Higgs boson production in association with a $t\bar{t}$ pair with the ATLAS detector

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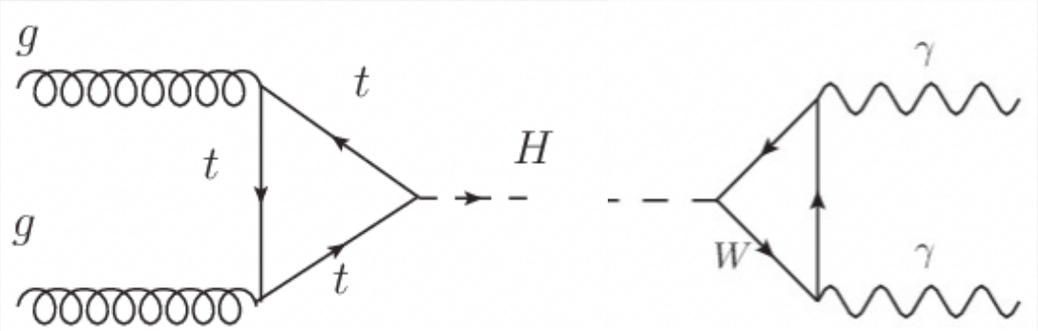
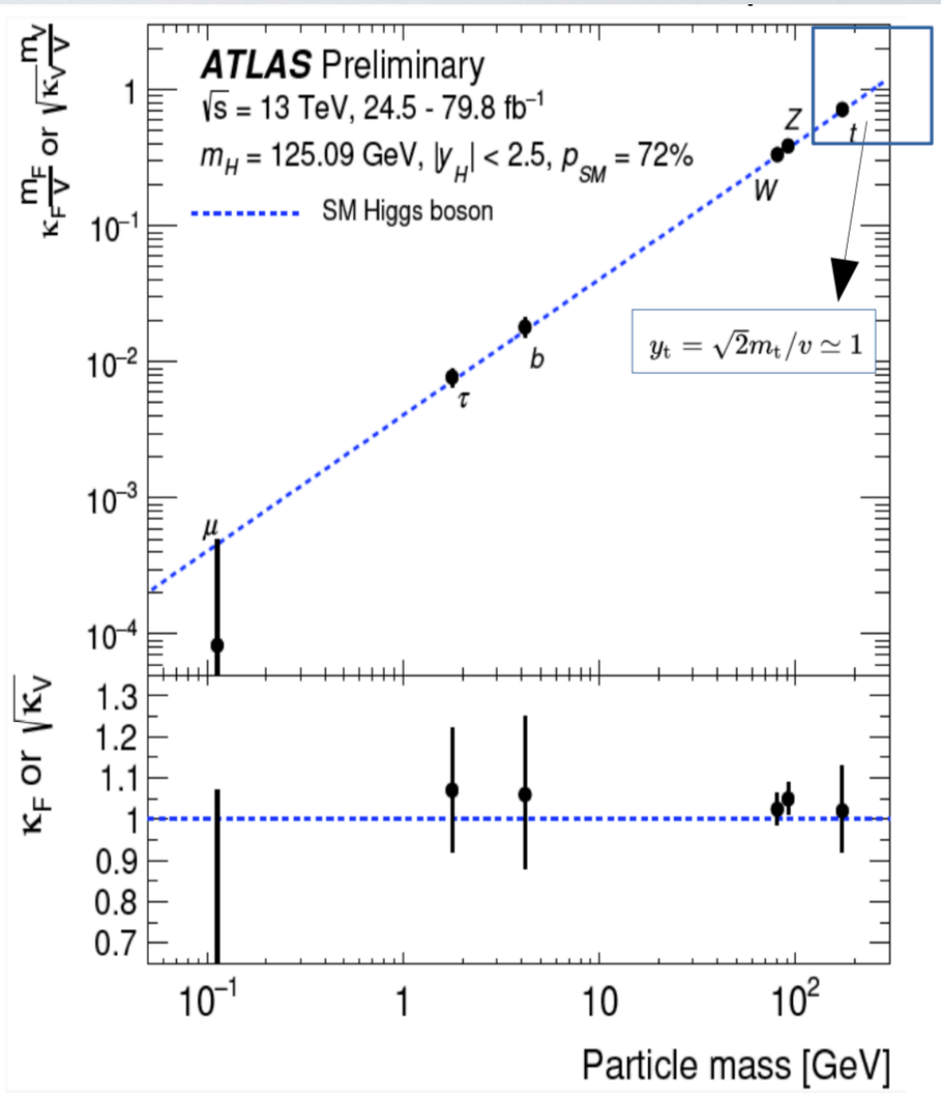
MOTIVATION: DIRECT MEASUREMENT OF TOP-HIGGS YUKAWA COUPLING

- Top-Higgs Yukawa coupling y_t
  - Largest Yukawa coupling in the SM, $y_t \cong 1$
  - Sensitive to new physics

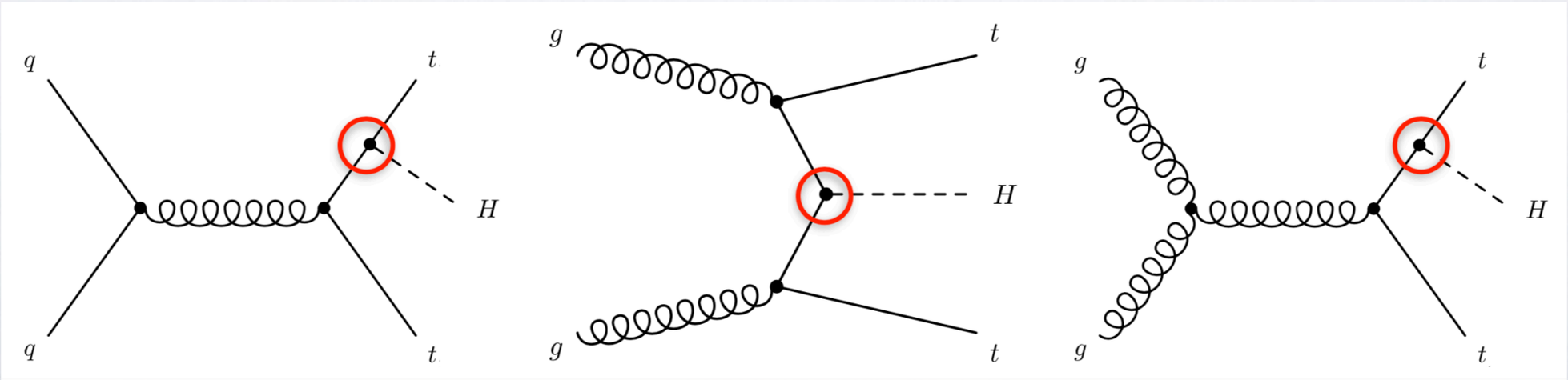
- Indirect measurements of y_t via ggF and $H \rightarrow \gamma\gamma$ loop
  - Must rely on assumptions of particles entering loops





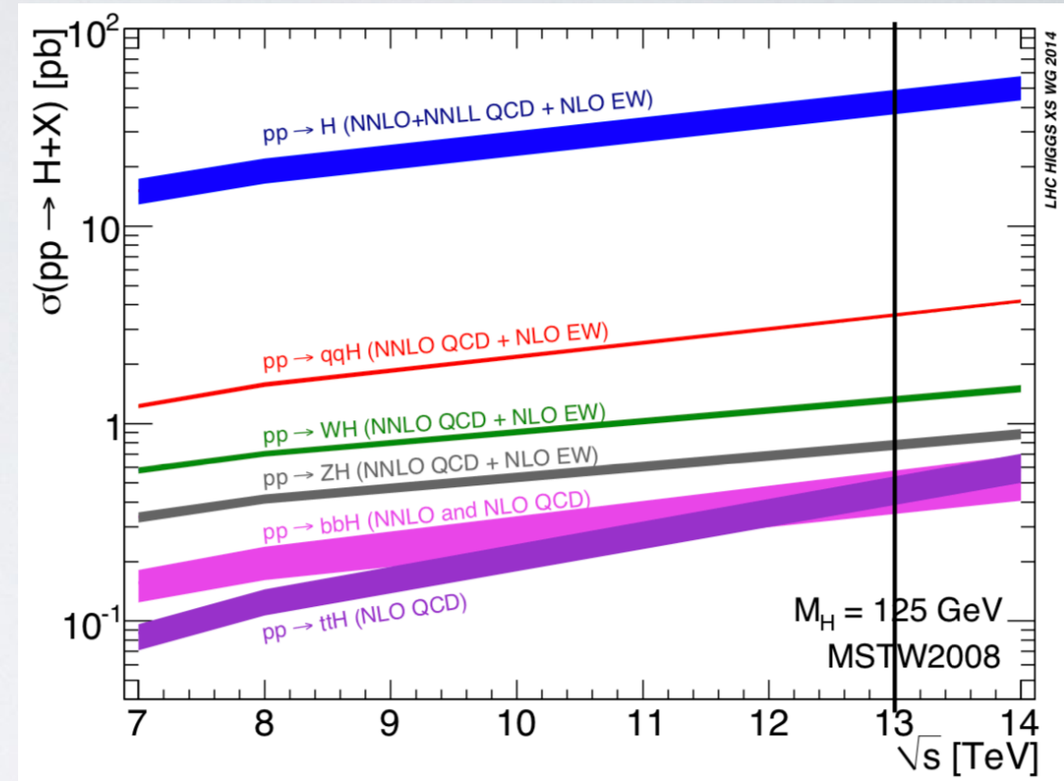
ATLAS-CONF-2018-031

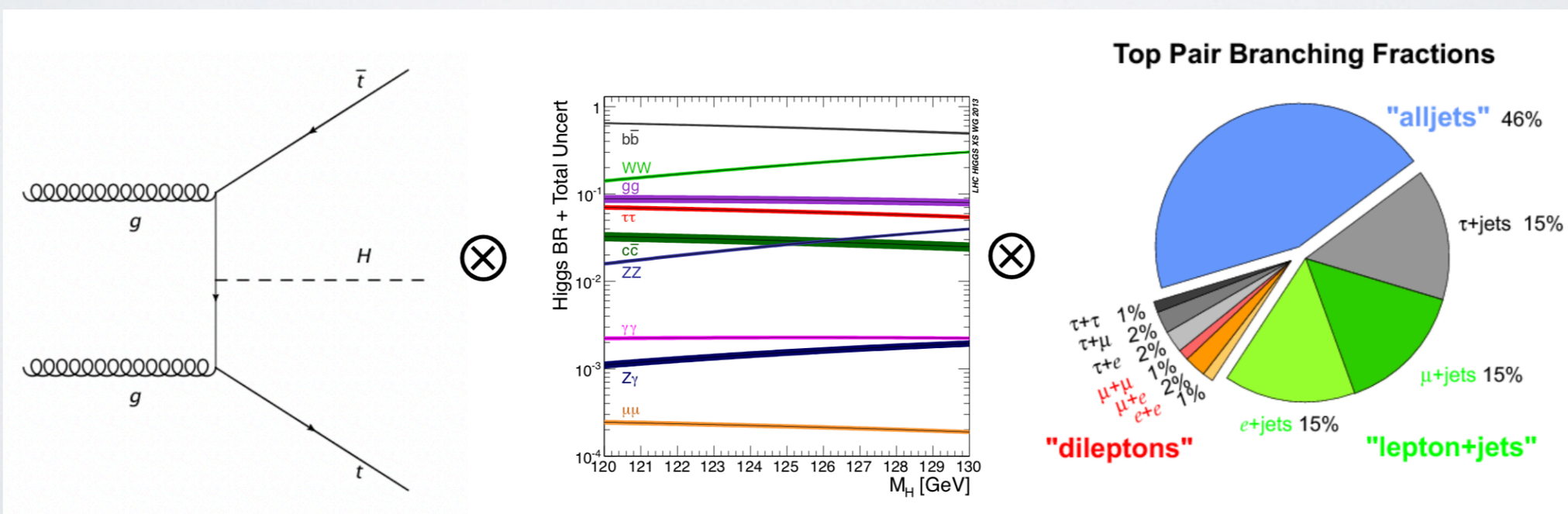
- ttH provides direct probe for top-Higgs Yukawa coupling y_t^2
  - Measurement is an important check of SM



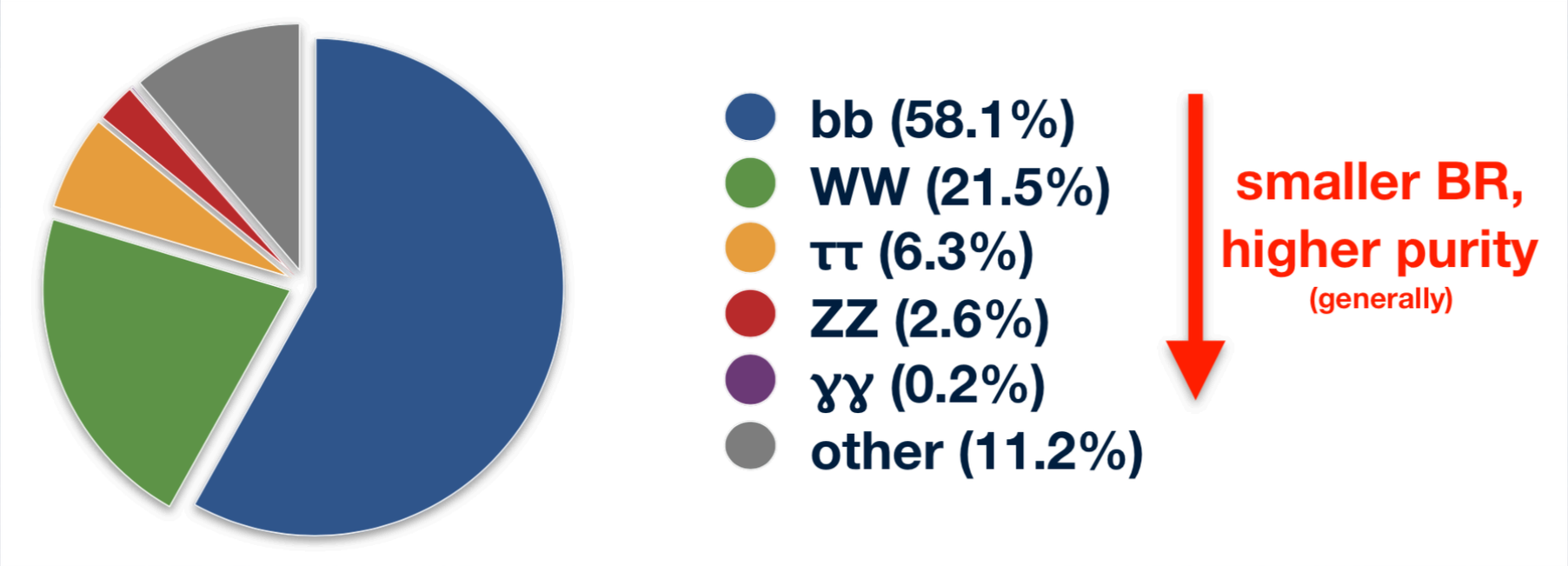
ttH: EXPERIMENTAL CHALLENGE

- ttH production cross-section at $\sqrt{s}$ = 13 TeV: only ~1% of the total Higgs cross section, 507 fb
- Wide range of analyses designed to target the various Higgs boson decays
- Final states with many objects: jets, b-jets, e, μ, hadronic τ, photons → many experiment handles to identify events





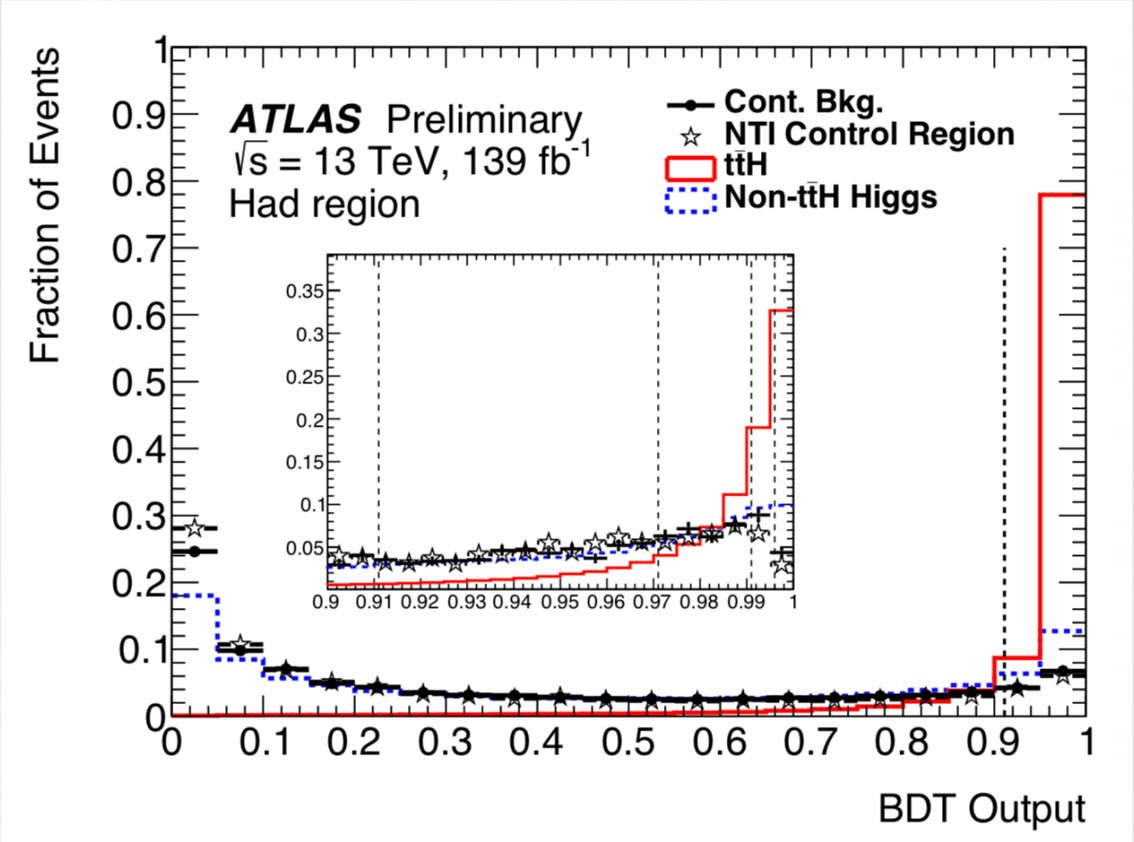
ANALYSES INCLUDED IN THIS TALK

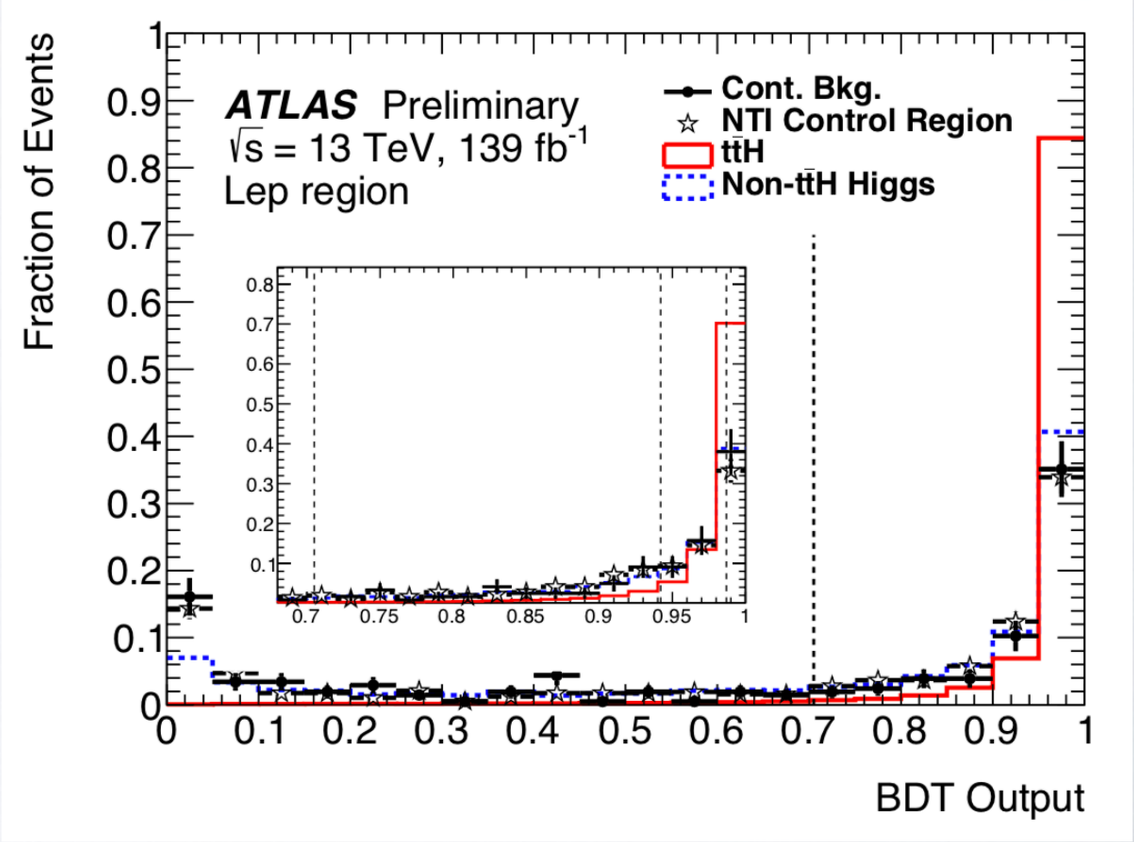


Channel	Dataset @ 13TeV	Paper
ttH(γγ)	140 fb^{-1}	ATLAS-CONF-2019-004
ttH multilepton (mostly H→WW* and H→ττ)	36 fb^{-1}	Phys. Rev. D 97, 072003
ttH(bb)	36 fb^{-1}	Phys. Rev. D 97, 072016
Combination	36 - 80 fb^{-1}	Phys. Lett. B784 (2018) 173-191

ttH(γγ): ANALYSIS STRATEGY

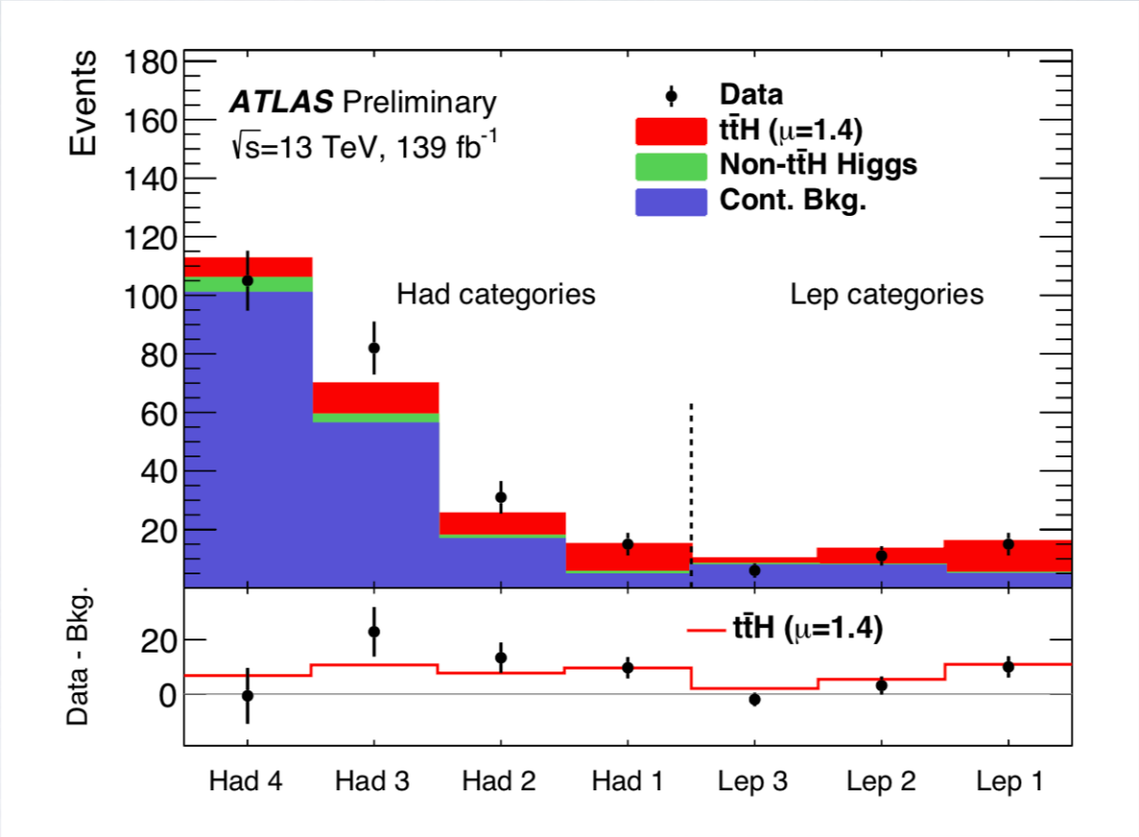
- **Di-photon events with 105 GeV < $m_{\gamma\gamma}$ < 160 GeV**
- **Analysis regions**
  - Leptonic region "Lep", targeting tt decays in which at least one of the W bosons decays to a μ/e
    - ≥1 b-tagged jet, ≥1 light lepton (e/μ)
  - Hadronic region "Had": targets hadronic top decays
    - ≥3 jets, ≥1 b-tag, no light leptons (e/μ)
- **Defining signal-enriched regions**
  - Boosted decision tree (BDT) dedicated to "Lep" / "Had"
  - **Inputs:** 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 with looser requirements on lepton quality and, only for "Lep", no *b*-tagged jets), other Higgs production (from simulation)
- **Perform cut on BDT output to veto backgrounds**
- **Categorize events passing BDT output cut, ordered by signal purity**



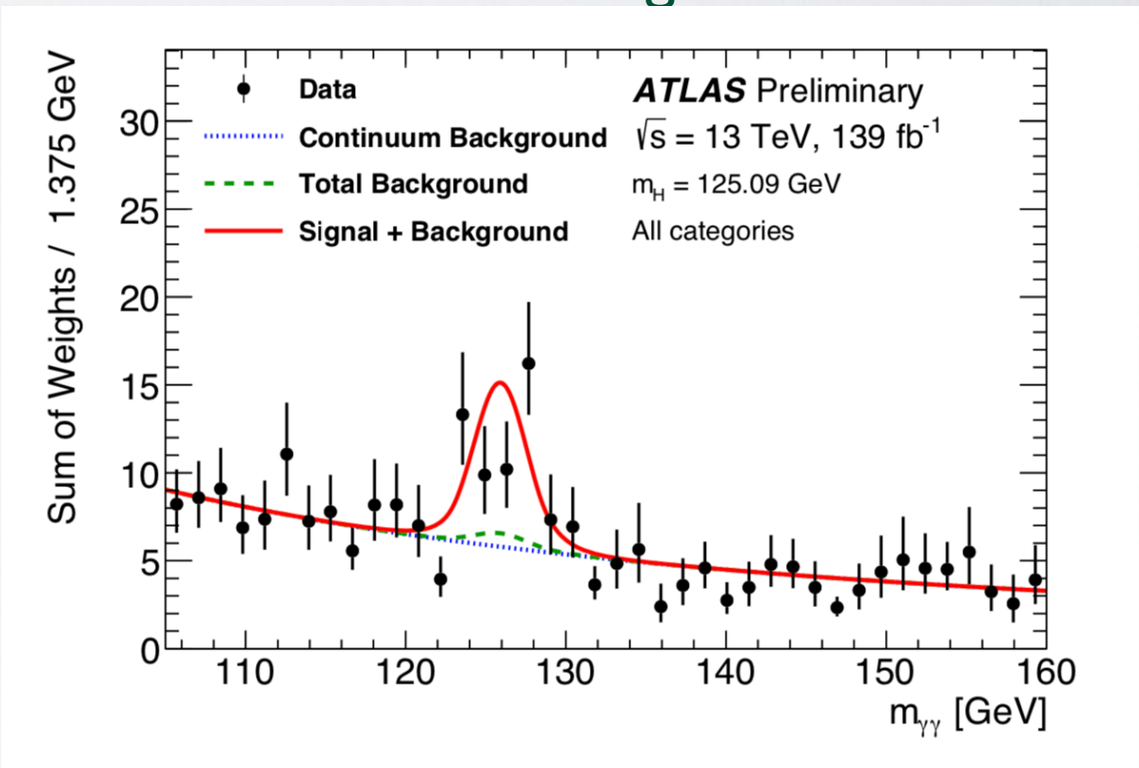


ttH(γγ): CATEGORIES

- **Analysis regions**
  - Leptonic region "Lep": 3 sub-categories, after BDT cut
  - Hadronic region "Had": 4 sub-categories, after BDT cut
- **Fit details**
  - ttH signal (includes all Higgs production modes): double-sided crystal ball
    - Non-ttH Higgs boson processes from MC samples normalized to their expected SM cross sections times the expected SM branching ratio to di-photons with a Higgs boson mass of 125.09 GeV
  - Continuum background: smooth functions (power-law or exponential)
  - Simultaneous unbinned fit of $m_{\gamma\gamma}$ (105-160 GeV) in all 7 categories



sum of categories



Category	$t\bar{t}H$ Signal	non-$t\bar{t}H$ Higgs	Continuum Background	Total (Expected)	Data
$t\bar{t}H$ "Lep" Category 1	7.9 ± 1.5	0.42 ± 0.12	4.6 ± 0.9	12.9 ± 1.8	15
$t\bar{t}H$ "Lep" Category 2	3.9 ± 0.6	0.43 ± 0.15	7.5 ± 1.2	11.8 ± 1.3	11
$t\bar{t}H$ "Lep" Category 3	1.45 ± 0.24	0.49 ± 0.19	7.5 ± 1.2	9.5 ± 1.2	6
$t\bar{t}H$ "Had" Category 1	6.9 ± 1.6	0.8 ± 0.5	4.5 ± 0.9	12.2 ± 1.9	15
$t\bar{t}H$ "Had" Category 2	5.6 ± 1.0	1.1 ± 0.8	16.5 ± 1.7	23.2 ± 2.3	31
$t\bar{t}H$ "Had" Category 3	7.7 ± 1.3	3.1 ± 2.2	56.0 ± 3.0	67 ± 4	82
$t\bar{t}H$ "Had" Category 4	4.9 ± 0.8	5 ± 4	101 ± 4	111 ± 6	105

ttH(γγ): RESULTS

- **Observed signal strength**

$$\mu_{t\bar{t}H} = 1.38\,^{+0.41}_{-0.36} = 1.38\,^{+0.33}_{-0.31}\,(\text{stat.})\,^{+0.13}_{-0.11}\,(\text{exp.})\,^{+0.22}_{-0.14}\,(\text{theo.})$$

- **Measured cross section times branching ratio**

$$\sigma_{t\bar{t}H} \times B_{\gamma\gamma} = 1.59^{+0.43}_{-0.39}\ \text{fb} = 1.59^{+0.38}_{-0.36}\,(\text{stat.})\,^{+0.15}_{-0.12}\,(\text{exp.})\,^{+0.15}_{-0.11}\,(\text{theo.})\ \text{fb}$$

SM: $t\bar{t}H(\rightarrow \gamma\gamma) = 1.15^{+0.09}_{-0.12}$ fb

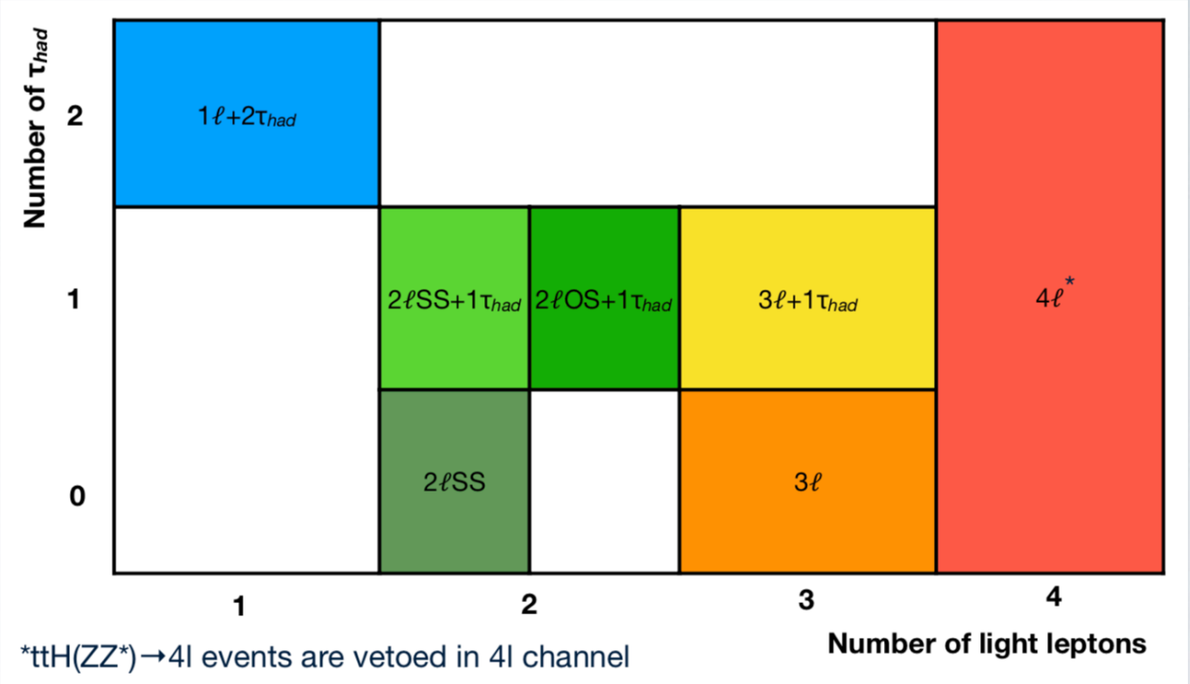
- **Combined observed significance: 4.9σ (4.2σ expected)**

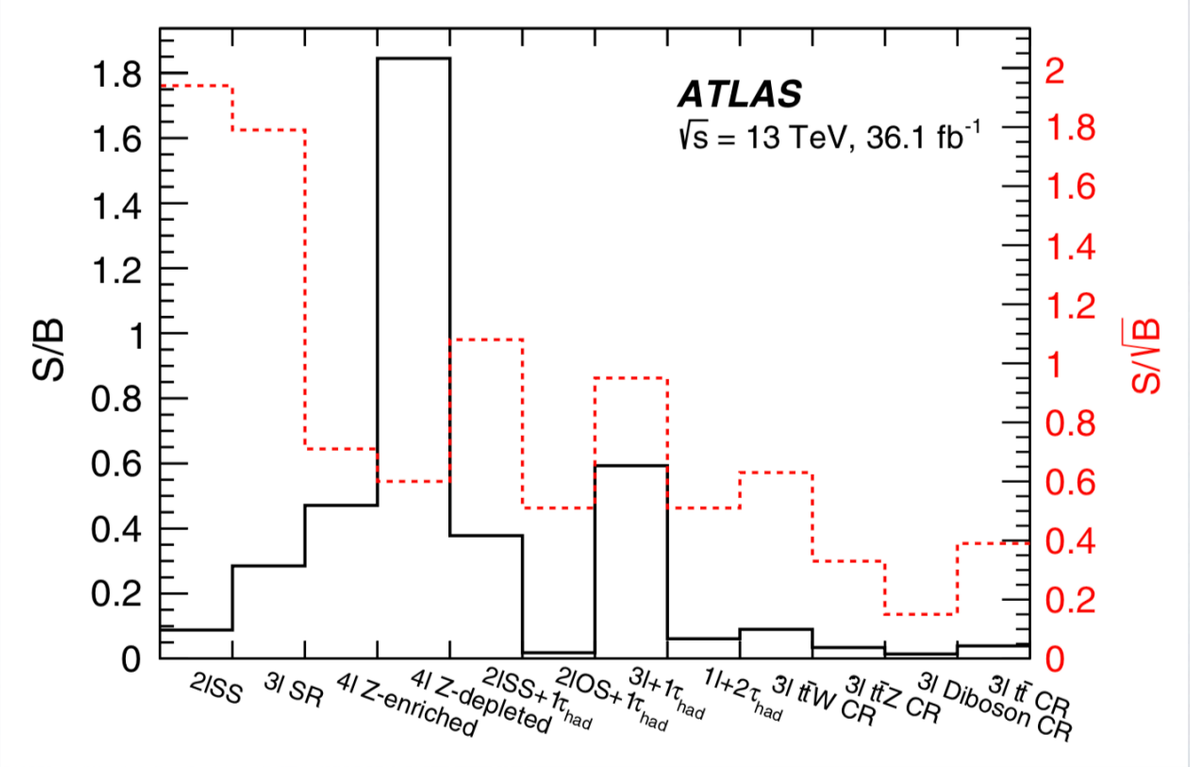
- **Dominant uncertainties**
  - Statistically dominated
  - Parton shower & underlying event
  - HF uncertainty on non-ttH resonant background (mainly ggH)
  - Photon isolation, resolution, scale

Uncertainty source	$\Delta\sigma_{\text{low}}/\sigma$ [%]	$\Delta\sigma_{\text{high}}/\sigma$ [%]
Theory uncertainties	6.6	9.7
Underlying Event and Parton Shower (UEPS)	5.0	7.2
Modeling of Heavy Flavor Jets in non-$t\bar{t}H$ Processes	4.0	3.4
Higher-Order QCD Terms (QCD)	3.3	4.7
Parton Distribution Function and α_S Scale (PDF+α_S)	0.3	0.5
Non-$t\bar{t}H$ Cross Section and Branching Ratio to $\gamma\gamma$ (BR)	0.4	0.3
Experimental uncertainties	7.8	9.1
Photon Energy Resolution (PER)	5.5	6.2
Photon Energy Scale (PES)	2.8	2.7
Jet/$E_{\text{T}}^{\text{miss}}$	2.3	2.7
Photon Efficiency	1.9	2.7
Background Modeling	2.1	2.0
Flavor Tagging	0.9	1.1
Leptons	0.4	0.6
Pileup	1.0	1.5
Luminosity and Trigger	1.6	2.3
Higgs Boson Mass	1.6	1.5

ttH MULTILEPTON: ANALYSIS STRATEGY

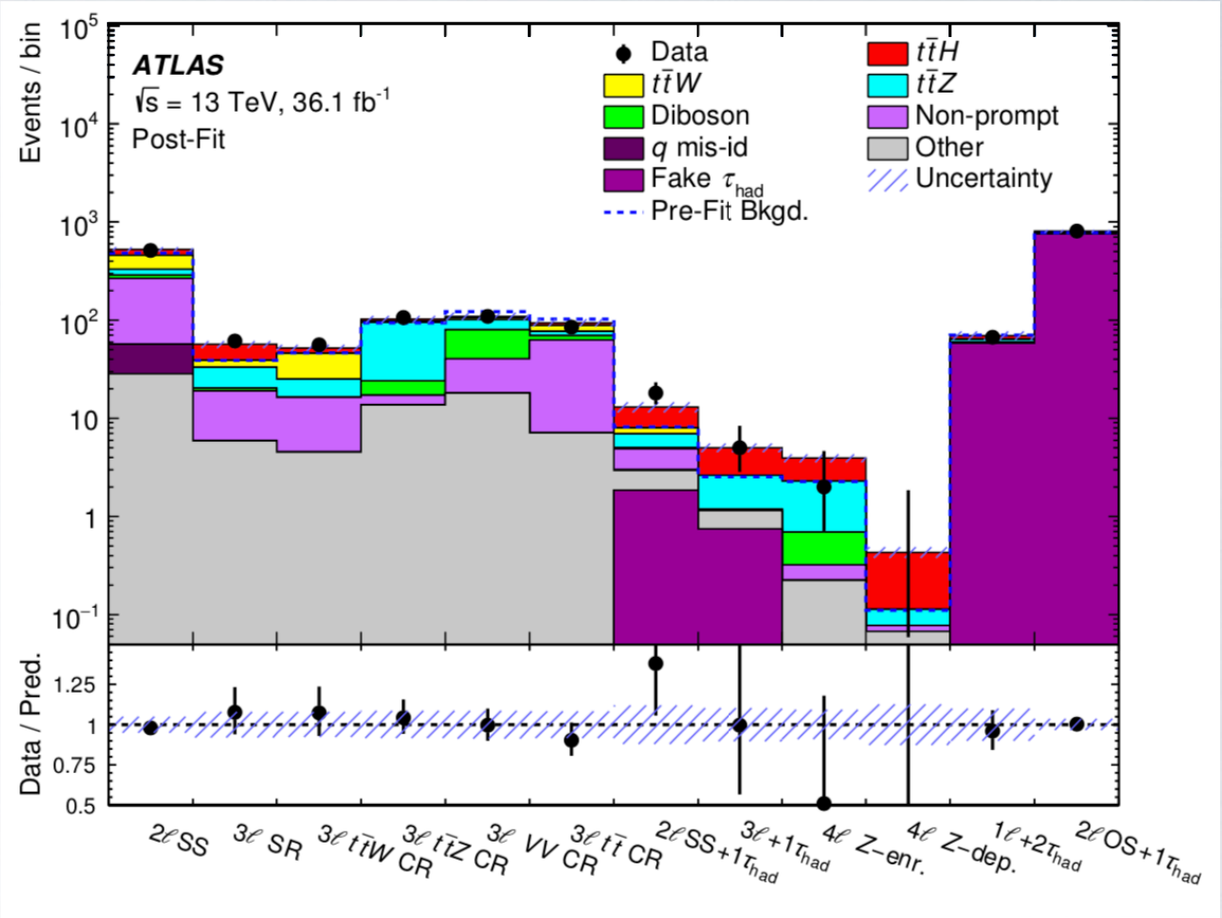
- **7 different analysis channels with different e/μ and hadronic τ multiplicity targeting to WW*/ZZ*/ττ Higgs decays**
  - ≥ 1 b-jet, 2-4 jets
- **Backgrounds**
  - **Irreducible:** dominated by ttV and VV
    - Taken from MC and validated in control regions only defined for the 3ℓ channel
  - **Reducible:** data-driven
    - non-prompt e/μ from semileptonic b-decays and γ-conversions
      - strongly reduced using a BDT trained on prompt and non-prompt leptons from simulated tt events
    - charge misidentified e/μ for SS channels
      - charge mis-ID BDT
    - fake τ's from jets and mis-identified electrons
- **Signal selection:** Dedicated MVA approaches in most channels

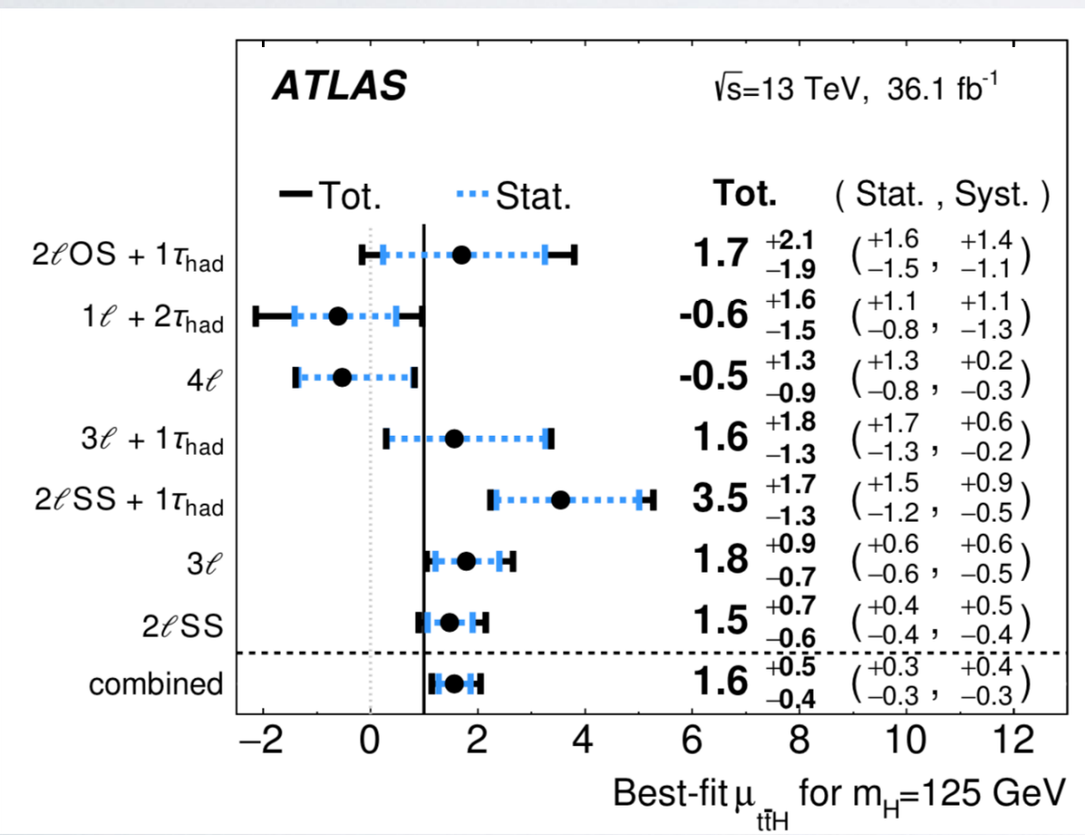




ttH MULTILEPTON: RESULTS

- **Signal extraction**
  - Combined binned profile likelihood fit of all signal and background control regions
- **Signal significance: 4.1σ (2.8σ expected)**

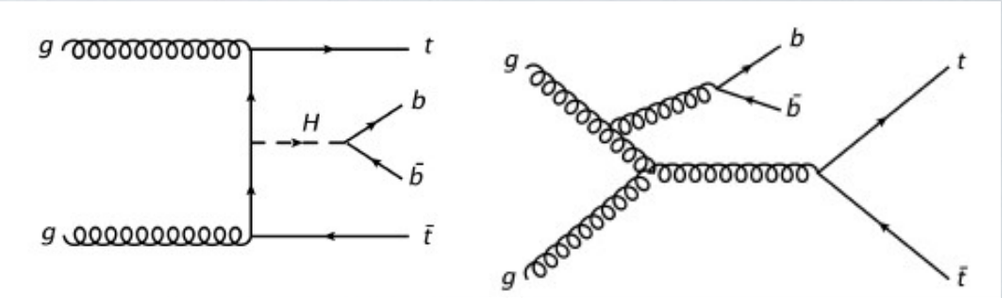


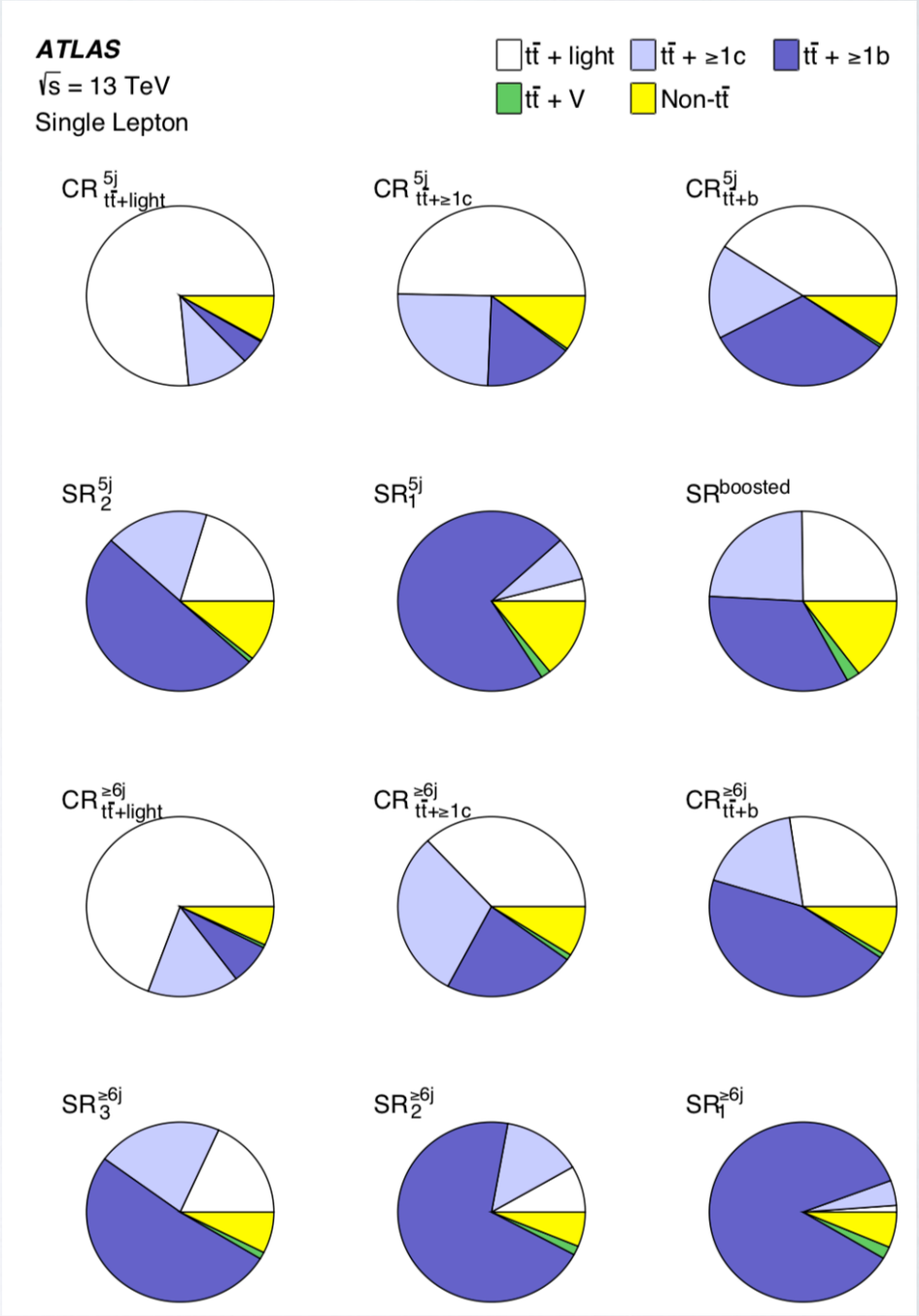


- **Dominant systematic uncertainties on μ_{ttH}**
  - ttH cross-section ($^{+0.20}_{-0.09}$)
  - Jet energy scale and resolution ($^{+0.18}_{-0.15}$)
  - Non-prompt e/μ estimates ($^{+0.15}_{-0.13}$)

ttH(bb): EVENT SELECTION

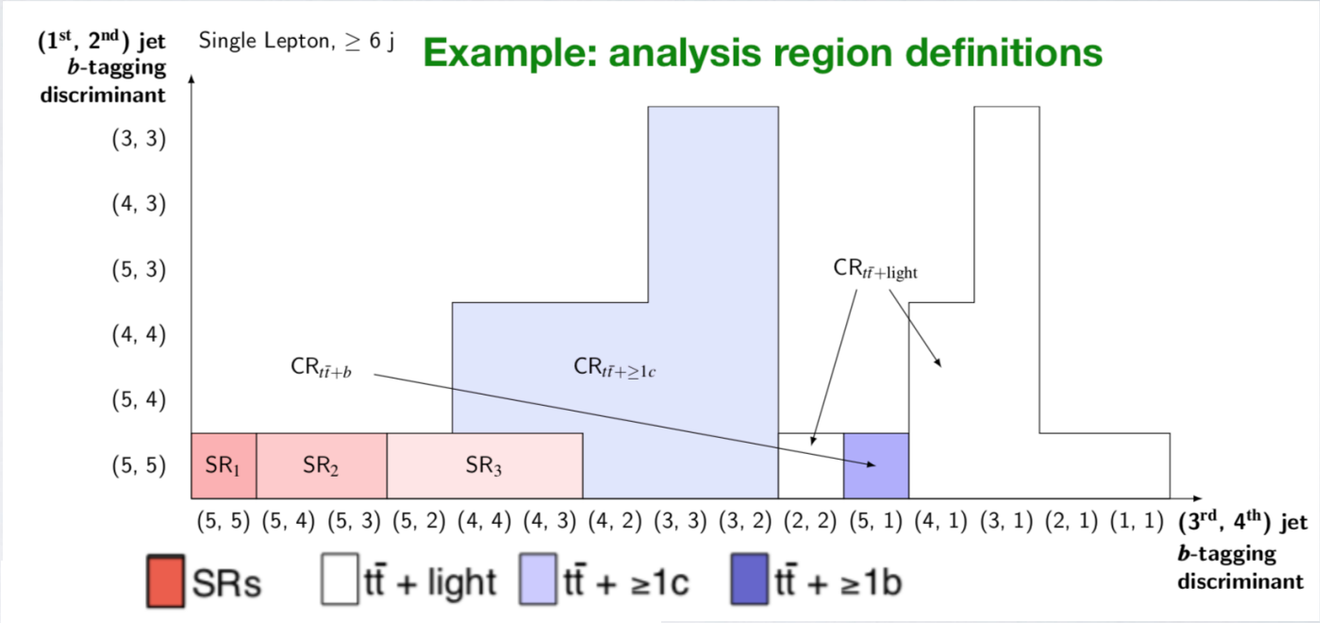
- **Main background: tt+jets**
  - tt + ≥1b (dominant), tt + ≥1c, tt + light
- **The selected events contain either one or two electrons/muons from the top-quark decays**
- **Analysis regions**
  - Single lepton channel: 1 light lepton (e,μ), ≥5 jets
  - Di-lepton channel: 2 light leptons (e,μ), ≥3 jets
  - Single lepton boosted channel: large-R top-like and Higgs-like jets



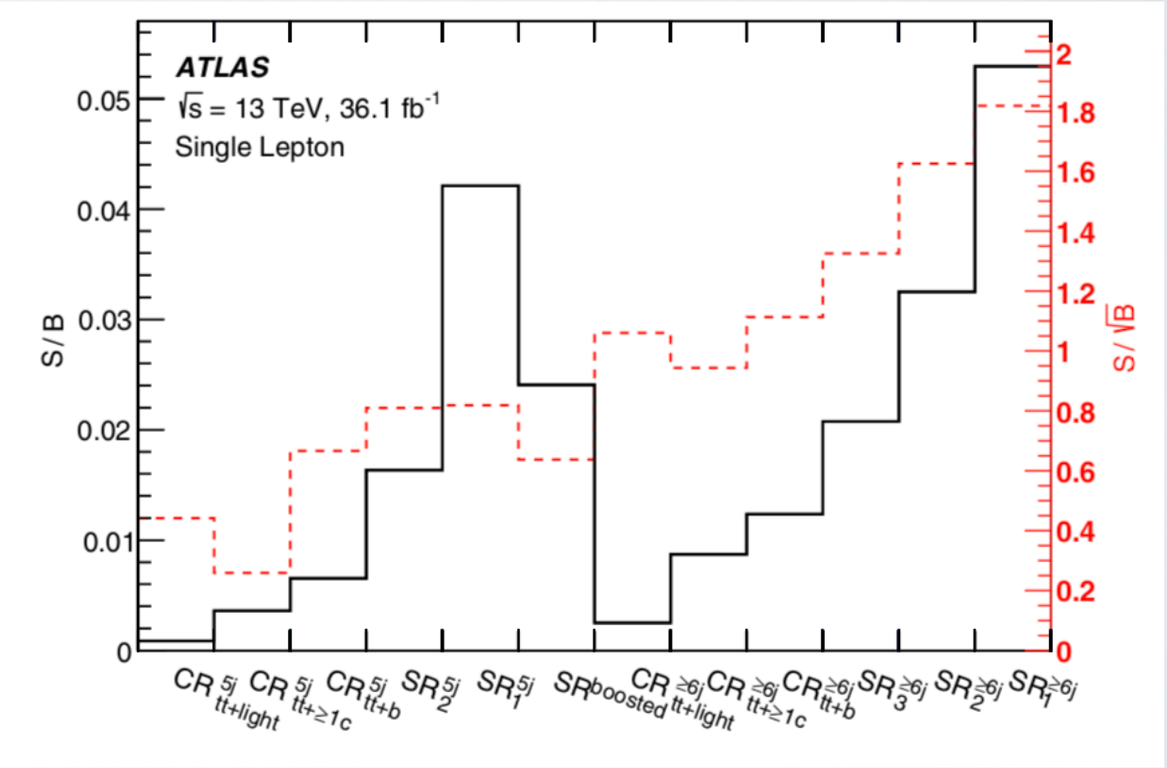


ttH(bb): ANALYSIS STRATEGY

- **Signal and control regions are defined through lepton and jet multiplicity and b-tag discriminant**
  - binning in b-tag efficiency
    - light jet (1), loose (85%,2), medium (77%,3), tight (70%,4), very tight (60%,5)
  - helps constrain tt + ≥1b, tt + ≥1c and tt + light modelling



- **In each category, intermediate MVAs aimed at signal reconstruction and maximise expected significance, were developed and applied**



- **Final Classification BDT**
  - general kinematic variables, b-tag discriminant, intermediate MVAs

ttH(bb): RESULTS

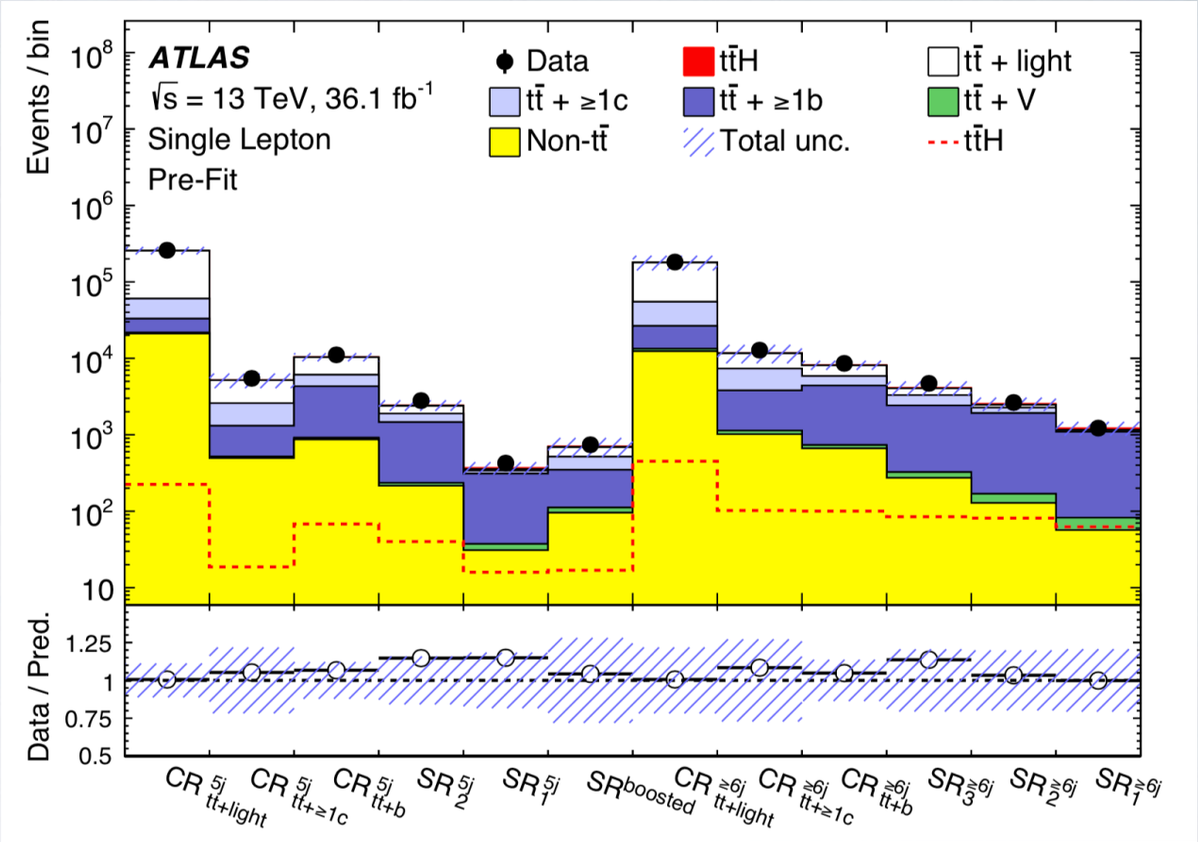
- **Profile likelihood fit of 10 control regions and 9 signal regions**

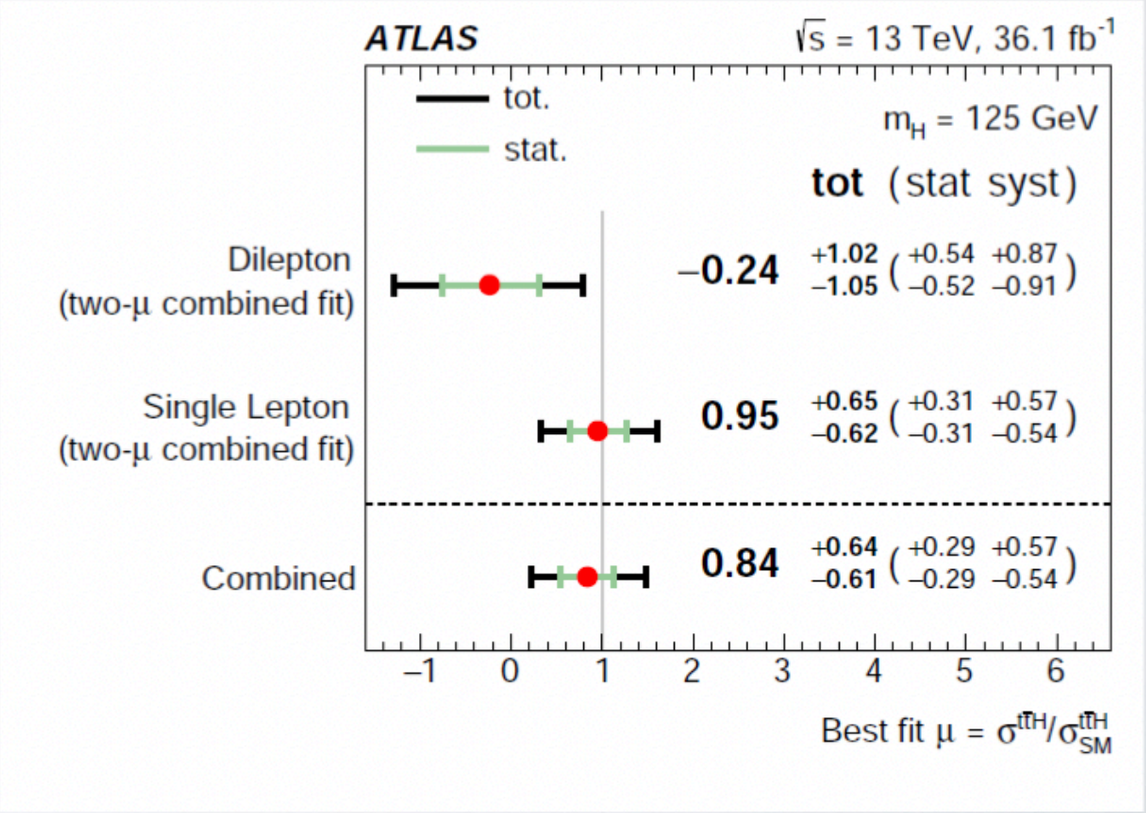
- **Significance w.r.t bkg only hypothesis:**

  1.4 (1.6) obs. (exp.)

- **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**

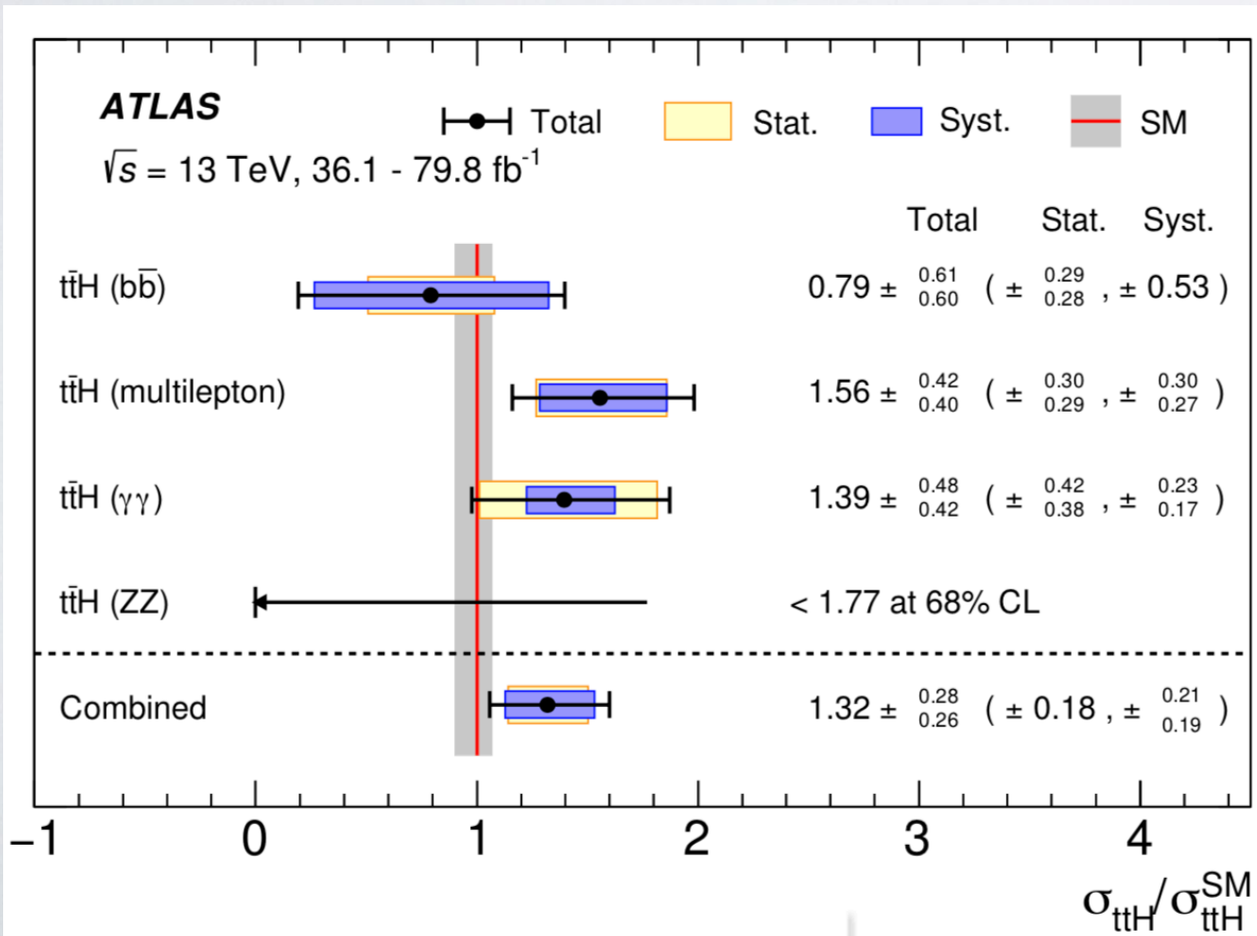


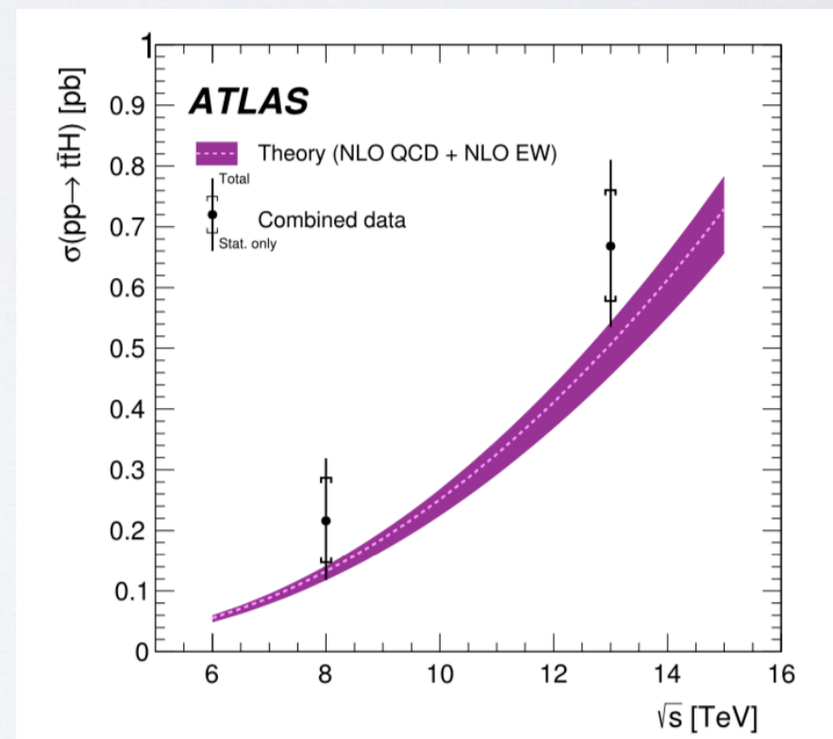


ttH: COMBINATION AND SUMMARY

- **Observation of Higgs boson production in association with a top quark pair: 6.3σ significance (5.1σ expected)**
  - up to 79.8 fb^{-1} @13 TeV, 4.5 fb^{-1} at 7 TeV and 20.3 fb^{-1} at 8 TeV
- Combination details
  - Theory uncertainties correlated
  - Experimental uncertainties largely uncorrelated
  - Other Higgs production modes fixed to SM
  - Assume SM branching ratios

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.)





Working on more ttH measurements with full 13 TeV