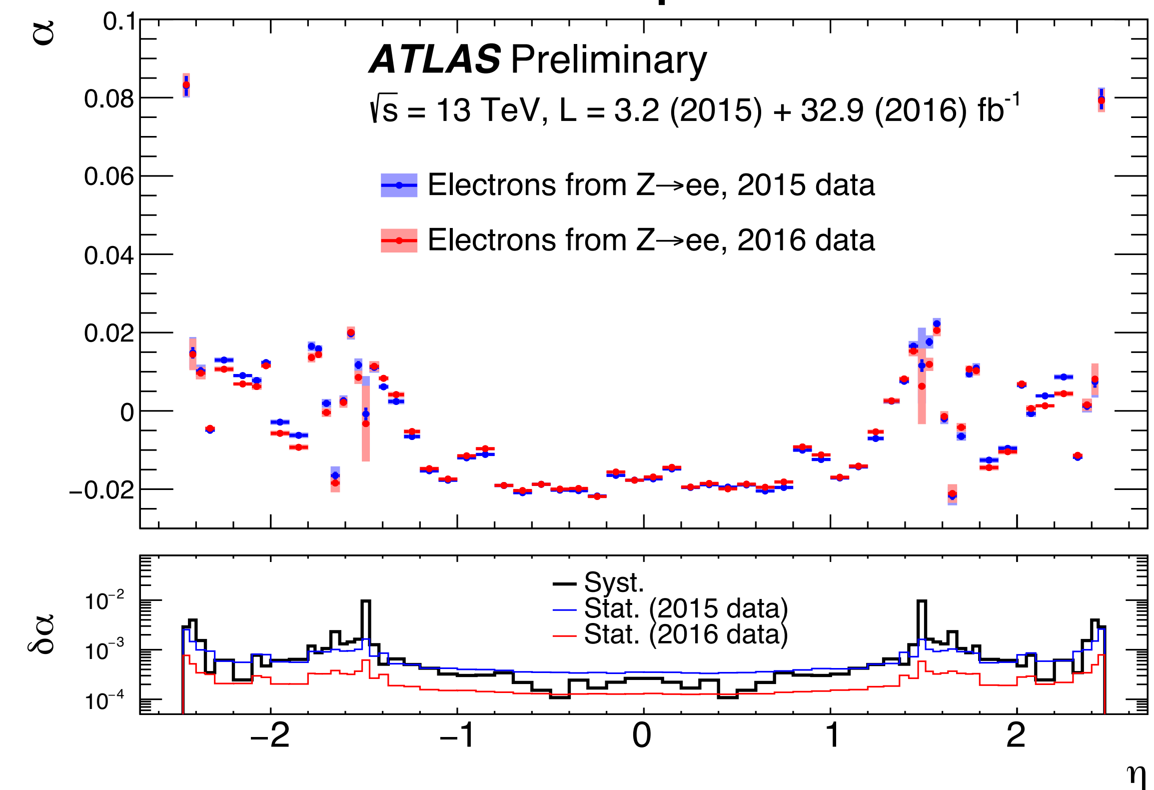




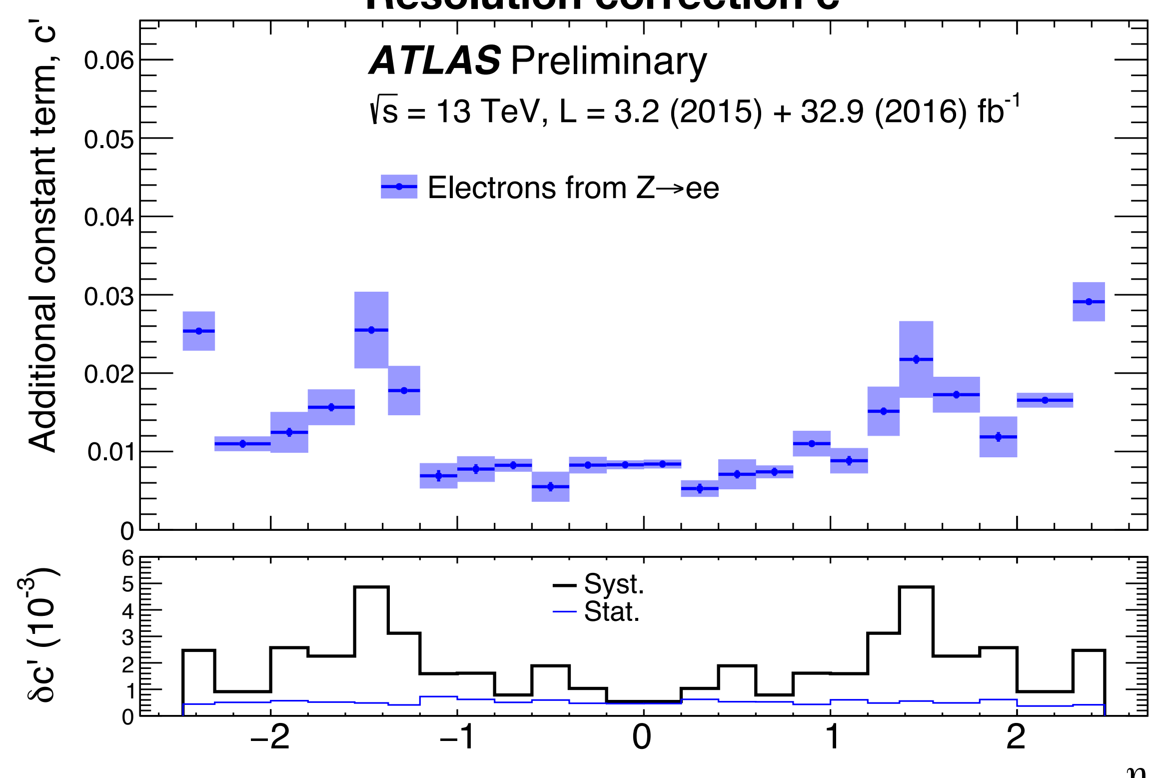
Electron and Photon Energy Measurement

- For both, reconstruction starts with a cluster in the EM calorimeter
  - Can be matched to track, conversion vertex, or nothing
- MVA calibration for e/γ energy
  - Trained on MC samples
  - Corrects for energy loss in material in front of calorimeter, punch-through, shower leakage, and variation of cluster response
  - Different corrections for electrons, converted photons, and photons
- Energy scale and resolution corrections
  - Z→ee decays used for final determination of resolution and scale
    - ✦ Data energy scale corrected to match MC
    - ✦ MC resolution corrected to match data
  - Uncertainty on scale<0.1% for e, few per mille for γ
    - ✦ From relative calibration of calo layers, material, energy response linearity, and e-γ shower shape differences

Scale correction parameter α

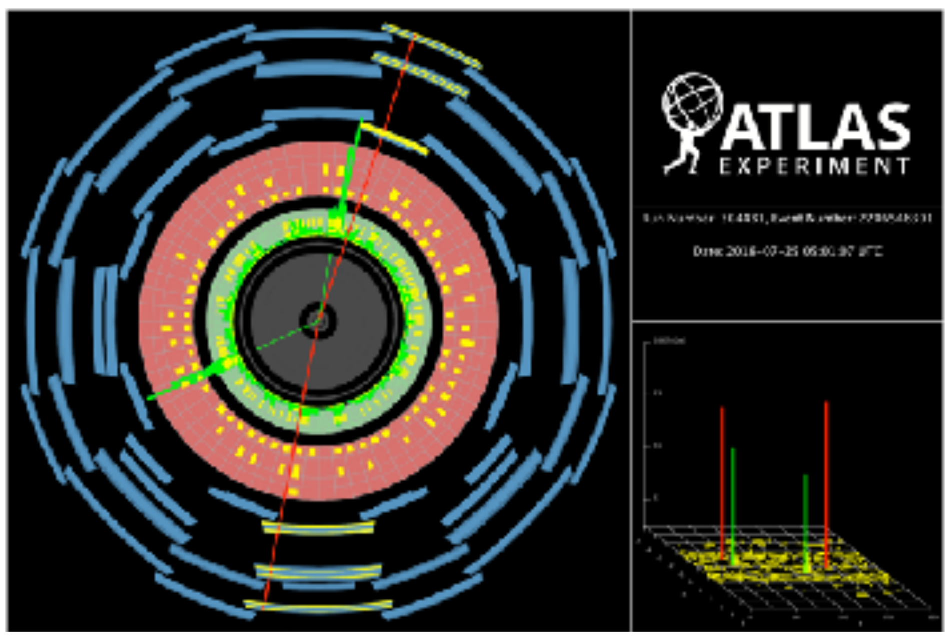


Resolution correction c’



$H \to ZZ^* \to 4l$

- Loose lepton isolation and identification requirements imposed
- Electrons and muons accepted down to p_T of 7 and 5 GeV respectively



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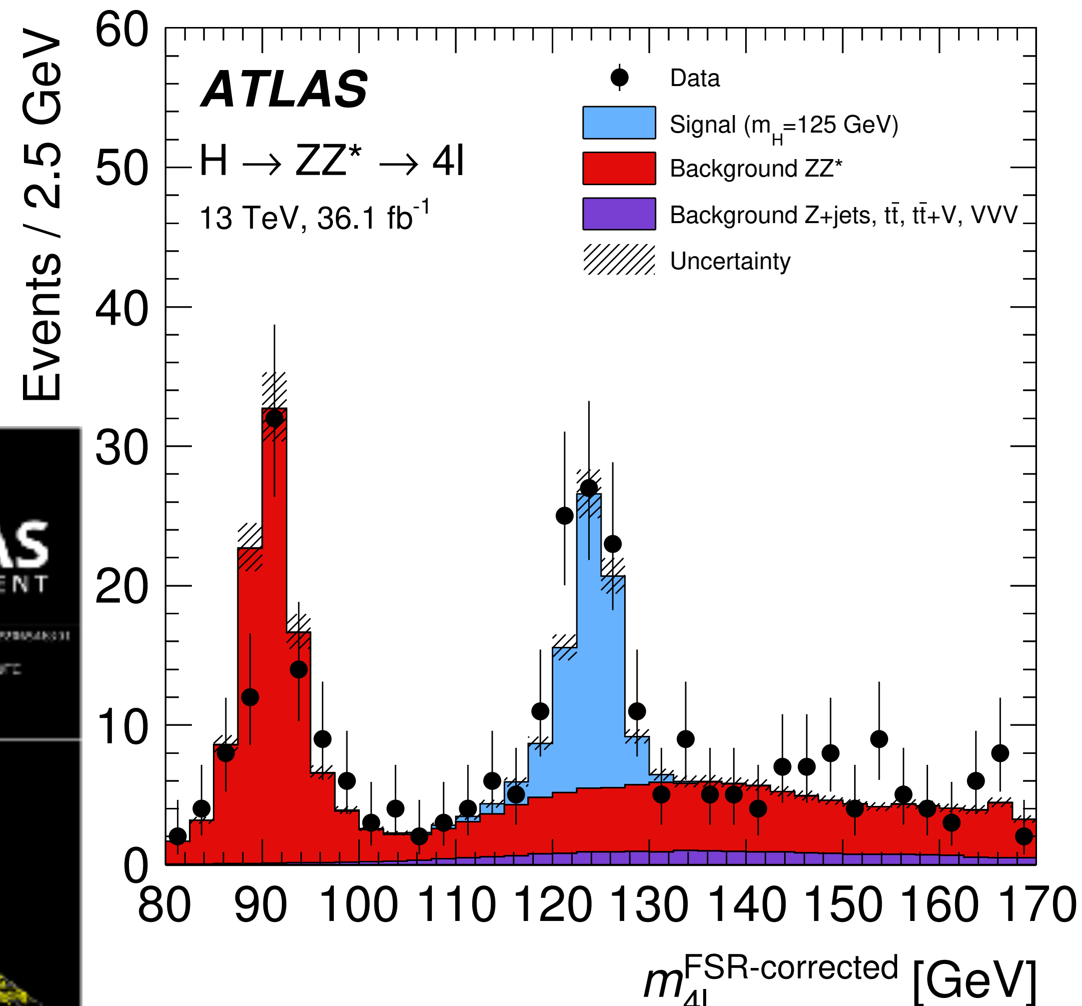


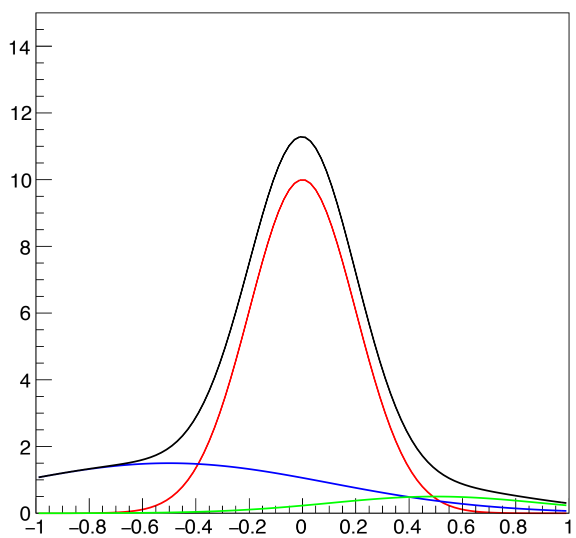
Final state	Signal (125 GeV)	ZZ^*	$Z+$jets, $t\bar{t}$, WZ, ttV,VVV	Expected	Observed
4μ	20.6 ± 1.7	15.9 ± 1.2	2.0 ± 0.4	38.5 ± 2.1	38
$2e2\mu$	14.6 ± 1.1	11.2 ± 0.8	1.6 ± 0.4	27.5 ± 1.4	34
$2\mu 2e$	11.2 ± 1.0	7.4 ± 0.7	2.2 ± 0.4	20.8 ± 1.3	26
$4e$	11.1 ± 1.1	7.1 ± 0.7	2.1 ± 0.4	20.3 ± 1.3	25
Total	57 ± 5	41.6 ± 3.2	8.0 ± 1.0	107 ± 6	123

- Main background is ZZ* production
  - qq->ZZ simulated at NLO with POWHEG, QCD+EW corrections as function of m_{ZZ}.
  - gg->ZZ simulated at LO with gg2VV, with k-factor for higher-order QCD effects

Reducible background from Z+jets and ttbar estimated using data-driven methods

- Use 4l vertexing constraint in event selection.
- FSR photons are identified and included in the mass calculation

Per-Event Response Method



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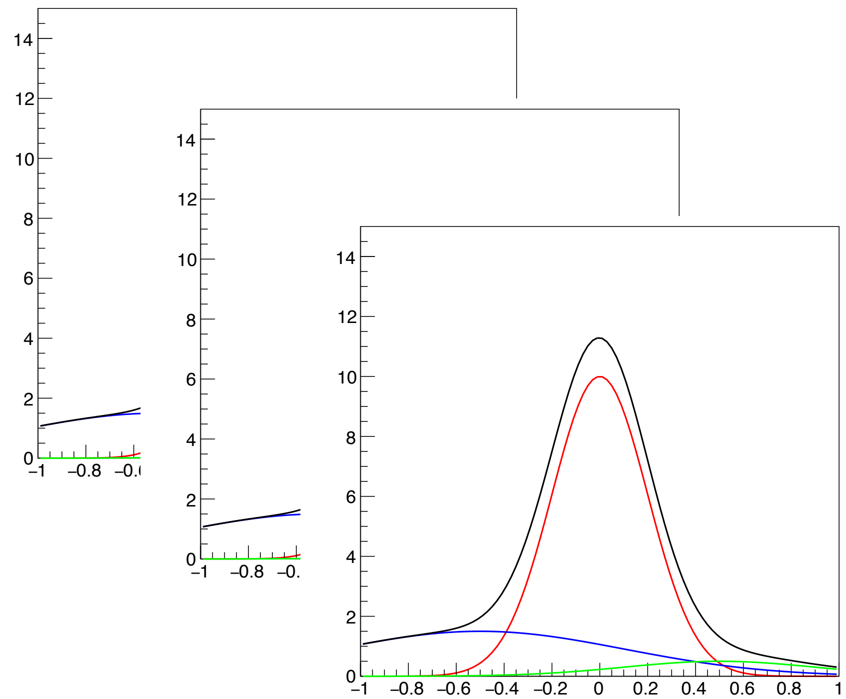

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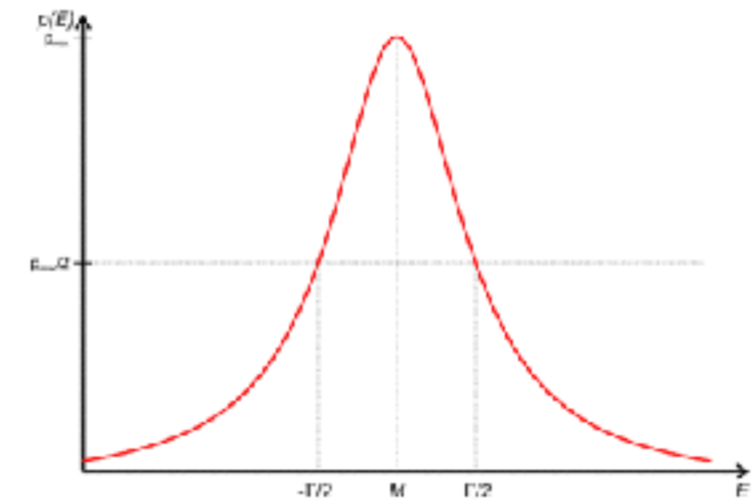
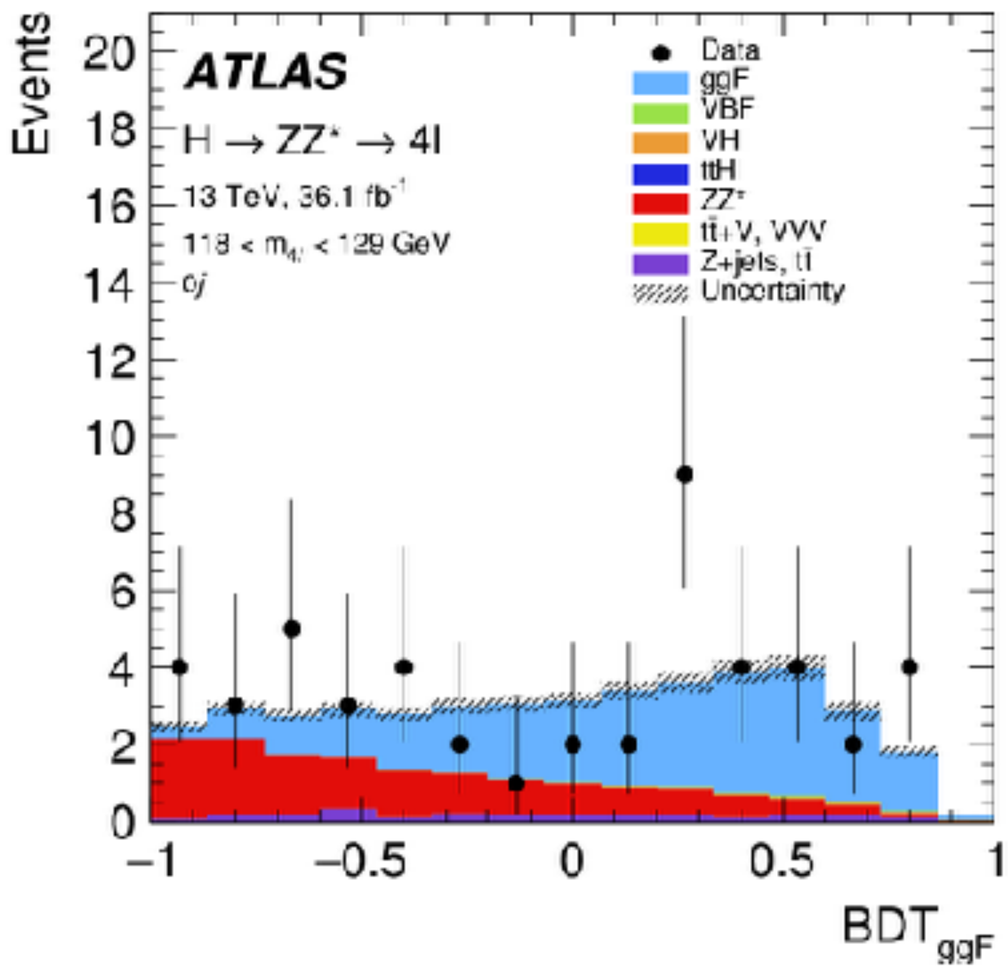


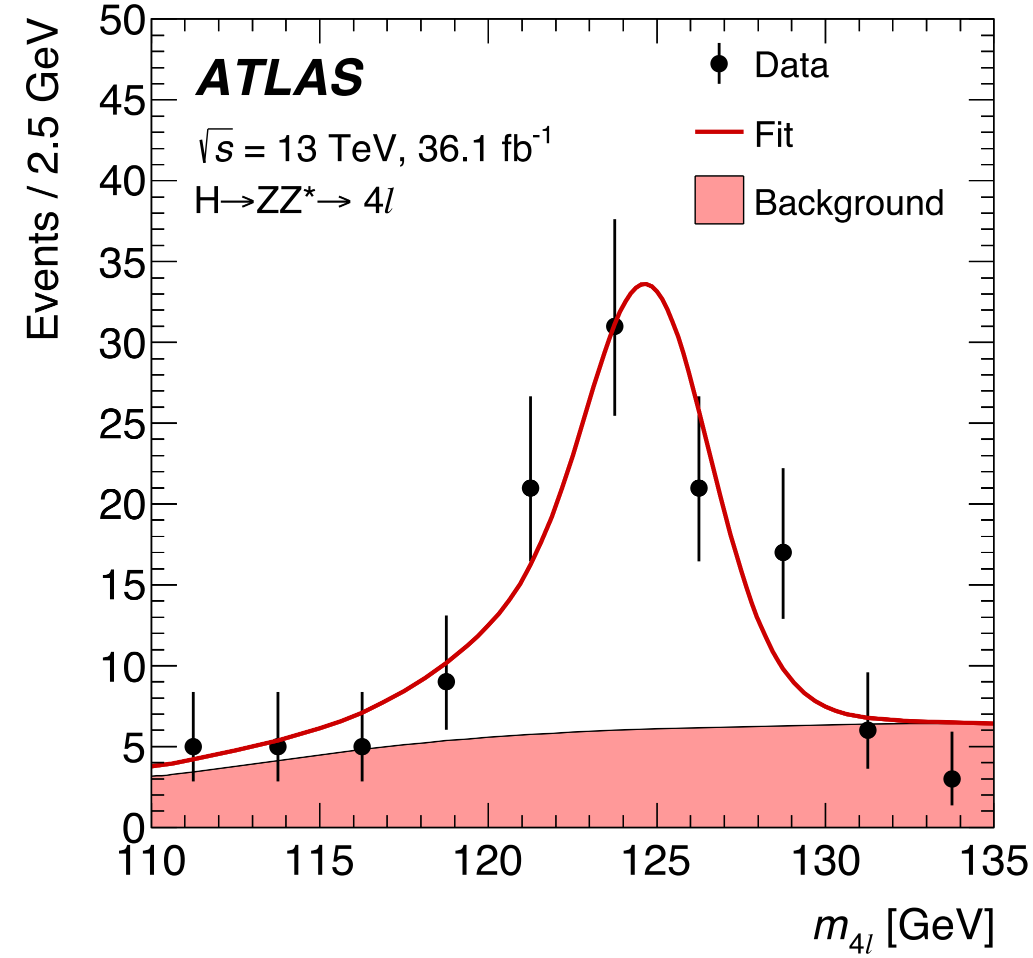
$= P(m_{4l};m_H,\Gamma_H,\text{kinematics})$

- Less susceptible to statistical fluctuations seen in low-stats measurements like this one
- Response of each e or μ in each η-E detector region modeled as sum of 3 gaussians
  - By fit to simulation
  - 3 ~ the core and radiative/bremsstrahlung tails
- To obtain 4l response, convolute responses of the 4 leptons
  - Gives 81 gaussians; merged to 4 without losing meaningful information
- PDF for given event obtained by convoluting 4l response with Breit-Wigner
  - Final PDF is convolution of each event's PDF
- Method validated on Z→4l events

Mass Measurement

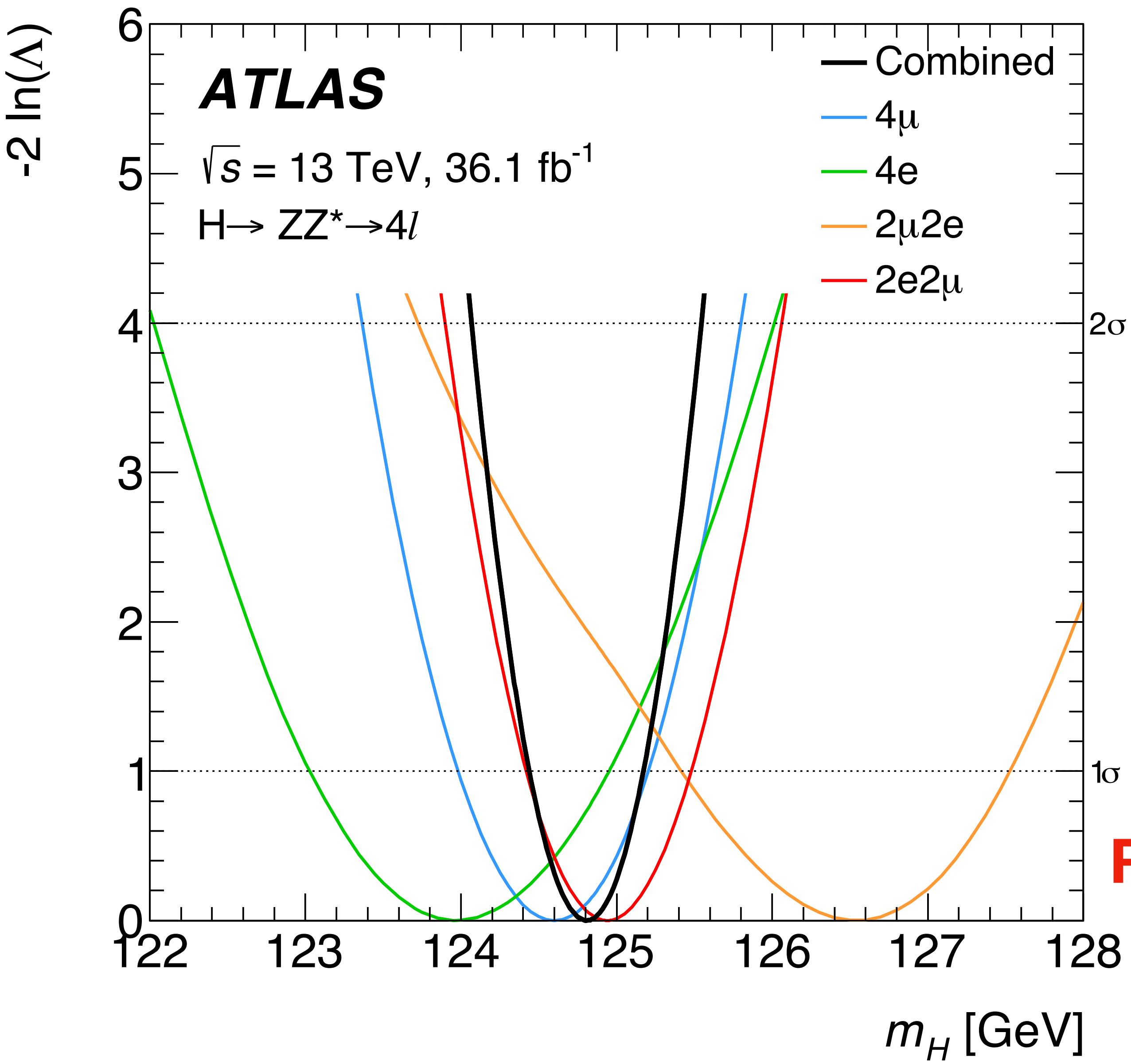
[JHEP 03 (2018) 095](#)





- m_{12} kinematically constrained to m_Z to improve the resolution (by ~15%)
- Data in $110<m_{4l,\mathrm{constrained}}<135$ GeV split by final state (4μ, 2μ2e, 2e2μ, 4e)
  - Resolution better for μ than e → ~ resolution bins
- Each final state is split into 4 bins using BDT trained to separate ggH and ZZ*
  - Gain 8% improvement in uncertainty thanks to improved significance
- Background model from smoothing m_{4l} distribution from simulated samples
- Simultaneous fit performed over all categories
  - Cross-check using template method: uncertainties are ~3% smaller with per-event

Results in the 4l Channel



Systematic effect	Uncertainty on $m_H^{ZZ^*}$ [MeV]
Muon momentum scale	40
Electron energy scale	26
Pile-up simulation	10
Simulation statistics	8

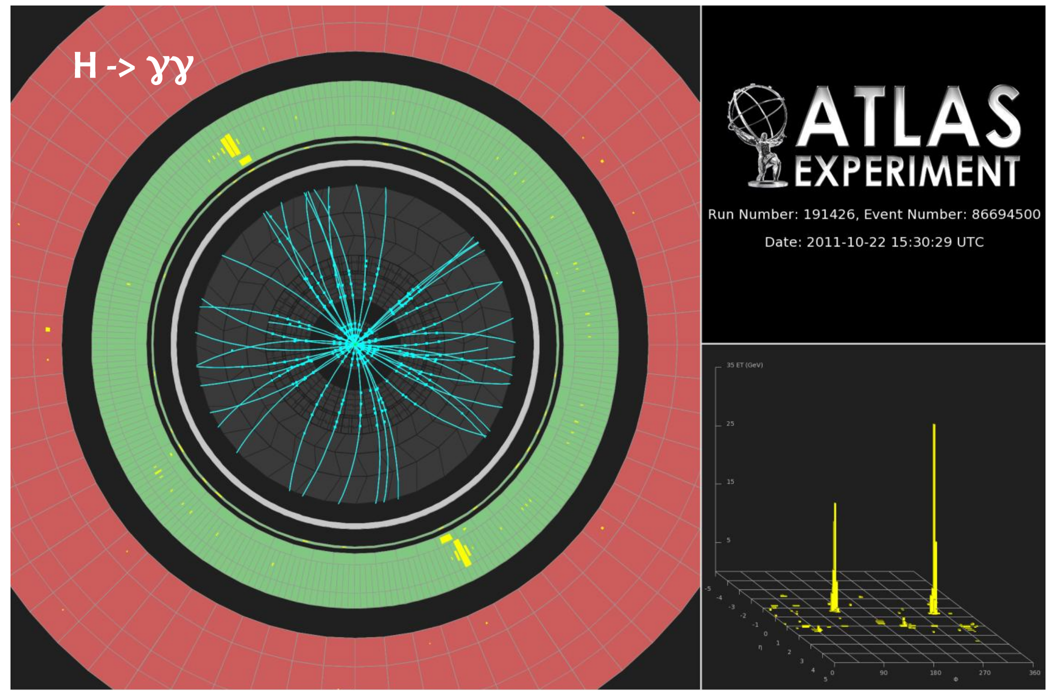
Run-2: m_H=124.79 ± 0.36 (stat) ± 0.05 (syst)

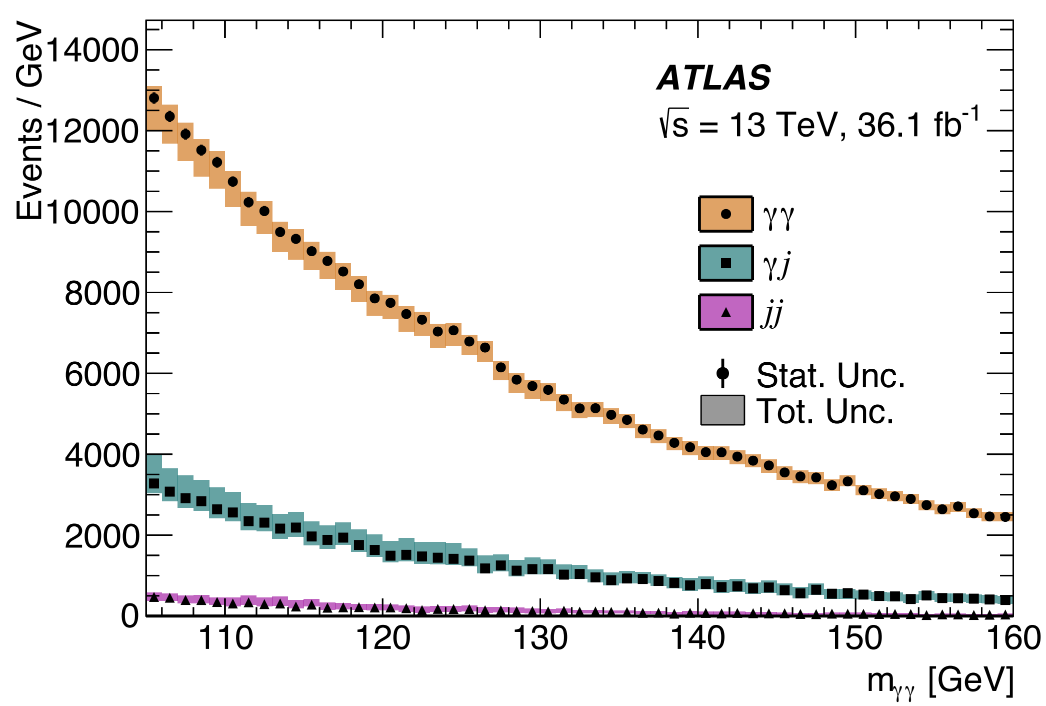
Run1+2: m_H=124.71 ± 0.30 (stat) ± 0.05 (syst)

- Total uncertainty of 0.37 GeV compatible with expected of 0.35 GeV
  - Main systematics from muon momentum and electron energy scale
- Combination with Run-1 reduces uncertainty further
  - Systematics are correlated, signal normalizations are not
- Result is still statistics-limited

$H \to \gamma\gamma$

- Tight isolation and identification requirements for photons
- Diphoton vertex chosen using a neural network
- Events sorted into 31 exclusive categories based on properties of photons and other objects in the event

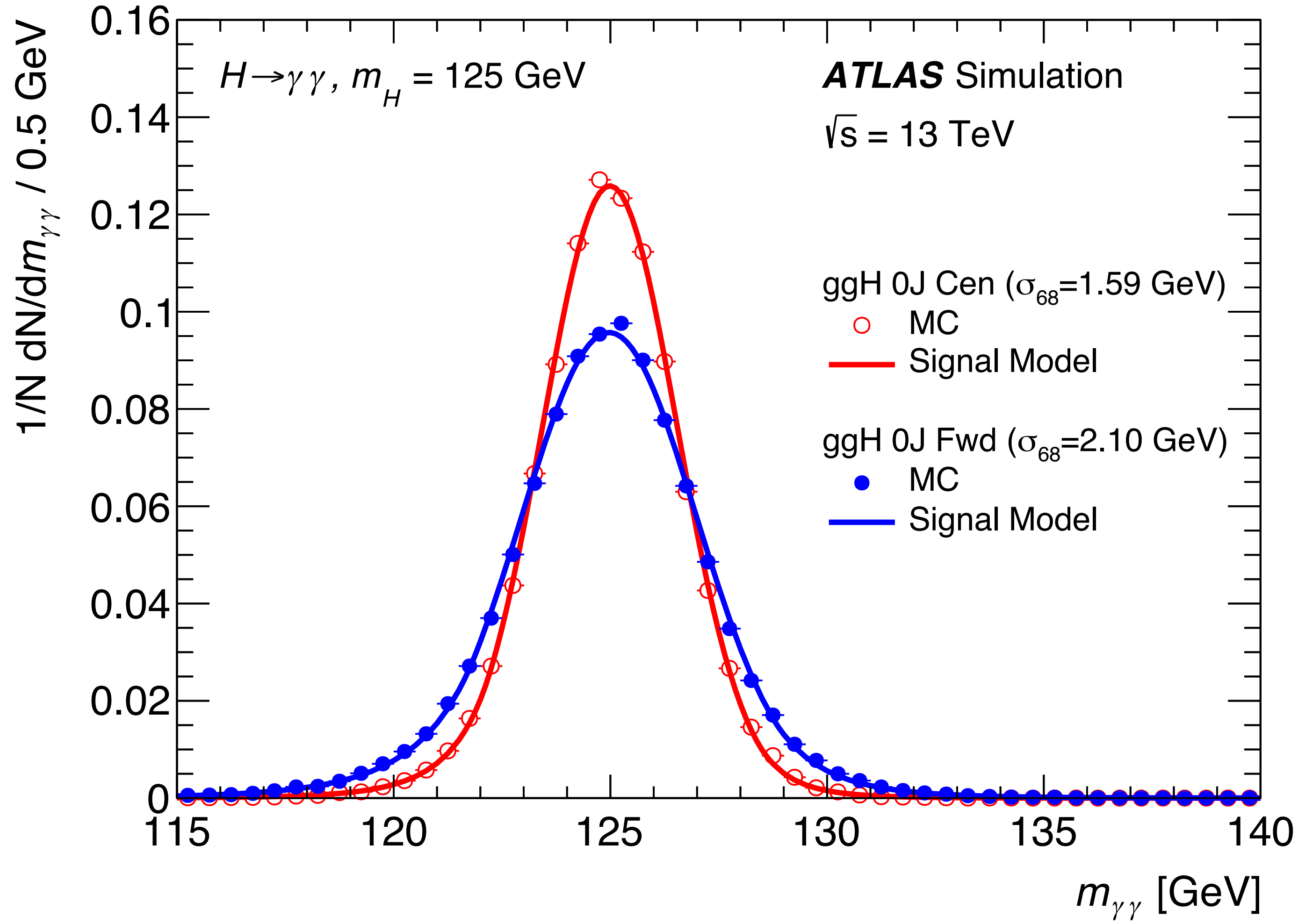




[arXiv:1802.04146](https://arxiv.org/abs/1802.04146)

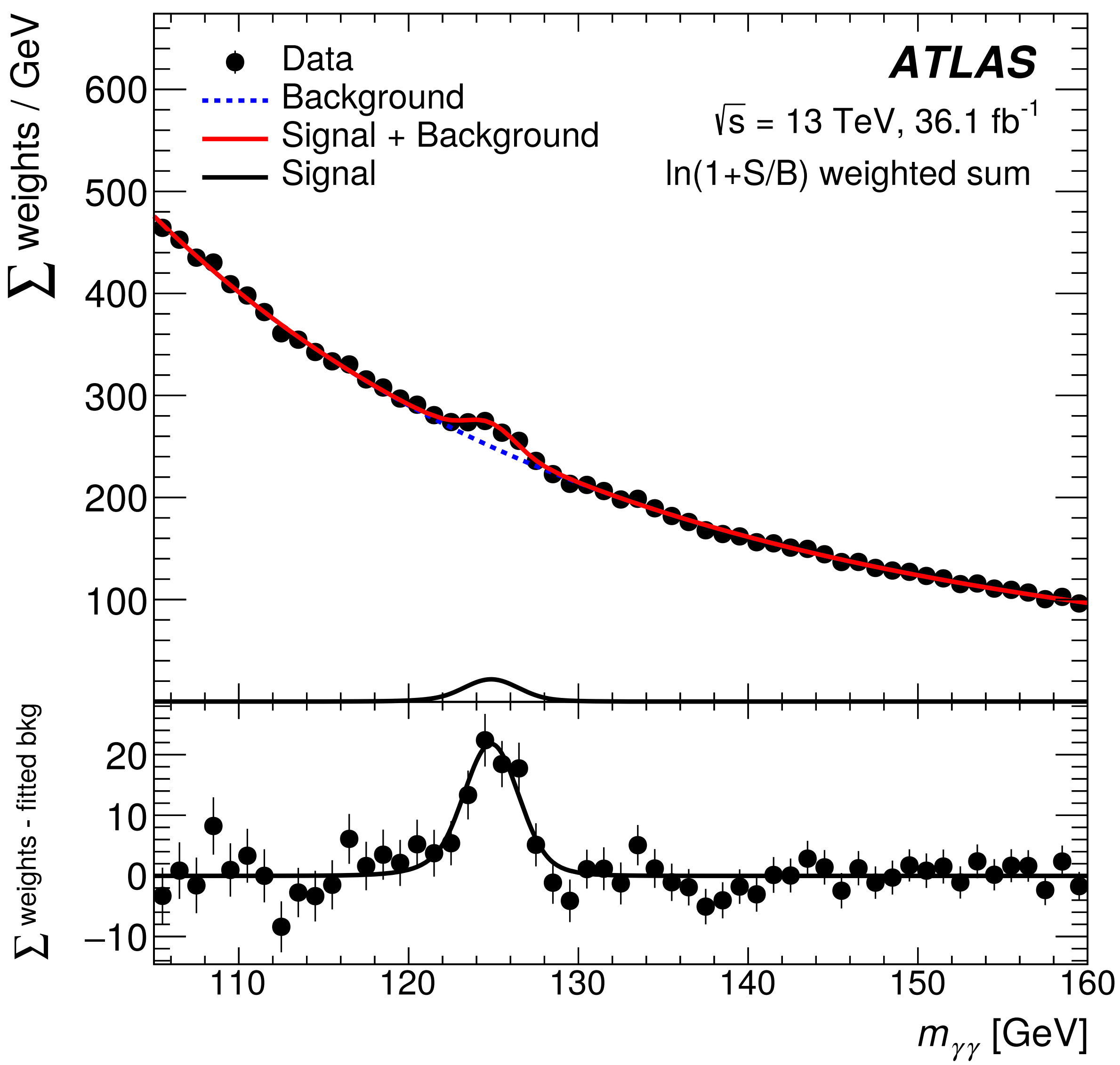
- Backgrounds from SM $\gamma\gamma$ production and jets faking photons
- Parametrized with functional form depending on category
  - Functional form for background chosen to ensure small fitted signal yield when fitting background-only samples

Diphoton Mass Parameterization



- Signal in each category modeled as double-sided Crystal Ball
  - Parameters are linear functions of m_H
  - Obtained from simultaneous fit to simulated samples at different m_H values
  - Cross-section and BR are both parametrized as function of m_H as well
    - Former by production mode

Diphoton Mass Measurement



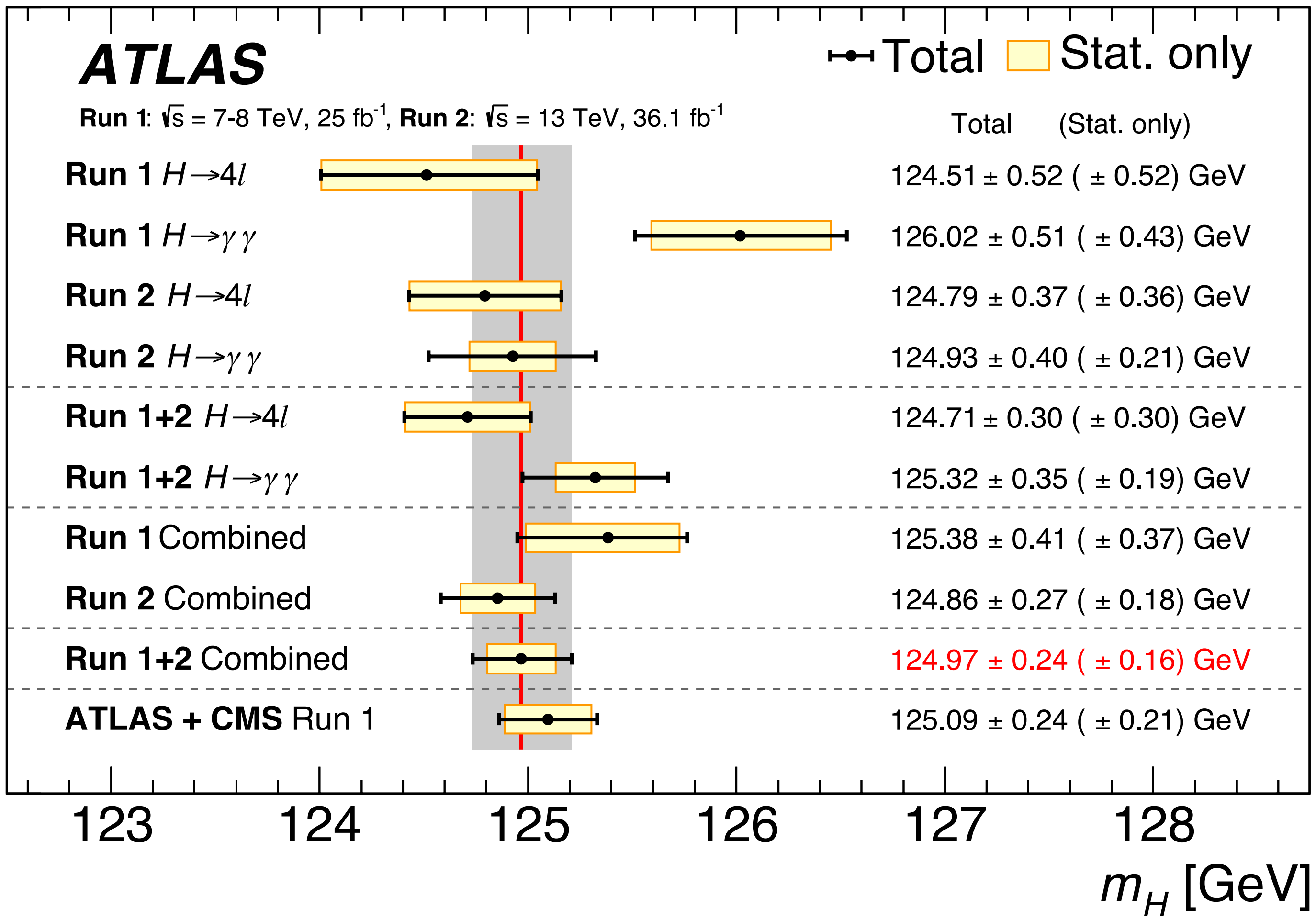
Source	Systematic uncertainty on $m_H^{\gamma\gamma}$ [MeV]
EM calorimeter cell non-linearity ←**Not correlated**	±180
EM calorimeter layer calibration	±170
Non-ID material	±120
ID material	±110
Lateral shower shape	±110
$Z \to ee$ calibration	±80
Conversion reconstruction	±50
Background model	±50
Selection of the diphoton production vertex	±40
Resolution	±20
Signal model	±20

Run-2: m_H=124.93 ± 0.21 (stat) ± 0.34 (syst)

Run1+2: m_H=125.32 ± 0.19 (stat) ± 0.29 (syst)

- Mass is obtained by a simultaneous fit over all categories
- Combination w/Run-1
  - Signal strengths not correlated
  - Part of photon energy scale systematics correlated

Combined Mass Measurement



Source	Systematic uncertainty in m_H [MeV]
EM calorimeter response linearity	60
Non-ID material	55
EM calorimeter layer intercalibration	55
$Z \to ee$ calibration	45
ID material	45
Lateral shower shape	40
Muon momentum scale	20
Conversion reconstruction	20
$H \to \gamma\gamma$ background modelling	20
$H \to \gamma\gamma$ vertex reconstruction	15
e/γ energy resolution	15
All other systematic uncertainties	10

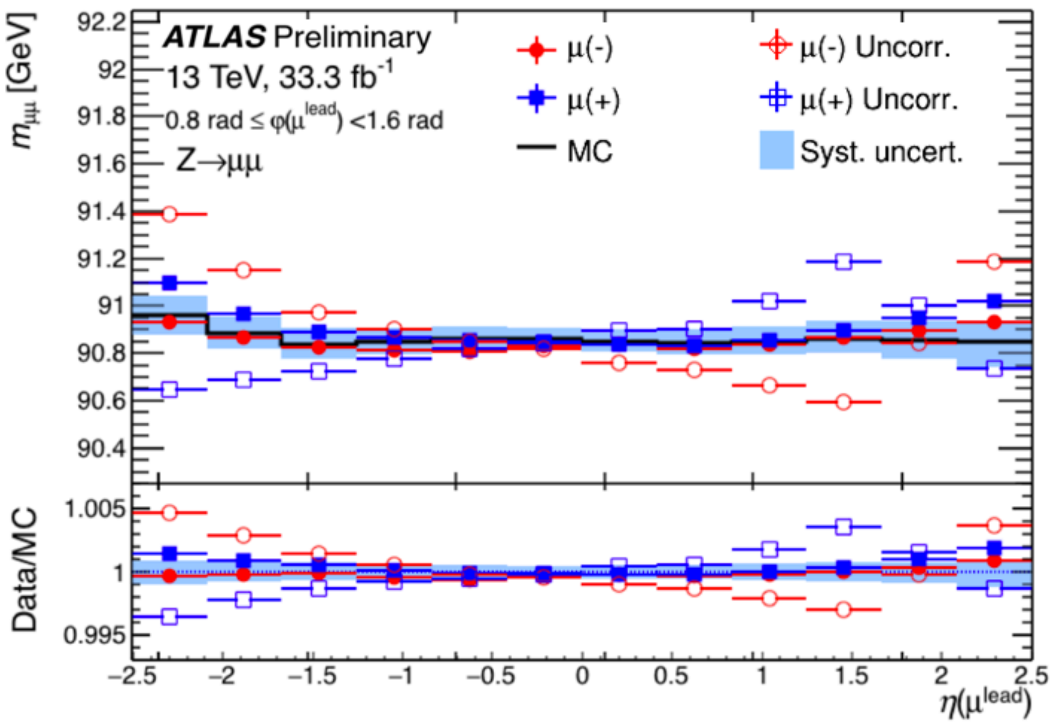
- Electron and photon calibration systematics are correlated between analyses
- Signal-strength parameters are left free
- Photon calibration systematics are the most important
- Final result compatible with Run-1 combined ATLAS+CMS measurement
- Mass measured with relative uncertainty of 0.2%!

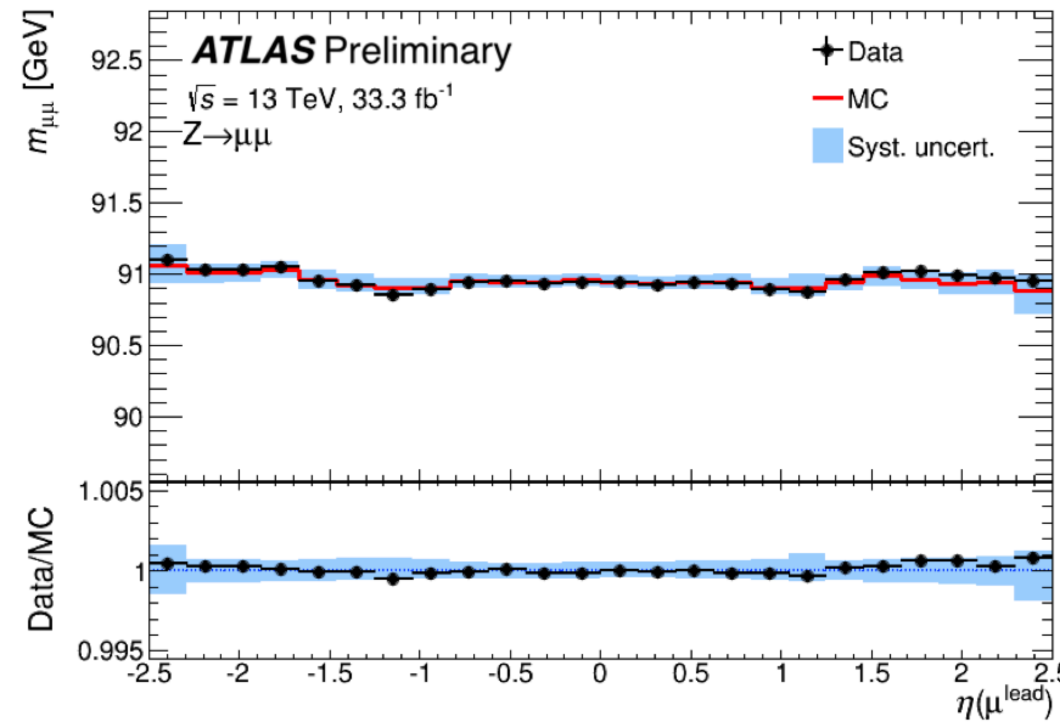
Summary

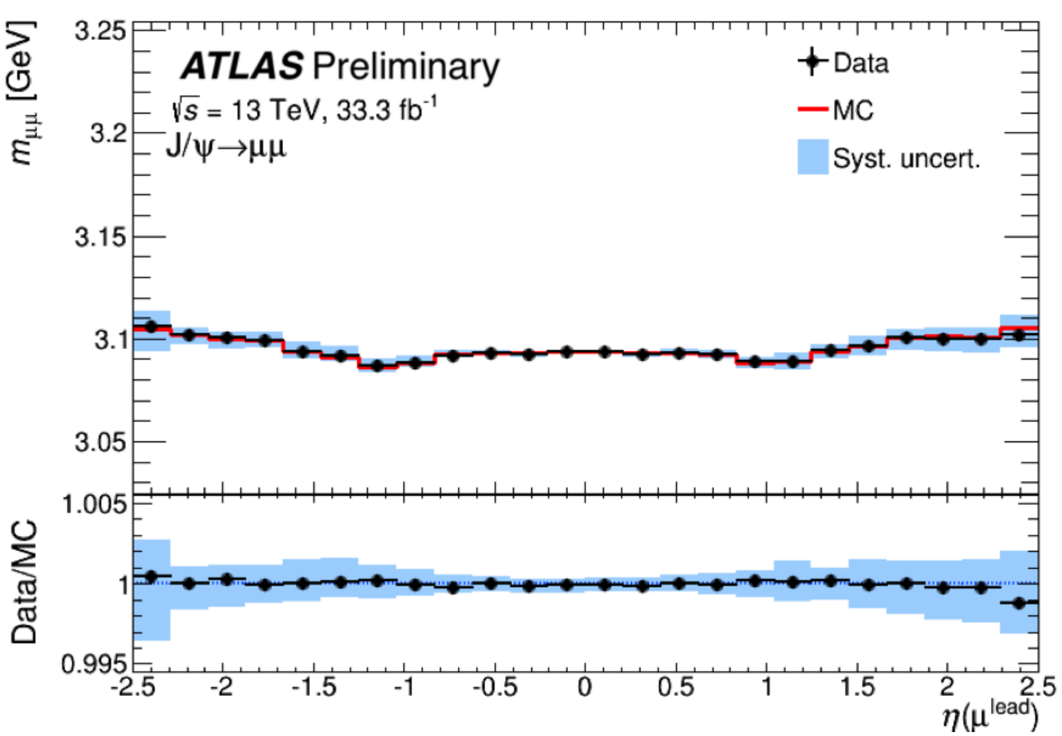
- The mass of the Higgs boson has been measured at the ATLAS detector in 36.1 fb^{-1} of 13 TeV data
- Results from the 4l and γγ channels are compatible
- Combined Run-2 result shows a significant increase of precision over combined Run-1 result
- Combined Run-1+Run-2 result of $m_H = 124.97 \pm 0.24$ GeV agrees well with combined ATLAS-CMS result from Run-1

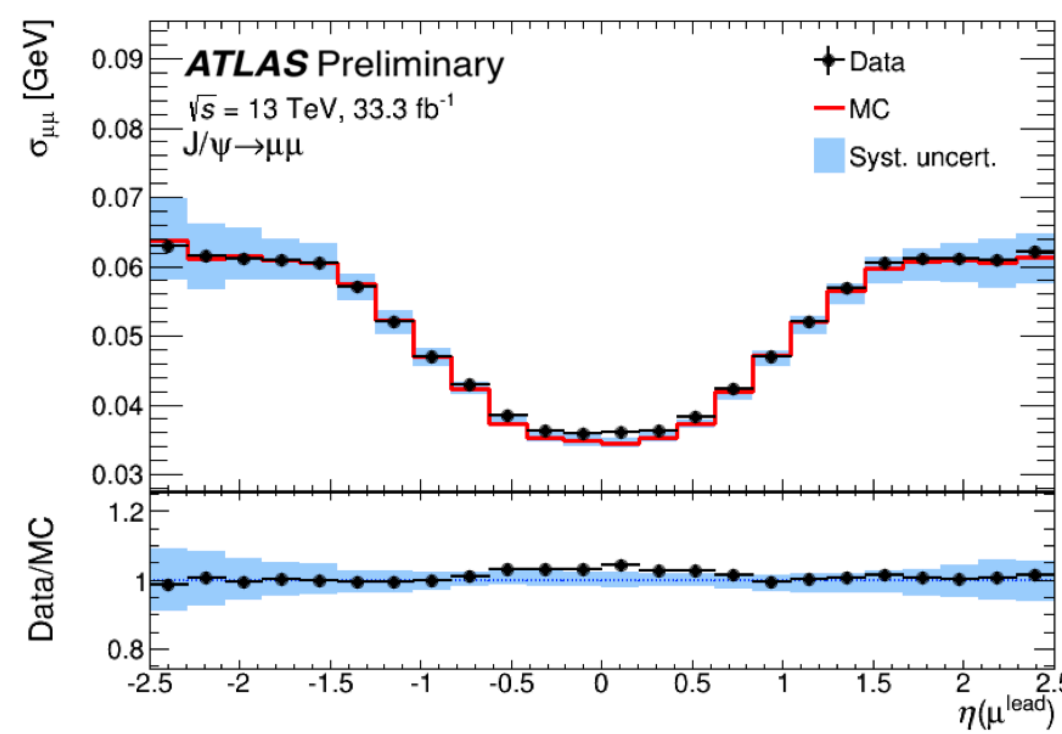
Backup

Muon Resolution and Scale









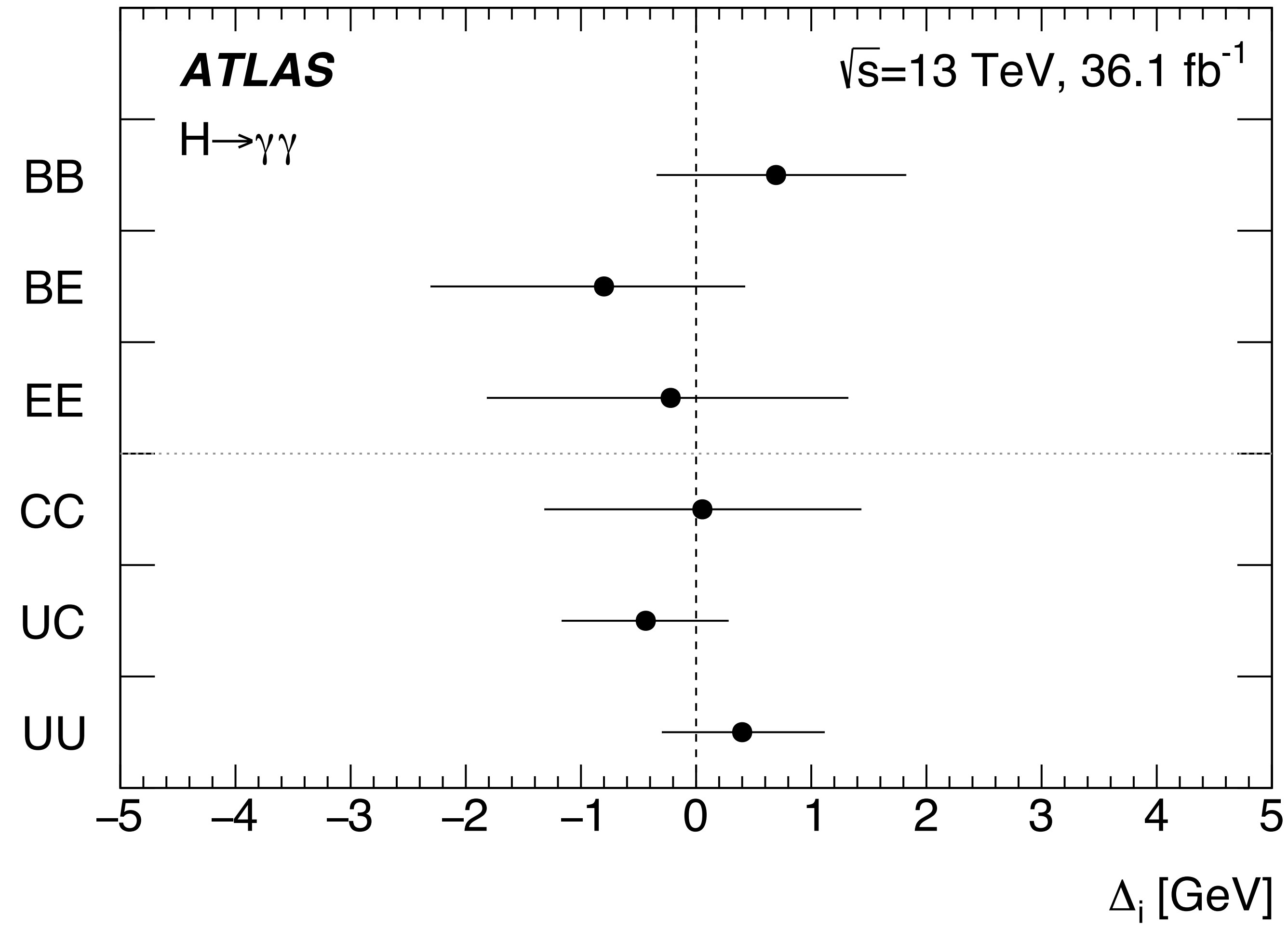
Full H4l Event Selection

Leptons and Jets requirements	
Electrons	
Loose Likelihood quality electrons with hit in innermost layer, $E_T > 7$ GeV and $\lvert\eta\rvert < 2.47$	
Muons	
Loose identification $\lvert\eta\rvert < 2.7$	
Calo-tagged muons with $p_T > 15$ GeV and $\lvert\eta\rvert < 0.1$	
Combined, stand-alone (with ID hits if available) and segment tagged muons with $p_T > 5$ GeV	
Jets	
anti-k_t jets with $p_T > 30$ GeV, $\lvert\eta\rvert < 4.5$ and passing pile-up jet rejection requirements	
Event Selection	
Quadruplet Selection	Require at least one quadruplet of leptons consisting of two pairs of same flavour opposite-charge leptons fulfilling the following requirements: p_T thresholds for three leading leptons in the quadruplet - 20, 15 and 10 GeV Maximum of one calo-tagged or standalone muon per quadruplet Select best quadruplet to be the one with the (sub)leading dilepton mass (second) closest the Z mass Leading dilepton mass requirement: 50 GeV $< m_{12} <$ 106 GeV Sub-leading dilepton mass requirement: $12 < m_{34} <$ 115 GeV Remove quadruplet if alternative same-flavour opposite-charge dilepton gives $m_{\ell\ell} < 5$ GeV $\Delta R(\ell, \ell') > 0.10$ (0.20) for all same(different)-flavour leptons in the quadruplet
Isolation	Contribution from the other leptons of the quadruplet is subtracted Muon track isolation ($\Delta R \leq 0.30$): $\Sigma p_T/p_T < 0.15$ Muon calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_T/p_T < 0.30$ Electron track isolation ($\Delta R \leq 0.20$) : $\Sigma E_T/E_T < 0.15$ Electron calorimeter isolation ($\Delta R = 0.20$) : $\Sigma E_T/E_T < 0.20$
Impact Parameter Significance	Apply impact parameter significance cut to all leptons of the quadruplet. For electrons : $\lvert d_0/\sigma_{d_0}\rvert < 5$ For muons : $\lvert d_0/\sigma_{d_0}\rvert < 3$
Vertex Selection	Require a common vertex for the leptons χ^2/ndof < 6 for 4μ and < 9 for others.

Hγγ Reconstructed Categories

Category	Selection
tH lep 0fwd	$N_{\mathrm{lep}} = 1,\ N^{\mathrm{cen}}_{\mathrm{jets}} \le 3,\ N_{b-\mathrm{tag}} \ge 1,\ N^{\mathrm{fwd}}_{\mathrm{jets}} = 0\ (p_{\mathrm{T}}^{\mathrm{jet}} > 25\,\mathrm{GeV})$
tH lep 1fwd	$N_{\mathrm{lep}} = 1,\ N^{\mathrm{cen}}_{\mathrm{jets}} \le 4,\ N_{b-\mathrm{tag}} \ge 1,\ N^{\mathrm{fwd}}_{\mathrm{jets}} \ge 1\ (p_{\mathrm{T}}^{\mathrm{jet}} > 25\,\mathrm{GeV})$
ttH lep	$N_{\mathrm{lep}} \ge 1,\ N^{\mathrm{cen}}_{\mathrm{jets}} \ge 2,\ N_{b-\mathrm{tag}} \ge 1,\ Z_{\ell\ell}$ veto $(p_{\mathrm{T}}^{\mathrm{jet}} > 25\,\mathrm{GeV})$
ttH had BDT1	$N_{\mathrm{lep}} = 0,\ N_{\mathrm{jets}} \ge 3,\ N_{b-\mathrm{tag}} \ge 1,\ \mathrm{BDT}_{\mathrm{ttH}} > 0.92$
ttH had BDT2	$N_{\mathrm{lep}} = 0,\ N_{\mathrm{jets}} \ge 3,\ N_{b-\mathrm{tag}} \ge 1,\ 0.83 < \mathrm{BDT}_{\mathrm{ttH}} < 0.92$
ttH had BDT3	$N_{\mathrm{lep}} = 0,\ N_{\mathrm{jets}} \ge 3,\ N_{b-\mathrm{tag}} \ge 1,\ 0.79 < \mathrm{BDT}_{\mathrm{ttH}} < 0.83$
ttH had BDT4	$N_{\mathrm{lep}} = 0,\ N_{\mathrm{jets}} \ge 3,\ N_{b-\mathrm{tag}} \ge 1,\ 0.52 < \mathrm{BDT}_{\mathrm{ttH}} < 0.79$
tH had 4j1b	$N_{\mathrm{lep}} = 0,\ N^{\mathrm{cen}}_{\mathrm{jets}} = 4,\ N_{b-\mathrm{tag}} = 1\ (p_{\mathrm{T}}^{\mathrm{jet}} > 25\,\mathrm{GeV})$
tH had 4j2b	$N_{\mathrm{lep}} = 0,\ N^{\mathrm{cen}}_{\mathrm{jets}} = 4,\ N_{b-\mathrm{tag}} \ge 2\ (p_{\mathrm{T}}^{\mathrm{jet}} > 25\,\mathrm{GeV})$
VH dilep	$N_{\mathrm{lep}} \ge 2,\ 70\,\mathrm{GeV} \le m_{\ell\ell} \le 110\,\mathrm{GeV}$
VH lep High	$N_{\mathrm{lep}} = 1,\ \lvert m_{e\gamma} - 89\,\mathrm{GeV}\rvert > 5\,\mathrm{GeV},\ p_{\mathrm{T}}^{\ell+E_{\mathrm{T}}^{\mathrm{miss}}} > 150\,\mathrm{GeV}$
VH lep Low	$N_{\mathrm{lep}} = 1,\ \lvert m_{e\gamma} - 89\,\mathrm{GeV}\rvert > 5\,\mathrm{GeV},\ p_{\mathrm{T}}^{\ell+E_{\mathrm{T}}^{\mathrm{miss}}} < 150\,\mathrm{GeV},\ E_{\mathrm{T}}^{\mathrm{miss}}$ significance > 1
VH MET High	$150\,\mathrm{GeV} < E_{\mathrm{T}}^{\mathrm{miss}} < 250\,\mathrm{GeV},\ E_{\mathrm{T}}^{\mathrm{miss}}$ significance > 9 or $E_{\mathrm{T}}^{\mathrm{miss}} > 250\,\mathrm{GeV}$
VH MET Low	$80\,\mathrm{GeV} < E_{\mathrm{T}}^{\mathrm{miss}} < 150\,\mathrm{GeV},\ E_{\mathrm{T}}^{\mathrm{miss}}$ significance > 8
jet BSM	$p_{\mathrm{T,j1}} > 200\,\mathrm{GeV}$
VH had tight	$60\,\mathrm{GeV} < m_{\mathrm{jj}} < 120\,\mathrm{GeV},\ \mathrm{BDT}_{\mathrm{VH}} > 0.78$
VH had loose	$60\ GeV < m_{\mathrm{jj}} < 120\,\mathrm{GeV},\ 0.35 < \mathrm{BDT}_{\mathrm{VH}} < 0.78$
VBF tight, high p_{T}^{Hjj}	$\lvert\Delta\eta_{jj}\rvert > 2,\ \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\mathrm{j1}} + \eta_{\mathrm{j2}})\rvert < 5,\ p_{\mathrm{T}}^{Hjj} > 25\,\mathrm{GeV},\ \mathrm{BDT}_{\mathrm{VBF}} > 0.47$
VBF loose, high p_{T}^{Hjj}	$\lvert\Delta\eta_{jj}\rvert > 2,\ \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\mathrm{j1}} + \eta_{\mathrm{j2}})\rvert < 5,\ p_{\mathrm{T}}^{Hjj} > 25\,\mathrm{GeV},\ -0.32 < \mathrm{BDT}_{\mathrm{VBF}} < 0.47$
VBF tight, low p_{T}^{Hjj}	$\lvert\Delta\eta_{jj}\rvert > 2,\ \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\mathrm{j1}} + \eta_{\mathrm{j2}})\rvert < 5,\ p_{\mathrm{T}}^{Hjj} < 25\,\mathrm{GeV},\ \mathrm{BDT}_{\mathrm{VBF}} > 0.87$
VBF loose, low p_{T}^{Hjj}	$\lvert\Delta\eta_{jj}\rvert > 2,\ \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\mathrm{j1}} + \eta_{\mathrm{j2}})\rvert < 5,\ p_{\mathrm{T}}^{Hjj} < 25\,\mathrm{GeV},\ 0.26 < \mathrm{BDT}_{\mathrm{VBF}} < 0.87$
ggH 2J BSM	≥ 2 jets, $p_{\mathrm{T}}^{\gamma\gamma} \ge 200\,\mathrm{GeV}$
ggH 2J High	≥ 2 jets, $p_{\mathrm{T}}^{\gamma\gamma} \in [120, 200]$ GeV
ggH 2J Med	≥ 2 jets, $p_{\mathrm{T}}^{\gamma\gamma} \in [60, 120]$ GeV
ggH 2J Low	≥ 2 jets, $p_{\mathrm{T}}^{\gamma\gamma} \in [0, 60]$ GeV
ggH 1J BSM	$= 1$ jet, $p_{\mathrm{T}}^{\gamma\gamma} \ge 200\,\mathrm{GeV}$
ggH 1J High	$= 1$ jet, $p_{\mathrm{T}}^{\gamma\gamma} \in [120, 200]$ GeV
ggH 1J Med	$= 1$ jet, $p_{\mathrm{T}}^{\gamma\gamma} \in [60, 120]$ GeV
ggH 1J Low	$= 1$ jet, $p_{\mathrm{T}}^{\gamma\gamma} \in [0, 60]$ GeV
ggH 0J Fwd	$= 0$ jets, one photon with $\lvert\eta\rvert > 0.95$
ggH 0J Cen	$= 0$ jets, two photons with $\lvert\eta\rvert \le 0.95$

H→γγ Cross-checks



- BB: both photons in barrel
- BE: one photon in barrel, one in endcap
- EE: both photons in endcap
- CC: both photons converted
- UC: one photon converted, one not
- UU: both photons unconverted

4l Fits in Final States