Studies of Higgs boson production in association with a ttbar pair

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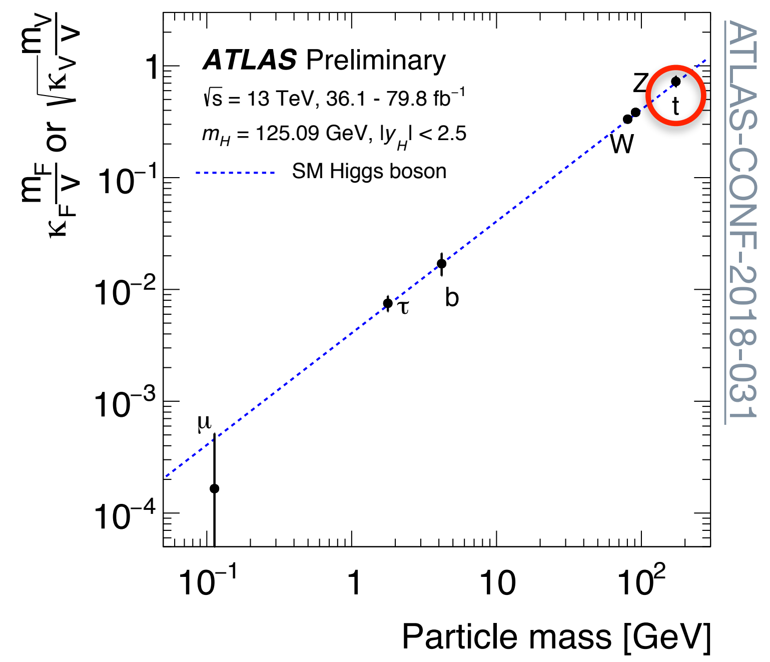
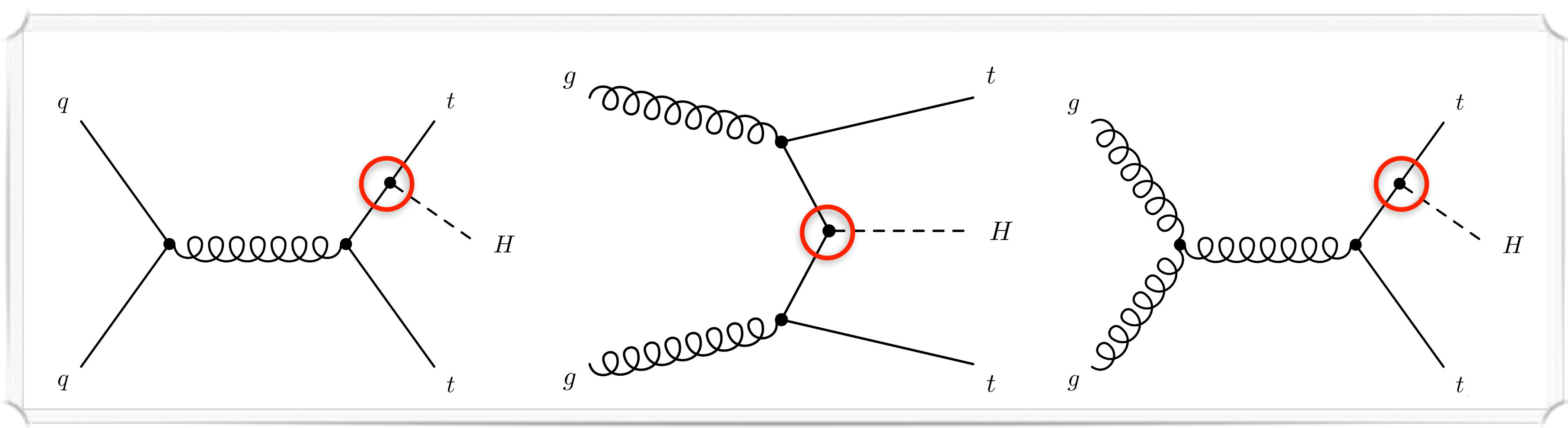
Introduction

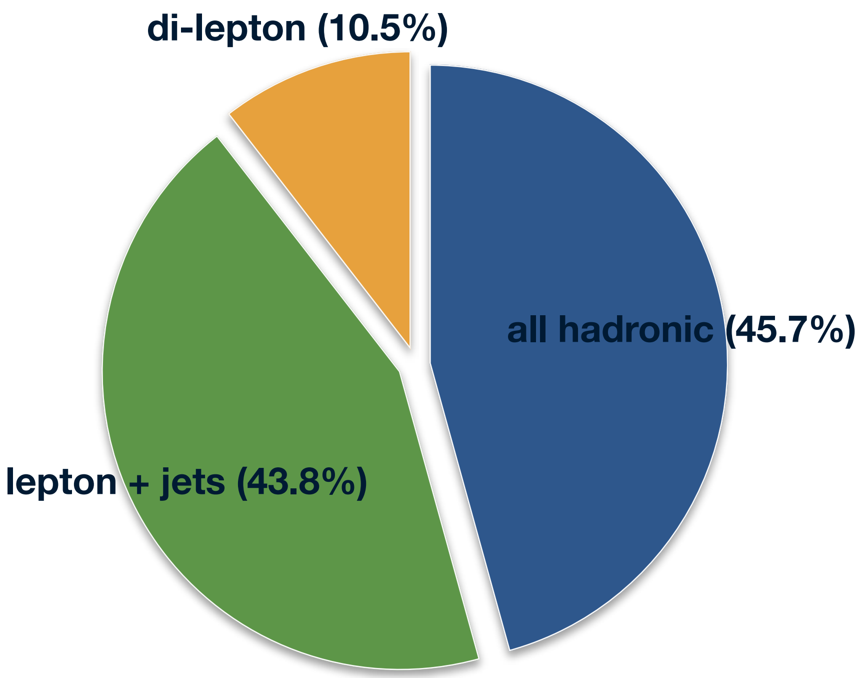
- **Top-Higgs Yukawa** coupling y_t
  - Largest Yukawa coupling in the SM, $y_t \cong 1$
  - Sensitive to new physics
- **Indirect measurements** of y_t via **ggF** and **H→γγ** loop
  - Must rely on assumptions of particles entering loops
- **ttH** provides **direct probe for top-Higgs Yukawa** coupling y_t^2
  - Measurement is important check of SM





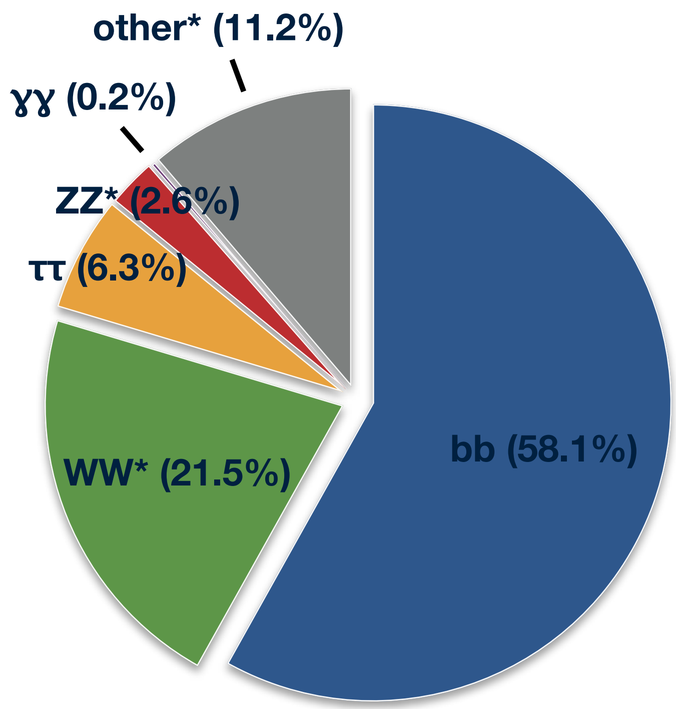
ttH signatures

ttbar decay BRs



- all hadronic (45.7%)
- lepton + jets (43.8%)
- di-lepton (10.5%)

Higgs decay BRs



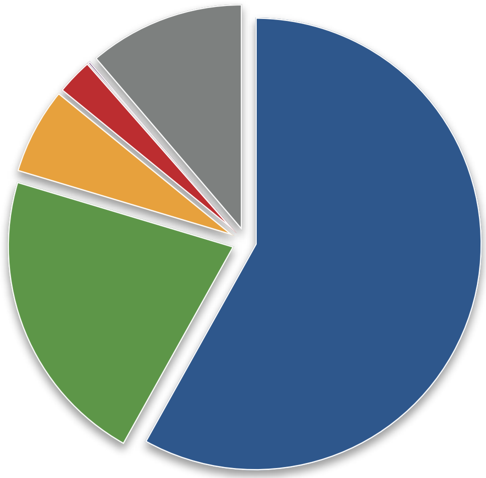
- bb (58.1%)
- WW* (21.5%)
- ττ (6.3%)
- ZZ* (2.6%)
- γγ (0.2%)
- other* (11.2%)

smaller BR, higher purity
(generally)

- **Wide variety of final states accessible**, good understanding of all reconstructed objects is crucial!

*other: gg, cc, Zγ, μμ etc.

Overview of results



- bb (58.1%)
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- γγ (0.2%)
- other (11.2%)

↓ **smaller BR, higher purity** (generally)

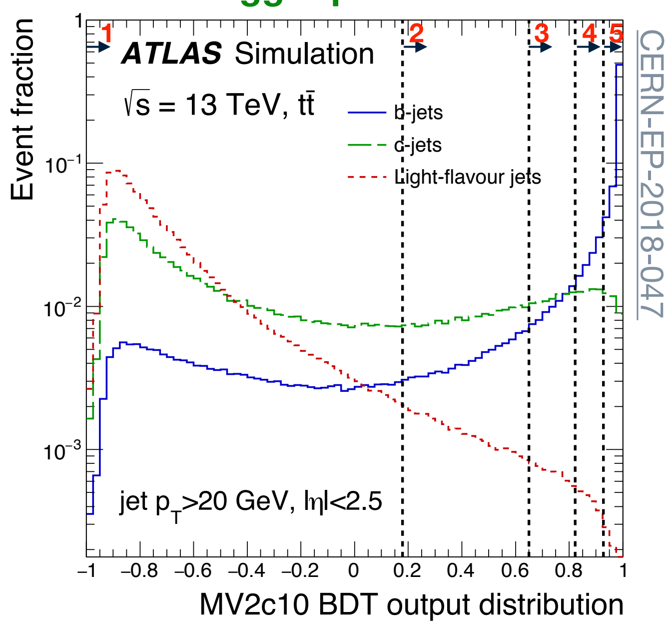
Channel	Dataset	Reference
ttH(bb)	36.1 fb^{-1}, 13 TeV	Phys. Rev. D 97, 072016
ttH multi-lepton (mostly H→WW* and H→ττ)	36.1 fb^{-1}, 13 TeV	Phys. Rev. D 97, 072003
ttH(ZZ*→4l)	79.8 fb^{-1}, 13 TeV	CERN-EP-2018-138 submitted to PLB
ttH(γγ)	79.8 fb^{-1}, 13 TeV	
ttH combination	36.1 - 79.8 fb^{-1}, 13 TeV	

ttH(bb): Introduction

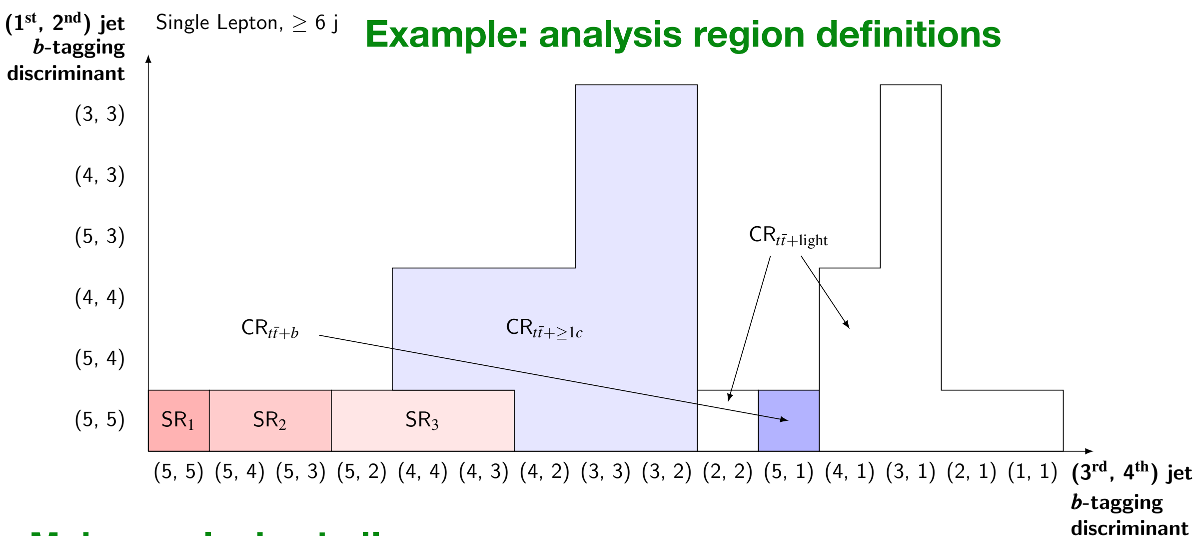
36.1 fb^{-1}

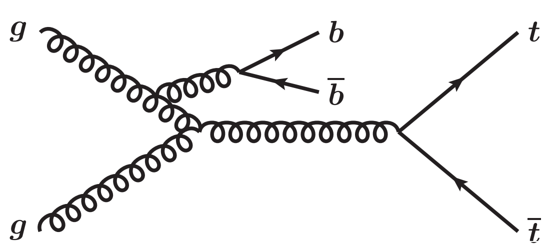
- **Analysis regions:**
  - **Single lepton channel:** 1 light lepton (e,μ), ≥5 jets
  - **Di-lepton channel:** 2 light leptons (e,μ), ≥3 jets
  - **Boosted channel:** large-R top-like and Higgs-like jets
  - Regions built using **5 b-tagging working points** and **N$_{jets}$**
    - Helps constrain tt + ≥1b / tt + ≥1c / tt + light modelling

b-tagger performance



Example: analysis region definitions





irreducible tt+bb background

- **Major analysis challenge:**
  - **Modelling** of **tt + heavy flavour** background
    - 5-flavour scheme sample, re-weighted tt + ≥1b components to 4-flavour scheme prediction
    - Large modelling uncertainties on ttbar (especially for tt + heavy flavour)

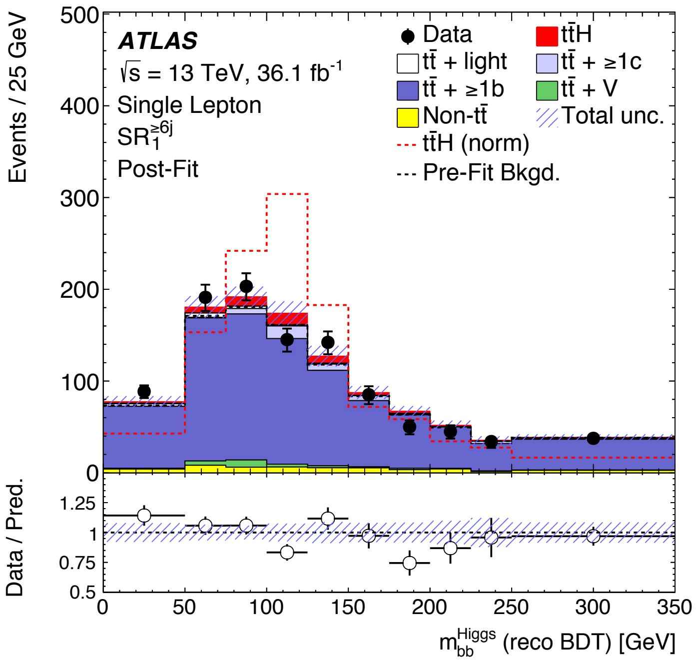
ttH(bb): Signal extraction

- **Signal extraction strategy:**
  - **Intermediate MVAs** aimed at signal reconstruction
  - Fit performed on **classification BDT** (inputs: **intermediate** step, kinematics, b-tagging info)

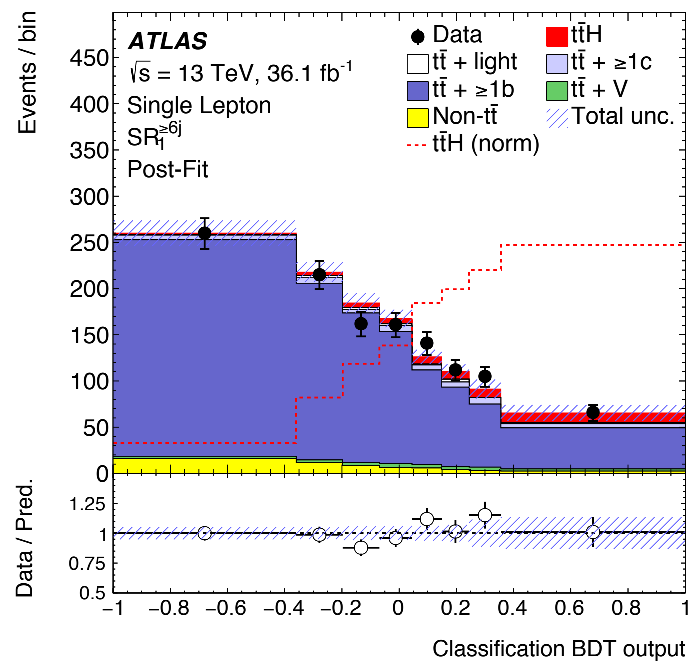
Intermediate MVAs:
- ttH system reconstruction BDT
- Likelihood discriminant
- Matrix Element Method

→ **Classification BDT**

example: reconstructed Higgs mass

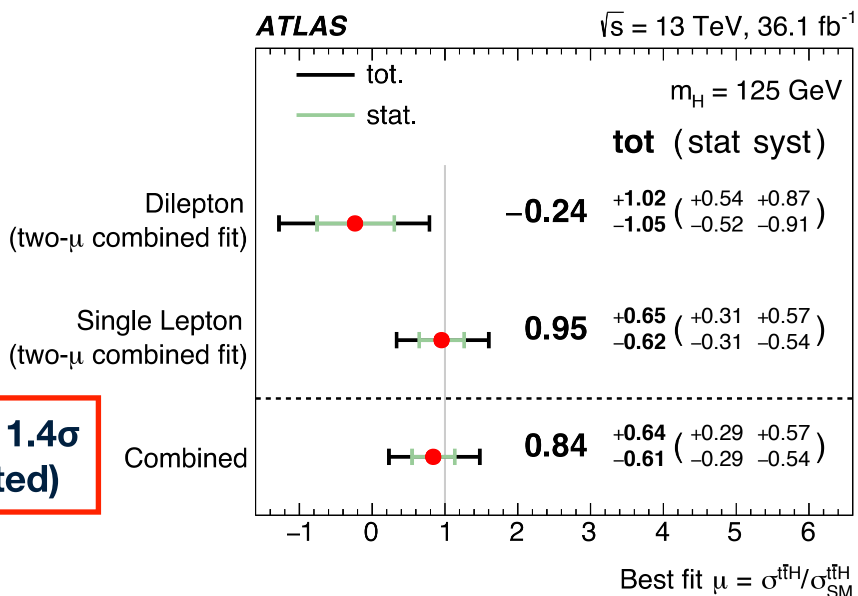


example: classification BDT

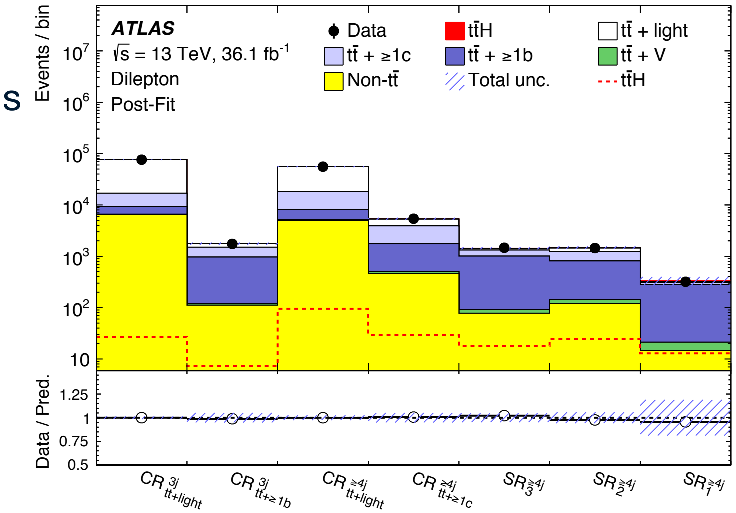


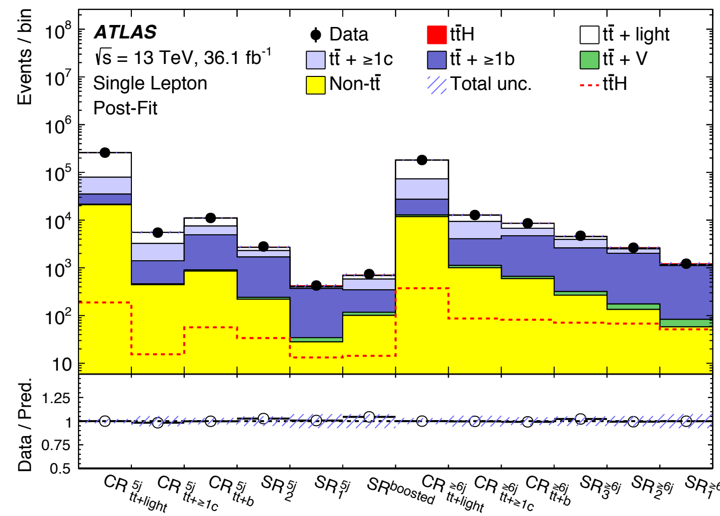
36.1 fb^{-1}

- **Fit model:**
  - Profile likelihood fit of 10 control regions and 9 signal regions
  - BDT distributions in all signal regions
  - H_T (scalar sum of jet p_T) or single bin in control regions
  - Free-floating tt + ≥1b and tt + ≥1c normalization



significance: 1.4σ (1.6σ expected)





- **Dominant uncertainties on μ_{ttH}:**
  - **tt + ≥1b modelling** ($^{+0.46}$, $_{-0.46}$)
  - MC statistical uncertainties ($^{+0.29}$, $_{-0.31}$)
  - b-tagging ($^{+0.16}$, $_{-0.16}$)

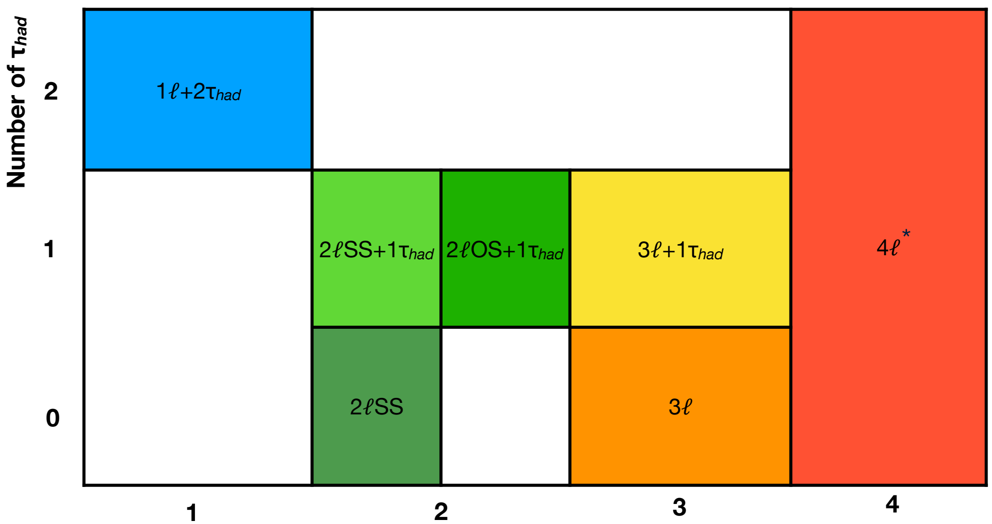
→ significant experimental and theoretical progress needed for further improvements!

ttH multi-lepton: Introduction

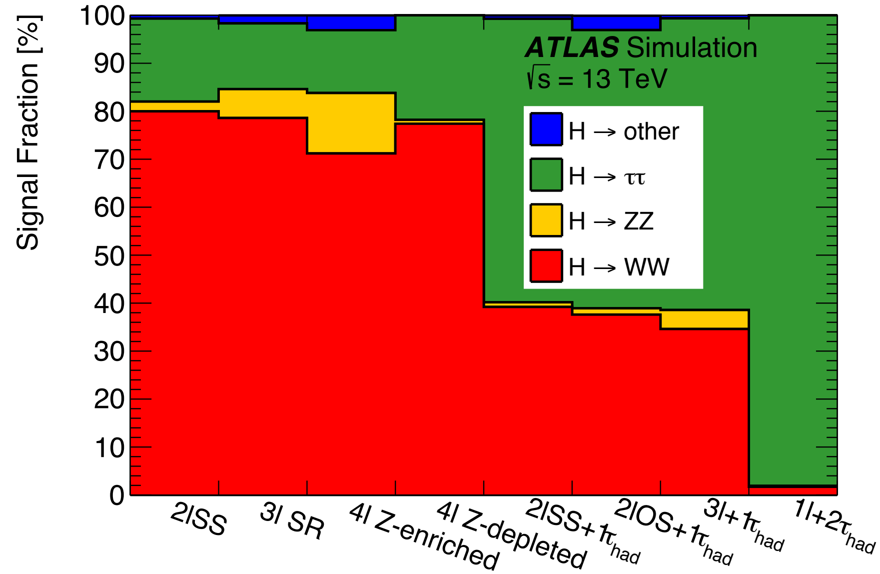
36.1 fb^{-1}

- **7 different analysis channels** with different **e/μ** and **hadronic τ multiplicity**
  - ≥1 b-jet, 2-4 jets
- **Isolation/b-tagging BDT** for light lepton selection, veto on **charge mis-ID BDT**

- **Backgrounds:**
  - **Irreducible**: dominated by **tt+V** and **VV**
    - Taken from MC and validated in data
  - **Reducible**: **non-prompt e/μ/τ**, charge misidentified **e/μ**
    - Estimated from data



ttH(ZZ)→4l events are vetoed in 4l channel

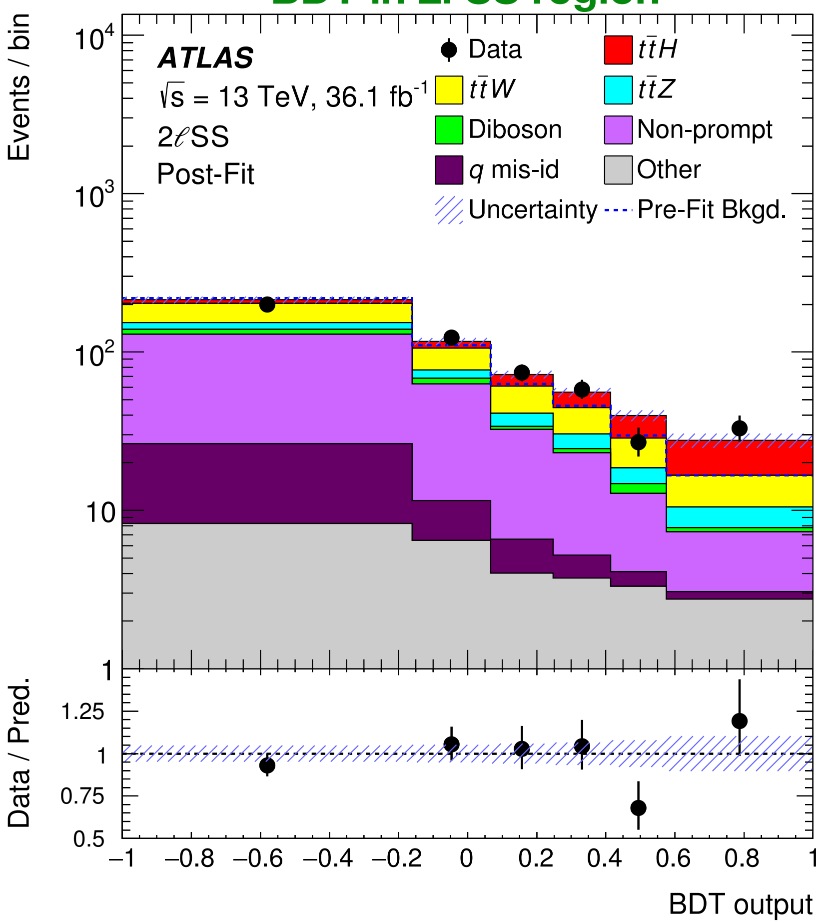


ttH multi-lepton: Signal extraction

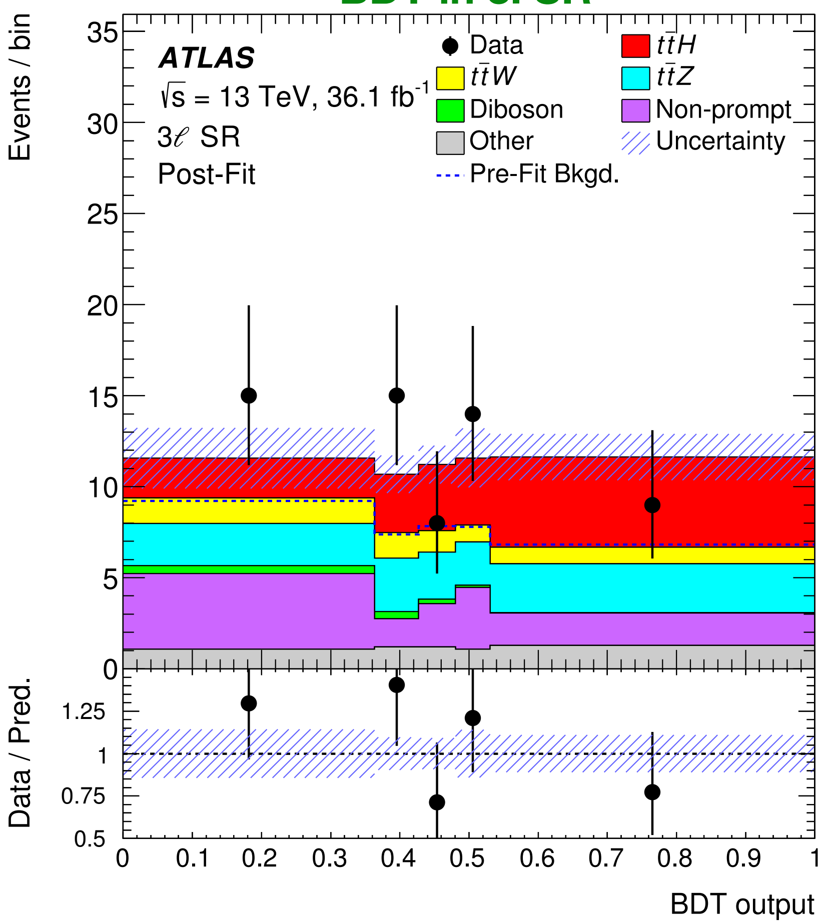
36.1 fb^{-1}

- **Signal extraction:**
  - **Dedicated MVA approaches** in most channels, examples:
    - **2l SS:** combination of two BDTs (trained against fakes and ttV)
    - **3l SR and CRs:** multi-class BDT (5 classes)

BDT in 2l SS region



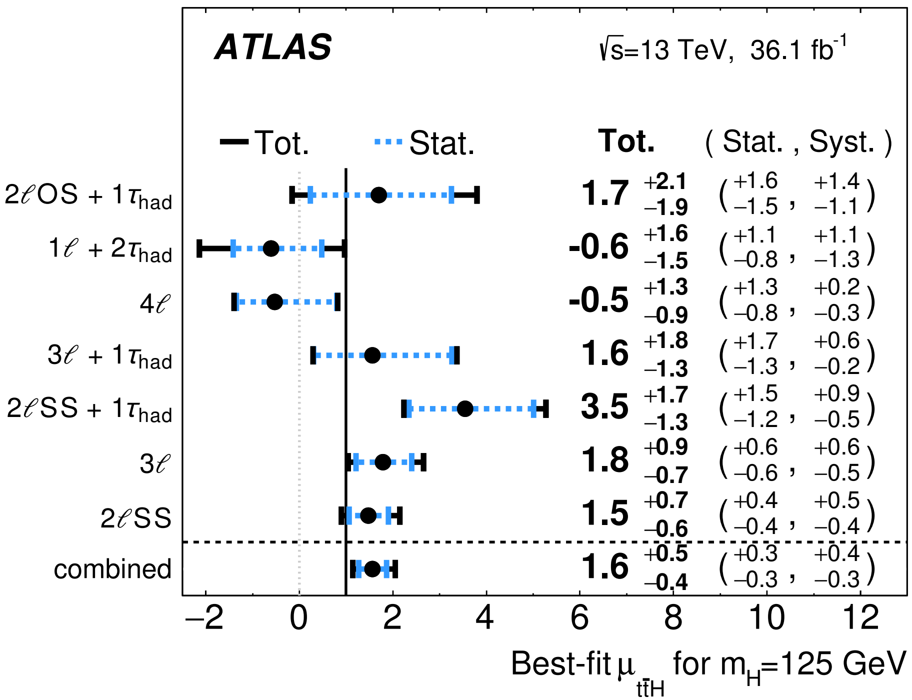
BDT in 3l SR

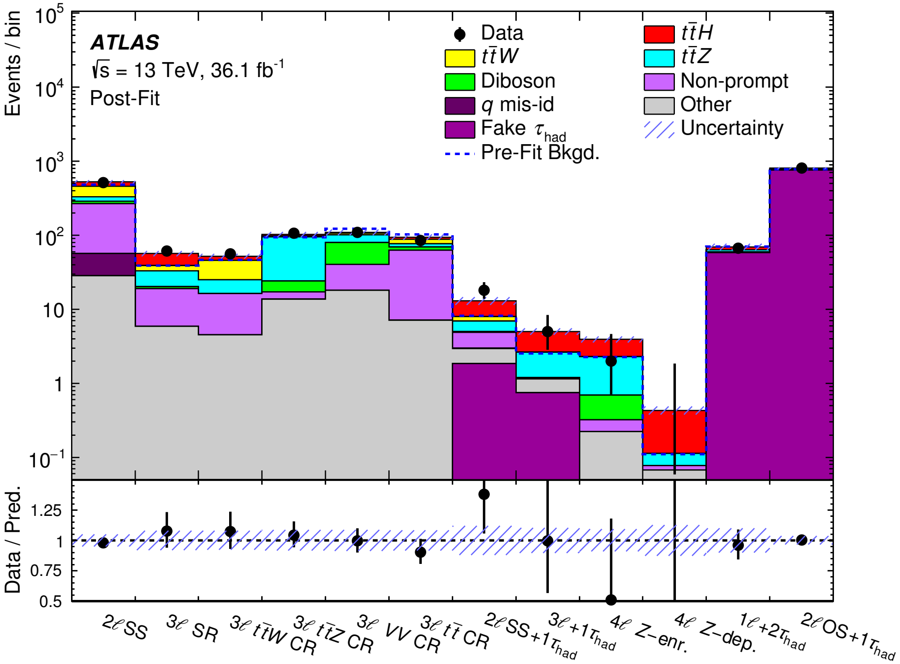


ttH multi-lepton: Results

36.1 fb^{-1}

- **Fit model:**
  - **Combined profile likelihood fit** of all signal and control regions
    - **BDT discriminants** in most signal regions
    - **Control regions** validate irreducible backgrounds



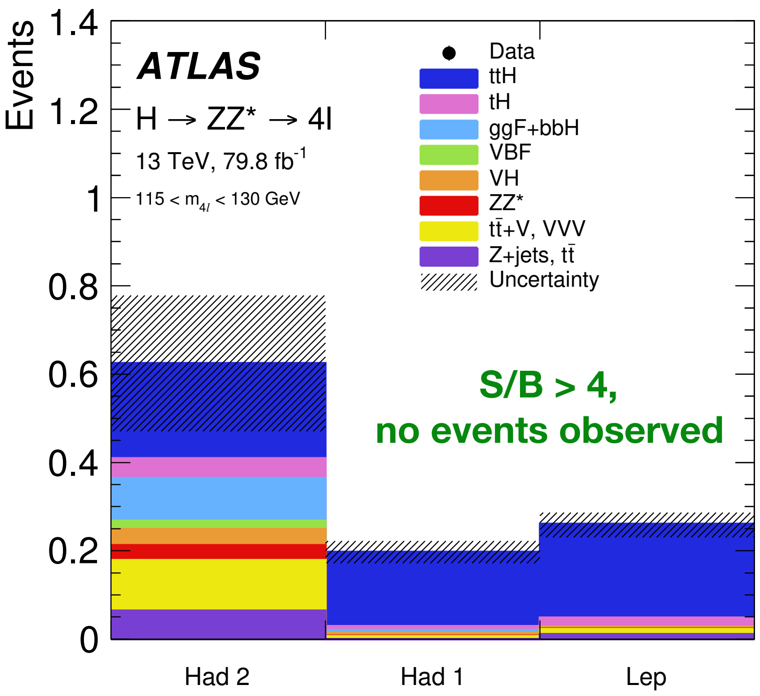


- **Dominant systematic uncertainties on μ_{ttH}:**
  - ttH cross-section ($^{+0.20}_{-0.09}$)
  - Jet energy scale and resolution ($^{+0.18}_{-0.15}$)
  - Non-prompt e/μ estimates ($^{+0.15}_{-0.13}$)

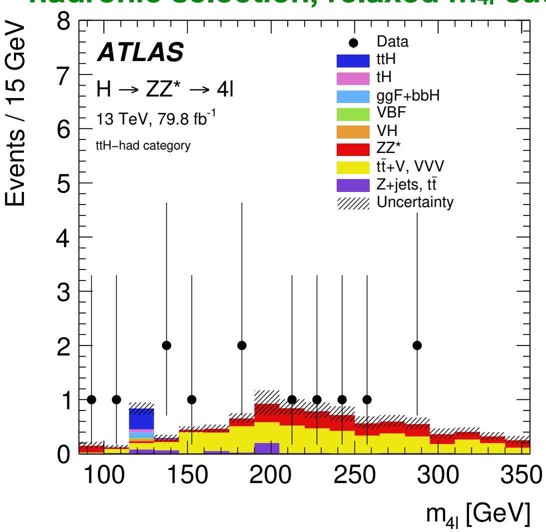
significance: 4.1σ (2.8σ expected)

79.8 fb⁻¹

- **New for summer 2018:** analysis with 79.8 fb^{-1}
- **Selection:**
  - **115 GeV < m_{4l} < 130 GeV**
  - **Hadronic-enriched region:**
    - ≥4 jets, ≥1 b-tag, no additional light leptons
    - Split in two bins using a BDT ("Had 1", "Had 2")
  - **Leptonic-enriched region**
    - ≥2 jets, ≥1 b-tag, ≥1 additional light lepton
- **Major backgrounds:**
  - ttV, other Higgs production modes
- **Extremely statistically limited:**
  - no events observed in signal region
    - 1.1 events expected (0.6 ttH)
  - Expected sensitivity: 1.2σ

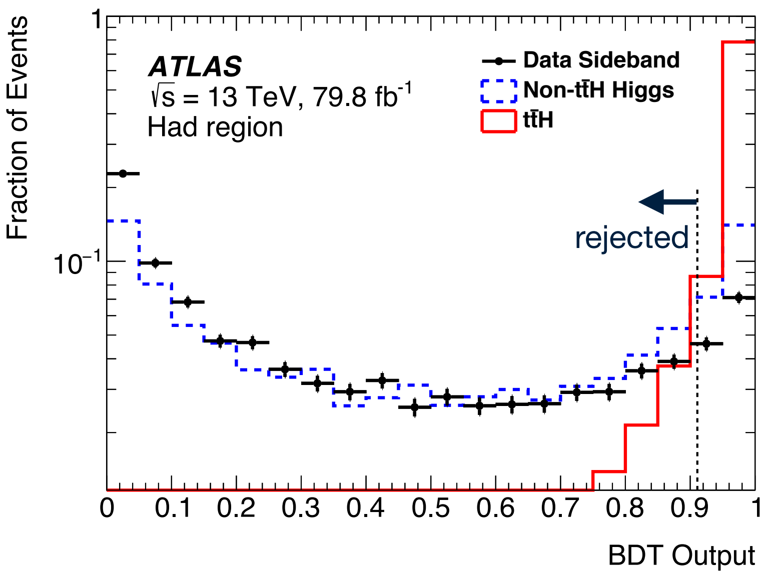


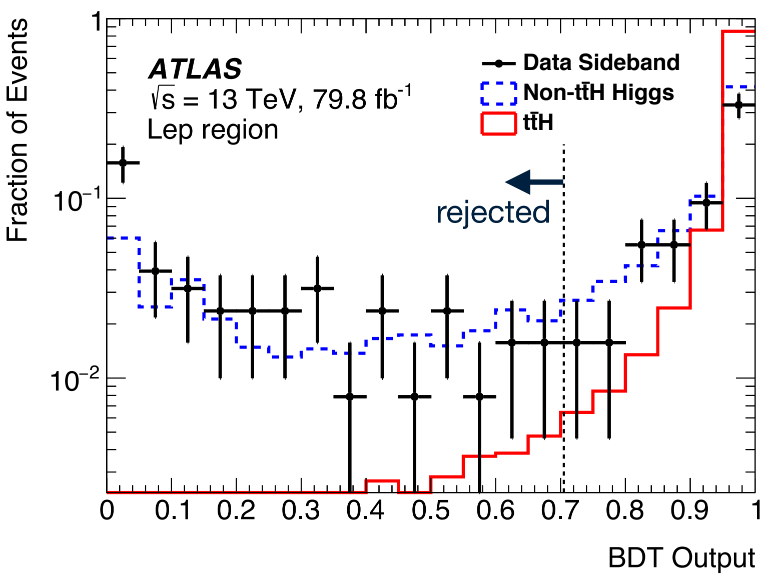
hadronic selection, relaxed m_{4l} cut



ttH(γγ): Design

79.8 fb^{-1}

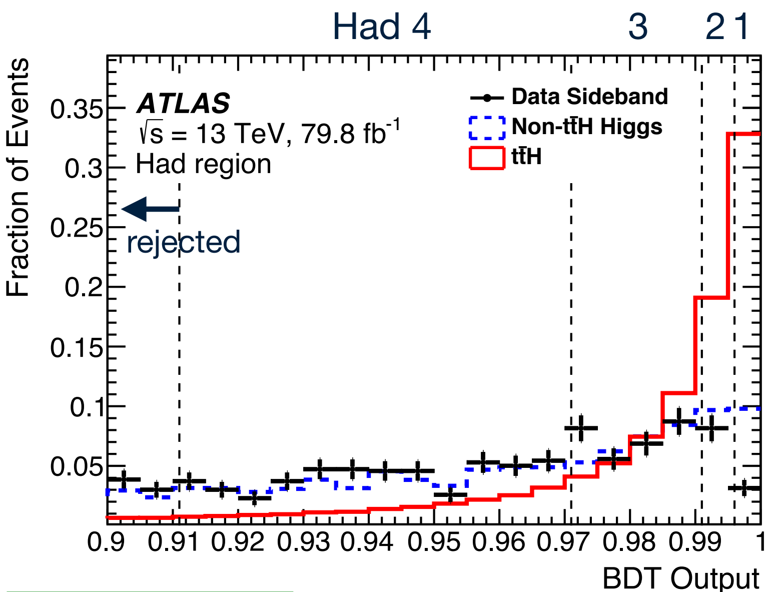




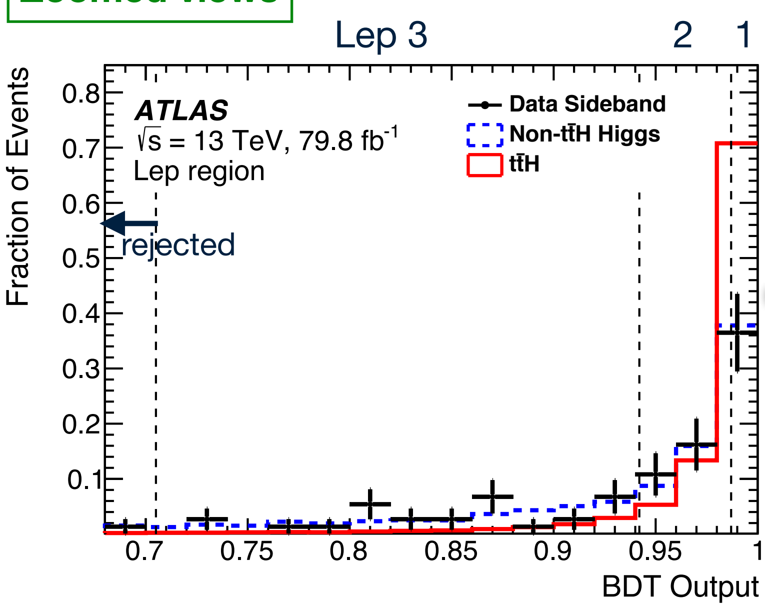
- **New for summer 2018:** analysis with 79.8 fb^{-1}
- **Analysis regions:**
  - **Hadronic region "Had":**
    - ≥3 jets, ≥1 b-tag, no light leptons (e/μ)
  - **Leptonic region "Lep":**
    - ≥1 b-tagged jet, ≥1 light lepton (e/μ)
- **Defining signal-enriched regions:**
  - **BDTs** implemented via **XGBoost**
    - **Inputs include:** photon kinematics ($p_T/m_{\gamma\gamma}$, η, ϕ) and jet 4-vectors
    - **Signal:** ttH (from simulation)
    - **Backgrounds:** γγ, tt+γγ (data in control regions), other Higgs production (from simulation)
  - Perform **cut on BDT** output to **veto backgrounds**
    - Categorize events passing cut

ttH(γγ): Categories

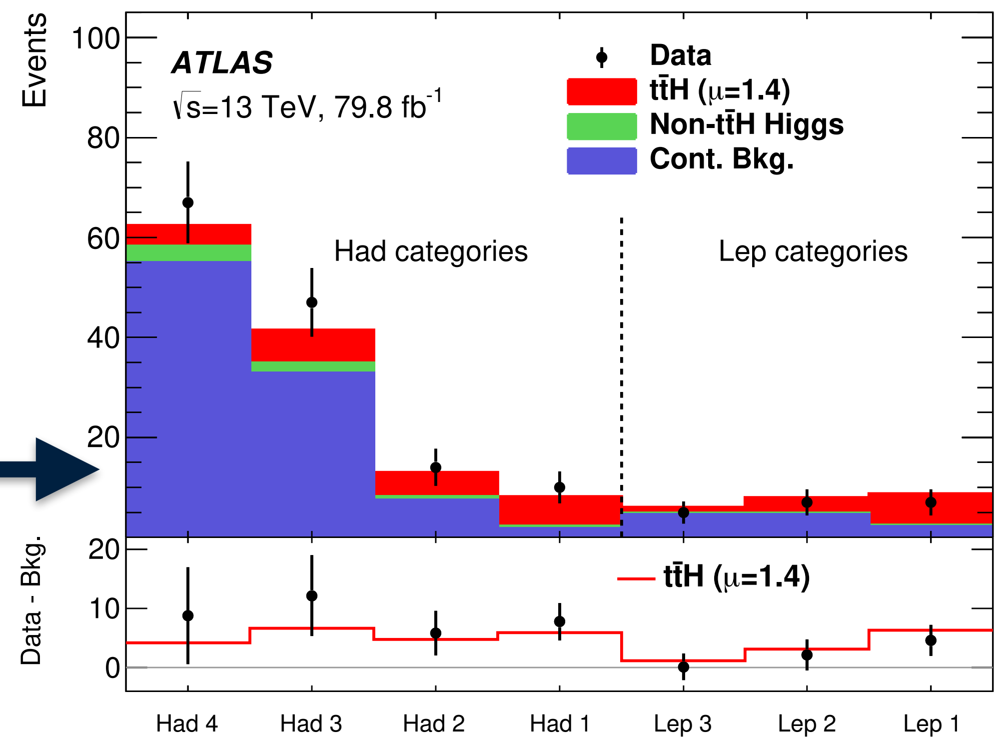
79.8 fb^{-1}



Zoomed views



- **Analysis regions:**
  - **Hadronic region "Had":**
    - 4 sub-categories, after BDT cut
  - **Leptonic region "Lep":**
    - 3 sub-categories, after BDT cut



ttH(γγ): Results

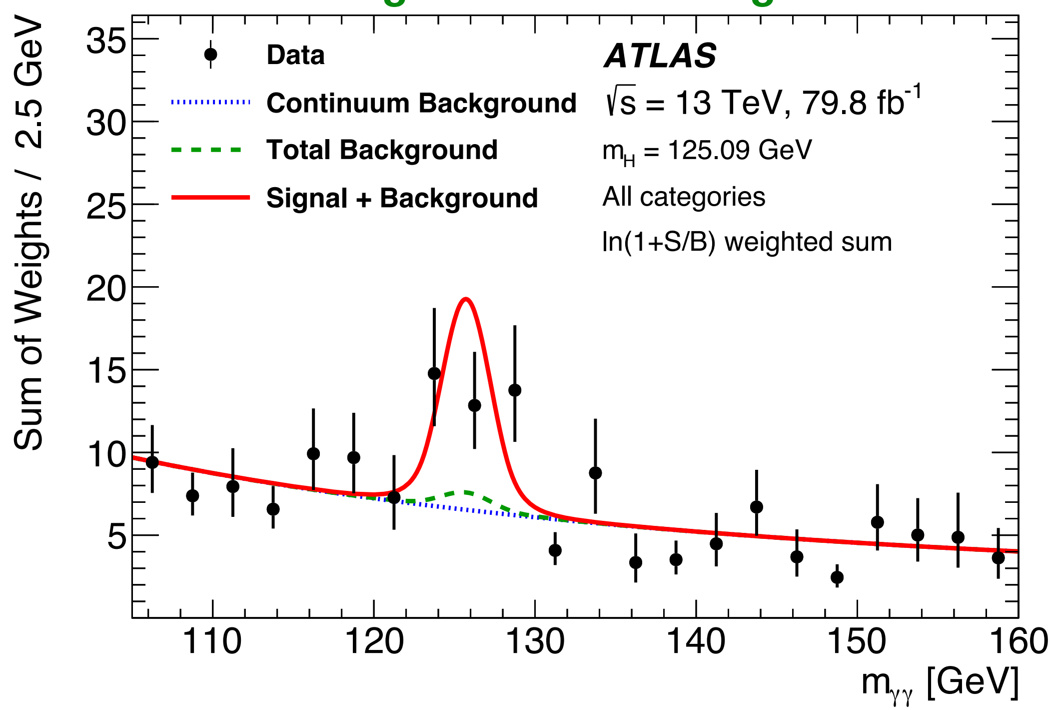
79.8 fb^{-1}

- **Fit details:**
  - **Simultaneous unbinned fit of $m_{\gamma\gamma}$** (105-160 GeV) in all 7 categories
  - **ttH signal:** double-sided crystal ball
  - **Continuum background:** smooth functions (power-law or exponential)

- **Significance:**
  - **4.1σ (3.7σ expected)**
    - Had: 3.8σ (2.7σ), Lep: 1.9σ (2.5σ)

- **Dominant uncertainties:**
  - Statistically dominated
  - ttH shower & hadronization (8%)
  - Photon isolation, resolution, scale (8%)
  - Jet energy scale (5%)

Weighted sum of categories

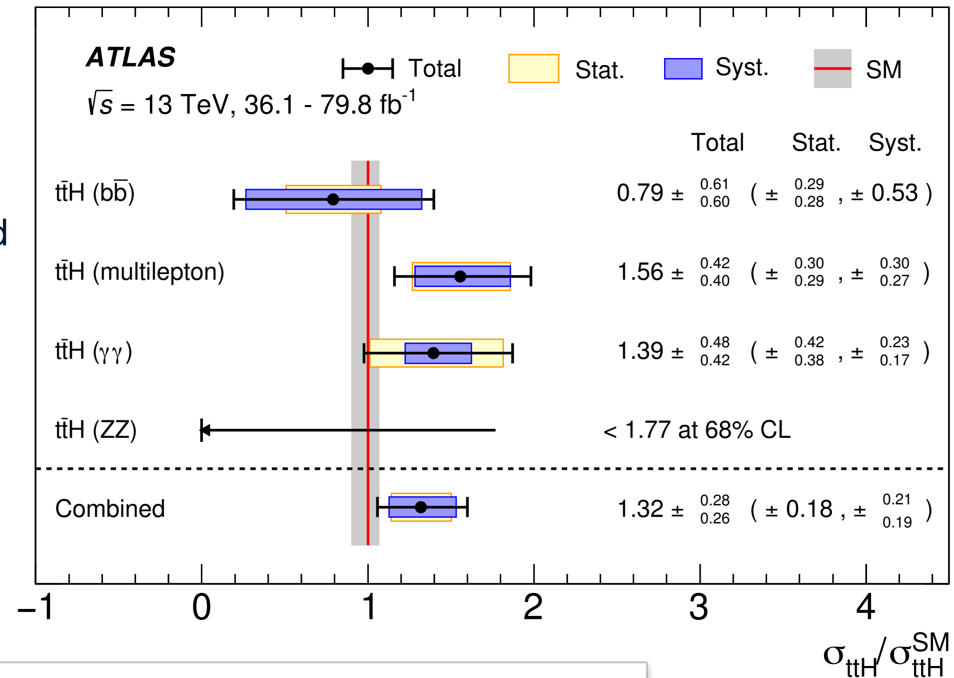


- **50% more sensitive than previous result:**
  - Inclusion of 4-momentum information of objects (30% improvement for same luminosity)
  - Improved reconstruction and selection

ttH combination

36.1 - 79.8 fb^{-1}

- **Inputs:**
  - bb, multi-lepton: 36.1 fb^{-1}; γγ, ZZ*→4l: 79.8fb^{-1}
- **Combination details:**
  - Theory uncertainties correlated
  - Experimental uncertainties largely uncorrelated
  - Other Higgs production modes fixed to SM
- **Dominant systematic uncertainties:**
  - tt + heavy flavour modelling (12%)
  - ttH modelling (10%)
  - Experimental uncertainties (9%)

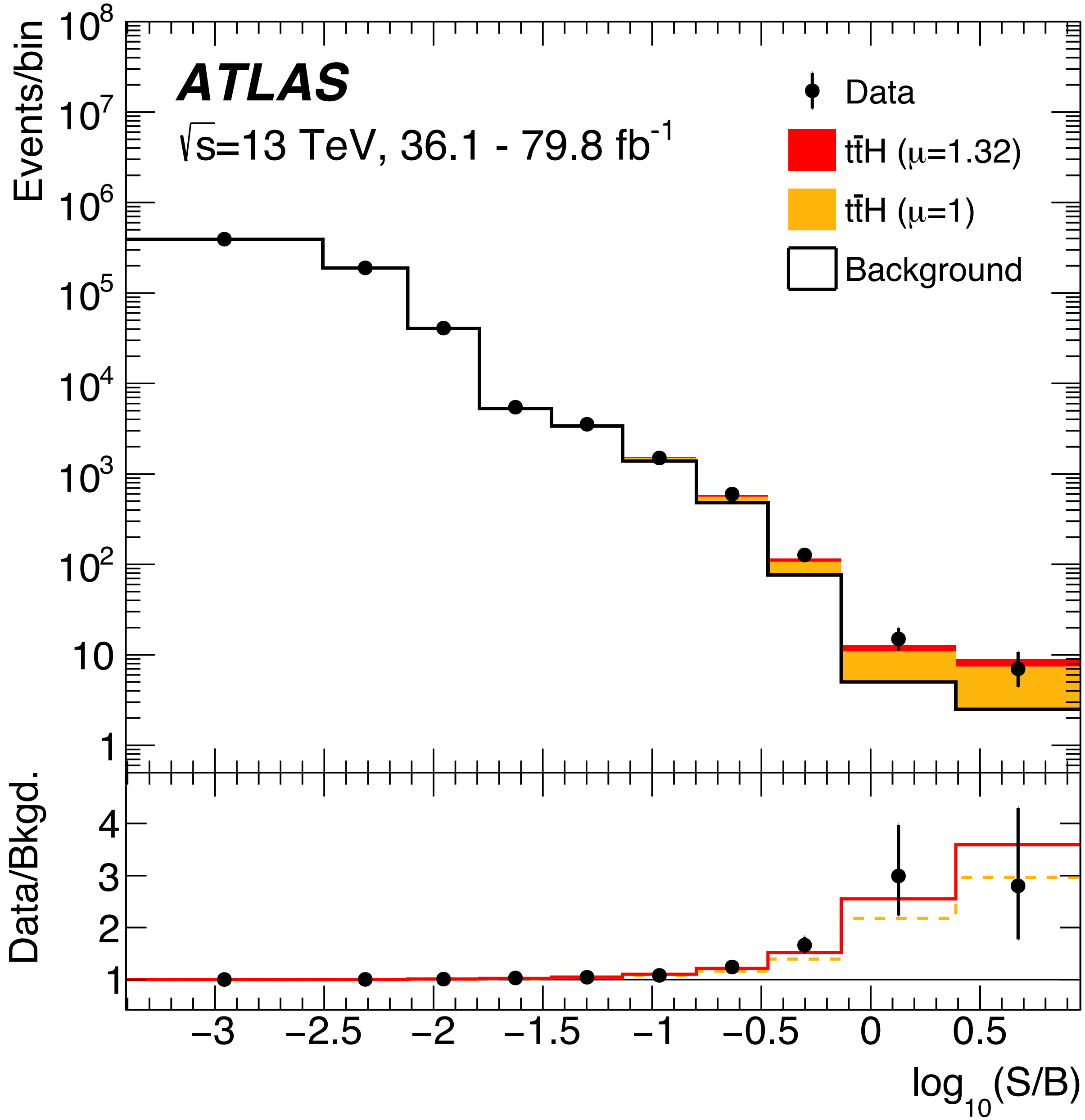


Analysis	Integrated luminosity [fb^{-1}]	Expected significance	Observed significance
$H \to \gamma\gamma$	79.8	3.7 σ	4.1 σ
$H \to$ multilepton	36.1	2.8 σ	4.1 σ
$H \to b\bar{b}$	36.1	1.6 σ	1.4 σ
$H \to ZZ^* \to 4\ell$	79.8	1.2 σ	0 σ
Combined (13 TeV)	36.1−79.8	4.9 σ	5.8 σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1−79.8	5.1 σ	6.3 σ

observation of ttH!

ttH combination

36.1 - 79.8 fb^{-1}

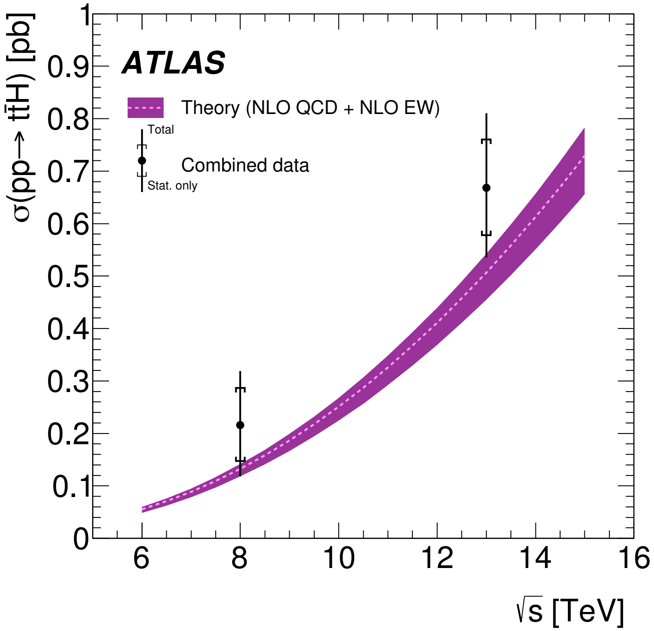


clear excess in high S/B bins, consistent with ttH signal

ttH cross-section

36.1 - 79.8 fb^{-1}

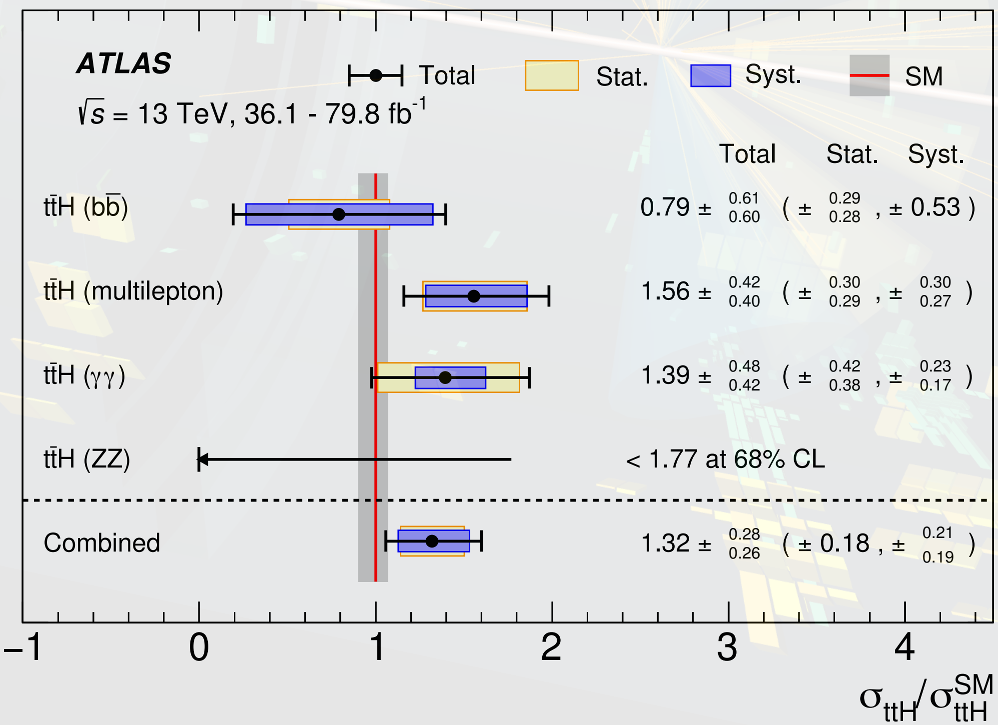
Analysis	Integrated luminosity [fb^{-1}]	$t\bar{t}H$ cross section [fb]
$H \to \gamma\gamma$	79.8	$710\ ^{+210}_{-190}$ (stat.) $^{+120}_{-90}$ (syst.)
$H \to$ multilepton	36.1	790 ± 150 (stat.) $^{+150}_{-140}$ (syst.)
$H \to b\bar{b}$	36.1	$400\ ^{+150}_{-140}$ (stat.) $\pm$ 270 (syst.)
$H \to ZZ^* \to 4\ell$	79.8	<900 (68% CL)
Combined (13 TeV)	36.1–79.8	670 ± 90 (stat.) $^{+110}_{-100}$ (syst.)

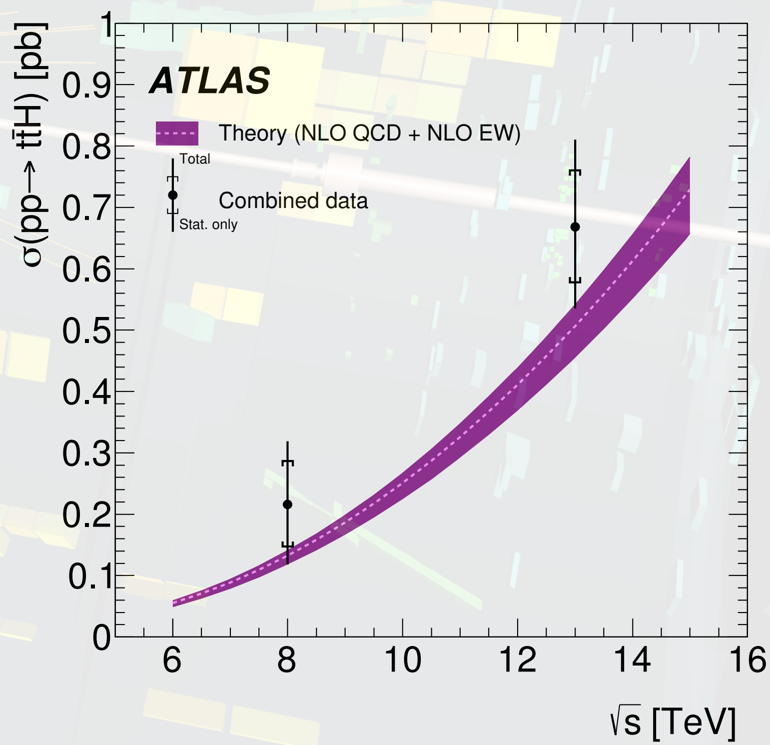


- Compare to: $\sigma^{SM}_{ttH} = 507^{+35}_{-50}$ fb
  - Measurement **consistent with SM prediction!**
- Combination is **assuming SM branching ratios**

Summary

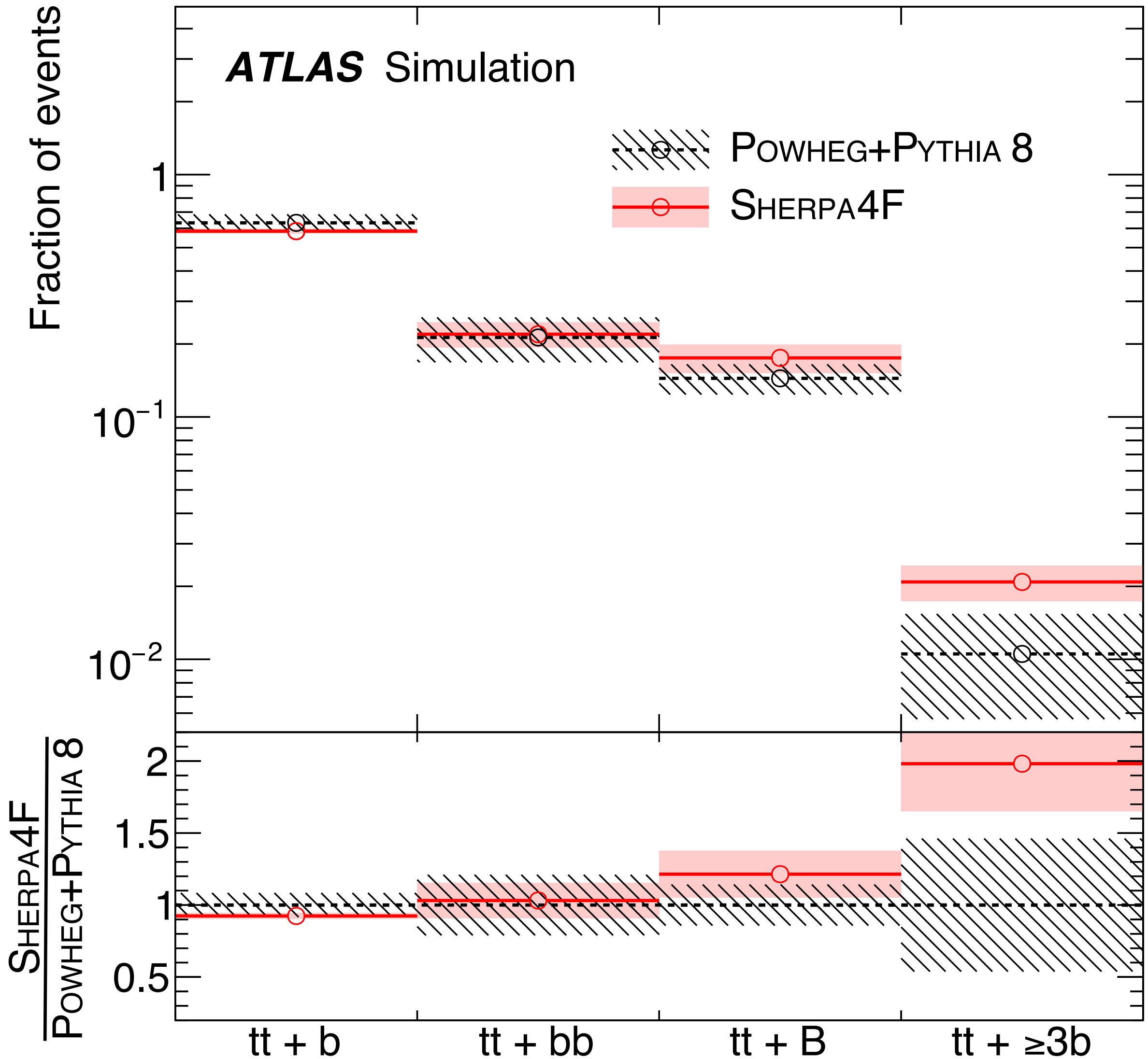
- **Observation of ttH production process:**
  - 6.3σ significance (5.1σ expected)
- **Good agreement with SM:** $\sigma_{t\bar{t}H} = 670 \pm 90\,(\text{stat.})\ {}^{+110}_{-100}\ (\text{syst.})$ fb





Backup

ttH(bb): tt+ ≥1b modelling



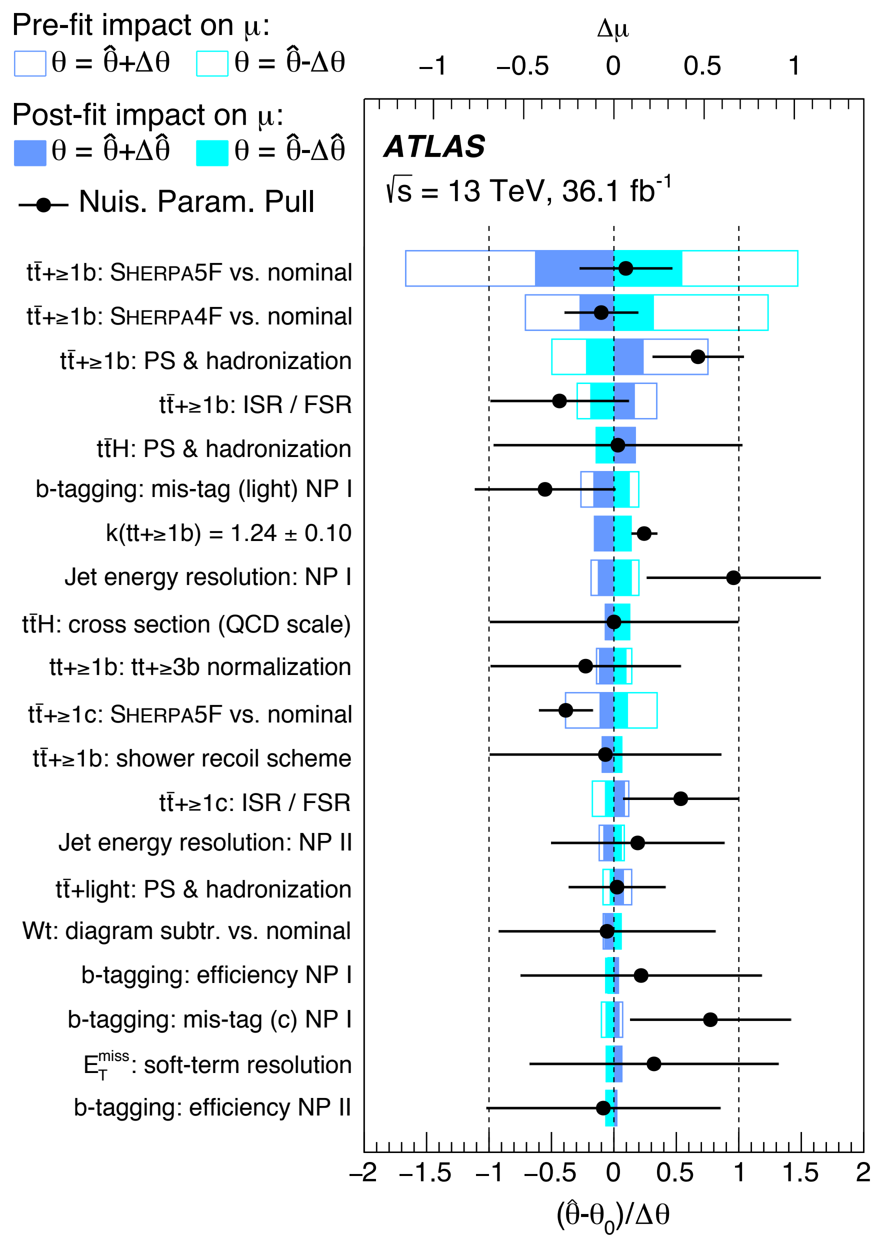
- Powheg + Pythia 8 (5FS) is re-weighted per tt+ ≥1b sub-category to Sherpa + OpenLoops NLO (4FS)

ttH(bb): tt modelling

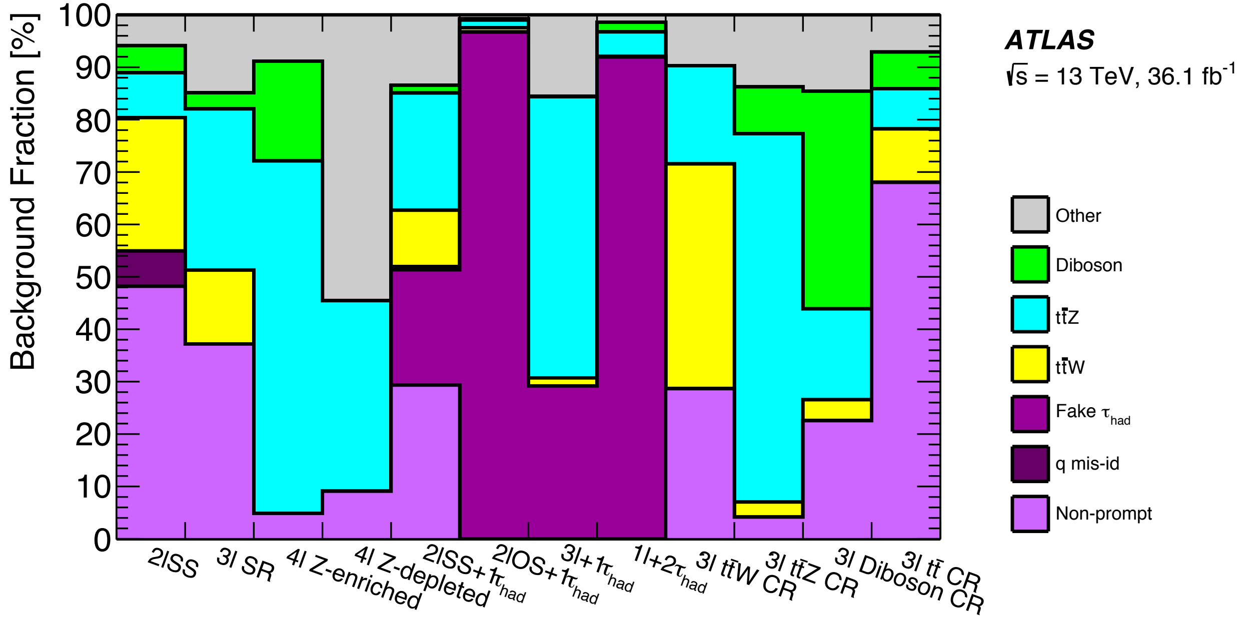
Systematic source	Description	$t\bar{t}$ categories
$t\bar{t}$ cross-section	Up or down by 6%	All, correlated
$k(t\bar{t}+\geq 1c)$	Free-floating $t\bar{t}+\geq 1c$ normalization	$t\bar{t}+\geq 1c$
$k(t\bar{t}+\geq 1b)$	Free-floating $t\bar{t}+\geq 1b$ normalization	$t\bar{t}+\geq 1b$
SHERPA5F vs. nominal	Related to the choice of NLO event generator	All, uncorrelated
PS & hadronization	POWHEG+HERWIG 7 vs. POWHEG+PYTHIA 8	All, uncorrelated
ISR / FSR	Variations of μ_{R}, μ_{F}, h_{damp} and A14 Var3c parameters	All, uncorrelated
$t\bar{t}+\geq 1c$ ME vs. inclusive	MG5_aMC@NLO+HERWIG++: ME prediction (3F) vs. incl. (5F)	$t\bar{t}+\geq 1c$
$t\bar{t}+\geq 1b$ SHERPA4F vs. nominal	Comparison of $t\bar{t}+b\bar{b}$ NLO (4F) vs. POWHEG+PYTHIA 8 (5F)	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ renorm. scale	Up or down by a factor of two	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ resumm. scale	Vary μ_{Q} from $H_{\mathrm{T}}/2$ to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ global scales	Set μ_{Q}, μ_{R}, and μ_{F} to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ shower recoil scheme	Alternative model scheme	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ PDF (MSTW)	MSTW vs. CT10	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ PDF (NNPDF)	NNPDF vs. CT10	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ UE	Alternative set of tuned parameters for the underlying event	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ MPI	Up or down by 50%	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 3b$ normalization	Up or down by 50%	$t\bar{t}+\geq 1b$

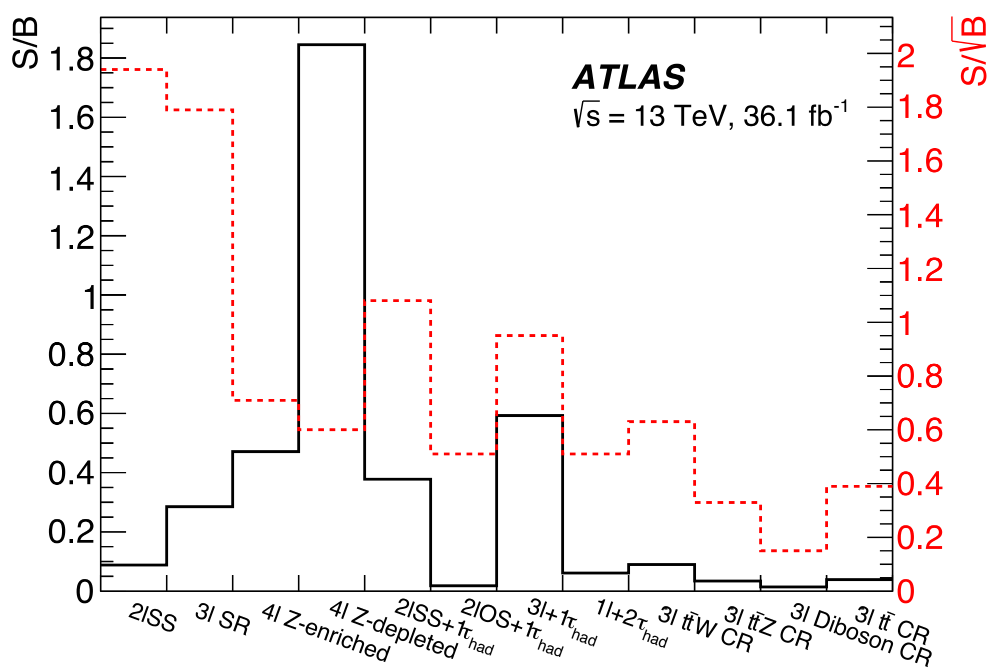
ttH(bb): Uncertainties

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



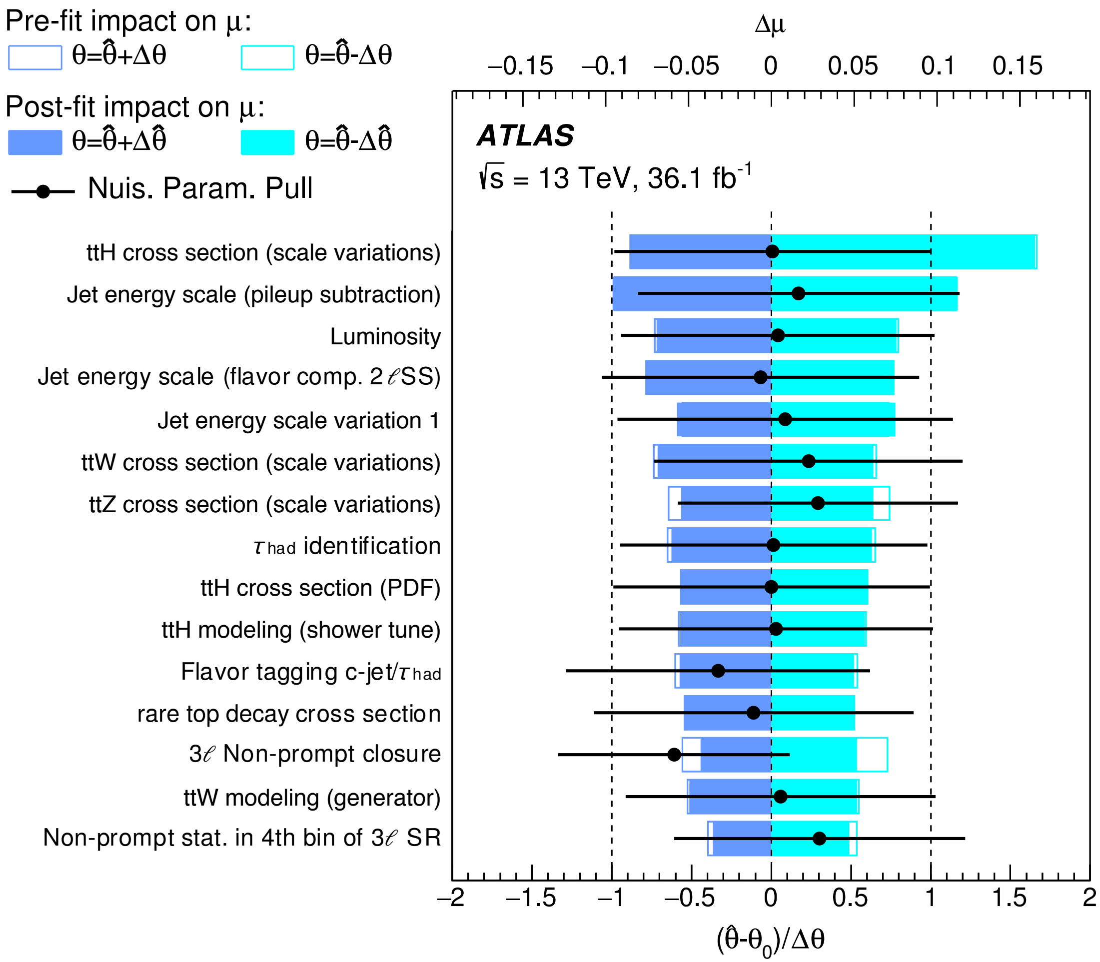
ttH multi-lepton: Backgrounds, S/B



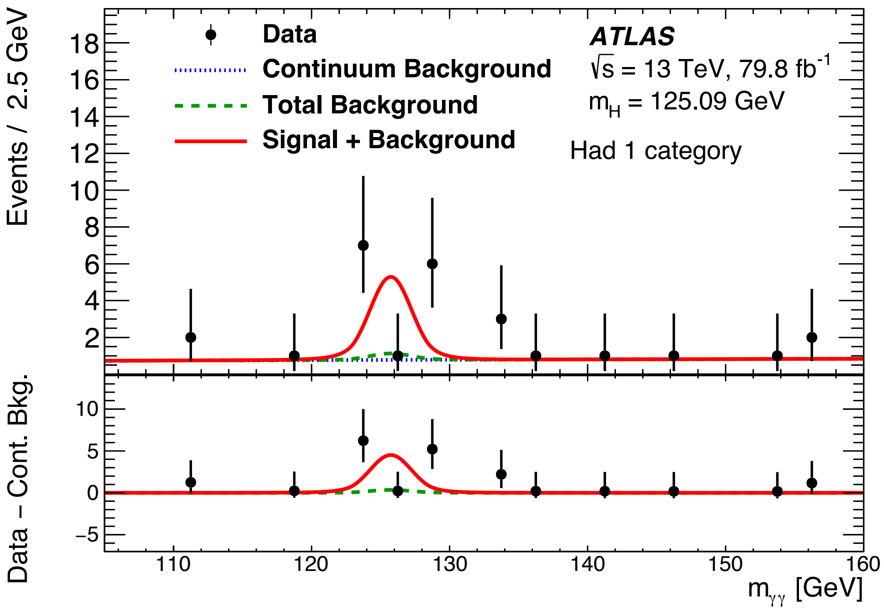


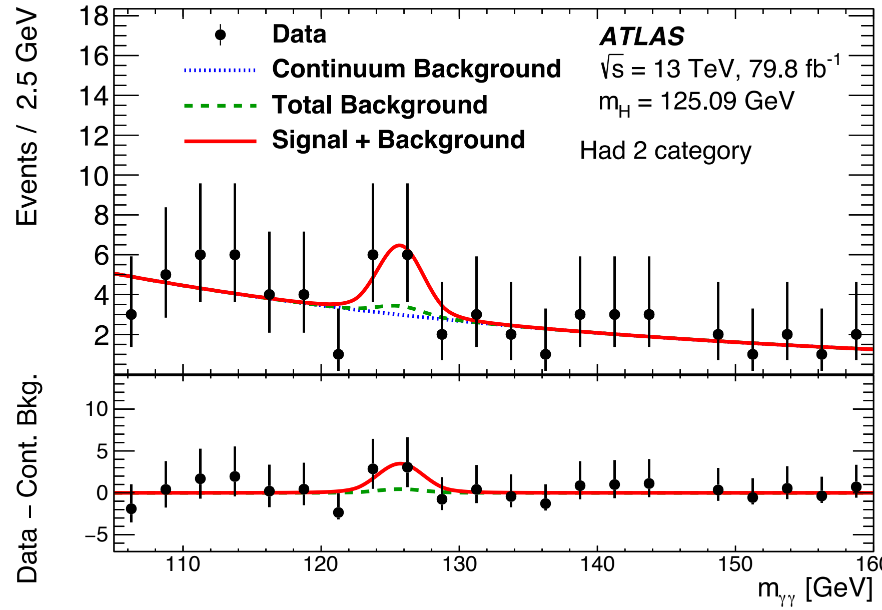
ttH multi-lepton: Uncertainties

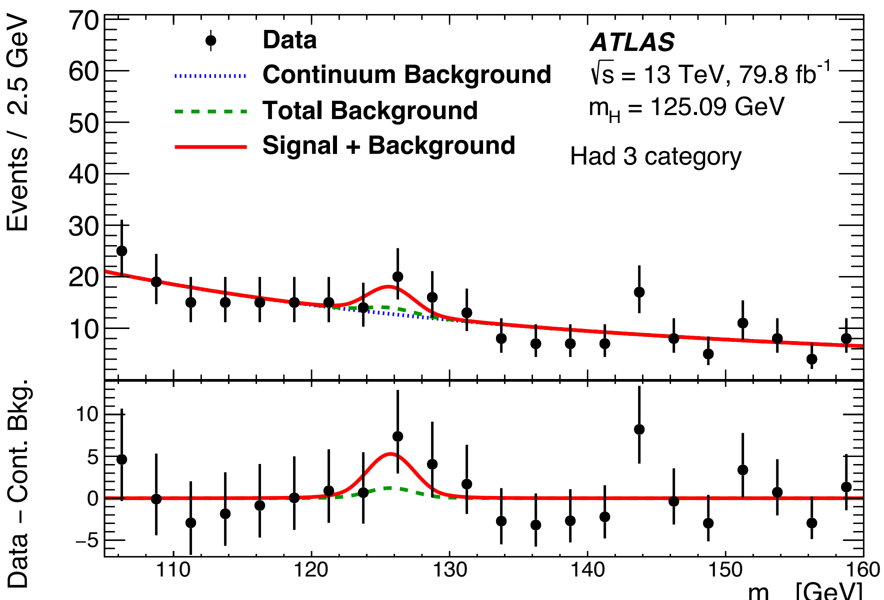
Uncertainty Source	$\Delta\mu$	
$t\bar{t}H$ modeling (cross section)	+0.20	−0.09
Jet energy scale and resolution	+0.18	−0.15
Non-prompt light-lepton estimates	+0.15	−0.13
Jet flavor tagging and τ_{had} identification	+0.11	−0.09
$t\bar{t}W$ modeling	+0.10	−0.09
$t\bar{t}Z$ modeling	+0.08	−0.07
Other 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

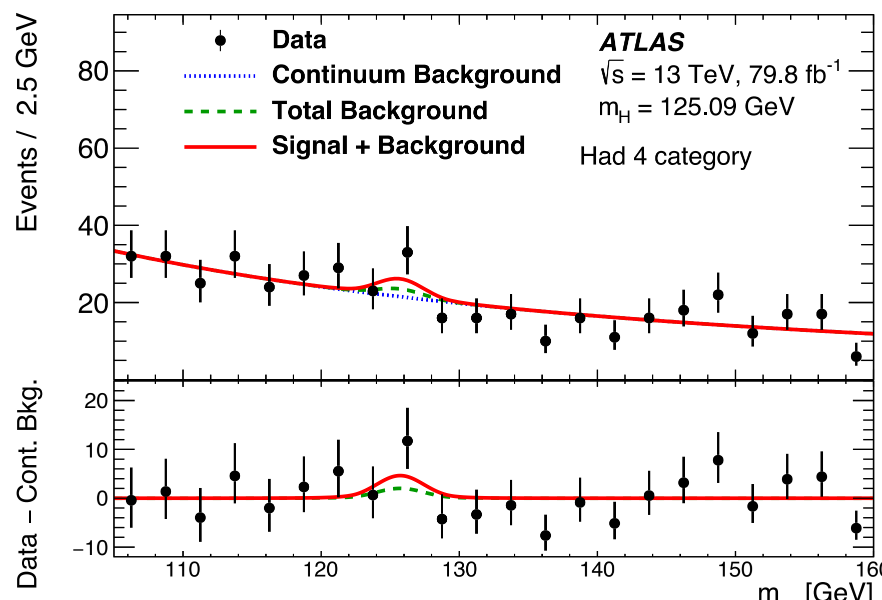


ttH(γγ): $m_{\gamma\gamma}$ distributions (Had category)

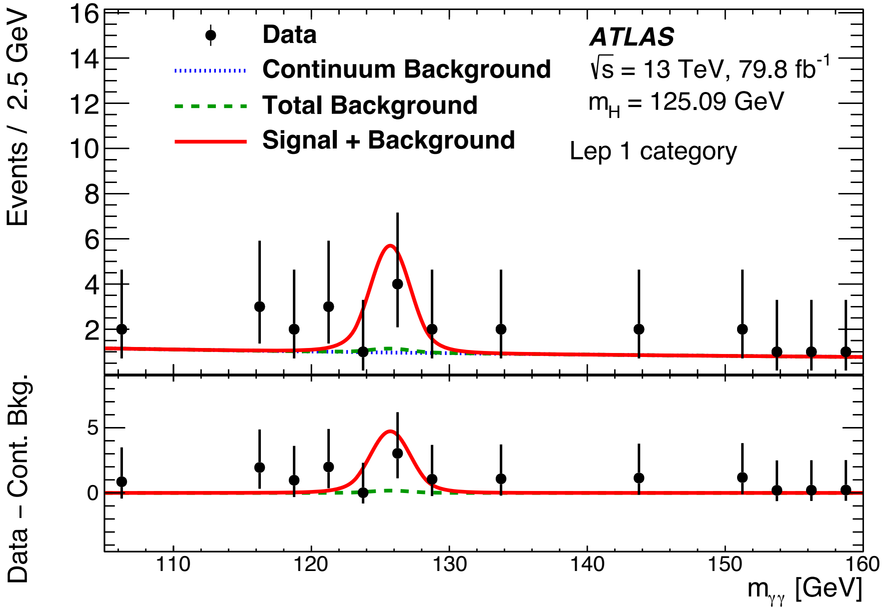


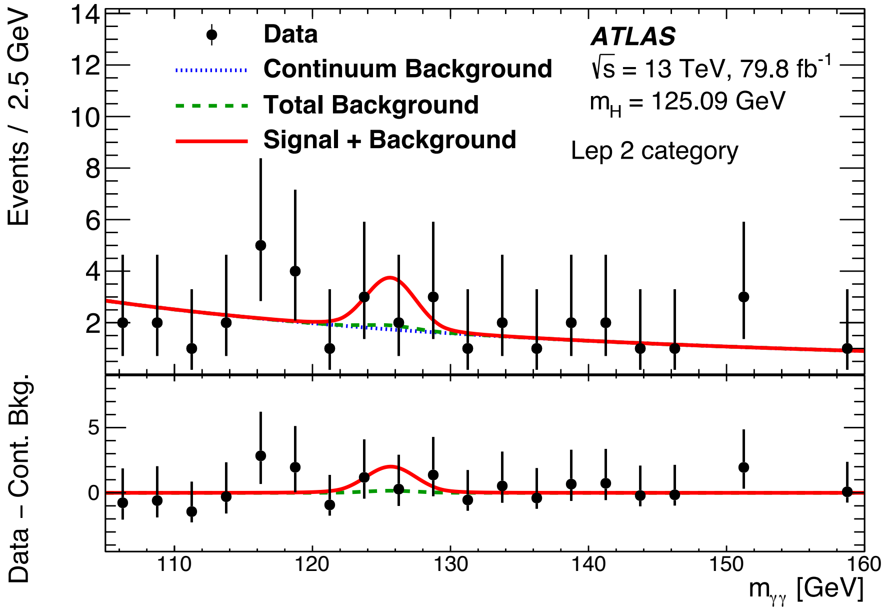


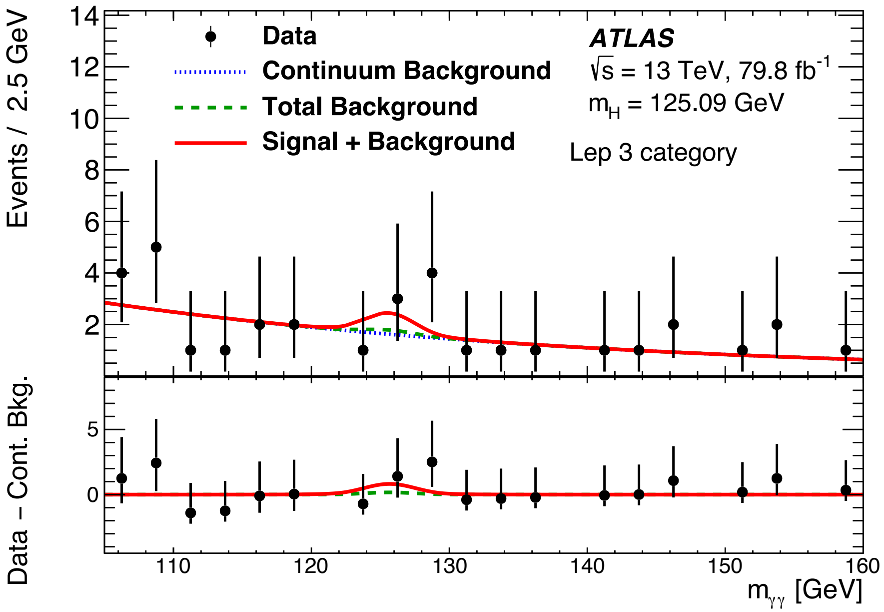




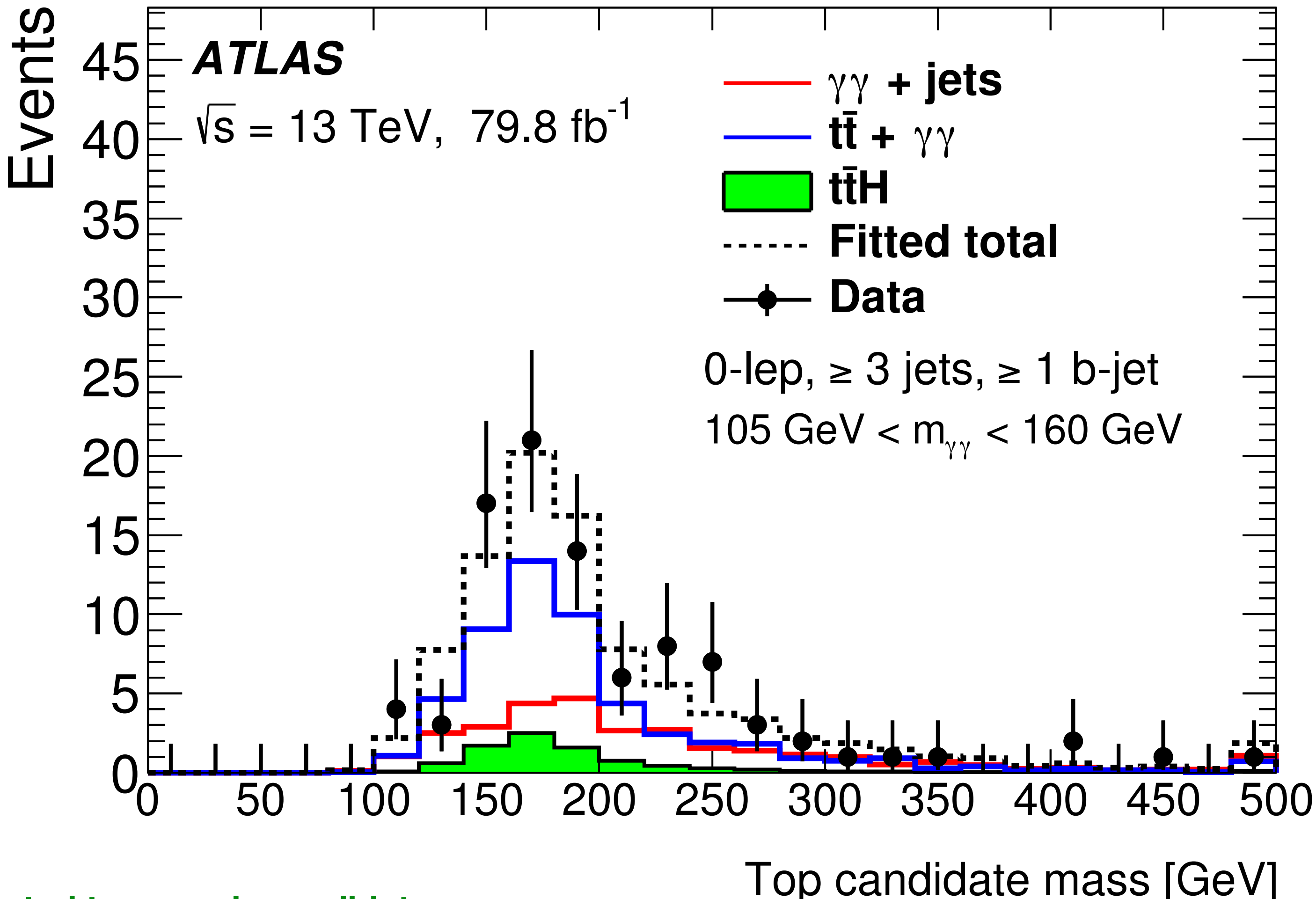
ttH(γγ): $m_{\gamma\gamma}$ distributions (Lep category)





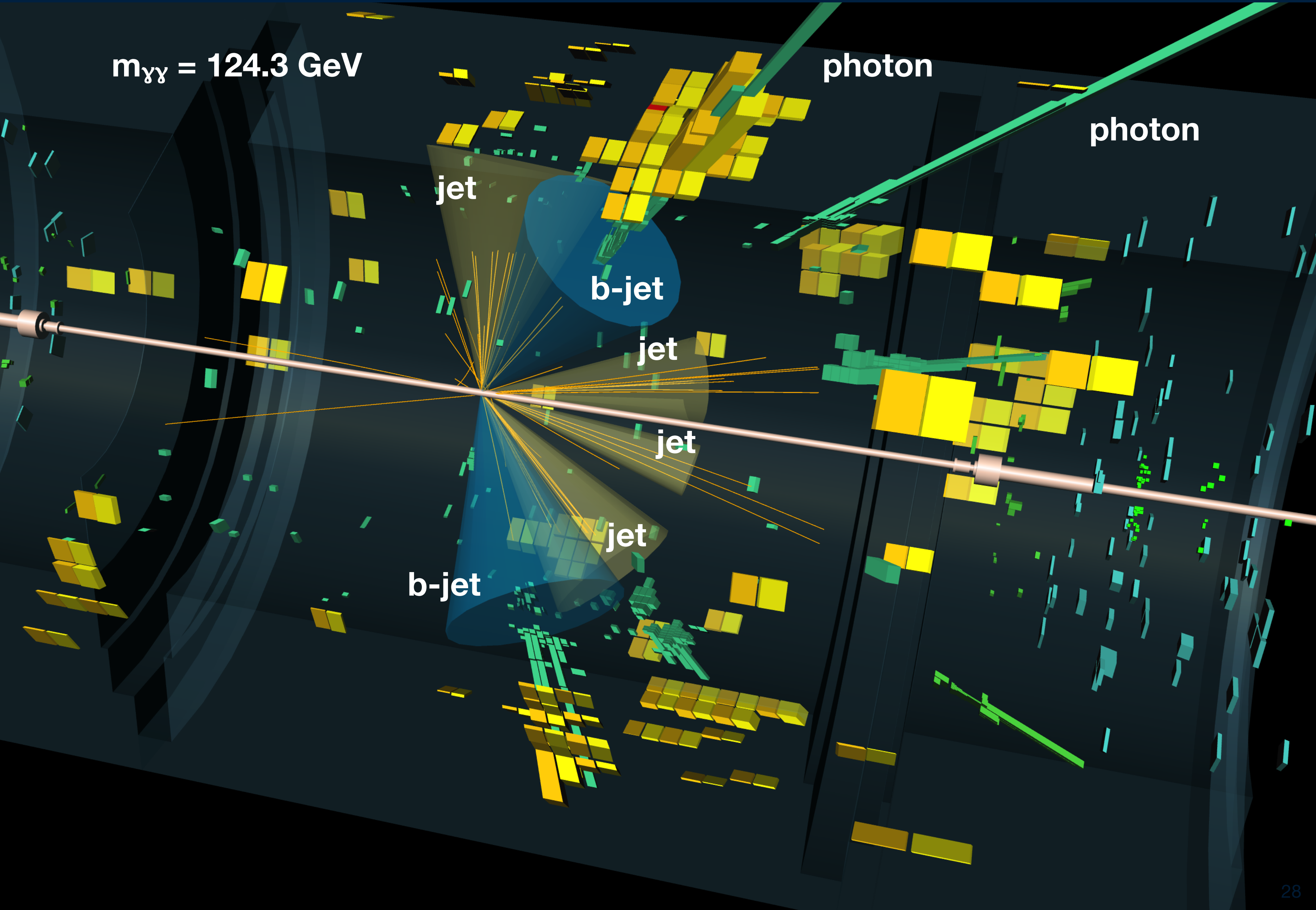


ttH(γγ): Validation



- **Reconstructed top-quark-candidate mass**
  - Built with **dedicated BDT** for validation purposes, not part of analysis
  - Events in the two Had bins with highest S/B, 105 GeV < $m_{\gamma\gamma}$ < 160 GeV
  - MC normalization from fitting top-candidate mass distributions to data (58% ttγγ, 32% γγ+jets)

ttH(γγ): Event display

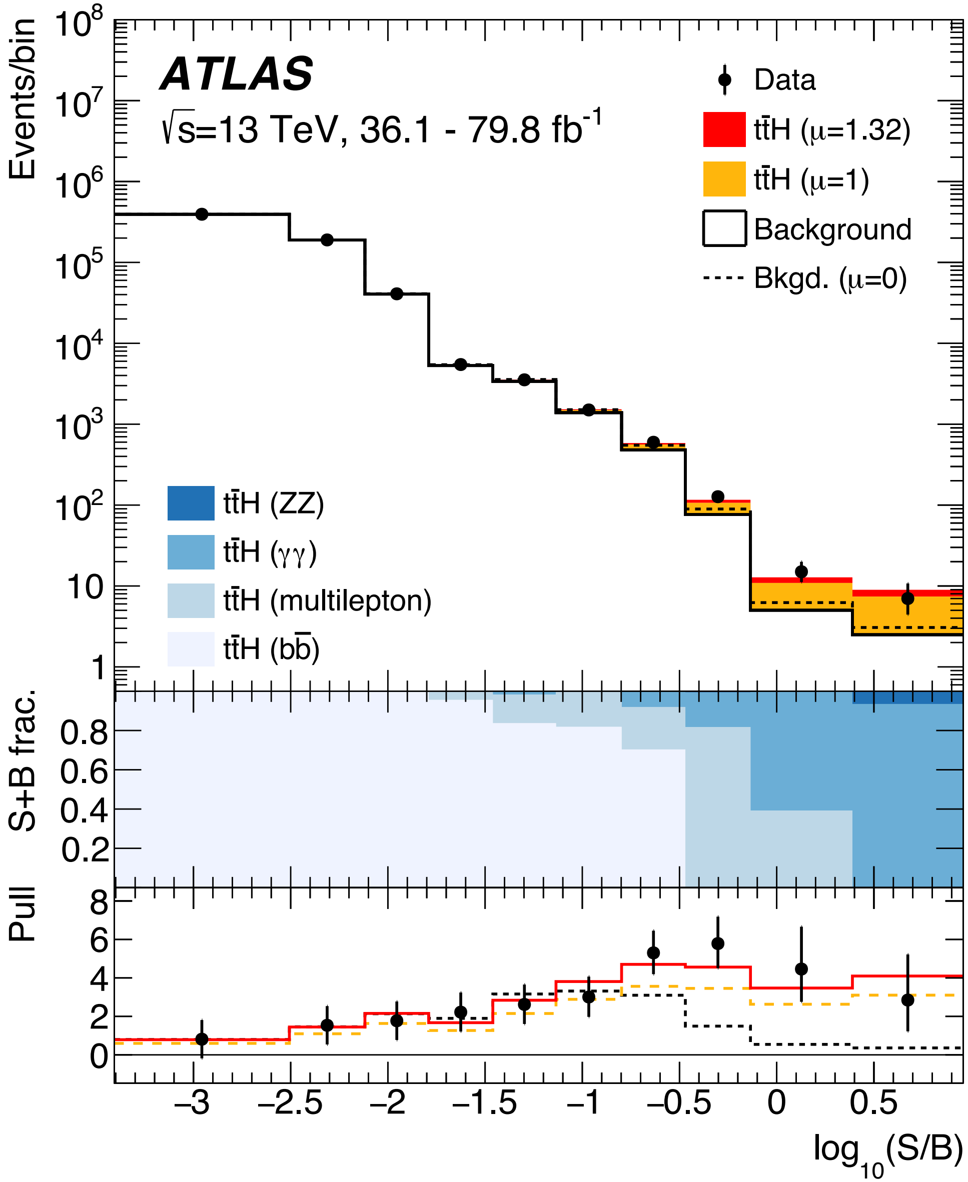


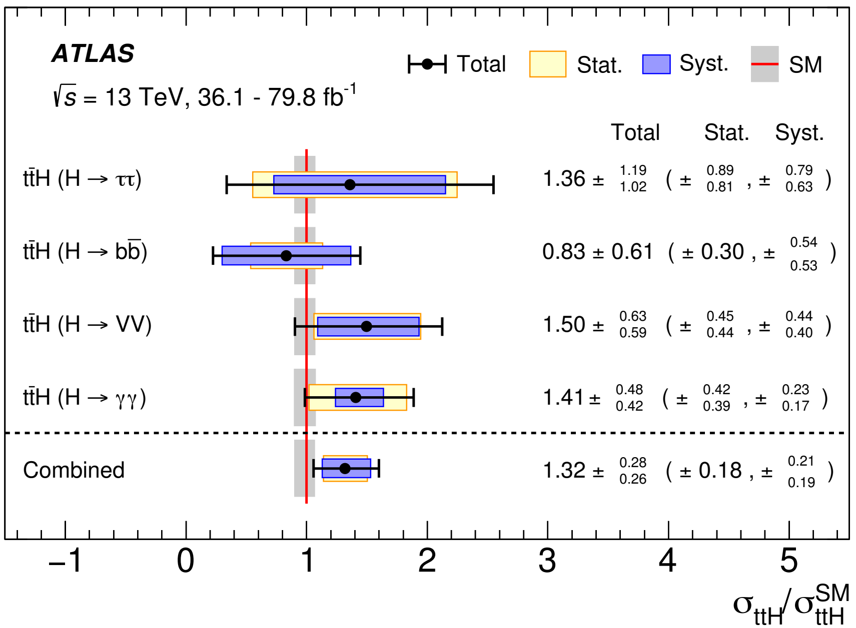
ttH(γγ), ttH(ZZ*→4l): Yields

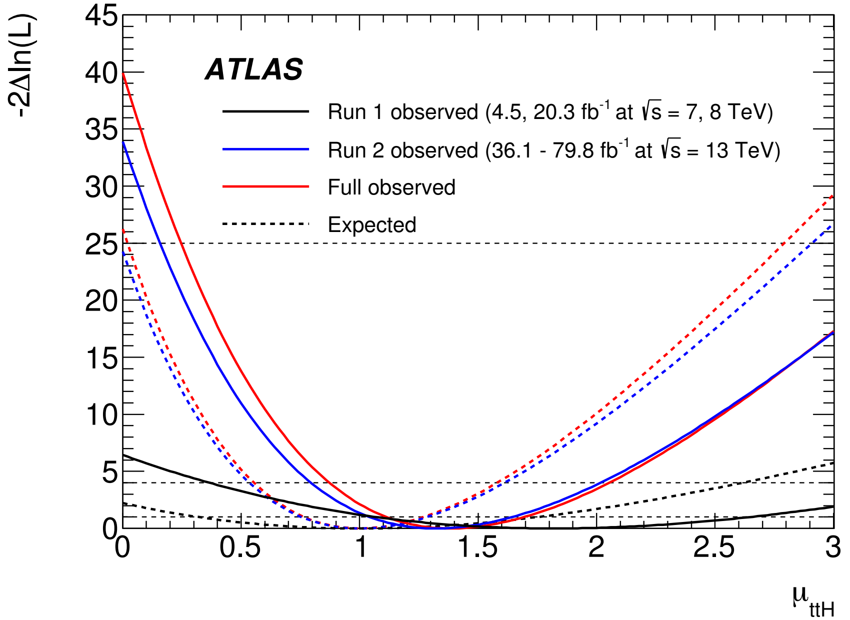
- **ttH(γγ)** analysis yields counted in smallest $m_{\gamma\gamma}$ window containing 90% of expected signal
- **ttH(ZZ*→4l)** analysis yields are in 115 GeV < m_{4l} < 130 GeV window

	Expected				Observed
Bin	$t\bar{t}H$ (signal)	Non-$t\bar{t}H$ Higgs	Non-Higgs	Total	Total
$H \to \gamma\gamma$					
Had 1	4.2(11)	0.49(33)	1.76(55)	6.4(13)	10
Had 2	3.41(74)	0.69(56)	7.5(11)	11.6(15)	14
Had 3	4.70(88)	2.0(17)	32.9(22)	39.6(32)	47
Had 4	3.00(55)	3.2(31)	55.0(28)	61.3(47)	67
Lep 1	4.5(10)	0.25(9)	2.19(59)	6.9(12)	7
Lep 2	2.23(39)	0.27(10)	4.59(91)	7.1(10)	7
Lep 3	0.82(18)	0.30(13)	4.58(91)	5.70(88)	5
$H \to ZZ^* \to 4\ell$					
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

ttH combination







ttH cross-section uncertainties

Uncertainty source	$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ [%]
Theory uncertainties (modelling)	11.9
$t\bar{t}$ + heavy flavour	9.9
$t\bar{t}H$	6.0
Non-$t\bar{t}H$ Higgs boson production modes	1.5
Other background processes	2.2
Experimental uncertainties	9.3
Fake leptons	5.2
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	4.9
Electrons, photons	3.2
Luminosity	3.0
τ-lepton	2.5
Flavour tagging	1.8
MC statistical uncertainties	4.4

Abstract

Studies of Higgs boson production in association with a ttbar pair

The search for the production of the Higgs Boson with a pair of top-anti-top quarks is both very important and very challenging. This talks presents the analyses using Higgs boson decays to bbbar pairs, to two Z bosons, to other multi-lepton final states, and to a pair of photons, using pp collision data collected at 13 TeV, as well as their combined results.