BEH Overview
(ATLAS)

Dr. Clara Nellist
Georg-August-Universität Göttingen
On behalf of the ATLAS Collaboration

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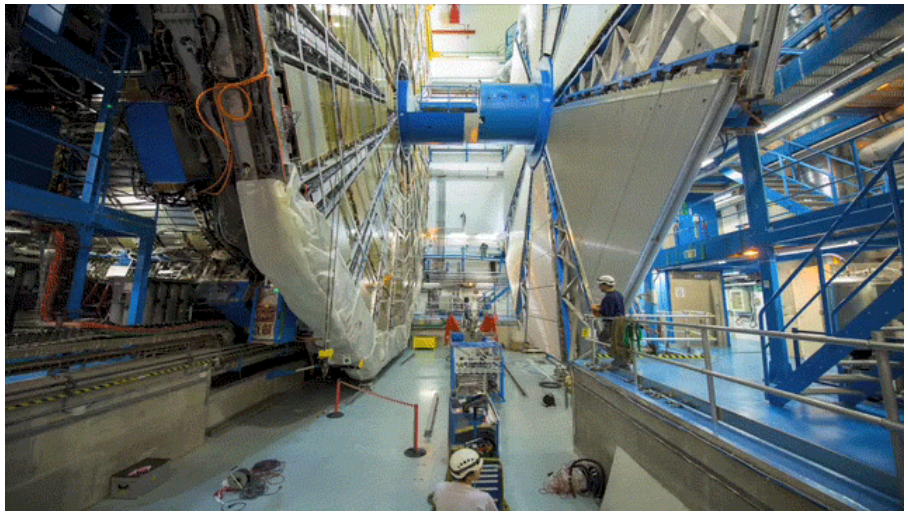
Overview

- 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.



The ATLAS Detector

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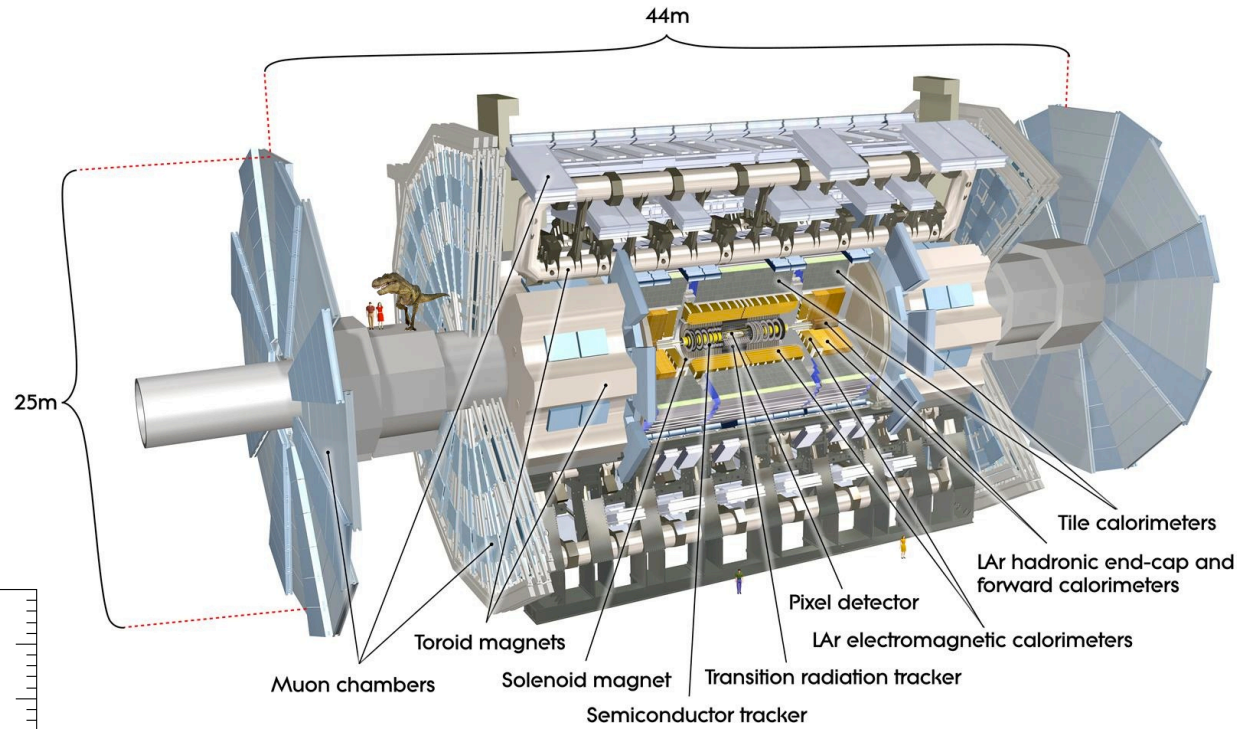
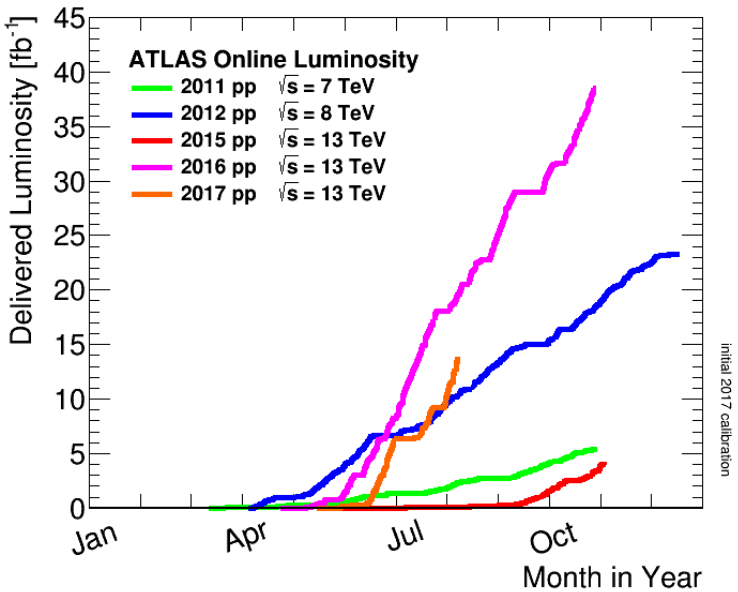
- Run 1:
  - 2011 at √s=7 TeV.
  - 2012 at √s=8 TeV.
  - Total ~29 fb^{-1}.

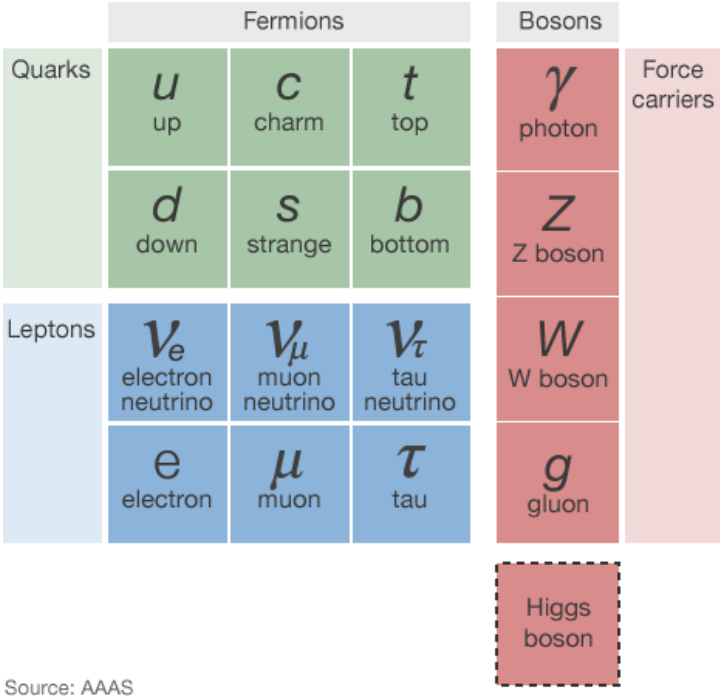




- Run 2:
  - 2015-2018 at √s=13 TeV.
  - ~ 36.1 fb^{-1} for 2015+2016.
  - ~ 14 fb^{-1} for 2017 so far…

Higgs Boson

- 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.



Higgs Boson Production

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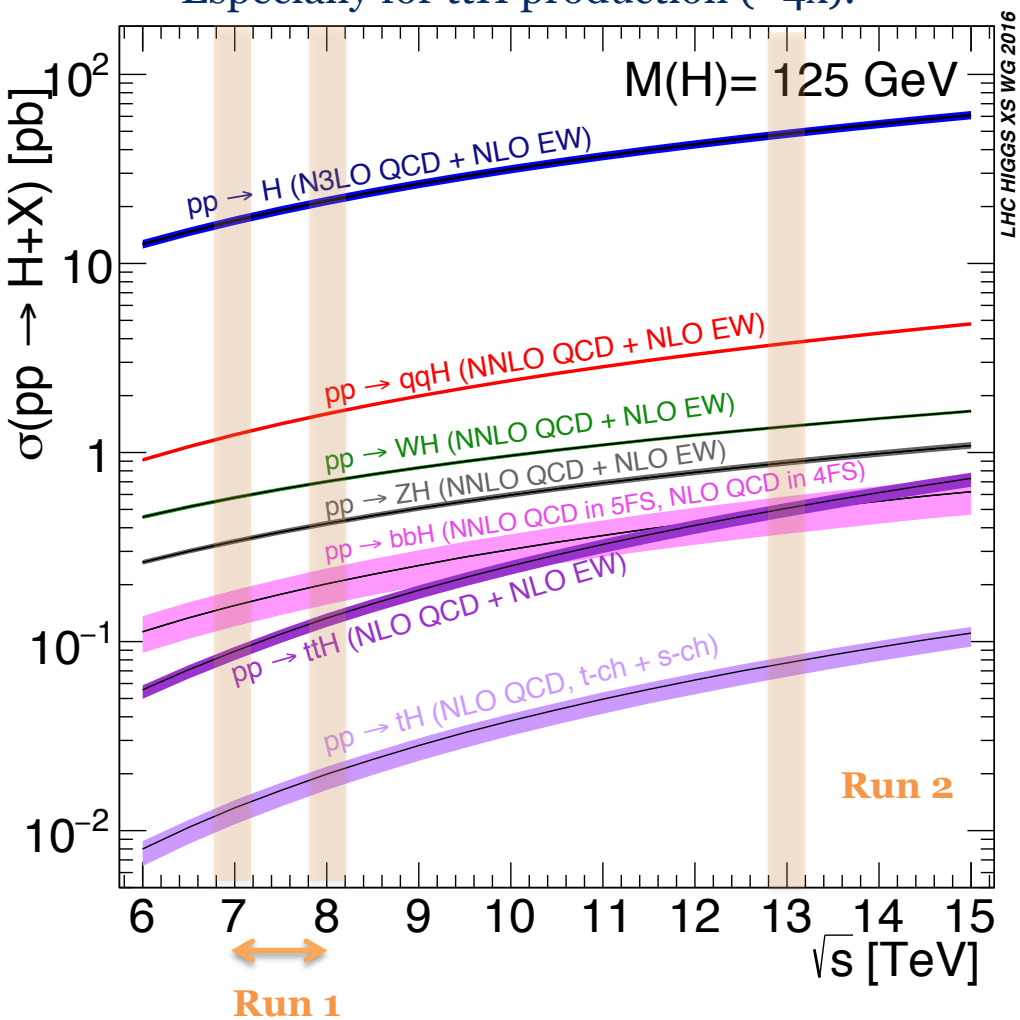
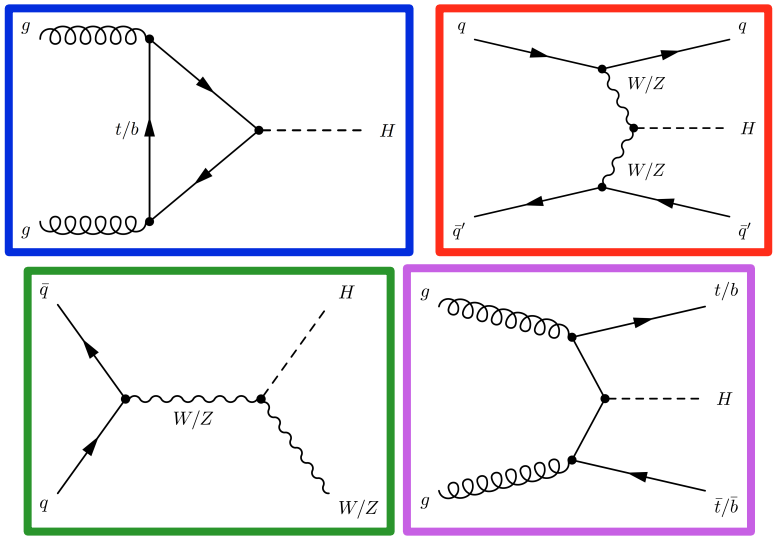
- Run 1 -> Run 2.
  - Increase of Higgs cross-sections.
  - Especially for ttH production (~4x).

Probing all channels!

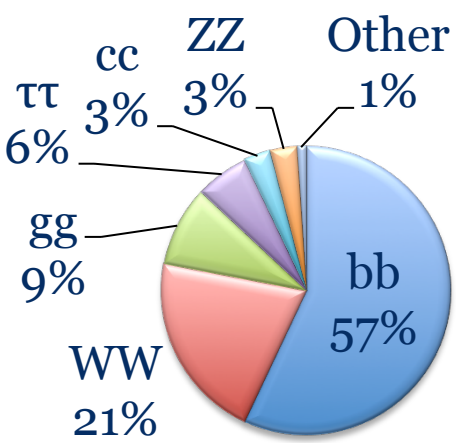


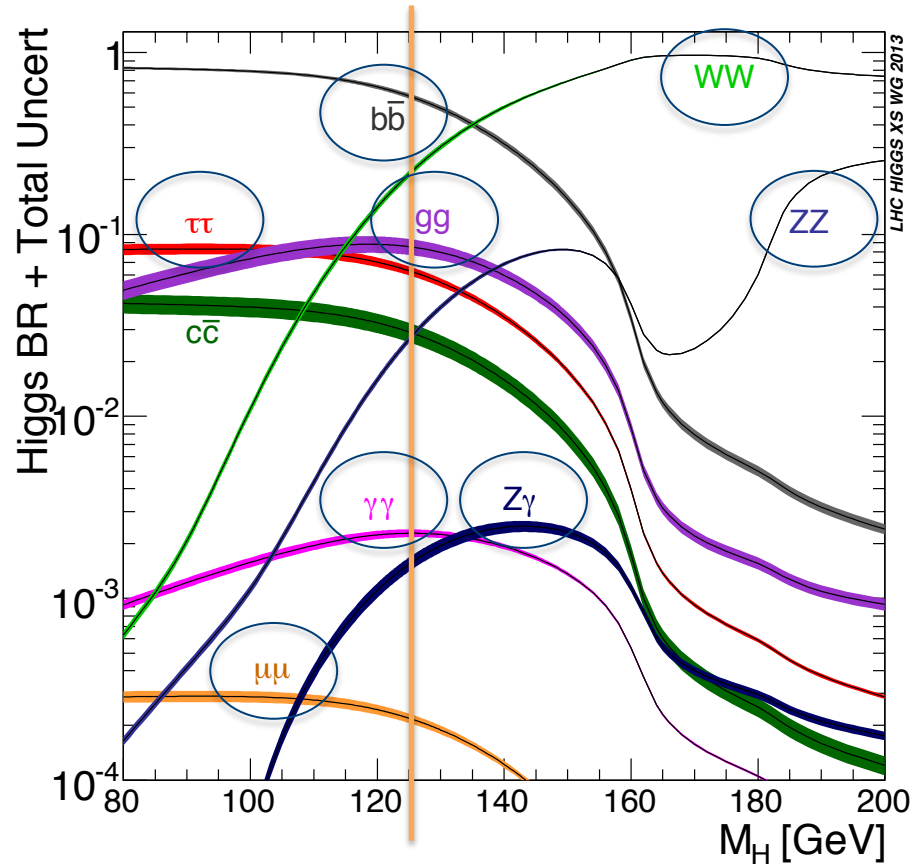


- **Gluon Gluon Fusion**
  - The dominant production mode.
- **VBF : Vector Boson Fusion**
  - Second most dominant.
  - Characterized by two forward jets produced along with a Higgs.
- **VH**
  - Composed of a Higgs produced in association with a vector boson.
- **ttH**
  - Higgs produced in association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

Decay methods

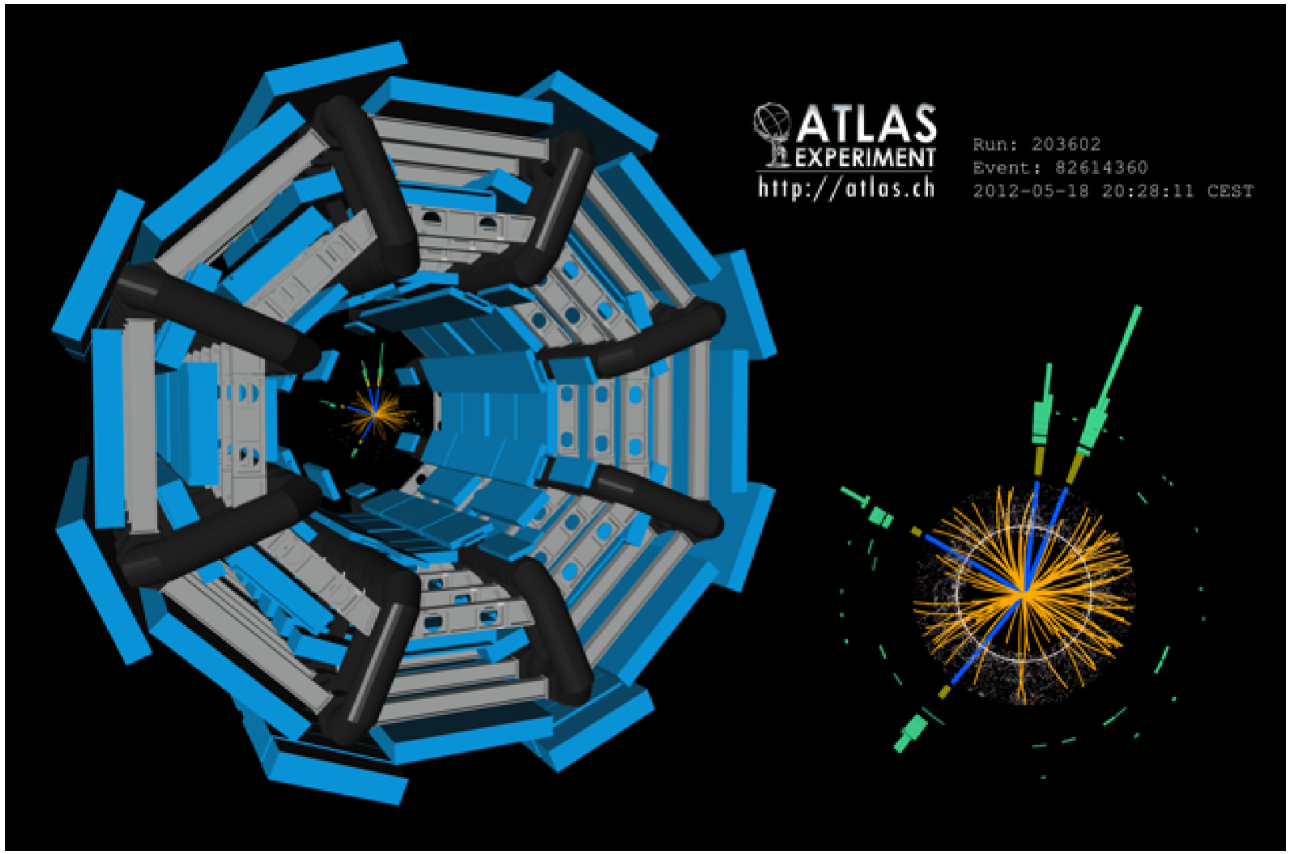
- For a standard model Higgs boson with a mass of ~125 GeV:
  - Decays with the highest branching ratios also have large irreducible backgrounds.
  - However, resolution and S/B are equally critical for the sensitivity.
  - Clean signals for low branching ratio signals:
    - $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ (ℓ=e,μ).
    - The 'discovery' channels.





Bosonic decay

- The discovery of the Higgs in 2012 was announced with bosonic decay channels.
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow ZZ^* \rightarrow 4\,\ell$ (ℓ=e,μ)
  - $H \rightarrow WW^*$



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

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

H → γγ

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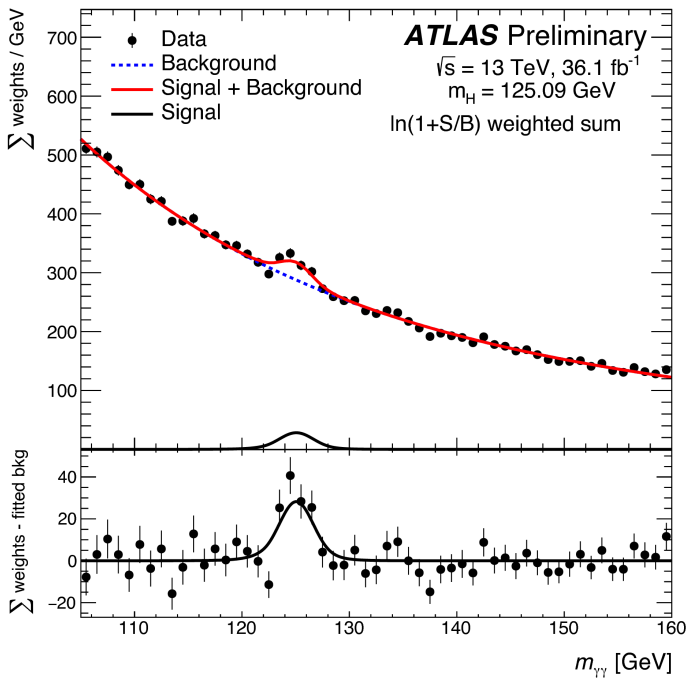
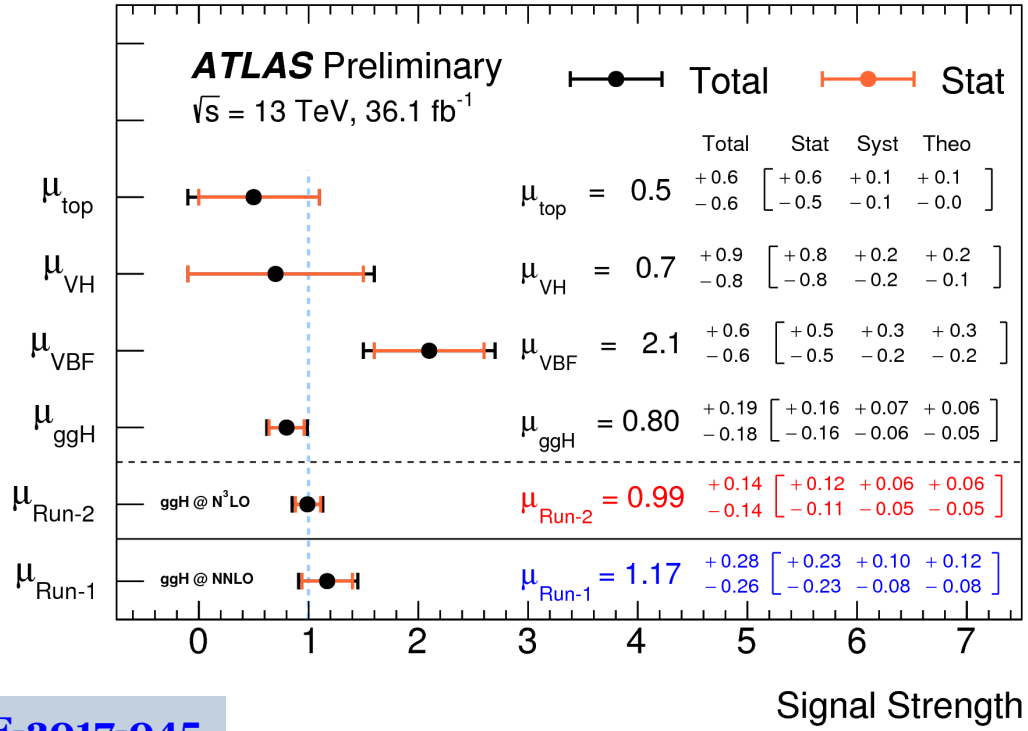
Run 2

Signal strength:

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

- 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 γγ, γ+jets and dijets.





ATLAS-CONF-2017-043 ATLAS-CONF-2017-045

H → ZZ* → 4 ℓ and H → WW*

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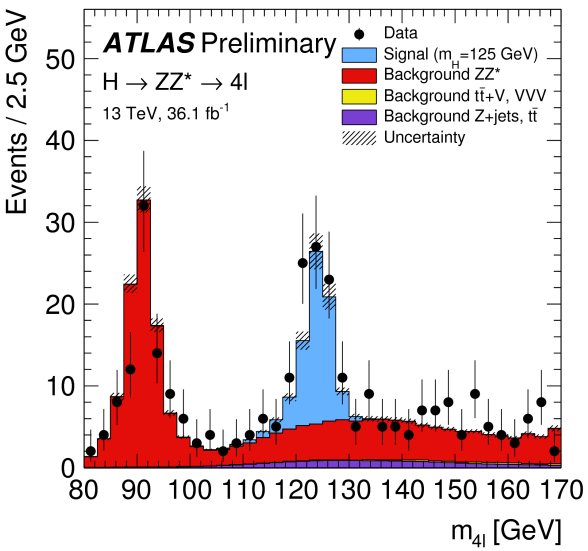
Run 2

H → ZZ* → 4 ℓ:

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

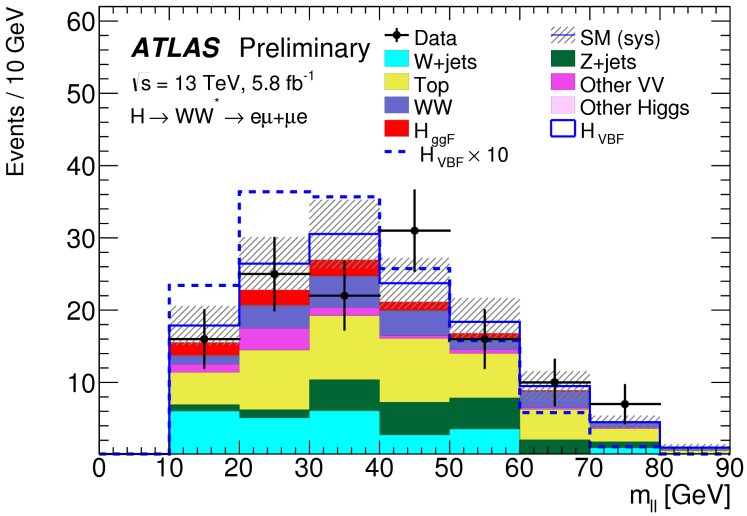


- The inclusive fiducial cross-section in the *H→ZZ*→4ℓ* decay channel is:
  - 3.62 +0.53−0.50 (stat) +0.25−0.20 (sys) fb
- Standard Model prediction of:
  - 2.91 ± 0.13 fb.
- Differential fiducial cross-section has also been measured.

ATLAS-CONF-2017-032

H → WW*:

- Second largest branching ratio.



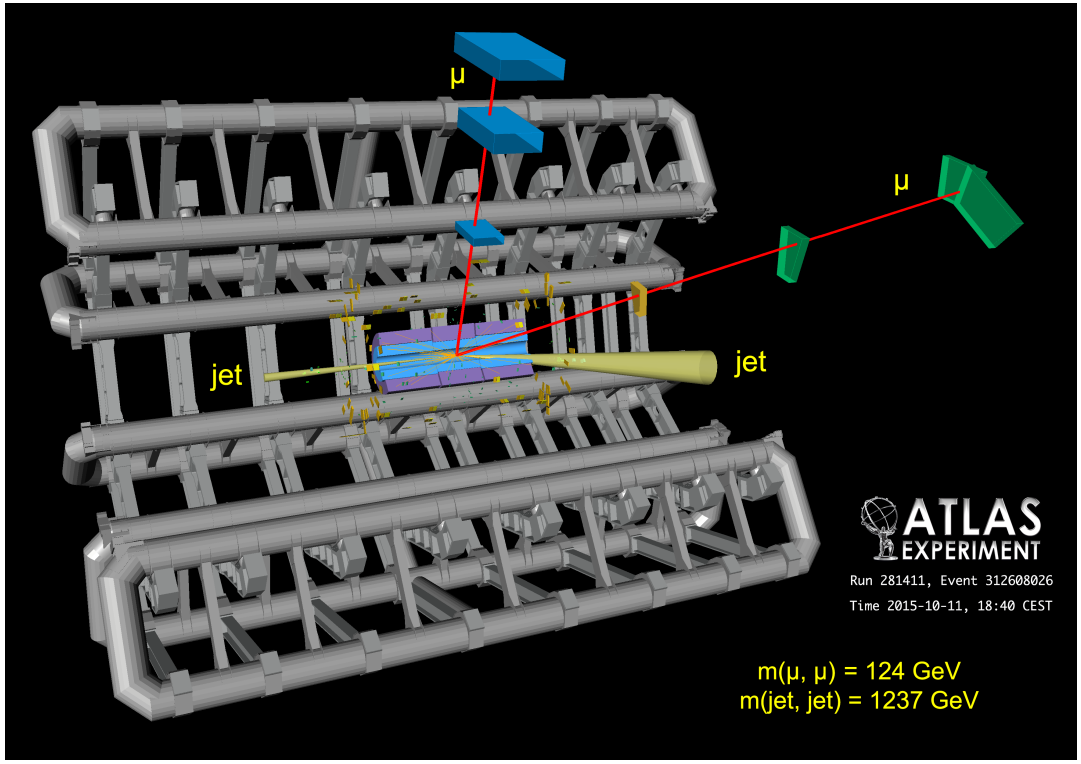
- Latest result with 5.8 fb^{-1} of Run 2 data.
  - Via VBF and associated *WH* production.
  - μ_{VBF} = 1.7 + 1.1 − 0.9
  - μ_{WH} = 3.2 + 4.4 − 4.2

ATLAS-CONF-2016-112

Fermionic Production & Decay

- 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



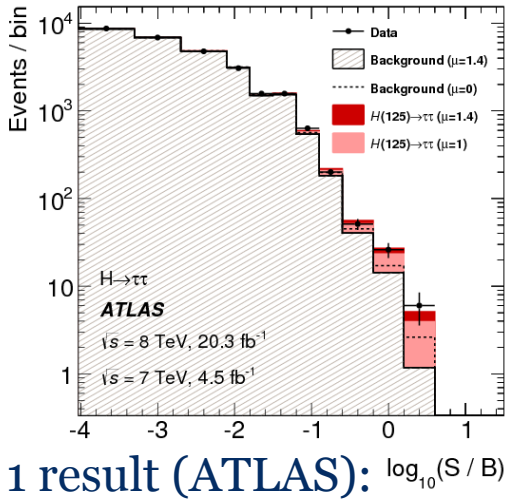
Candidate $H \rightarrow \mu\mu$ event at $\sqrt{s} = 13$ TeV .

H → ττ and H → μμ

H → ττ

- Two production modes: ggF and VBF
- Three decay modes: $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$
  - Requires good tau identification.
- Z → ττ is the main background.

ATLAS-CONF-2017-29



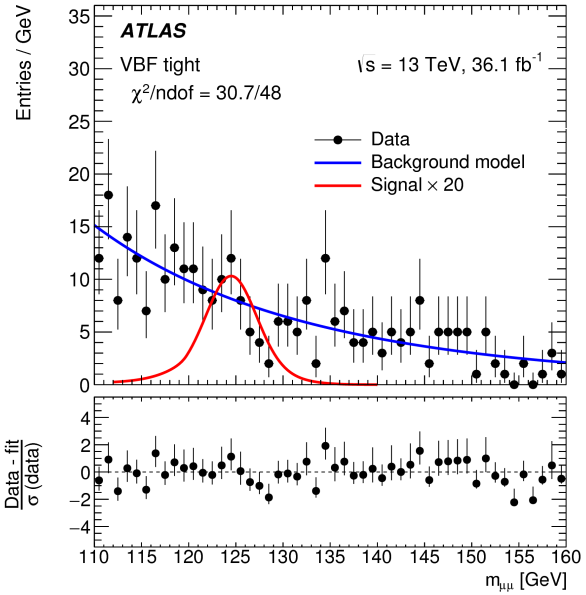
- Run 1 result (ATLAS):
  - **4.5σ** (3.4σ) **observed** (expected).
- Combined ATLAS & CMS:
  - **5.5σ** (5.0σ) **observed** (expected).

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.

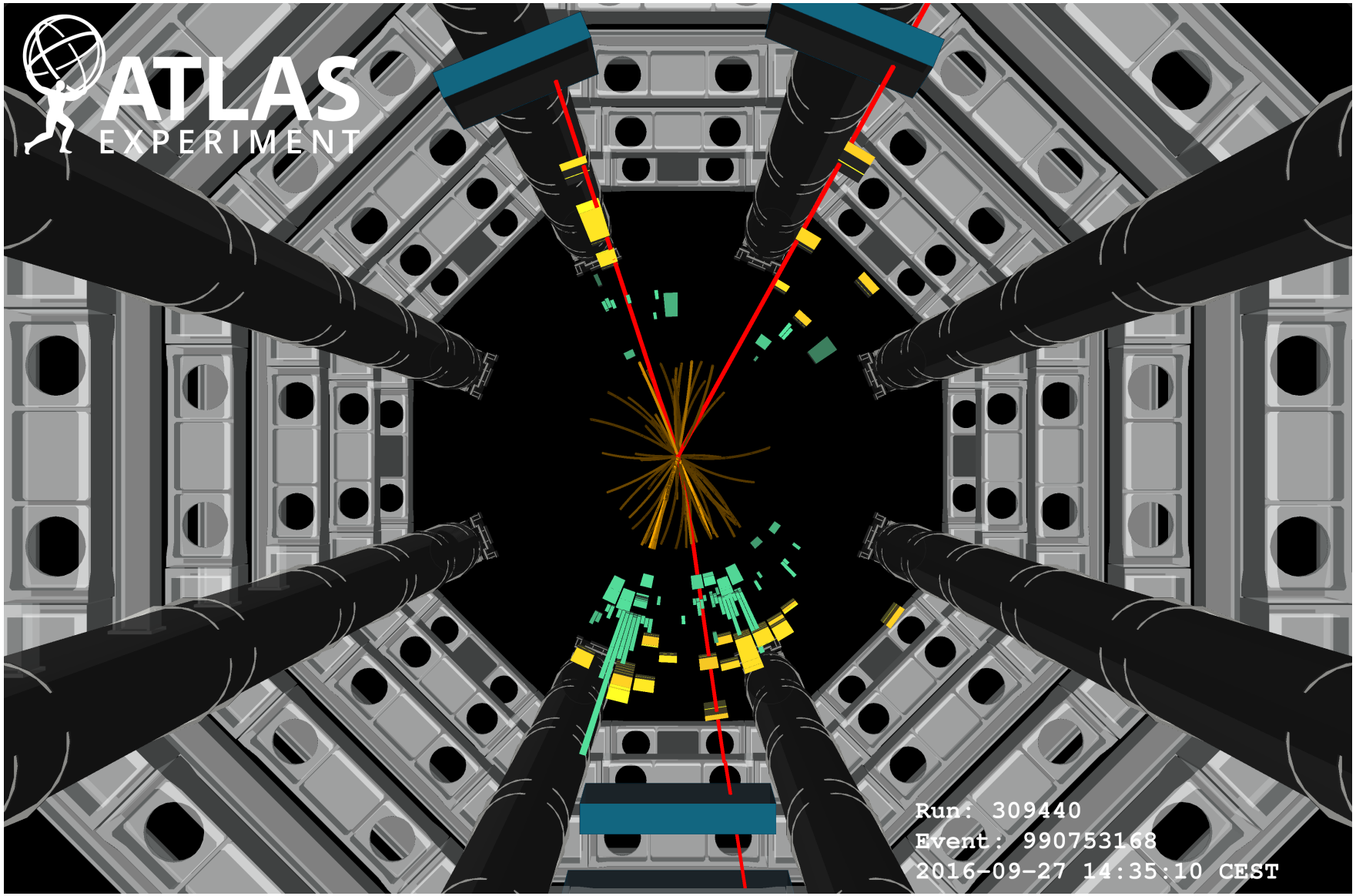


Result (Run 1 + 2):

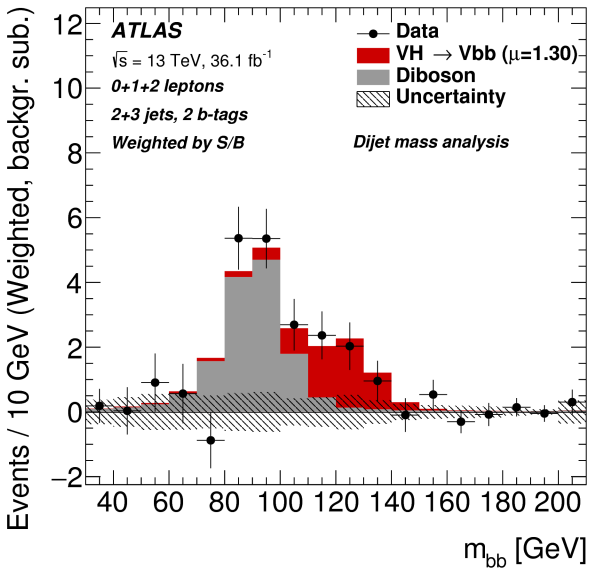
- μ < **2.8** (2.9) **observed** (expected).
- Consistent with SM expectation that Higgs coupling is proportional to mass.

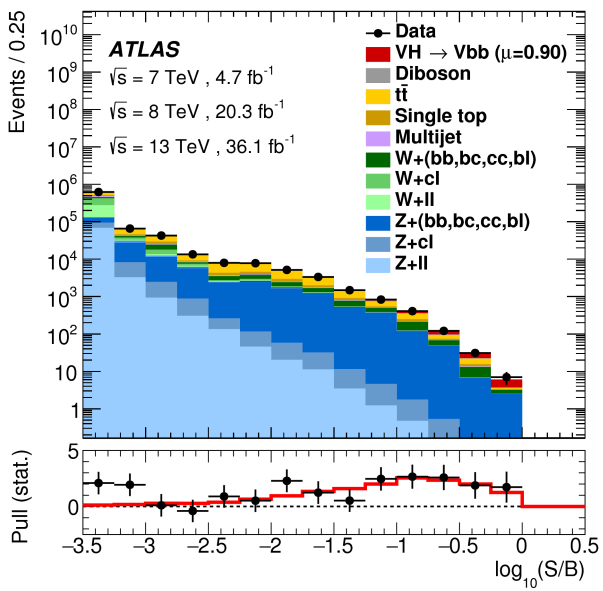
Phys. Rev. Lett. 119 (2017) 051802

H → bb candidate event



H → bb





- 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:
  3.5σ (3.0σ) **observed** (expected).
- Combined significance for Run 1 + Run 2:
  3.6σ (4.0σ) **observed** (expected).
- Signal strength (combined Run 1 + Run 2):
  μ = 0.90 ± 0.18(stat.)+0.21 - 0.19(syst.)
- Measurement of VZ, where Z → bb was used as a cross-check, gave a significance of:
  5.8σ (5.3σ) **observed** (expected).

arXiv:1708.03299 [hep-ex]

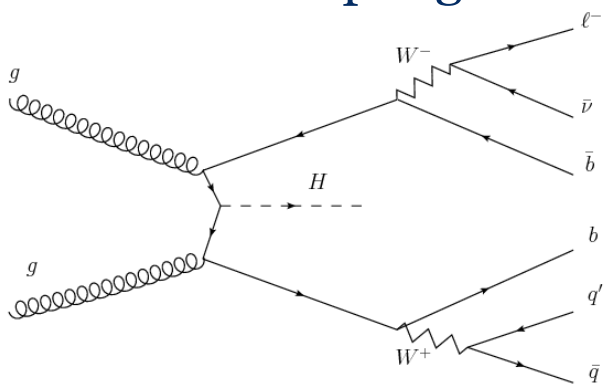
Run 2

ttH

- 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 Hadef

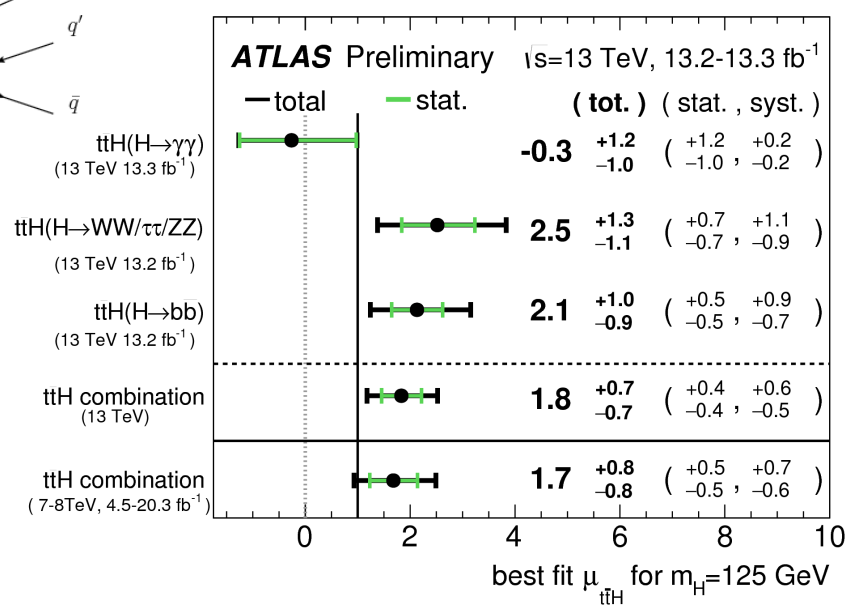
Run 2



- **ttH Channels:**
  - $H \rightarrow \gamma\gamma$
    - both the hadronic and leptonic $t\bar{t}$ decay channels.
  - $H \rightarrow (WW(*), \tau\tau, ZZ(*)) \rightarrow$ leptons
    - two – four final lepton states.
  - $H \rightarrow b\bar{b}$
    - single lepton,
    - opposite-sign dilepton.

Note: leptons are electrons & muons.

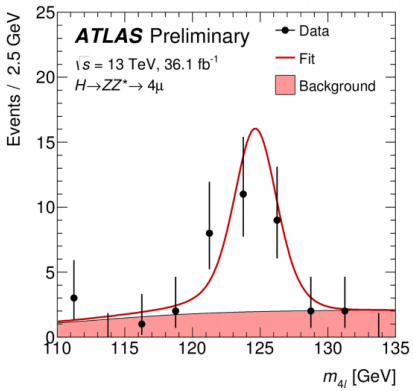
2015+2016

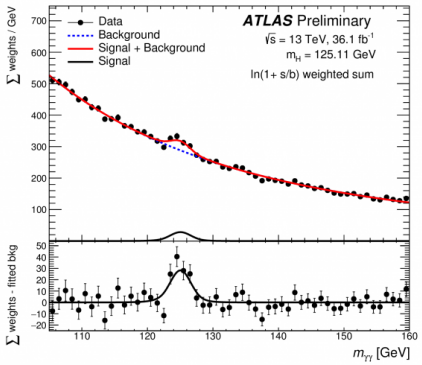


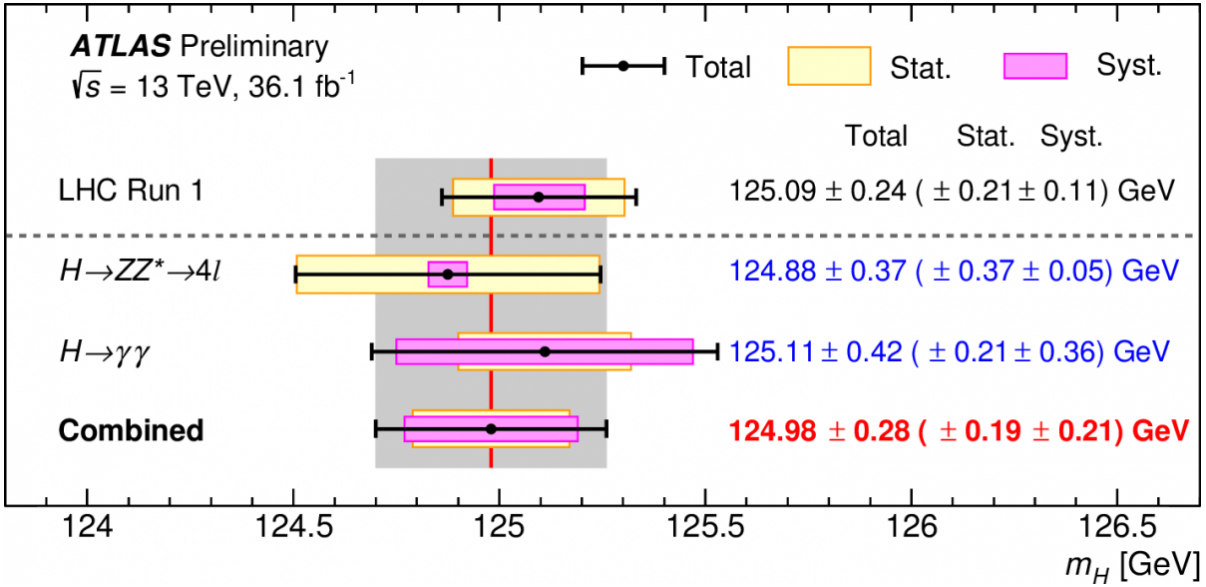
ATLAS-CONF-2016-068

Mass Measurements

- The mass of the Higgs is measured using the two 'discovery' channels:
  - $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\,\ell$ (ℓ=e,μ).
- H->ZZ->4l is still statistically limited, while H->γγ 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

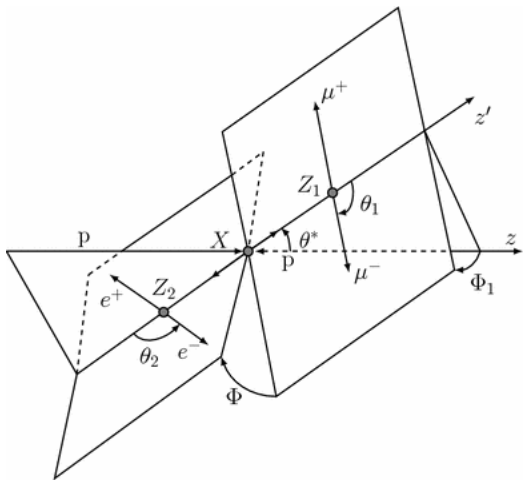
Run 2

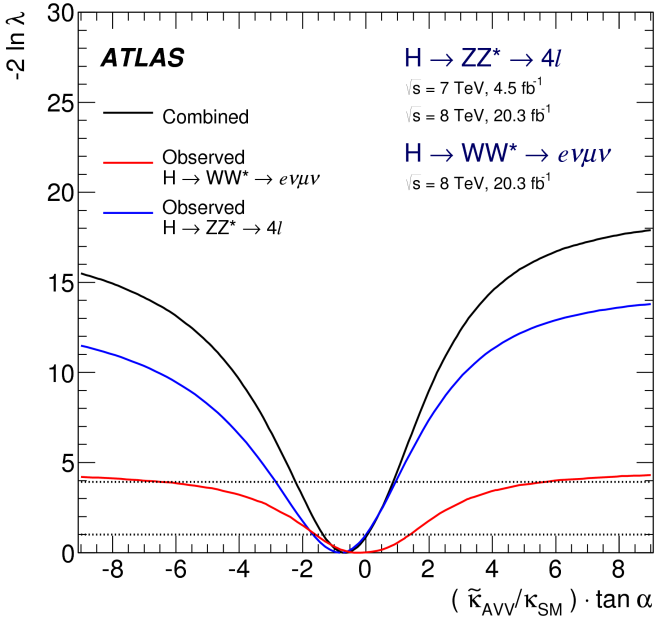
Spin / Parity

- Measurement using:
  - H→ZZ*→4ℓ, H→WW*→eνμν and H→γγ decay processes.
  - Using 25 fb^{-1} at Run 1 (√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->ZZ (which dominates) and H→WW sets an upper limit of:
    f_{g4} < 45 % at 95% CL on the CP-odd component.





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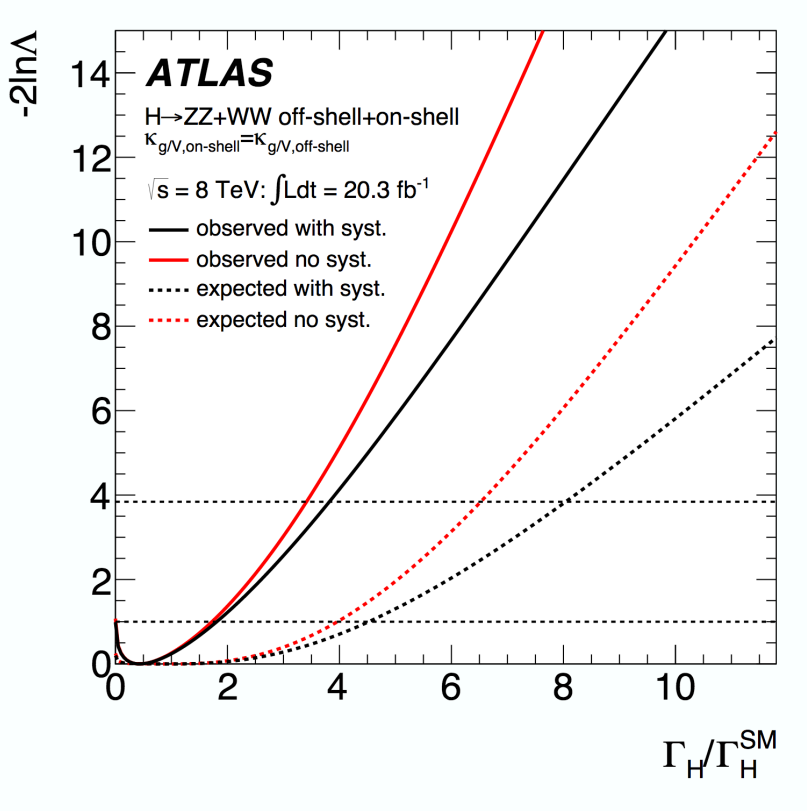
Width

Eur. Phys. J. C75 (2015) 335

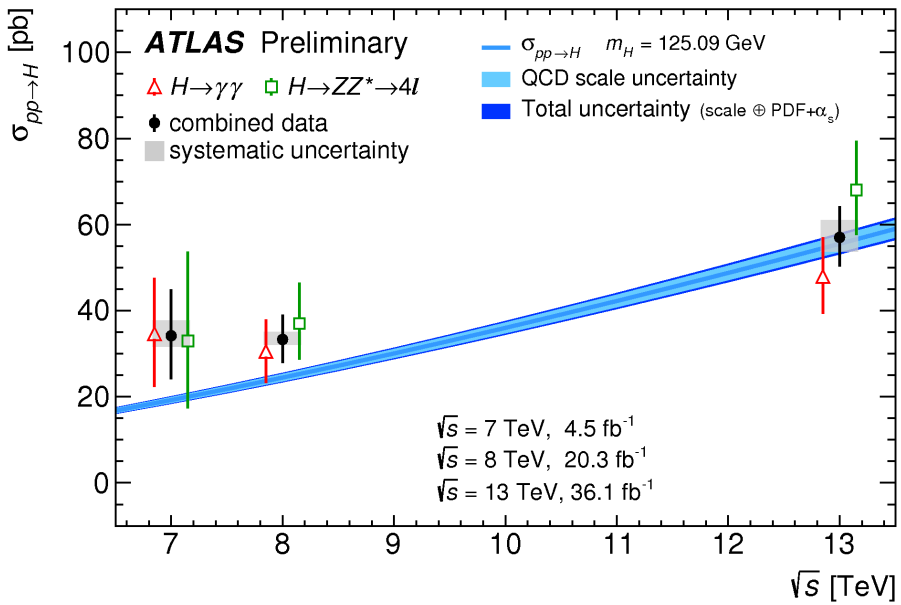


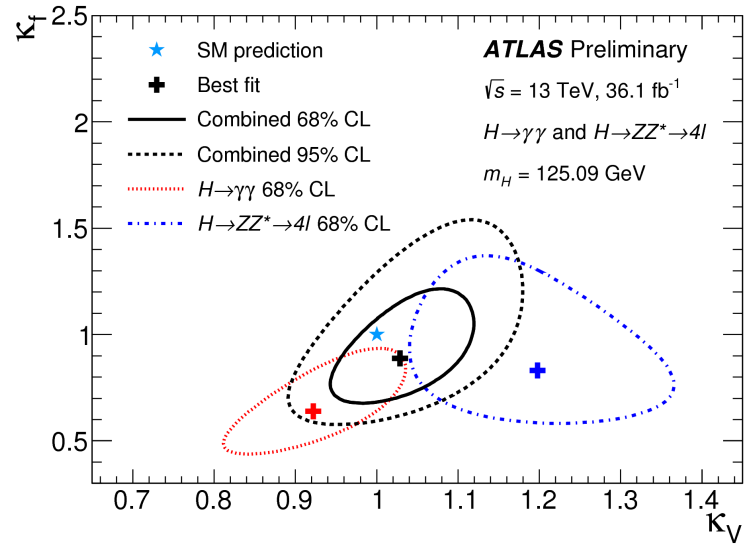
- Measurements of ZZ and WW final states in the mass range above the $2m_Z$ and $2m_W$ thresholds allow measurement of the off-shell coupling strength of the Higgs.
- Using 20.3 fb^{-1} at $\sqrt{s}$=8 TeV (Run 1).
- $ZZ \rightarrow 4\ell$, $ZZ \rightarrow 2\ell 2\nu$ and $WW \rightarrow e\nu\mu\nu$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

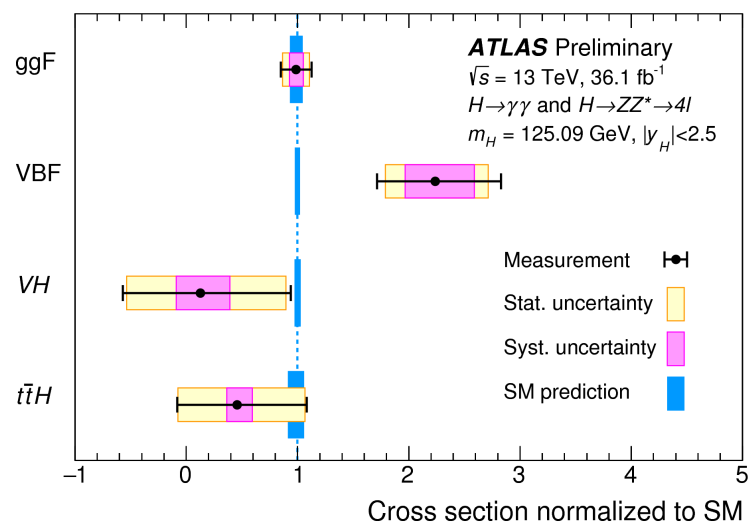
  4.5–7.5 (6.5–11.2).

Couplings

- Coupling strength modifiers, κ, are used to probe the coupling strengths and test for deviations from the SM expectations.
- H→γγ and H → ZZ* → 4 ℓ (ℓ=e,μ).
- Run 2 with 36.1 fb^{-1}.



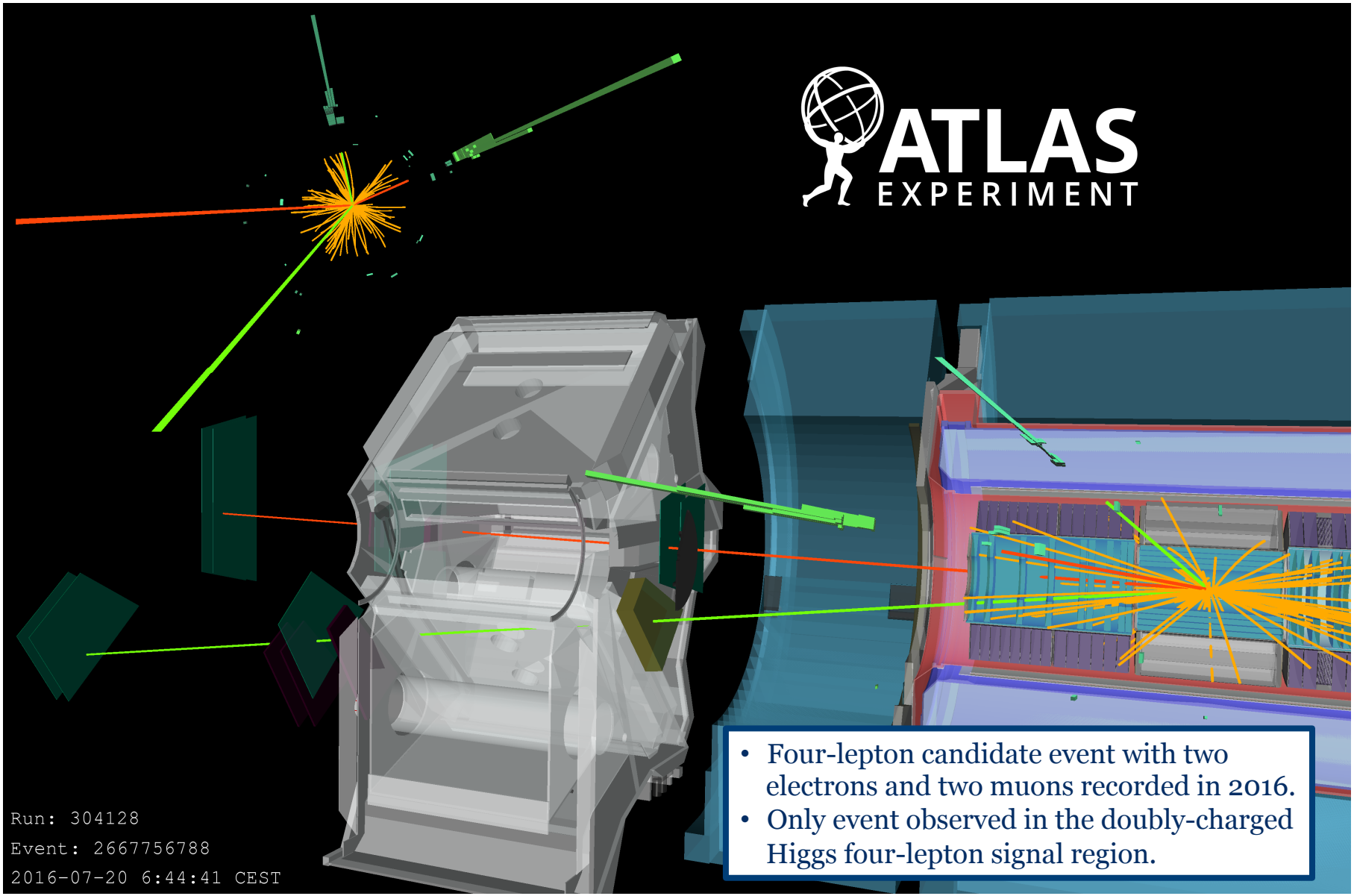




- No significant deviations from the SM expectations are observed.

ATLAS-CONF-2017-047

Higgs beyond the SM

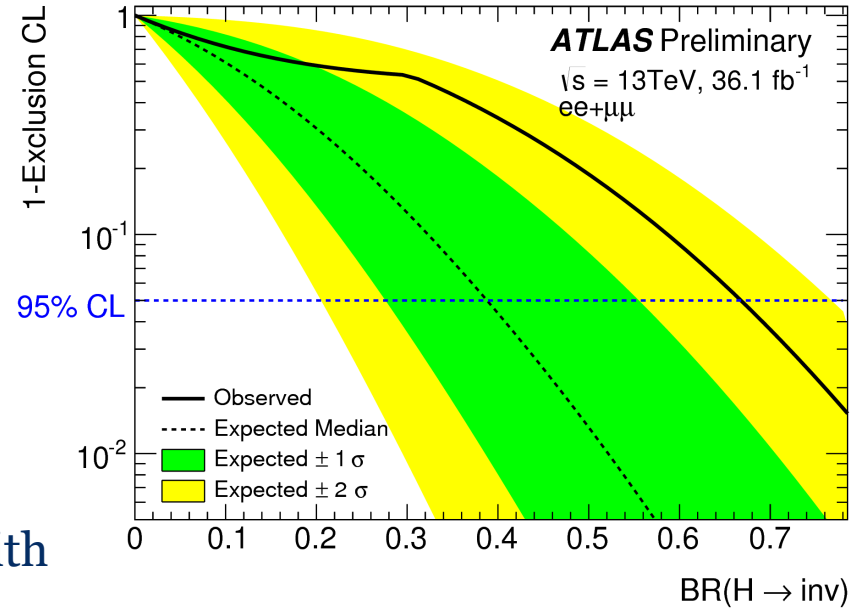


- Four-lepton candidate event with two electrons and two muons recorded in 2016.
- Only event observed in the doubly-charged Higgs four-lepton signal region.

Higgs beyond the SM

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

- H → invisible **ATLAS-CONF-2017-040**
  - pp→ZH→ll + missing energy with 2015+2016 Run 2 data (36.1 fb^{-1}).
  - BR(H(125) -> 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 $H \rightarrow l_{(e,\mu)}\tau_{had}$ and $H \rightarrow e\tau_{lep}$.
  - No significant excess observed. Set upper limits at 95% confidence level:
    - $Br(H\rightarrow e\tau)<1.04\%$
    - $Br(H\rightarrow \mu\tau)<1.43\%$,
    - $Br(Z\rightarrow \mu\tau)<1.69\times10-5$.

Eur. Phys. J. C 77 (2017) 70

Higgs beyond the SM (2)

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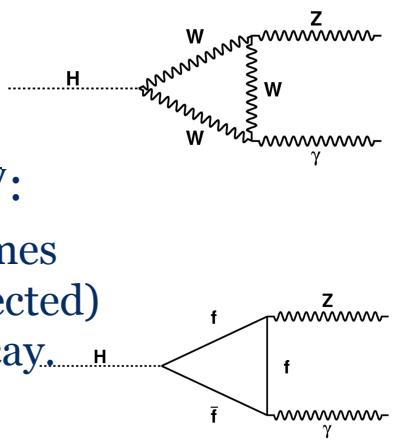
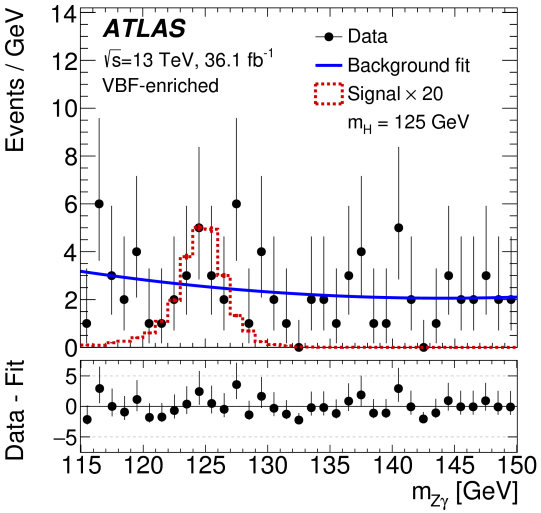
- $H \rightarrow Z\gamma$ **arXiv:1708.00212 [hep-ex]**
  - Produced via loop diagrams:
  - Preliminary results at 95% CL upper limit with m_H = 125.09 GeV:
    - Cross-section * BR = **6.6** (5.2) times the SM prediction observed (expected) assuming SM production and decay.





- $H \rightarrow \varphi\gamma$, $H \rightarrow \rho\gamma$
  - 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:
    - $BR(H \rightarrow \varphi\gamma) = 4.8\times10^{-4}$,
    - $BR(H \rightarrow \rho\gamma) = 8.8\times10^{-4}$.

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

Summary and Conclusion

- 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

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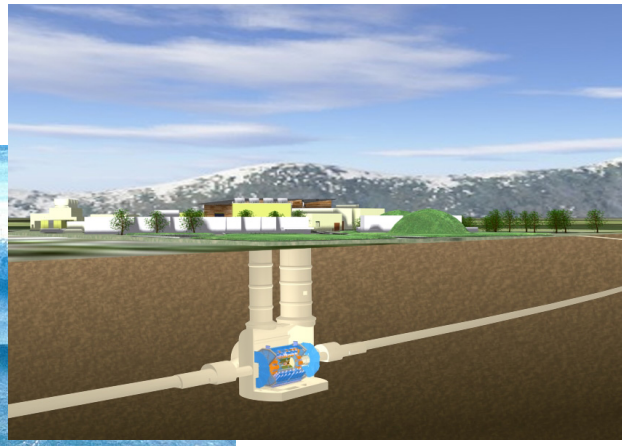
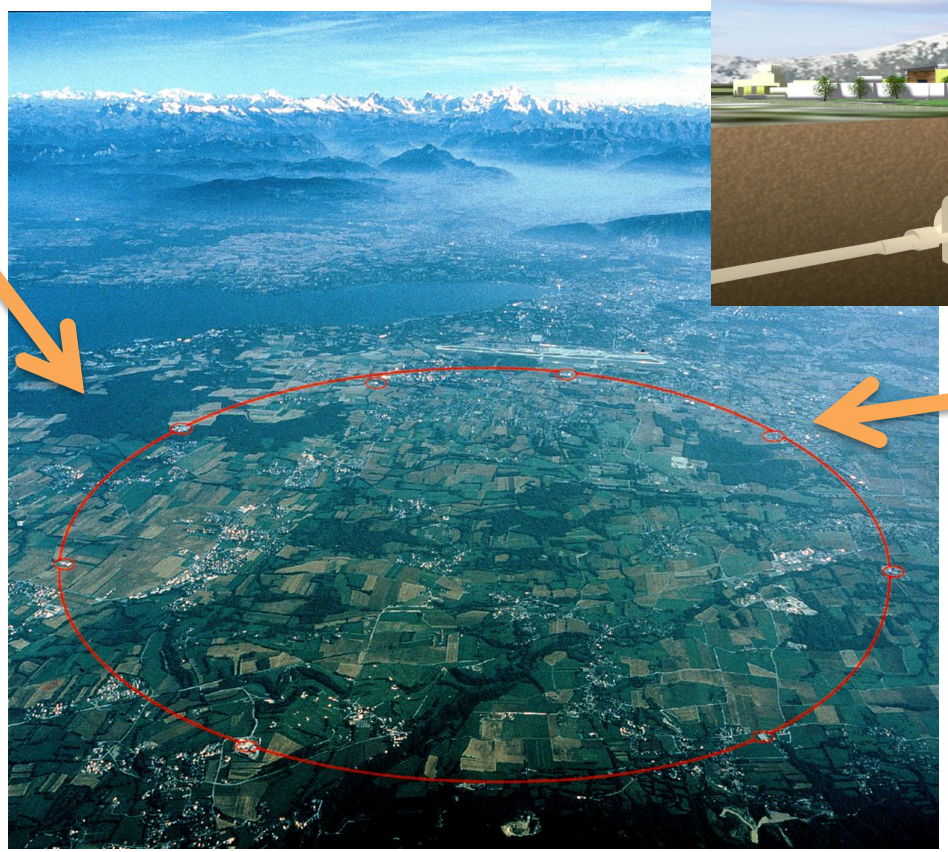
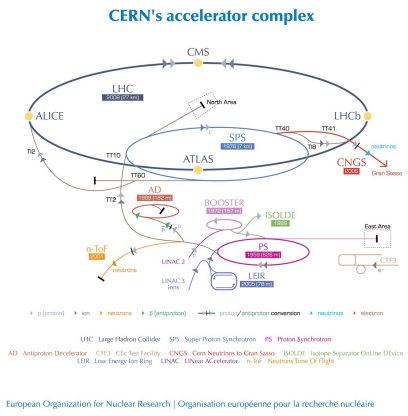
Large Hadron Collider at CERN (Geneva, Switzerland)





ATLAS Detector



Mass Measurements

- $H \rightarrow \gamma\gamma$ 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.

Mass - systematics

- 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

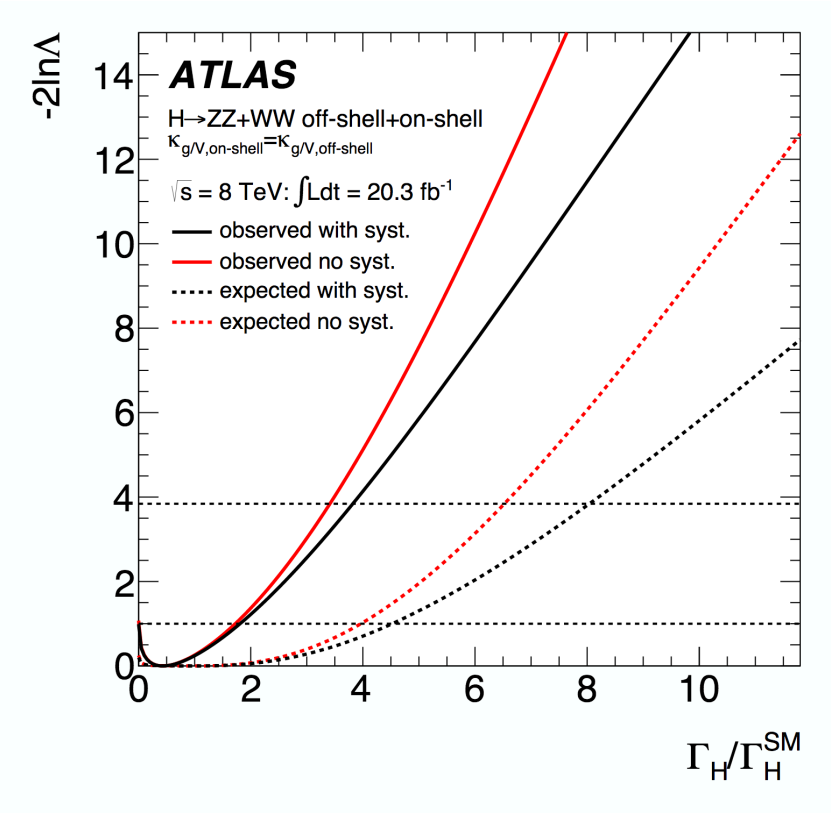
- Main sources of systematic uncertainty on $m_H^{\gamma\gamma}$.

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

Width



Scan of the negative log-likelihood as a function of Γ_H/Γ^{SM}_H 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.

TITLE

- CONTENT