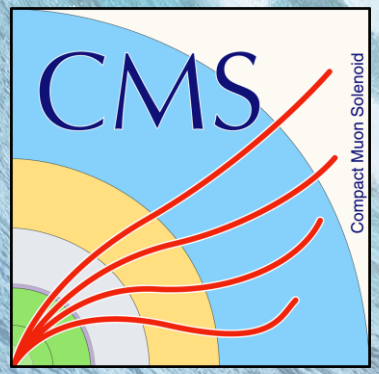
ttH searches at ATLAS and CMS



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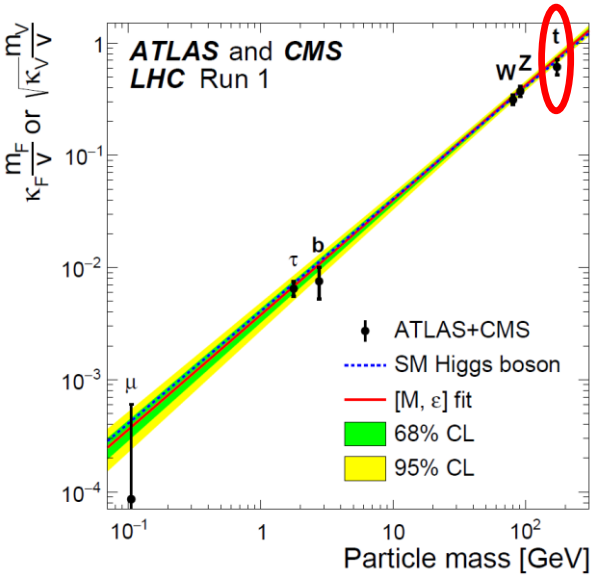
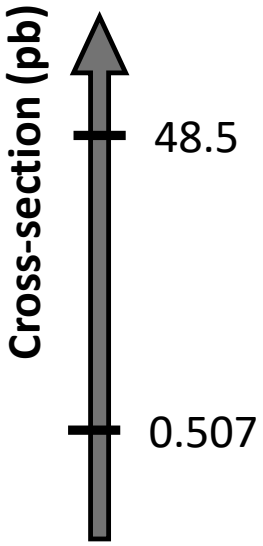
SM@LHC2018
Apr 11th, 2018

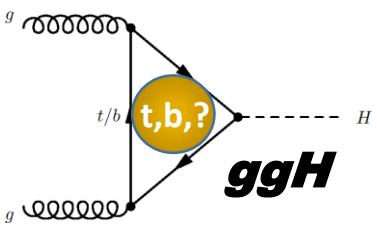
The Higgs – Top Sector

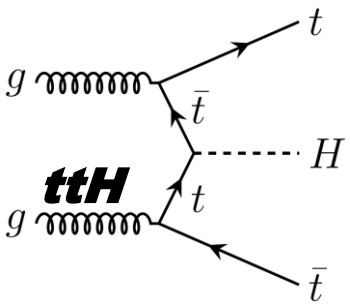
- Higgs boson discovery in 2012
  - Large effort to characterize this boson
- Yukawa coupling to top quark = crucial role:
  - $Y_f \propto m_f$ & top heaviest known particle
  - Sensitive to new physics



- Top – Higgs sector at the LHC:







Leading contribution to Higgs loops:
ggH (also H→γγ)
- ✓ Large constrain on coupling: $\mathcal{O}(15\%)$
- ✗ Very model dependent

ATLAS+CMS Run 1: JHEP 08 (2016) 045

Direct access in ttH production
- ✗ Lower constrain on coupling: $\mathcal{O}(30\%)$
- ✓ Less model dependent

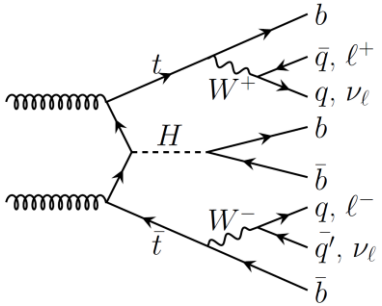
ttH Channels

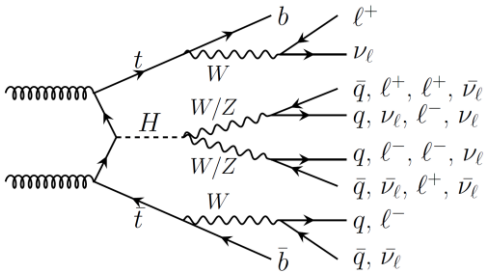
- Largest Yukawa does not mean easiest:
  - 1% produced Higgs come from ttH (cross section 0.507 pb)
  - Multitude of possible complex final states
  - Separated in 4 analyses

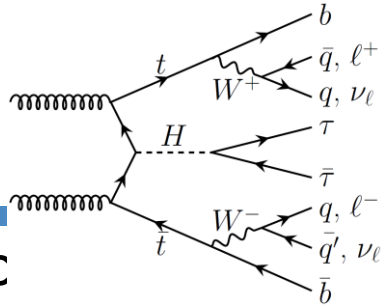
ttH(bb) **ttH multi-leptons** **ttH(γγ)** **ttH(ZZ*→4l)**

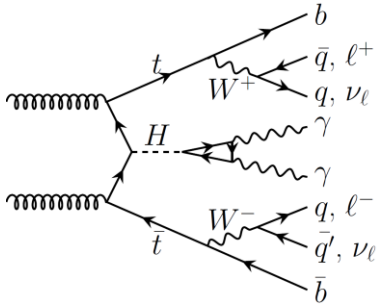
Low S/B (need MVAs) — Clear peak (bump hunt)

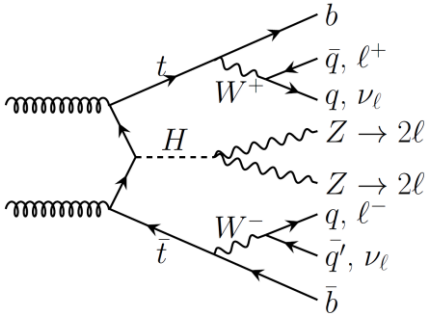
High Higgs Branching Ratios — Low Higgs Branching Ratios







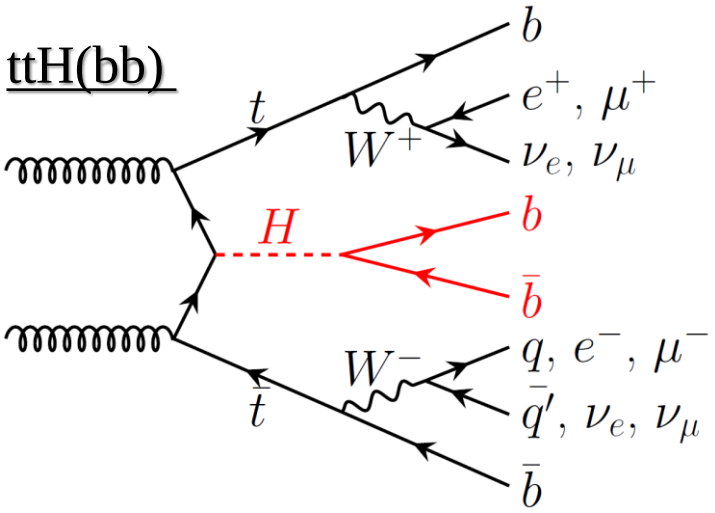




ttH(bb): 1 and 2 leptons

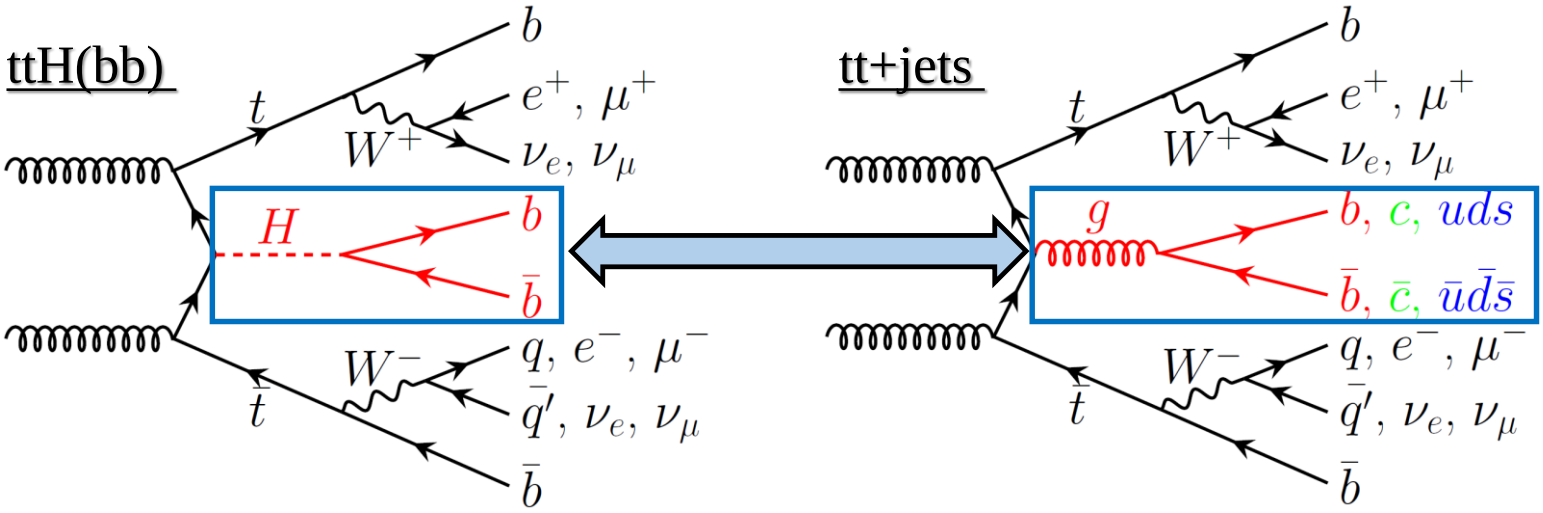
ATLAS: arXiv:1712.08895
CMS: CMS-PAS-HIG-17-026

ttH(bb) Challenges



1. Complex final state
   - ❖ Split in 1-lepton and 2-lepton channels
   - ❖ Sensitive to b-tagging, jet, lepton, MET uncertainties
   - ❖ Complex jet combinatorics: difficult Higgs boson reconstruction

ttH(bb) Challenges



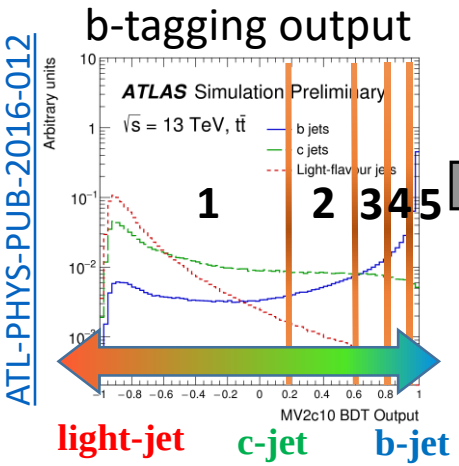
2. tt+jets background
   - ❖ 3 main components: **tt+lf (uds), tt+cc, tt+bb**
     - ➢ tt+bb: irreducible, 30*signal, large uncertainties $\mathcal{O}(35\%)$
   - ❖ Analysis sensitivity ∝ ability to separate and control tt+lf/cc/bb/H

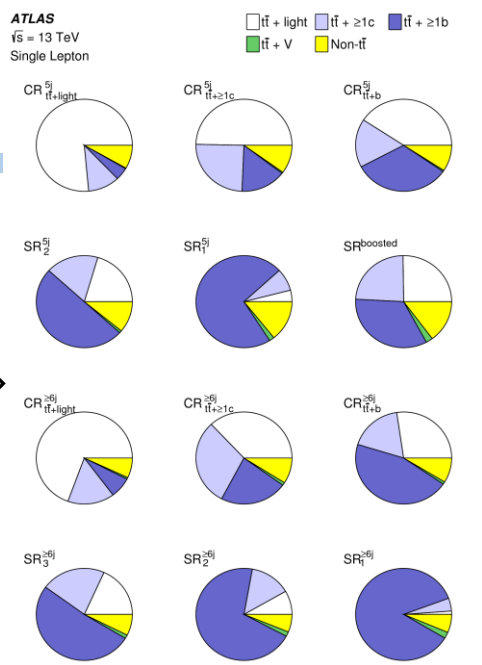
ATLAS strategy

Two stage signal separation

Categorization:

- Split in N(jet)
- Use b-tagging discriminant
- Categories enriched in tt+lf, cc, or [bb and H]

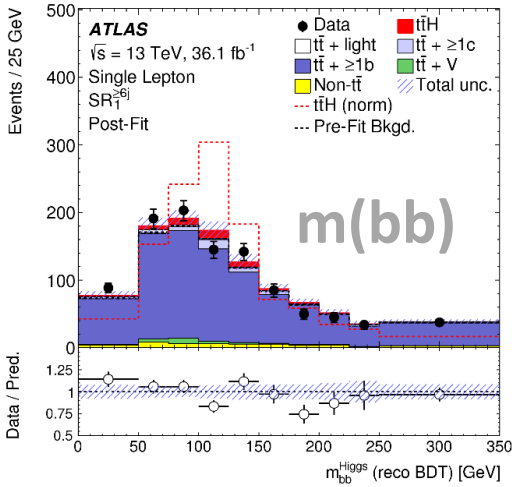




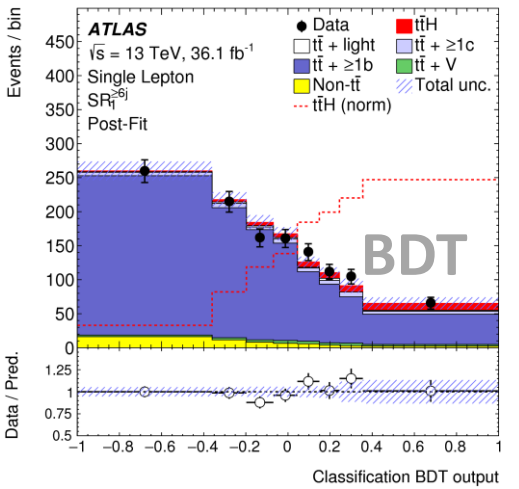
Kinematic/topological MVAs:

1. **Final state reconstruction**
   ⇒ find b-jets from Higgs
   ⇒ main in put to step 2
2. **Classification BDT**
   ⇒ ttH(bb) VS tt+bb discriminant

Reconstruction

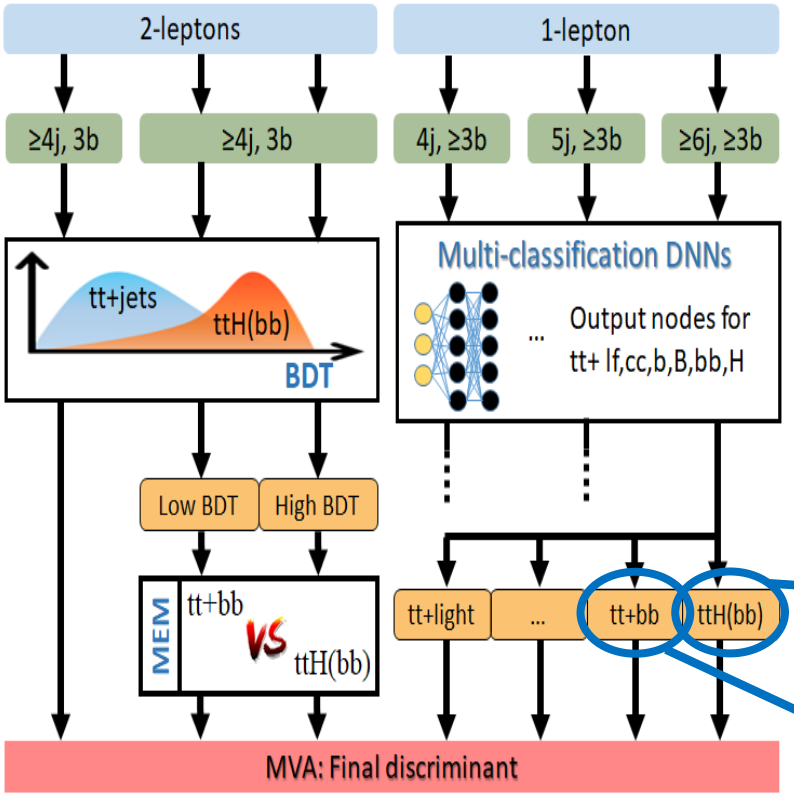


Classification



CMS strategy

- Channel dependent strategy
- Combine b-tag and event kinematic/topology already in categorization

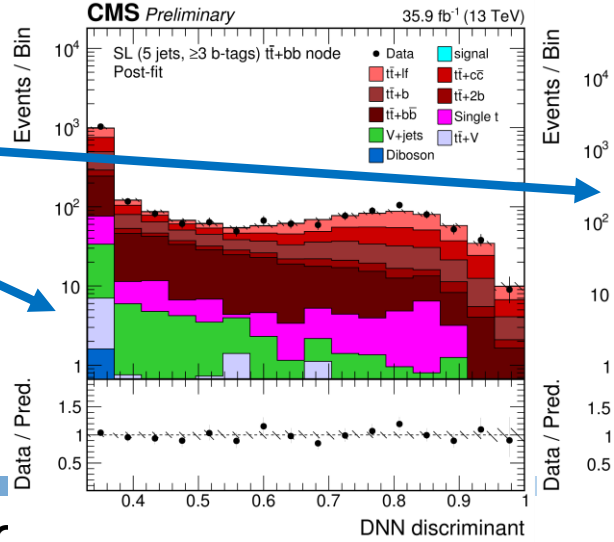


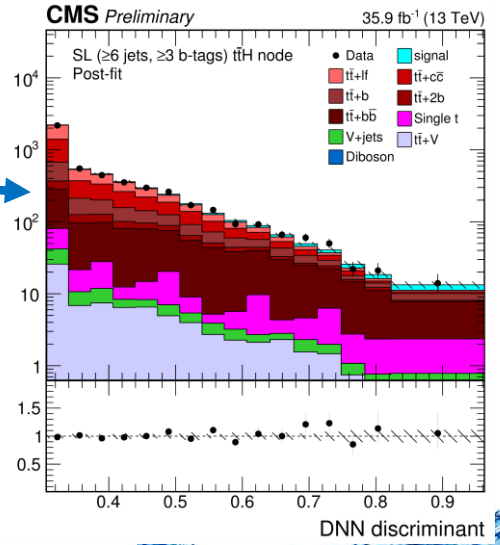
1: Simple N(b-tags) or N(jets) classification

2: Multiple MVAs

- 2-lep: tt+jets VS ttH(bb) then tt+bb VS ttH(bb)
- 1-lep: separate tt+lf, cc, b, B, bb, H

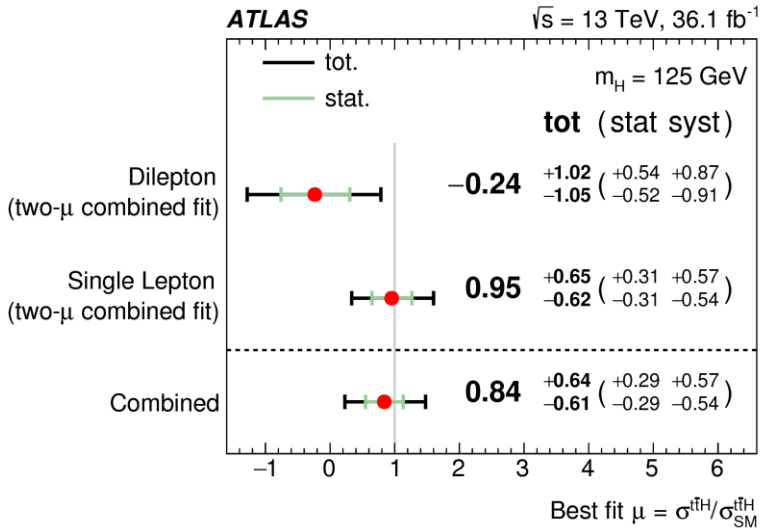
Refine categorization, fit MVA discriminant

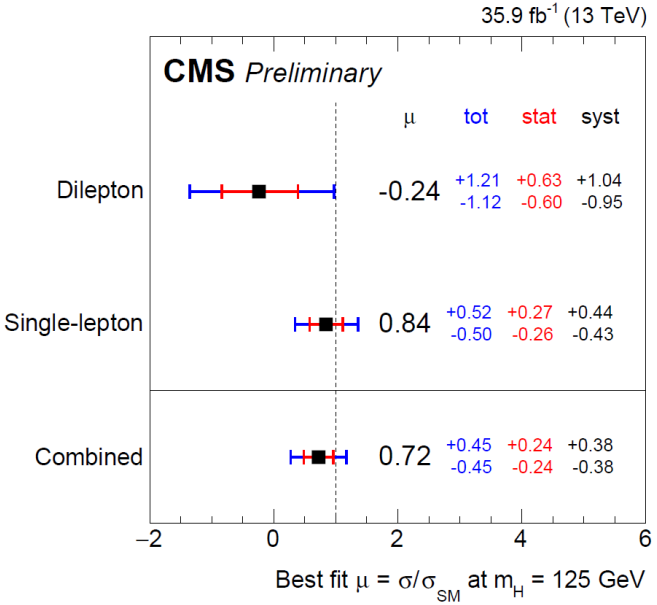




ttH(bb) results

- All categories matched to data simultaneously (profile likelihood)
- Signal parametrized by with $\mu = \frac{\sigma}{\sigma_{SM}}$





Central value:

- Compatibility ATLAS – CMS – SM

40% higher uncertainty in ATLAS

Significance	Observed	Expected
ATLAS	1.4σ	1.6σ
CMS	1.6σ	2.2σ

Uncertainty Sources

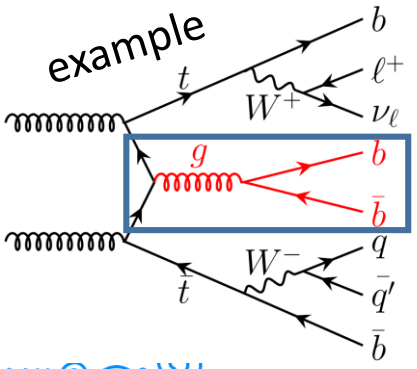
CMS uncertainty sources

Uncertainty source	$\pm\sigma_\mu$ (observed)	$\pm\sigma_\mu$ (expected)
total experimental	+0.15/-0.16	+0.19/-0.17
b tagging	+0.11/-0.14	+0.12/-0.11
jet energy scale and resolution	+0.06/-0.07	+0.13/-0.11
total theory	+0.28/-0.29	+0.32/-0.29
$t\bar{t}$+hf cross-section and parton shower	+0.24/-0.28	+0.28/-0.28
size of MC samples	+0.14/-0.15	+0.16/-0.16
total systematic	+0.38/-0.38	+0.45/-0.42
statistical	+0.24/-0.24	+0.27/-0.27
total	+0.45/-0.45	+0.53/-0.49

ATLAS uncertainty sources

Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modeling	+0.46	−0.46
Background-model stat. unc.	+0.29	−0.31
b-tagging efficiency and mis-tag rates	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modeling	+0.22	−0.05
$t\bar{t}+\geq 1c$ modeling	+0.09	−0.11
JVT, pileup modeling	+0.03	−0.05
Other background modeling	+0.08	−0.08
$t\bar{t}+$ light modeling	+0.06	−0.03
Luminosity	+0.03	−0.02
Light lepton (e,μ) id., isolation, trigger	+0.03	−0.04
Total systematic uncertainty	+0.57	−0.54
$t\bar{t}+\geq 1b$ normalization	+0.09	−0.10
$t\bar{t}+\geq 1c$ normalization	+0.02	−0.03
Intrinsic statistical uncertainty	+0.21	−0.20
Total statistical uncertainty	+0.29	−0.29
Total uncertainty	+0.64	−0.61

- ❖ tt+bb major source of uncertainty:
  - ➢ Leading contribution to difference between ATLAS and CMS
  - ➢ Both analysis validated comparing multiple tt+bb models



Sherpa+OpenLoops 4 flavor:
- ➢ bb from ME at NLO

Powheg+Pythia8 5 flavor:
- ➢ bb from PS

❖ **CMS:**
Difference within uncertainties
Not considered as uncertainty

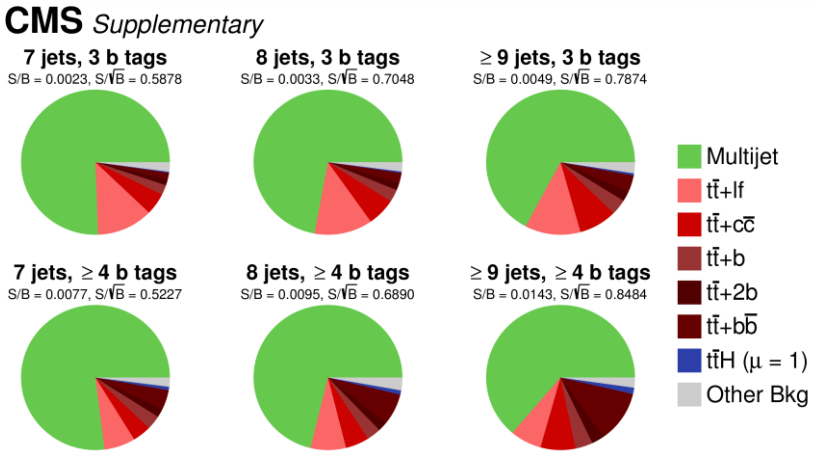
❖ **ATLAS:**
Difference as systematic uncertainty
Second largest impact on signal

ttH(bb): 0-lepton

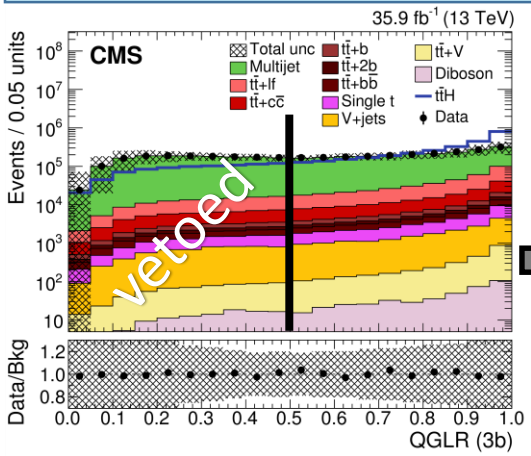
ATLAS only Run 1 (not discussed): arXiv:1604.03812
CMS: arXiv:1803.06986

ttH(bb): 0-lepton

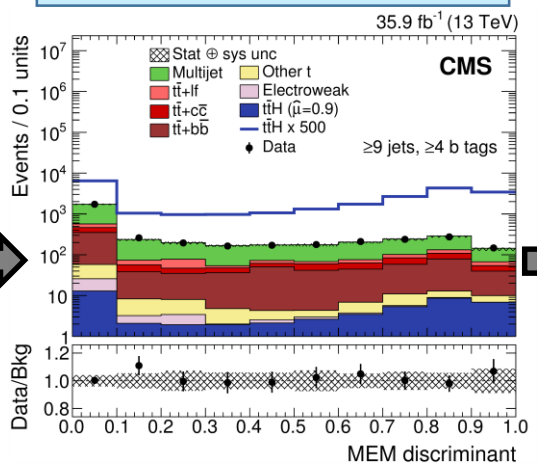
- Very challenging analysis:
  - Categories from 7 to ≥9 jets
  - No lepton to reduce QCD
- 2 main backgrounds: QCD and tt+jets
  - Reduced with MVAs



Quark/gluon discriminant: cut QCD like events



tt+jets MEM: final discriminant



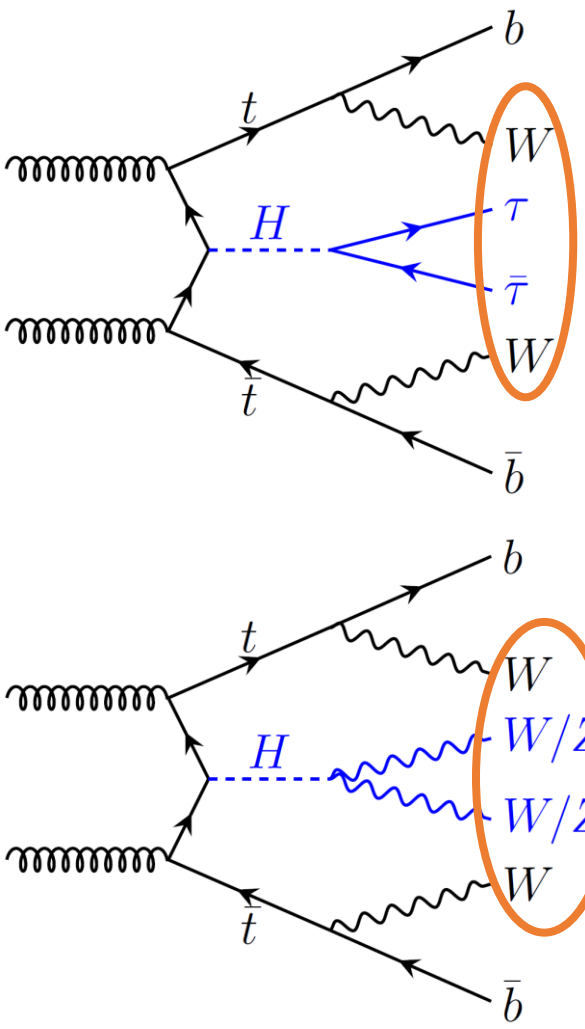
Observed $\mu = 0.9 \pm 1.5$

Channel	Uncertainty on μ
0-lepton	$\mathcal{O}(1.5)$
1-lepton	$\mathcal{O}(1.0)$
2-lepton	$\mathcal{O}(0.5)$

ttH(WW*, ττ, ZZ*)

ATLAS: Phys. Rev. D 97 (2018) 072003
CMS: arXiv:1803.05485

ttH(multi-leptons) Challenges



Primarily target: H→WW, ττ and ZZ

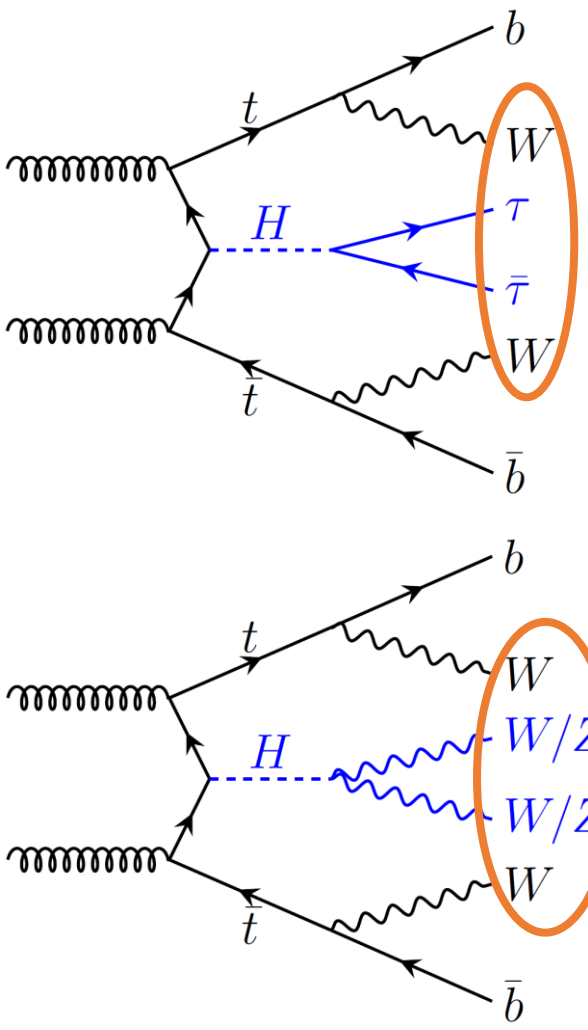
Complex final state:

- Lepton, MET, b-tagging, jet uncertainties

Various topologies: 1 to 4 leptons ---- 0 to 2 taus

- Require optimization on many objects
- Veto H→ZZ→4ℓ

ttH(multi-leptons): the Many Channels



Primarily target: H→WW, ττ and ZZ

Complex final state:

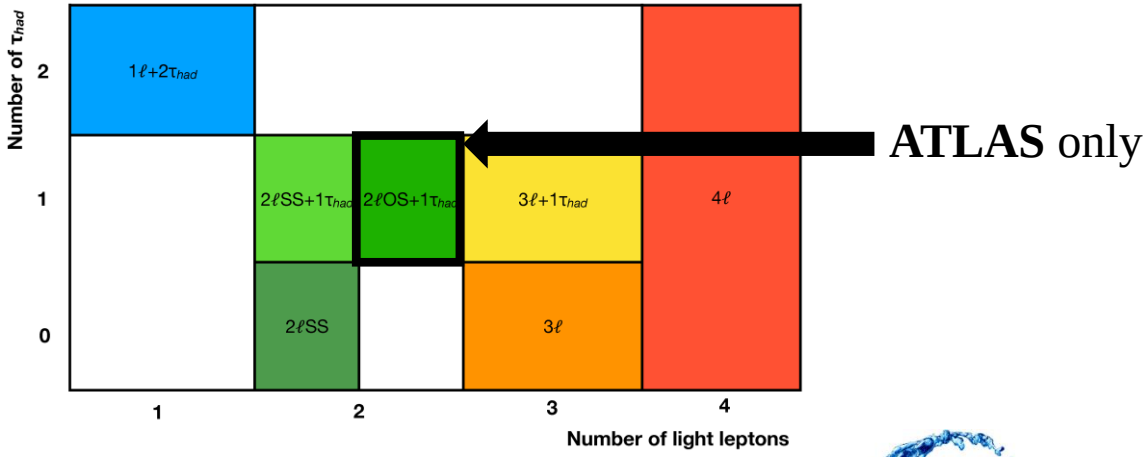
- Lepton, MET, b-tagging, jet uncertainties

Various topologies: 1 to 4 leptons ---- 0 to 2 taus

- Require optimization on many objects
- Veto H→ZZ→4ℓ

Split in several channels:

- Use N(τ-had), N(lep), charge(lep)



ttH(multi-leptons) Challenges

Various background sources

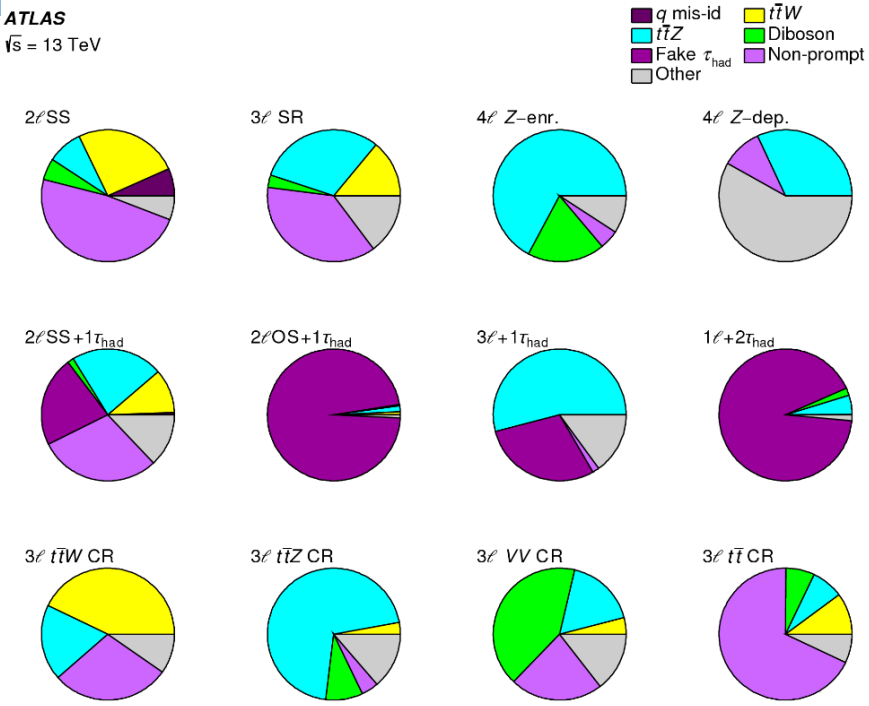
1. Prompt leptons:
   - Estimated from MC simulation

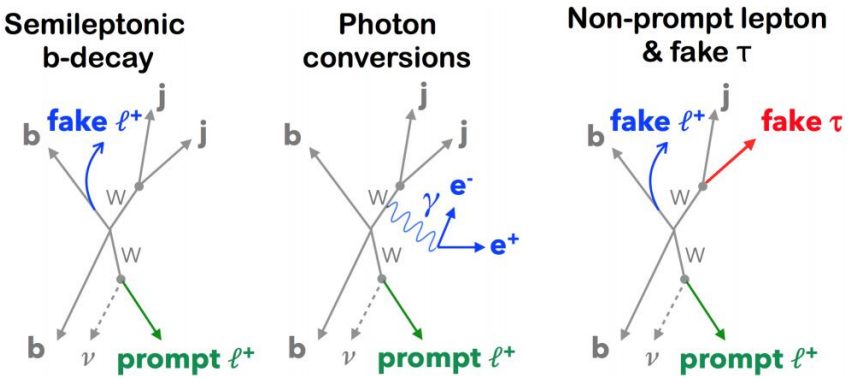
$t\bar{t}W$ $t\bar{t}Z$ Diboson

2. Non-prompt and fake leptons:
   - Data-driven estimates

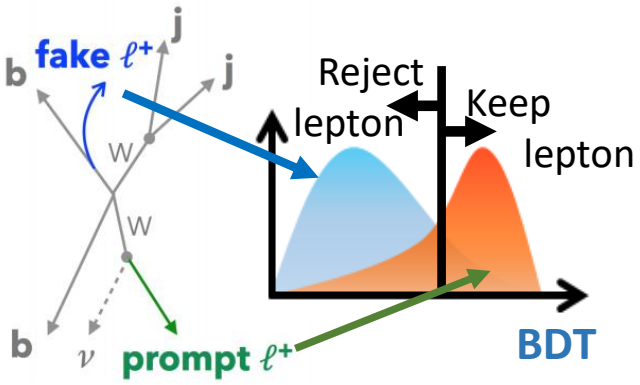
Non-prompt Fake τ_{had}

q mis-id



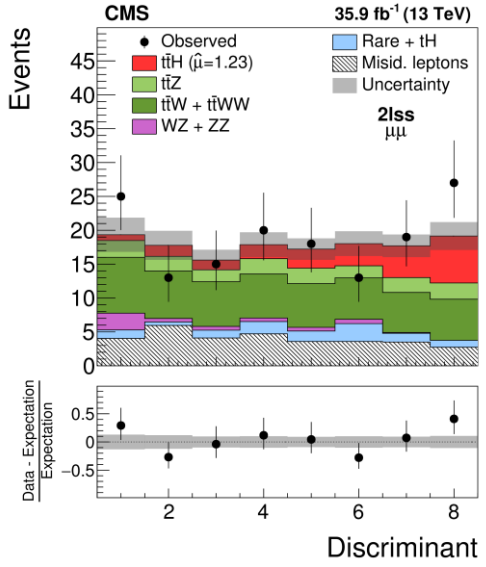


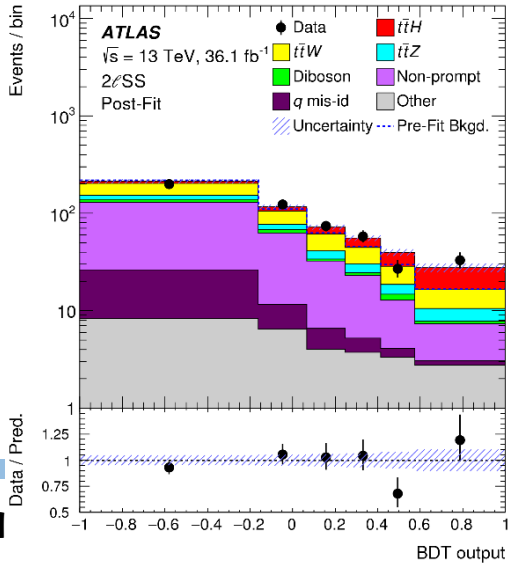
Analysis Strategy I



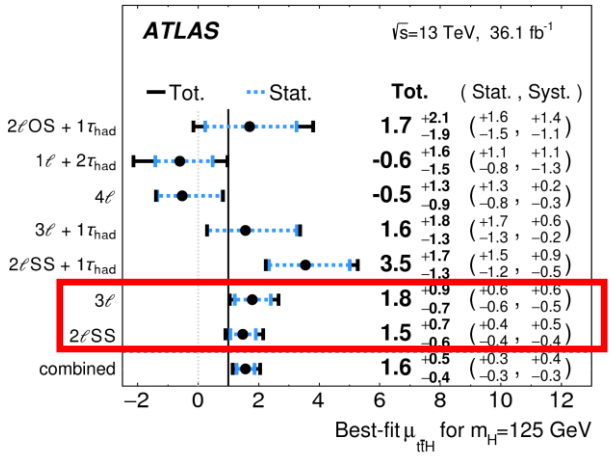
1. Object level MVAs: remove "bad" leptons
   - Non-prompts: "isolation-like" BDT
   - Charge mis-Id: track quality cuts (CMS), BDT (ATLAS)

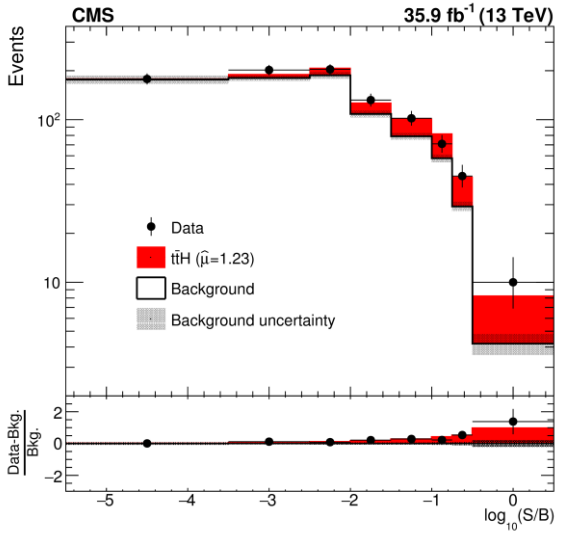
2. Event level MVAs: ttH(bb) VS background(s)
   - Channel dependent strategy:
     - BDT, MEM in CMS, event count
   - In 2ℓSS and 3ℓ (most sensitive):
     - Combine multiple BDTs with multi-dimensional binning





ttH(multi-leptons): Fit Strategy





- Signal parametrized by $\mu = {}^{\sigma}/_{\sigma_{SM}}$
  - ATLAS: $\mu = 1.6^{+0.5}_{-0.4}$ $\left[{}^{+0.3}_{-0.3}(stat) \quad {}^{+0.4}_{-0.3}(syst) \right]$
  - CMS: $\mu = 1.23^{+0.45}_{-0.43}$ $\left[{}^{+0.26}_{-0.25}(stat) \quad {}^{+0.37}_{-0.35}(syst) \right]$
- Sensitivity lead by 3ℓ and 2ℓSS channels
- Compatibility ATLAS – CMS – SM

- Clear signal above the background:
  - Event yields after combining analysis bins in log(S/B) bins

Significance	Observed	Expected
ATLAS	4.1σ	2.8σ
CMS	3.2σ	2.8σ

CMS: Evidence for ttH production in the multi-lepton final state

Uncertainty Sources

ATLAS uncertainty sources

Uncertainty Source	$\Delta\mu$		$\Delta\mu/\mu$ [%]
$t\bar{t}H$ modeling (cross section)	+0.20	−0.09	+13 -5
Jet energy scale and resolution	+0.18	−0.15	+11 -9
Non-prompt light-lepton estimates	+0.15	−0.13	+9 -8
Jet flavor tagging and τ_{had} identification	+0.11	−0.09	
$t\bar{t}W$ modeling	+0.10	−0.09	
$t\bar{t}Z$ modeling	+0.08	−0.07	
Other background modeling	+0.08	−0.07	
Luminosity	+0.08	−0.06	
$t\bar{t}H$ modeling (acceptance)	+0.08	−0.04	
Fake τ_{had} estimates	+0.07	−0.07	
Other experimental uncertainties	+0.05	−0.04	
Simulation sample size	+0.04	−0.04	
Charge misassignment	+0.01	−0.01	
Total systematic uncertainty	+0.39	−0.30	

CMS uncertainty sources

Source	Uncertainty [%]	$\Delta\mu/\mu$ [%]
e, μ selection efficiency	2–4	11
τ_h selection efficiency	5	4.5
b tagging efficiency	2–15 [?]	6
Reducible background estimate	10–40	11
Jet energy calibration	2–15 [?]	5
τ_h energy calibration	3	1
Theoretical sources	≈10	12
Integrated luminosity	2.5	5

Syst ↔ Stat: $\Delta\mu = \pm 0.3 \Leftrightarrow \Delta\mu/\mu \sim 20\%$

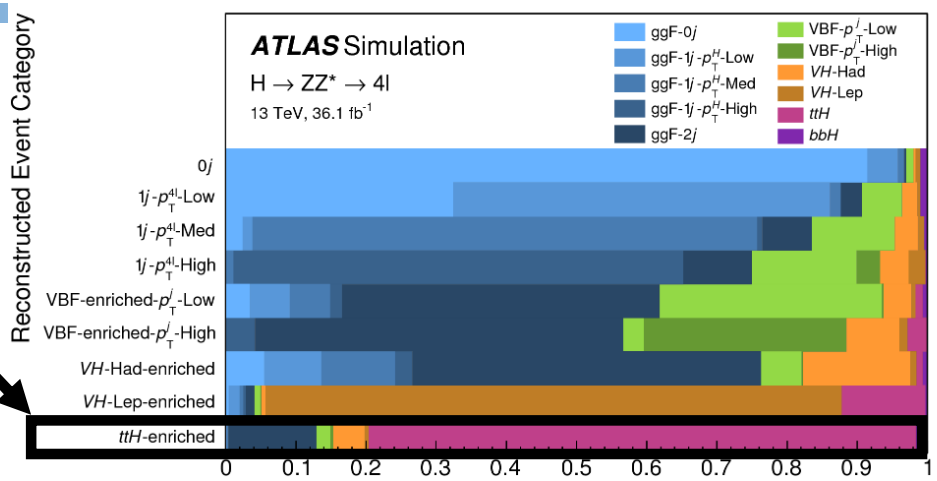
- Potential gain from more data:
  - Impact of stat and syst unc on signal uncertainty similar
  - Important impact of non-prompt/fake estimate (data driven)
- Leading uncertainty from signal modelling:
  - Would not affect a cross-section measurement
- Object reconstruction: jet (ATLAS) and lepton (CMS) uncertainties

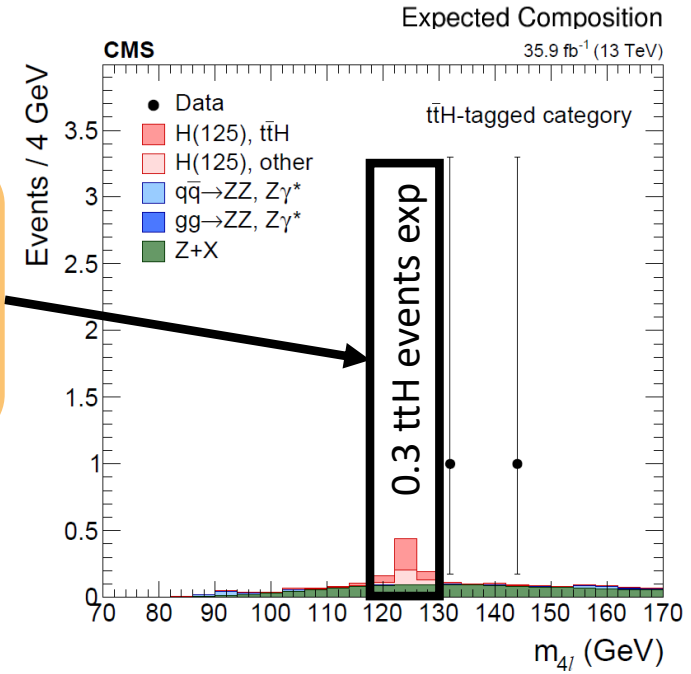
ttH(ZZ*→4l)

ATLAS: JHEP 03 (2018) 095
CMS: JHEP 11 (2017) 047

ttH(ZZ*→4l): ATLAS and CMS

- Included in H→ZZ*→4ℓ analysis:
  - Inclusive H→ZZ*→4ℓ selection
  - N(jets) and N(b-tags) ⇒ ttH
- Very pure channel:
  - S/B ~ 125 to 300%
- Very low statistic:
  - $\sigma \times BR = 0.507\ pb \times 0.0001251$





No data event in signal regions => set limit

ATLAS: 95% CL upper limit $\sigma \cdot B$ at 7.1 times SM

CMS: $\frac{\sigma}{\sigma_{SM}} = 0.00^{+1.18}_{-0.00}$

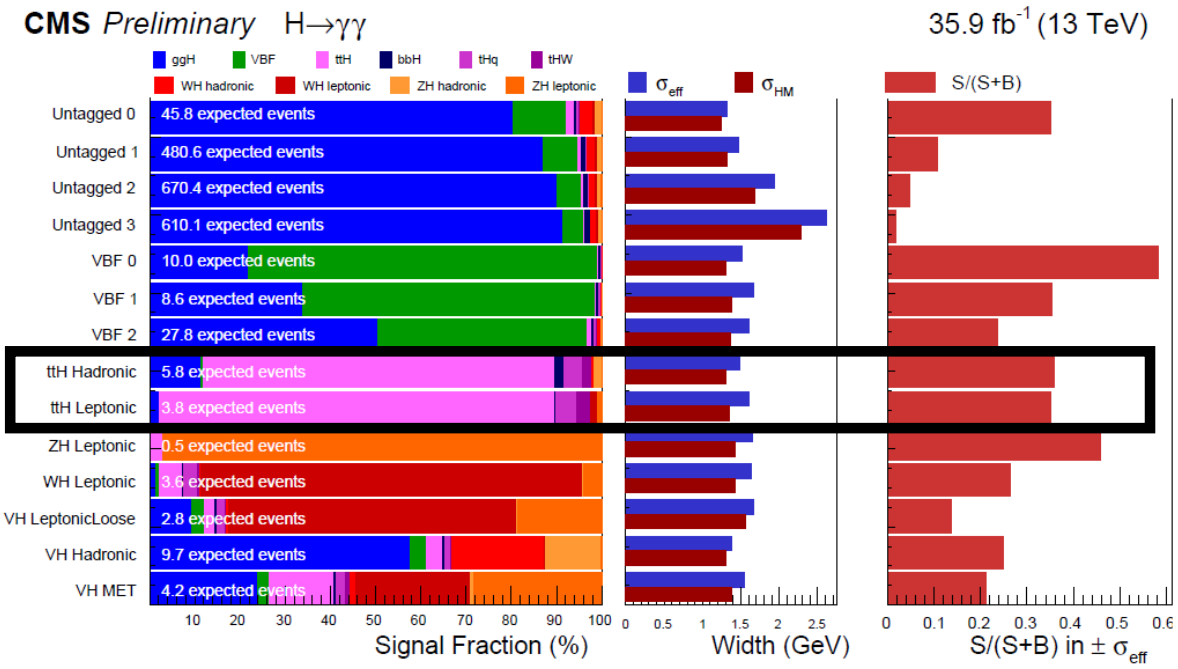
Need higher luminosities

ttH($\gamma\gamma$)

ATLAS: arXiv:1802.04146
CMS: CMS-PAS-HIG-16-040

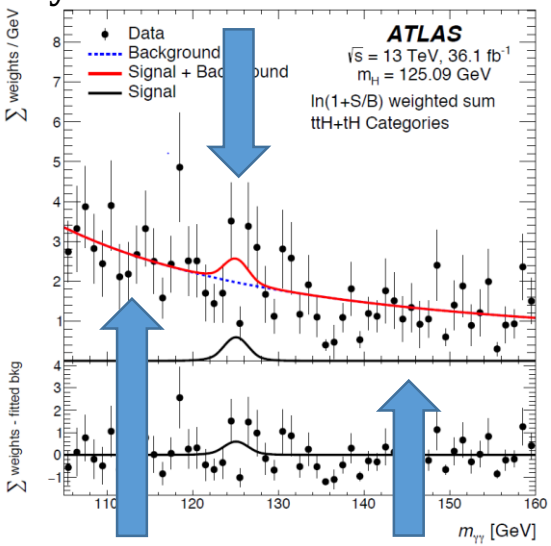
ttH(γγ): ATLAS and CMS

- Low statistic channel ($\sigma \times BR = 0.507pb \times 0.00227$)
  - 0.2% of the ttH events & 1% of the H→γγ events
- Included in main H→γγ analysis:
  - Inclusive H→γγ event selection
  - ttH enriched category at high N(jets) and N(b-tags)
  - Leptonic and hadronic categories



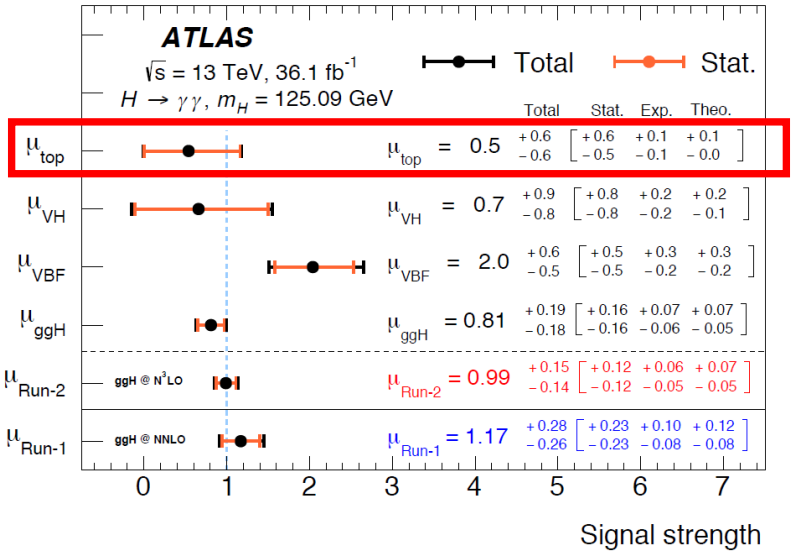
- Rely on the excellent M(γγ) resolution

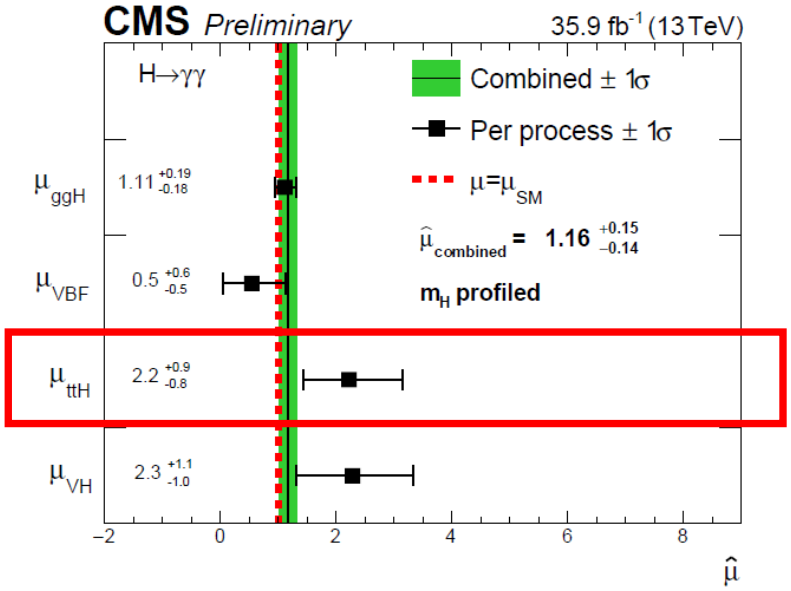
Signal as double sided crystal ball around 125 GeV



Extract background from side bands

ttH(γγ) ATLAS and CMS





Combined fit with all H→γγ channels:

- ATLAS: $\mu_{top} = 0.5 \pm 0.6(tot)\ ^{+0.6}_{-0.5}(stat)\ ^{+0.1}_{-0.1}(syst)$
- CMS: $\mu_{ttH} = 2.2\ ^{+0.9}_{-0.8}(tot)$

Sensitivity limited by statistical uncertainty

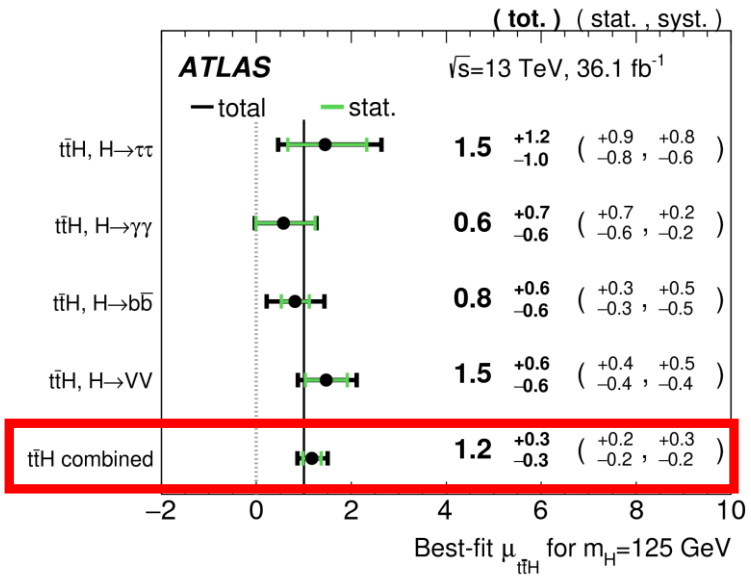
ttH combination

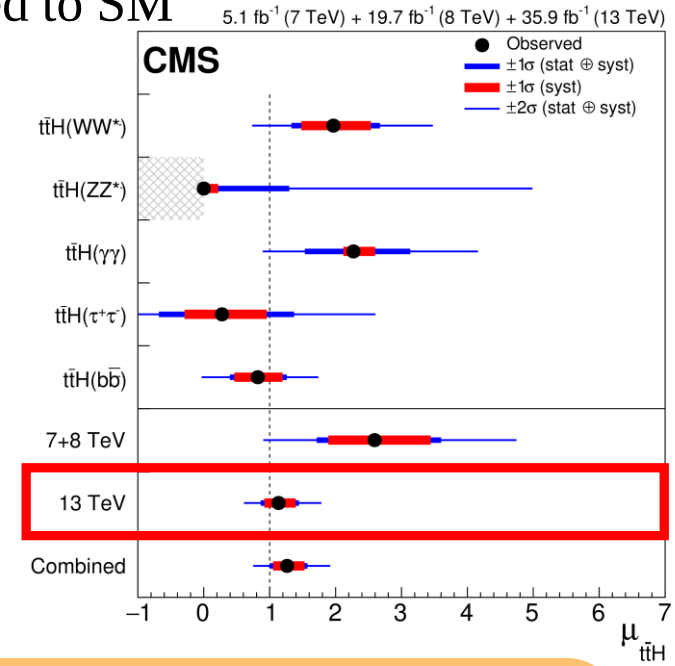
ATLAS: Phys. Rev. D 97 (2018) 072003
CMS: arXiv:1804.02610

ttH Combination Run 2 Result

Combine all ttH analyses:

- Other Higgs boson production modes fixed to SM





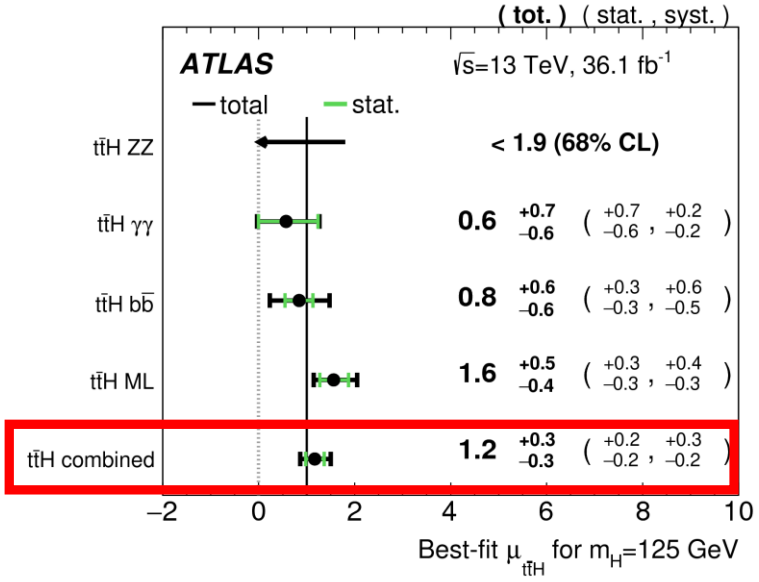
Compatibility ATLAS – CMS – SM

- ATLAS Run 2: $\mu = 1.2 \pm 0.3 \left[{}^{+0.2}_{-0.2}(stat) \quad {}^{+0.3}_{-0.2}(syst) \right]$
- CMS Run 2: $\mu = 1.14 \, {}^{+}_{-} \, {}^{0.31}_{0.27} \left[{}^{+0.17}_{-0.16}(stat) \quad {}^{+0.26}_{-0.22}(syst) \right]$

ttH Combination Run 2 Result

Combine all ttH analyses:

- Other Higgs boson production modes fixed to SM



ATLAS

Channel	Significance	
	Observed	Expected
Multilepton	4.1σ	2.8σ
$H \to b\bar{b}$	1.4σ	1.6σ
$H \to \gamma\gamma$	0.9σ	1.7σ
$H \to 4\ell$	—	0.6σ
Combined	4.2σ	3.8σ

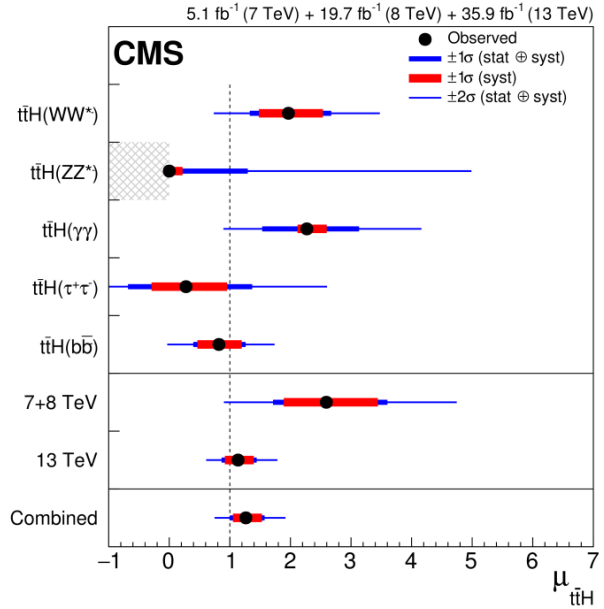
First evidence of ttH production (Nov 2017): ATLAS Run 2 data

ttH cross-section measurement: $\sigma(ttH) = 590^{+160}_{-150}\ fb\ (SM: 507^{+35}_{-50})$

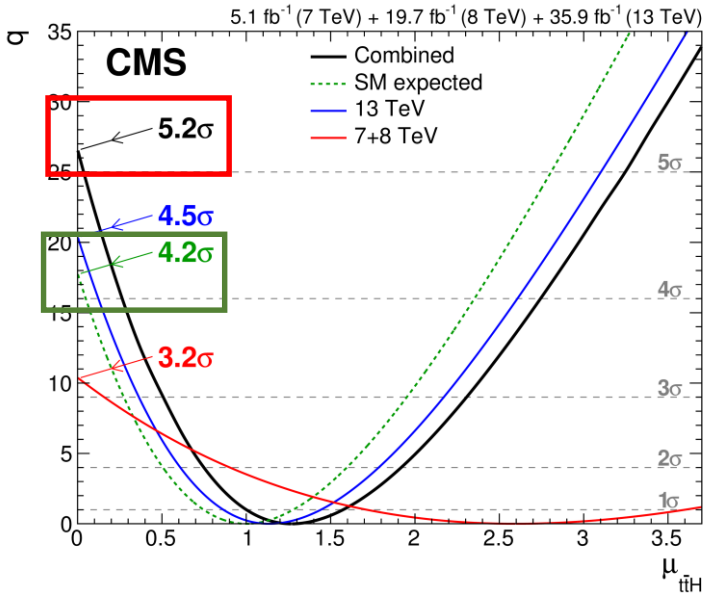
ttH Combination Run 1 + Run 2

Combine Run 1 and Run 2 data:

- Correlate only signal inclusive and some background uncertainties



NEW



First ttH observation (yesterday): CMS Run 1 + Run 2 data

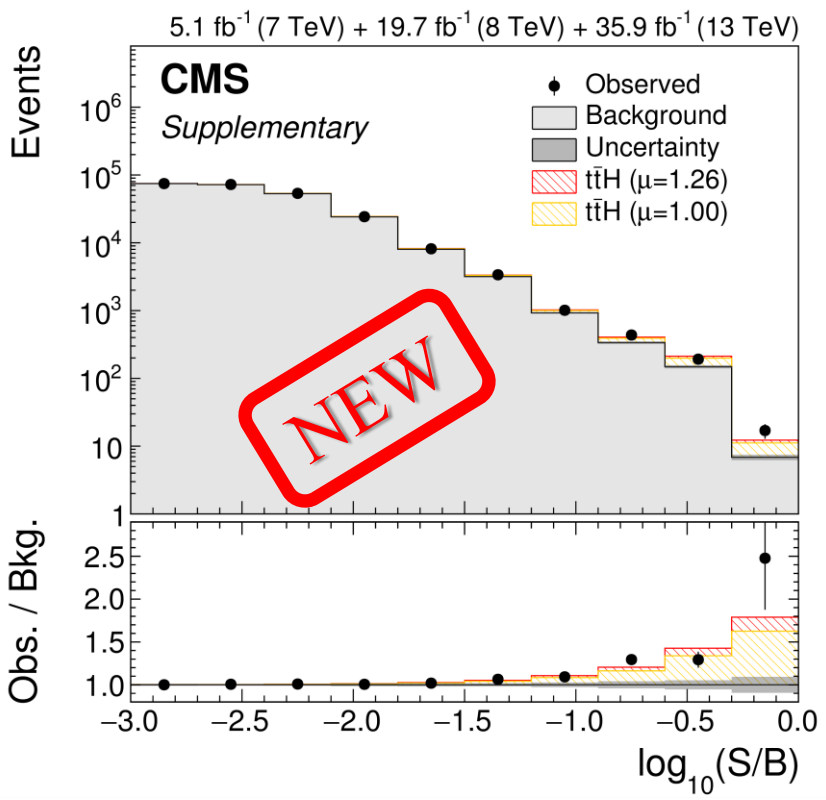
5.2σ (4.2σ) observed (expected) significance

$$\mu = 1.26^{+0.31}_{-0.26}\left[\ ^{+0.16}_{-0.16}(stat)\ \ ^{+0.17}_{-0.15}(expt)\ \ ^{+0.14}_{-0.13}(ThBkg)\ \ ^{+0.15}_{-0.07}(ThSig)\right]$$

ttH Combination Run 1 + Run 2

Combine Run 1 and Run 2 data:

- Correlate only signal inclusive and some background uncertainties



- ~90 categories (many with MVA distributions)
- Combine in $\log_{10}$(S/B) bins
- Clear signal over the background

Run 2 Higgs Coupling Constraints

CMS Higgs combination PAS: CMS-PAS-HIG-17-031

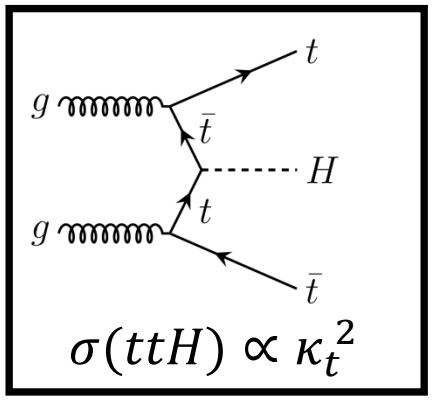
CMS: Run 2 Higgs Coupling Constraints

Combining all Higgs boson analyses:

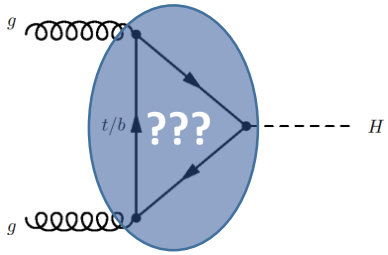
- Global fit with all production and decay modes included

Use the coupling modifiers: $\kappa_i^2 = {}^{\sigma}/_{\sigma_{SM}}$ or $\kappa_i^2 = {}^{\Gamma}/_{\Gamma_{SM}}$

- For our two favorite processes

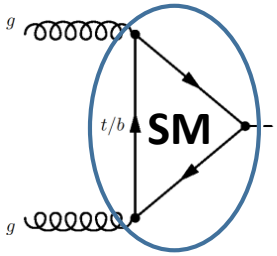


$\sigma(ttH) \propto \kappa_t^2$



$\sigma(ggH) \propto \kappa_g^2$

OR



$$\sigma(ggH) \propto 1.04 \cdot \kappa_t^2 + 0.02 \cdot \kappa_b^2 - 0.038 \cdot \kappa_t \cdot \kappa_b$$

Exp unc on κ_t	SM	If BSM in loop
ATLAS+CMS Run 1	$\mathcal{O}(15\%)$	$\mathcal{O}(30\%)$
CMS Run 2	$\mathcal{O}(12\%)$	$\boldsymbol{\mathcal{O}(15\%)}$

CMS: top Yukawa sensitivity

- Constraint from ttH alone improved by factor 2
- ttH and ggH sensitivities approaching

Conclusions

Conclusions

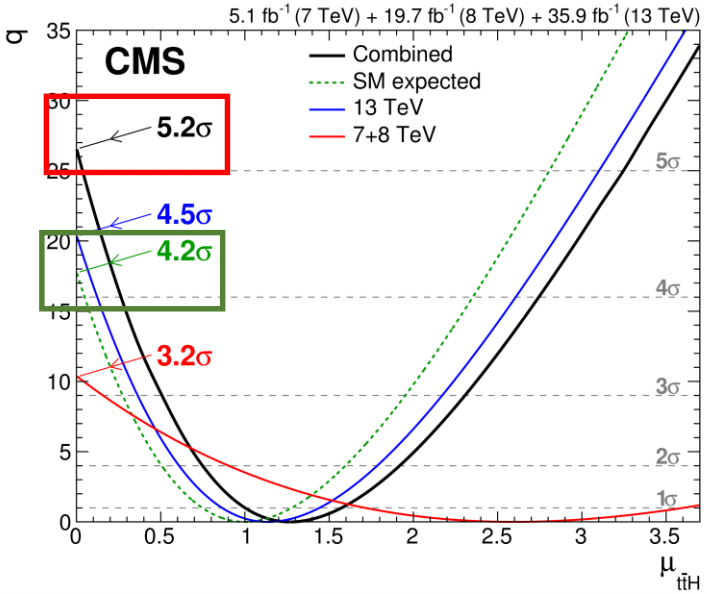
After Run 1: ttH search is a challenging analysis

November 2017: ATLAS announce evidence of ttH production in Run 2 data !

- ✓ Significance of 4.2σ (3.8σ) obs (exp)
- ✓ Cross-section: $590^{+160}_{-150}\ fb$ $(SM: 507^{+35}_{-50})$

Yesterday: CMS announce observation of ttH production in Run 1 + Run 2 data !

- ✓ Significance of 5.2σ (4.2σ) obs (exp)



$$\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26} = 1.26^{+0.16}_{-0.16}(\text{stat})^{+0.17}_{-0.15}(\text{expt})^{+0.14}_{-0.13}(\text{bkg th})^{+0.15}_{-0.07}(\text{sig th})$$

Next steps ?

- Measuring coupling:
  - ➢ Sensitivity in CMS →
- Going differential ?

Exp unc on κ_t	SM	BSM in loop
ATLAS+CMS Run 1	$\mathcal{O}(15\%)$	$\mathcal{O}(30\%)$
CMS Run 2	$\mathcal{O}(12\%)$	$\mathcal{O}(15\%)$

Thank you for your attention

backup

ttH Combination: Uncertainties

ATLAS uncertainty sources

Uncertainty Source	$\Delta\mu$	
$t\bar{t}$ modeling in $H \to bb$ analysis	+0.15	−0.14
$t\bar{t}H$ modeling (cross section)	+0.13	−0.06
Non-prompt light-lepton and fake τ_{had} estimates	+0.09	−0.09
Simulation statistics	+0.08	−0.08
Jet energy scale and resolution	+0.08	−0.07
$t\bar{t}V$ modeling	+0.07	−0.07
$t\bar{t}H$ modeling (acceptance)	+0.07	−0.04
Other non-Higgs boson backgrounds	+0.06	−0.05
Other experimental uncertainties	+0.05	−0.05
Luminosity	+0.05	−0.04
Jet flavor tagging	+0.03	−0.02
Modeling of other Higgs boson production modes	+0.01	−0.01
Total systematic uncertainty	+0.27	−0.23
Statistical uncertainty	+0.19	−0.19
Total uncertainty	+0.34	−0.30

CMS uncertainty sources

Uncertainty source	$\Delta\mu$	
Signal theory	+0.15	−0.07
Inclusive ttH normalisation (cross section and BR)	+0.15	−0.07
ttH acceptance (scale, pdf, PS and UE)	+0.004	−0.004
Other Higgs boson production modes	+0.002	−0.003
Background theory	+0.14	−0.13
tt + bb/cc prediction	+0.13	−0.11
tt + V(V) prediction	+0.06	−0.06
Other background uncertainties	+0.03	−0.03
Experimental	+0.17	−0.15
Lepton (inc. τ_h) trigger, ID and iso. efficiency	+0.08	−0.06
Misidentified lepton prediction	+0.06	−0.06
b-Tagging efficiency	+0.05	−0.04
Jet and τ_h energy scale and resolution	+0.04	−0.04
Luminosity	+0.04	−0.03
Photon ID, scale and resolution	+0.01	−0.01
Other experimental uncertainties	+0.01	−0.01
Finite number of simulated events	+0.08	−0.07
Statistical	+0.16	−0.16
Total	+0.31	−0.26

- Statistical, experimental, signal modelling and background modelling have similar impact on sensitivity
- Leading channels: ttH(bb)-1-lepton, ttH(ml)-2lSS, ttH($\gamma\gamma$)

Leading uncertainty: tt+bb modeling, signal modeling, statistic