Observation of ttH Production with the ATLAS Detector

Lianliang MA（马连良）

Shandong University

June 20-24, 2018@Shanghai

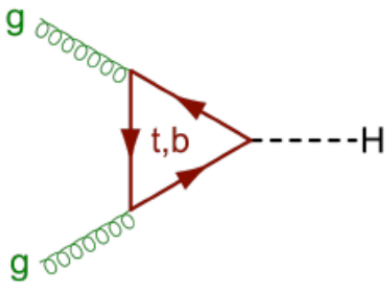
Outline

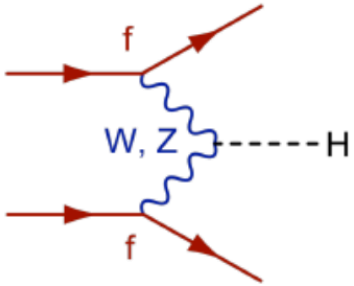
- Introduction
- Search for ttH production at ATLAS
  - ✓ ttH, H→ $\gamma\ \gamma$ with 79.1 fb^{-1}
  - ✓ ttH, H→ZZ* with 79.1 fb^{-1}

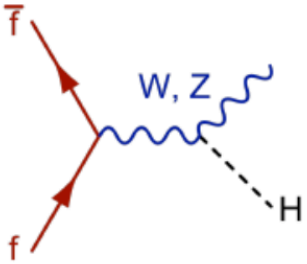
  } arXiv:1806.00425

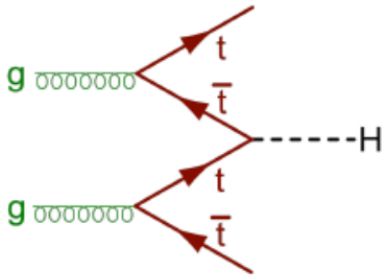
  - ✓ ttH in multi-lepton with 36.1 fb^{-1} Phys. Rev. D **97**, 072003 (2018)
  - ✓ ttH, H→bb with 36.1 fb^{-1} Phys. Rev. D **97**, 072016 (2018)
- Combined results and summary

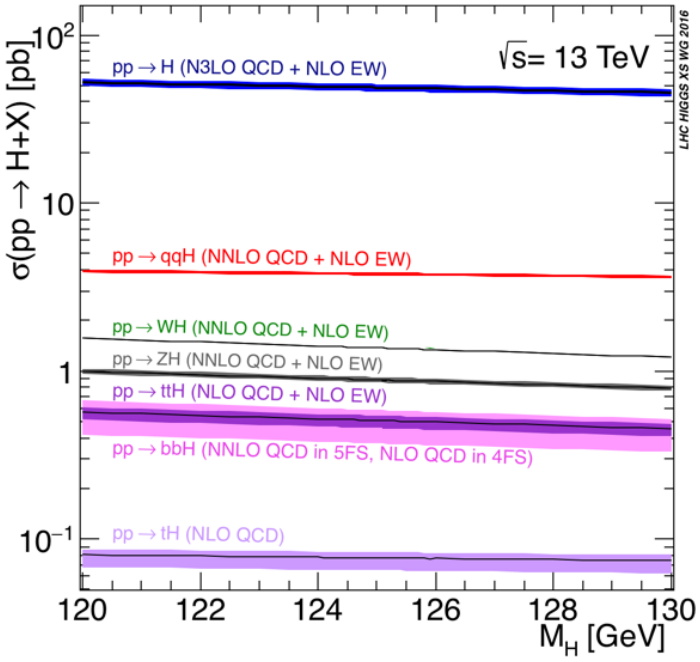
Higgs Production at LHC





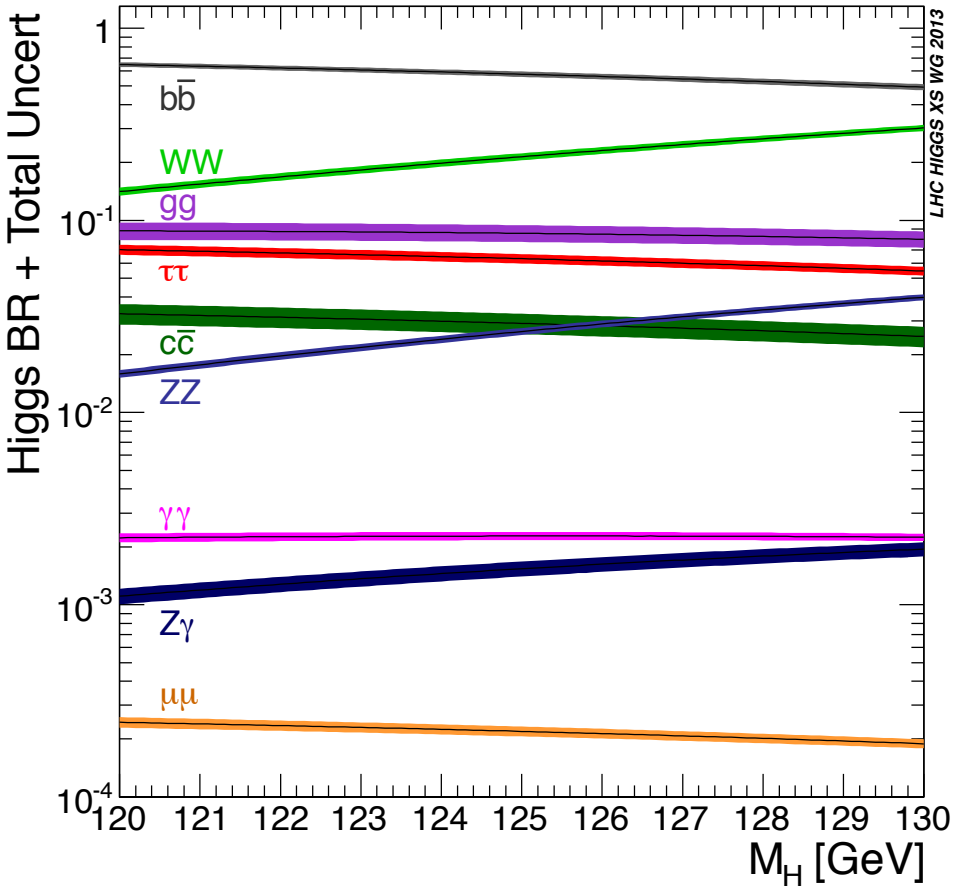






- ✧ **87.2%: gluon-gluon fusion (ggF)**
- ✧ **6.8%: vector boson fusion (VBF)**
- ✧ **4.1%: WH/ZH**
- ✧ **0.9%: ttH**
- ✧ **Observed modes: ggF and VBF**
- ✧ **Cross sections increases from Run I to Run II by a factor of 3.9 for ttH**

Higgs Boson Decays



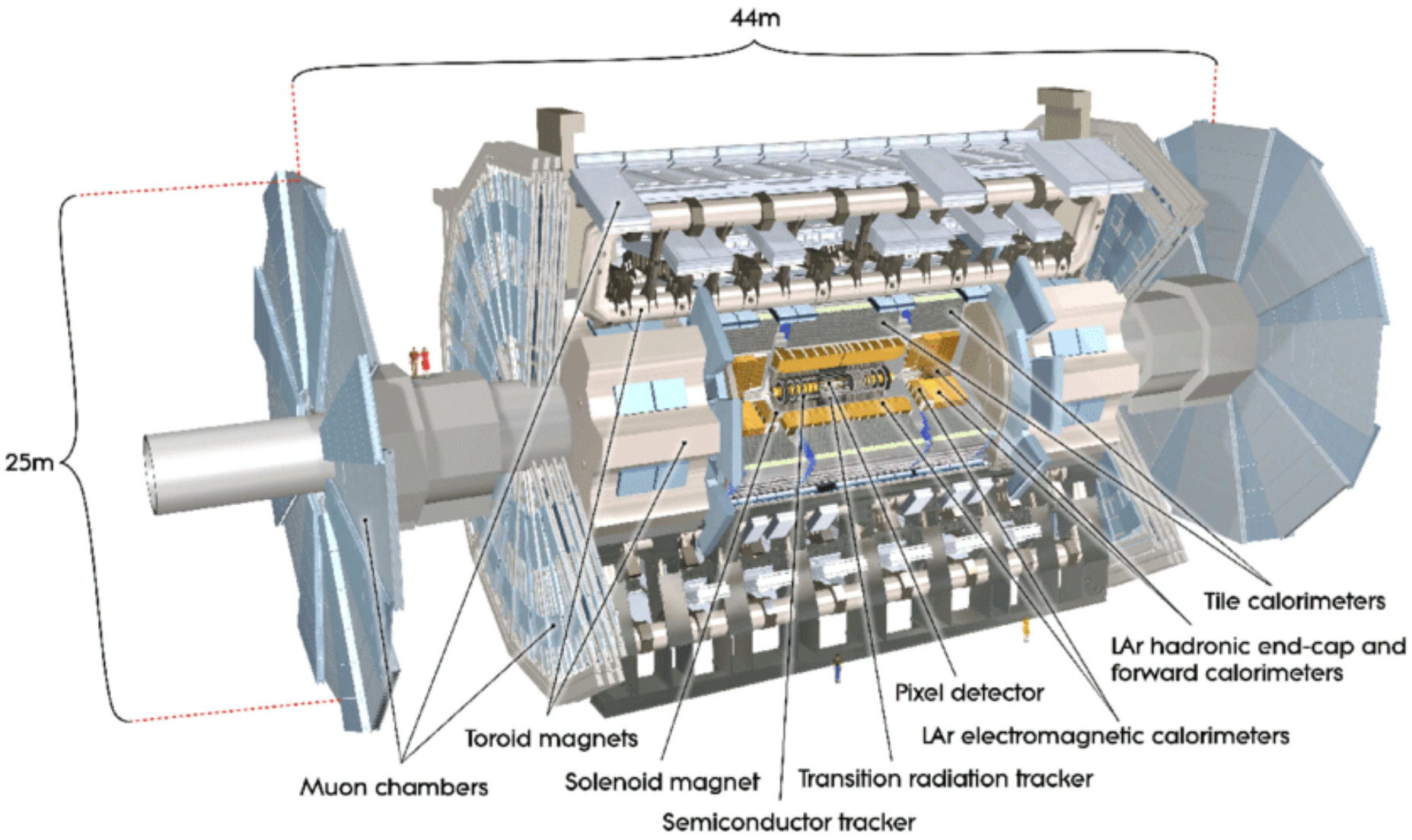
γγ, ZZ*, WW*, ττ observed in Run I (significance >5σ)

In order to maximize the analysis sensitivity, all possible Higgs decay modes of bb, WW*, γγ, ZZ*, ττ are analyzed in searching for ttH process.

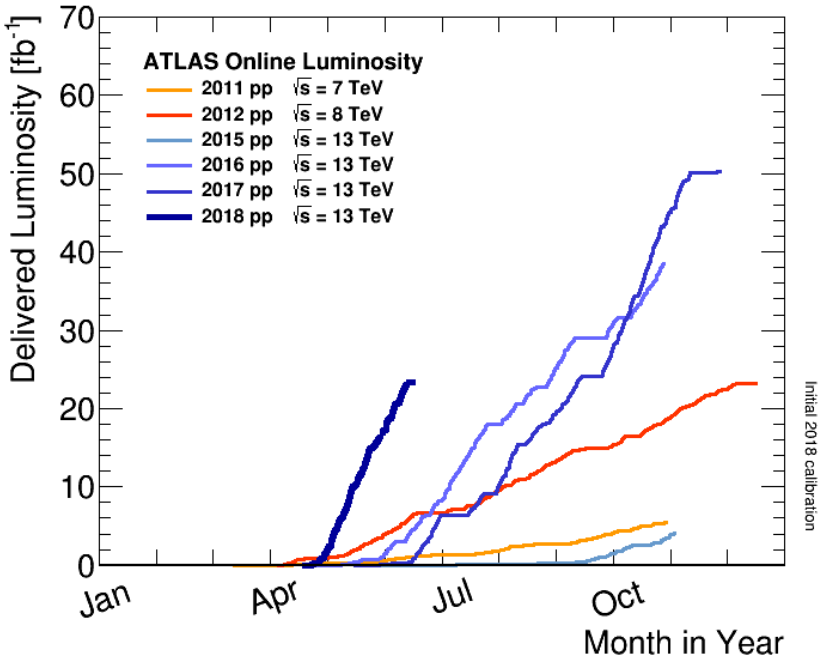
Importance of ttH:

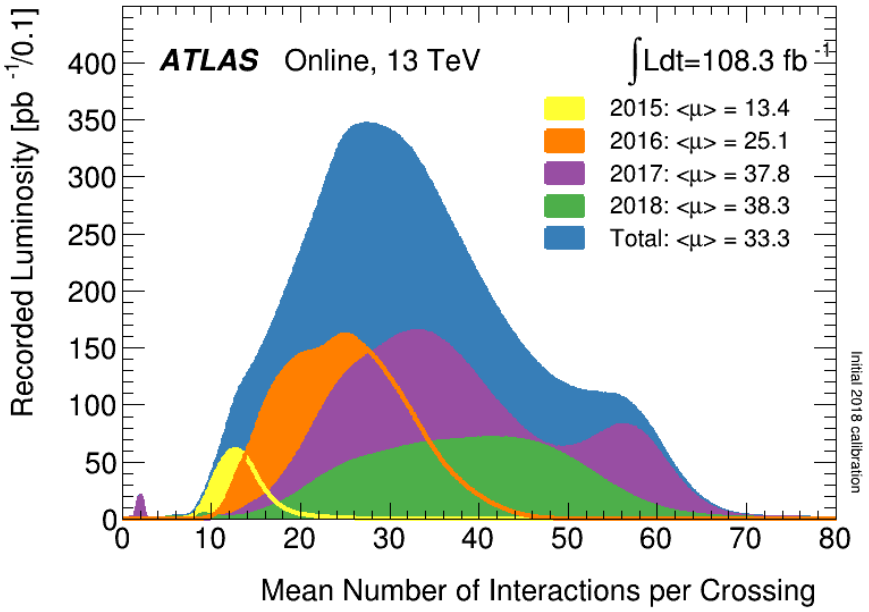
- Establish one of the main Higgs production modes
- Direct measurement of Higgs coupling to top quark, the heaviest particle in SM

ATLAS Detector



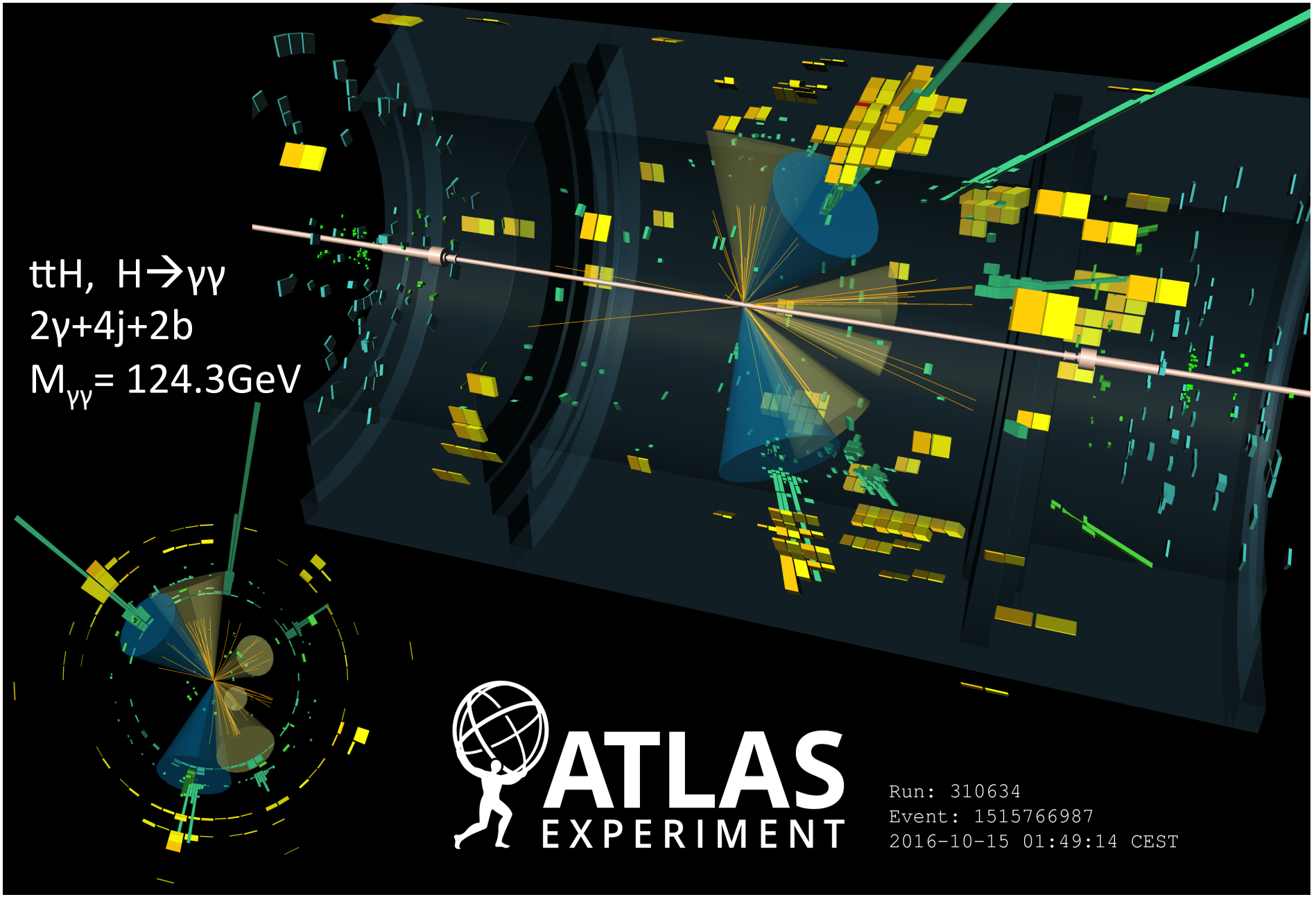
Data Collected by ATLAS





Evolution of ttH results from ATLAS experiment:

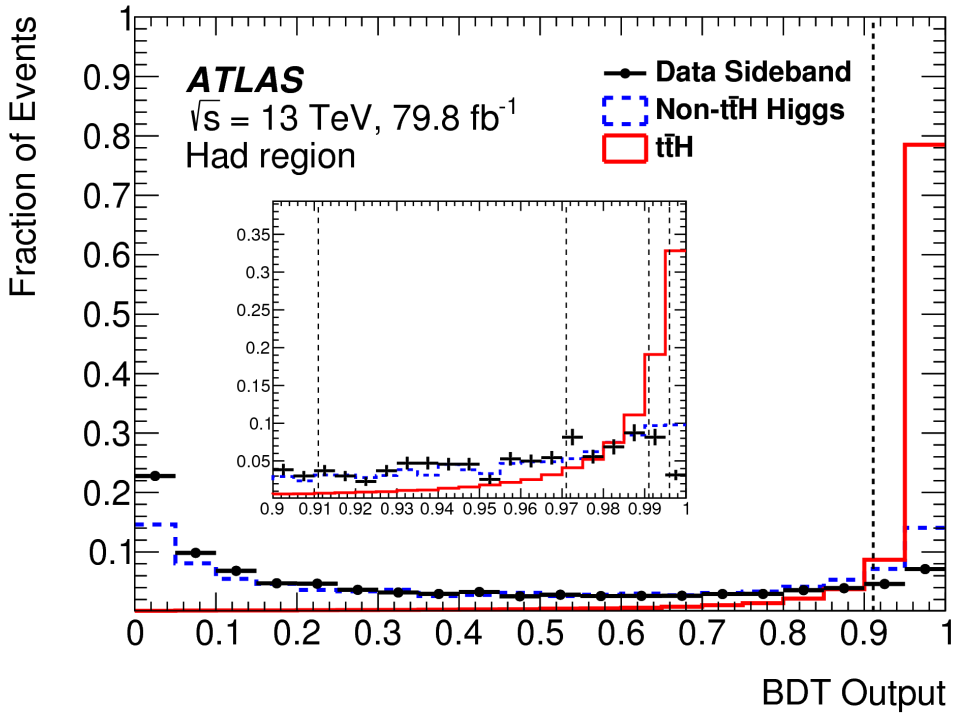
- ✧ Run I (20.3 fb^{-1}): 2.5 σ (1.5 σ expected) Eur. Phys. J. C (2016) 76:6
- ✧ Run I + Run II (36.1 fb^{-1}): 4.2 σ (3.8 σ expected) Phys. Rev. D **97**, 072003 (2018)
- ✧ Run I + Run II up to 78.1 b^{-1}: observation in this talk


ttH, H→γγ
2γ+4j+2b
$M_{\gamma\gamma}$= 124.3GeV
ATLAS
EXPERIMENT
Run: 310634
Event: 1515766987
2016-10-15 01:49:14 CEST

ttH, H→γγ： Analysis Overview

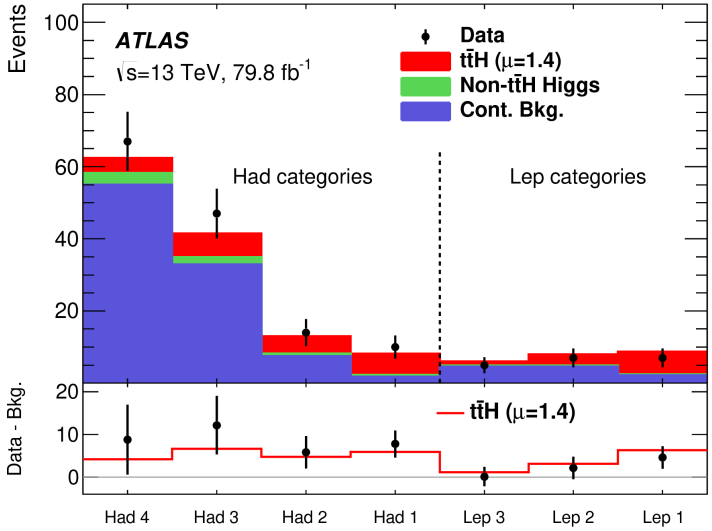
- Small rate, but Higgs signal as a narrow peak
- Leptonic (≥1ℓ) and hadronic (0ℓ) categories based on ttbar decay
- BDT training ttH (MC) from the main backgrounds: γγ/ttγγ (Control Regions), and other Higgs (MC)

- Further categorization on selected events with high BDT score: 3/4 bins for the leptonic/ hadronic category, based on expected sensitivity optimization
- 50% improvement in sensitivity: changes in analysis strategy and update to ATLAS software

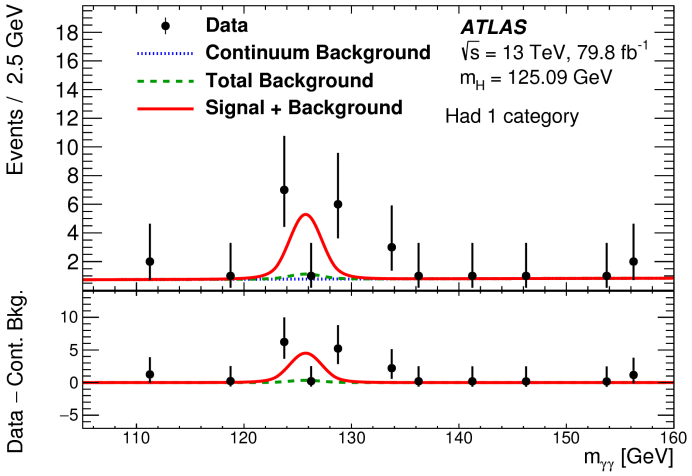


ttH, H→γγ: Event Yield

Bin	Expected $t\bar{t}H$ (signal)		Non-$t\bar{t}H$ Higgs		Non-Higgs		Total		Observed Total
				$H \to \gamma\gamma$					
Had 1	4.2	± 1.1	0.49	± 0.33	1.8	± 0.5	6.4	± 1.3	10
Had 2	3.4	± 0.7	0.7	± 0.6	7.5	± 1.1	11.6	± 1.5	14
Had 3	4.7	± 0.9	2.0	± 1.7	32.9	± 2.2	39.6	± 3.2	47
Had 4	3.0	± 0.5	3.2	± 3.1	55.0	± 2.8	61	± 5	67
Lep 1	4.5	± 1.0	0.24	± 0.09	2.2	± 0.6	6.9	± 1.2	7
Lep 2	2.2	± 0.4	0.27	± 0.10	4.6	± 0.9	7.1	± 1.0	7
Lep 3	0.82	± 0.18	0.30	± 0.13	4.6	± 0.9	5.7	± 0.9	5



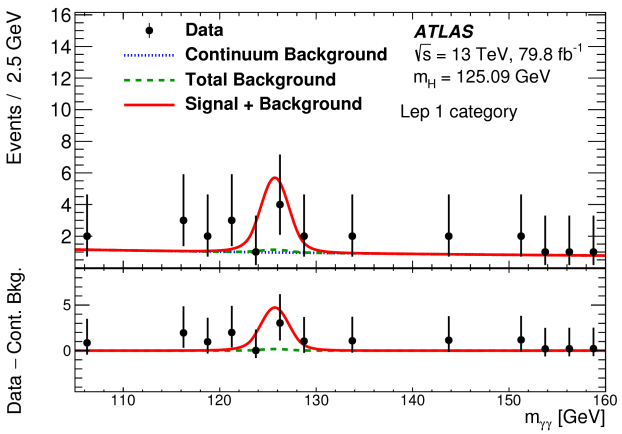
Look at the mγγ for each category

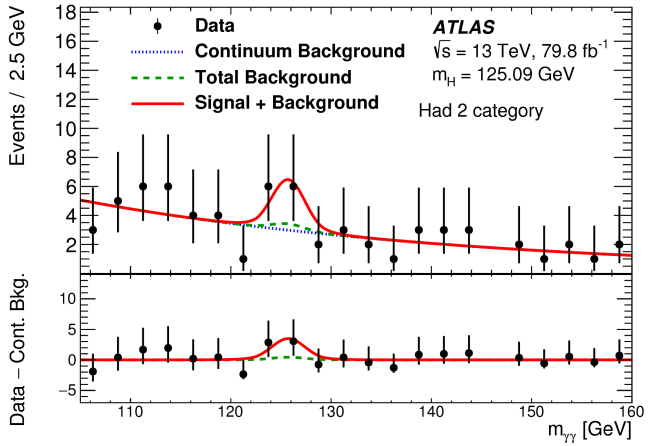


ttH, H→γγ: Result

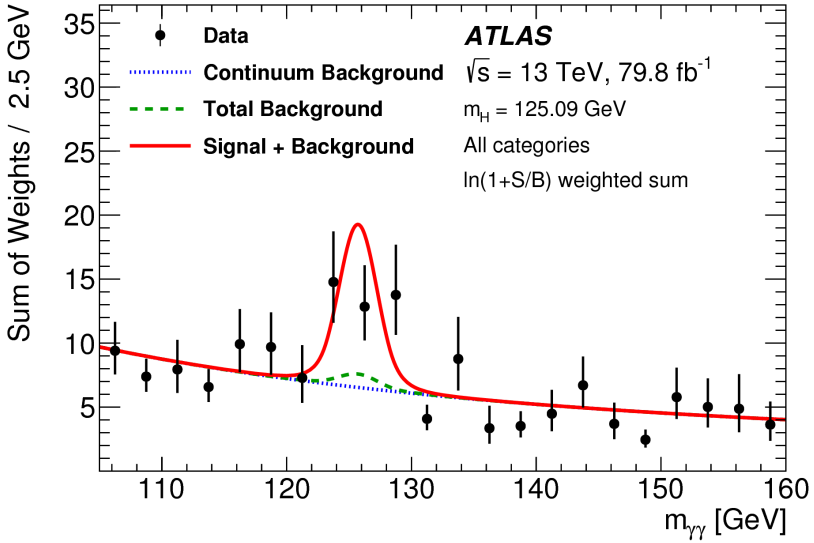
Simultaneous unbinned fit performed on $m_{\gamma\gamma}$ spectra (105-160 GeV) in all 7 categories

Signal with double-sided Crystal Ball function





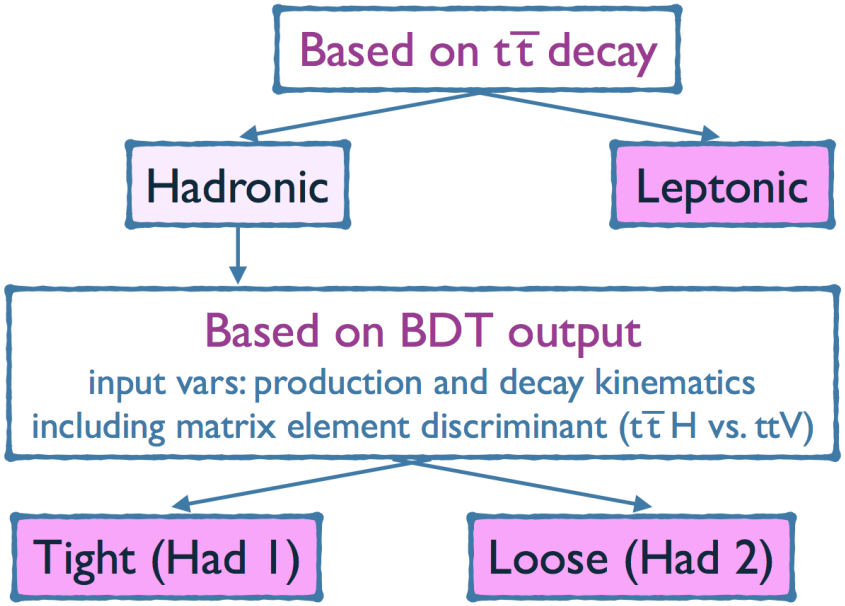
weighted by $\ln(1 + S_{90}/B_{90})$

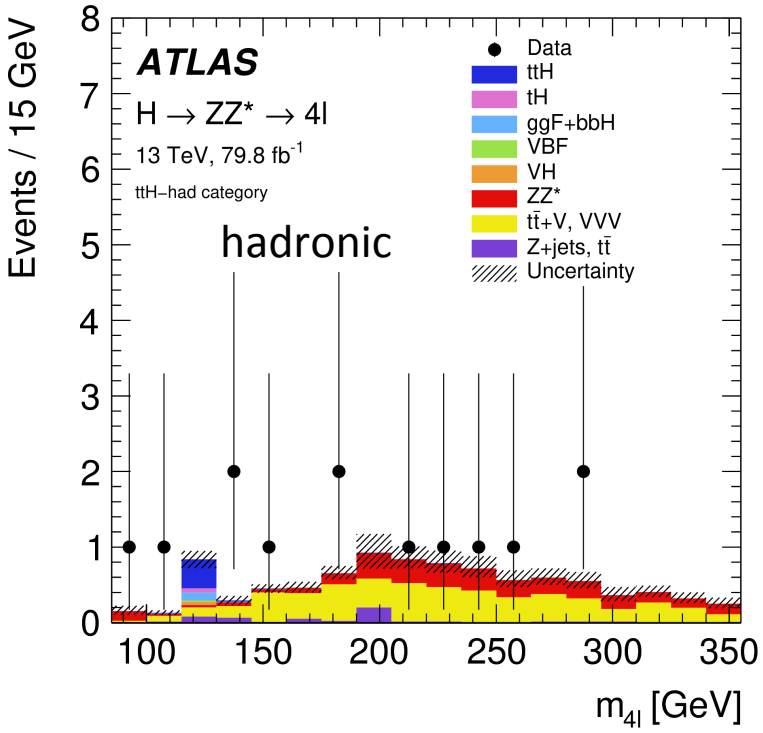


- Significance:
  4.1σ (exp. 3.7 σ)
- Dominant systematics:
  - Stats.: 29%
  - ttH PS model: 8%

ttH, H→ZZ*： Analysis Overview

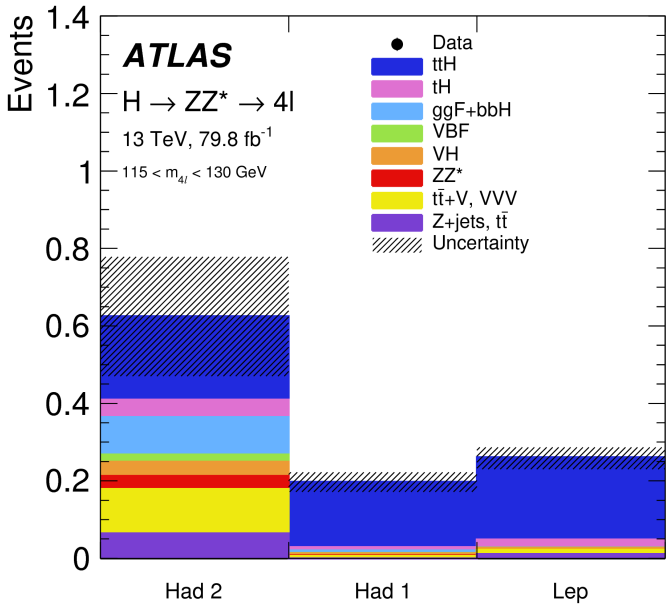
- Hadronic region: 4-lep + >=1b-jet + >=3j + additional lepton veto
- Leptonic region: 4-lep + >=1b-jet + >=1jv+ >= 1 lepton
- Final fit to the event yields in 2 hadronic BDT bins and 1 leptonic region with 4-lep mass window of 115 GeV < m4ℓ <135 GeV





ttH, H→ZZ*： Analysis Result

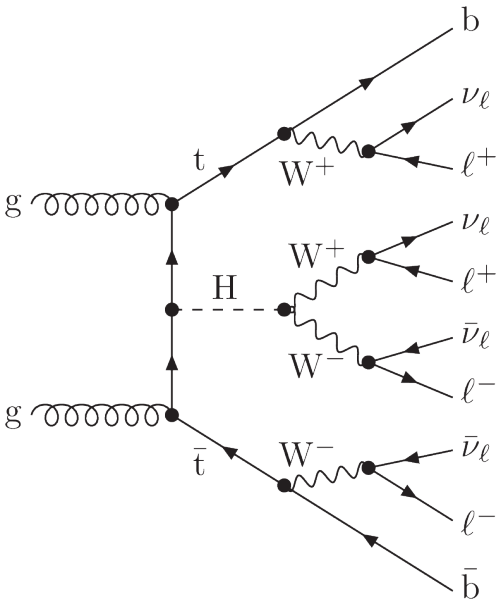
Bin	Expected $t\bar{t}H$ (signal)	Non-$t\bar{t}H$ Higgs	Non-Higgs	Total	Observed Total
		$H \to ZZ^* \to 4\ell$			
Had 1	0.169(31)	0.021(7)	0.008(8)	0.198(33)	0
Had 2	0.216(32)	0.20(9)	0.22(12)	0.63(16)	0
Lep	0.212(31)	0.0256(23)	0.015(13)	0.253(34)	0

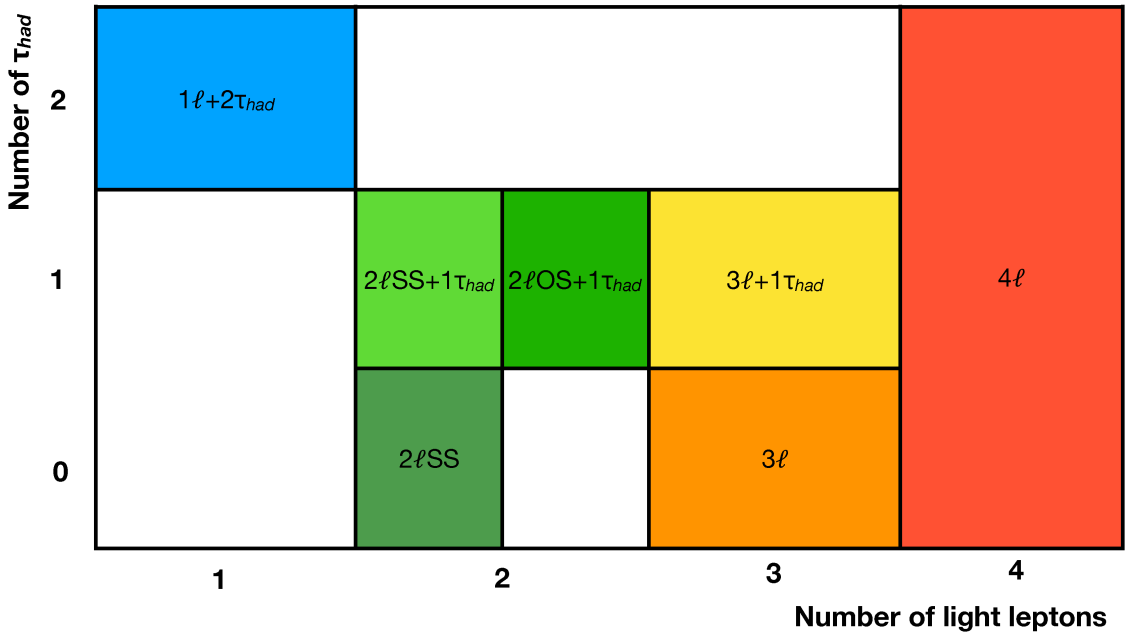


- The expected significance is 1.2 σ
- No event is observed
- More statistics needed for this analysis

ttH in multi-lepton: Analysis Overview

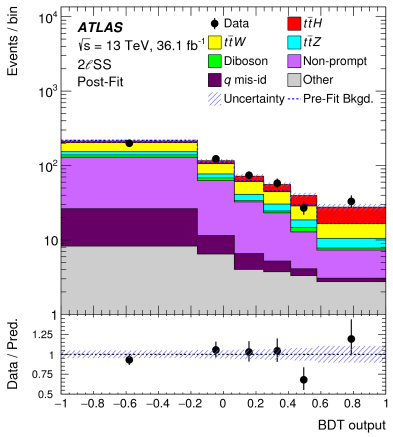
- Signals mainly from H→WW* and H→ττ, small from H→ZZ*
- Signature: 2-4 leptons (τ_{had}), >= 2-jets and >= 1 b-jet
- Main backgrounds: ttW/ttZ from MC but validated to data,
  non-prompt bkg. (mainly ttbar) is data-driven
- Dominant syst.: estimations for fake lepton and non-prompt bkg.

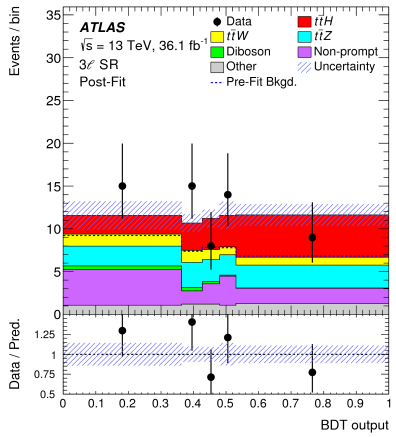


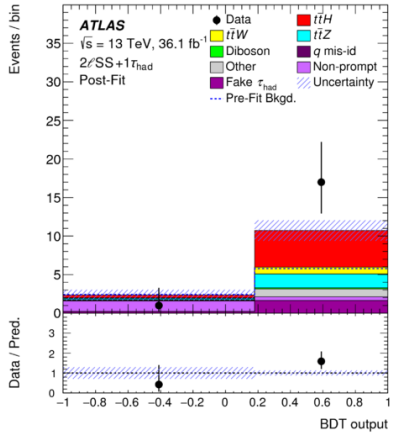


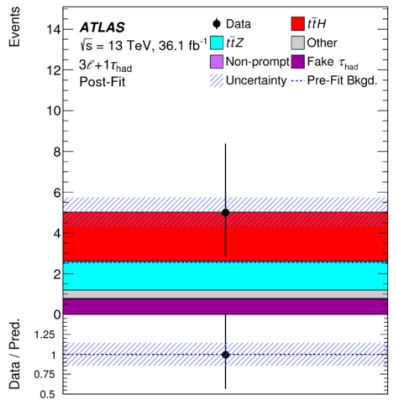
ttH in multi-lepton: 8 SRs

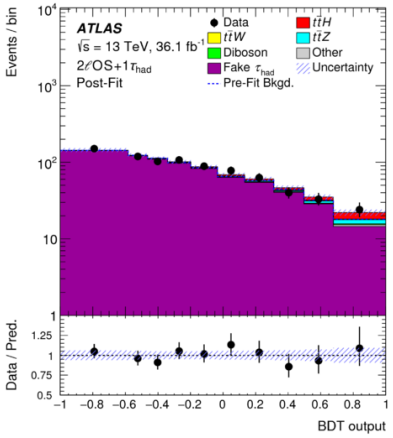
Signal extracted by a binned fit to all categories: 8 signal regions as below, and 4 control regions (ttZ, ttW, di-boson, ttbar in 3-lep)

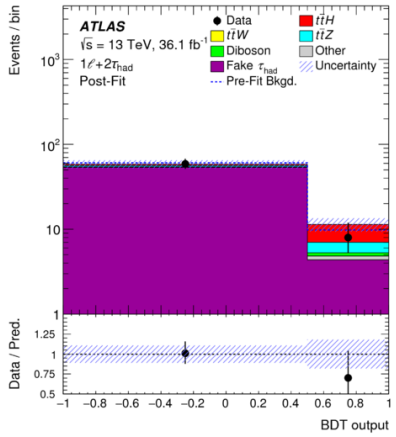


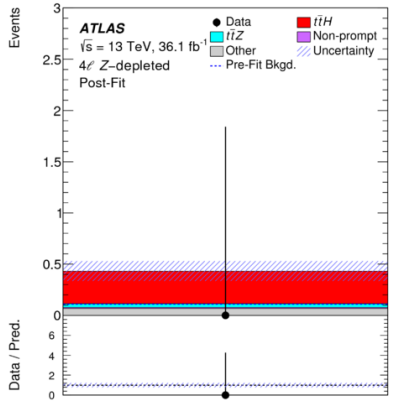


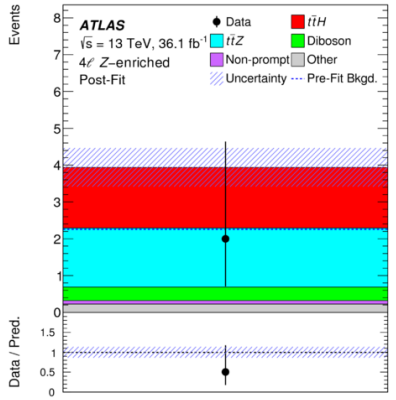




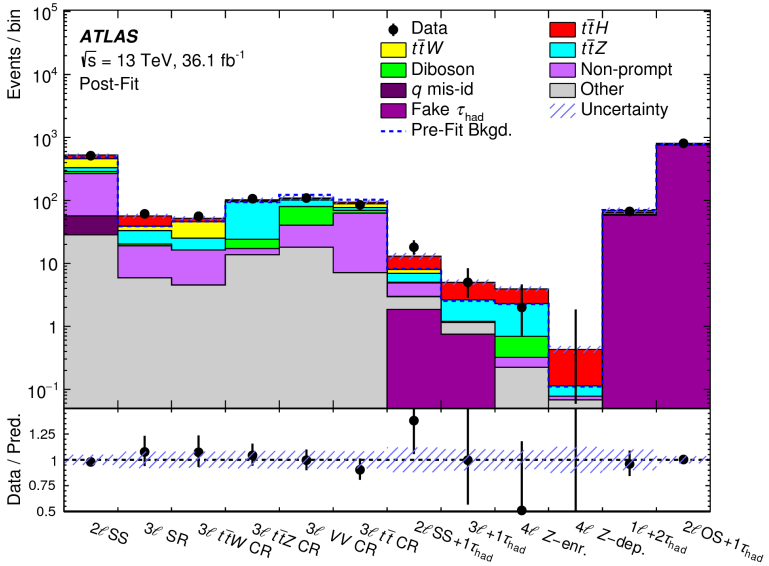


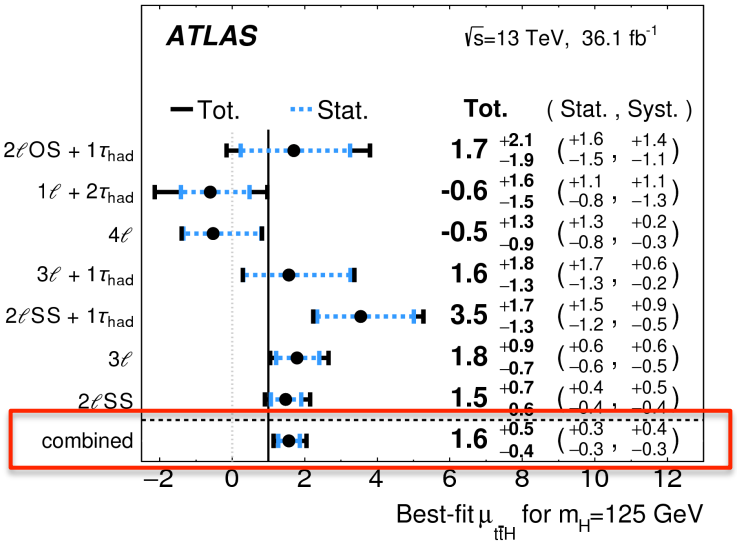


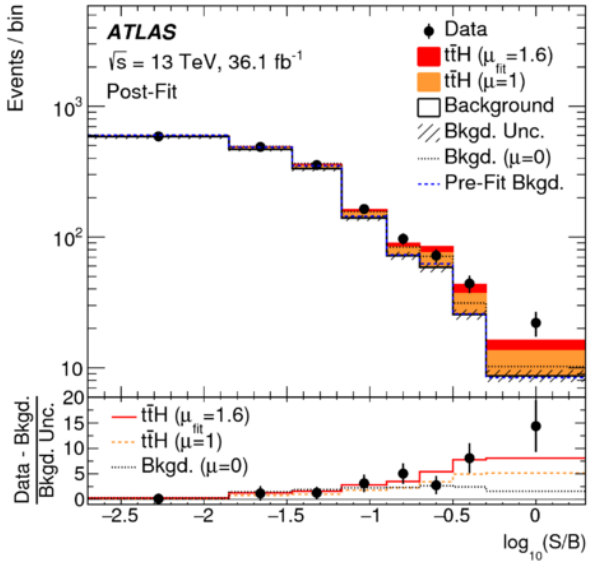




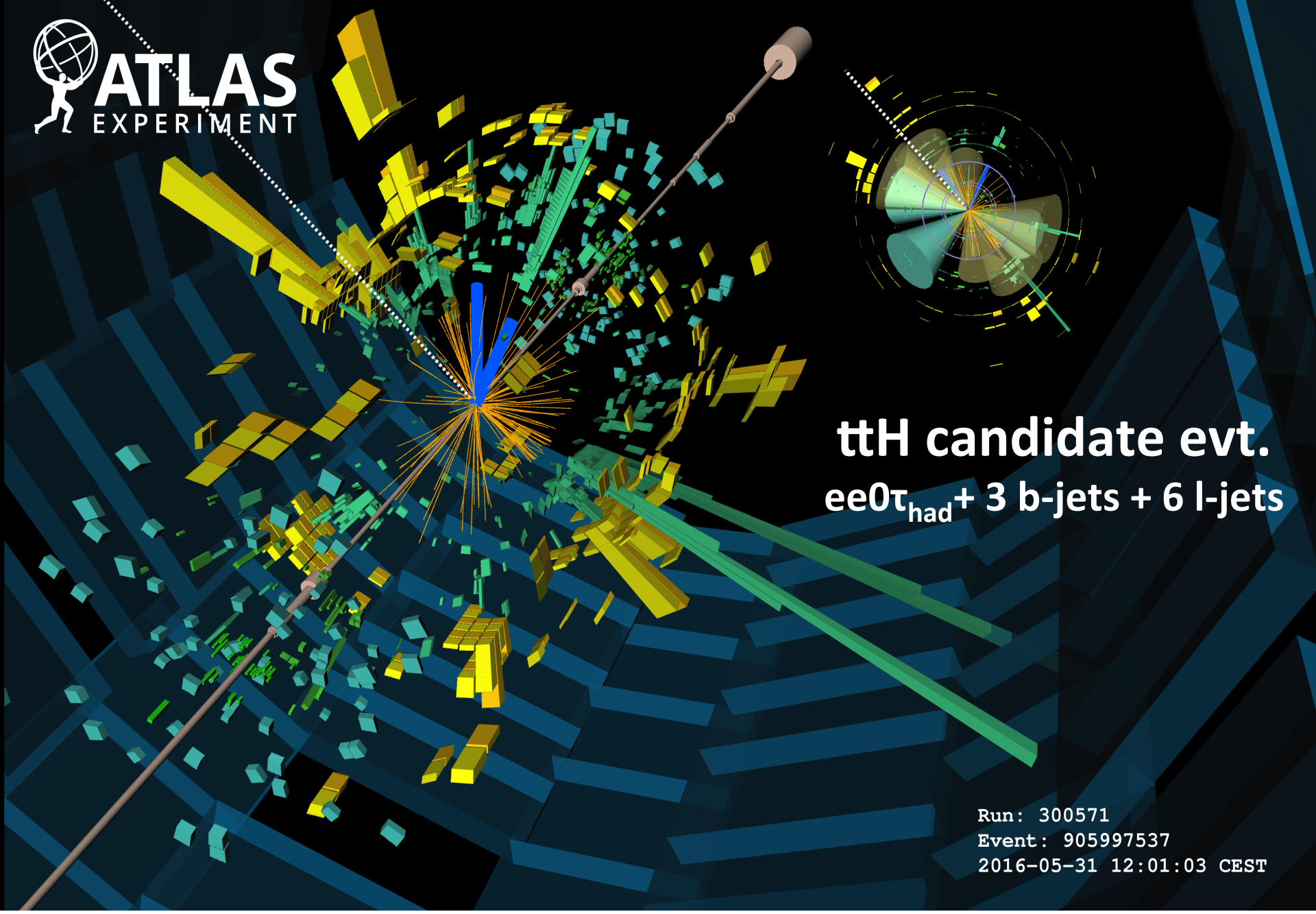
ttH in multi-lepton: Results



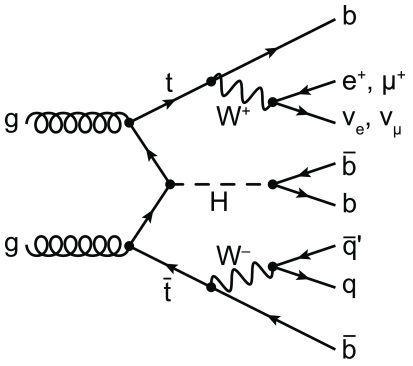




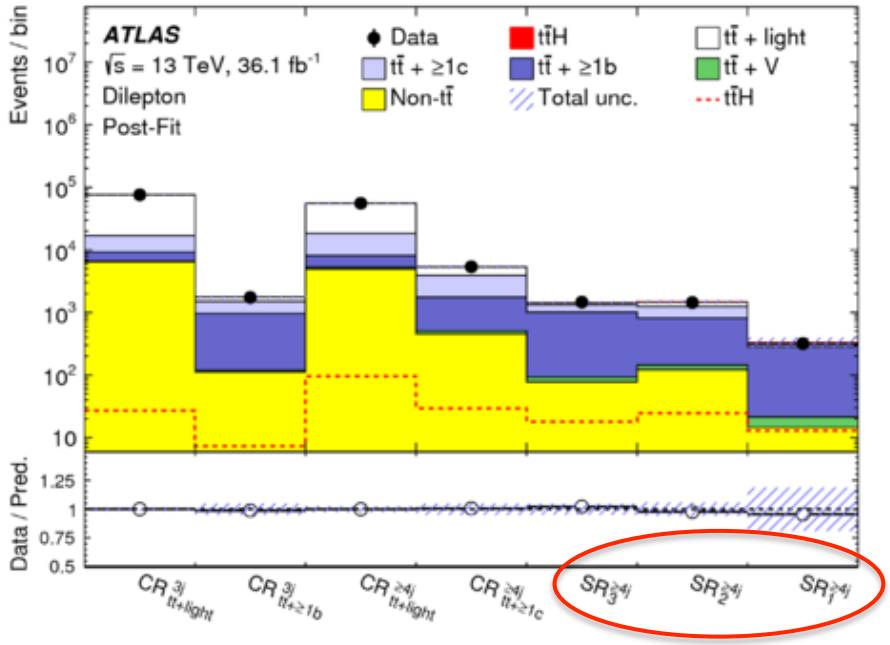
- Signal strength: $1.6^{+0.5}_{-0.4}$
- Significance: 4.1 σ (expected 2.8 σ)
- Dominant systematics:
  - ttH modelling (+0.20, -0.09)
  - Jet energy scale/resolution (+0.18, -0.15)
  - Non-prompt e/μ (+0.15, -0.13), limited stats.

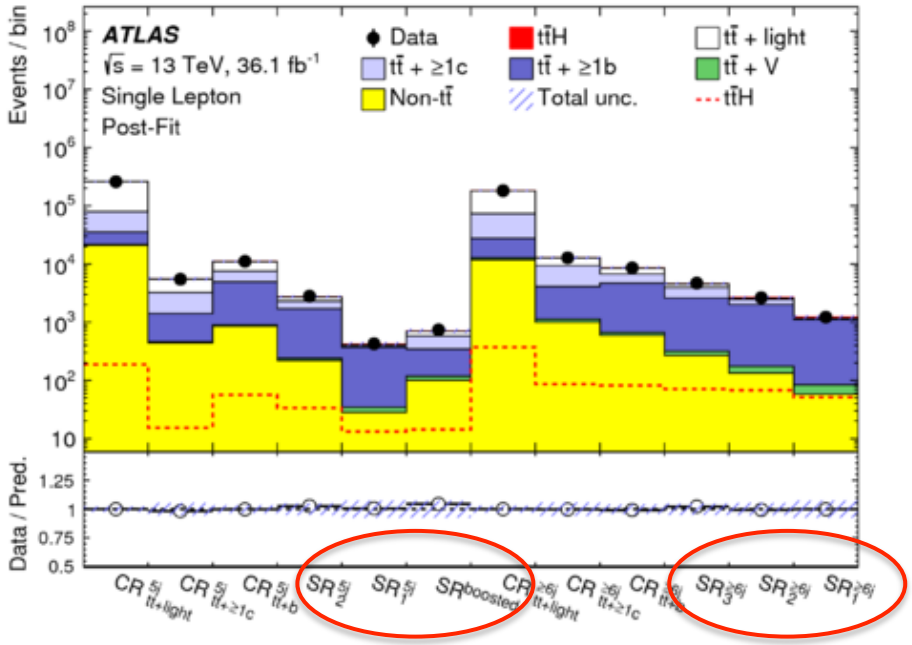

ATLAS
EXPERIMENT
ttH candidate evt.
ee0τhad + 3 b-jets + 6 l-jets
Run: 300571
Event: 905997537
2016-05-31 12:01:03 CEST

ttH, H→bb



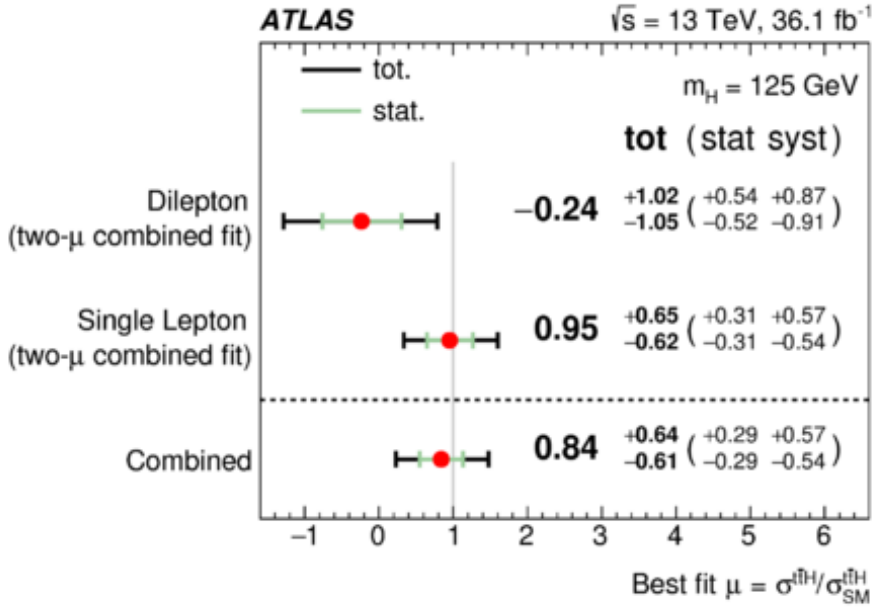
- Events categorized based on leptons, n-jets, b-tag score of jets: 9 signal regions + 10 control regions
- Main bkg.: tt+heavy flavour, difficult to predict from MC

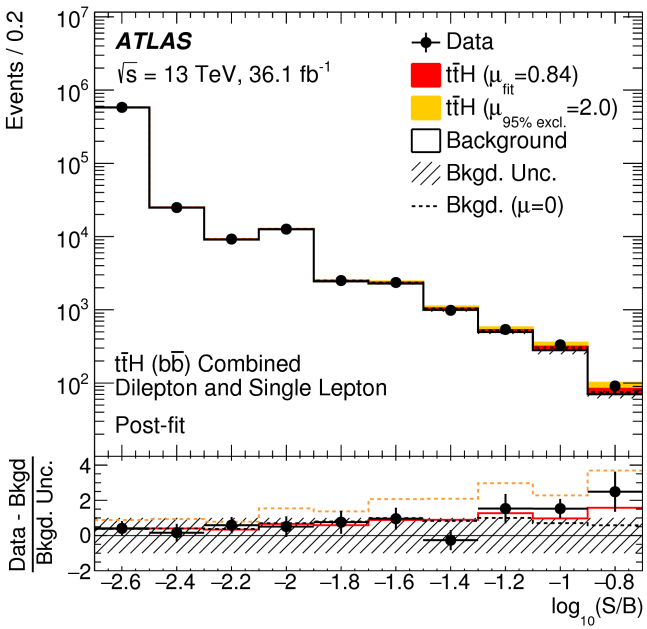




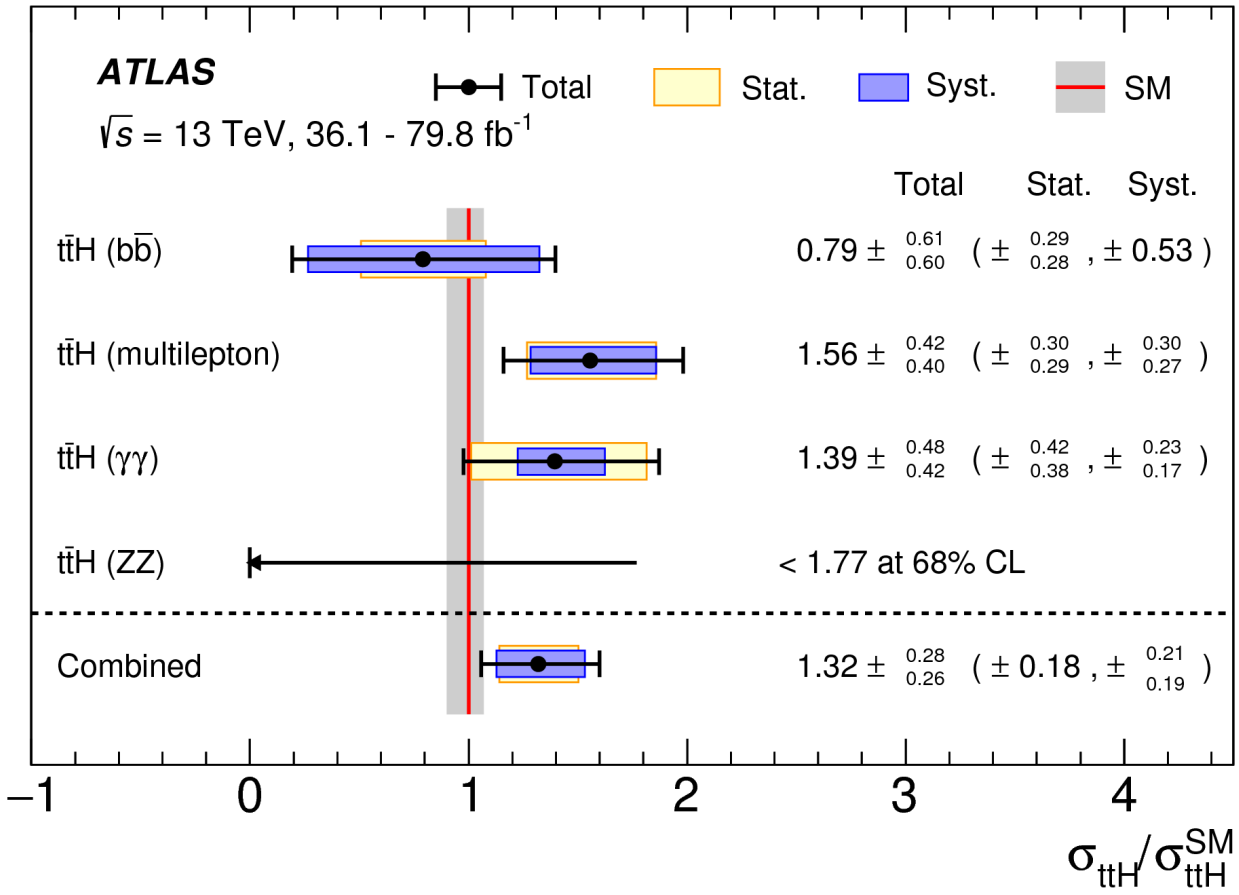
ttH, H→bb

- The simultaneous fit to the discriminant distributions from all categories: BDT in signal regions, total event yields in CRs except 2 CRs for tt + ≥1*c* in 5j and 6j ((H$_T^{had}$: scalar sum of jet pt)
- Significance: 1.4 σ (expected 1.6 σ)
- Systematically limited, and dominant syst.: signal and bkg. modeling, JES, b-tagging, such as tt+≥1b modeling (±0.46 on mu)





ttH Combined Results



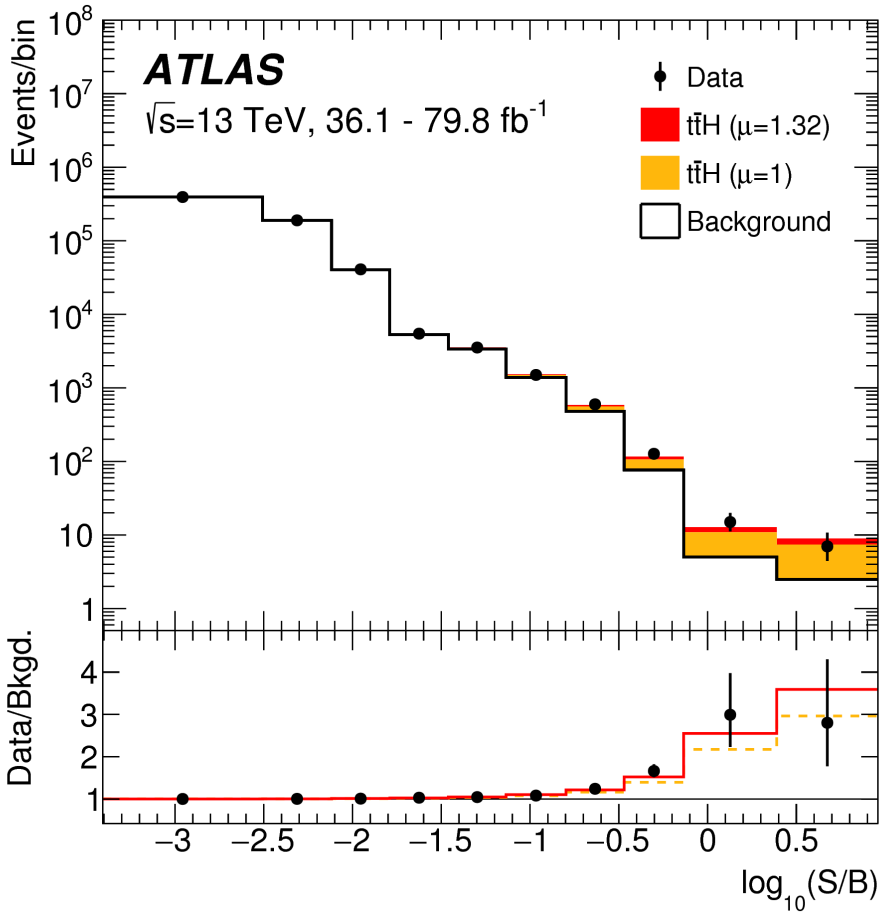
Significance	
obs.	exp.
1.6σ	1.4σ
4.1σ	2.8σ
4.1σ	3.8σ
0 σ	1.2σ
5.8σ	4.9σ

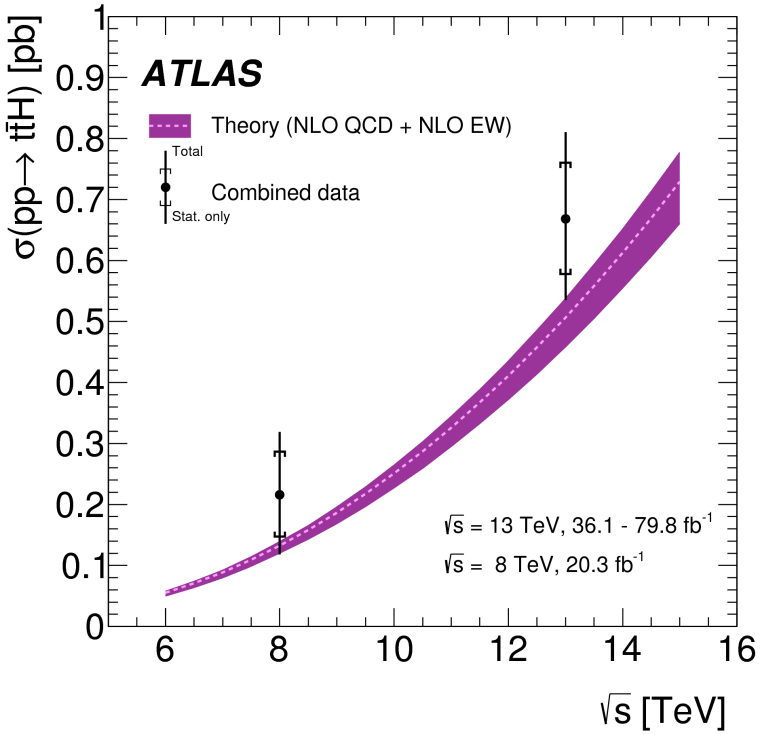
- Observation of ttH production with 13 TeV dataset only
- 6.3 σ with combination with Run I data (5.1 σ expected)

ttH Combined Results

$$\sigma_{t\bar{t}H}(13TeV) = 670 \pm 90(stat.)^{+100}_{-100}(sys.)\,fb$$

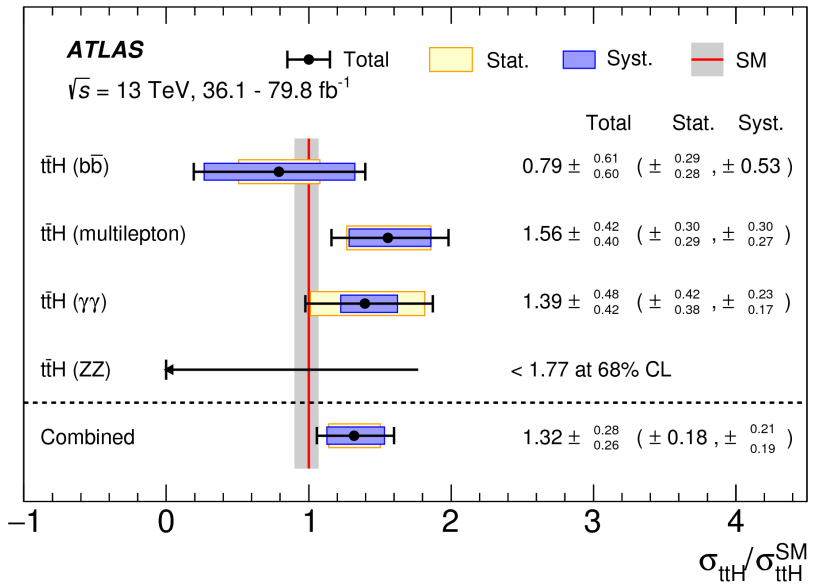
$$\sigma_{t\bar{t}H,SM}(13TeV) = 507 \pm^{+35}_{-50}(sys.)\,fb$$

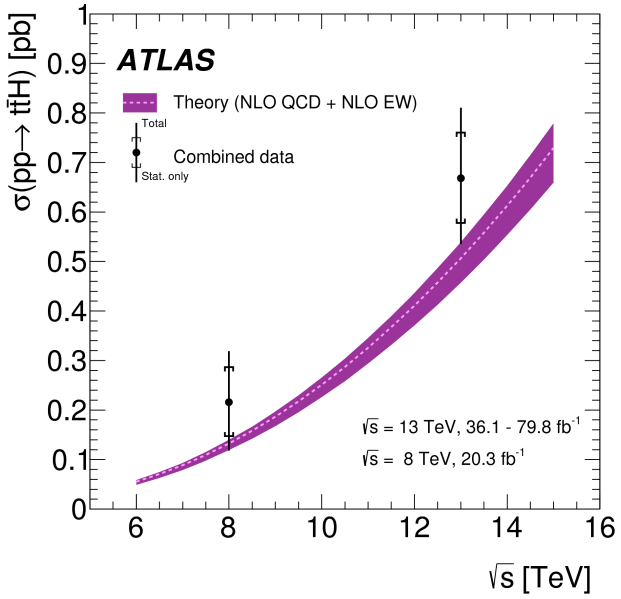




Summary

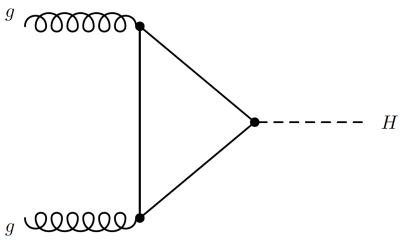
- Observation of ttH production with a significance of 6.3 σ (expected 5.1 σ)
- Signal strength: $1.32 \pm 0.18(stat.)^{+0.21}_{-0.19}(sys.)$, higher than the SM prediction, but compatible at 1σ level

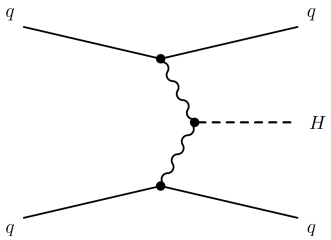


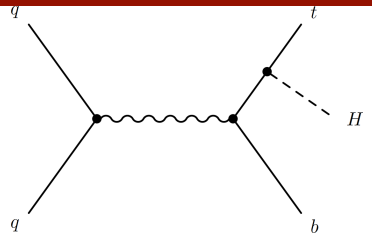


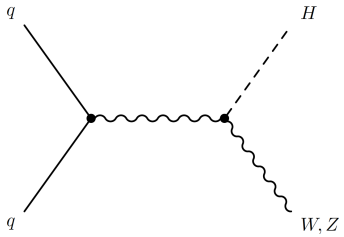
Thanks!

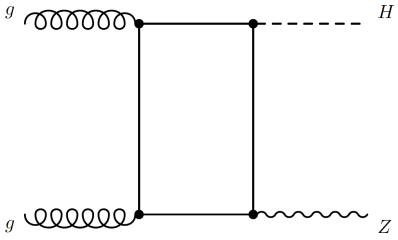
Higgs Production

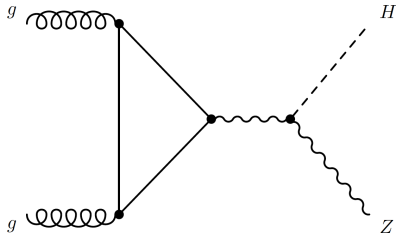


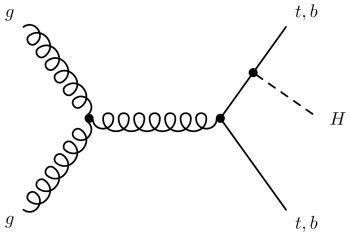


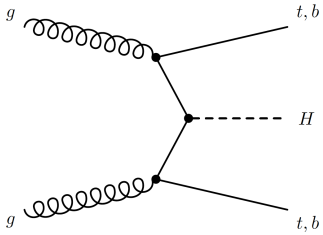


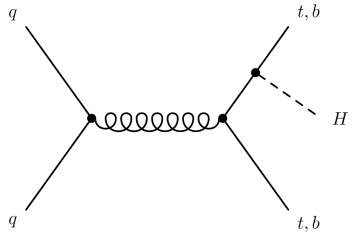






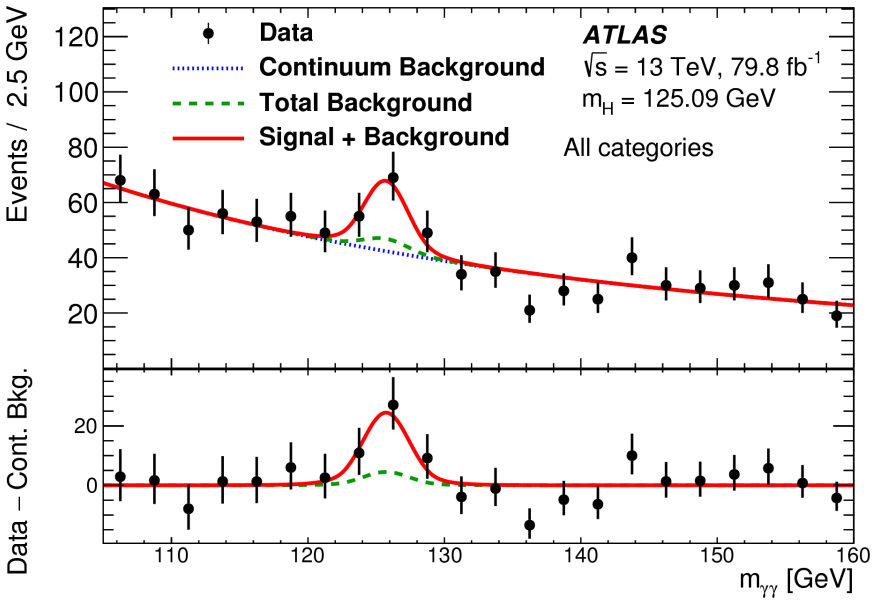




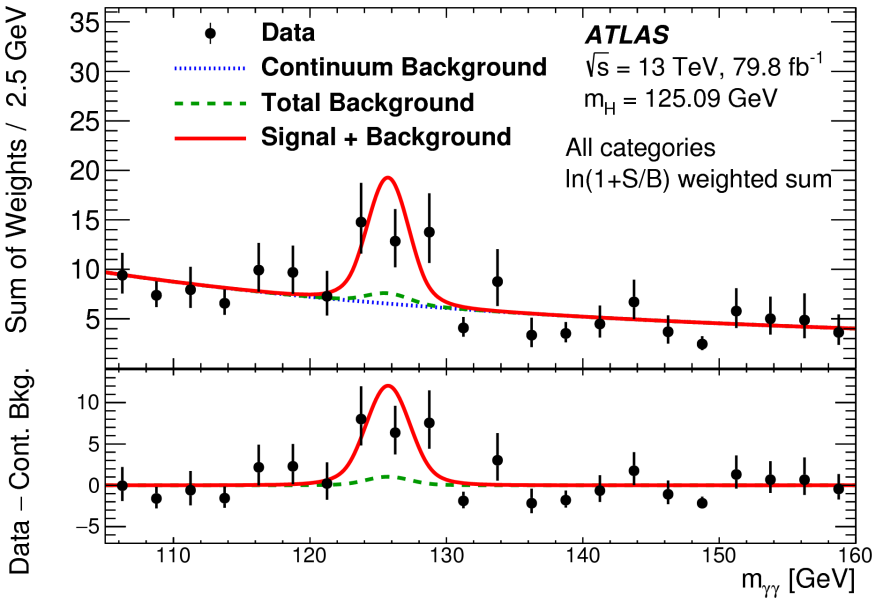


ttH, H→γγ: Mass Spectrum

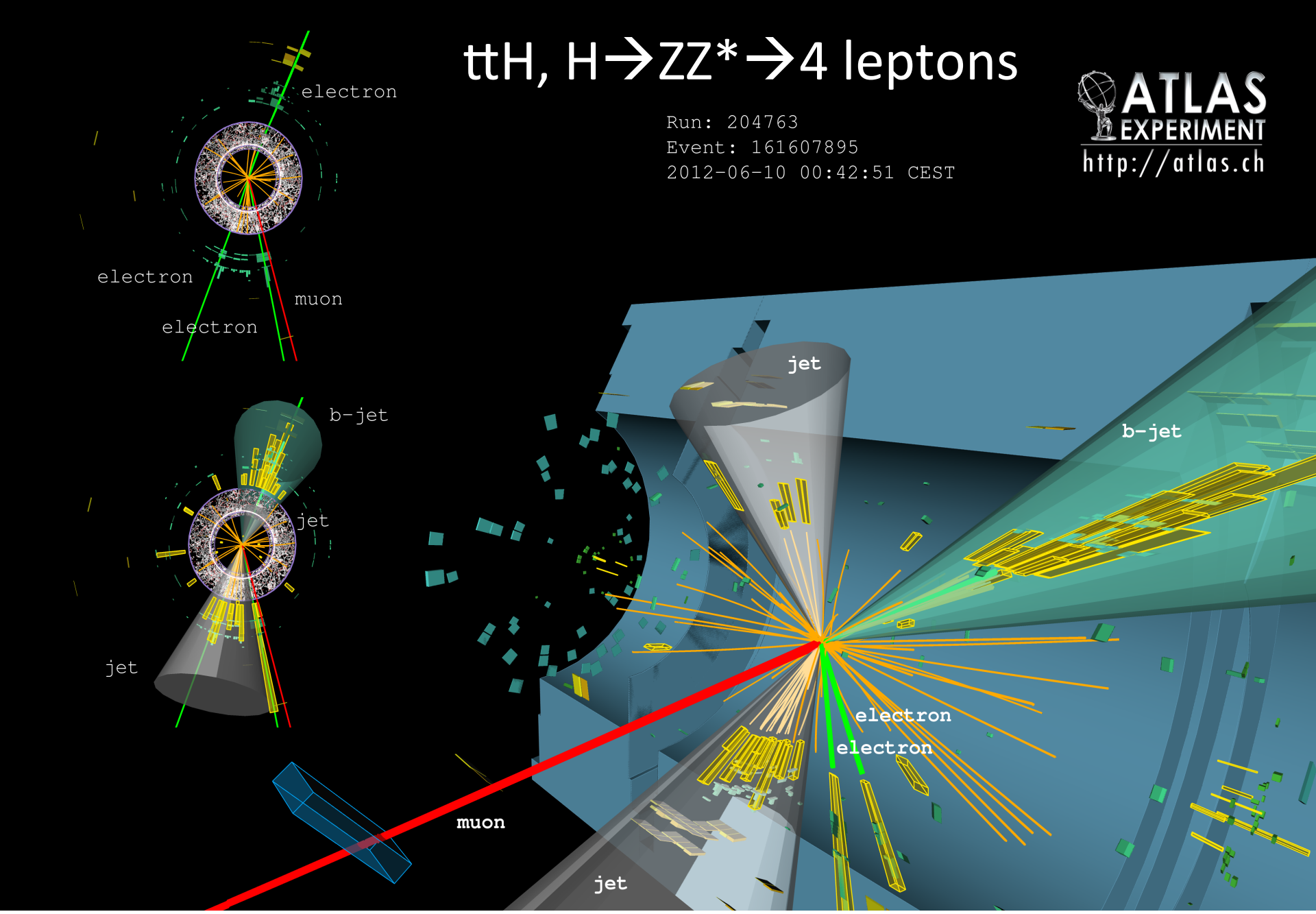
Unweighted



Weighted



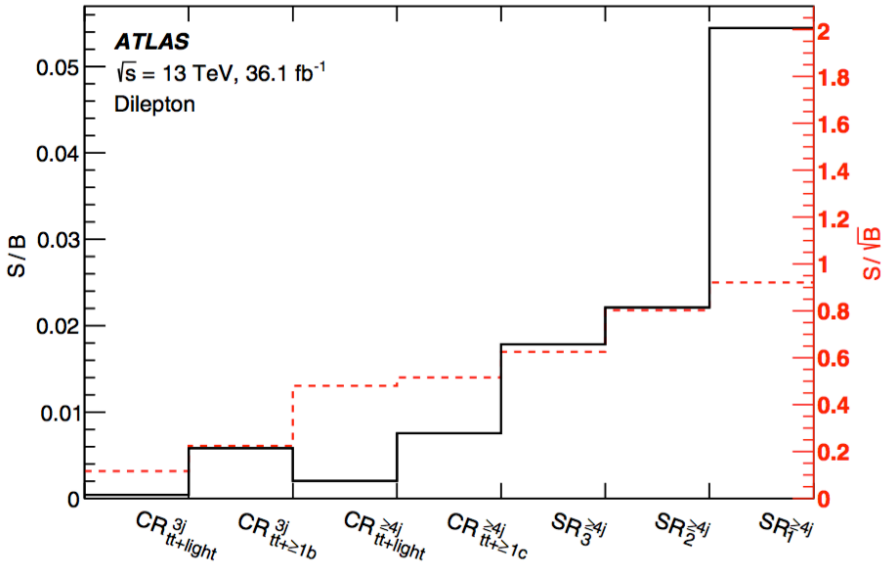
ttH, H→ZZ*→4 leptons

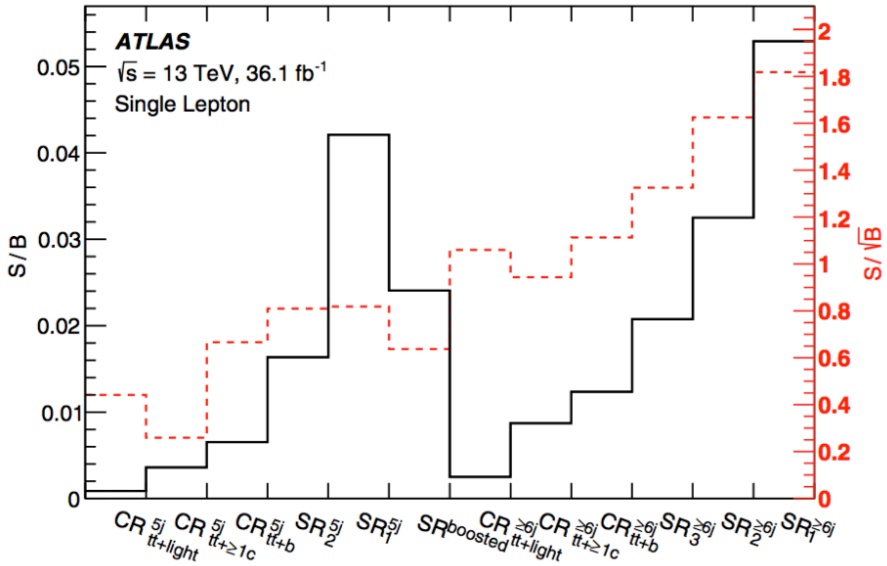


Event Selection in ttH, multi-lepton

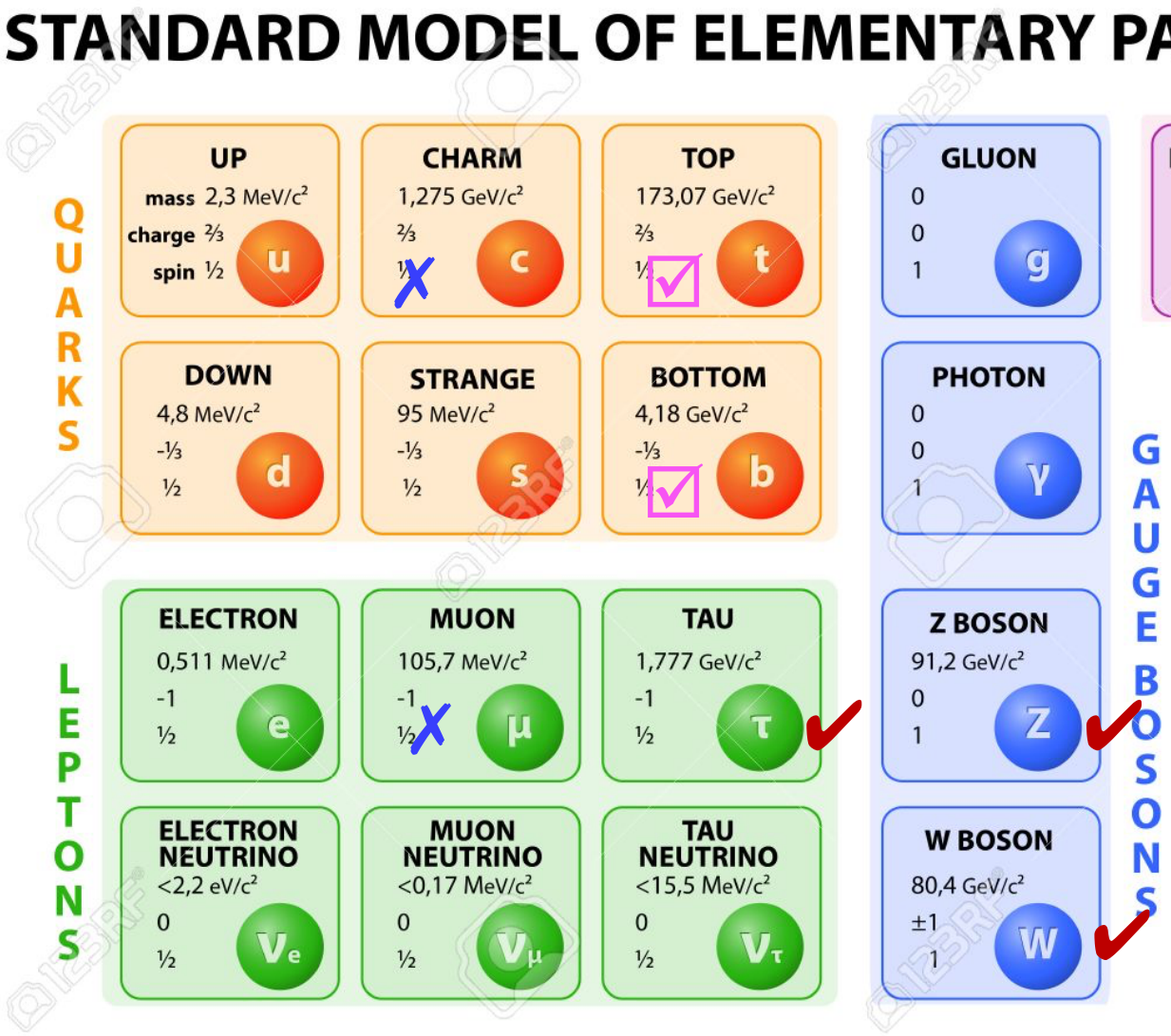
Channel	Selection criteria
Common	$N_{\text{jets}} \geq 2$ and $N_{b\text{-jets}} \geq 1$
2ℓSS	Two very tight light leptons with $p_{\text{T}} > 20$ GeV Same-charge light leptons Zero medium τ_{had} candidates $N_{\text{jets}} \geq 4$ and $N_{b\text{-jets}} < 3$
3ℓ	Three light leptons with $p_{\text{T}} > 10$ GeV; sum of light-lepton charges ± 1 Two same-charge leptons must be very tight and have $p_{\text{T}} > 15$ GeV The opposite-charge lepton must be loose, isolated and pass the nonprompt BDT Zero medium τ_{had} candidates $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert > 10$ GeV for all SFOC pairs $\lvert m(3\ell) - 91.2\text{ GeV}\rvert > 10$ GeV
4ℓ	Four light leptons; sum of light-lepton charges 0 Third and fourth leading leptons must be tight $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert > 10$ GeV for all SFOC pairs $\lvert m(4\ell) - 125\text{ GeV}\rvert > 5$ GeV Split two categories: Z-depleted (0 SFOC pairs) and Z-enriched (two or four SFOC pairs)
$1\ell + 2\tau_{\text{had}}$	One tight light lepton with $p_{\text{T}} > 27$ GeV Two medium τ_{had} candidates of opposite charge, at least one being tight $N_{\text{jets}} \geq 3$
$2\ell\text{SS} + 1\tau_{\text{had}}$	Two very tight light leptons with $p_{\text{T}} > 15$ GeV Same-charge light leptons One medium τ_{had} candidate, with charge opposite to that of the light leptons $N_{\text{jets}} \geq 4$ $\lvert m(ee) - 91.2\text{ GeV}\rvert > 10$ GeV for ee events
$2\ell\text{OS} + 1\tau_{\text{had}}$	Two loose and isolated light leptons with $p_{\text{T}} > 25, 15$ GeV One medium τ_{had} candidate Opposite-charge light leptons One medium τ_{had} candidate $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert > 10$ GeV for the SFOC pair $N_{\text{jets}} \geq 3$
$3\ell + 1\tau_{\text{had}}$	3ℓ selection, except: One medium τ_{had} candidate, with charge opposite to the total charge of the light leptons The two same-charge light leptons must be tight and have $p_{\text{T}} > 10$ GeV The opposite-charge light lepton must be loose and isolated

ttH, H→bb Category





Search for ttH Process



Importance:

- Establish one of the main Higgs production modes
- Direct measurement of Higgs coupling to top quark, the heaviest particle in SM