Search for ttH, H→bb in ATLAS

On behalf of ATLAS collaboration

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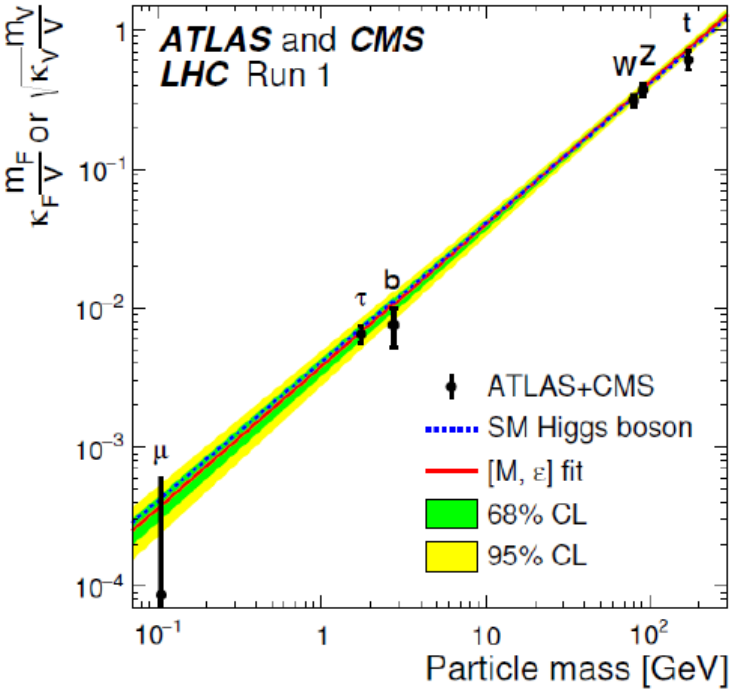
Higgs coupling 2016

SLAC, 2016 November 10

Search for ttH production

- To measure top Yukawa coupling
- History of ttH analysis
  - Tevatron (CDF & DZero)
    - μ (=σ_{ttH} (obs)/ σ_{ttH} (SM)) < 20 @95%CL
      PRL 109 (2012) 181802, D0-conf-H75
  - LHC Run-1
    - ATLAS: $\mu = 1.4 \pm 1.0$ (ttH, H→bb)
      EPJ. C (2015) 75:349, JHEP 05 (2016) 160
    - CMS : $\mu = 0.7 \pm 1.9$ (ttH, H→bb)
      JHEP 1409 (2014) 087
    - Coupling combination
      - 4.4 (2.0) σ observed (expected)
        JHEP 08 (2016) 045
  - LHC Run-2
    - CMS: $\mu = -2.0 \pm 1.8$ @ 2.7 fb^{-1}. CMS-PAS-HIG-16-004



Direct measurement has not been observed yet.

- Today
  - Run-2 ATLAS result on ttH, H→bb with 13.2 fb^{-1}
    - Focus on 1- and 2-lepton final state

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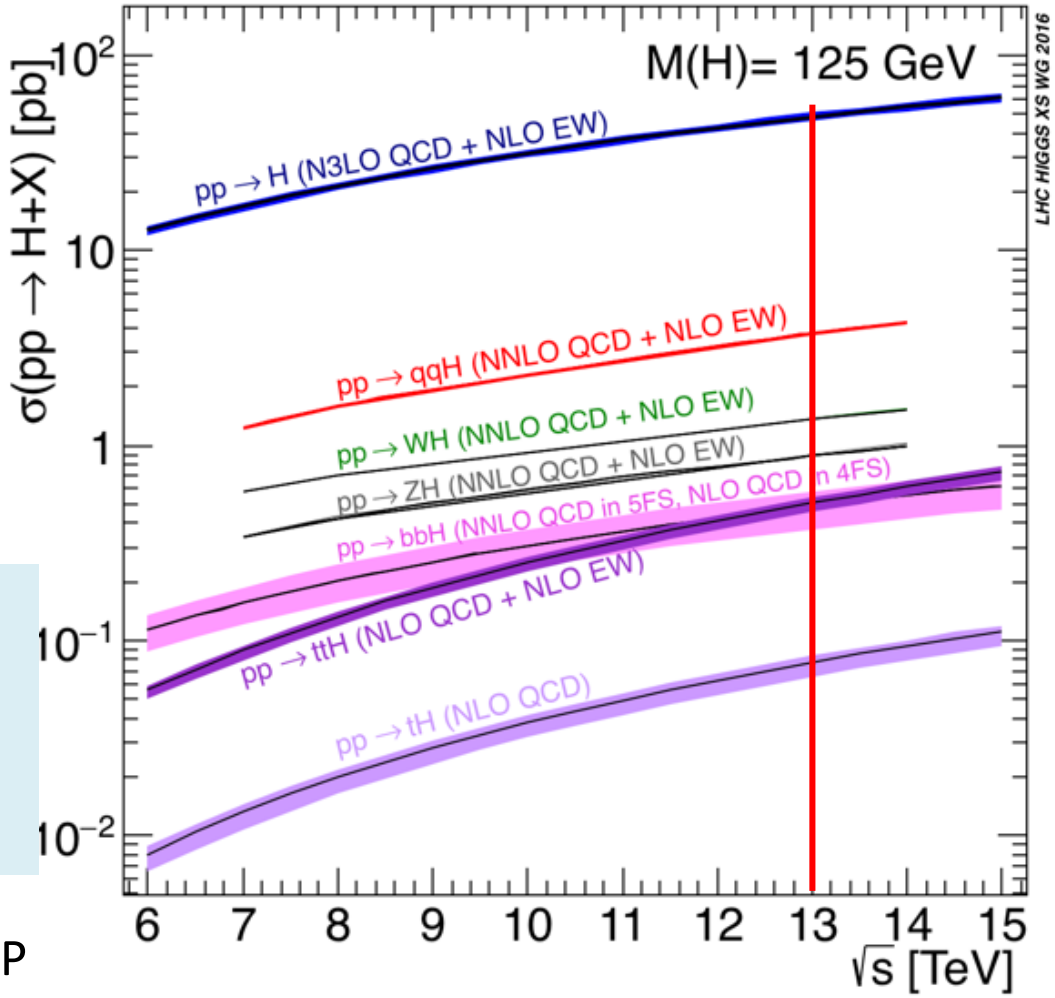
Run-1 to Run-2

- Run-2 at 13 TeV

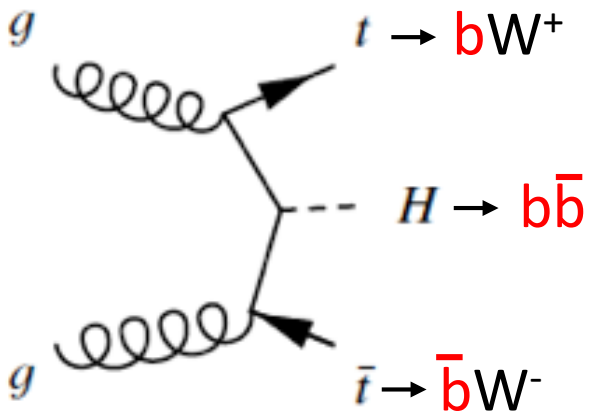
Higgs production X-section
@mH=125 GeV
19.3 pb @7 TeV
24.5 pb @8 TeV
55.7 pb @13 TeV
62.7 pb @14 TeV

8→13 TeV:
ggF: ×2.3
ttH: ×3.9
(ttbar inclusive : x 3.4)



ATLAS released ttH analysis at ICHEP
$\int L\,dt = 13.2\ fb^{-1}$ @13 TeV
ttH(σ_{SM}=0.51 pb): 6730 ttH events!

ttH, H→bb analysis



Depends on W decay:

0-lepton (Full hadronic, not yet for Run-2)

1-lepton (one of W decays leptonically)

Lepton p_T > 25 GeV

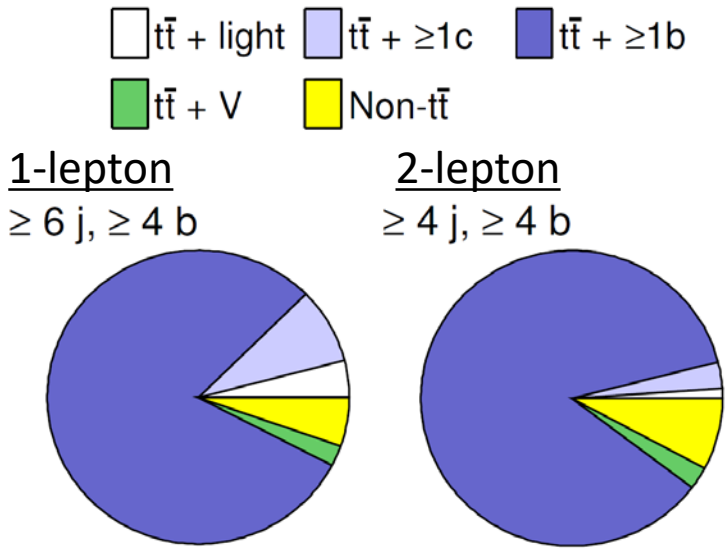
2-lepton (both Ws decay leptonically)

Lepton p_T^1 > 25 GeV, p_T^2 >15 (10) GeV for e(μ)

+ Jets (antiKt) pT>25 GeV, $|\eta|$<2.5

b-tagging (70%) is applied.

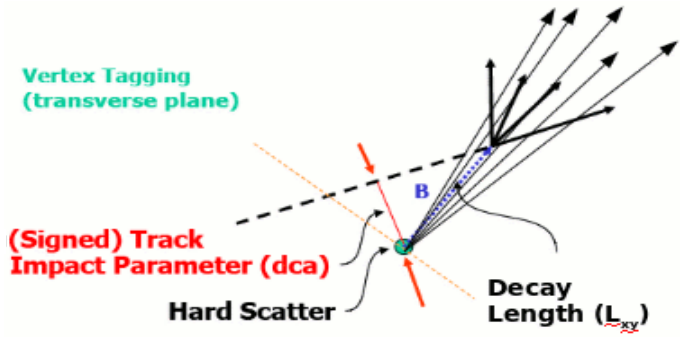
- Backgrounds
  - W+jets, Z+jets, single-top, Multi-jets
  - **ttbar (light, bb, cc)**
  - ttbar+vector boson
- b-jet identification and ttbar modeling are the key for this analysis.

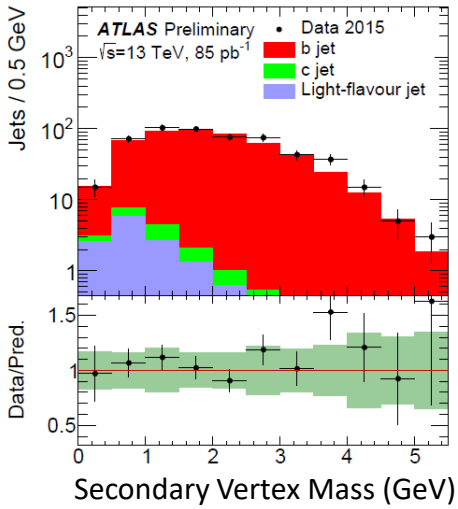


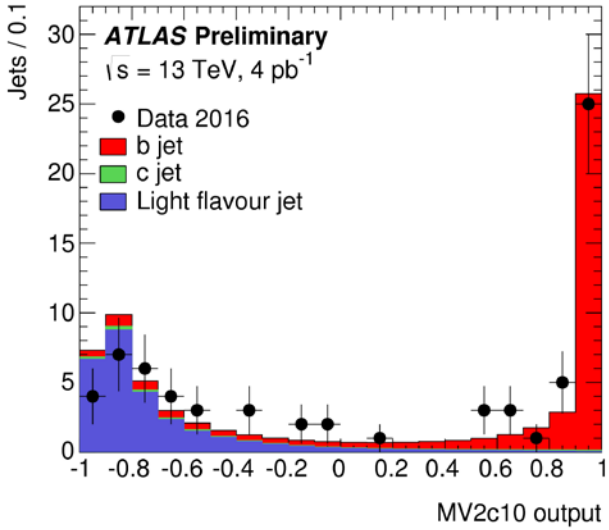
b-Jet tagging

ATLAS-FTAG-2016-001
ATL-PHYS-PUB-2015-022
ATL-PHYS-PUB-2015-039

- Utilize long life of B hadrons





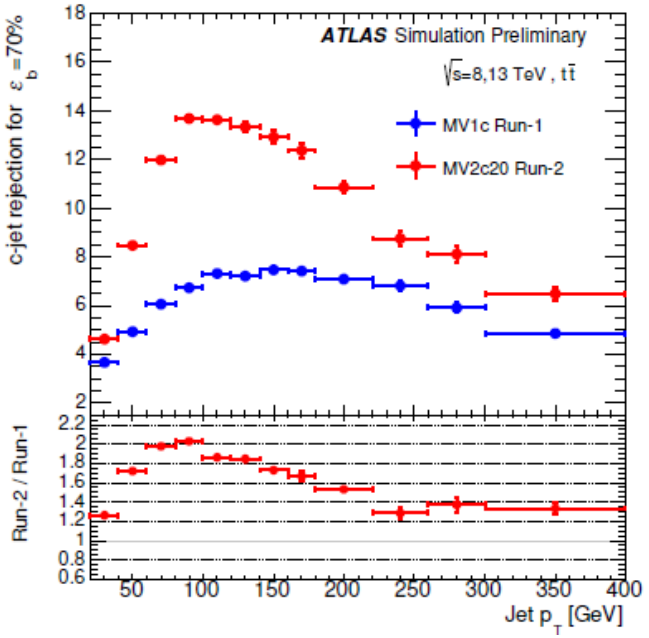


Improvements from Run-1 to Run-2

1. Training scheme of Multi Variate Analysis.
   Run-1 training: b-jet vs light jet
   → Run-2: b-jets vs (80% light + 20% **charm**)
2. Detector improvement
   Additional Pixel layer (IBL)

Low jet pT
→ **IBL** + **algorithm**

High jet pT
→ mainly **algorithm**

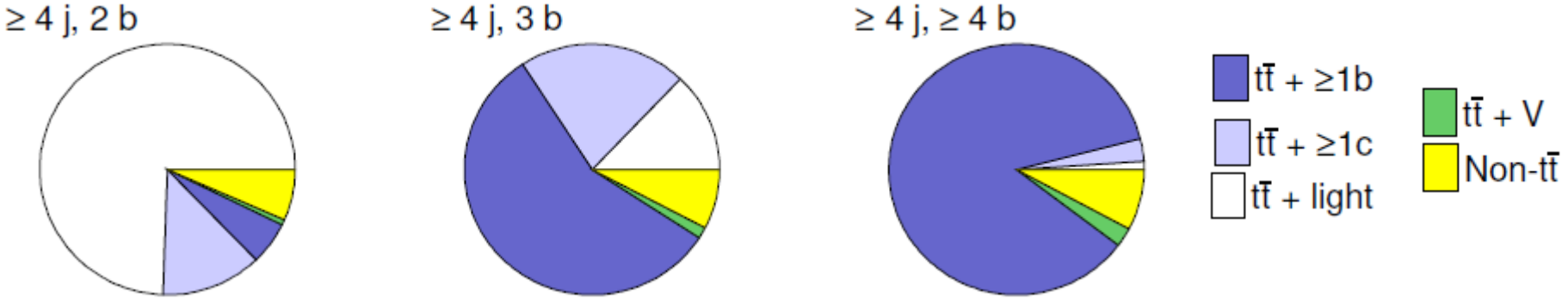


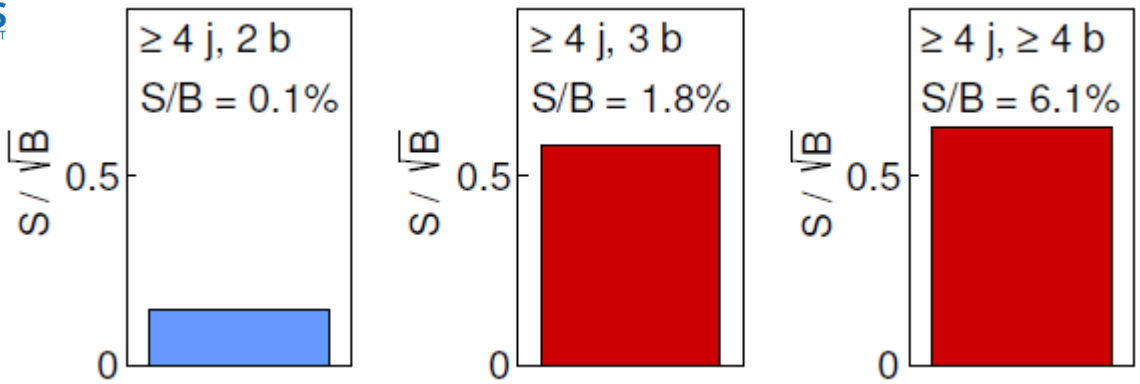
b-Jet tagging

- In the analysis

ATLAS Run2 b-tag performance
b: 70% eff., charm (light) rejection: 1/12 (1/380)

– Categorize event with number b-jet (i.e. 70% OP)





Example case for ATLAS ttH H→bb, dilepton

In most sensitive cat.
Expected # of ttH
6.6 events (2-lep)
45 events (1-lep)

Difficult points on ttH and solution

- **Event reconstruction**
  - 6 (4) jets with 4 b-jets for 1-(2-) lepton
    → Hundreds possibilities.
  - Solution: **Reconstruction BDT**
  - Newly introduced in Run-2!
- **Discriminate signal from background**
  - Solution: **Classification BDT**
    - Dilepton 3j3b: NN without reco BDT.
    - Run-1 used Matrix Element, but not yet for Run-2.
- **Background modeling**
  - ttbar + jets system is quite difficult to model correctly
    → numbers of systematic effect evaluated
  - Solution: Use control region to maximize systematic constraint
    H_T distributions are used for low S/N category
    - 1-lepton: H_T^{had} → scalar sum of E_T on Jets
    - 2-lepton: H_T^{all} → scalar sum of E_T on Jets and Leptons

Reconstruction BDT

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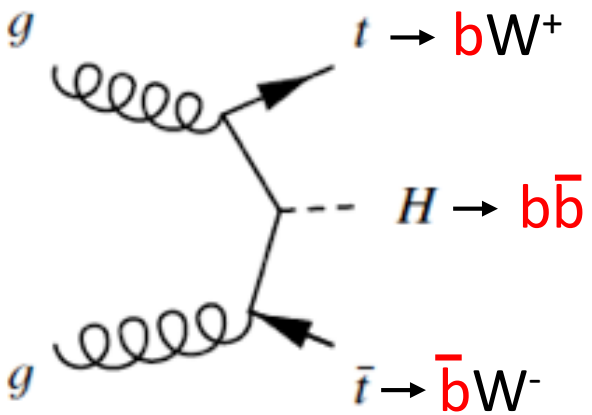
New approach in Run-2!

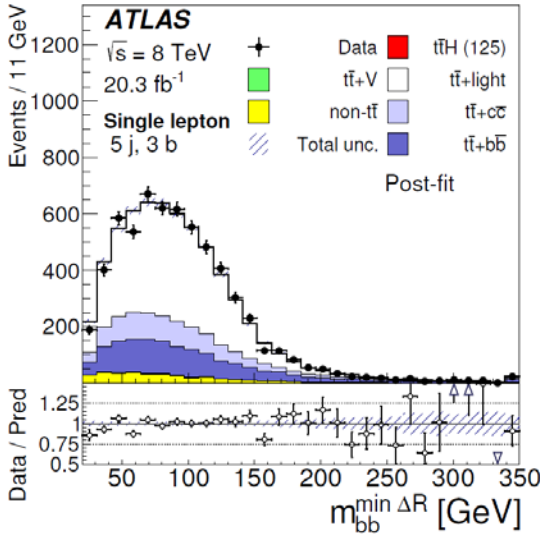


- How to find "right" assignment?
  - Examine angles and mass on reconstructed objects
    - Top, anti-top system
    - With H→bb
  - Train BDT with ttH MC
    - Signal: right assignment
    - BG : wrong assignments

Ex:

1-lep: 6 j4b → 19 variables.

2-lep: 4 j4b → 18 variables.



With reconstruction BDT

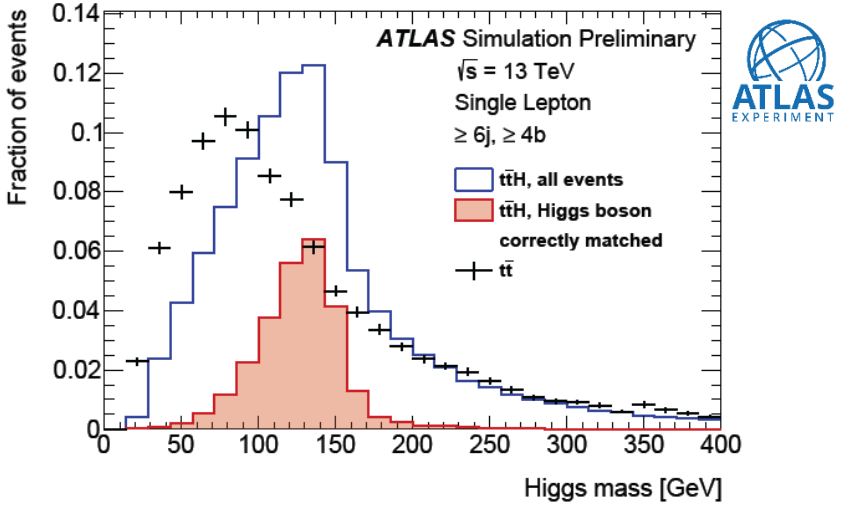
Fully correct assignment can be achieved

12% (max. 38%) for 1-lepton

42% (max. 93%) for 2-lepton

due to acceptance.

Note: 30% of event are matched H→bb.

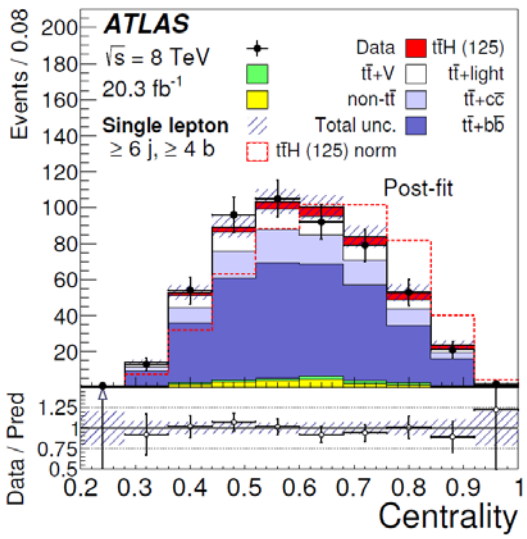


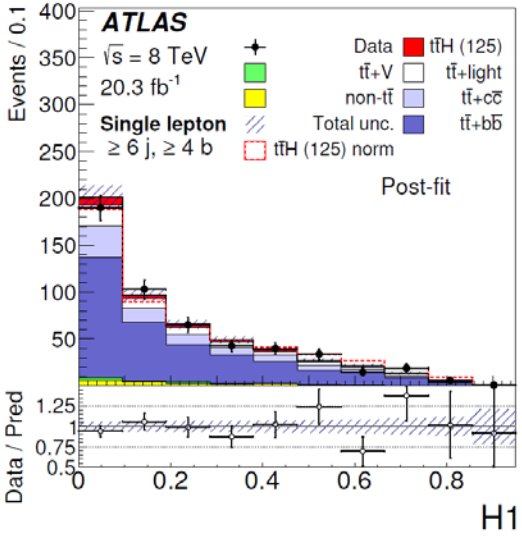
Classification BDT

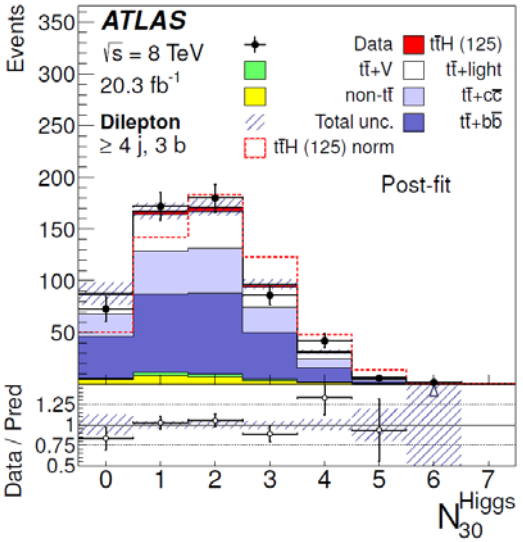
- Discriminate background from signal
  - BDT is used (NN for 2-lepton 3jet, 3 b-tag).
  - Object assignment from Reco BDT.
    - Reco BDT itself is also one of input variable.
    - Event shape information
      - Aplanarity, Centrality, Fox-Wolfram moment, HT, Njets
    - Mass, angles : mH, ΔR(H,ttbar), ΔR(H,lep/Had top)

Total:
~ 15 Variables

Examples on Input variables (from Run-1 analysis)







ttbar background modeling

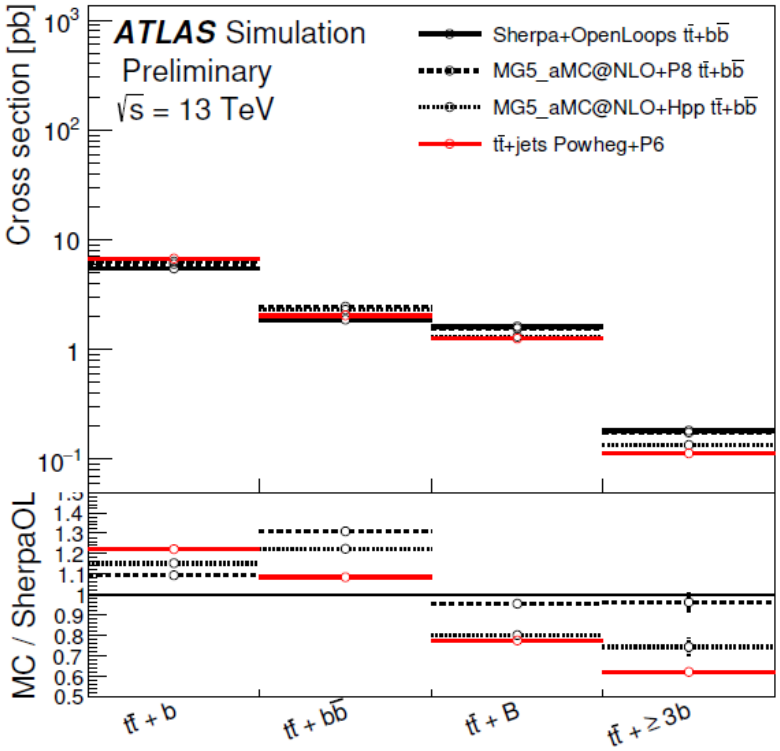
- No perfect generator!
  - NLO generators
- Default ttbar sample:
  - Powheg-box NLO +Pythia6.4
  - Top and ttbar system pT are corrected to NNLO calculation(arXiv: 1606.03350)
- ttbar + bb/cc
  - Reweight to Sherpa+OpenLoops
    - Each n-hadron bin separately.

Labeling on R=0.4 anti-kT jet

b/c denotes 1 b/c hadron

B/C denotes 2 b/c hadrons

ME gen.	MG5_aMC	MG5_aMC	SherpaOL
PS/UE gen.	Herwig++ 2.7.1	Pythia 8.210	Sherpa
Renorm. scale	μ_{CMMPS}	μ_{CMMPS}	μ_{CMMPS}
Fact. scale	$H_T/2$	$H_T/2$	$H_T/2$
Resumm. scale	$f_Q\sqrt{\hat{s}}$	$f_Q\sqrt{\hat{s}}$	$H_T/2$
ME PDF	NNPDF3.0 4F	NNPDF3.0 4F	CT10 4F
PS/UE PDF	CTEQ6L1	NNPDF2.3	
Tune	UE-EE-5	A14	Author's tune



Systematic on ttbar background

Cross section on ttbar: 6%, all correlated

All components, uncorrelated

Source	Evaluation
Generator	Powheg to MG5_aMC
Radiation	Scale variation
PS & had.	Pythia to Herwig

tt+c, tt+light components, uncorrelated

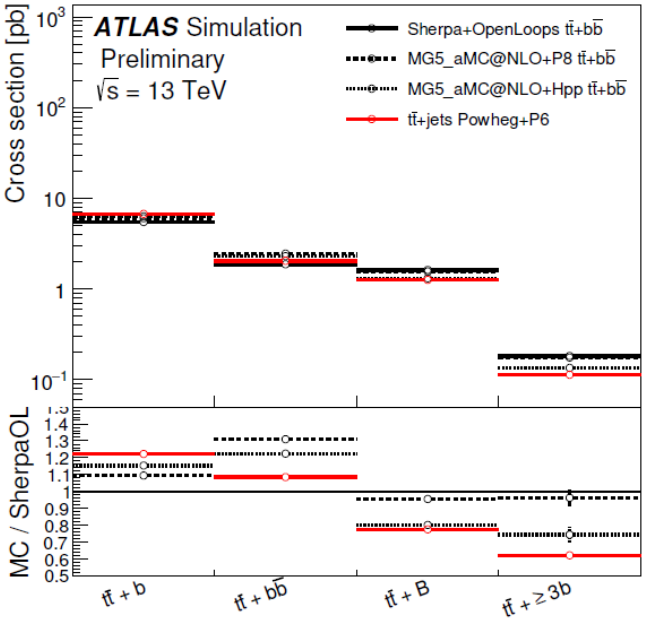
Source	Evaluation
tt+cc ME calc.	MG5_aMC to ME pred.
Top and ttbar pT	Variation in NLO Gen.

tt+b components

Source	Evaluation
Generator	SherpaOL to aMC@NLO
Scales	Renom., Resumm.,global
Shower recoil	Alternative model
Others	PDF, PS, FSR, MPI

nuisance parameters in the final fit.

ME gen. PS/UE gen.	MG5_aMC Herwig++ 2.7.1	MG5_aMC Pythia 8.210	SherpaOL Sherpa
Renorm. scale	μ_{CMMPS}	μ_{CMMPS}	μ_{CMMPS}
Fact. scale	$H_T/2$	$H_T/2$	$H_T/2$
Resumm. scale	$f_Q\sqrt{\hat{s}}$	$f_Q\sqrt{\hat{s}}$	$H_T/2$
ME PDF	NNPDF3.0 4F	NNPDF3.0 4F	CT10 4F
PS/UE PDF	CTEQ6L1	NNPDF2.3	
Tune	UE-EE-5	A14	Author's tune



These syst. make variations:

tt+b/bb/B composition in ttbar+HF

Migration across N_{jets} & N_{bJets}

Classification MVA distribution

ttH Hbb fit model

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- Perform simultaneous fit signal region (SR) with control regions (CR)

	# of SR	# of CR
1-lepton	3	6
2-lepton	3	2

CRs : HT distribution

SRs: Class. MVA distribution

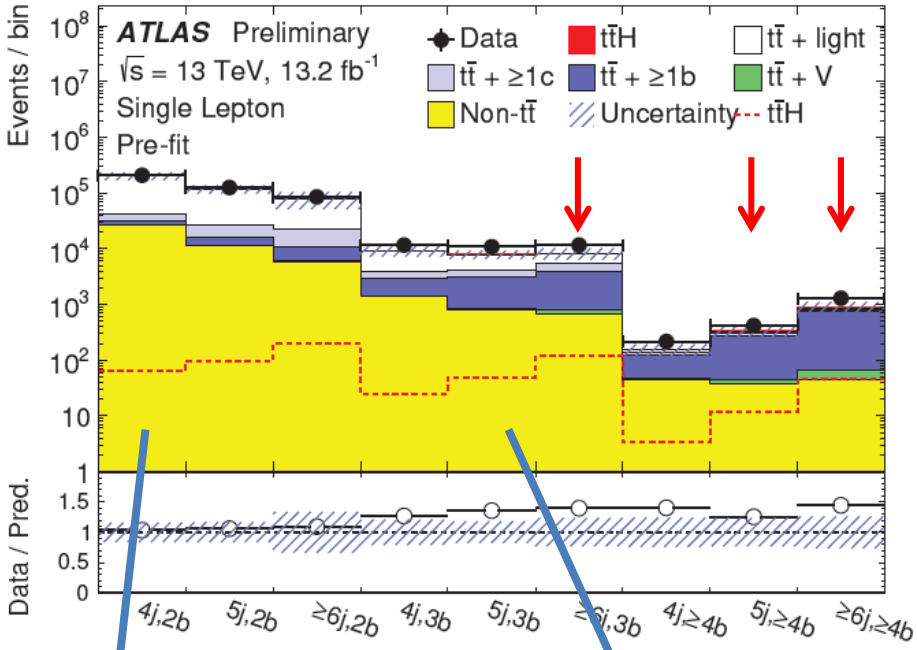
- Parameter in the fit
  - POI:

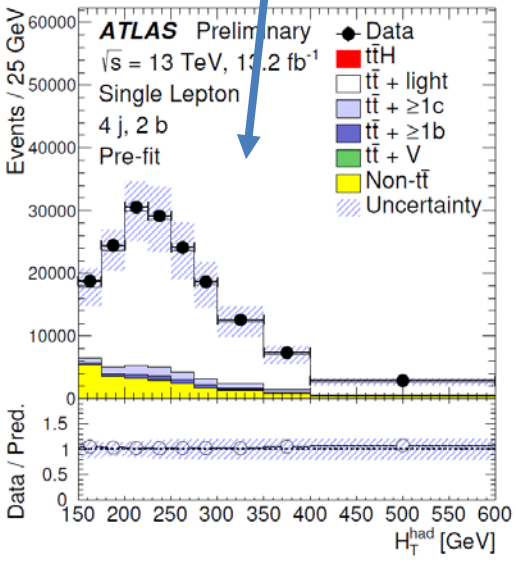
    $\mu=\sigma_{ttH}$ (obs)/ σ_{ttH} (SM)
  - Normalization
    - ttbar+b : κ_b
    - ttbar+c : κ_c
  - Nuisance parameter
    - Systematic variation

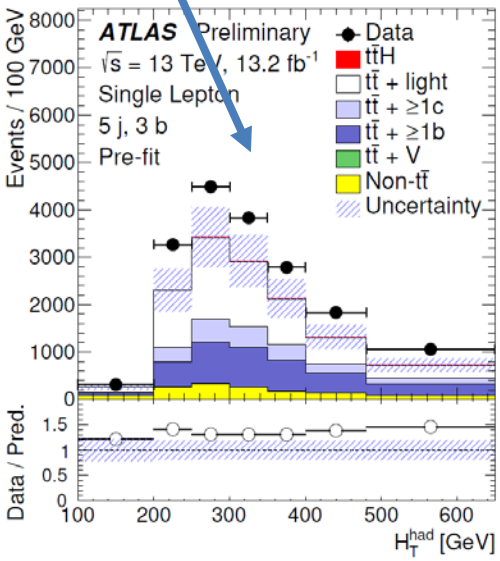
      Theoretical

      Experimental

      → b-tag, JES, JER







ttH, Hbb effect on systematics

1 lepton 6jet 4 btag

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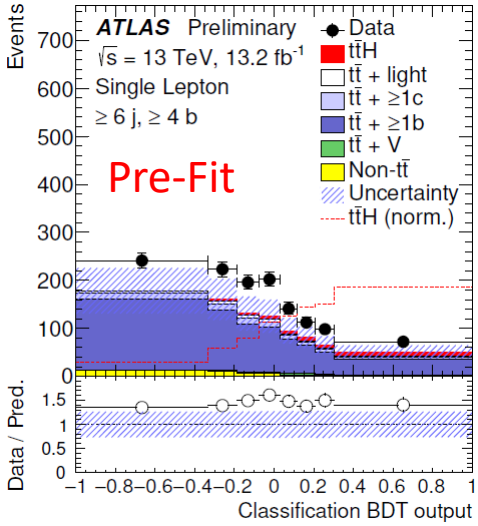
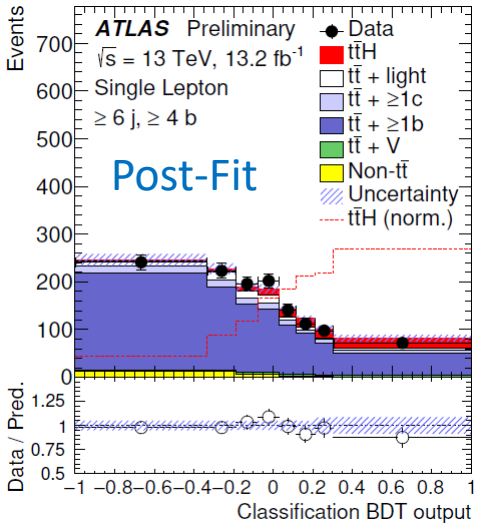
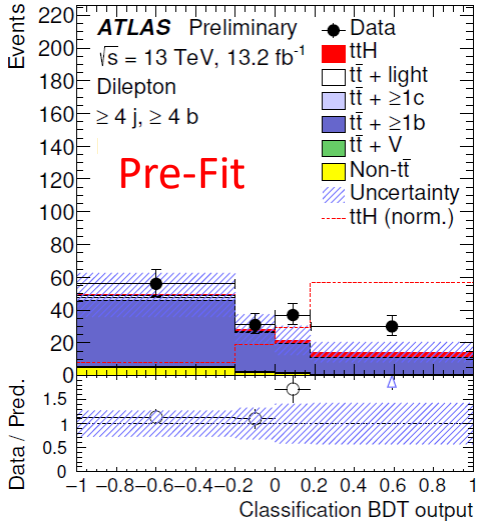
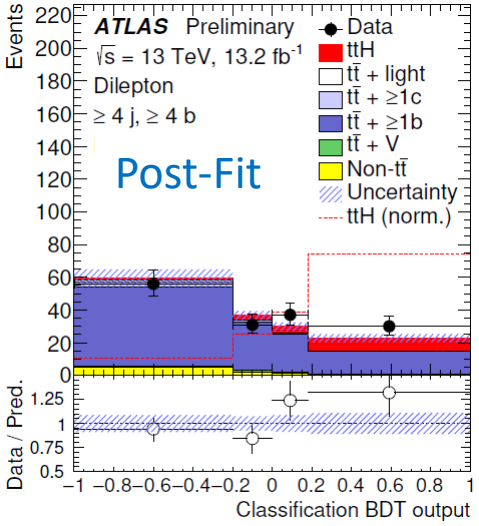




2 lepton 4jet 4btag





$$\kappa_b = 1.33^{+0.18}_{-0.17},\ \kappa_c = 1.31^{+0.53}_{-0.40}$$

Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.53	−0.53
Jet flavour tagging	+0.26	−0.26
$t\bar{t}H$ modelling	+0.32	−0.20
Background model statistics	+0.25	−0.25
$t\bar{t}+\geq 1c$ modelling	+0.24	−0.23
Jet energy scale and resolution	+0.19	−0.19
$t\bar{t}$+light modelling	+0.19	−0.18
Other background modelling	+0.18	−0.18
Jet-vertex association, pileup modelling	+0.12	−0.12
Luminosity	+0.12	−0.12
$t\bar{t}Z$ modelling	+0.06	−0.06
Light lepton (e, μ) ID, isolation, trigger	+0.05	−0.05
Total systematic uncertainty	+0.90	−0.75
$t\bar{t}+\geq 1b$ normalisation	+0.34	−0.34
$t\bar{t}+\geq 1c$ normalisation	+0.14	−0.14
Statistical uncertainty	+0.49	−0.49
Total uncertainty	+1.02	−0.89

ttH, Hbb result

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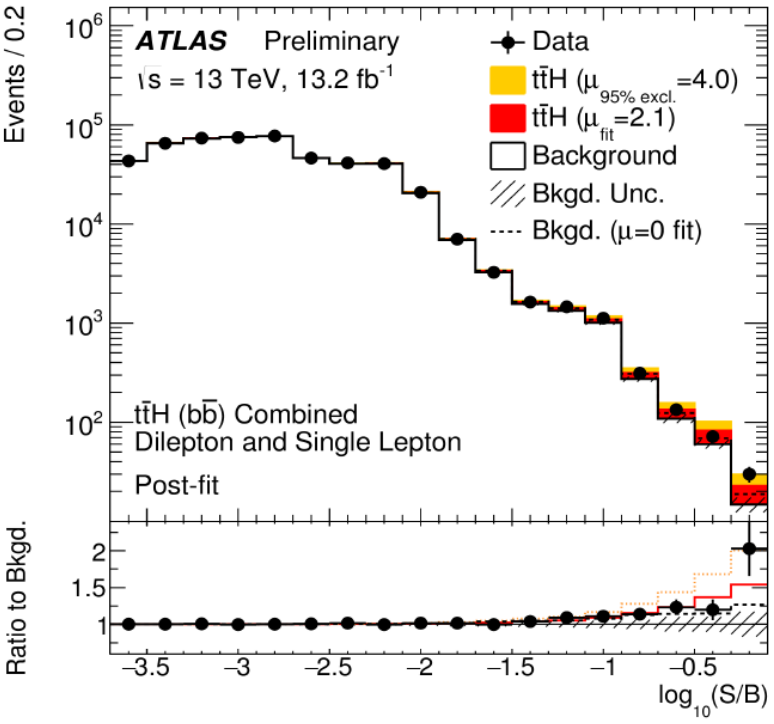
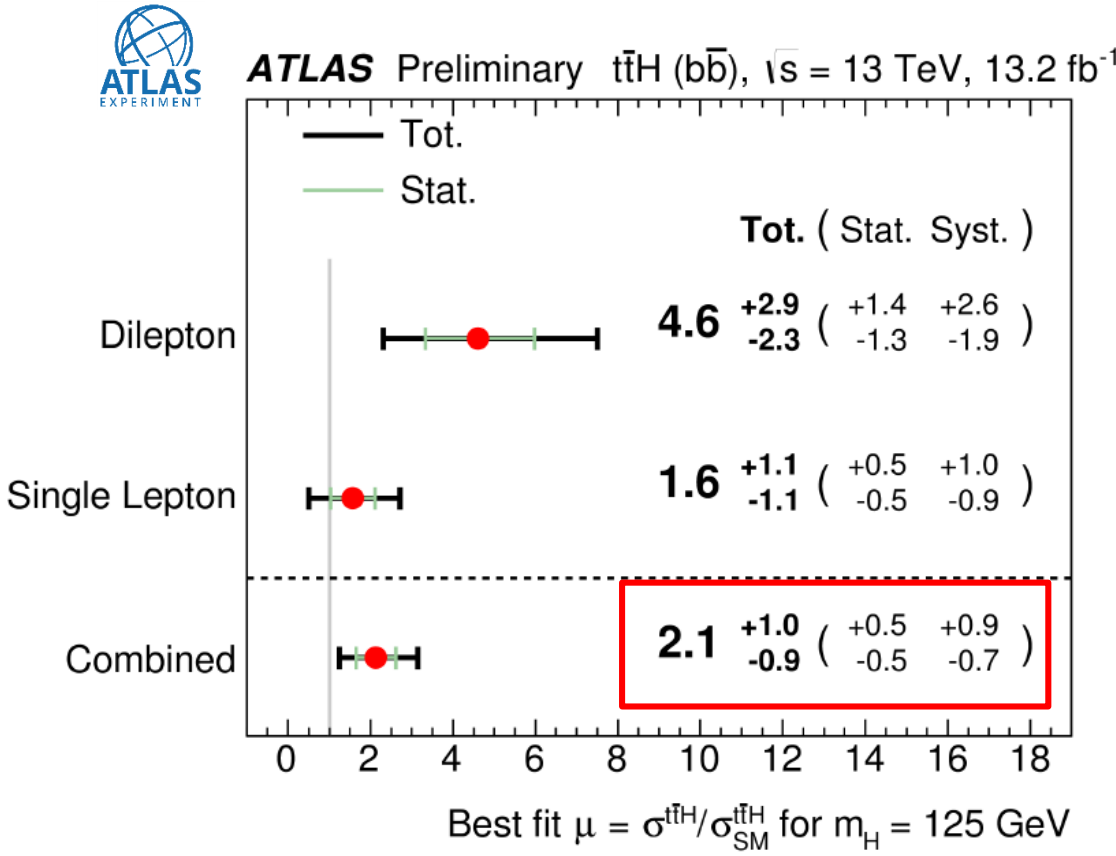




ATLAS Run-1
ttH, H→bb

$\mu = 1.5 \pm \underline{1.1}\ (\underline{0.7})$
tot. (stat.)

Sensitivity exceeded the ATLAS Run-1 result.
Already entered the systematic dominant regime.
Observed results are consistent with SM expectation.

Summary

- First Run-2 ttH H→bb with 13.2 fb^{-1} data at $\sqrt{s}$=13 TeV
- Quite complex final state, challenging analysis!
  - Improved flavor tag
  - 2 stage multivariate technique is used
  - Systematic uncertainty set the sensitivity on ttH.
    - Modeling understanding is vital
      Especially ttbar+HF background modeling
      signal modeling

      } need to be improved.
- **Run-2 sensitivity exceeded Run-1 result**.
- ttH Hbb results show a bit higher than expected but consistent with Standard model.

$$\mu=\sigma_{ttH}\,(\text{obs})/\,\sigma_{ttH}\,(\text{SM}) = 2.1\ ^{+1.0}_{-0.9}\ (^{+0.5}_{-0.5}\ ^{+0.9}_{-0.7})$$

Tot. (Stat. Syst.)

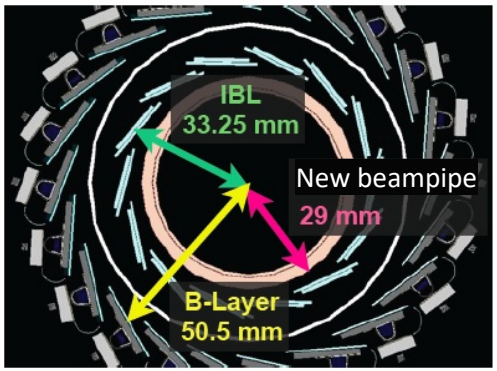
We have collected three times more data!

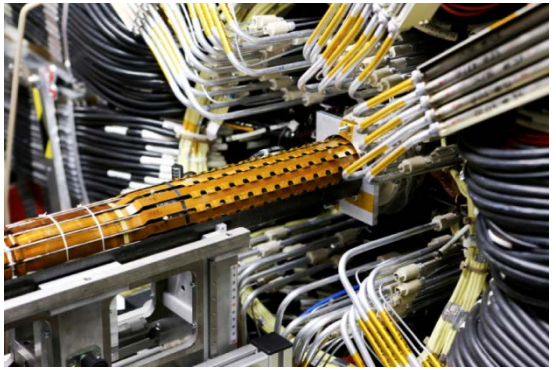
Please stay tuned!

Additional materials

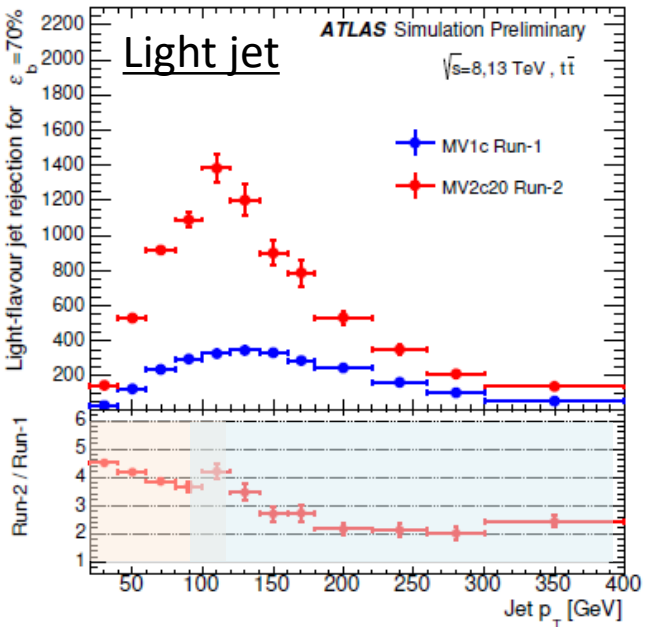
Improvement on b-tagging at Run-2

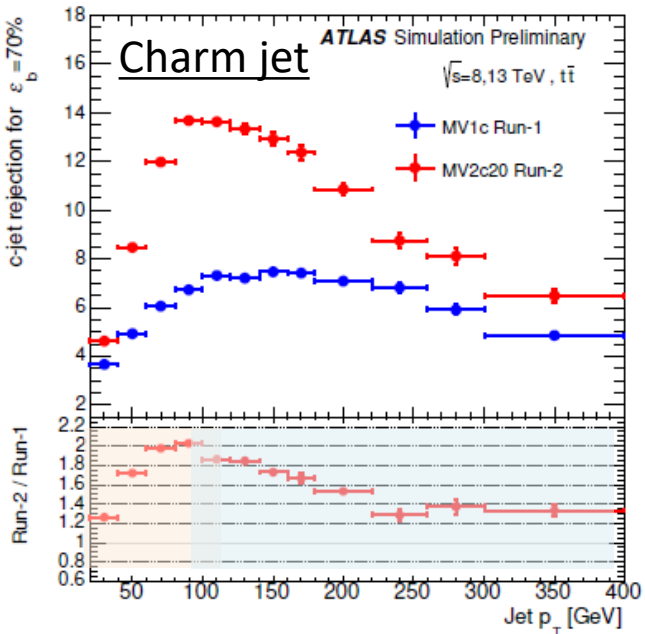
- IBL
  - Additional Pixel layer
  - Resolution of impact param. for track pT range of 5-10 GeV
    → 30-60% improvement





- MVA training scheme
  - Run-1 training: b-jet vs light jet
    → Run-2: b-jets vs (80% light + 20% charm)





Improvements on rejection factor

Low jet pT
→ **IBL** + **algorithm**

High jet pT
→ mainly **algorithm**

ttbar MC samples in ttH analysis

ME gen.	Powheg-Box	Powheg-Box	MG5_aMC	Powheg-Box	Powheg-Box
PS/UE gen.	Pythia 6.428	Herwig++2.7.1	Herwig++2.7.1	Pythia 6.428	Pythia 6.428
Ren. scale	$\sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$	$\sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$	$\sqrt{m_t^2 + \frac{1}{2}(p_{\mathrm{T,t}}^2 + p_{\mathrm{T,\bar{t}}}^2)}$	$\frac{1}{2} \cdot \sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$	$2 \cdot \sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$
Fact. scale	$\sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$	$\sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$	$\sqrt{m_t^2 + \frac{1}{2}(p_{\mathrm{T,t}}^2 + p_{\mathrm{T,\bar{t}}}^2)}$	$\frac{1}{2} \cdot \sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$	$2 \cdot \sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$
hdamp	m_t	m_t	–	$2 \cdot m_t$	m_t
ME PDF	CT10	CT10	CT10	CT10	CT10
PS/UE PDF	CTEQ6L1	CTEQ6L1	CTEQ6L1	CTEQ6L1	CTEQ6L1
Tune	P2012	UE-EE5	UE-EE5	P2012 radHi	P2012 radLo

Table 3: Summary of the settings used for the simulation of the inclusive $t\bar{t}$ samples. For the renormalisation and factorisation scales, $p_{\mathrm{T,t}}$ ($p_{\mathrm{T,\bar{t}}}$) indicates the transverse momentum of the top (anti-top) quark in the $t\bar{t}$ centre-of-mass reference frame.

ME gen.	MG5_aMC	MG5_aMC	SherpaOL
PS/UE gen.	Herwig++ 2.7.1	Pythia 8.210	Sherpa
Renorm. scale	μ_{CMMPS}	μ_{CMMPS}	μ_{CMMPS}
Fact. scale	$H_{\mathrm{T}}/2$	$H_{\mathrm{T}}/2$	$H_{\mathrm{T}}/2$
Resumm. scale	$f_{\mathrm{Q}}\sqrt{\hat{s}}$	$f_{\mathrm{Q}}\sqrt{\hat{s}}$	$H_{\mathrm{T}}/2$
ME PDF	NNPDF3.0 4F	NNPDF3.0 4F	CT10 4F
PS/UE PDF	CTEQ6L1	NNPDF2.3	
Tune	UE-EE-5	A14	Author's tune

Table 4: Summary of the settings used for the simulation of $t\bar{t} + b\bar{b}$ 4F NLO samples. For the resummation scale, $\sqrt{\hat{s}}$ is the Born-level partonic centre-of-mass energy, while f_{Q} is a random pre-factor allowed to vary in the range [0.1, 0.25].

Systematic variation on ttbar BG

Systematic source	How evaluated	$t\bar{t}$ categories
$t\bar{t}$ cross-section	±6%	All, correlated
NLO generator (*residual*)	Powheg-Box + Herwig++ vs. MG5_aMC + Herwig++	All, uncorrelated
Radiation (*residual*)	Variations of μ_R, μ_F, and *hdamp*	All, uncorrelated
PS & hadronisation (*residual*)	Powheg-Box + Pythia 6 vs. Powheg-Box + Herwig++	All, uncorrelated
NNLO top & $t\bar{t}$ p_T	Maximum variation from any NLO prediction	$t\bar{t}+\geq 1c$, $t\bar{t}$ +light, uncorr.
$t\bar{t}+b\bar{b}$ NLO generator *reweighting*	SherpaOL vs. MG5_aMC+ Pythia8	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ PS & hadronis. *reweighting*	MG5_aMC + Pythia8 vs. MG5_aMC + Herwig++	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ renorm. scale *reweighting*	Up or down a by factor of two	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ resumm. scale *reweighting*	Vary μ_Q from $H_T/2$ to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ global scales *reweighting*	Set μ_Q, μ_R, and μ_F to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ shower recoil *reweighting*	Alternative model scheme	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ PDF *reweighting*	CT10 vs. MSTW or NNPDF	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ MPI	Up or down by 50%	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ FSR	Radiation variation samples	$t\bar{t}+\geq 1b$
$t\bar{t}+c\bar{c}$ ME calculation	MG5_aMC + Herwig++ inclusive vs. ME prediction	$t\bar{t}+\geq 1c$

Input varialbes to BDT

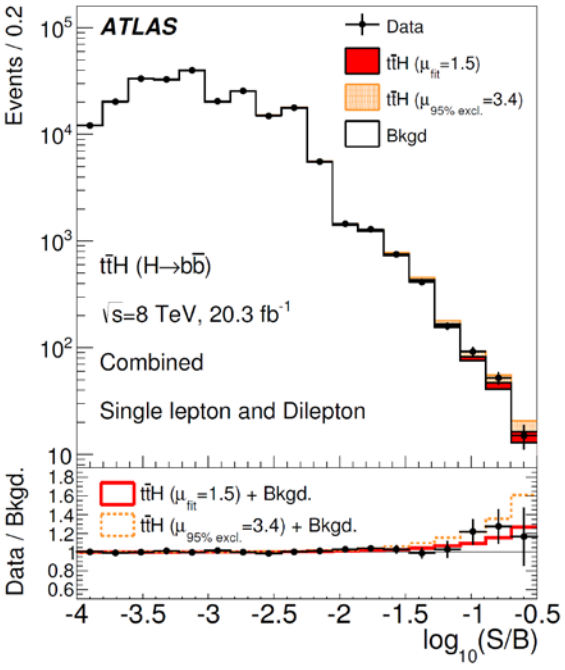
Reconstruction BDT

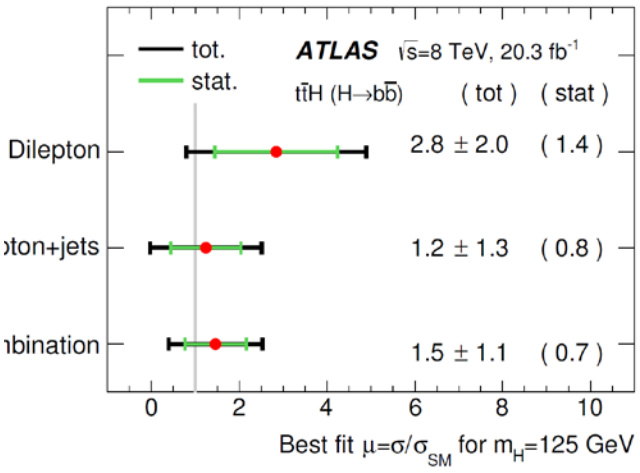
Variable
Topological information from $t\bar{t}$:
$\Delta R(b$ from t, lep from $t)$
$\Delta R(b$ from $\bar{t}$, lep from $\bar{t})$
Mass of b from t and lep from t
Mass of b from $\bar{t}$ and lep from $\bar{t}$
$p_{\mathrm{T}}(b$ from t, lep from $t)$
$p_{\mathrm{T}}(b$ from $\bar{t}$, lep from $\bar{t})$
$\Delta R(b$ from t, b from $\bar{t})$
$\lvert\Delta R(b$ from t, lep from $t)$ - $\Delta R(b$ from $\bar{t}$, lep from $\bar{t})\rvert$
Min. $\Delta R(b$ from $t\bar{t}$, lep)
Max. $\Delta R(b$ from $t\bar{t}$, lep)
Topological information from Higgs :
Higgs Mass
$\Delta R(b_1$ from Higgs, b_2 from Higgs)
ΔR(Higgs, $t\bar{t}$)
$\lvert\Delta R(b_1$ from Higgs, b_2 from Higgs) - $\Delta R(b$ from t, b from $\bar{t})\rvert$
Min. ΔR(Higgs, lep)
Max. ΔR(Higgs, lep)
Min. ΔR(Higgs, b from $t\bar{t}$)
Max. ΔR(Higgs, b from $t\bar{t}$)

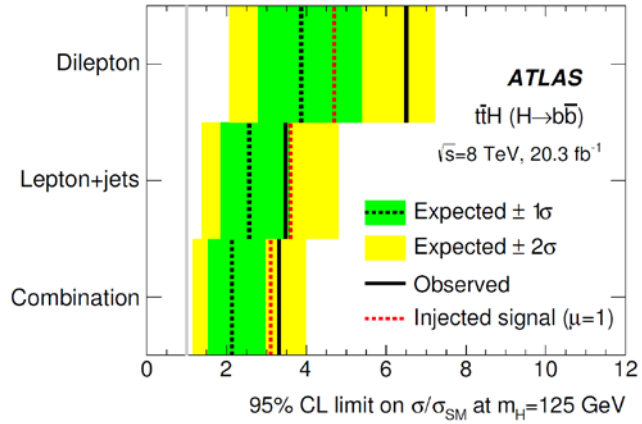
Classification BDT

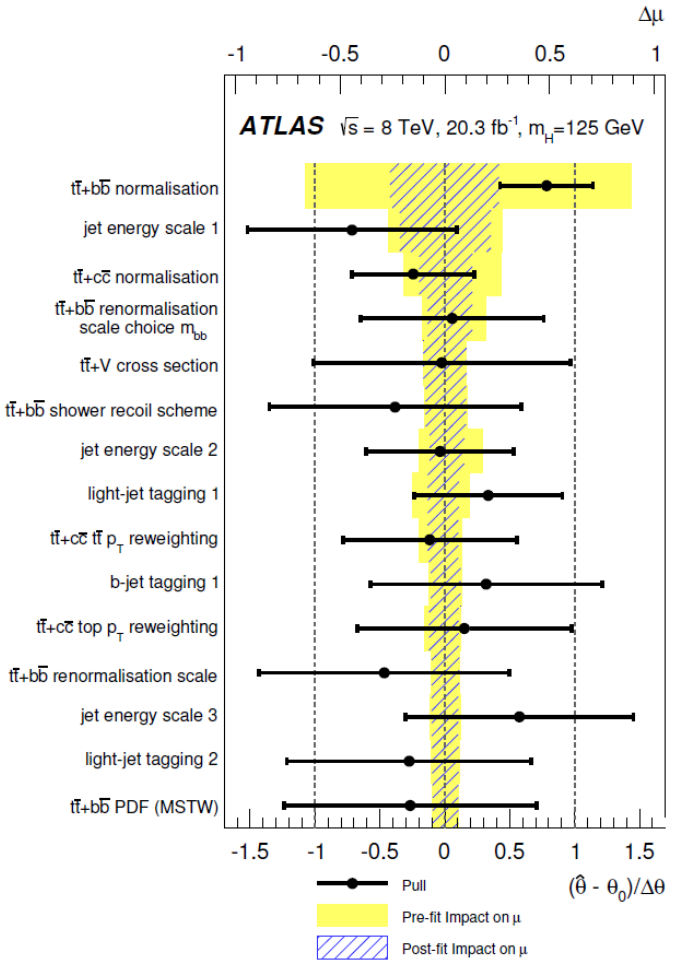
Variable	≥6j, ≥4b	≥6j, =3b	=5j, ≥4b
Topological information from $t\bar{t}$:			
t_{lep} mass	✓	✓	✓
t_{had} mass	✓	✓	–
Incomplete t_{had} mass	–	–	✓
W_{had} mass	✓	✓	–
Mass of W_{had} and b from t_{lep}	✓	✓	–
Mass of q from W_{had} and b from t_{lep}	–	–	✓
Mass of W_{lep} and b from t_{had}	✓	✓	✓
$\Delta R(W_{\mathrm{had}}, b$ from $t_{\mathrm{had}})$	✓	✓	–
$\Delta R(q$ from W_{had}, b from $t_{\mathrm{had}})$	–	–	✓
$\Delta R(W_{\mathrm{had}}, b$ from $t_{\mathrm{lep}})$	✓	✓	–
$\Delta R(q$ from W_{had}, b from $t_{\mathrm{lep}})$	–	–	✓
ΔR(lep, b from $t_{\mathrm{lep}})$	✓	✓	✓
ΔR(lep, b from $t_{\mathrm{had}})$	✓	✓	✓
$\Delta R(b$ from t_{lep}, b from $t_{\mathrm{had}})$	✓	✓	✓
$\Delta R(q_1$ from W_{had}, q_2 from $W_{\mathrm{had}})$	✓	✓	–
$\Delta R(b$ from t_{had}, q_1 from $W_{\mathrm{had}})$	✓	✓	–
$\Delta R(b$ from t_{had}, q_2 from $W_{\mathrm{had}})$	✓	✓	–
min. $\Delta R(b$ from t_{had}, q from $W_{\mathrm{had}})$	✓	✓	–
ΔR(lep, b from $t_{\mathrm{lep}})$ - min. $\Delta R(b$ from t_{had}, q from $W_{\mathrm{had}})$	✓	✓	–
ΔR(lep, b from $t_{\mathrm{lep}})$ - $\Delta R(b$ from t_{had}, q from $W_{\mathrm{had}})$	–	–	✓
Topological information from Higgs :			
Higgs mass	✓	✓	✓
Mass of Higgs and q_1 from W_{had}	✓	✓	✓
$\Delta R(b_1$ from Higgs, b_2 from Higgs)	✓	✓	✓
$\Delta R(b_1$ from Higgs, lep)	✓	✓	✓
$\Delta R(b_1$ from Higgs, b from $t_{\mathrm{lep}})$	–	✓	✓
$\Delta R(b_1$ from Higgs, b from $t_{\mathrm{had}})$	–	✓	✓

Run1 result


ATLAS
Data
tt̄H (μfit=1.5)
tt̄H (μ95% excl.=3.4)
Bkgd
tt̄H (H→bb̄)
√s=8 TeV, 20.3 fb-1
Combined
Single lepton and Dilepton
Events / 0.2
Data / Bkgd.
tt̄H (μfit=1.5) + Bkgd.
tt̄H (μ95% excl.=3.4) + Bkgd.
log10(S/B)


tot.
stat.
ATLAS √s=8 TeV, 20.3 fb-1
tt̄H (H→bb̄) (tot) (stat)
Dilepton
2.8 ± 2.0 (1.4)
1.2 ± 1.3 (0.8)
1.5 ± 1.1 (0.7)
Best fit μ=σ/σSM for mH=125 GeV


Dilepton
Lepton+jets
Combination
ATLAS
tt̄H (H→bb̄)
√s=8 TeV, 20.3 fb-1
Expected ± 1σ
Expected ± 2σ
Observed
Injected signal (μ=1)
95% CL limit on σ/σSM at mH=125 GeV


Δμ
ATLAS √s = 8 TeV, 20.3 fb-1, mH=125 GeV
tt̄+bb̄ normalisation
jet energy scale 1
tt̄+cc̄ normalisation
tt̄+bb̄ renormalisation scale choice mbb
tt̄+V cross section
tt̄+bb̄ shower recoil scheme
jet energy scale 2
light-jet tagging 1
tt̄+cc̄ tt̄ pT reweighting
b-jet tagging 1
tt̄+cc̄ top pT reweighting
tt̄+bb̄ renormalisation scale
jet energy scale 3
light-jet tagging 2
tt̄+bb̄ PDF (MSTW)
Pull
Pre-fit Impact on μ
Post-fit Impact on μ
(θ̂ - θ0)/Δθ

Summary on ttH analyses (σ_{obs}/σ_{SM})

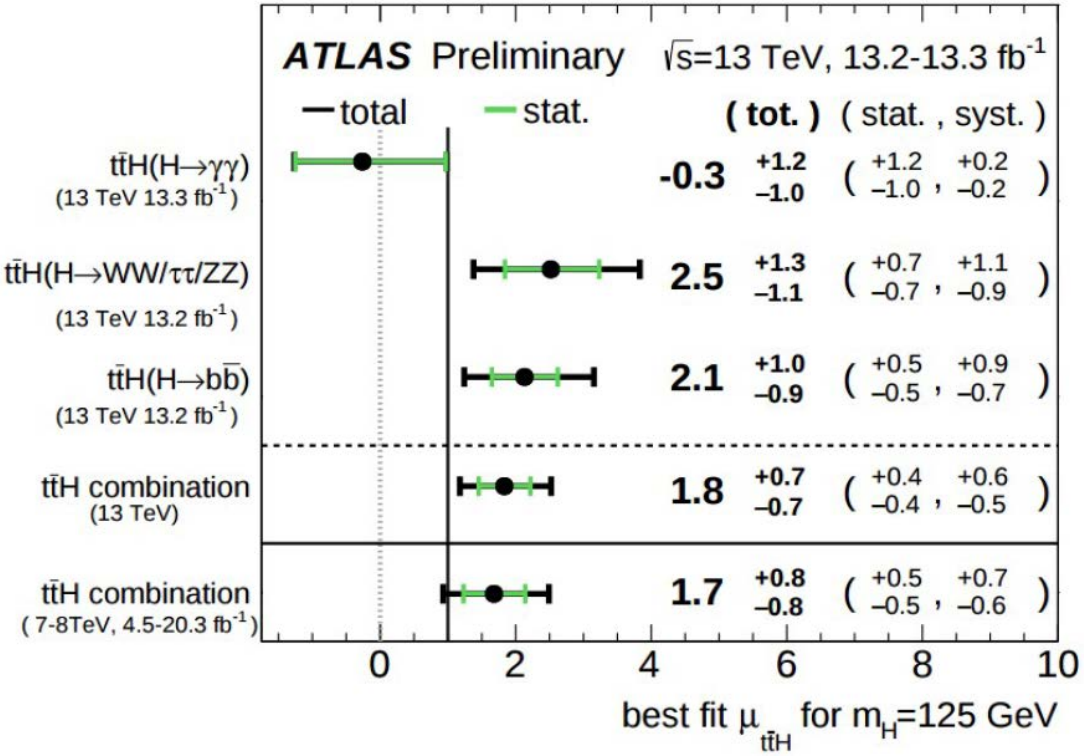
CMS

ttH Channel	$\mu = \sigma/\sigma_{SM}$ ($m_H = 125.7$ GeV)
$\gamma\gamma$	$1.9^{+1.5}_{-1.2}$
$b\bar{b}$	-2.0 ± 1.8 (2.7 fb^{-1})
$\tau\tau$	$-1.4^{+6.3}_{-5.5}$ (**Run1**)
4l	$2.0^{+0.8}_{-0.7}$
3l	
Same-sign 2l	
Combined	$+2.5^{+1.1}_{-1.0}$ (**Run1**)

Combination for run2 is not yet done.

CMS-PAS-HIG-16-022
CMS-PAS-HIG-16-020
CMS-PAS-HIG-15-008

ATLAS (Run-2)



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