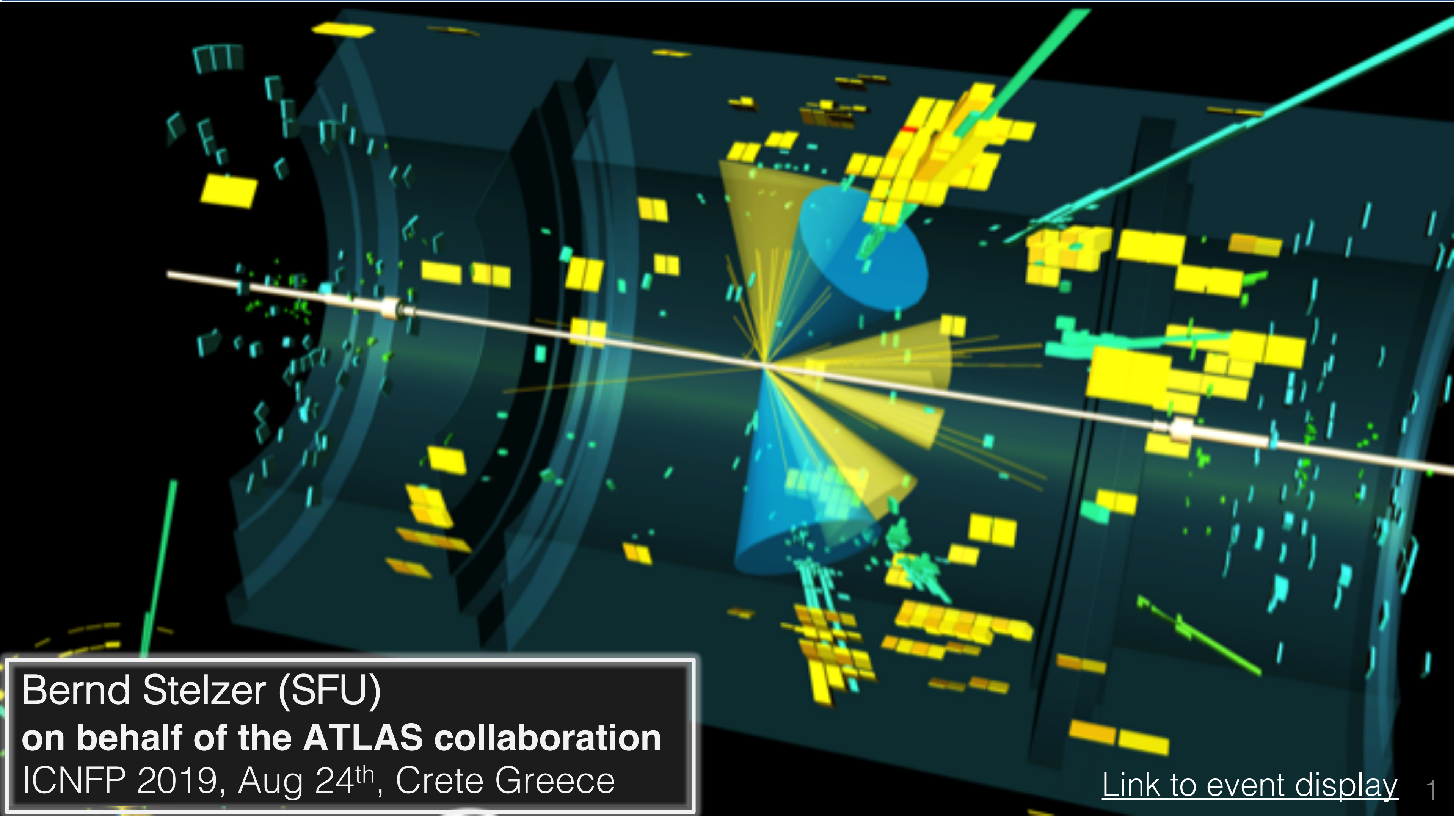
ATLAS Results on tt+Higgs



Bernd Stelzer (SFU)

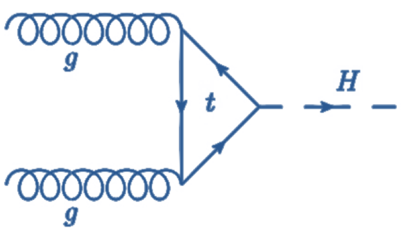
on behalf of the ATLAS collaboration

ICNFP 2019, Aug 24th, Crete Greece

Link to event display

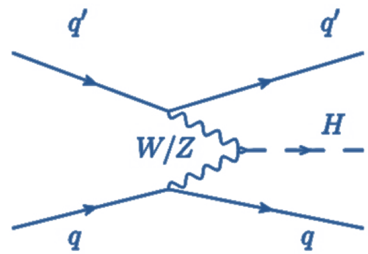
Introduction – Higgs boson production at the LHC

Gluon Fusion



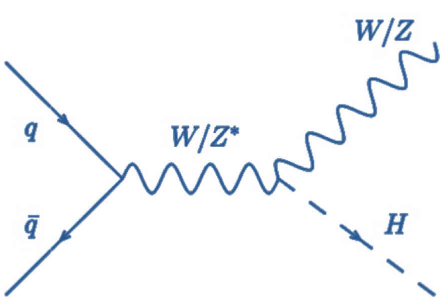
$\sigma_{H,ggF} \sim 49$ pb

Vector Boson Fusion



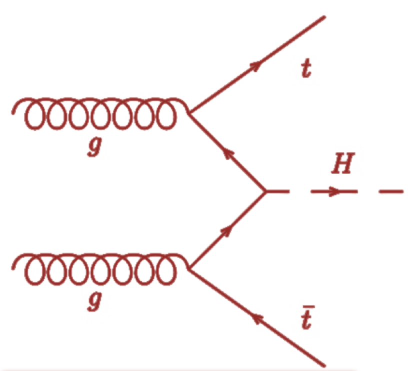
$\sigma_{VBF} \sim 3.8$ pb

Higgs-Strahlung

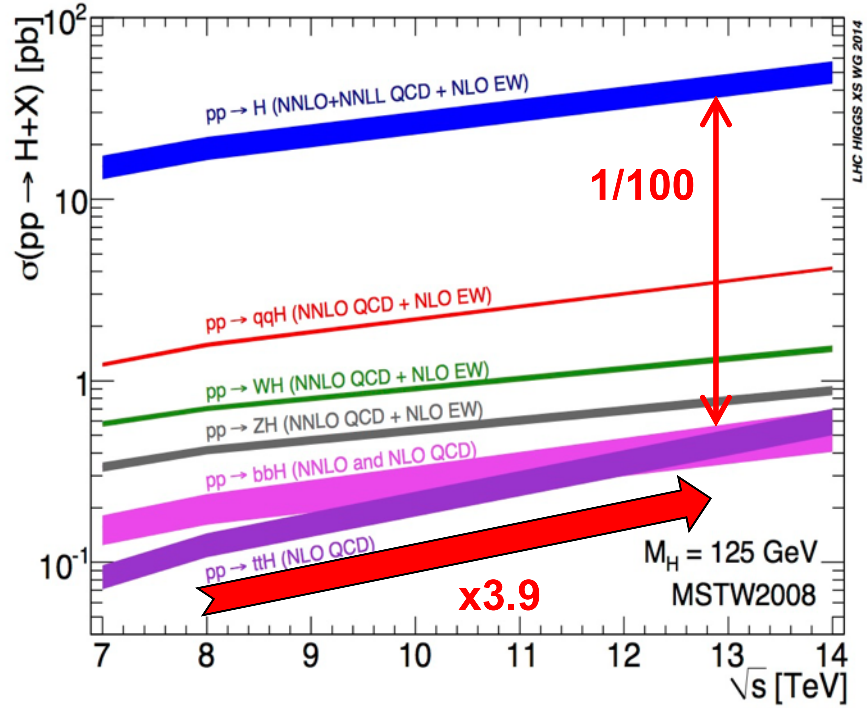


$\sigma_{W/Z+H} \sim 1.4/0.9$ pb

ttH Production



$\sigma_{ttH} \sim 0.507$ pb



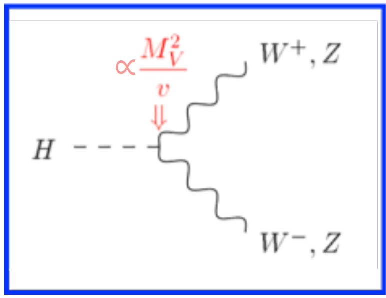
Run-1 Run-2

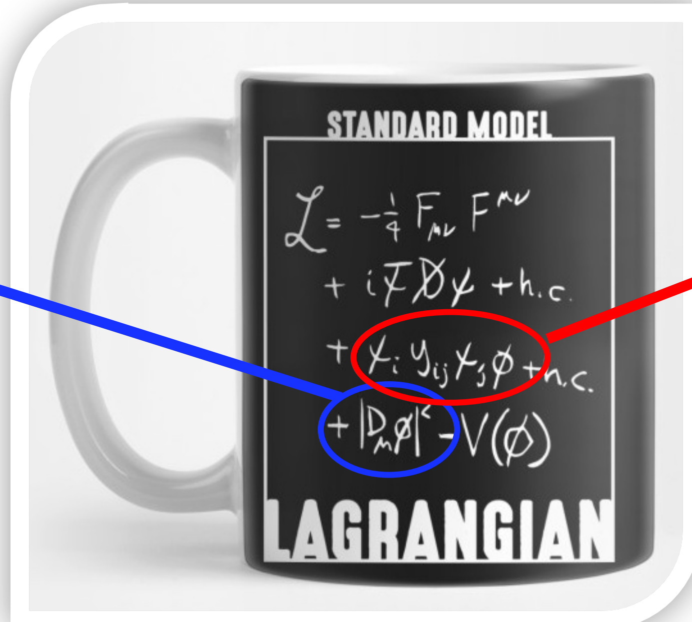
- ttH has **small cross section** (1/100 ggF)
- Large increase 8TeV→13 TeV (x3.9)
- Complex final states
- Large Standard Model (SM) backgrounds

Cross sections for $m_H = 125$ GeV, $\sqrt{s} = 13$ TeV

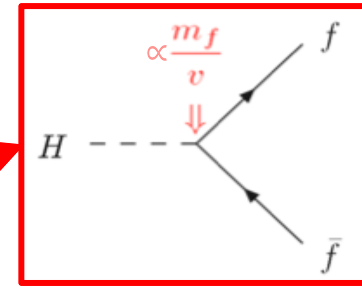
Introduction – Higgs Boson Interactions

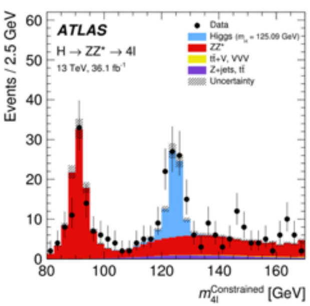
Gauge couplings: Key in Higgs discovery (ZZ, WW, $\gamma\gamma$)

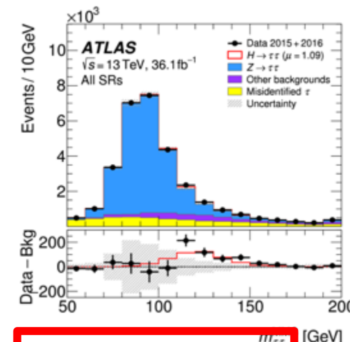


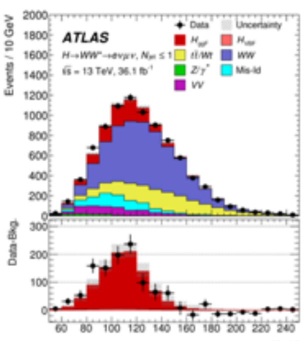


Yukawa couplings:
Higgs boson properties









Yukawas at LHC		tau	b	top
ATLAS	Exp. Sig.	5.4 σ	5.5 σ	5.1 σ
	Obs. Sig.	6.4 σ	5.4 σ	6.3 σ
	mu	1.09 $\pm$ 0.35	1.01 $\pm$ 0.20	1.34 $\pm$ 0.21 *
CMS	Exp. Sig.	5.9 σ	5.6 σ	4.2 σ
	Obs. Sig.	5.9 σ	5.5 σ	5.2 σ
	mu	1.09 $\pm$ 0.27 *	1.04 $\pm$ 0.20	1.26 $\pm$ 0.26 **

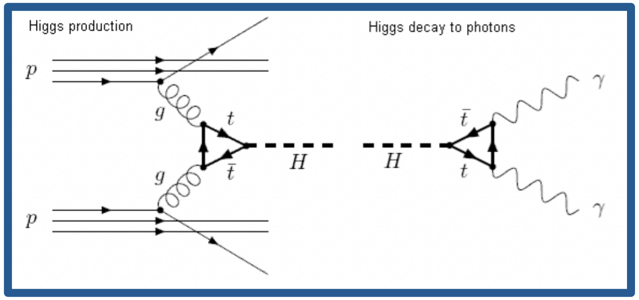
This talk

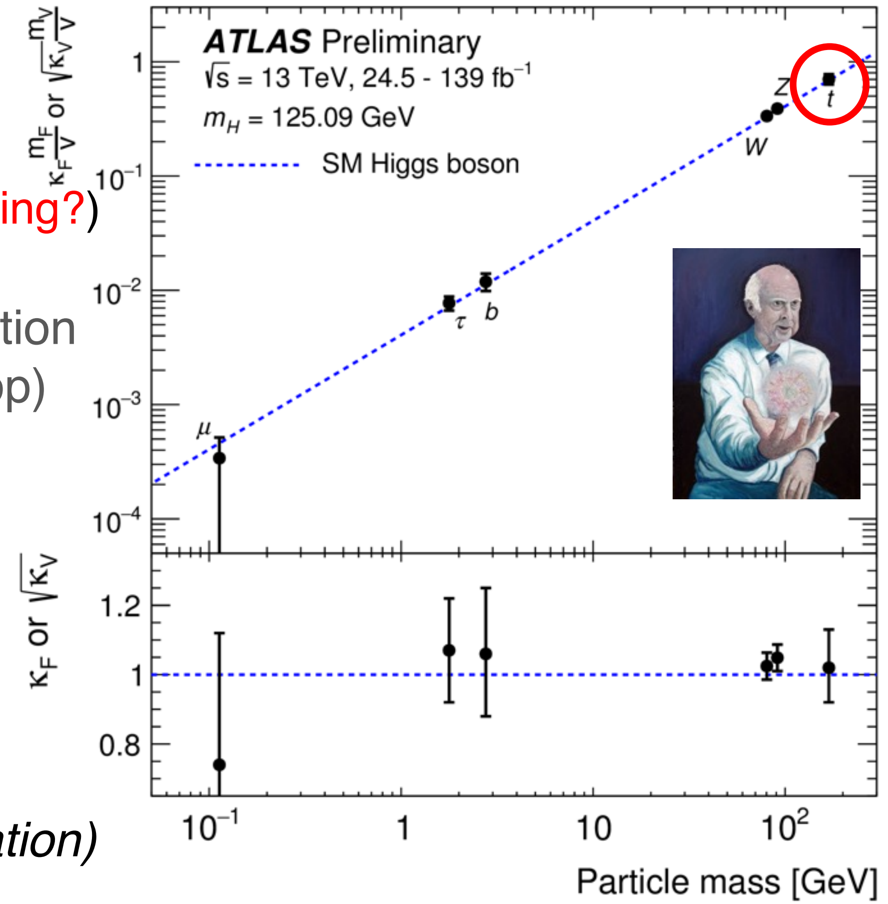
* 13 TeV only derived from cross section measurements

Key Run 2 milestones accomplished - **Discovery of 3rd generation Higgs boson Yukawas**!

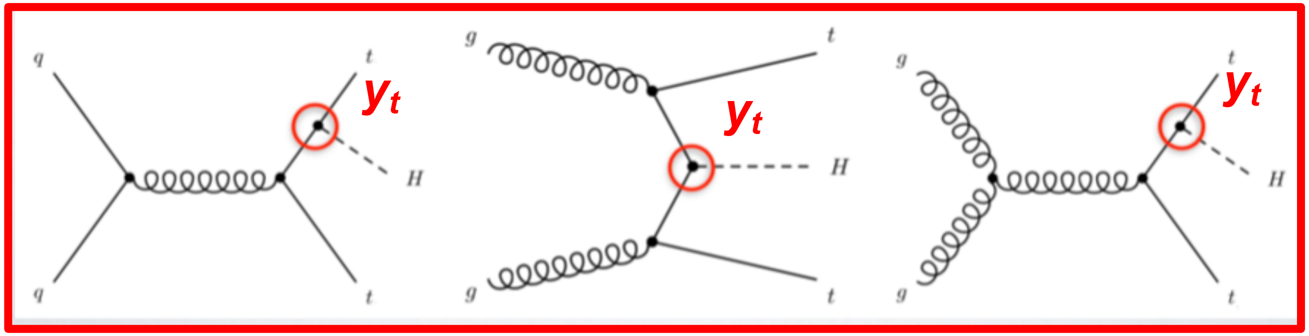
Introduction – Motivation for ttH Measurement

- All LHC Higgs property measurements consistent with SM so far…
- Goal: Probing the **top-Higgs Yukawa y_t**
  - Largest in the SM: $y_t = \sqrt{2}\, m_t / v \approx 1$ (intriguing?)
  - Sensitive to potential New Physics
- *Indirect measurement of y_t* from ggF production and $H \rightarrow \gamma\gamma$ (but relies on assumptions in loop)



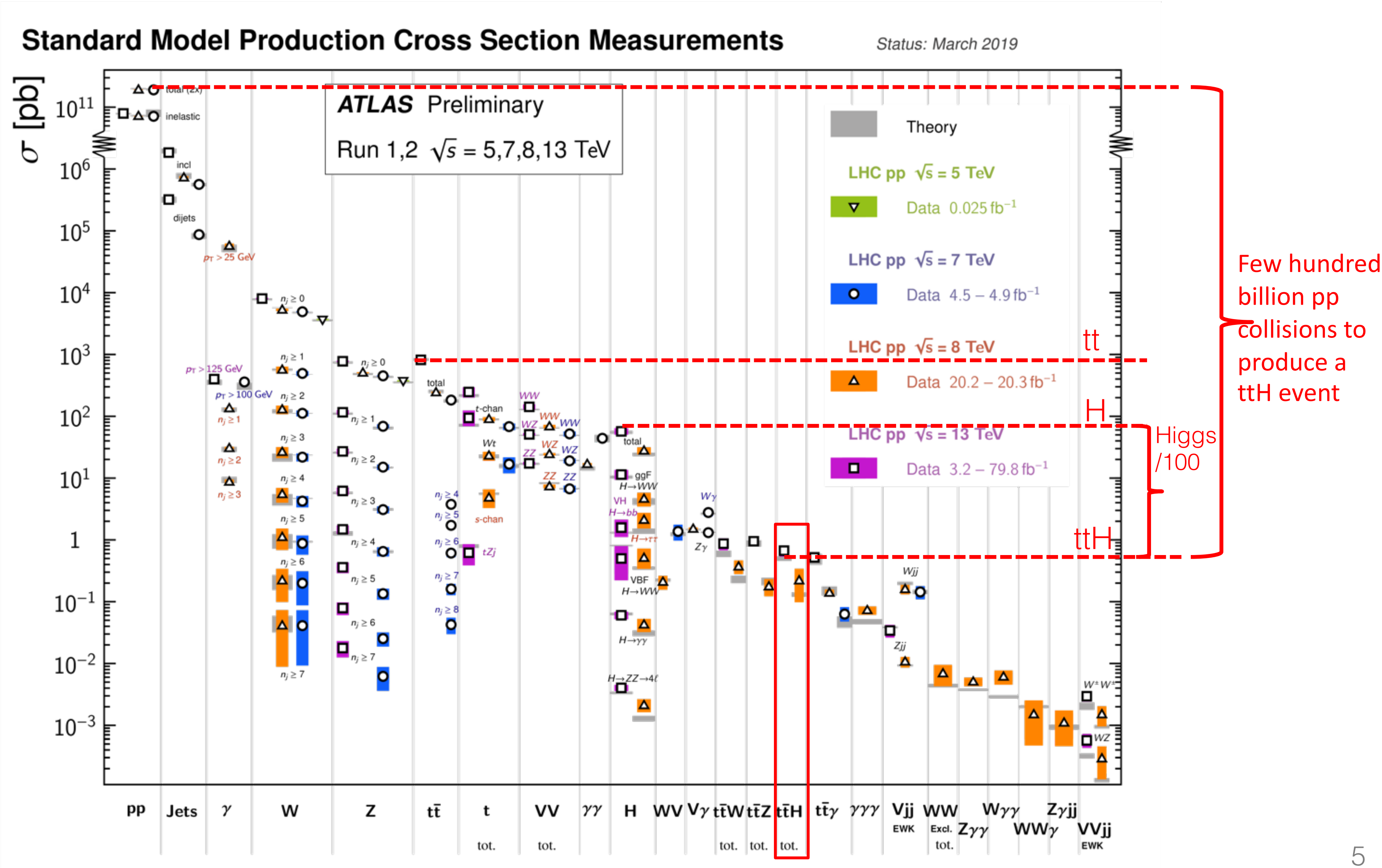


- <u>ttH production</u> provides **<u>direct</u> probe of y_t**
  (tH also contributes complementary information)

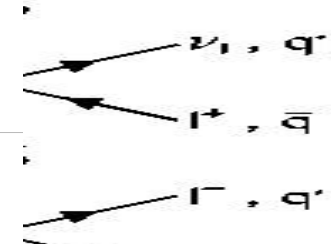


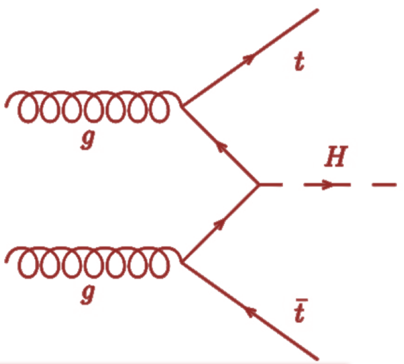
Direct and indirect probes of y_t allow to simultaneously constrain top Yukawa coupling and possible New Physics effects…

Introduction – Standard Model Cross Sections Measurements



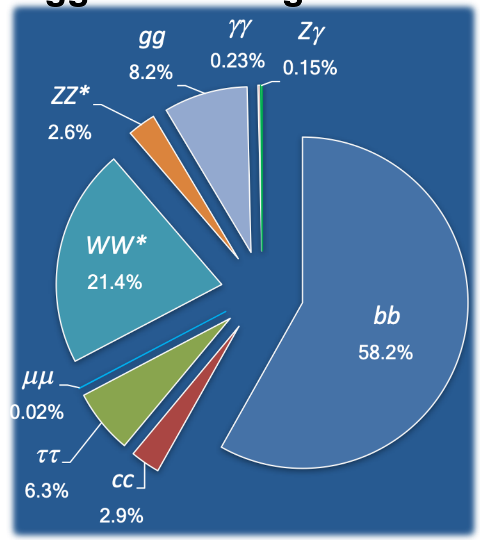
ttH Signatures – The Decay of the ttH System





σ_{ttH} ~ 0.507 pb

×



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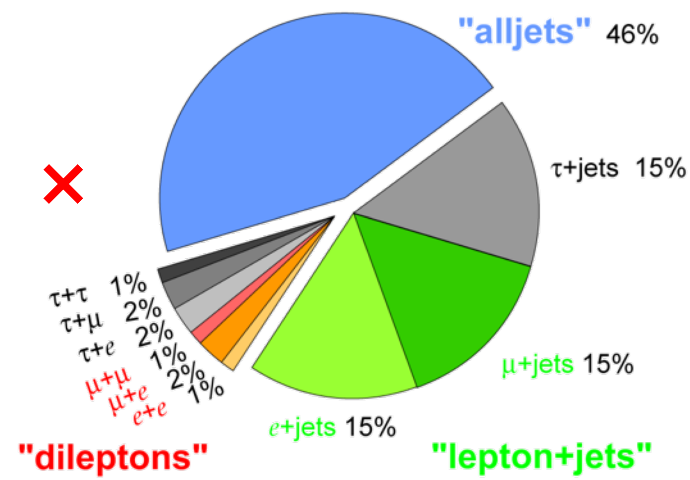


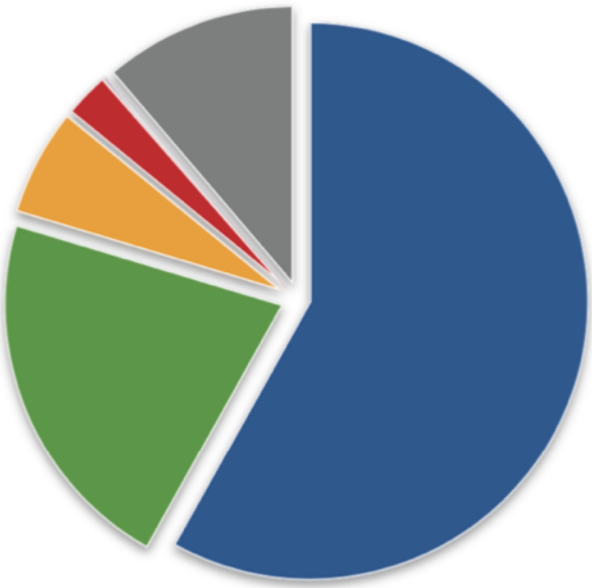
- Top quark (t→Wb) and Higgs boson decays (H→X) result in rich spectrum of signatures
- Broad range of analyses explored to capture these complex final states with many objects: Leptons [e, μ, τ_{had}], jets, b-jets, photons, ET_{miss}

  → Need good understanding of reconstructed objects

  → Good efficiency (excellent detector performance, hard work of performance groups!)
- ATLAS explored all of these multiple final states given small ttH production rate

Combination of all these analyses for best sensitivity and cross-check

ATLAS ttH Analyses



Higgs decay

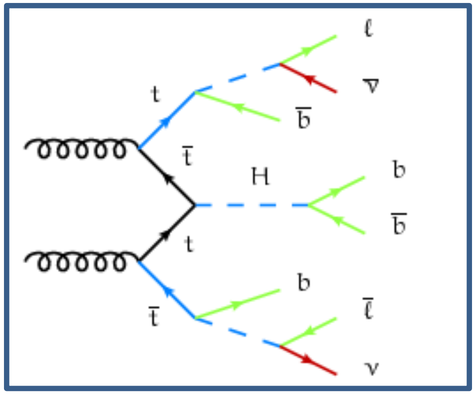
- bb (58.1%)
- WW (21.5%)
- ττ (6.3%)
- ZZ (2.6%)
- γγ (0.2%)
- other (11.2%)

smaller BR, higher purity (generally)

ttH - **Multilepton** (H→WW*, ZZ* and H→ττ)	36 fb^{-1}	Phys. Rev. D 97, 072003
ttH (H→**bb**)	36 fb^{-1}	Phys. Rev. D 97, 072016
Combination	36 - 80 fb^{-1}	Phys. Lett. B784 (2018) 173-191
ttH (H→γγ) - **Diphoton**	140 fb^{-1}	ATLAS-CONF-2019-004 NEW
ttH (H→ZZ*→4l)	140 fb^{-1}	ATLAS-CONF-2019-025 NEW

ATLAS casts a wide net, with analyses designed to target the various Higgs boson decays

ttH (H→bb) Analysis



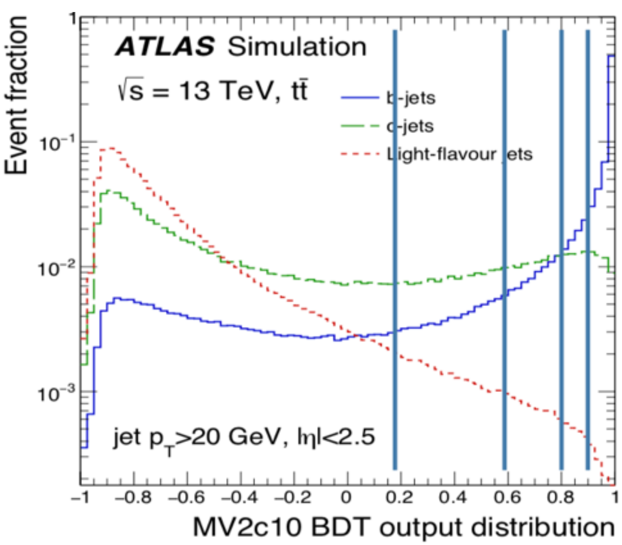
- ttH(bb) most abundant (BR=58%), but large irreducible background with big theoretical uncertainty (from tt+bb)
- Higgs boson reconstruction possible, but challenging due to b_{jet} , b_{parton} combinatorics (b_{jets} from Higgs and top quark decay)
- Challenge: Modeling of tt+HeavyFlavor background
- Define various signal (SRs) and data control regions (CRs)

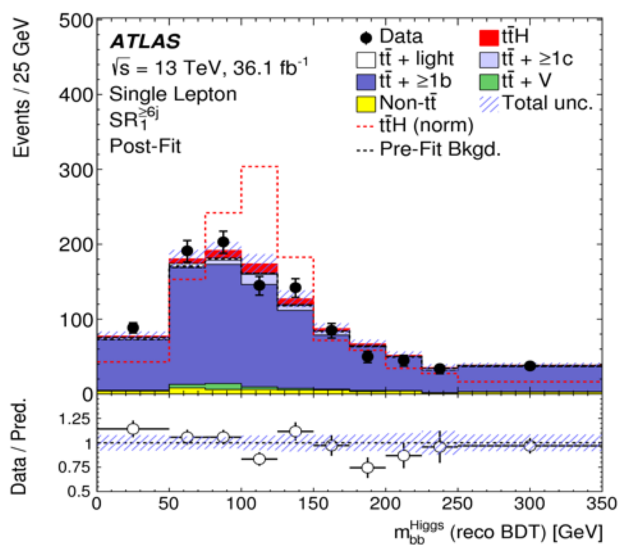
Analysis Strategy –- Cascade of MVAs

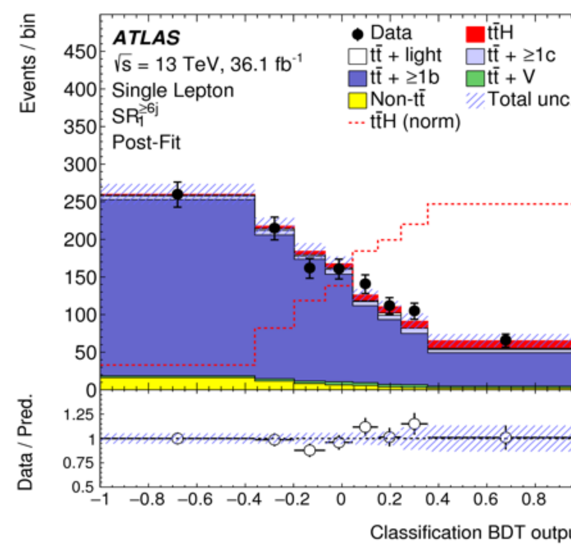
Categorization:
- 10 CRs normalizing backgrounds
- 9 SRs to enhance purity, #jets, b-tagging (4 working points)

Reconstruction:
- Reco-BDT
- Matrix element method
- Likelihood discriminant

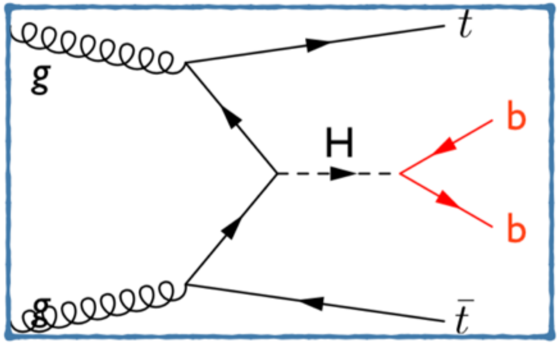
Classification
- BDT ttH vs tt-background
- Include event kinematics, b-tag info, reco MVAs





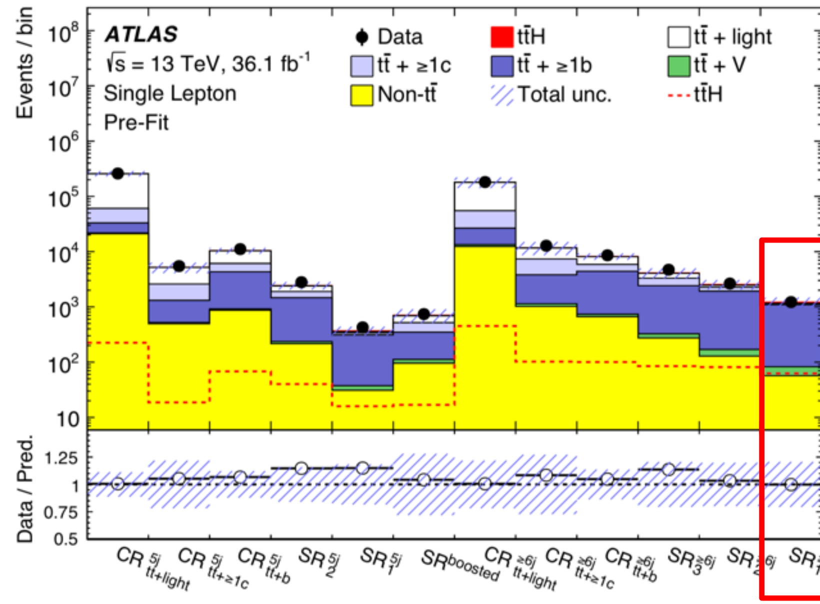


ttH (H→bb) Analysis

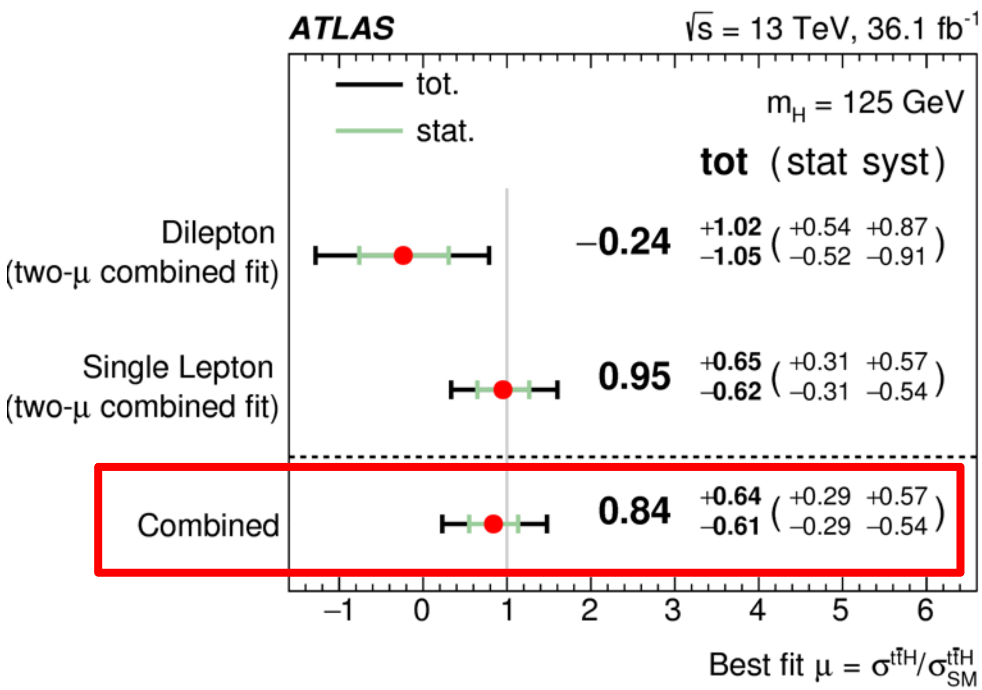


Signal extraction:

Binned profile likelihood fit to all signal and control regions.
Normalisation of tt ≥1b and tt ≥1c left free-floating in the fit.



Signal strength: $\mu=\sigma/\sigma_{SM}$



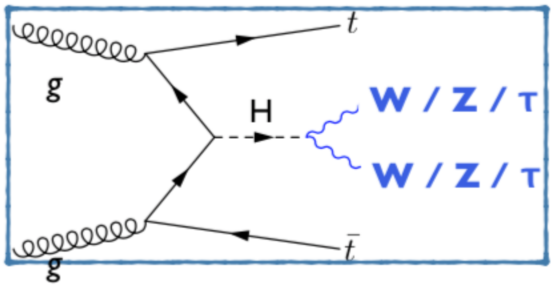
Significance: 1.4σ (expected 1.6σ)

Dominant systematics (Δμ)

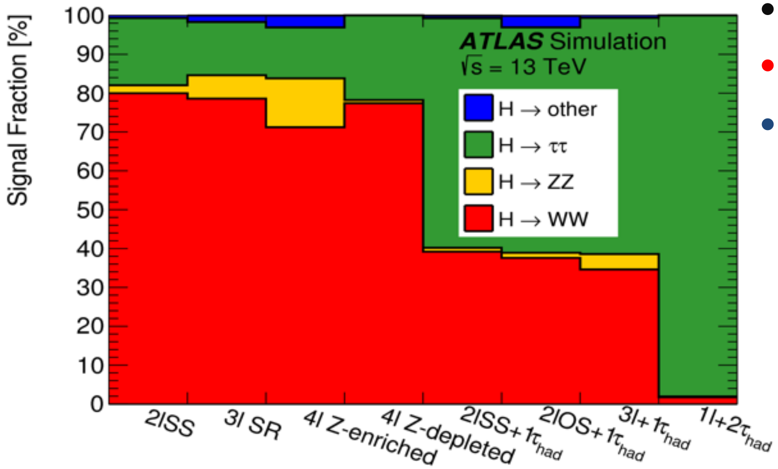
- Modelling of $t\bar{t}$ +≥1b (±0.46)
- Monte Carlo statistics (±0.30)
- Jet flavour tagging (±0.16)
- Jet energy scale & resolution (±0.16)

Analysis is systematically limited
Requires improvements from both theory and experimental communities!

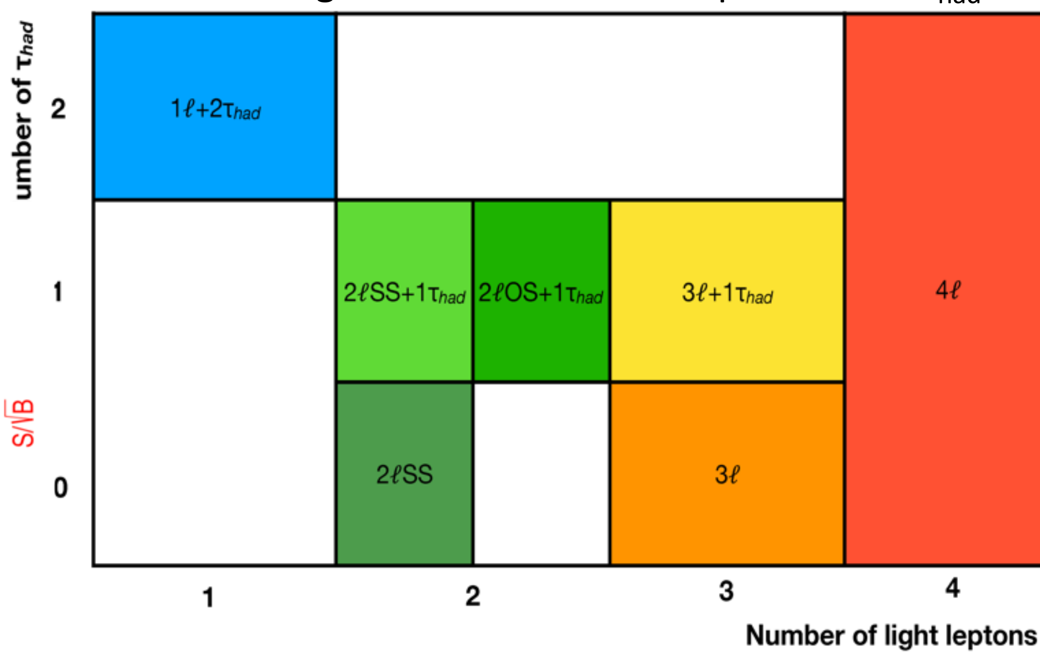
ttH – Multilepton Analysis

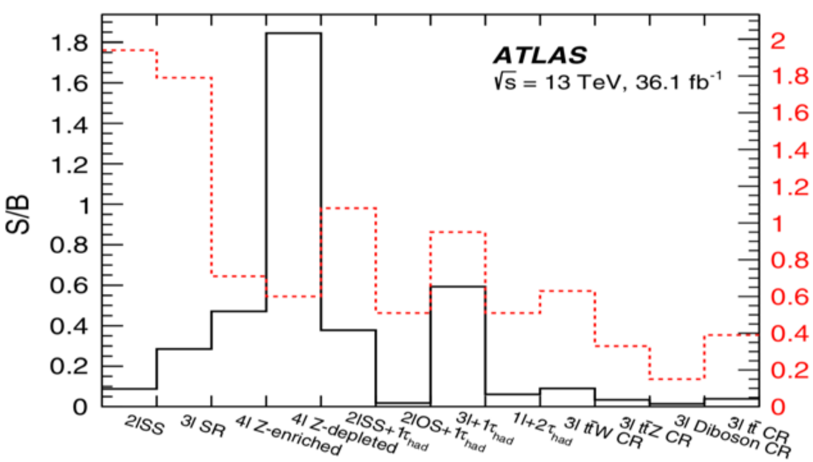


- Targeting: **ttH H→WW*→(lvlv, lvqq)**, **H→ττ** and **H→ZZ*(→ llvv, llqq)** decays
- With leptonic tt decays, this leads to distinct signatures
- 7 orthogonal channels categorised by multiplicity of e/μ and hadronic tau (τ_{had}) candidates, b-jet multiplicity
- Develop CRs to normalize backgrounds
- Use of BDTs in SRs to further improve purity
- Analysis does not rely on Higgs mass reconstruction

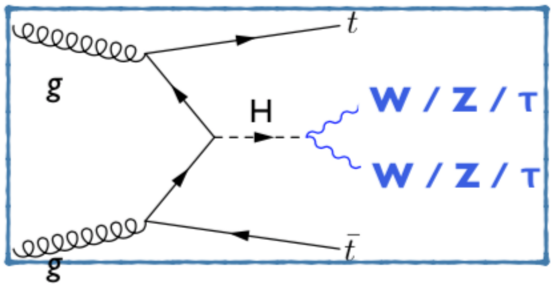


Event categorization based on #leptons and #τ_{had}





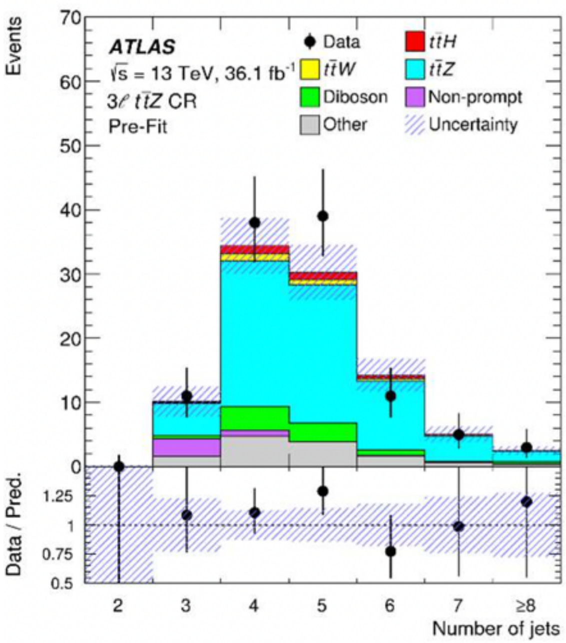
ttH – Multilepton Analysis



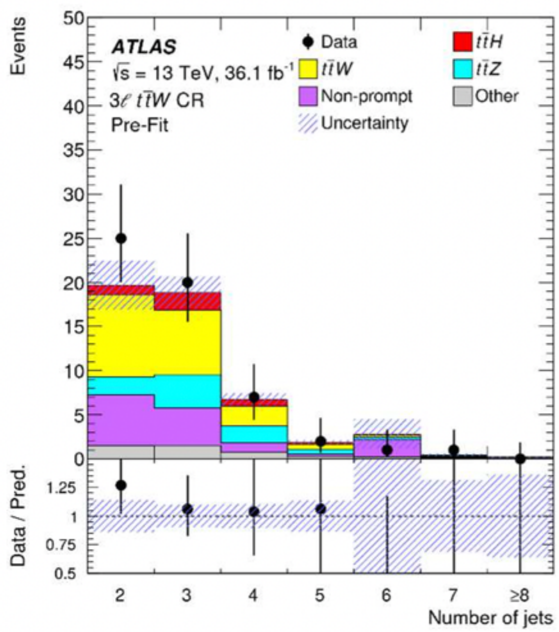
Main backgrounds:

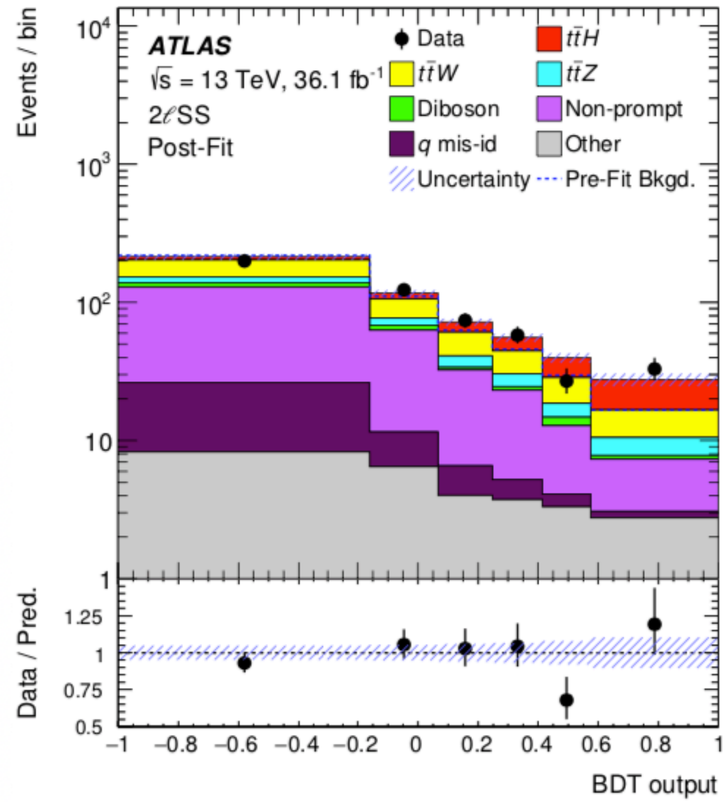
- **Reducible**: Non-prompt e, μ and hadronic τ and prompt light leptons with misidentified charge
- Develop object level discrimination to reduce these backgrounds
  - → Isolation BDT to reduce non-prompt background
  - → Charge mis-ID BDT
- **Irreducible**: ttV and VV – estimated from MC and validated in data.

tt+Z validation



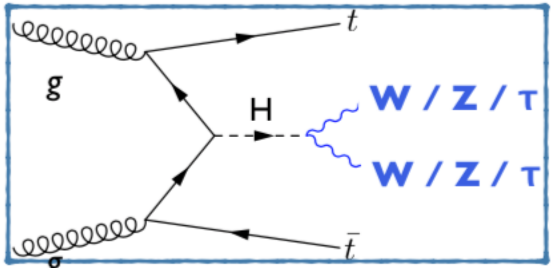
tt+W validation





Example signal region (2lepSS)

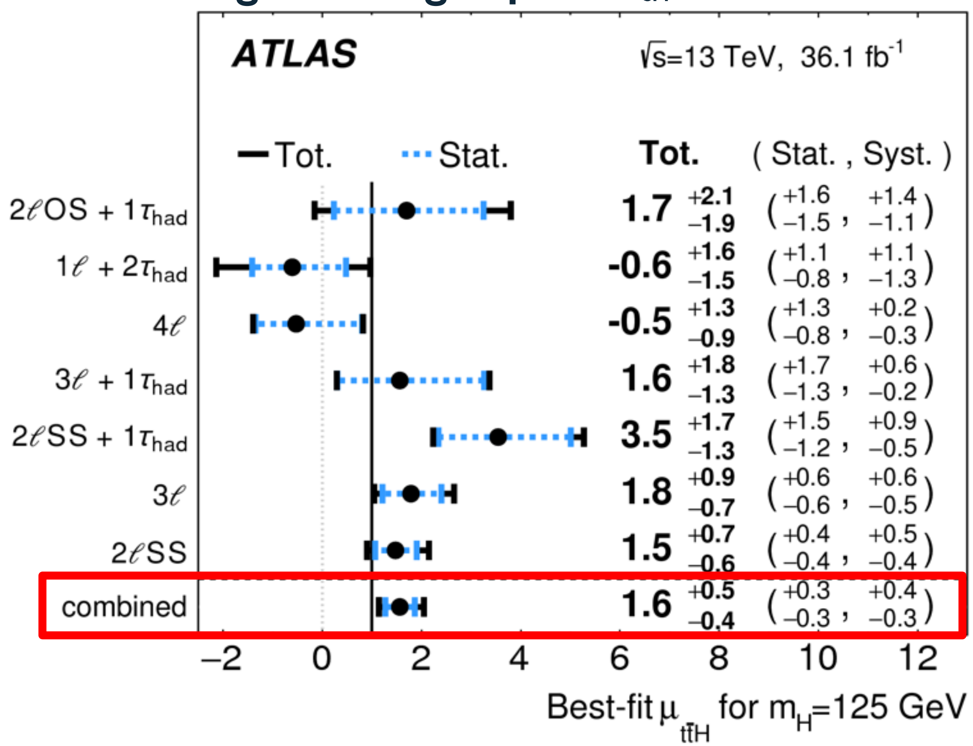
ttH – Multilepton Analysis



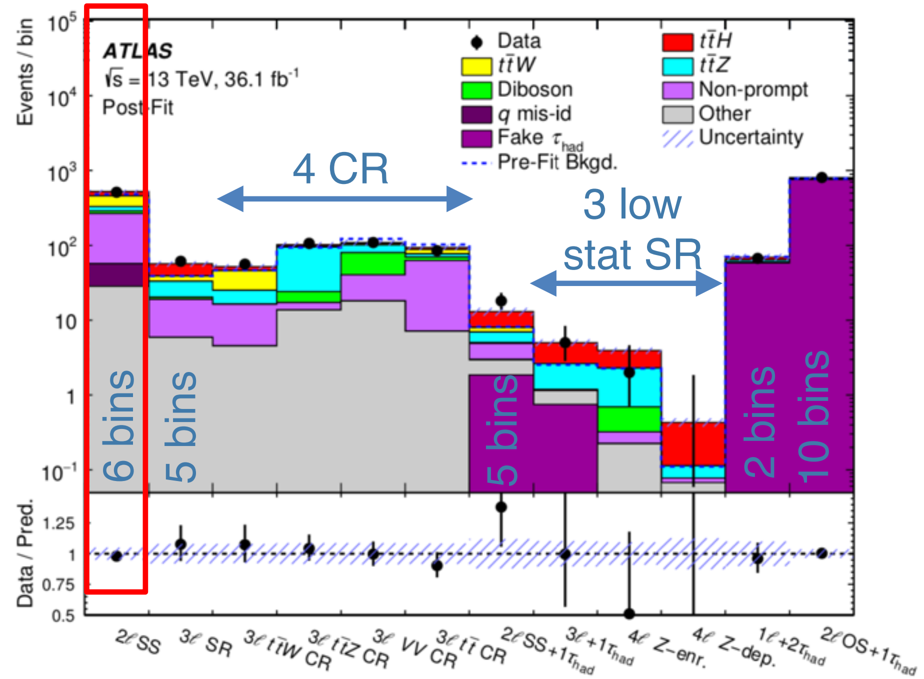
Signal extraction:

Simultaneous likelihood fit to all categories including control regions of main backgrounds

Signal strength: $\mu=\sigma/\sigma_{SM}$



Significance: 4.1σ (expected 2.8σ)



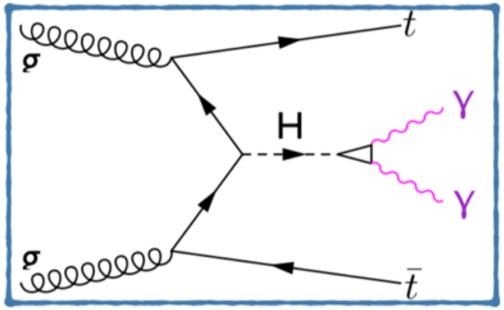
Dominant systematics (Δμ)

- Modelling of ttH (+0.20, -0.10)
- Jet energy scale, b-tagging (±0.16)
- Non-prompt e/μ (±0.14)
- ttV backgrounds (±0.10)

More data will improve the precision on channels that are still stats. limited and help constraining ttZ & ttW background.

ttH – Diphoton Analysis

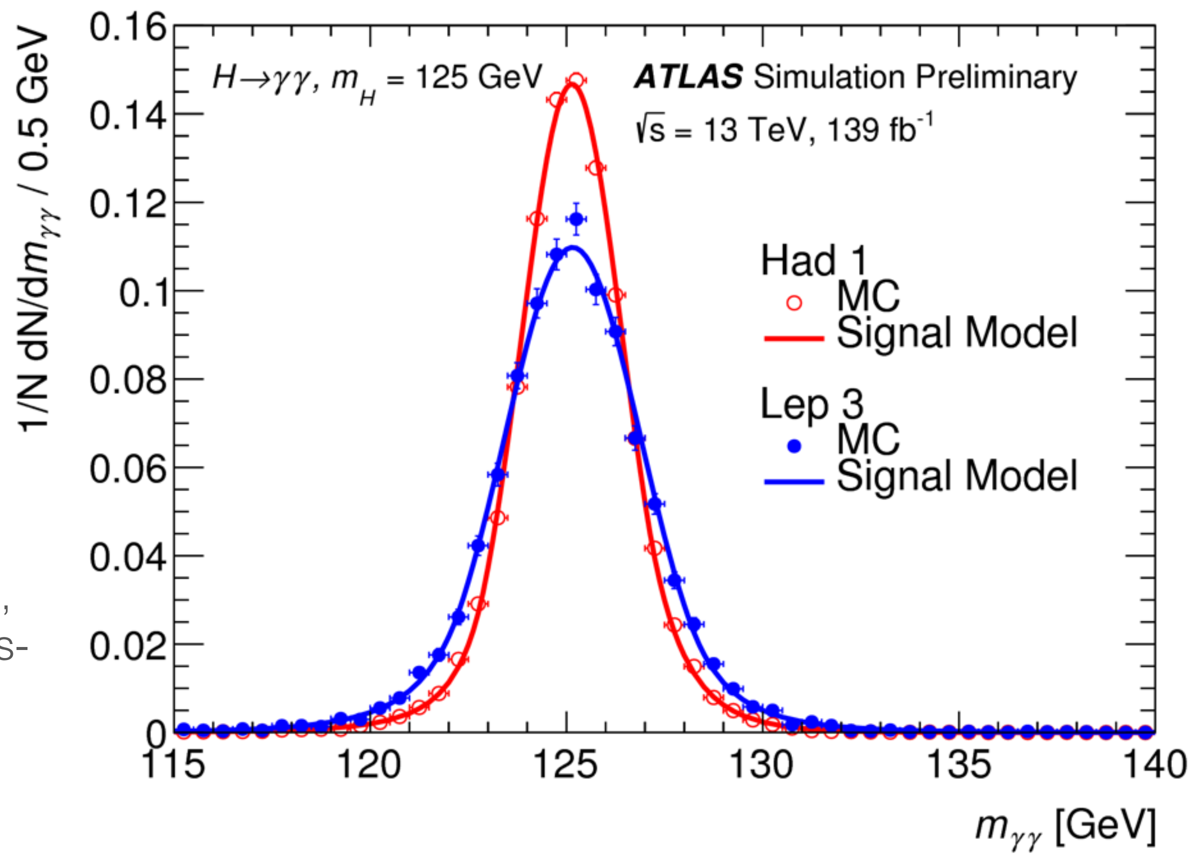
NEW



- Very small rate !!
- Remember σ_{ttH} =1% σ_{ggF} **and** BR(H→γγ) = 0.2%
- Select two isolated photons with 105 GeV < $M_{\gamma\gamma}$ < 160 GeV
- Additional selection using MVAs for hadronic and leptonic tt decay to improve purity (enabling this analysis)

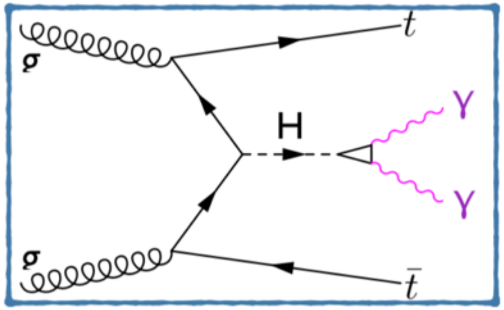
Very similar strategy for 79.8 fb^{-1} and full Run 2 (139 fb^{-1}) analysis

- Split sample by leptonic (≥1ℓ) and hadronic x(0ℓ) ttbar decays (incl. b-tag)
- Boosted Decision Trees (BDT) to enhance purity in sample
- BDT input based on lepton, jet, photon 4-vectors (trained mass-independent), E_T^{miss} and b-tag



ATLAS-CONF-2019-004

ttH – Diphoton Analysis



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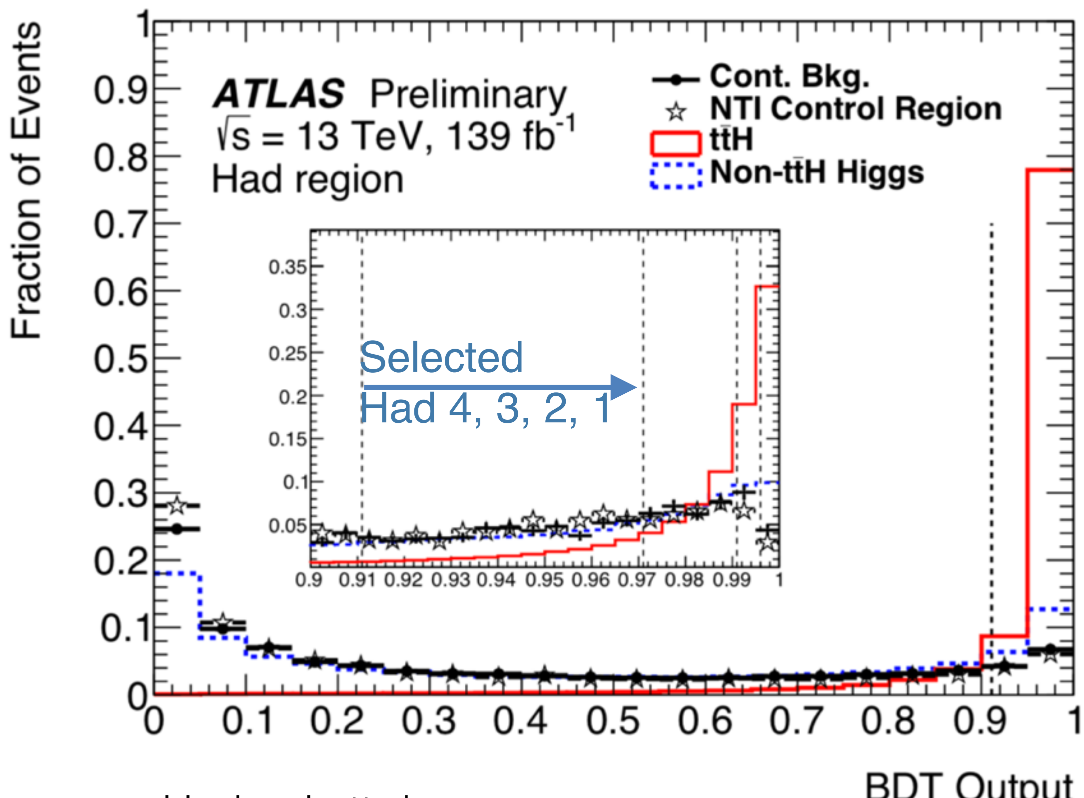
- Select two isolated photons with 105 GeV <$M_{\gamma\gamma}$ < 160 GeV
- Additional selection using MVAs for hadronic and leptonic tt decay to improve purity (enabling this analysis)

Categorize events by BDT score (signal purity)

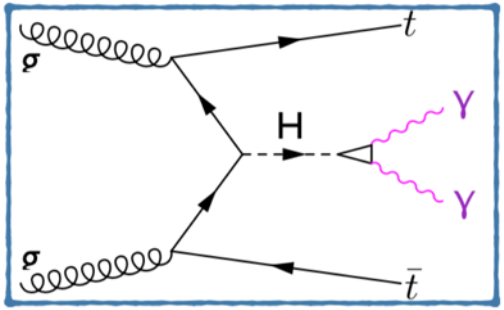
- Select 4 hadronic (HAD1-HAD4) and 3 leptonic (LEP1-LEP3) categories
- BDT sub-samples optimized for best sensitivity
- Low BDT score events are rejected



Hadronic tt decay

ATLAS-CONF-2019-004

ttH – Diphoton Analysis



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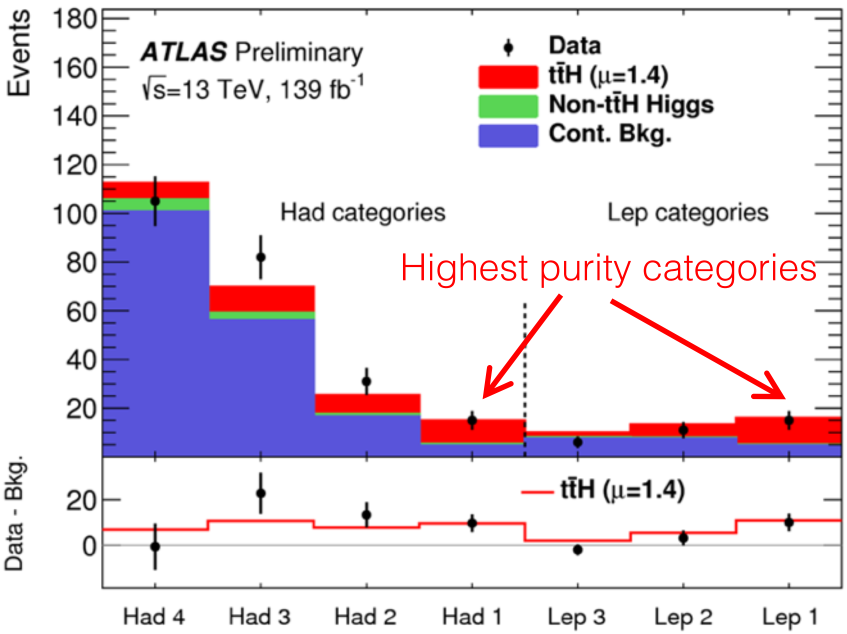
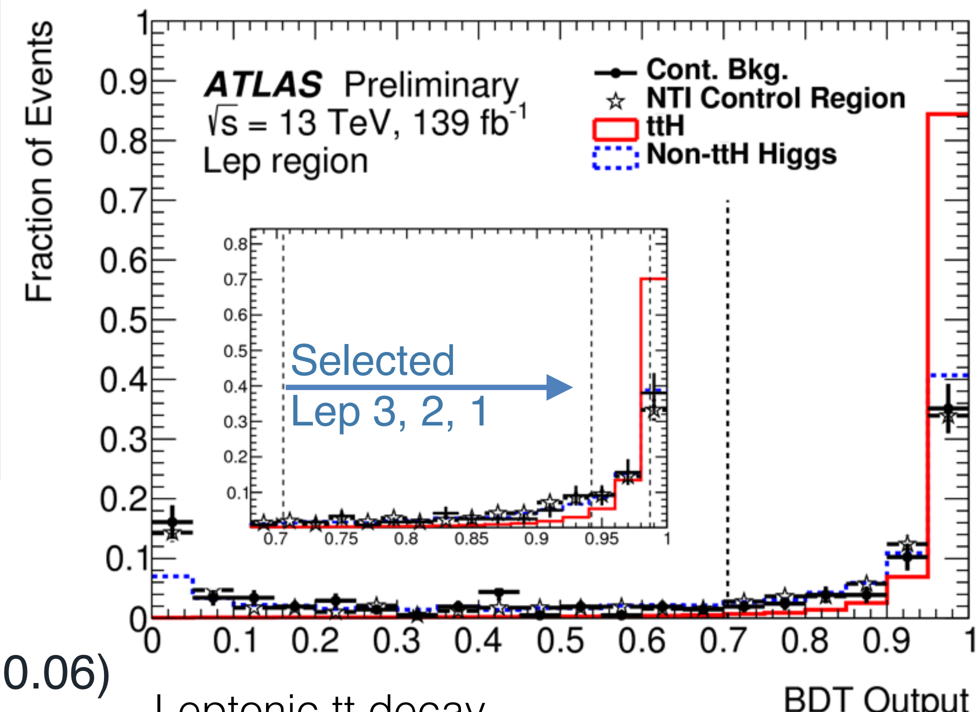




Leptonic tt decay

ATLAS-CONF-2019-004

Dominant uncertainties

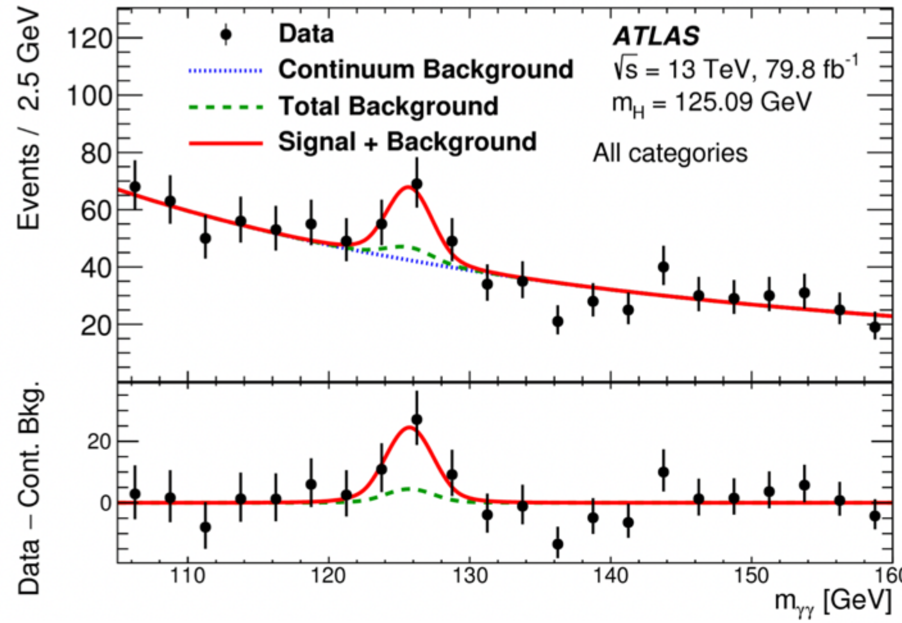
- Parton shower & underlying event (±0.06)
- Photon energy resolution, scale (±0.06)

ttH – Diphoton Analysis (80 fb^{-1} result)

Signal extraction

Performed by simultaneous **unbinned maximum likelihood fit** of **$m_{\gamma\gamma}$** spectra (105-160 GeV) in all **7 categories**

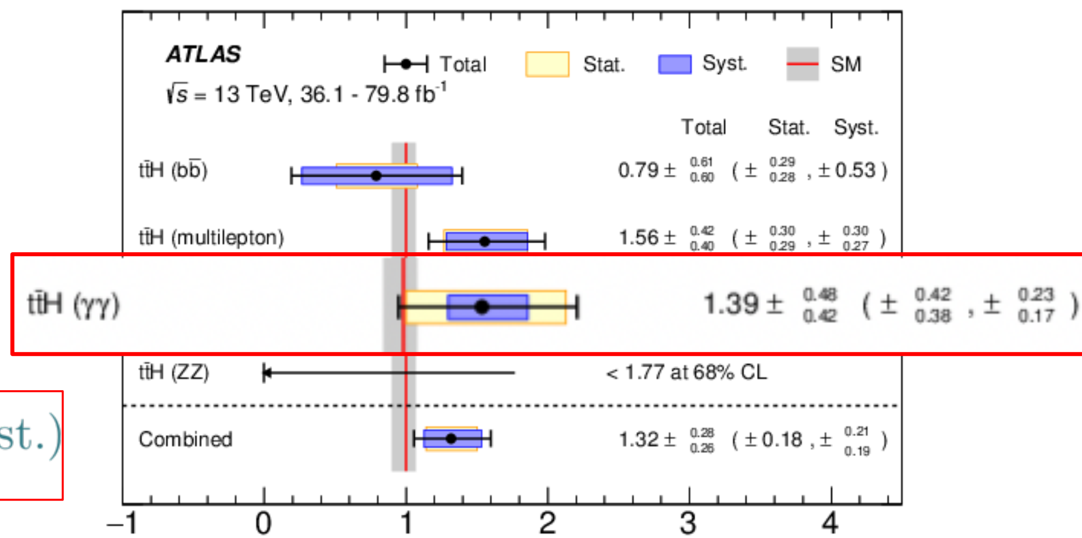
- H mass constrained
- **Signal and background** modeled with analytic functions



Observed significance: 4.1σ
(Expected: 3.7σ)

$$\sigma_{ttH} = 710\ ^{+210}_{-190}(\text{stat.})\ ^{+120}_{-90}(\text{syst.})\ \text{fb}$$

$$\frac{\sigma_{ttH}}{\sigma^{SM}_{ttH}} = 1.39\ \pm^{0.42}_{0.38}\ (\text{Stat.})\ \pm^{0.23}_{0.17}\ (\text{Syst.})$$



Part of ttH combination

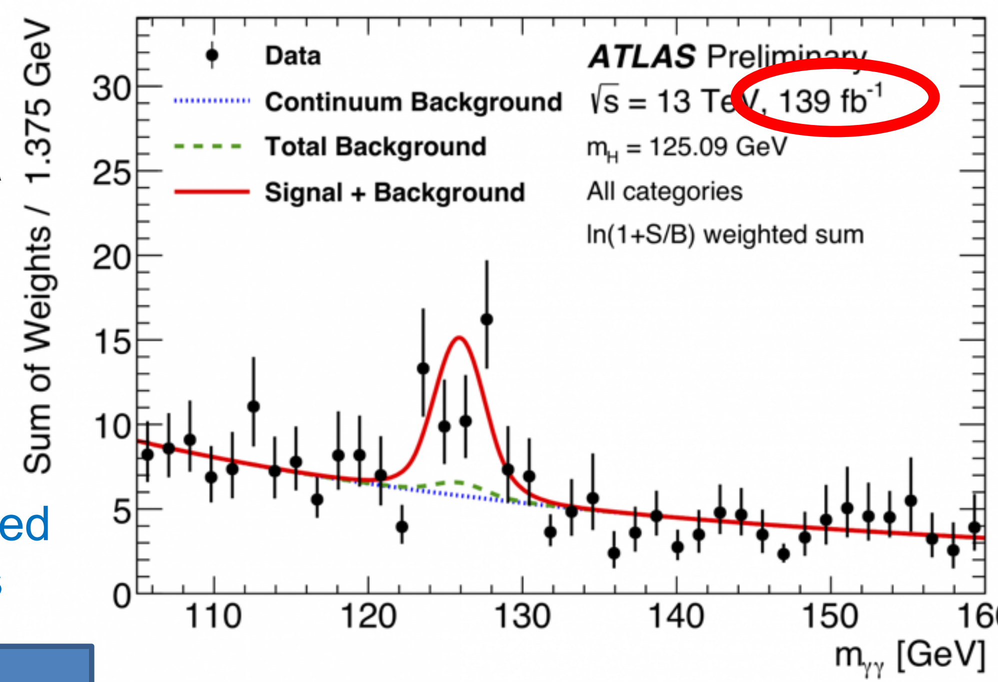
ttH – Diphoton Analysis (140 fb^{-1} result)

NEW

Signal extraction

Performed by simultaneous **unbinned maximum likelihood fit** of **$m_{\gamma\gamma}$** spectra (105-160 GeV) in all **7 categories**

- H mass constrained
- **Signal and background** modeled with analytic functions
- Analyze full Run-2 dataset with updated photon-ID, energy and jet calibrations



2019: First observation of single ttH channel with 4.9σ significance (4.2σ exp)

$$\sigma_{ttH} \times B_{\gamma\gamma} = 1.59\ ^{+0.38}_{-0.36}(\text{stat.})\ ^{+0.15}_{-0.12}(\text{exp.})\ ^{+0.15}_{-0.11}(\text{theo.})\ \text{fb}$$

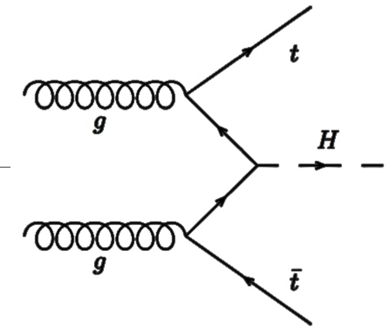
$$\frac{\sigma_{ttH}}{\sigma^{SM}_{ttH}} = 1.38\ \pm^{0.33}_{0.31}\ (\text{Stat.})\ \pm^{0.13}_{0.11}\ (\text{exp.})\ \pm^{0.22}_{0.14}\ (\text{theo.})$$

Note:

- *Events weighted by purity*
- *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 GeV*

Analysis still stats limited!

Combination of ttH Analyses (36…80 fb^{-1})



2018: Combining 4 analyses: 6.3σ Observation (5.1σ Exp)

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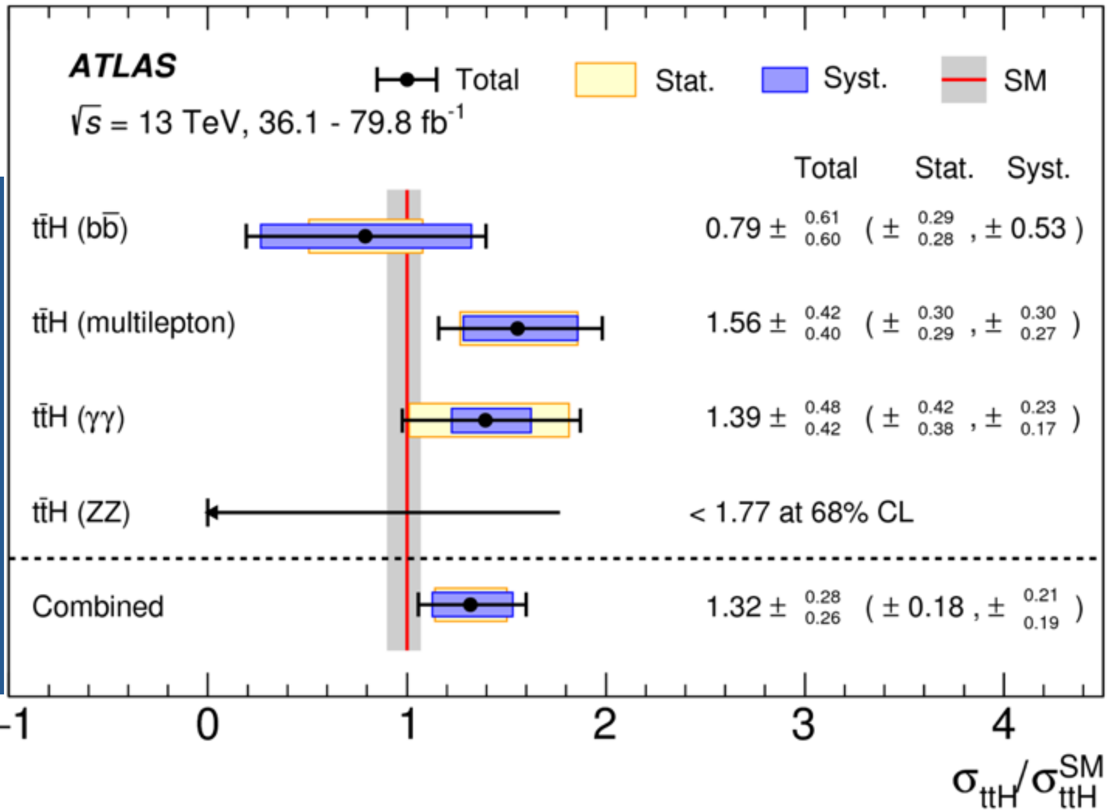


Significance

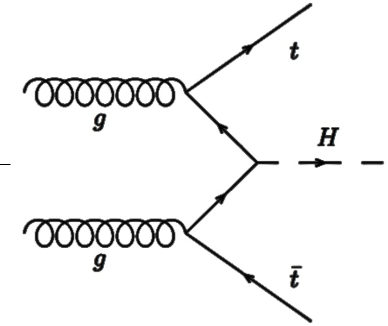
Obs	(Exp)	
1.4σ	(1.6σ)	
4.1σ	(2.8σ)	
4.1σ	(3.7σ)	
0σ	(1.2σ)	
5.8σ 13 TeV only	**(4.9σ)**	**6.3σ (5.1σ)** 7,8 and 13 TeV

Major milestone in Run-2 accomplished

Some details:

- Theory uncertainties correlated, experimental uncertainties mostly uncorrelated
- Other Higgs boson production modes constrained to Standard Model prediction
- Assume Standard Model branching ratios

Combination of ttH Analyses – First Observation!



by ATLAS

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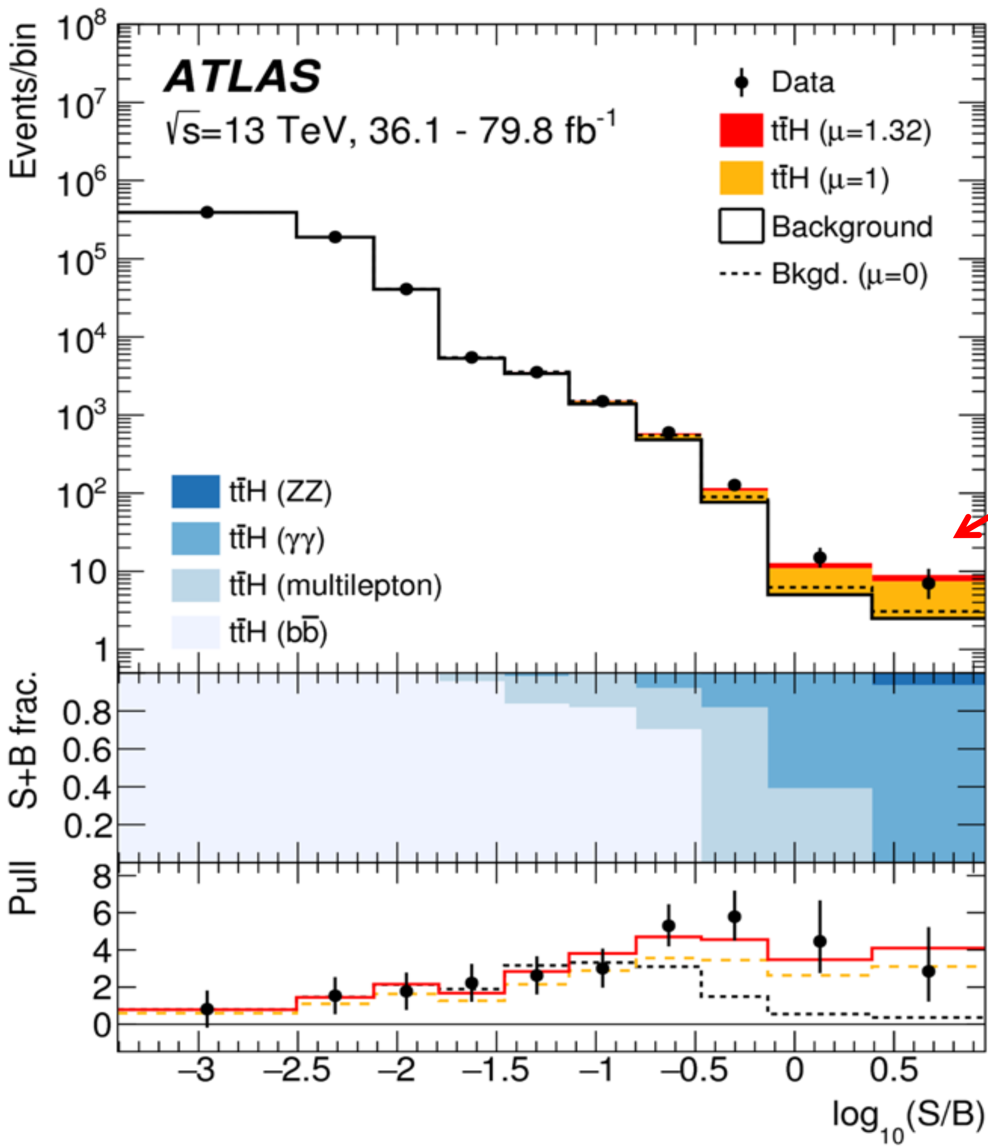


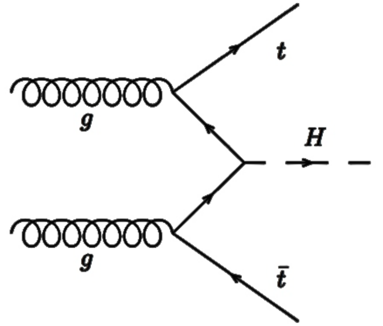
ttH signal excess

Visualize of ttH signal signal across all channels binned according to purity

$\sigma_{ttH}{}^{SM}$ = 507 fb

Combined (13 TeV) 36.1–79.8 $670 \pm 90\,(\text{stat.})\,^{+110}_{-100}\,(\text{syst.})$

Total ttH cross-section



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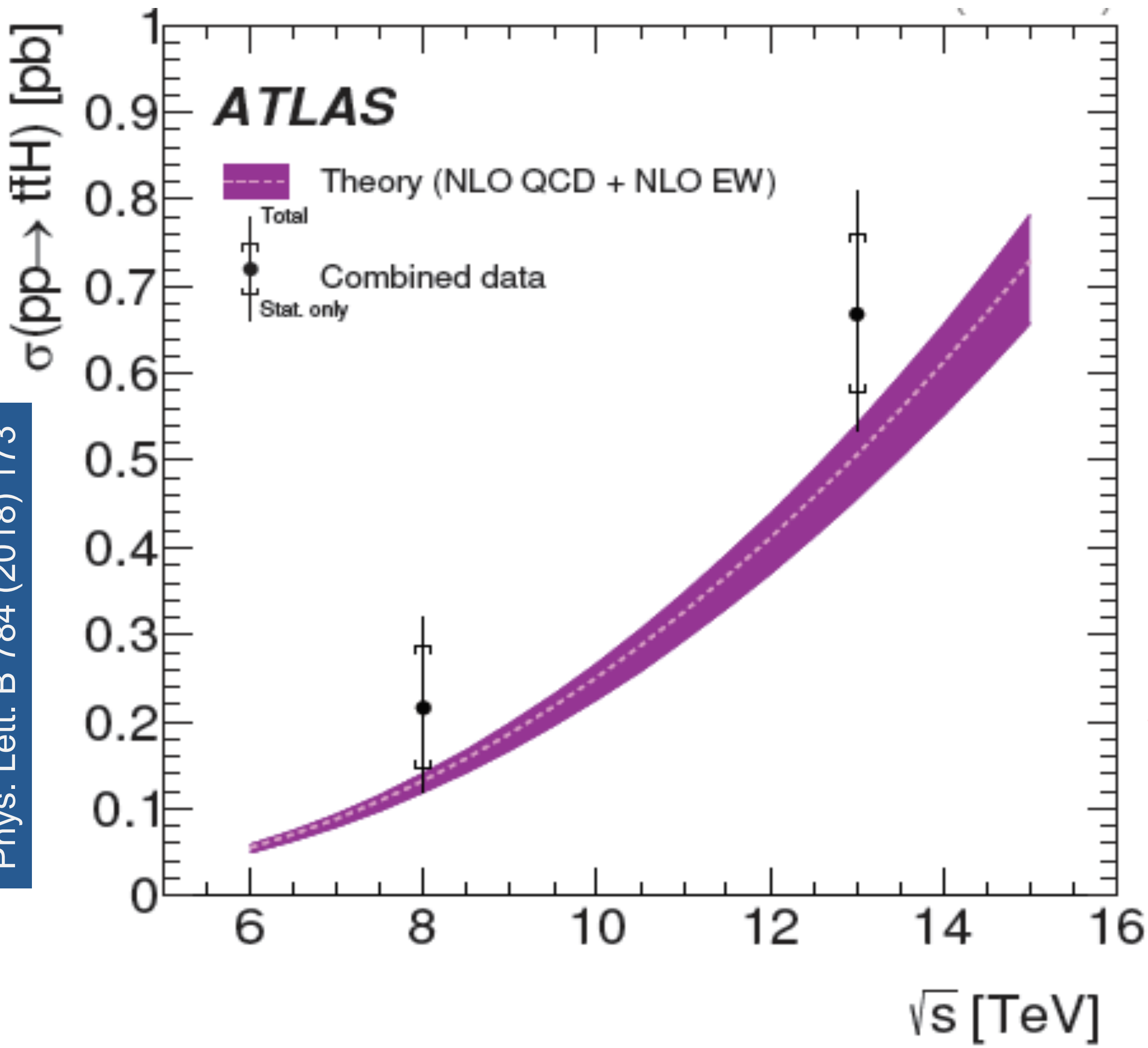


670 ± 90 (stat) ±105 (syst) fb

(13%) (16%)

220 ± 100 (stat) ± 70 (syst) fb

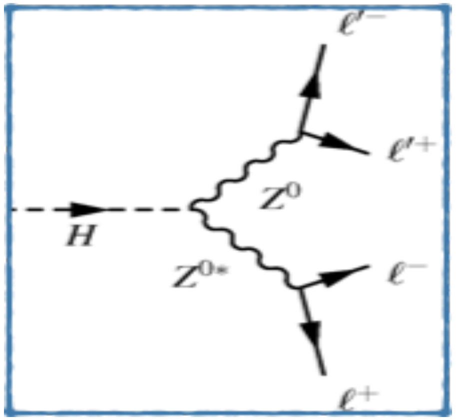
(45%) (32%)

Data agrees with predicted strong (×3.9) rise in cross-section vs √s

Cross-section extracted assuming SM Higgs branching fractions

ttH (H→ZZ*→4l) Analysis

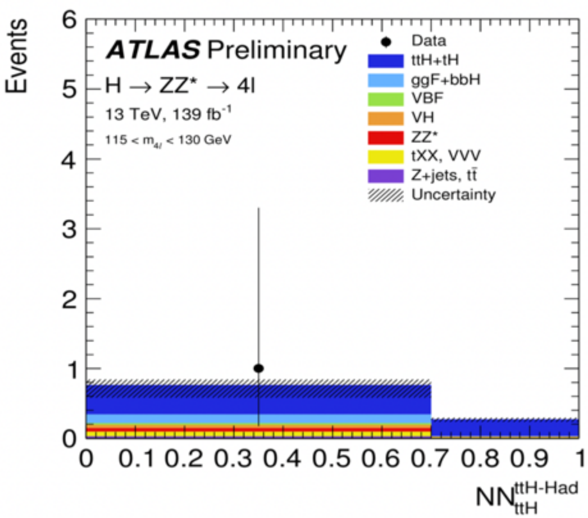
NEW

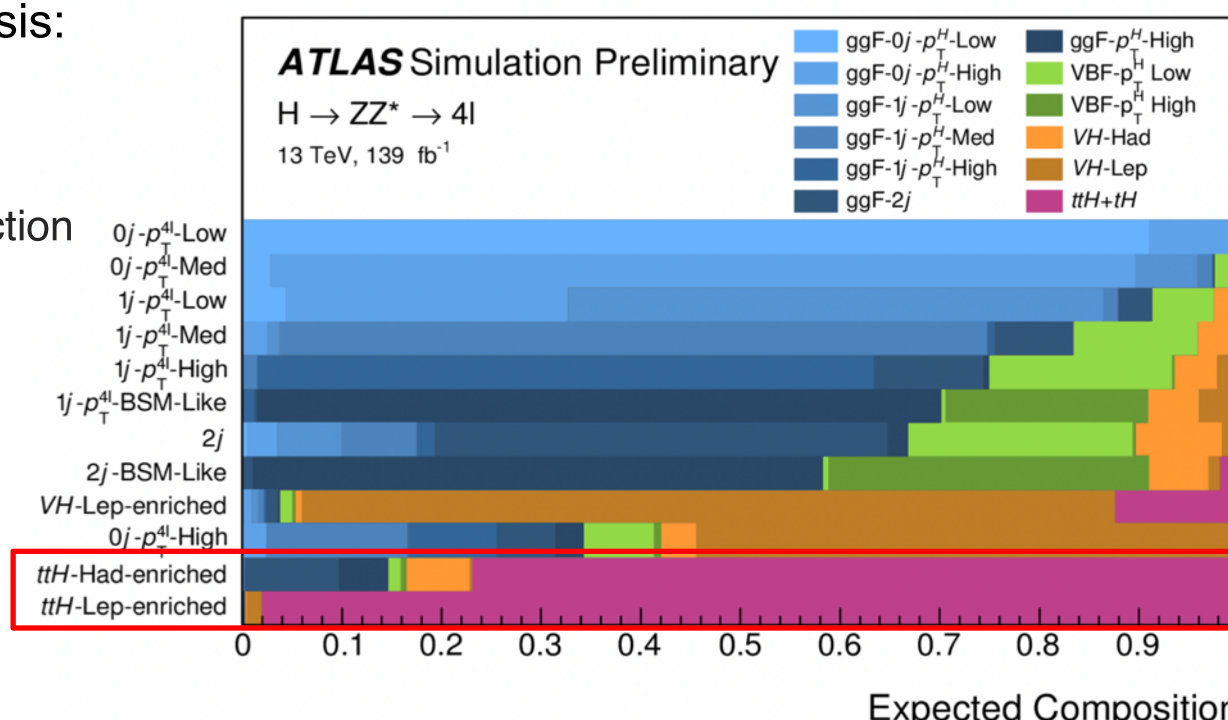


- New ATLAS H→ZZ*→4l analysis targeting all production modes
- Select two same-flavor lepton pairs in Higgs mass window
- Various event categorization depending on production mode
- For ttH, extremely small rate [BR(H→ZZ*→4l)= 0.0124%]
- 79.8 fb^{-1}: similar strategy but only focusing on ttH
  → *Expected significance* ***1.2 σ,*** *no events were observed*

Two categories for ttH analysis:

- **Lep**: at least one leptonically decaying W (from top decay)
- **Had**: Fully hadronic tt decay
- Further Neural Net (NN) selection





ATLAS-CONF-2019-025

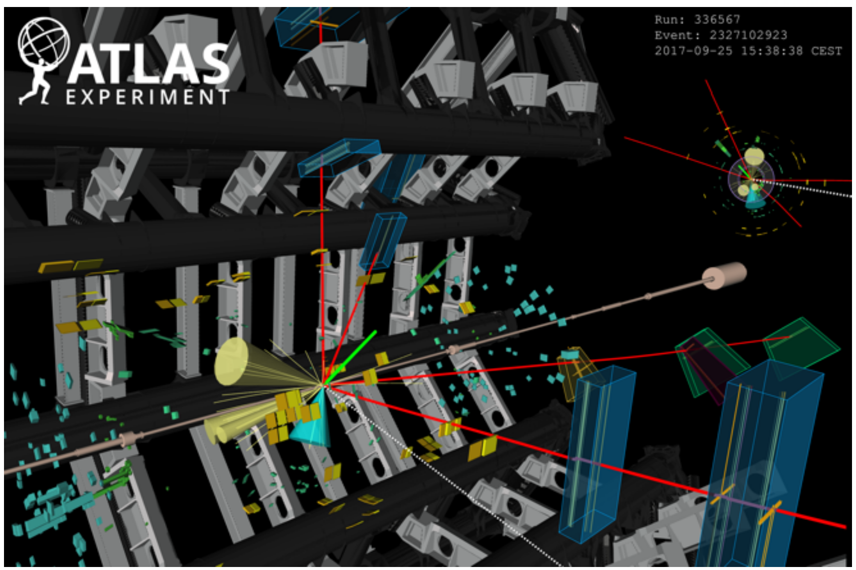
ttH (H→ZZ*→4l) Analysis

NEW

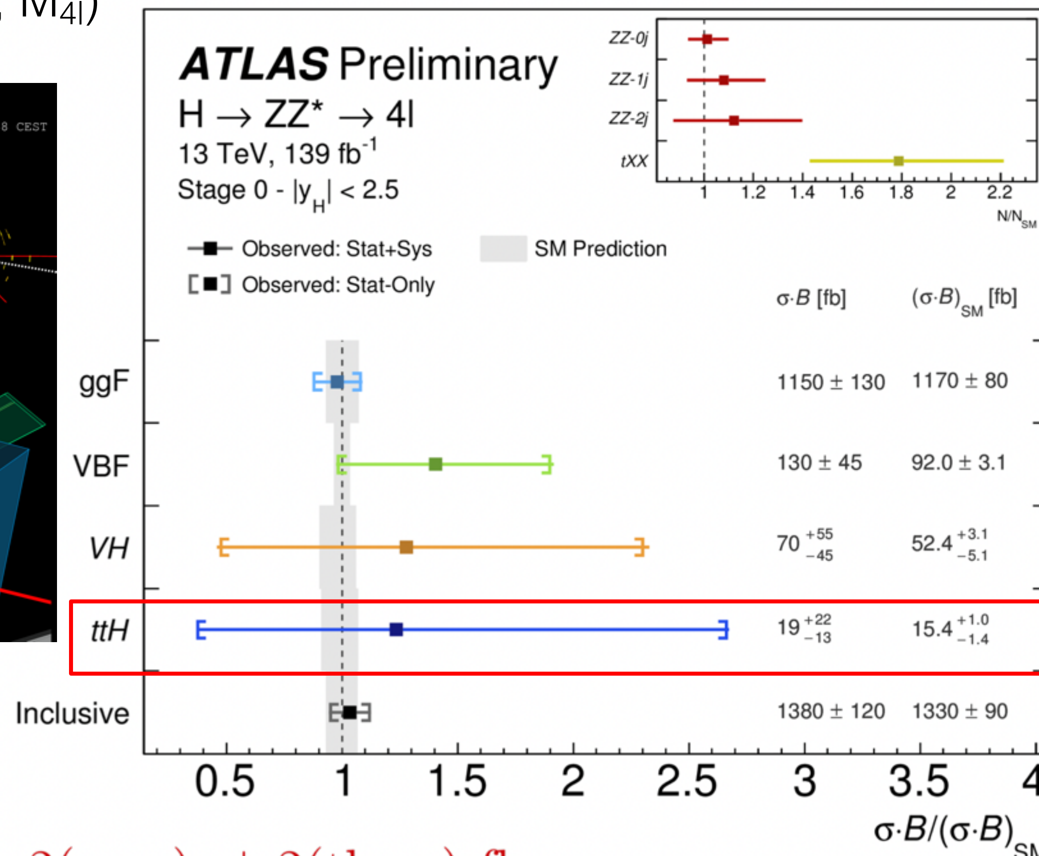
Signal extraction

Maximum likelihood fit to NN output

- Most important ttV backgrounds constrained from control region (selected based on (b)-jets, MET, M_{4l})



Reconstructed event category	Total expected events	Observed events
ttH-Had-enriched	1.32 ± 0.17	1
ttH-Lep-enriched	0.42 ± 0.04	1



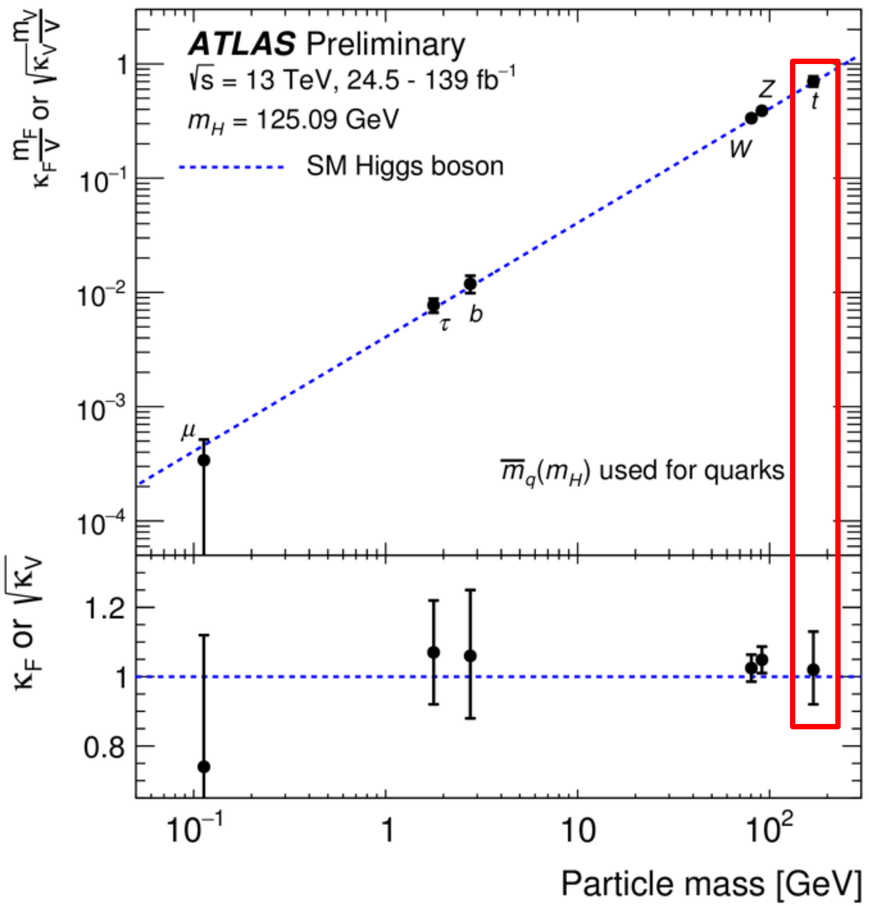
$$\sigma_{\mathrm{ttH}} \times B_{ZZ^* \to 4\ell}\ (\mathrm{SM}) = 15.4\ ^{+1.0}_{-1.4}\ \mathrm{fb}$$

$$\sigma_{\mathrm{ttH}} \times B_{ZZ^* \to 4\ell} = 19\ ^{+22}_{-13}(\mathrm{stat.})\ \pm 2(\mathrm{exp.})\ \pm 2(\mathrm{theo.})\ \mathrm{fb}$$

ATLAS-CONF-2019-025

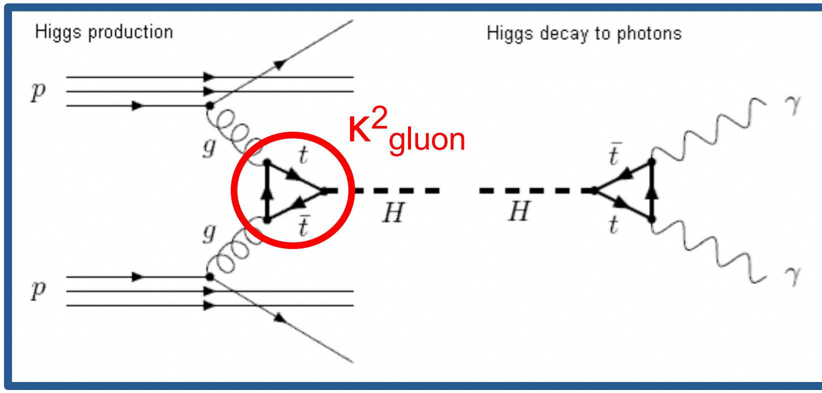
Measurement of top-Higgs Yukawa Coupling (up to **80 fb^{-1}**)

Assuming only Standard Model particles



$\kappa_{top} = y_t/y_t^{SM} = 1.02^{+0.11}_{-0.10}$

Allowing New Particles in the Loops



$\kappa_{top} = y_t/y_t^{SM} = 1.14^{+0.19}_{-0.18}$

- Analysis using up to 80 fb^{-1}
- Included single parameter B_{BSM} in model
- Constrains BSM contribution in the loop *(ATLAS evaluates 2HDM and MSSM as benchmark models)*
- Consistent with SM Higgs boson coupling

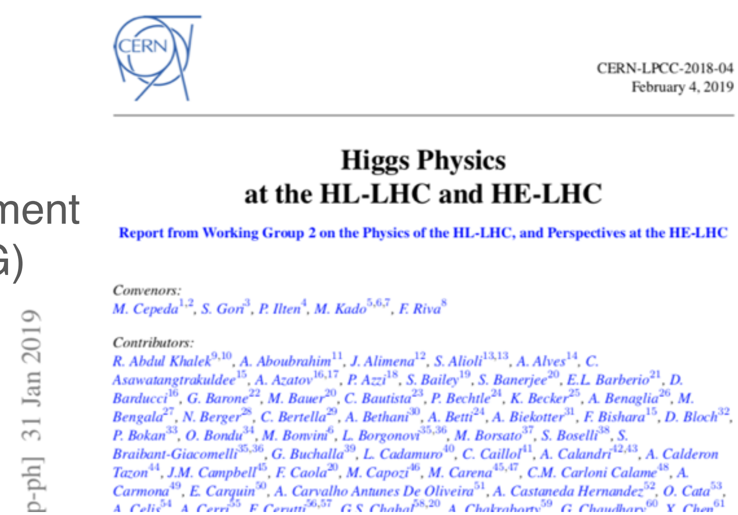
ATLAS-CONF-2019-005

Conclusions

- ATLAS has established observation of ttH production **6.3σ** (5.1σ expected) by combining the H→bb, multilepton and diphoton channels
- Recent ATLAS ttH observation (4.9σ) using H→γγ *channel* alone
- Top-Higgs Yukawa coupling consistent with SM (within uncertainties)
- Future measurements of tH production will add complementary information
- Discovery of all 3rd generation Higgs boson Yukawas (together with H→bb, $\tau\tau$)

Looking into the future

- Upgrades for the HL-LHC are underway
- HL-LHC Higgs physics shows impressive goals
  - ttH (H→bb) to 7-11% (requires ×2-3 improvement in tt+HF uncertainty, ongoing work in HXSWG)
  - ttH (H→multilepton) measured to 7-11% ($\Delta\mu$)
  - *No projection for ttH (H→γγ) yet*
- New ideas will continue to push the frontiers of particle physics at the LHC.



CERN

CERN-LPCC-2018-04
February 4, 2019

p-ph] 31 Jan 2019

Higgs Physics
at the HL-LHC and HE-LHC

Report from Working Group 2 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

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https://arxiv.org/pdf/1902.00134.pdf

Thank you

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