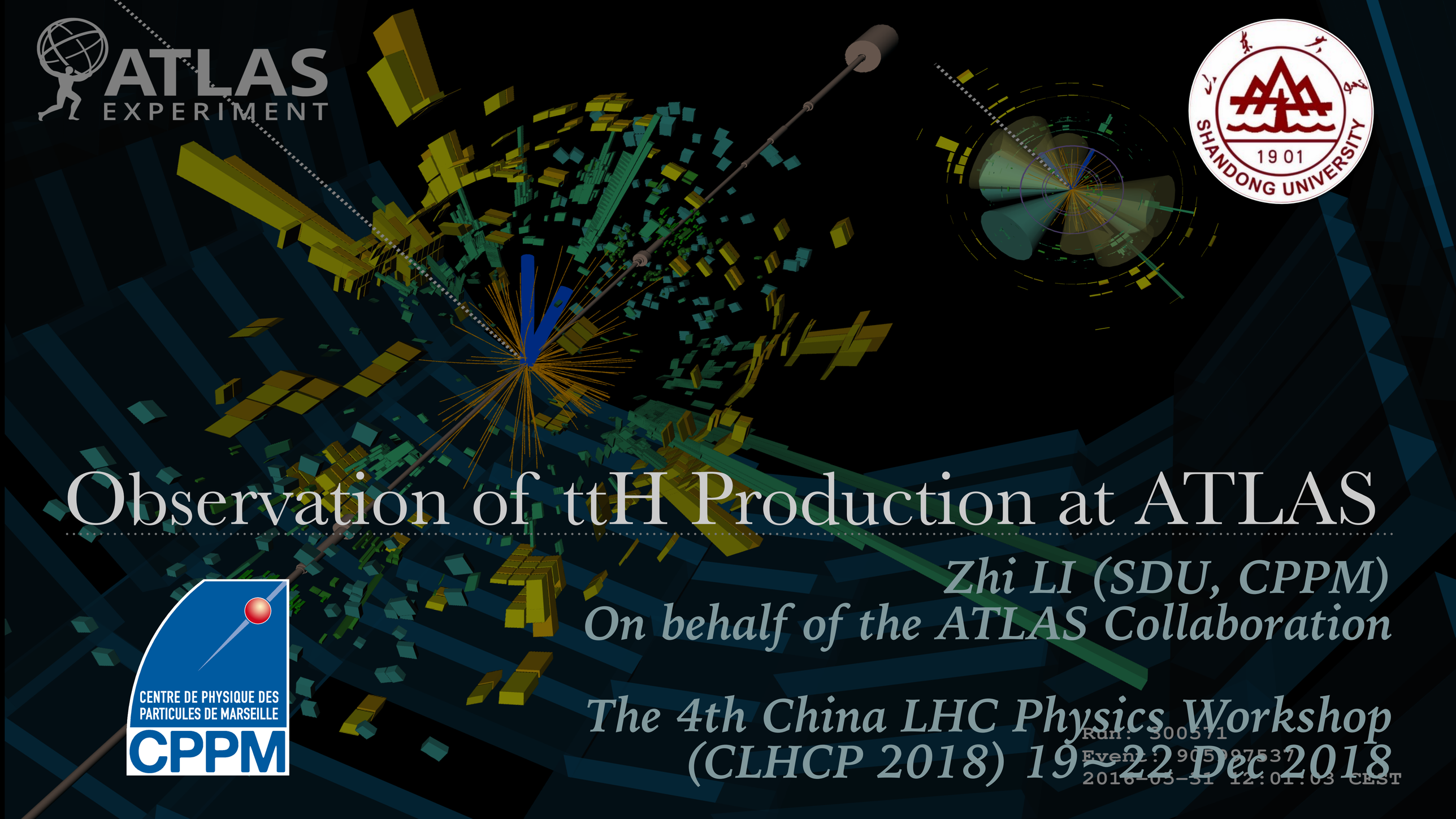


Observation of ttH Production at ATLAS

Zhi LI (SDU, CPPM)
On behalf of the ATLAS Collaboration

The 4th China LHC Physics Workshop (CLHCP 2018) 19~22 Dec 2018

Motivations

Top quark Yukawa coupling $\lambda_t = \sqrt{2}\, m_t/v \approx 1$*:*

2 complementary measurements of λ_t*:*

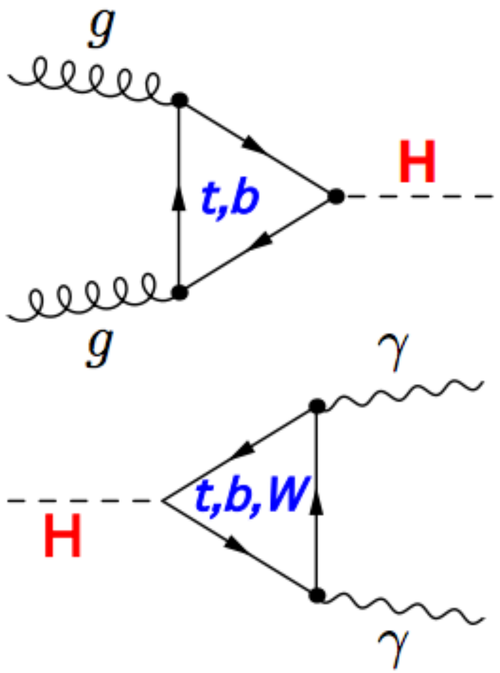
- *Indirect constraints: ggF,* $H \to \gamma\gamma$ *decay.*
  - *Contributions enter from top quark loops by* λ_t^2*.*
  - *Run1 ATLAS+CMS combination measured:*

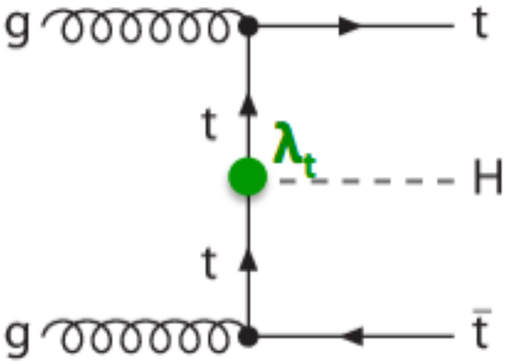
  $\kappa_t = \lambda_t/\lambda_t^{SM} = 0.87 \pm 0.15$

- $t\bar{t}H$ *production, best direct way to measure top quark Yukawa coupling:*
  - *Tree-level process, cross-section proportional to* λ_t^2*.*
  - *Run 1 ATLAS+CMS result on signal strength:*

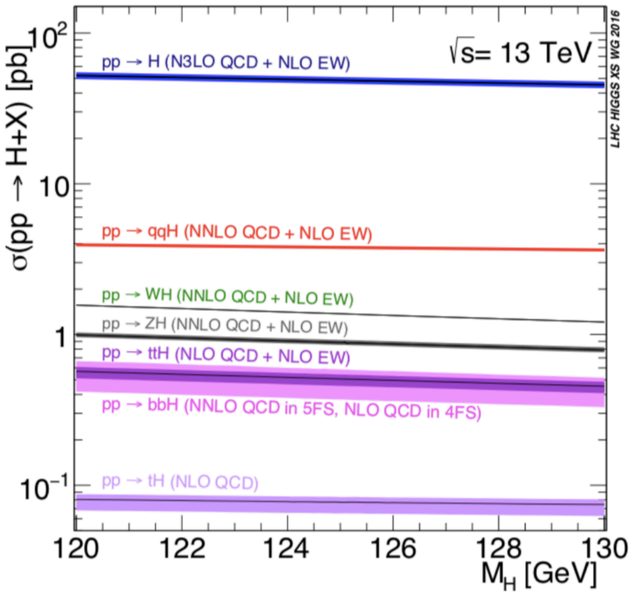
  $\mu_{ttH} = \sigma_{ttH}/\sigma_{ttH}^{SM} = 2.3^{+0.7}_{-0.6}$,

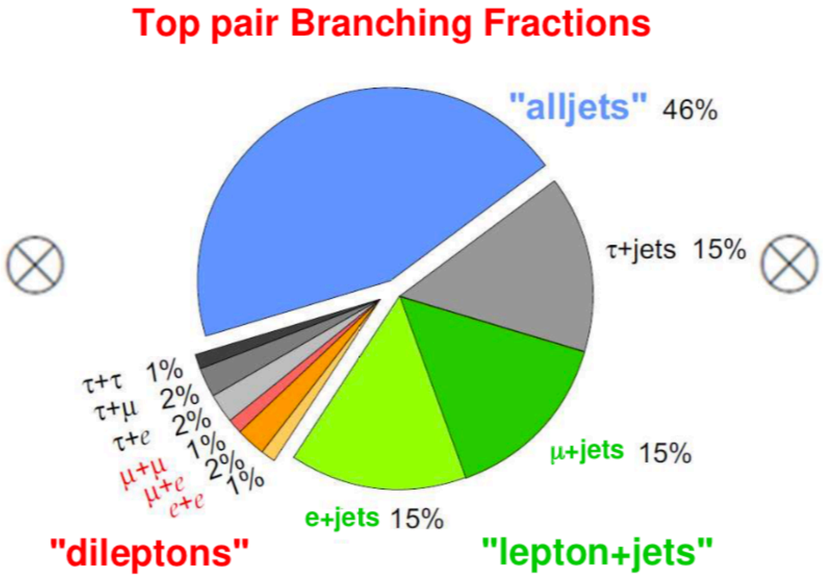
  Obs. (exp.) significance of 4.4σ (2.0σ)*.*

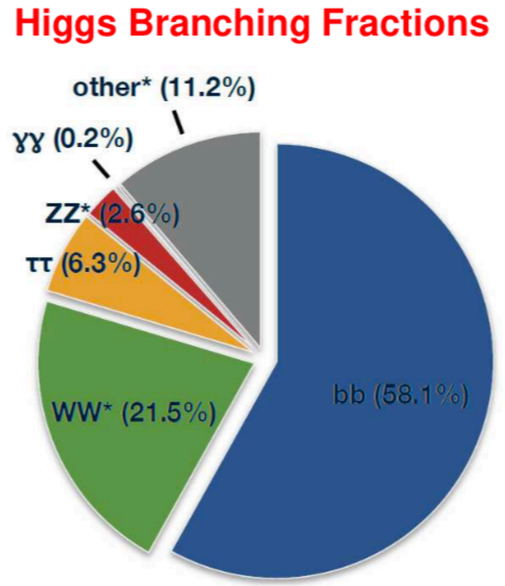




ttH Cross-Section and Branching Fractions







- *$t\bar{t}H$ cross-section at $\sqrt{s}$=13 TeV: 0.507 pb (~1/100 to H_{total} cross-section).*
- *Complex final states:*
  - *Good understanding of all reconstructed objects.*
  - *Combination of all these analyses to optimize sensitivity.*

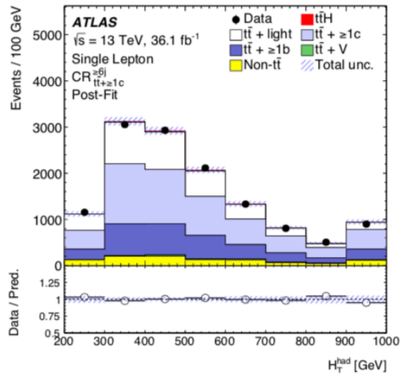
At $\sqrt{s}$=13 TeV:

$t\bar{t}H$, H→bb, 36.1 /fb BR~58%, S/B~1-5%	$t\bar{t}H$, Multi-lepton, 36.1 /fb BR~30%, S/B~2-60%	$t\bar{t}H$, H→γγ, 79.8 /fb BR~0.23%, S/B~5-200%	$t\bar{t}H$, H→ZZ*→4l, 79.8 /fb BR~0.01%, S/B~50-500%

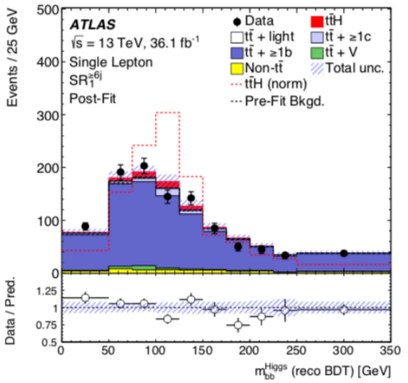
Large BR / Low Purity → *Small BR / High Purity*

ttH, H→bb

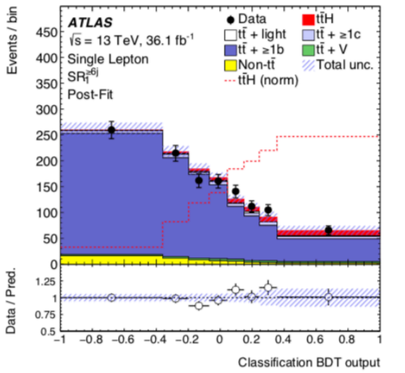
- *Use 36.1 fb^{-1} of p-p collision data from ATLAS experiment in 2015-2016.*
- *Benefit from large H→$b\bar{b}$ branching ratio (~58%).*
- *Main background: $t\bar{t}$ +heavy flavor production.*
- *Categorization:*
  - *2 separated channels by $t\bar{t}$ decay: 1-lepton and 2-lepton. (Fully hadronic channel from Run-1 at 8 TeV still at work)*
  - *Further categorization based on jet multiplicity and b-tag score of jets (4 working points, ε_b=85%→60%).*
  - *9 SRs +10 CRs with very different signal purity (best at ~5%) and background fractions ($t\bar{t}$+light, $t\bar{t}$+≥1c, $t\bar{t}$+≥1b), with a "boosted" category targeting high p_T top/Higgs.*
- *Cascade of MVA classifiers in Signal Regions to enhance signal sensitivity.*
  - *Reconstruction: Identify best jet-parton assignment and reconstruct final state.*
  - *Classification: BDT for ttH vs background in each SR.*



(a) CRs: H_T distribution.



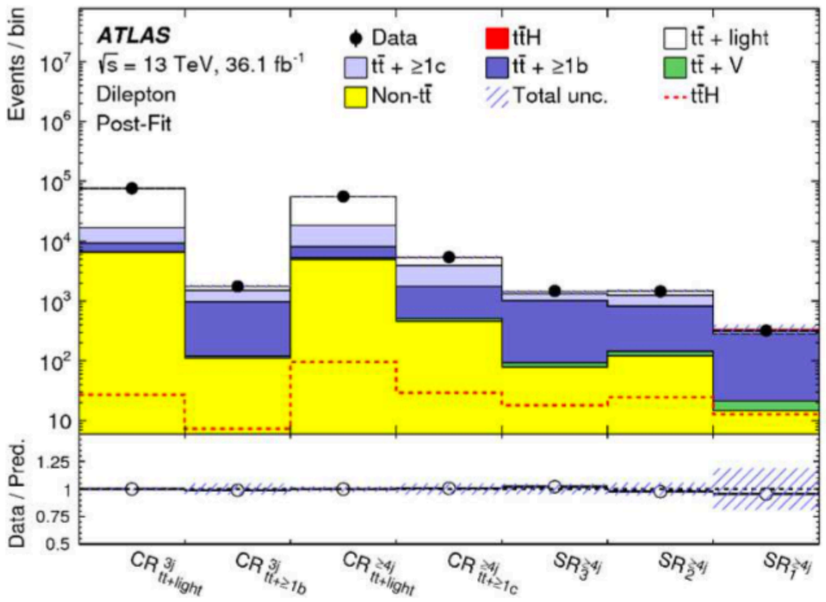
(b) SRs: reconstruction BDT.

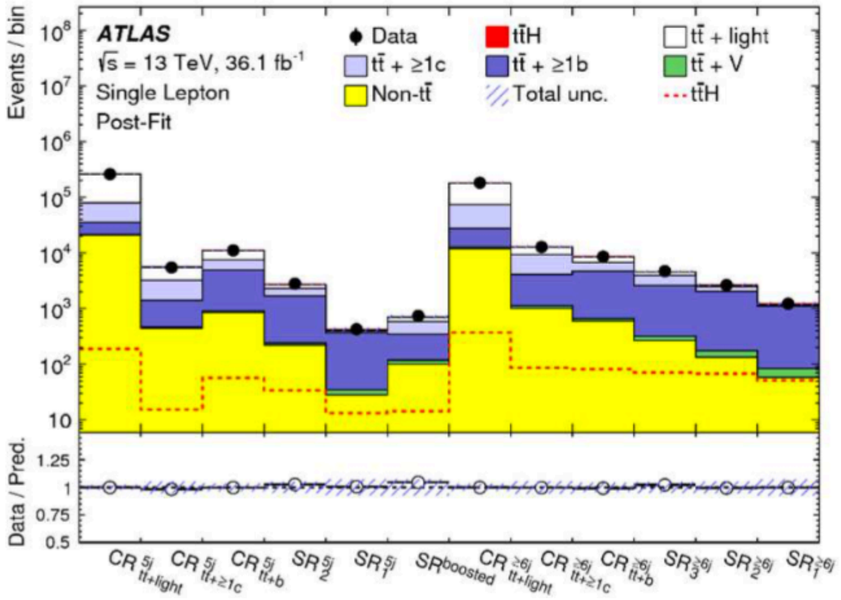


(c) Classification BDT to separate signal from background.

PhysRevD.97.072016 (2018)

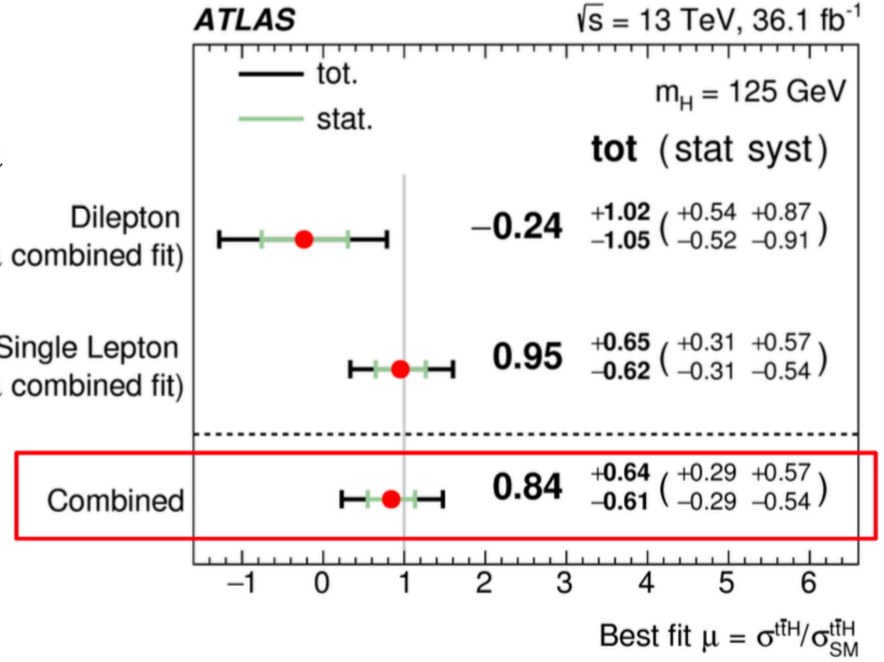
ttH, H→bb





- *Simultaneous fit to all SRs and CRs.*
  - *Classification BDT output in SRs.*
  - *Event yields in most CRs.*
- *Normalization of $t\bar{t}+\geq 1b$ & $t\bar{t}+\geq 1c$ free-floating.*
- *Leading systematics: modeling of $t\bar{t}+\geq 1b$ [PowhegPy8 vs Sherpa 5FS].*

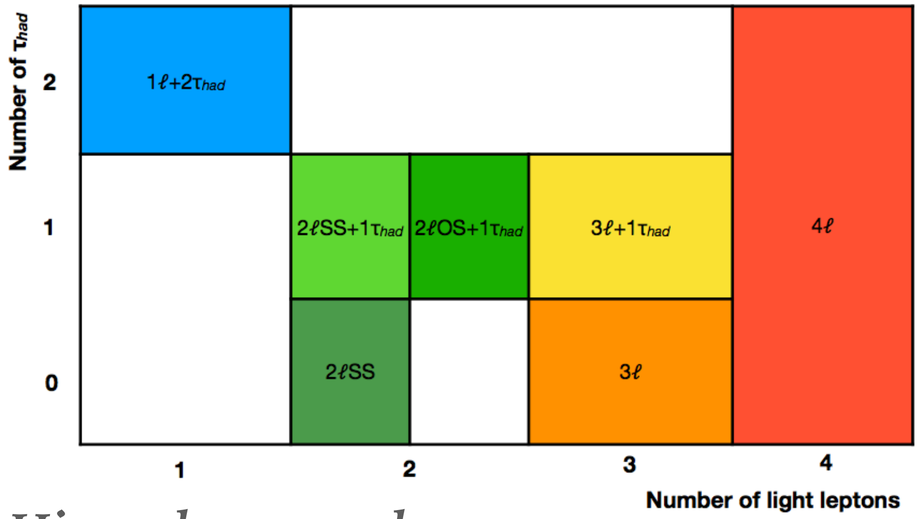
- *Good agreement with SM predictions.*
- *Significance:*
  - *Observed: 1.4σ*
  - *Expected: 1.6σ*



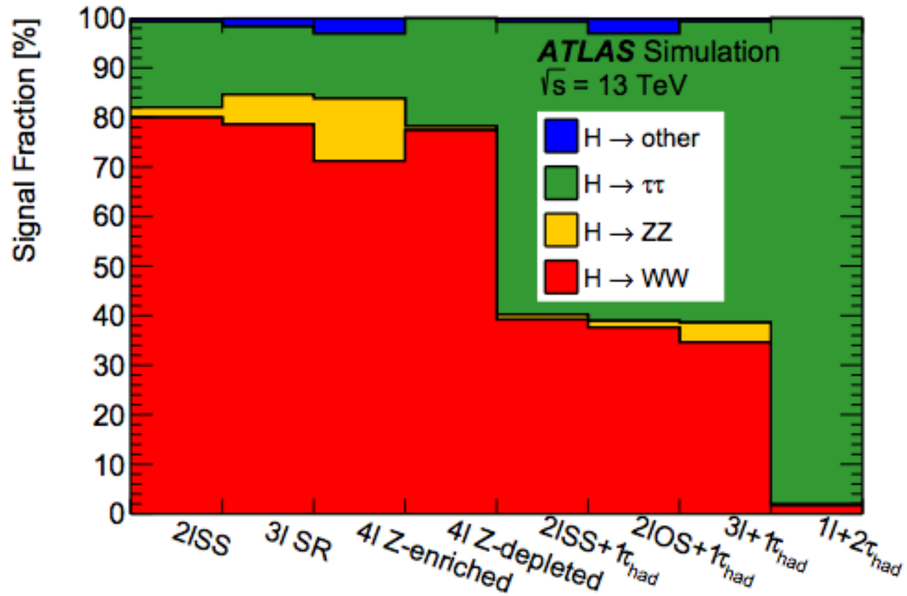
ttH, multi-lepton

- *Use 36.1 fb^{-1} of p-p collision data from ATLAS experiment in 2015-2016.*
- *Analysis targeting at $t\bar{t}H$, $H \to WW^*$, $\tau\tau$, ZZ^* with ≥ 2 (1 light) leptons in their final states.*
- *7 Channels orthogonal in light leptons ($\ell = e, \mu$) and hadronic tau (τ_{had}) multiplicity.*
  - *High lepton multiplicity requirement reduces background.*
  - *Jet requirements: $N_{jet} \geq 2$, $N_{b\text{-}tag} \geq 1$:*
    - *2lSS, 2lSS+1τ_{had} : $N_{jet} \geq 4$*
    - *2lOS+1τ_{had}, 1l+2τ_{had} : $N_{jet} \geq 3$*
- *ML+ 0τ: primary sensitive to $H \to WW$.*
- *ML+ $\geq$1τ: primary sensitive to $H \to \tau\tau$.*

Analysis organized channels:



Higgs decay modes:

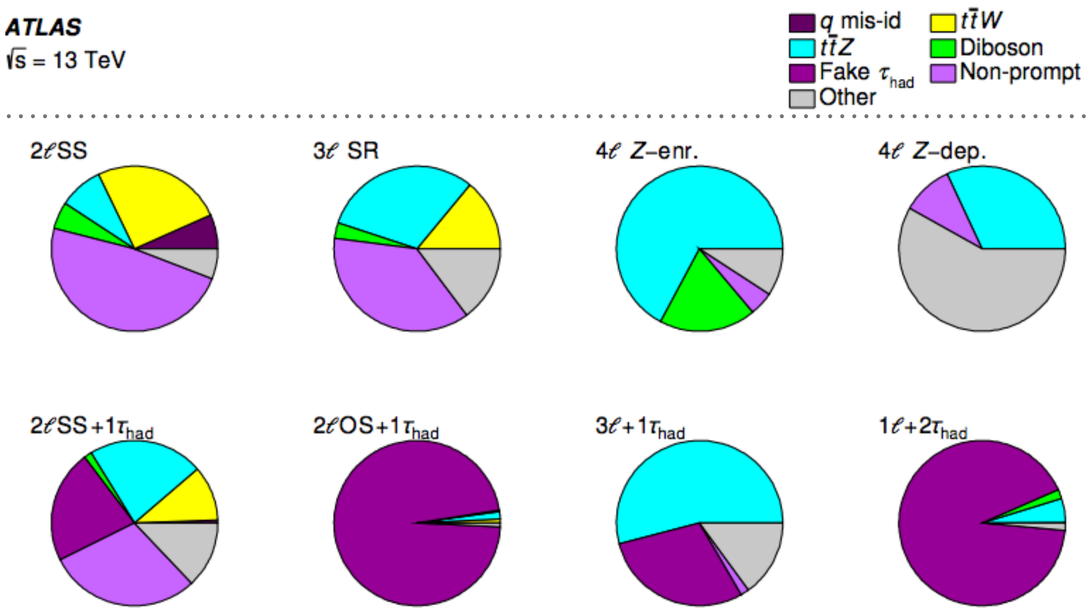


Phys. Rev. D 97 (2018) 072003

ttH, multi-lepton

Signal region background compositions:

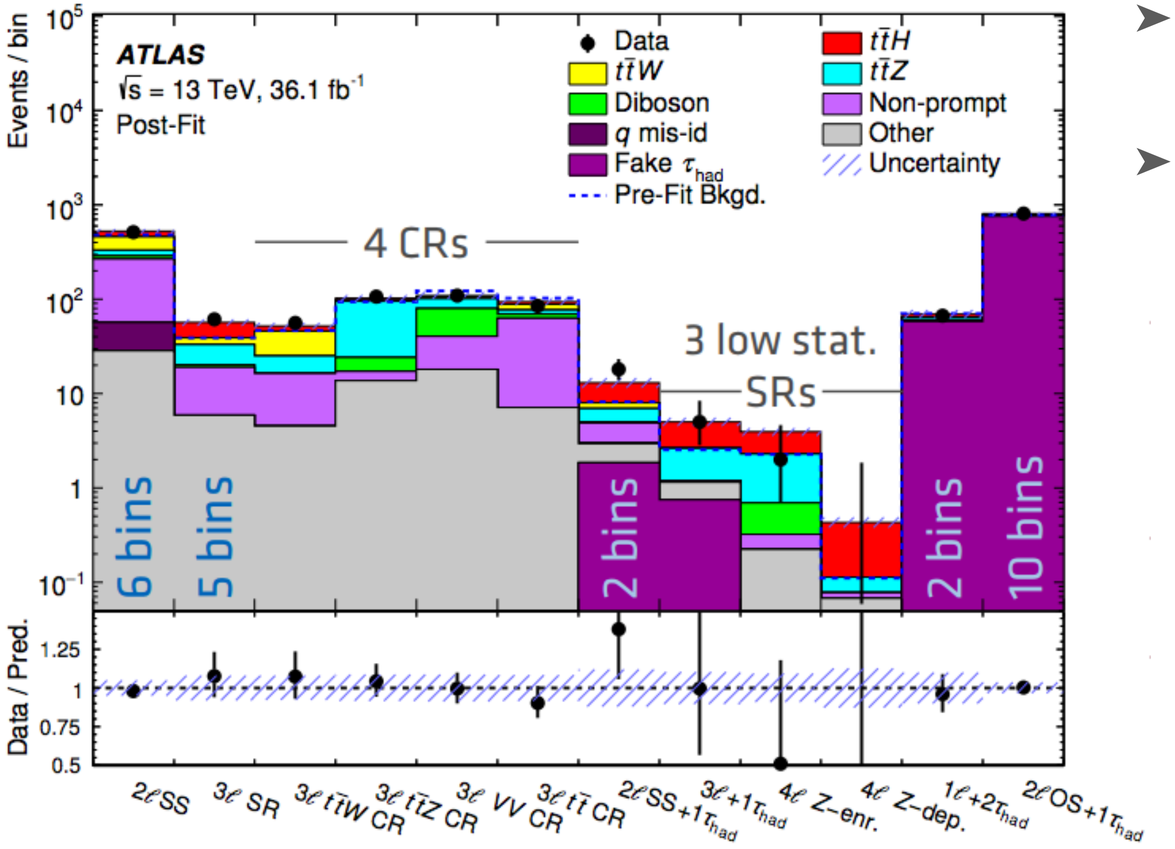
- *Irreducible backgrounds: $t\bar{t}W$, $t\bar{t}Z$, VV.*
  - *Estimated from MC.*
  - *Validated in 3ℓ CRs.*
- *Reducible backgrounds:*
  - *estimated from data-driven.*
  - *Non-prompt light leptons: from b-hadron decays ($t\bar{t}$) and photon conversions.*
  - *Electron charge mis-identification (q mis-id): from 2ℓOS $t\bar{t}$ events.*
  - *Fake τ_{had}: from light flavor jets and mis-identified electrons.*



- *Backgrounds are reduced with cut-and-count and boosted decision trees (BDTs) using lepton isolation, track variables, (b-tagged) jet multiplicity as well as some other variables on MET/τ_{had}. (list of input variables)*
- *Cut-and-count cross checks for 3 most powerful channels ($2\ell SS$, 3ℓ and $2\ell SS+1\tau_{had}$) compatible.*

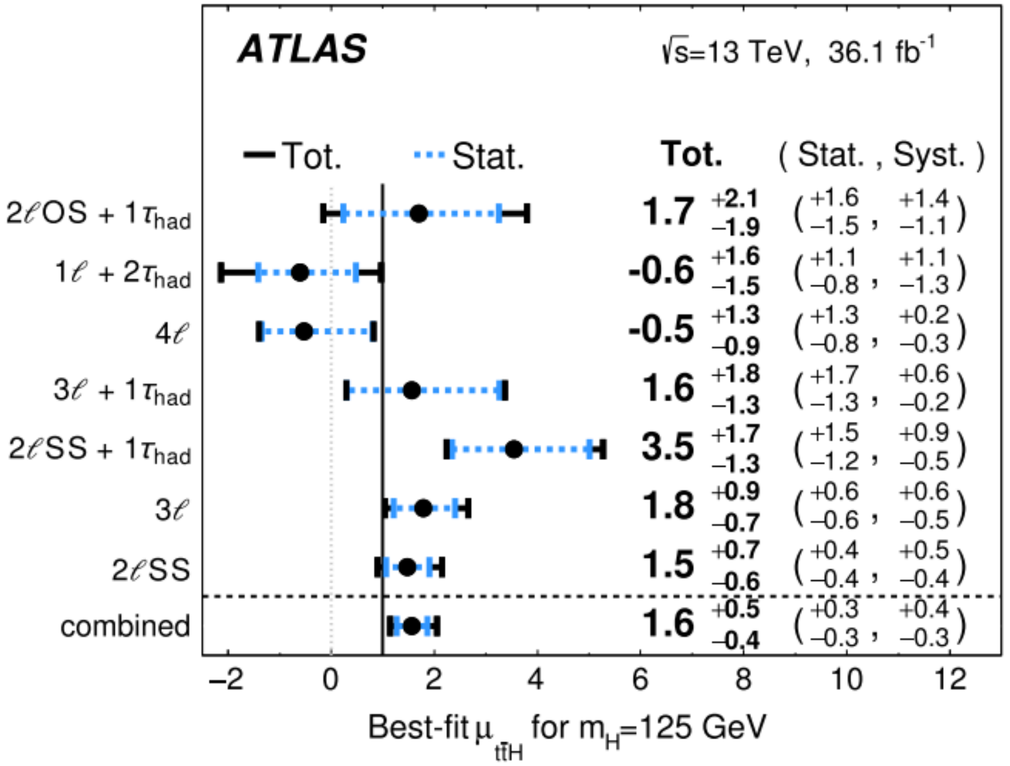
	2ℓSS	3ℓ	4ℓ	$1\ell + 2\tau_{\text{had}}$	$2\ell\text{SS} + 1\tau_{\text{had}}$	$2\ell\text{OS} + 1\tau_{\text{had}}$	$3\ell + 1\tau_{\text{had}}$
BDT trained against	Fakes and $t\bar{t}V$	$t\bar{t}$, $t\bar{t}W$, $t\bar{t}Z$, VV	$t\bar{t}Z$ /-	$t\bar{t}$	all	$t\bar{t}$	...
Discriminant	2 × 1D BDT	5D BDT	Event count	BDT	BDT	BDT	Event count
Number of bins	6	5	1/1	2	2	10	1
Control regions	...	4	...	...	...	...	...

ttH, multi-lepton



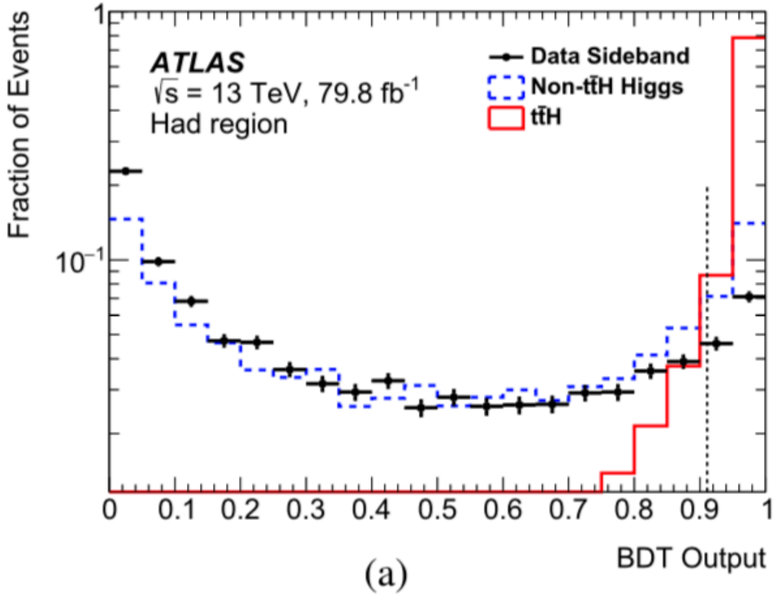
- *Best-fit signal strength $\mu_{ttH} = 1.6\ ^{+0.5}_{-0.4}$, obs. (exp.) significance: 4.1σ (2.8σ).*
- *Good agreement with SM predictions*
- *Evidence of tt̄H production.*

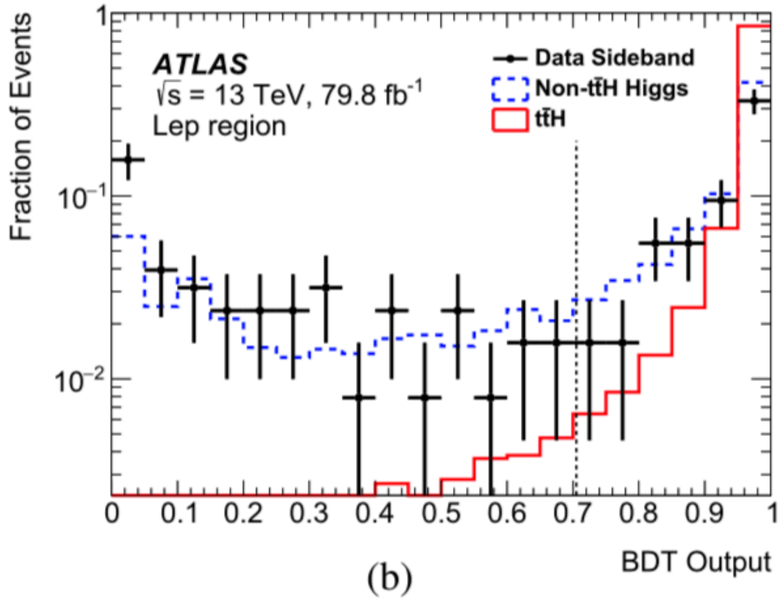
- *Binned maximum-likelihood fit is performed in 8 SRs + 4 CRs simultaneously (32 bins).*
- *Systematic uncertainties with largest impact on errors on μ_{ttH} are: tt̄H cross section uncertainty (theory), jet energy scale and resolution and non-prompt light lepton estimates (large contribution of tt̄/tt̄γ CR statistics for DD Fakes estimation).*



ttH, H→$\gamma\gamma$

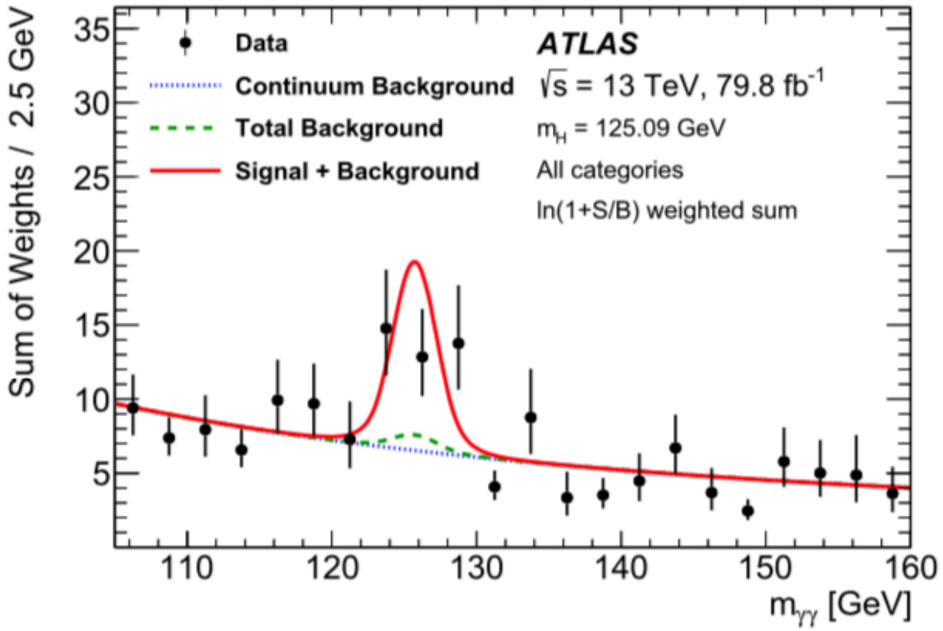
- *Use 79.8 fb^{-1} of p-p collision data from ATLAS experiment in 2015-2017.*
- *Small rate but narrow peak in $m_{\gamma\gamma}$ over smooth continuum background, extrapolated from side-bands in data.*
- *Standard H$\gamma\gamma$ selection: 2 high-E_T isolated photons $p_T/m_{\gamma\gamma}$ >0.35 (0.25), 105<$m_{\gamma\gamma}$<160 GeV.*
- *Categorization based on $t\bar{t}$ decay:*
  - *Lep (≥1l, ≥1j, ≥1b) and Had (0l, ≥3j, ≥1b).*
  - *Further into 4 hadronic and 3 leptonic categories separated by XGBoost BDT, events with low BDT score are rejected. Low level variables are used in the MVA. (Input variables)*
- *Main background:*
  - *Had regions: continuum bkg. ($\gamma\gamma$, etc.) and non-$t\bar{t}$H Higgs (ggH, etc.).*
  - *Lep regions: continuum bkg. ($t\bar{t}\gamma\gamma$, etc) and resonant bkg. (tH, etc.).*





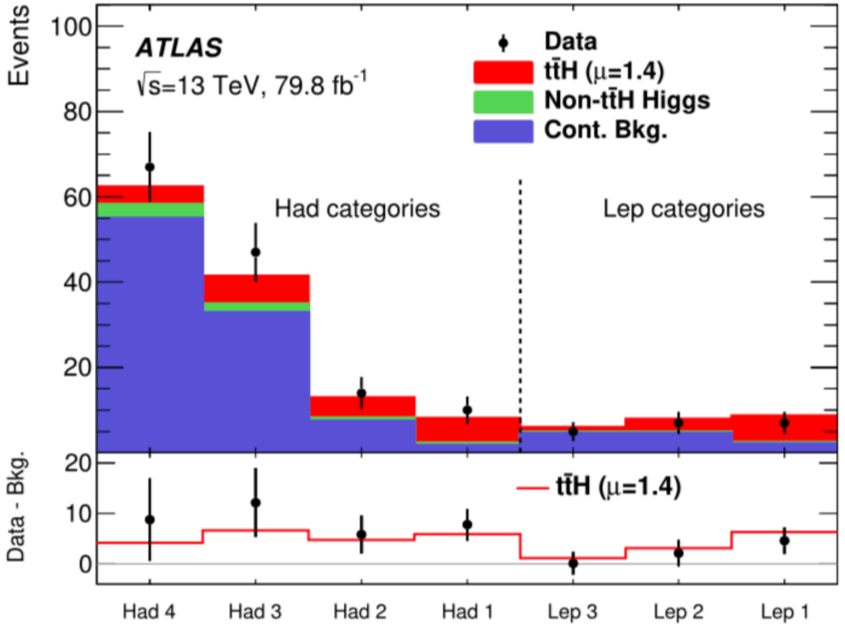
Physics Letters B 784 (2018)

ttH, H→$\gamma\gamma$



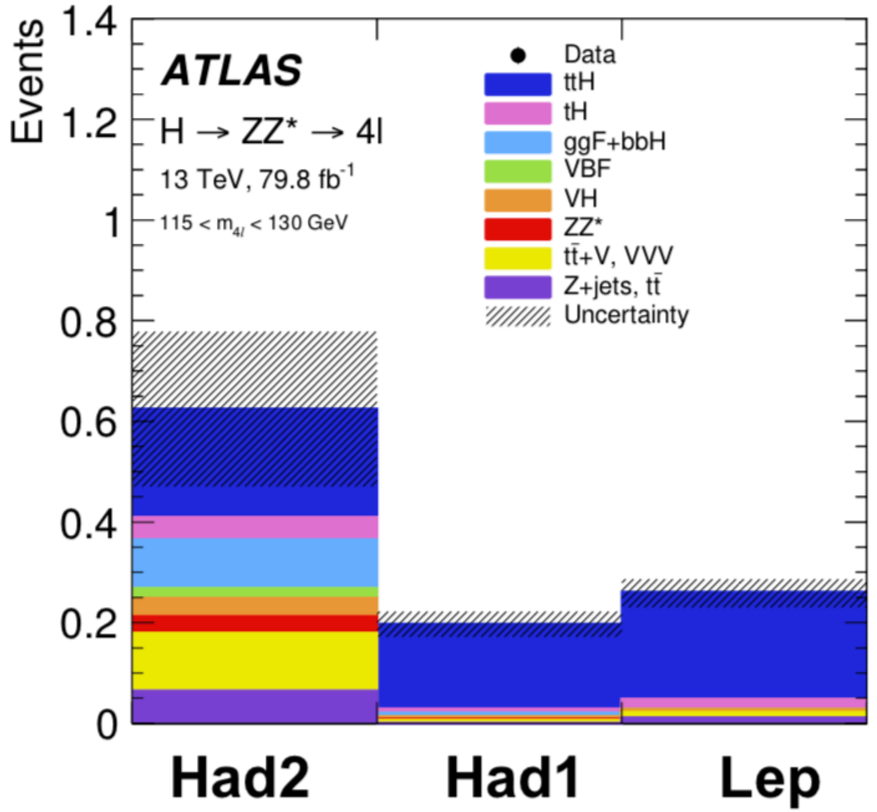
- *Combined unbinned fit to $m_{\gamma\gamma}$ distributions in the 7 categories.*
- *Signal modeling: Parameterize MC with double-sided crystal ball functions, normalized to 80 fb^{-1}.*
- *Background modeling: Analytical functions fitted on data. Functional forms and associated uncertainties are studied from dedicated background-only samples.*

- *The expected and observed event yields are in good agreement (Event count in mass window containing 90% of $t\bar{t}H$ signal).*
- *Signal significance: 4.1σ observed, 3.7σ expected.*
- *Still statistically limited!*
- *Dominant systematics: $t\bar{t}H$ parton shower model (8%), photon energy resolution (6%).*
- *Good agreement with SM predictions.*



ttH, H→ZZ*→4l

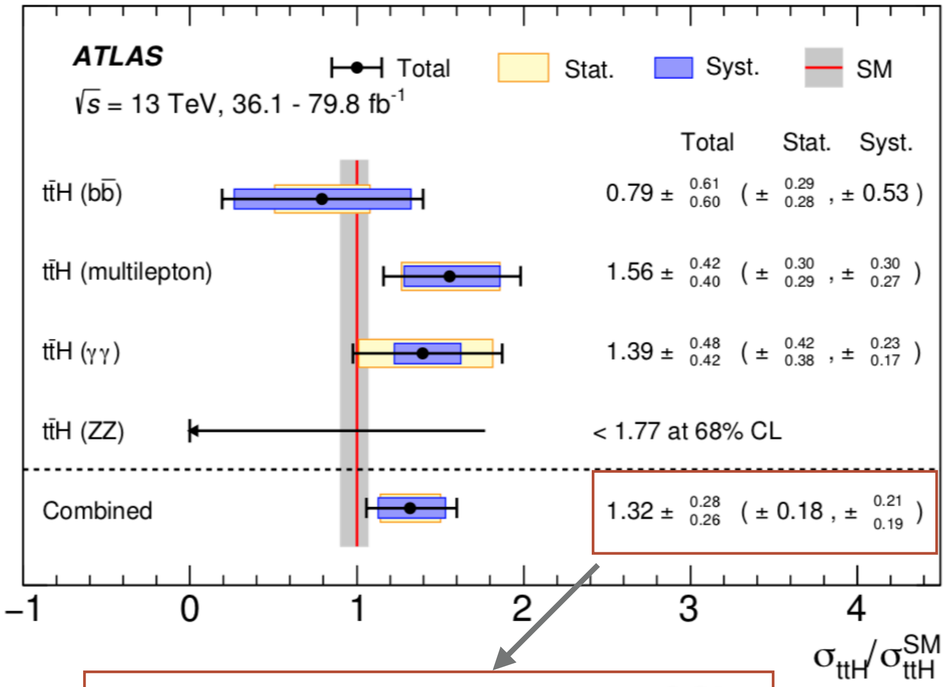
- *Use 79.8 fb^{-1} of p-p collision data from ATLAS experiment in 2015-2017.*
- *Very low statistics but large S/B.*
- *Selected as 4 isolated leptons formed into 2 same-flavor opposite-charge lepton pairs with $115<m_{4l}<130$ GeV and at least one b-tagged jet.*
  - *Lep region: ≥1l, ≥2j, ≥1b.*
  - *Had regions: 0l, ≥4j, ≥1b, further separated into 2 BDT discriminant.*
- *Background: ttV and non-$t\bar{t}H$ Higgs productions to SM).*
- *Expected significance 1.2σ (0.6 $t\bar{t}H$ events).*
- *Observed significance 0σ (0 $t\bar{t}H$+Bkg events).*
- *Largely statistically limited!*



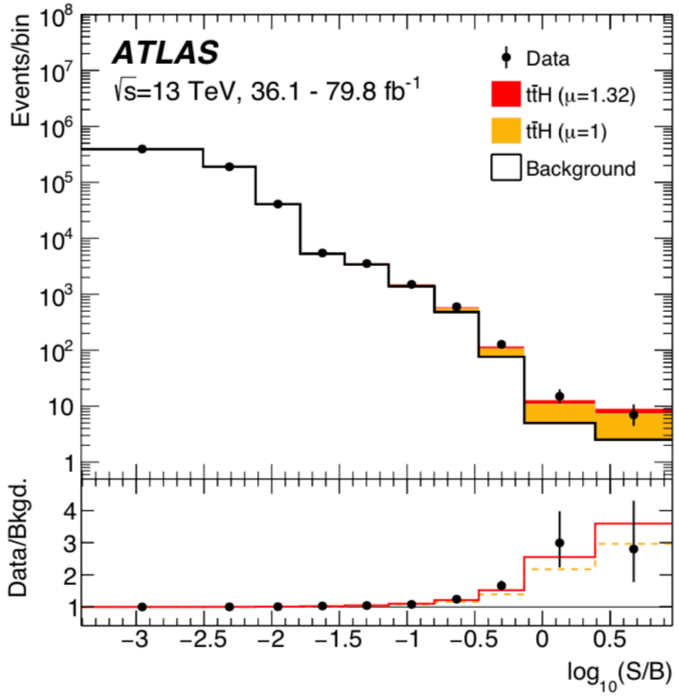
Physics Letters B 784 (2018)

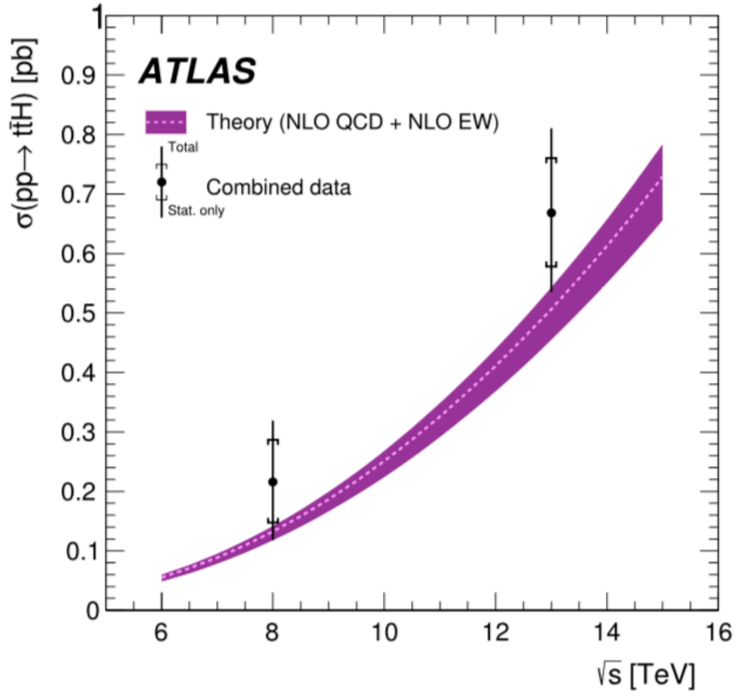
Combination

- *Combine the four 13 TeV $t\bar{t}H$ analyses based on simultaneous fits to the signal regions and control regions of the individual analyses.*
  - *$t\bar{t}H$, $H\to bb$, $t\bar{t}H$, Multi-lepton 36.1 fb^{-1},*
  - *$t\bar{t}H$, $H\to\gamma\gamma$, $t\bar{t}H$, $H\to ZZ^*\to 4l$ 79.8 fb^{-1}.*
- *Correlation scheme of all systematics has been studied.*
- *Non-ttH Higgs production are fixed to SM predictions.*



$$1.32 \pm {}^{0.28}_{0.26} \quad (\pm 0.18 , \pm {}^{0.21}_{0.19})$$





- *Observed event yields in all analysis categories, ranked by $\log_{10}(S/B)$.*
- *$t\bar{t}H$ cross sections in pp collisions at centre-of-mass energies of 8 TeV and 13 TeV are in agreement with SM prediction.*

Physics Letters B 784 (2018)

Combination

- *Total cross-section at $\sqrt{s}=13$ TeV measured with 20% precision.*
- *The observed (expected) signal significance is 5.8σ (4.9σ) in the Run 2 $t\bar{t}H$ combination.*
- *The observed (expected) signal significance is 6.3σ (5.1σ) in the Run 1 + Run 2 $t\bar{t}H$ combination.*
- *Observation of $t\bar{t}H$ process: major milestone in LHC Run-2 already reached!*

Analysis	Integrated luminosity [fb^{-1}]	$t\bar{t}H$ cross section [fb]	Obs. sign.	Exp. sign.
$H \to \gamma\gamma$	79.8	$710\ ^{+210}_{-190}$ (stat.) $^{+120}_{-90}$ (syst.)	4.1σ	3.7σ
$H \to$ multilepton	36.1	790 ± 150 (stat.) $^{+150}_{-140}$ (syst.)	4.1σ	2.8σ
$H \to b\bar{b}$	36.1	$400\ ^{+150}_{-140}$ (stat.) $\pm$ 270 (syst.)	1.4σ	1.6σ
$H \to ZZ^* \to 4\ell$	79.8	<900 (68% CL)	0σ	1.2σ
Combined (13 TeV)	36.1–79.8	670 ± 90 (stat.) $^{+110}_{-100}$ (syst.)	5.8σ	4.9σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1–79.8	–	6.3σ	5.1σ

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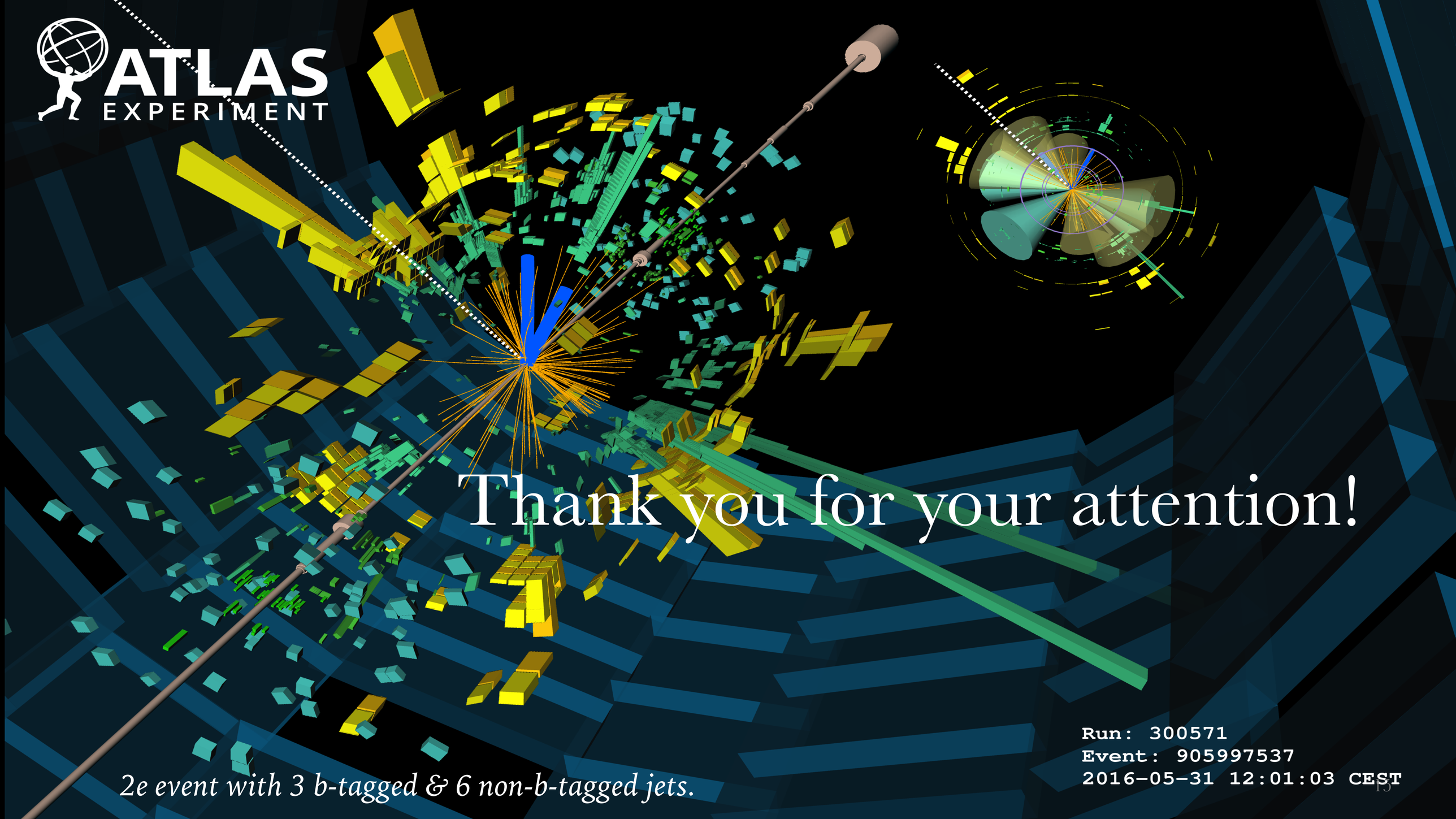
Conclusion

- ***The production of the $t\bar{t}H$ is observed (expected) with a significance of 6.3σ (5.1σ) combining 7, 8 and 13 TeV data.***
- ***The $t\bar{t}H$ production cross section at 13 TeV is measured to be*** $670 \pm 90\ (\text{stat.})\ ^{+110}_{-100}\ (\text{syst.})$***, in agreement with the Standard Model prediction*** $(507^{+35}_{-50}\ \text{fb})$***.***
- ***This constitutes a direct observation of the Yukawa coupling between the Higgs boson and the top quark.***



2e event with 3 b-tagged & 6 non-b-tagged jets.

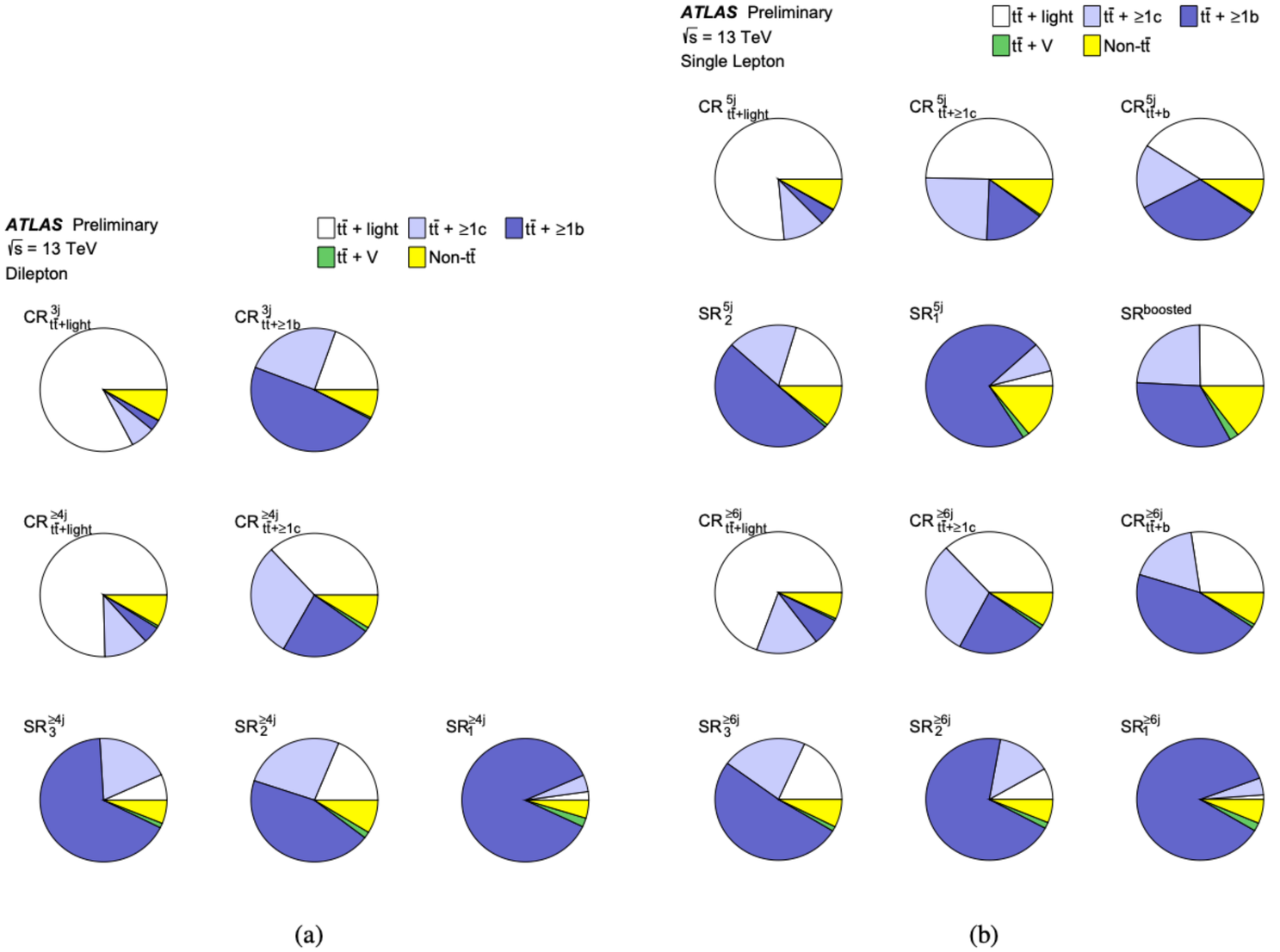


Figure 5: Fractional contributions of the various backgrounds to the total background prediction in each analysis category (a) in the dilepton channel and (b) in the single-lepton channel. The $t\bar{t}$ background is divided as described in Section 4. Figure 26 in Appendix E shows these contributions with a finer classification for the $t\bar{t} + \geq 1b$ background component.

Reconstruction BDT in dilepton channel

Variables	BDT with Higgs info. $SR_{1,2}^{\geq 4j}$	BDT with Higgs info. $SR_{3}^{\geq 4j}$	BDT w/o Higgs info. $SR_{1,2}^{\geq 4j}$	BDT w/o Higgs info. $SR_{3}^{\geq 4j}$
Topological information from $t\bar{t}$				
Mass of top	✓	✓	✓	✓
Mass of anti-top	✓	✓	✓	✓
Mass difference between top and anti-top	✓	✓	✓	✓
$\Delta R(\ell, b)$ from top	✓	✓	✓	✓
$\Delta R(\ell, b)$ from anti-top	✓	✓	✓	✓
—$\Delta R(\ell, b)$ from top - $\Delta R(\ell, b)$ from anti-top—	-	-	✓	✓
$\Delta\phi(b$ from top, b from anti-top)	-	✓	✓	✓
$\Delta R(b$ from top, b from anti-top)	✓	-	-	-
p_T b from top	-	-	✓	✓
p_T b from anti-top	-	-	✓	✓
Min. $\Delta\eta(\ell, b$ from top or anti-top)	-	-	✓	✓
Topological information from the Higgs-boson candidate				
Min. $\Delta R(b$ from Higgs, $\ell)$	-	✓	-	-
Max. ΔR(Higgs, b from top or anti-top)	✓	-	-	-
Mass of Higgs	✓	✓	-	-
$\Delta\phi$(Higgs,$t\bar{t}$)	-	✓	-	-
ΔR(Higgs,$t\bar{t}$)	✓	-	-	-
p_T b from Higgs with lowest b-tagging discriminant	-	✓	-	-
$\Delta R(b_1$ from Higgs, b_2 from Higgs)	✓	✓	-	-

Reconstruction BDT in 1-lepton channel

Variable	$SR^{\geq 6j}_{1,2,3}$	$SR^{5j}_{1,2}$
Topological information from $t\bar{t}$		
Mass of top_{lep}	✓	✓
Mass of top_{had}	✓	–
Mass of q_1 from W_{had} and b from top_{had}	–	✓
Mass of W_{had}	✓	–
Mass of W_{had} and b from top_{lep}	✓	–
Mass of q_1 from W_{had} and b from top_{lep}	–	✓
Mass of W_{lep} and b from top_{had}	✓	✓
$\Delta R(W_{\text{had}}, b \text{ from } \text{top}_{\text{had}})$	✓	–
$\Delta R(q_1 \text{ from } W_{\text{had}}, b \text{ from } \text{top}_{\text{had}})$	–	✓
$\Delta R(W_{\text{had}}, b \text{ from } \text{top}_{\text{lep}})$	✓	–
$\Delta R(q_1 \text{ from } W_{\text{had}}, b \text{ from } \text{top}_{\text{lep}})$	–	✓
$\Delta R(\ell, b \text{ from } \text{top}_{\text{lep}})$	✓	✓
$\Delta R(\ell, b \text{ from } \text{top}_{\text{had}})$	✓	✓
$\Delta R(b \text{ from } \text{top}_{\text{lep}}, b \text{ from } \text{top}_{\text{had}})$	✓	✓
$\Delta R(q_1 \text{ from } W_{\text{had}}, q_2 \text{ from } W_{\text{had}})$	✓	–
$\Delta R(b \text{ from } t_{\text{had}}, q_1 \text{ from } W_{\text{had}})$	✓	–
$\Delta R(b \text{ from } t_{\text{had}}, q_2 \text{ from } W_{\text{had}})$	✓	–
Min. $\Delta R(b \text{ from } \text{top}_{\text{had}}, q_i \text{ from } W_{\text{had}})$	✓	–
$\Delta R(\text{lep}, b \text{ from } \text{top}_{\text{lep}})$ - min. $\Delta R(b \text{ from } \text{top}_{\text{had}}, q_i \text{ from } W_{\text{had}})$	✓	✓
Topological information from the Higgs-boson candidate		
Mass of Higgs	✓	✓
Mass of Higgs and q_1 from W_{had}	✓	✓
$\Delta R(b_1 \text{ from Higgs}, b_2 \text{ from Higgs})$	✓	✓
$\Delta R(b_1 \text{ from Higgs}, \text{lepton})$	✓	✓
$\Delta R(b_1 \text{ from Higgs}, b \text{ from } \text{top}_{\text{lep}})$	–	✓
$\Delta R(b_1 \text{ from Higgs}, b \text{ from } \text{top}_{\text{had}})$	–	✓

pdfs used in calculation of signal and background probabilities for likelihood discriminant variables

$\mathrm{SR}^{\geq 6\mathrm{j}}_{1,2,3}$	$\mathrm{SR}^{5\mathrm{j}}_{1,2}$
$M_H(b_1, b_2)$	$M_H(b_1, b_2)$
$M_{t_l}(l, \nu, b_l)$	$M_{t_l}(l, \nu, b_l)$
$M_{W_h}(q_1, q_2)$	–
$[M_{t_h} - M_{W_h}](b_h, q_1, q_2)$	$M_{t_h}(b_h, q_1)$
$[M_{t_h t_l} - M_{t_h} - M_{t_l}](l, \nu, b_l, b_h, q_1, q_2)$	$[M_{t_h t_l} - M_{t_h} - M_{t_l}](l, \nu, b_l, b_h, q_1)$
$[M_{t_h t_l b_1 b_2} - M_{t_l t_h} - M_H](l, \nu, b_l, b_h, q_1, q_2, b_1, b_2)$	$[M_{t_h t_l b_1 b_2} - M_{t_l t_h} - M_H](l, \nu, b_l, b_h, q_1, b_1, b_2)$
$\cos\theta^*_{b_{1/2},H}(b_1, b_2)$	$\cos\theta^*_{b,H}(b_1, b_2)$
$\cos\theta^*_{b_1 b_2, t_h t_l b_1 b_2}(l, \nu, b_l, b_h, q_1, q_2, b_1, b_2)$	$\cos\theta^*_{b_1 b_2, t_h t_l b_1 b_2}(l, \nu, b_l, b_h, q_1, b_1, b_2)$

Classification BDT in boosted channel

Variable	Definition
Variables from jet reclustering	
$\Delta R_{H,t}$	ΔR between the Higgs-boson and top-quark candidates
$\Delta R_{t,b^{\mathrm{add}}}$	ΔR between the top-quark candidate and additional b-jet
$\Delta R_{H,b^{\mathrm{add}}}$	ΔR between the Higgs-boson candidate and additional b-jet
$\Delta R_{H,\ell}$	ΔR between the Higgs-boson candidate and lepton
$m_{\text{Higgs candidate}}$	Higgs-boson candidate mass
$\sqrt{d_{12}}$	Top-quark candidate first splitting scale [101]
Variables from b-tagging	
$w_{b\text{-tag}}$	Sum of b-tagging discriminants of all b-jets
$w^{\mathrm{add}}_{b\text{-tag}}/w_{b\text{-tag}}$	Ratio of sum of b-tagging discriminants of additional b-jets to all b-jets

Classification BDT in dilepton channel

Variable	Definition	$SR_1^{\geq 4j}$	$SR_2^{\geq 4j}$	$SR_3^{\geq 4j}$
General kinematic variables				
m_{bb}^{min}	Minimum invariant mass of a b-tagged jet pair	✓	✓	-
m_{bb}^{max}	Maximum invariant mass of a b-tagged jet pair	-	-	✓
$m_{bb}^{\text{min } \Delta R}$	Invariant mass of the b-tagged jet pair with minimum ΔR	✓	-	✓
$m_{\text{jj}}^{\text{max } p_{\text{T}}}$	Invariant mass of the jet pair with maximum p_{T}	✓	-	-
$m_{bb}^{\text{max } p_{\text{T}}}$	Invariant mass of the b-tagged jet pair with maximum p_{T}	✓	-	✓
$\Delta\eta_{bb}^{\text{avg}}$	Average $\Delta\eta$ for all b-tagged jet pairs	✓	✓	✓
$\Delta\eta_{\ell,\text{j}}^{\text{max}}$	Maximum $\Delta\eta$ between a jet and a lepton	-	✓	✓
$\Delta R_{bb}^{\text{max } p_{\text{T}}}$	ΔR between the b-tagged jet pair with maximum p_{T}	-	✓	✓
$N_{bb}^{\text{Higgs 30}}$	Number of b-tagged jet pairs with invariant mass within 30 GeV of the Higgs-boson mass	✓	✓	-
$n_{\text{jets}}^{p_{\text{T}}>40}$	Number of jets with $p_{\text{T}} > 40$ GeV	-	✓	✓
$\text{Aplanarity}_{b\text{-jet}}$	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor [100] built with all b-tagged jets	-	✓	-
$H_{\text{T}}^{\text{all}}$	Scalar sum of p_{T} of all jets and leptons	-	-	✓
Variables from reconstruction BDT				
BDT output	Output of the reconstruction BDT	✓**	✓**	✓
m_{bb}^{Higgs}	Higgs candidate mass	✓	-	✓
$\Delta R_{H,t\bar{t}}$	ΔR between Higgs candidate and $t\bar{t}$ candidate system	✓*	-	-
$\Delta R_{H,\ell}^{\text{min}}$	Minimum ΔR between Higgs candidate and lepton	✓	✓	✓
$\Delta R_{H,b}^{\text{min}}$	Minimum ΔR between Higgs candidate and b-jet from top	✓	✓	-
$\Delta R_{H,b}^{\text{max}}$	Maximum ΔR between Higgs candidate and b-jet from top	-	✓	-
$\Delta R_{bb}^{\text{Higgs}}$	ΔR between the two jets matched to the Higgs candidate	-	✓	-
Variables from b-tagging				
$w_{b\text{-tag}}^{\text{Higgs}}$	Sum of b-tagging discriminants of jets from best Higgs candidate from the reconstruction BDT	-	✓	-

Classification BDT in single lepton channel

Variable	Definition	$SR^{\geq 6j}_{1,2,3}$	$SR^{5j}_{1,2}$
General kinematic variables			
$\Delta R_{bb}^{\text{avg}}$	Average ΔR for all b-tagged jet pairs	✓	✓
$\Delta R_{bb}^{\text{max } p_T}$	ΔR between the two b-tagged jets with the largest vector sum p_T	✓	–
$\Delta\eta_{jj}^{\text{max}}$	Maximum $\Delta\eta$ between any two jets	✓	✓
$m_{bb}^{\text{min } \Delta R}$	Mass of the combination of two b-tagged jets with the smallest ΔR	✓	–
$m_{jj}^{\text{min } \Delta R}$	Mass of the combination of any two jets with the smallest ΔR	–	✓
$N_{bb}^{\text{Higgs } 30}$	Number of b-tagged jet pairs with invariant mass within 30 GeV of the Higgs-boson mass	✓	✓
H_T^{had}	Scalar sum of jet p_T	–	✓
$\Delta R_{\ell,bb}^{\text{min}}$	ΔR between the lepton and the combination of the two b-tagged jets with the smallest ΔR	–	✓
Aplanarity	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor [100] built with all jets	✓	✓
H_1	Second Fox–Wolfram moment computed using all jets and the lepton	✓	✓
Variables from reconstruction BDT			
BDT output	Output of the reconstruction BDT	✓*	✓*
m_{bb}^{Higgs}	Higgs candidate mass	✓	✓
$m_{H,b_{\text{lep top}}}$	Mass of Higgs candidate and b-jet from leptonic top candidate	✓	–
$\Delta R_{bb}^{\text{Higgs}}$	ΔR between b-jets from the Higgs candidate	✓	✓
$\Delta R_{H,t\bar{t}}$	ΔR between Higgs candidate and $t\bar{t}$ candidate system	✓*	✓*
$\Delta R_{H,\text{lep top}}$	ΔR between Higgs candidate and leptonic top candidate	✓	–
$\Delta R_{H,b_{\text{had top}}}$	ΔR between Higgs candidate and b-jet from hadronic top candidate	–	✓*
Variables from likelihood and matrix element method calculations			
LHD	Likelihood discriminant	✓	✓
MEM_{D1}	Matrix element discriminant (in $SR_1^{\geq 6j}$ only)	✓	–
Variables from b-tagging (not in $SR_1^{\geq 6j}$)			
$w_{b\text{-tag}}^{\text{Higgs}}$	Sum of b-tagging discriminants of jets from best Higgs candidate from the reconstruction BDT	✓	✓
B_{jet}^3	3^{rd} largest jet b-tagging discriminant	✓	✓
B_{jet}^4	4^{th} largest jet b-tagging discriminant	✓	✓
B_{jet}^5	5^{th} largest jet b-tagging discriminant	✓	✓

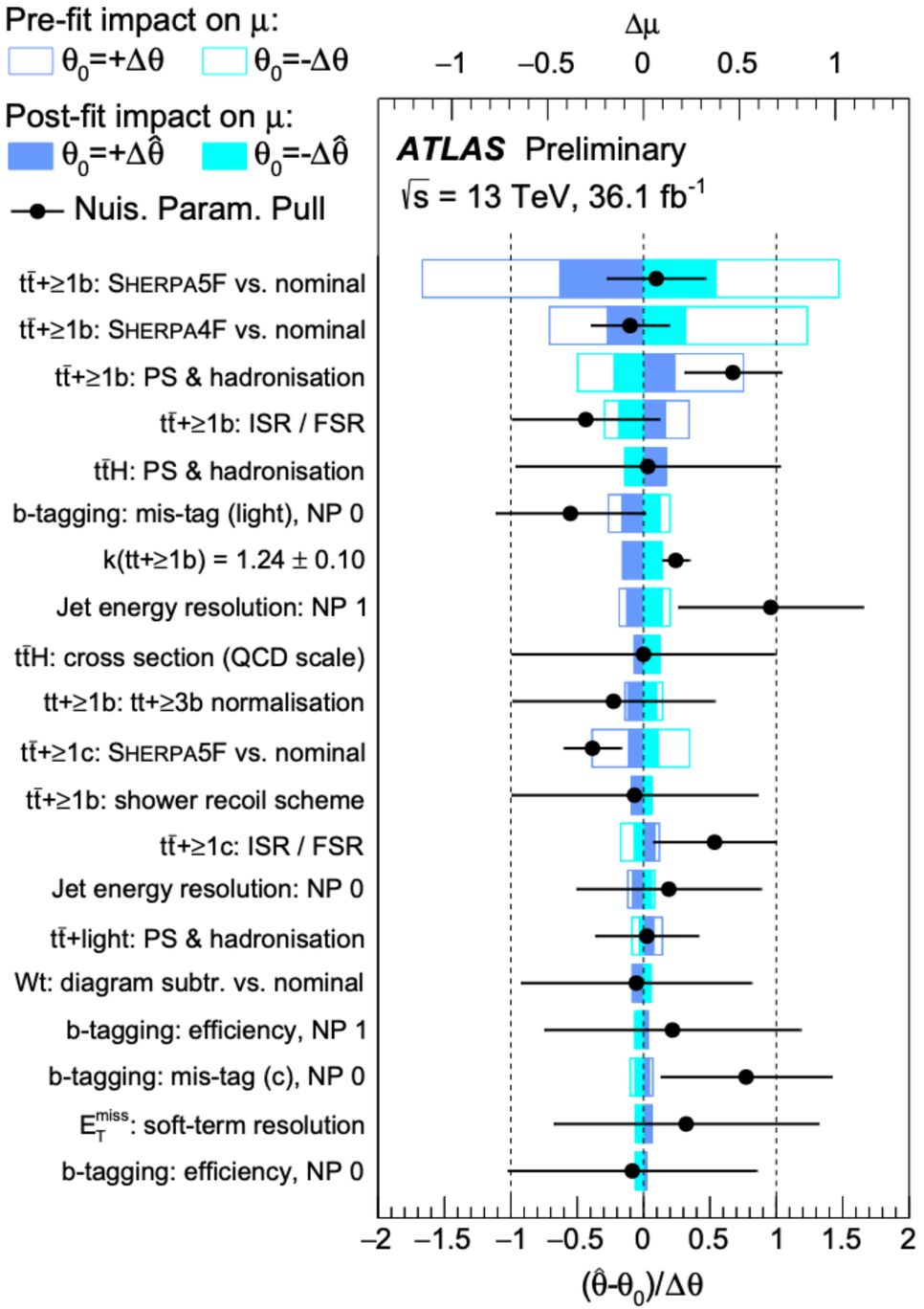

Pre-fit impact on μ:
θ0=+Δθ
θ0=-Δθ
Post-fit impact on μ:
θ0=+Δθ̂
θ0=-Δθ̂
Nuis. Param. Pull
Δμ
−1
−0.5
0
0.5
1
ATLAS Preliminary
√s = 13 TeV, 36.1 fb-1
tt̄+≥1b: SHERPA5F vs. nominal
tt̄+≥1b: SHERPA4F vs. nominal
tt̄+≥1b: PS & hadronisation
tt̄+≥1b: ISR / FSR
tt̄H: PS & hadronisation
b-tagging: mis-tag (light), NP 0
k(tt+≥1b) = 1.24 ± 0.10
Jet energy resolution: NP 1
tt̄H: cross section (QCD scale)
tt+≥1b: tt+≥3b normalisation
tt̄+≥1c: SHERPA5F vs. nominal
tt̄+≥1b: shower recoil scheme
tt̄+≥1c: ISR / FSR
Jet energy resolution: NP 0
tt̄+light: PS & hadronisation
Wt: diagram subtr. vs. nominal
b-tagging: efficiency, NP 1
b-tagging: mis-tag (c), NP 0
E_T^miss: soft-term resolution
b-tagging: efficiency, NP 0
−2
−1.5
−1
−0.5
0
0.5
1
1.5
2
(θ̂-θ0)/Δθ

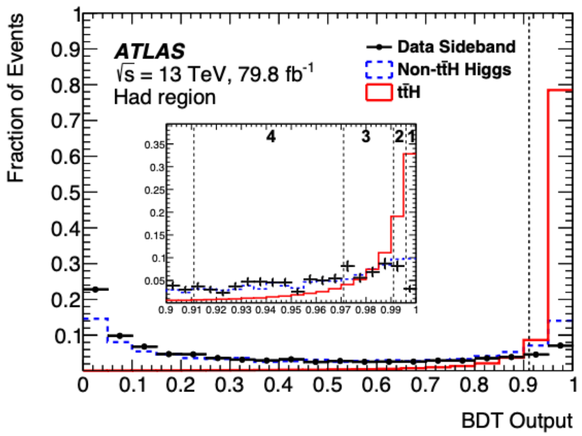
Table 10: Variables used in the multivariate analysis (denoted by $\times$) for the 2ℓSS, 3ℓ, 4ℓ (Z-enriched category), 1ℓ+$2\tau_{\text{had}}$, 2ℓSS+$1\tau_{\text{had}}$ and 2ℓOS+$1\tau_{\text{had}}$ channels. For 2ℓSS and 2ℓSS+$1\tau_{\text{had}}$, lepton 0 and lepton 1 are the leading and subleading leptons, respectively. For 3ℓ, lepton 0 is the lepton of opposite charge to the same-charge pair, while the same-charge leptons are labelled with increasing index as the distance from the opposite-charge lepton increases. The best Z-candidate dilepton invariant mass is the mass of the dilepton pair closest to the Z boson mass. The variables also used in the cross-check analyses are indicated by a $*$.

	Variable	2ℓSS	3ℓ	4ℓ	1ℓ+$2\tau_{\text{had}}$	2ℓSS+$1\tau_{\text{had}}$	2ℓOS+$1\tau_{\text{had}}$
Lepton properties	Leading lepton p_{T}		×				
	Second leading lepton p_{T}	×	×			×	
	Third lepton p_{T}		×				
	Dilepton invariant mass (all combinations)	×	×*				×
	Three-lepton invariant mass		×				
	Four-lepton invariant mass			×			
	Best Z-candidate dilepton invariant mass			×			
	Other Z-candidate dilepton invariant mass			×			
	Scalar sum of all leptons p_{T}			×			×
	Second leading lepton track isolation					×	
	Maximum $\lvert\eta\rvert$ between two leptons	×				×*	
	Lepton flavour	×*	×*				
	Lepton charge		×				
Jet properties	Number of jets	×*	×*		×	×	×
	Number of b-tagged jets	×*	×*		×	×	×
	Leading jet p_{T}						×
	Second leading jet p_{T}		×			×*	
	Leading b-tagged jet p_{T}		×				
	Scalar sum of all jets p_{T}		×		×	×	×
	Scalar sum of all b-tagged jets p_{T}						×
	Has leading jet highest b-tagging weight?		×				
	b-tagging weight of leading jet		×				
	b-tagging weight of second leading jet		×			×	
	b-tagging weight of third leading jet					×	
	Pseudo-rapidity of fourth leading jet					×	
τ_{had}	Leading τ_{had} p_{T}				×		×
	Second leading τ_{had} p_{T}				×		
	Di-tau invariant mass				×		
	Invariant mass τ_{had} –furthest lepton					×	
Angular distances	ΔR lepton 0–lepton 1		×				
	ΔR lepton 0–lepton 2		×				
	ΔR lepton 0–closest jet	×	×				
	ΔR lepton 0–leading jet		×			×	
	ΔR lepton 0–closest b-jet		×				
	ΔR lepton 1–closest jet	×	×				
	ΔR lepton 2–closest jet		×				
	Smallest ΔR lepton–jet		×				×
	Smallest ΔR lepton–b-tagged jet						×
	Smallest ΔR non-tagged jet–b-tagged jet						×
	ΔR lepton 0–τ_{had}						×
	ΔR lepton 1–τ_{had}						×
	Minimum ΔR between all jets				×		
	ΔR between two leading jets					×	
$\vec{p}_{\text{T}}^{\text{miss}}$	Missing transverse energy $E_{\text{T}}^{\text{miss}}$	×		×			
	Azimuthal separation leading jet-$\vec{p}_{\text{T}}^{\text{miss}}$		×				
	Transverse mass leptons (H/Z decay) - $\vec{p}_{\text{T}}^{\text{miss}}$			×			
	Pseudo-Matrix-Element			×			

Hadronic channel

ttH (H→γγ)

- Target: all-hadronic top-quark pair decays, or semi-leptonic top-quark pair decays with leptons not identified
- BDT trained with ttH simulation and data control region, using:
  - pT, η, ϕ, and b-tag status of first 6 jets (sorted by pT)
  - MET and ϕ(MET)
  - pT/mγγ, η, and ϕ of 2 photons

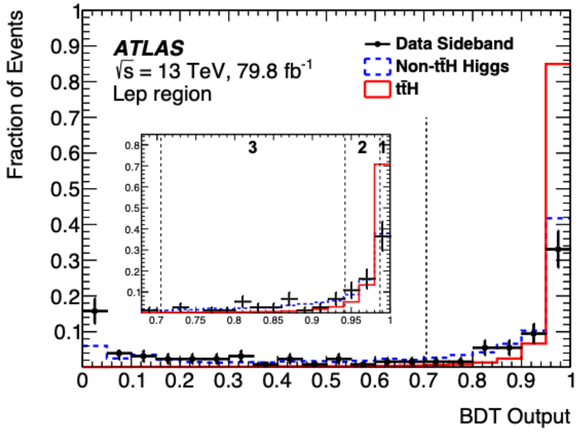


- Define 4 categories in hadronic channel based on BDT output, to exploit its good separation power

Leptonic channel

ttH (H→γγ)

- Target: semi-leptonic top-quark pair decays
- BDT trained with ttH simulation and data control region, using:
  - pT, η, ϕ of first 4 jets, first 2 leptons (sorted by pT)
  - MET and ϕ(MET)
  - pT/mγγ, η, and ϕ of 2 photons



- Define 3 categories in leptonic channel based on BDT output, to exploit its good separation power