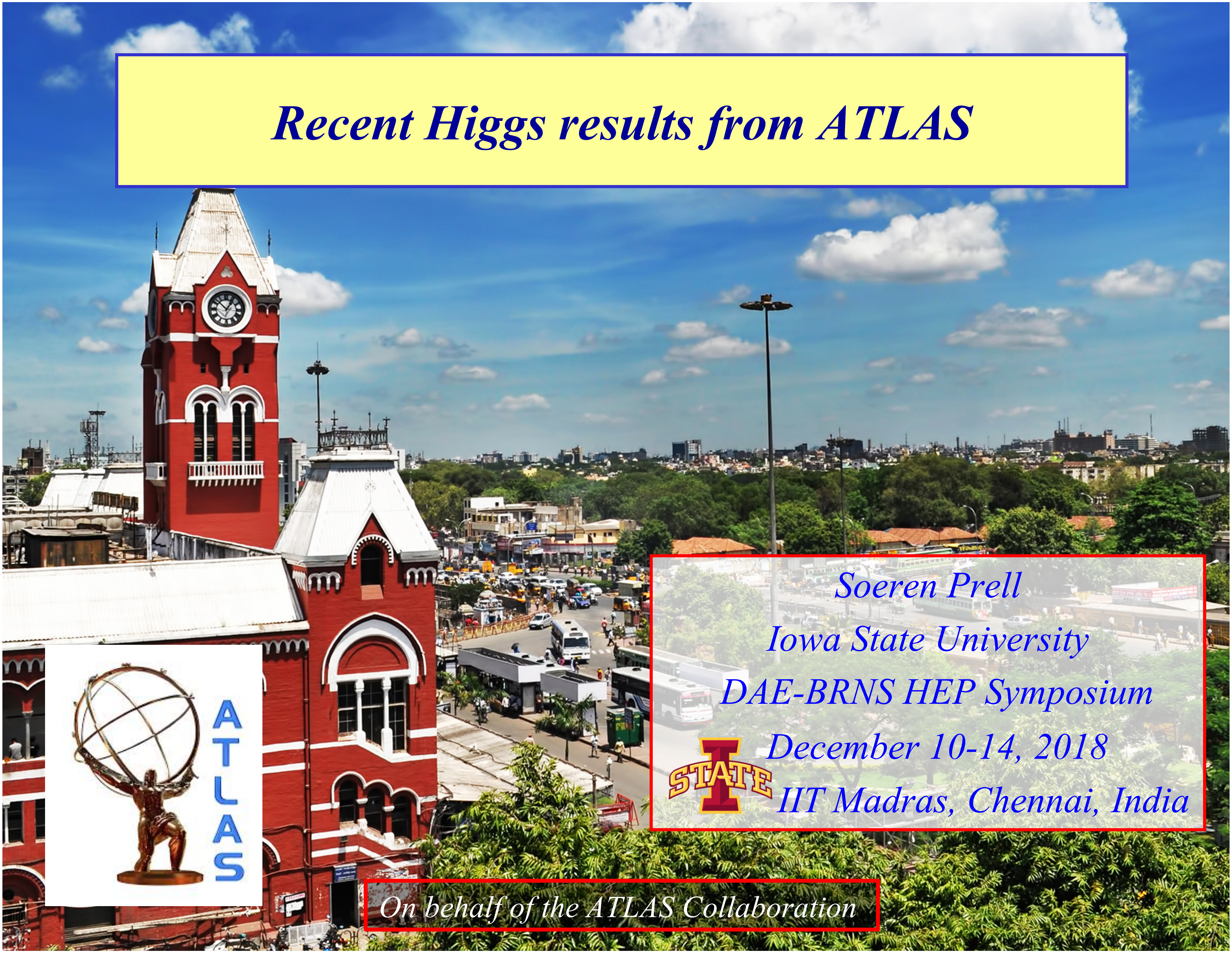


# *Recent Higgs results from ATLAS*


*Soeren Prell*

*Iowa State University*


*DAE-BRNS HEP Symposium*

*December 10-14, 2018*

*IIT Madras, Chennai, India*

*On behalf of the ATLAS Collaboration*

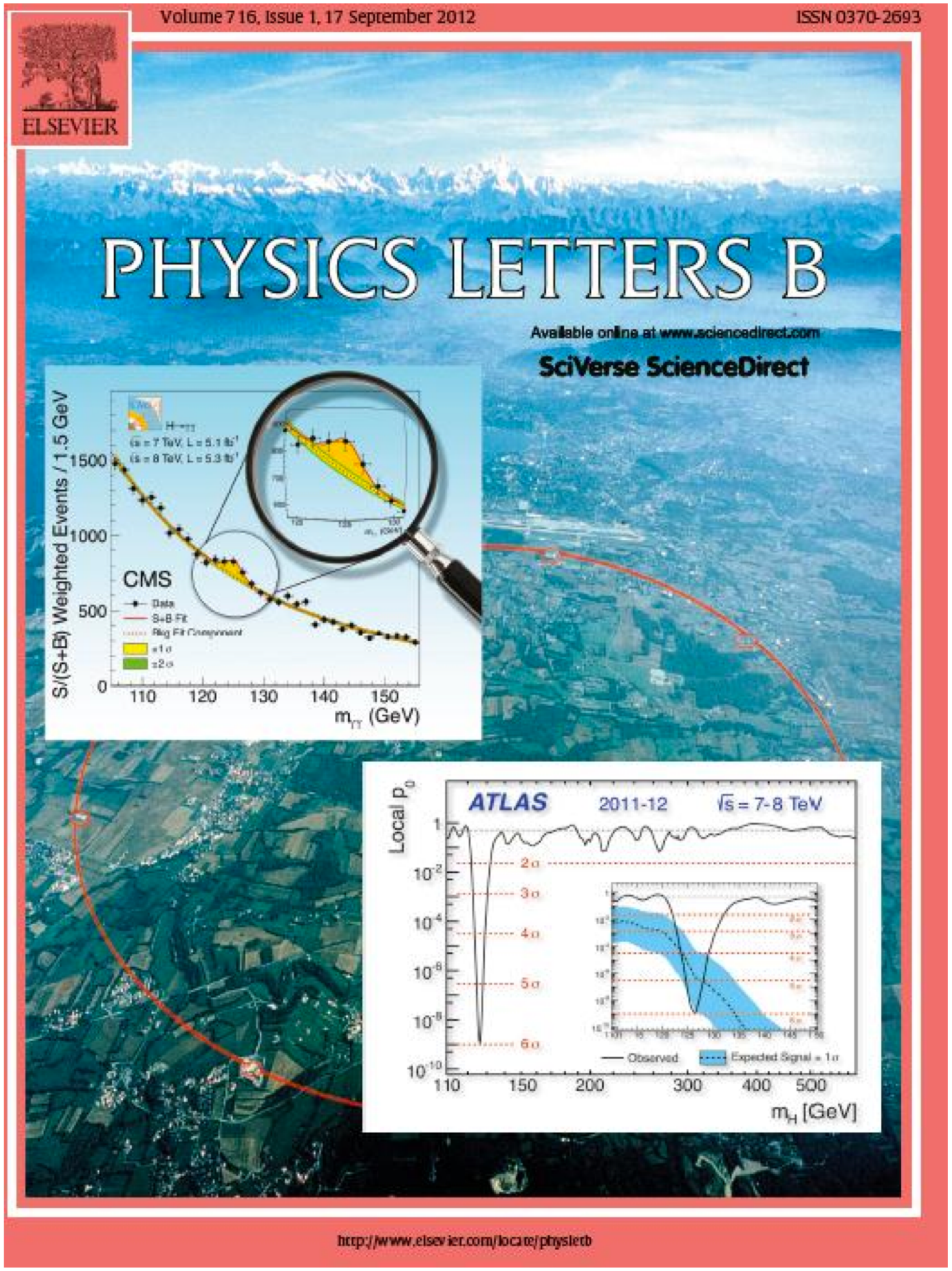
*Big question in HEP until 2012:*

*Does the Standard Model Higgs boson or a Higgs-like particle exist?*

# *LHC Run 1:*

## *The Higgs Discovery Phase*

# *Higgs Discovery (July 4, 2012)*

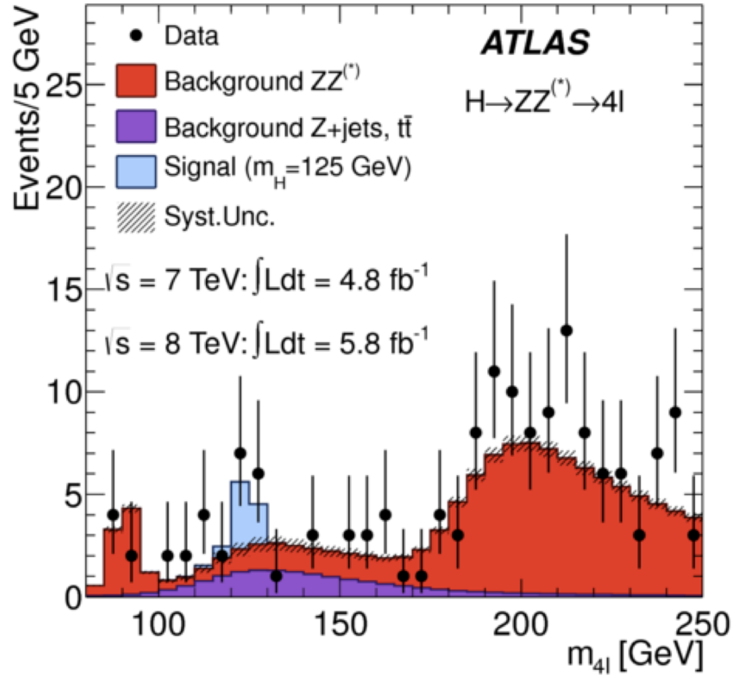




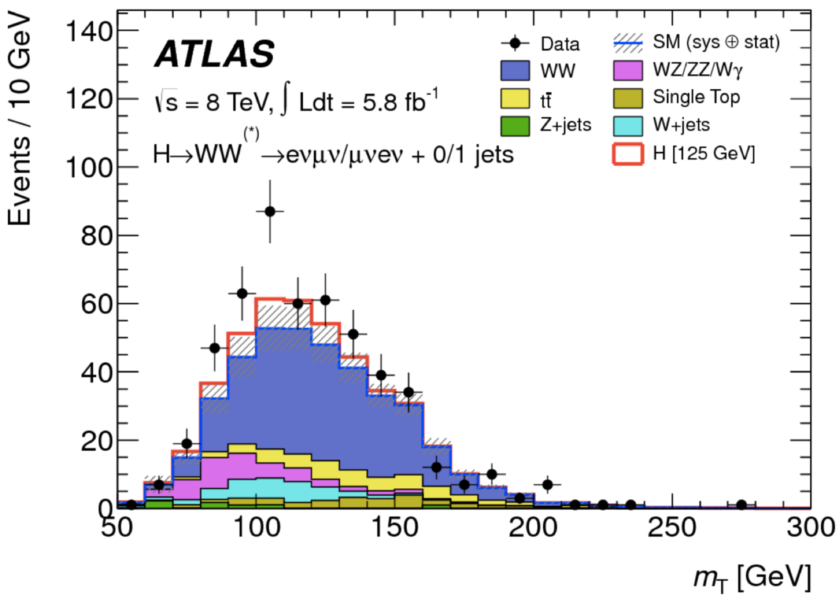


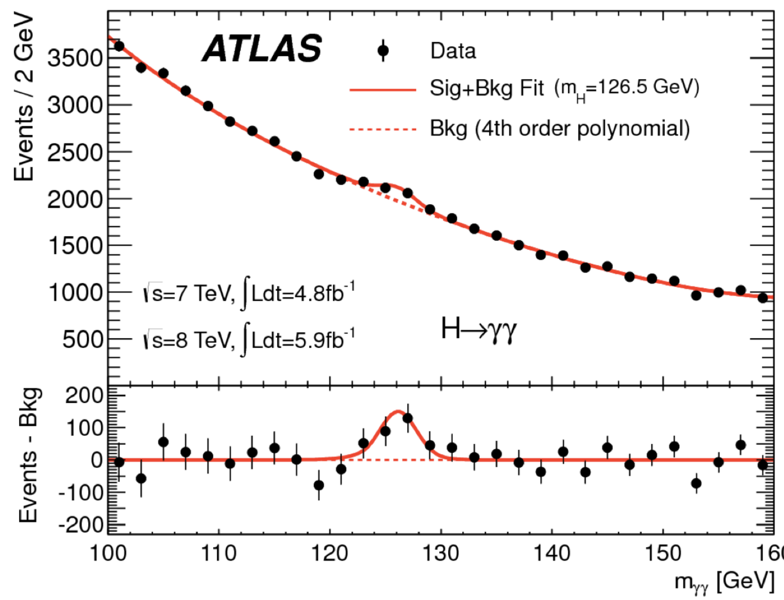

# *Higgs Discovery 2012*

- *ATLAS analysis based on partial Run 1 dataset*
  - *4.8 $fb^{-1}$ @ 7 TeV; 5.9 $fb^{-1}$ @ 8 TeV pp collisions*
- *Searched in several Higgs decay channels*
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow ZZ^*$ *(4 leptons)*
  - $H \rightarrow WW^*$ *($e\nu\mu\nu$)*
  - $H \rightarrow \tau\tau$ *(lep-lep, lep-had, had-had)*
  - $H \rightarrow bb$



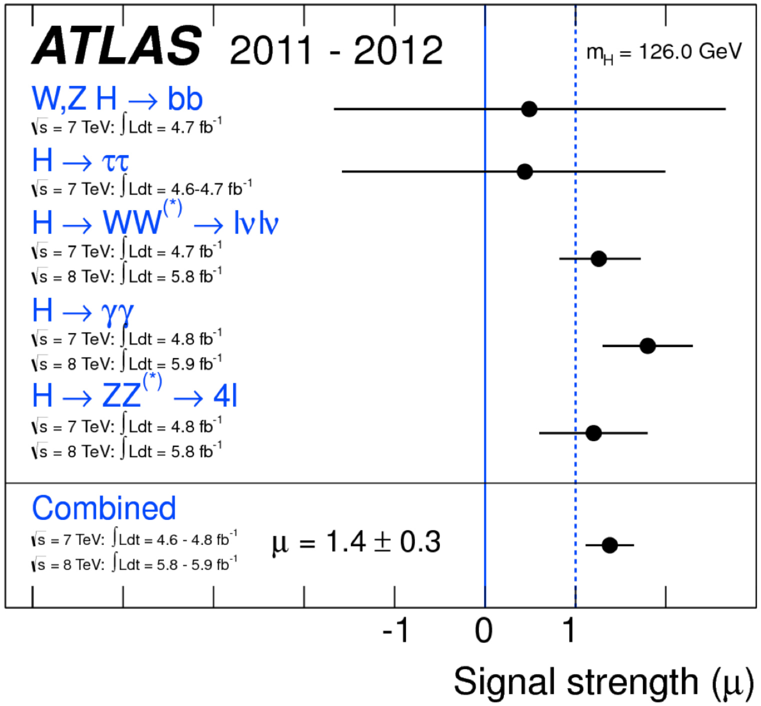

*Phys. Lett. B 716 (2012) 1*



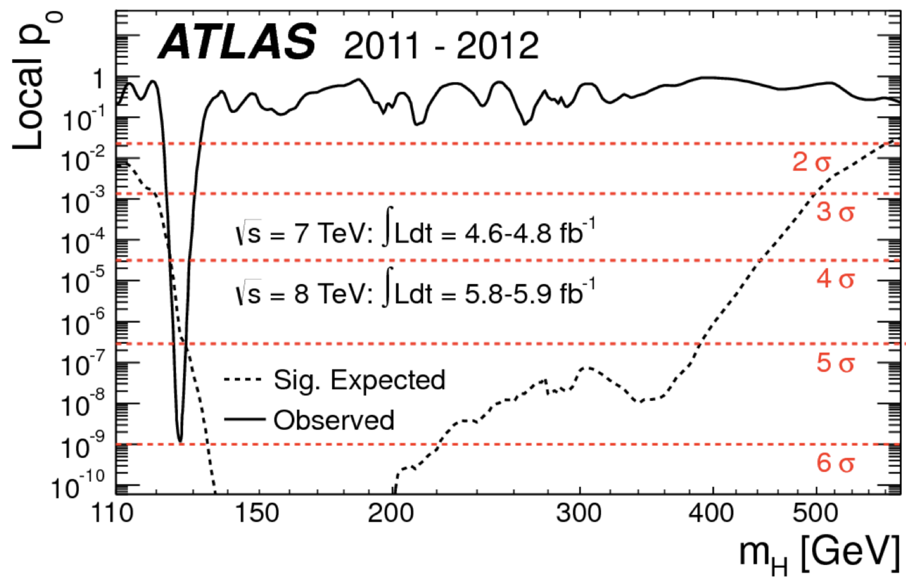
# Higgs Discovery 2012 (cont'd)

- *CMS results were very similar (PLB 716 (2012) 30)*
- *ATLAS and CMS discovered a 125 GeV boson that couples to the EW gauge bosons*
  - *Decay to photons was also as expected for the SM Higgs*
  - *5.9σ and 5.8σ significance, respectively, for ATLAS and CMS*
- *All measurements were consistent with SM predictions (μ = 1)*




Signal strength μ

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}}$$



# *2013 Nobel Prize in Physics*

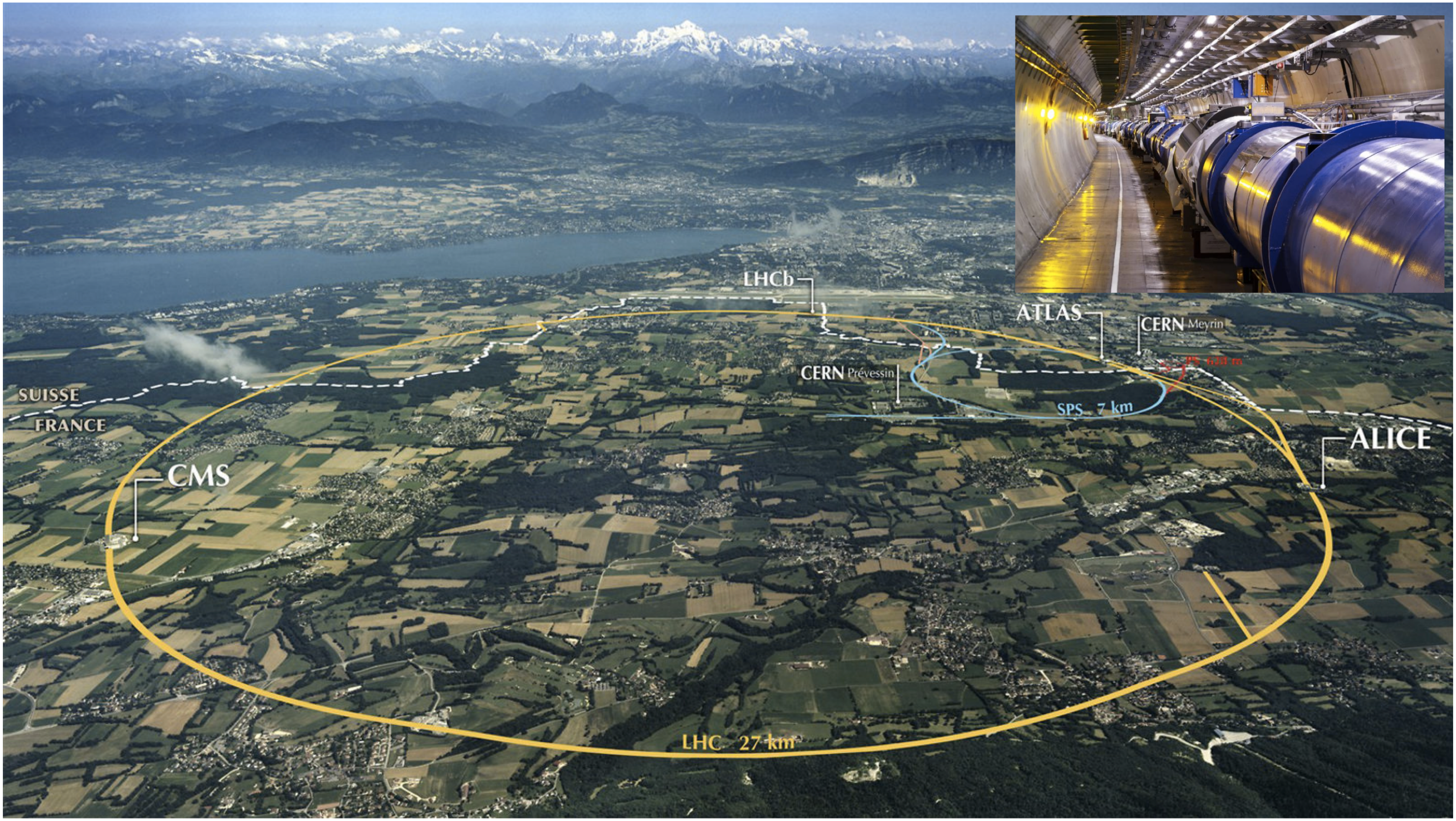
October 8, 2013


*François Englert (Université Libre de Bruxelles, Brussels, Belgium)*
*Peter W. Higgs (University of Edinburgh, UK)*

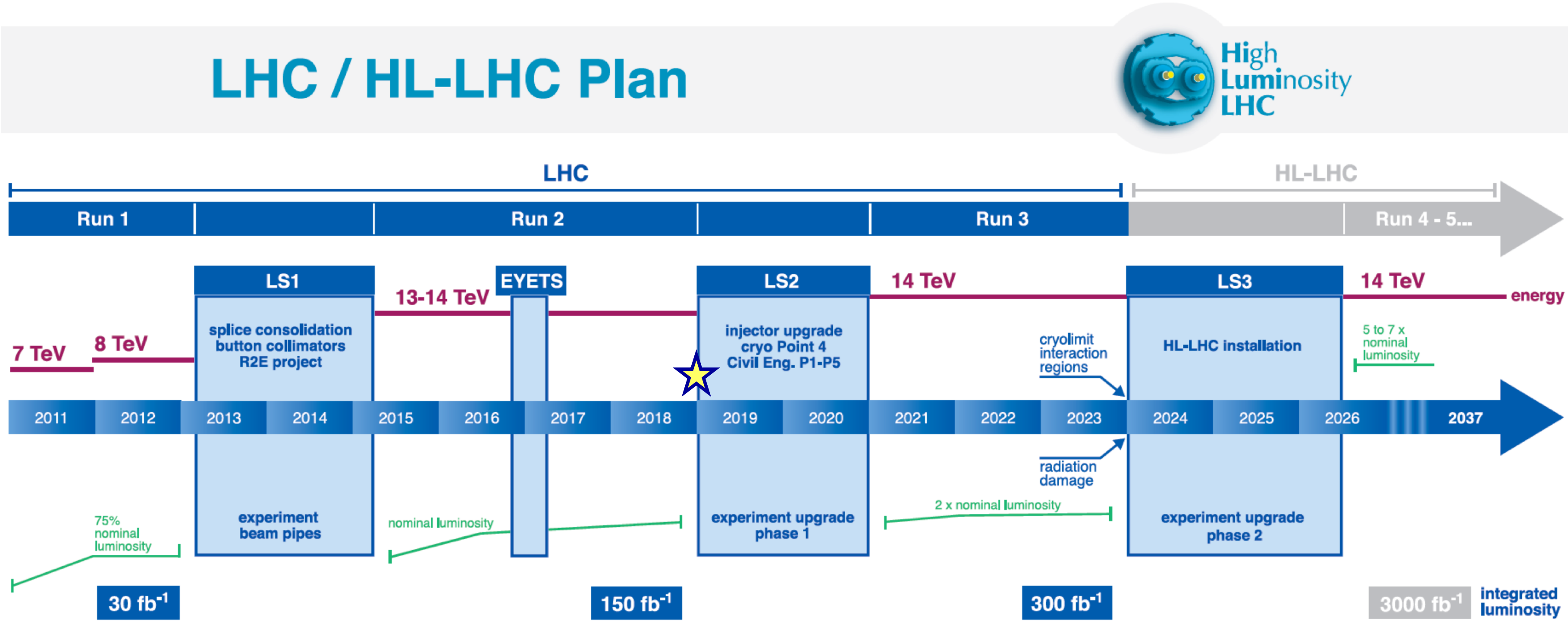
*"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

# *The Large Hadron Collider*

- *27 km circumference, located near Geneva, CH*
- *up to 13 TeV pp collisions (+HI), 4 major experiments (ALICE, ATLAS, CMS, LHCb)*

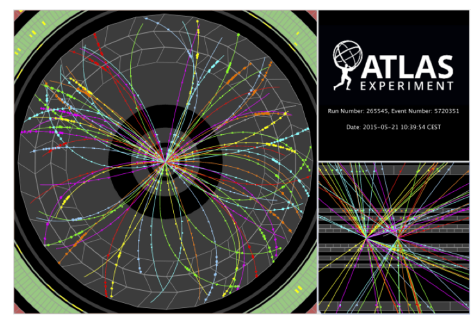


# *LHC Timeline*




*First pp collisions (2009)*

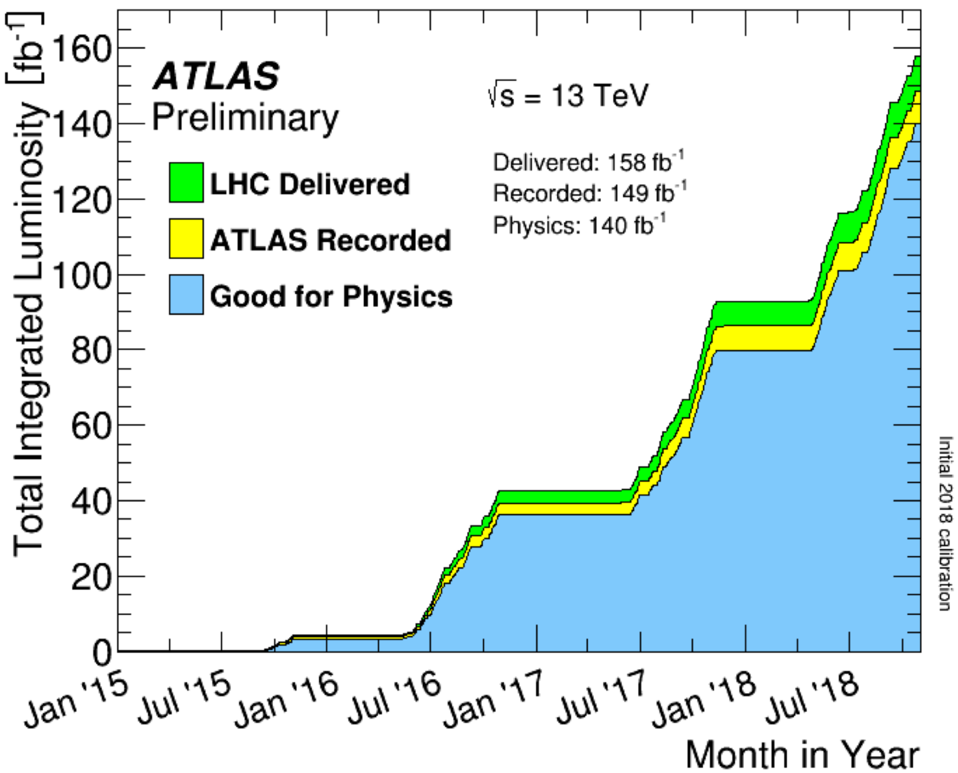
*Higgs Discovery (2012)*

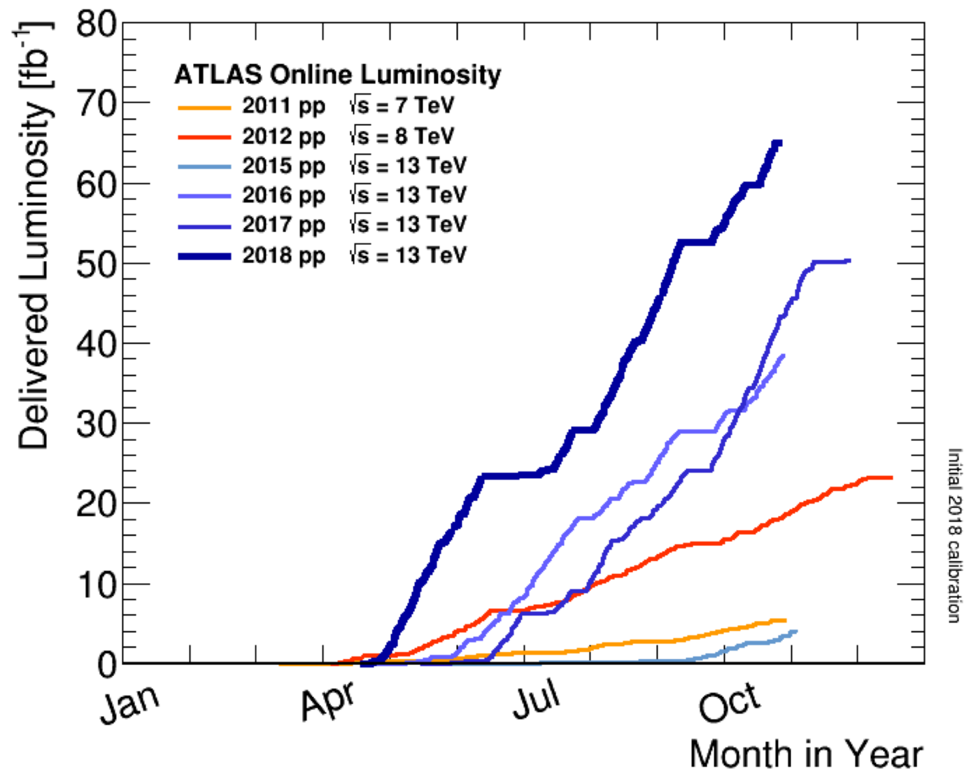



*13 TeV Collisions (2015)*

# ATLAS Dataset Today

*Run 1 @ 7 TeV (5/fb) & 8 TeV (20/fb) + Run 2 @ 13 TeV (140/fb)*

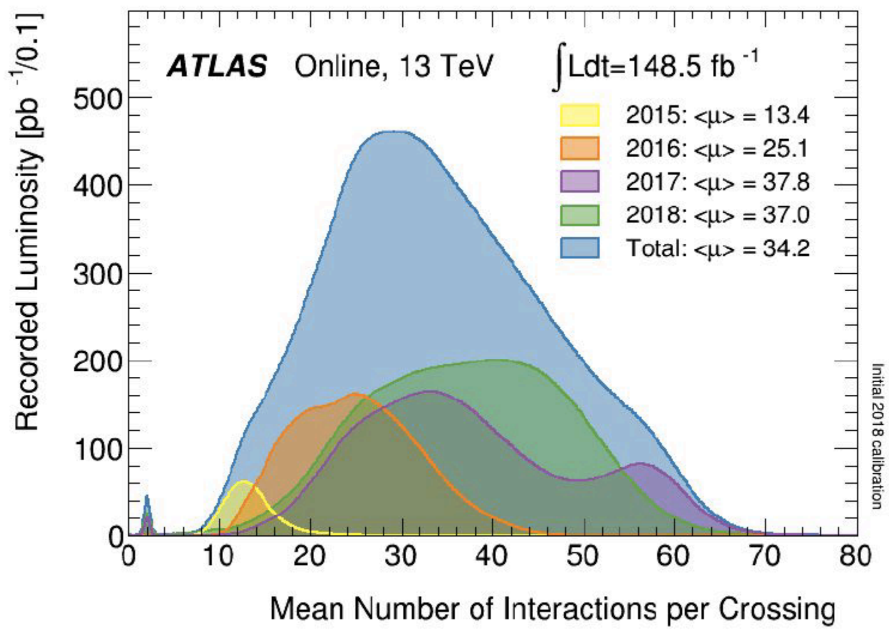



- *Just finished Run 2 data taking (pp + HI runs)*
- *LHC reached up to $L = 2\times10^{34}$ $cm^{-2}$ $s^{-1}$ (2× design luminosity) at 13 TeV*
- *Only about 5% of expected total data taken so far*
- *Most recent results shown today use up to 80/fb*

# Run 2 Challenges and Data Quality

- *Up to 70 collisions / bunch crossing ("pile-up")*
  - *Lots of low $p_T$-tracks, low energy deposits underlie collision of interest*
- *Challenges for detectors & data preparation*
  - *Increased occupancies and radiation effects*
  - *High trigger rate, readout bandwidth, computing demands*
- *Performance degradation mitigated by powerful reconstruction techniques*
  - *Good description of detector response by Monte Carlo simulation*




- *Very efficient data taking by ATLAS*
  - *93.0% of delivered LHC luminosity recorded*
  - *97.5% of data "Good for physics"*
- *> 95% of detector channels still operational*
  - *~100% efficiency remains thanks to redundancy*
- *Computing (Data Reconstruction)*
  - *Smooth and sustained production*
  - *Tier 0: 23.000 cores, Total GRID: 300.000 - 350.000 cores*
  - *Data throughput > 1 PB/day, 20 GB/s, 1.500.000 - 2.000.000 files / day*

**ATLAS pp data: April 25-October 24 2018**

| Inner Tracker | | | Calorimeters | | Muon Spectrometer | | | | Magnets | |
|---|---|---|---|---|---|---|---|---|---|---|
| Pixel | SCT | TRT | LAr | Tile | MDT | RPC | CSC | TGC | Solenoid | Toroid |
| 99.8 | 99.8 | 100 | 99.7 | 100 | 99.8 | 99.7 | 100 | 100 | 100 | 99.6 |

**Good for physics: 97.5% (60.1 $fb^{-1}$)**

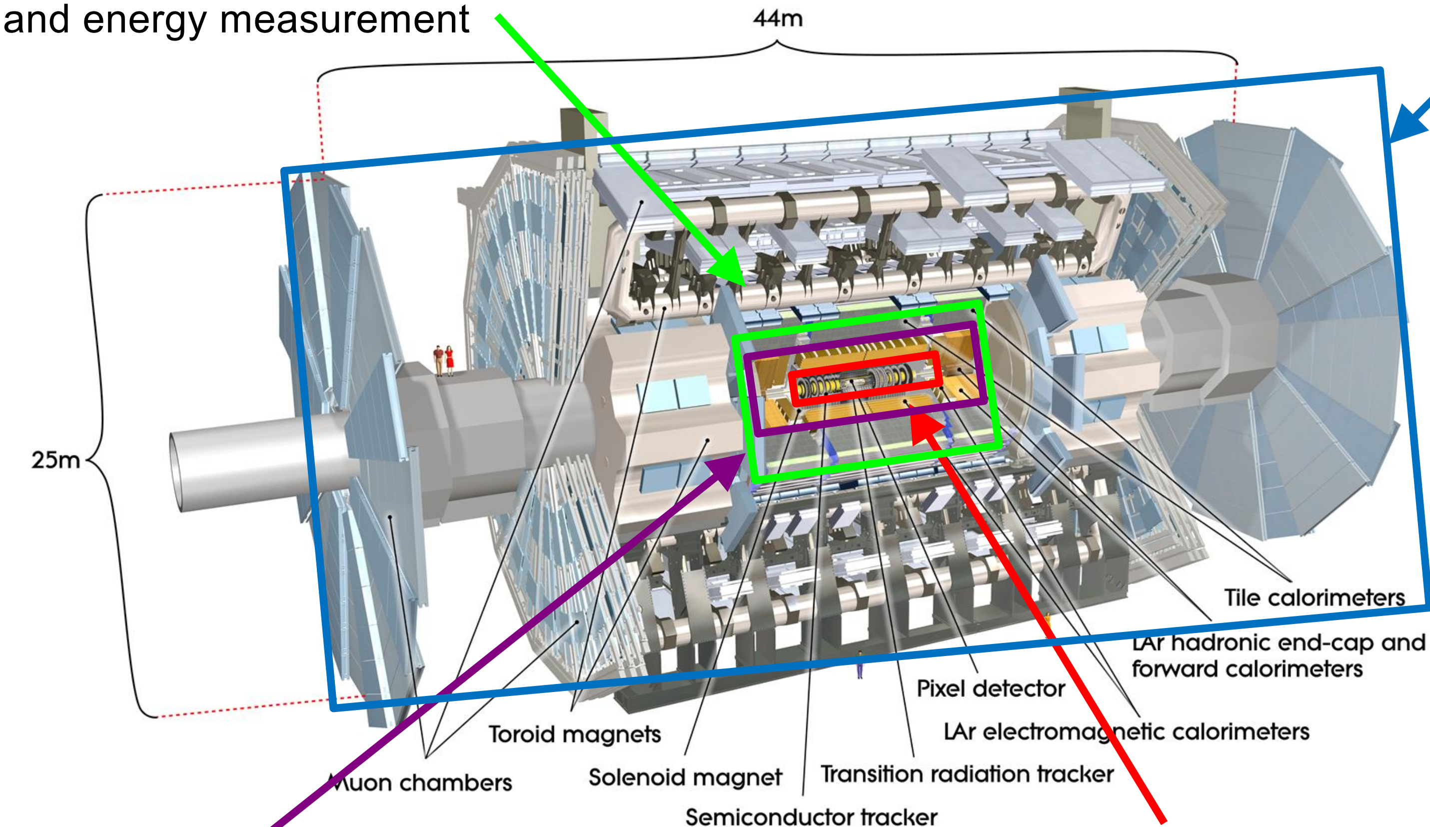
Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions at $\sqrt{s}$=13 TeV between April 25 – October 24 2018, corresponding to a delivered integrated luminosity of 63.8 $fb^{-1}$ and a recorded integrated luminosity of 61.7 $fb^{-1}$. Dedicated luminosity calibration activities during LHC fills used 0.7% of recorded data and are included in the inefficiency. The luminosity includes 193 $pb^{-1}$ of good data taken at an average pileup of μ=2.

# The ATLAS Detector

*Weight 7000t, 44 m long, 25 m diameter*

Hadronic calorimeter ($|\eta|<4.9$):
Jets and MET trigger, identification and energy measurement

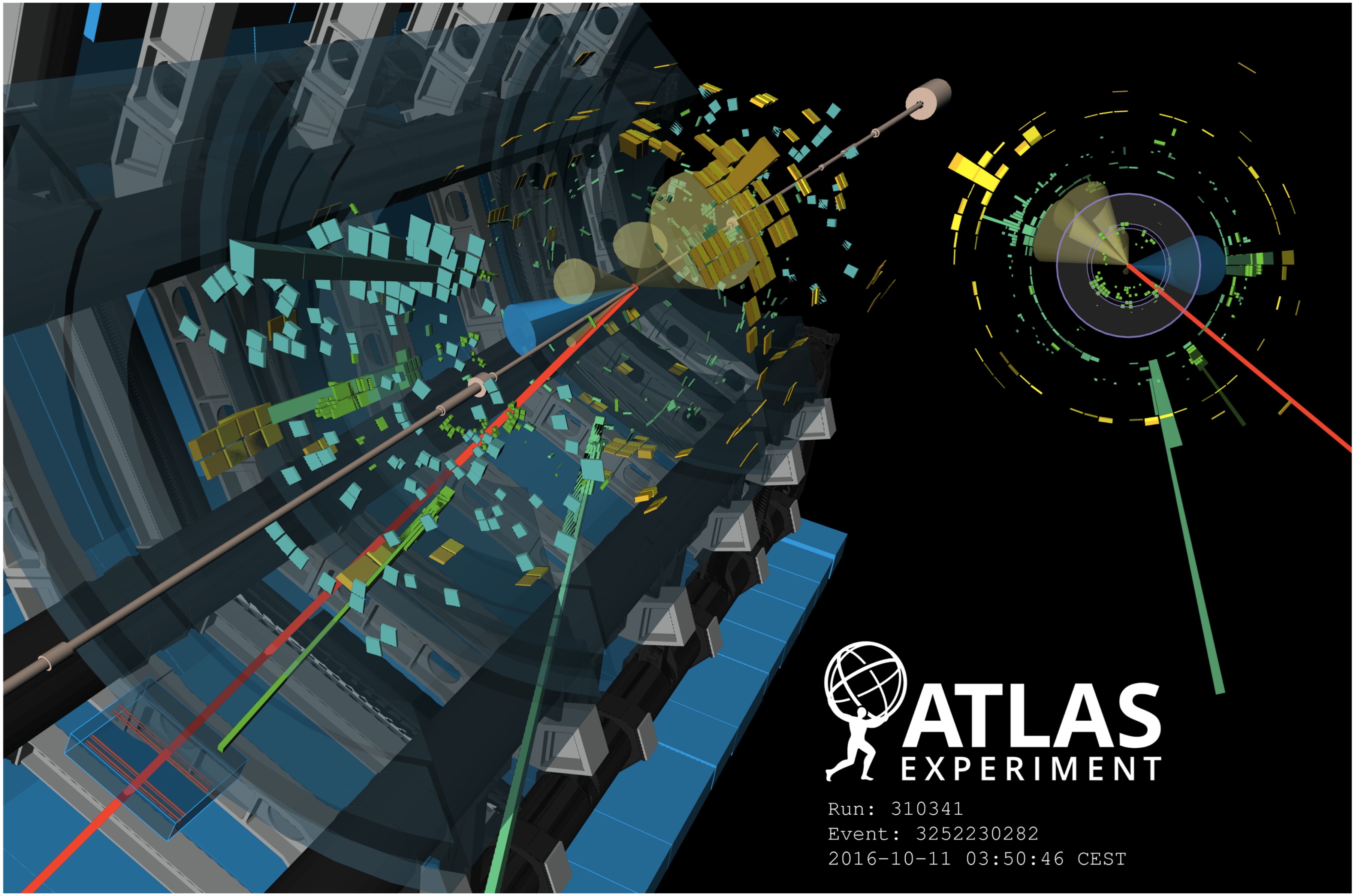
Muon spectrometer ($|\eta|<2.7$):
Muon trigger, identification and momentum measurement




EM calorimeter($|\eta|<3.2$):
$e/\gamma$ trigger, identification and energy measurement

Inner detector ($|\eta|<2.5$) in 2T Solenoid (Pixels, SCT and TRT):
Charged-particle tracking, momentum and vertex measurement

# A ttH(→γγ) Candidate




*A complex signal event: 1 muon, 2 photons, 5 jets (one of them b-tagged)*

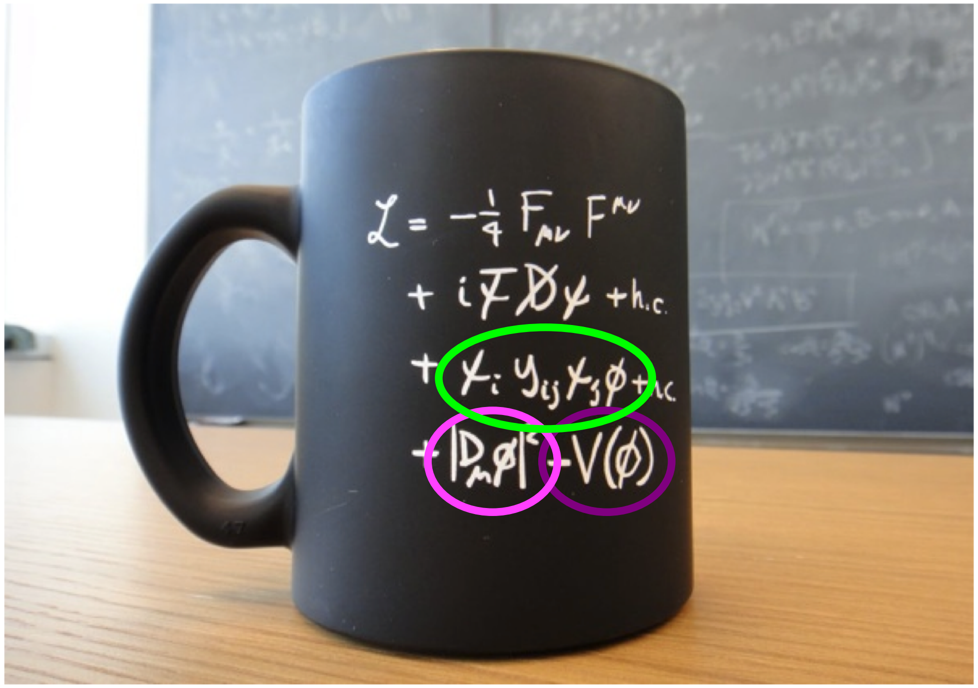
# *The ATLAS Collaboration*

# *Higgs Questions*

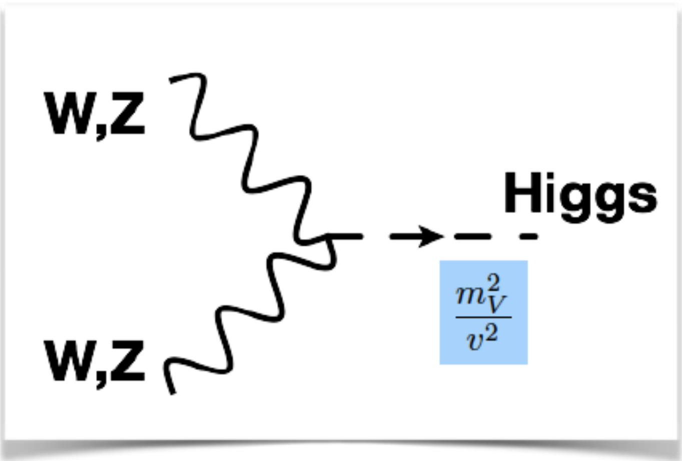
- *The Higgs discovery opened up many new questions:*
  - *How does the Higgs couple to fermions ?*
    - *Does the Higgs couple to quarks ? Does it couple to all quarks ?*
    - *Does the Higgs couple to leptons ? Does it couple to all leptons ?*
    - *Are the fermion couplings proportional to the fermion masses? Does the Higgs give mass to all fermions?*
  - *Does the Higgs couple to itself?*
  - *Are there more Higgs-like particles?*
- *ATLAS and CMS have put these questions to the test !*

# The Higgs in the Standard Model

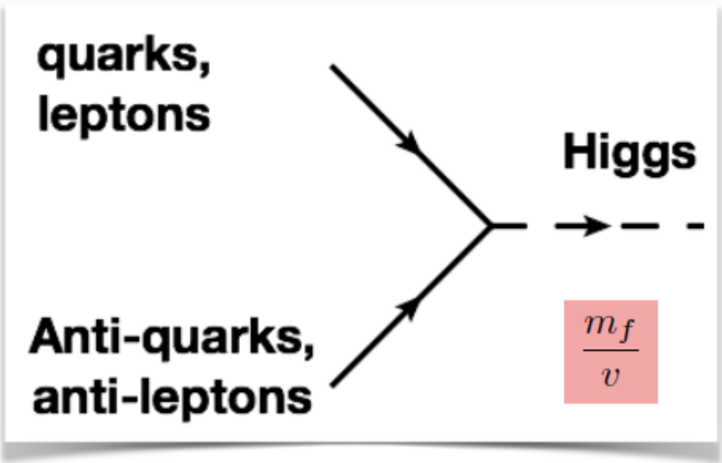
- *Higgs sector is a fundamental component of the SM Lagrangian*
  - *Describes Higgs couplings to* ***fermions*** *and* ***gauge bosons*** *and* ***Higgs self-coupling***
- *Results in precise predictions for the decay rates to gauge bosons and fermions and for the Higgs production modes*
  - *The predictions are being tested by ATLAS and CMS*



**Couplings to bosons**




**Couplings to fermions**



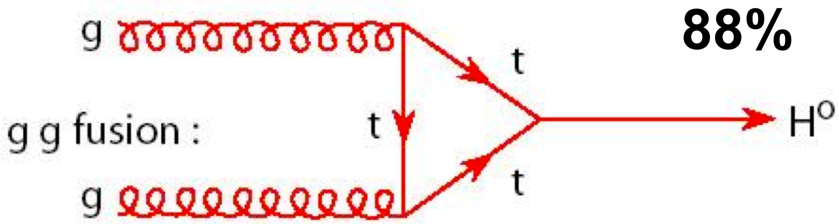
# *LHC Run 2:*

## *The Higgs Intense Study Phase*

# *Higgs Production at the LHC*

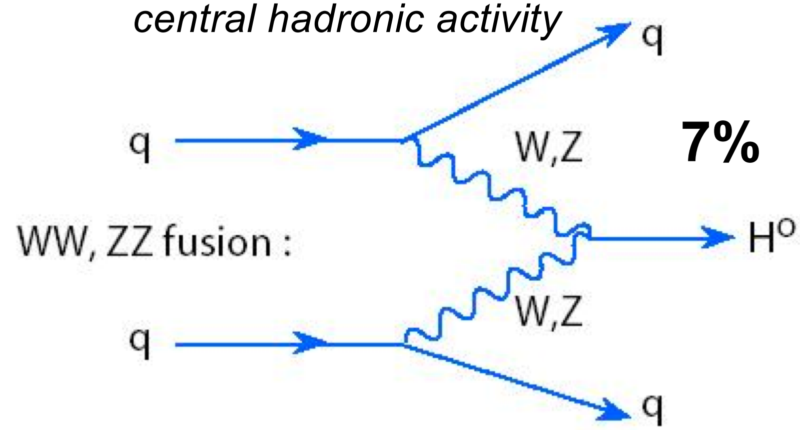
*Dominant production channel*

**88%**



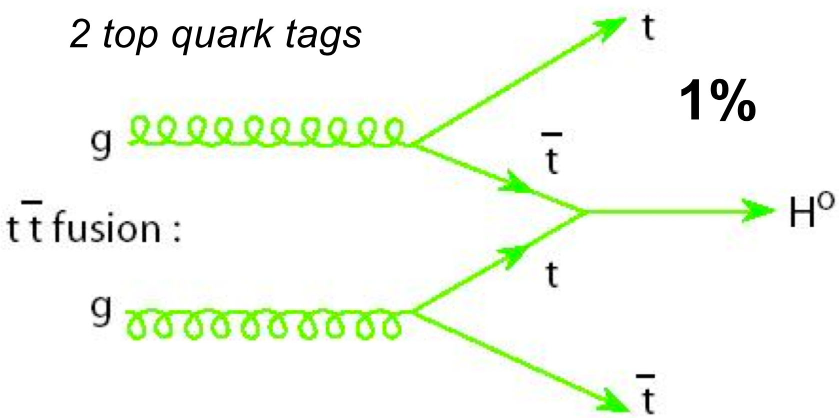

*2 forward jets, little central hadronic activity*

**7%**



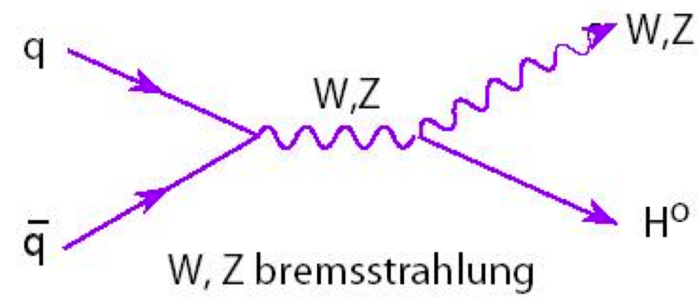

*2 top quark tags*

**1%**



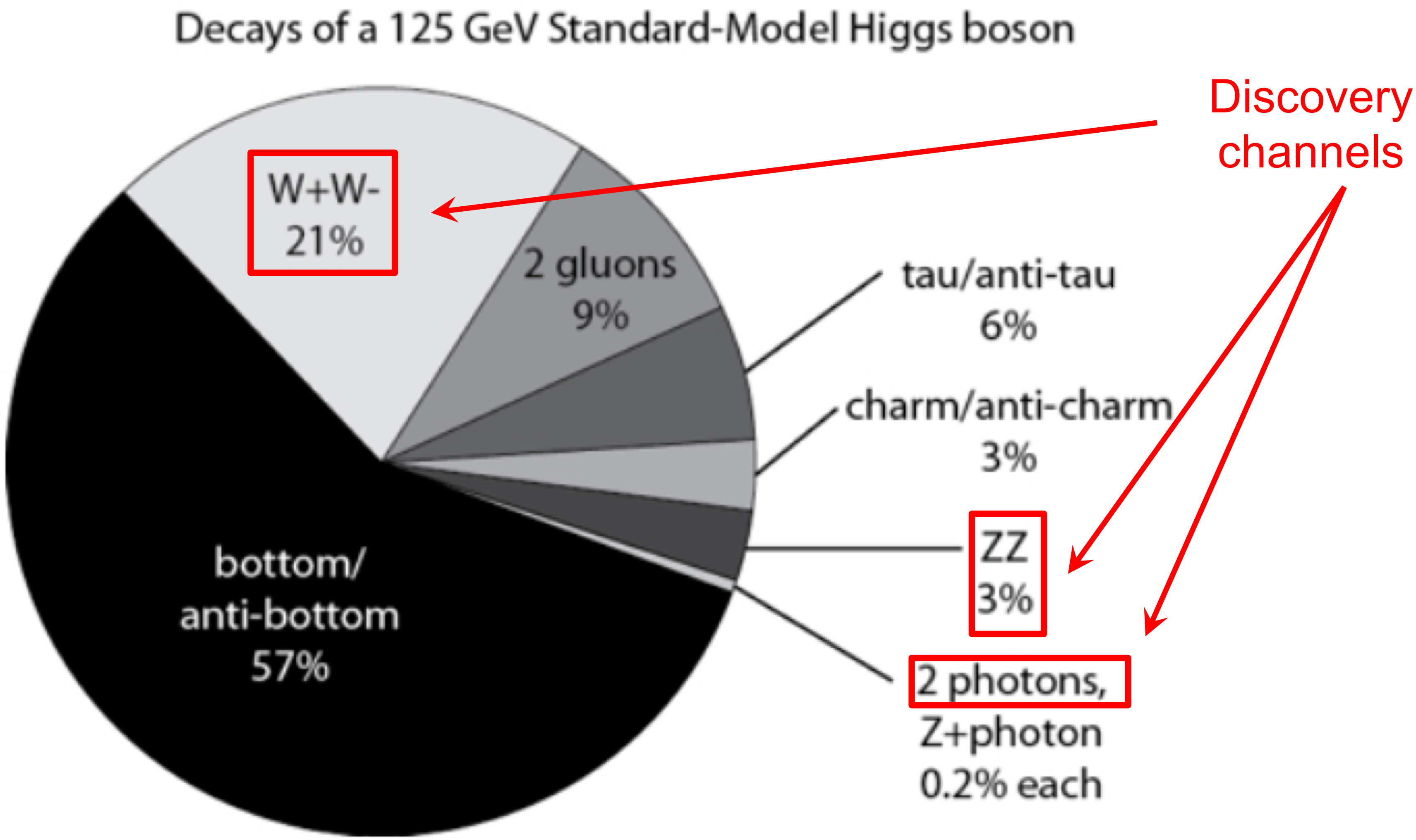

*gauge boson tag*

**4%**




*Why even bother with anything but gluon-gluon fusion?*
*Cleaner signatures of sub-dominant modes !*

# *Higgs Decay*

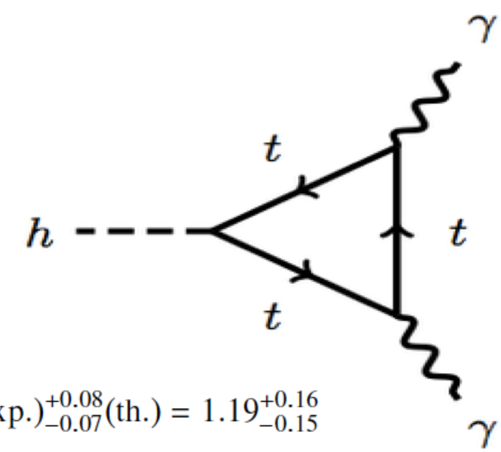



*Discovery potential of a decay channel depends on event yield (σ × BF) and background level !*

## *Higgs Couplings to Bosons*

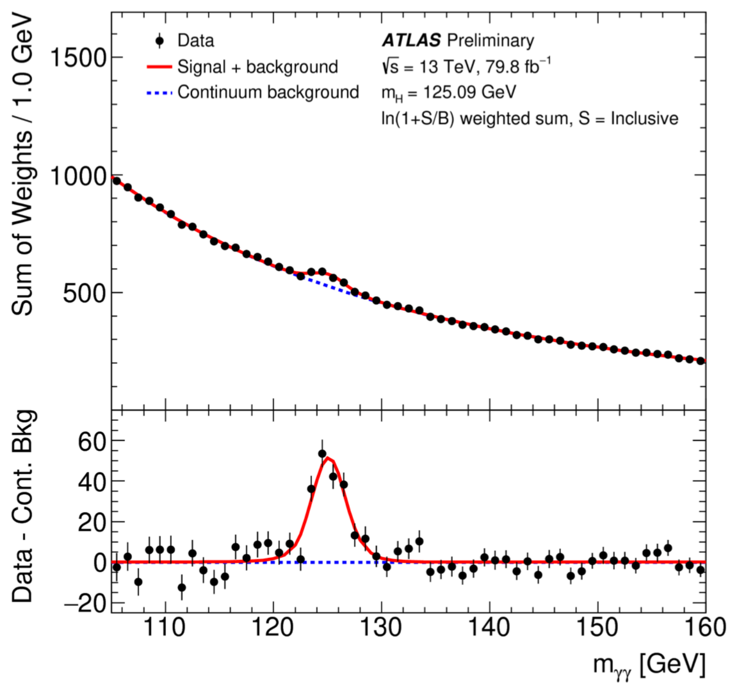
# Discovery Channels Today: $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$

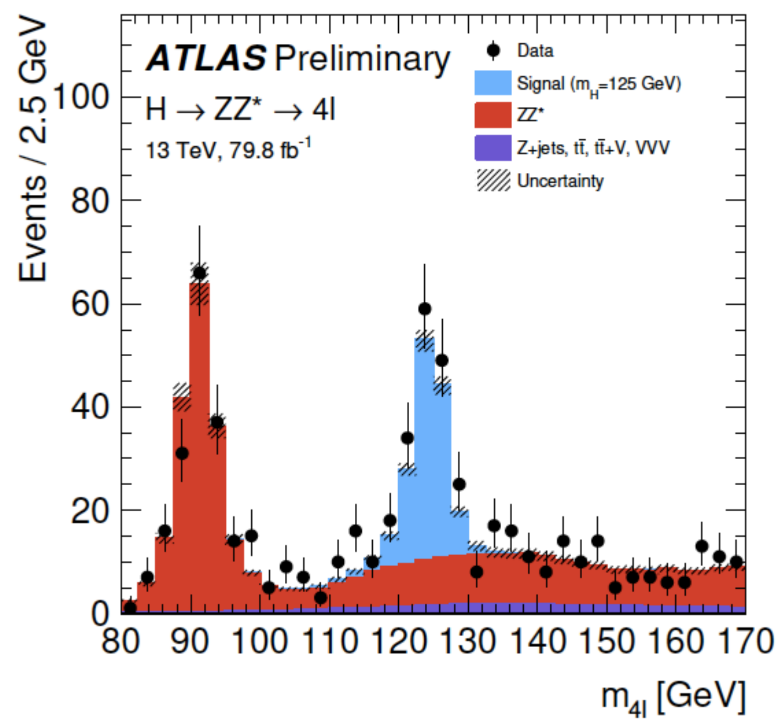
- *Similar signal strength uncertainties for the two channels*
- *Factor of 4 improvement since discovery*
- *Inclusive yields compatible with SM predictions*
- *Theory uncertainty is becoming important*




$\mu = 1.06\,^{+0.14}_{-0.12} = 1.06 \pm 0.08\,(\text{stat.})\,^{+0.08}_{-0.07}\,(\text{exp.})\,^{+0.07}_{-0.06}\,(\text{theo.})$

$\mu = 1.19 \pm 0.12(\text{stat.}) \pm 0.06(\text{exp.})^{+0.08}_{-0.07}(\text{th.}) = 1.19^{+0.16}_{-0.15}$




ATLAS-CONF-2018-28

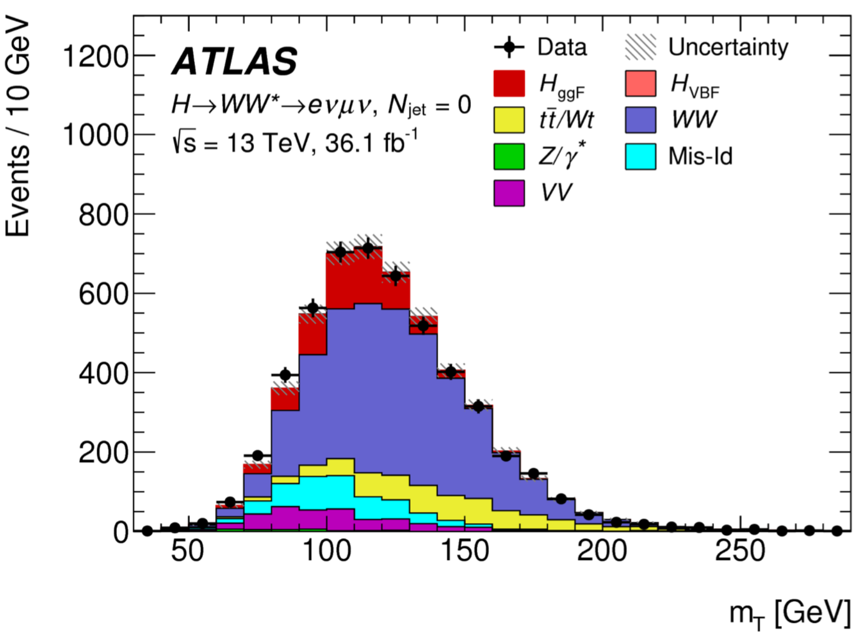
ATLAS-CONF-2018-18

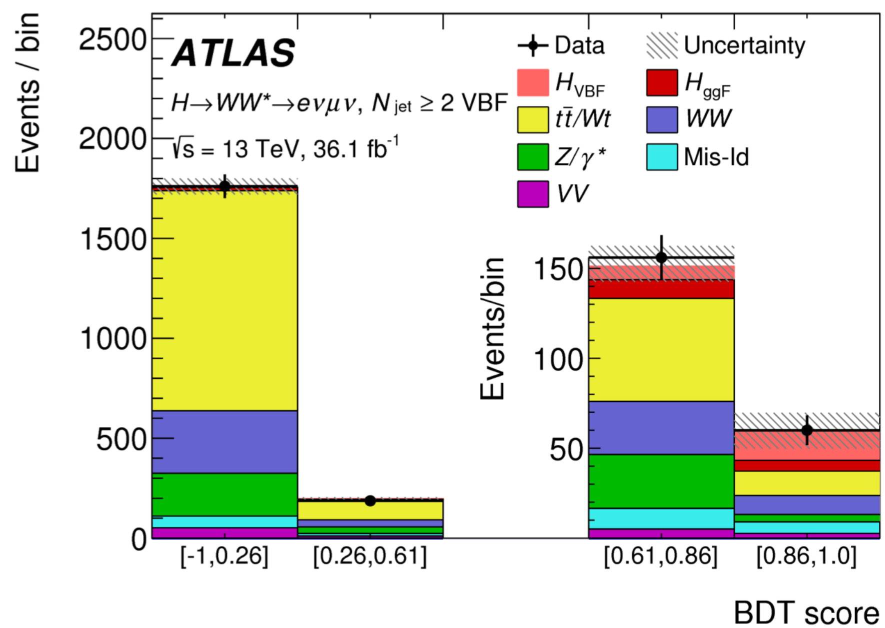
# $H \rightarrow WW^*$

- *$H \rightarrow WW^*$ cross-sections are measured in $(e\nu)(\mu\nu)$ final state for gluon-gluon fusion and VBF production*

$$\mu_{\text{ggF}} = 1.21 \pm 0.10(\text{stat.})^{+0.13}_{-0.12}(\text{theo syst.}) \pm 0.15(\text{exp syst.}) = 1.21^{+0.22}_{-0.21}$$
$$\mu_{\text{VBF}} = 0.62^{+0.30}_{-0.28}(\text{stat.}) \pm 0.13(\text{theo syst.}) \pm 0.16(\text{exp syst.}) = 0.62^{+0.37}_{-0.36}$$

arXiv:1808.09054 (submitted to PLB)

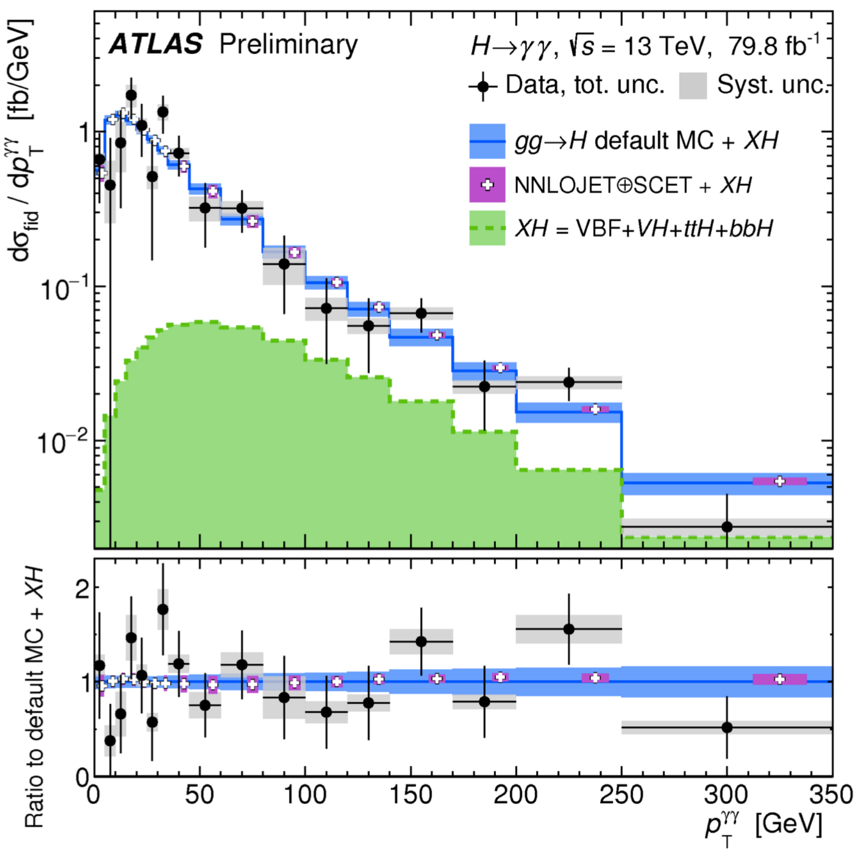


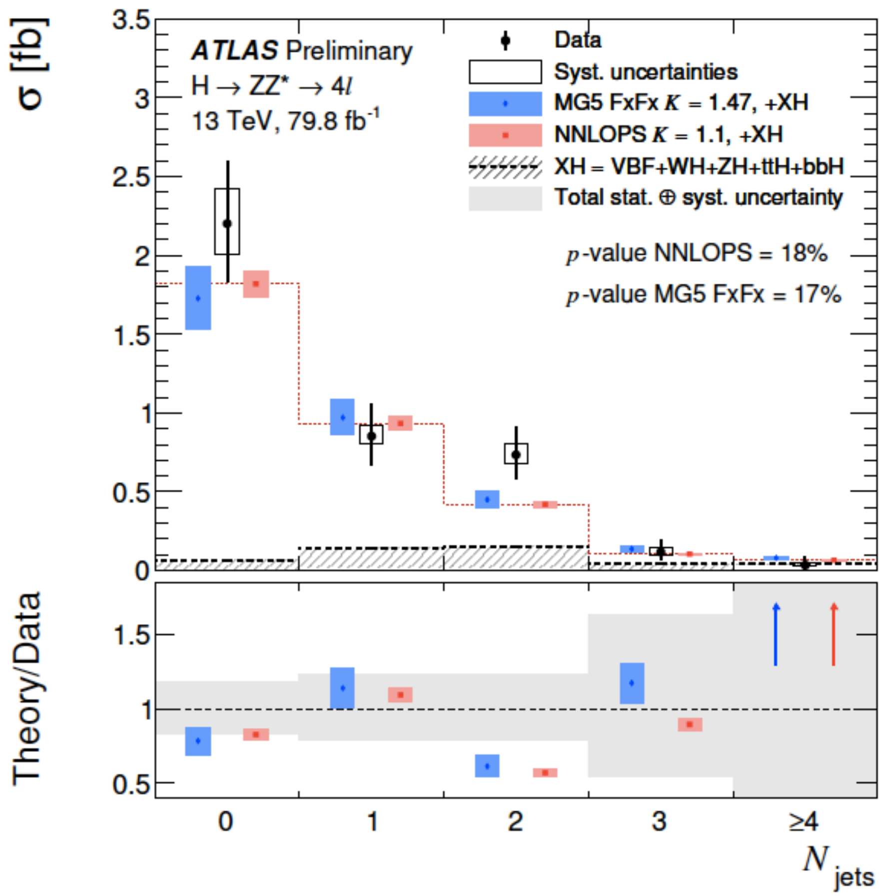
# Differential Distributions

- *Model-independent measurements of production and decay kinematics*
- *Comparison to SM calculations are sensitive to New Physics contributions (e.g. additional loop diagrams, non-SM spin-parity)*

ATLAS-CONF-2018-028




ATLAS-CONF-2018-18



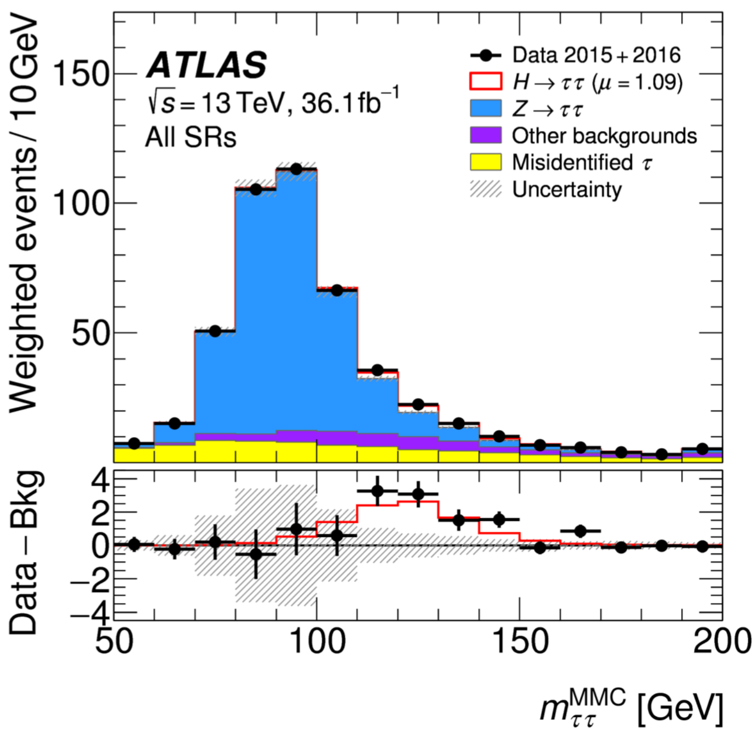
*Higgs Couplings to Fermions*

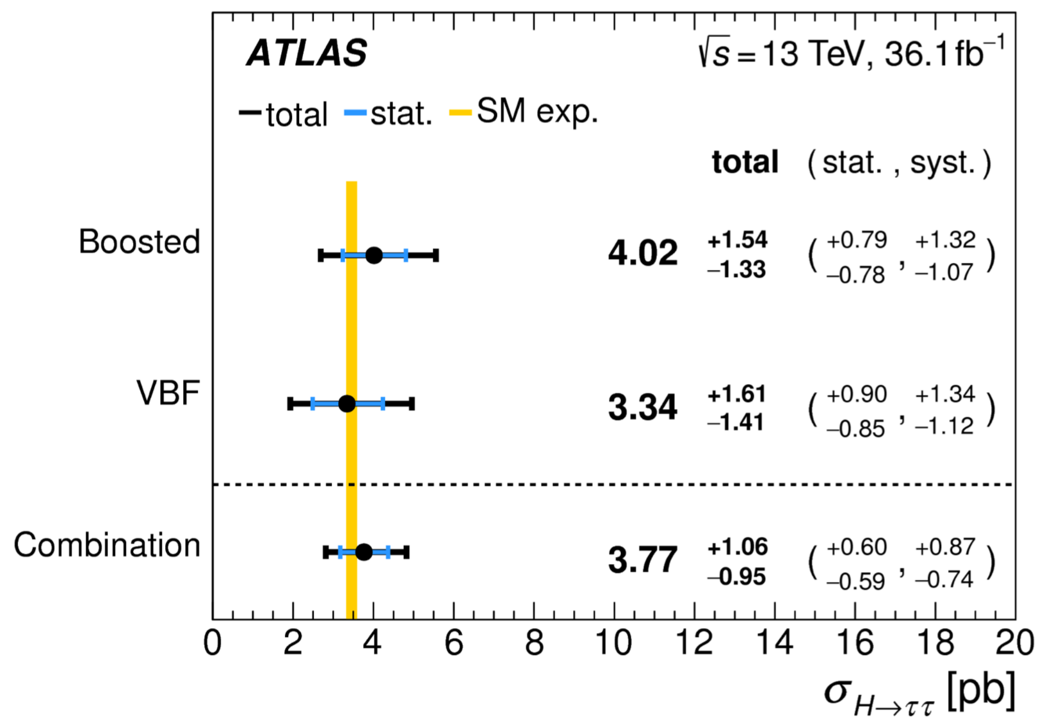
# *Observation of Coupling to τ Leptons*

- *All combinations of leptonic and hadronic τ decays and VBF and boosted production ($p_T^{\tau\tau}$ > 100 GeV) are considered*
- *Observed (expected) significance of 4.4σ (4.1σ) in 36.1/fb of Run 2 data Combined with Run 1 data, observed (expected) significance is 6.4σ (5.4σ)*
- *Results are compatible with SM prediction*

$$\mu = 1.09^{+0.18}_{-0.17}(\text{stat.})^{+0.26}_{-0.22}(\text{syst.})^{+0.16}_{-0.11}(\text{theo.})$$

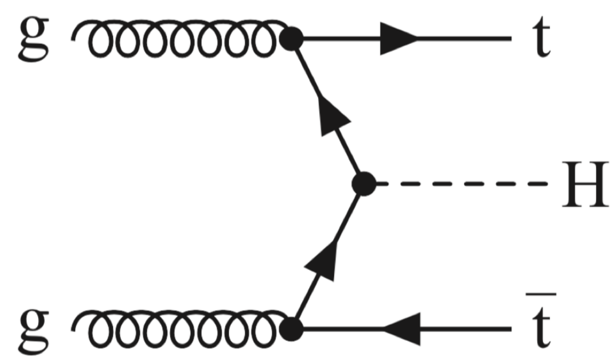
1811.08856 (submitted to PRD)



# *Observation of Higgs coupling to top quark*

- *Higgs too light to decay directly to top quark pair*
- *ttH production provides a direct probe of Yukawa coupling of the Higgs to top quark*
- *6.3 σ observation for ttH production through the combination of four major decay modes*

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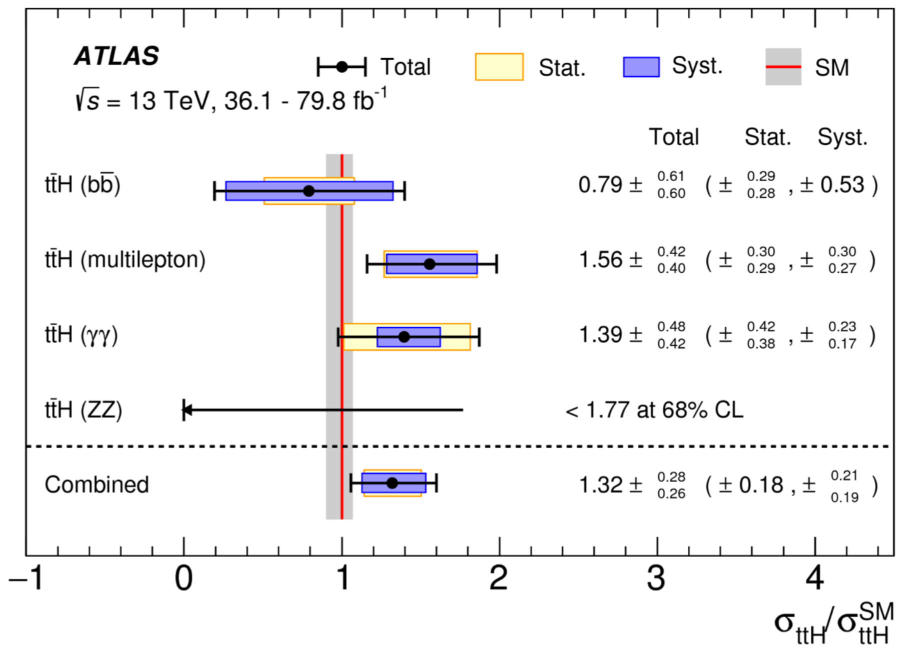
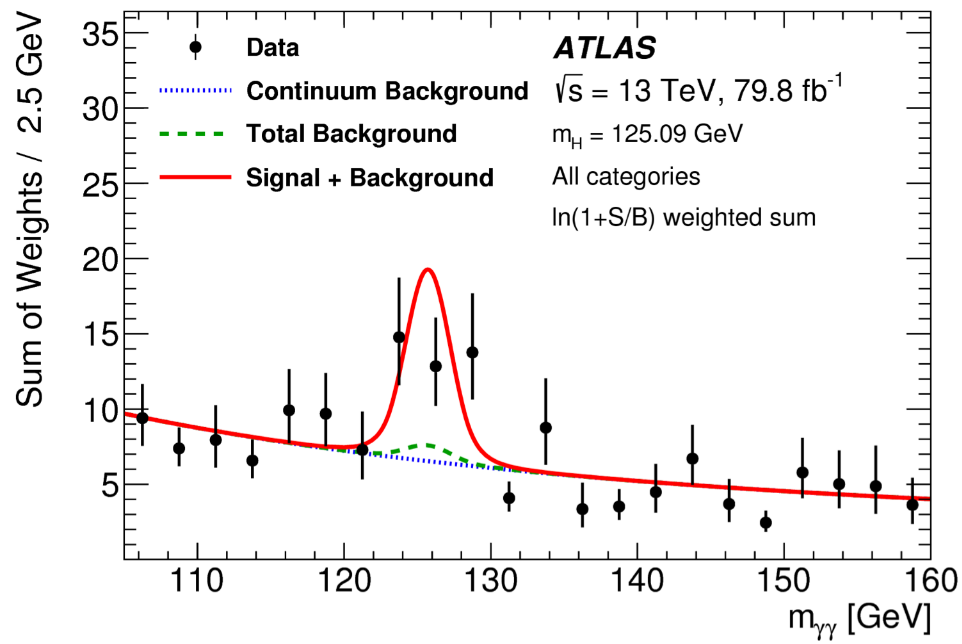
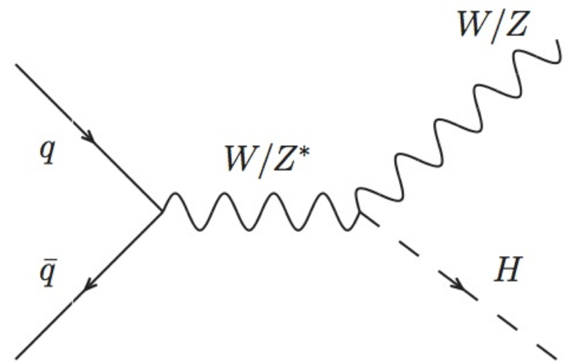


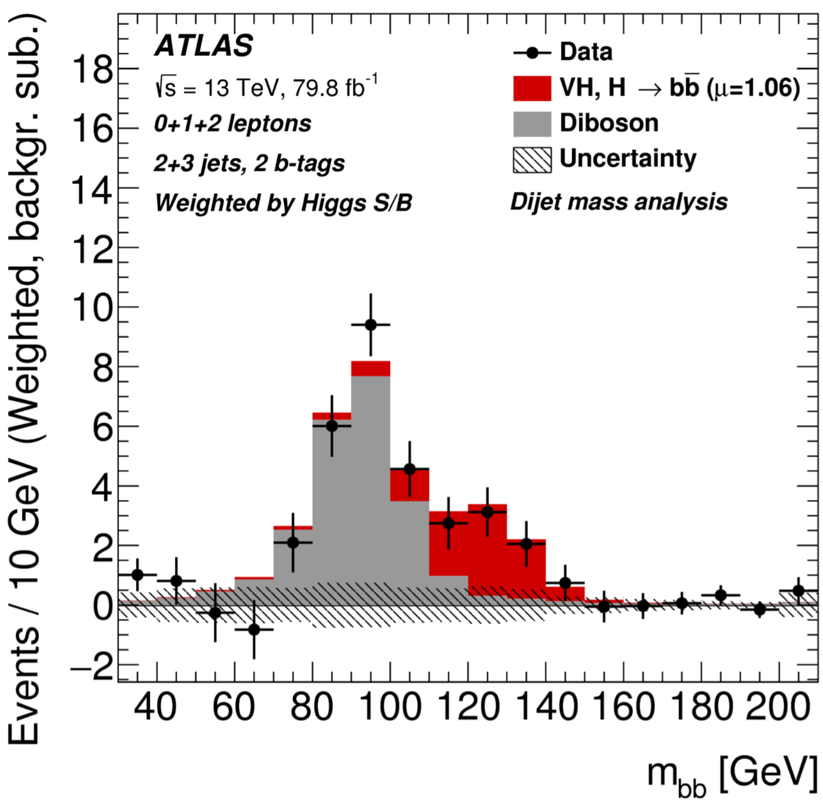
# Observation of VH Production and H → bb Decay

- *Despite large BF (57%) H → bb from ggF hard to detect because of large multi-jet background*
- *Most sensitive channel is VH production*
  - *suppress background by "tagging" EW process with Z or W boson in leptoninc (ll, lv, vv) final state*

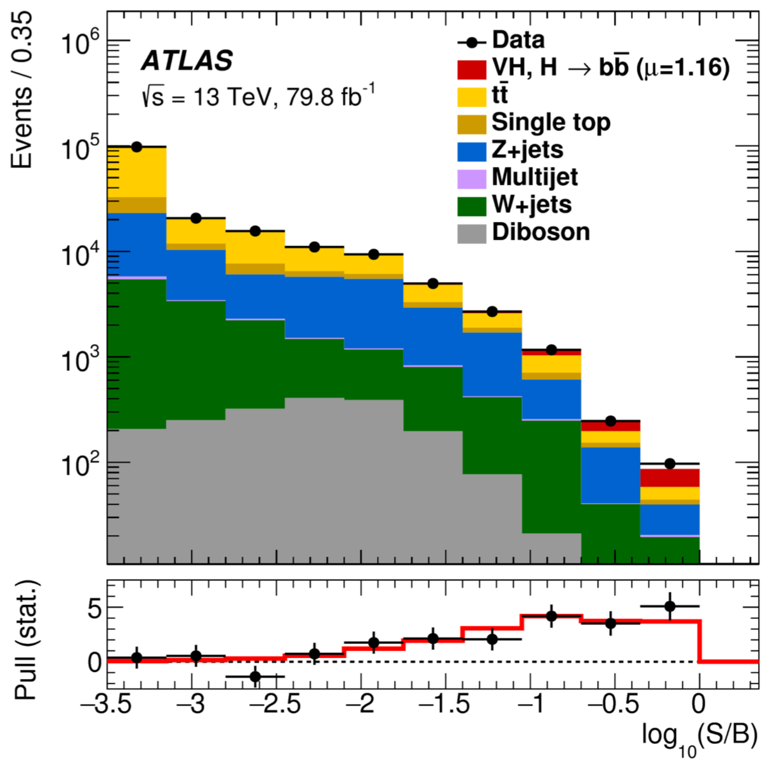



$$\mu_{VH}^{bb} = 1.16^{+0.27}_{-0.25} = 1.16 \pm 0.16(\text{stat.})^{+0.21}_{-0.19}(\text{syst.})$$

4.9σ observed (4.3σ expected)




Phys. Lett. B 786 (2018) 59



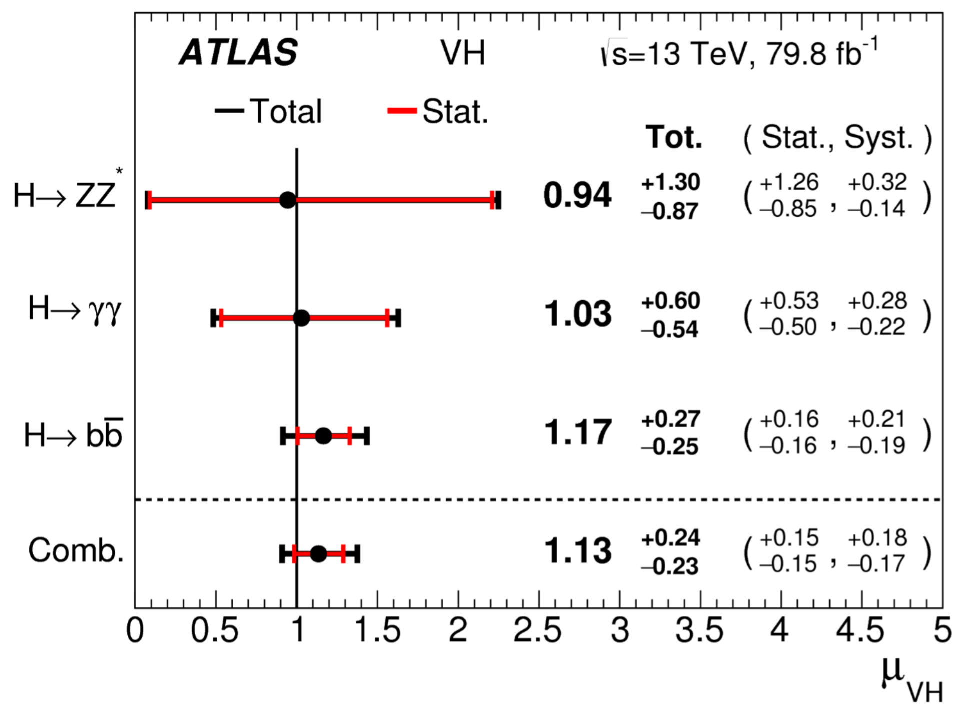
# *Observation of VH and H → bb (cont'd)*

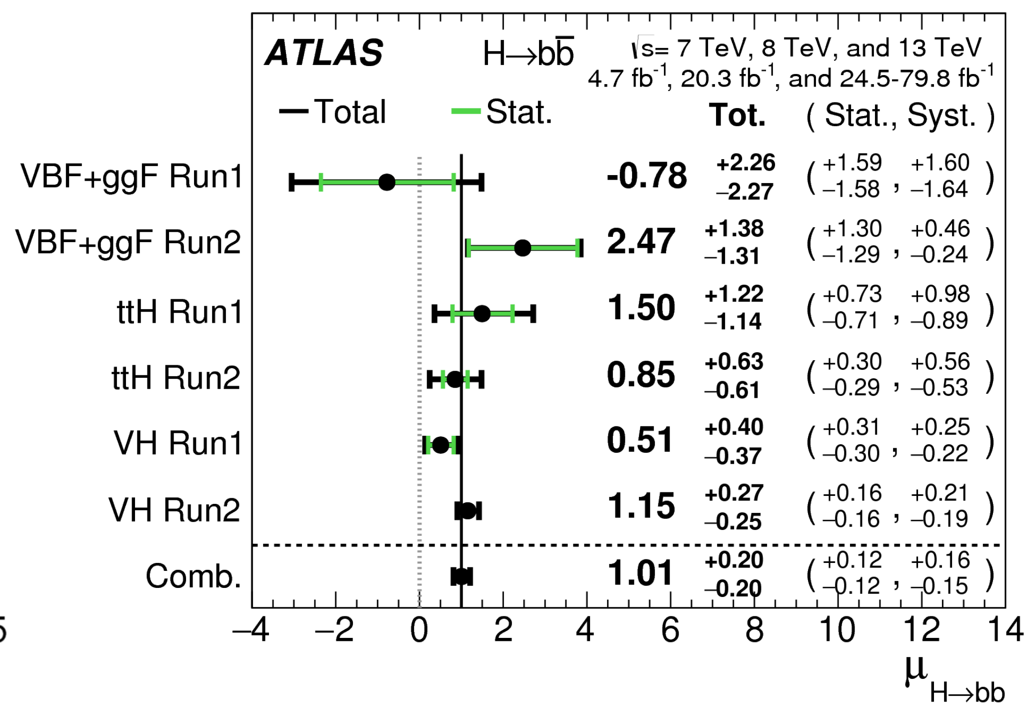
- *VZ(→bb) production measurement as a cross-check*

$$\mu_{VZ}^{bb} = 1.20^{+0.20}_{-0.18} = 1.20 \pm 0.08(\text{stat.})^{+0.19}_{-0.16}(\text{syst.})$$

- *Combinations*
  - *Combined V = Z, W (0, 1, or 2 charged leptons channels)*
  - ***5.3 σ for VH production** from combination of H → bb, ZZ*, and γγ decays*
  - ***5.4 σ for H → bb decay** from combination of VH, VBF+ggF and ttH production in Run 1+2 data*

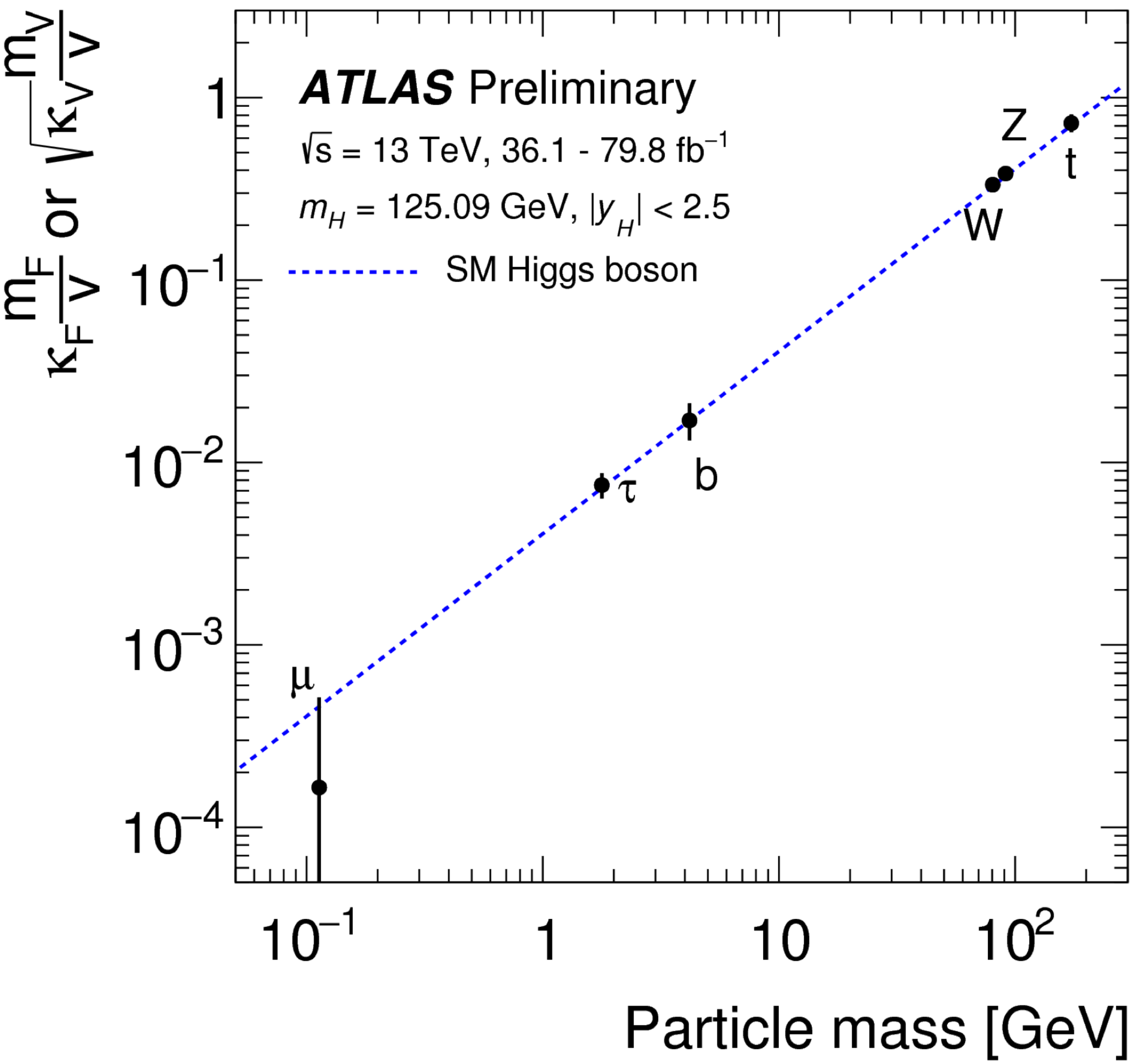
Phys. Lett. B 786 (2018) 59



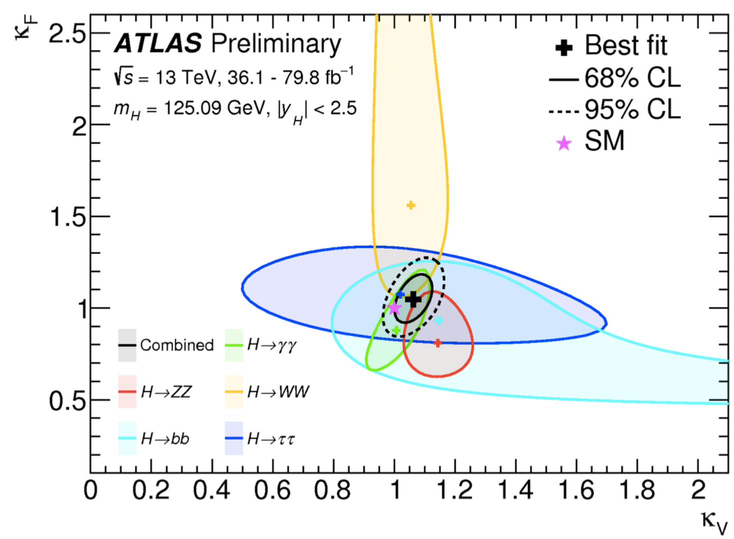



# *Higgs Coupling vs Mass*

ATLAS-CONF-2018-031

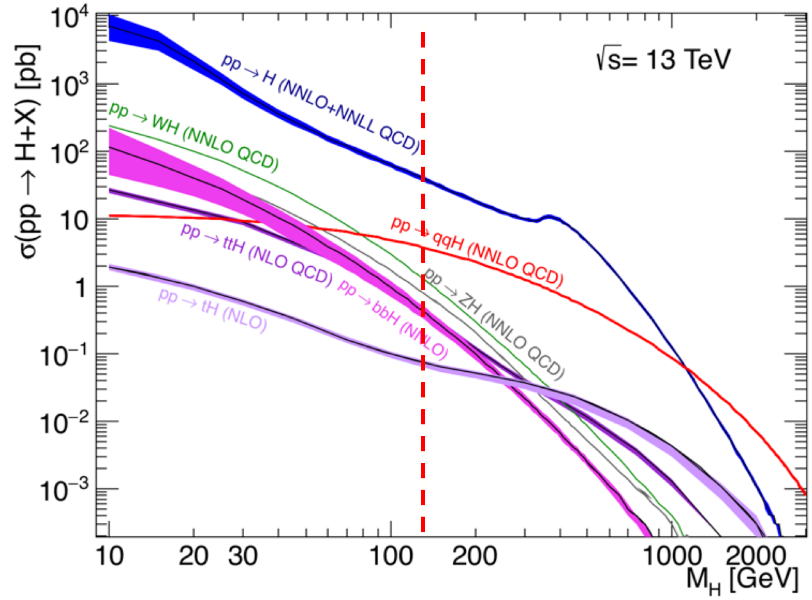



- *The Higgs has been measured to couple to*
  - *Gauge bosons W,Z*
  - *Leptons: τ*
  - *Quarks: b,t*
- *The couplings are as expected for a 125 GeV SM Higgs*

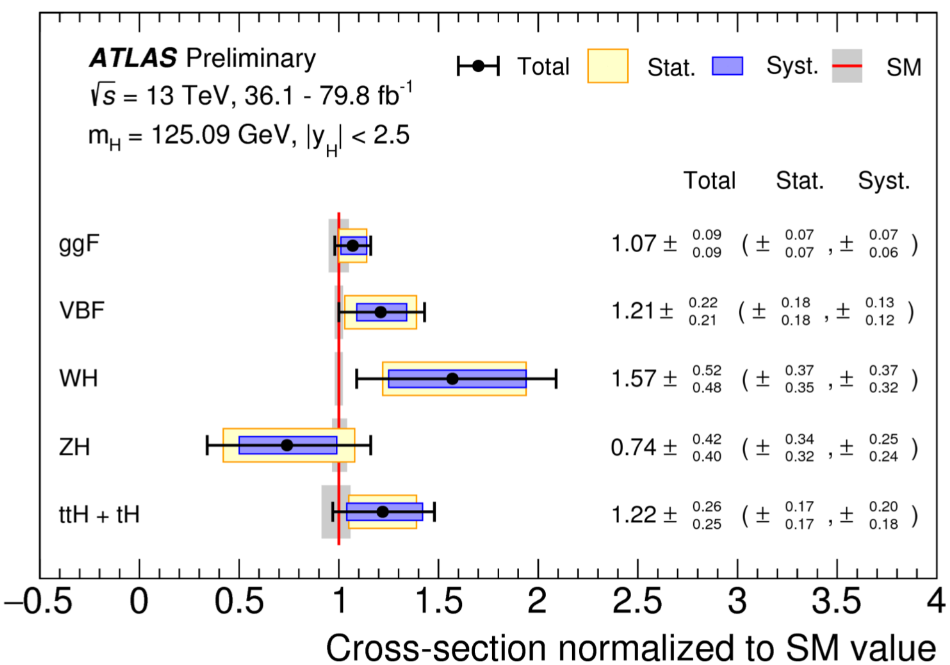


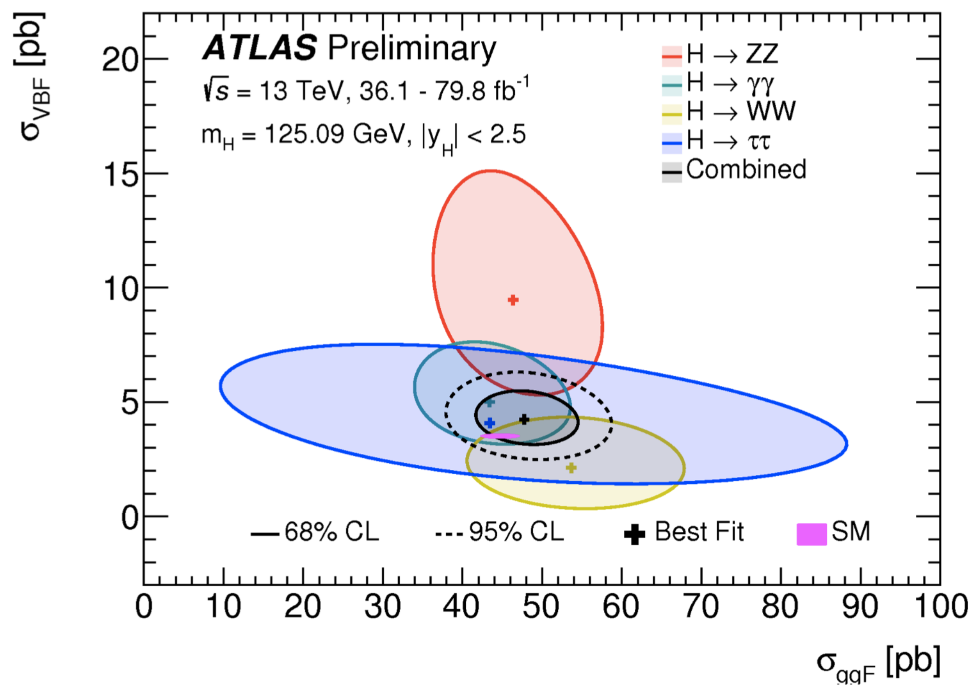
# *Higgs Production*

- *Relative strengths of Higgs production cross sections predicted in SM*
- *Combined Higgs production cross sections measured from in γγ, ZZ*, WW*, ττ, μμ and bb final states*
- *All 4 major Higgs production mechanisms have been observed*
  - *Good agreement with SM predictions*



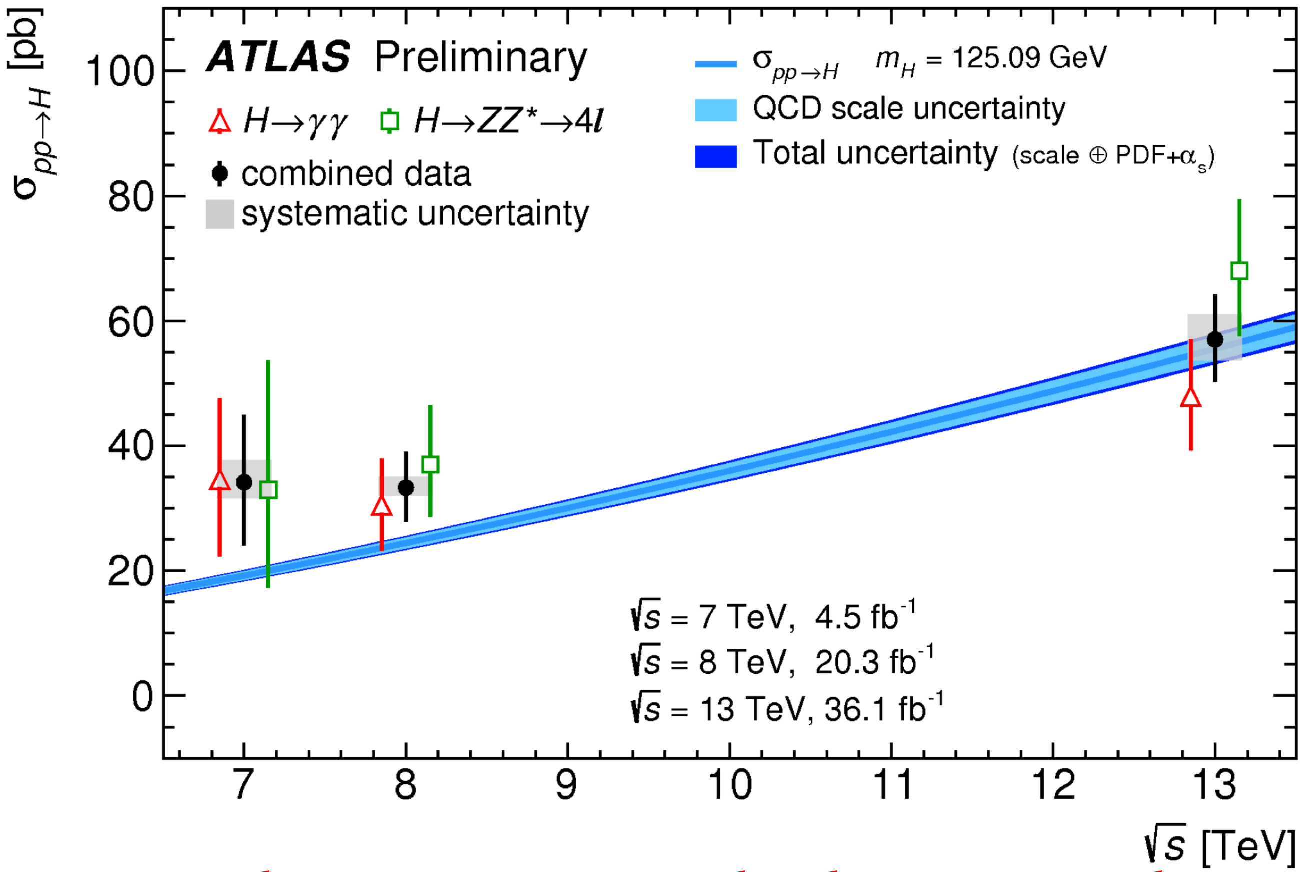

ATLAS-CONF-2018-031



# *Production Cross Section vs. Energy*

[ATLAS-CONF-2017-47]

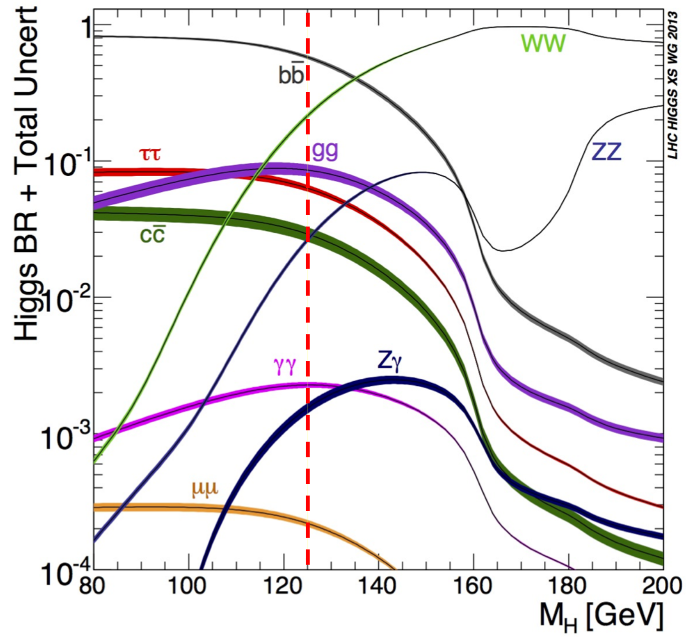



- *Total Higgs production cross section has been measured at 7 TeV, 8 TeV and 13 TeV*
  - *Good agreement between with SM prediction*
- *Theory precision ($N^3LO$) improved by factor 2 since Run 1* *(e.g. gluon-gluon fusion, Anastasiou et al.; 1602.00695)*

## *Rare and Forbidden Higgs Production and Decays*

# Searches for Rare Higgs Decays

- *Search the large ATLAS data set for rare Higgs decay modes predicted by the SM*
- *95% C.L. limits on decays to lighter quarks*
  - *$H \rightarrow cc$ (VH) : $\mu < 110$*
  - *$H \rightarrow cc$ ($J/\psi\ \gamma$) : $\mu < 120$*
  - *$H \rightarrow ss$ ($\varphi\ \gamma$) : $\mu < 208$*
  - *$H \rightarrow uu, dd$ ($\rho\ \gamma$) : $\mu < 52$*

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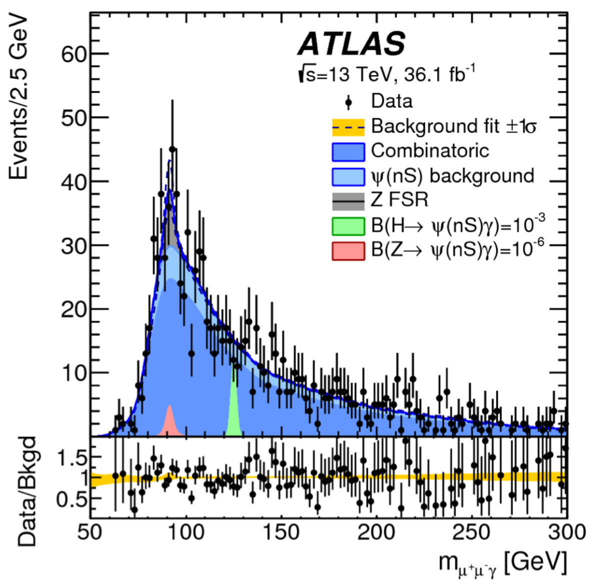
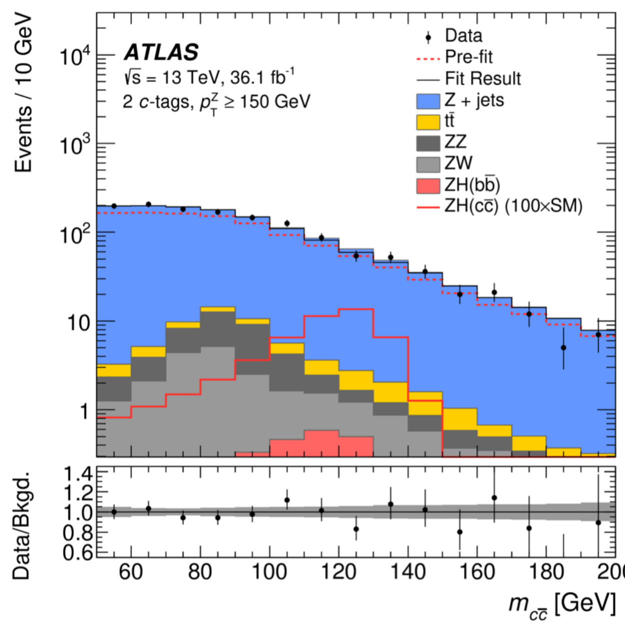
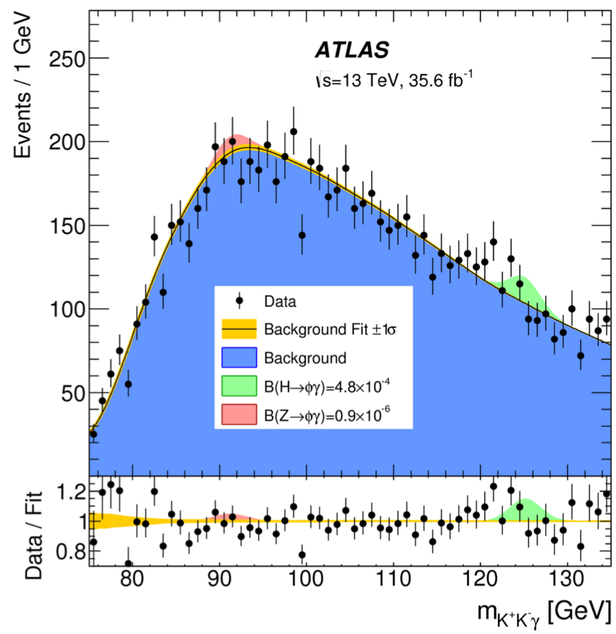



Phys. Rev. Lett. 120 (2018) 21180



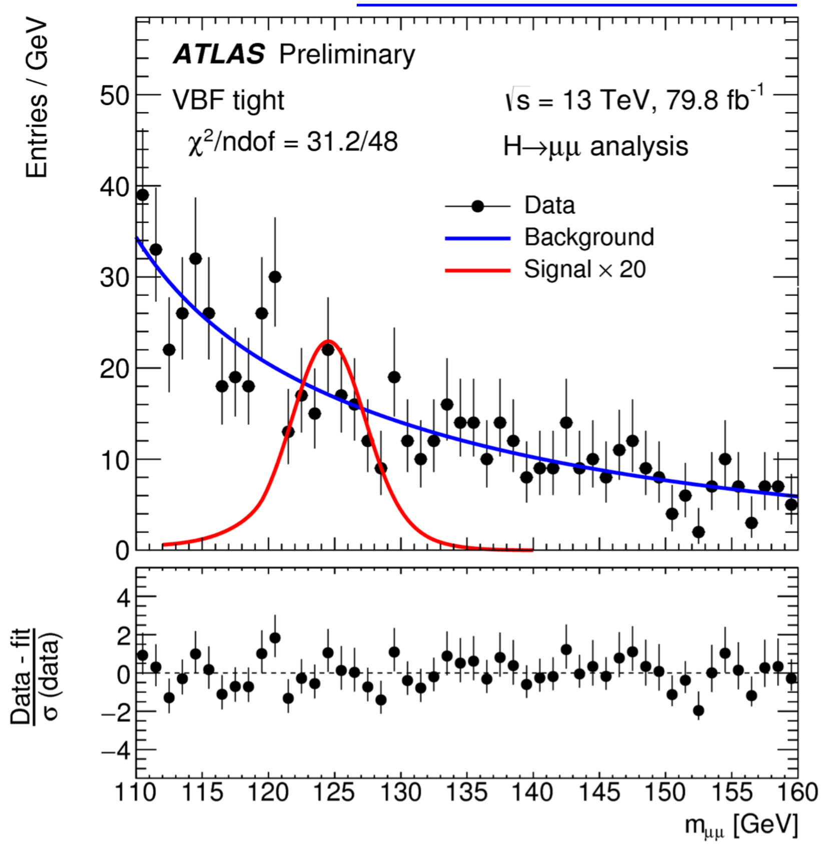

JHEP 07 (2018) 127



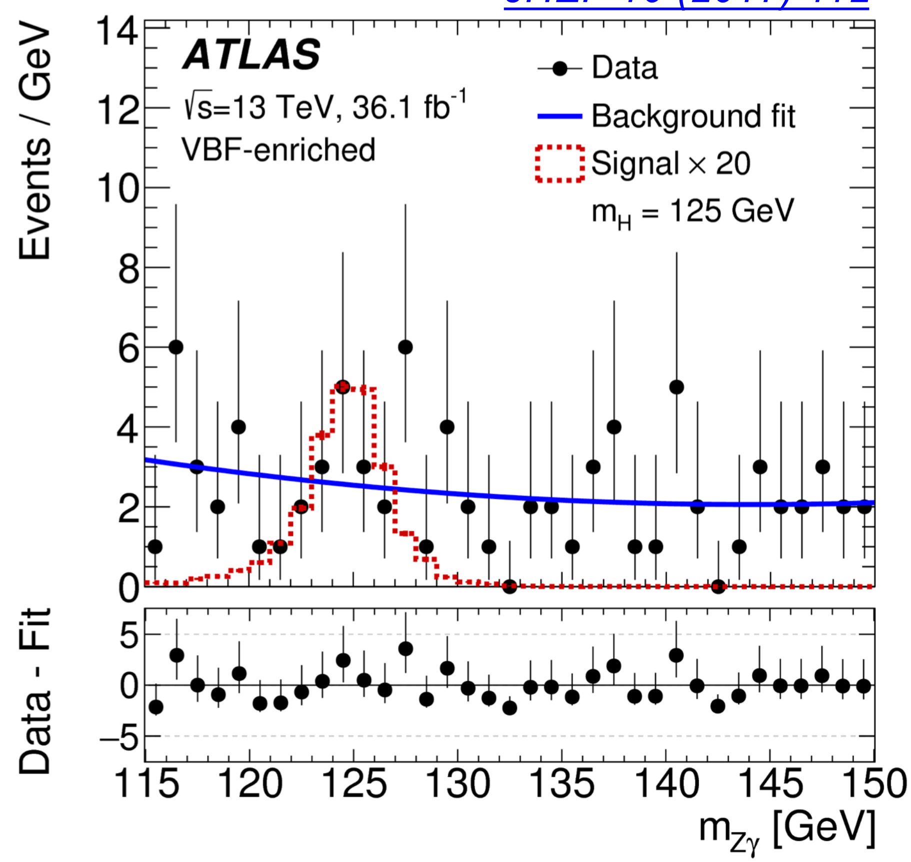
# *Searches for Rare Higgs Decays (cont'd)*

- *$H \rightarrow \mu\mu$ : $\mu < 2.1$ ($\mu = 0.1^{+1.0}_{-1.1}$)*
  - *Tests coupling to second-generation leptons; SM BF $2.2\times 10^{-4}$*
- *$H \rightarrow Z\gamma$: $\mu < 6.6$*
  - *BF could be enhanced e.g. if Higgs is composite state, in models with additional colorless charged scalars, leptons or vector bosons coupled to the Higgs boson*

ATLAS-CONF-2018-026



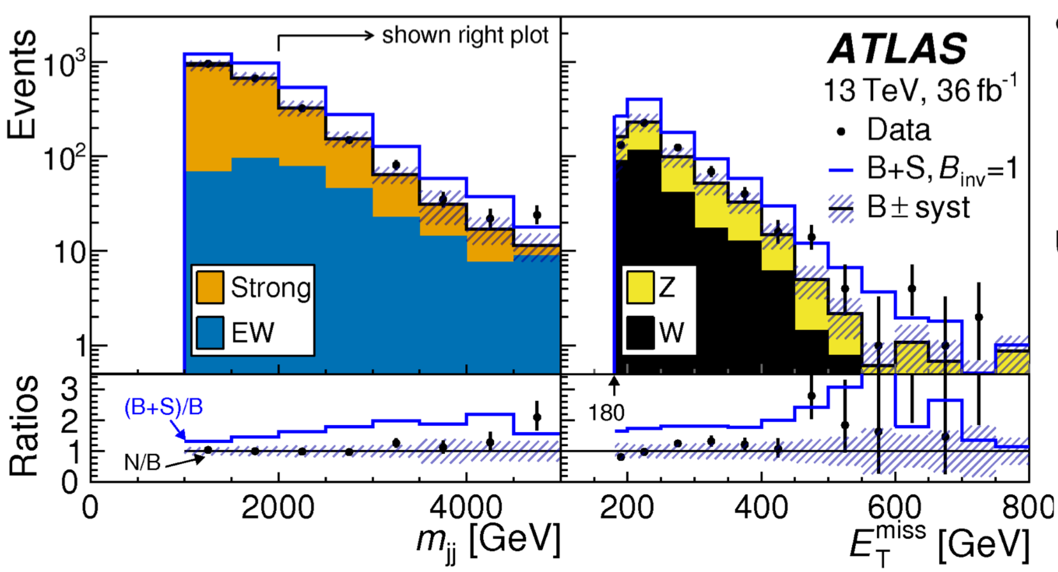

JHEP 10 (2017) 112



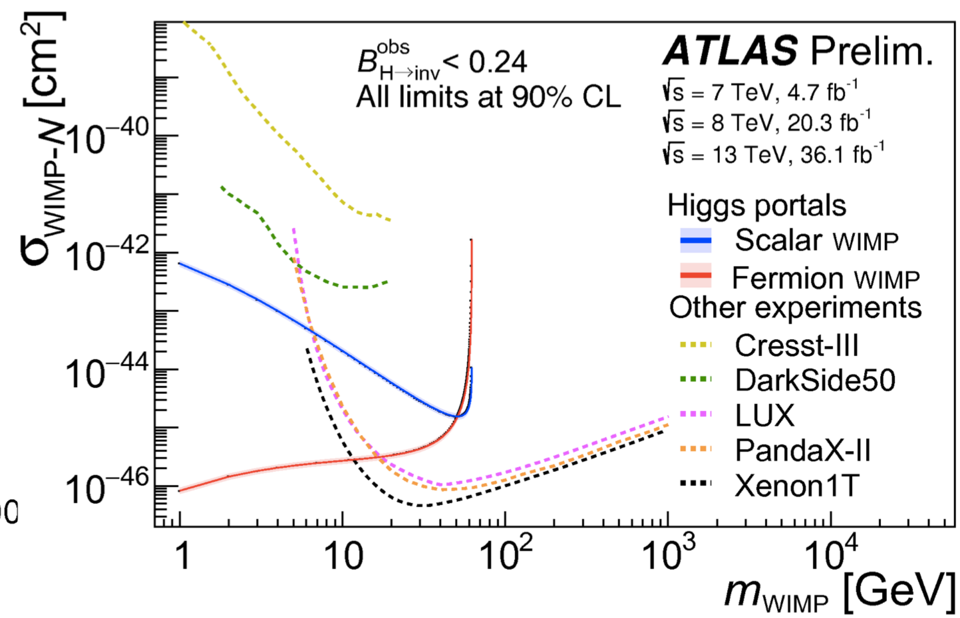
# Higgs to Invisible

- SM branching fraction for $H \rightarrow ZZ^* \rightarrow 4\nu$ is $1.2 \times 10^{-3}$
  - Branching fraction could be enhanced by decays to undetected BSM particles
- Searched for $H \rightarrow$ invisible in VBF and (W/Z)H processes
  - Combination: observed (expected) BR($H \rightarrow$ invisible) < 26% (17%) @ 95% C.L.
  - Much better limit/measurement could be achieved at future 250 GeV $e^+e^-$ collider
- Set limits on Higgs coupling to dark matter particles

1809.06682 (submitted to PLB)




ATLAS-CONF-2018-054

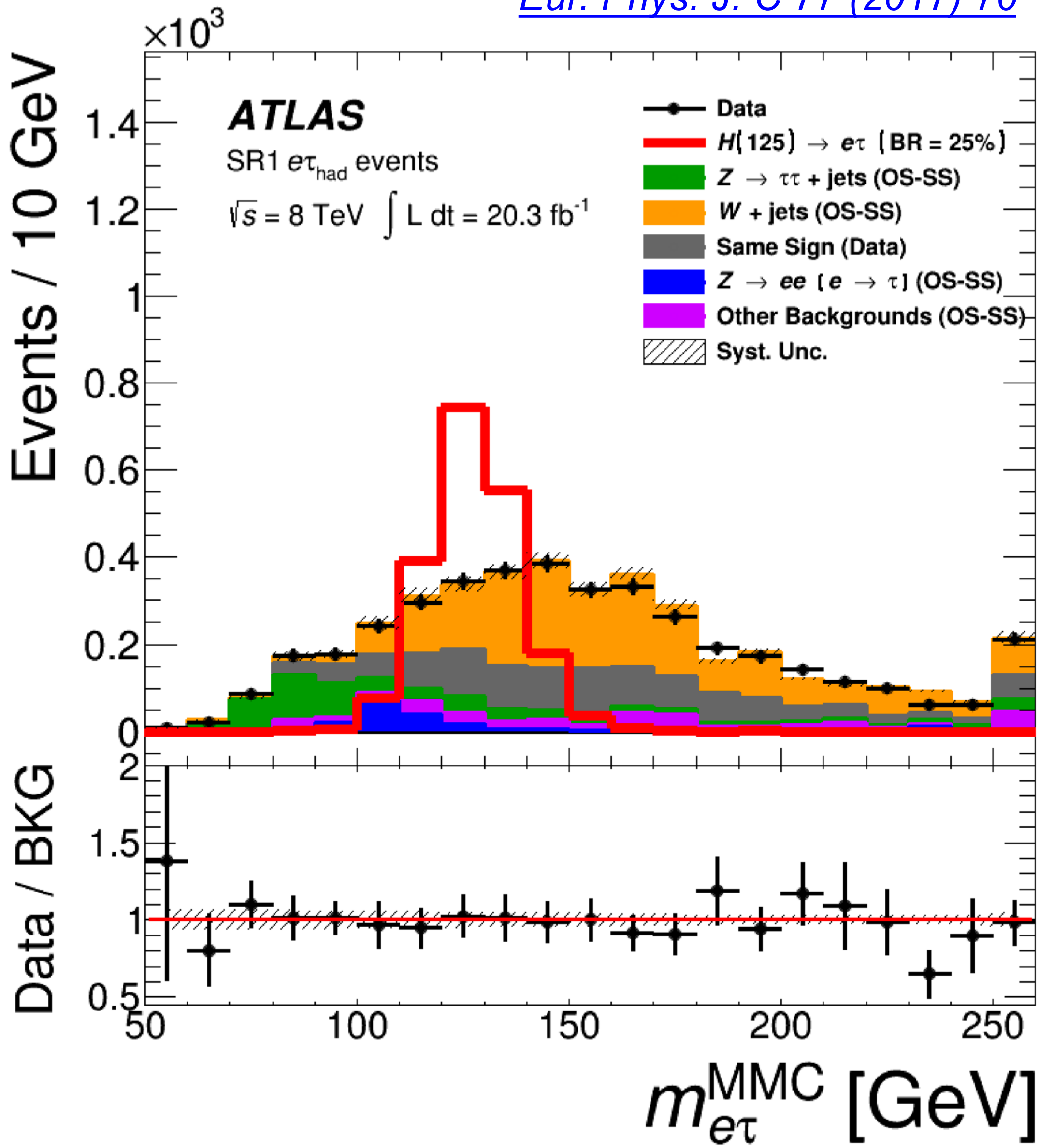


# *Lepton-flavor violating Higgs Decays*

- *Lepton-flavor violating (LFV) decays are forbidden in the SM*
  - *LFV can occur e.g. in 2HDM, composite Higgs models, models with flavor symmetries, Randall– Sundrum models*

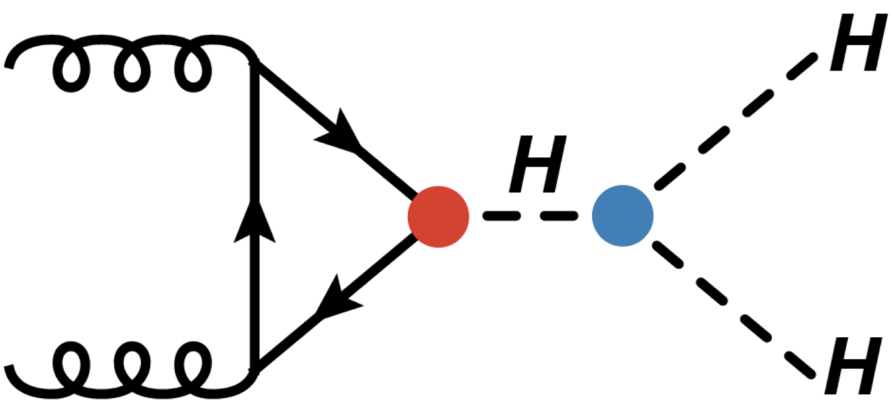
- *Search for LFV in $H \to e\tau$ and $H \to \mu\tau$ final states*
  - *$B(H \to e\tau) < 1.04\%$*
  - *$B(H \to \mu\tau) < 1.43\%$*

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

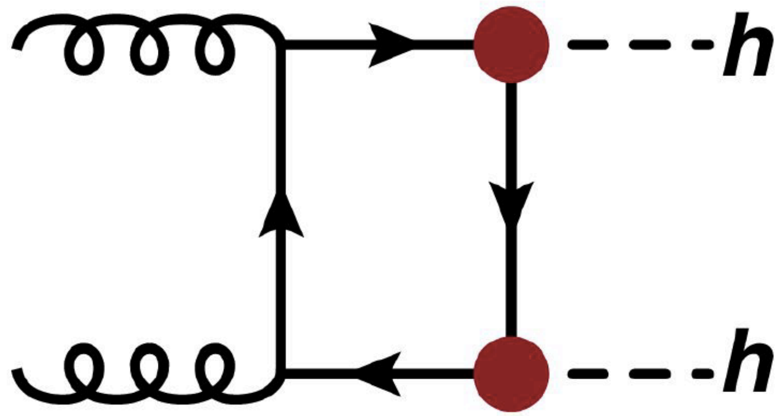


# Di-Higgs Production

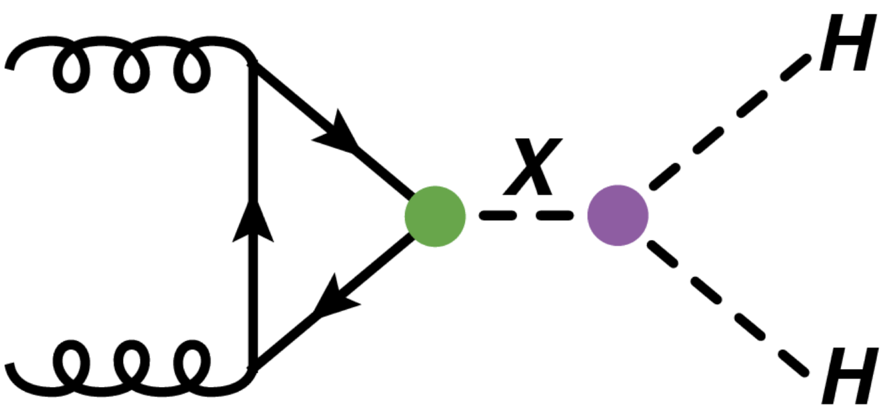
- *Higgs boson has mass and therefore couples to itself*
- *(Non-resonant) di-Higgs production tests Higgs self-coupling*
- *Small cross-section (33 fb) due to destructive interference of two diagrams*



Higgs self-coupling



"Background"



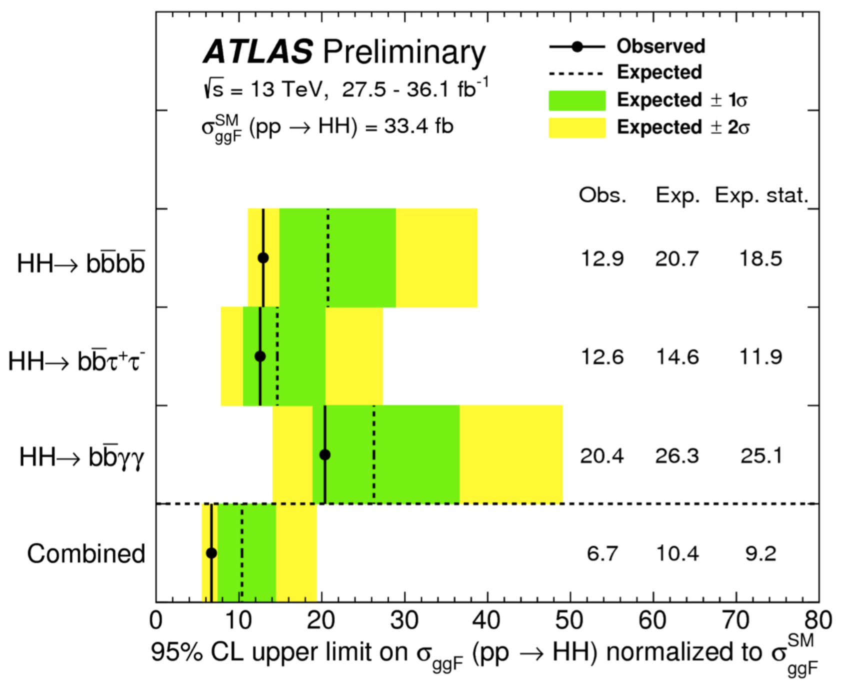
New Physics

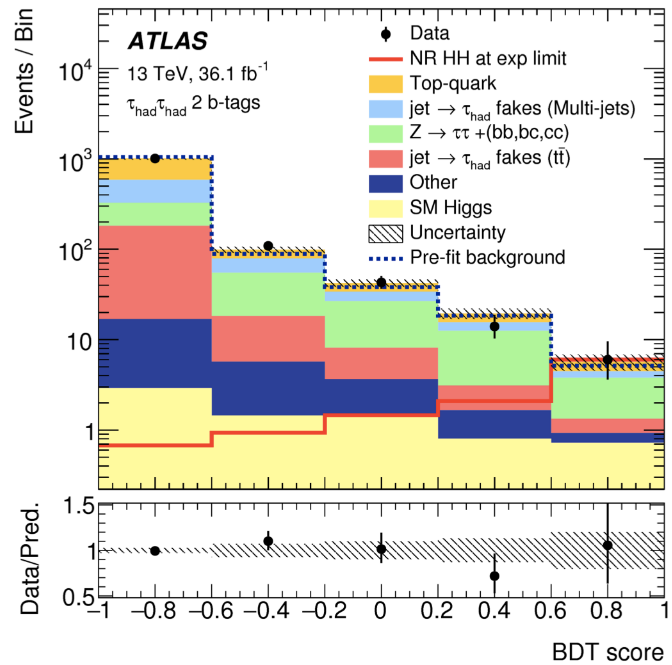
# *Double Higgs Production (cont'd)*

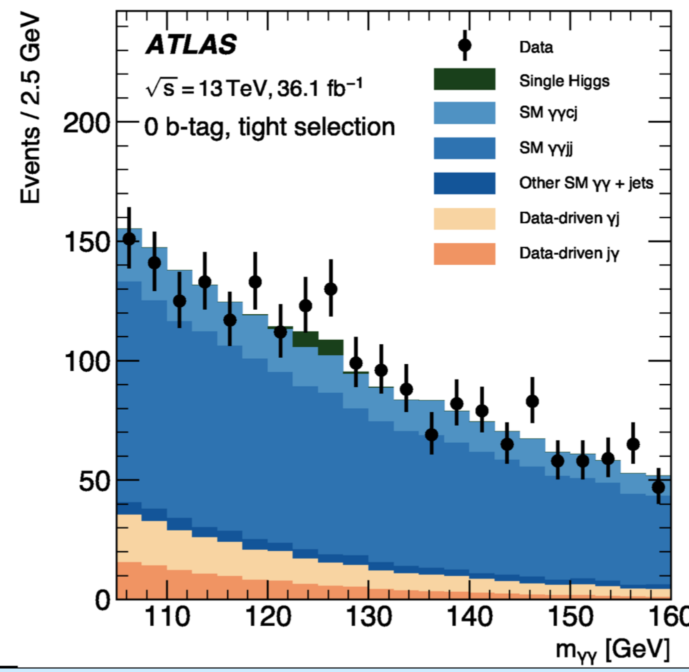
- *Several combinations of Higgs final states*

| Final state | μ < @ 95% C.L. | Reference |
|---|---|---|
| bbbb | 13 | 1804.06174 |
| bbττ | 12.7 | PRL 121 (2018) 191801 |
| bbWW | 300 | 1811.04671 |
| bbγγ | 22 | JHEP 11 (2018) 040 |
| WWγγ | 230 | 1807.08567 |

ATLAS-CONF-2018-043



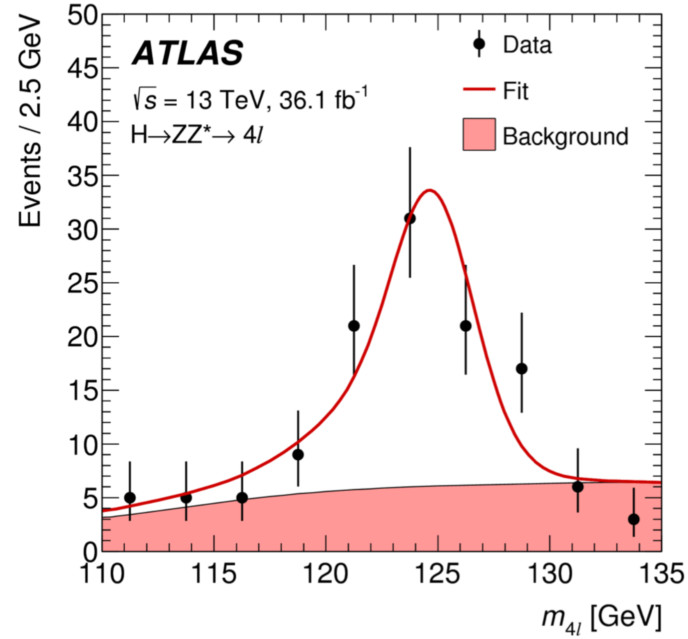



*Higgs Properties*

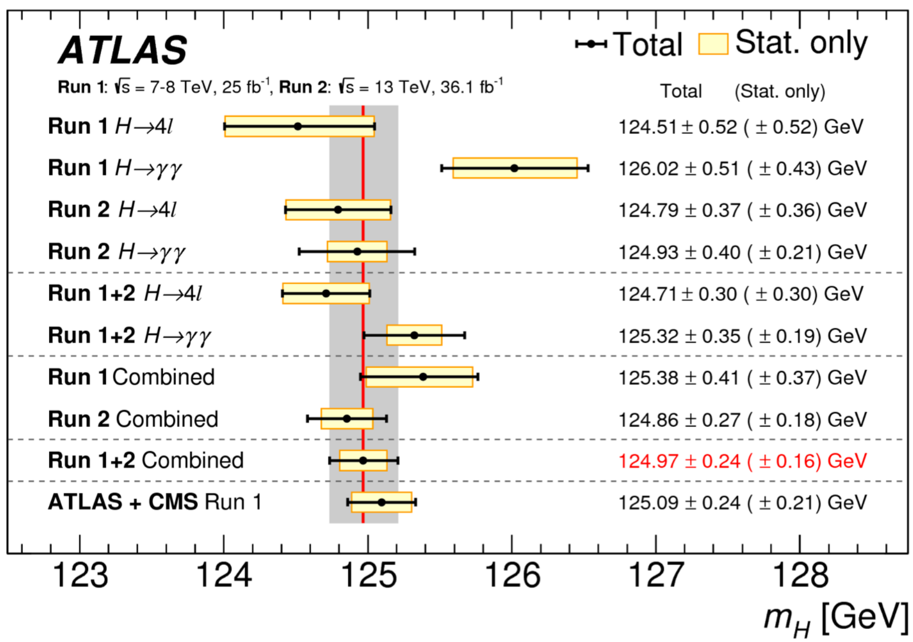
# Higgs Mass

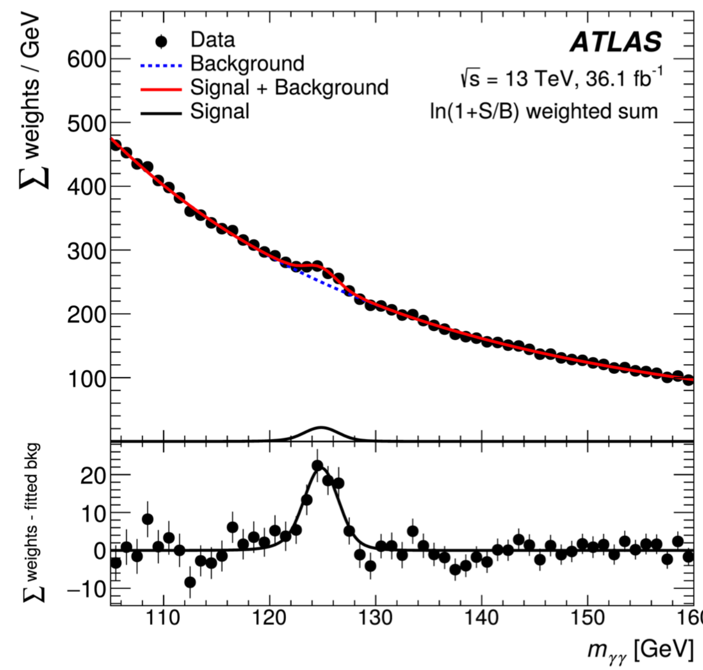
- *Higgs mass only loosely connected to top and W masses through quantum loops*




- *Much better measured directly from precision Higgs decays to ZZ* and γγ*
  - *Relative uncertainty is 0.2 %*
  - *dominated by statistics (ZZ*) and electromagnetic calorimeter calibration (γγ)*

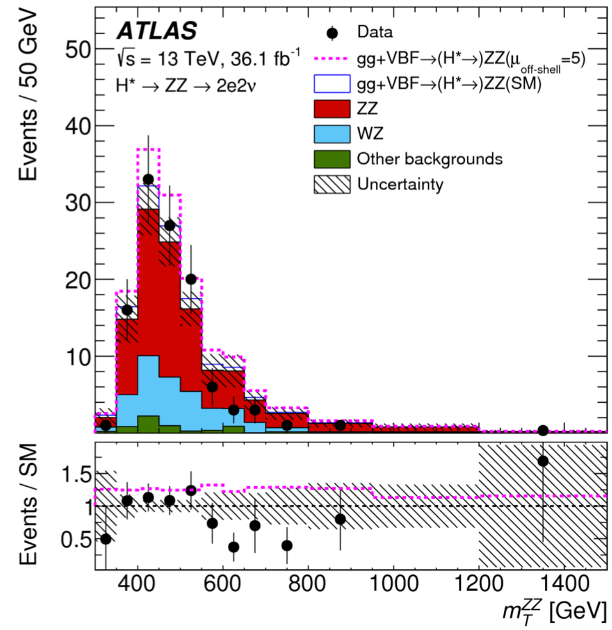
[Phys. Lett. B 784 (2018) 345]



# Higgs Width

- *Sensitivity of direct measurements is 3 orders of magnitude larger than SM prediction (Γ = 4.2 MeV)*
- *Indirect constraint on Higgs width from measurement of on-shell vs off-shell H→ZZ* cross section (Kauer & Passarino, JHEP (2012) 116; Caola & Melnikov, PRD88 (2013) 054024)*




*Γ < 14.4 MeV (3.5 × $\Gamma_{SM}$)*

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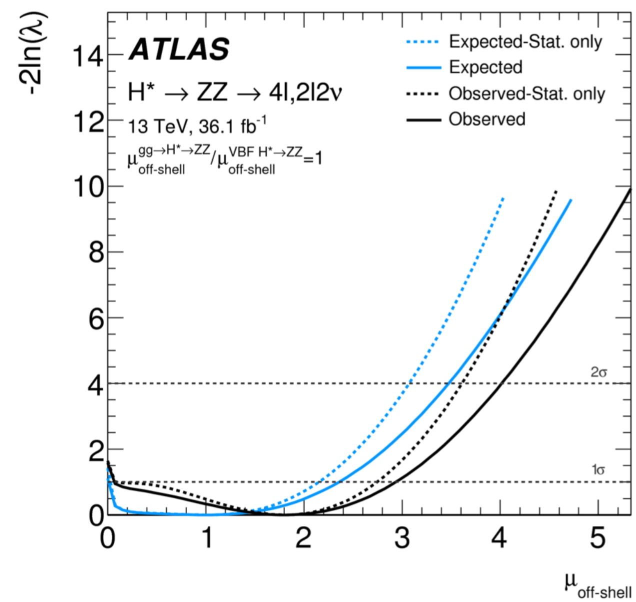
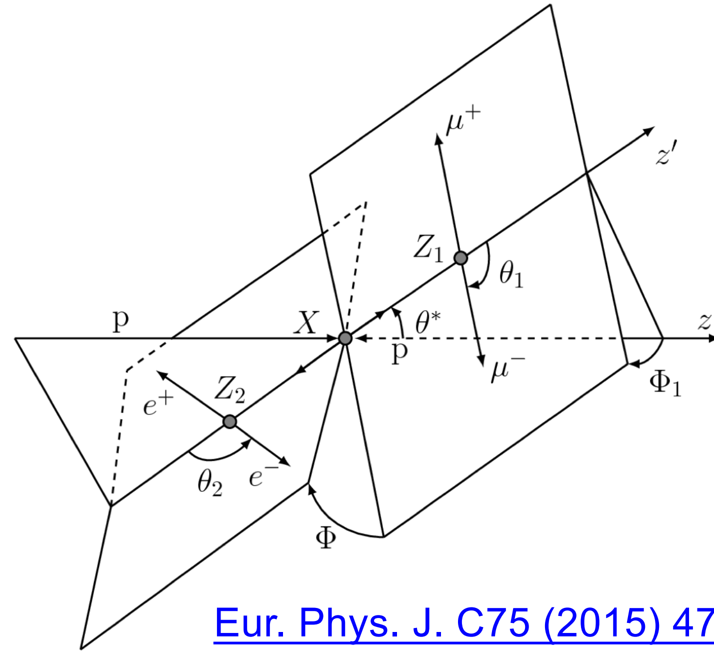
| | | Observed | Median | Expected ±1 σ | ±2 σ |
|---|---|---|---|---|---|
| $\mu_{\text{off-shell}}$ | $ZZ \to 4\ell$ analysis | 4.5 | 4.3 | [3.3, 5.4] | [2.7, 7.1] |
| | $ZZ \to 2\ell 2\nu$ analysis | 5.3 | 4.4 | [3.4, 5.5] | [2.8, 7.0] |
| | Combined | 3.8 | 3.4 | [2.7, 4.2] | [2.3, 5.3] |
| $\Gamma_H/\Gamma_H^{\text{SM}}$ | Combined | 3.5 | 3.7 | [2.9, 4.8] | [2.4, 6.5] |
| $R_{gg}$ | Combined | 4.3 | 4.1 | [3.3, 5.6] | [2.7, 8.2] |

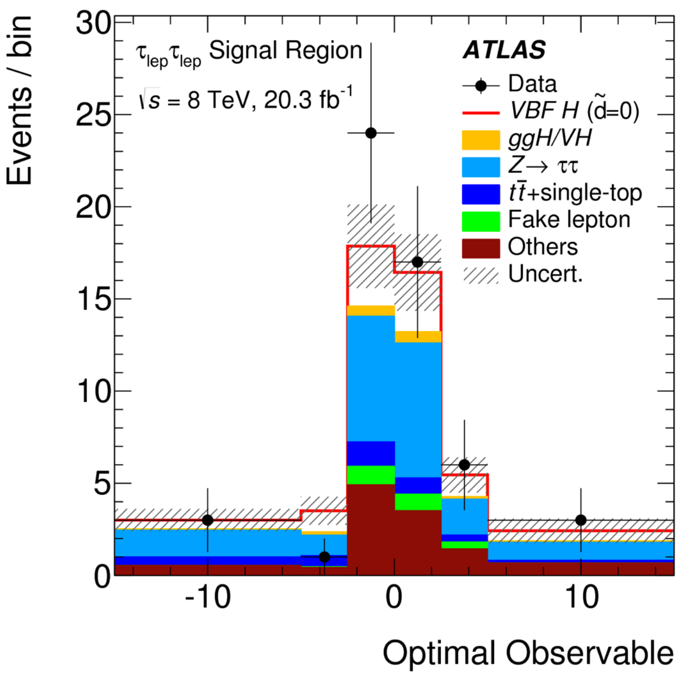


# *Higgs Quantum Numbers and CP Violation*

- *SM predicts $J^{PC} = 0^{++}$*
- *Decay angular distributions in $H \to \tau\tau$, $ZZ^*$, $WW^*$ and $\gamma\gamma$ are sensitive to $J^P$*
- *All tested alternative models (incl. non-SM spin-0 and spin-2 models with universal/non-universal couplings) excluded > 99.9% C.L.*

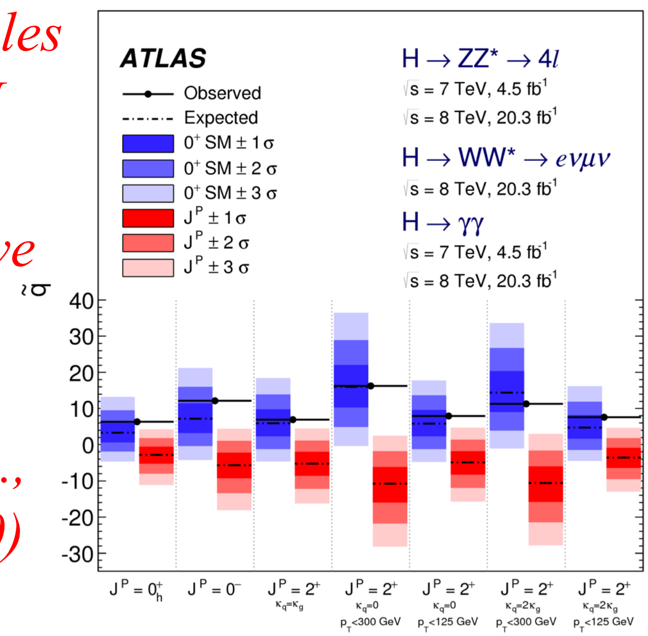



Eur. Phys. J. C76 (2016) 658




- *Measured CPV observables in $H \to \tau\tau$ agree with SM and no CPV*
- *EFT parameter $\tilde{d}$ sensitive to CPV interactions*
- *$\tilde{d}$ constrained to range $[-0.11, 0.05]$ at 68% C.L., consistent with SM ($\tilde{d} = 0$)*

Eur. Phys. J. C75 (2015) 476



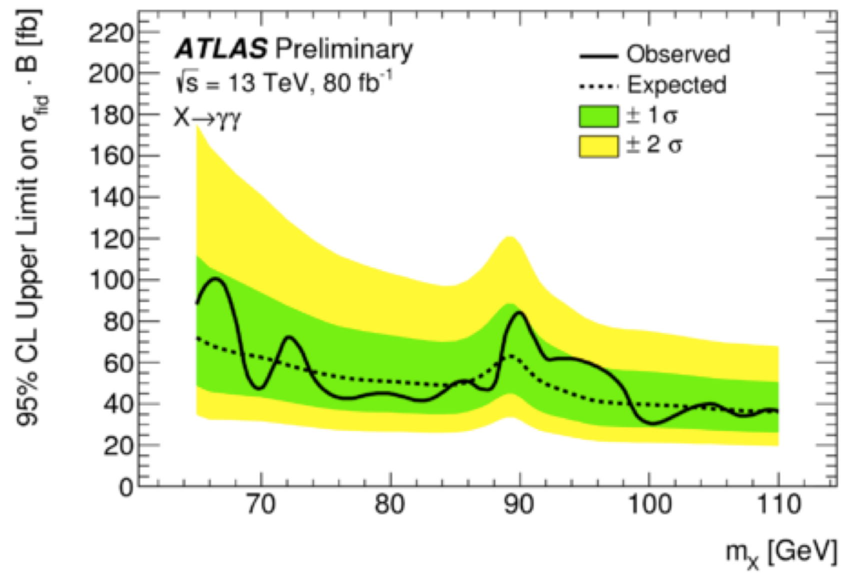
*Are there other Higgs bosons?*

# Additional Higgs Bosons

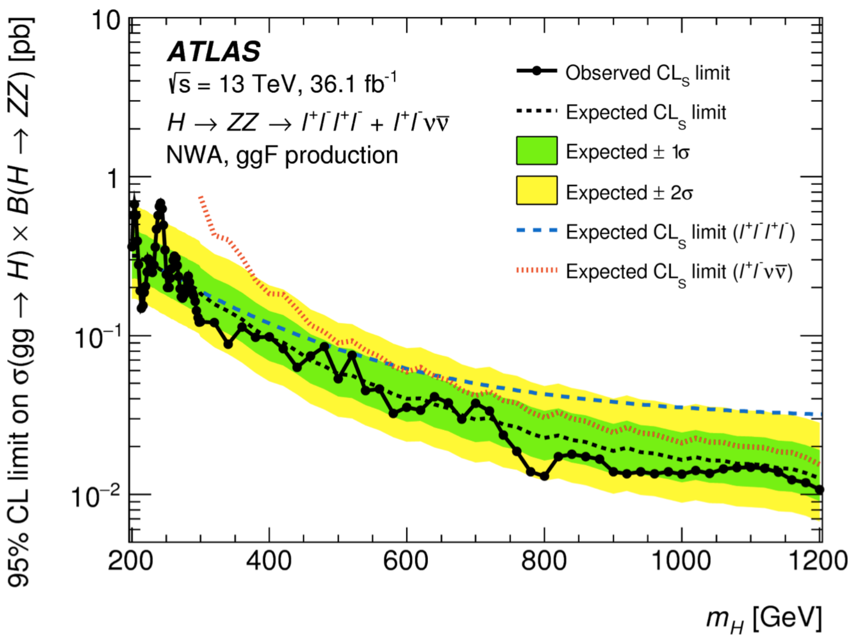
*Many BSM models (incl. SUSY) predict additional neutral or charged Higgs bosons*

Additional neutral SM-like Higgs bosons with different mass

ATLAS-CONF-2018-025

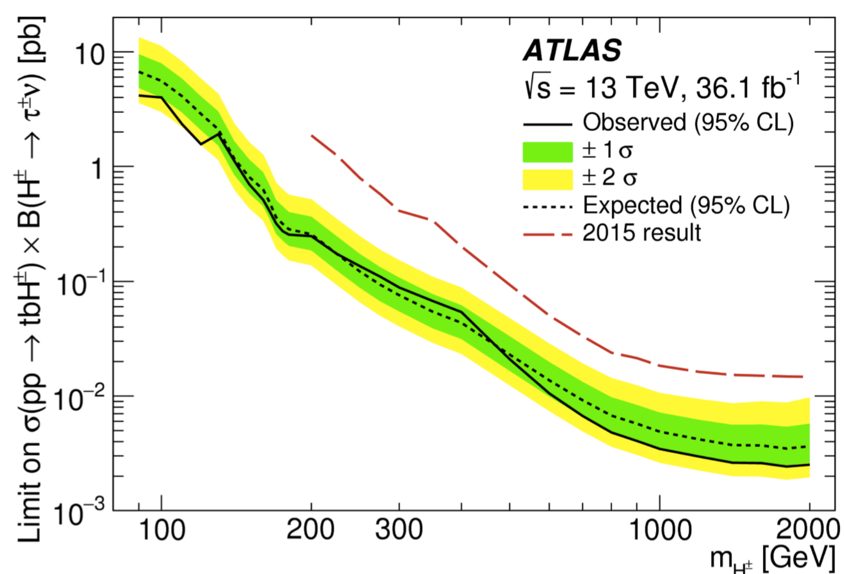



*Phys. J. C 78 (2018) 293*




*JHEP 09 (2018) 139*

Charged Higgs bosons




*No additional Higgs(-like) particles observed so far.*

# *Conclusions*

- *ATLAS rapidly moved from Higgs discovery to intense studying*
- *All main production and decay modes have been observed*
  - *Exploration of the fermionic sector in Run 2*
- *Higgs mass measured to 0.2% precision*
- *Constraints on Higgs width from off-shell measurements*
- *Higgs charge- and parity quantum numbers consistent with SM*
- *Searches for subdominant SM decay modes are being developed*
- *Search for di-Higgs production has begun*
- *Searches for rare or non-SM Higgs decays and extra Higgs bosons*

*So far, the data have been in excellent agreement with the SM*
*... but maybe that changes with the remaining 95% of LHC data*

Many more ATLAS Higgs results and details at https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

*Back-Up Slides*

# ATLAS Prospects for HL-LHC

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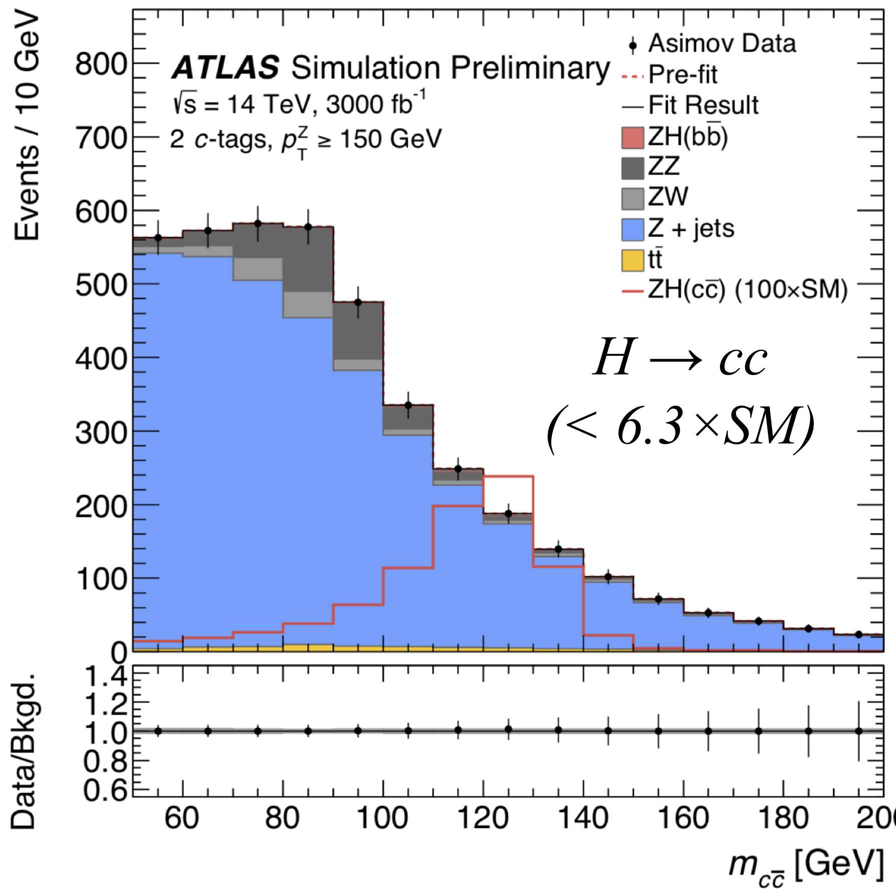


ATL-PHYS-PUB-2018-006