



GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

BEH Overview (ATLAS)

Dr. Clara Nellist

Georg-August-Universität Göttingen
On behalf of the ATLAS Collaboration

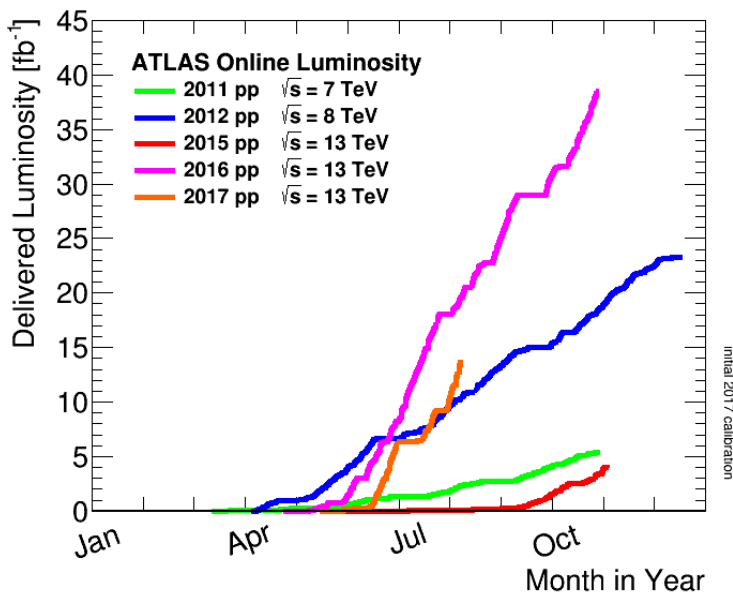
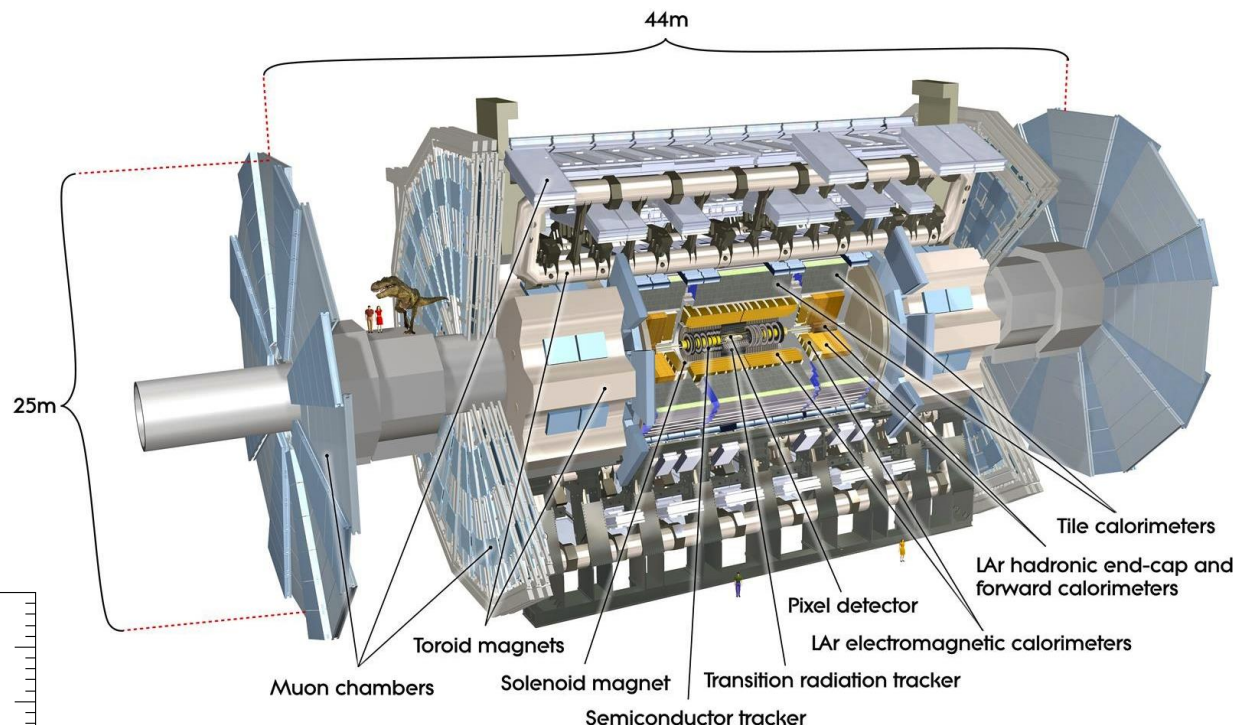
International Conference on New Frontiers in Physics
Crete, Greece - 2017

- Higgs Boson Production and Decay:
 - Bosonic Decays,
 - Fermionic Production and Decay.
- Higgs Properties:
 - Mass Measurements,
 - Spin / Parity,
 - Width,
 - Higgs Couplings.
- Higgs beyond the Standard Model.
- Conclusion and Summary.



- Run 1:

- 2011 at $\sqrt{s}=7$ TeV.
- 2012 at $\sqrt{s}=8$ TeV.
- Total $\sim 29 \text{ fb}^{-1}$.



- Run 2:

- 2015-2018 at $\sqrt{s}=13$ TeV.
- $\sim 36.1 \text{ fb}^{-1}$ for 2015+2016.
- $\sim 14 \text{ fb}^{-1}$ for 2017 so far...

- The Brout-Englert-Higgs (BEH) mechanism extended spontaneous symmetry breaking to gauge fields.
 - The process generates mass for fundamental particles.
- It also predicted a scalar particle, often referred to as the Higgs boson.
 - However, the mass of the Higgs boson is not predicted in the SM.
- In 2012, CERN announced the discovery!
- Once the Higgs mass is measured, the other parameters become fixed and can be measured and compared to SM predictions.

These other parameters are:

- Mass measurements
- Spin/Parity
- Width
- Higgs couplings.
- Small deviations in the Higgs boson's properties from those predicted could give hints of new physics.
- The exploration of this new particle is still in early stages.
 - We have collected only ~1% of the anticipated luminosity from the LHC.

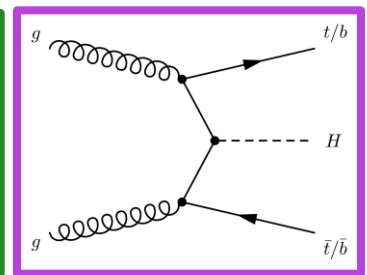
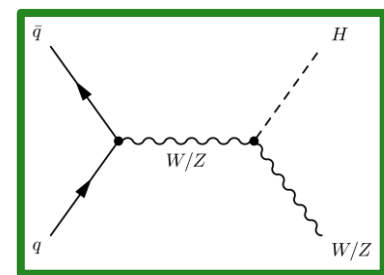
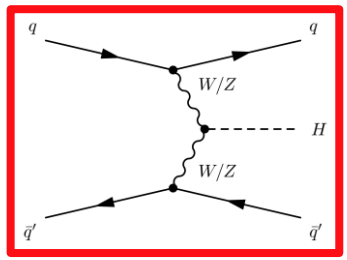
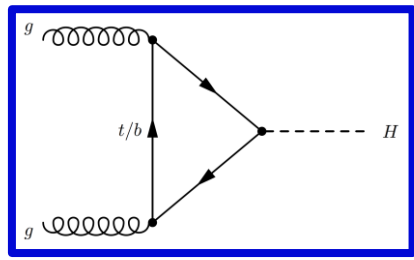
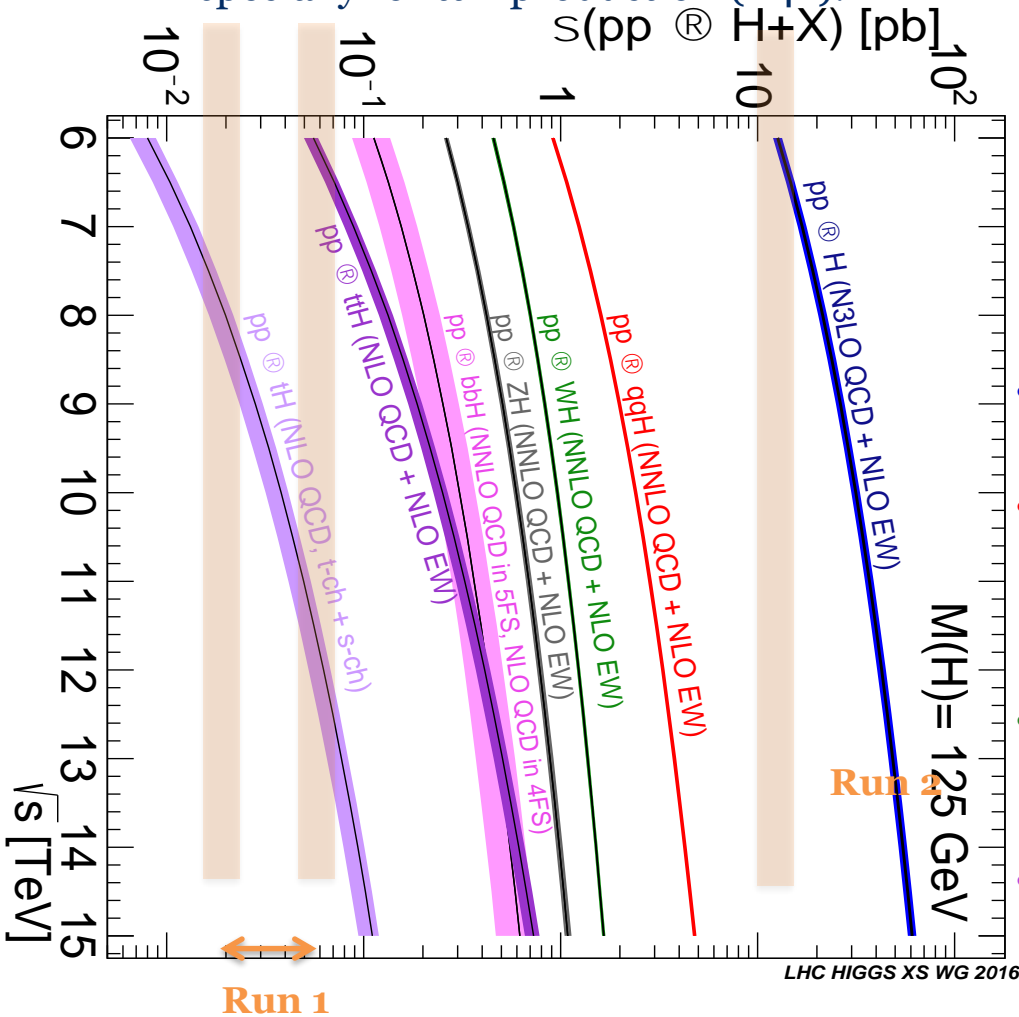
	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	
				Higgs boson	

Source: AAAS

Higgs Boson Production

- Run 1 -> Run 2.
 - Increase of Higgs cross-sections.
 - Especially for ttH production (~4x).

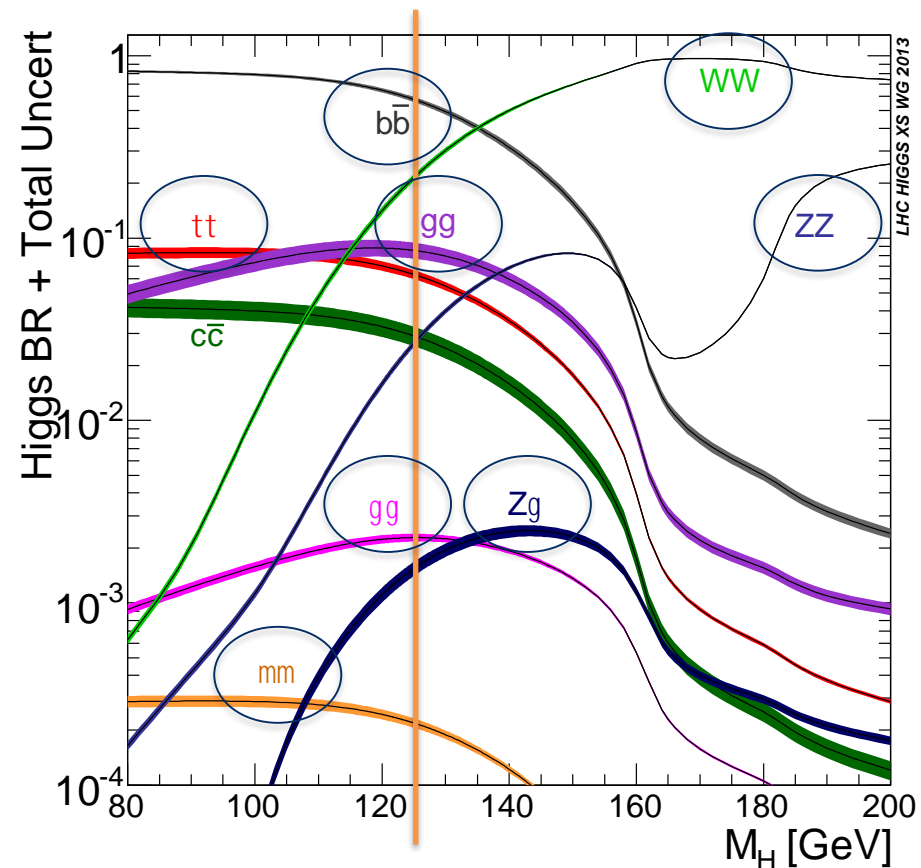
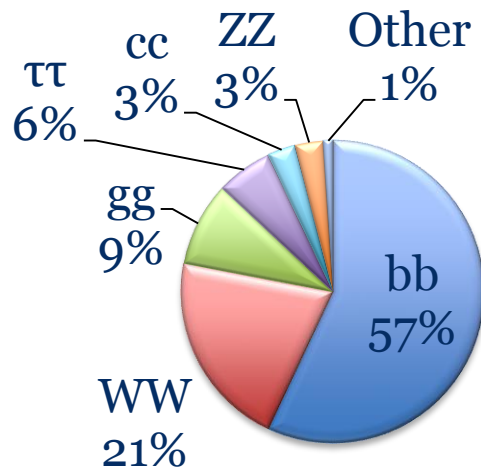
Probing all channels!



- **Gluon Gluon Fusion**
 - The dominant production mode.
- **VBF : Vector Boson Fusion**
 - Second most dominant.
 - Characterized by two forward jets produced along with a Higgs.
- **VH**
 - Composed of a Higgs produced in association with a vector boson.
- **ttH**
 - Higgs produced in association with ttbar pair.

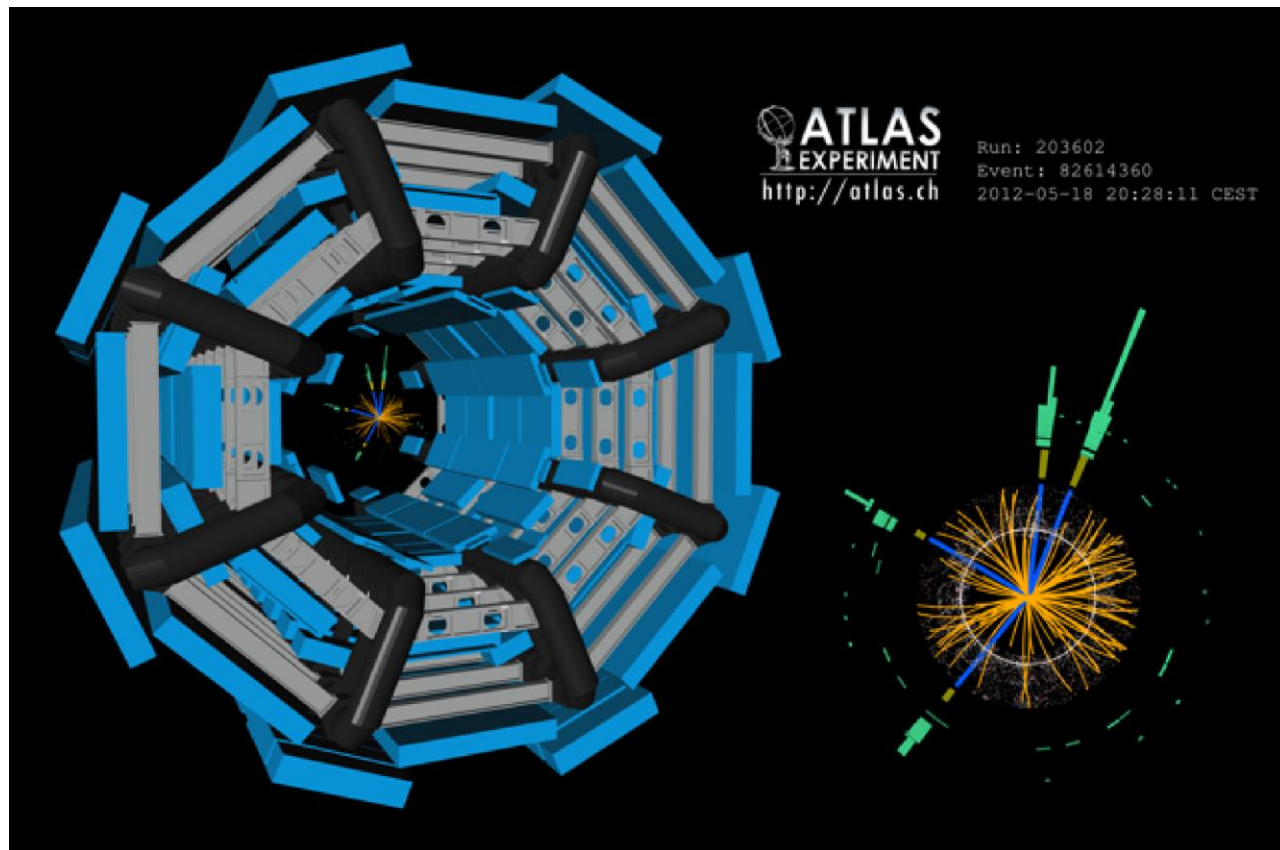
- For a standard model Higgs boson with a mass of ~ 125 GeV:
 - Decays with the highest branching ratios also have large irreducible backgrounds.
 - However, resolution and S/B are equally critical for the sensitivity.
 - Clean signals for low branching ratio signals:

- $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ ($\ell=e,\mu$).
- The 'discovery' channels.



- The discovery of the Higgs in 2012 was announced with bosonic decay channels.

- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ^* \rightarrow 4\ell$
($\ell=e,\mu$)
- $H \rightarrow WW^*$



See detailed talk:
*Measurement of cross sections
and couplings of the Higgs
Boson in bosonic decay
channels with the ATLAS
detector* Nikita Belyaev

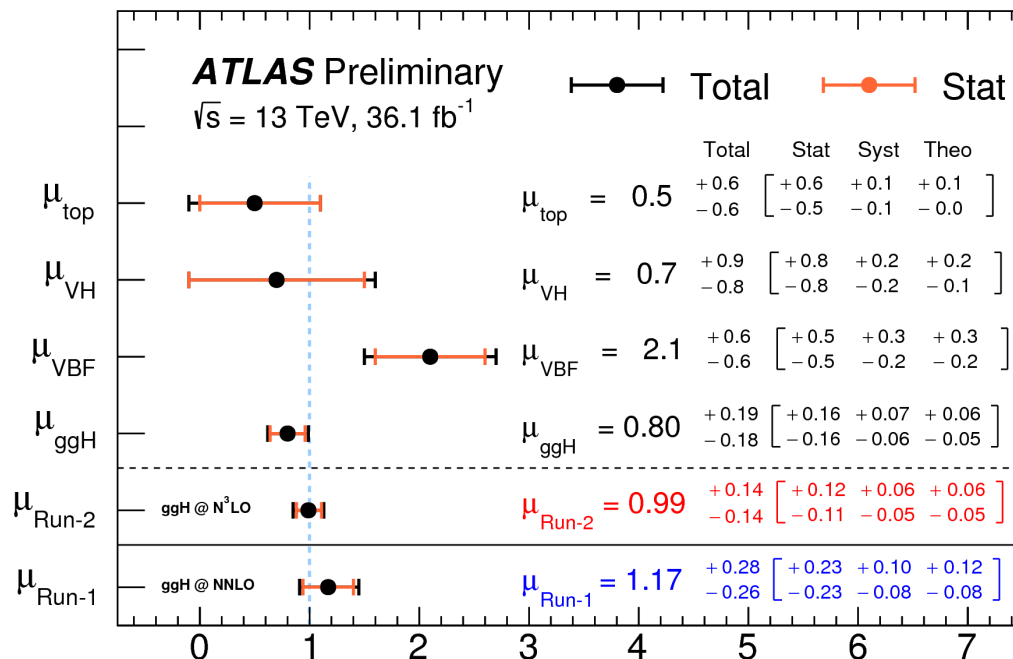
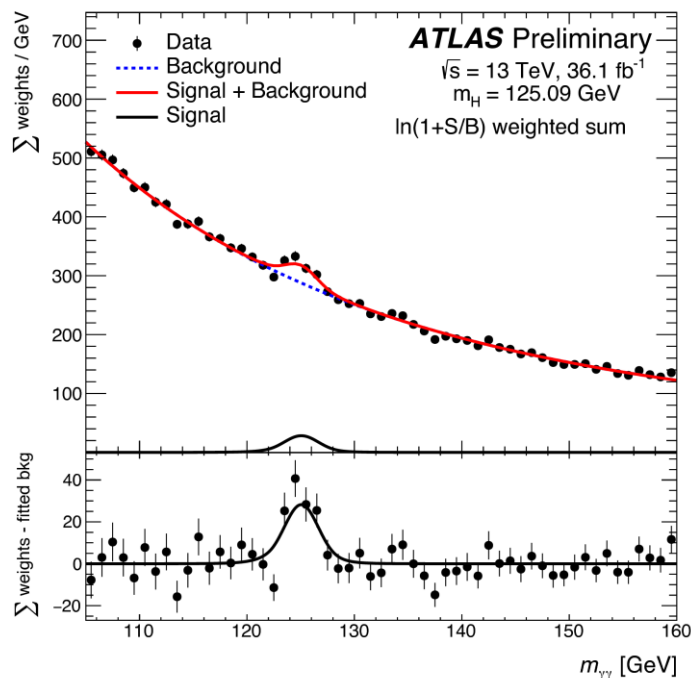
Display of a $4e$ candidate event.
 $m_{4\ell}=124.2$ GeV

Run 2

- Signal is extracted using a maximum-likelihood fit to the diphoton invariant mass.
 - Simultaneous fit for a bump on top of a smoothly falling background.
- The main backgrounds for this channel are $\gamma\gamma$, γ +jets and dijets.

Signal strength:

$$\mu = \frac{\sigma \times \text{BR}}{(\sigma \times \text{BR})_{SM}}$$



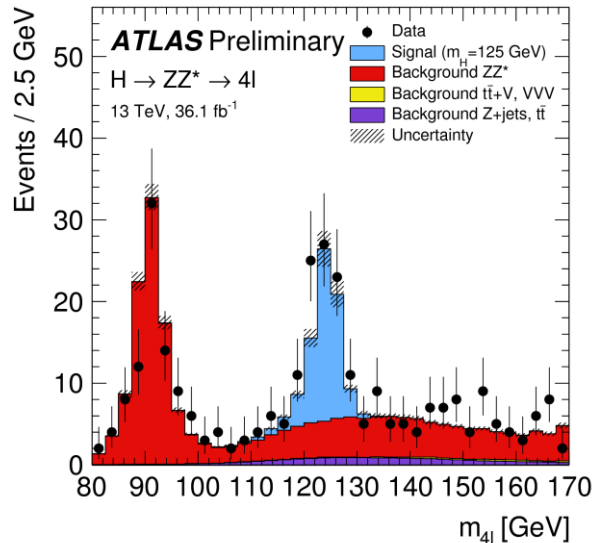
Signal Strength

[ATLAS-CONF-2017-043](#)

[ATLAS-CONF-2017-045](#)

$H \rightarrow ZZ^* \rightarrow 4\ell$:

- High signal to background ratio.
- Extract signal via four-lepton invariant mass.



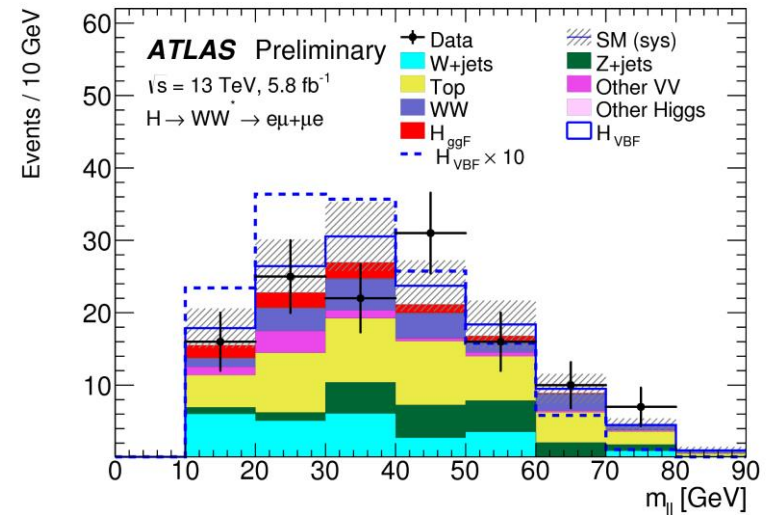
- The inclusive fiducial cross-section in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel is:
 - $3.62 + 0.53 - 0.50$ (stat) $+ 0.25 - 0.20$ (sys) fb
- Standard Model prediction of:
 - 2.91 ± 0.13 fb.
- Differential fiducial cross-section has also been measured.

[ATLAS-CONF-2017-032](#)

Run 2

$H \rightarrow WW^*$:

- Second largest branching ratio.



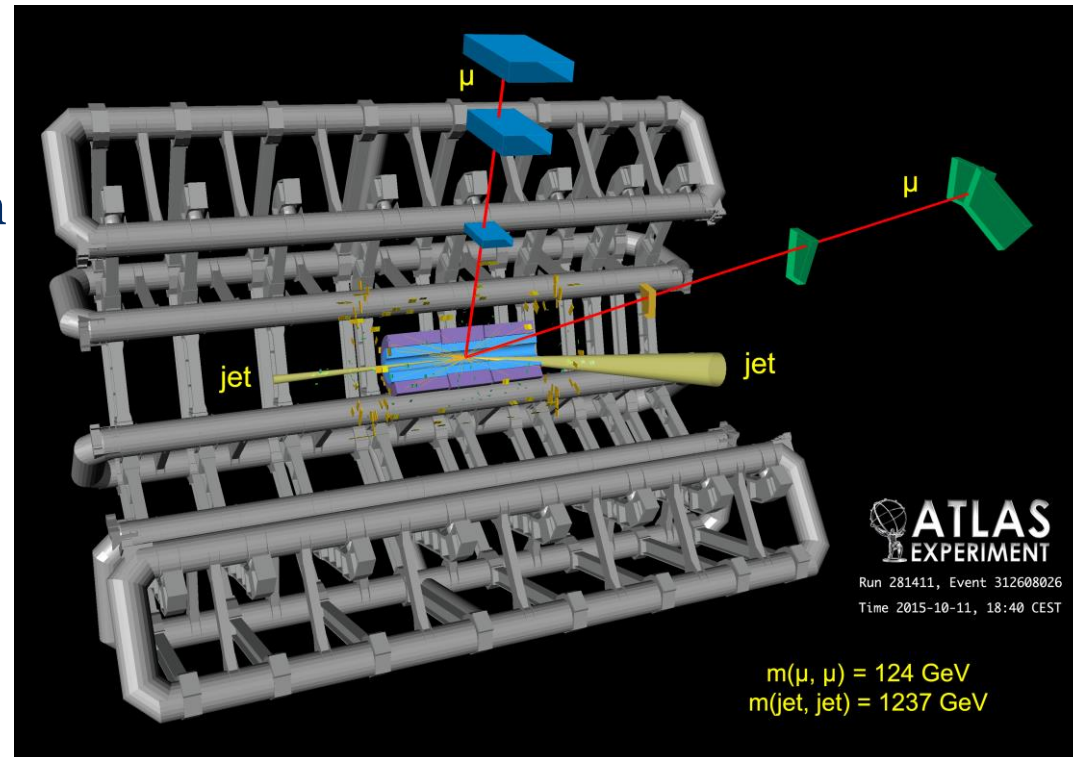
- Latest result with 5.8 fb⁻¹ of Run 2 data.
 - Via VBF and associated WH production.
 - $\mu_{VBF} = 1.7 + 1.1 - 0.9$
 - $\mu_{WH} = 3.2 + 4.4 - 4.2$

[ATLAS-CONF-2016-112](#)

- Want to confirm that the Higgs boson is the one predicted in the SM and therefore testing the direct coupling with fermions is high priority.

- $H \rightarrow \tau\tau$
- $H \rightarrow \mu\mu$
- $H \rightarrow bb$
- ttH

See detailed talk:
Measurement of cross sections and couplings of the Higgs Boson in fermionic production and decay modes with the ATLAS detector
Liaoshan Shi

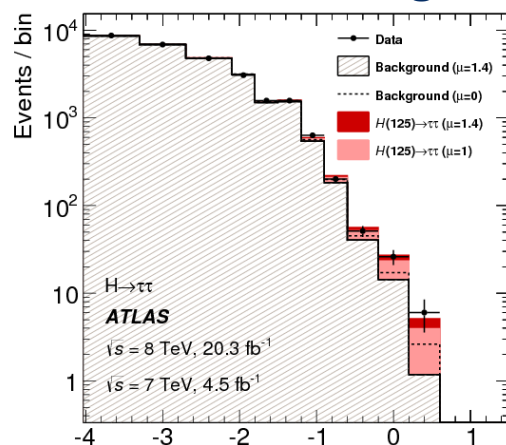


Candidate $H \rightarrow \mu\mu$ event at $\sqrt{s} = 13 \text{ TeV}$.

H → ττ and H → μμ

H → ττ

- Two production modes: ggF and VBF
- Three decay modes: [ATLAS-CONF-2017-29](#)
 - $\tau_{\text{lep}}\tau_{\text{lep}}, \tau_{\text{lep}}\tau_{\text{had}}, \tau_{\text{had}}\tau_{\text{had}}$
 - Requires good tau identification.
- Z → ττ is the main background.



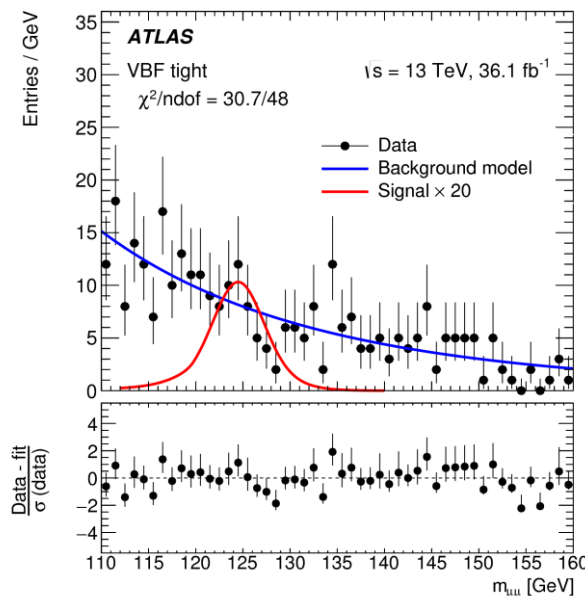
- Run 1 result (ATLAS): $\log_{10}(S/B)$
 - **4.5σ (3.4σ) observed (expected)**
- Combined ATLAS & CMS:
 - **5.5σ (5.0σ) observed (expected)**

[JHEP 04 \(2015\) 117](#)

H → μμ

Run 2

- Allows a direct observation of the Higgs Yukawa coupling to 2nd generation fermions.
- Clean signal, but low decay rate and a large background from Z → μμ (4x SM).
- Channel is statistically limited.

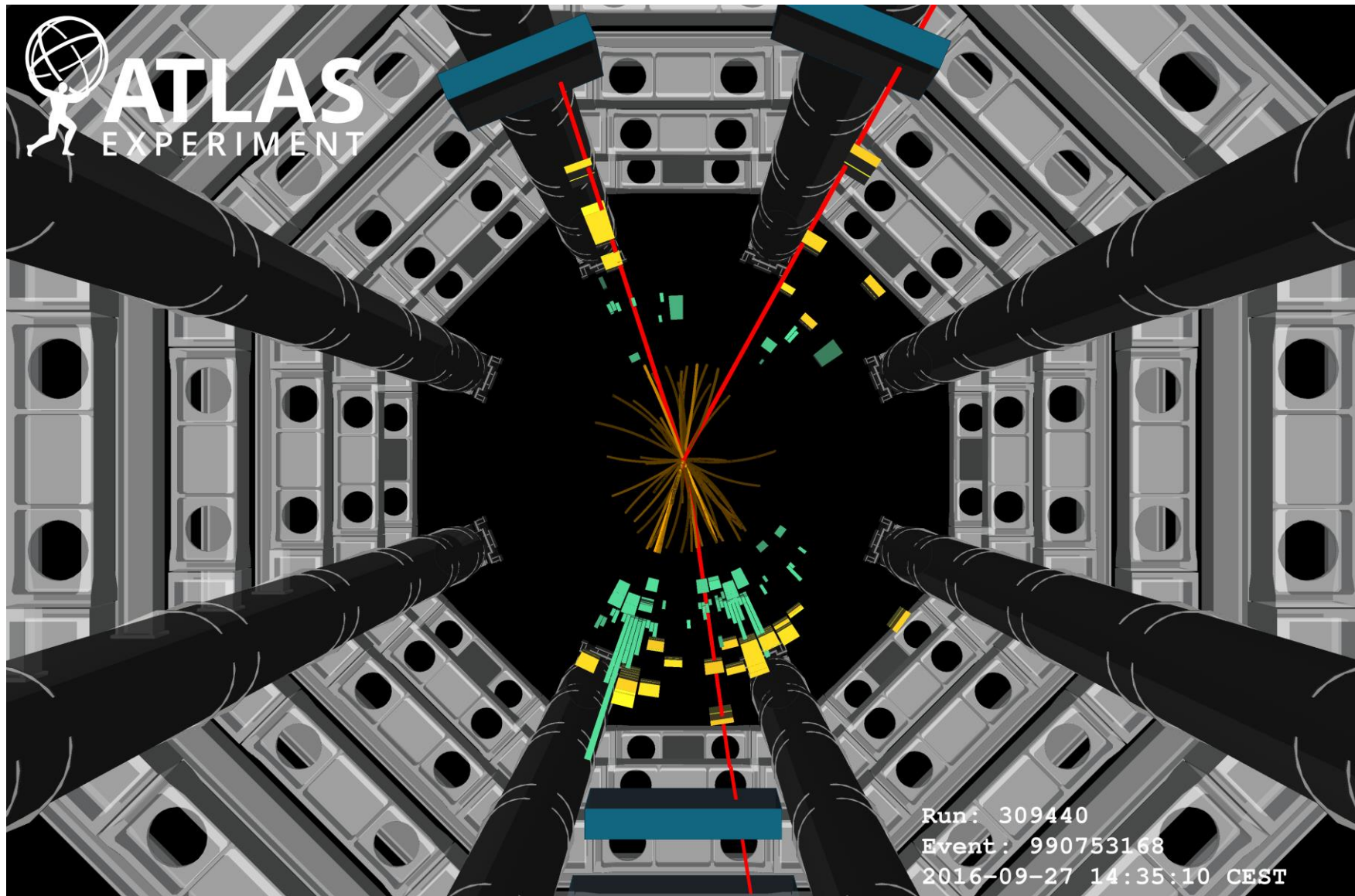


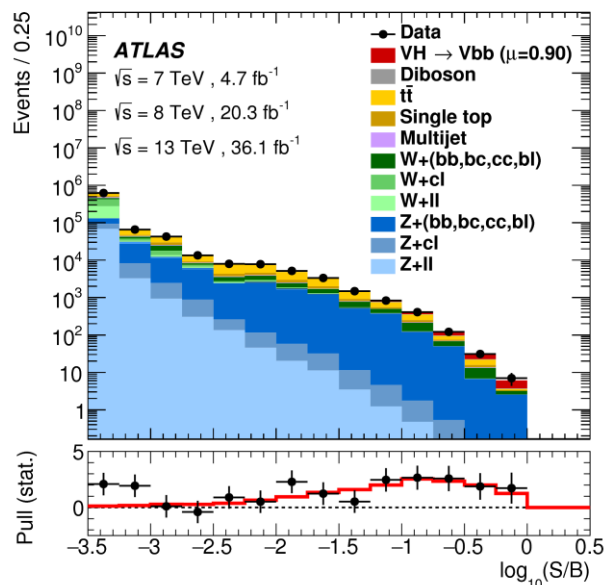
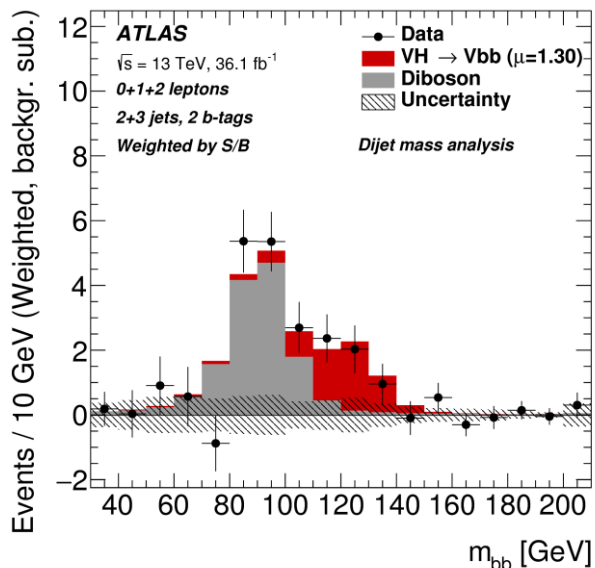
Result
(Run 1 + 2):

- $\mu < \mathbf{2.8}$ (**2.9**)
observed
(expected).
- Consistent with SM expectation that Higgs coupling is proportional to mass.

[Phys. Rev. Lett. 119 \(2017\) 051802](#)

H \rightarrow bb candidate event





- The most common decay for a SM Higgs at 58% **but** there are large backgrounds which are difficult to separate from signal.
- New result released recently via associated production with a W/Z boson.
- Gives the first evidence from the LHC of H → bb, with a significance, for the BDT Run 2 result, of:
 - **3.5 σ** (3.00) **observed** (expected).
- Combined significance for Run 1 + Run 2:
 - **3.6 σ** (4.00) **observed** (expected).
- Signal strength (combined Run 1 + Run 2):
 - **$\mu = 0.90 \pm 0.18(\text{stat.}) + 0.21 - 0.19(\text{syst.})$**
- Measurement of VZ, where Z → bb was used as a cross-check, gave a significance of:
 - **5.8 σ** (5.30) **observed** (expected).

[arXiv:1708.03299 \[hep-ex\]](https://arxiv.org/abs/1708.03299)

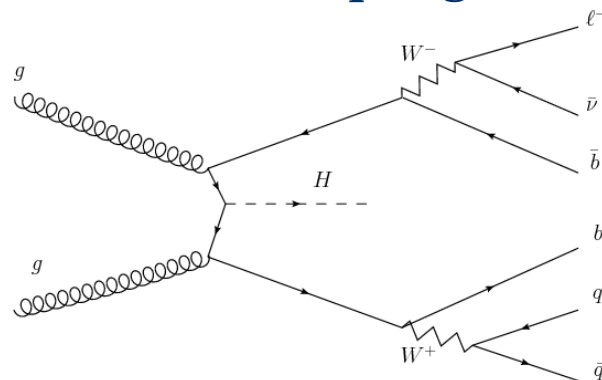
Run 2

- Indirect constraints on the top Yukawa coupling to the Higgs can be inferred from ggF production, and from $H \rightarrow \gamma\gamma$ decays.
- Also want to measure direct couplings.

See detailed talk:
ttH Coupling Measurement with the ATLAS Detector at the LHC
Asma Hadeef

Run 2

ttH Channels:



- $H \rightarrow \gamma\gamma$

- both the hadronic and leptonic tt decay channels.

- $H \rightarrow (WW(*), \tau\tau, ZZ(*)) \rightarrow$ leptons

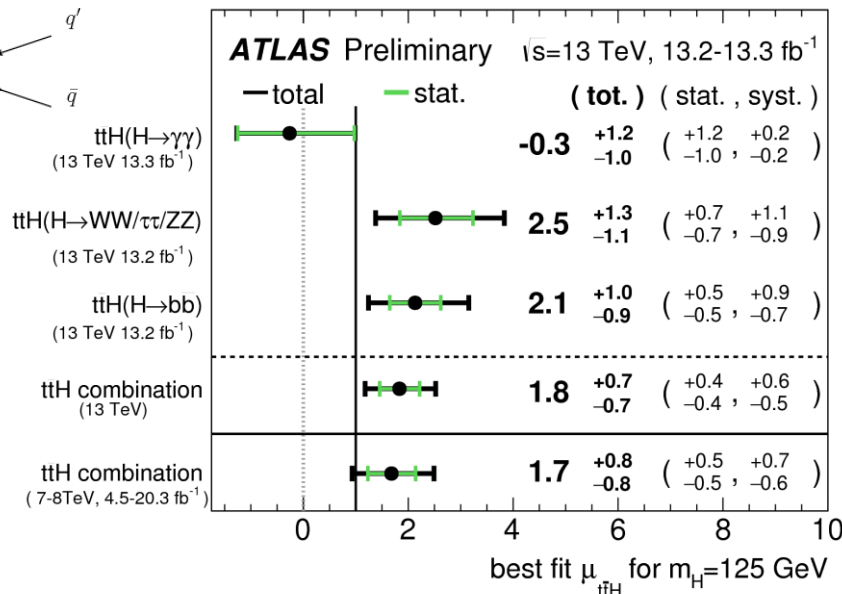
- two – four final lepton states.

- $H \rightarrow bb$

- single lepton,
- opposite-sign dilepton.

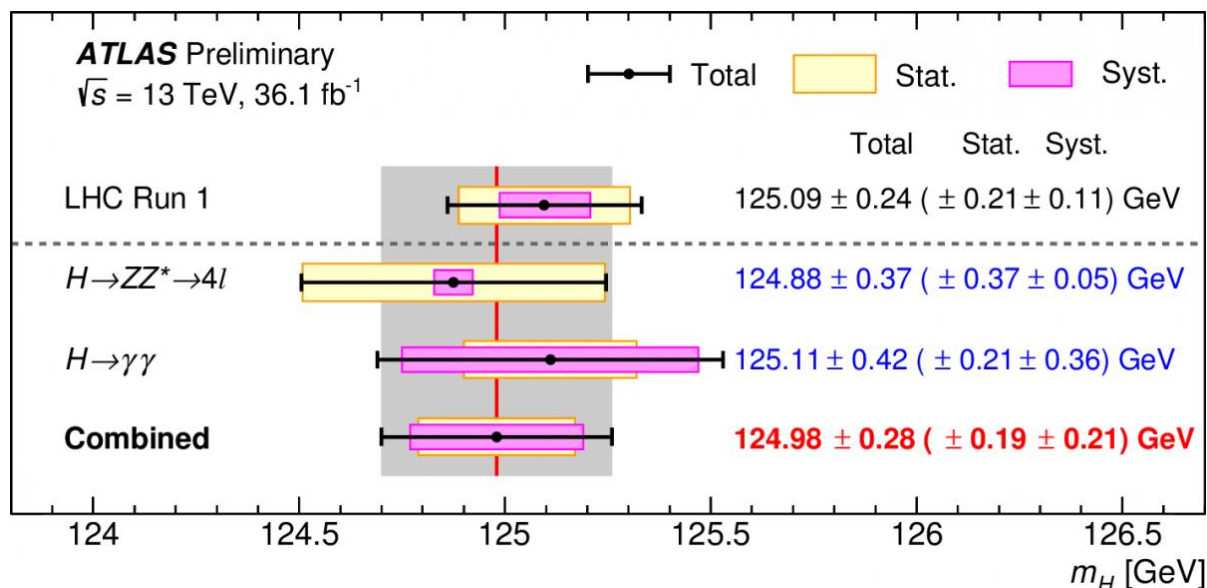
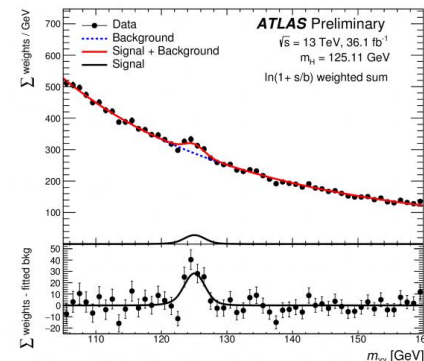
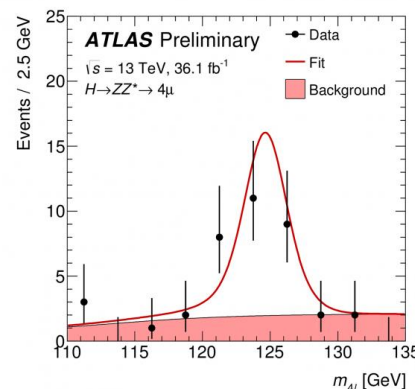
Note: leptons are electrons & muons.

2015+2016



[ATLAS-CONF-2016-068](#)

- The mass of the Higgs is measured using the two ‘discovery’ channels:
 - $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ ($\ell=e,\mu$).
- $H \rightarrow ZZ \rightarrow 4\ell$ is still statistically limited, while $H \rightarrow \gamma\gamma$ is systematically limited.
- Combined Run 2 measurement with 36 fb^{-1} .



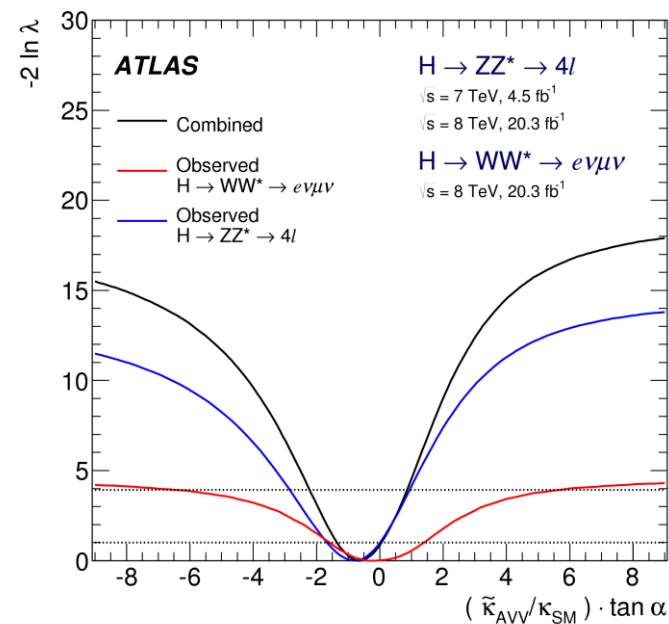
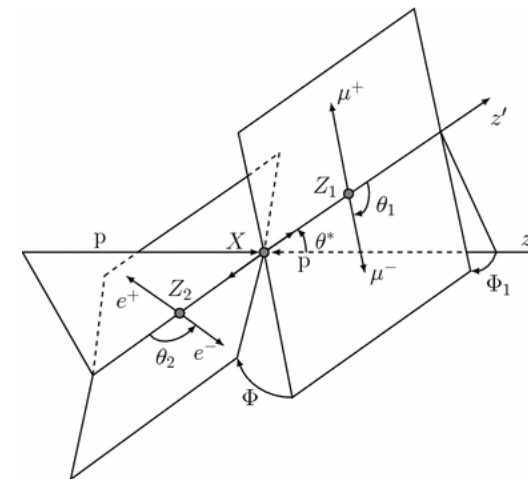
Result: $m_H = 124.98$

± 0.19 (statistical) ± 0.21 (systematic) GeV

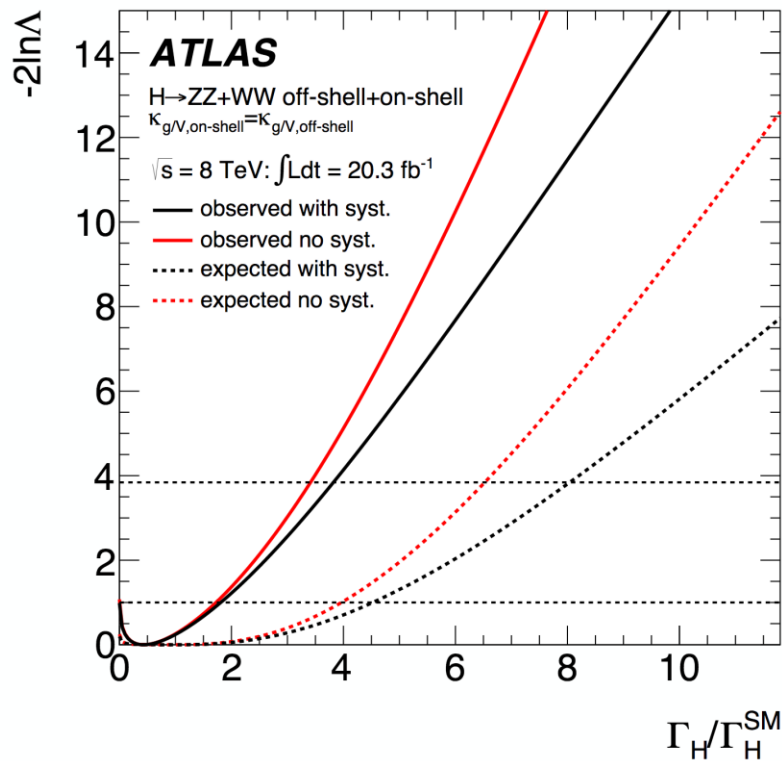
[ATLAS-CONF-2017-046](#)

Run 2

- Measurement using:
 - $H \rightarrow ZZ^* \rightarrow 4\ell$, $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ and $H \rightarrow \gamma\gamma$ decay processes.
 - Using 25 fb^{-1} at Run 1 ($\sqrt{s}=7$ and 8 TeV).
- Spin:
 - The SM Higgs hypothesis ($JP=0+$) is tested against alternative spin scenarios:
 - Non-SM spin-0 and spin-2 models with universal and non-universal couplings to fermions and vector bosons.
 - Result: All tested alternative models are excluded in favour of SM Higgs hypothesis at $> 99.9 \%$ Confidence Level (CL).
- Parity:
 - Want to test the parity as there can be CP mixtures in various BSM models, such as SUSY.
 - x-axis: observed CP-odd fraction of the event yield f_{g4}
The combination of $H \rightarrow ZZ$ (which dominates) and $H \rightarrow WW$ sets an upper limit of:
 $f_{g4} < 45 \%$ at 95% CL on the CP-odd component.

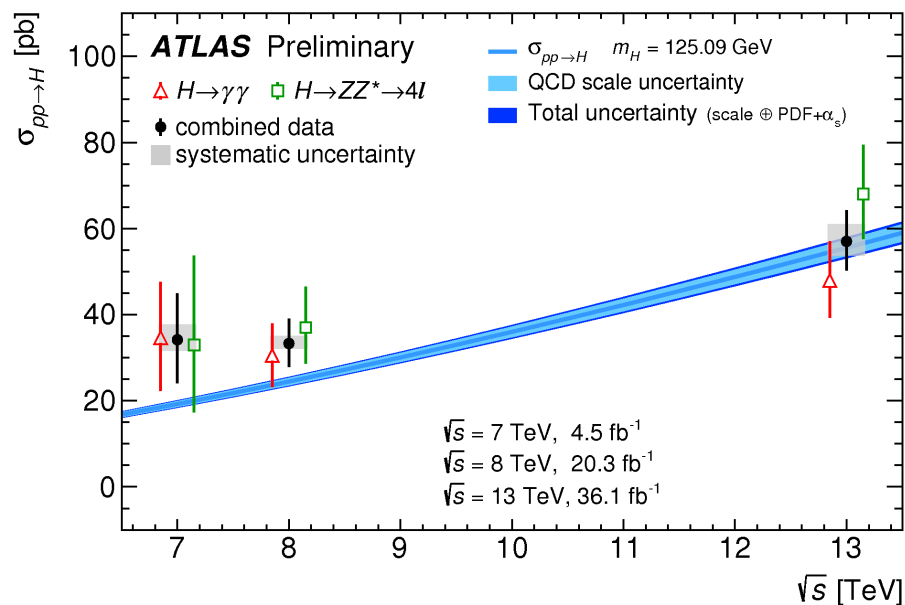


[Eur. Phys. J. C75 \(2015\) 335](#)



- Measurements of ZZ and WW final states in the mass range above the $2m_Z$ and $2m_W$ thresholds allow measurement of the off-shell coupling strength of the Higgs.
- Using 20.3 fb^{-1} at $\sqrt{s}=8 \text{ TeV}$ (Run 1).
- $ZZ \rightarrow 4\ell$, $ZZ \rightarrow 2\ell 2\nu$ and $WW \rightarrow e\nu\mu\nu$ final states.
- Result: a combination with the on-shell measurements yields, at 95 % CL upper limit, an **observed** (expected) total width, $\Gamma_H/\Gamma_H^{\text{SM}}$, in the range of :
 $4.5\text{--}7.5$ ($6.5\text{--}11.2$).

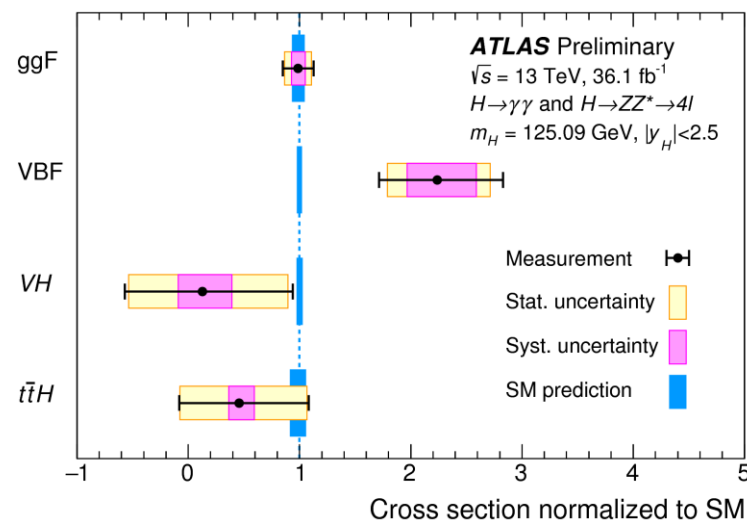
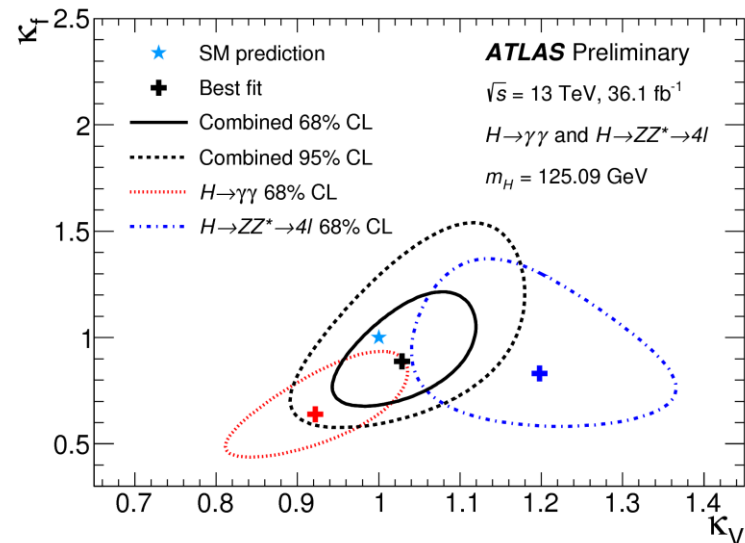
- Coupling strength modifiers, κ , are used to probe the coupling strengths and test for deviations from the SM expectations.
- $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ ($\ell=e,\mu$).
- Run 2 with 36.1 fb^{-1} .

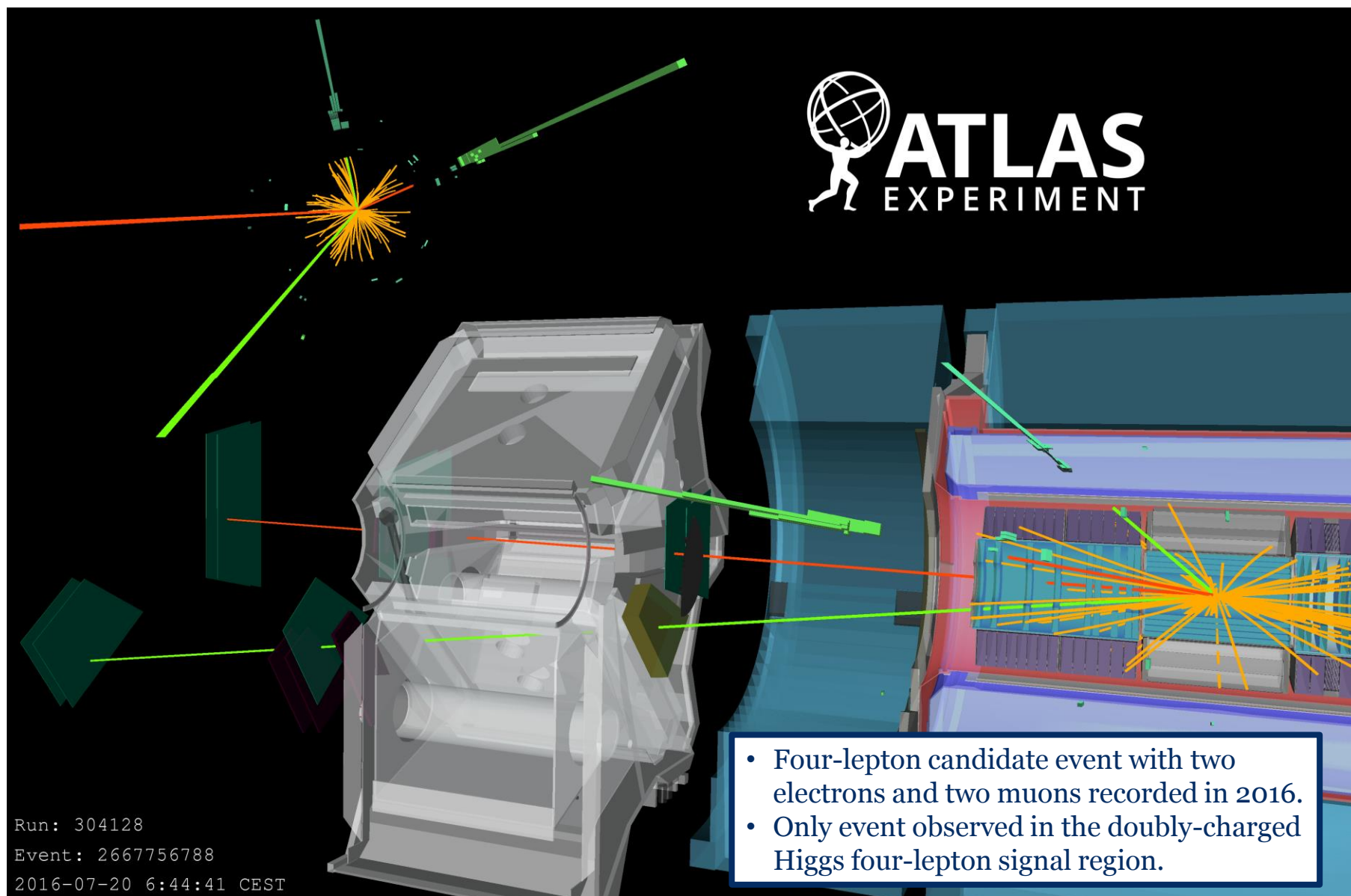


- No significant deviations from the SM expectations are observed.

[ATLAS-CONF-2017-047](#)

Coupling strength modifiers, κ , are used to probe the coupling strengths and test for deviations from the SM expectations.





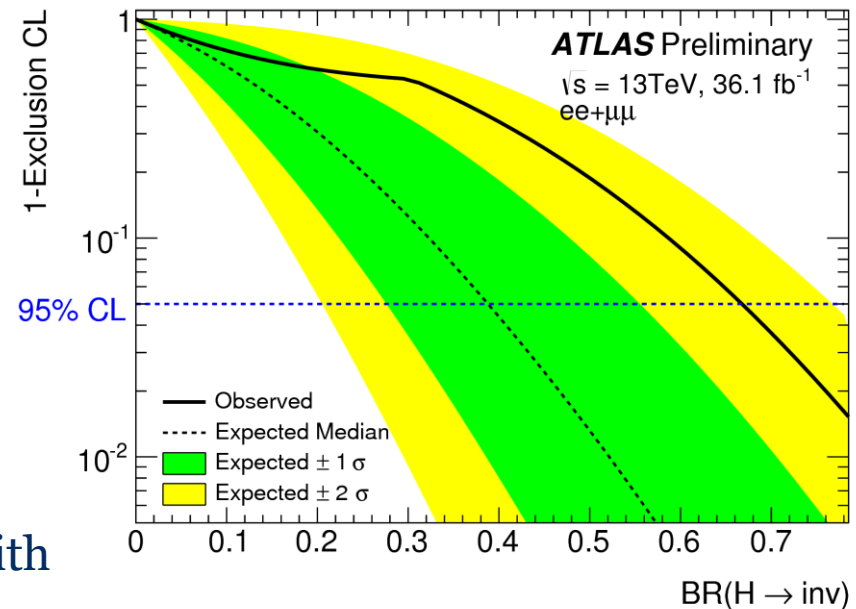
The Higgs can be used to probe for physics beyond the Standard Model (BSM) if there are anomalous or new Higgs couplings.

- $H \rightarrow$ invisible [ATLAS-CONF-2017-040](#)
 - $pp \rightarrow ZH \rightarrow ll +$ missing energy with 2015+2016 Run 2 data (36.1 fb^{-1}).
 - $\text{BR}(H(125) \rightarrow \text{invisible}) < 67\%$ obs. (39% exp.) at 95% CL, assuming SM ZH production rate.

- Lepton flavour violation

- Decay of the Higgs boson to leptons with different flavours.
- 20.3 fb^{-1} of 8 TeV Run 1 data.
- Reconstruct the Higgs mass for $H \rightarrow l_{(e, \mu)} \tau_{\text{had}}$ and $H \rightarrow e \tau_{\text{lep}}$.
- No significant excess observed. Set upper limits at 95% confidence level:
 - $\text{BR}(H \rightarrow e \tau) < 1.04\%$
 - $\text{BR}(H \rightarrow \mu \tau) < 1.43\%$,
 - $\text{BR}(Z \rightarrow \mu \tau) < 1.69 \times 10^{-5}$.

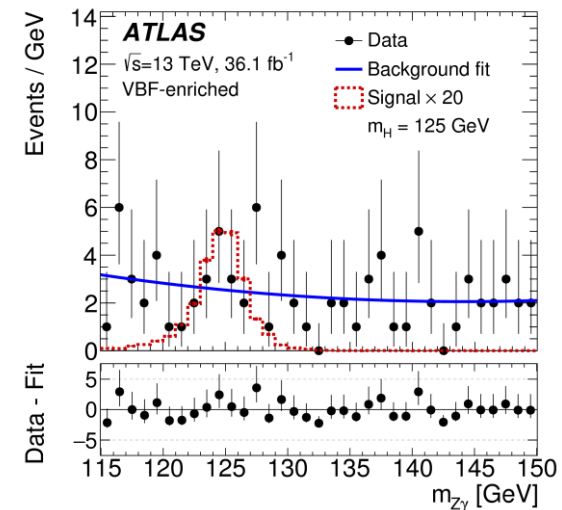
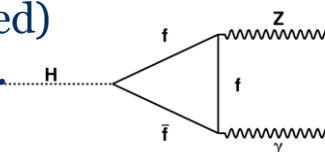
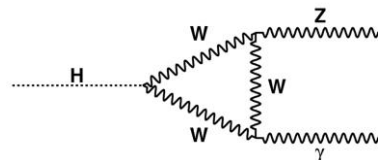
[Eur. Phys. J. C 77 \(2017\) 70](#)



- $H \rightarrow Z\gamma$

[arXiv:1708.00212 \[hep-ex\]](https://arxiv.org/abs/1708.00212)

- Produced via loop diagrams:
- Preliminary results at 95% CL upper limit with $m_H = 125.09$ GeV:
 - Cross-section * BR = **6.6** (5.2) times the SM prediction observed (expected) assuming SM production and decay.



- $H \rightarrow \phi\gamma$, $H \rightarrow \rho\gamma$

- Probe of the Higgs couplings to light quarks.
- Measurement with 2015+2016 Run 2 data (35.6 fb⁻¹).
- No significant excess of events is observed above background, in agreement with SM expectations. Upper limits at 95% CL:
 - $BR(H \rightarrow \phi\gamma) = 4.8 \times 10^{-4}$,
 - $BR(H \rightarrow \rho\gamma) = 8.8 \times 10^{-4}$.

[ATLAS-CONF-2017-057](#)

See detailed talk:

Search for neutral and charged BSM Higgs Bosons with the ATLAS detector

Pawel Bruckman de Renstrom

See detailed talk:

Search for rare and exotic Higgs Boson decay modes and Higgs boson pair production with the ATLAS detector

Suyog Shrestha

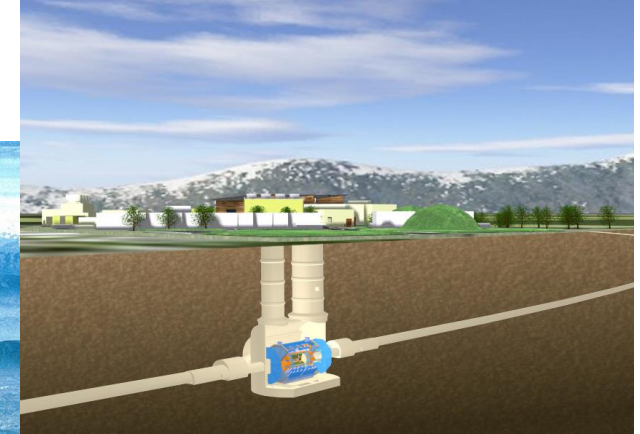
- The highlight of Run 1 was the discovery of a SM Higgs boson.
- Significant aim of Run 2 is to measure the properties of this boson and use it to probe for new physics.
 - Measurements for mass, spin/parity, width and couplings have been presented. Evidence of the Higgs decaying into fermions, such as tau leptons and b quarks, has been shown.
 - So far, no observation of deviations from the SM expectations.
- But: the exploration of this new particle is still in the early stages.
 - We have collected only **~1%** of the anticipated luminosity from the LHC.
- Lots of interesting ATLAS Higgs talks at this conference for further details!



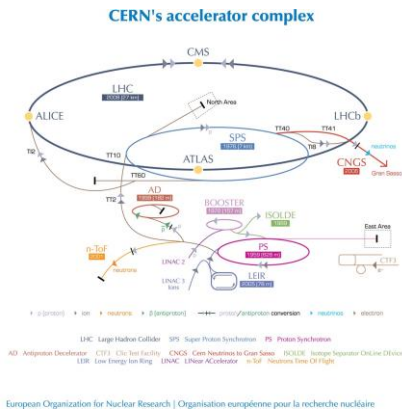
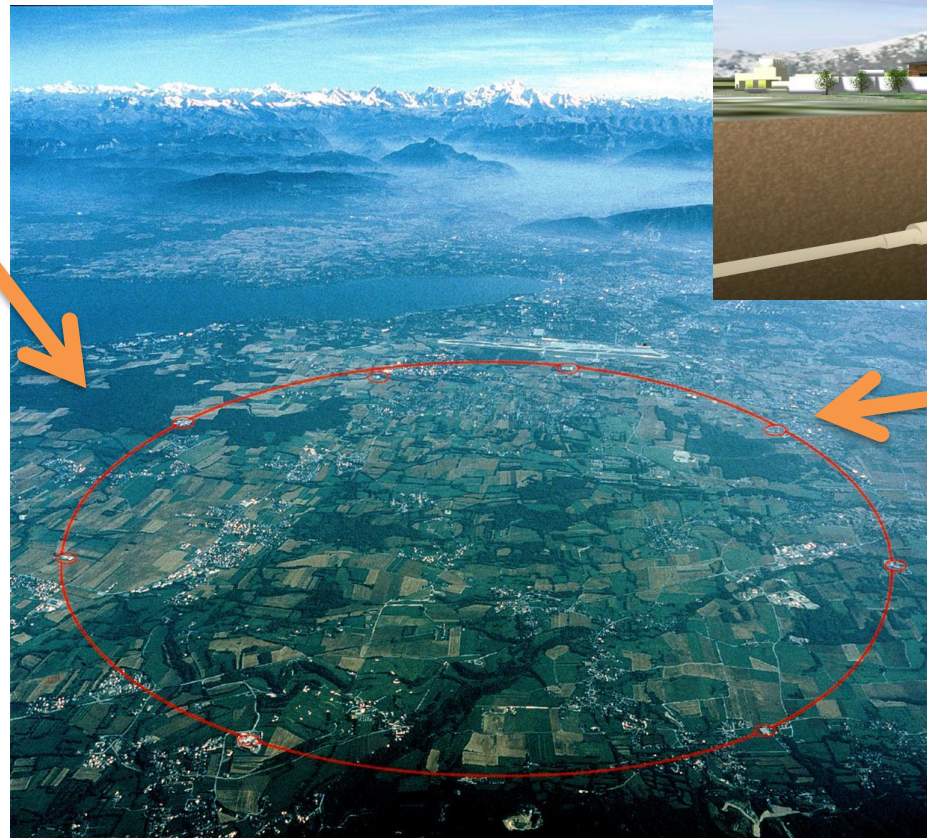
Thank you for your attention.

Backup

Large Hadron Collider at CERN (Geneva, Switzerland)



ATLAS
Detector



- $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4 \ell$ ($\ell=e,\mu$).
- Why these channels?
 - In these channels all of the decay particles can be measured by the ATLAS detector with high precision.
 - Also no missing energy in the final state.
- How are they precise?
 - The key lies in the resolution and calibration of the ATLAS detector. Many different parts are used:
 - the muon momentum is measured in the Inner Detector and the Muon Spectrometer
 - the electron and photon energy is reconstructed in the Liquid Argon electromagnetic calorimeter.
 - Understanding the alignment of the tracking detectors provides the precision of the muon momentum, and the calibration of the calorimeter response is key for electrons and photons.
 - The uncertainty of the muon momentum is known to 0.1–0.5%, depending on the position of the muon, while the uncertainty on the electron (photon) energy scale is 0.02–0.8% (0.4–0.8%) depending on their energy and position.
 - The quality of the alignment and calibration of the data can be seen below, where the abundant Z bosons decay into two muons and into two electrons.

- Leading sources of systematic uncertainty on m_H in the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel.

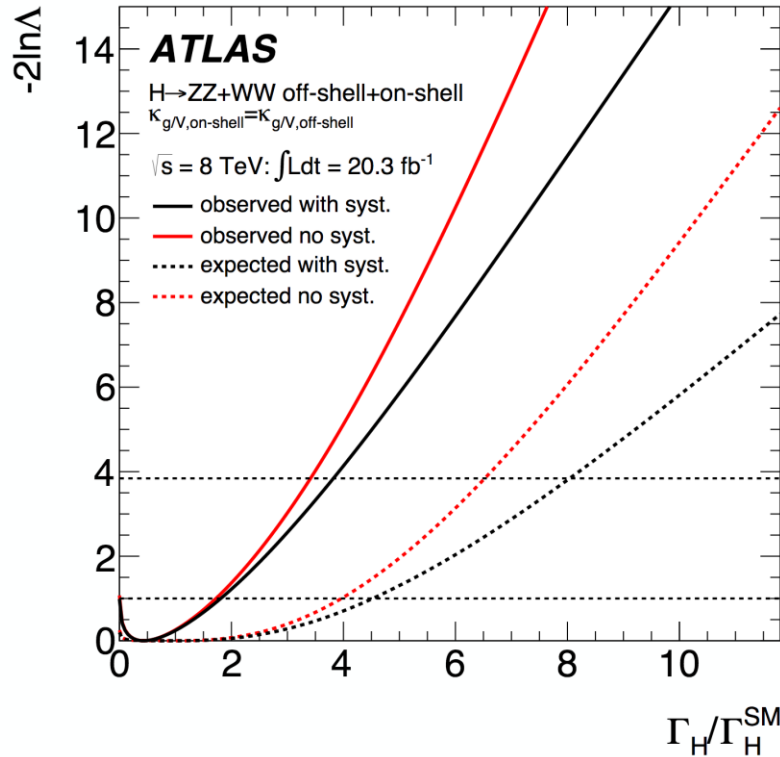
Systematic effect	Uncertainty on $m_H^{ZZ^*}$ [MeV]
Muon momentum scale	40
Electron energy scale	20
Background modelling	10
Simulation statistics	8

- Main sources of systematic uncertainty on $m_H^{\gamma\gamma}$.

Source	Systematic uncertainty on $m_H^{\gamma\gamma}$ [MeV]
LAr cell non-linearity	± 200
LAr layer calibration	± 190
Non-ID material	± 120
Lateral shower shape	± 110
ID material	± 110
Conversion reconstruction	± 50
$Z \rightarrow ee$ calibration	± 50
Background model	± 50
Primary vertex effect on mass scale	± 40
Resolution	$+20$ -30
Signal model	± 20

- Main sources of systematic uncertainty on the combined mass m_H .

Source	Systematic uncertainty on m_H [MeV]
LAr cell non-linearity	90
LAr layer calibration	90
Non-ID material	60
ID material	50
Lateral shower shape	50
$Z \rightarrow ee$ calibration	30
Muon momentum scale	20
Conversion reconstruction	20



Scan of the negative log-likelihood as a function of $\Gamma_H / \Gamma_H^{\text{SM}}$ when profiling the coupling scale factors κ_g and κ_V associated with the on- and off-shell $gg \rightarrow H$ (*) and VBF production and the H (*) $\rightarrow VV$ decay.