Search for a neutral heavy Higgs boson in the $H \rightarrow ZZ$ decay channels with ATLAS

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IRFU DDays, 1/7/2015

About me

Enrolled at ED 517 (Université Paris-Sud)

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Doing my PhD on the ATLAS experiment at the LHC at CERN

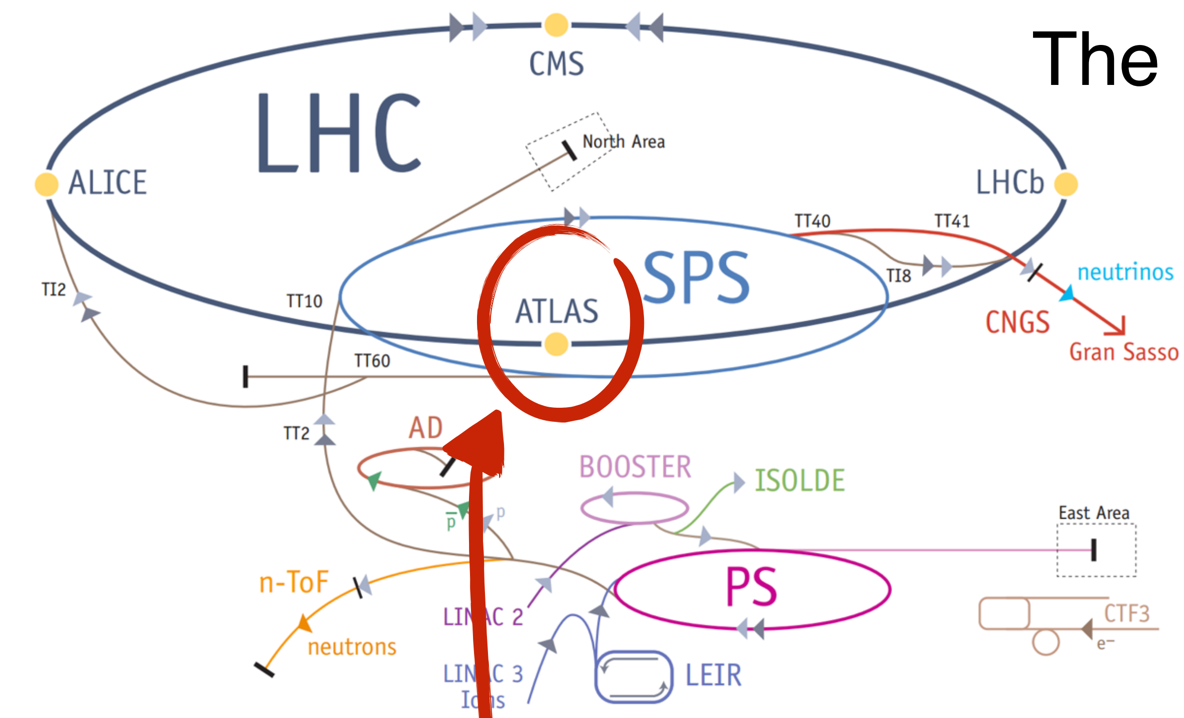
My thesis has two components:

1) Physics analysis
- Search for a beyond the Standard Model heavy Higgs boson in $H \rightarrow ZZ$ decay channels

2) Detector physics
- Development and commissioning of gas and scintillation detectors
- Prototyping of MicroMegas detectors for the upgrade of the ATLAS Muon Spectrometer

Today's presentation will focus on the heavy Higgs search

The LHC and the ATLAS Experiment

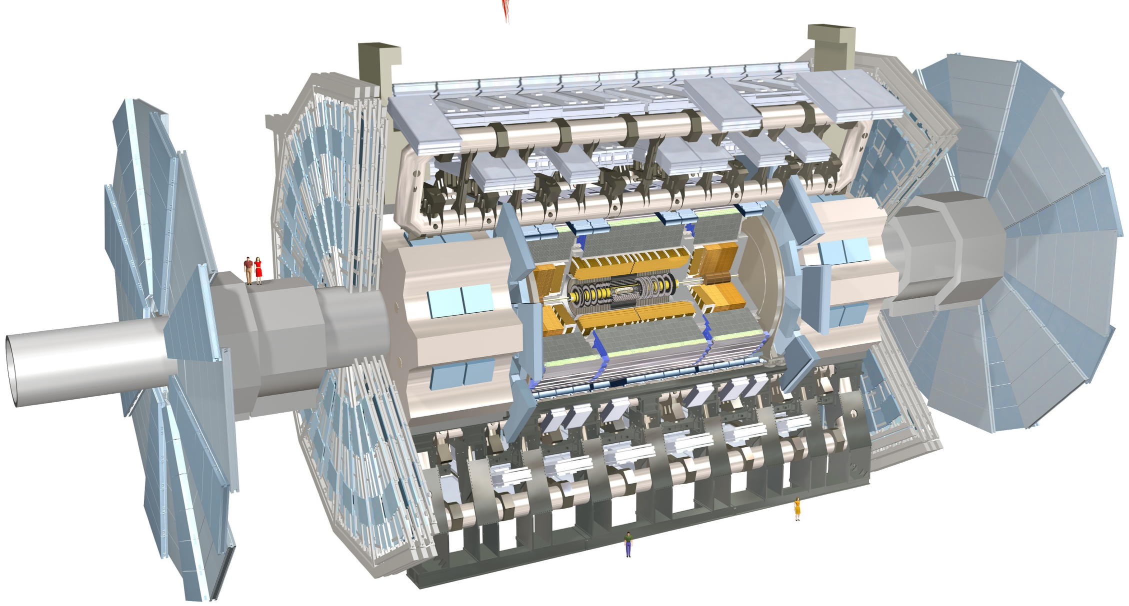


The Large Hadron Collider (LHC) is a ~27 km proton-proton collider situated at CERN

The LHC is the largest and most powerful particle collider ever built

- Able to probe a previously inaccessible kinematic regime

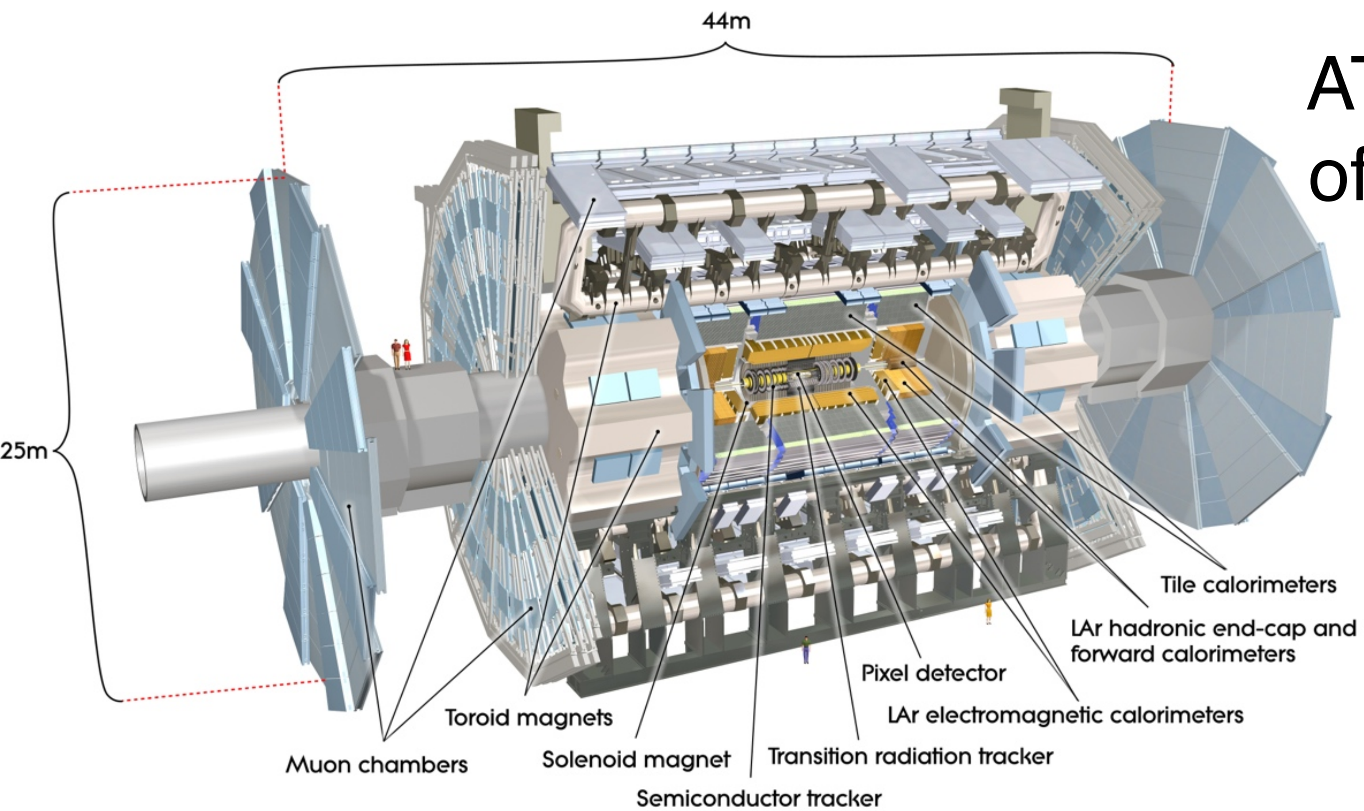
ATLAS is one of four experiments at the LHC



ATLAS is designed as a *general purpose* experiment to perform a broad range of physics measurements and searches

- Higgs boson
- Super Symmetric (SUSY) particles
- Heavy, exotic resonances
- Many more!

The LHC and the ATLAS Experiment



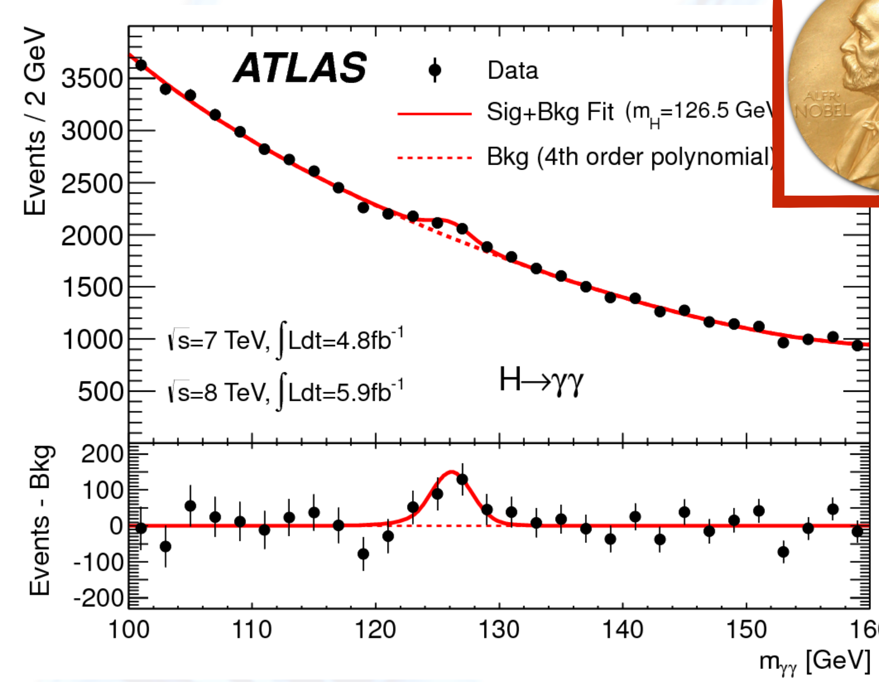
ATLAS works by reconstructing a variety of final state particles with a composition of different detector technologies

- Photons
- Electrons
- Muons
- Jets
- Missing transverse energy

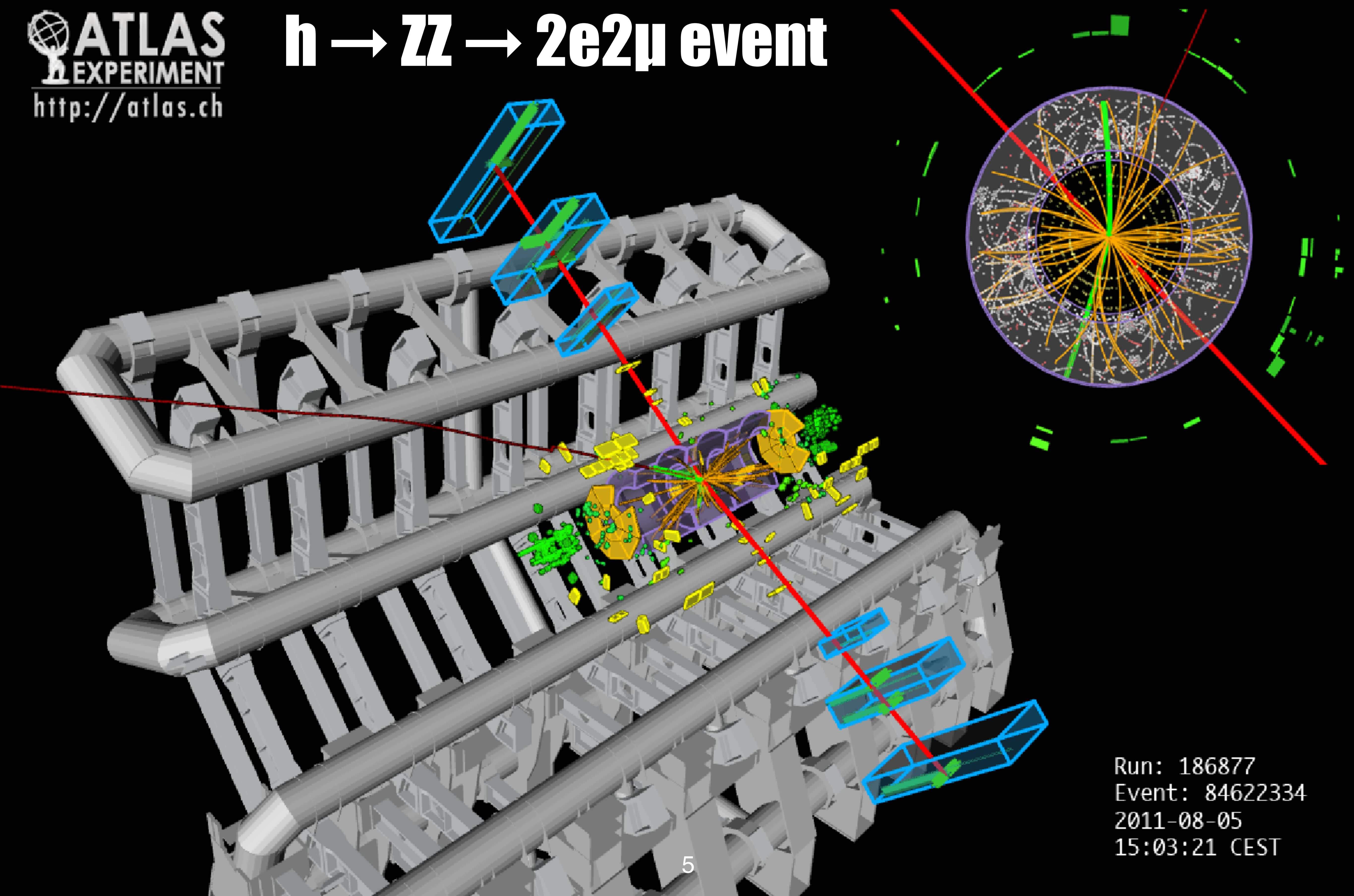
ATLAS successfully took data in ***Run-1,*** the period from 2010 - 2013

- 5.1 fb^{-1} recorded at $\sqrt{s}$ = 7 TeV
- 21.3 fb^{-1} recorded at $\sqrt{s}$ = 8 TeV

The Run-1 dataset constituted the foundation for the Higgs boson discovery in 2012

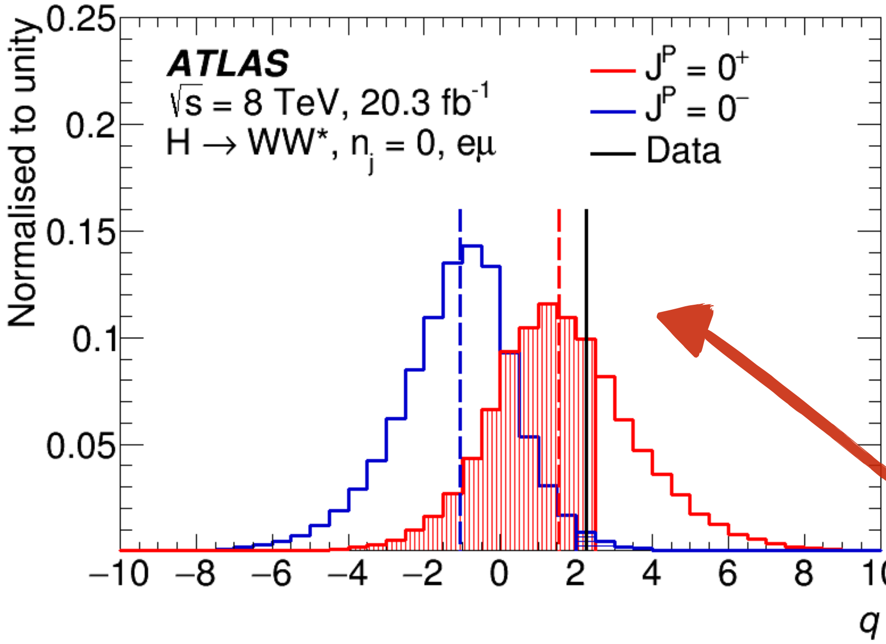


The LHC and the ATLAS Experiment

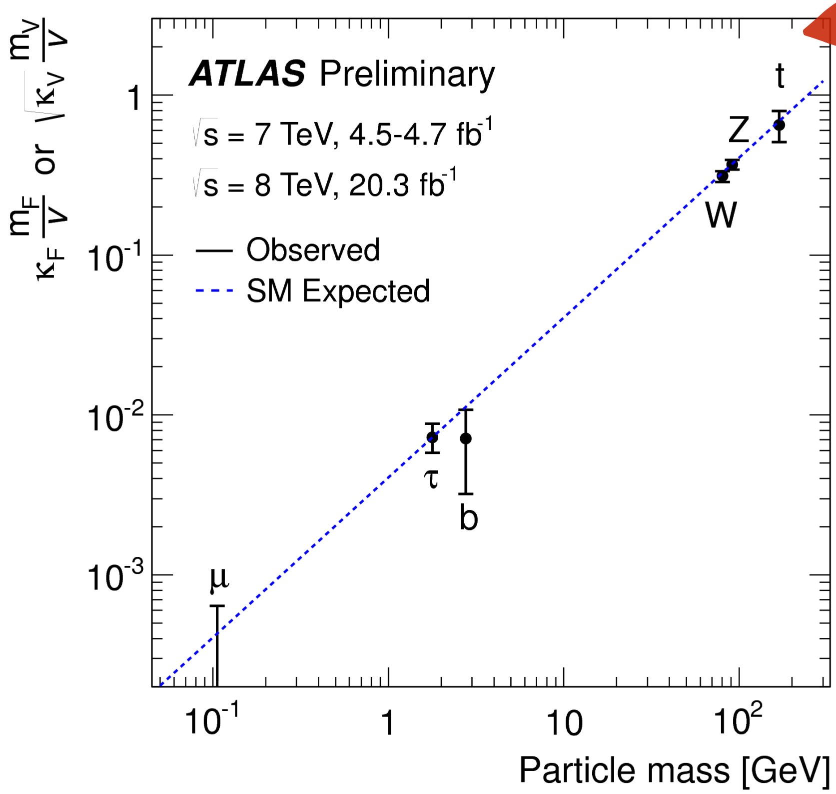


Introduction to heavy Higgs search

arXiv:1503.03643



ATLAS-CONF-2015-007



The new boson strongly resembles the Standard Model (SM) Higgs boson

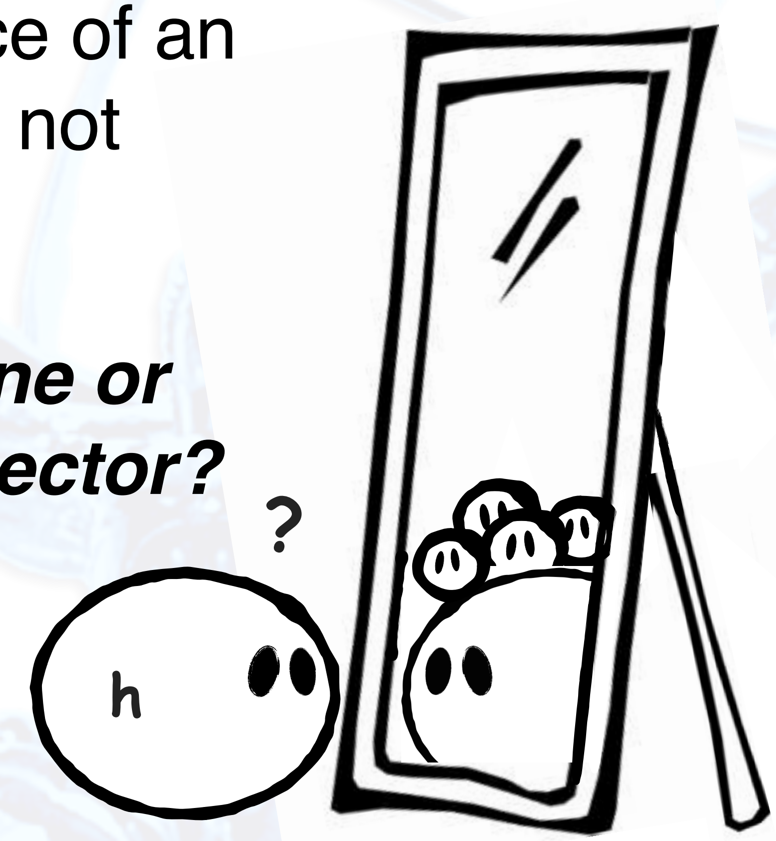
- The last undiscovered particle in the SM

Its compatibility with the SM Higgs boson was determined by measuring its *properties*

- Mass, spin, coupling strength to other particles

Although this new particle is compatible with the SM, the existence of an extended Higgs sector is not ruled out

Is our Higgs boson alone or part of a larger Higgs sector?



Introduction to heavy Higgs search

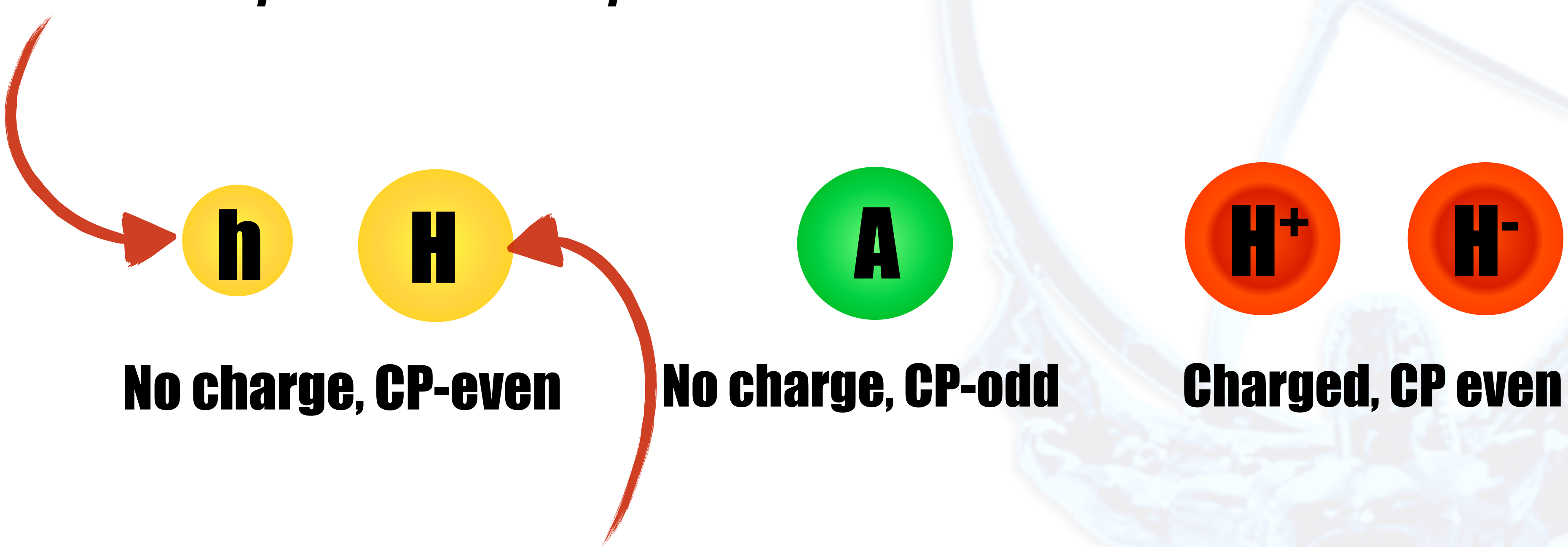
In the SM one Higgs boson appears after spontaneous symmetry breaking

One of the simplest extensions to the SM is obtained by adding a second electroweak doublet: ***2-Higgs Doublet Model (2HDM)***

- A very generic model that constitutes a basis for more advanced theories
  - The Higgs sector in Super Symmetry (SUSY) is a 2HDM variety

In 2HDM, multiple Higgses appear after spontaneous symmetry breaking

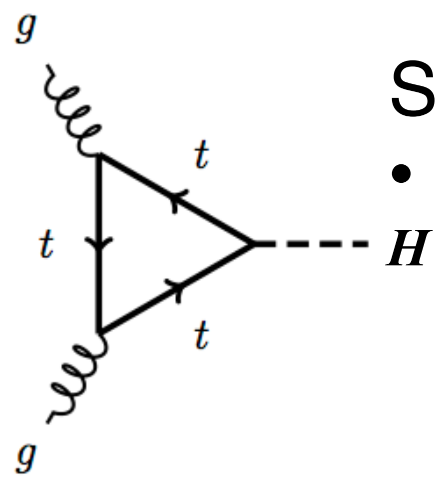
- ***Our 125 GeV particle interpreted as h***



We search for the heavier H!

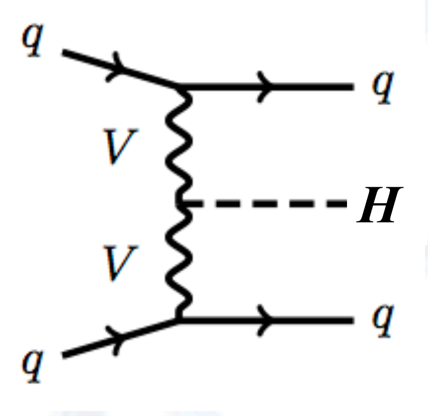
Main Higgs production modes at the LHC

Gluon fusion (ggF)



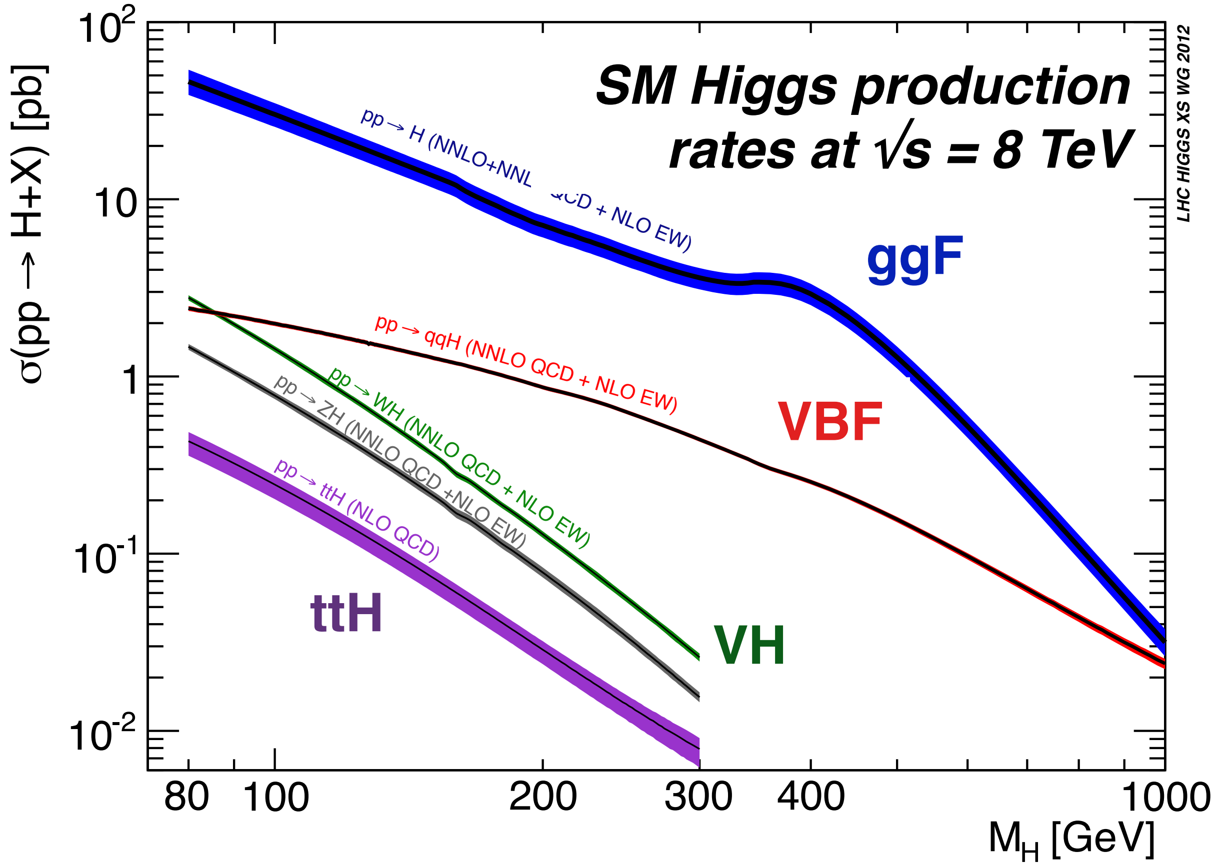
Signature
- Higgs produced with no by-products

Vector boson fusion (VBF)



Signature
- Higgs produced with two energetic jets in opposite, forward region

Assume H will also be produced through these mechanisms
- Production rate heavily dependent on its mass



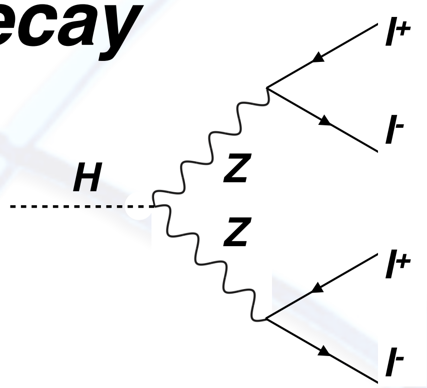
Number of Higgs bosons produced via ggF with 21.3 fb^{-1} at $\sqrt{s}$ = 8 TeV
- ***m_H = 125 GeV: 410k***
- ***m_H = 300 GeV: 77k***
- ***m_H = 600 GeV: 11k***
- ***m_H = 900 GeV: 1k***
  - H → ZZ branching ratio and experimental acceptance should be multiplied to these numbers

Overview of search

We search for a heavy Higgs in the range 140 GeV - 1000 GeV

The Run-1 dataset (20.3 fb^{-1} @ $\sqrt{s}$ = 8 TeV) is used

We search independently in four different H → ZZ decay channels and afterwards statistically combine them

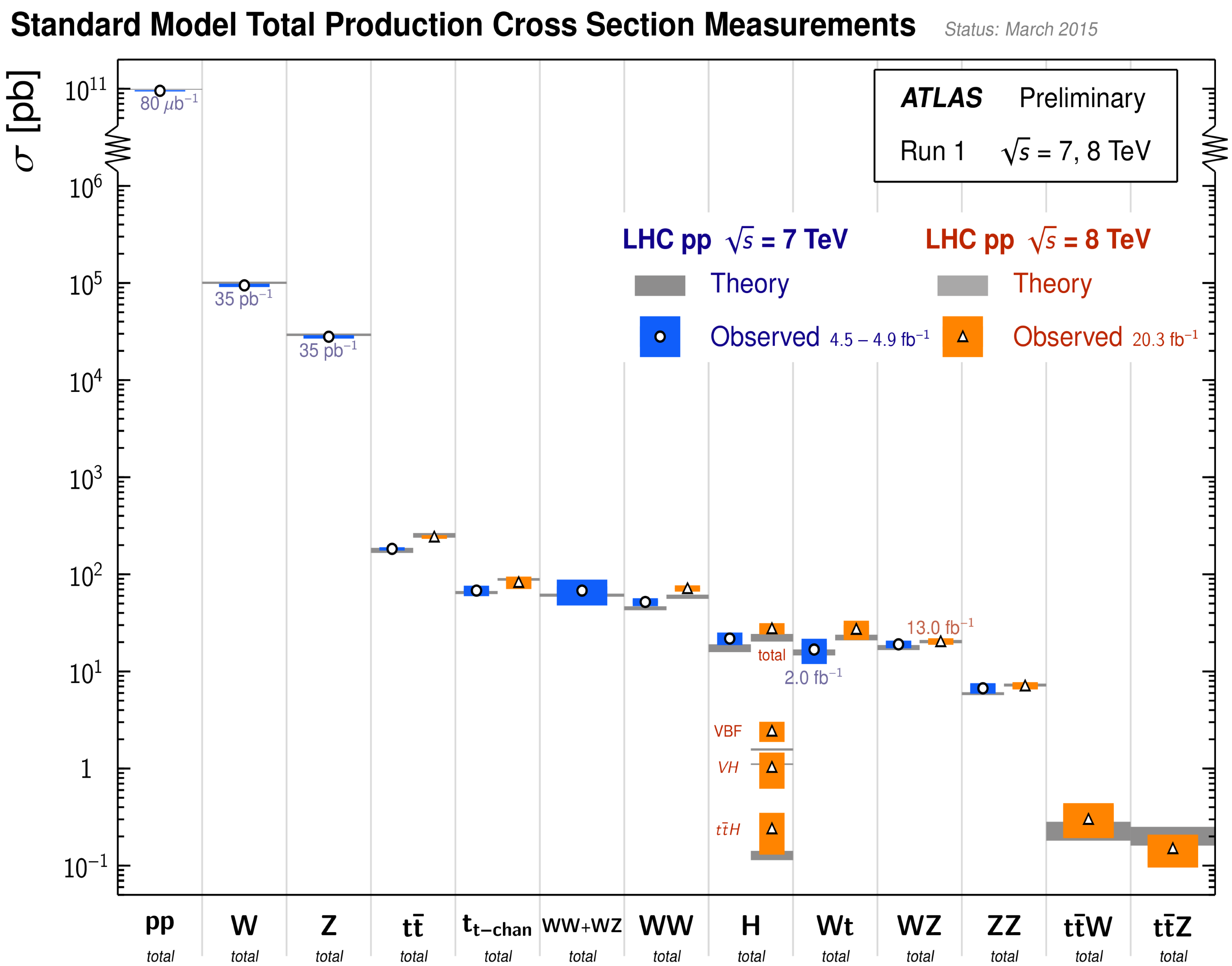


- First analysis on ATLAS to combine these channels
- The full ATLAS detector is used to reconstruct the many different final state objects → *complex analysis!*

Channel	Sensitive mass range	Reconstructed final state
H → ZZ → 4l	Low	2 lepton pairs ($\mu^+\mu^-$ or e^+e^-)
H → ZZ → 2l2v	Intermediate	1 lepton pair ($\mu^+\mu^-$ or e^+e^-) Missing transverse energy
H → ZZ → 2l2q	High	1 lepton pair ($\mu^+\mu^-$ or e^+e^-) 2 jets
H → ZZ → 2v2q	High	Missing transverse energy 2 jets

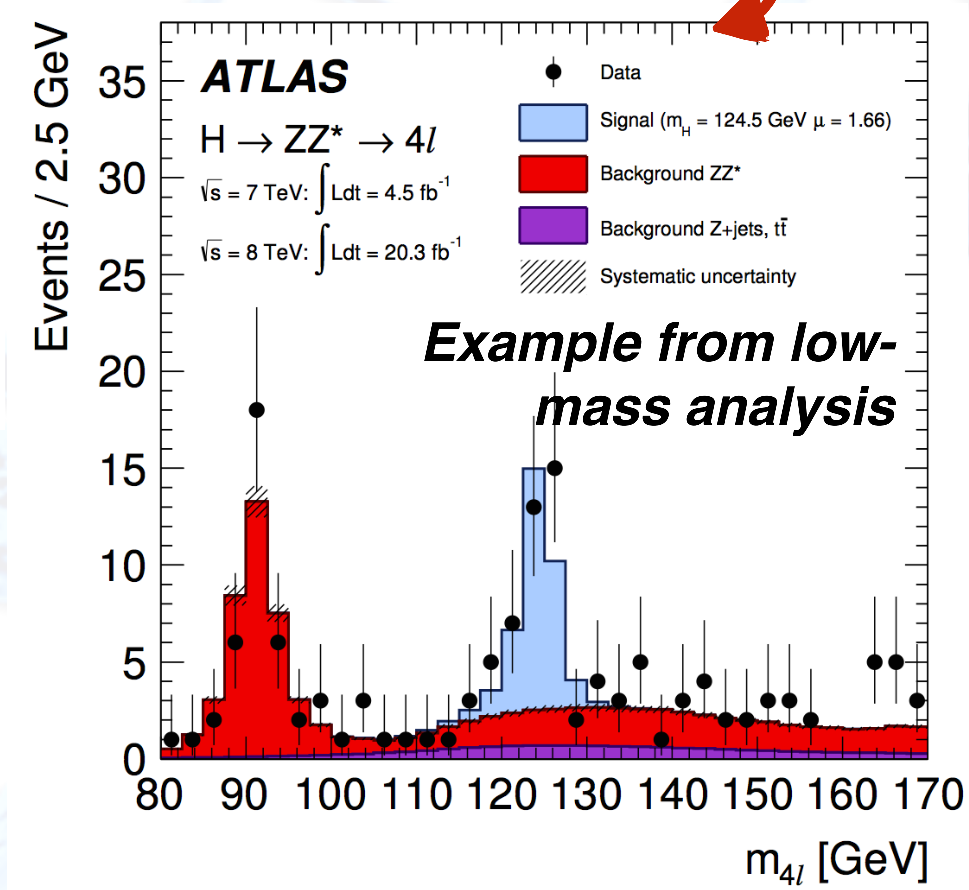
Channels have different mass resolution (O(1) - O(100) GeV)

Overview of search



The principle behind each analysis is to separate signal-like events from the many background events

- At first events are sorted with a sequence of requirements (***cuts***) imposed to data
- Afterwards the shape of a ***discriminant*** is used

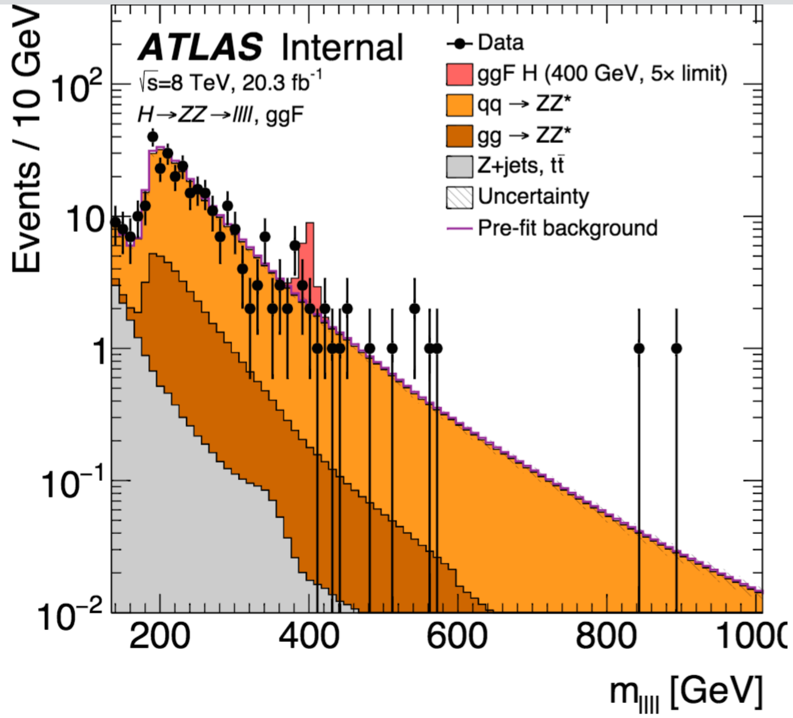


My contribution was to the H → ZZ → 4l analysis, to the combination of the decay channels and to the statistical treatment

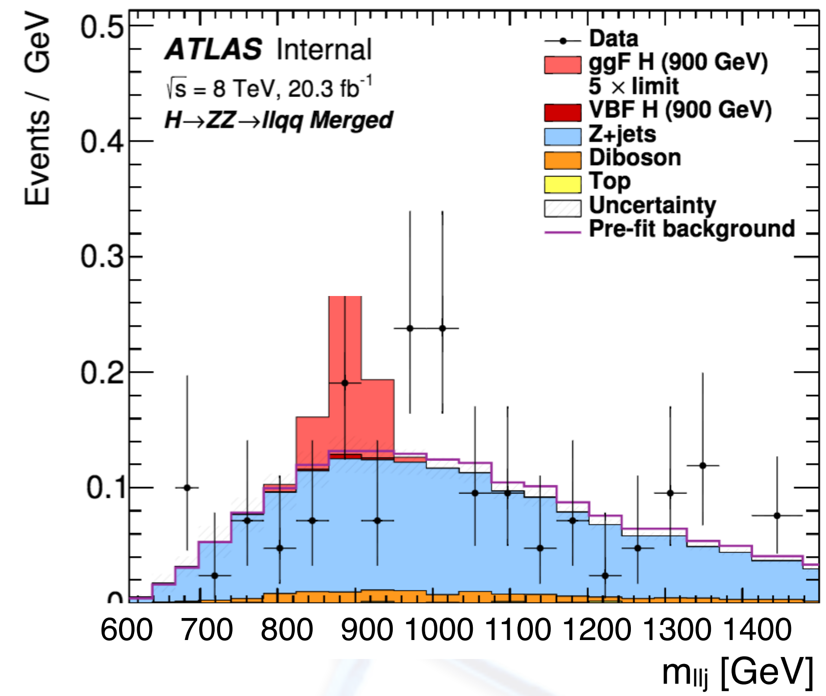
Overview of search

Discriminants of the four different H → ZZ decay channels

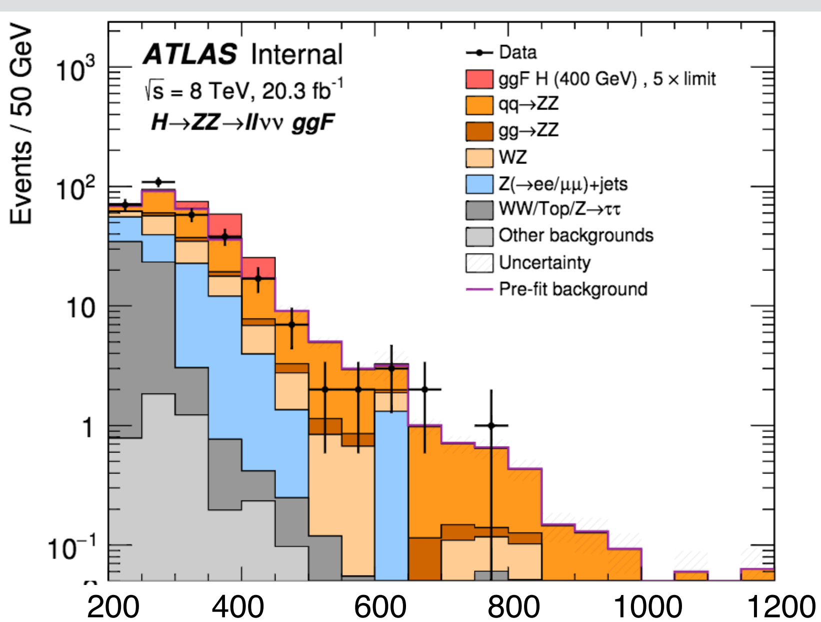
4l: inv. mass of 4 leptons



2l2q: inv. mass of jets and leptons

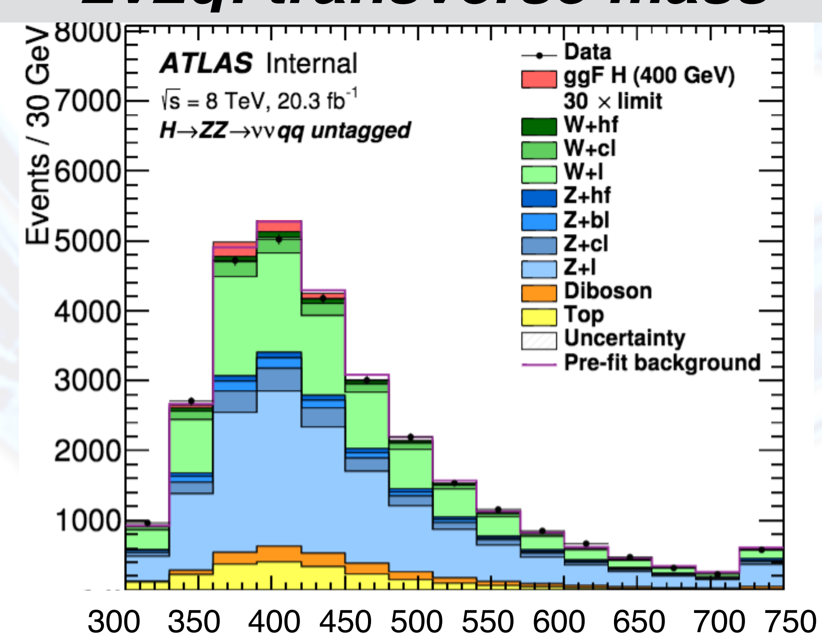


2l2ν: transverse mass



$$(m_T^{ZZ})^2 \equiv \left(\sqrt{m_Z^2 + |p_T^{\ell\ell}|^2} + \sqrt{m_Z^2 + |E_T^{miss}|^2}\right)^2 - |\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{miss}|^2$$

2ν2q: transverse mass

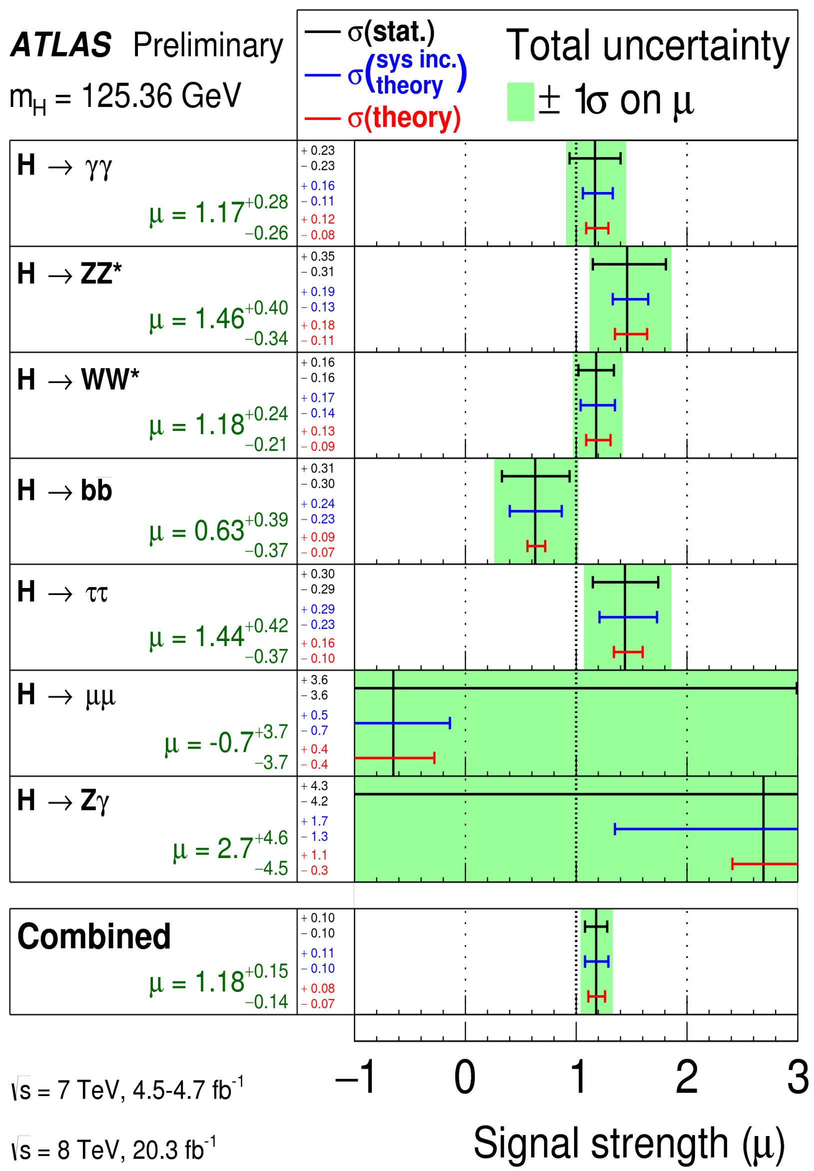


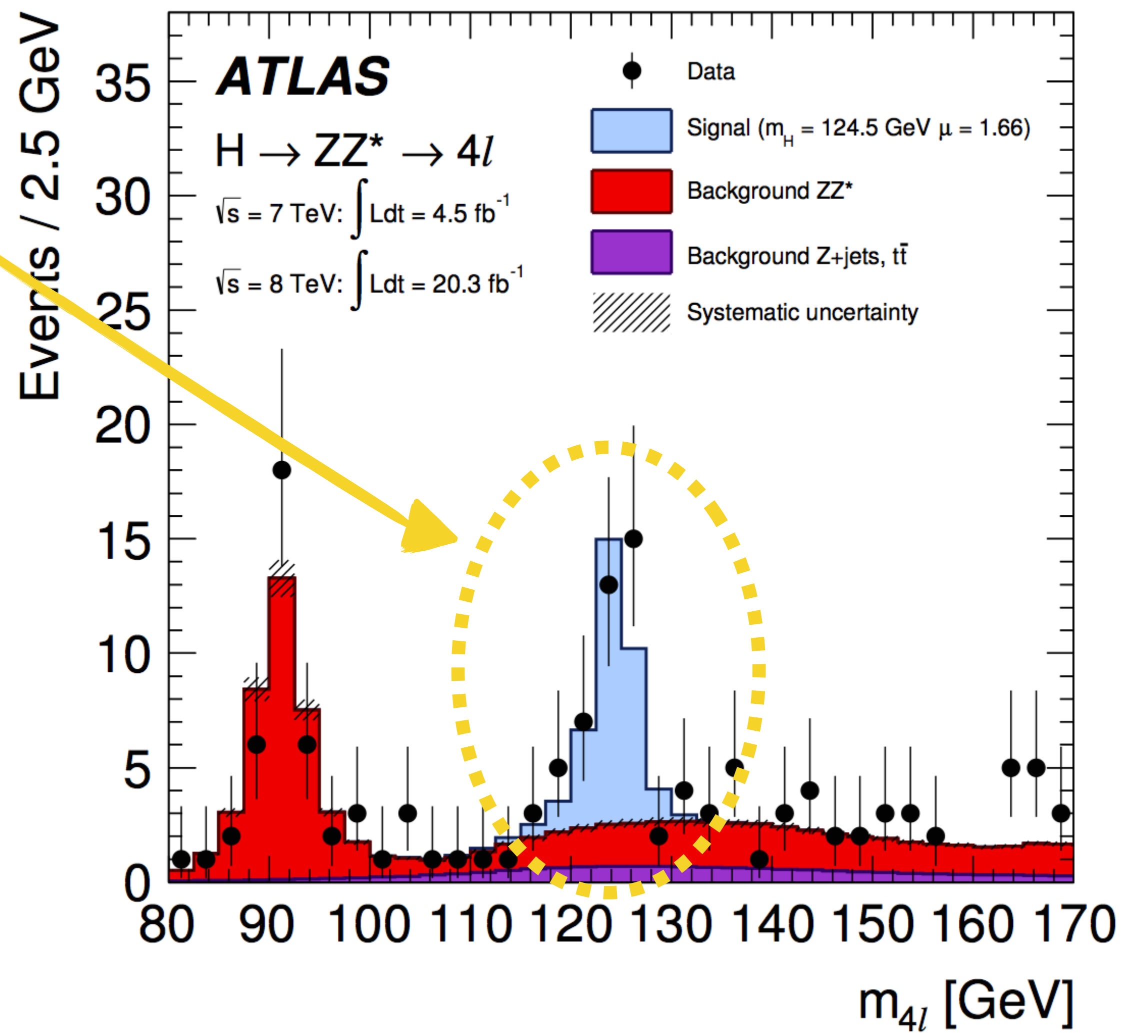
$$(m_T^{ZZ})^2 \equiv \left(\sqrt{m_Z^2 + |p_T^{jj}|^2} + \sqrt{m_Z^2 + |E_T^{miss}|^2}\right)^2 - |\vec{p}_T^{\,jj} + \vec{E}_T^{miss}|^2$$

Statistical treatment and combination

The signal production rate is quantified with the ***signal strength μ***

- Acts as signal scale factor





μ = observed rate/rate predicted by theory

- μ = 0: data matches background only prediction
- μ = 1: data matches theoretical signal prediction

Our final results rely on the determination of μ

Statistical treatment and combination

μ is determined by the use of a ***likelihood function***

- Parametrisation of our assumptions about signal and background
- Represents the probability for our dataset to originate from our model with a signal scaled by *μ*

$$\mathscr{L}(\mu) = \mathrm{Pois}(x_1 ... x_n | \mu S + B) \left[\prod_{e=1}^{n} \frac{\mu S f_s(x_e) + B f_B(x_e)}{\mu S + B} \right]$$

The power of the search is enhanced by ***combining the H → ZZ channels***, done by merging the *i* individual likelihood functions

$$L(\mu) = \prod_i L_i(\mu)$$

- Assume channels are statistically independent
- μ is common between channels
- Define which systematic uncertainties are correlated between channels

The combined likelihood is used to fit the data from all channels

- Increased statistics enhances sensitivity

Results

Our final results are under circulation in ATLAS, therefore, material for this section is limited

- Examples on the next slide borrowed from an earlier analysis

The combined likelihood is used to derive two types of results

Model-independent limits on the heavy Higgs boson production

- Reduce assumptions about underlying model to make search general

Model-specific interpretation

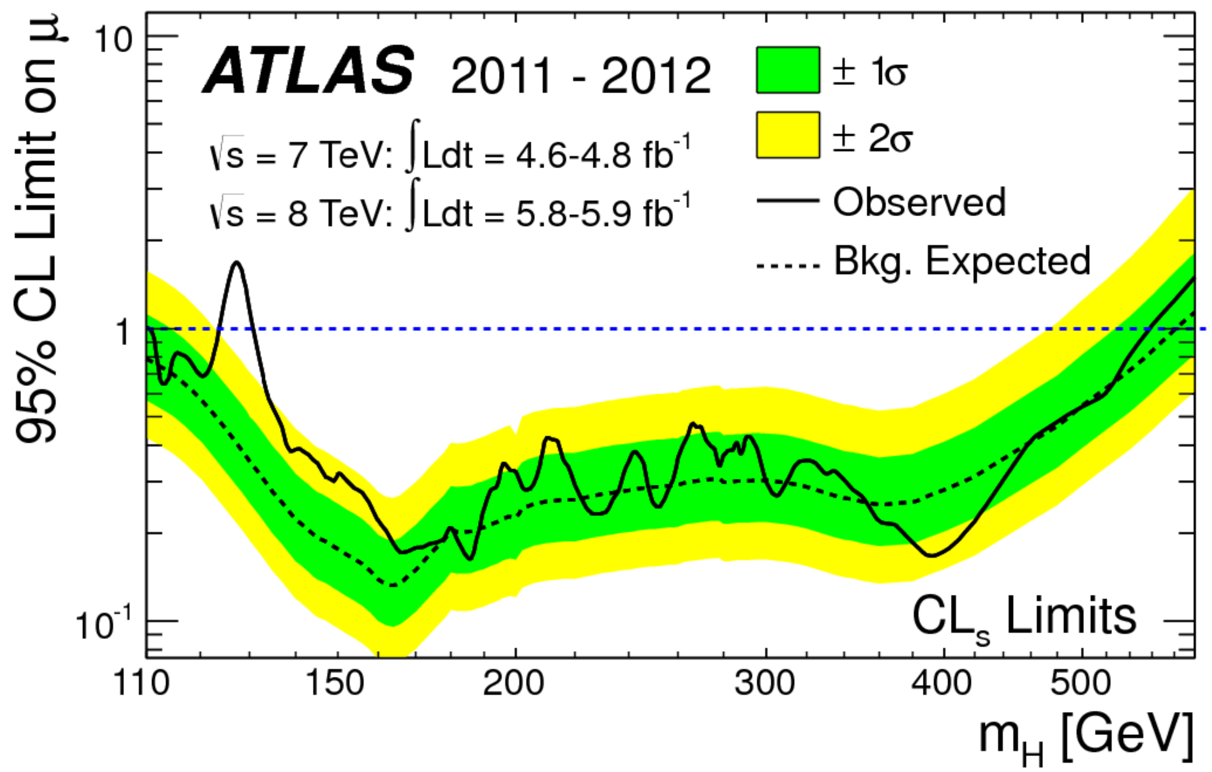
- Limits on the 2HDM parameter-space in certain benchmark scenarios
- Detailed information about this still confined to ATLAS

Results

Our ***model-independent*** results are shown as upper limit on the heavy Higgs boson cross-section × the H → ZZ branching ratio

- Limit converted from μ to fb
- Computed with the CLs technique separately for each mass point

arXiv:1207.7214



The ***expected limit*** represents the maximum possible signal rate (at 95% CL) assuming the data is modelled by the background only hypothesis (μ = 0)

- The more data, the smaller rates can be probed
- Background fluctuation represented by the yellow/green bands

New physics would show as ***data excess above the expected limits***

Summary and outlook

Presented an overview of my main thesis topic: the search for a heavy Higgs boson in the $H \rightarrow ZZ$ channels using $\sqrt{s}$ = 8 TeV data recorded with ATLAS

Our analysis is complete at this point and going through the final internal ATLAS review

The LHC Run-2 data-taking period just began (in May this year)

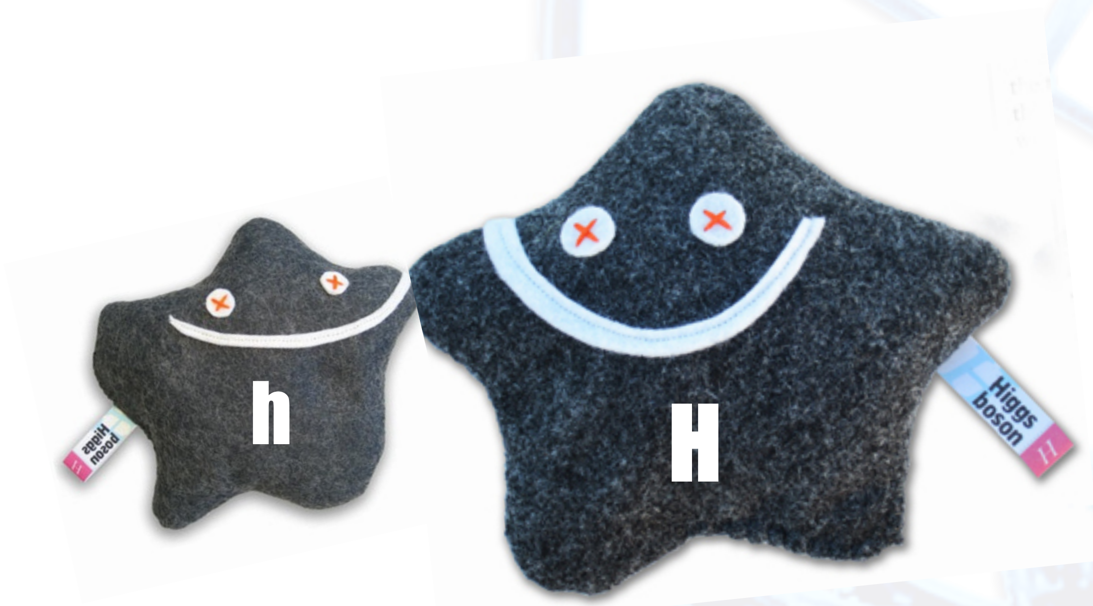
- Collisions at $\sqrt{s}$ = 13 TeV
- Expect ~5 fb^{-1} towards end of year

A corresponding search is foreseen with the early Run-2 data

- Sensitivity of Run-1 search expected to be exceeded in Run-2 with as little as <10 fb^{-1}

At the moment I work on finishing the final details with the Run-1 paper and in parallel prepare for the Run-2 search

Thanks for your attention



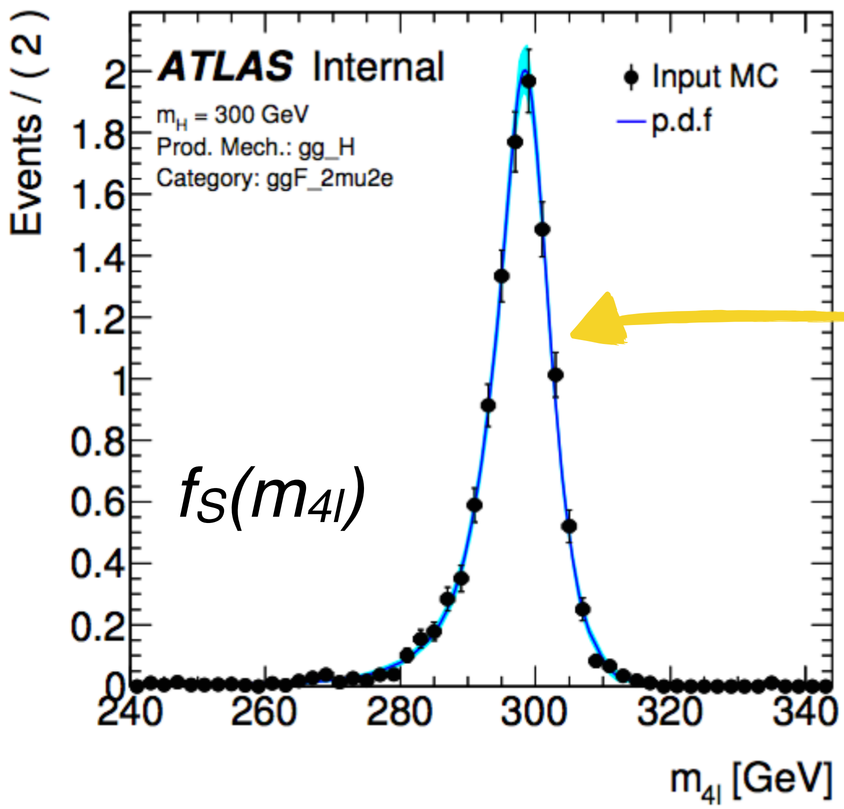
Backup

Statistical treatment and combination

μ is determined by the use of a ***likelihood function****

- Parametrisation of our assumptions about signal and background
- Represents the probability for our dataset to originate from our model with a signal scaled by *μ*

$$\mathscr{L}(\mu) = \text{Pois}(x_1 \ldots x_n | \mu S + B) \left[\prod_{e=1}^{n} \frac{\mu S f_s(x_e) + B f_B(x_e)}{\mu S + B} \right]$$



The likelihood consists of

- $\boldsymbol{x_e}$: dataset of *n* events in units of the discriminant
- ***S/B:*** expected signal/background events
- $\boldsymbol{f_{S/B}(x_e)}$: function describing signal/background

By minimising the likelihood, the value of μ favoured by data is found

***Examples on this page from the H→ZZ→4l channel**

Statistical treatment and combination

A crucial (and time-consuming) aspect of the analyses is the determination of ***systematic uncertainties***

- For example, the uncertainty on the jet energy scale is 1-3% (depending on the jet momentum)

Three types of systematics are defined, affecting

- Experimental factors
- Signal modelling
- Background estimation

The systematic uncertainties affecting our search are integrated into the statistical procedure as ***nuisance parameters (NP)***

Each systematic is represented with a NP, which models it as a distribution with mean and width representing its value and uncertainty

- Usually a normal distribution or Poissonian

A systematic with the measured value $\tilde{\theta} \pm \sigma_\theta$ would be constrained by the normal distribution $G(\theta|\tilde{\theta}, \sigma_\theta)$

Statistical treatment and combination

The NPs are added to the likelihood function as ***constraint terms***

$$\mathscr{L}(\mu,\theta) = \mathrm{Pois}(x_1 \ldots x_n | \mu S + B) \left[\prod_{e=1}^{n} \frac{\mu S f_s(x_e) + B f_B(x_e)}{\mu S + B} \right] \prod_i G(\theta_i | \tilde{\theta}_i, \sigma_{\theta_i})$$

The NP values favoured by data is found by minimising the likelihood w.r.t. each NP

- Profile likelihood approach
- The data constrains the NPs

The presence of nuisance parameters broadens the profile likelihood scan

- Reflects the loss of information due to the systematic uncertainties