Search for ttH and tH production (not including H→bb) at the LHC

Josh McFayden
on behalf of the ATLAS and CMS collaborations

Top2015
Ischia

17/09/2015

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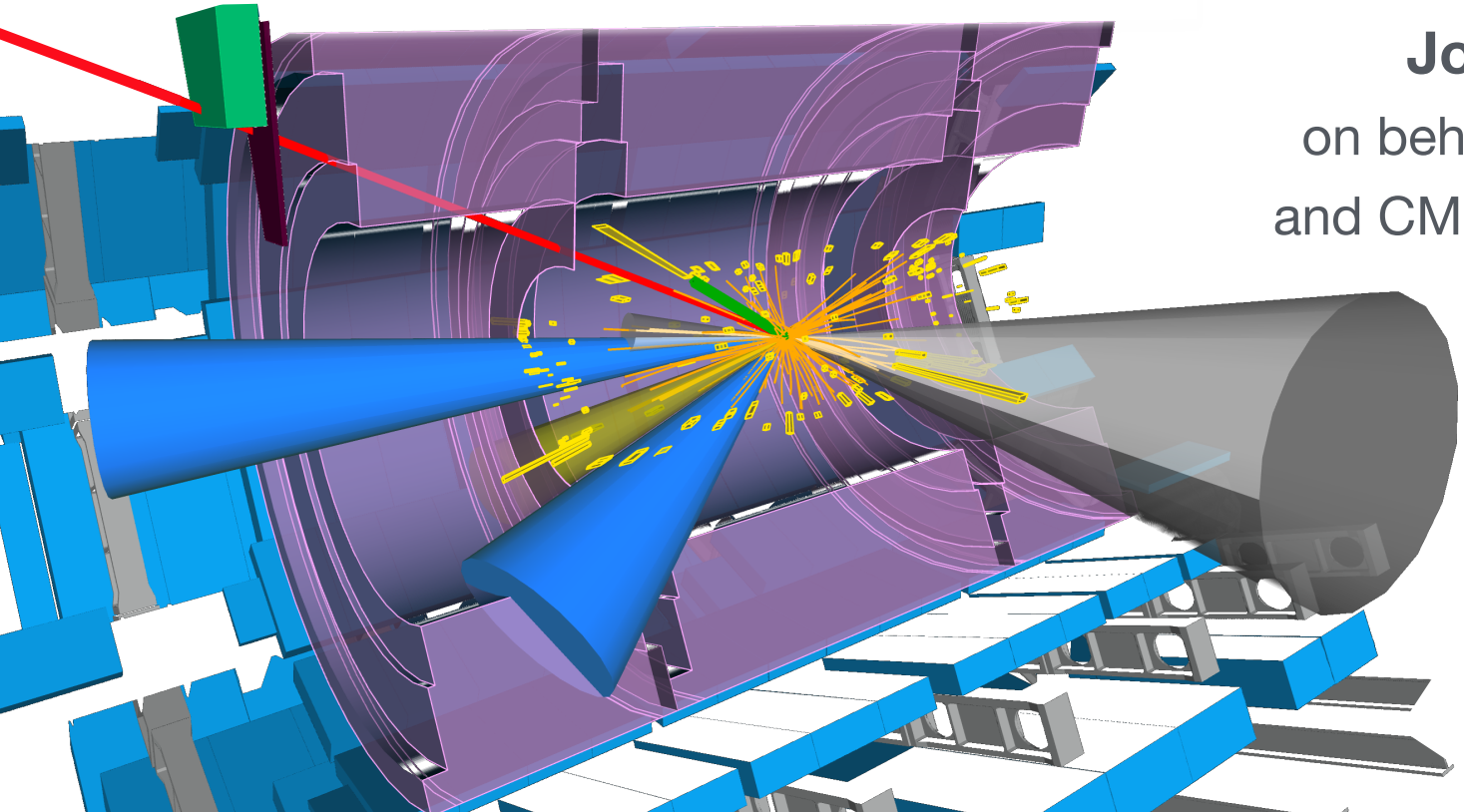

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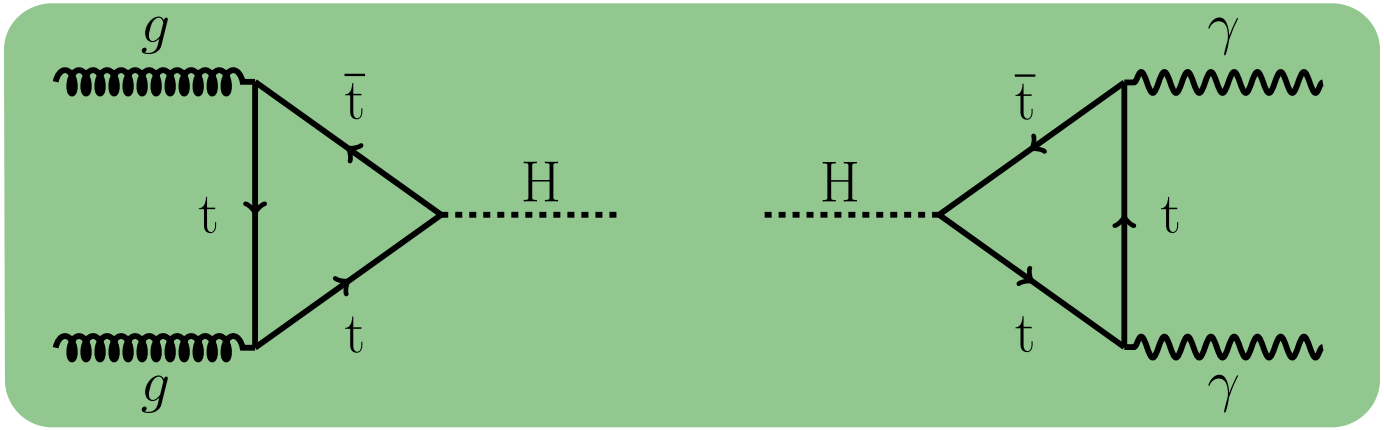
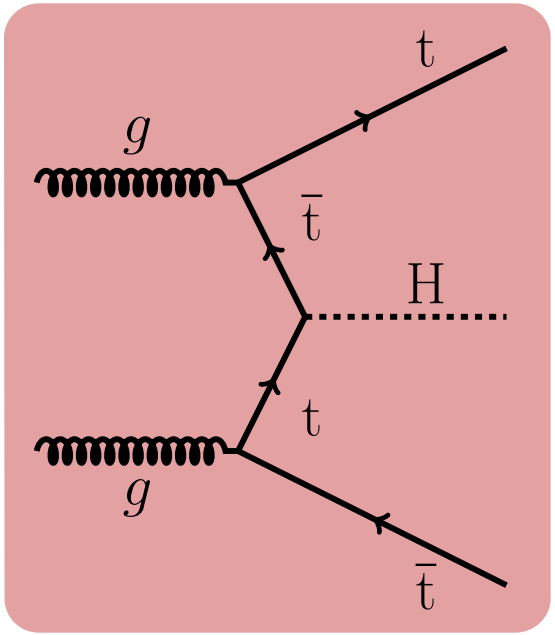
Introduction

- Since the Higgs discoveries the focus of experiment has been to measure its properties including its coupling to SM particles.
  - Higgs observed decaying to $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$, $H \to WW^* \to \ell\upsilon\ell\upsilon$, evidence for $H \to \tau\tau$.
- The large mass of the top quark implies a top Yukawa coupling ~1.
- There is already sensitivity in to the top-Higgs coupling from ggF Higgs production and from the decay to photons via loop interactions:

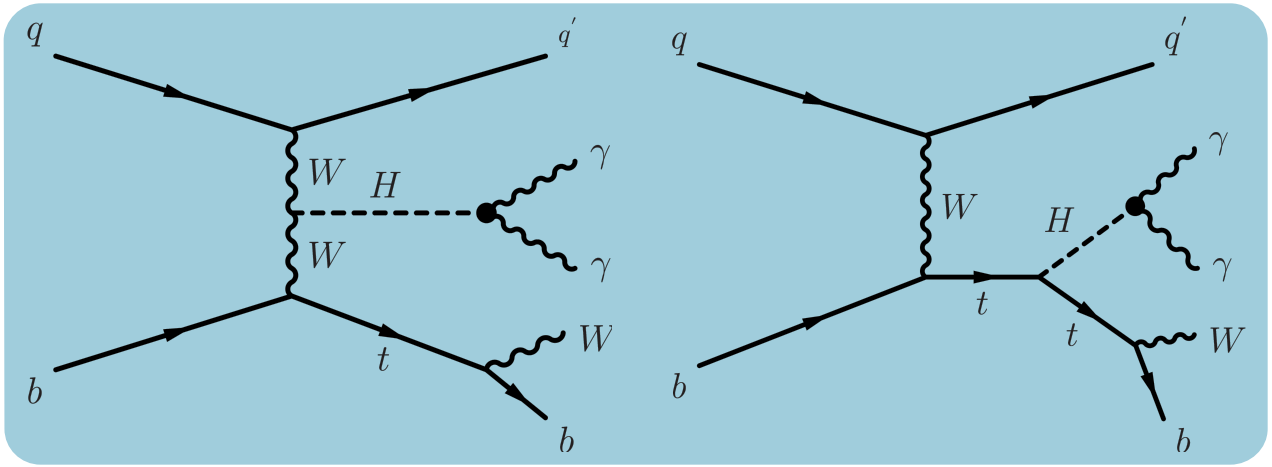


Introduction

- Production in association with **ttbar** would permit a direct measurement of the top-Higgs coupling
  - Removing possible BSM effects in the loops.

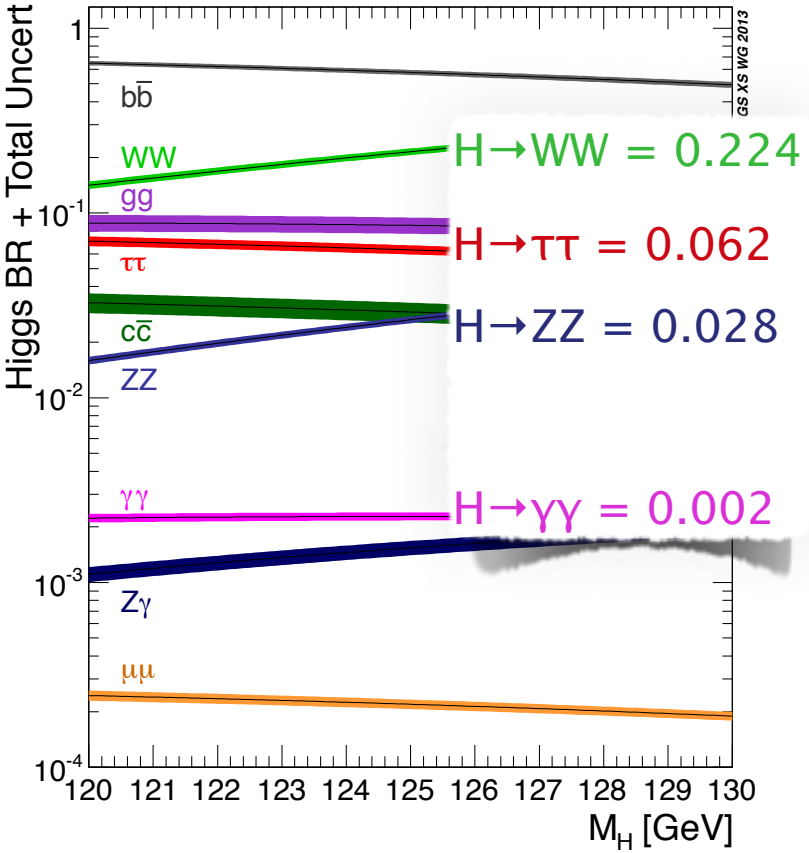


- Production in association with a **single top quark** is sensitive to W-t interference and relative sign of the top-Higgs coupling
  - Tree level interference in all channels and in Hγγ loop for H→γγ



Analyses covered

- ATLAS and CMS analyses searching for a Higgs produced in association with **top quark pairs (ttH)** and **single top quarks (tH)** are presented.
- This talk focuses on searches in decay modes not including H→bb
  - In reality this means H→γγ, H→ZZ*, H→WW* and H→ττ.
  - Signatures are di-photons, same-sign (SS) di-lepton and multi-lepton final states



t[t]H(→γγ):
Physics Letters B 740 (2015) 222–242

t[t]H(→leptons):
Physics Letters B 749 (2015) 519–541

ttH(H→all):
J. High Energy Phys. 09 (2014) 087

tH(→γγ):
HIG-14-001

ttH(H→leptons):
HIG-13-020

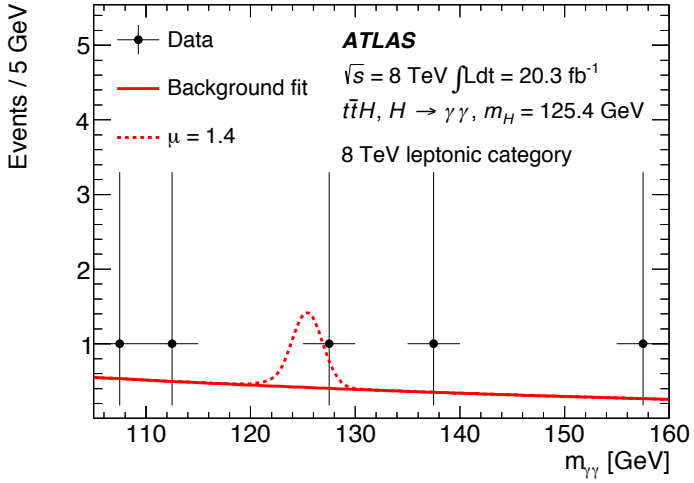
tH(→leptons):
HIG-14-026

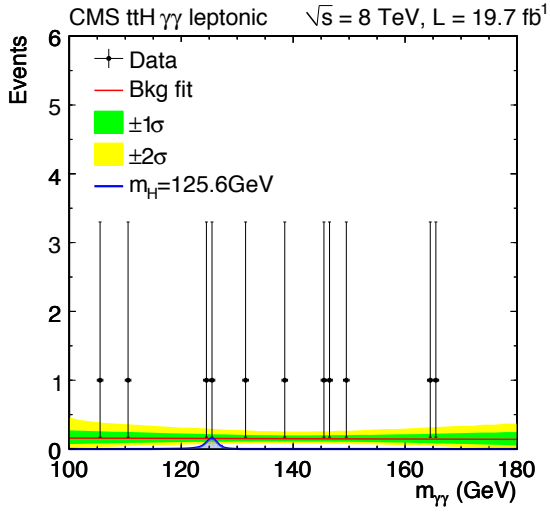
$H \rightarrow \gamma\gamma$

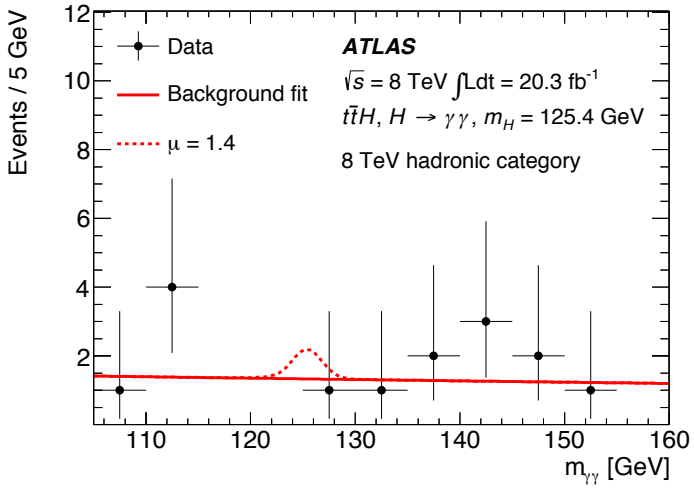
t[t]H→γγ | Analysis strategy

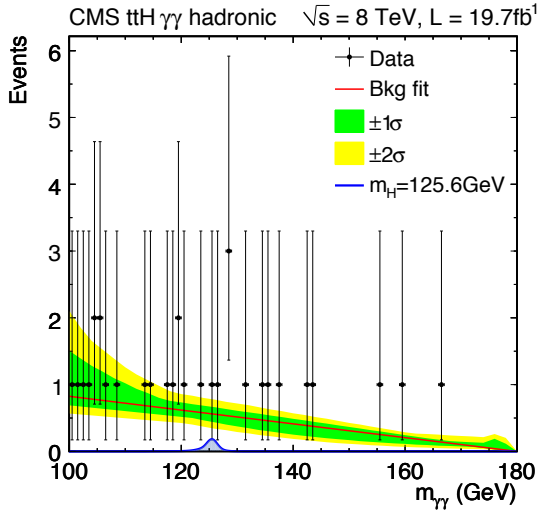
- ATLAS and CMS use both $\sqrt{s}$ = 7 & 8 TeV datasets for this analysis.
  - ATLAS includes tH in the definition of signal whilst CMS has a separate analysis.
- Two signal regions defined by top decay modes
  - Leptonic and hadronic categories.
- Use excellent $m_{\gamma\gamma}$ resolution to extract signal peak from falling continuum background.
  - Background estimated from data using $m_{\gamma\gamma}$ sidebands.
- Signal strength, μ, is extracted from fit to $m_{\gamma\gamma}$ distribution
  - Higgs mass is fixed while μ is allowed to float but is common across the different signal regions.

- Dominant systematic uncertainties are:
  - Photon ID
  - Background modelling
  - Jet energy scale
  - Theory & MC modelling
- Results are consistent with the SM expectation





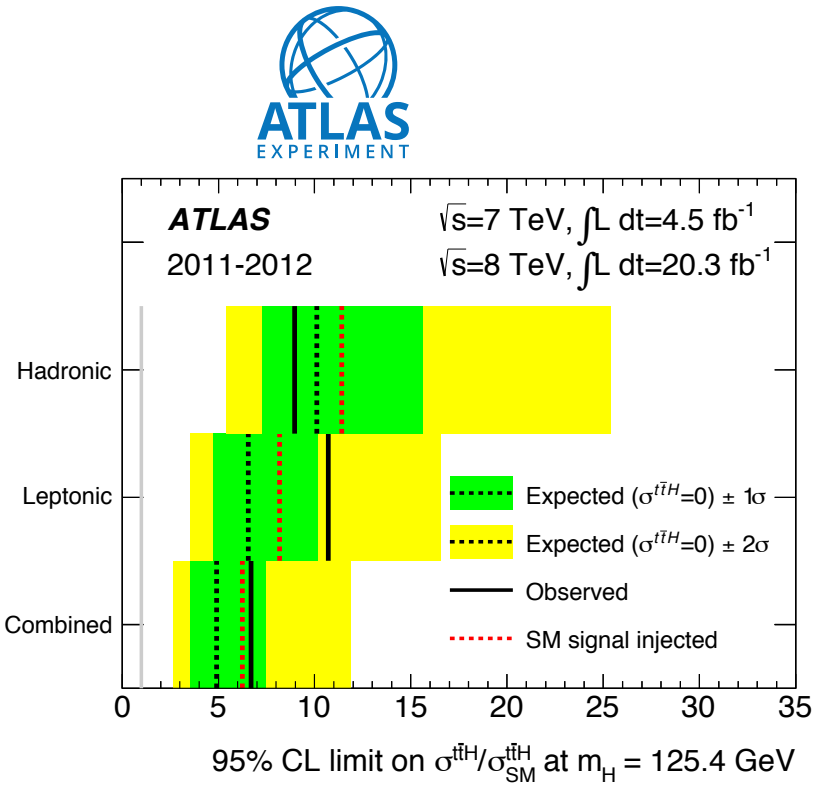


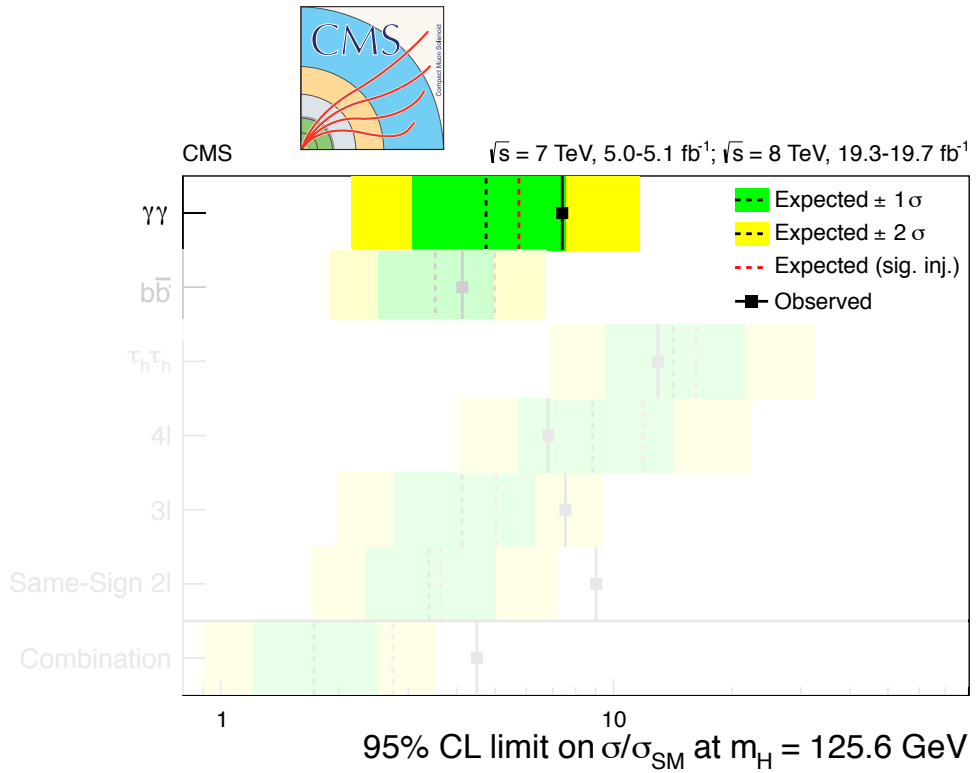


t[t]H→γγ | ttH Interpretation

- The **H→γγ** observed (exp.) **95%CL upper limits on σ/σ_{SM}**:
  - ATLAS: 6.7 ($4.9^{+2.6}_{-1.4}$)
  - CMS: 7.4 ($4.7^{+2.9}_{-1.6}$)

- The **H→γγ** best-fit **ttH signal strengths**:
  - ATLAS: $\mu_{ttH}=1.3^{+2.6}_{-1.7}$
  - CMS: $\mu_{ttH}=2.7^{+2.6}_{-1.8}$



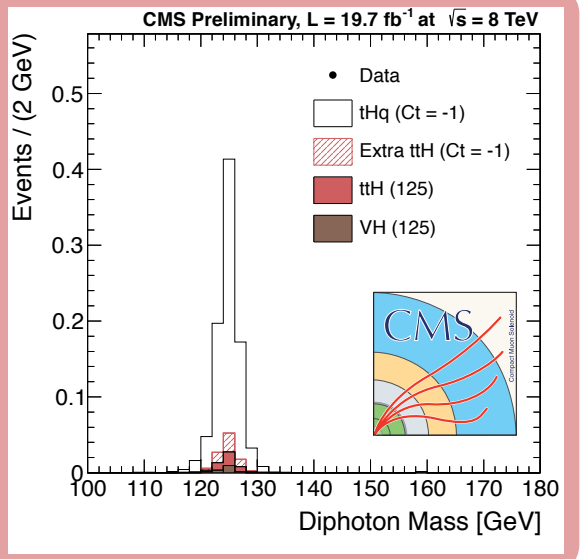


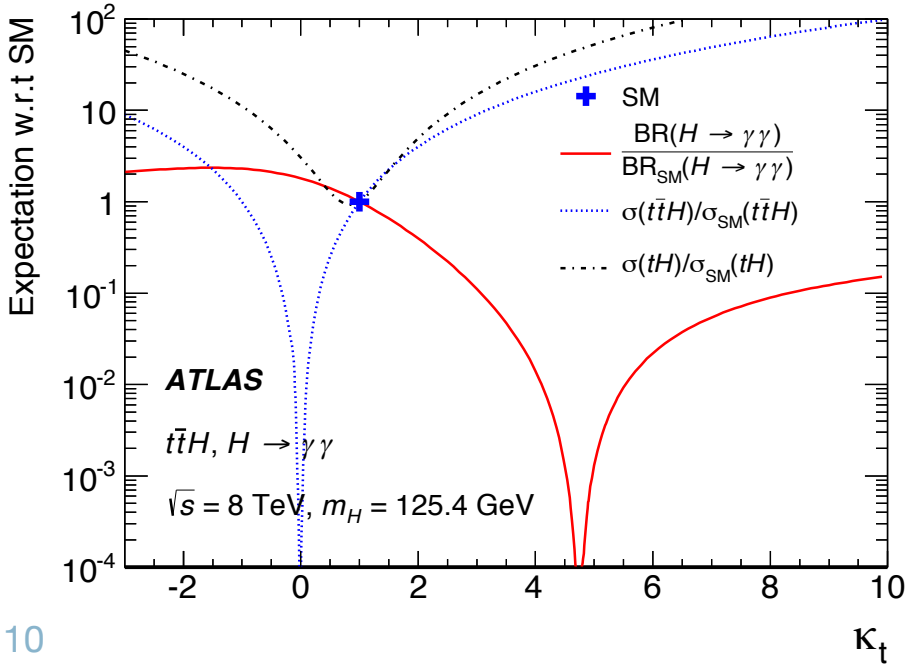
t[t]H→γγ | tH Interpretation

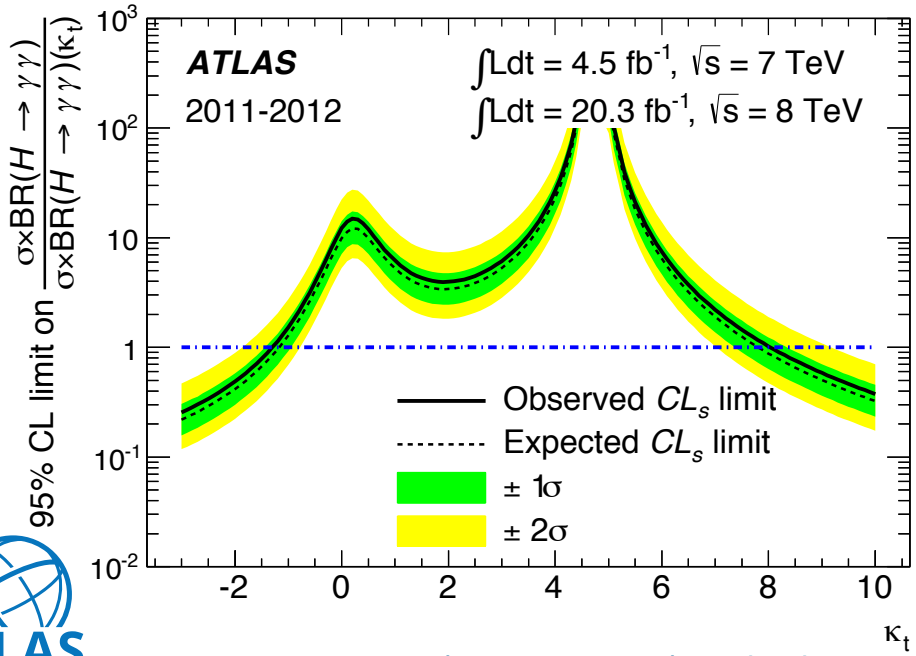
- Results can also be interpreted in terms of the scale of the top Yukawa coupling, κ_t or C_t.

- At the 95% CL ATLAS exclude $\kappa_t < -1.3$ and $\kappa_t > 8.0$.
  - Limits constrain BSM models.

tH Results:
- ATLAS result included in ttH search
- CMS dedicated search for tHq. No events observed:
95%CL upper limit on σ/σ_{SM} of 4.1 for inverted coupling (C_t=-1).







H→leptons

ttH→leptons | Analysis strategy

- Final state considered is the following:
  p p → t t **H** → b b W W W W
  b b W W τ τ

ℓ=e,μ

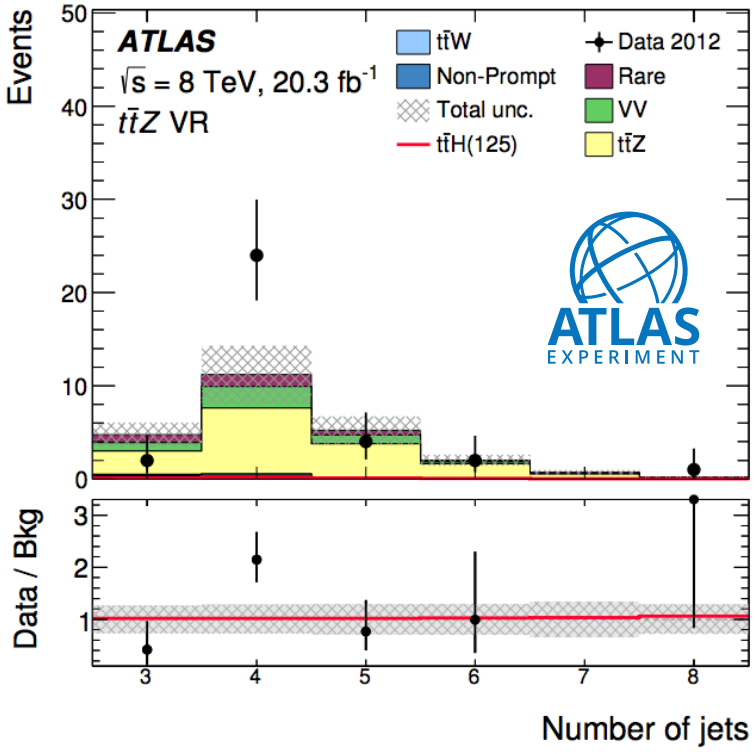
ATLAS signal category by Higgs decay mode (CMS ~same)

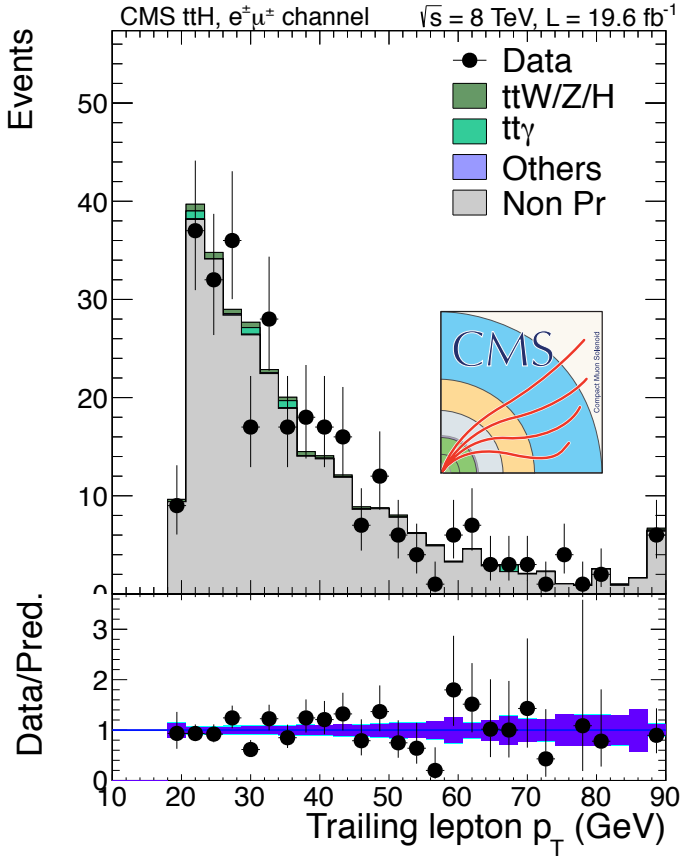
Category	WW^*	$\tau\tau$	ZZ^*
$2\ell 0\tau_{had}$	80%	15%	3%
3ℓ	74%	15%	7%
$2\ell 1\tau_{had}$	35%	62%	2%
4ℓ	69%	14%	14%
$1\ell 2\tau_{had}$	4%	93%	0%

- Signal regions selection:
  - 2ℓ SS 0τhad
  - 2ℓ SS 1τhad
  - 3ℓ
  - 4ℓ
  - 2τhad
- Common selection:
  - m(ℓℓ) cuts
  - E_T^{miss}/H_T
- Fit strategy:

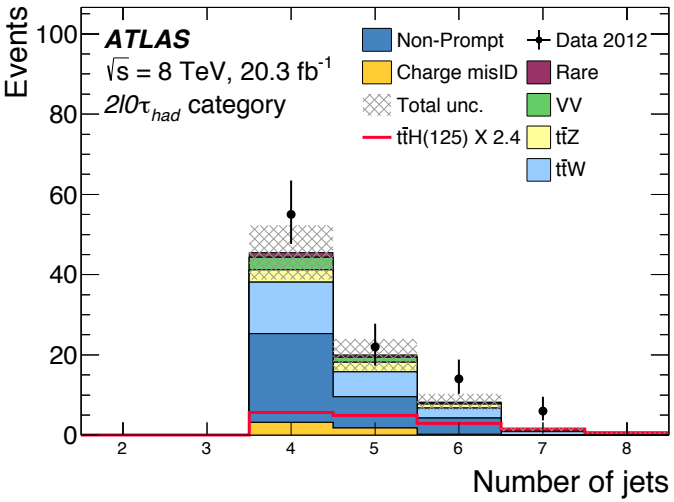
ATLAS EXPERIMENT	CMS
≥4j, ≥1b	≥4j, ≥1b$_{tight}$ || 2b$_{loose}$
≥4j, ≥1b	
≥4j, ≥1b || ≥3j, ≥2b	≥2j, ≥1b$_{tight}$ || 2b$_{loose}$
≥2j, ≥1b, Z$_{enriched/deprived}$	N_{jets}
1ℓ, ≥3j, ≥1b	Within H→bb framework
veto for low mass resonances & Z candidates	
-	L_D cut to remove Z+jets
Yield in SRs (2ℓ0τhad split SRs by N_{jets} & ℓ-flav)	Shape: BDT bins & N_{jets} (N_{jets} is used in 4ℓ-only)

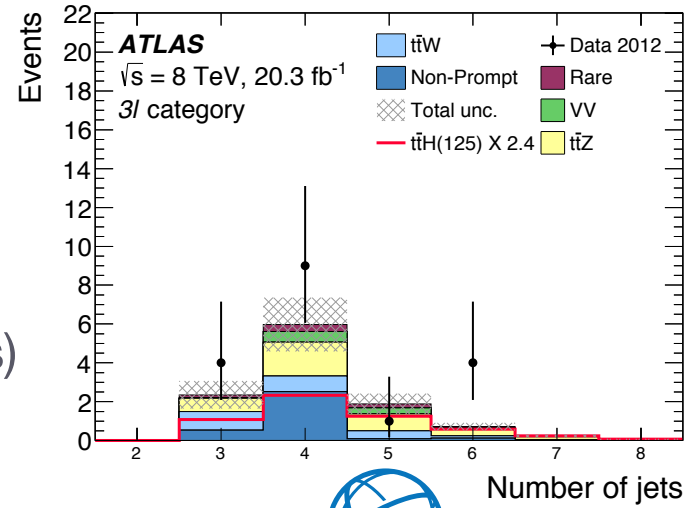
- Dominant backgrounds can be split into two categories
  - **Irreducible**: ttV, diboson(+bjet)
    - Use validation regions to validate MC with data
  - **Reducible**: non-prompt leptons
    - Use control regions with loosened isolation requirements to extrapolate to signal region

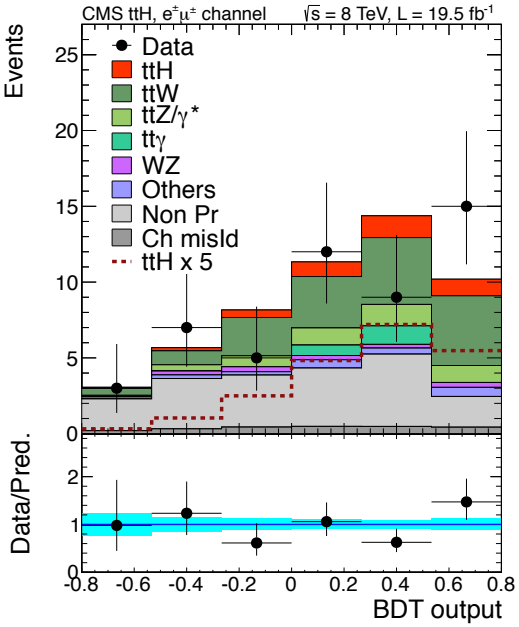


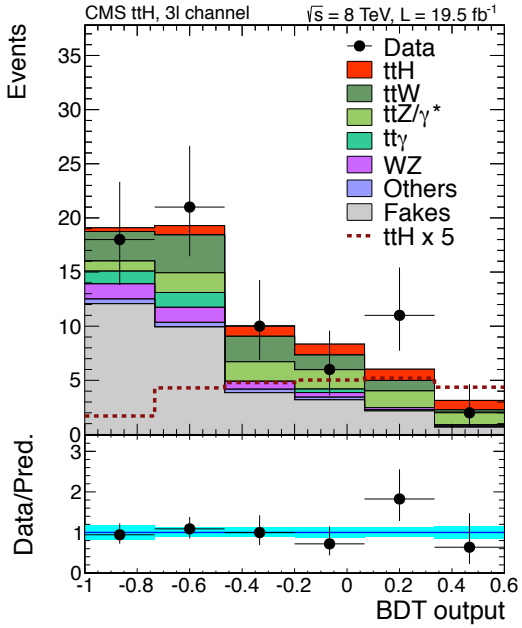


- Dominant systematic uncertainties:
  - Non-prompt lepton background estimation
  - Theory & MC modelling
  - Jet energy scale
- Signal strength extraction from fit to:
  - 11 signal region yields
  - Shape of 4 BDT & 1 N_{jet} distribution(s)









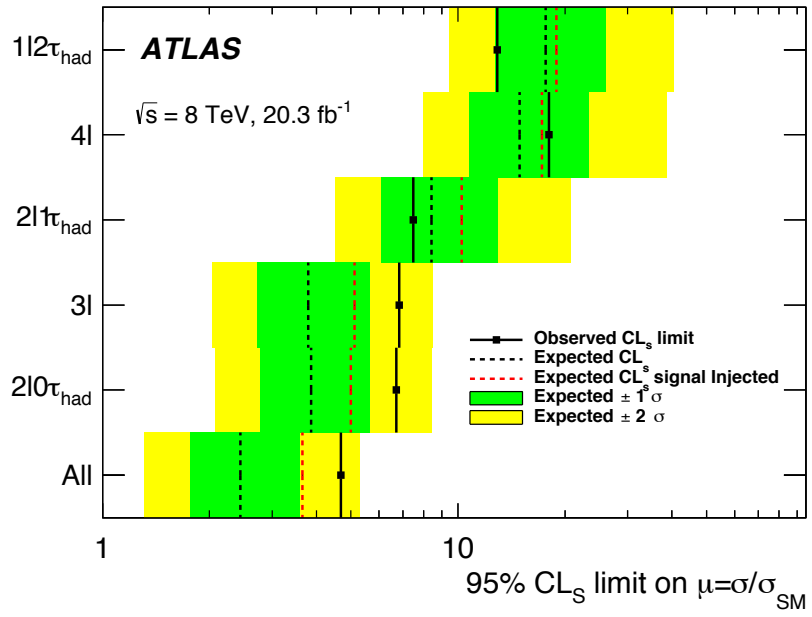
ttH→leptons | Limits on σ/σ_{SM}

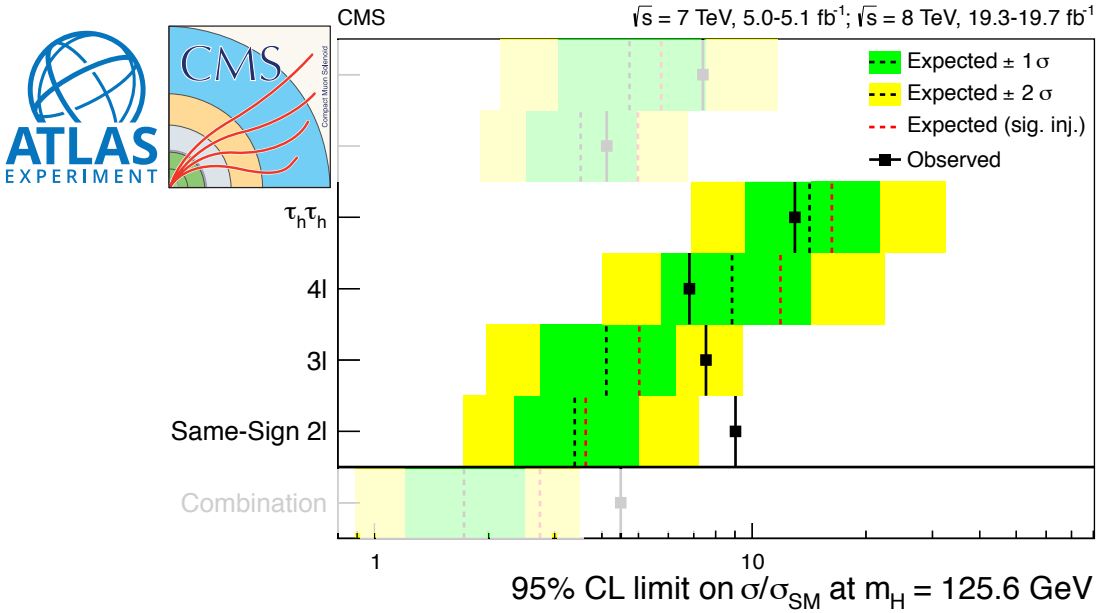
- The results are compatible with the SM expectation, although an excess is observed by both experiments.
- 2ℓ SS and 3ℓ categories are the most sensitive

- The **H→leptons** observed (exp.) **95%CL upper limits on σ/σ_{SM}**:

ATLAS - 4ℓ: 18 (15^{+8}_{-4})
3ℓ: 6.8 ($3.8^{+1.9}_{-1.1}$)
$2\ell 0\tau_{had}$: 6.7 ($3.9^{+1.8}_{-1.1}$)

CMS - 4ℓ: 6.8 ($8.8^{+1.2}_{-5.5}$)
3ℓ: 7.5 ($4.1^{+2.2}_{-1.3}$)
2ℓ: 9.0 ($3.4^{+1.6}_{-1.1}$)





ttH→leptons | Signal strength

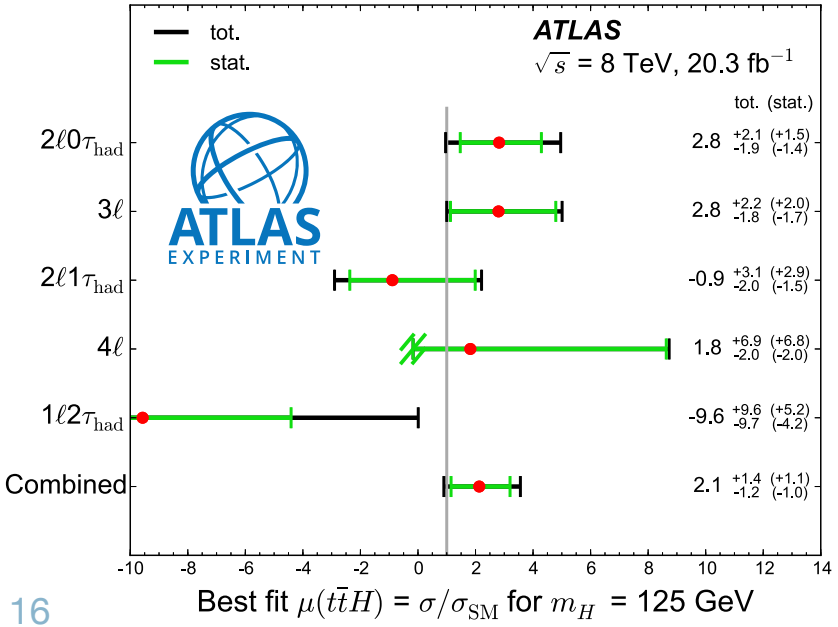
- The results are compatible with the SM expectation, although an excess is observed by both experiments.
- 2ℓ SS and 3ℓ categories are the most sensitive.

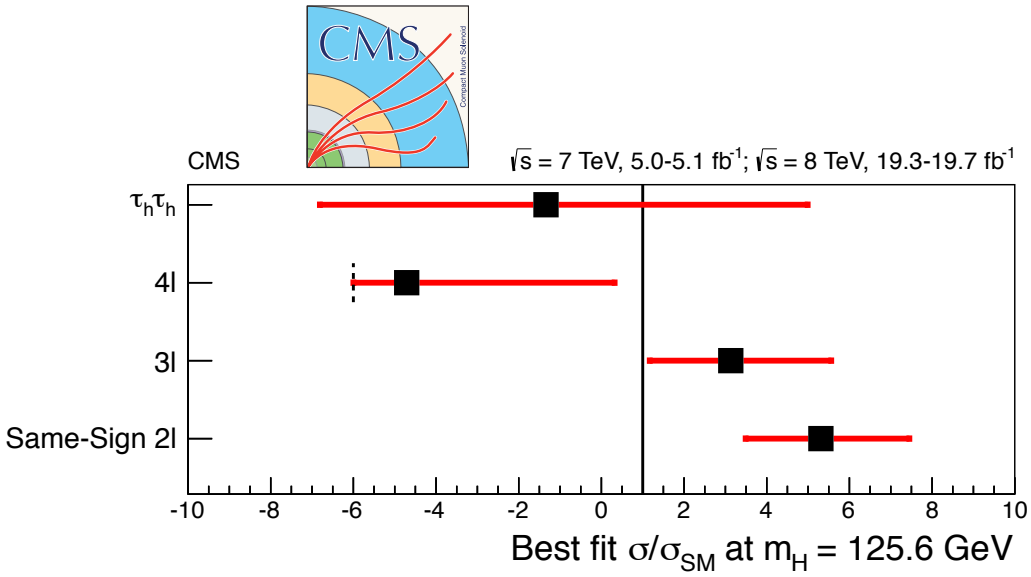
- The **H→leptons** observed **best-fit signal strengths**:

ATLAS - 4ℓ: $1.8^{+6.9}_{-2.0}$ CMS - 4ℓ: $-4.7^{+5.0}_{-1.3}$

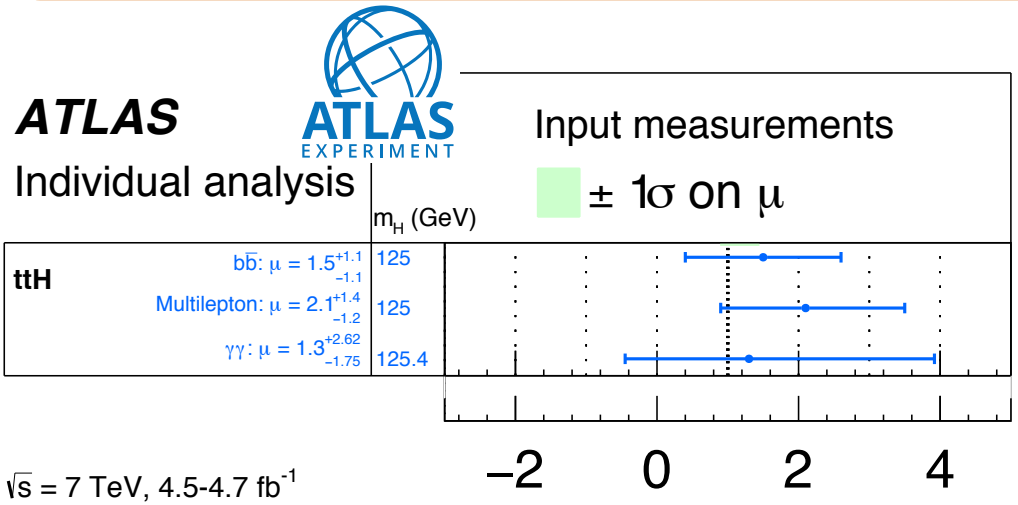
3ℓ: $2.8^{+2.2}_{-1.8}$ 3ℓ: $3.1^{+2.4}_{-2.0}$

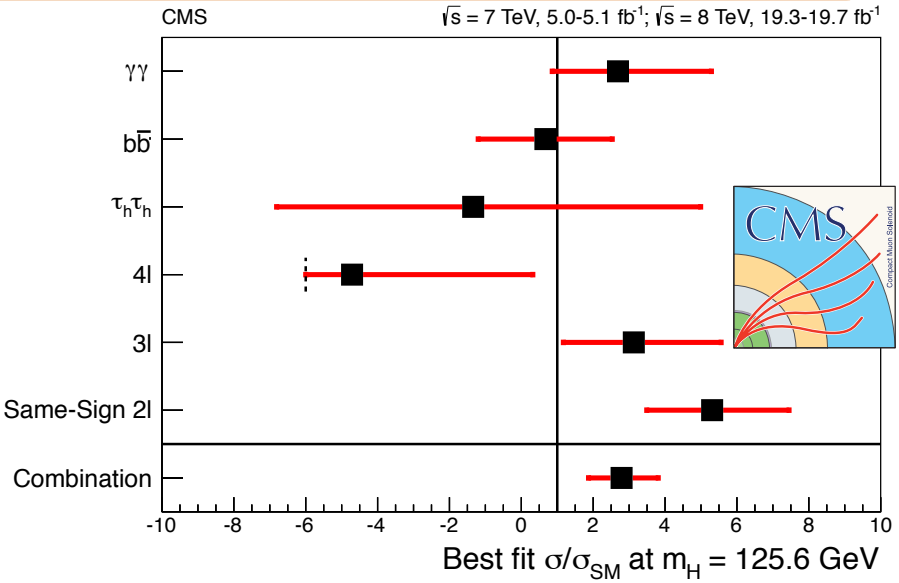
2ℓ0τhad: $2.8^{+2.1}_{-1.9}$ 2ℓ: $5.3^{+2.1}_{-1.8}$

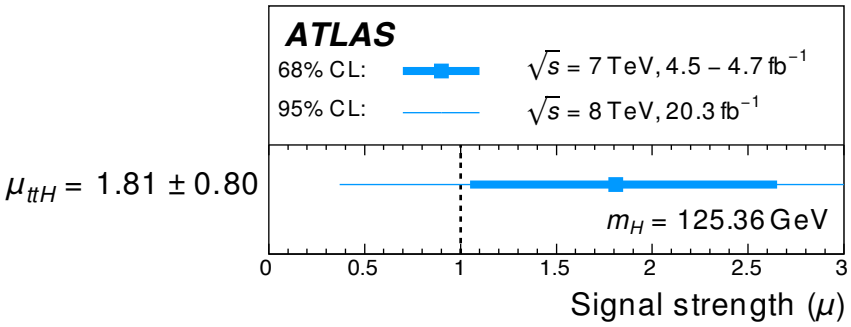


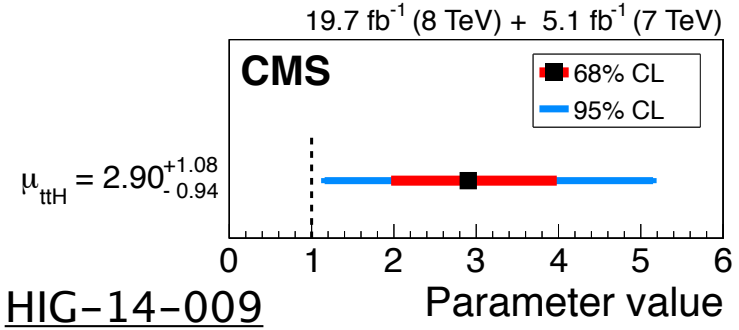


- The **combined** observed (exp.) **95%CL upper limits on σ/σ_{SM}:**
  ATLAS: 3.2 (1.4) CMS: 4.5 ($1.7^{+0.8}_{-0.5}$)
- The **combined** observed **best-fit signal strengths**:
  ATLAS: $\mu=1.81^{+0.8}_{-0.8}$ CMS: $\mu=2.90^{+1.08}_{-0.94}$









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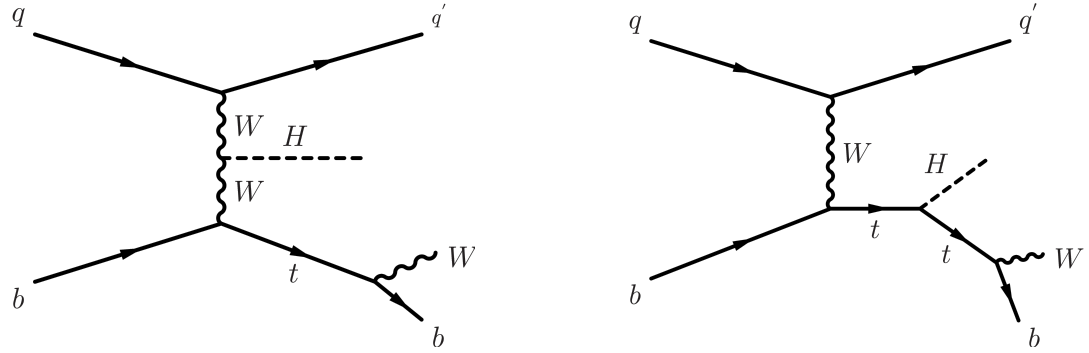
HIG-14-009

- Search for single top+H production in leptonic channels

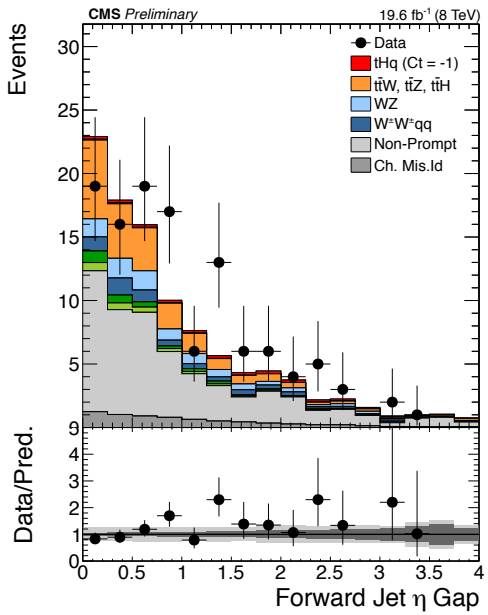


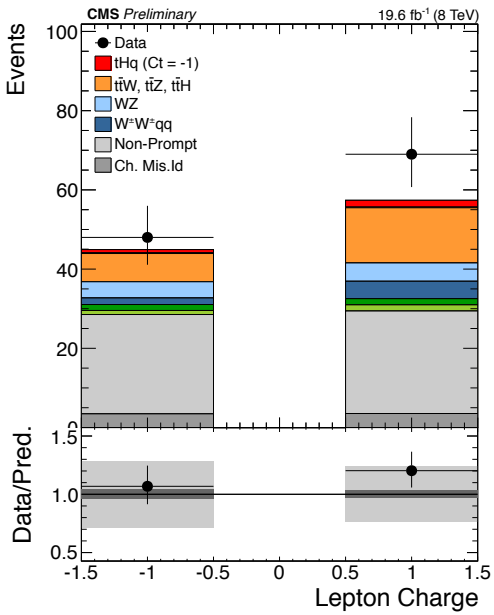
  - Focus on the H→WW* and H→ττ decay modes.

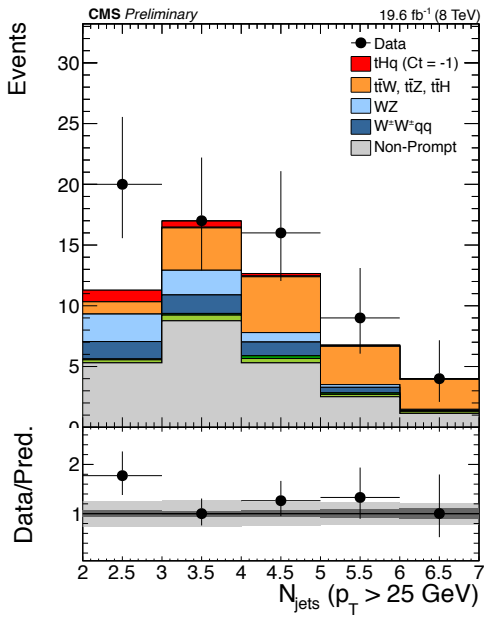
- 2ℓ SS ($e^{\pm}\mu^{\pm}$ and $\mu^{\pm}\mu^{\pm}$) and 3ℓ selections
  - Several discriminating kinematic variables are combined into a single likelihood discriminant for each channel.

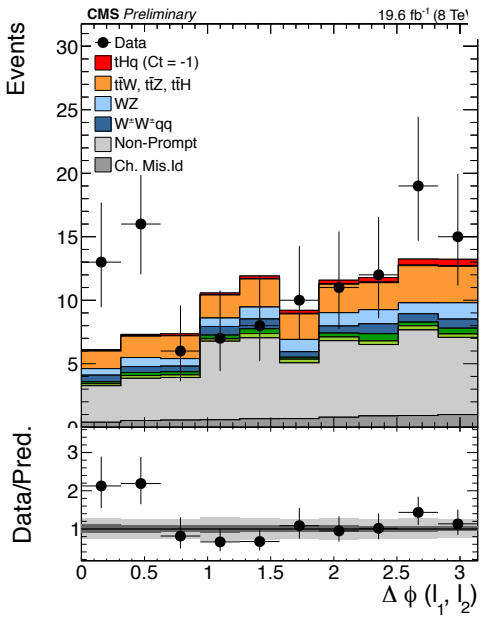
- The dominant backgrounds:
  - Non-prompt leptons
    - Control regions defined by looser lepton selections then used to extract extrapolation factors back to signal regions
  - ttW
    - Estimated purely from MC.

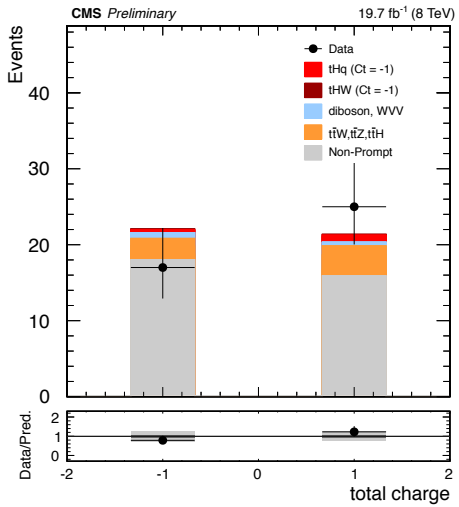
tH→leptons | Likelihood discriminant

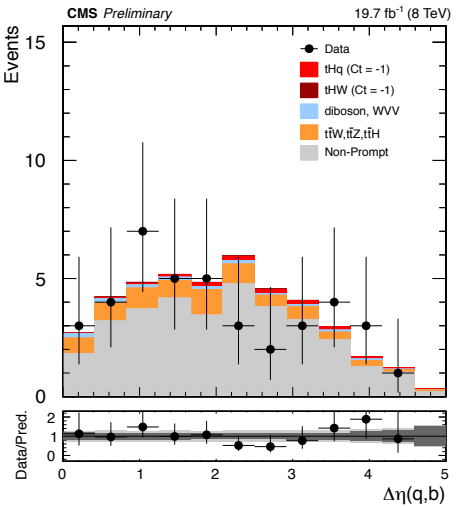


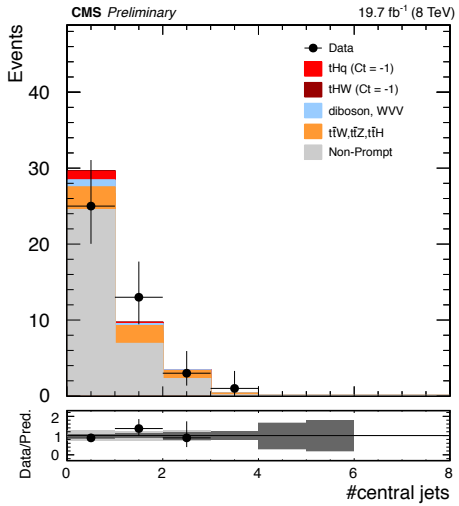


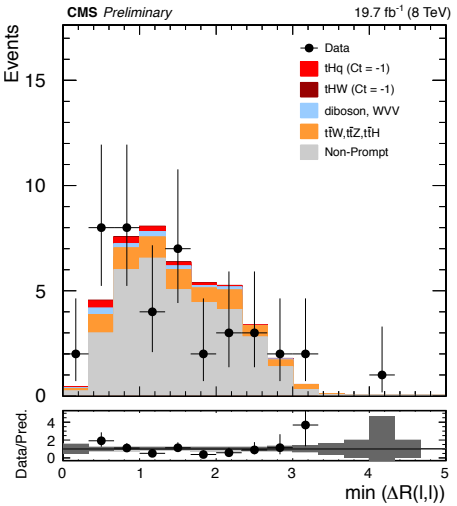




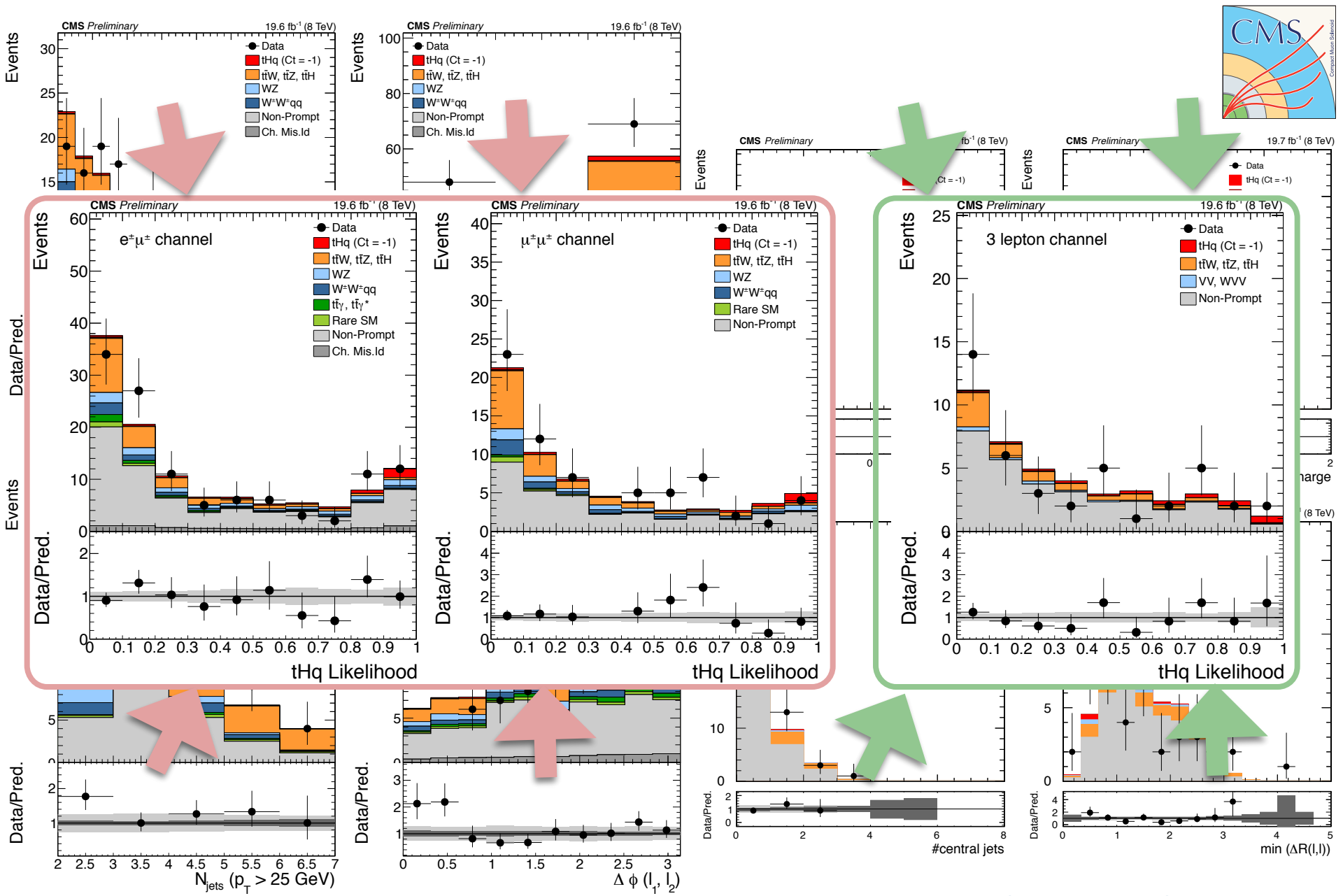








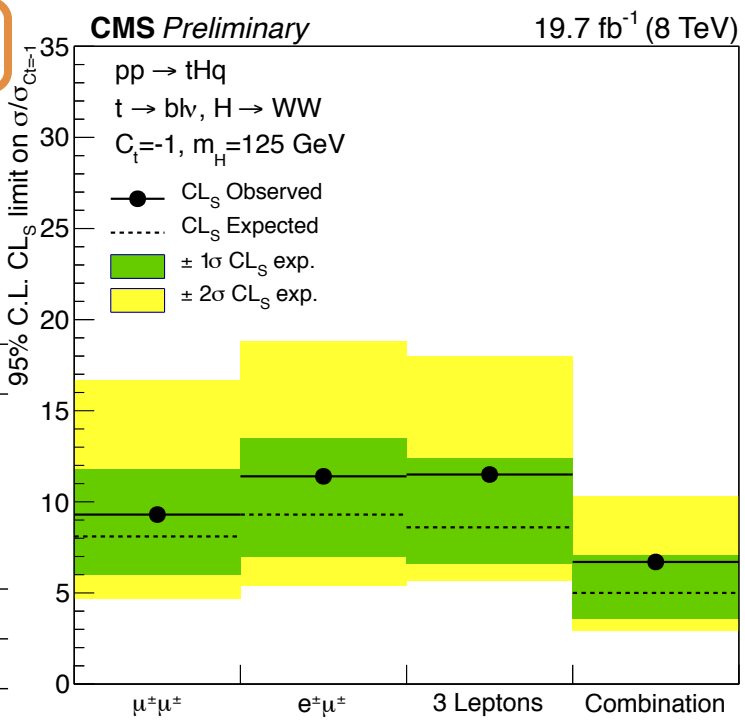
tH→leptons | Likelihood discriminant



- The results are compatible with the SM expectation.
- The dominant systematic uncertainty comes from the estimation of the non-prompt lepton backgrounds.
- A simultaneous fit to the likelihood discriminators is used to extract the signal cross section upper limit.
- Combined **95% CL upper limit assuming C_t=-1 on σ/σ_{SM}:**

observed: 6.7, expected: $5.0^{+2.1}_{-1.4}$

Total Background	**60.07 ± 8.95**	**112.13 ± 13.53**	**39.50 ± 6.55**
$tH(\tau\tau)W$	0.10 ± 0.12	0.13 ± 0.14	0.12 ± 0.12
$tH(WW)W$	0.28 ± 0.29	0.47 ± 0.48	0.35 ± 0.35
$tH(\tau\tau)q$	0.59 ± 0.61	0.90 ± 0.91	0.56 ± 0.58
$tH(WW)q$	2.55 ± 2.62	3.73 ± 3.84	1.73 ± 1.80
Total Signal	**3.53 ± 2.71**	**5.22 ± 3.98**	**2.76 ± 1.93**
Data	**66**	**117**	**42**

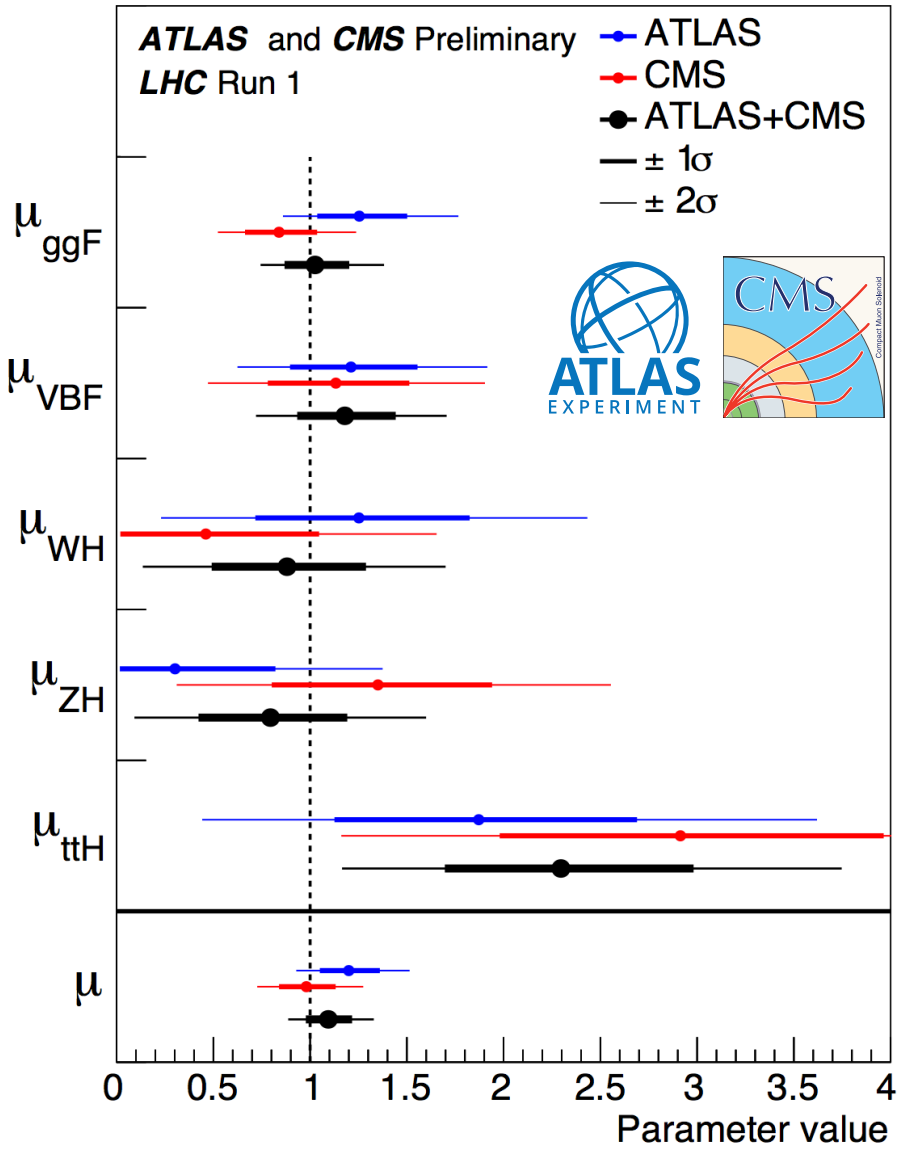


ATLAS & CMS Combination

- Recently ATLAS & CMS published the Run-1 combined measurements of the Higgs production and decay rates and constraints on its couplings.

- This includes the combined value for the ttH signal strength:
  - $\mu_{ttH} = 2.3^{+0.7}_{-0.6}$
  - Significance: 4.4σ (2.0σ expected)

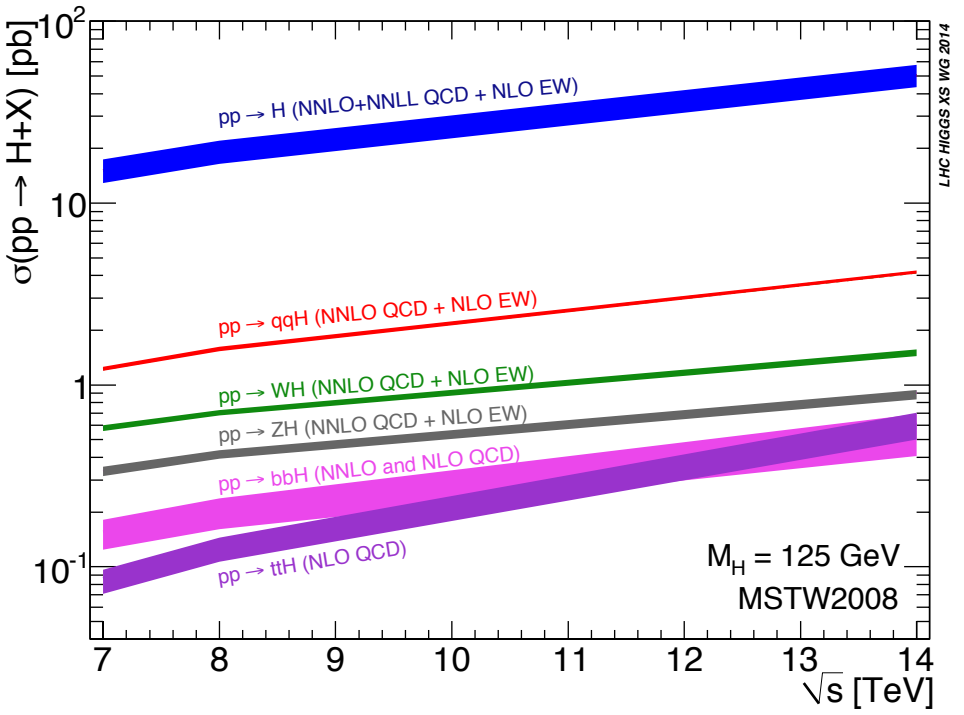
- Total combined signal strength:
  - $\mu = 1.09^{+0.11}_{-0.10}$



Summary and outlook

- First searches for the production of a Higgs boson in association with top(s) has been performed during Run-1
  - These have allowed direct measurement of magnitude and sign of top Yukawa coupling, a key parameter of EWSB in SM

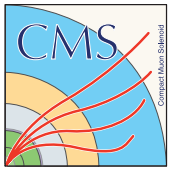
- The prospects for t[t]H measurements are good in Run-2.
  - Improvement upon on Run-1 sensitivity should be fast.
  - At 13 TeV the **ttH** cross section is a factor of 4 larger than in Run-1.
  - Greater precision for top Yukawa measurement.



Back-ups

H → Photons H → γγ	Leptonic ($t\bar{t}H \to \ell\nu jjbb\gamma\gamma$, $t\bar{t}H \to \ell\nu\ell\nu bb\gamma\gamma$)	Diphoton	2 γ, $p_T > m_{\gamma\gamma}/2$ (25) GeV for 1st (2nd) ≥1 e/μ, $p_T > 20$ GeV ≥2 jets + ≥1 b-tags, $p_T > 25$ GeV
	Hadronic ($t\bar{t}H \to jjjjbb\gamma\gamma$)	Diphoton	2 γ, $p_T > m_{\gamma\gamma}/2$ (25) GeV for 1st (2nd) 0 e/μ, $p_T > 20$ GeV ≥4 jets + ≥1 b-tags, $p_T > 25$ GeV

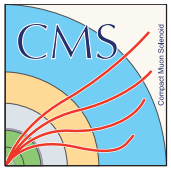
- Objects:
  - **γ**: ET>0.35,0.25×mγγ, |η| < 2.37 (excl. transition region),105<mγγ<160
  - **e**: ET>15 GeV, |η| < 2.37, [E,p]Tcone/pT<20%,15% E_T(e)
  - **μ**: pT>10, |η| < 2.7 [E,p]Tcone/pT<20%,15% pT(μ)
  - **jets**: pT > 25 GeV and |η| < 2.5, btagging (8TeV): 60%,70%,80% working points:
- **Leptonic**: ≥1ℓ, ≥1bj(80%), ETmiss>20 GeV, Z-veto: 84<$m_{e\gamma}$<94 GeV
- **Hadronic**: ≥6j ≥2bj(80%), ≥5j(30 GeV) ≥2bj(70%), ≥6j(30 GeV) ≥1bj(60%)



- The ttH signal is modelled using the PYTHIA6.
- The background processes ttW, ttZ, tt+jets, Drell–Yan+jets, W+jets, ZZ +jets, WW+jets, and WZ+jets are all generated with the MADGRAPH.
- The rare WWZ, WWW, tt + γ+jets, and ttWW processes are generated similarly.
- Single top is generated with POWHEG.

- ttH: “PowHel"+Pythia8
- tHqb: MadGraph+Pythia8 (4-FS)
- WtH: MadGraph5_aMC@NLO+Herwig++ (5-FS)
- ggH and VBF: Powheg+Pythia8
- VH: Pythia8

ttH→γγ | Yields & uncertainties



	7 TeV	8 TeV	
	All decays	Hadronic channel	Leptonic channel
$t\bar{t}H$	0.21	0.51	0.45
$gg \rightarrow H$	0.01	0.02	0
VBF H	0	0	0
WH/ZH	0.01	0.01	0.01
Total H	0.23	0.54	0.46
Data	9	32	11

ATLAS EXPERIMENT

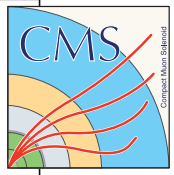
120<$m_{\gamma\gamma}$<130 GeV:

Category	N_H	ggF	VBF	WH	ZH	$t\bar{t}H$	$tHqb$	WtH	N_B
7 TeV leptonic selection	0.10	0.6	0.1	14.9	4.0	72.6	5.3	2.5	$0.5^{+0.5}_{-0.3}$
7 TeV hadronic selection	0.07	10.5	1.3	1.3	1.4	80.9	2.6	1.9	$0.5^{+0.5}_{-0.3}$
8 TeV leptonic selection	0.58	1.0	0.2	8.1	2.3	80.3	5.6	2.6	$0.9^{+0.6}_{-0.4}$
8 TeV hadronic selection	0.49	7.3	1.0	0.7	1.3	84.2	3.4	2.1	$2.7^{+0.9}_{-0.7}$

	$t\bar{t}H$ [%]		$tHqb$ [%]		WtH [%]		ggF [%]	WH [%]
	had.	lep.	had.	lep.	had.	lep.	had.	lep.
Luminosity	±2.8							
Photons	±5.6	±5.5	±5.6	±5.5	±5.6	±5.5	±5.6	±5.5
Leptons	< 0.1	±0.7	< 0.1	±0.6	< 0.1	±0.6	< 0.1	±0.7
Jets and E_T^{miss}	±7.4	±0.7	±16	±1.9	±11	±2.1	±29	±10
Bkg. modeling	0.24 evt.	0.16 evt.	applied on the sum of all Higgs boson production processes					
Theory ($\sigma \times$ BR)	+10,−13		+7,−6		+14,−12		+11,−11	+5.5,−5.4
MC modeling	±11	±3.3	±12	±4.4	±12	±4.6	±130	±100

ttH→leptons | Selection

H → Leptons H → WW H → ττ H → ZZ	Same-Sign Dilepton ($t\bar{t}H \to \ell^{\pm}\nu\ell^{\pm}[\nu]jjj[j]bb$)	Dilepton	2 e/μ, $p_T > 20$ GeV ≥4 jets + ≥1 b-tags, $p_T > 25$ GeV
	3 Lepton ($t\bar{t}H \to \ell\nu\ell[\nu]\ell[\nu]j[j]bb$)	Dilepton, Trielectron	1 e/μ, $p_T > 20$ GeV 1 e/μ, $p_T > 10$ GeV 1 e(μ), $p_T > 7(5)$ GeV ≥2 jets + ≥1 b-tags, $p_T > 25$ GeV
	4 Lepton ($t\bar{t}H \to \ell\nu\ell\nu\ell[\nu]\ell[\nu]bb$)	Dilepton, Trielectron	1 e/μ, $p_T > 20$ GeV 1 e/μ, $p_T > 10$ GeV 2 e(μ), $p_T > 7(5)$ GeV ≥2 jets + ≥1 b-tags, $p_T > 25$ GeV



- CMS b-tagging: **medium:**70% eff, 2% mistag, **loose:**85% eff, 10% mistag

- **ATLAS**:
  - jets: $p_T > 25$ GeV and $|\eta| < 2.5$, b-tagging: eft 70%, 1% mistag
  - $p_T(\ell)$>10 GeV
  - τ_{had} p_T>25 GeV and $|\eta| < 2.47$
- **2ℓ0τ$_{had}$**: $p_T(\ell)$>25,20 GeV, $[E,p_T]^{cone}/p_T$:<0.05, $|\eta(e)|$<1.37
- **3ℓ**: $\Sigma q(\ell)=\pm 1$, $p_T(\ell)$>20 GeV (same charge ℓ)
- **2ℓ1τ$_{had}$**: $p_T(\ell)$>25,15 GeV, τ_{had} opposite charge to ℓ's
- **1ℓ2τ$_{had}$**: $p_T(\ell)$>25,15 GeV, τ_{had} opposite charge to ℓ's
- **4ℓ**: $\Sigma q(\ell)=0$, $p_T(\ell)$>25,15 GeV, 100<$m_{4\ell}$<500 GeV, $Z_{enriched/depleted}$ ℓℓ=SFOS

Category	q mis-id	Non-prompt	$t\bar{t}W$	$t\bar{t}Z$	Diboson	Expected bkg.	$t\bar{t}H$ ($\mu = 1$)	Observed
$ee + \geq 5j$	1.1 ± 0.5	2.3 ± 1.2	1.4 ± 0.4	0.98 ± 0.26	0.47 ± 0.29	6.5 ± 1.8	0.73 ± 0.14	10
$e\mu + \geq 5j$	0.85 ± 0.35	6.7 ± 2.4	4.8 ± 1.2	2.1 ± 0.5	0.38 ± 0.30	15 ± 3	2.13 ± 0.41	22
$\mu\mu + \geq 5j$	–	2.9 ± 1.4	3.8 ± 0.9	0.95 ± 0.25	0.69 ± 0.39	8.6 ± 2.2	1.41 ± 0.28	11
$ee + 4j$	1.8 ± 0.7	3.4 ± 1.7	2.0 ± 0.4	0.75 ± 0.20	0.74 ± 0.42	9.1 ± 2.1	0.44 ± 0.06	9
$e\mu + 4j$	1.4 ± 0.6	12 ± 4	6.2 ± 1.0	1.5 ± 0.3	1.9 ± 1.0	24 ± 5	1.16 ± 0.14	26
$\mu\mu + 4j$	–	6.3 ± 2.6	4.7 ± 0.9	0.80 ± 0.22	0.53 ± 0.30	12.7 ± 2.9	0.74 ± 0.10	20
3ℓ	–	3.2 ± 0.7	2.3 ± 0.7	3.9 ± 0.8	0.86 ± 0.55	11.4 ± 2.3	2.34 ± 0.35	18
$2\ell 1\tau_{\text{had}}$	–	$0.4^{+0.6}_{-0.4}$	0.38 ± 0.12	0.37 ± 0.08	0.12 ± 0.11	1.4 ± 0.6	0.47 ± 0.08	1
$1\ell 2\tau_{\text{had}}$	–	15 ± 5	0.17 ± 0.06	0.37 ± 0.09	0.41 ± 0.42	16 ± 5	0.68 ± 0.13	10
4ℓ Z-enr.	–	$\lesssim 10^{-3}$	$\lesssim 3 \times 10^{-3}$	0.43 ± 0.12	0.05 ± 0.02	0.55 ± 0.15	0.17 ± 0.02	1
4ℓ Z-dep.	–	$\lesssim 10^{-4}$	$\lesssim 10^{-3}$	0.002 ± 0.002	$\lesssim 2 \times 10^{-5}$	0.007 ± 0.005	0.025 ± 0.003	0

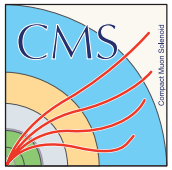
ATLAS EXPERIMENT

	ee	eμ	$\mu\mu$	3ℓ	4ℓ
$t\bar{t}H$, $H \to WW$	1.0 ± 0.1	3.2 ± 0.4	2.4 ± 0.3	3.4 ± 0.5	0.29 ± 0.04
$t\bar{t}H$, $H \to ZZ$	—	0.1 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.09 ± 0.02
$t\bar{t}H$, $H \to \tau\tau$	0.3 ± 0.0	1.0 ± 0.1	0.7 ± 0.1	1.1 ± 0.2	0.15 ± 0.02
$t\bar{t}W$	4.3 ± 0.6	16.5 ± 2.3	10.4 ± 1.5	10.3 ± 1.9	—
$t\bar{t}Z/\gamma^*$	1.8 ± 0.4	4.9 ± 0.9	2.9 ± 0.5	8.4 ± 1.7	1.12 ± 0.62
$t\bar{t}WW$	0.1 ± 0.0	0.4 ± 0.1	0.3 ± 0.0	0.4 ± 0.1	0.04 ± 0.02
$t\bar{t}\gamma$	1.3 ± 0.3	1.9 ± 0.5	—	2.6 ± 0.6	—
WZ	0.6 ± 0.6	1.5 ± 1.7	1.0 ± 1.1	3.9 ± 0.7	—
ZZ	—	0.1 ± 0.1	0.1 ± 0.0	0.3 ± 0.1	0.47 ± 0.10
Rare SM bkg.	0.4 ± 0.1	1.6 ± 0.4	1.1 ± 0.3	0.8 ± 0.3	0.01 ± 0.00
Non-prompt	7.6 ± 2.5	20.0 ± 4.4	11.9 ± 4.2	33.3 ± 7.5	0.43 ± 0.22
Charge misidentified	1.8 ± 0.5	2.3 ± 0.7	—	—	—
All signals	1.4 ± 0.2	4.3 ± 0.6	3.1 ± 0.4	4.7 ± 0.7	0.54 ± 0.08
All backgrounds	18.0 ± 2.7	49.3 ± 5.4	27.7 ± 4.7	59.8 ± 8.0	2.07 ± 0.67
Data	19	51	41	68	1

CMS

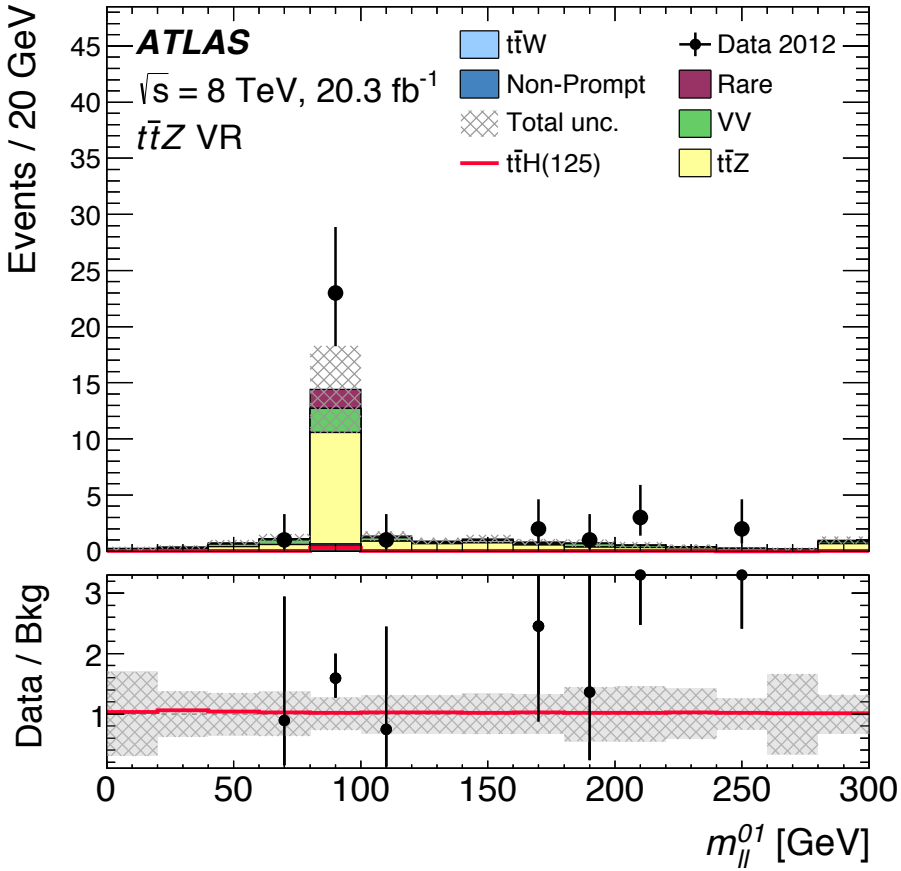
ttH→leptons | Systematic uncertainties

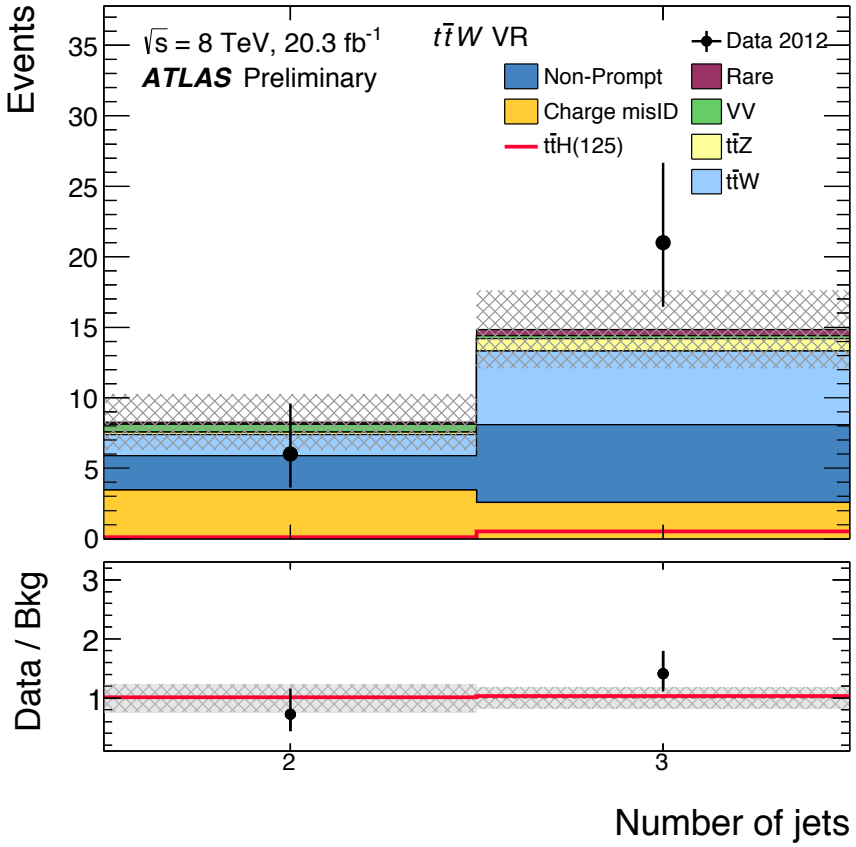
Source	$\Delta\mu$	
$2\ell 0\tau_{\text{had}}$ non-prompt muon transfer factor	+0.38	−0.35
$t\bar{t}W$ acceptance	+0.26	−0.21
$t\bar{t}H$ inclusive cross section	+0.28	−0.15
Jet energy scale	+0.24	−0.18
$2\ell 0\tau_{\text{had}}$ non-prompt electron transfer factor	+0.26	−0.16
$t\bar{t}H$ acceptance	+0.22	−0.15
$t\bar{t}Z$ inclusive cross section	+0.19	−0.17
$t\bar{t}W$ inclusive cross section	+0.18	−0.15
Muon isolation efficiency	+0.19	−0.14
Luminosity	+0.18	−0.14



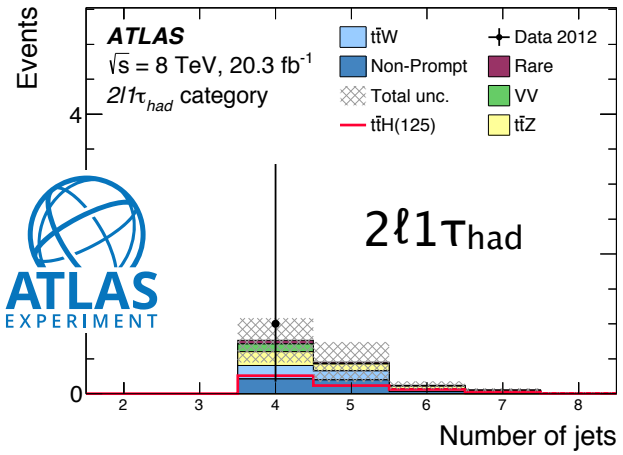
Source	Rate uncertainty Signal	Backgrounds	Shape
Experimental			
Integrated luminosity	2.2–2.6%	2.2–2.6%	No
Jet energy scale	0.0–8.4%	0.1–11.5%	Yes
CSV b-tagging	0.9–21.7%	3.0–29.0%	Yes
Lepton reco. and ID	0.3–14.0%	1.4–14.0%	No
Lepton misidentification rate (H → leptons)	—	35.1–45.7%	Yes
Tau reco. and ID (H → hadrons)	11.3–14.3%	24.1–28.8%	Yes
Photon reco. and ID (H → photons)	1.6–3.2%	—	Yes
MC statistics	—	0.2–7.0%	Yes
Theoretical			
NLO scales and PDF	9.7–14.8%	3.4–14.7%	No
MC modeling	2.3–5.1%	0.9–16.8%	Yes
Top quark p_{T}	—	1.4–6.9%	Yes
Additional hf uncertainty (H → hadrons)	—	50%	No
H contamination (H → photons)	36.7–41.2%		No
WZ (ZZ) uncertainty (H → leptons)	—	22% (19%)	No

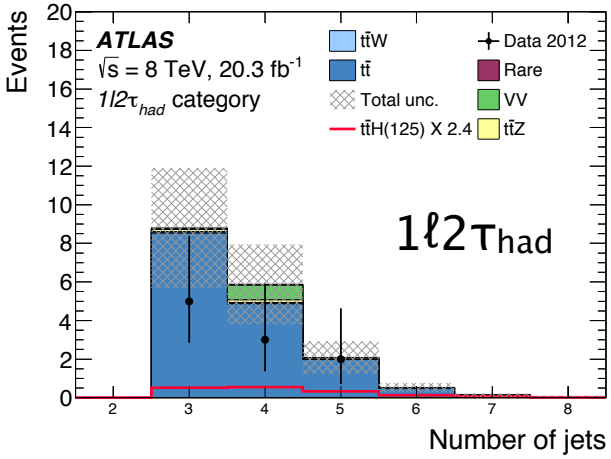
- Validation regions for the ttV background.
  - ttZ and ttW enhanced regions to validate MC against data

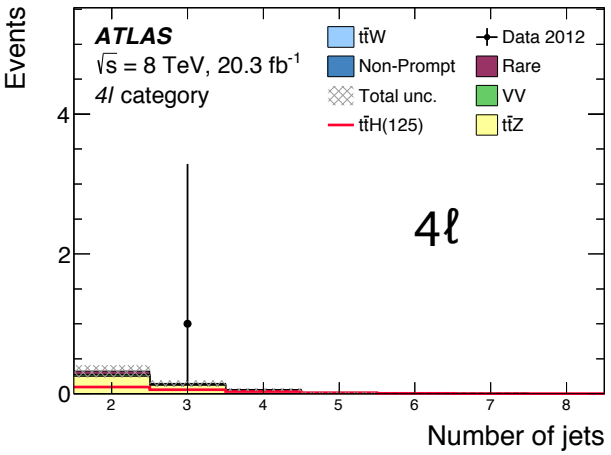


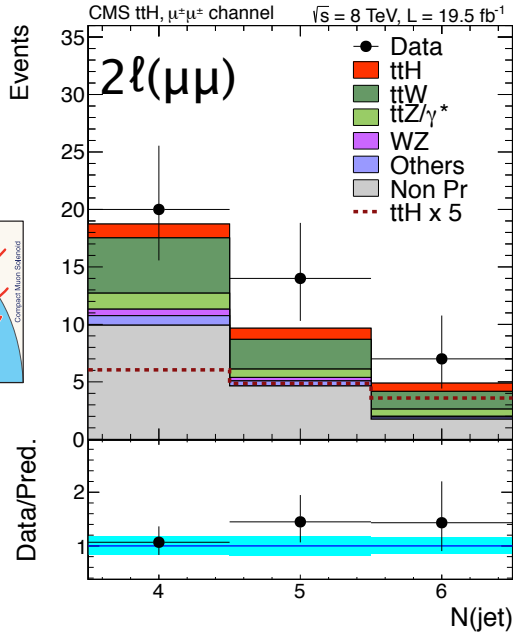


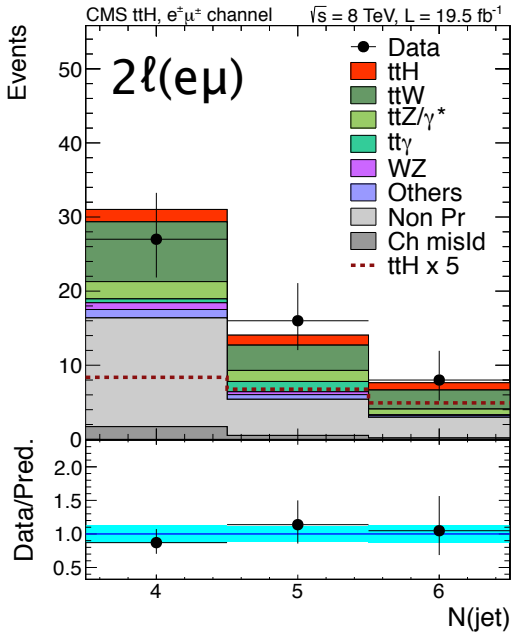
ttH→leptons | Other signal regions - Njets

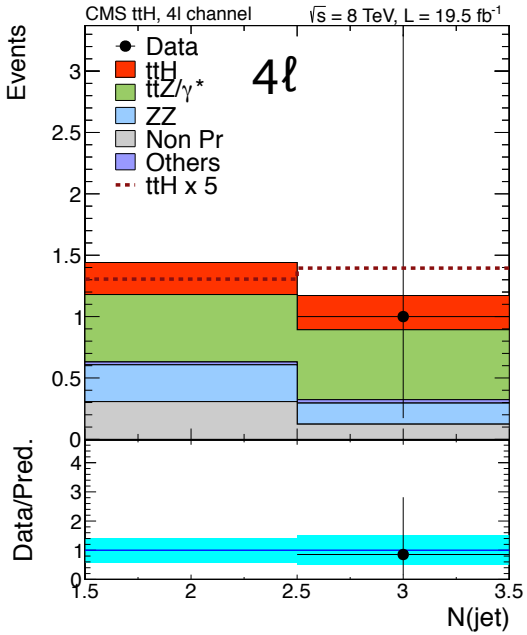












ttH(125.6) x 30

tt̄

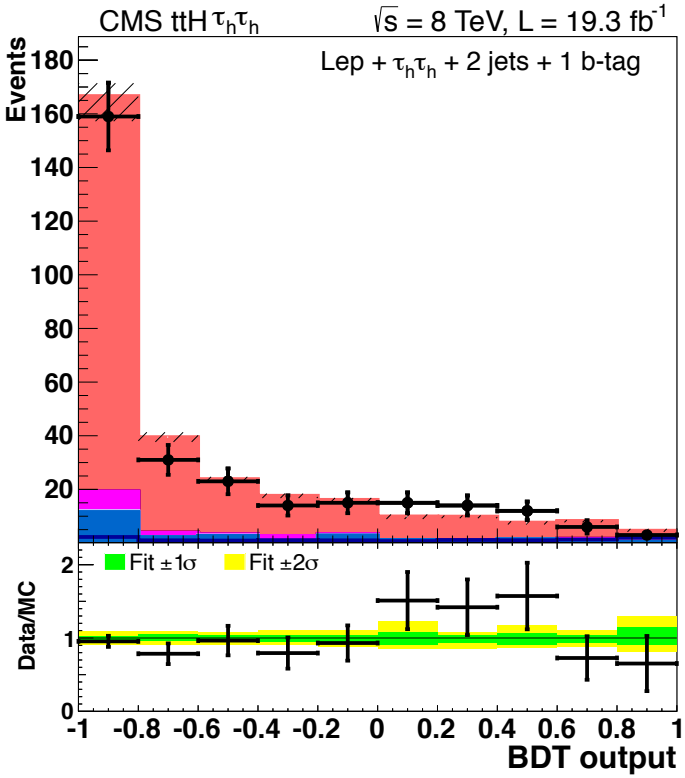
Single t

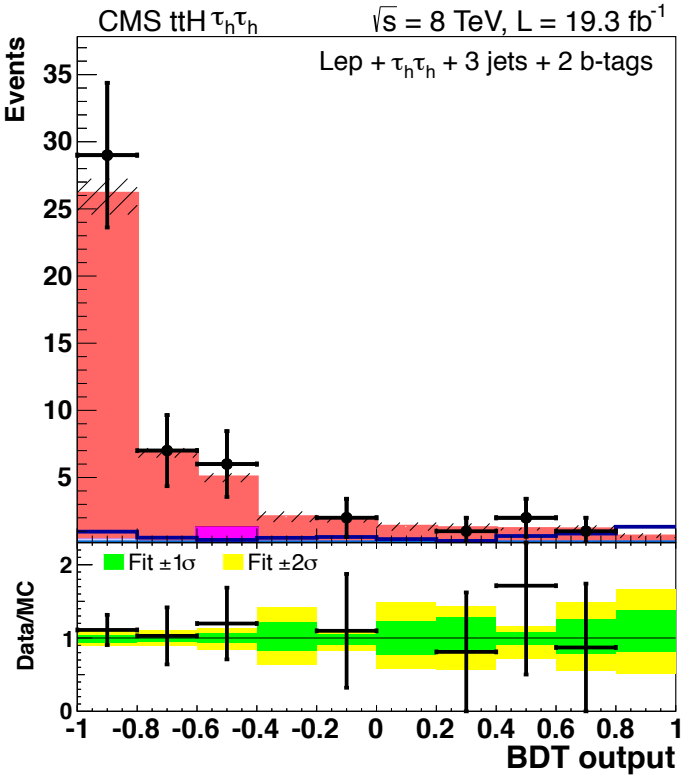
tt̄ + W,Z

EWK

Bkg. Unc.

Data





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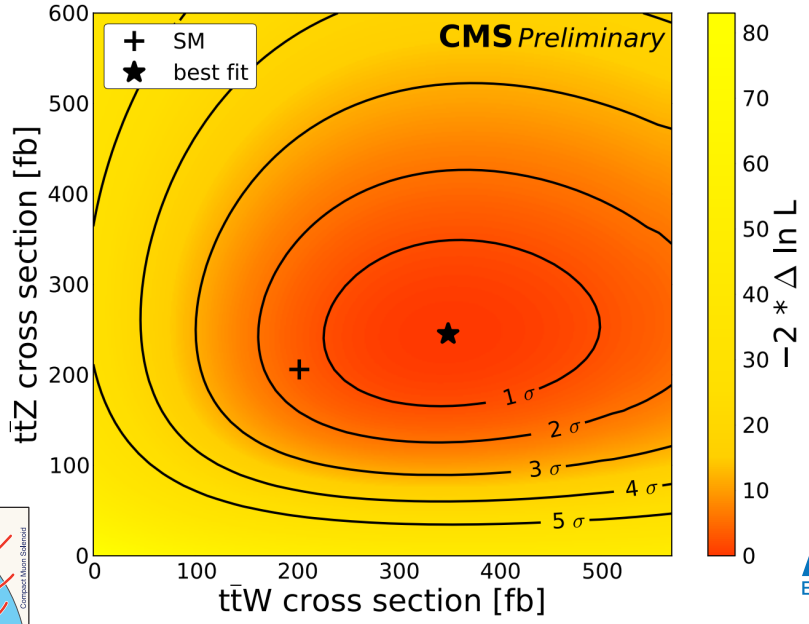
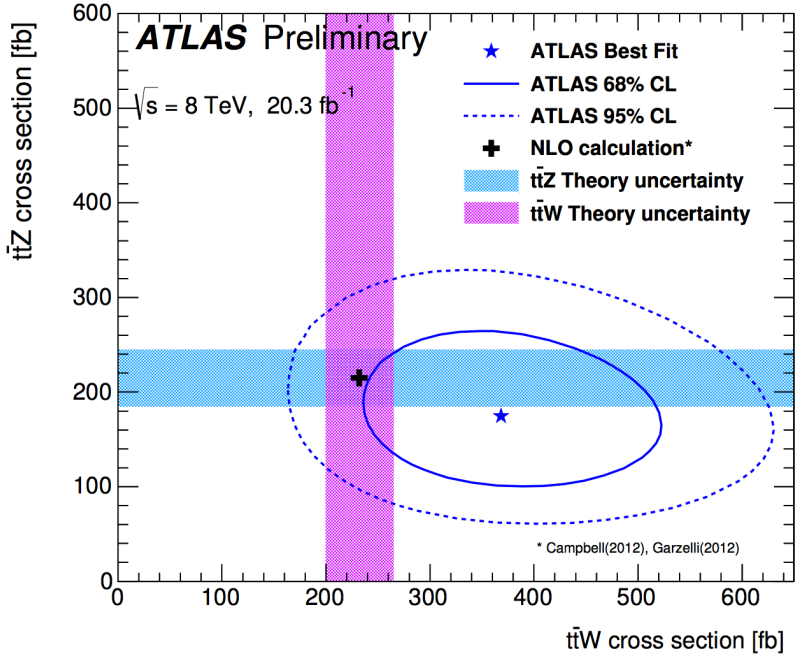
- The rare WWZ, WWW, tt + γ+jets, and ttWW processes are generated similarly.
- Single top is generated with POWHEG.

Process	ME Generator	Parton Shower	PDF	Tune
$t\bar{t}H$	HELAC-Oneloop [41, 42] + POWHEG-BOX [48–50]	PYTHIA 8 [43]	CT10 [44]/CTEQ6L1 [45, 46]	AU2 [47]
$tHqb$	MADGRAPH [33]	PYTHIA 8	CT10	AU2
tHW	MG5_aMC@NLO [29]	HERWIG++ [51]	CT10/MRST LO** [52]	UE-EE-4 [53]
$t\bar{t}W$ + ≤ 2 partons	MADGRAPH	PYTHIA 6 [54]	CTEQ6L1	AUET2B [55]
$t\bar{t}(Z/\gamma^*)$ + ≤ 1 parton	MADGRAPH	PYTHIA 6	CTEQ6L1	AUET2B
$t(Z/\gamma^*)$	MADGRAPH	PYTHIA 6	CTEQ6L1	AUET2B
$q\bar{q}, qg \to WW, WZ$	SHERPA [56]	SHERPA	CT10	SHERPA default
$qq \to qqWW, qqWZ, qqZZ$	SHERPA	SHERPA	CT10	SHERPA default
$q\bar{q}, qg \to ZZ$	POWHEG-BOX [57]	PYTHIA 8	CT10	AU2
$gg \to ZZ$	GG2ZZ [58]	HERWIG [59]	CT10	AUET2 [60]
$t\bar{t}$	POWHEG-BOX [61]	PYTHIA 6	CT10/CTEQ6L1	Perugia2011C [62]
s-, t-channel, Wt single top	POWHEG-BOX [63, 64]	PYTHIA 6	CT10/CTEQ6L1	Perugia2011C
$Z \to \ell^+\ell^-$ + ≤ 5 partons	ALPGEN [65]	PYTHIA 6	CTEQ6L1	Perugia2011C
$W \to \ell\nu$ + ≤ 5 partons	ALPGEN	PYTHIA 6	CTEQ6L1	Perugia2011C

ttV 8 TeV results



Channel	$t\bar{t}W$ significance Expected	$t\bar{t}W$ significance Observed	$t\bar{t}Z$ significance Expected	$t\bar{t}Z$ significance Observed
2ℓOS	0.4	0.1	1.4	1.1
2ℓSS	2.8	5.0	-	-
3ℓ	1.4	1.0	3.7	3.3
4ℓ	-	-	2.0	2.4
Combined	3.2	5.0	4.5	4.2



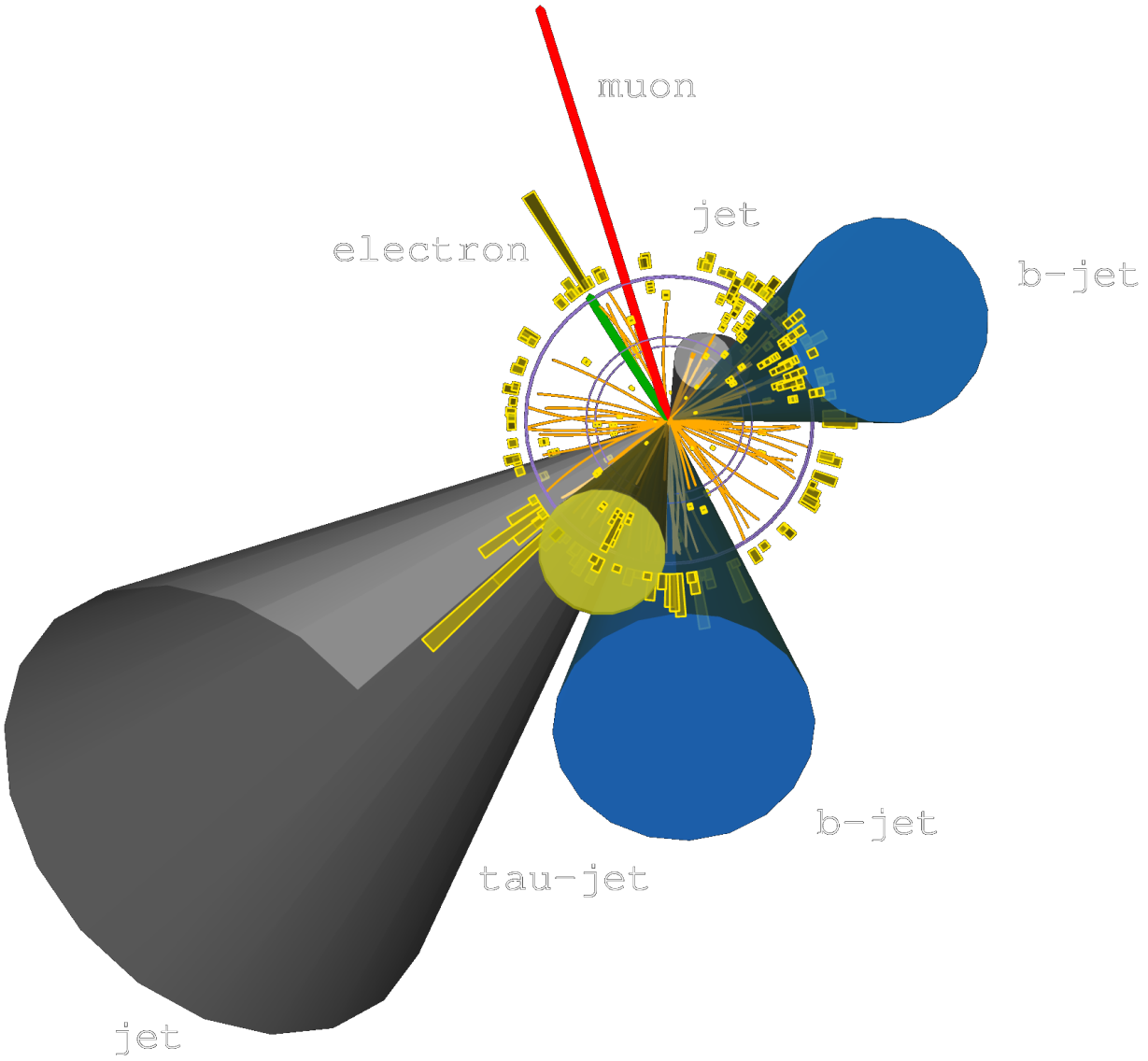
$t\bar{t}W$

Channels	Cross section (fb) Expected	Cross section (fb) Observed	Signal strength (μ) Expected	Signal strength (μ) Observed	Significance Expected	Significance Observed
SS	203^{+88}_{-73}	414^{+135}_{-112}	$1.0^{+0.45}_{-0.36}$	$2.04^{+0.74}_{-0.61}$	3.4	4.9
3ℓ	203^{+215}_{-194}	210^{+225}_{-203}	$1.0^{+1.09}_{-0.96}$	$1.03^{+1.07}_{-0.99}$	1.0	1.0
SS + 3ℓ	203^{+84}_{-71}	382^{+117}_{-102}	$1.0^{+0.43}_{-0.35}$	$1.88^{+0.66}_{-0.56}$	3.5	4.8

$t\bar{t}Z$

Channels	Cross section (fb) Expected	Cross section (fb) Observed	Signal strength (μ) Expected	Signal strength (μ) Observed	Significance Expected	Significance Observed
OS	206^{+142}_{-118}	257^{+158}_{-129}	$1.0^{+0.72}_{-0.57}$	$1.25^{+0.76}_{-0.62}$	1.8	2.1
3ℓ	206^{+79}_{-63}	257^{+85}_{-67}	$1.0^{+0.42}_{-0.32}$	$1.25^{+0.45}_{-0.36}$	4.6	5.1
4ℓ	206^{+153}_{-109}	228^{+150}_{-107}	$1.0^{+0.77}_{-0.53}$	$1.11^{+0.76}_{-0.52}$	2.7	3.4
OS + 3ℓ + 4ℓ	206^{+62}_{-52}	242^{+65}_{-55}	$1.0^{+0.34}_{-0.27}$	$1.18^{+0.35}_{-0.29}$	5.7	6.4

- Event display for candidate event in the 2ℓ1τhad category.
  - Muon
    - pT = 42 GeV
  - Electron,
    - pT = 16 GeV
  - τ candidate
    - pT = 52 GeV
  - b-tagged jets
    - pT = 85, 53 GeV
  - Non-b-tagged jets
    - pT = 76, 26 GeV



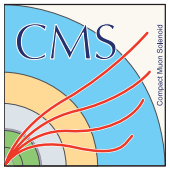
- μ extraction dependant on ttW and ttZ cross sections:

$$\mu(t\bar{t}H) = 2.1 - 1.4\left(\frac{\sigma(t\bar{t}W)}{232\text{ fb}} - 1\right) - 1.3\left(\frac{\sigma(t\bar{t}Z)}{206\text{ fb}} - 1\right)$$

tH→leptons | Yields and uncertainties

Process	$\mu\mu$	$e\mu$	$\ell\ell\ell$
$W^{\pm}W^{\pm}qq$	4.60 ± 0.68	6.03 ± 0.85	–
WZ, WW, ZZ	5.47 ± 2.10	8.83 ± 3.25	1.19 ± 0.14
Rare SM bkg.	1.40 ± 0.68	2.57 ± 1.23	0.11 ± 0.03
$t\bar{t}\gamma^*$	0.50 ± 0.20	1.04 ± 0.42	–
$t\bar{t}\gamma$	0.09 ± 0.03	2.02 ± 0.60	–
$t\bar{t}Z$	2.23 ± 0.41	2.87 ± 0.50	2.21 ± 0.36
$t\bar{t}W^{\pm}$	10.18 ± 2.24	14.85 ± 3.32	3.03 ± 0.51
$t\bar{t}H$	2.26 ± 0.34	3.24 ± 0.47	1.52 ± 0.18
Charge Mis-ID	–	6.96 ± 1.76	–
Non-Prompt	33.34 ± 8.34	63.74 ± 12.46	31.44 ± 6.52
Total Background	$\mathbf{60.07 \pm 8.95}$	$\mathbf{112.13 \pm 13.53}$	$\mathbf{39.50 \pm 6.55}$
$tH(\tau\tau)W$	0.10 ± 0.12	0.13 ± 0.14	0.12 ± 0.12
$tH(WW)W$	0.28 ± 0.29	0.47 ± 0.48	0.35 ± 0.35
$tH(\tau\tau)q$	0.59 ± 0.61	0.90 ± 0.91	0.56 ± 0.58
$tH(WW)q$	2.55 ± 2.62	3.73 ± 3.84	1.73 ± 1.80
Total Signal	$\mathbf{3.53 \pm 2.71}$	$\mathbf{5.22 \pm 3.98}$	$\mathbf{2.76 \pm 1.93}$
Data	**66**	**117**	**42**

Source of uncertainty	Type	Exclusive source (%)	Removal (%)
Luminosity	rate	< 1	< 1
Pileup	rate	< 1	< 1
Lepton trigger efficiency	rate	< 1	< 1
Lepton selection efficiencies	rate	< 1	< 1
Electron energy scale	shape	< 1	< 1
Jet energy corrections	shape	< 1	< 1
b-tagging efficiencies	shape	< 1	< 1
Flavour Scheme	rate	2	1
Higgs branching fractions	rate	< 1	< 1
Renormalization/factorization scale	rate	< 1	< 1
Parton density functions (pdf)	rate	< 1	< 1
Irreducible background normalization	rate	< 1	< 1
μ fake-rate normalization (SS)	rate	26	19
e fake-rate normalization (SS)	rate	12	5
μ fake-rate leptons shape (SS)	shape	< 1	1
e fake-rate leptons shape (SS)	shape	< 1	2
Non-prompt closure test (3ℓ)	rate	3	3
QCD control region variation for fake-rate (3ℓ)	shape	1	< 1
Fake-rate variation within stat. uncert. (3ℓ)	shape	1	< 1
Charge misidentification (SS)	rate	< 1	< 1
Stat. uncert. for non-prompt leptons (3ℓ)	shape	2	3
Stat. uncert. for non-prompt leptons (SS)	shape	4	3



Channel	Observed	Expected	68% prob. band	95% prob. band
SS $\mu\mu$	9.3	8.1	[6.0, 11.8]	[4.7, 16.7]
SS $e\mu$	11.4	9.3	[7.0, 13.5]	[5.4, 18.8]
3ℓ	11.5	8.6	[6.6, 12.4]	[5.7, 18.0]
combined	6.7	5.0	[3.6, 7.1]	[2.9, 10.3]