Measurement of Higgs boson mass in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel with ATLAS detector at LHC

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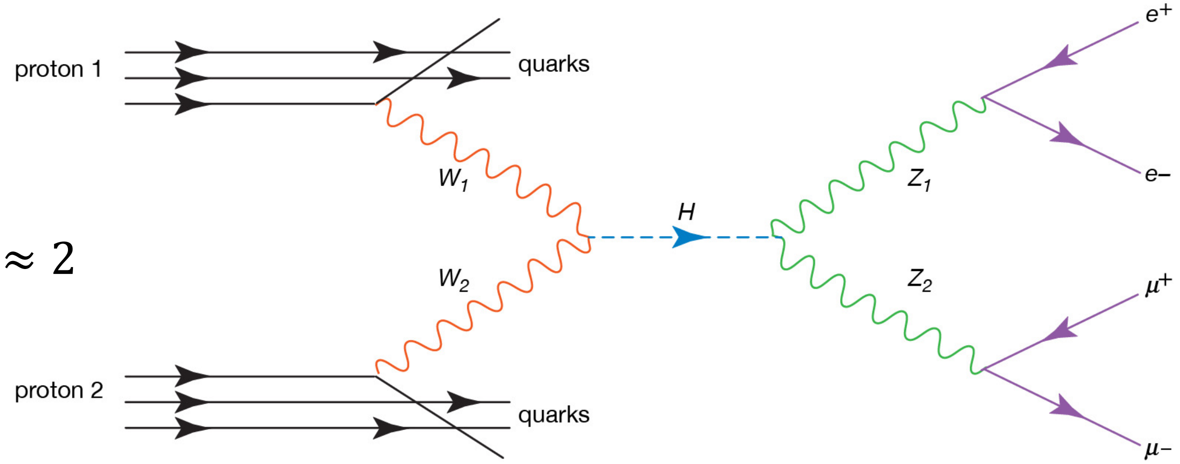
Outline

- Strategy overview
  - Introduction to Higgs to ZZ^* to 4 leptons decay channel.
  - Definition of reconstructed four-lepton invariant mass $m_{4l}^{constrained}$
- Final state radiation (FSR) recovery and the Z-Mass Constraint (ZMC)
- Signal-background discriminant and event level resolution
- Reducible background estimation for $ll\mu\mu$ and $llee$
- Signal model, background model and final fit results.
- Summary

Introduction

➢ Higgs to ZZ* to 4l decay

Advantage of H to 4l channel:
- More sensitive
- High signal-to-background ratio ≈ 2



➢ Final states

$\mu^+\mu^-, \mu^+\mu^-$ (4μ);
e^+e^-, e^+e^- (4e);
$\mu^+\mu^-, e^+e^-$ (2μ2e);
$e^+e^-, \mu^+\mu^-$ (2e2μ);

➢ Defining m_{4l}
- The reconstructed four-lepton invariant mass is the main observable used to determine m_H.
- Final state radiation (FSR) recovery and the Z-Mass Constraint (ZMC) are applied to define the observable ($m_{4l}^{constrained}$) used in final fit.
- Neural Network discriminant and event level resolution.

➢ The final fit is simultaneously performed in 4 categories, based on the final state flavour of each event ($4\mu,\ 4e,\ 2\mu 2e,\ 2e2\mu$).
- The first di-lepton come from on-shell Z boson, with di-lepton invariant mass closest to nominal Z boson mass.
- The second di-lepton come from off-shell Z boson, is the remaining pair of leptons in the 4-lepton system.

Simulation samples and Event Selection

- **Signal:**
  - ggF(gluon fusion) 87.4%
  - VBF(vector boson fusion) 6.8%
  - VH(associated vector boson) 3.5%
  - $t\bar{t}$H(with a top quark pair) 0.9%
  - $b\bar{b}$H(with a bottom quark pair) 0.9%
  - tH(with a single top quark) 0.2%

- **Background:**
  - ZZ* continuum background (89%):
    1. qqZZ(quark-antiquark annihilation),
    2. ggZZ(gluon-initiated)
    3. EW ZZ(vector boson scattering)
  - WZ production, Z + jets production, $t\bar{t}$ pair (total 9%)
  - VVV(three electroweak bosons), tXX($t\bar{t}$ pair and one or more top quarks or electroweak bosons)(total 2%)

- **Event Selection**

Physics Objects:

electrons:

Loose Likelihood quality with hit in innermost layer

$E_T > 7GeV$, $|\eta| < 2.47$, $|z_0 \cdot sin\theta| < 0.5mm$

muon:

Loose identification, $p_T > 5GeV$, $|\eta| < 2.7$

$|d_0| < 1mm$ and $|z_0 \cdot sin\theta| < 0.5mm$

Jet:

anti-k_T jets, $p_T > 30GeV$, $|\eta| < 4.5$

b-tagging:

selected jets with $|\eta| < 2.5$ are assigned a b-tagging

overlap removal:

Jets within ΔR < 0.2 of an electron or ΔR < 0.1 of a muon are removed

To reconstruct Higgs

4-lepton candidates:

At least 4 leptons fulfilling the following requirements:

- two pairs of same-flavour, opposite charge leptons
- p_T thresholds for three leading leptons: p_{T1}>20GeV, p_{T2}>15GeV, p_{T3}>10 GeV.
- At most 1 calo-tagged, stand-alone or silicon-associated muon per quadruplet.
- Leading di-lepton mass requirement: 50 GeV < m_{12}< 106 GeV
- Sub-leading di-lepton mass requirement: : $m_{threshold}$ < m_{34} < 115 GeV
- ΔR(l, l')>0.1 for all lepton pair
- remove the events if di-lepton m_{ll}< 5 GeV to veto the J/ψ (3.1 GeV)

Isolation: contribution from the other leptons of the quadruplet is subtracted

Impact parameter: For electrons $d_0/\sigma_{d0} < 5$; For muons $d_0/\sigma_{d0} < 3$

Vertex selection: Require a common vertex for the leptons:

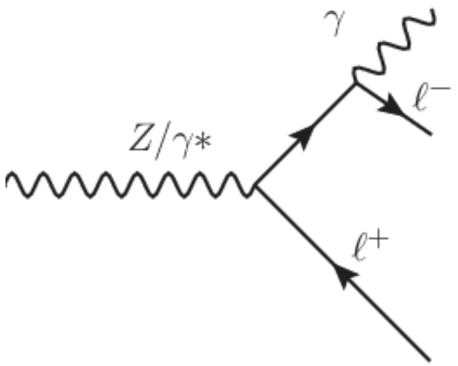
$$\chi^2/ndof < 6\ for\ 4\mu\ and < 9\ for\ other\ decay\ channels$$

Best quadruplet: if more than one quadruplet has been selected, choose the quadruplet with highest Higgs decay matrix element.

Final state radiation (FSR) recovery and the Z-Mass Constraint (ZMC)

Final state radiation recovery

- The leptons from the Z boson can emit Final State Radiation (FSR) when interacting with the detector material or when bending in a magnetic field. If the FSR have enough energy and without recovery, the 4l invariant mass will shift to lower value.
- From simulation, it is estimated that ~ 3% of signal events are affected by FSR, recovery algorithm is used to target and recover these FSR particles.



← Final state radiation

Z-Mass Constraint

- In the $H \rightarrow ZZ^* \rightarrow 4\ell$ process, the leading lepton pair is produced from the on-shell Z-boson. Z mass constraint allows for an improvement in the 4-lepton mass resolution by constraining the mass of leading pair to the Z line shape using the lepton momentum and its uncertainties.

- Based on the Z line shape, the invariant mass of the leading pair is pulled toward Z boson mass by changing the momenta, within the range of the lepton's uncertainty.

Signal-background discriminant and event level resolution

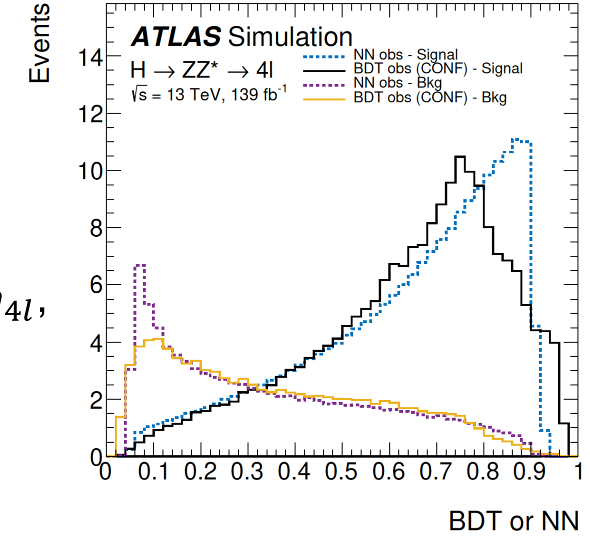
➢ Signal-background discriminant

- The use of machine learning algorithms can reduce the uncertainty on m_H by creating a classifier that can discriminate signal from the ZZ background and improve the signal-background ratio.

- The Neural Network classifier $NN_{ZZ}^{Disc.}$ was trained separately for same-flavour (4μ and $4e$) and opposite-flavour ($2\mu 2e$ and $2e2\mu$) final states.
- The training variables were the four-lepton transverse momentum, p_T^{4l}, four-lepton pseudorapidity, η_{4l}, and KD(ZZ*) (a kinematic discriminant based on the calculated matrix elements).

- Small improvement (+0.5−1%) using NN compare to previous BDT model.

Comparison of NN and BDT,
BDT distributions are shifted to [0,1]



➢ Event level resolution

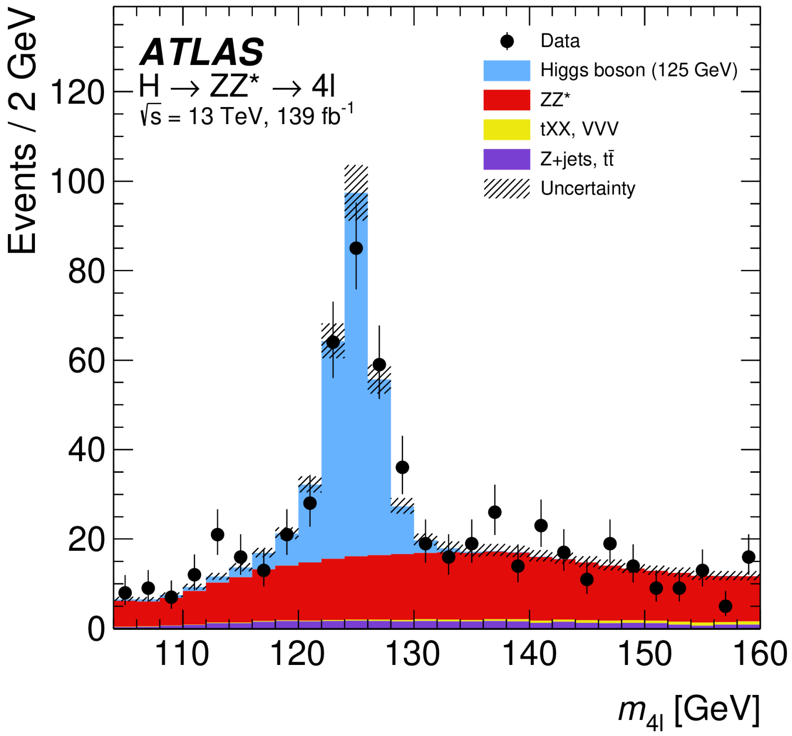
- Not all events have the same "quality", some events can have better resolution due to signal topology and detector response.
- A per-event error method is used by making the signal model conditional on the expected resolution of the event.

- A Quantile Regression Neural Network (QRNN) can be used to predict the σ of DCB for each event.

  - Achieved by predicting target quantile of $|m_{4l}^{constrained} - m_{4l}^{truth}|$, calibrated to match σ_i of DCB.
  - Trained with lepton p_T , η , φ , $p_{T,4l}^{constrained}$, $\sigma_{m4l}^{constrained}$ in each final state using all m_H samples.

Pre-fit $m_{4l}^{constrained}$ distribution

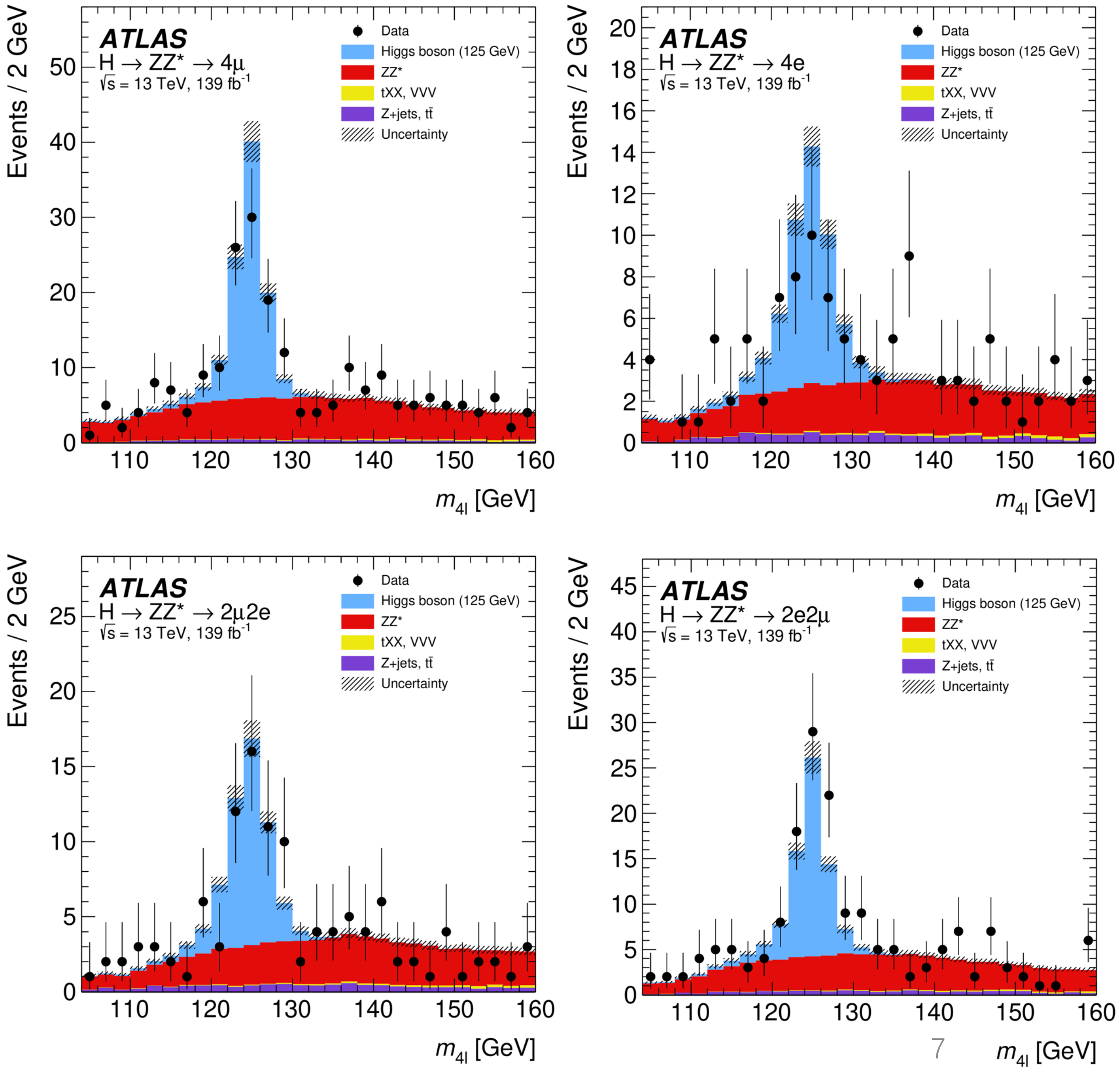
➢ The inclusive $m_{4l}^{constrained}$ distribution



➢ The expected and observed yields in [105 - 160] GeV

Final state	Higgs	ZZ, tXX, VVV	Reducible Backgrounds	Total	Observed
4μ	81 ± 5	124 ± 7	10.9 ± 0.7	215 ± 9	217
$2e2\mu$	56.0 ± 3.3	84 ± 5	11.2 ± 0.7	151 ± 6	169
$2\mu2e$	43.1 ± 3.1	64 ± 5	11.6 ± 1.6	119 ± 6	115
$4e$	38.9 ± 2.9	55 ± 6	9.6 ± 1.1	104 ± 6	103
Total	219 ± 13	327 ± 21	43.7 ± 3.1	589 ± 25	604

The $m_{4l}^{constrained}$ distribution for each of the decay channels ↓



Reducible background estimation

- Background component

ZZ* continuum background (89%): exactly the same topology as the signal

WZ production, Z + jets production, $t\bar{t}$ pair (total 9%): refer to as "Reducible background"

VVV, tXX (total 2%)

- The reducible background processes which contain fake and non-isolated leptons, the simulation is not robust in the determination of selection efficiencies.

- Use data driven method to get SR yield:

1. define control regions (CR) to enhance some background processes.
2. expected background in the signal region (SR) is extrapolated from the control region using transfer factors.

$$expected\ yield\ in\ SR = transfer\ factor \times events\ in\ CR\ (\mathrm{data})$$

- Strategy

- The background estimation is performed separately for the $ll + \mu\mu$ and the $ll + ee$ final states.
  Because the composition of reducible backgrounds depends on the flavour of the subleading pair.
  1. $ll + \mu\mu$ estimation: consist of 4μ and $2e2\mu$ final states.
  2. $ll + ee$ estimation: consist of $4e$ and $2\mu 2e$ final states.

$ll\mu\mu$ background estimation

➢ Background component

Observable: mass of leading pair

$Z + jets$: The peaks at the Z mass

Z+ heavy-flavor jets

Z+ light-flavor jets

$t\bar{t}$: The broad distribution

WZ production

➢ Control Region

(1) inverted d0 CR: Inverted impact parameter selection (enhanced in Z+HF, $t\bar{t}$)

(2) inverted Isolation CR: Inverted isolation to subleading pair (enhanced in Z+LF, $t\bar{t}$)

(3) $e\mu + \mu\mu$ CR: different flavour for leading pair (enhanced in $t\bar{t}$)

(4) same-sign CR: Same-sign subleading pair (all)

(5) relaxed CR : Relaxed the d0 and isolation selection

➢ Background shape model

	Relaxed Iso & d_0	Inverted Isolation	Inverted d_0	Same-sign	$e\mu$+$\mu\mu$
Z + LF jets	BW $*$ CB$_1$	BW $*$ CB$_1$	BW $*$ CB$_1$	BW $*$ CB$_1$	1st Poly
Z + HF jets	BW $*$ CB$_1$	BW $*$ CB$_1$	BW $*$ CB$_1$	BW $*$ CB$_1$	1st Poly
$t\bar{t}$	2nd Cheb	2nd Cheb	2nd Cheb	2nd Cheb	2nd Cheb
Diboson	BW $*$ CB$_2$ + G	BW $*$ CB$_2$ + G	BW $*$ CB$_2$	BW $*$ CB$_2$	1st Poly

➢ To get the expected events for each component and each CR by the simultaneous fit. Then use the Transfer factor obtained from MC to calculate the events in the signal region.

4μ+$2e2\mu$ - Full Run2 data			
type	data fit	extrapolation factor [%]	SR yield
$t\bar{t}$	3044 ± 38	0.25 ± 0.01	$7.51 \pm 0.09 \pm 0.51$
Z+jets (HF)	2835 ± 131	0.44 ± 0.01	$12.36 \pm 0.57 \pm 0.70$
Z+jets (LF)	408 ± 98	1.08 ± 0.11	$4.41 \pm 1.06 \pm 0.54$
Z+jets (HF+LF)	3289 ± 64		$14.50 \pm 0.28 \pm 1.49$
WZ	MC-based estimation		4.52 ± 0.39

$llee$ background estimation

- ➢ Background component (Observable: $n_{InnerPix}$ the number of IBL hits)
- (f) fake electron from light jets
- (q) electrons from semileptonic decays of heavy quarks
- (γ) photon conversions or FSR

- ➢ Control Region
- Z+X CR (more statistic): on-shell Z decays accompanied by an electron candidate that satisfy the relaxed identification criteria. To get fit template and transfer factor.

- 3l+X CR: X is lower pT electron in the subleading pair, selection and identification criteria for X are relaxed. To get events of each component from data fit.

- ➢ Data fit result and SR yield

$4e$+$2\mu 2e$ - Full Run2 data				
type	data fit	ZZ*+HF	efficiency[%]	SR yield
f	10590 ± 105	1296 ± 6.8	0.165 ± 0.04	15.37 ± 0.54 ± 2.42
γ	761 ± 34	109 ± 0.8	0.667 ± 0.14	4.35 ± 0.71 ± 0.94
q	MC-based estimation			11.40 ± 3.42

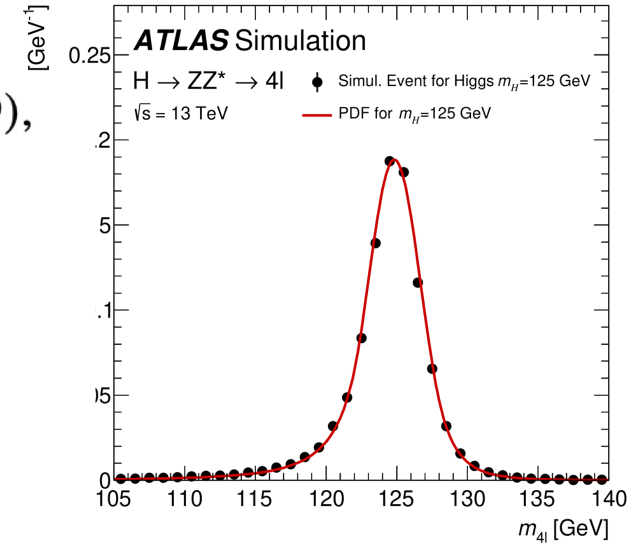
Signal and Backgrounds model

- Signal model can decompose as:

$$P_s = P_s(m_{4\ell}|D,\sigma,m_H)\cdot P_s(D|m_H)\cdot \underline{P_s(\sigma)}$$
$$\approx \underline{P_s(m_{4\ell}|D,\sigma,m_H)}\cdot \underline{P_s(D|m_H)}.$$

- Double-Sided Crystal Ball (DCB):

$$P_s(m_{4\ell}|D,\sigma,m_H) = DCB(\mu = f_\mu(m_H,D),$$
$$w = f_\sigma(D,\sigma),$$
$$\alpha_{Lo} = f_{\alpha_{Lo}}(D),$$
$$n_{Lo} = f_{n_{Lo}}(D),$$
$$\alpha_{Hi},$$
$$n_H$$
$$|\sigma)$$



- DCB mean parameterized as a function of m_H :

$$P_s(m_{4\ell}|m_H) = DCB(m_{4\ell}|\mu = S\times(m_H - 125.0) + I(D), \sigma(\sigma_i), \alpha_{hi}, \alpha_{low}, n_{hi}, n_{low})$$

$$I(D) = S_D\times(D-0.5)+I. \qquad \sigma(\sigma_i) = SF\times\sigma_i$$

- $P_s(\sigma)$
  - The same for signal and background so it factors out in the full likelihood.

- $P_s(\mathrm{D}|m_H)$ MC template
  - Generated at m_H = 124, 125, 126 GeV using ggH, VBF and VH
  - Morphed with mH

- Backgrounds model can decompose as:

$$P_b = P_b(m_{4\ell},D)\cdot P_b(\sigma)$$
$$\approx P_b(m_{4\ell},D),$$

- All backgrounds PDFs are templates made using 2D kernel smoothing techniques

ZZ* background
- Templates made for qqZZ, ggZZ, EWZZ separately since we consider the relative composition systematics when floating the ZZ normalization.

Z+Jets, ttbar
- Template taken from MC
- Normalization estimated by data-driven method.

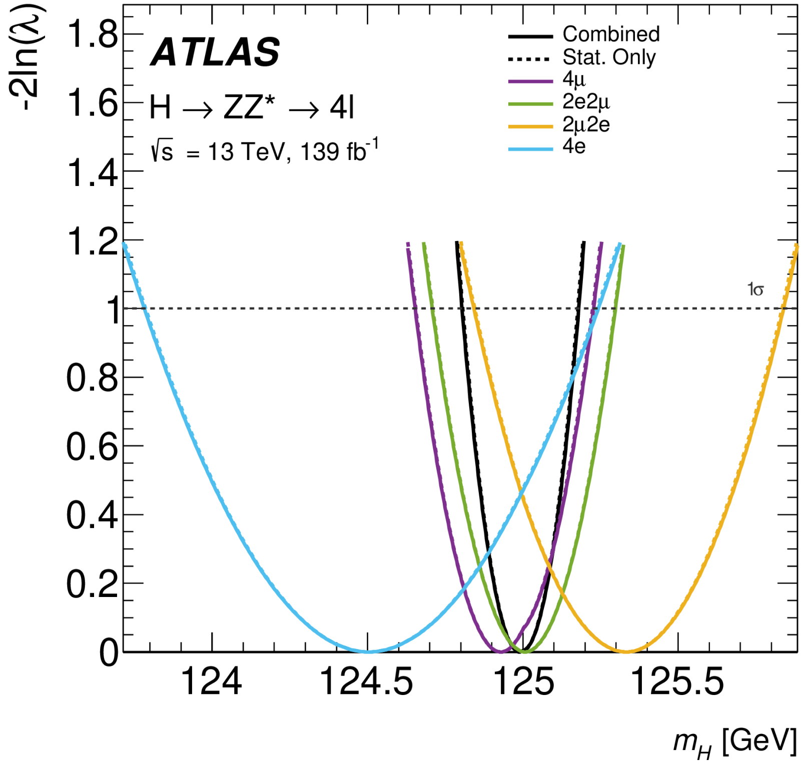
tXX, VVV background
- All processes considered together for PDF.
- Template and normalization taken from simulation.

Final fit results

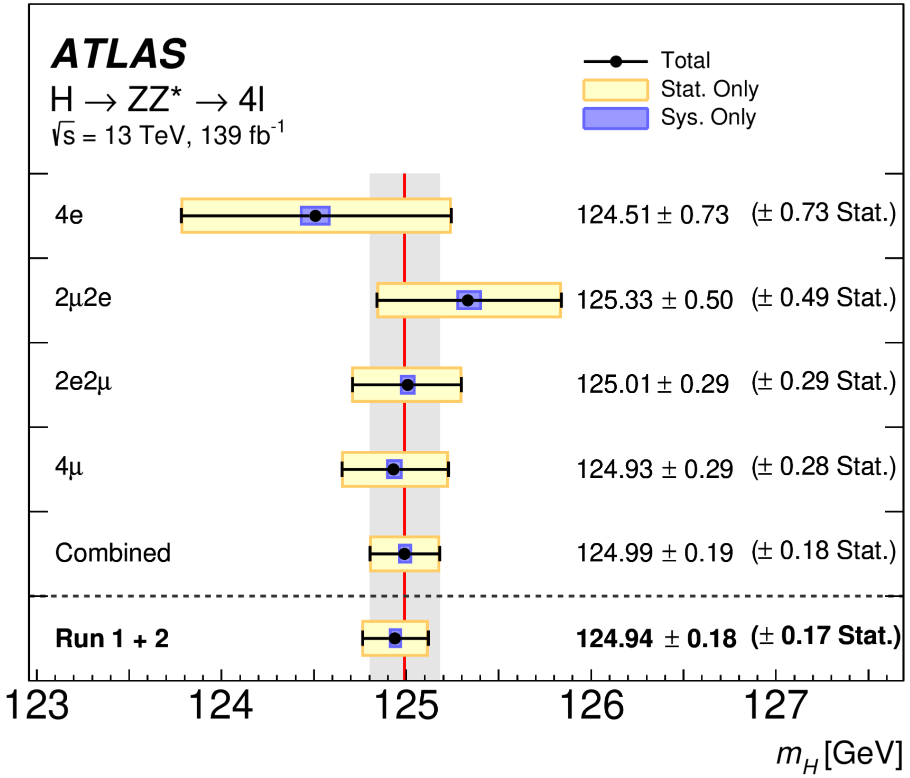
➢ The combined measurement of m_H in $H \to 4l$ channel was found to be:

$$m_H = 124.99 \pm 0.19 = 124.99 \pm 0.18(Stat.) \pm 0.04(Sys.)$$

- The NLL scan on observed data for each of the decay channels with full and statistic



- The summary plot of data fit for the combined channel and individual decay channels



- largest contributions to the systematic uncertainty

Systematic Uncertainty	Contribution [MeV]
Muon momentum scale	±28
Electron energy scale	±19
Signal-process theory	±14

Summary

- Presenting full Run-2 Higgs mass measurement in $H \rightarrow ZZ^* \rightarrow 4\ell$ channel. (https://arxiv.org/abs/2207.00320)

- This analysis is an improvement on previous results:
  - Extension of likelihood model to include the NN discriminant for both signal and background.
  - Update the MCP recommendations.
  - Update the Electron ID recommendations.

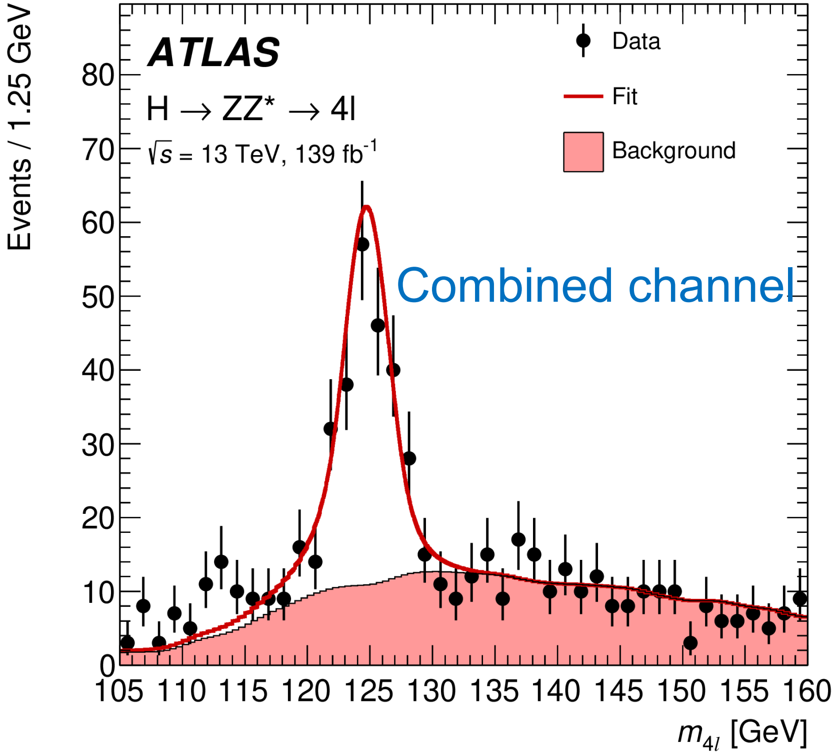
The final observed mass using the full Run 2 dataset in $H \rightarrow ZZ^* \rightarrow 4\ell$ is

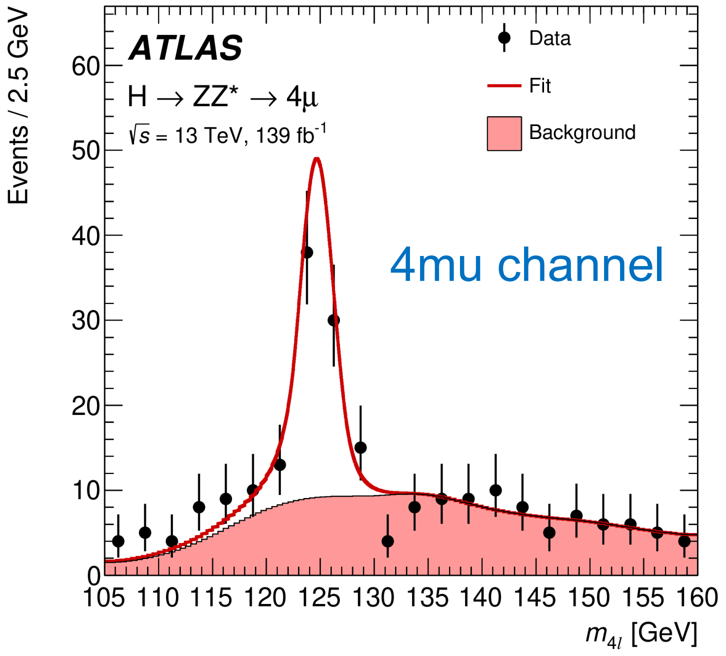
$$m_H = 124.99 \pm 0.19 = 124.99 \pm 0.18(Stat.) \pm 0.04(Sys.)$$

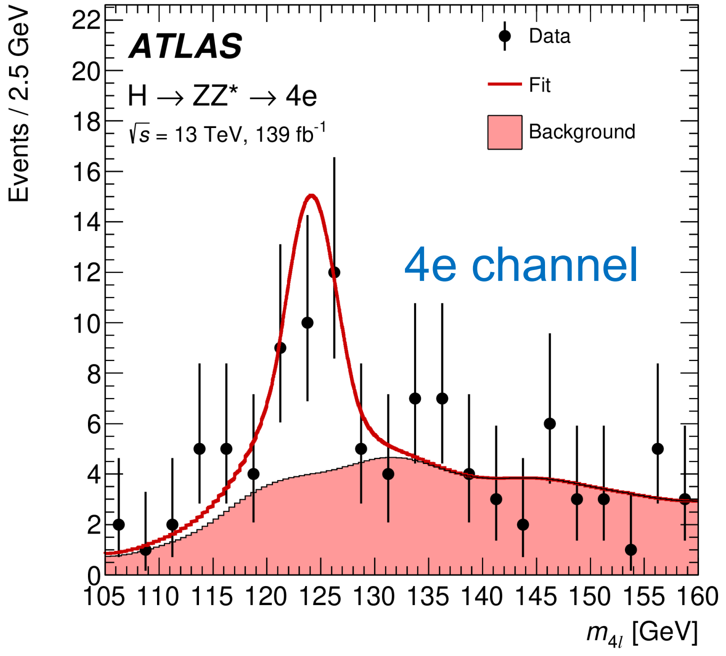
Thank you !

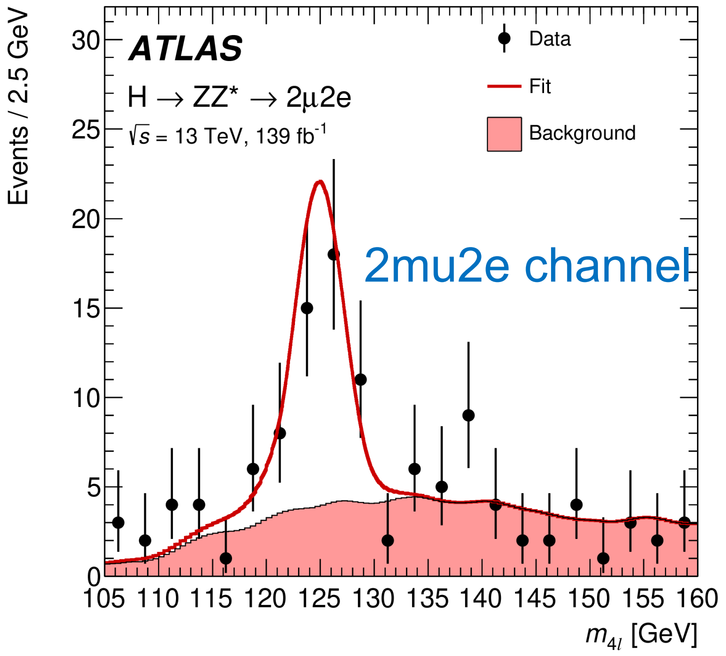
Backup

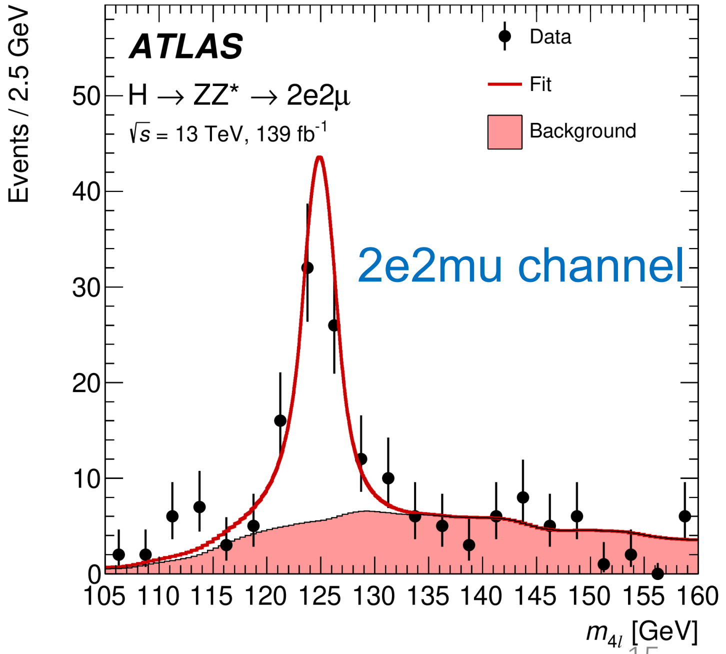
Post-fit m4l


ATLAS
H → ZZ* → 4l
√s = 13 TeV, 139 fb-1
Data
Fit
Background
Combined channel
Events / 1.25 GeV
m4l [GeV]

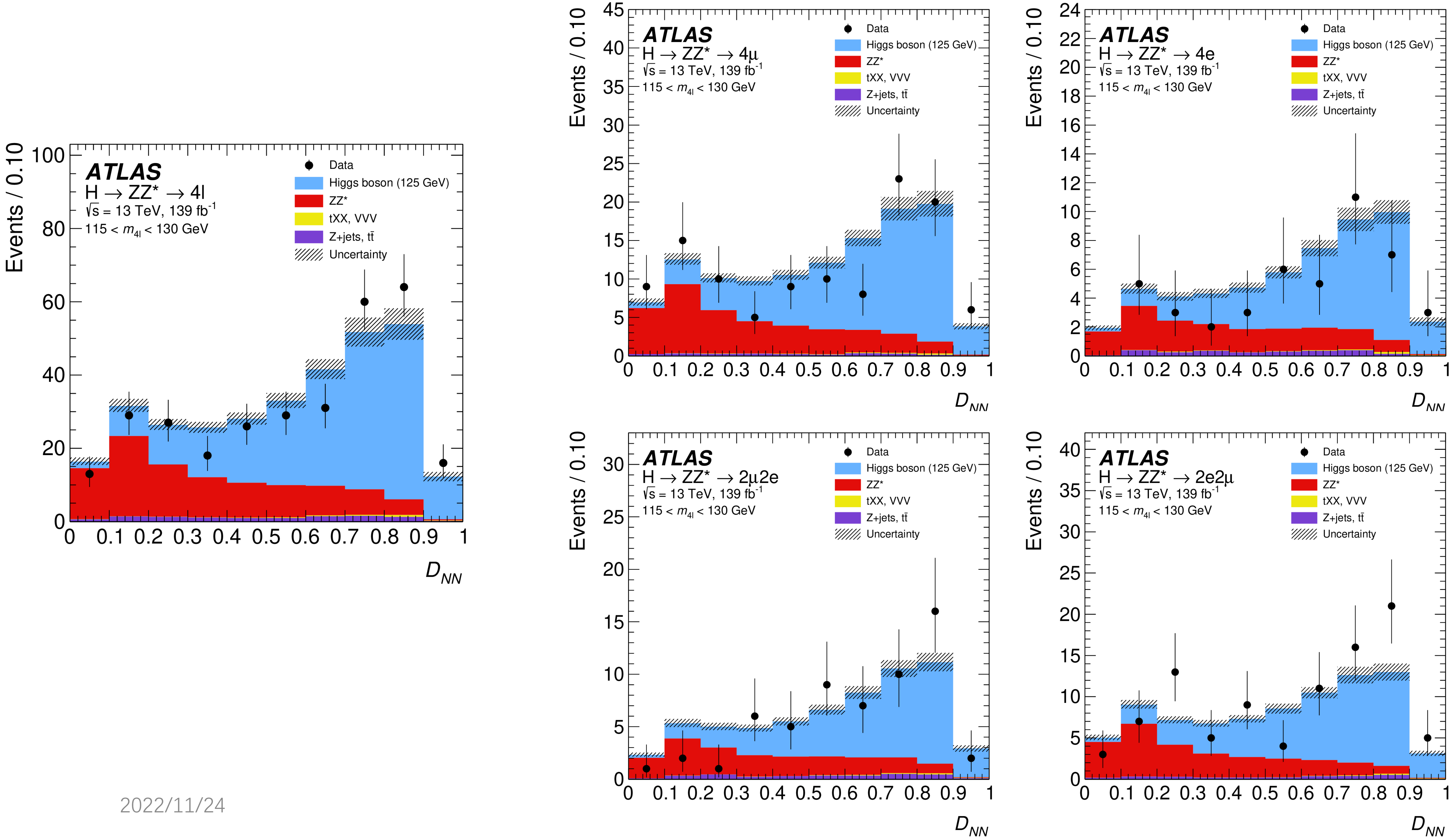

ATLAS
H → ZZ* → 4μ
√s = 13 TeV, 139 fb-1
Data
Fit
Background
4mu channel
Events / 2.5 GeV
m4l [GeV]


ATLAS
H → ZZ* → 4e
√s = 13 TeV, 139 fb-1
Data
Fit
Background
4e channel
Events / 2.5 GeV
m4l [GeV]

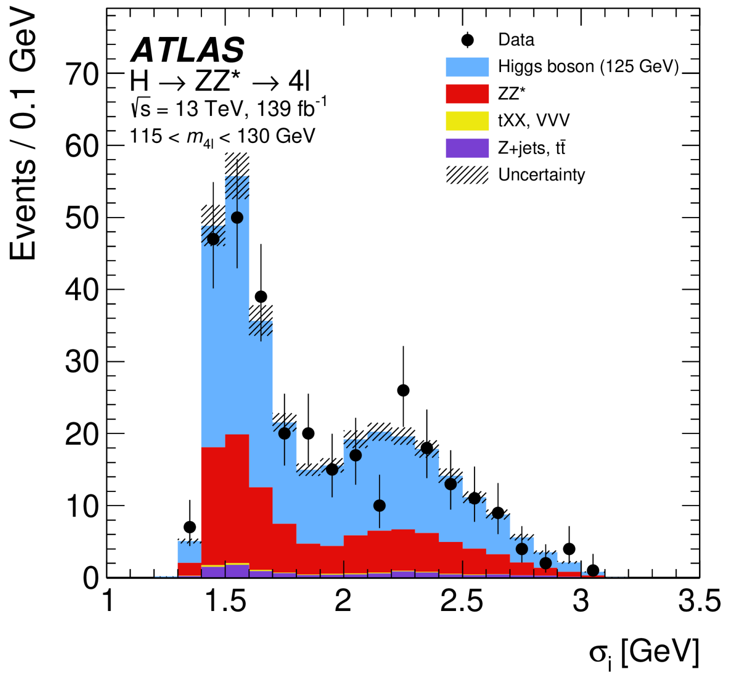

ATLAS
H → ZZ* → 2μ2e
√s = 13 TeV, 139 fb-1
Data
Fit
Background
2mu2e channel
Events / 2.5 GeV
m4l [GeV]

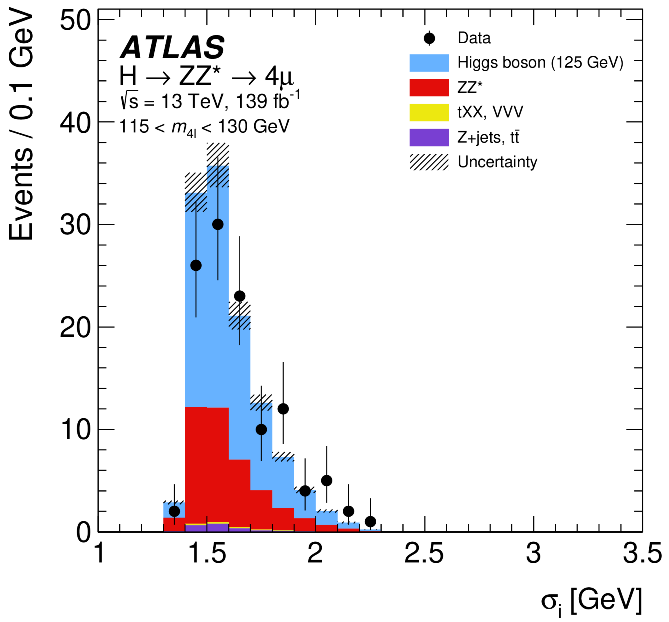

ATLAS
H → ZZ* → 2e2μ
√s = 13 TeV, 139 fb-1
Data
Fit
Background
2e2mu channel
Events / 2.5 GeV
m4l [GeV]

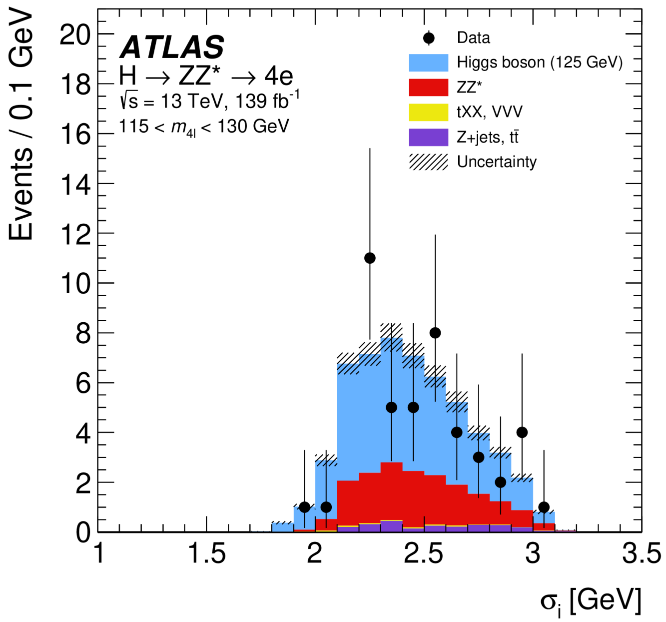
Pre-fit Neural Network classifier

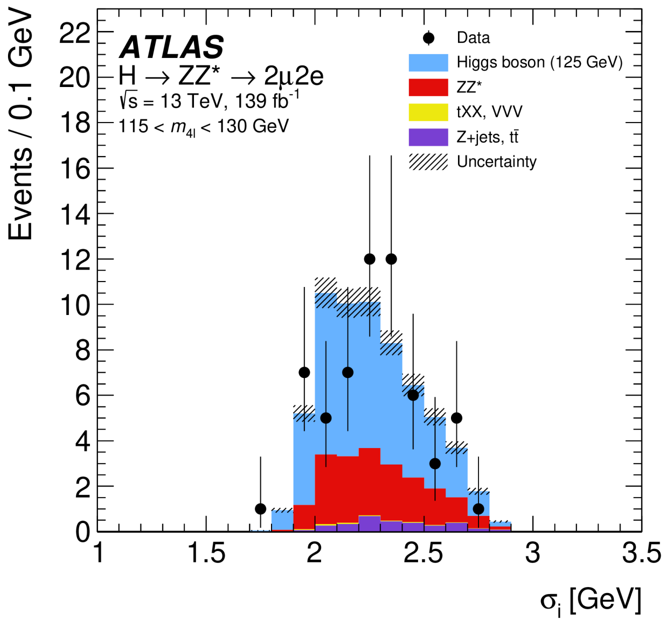


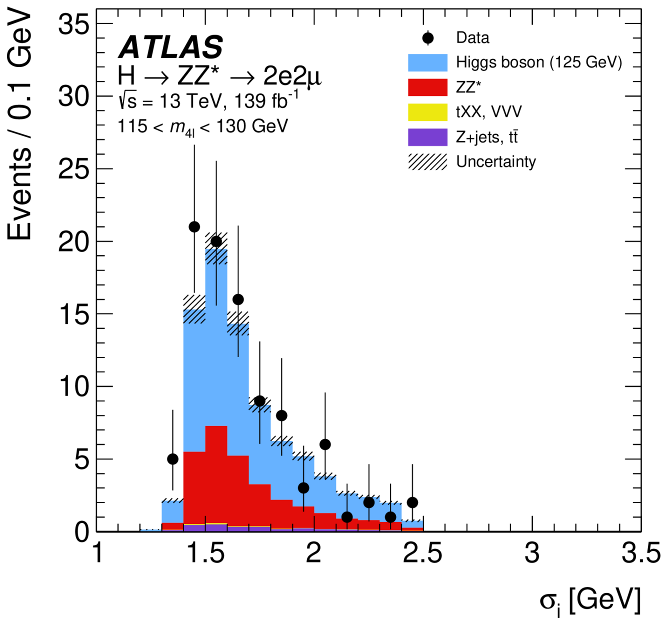
Pre-fit event-level resolution



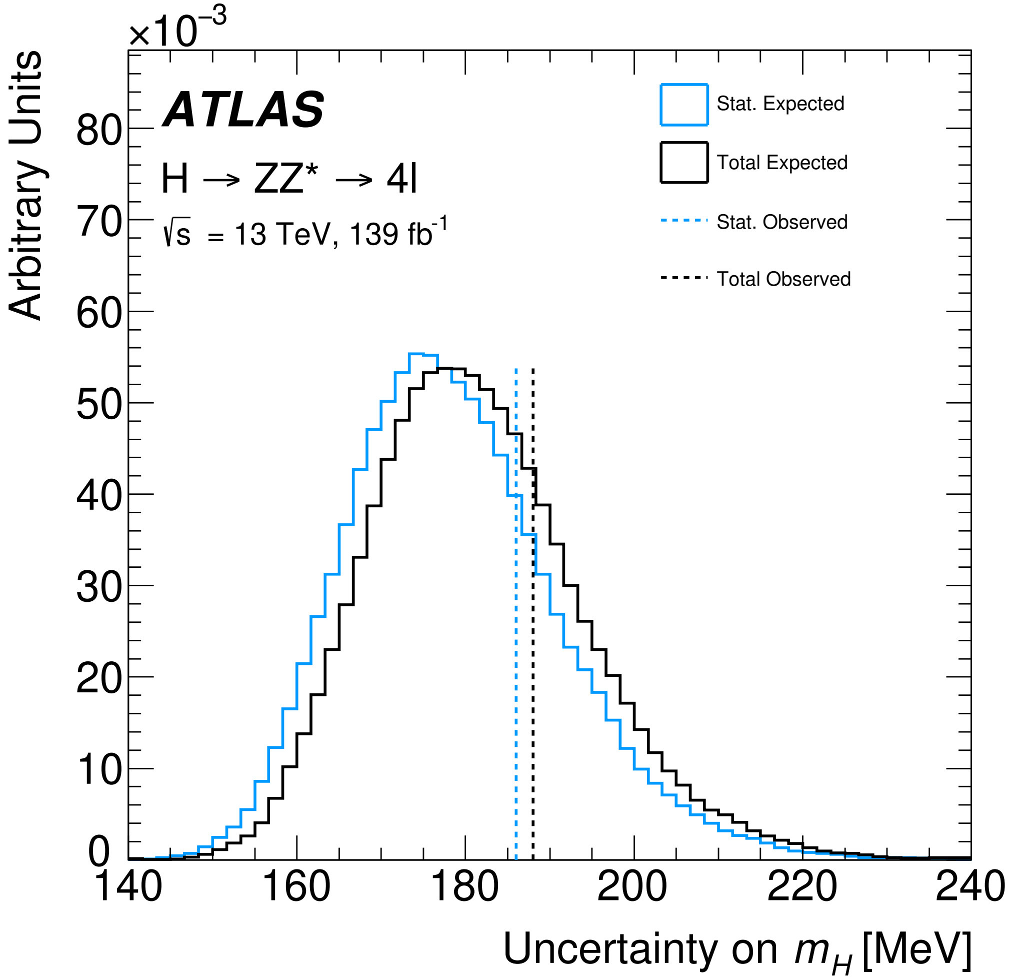








mH uncertainty from pseudo-experiments



The distributions of the total mH uncertainty from pseudo-experiments assuming mH=125 GeV are shown, for when the fit does (black) and does not (blue) take into account systematic uncertainties. The solid lines correspond to the expected uncertainty distribution from pseudo-experiments, while the vertical dashed lines indicate the observed values of the uncertainties.