

Search for the Higgs boson production in association with top quarks at $\sqrt{s} =$ 13 TeV

Haichen Wang
Lawrence Berkeley National Laboratory

for the ATLAS Collaboration

Division of Particles and Fields, APS
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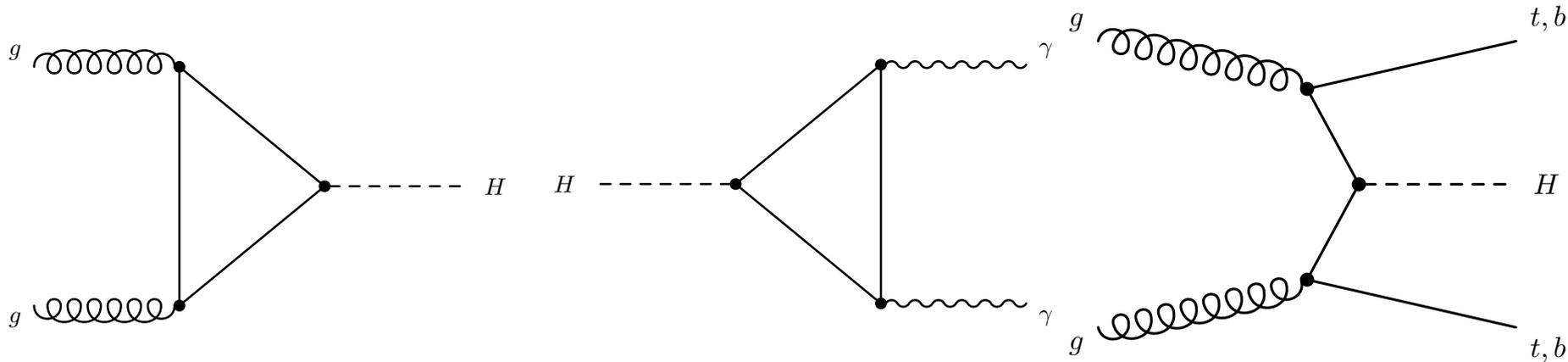
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Introduction

- The observation of the $t\bar{t}H$ production will be a direct evidence of the top-Higgs coupling and measurements of $t\bar{t}H$ process will provide insight on potential new physics
- The three main search channels
 - *Multilepton* (see Harish Potti's talk)
 - *bb* (13.8 fb^{-1} , 13 TeV)
 - *diphoton* (36.1 fb^{-1} , 13 TeV)

See Zirui Wang's talk on ATLAS $H \rightarrow \gamma\gamma$
Hongtao Yang's talk on ATLAS Higgs
combination

Top-Higgs coupling



Three main measurements sensitive to the Higgs-top coupling

- 1) Gluon fusion $gg \rightarrow H$
- 2) $H \rightarrow \gamma\gamma$ decay
- 3) ttH production

- First two measure loop-processes and are an indirect probe
- ttH production, a direct probe

Process ($ y_H < 2.5$)	SM prediction [pb]
ggF	$44.5^{+2.0}_{-3.0}$
VBF	$3.52^{+0.08}_{-0.07}$
VH	$1.99^{+0.06}_{-0.05}$
$t\bar{t}H$	$0.59^{+0.03}_{-0.05}$

Decay mode	Branching fraction [%]
$H \rightarrow bb$	57.5 ± 1.9
$H \rightarrow WW$	21.6 ± 0.9
$H \rightarrow gg$	8.56 ± 0.86
$H \rightarrow \tau\tau$	6.30 ± 0.36
$H \rightarrow cc$	2.90 ± 0.35
$H \rightarrow ZZ$	2.67 ± 0.11
$H \rightarrow \gamma\gamma$	0.228 ± 0.011
$H \rightarrow Z\gamma$	0.155 ± 0.014
$H \rightarrow \mu\mu$	0.022 ± 0.001

Assume the SM, $m_H = 125.09$ GeV, and 36.1 fb^{-1}
 $\sim 18,000$ ttH events

Three main search channels

- bb, largest branching ratio, high yield, challenging background
- Multilepton, collecting WW/ $\tau\tau$ /ZZ events, clean
- $\gamma\gamma$, well established fit procedure fro background estimation, small yield ~ 40

Search for $t\bar{t}H \rightarrow b\bar{b}$ with 13.2 fb^{-1} , 13 TeV data

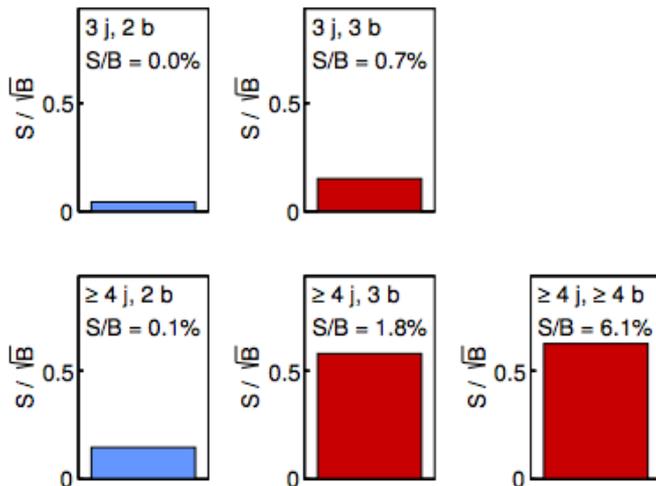
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- Focus on final states with leptons, for easy trigger
 - Single μ (24 GeV), single e (24 GeV)
 - Triggers with looser quality requirement and higher threshold also used
- Classify events to signal region (SR) and control region (CR) based on the multiplicities of lepton, jet and b-jet
- In each SR, a Boosted Decision Tree (BDT) or Neural Network (NN) classifier is trained from object kinematic or event level variables.
- Statistical test performed on SR BDT/NN spectra

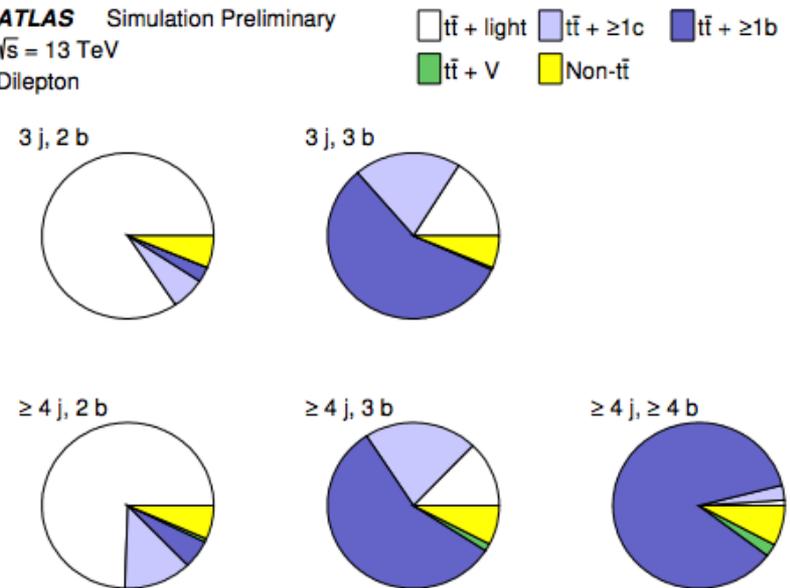
Dilepton channel

- Leptons $p_T > 25, 15$ GeV (10 GeV) for ee ($\mu\mu, e\mu$) events
- $m_{ll} < 83$ GeV or $m_{ll} > 99$ GeV, for $ee, \mu\mu$
- At least 3 jets ($p_T > 25$ GeV), including two b-tagged

ATLAS Simulation Preliminary
 $\sqrt{s} = 13$ TeV, 13.2 fb^{-1}
 Dilepton



ATLAS Simulation Preliminary
 $\sqrt{s} = 13$ TeV
 Dilepton

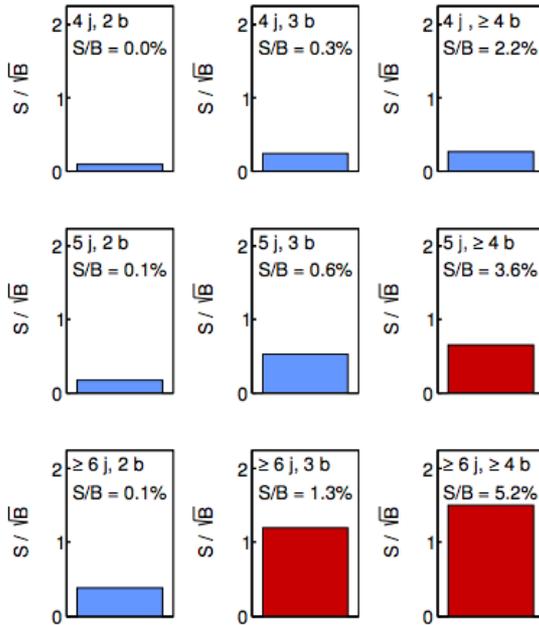


- Main background $t\bar{t} + b\bar{b}$

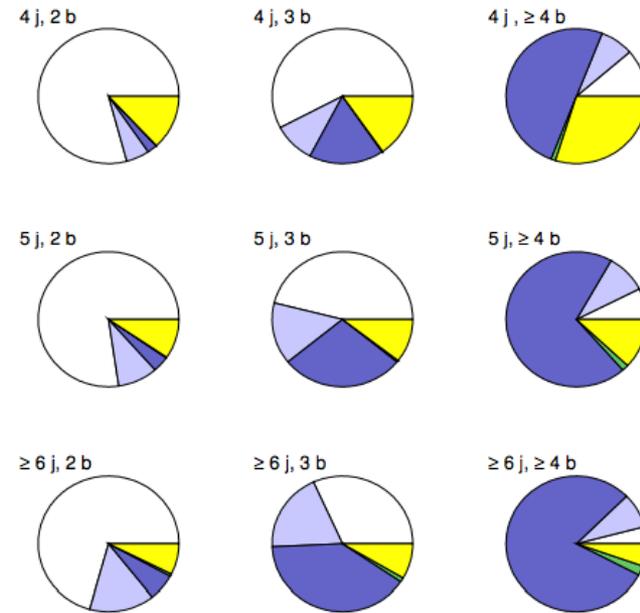
Single lepton channel

- Not selected by dilep. channel; $p_T > 25$ GeV
- Four jets, including two b-tagged

ATLAS Simulation Preliminary
 $\sqrt{s} = 13$ TeV, 13.2 fb^{-1}
 Single Lepton



ATLAS Simulation Preliminary
 $\sqrt{s} = 13$ TeV
 Single Lepton



Training variables

Single lepton

Variable	Definition	Region		
		$\geq 6j, \geq 4b$	$\geq 6j, 3b$	$5j, \geq 4b$
General kinematic variables				
ΔR_{bb}^{avg}	Average ΔR for all b -tagged jet pairs	✓	✓	✓
$\Delta R_{bb}^{max p_T}$	ΔR between the two b -tagged jets with the largest vector sum p_T	✓	–	–
$\Delta \eta_{jj}^{max}$	Maximum $\Delta \eta$ between any two jets	✓	✓	✓
$m_{bb}^{min \Delta R}$	Mass of the combination of the two b -tagged jets with the smallest ΔR	✓	✓	–
$m_{jj}^{min \Delta R}$	Mass of the combination of any two jets with the smallest ΔR	–	–	✓
$m_{bj}^{max p_T}$	Mass of the combination of a b -tagged jet and any jet with the largest vector sum p_T	–	✓	–
p_T^{jet5}	p_T of the fifth leading jet	✓	✓	✓
$N_{bb}^{Higgs 30}$	Number of b -jet pairs with invariant mass within 30 GeV of the Higgs boson mass	✓	–	✓
N_{40}^{jet}	Number of jets with $p_T \geq 40 GeV$	–	✓	–
H_T^{had}	Scalar sum of jet p_T	–	✓	✓
$\Delta R_{lep-bb}^{min \Delta R}$	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 [42] built with all jets	✓	✓	✓
Centrality	Scalar sum of the p_T divided by sum of the E for all jets and the lepton	✓	✓	✓
$H1$	Second Fox–Wolfram moment computed using all jets and the lepton	✓	✓	✓
Variables from reconstruction BDT output				
BDT output		✓*	✓*	✓*
m_H	Higgs boson mass	✓	✓	✓
$m_{H,blep top}$	Mass of Higgs boson and b -jet from leptonic top	✓	–	–
$\Delta R_{Higgs bb}$	ΔR between b -jets from the Higgs boson	✓	✓	✓
$\Delta R_{H,t\bar{t}}$	ΔR between Higgs boson and $t\bar{t}$ system	✓*	✓*	✓*
$\Delta R_{H,lep top}$	ΔR between Higgs boson and leptonic top	✓	–	–
$\Delta R_{H,bhad top}$	ΔR between Higgs boson and b -jet from hadronic top	–	✓*	✓*

Dilepton

Variable	Definition	Region		
		$\geq 4j, \geq 4b$	$\geq 4j, 3b$	$3j, 3b$
General kinematic variables				
$\Delta \eta_{bb}^{avg}$	Average $ \Delta \eta $ among pairs of b -jets	✓	–	–
$\Delta \eta_{bb}^{max}$	Maximum $\Delta \eta$ between any two b -jets	–	✓	✓
$\Delta \eta_{jj}^{avg}$	Average $\Delta \eta$ among jet pairs	–	✓	–
$\Delta R_{bb}^{max p_T}$	ΔR between the two b -tagged jets with the largest vector sum p_T	✓	✓	✓
ΔR_{bb}^{Higgs}	ΔR between the two b -tagged jets with mass closest to the Higgs boson mass	✓	–	–
$\Delta R_{bb}^{max m}$	ΔR between the two b -jets with the largest invariant mass	✓	✓	✓
$m_{bb}^{max p_T}$	Mass of the two b -tagged jets with the largest vector sum p_T	–	–	✓
m_{bb}^{Higgs}	Mass of the two b -tagged jets closest to the Higgs boson mass	✓	✓	✓
m_{bb}^{min}	Minimum mass of two b -tagged jets	–	–	✓
$m_{bb}^{min \Delta R}$	Mass of the combination of the two b -tagged jets with the smallest ΔR	✓	✓	✓
$p_{T,b}^{min}$	Minimum b -tagged jet p_T	–	–	✓
H_T^{all}	Scalar p_T sum of all leptons and jets	–	✓	✓
$N_{bb}^{Higgs 30}$	Number of b -jet pairs with invariant mass within 30 GeV of the Higgs boson mass	✓	–	✓
$N_{jj}^{Higgs 30}$	Number of jet pairs with invariant mass within 30 GeV of the Higgs boson mass	–	✓	–
Aplanarity	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor [42] built with all jets	✓	✓	✓
Centrality	Sum of the p_T divided by sum of the E for all jets and leptons	✓	–	✓
$H2_{jets}$	Third Fox–Wolfram moment computed using all jets	–	✓	–
$H4_{all}$	Fifth Fox–Wolfram moment computed using all jets and leptons	–	–	✓
Variables from reconstruction BDT output				
BDT output		✓*	✓*	–
m_H	Higgs boson mass	✓ ^(*)	✓ ^(*)	–
$\Delta \eta_{H,l}^{min}$	Minimum $\Delta \eta$ between the Higgs boson and a lepton	✓*	✓	–
$\Delta \eta_{H,l}^{max}$	Maximum $\Delta \eta$ between the Higgs boson and a lepton	✓*	✓	–
$\Delta \eta_{H,b}^{min}$	Minimum $\Delta \eta$ between the Higgs boson and a b -jet	✓*	–	–

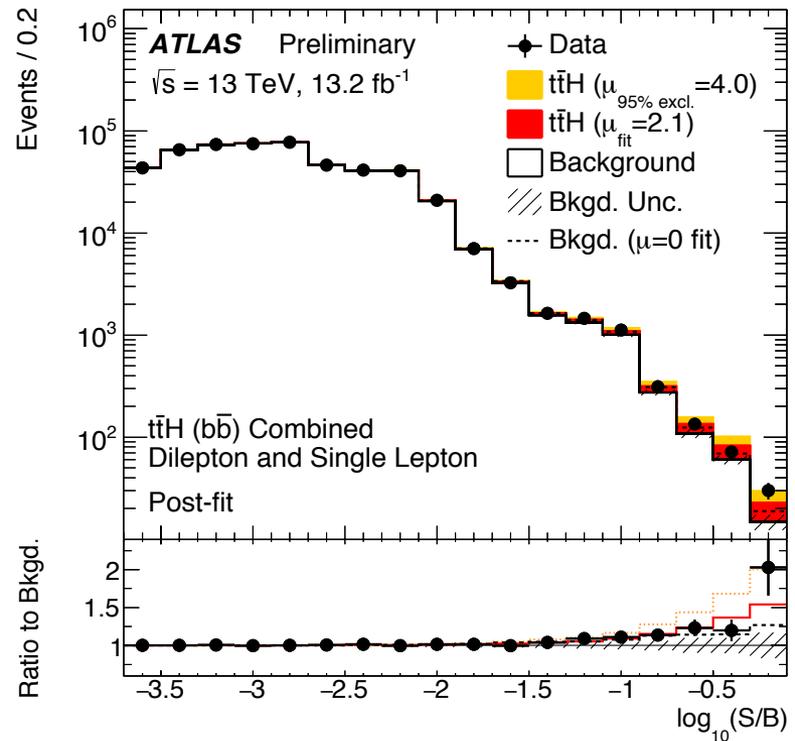
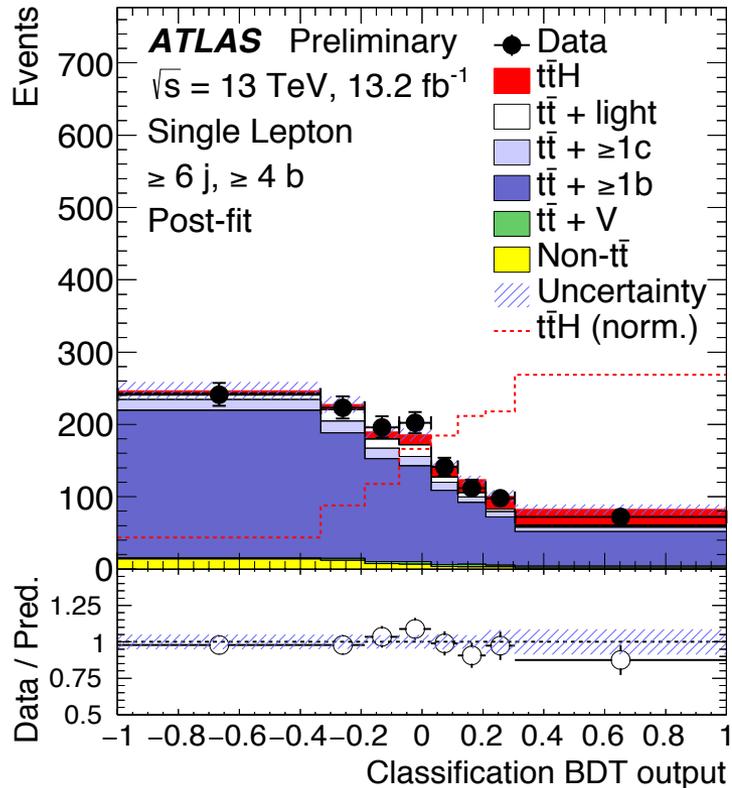
Event kinematics

- Multiplicity, p_T , H_T , etc.
- Angular information: $\Delta R, \Delta \eta$ between jets, b -jets, leptons, etc.

Event reconstruction BDT

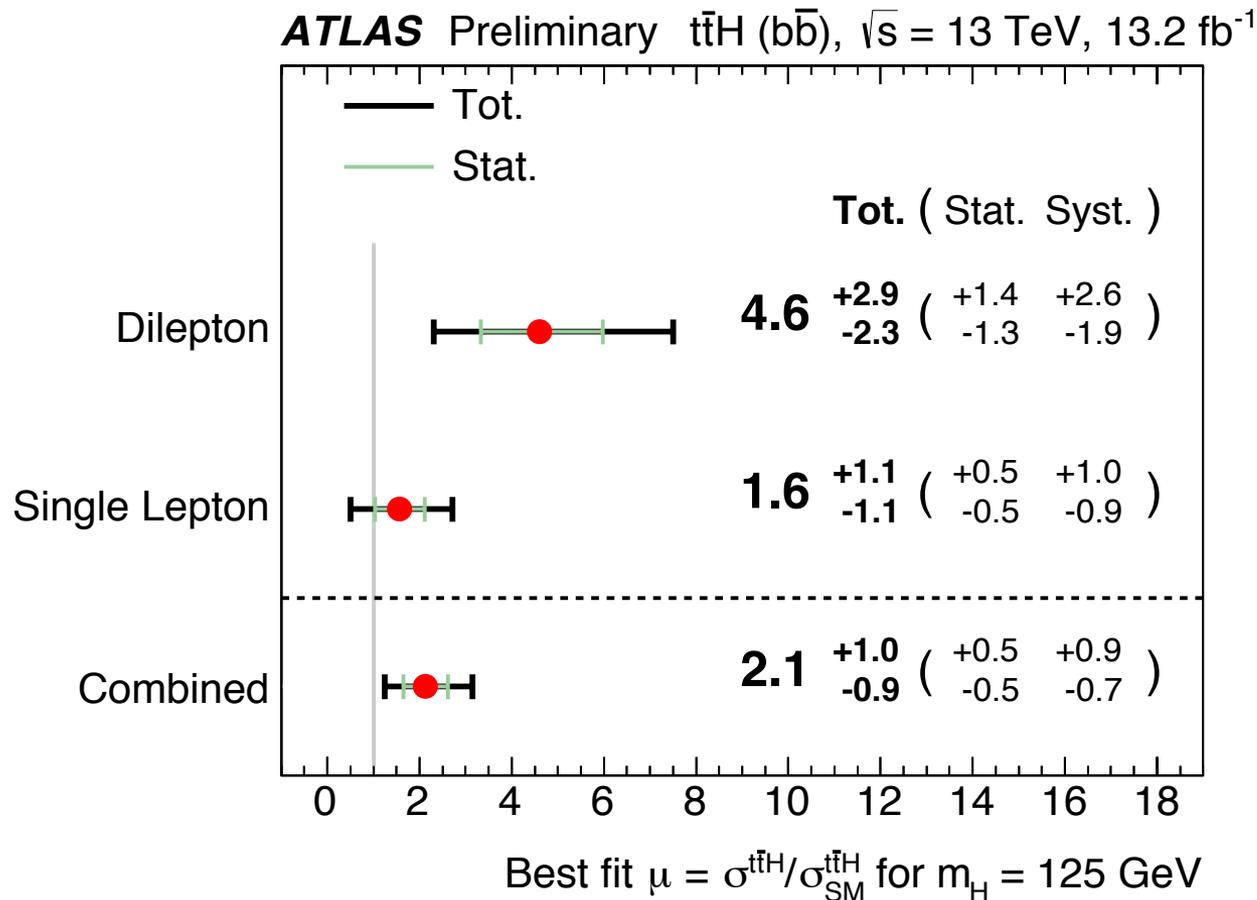
- Train a BDT to identify the correct object assignments for $t\bar{t}H$ events
- $m_H, \Delta R$ can be calculated from the resolved object assignments

Training variables



- Statistical test done on the 6 SR BDT (NN) distributions
- Left: Example distribution from (6j, 4b) SR
- Right: all bins used in the test sorted by S/B

Results with 13.2 fb⁻¹



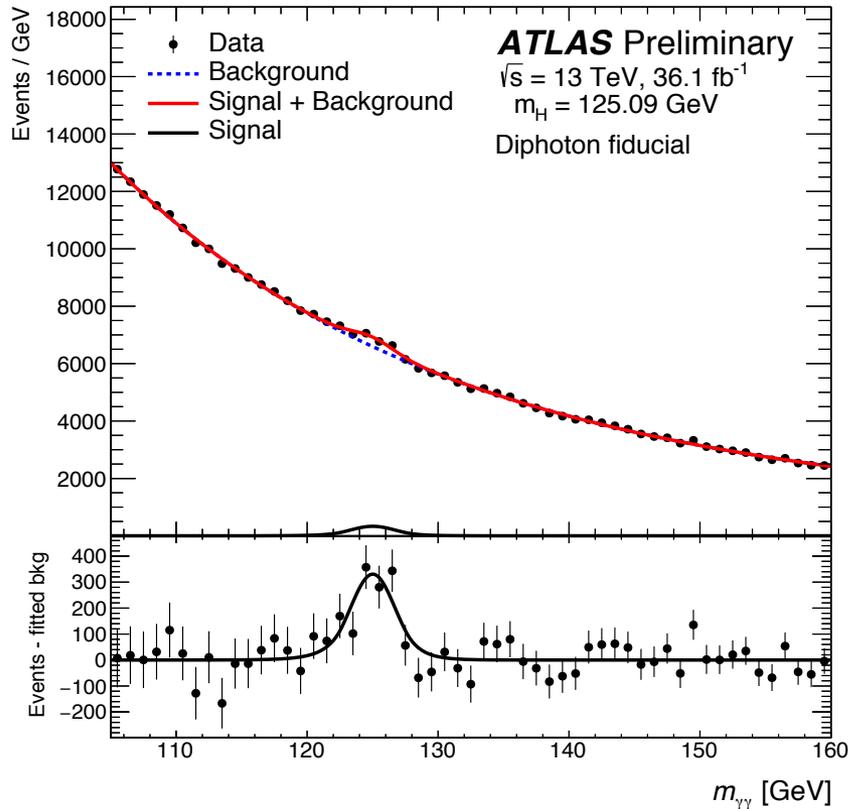
- $\sim 1 \sigma$ level sensitivity at 13.2 fb⁻¹ ; observed $\sim 2 \sigma$
- Uncertainty dominated by systematics
- Update coming soon

Search for $t\bar{t}H \rightarrow \gamma\gamma$ with 36.1 fb^{-1} , 13 TeV data

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Search for ttH in $\gamma\gamma$ final state

Use $\gamma\gamma$ to tag the Higgs boson; use additional objects (b-jet, lepton, jets) to single out the ttH events from all Higgs events.



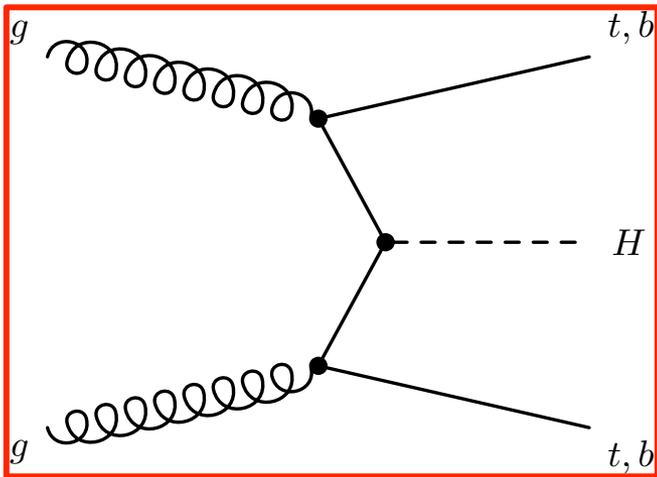
Diphoton selection

- $p_T/m > 0.4, 0.35$
- $|\eta| < 1.37$ | or | $1.52 < |\eta| < 2.37$
- Photon quality, Isolated

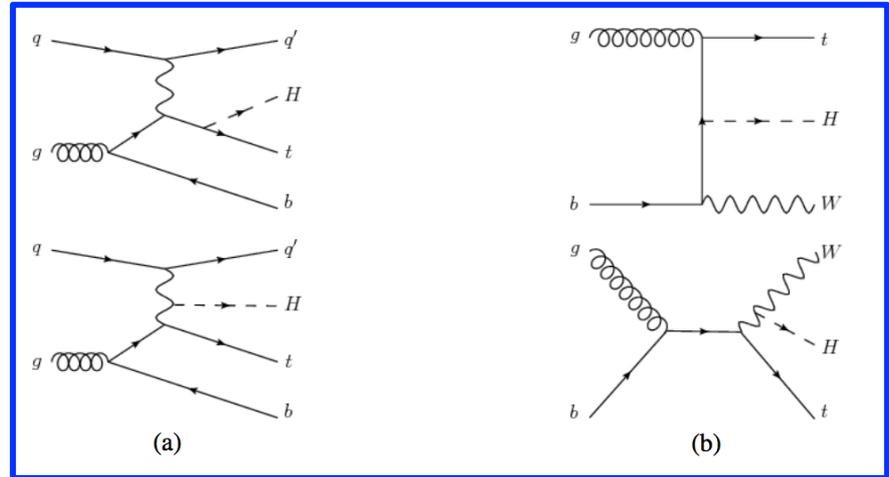
Events are classified to 31 categories, targeting different Higgs boson production modes

9 ttH categories; the other 22 categories used to constrain SM Higgs background

Categorization of ttH candidate events



ttH production



Single top Higgs (tH)

ttH categories and tH ($tWH+tHjb$) enriched categories

Leptonic events (≥ 1 lepton, ≥ 1 b-jet)

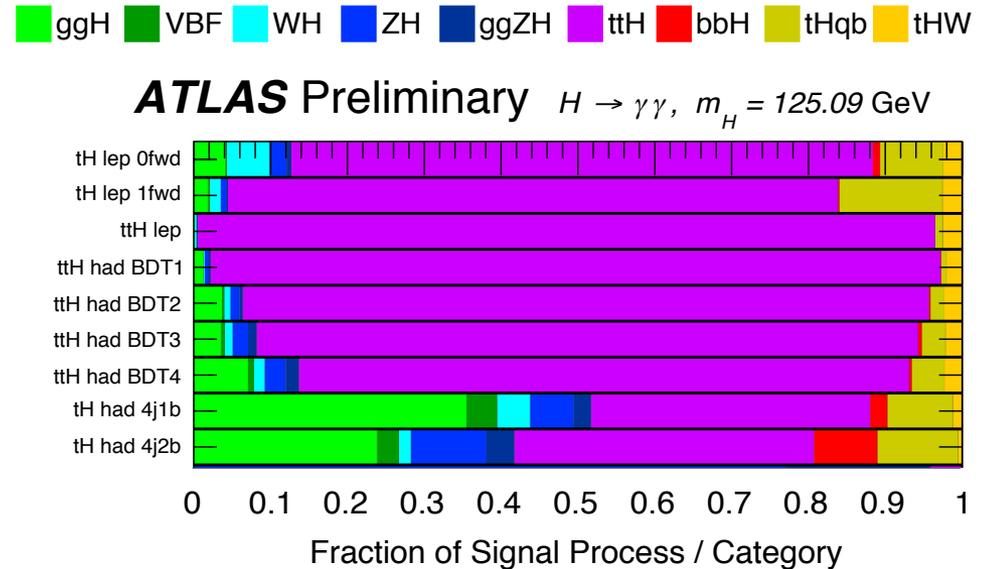
- #lep. = 1, #jet ($|\eta| < 2.5$) < 4, #jet ($|\eta| > 2.5$) = 0,
- #lep. = 1, #jet ($|\eta| < 2.5$) < 5, #jet ($|\eta| > 2.5$) > 0
- #lep. ≥ 1 , #jet ($|\eta| < 2.5$) ≥ 2 , mll veto

Hadronic events (≥ 1 lepton, ≥ 1 b-jet)

- #jet, #jet($|\eta| < 2.5$), #b-jet, H_T , mass of multijets trained to a BDT
- Four categories defined by BDT score
- #jet ($|\eta| > 2.5$) = 4, #b-jet = 1
- #jet ($|\eta| > 2.5$) = 4, #b-jet > 1

Categorization of ttH candidate events

- Signal acceptance ~ 40%
- ~16 ttH evnets selected, ~10.5 in the ttH categories



- ttH purity reaches 95% in the best categories (ttH lep and ttH had BDT1)
- tH fraction reaches 10 – 15 % in dedicated tH-enriched categories

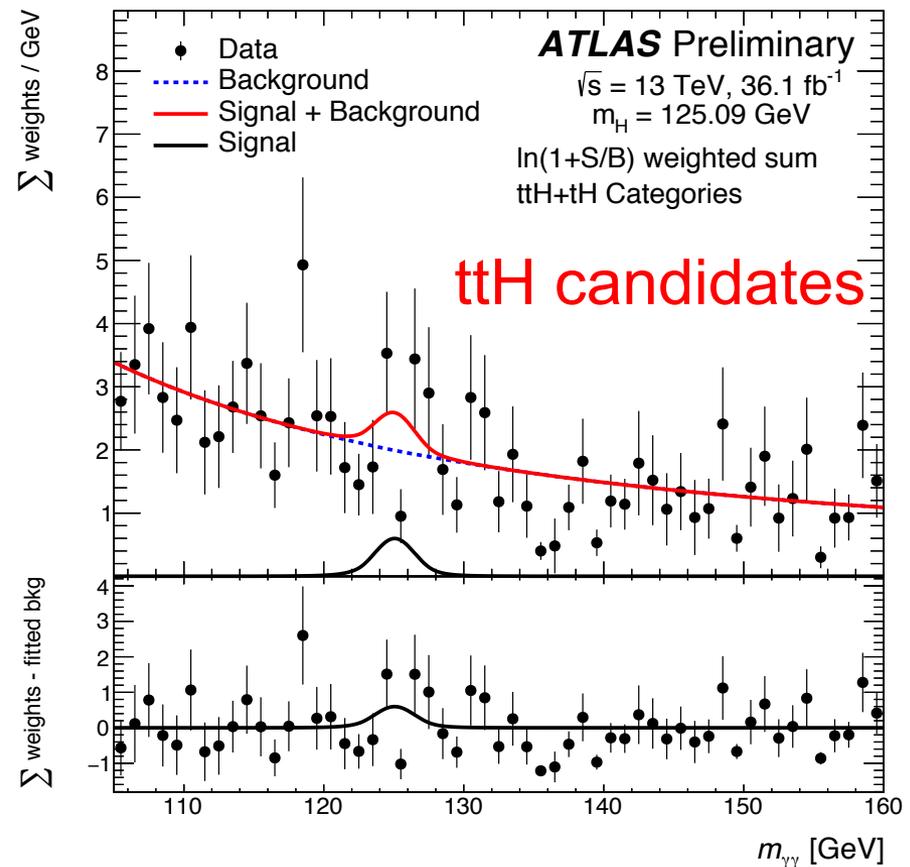
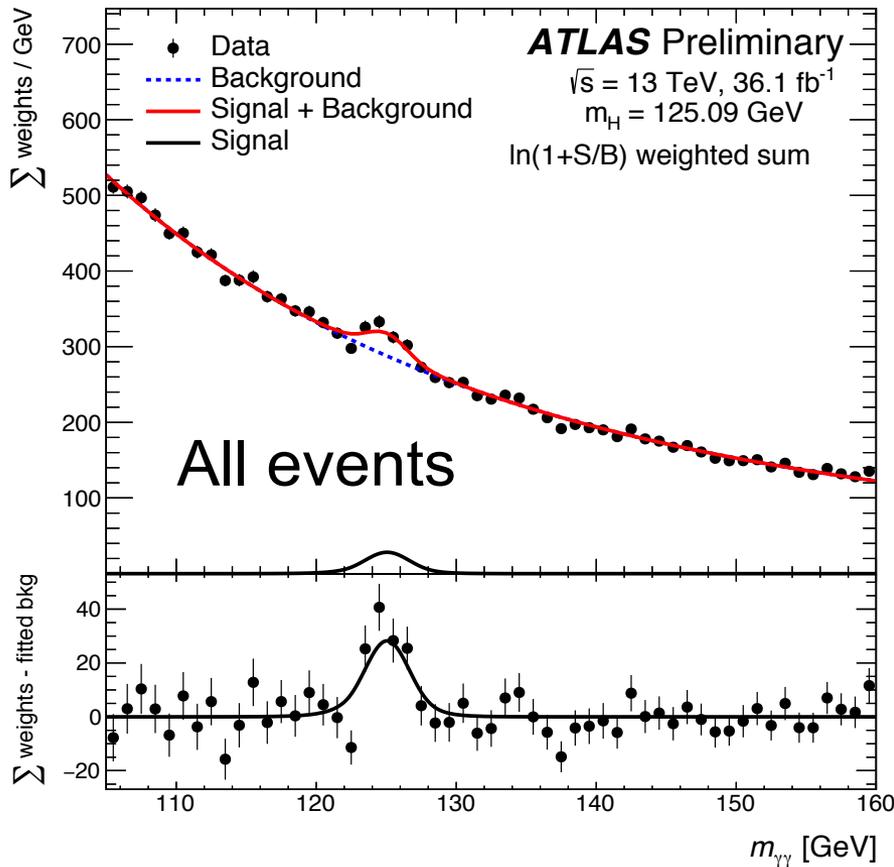
Categorization of ttH candidate events

Category	B_{90}	S_{90}	f_{90}	Z_{90}
tHhad_4j2b	6.8	0.56	0.08	0.2
tHhad_4j1b	48	2.3	0.05	0.3
ttHhad_BDT4	14	2.3	0.14	0.6
ttHhad_BDT3	2.3	0.55	0.19	0.4
ttHhad_BDT2	3.9	1.6	0.29	0.8
ttHhad_BDT1	2.0	1.3	0.40	0.9
ttHlep	2.7	2.2	0.44	1.2
tHlep_1fwd	1.9	1.0	0.35	0.7
tHlep_0fwd	3.6	0.92	0.20	0.5

- S/B varies between 16% and 65% for hadronic BDT categories, 25 – 81 % in leptonic categories

- Main background from $\gamma\gamma$ +jets / γ +jets in hadronic events; top + γ /jet important in leptonic events
- The largest Higgs background is ggH in hadronic events < 10 %

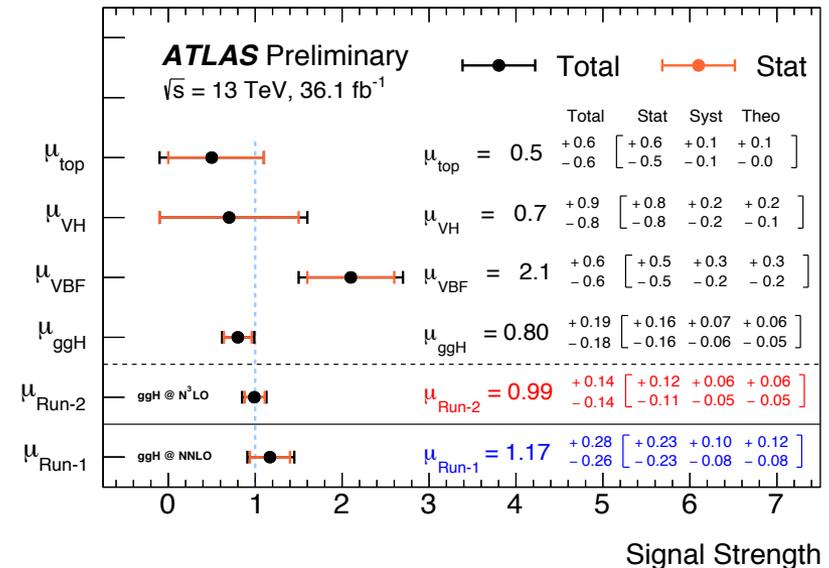
The observed mass spectra



- Weighted invariant mass distributions, based on $\log(1+s/b)$ of the category
- Visualization of category analysis

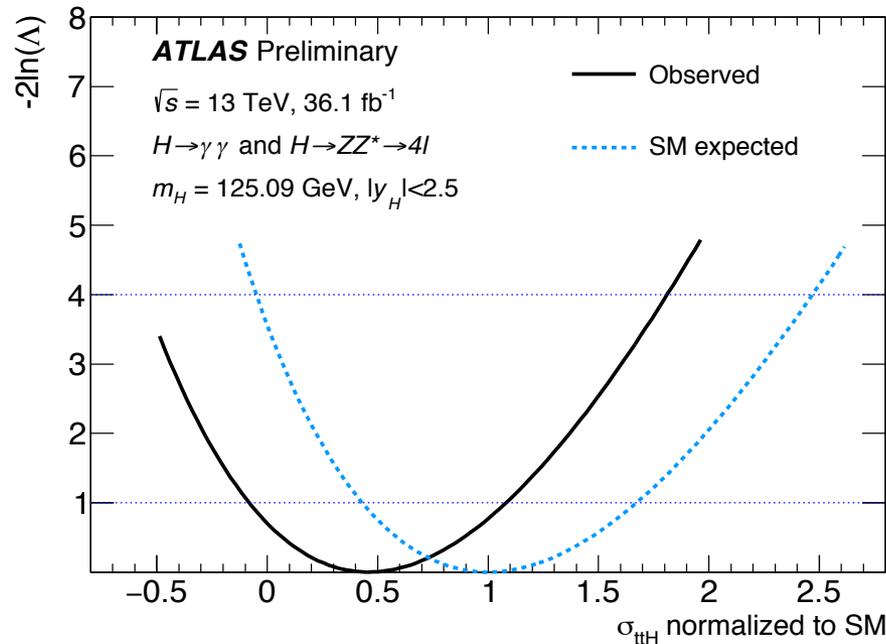
Measurement results

Measurement	Exp. Z_0	Obs. Z_0
μ_{top}	1.8σ	1.0σ



- Statistics test considers all ttH and tH processes as signal; other Higgs production modes treated as nuisance parameters
- Expected 1.8σ , observed 1.0σ
- ttH signal strength 0.5 ± 0.6 (0.5 stat. error)

Combination with 4l channel to better constrain other Higgs background processes



Result	Uncertainty		SM prediction
	Total	Stat. Syst.	
0.3	$+0.5$ -0.4	$\left(\begin{array}{c} +0.5 \\ -0.4 \end{array} \right) \pm 0.1$ pb	$0.59^{+0.04}_{-0.05}$ pb

Result essentially the same as $\gamma\gamma$ standalone, indicating measurement of ttH is largely decoupled from measurements of other Higgs processes

Summary

- Searches for ttH production in bb and $\gamma\gamma$ final states
 - ttH \rightarrow bb, result with 13.2 fb^{-1}
 - Lepton trigger, high jet multiplicity and high b-jet multiplicity, extensive multivariate analysis
 - Sensitivity at 1 sigma level
 - Expect an update soon
 - ttH \rightarrow $\gamma\gamma$, using 2015 and 2016 data, 36.1 fb^{-1}
 - Use diphoton to tag Higgs decay; use lepton, jet and b-jet to single out ttH events
 - Cut-based categorization for leptonic events; BDT-based for hadronic events
 - Expected 1.8 sigma; observed 1.0 sigma
 - Signal strength 0.5 ± 0.6