Measurement of the $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^*\rightarrow 4l$ cross-sections in pp collisions at $\sqrt{s}$=13.6 TeV with the ATLAS detector [1]

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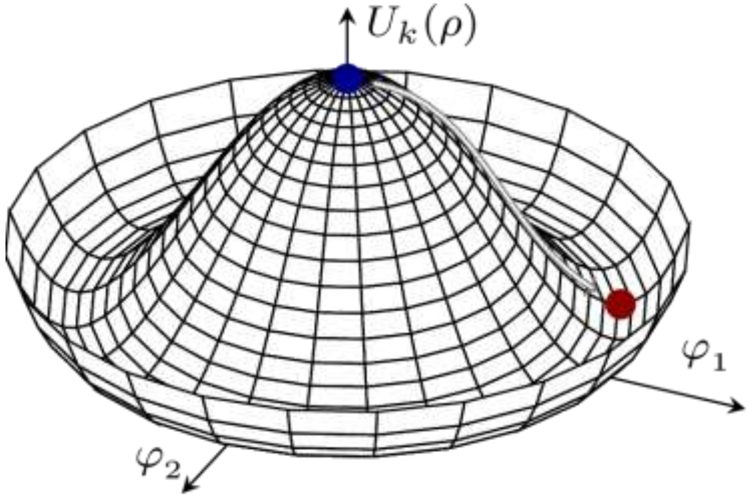
Contents

Introduction to the Higgs Boson

- Theoretical description of the Higgs Boson

  Massive boson with zero spin, no charge, the Higgs field gives elementary particles mass, causes spontaneous symmetry breaking.
- What is interesting about the Higgs Boson?

  The Higgs Boson is a newly discovered particle and the final particle of the Standard Model being observed!



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Spontaneous symmetry breaking

A scalar field Lagrangian is invariant except in the case of the ground state.

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 + \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4!}\phi^4.$$

The potential is minimal when the (ground) state is:

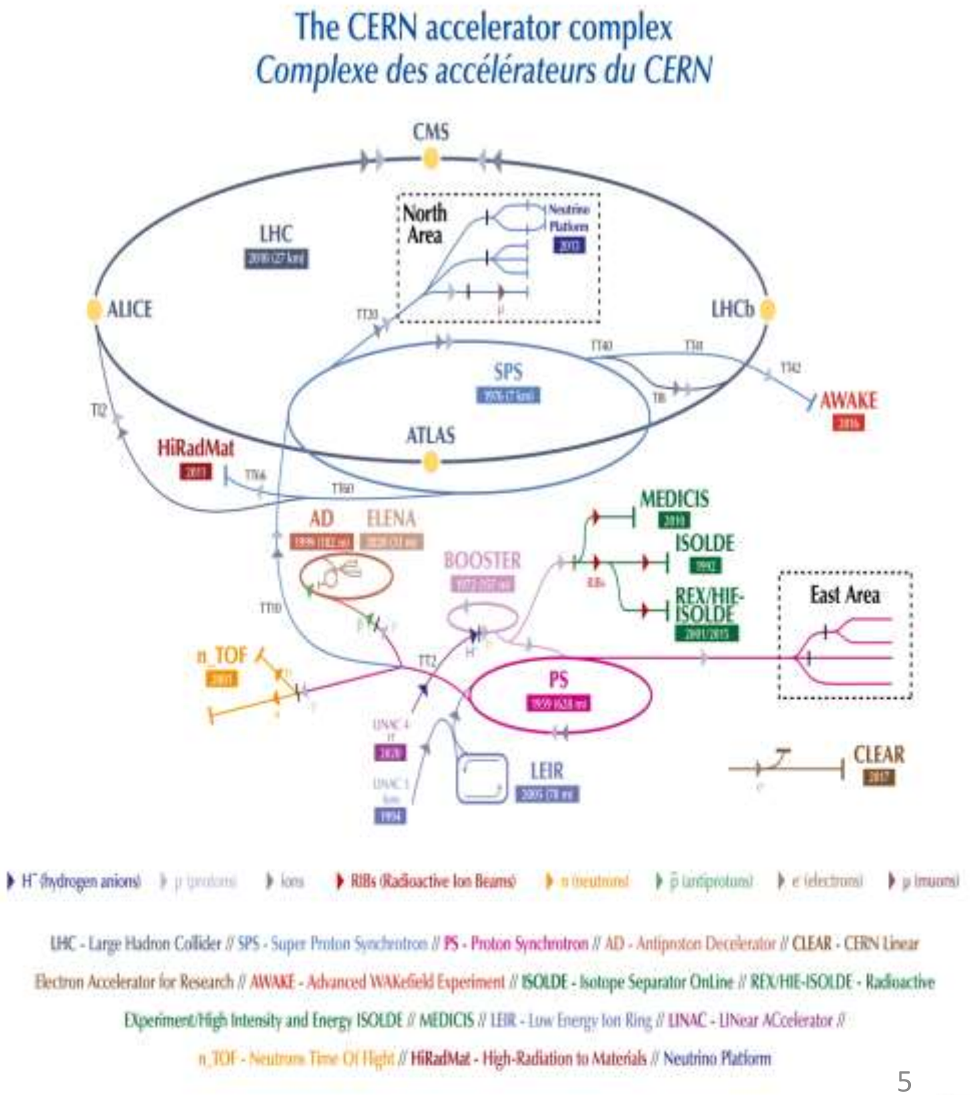
$$\phi = \pm\sqrt{\frac{6m^2}{\lambda}}$$

This means that we have to choose one of the two solutions and it follows that the Lagrangian under the Z_2 transformation for a state which is expanded around both of the ground states is not invariant.

The cause of the symmetry breaking is claimed to be the Higgs field!

LHC

- Through the LHC (Large Hadron Collider) inelastic interactions between accelerated particles are investigated.
- The particles are accelerated through a linear accelerator, they reach a very high energy and get injected in a synchrotron.
- Two beams of particles with contrary directions are focused so they collide.



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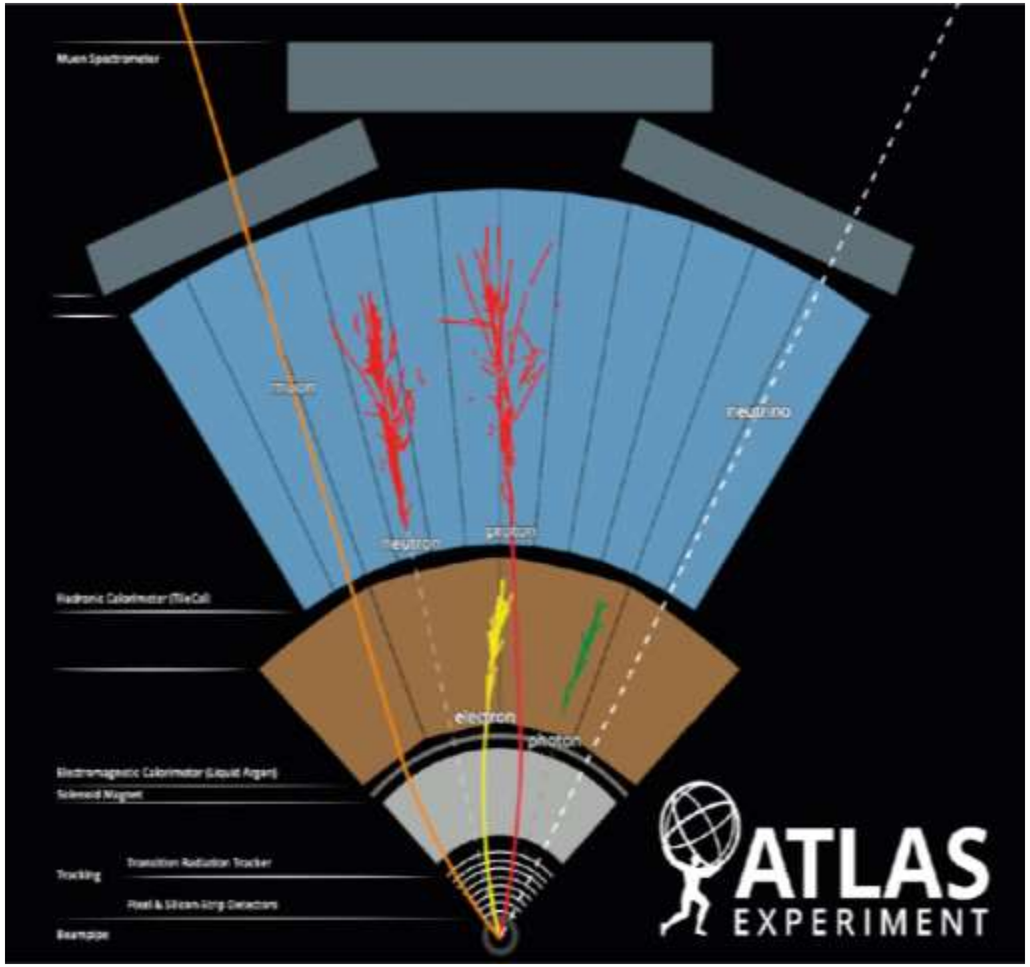
ATLAS

The ATLAS detector is a general purpose detector and one of it's aims of the is to detect the Higgs Boson. The main components of the ATLAS detector are the inner tracking detector, electromagnetic and hadron calorimeter and muon spectrometer.



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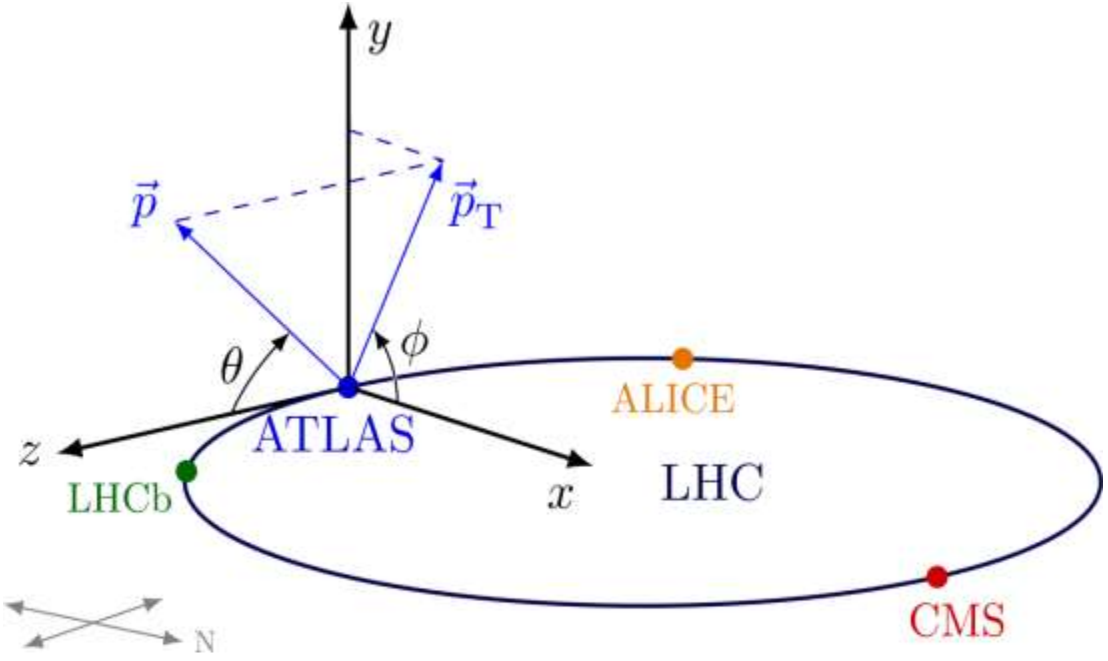
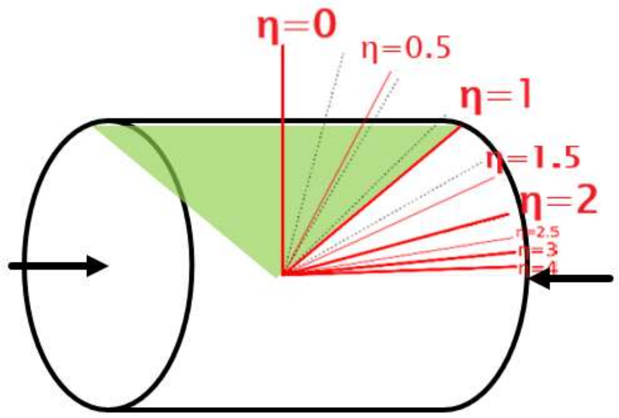
Coordinate system for the detector

- Transverse momentum
  $p_T = p.\sin\theta$
  orthogonal component to the beam axis

- Pseudorapidity η
  $\eta = -\ln(tg(\theta/2))$
  estimates the particle direction with boost in z-direction





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Diphoton and Four-Lepton Decay Channels of the Higgs Boson

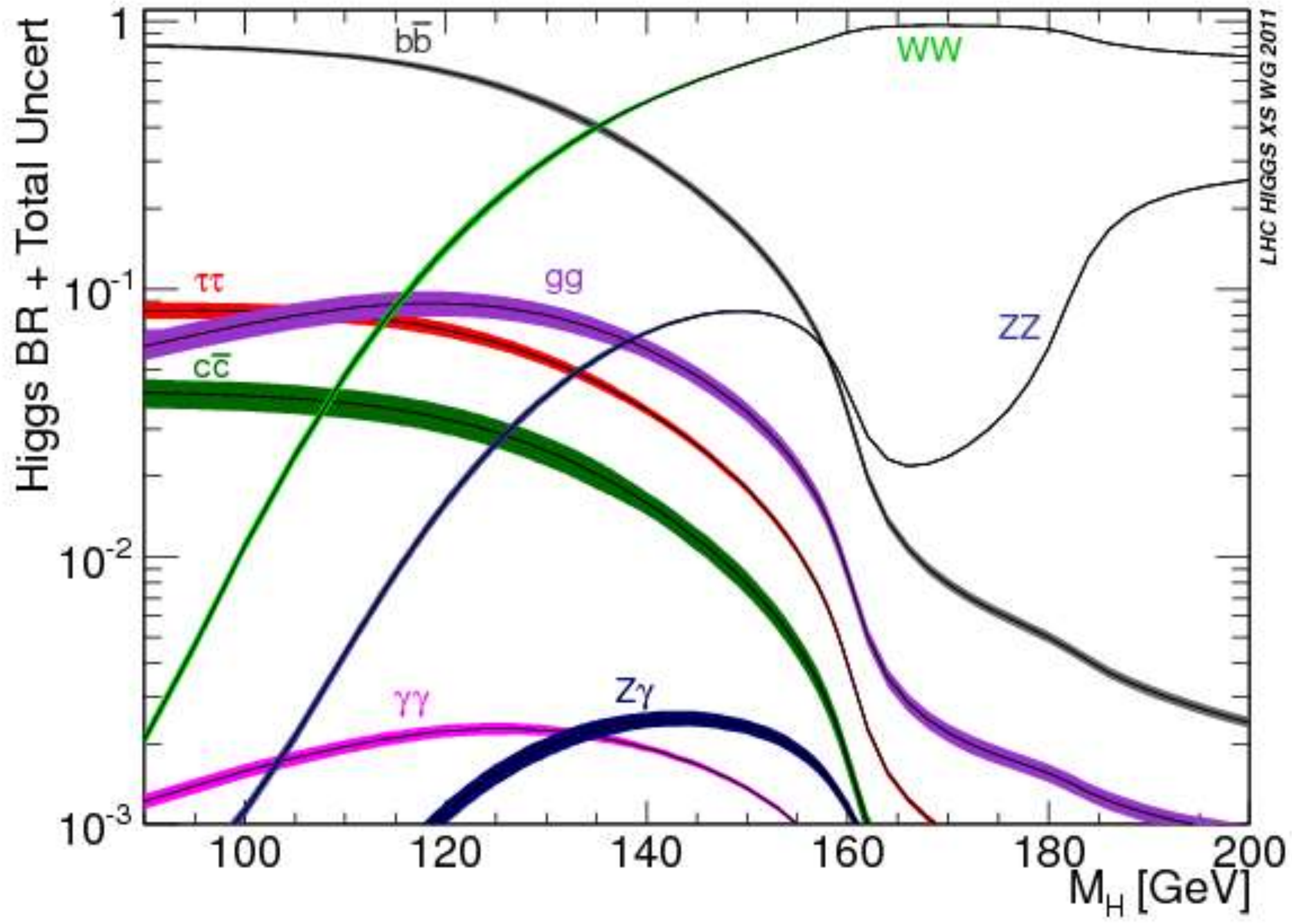
Why do we choose exactly these channels?

-there are relatively flat background distributions which makes the signal from the Higgs boson decay more distinguishable

-we have a better understanding about the properties of photons, electrons and muons

-particles from other decay modes of the Higgs boson are harder to detect and reconstruct

Branching Ratio Graph



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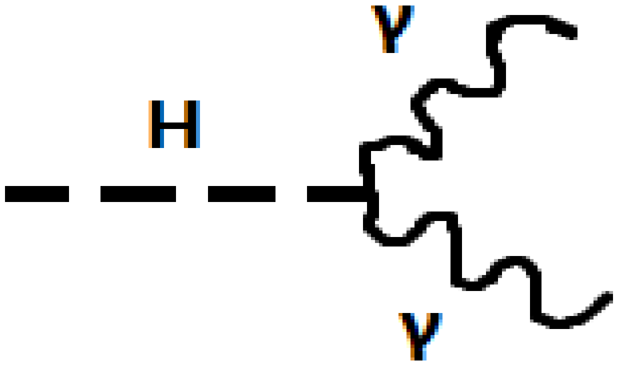
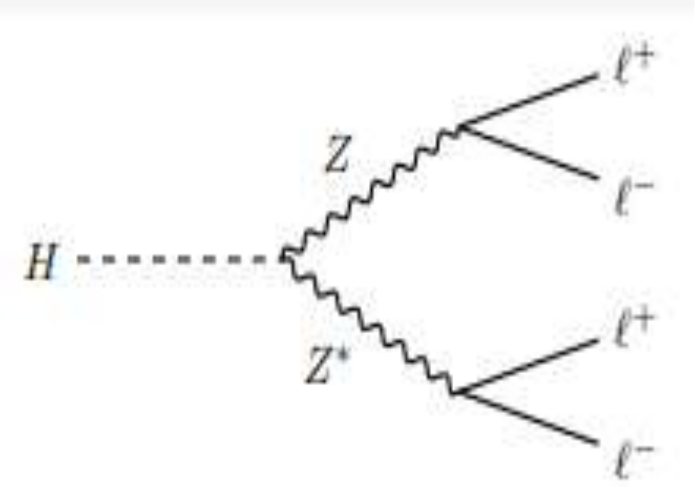
Feynman Diagrams

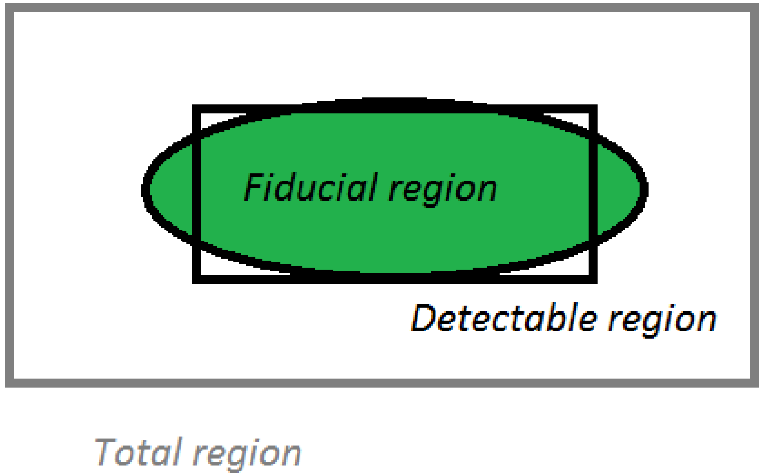
Through the Feynman rules extracted from a Feynman diagram the transition amplitude and consequently the cross-section can be theoretically calculated. The Feynman diagrams for the H→γγ and H→ZZ*→4l channels are represented below:





Fiducial phase space

The Fiducial phase space is the region where the particle events are investigated so that it is easier to derive the results for the total region because it minimises extrapolation in the phase space and hence is maximally model-independent. The fiducial region is defined to closely correspond to the limited region experimentally detected by the detector.



Cross-section estimation

The fiducial cross-section is obtained through the signal yield N_s. Then through the fiducial cross-section the total cross-section is derived.

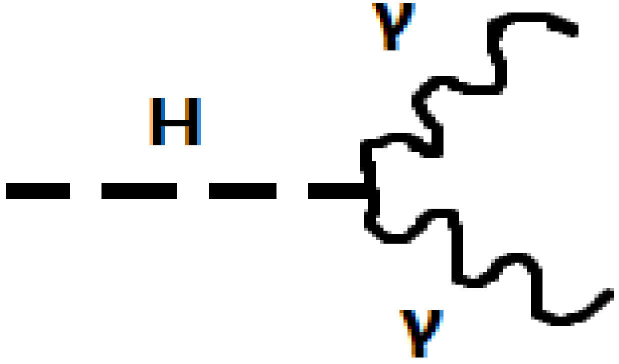
- $N_s = \sigma_{fid} \times L \times C_F$
- $\sigma_{fid} = \sigma_{tot} \times B \times A$

Where L is luminocity and B is the branching ratio. C_F and A are the efficiency and acceptance of the detector respectively.

- $C_F = N_{reco}/N_{fid}$
- $A = N_{fid}/N_{tot}$

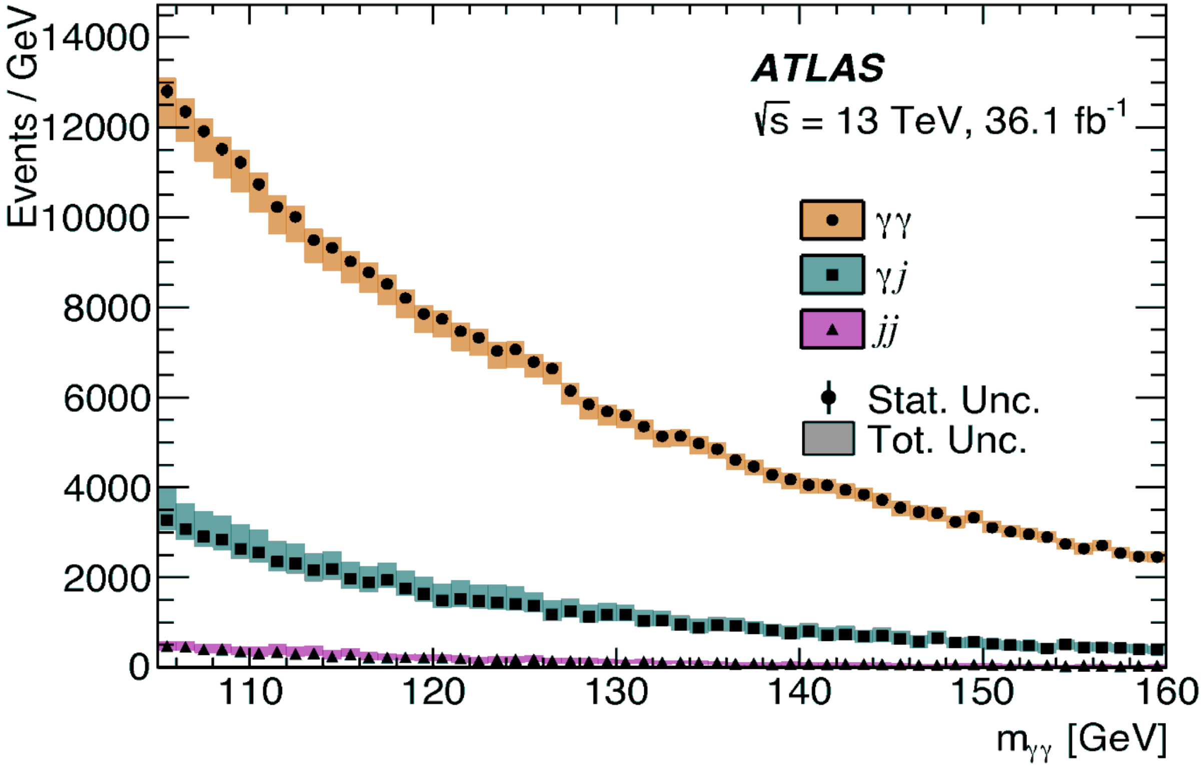
H→γγ measurement

Satisfying given event selection criteria the two photons can be reconstructed. The main preselection requirement is that each photon must have a transverse energy higher than 25 GeV (E_T>25GeV). The two candidates with the highest E_T are the selected photons.



H→γγ backgrounds

The backgrounds for the diphoton decay channel are production of hadronic jets. The two main cases are the γj and jj backgrounds.



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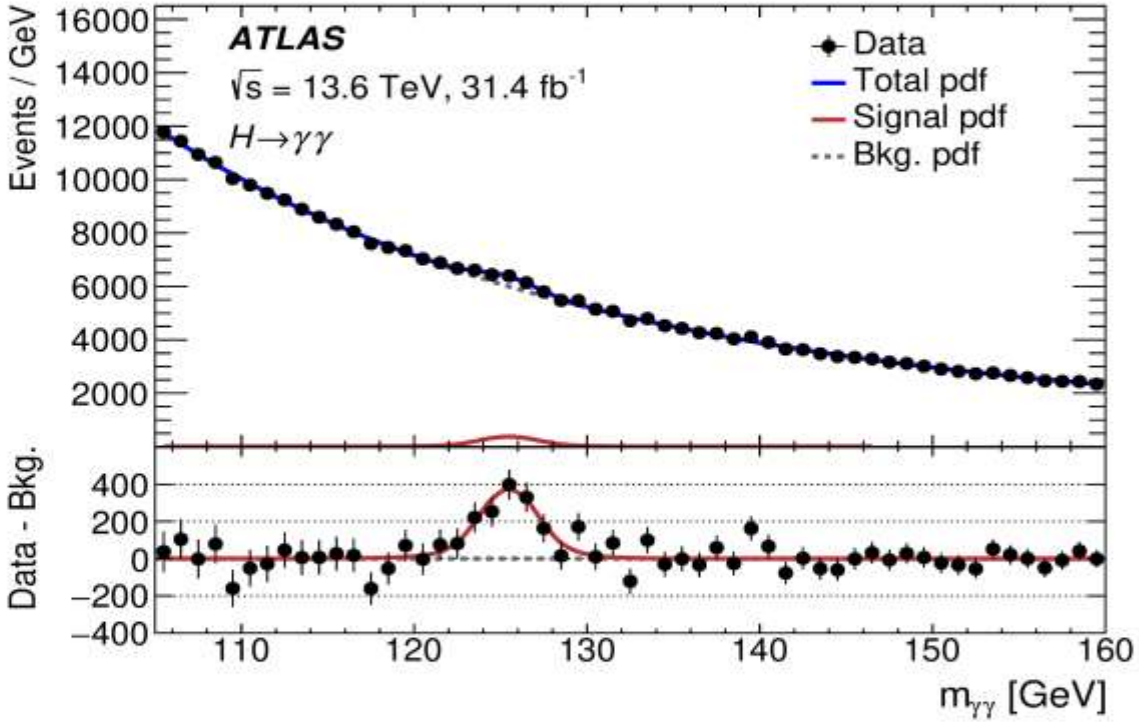
H→γγ channel event selection

Photons	
Leading (sub-leading) p_{T}^{γ}	$p_{\mathrm{T}}^{\gamma}/m_{\gamma\gamma} > 0.35(0.25)$
Pseudorapidity	$\|\eta\| < 2.47$ and outside $1.37 < \|\eta\| < 1.52$
Isolation	$E_{\mathrm{T}}^{\mathrm{iso}}/E_{\mathrm{T}}^{\gamma} < 0.05$
Di-photon system	
Mass window	$105\ \mathrm{GeV} < m_{\gamma\gamma} < 160\ \mathrm{GeV}$

Di-photon invariant mass distribution

In the graph below we can observe a peak for the number of events when the centre-of-mass energy of the selected photon pair is approximately 125,09 GeV.



Fiducial cross-section for the H→γγ channel

The fiducial cross-section is obtained by applying a fit and it's value is:

$$\sigma_{fid} = 76 \pm 11\ (stat.)\ {+9}\ {-7}\ (syst.)\ fb$$

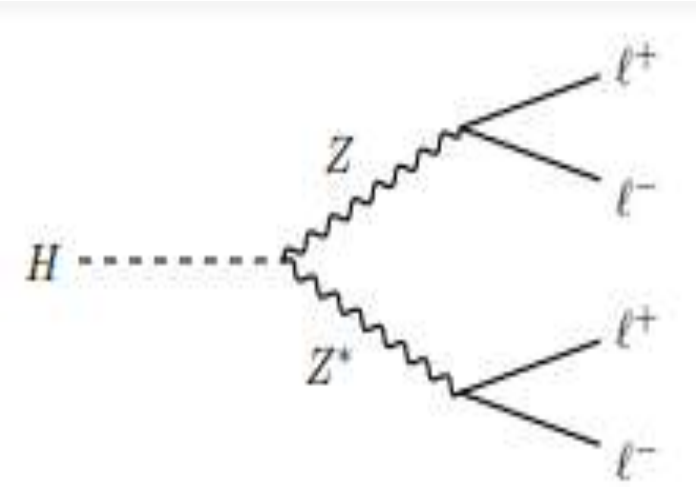
The Standard Model value is calculated to be: $\sigma_{fid,SM} = 67.6 \pm 3.7$ fb. Both values are in correspondence to each other. A breakdown of the uncertainties is presented in the table below:

Source	Uncertainty [%]
Statistical uncertainty	14.0
Systematic uncertainty	10.3
Background modelling (spurious signal)	6.0
Photon trigger and selection efficiency	5.8
Photon energy scale & resolution	5.5
Luminosity	2.2
Pile-up modelling	1.2
Higgs boson mass	0.1
Theoretical (signal) modelling	<0.1
Total	17.4

H→ZZ*→4l measurement

The reconstruction of the quadruplet of leptons has to define the Higgs boson candidate. Through the selection rules for the reconstruction the Higgs signal can be observed clearly.

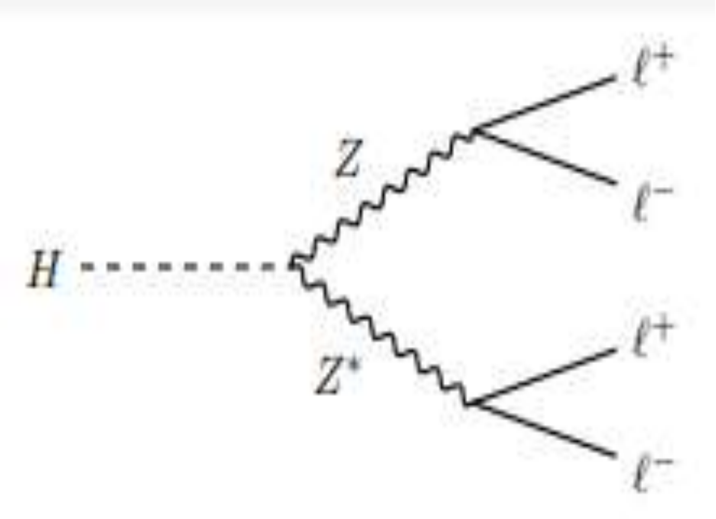
- Firstly, the fiducial cross-sections for the four different four-lepton cases are derived.
- Secondly, the cases are combined so that the total fiducial cross-section is estimated.
- Lastly, the total cross-section is defined.



Products from the H→ZZ*→4l channel

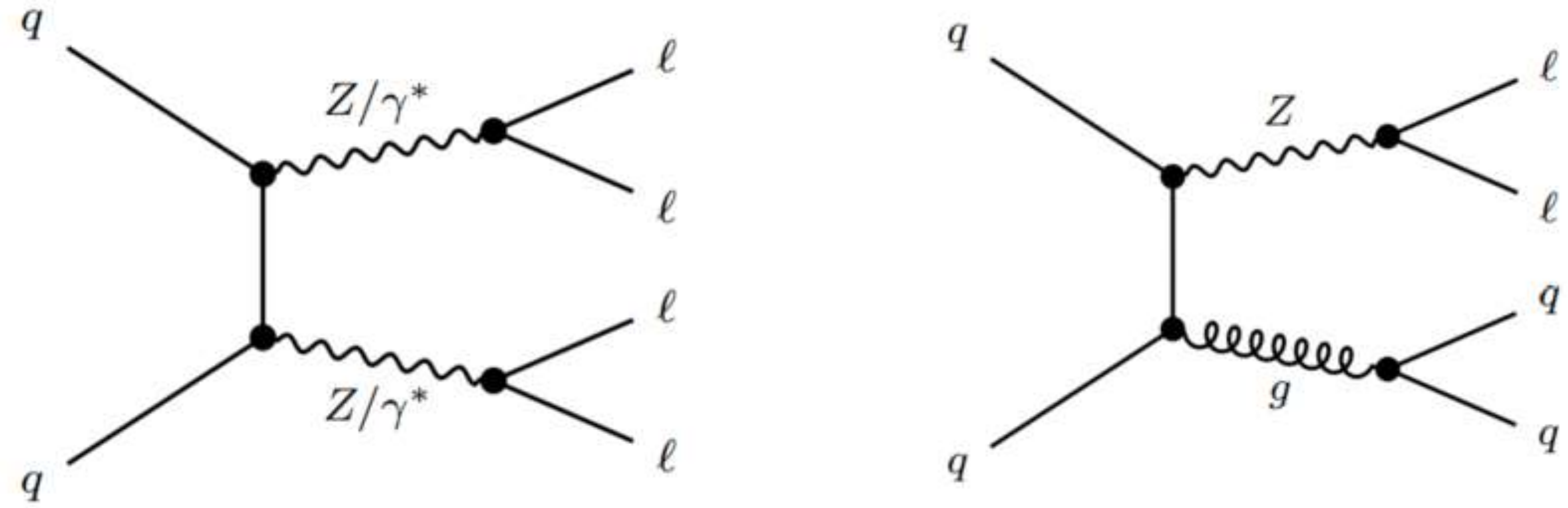
Four possible outcomes from the H→ZZ*→4l decay channel are possible.

- 4e
- 4μ
- 2e2μ
- 2μ2e



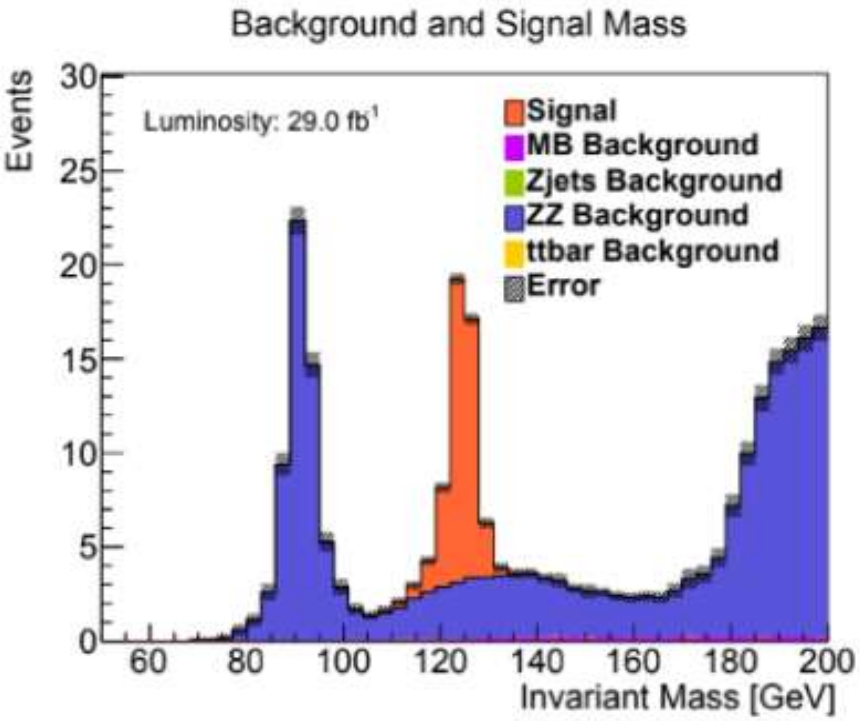
Backgrounds of the H→ZZ*→4l channel

The event selection is designed to minimise the amount of background present in the region of interest. There are two types of backgrounds: reducible and irreducible. Mainly the background is caused by the direct decaying of a two Z-bosons and Z-jets.



H→ZZ*→4l invariant mass distribution in an extended mass region

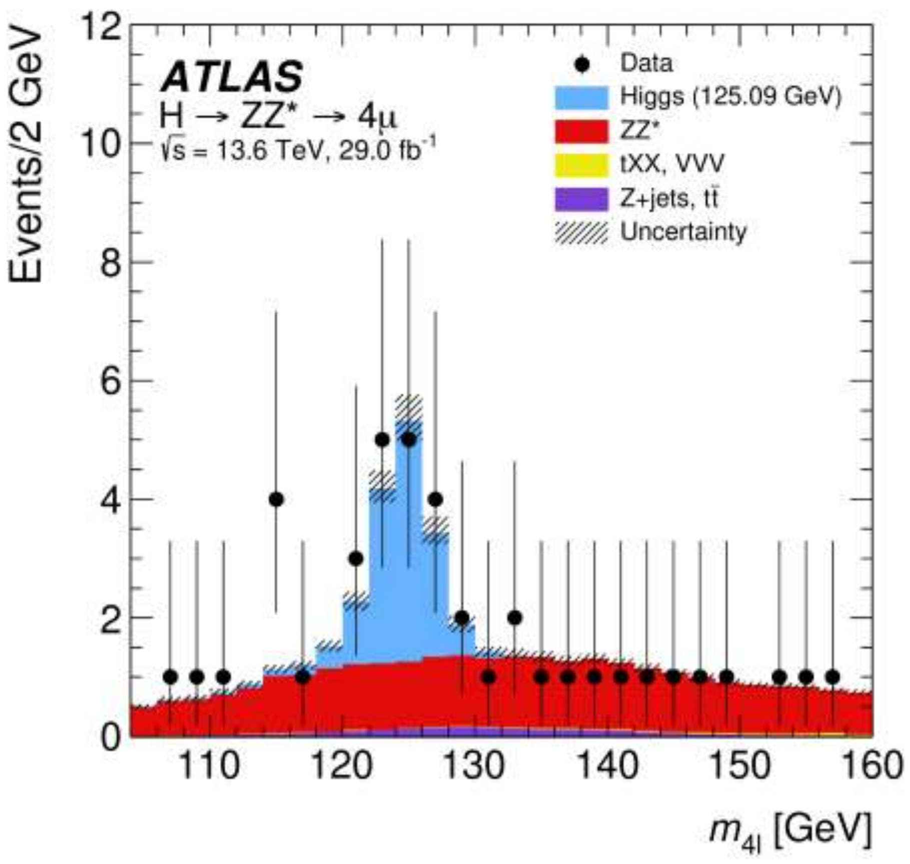
On the graph there are three main peaks (at 91GeV, 125GeV and 182GeV) which means that without the event selection for the mass range the background is higher.

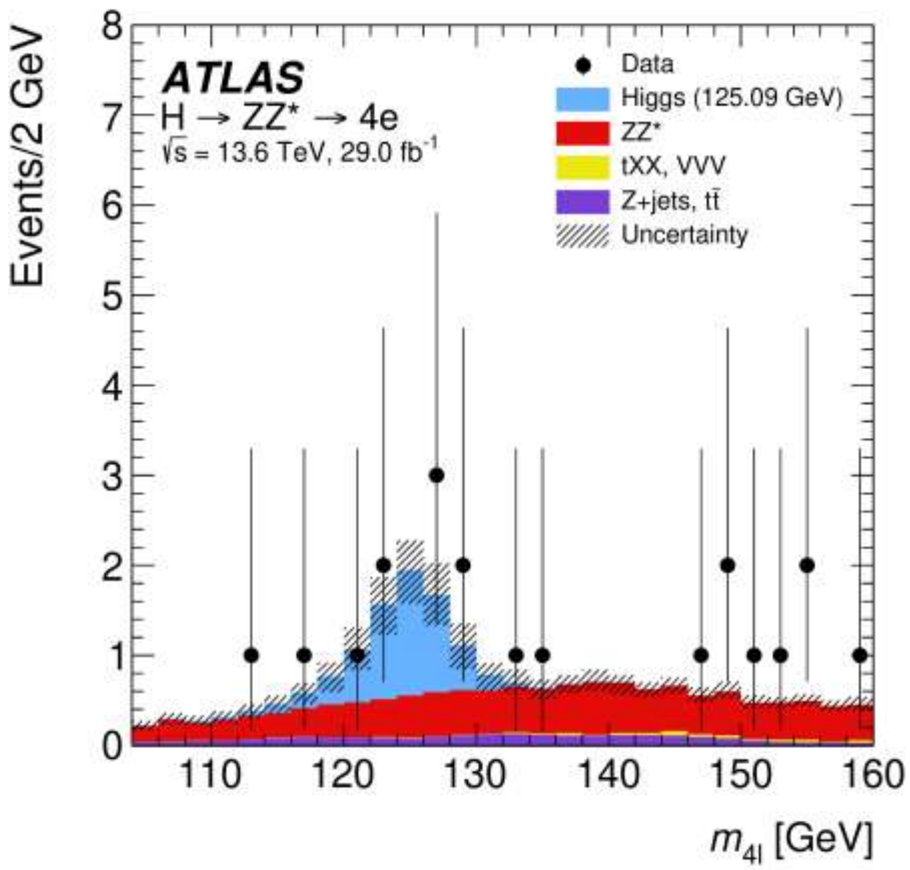


H→ZZ*→4l channel event selection

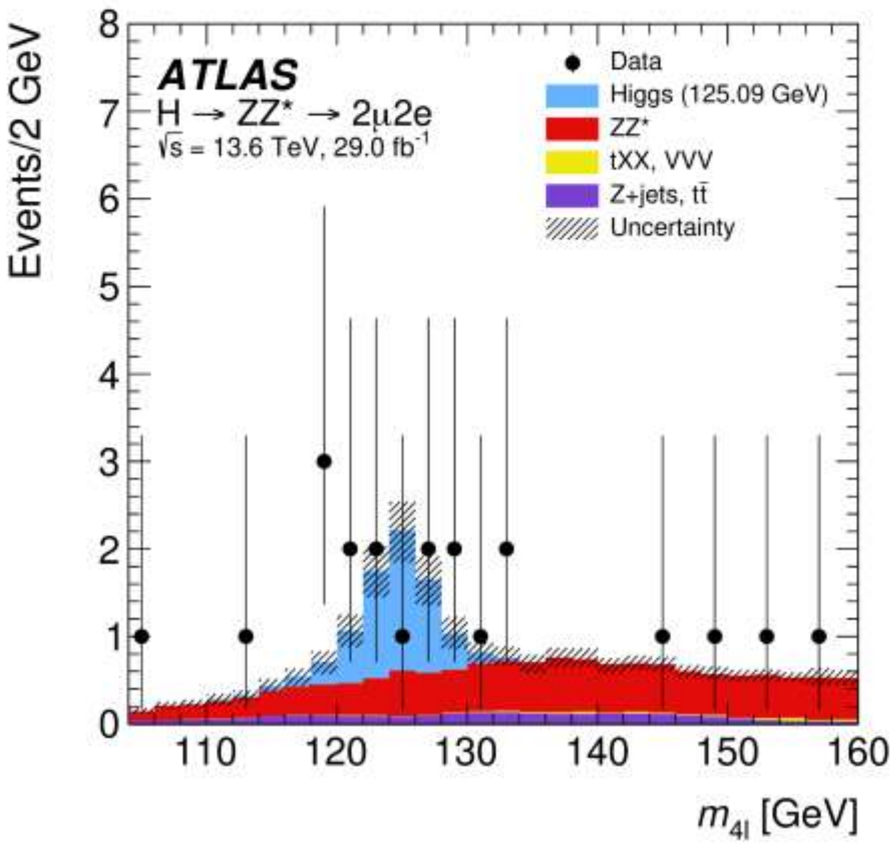
Leptons	
Muons	$p_T > 5$ GeV, $\|\eta\| < 2.5$
Electrons	$E_T > 7$ GeV, $\|\eta\| < 2.47$
Lepton selection and pairing	
Lepton kinematics	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Subleading pair (m_{34})	remaining SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Event selection (at most one Higgs boson candidate per channel)	
Mass requirements	50 GeV$< m_{12} < 106$ GeV and $m_{\mathrm{threshold}} < m_{34} < 115$ GeV
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs
Impact parameter	$\|d_0\|/\sigma(d_0)$ <5 (3) for electrons (muons)
Mass window	105 GeV $< m_{4\ell} < 160$ GeV
Vertex selection	$\chi^2/N_{\mathrm{dof}} < 6$ (9) for 4μ (other channels)
If extra lepton with $p_T > 12$ GeV	quadruplet with largest ME value

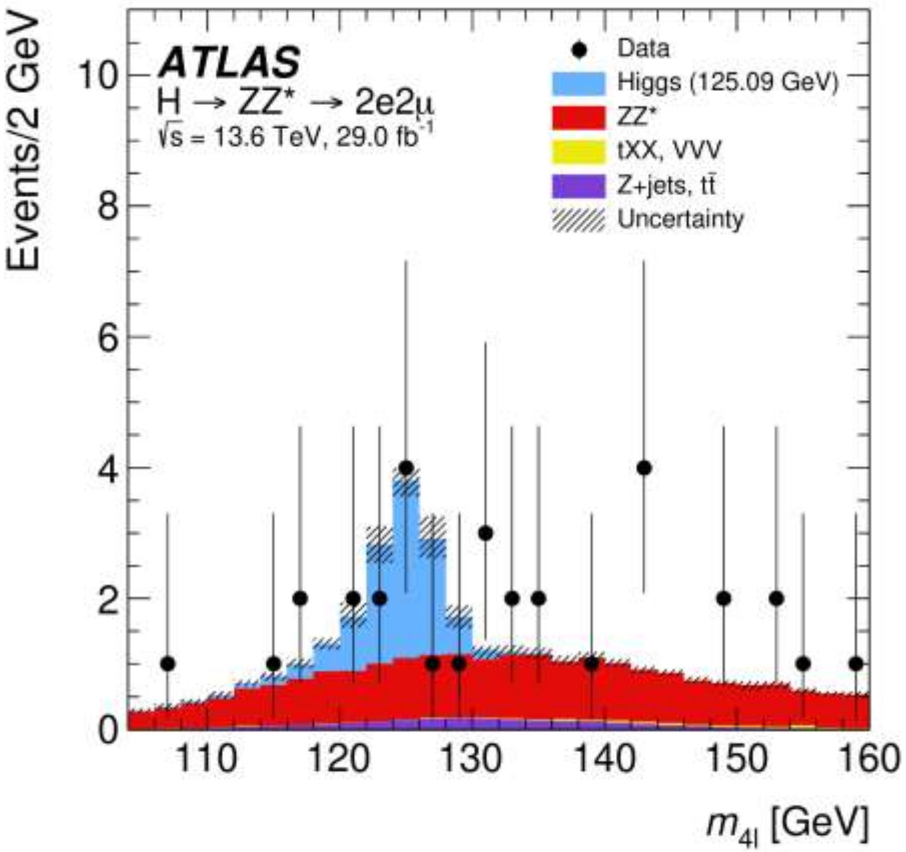
Same Flavour Graphs for the H→ZZ*→4l channel





Different Flavour Graphs for the H→ZZ*→4l channel





Event yields for each case of the $H \to ZZ^* \to 4l$ channel

In the following table the expected number of events with its statistical and systematic uncertainties and the observed numbers are represented.

Final state	Signal SM (pre-fit)	Signal (post-fit)	ZZ^* background	Other backgrounds	Total	Observed
4μ	14.8 ± 1.0	11.3 ± 0.8	8.3 ± 0.6	1.0 ± 0.3	20.6 ± 1.0	23
$2e2\mu$	11.1 ± 0.8	8.5 ± 0.6	6.5 ± 0.4	1.0 ± 0.3	16.0 ± 0.8	13
$2\mu 2e$	7.0 ± 1.3	5.4 ± 1.0	3.2 ± 0.6	0.9 ± 0.1	9.4 ± 1.2	12
$4e$	7.4 ± 1.5	5.7 ± 1.1	3.1 ± 0.7	0.8 ± 0.2	9.6 ± 1.4	9
Total	40.3 ± 3.8	30.9 ± 2.9	21.1 ± 2.0	3.6 ± 0.7	55.6 ± 4.4	57

Fiducial cross-section for the H→ZZ*→4l channel

After combining the event yields for each case the fiducial cross-section for the four-lepton decay channel is maintained:

$$\sigma_{\text{fid}} = 2.80 \pm 0.70\ (\text{stat.}) \pm 0.21\ (\text{syst.})\ \text{fb}$$

which is close to the Standard Model prediction: $\sigma_{\text{fid,SM}} = 3.67 \pm 0.19$ fb. The following uncertainties appear:

Source	Uncertainty [%]
Statistical uncertainty	25.1
Systematic uncertainty	7.9
Electron uncertainties	6.3
Muon uncertainties	3.8
Luminosity	2.2
ZZ^* theoretical uncertainties	0.7
Reducible background estimation	0.6
Other uncertainties	<1.0
Total	26.4

Total cross-section results

Finally from the results of the fiducial cross section from both channels and using their branching ratios and the acceptance of the detector both of the total cross-sections at 13,6 TeV pp collisions are found:

- $\sigma(p\,p \to H)$ = 67+12 −11 pb for the H→yy channel
- $\sigma(p\,p \to H)$ = 46 ± 12 pb for the H→ZZ*→4l channel.

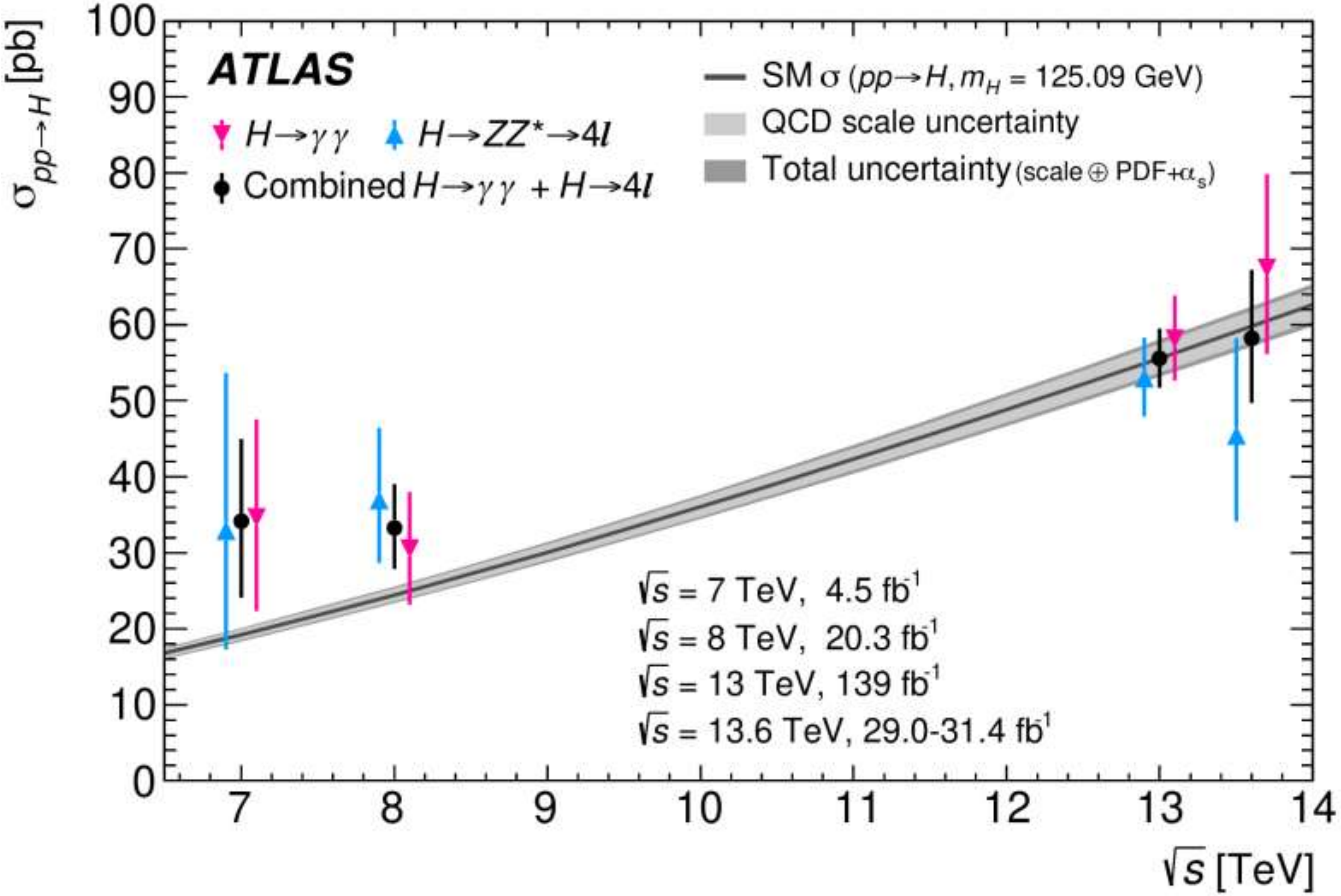
Both cross-sections are combined and the final result for the total cross-section of the decay of the Higgs boson is:

$\sigma(p\,p \to H)$ = 58.2 ± 8.7 pb

which is in correspondence with the Standard Model prediction

$\sigma(p\,p \to H)_{SM}$ = 59.9 ± 2.6 pb.

σ(pp → H) measurements as a function of the pp centre-of-mass energy



Conclusion

The following conclusions can be made from the results of the Run 3 paper:

- The creation of a Higgs boson is more probable when the inelastic interaction between the hadrons is carried out with higher energy.
- The Higgs boson has a very small life time and decays in two photons with higher total cross-section or in two massive bosons which decay in four leptons with lower total cross-section.

References

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