Search for the Higgs boson produced in association with top quarks and decaying into bottom quarks with the ATLAS detector

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ATLAS EXPERIMENT

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Japan Society for the Promotion of Science 日本学術振興会

Top Quarks and Higgs Bosons

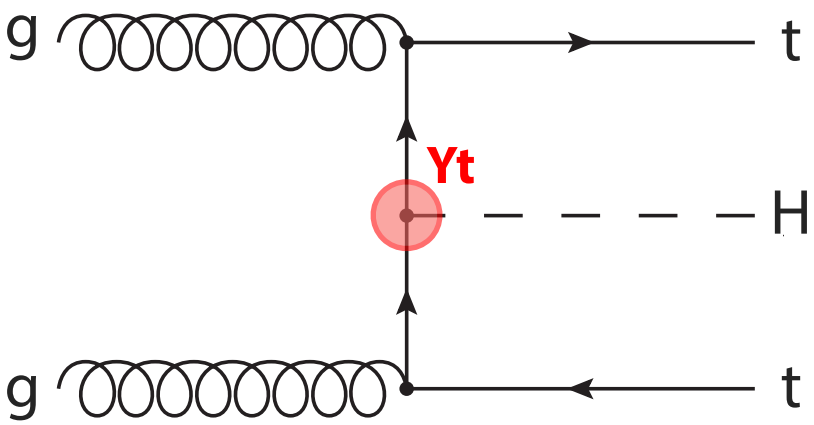
Top Quark: Largest and unique mass value m_{top} = 173.3 GeV ~ v / √2

→ Top-Yukawa coupling Yt ~ 1: a key parameter of the SM

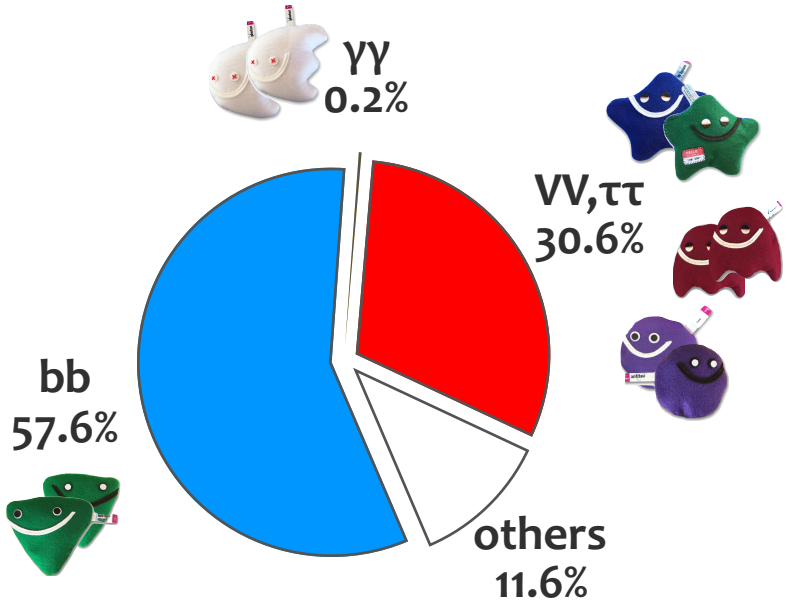
Yt probes BSM such as VLQ, SUSY, …

The ttH production allows the direct measurement of top-Yukawa with significant sensitivities in LHC Run2.

Small cross sections, but distinct signatures in various decay channels in Higgs and ttbar

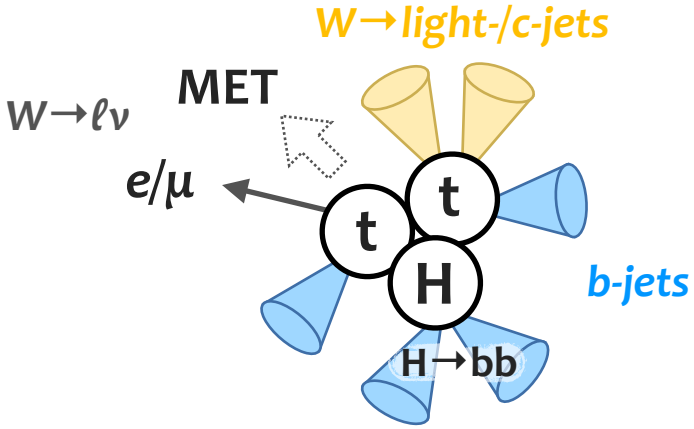


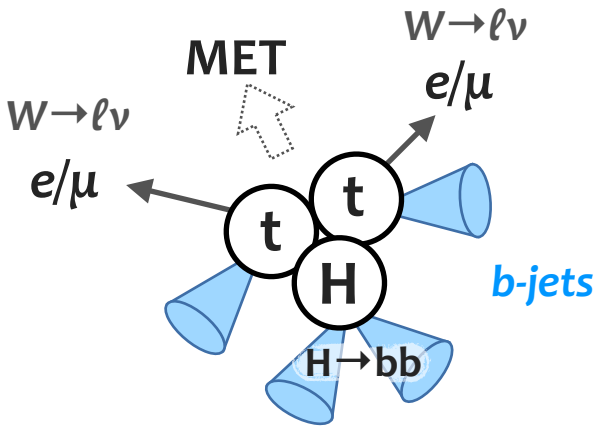
Cross-section = 0.51 pb at 13TeV



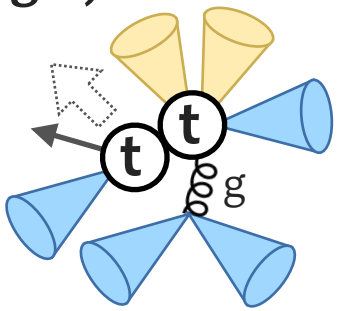
ttH(H→bb) Objects

ttH → 6jets(4b-jets), 1lepton, MET / 4jets(4b-jets), 2leptons, MET





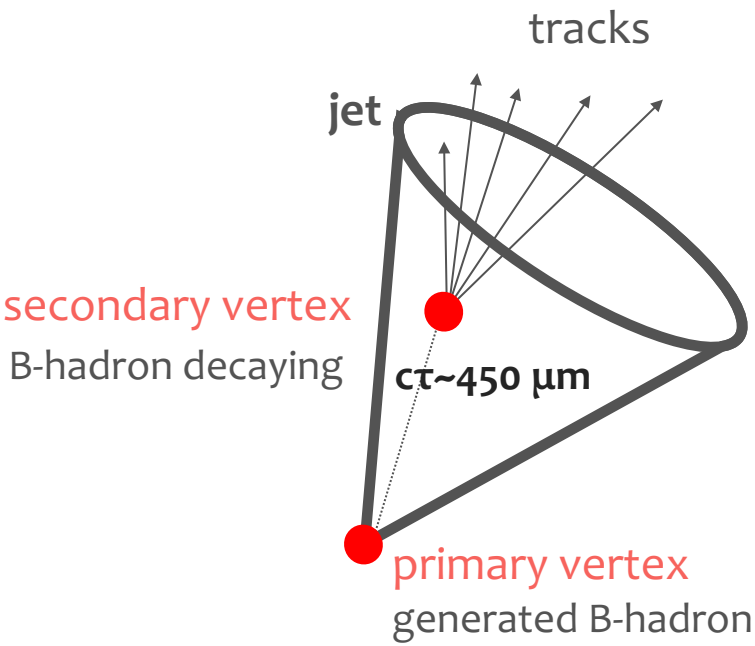
Background sources: tt+jets (85-96% of total Bkgd.)
(generated gluon instead of Higgs)

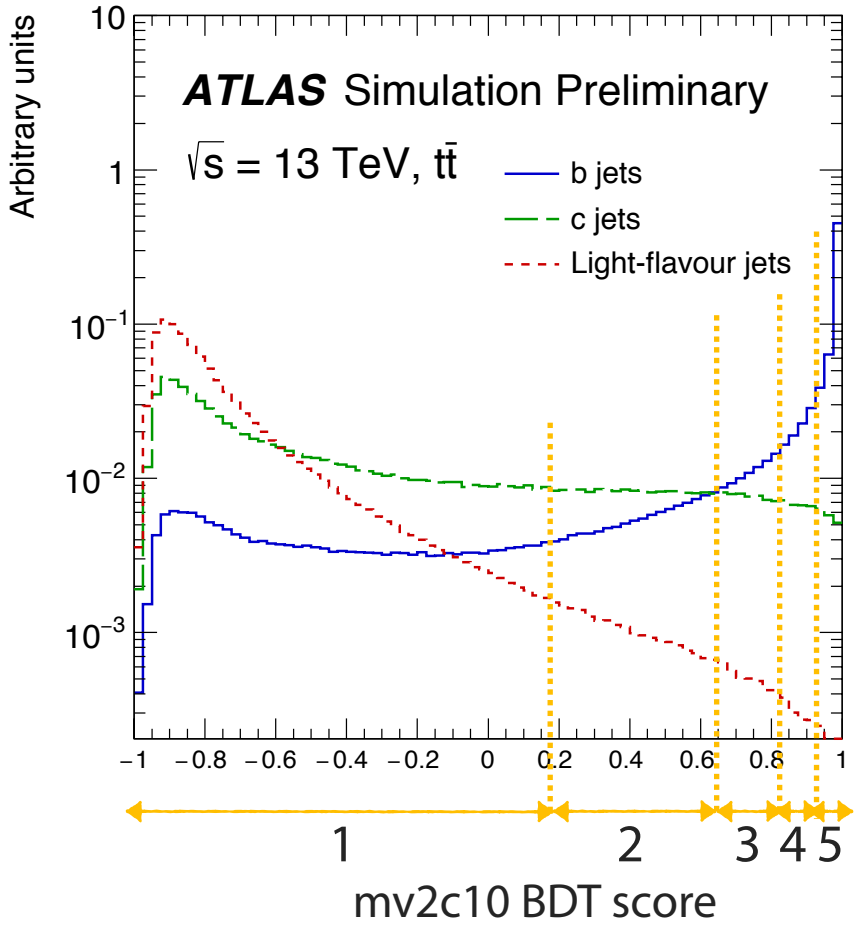


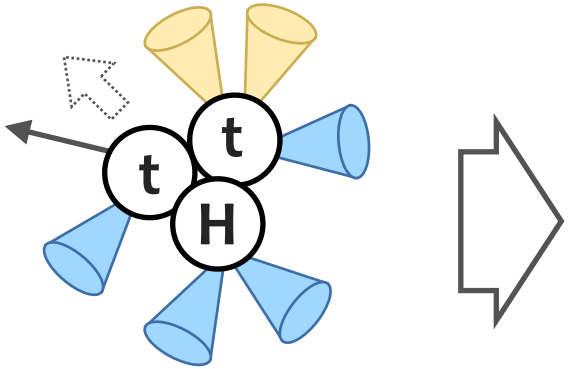
tt+bb: 4b-jets
→ same final states: irreducible

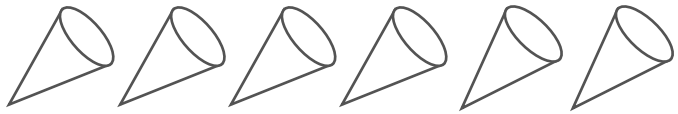
tt+cc: 2b-jets + 2c-jets / tt+light: 2b-jets + 2 light-jets
→ reducible BKG with b-jet identification (=> b-tagging)

Flavor Tagging (b-tagging)



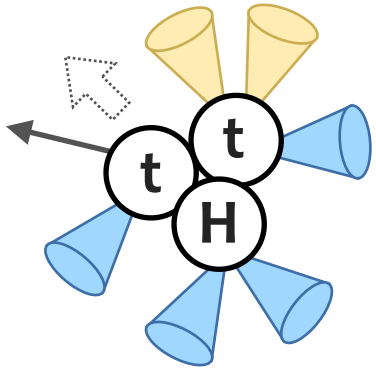






larger 5 5 4 3 1 1 smaller

Region Definition



Using four highest btagging scores per event:

larger 5 5 4 3 1 1 smaller

Single Lepton, ≥ 6 j

(1^{st}, 2^{nd}) jet *b*-tagging discriminant

(3, 3)
(4, 3)
(5, 3)
(4, 4)
(5, 4)
(5, 5)

>30% of tt+b
$CR_{t\bar{t}+b}$

>30% of tt+≥1c
$CR_{t\bar{t}+\geq 1c}$

remaining bins:
$CR_{t\bar{t}+light}$

SR_1 >60%
SR_2 >45%
SR_3 >30%

(5, 5) (5, 4) (5, 3) (5, 2) (4, 4) (4, 3) (4, 2) (3, 3) (3, 2) (2, 2) (5, 1) (4, 1) (3, 1) (2, 1) (1, 1)

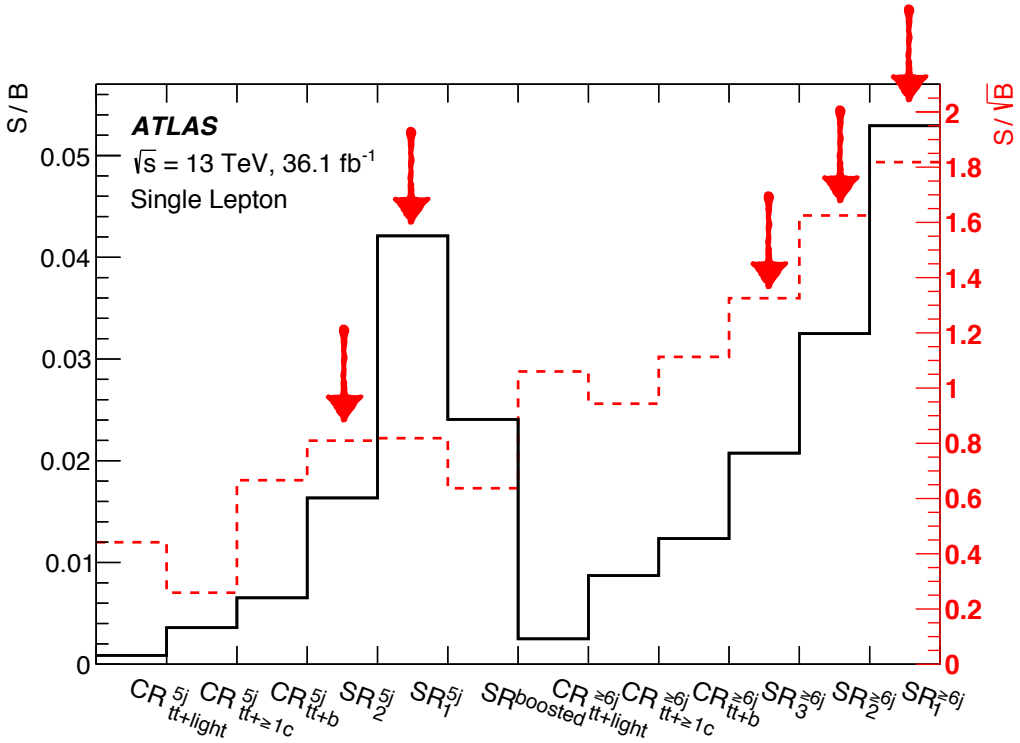
of tt+≥2b

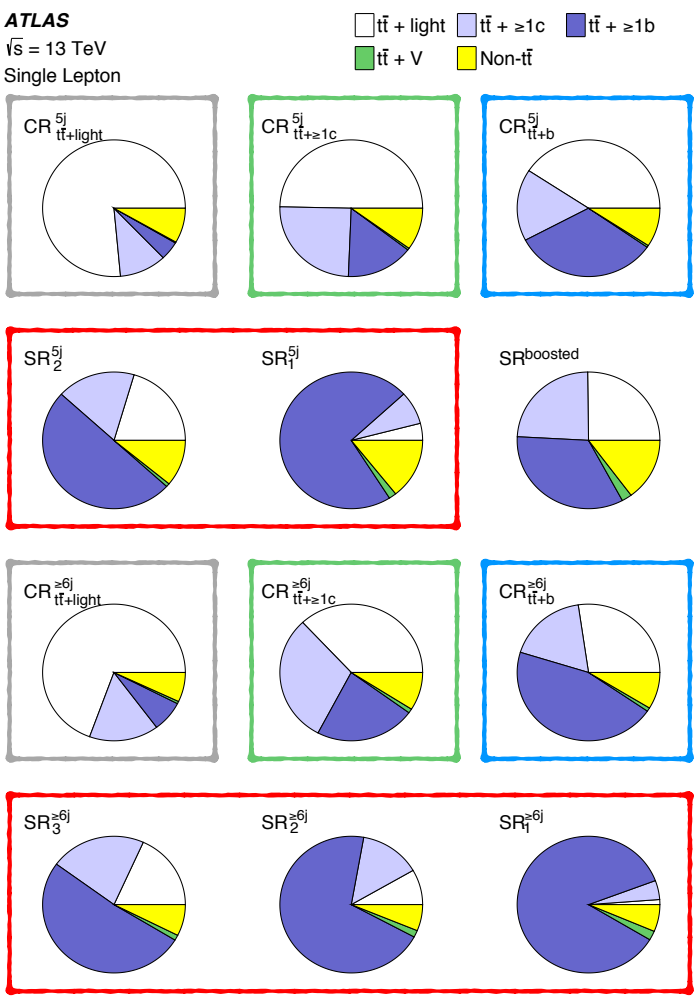
(3^{rd}, 4^{th}) jet *b*-tagging discriminant

Defined Regions

12 regions for single-lepton channel (5jets, ≥6jets)

- two control regions enriched by tt+light, tt+≥1c or tt+b
- five tt+bb and signal enriched regions
- one boosted region





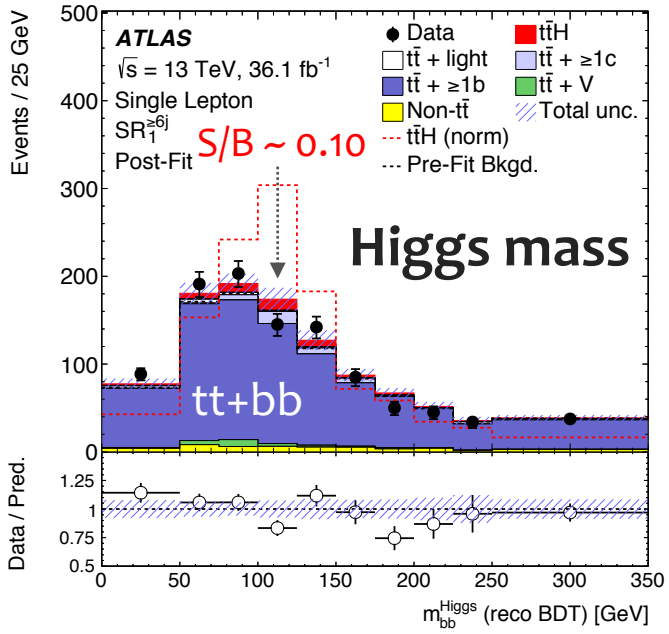
7 Multi-Variate Analysis: ttH and tt+bb Separation

Reconstruction kinematics

identify jet assignments

for top/Higgs candidates

using MVA algorithm



Simple kinematic variables

- $\Delta R_{bb}^{max.pT}$, $m_{bb}^{min.\Delta R}$, …
- b-tagging scores for each jet

Advanced discriminants :

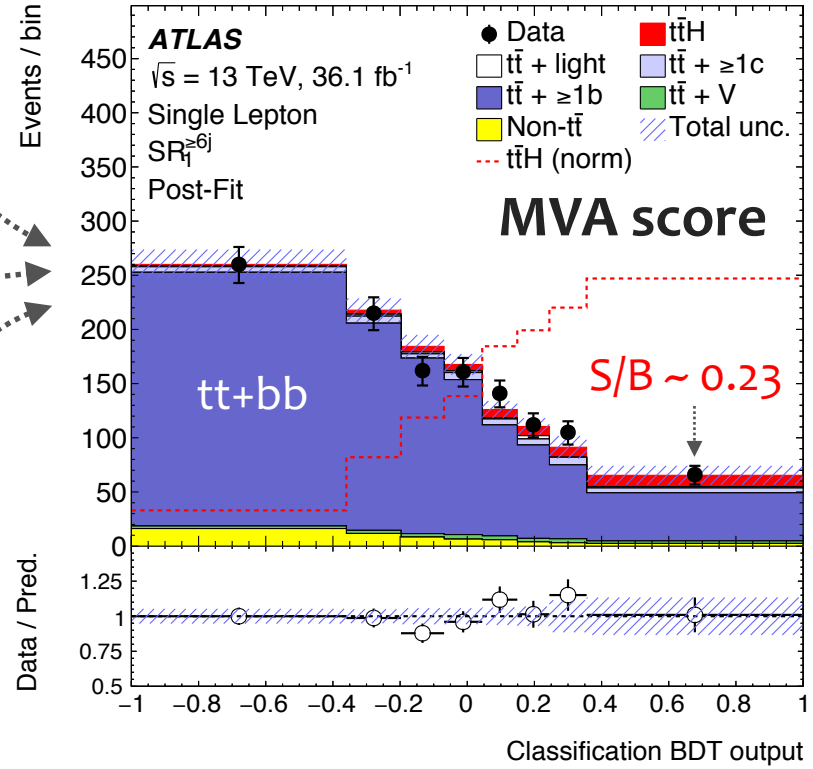
MEM discriminant

uses Signal / Bkgd. probability via ME calculation

LH discriminant

uses various PDFs of masses/angles,

considering missing object prob.

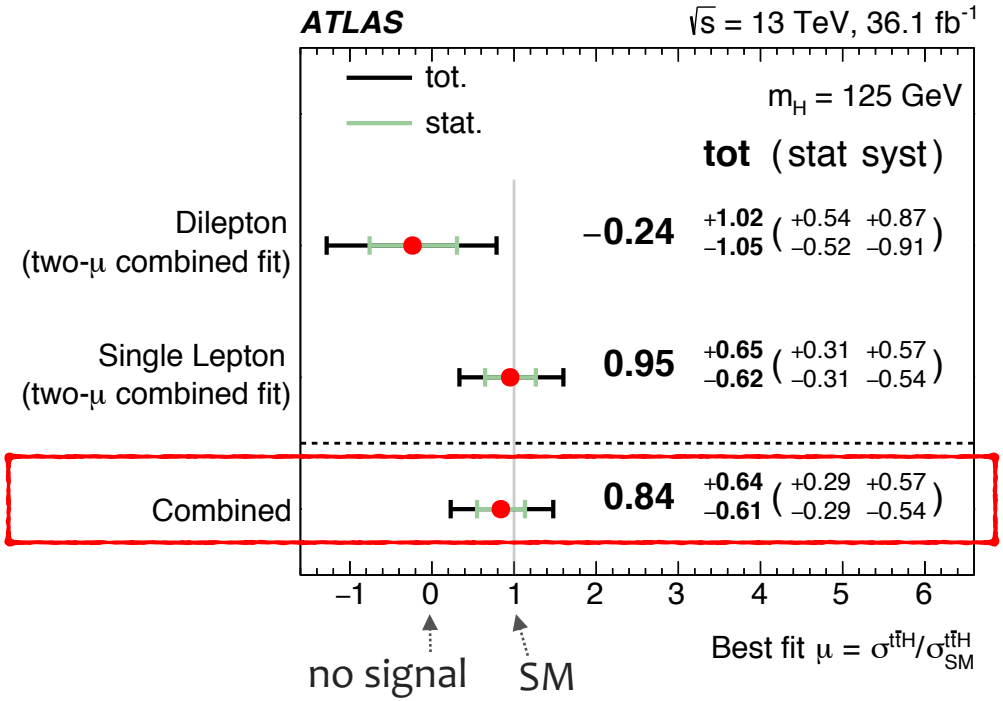


Results

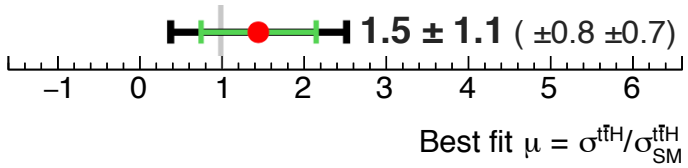
Observed (Expected) excess = 1.4σ (1.6σ) over SM bkgd.

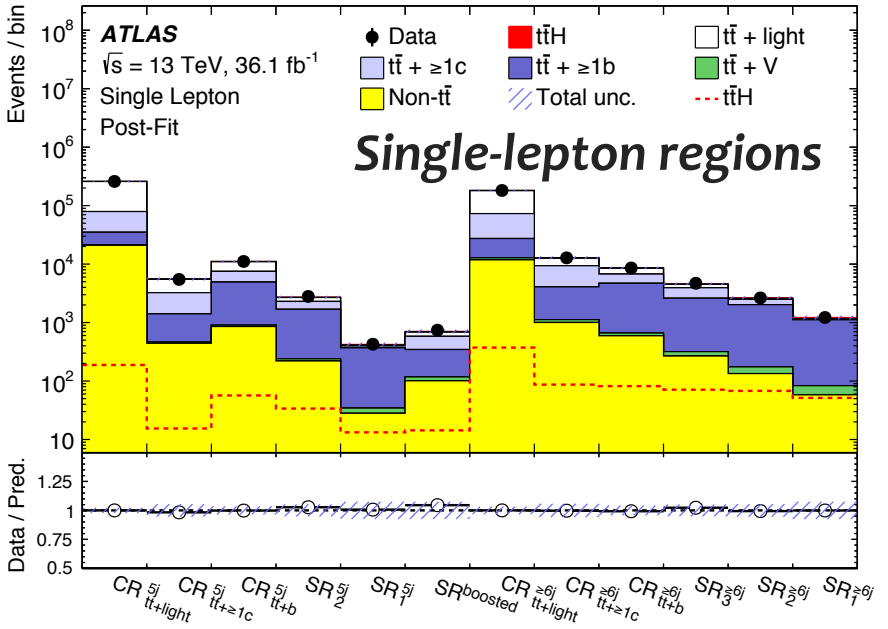
determined with free-floating normalizations for tt+HF:

- tt+≥1b: 1.24±0.10, tt+≥1c: 1.63±0.23



Run1:



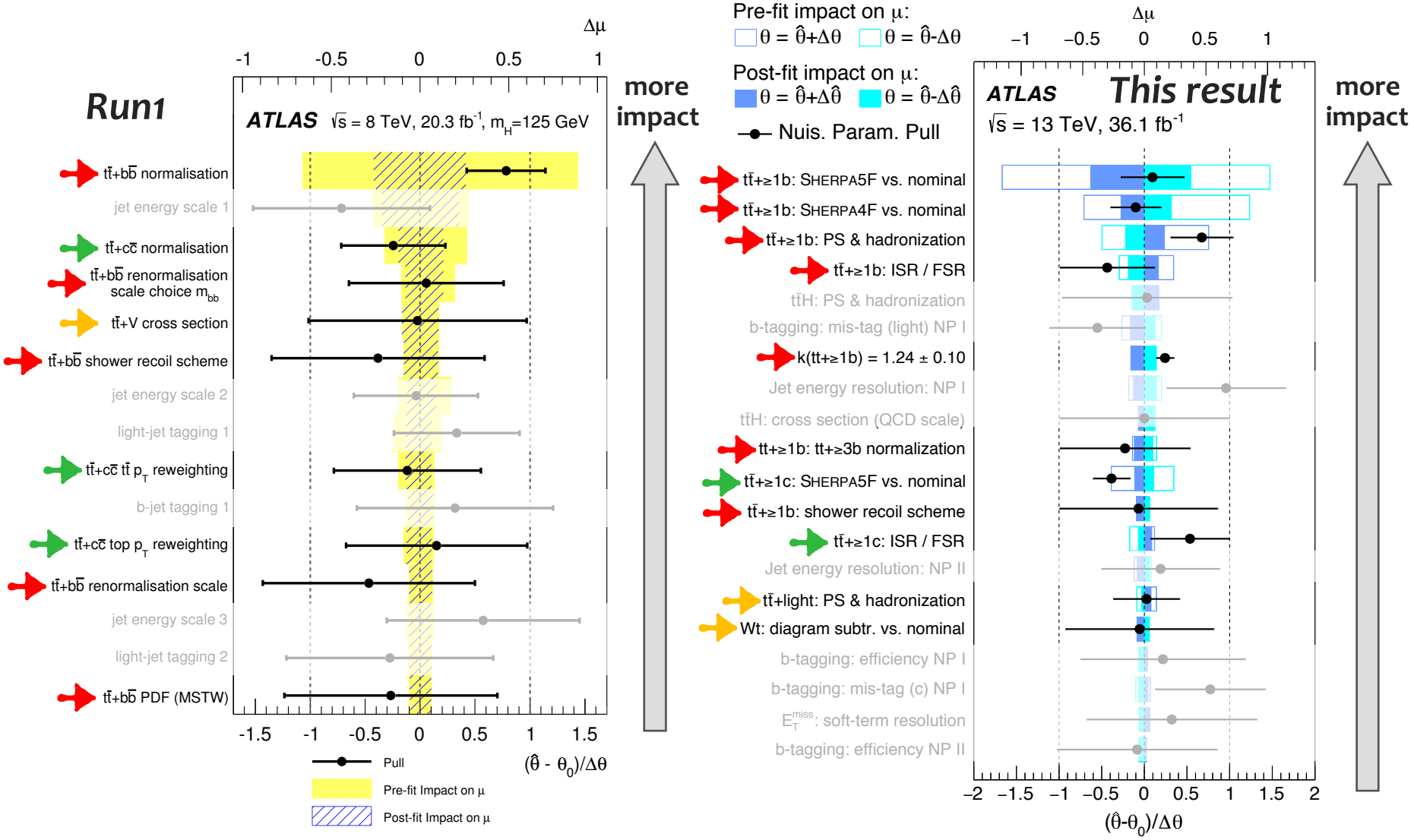


normalizations in all regions:

consistent btw data and pred.

→40% improvements from Run1

Systematic Uncertainties (15 Unc. with Largest Impacts on μ-value)



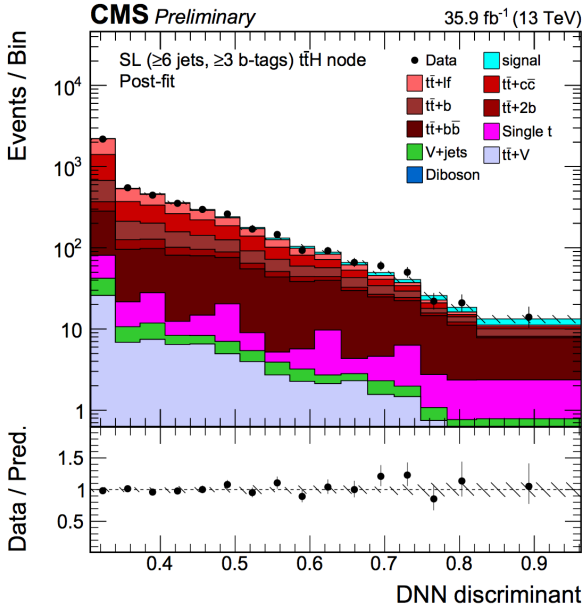
Less impacts from tt+cc, other Bkgd. modelings

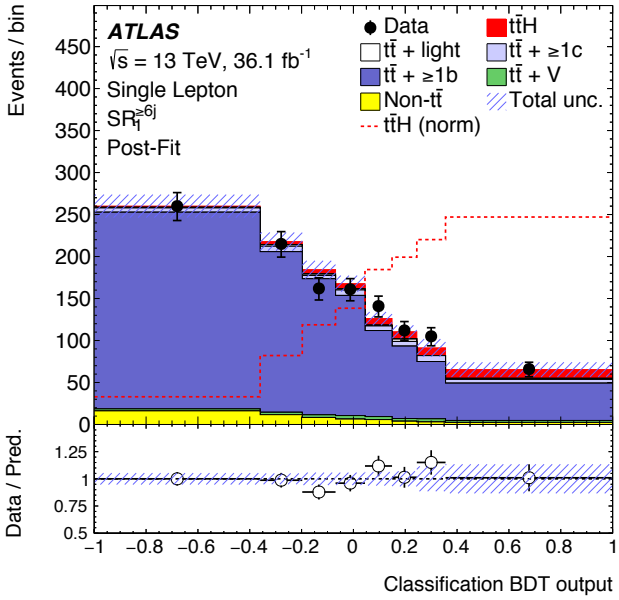
But still large impact by tt+bb modeling also in new results.

Comparison btw. ATLAS and CMS

most sensitive region

good consistencies in all bins.





Result

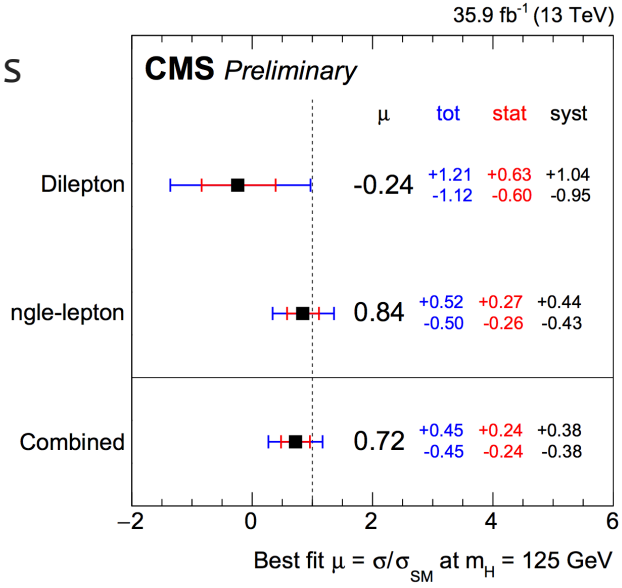
~ same results in both analysis

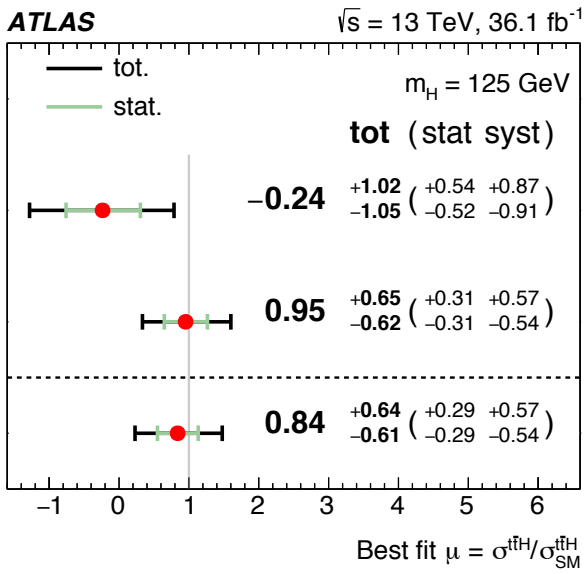
but smaller unc. in CMS.

different treatments for tt+jets modeling

+0.24/-0.28 for CMS

+0.46/-0.46 for ATLAS





Conclusion

The ttH production allows the direct measurement of top-Yukawa:
largest and unique coupling value = a key for SM/BSM physics.

Searched for ttH production with H->bb

Key point: large systematic uncertainties in tt+jets modeling

Run1 result: 1.4σ observed (1.1σ expected)

Developed MVAs for optimized event categorization

→ **$\mu=\sigma_{ttH}^{obs}/\sigma_{ttH}^{SM} = 0.8\pm0.6$: 1.4σ observed (1.6σ expected)**

Backup

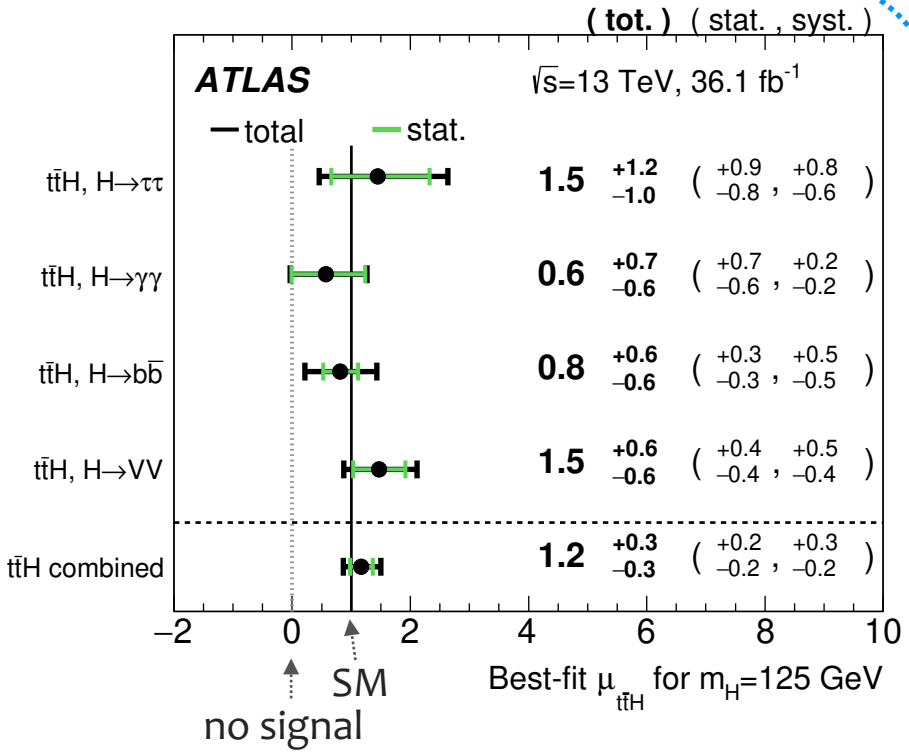
ttH Combination Results

Observed (Expected) excess = 4.2σ (3.8σ) over SM bkgd.

: evidence for ttH production

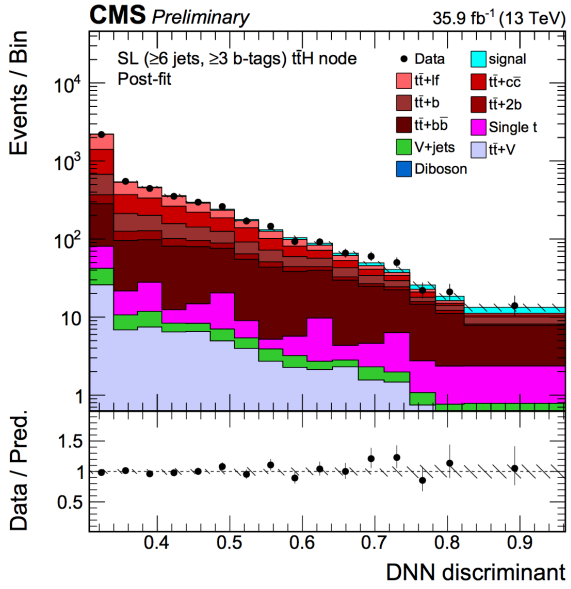
- tHqb, WtH and other Higgs prod. treated as bkgd. and fixed to SM pred.
- Higgs decays are fixed to SM pred.

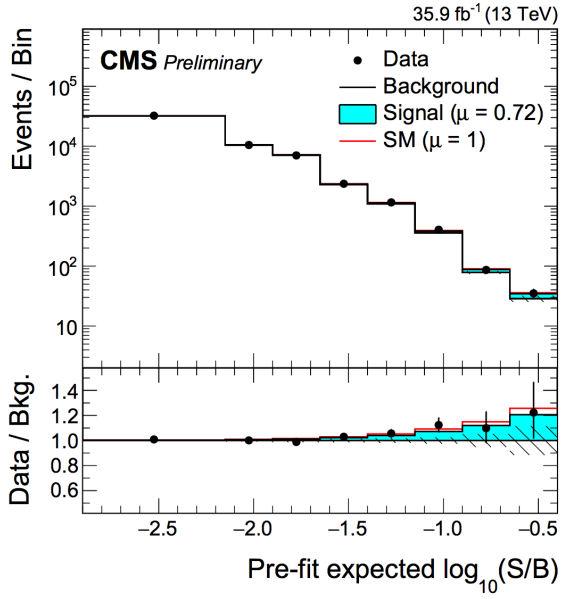
Largest impact by tt+bb modeling also seen in combined result.

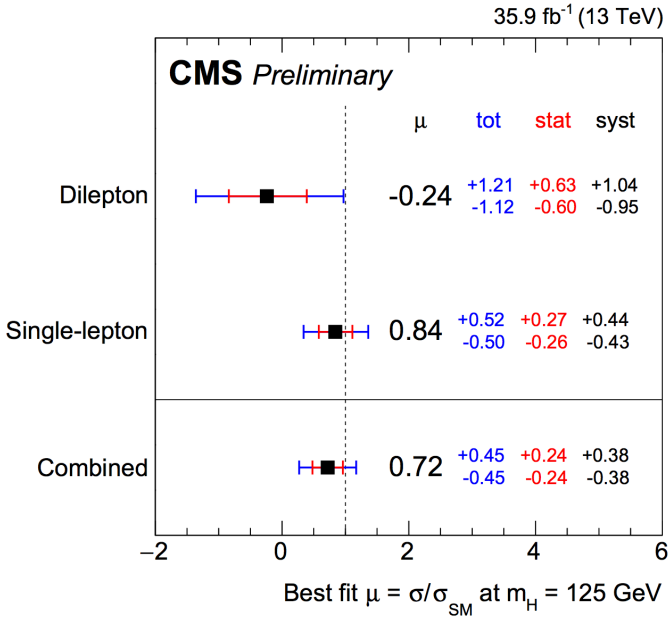


Uncertainty Source	$\Delta\mu$	
$t\bar{t}$ modeling in $H \to b\bar{b}$ analysis	+0.15	−0.14
$t\bar{t}H$ modeling (cross section)	+0.13	−0.06
Non-prompt light-lepton and fake τ_{had} estimates	+0.09	−0.09
Simulation statistics	+0.08	−0.08
Jet energy scale and resolution	+0.08	−0.07
$t\bar{t}V$ modeling	+0.07	−0.07
$t\bar{t}H$ modeling (acceptance)	+0.07	−0.04
Other non-Higgs boson backgrounds	+0.06	−0.05
Other experimental uncertainties	+0.05	−0.05
Luminosity	+0.05	−0.04
Jet flavor tagging	+0.03	−0.02
Modeling of other Higgs boson production modes	+0.01	−0.01
Total systematic uncertainty	+0.27	−0.23
Statistical uncertainty	+0.19	−0.19
Total uncertainty	+0.34	−0.30

CMS Latest Results (H->bb)





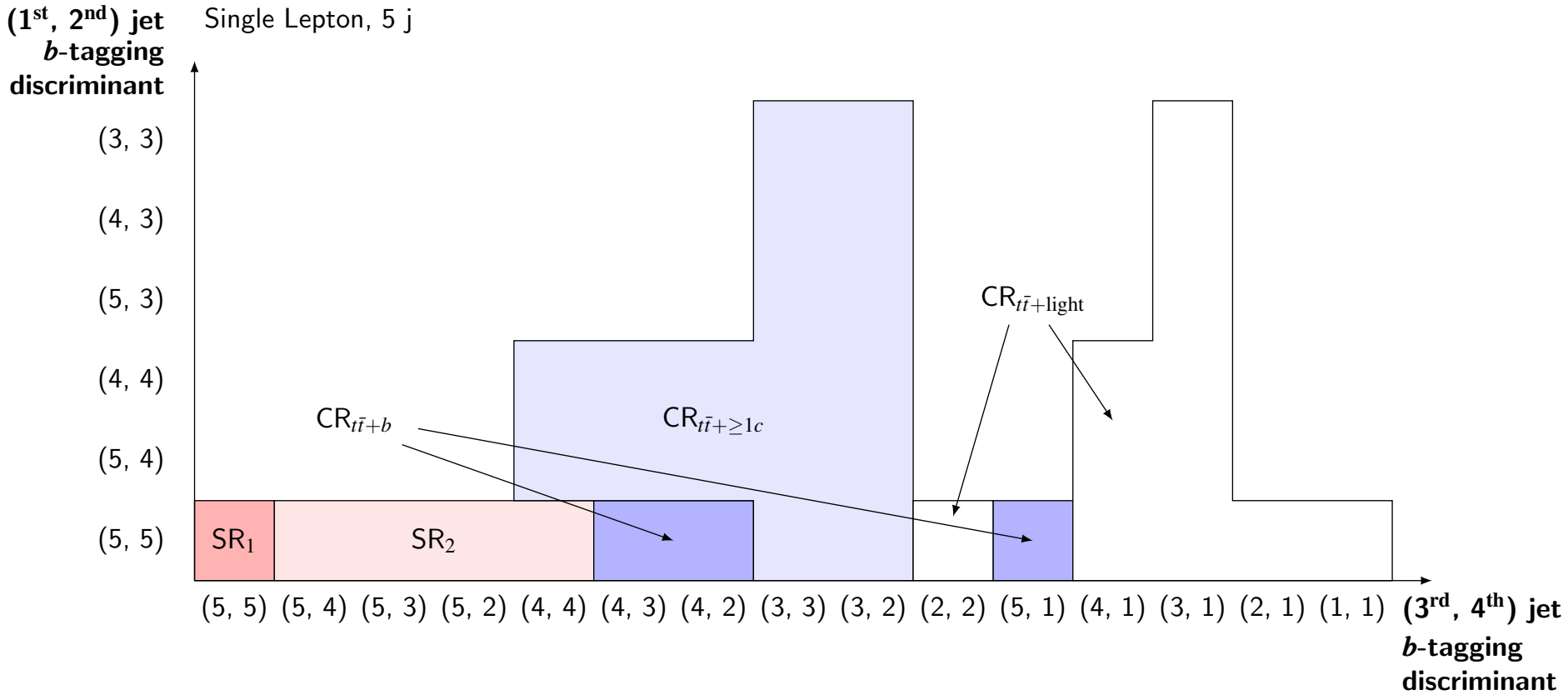


Channel	Limit		Best-fit μ
	observed	expected	$\pm$tot ($\pm$stat $\pm$ syst)
Dilepton	2.34	$2.48^{+1.17}_{-0.76}$	$-0.24^{+1.21}_{-1.12}(\text{tot})\ ^{+0.63}_{-0.60}(\text{stat})\ ^{+1.04}_{-0.95}(\text{syst})$
Single-lepton	1.75	$1.03^{+0.44}_{-0.29}$	$0.84^{+0.52}_{-0.50}(\text{tot})\ ^{+0.27}_{-0.26}(\text{stat})\ ^{+0.44}_{-0.43}(\text{syst})$
Combined	1.51	$0.92^{+0.39}_{-0.26}$	$0.72^{+0.45}_{-0.45}(\text{tot})\ ^{+0.24}_{-0.24}(\text{stat})\ ^{+0.38}_{-0.38}(\text{syst})$

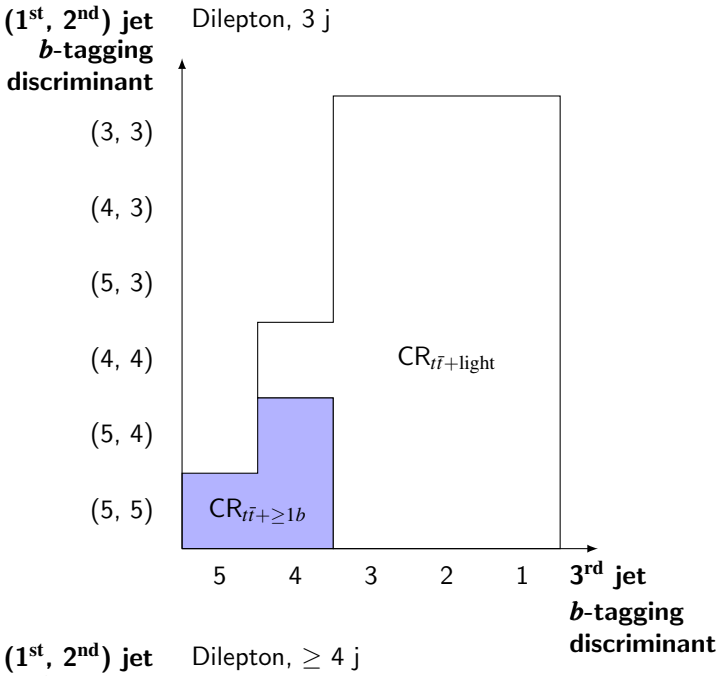
Large different treatments for tt+jets modeling unc. from ATLAS.

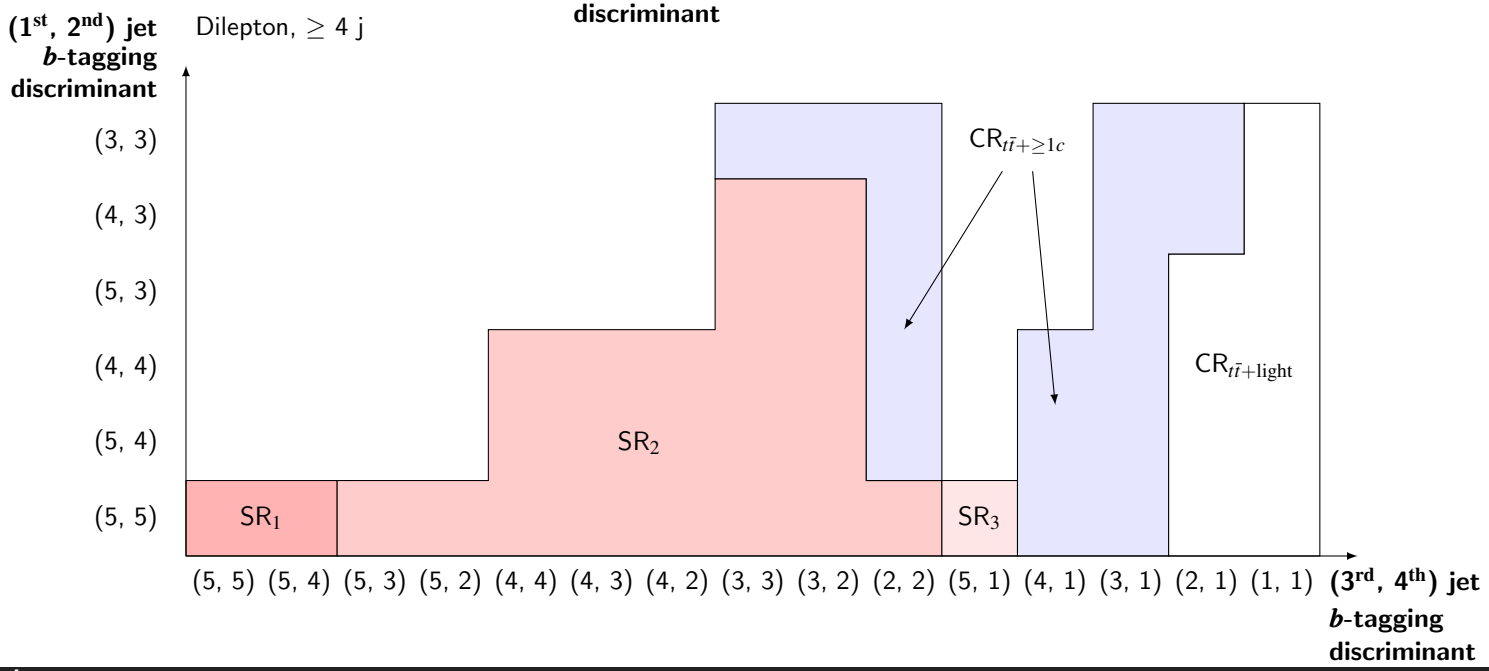
Uncertainty source	$\pm\sigma_\mu$ (observed)	$\pm\sigma_\mu$ (expected)
total experimental	+0.15/-0.16	+0.19/-0.17
b tagging	+0.11/-0.14	+0.12/-0.11
jet energy scale and resolution	+0.06/-0.07	+0.13/-0.11
total theory	+0.28/-0.29	+0.32/-0.29
tt̄+hf cross-section and parton shower	+0.24/-0.28	+0.28/-0.28
size of MC samples	+0.14/-0.15	+0.16/-0.16
total systematic	+0.38/-0.38	+0.45/-0.42
statistical	+0.24/-0.24	+0.27/-0.27
total	+0.45/-0.45	+0.53/-0.49

Region Definition in 5J

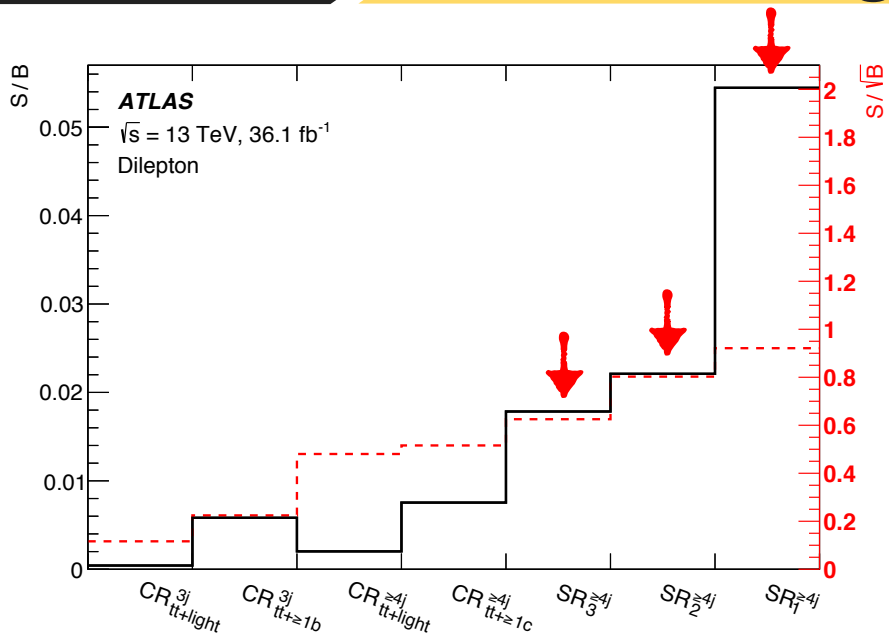


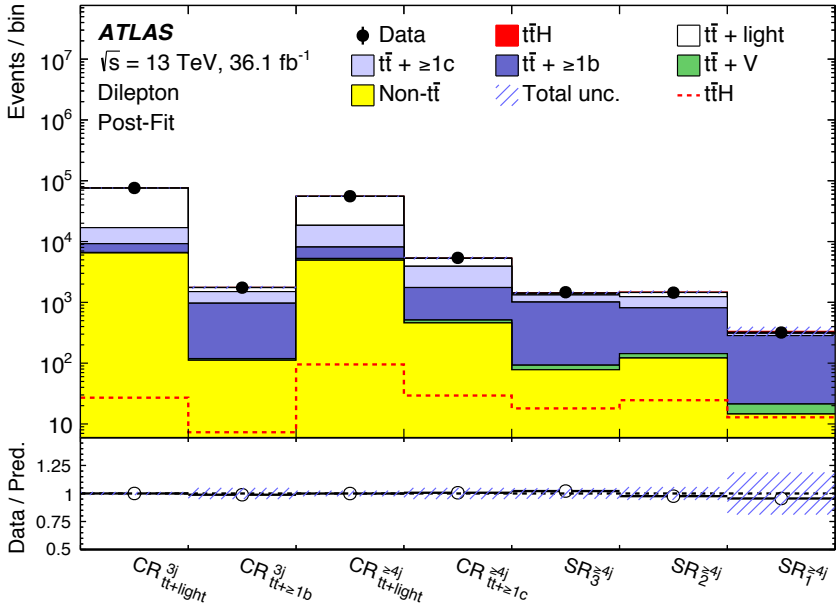
Region Definition in Dilepton Channel





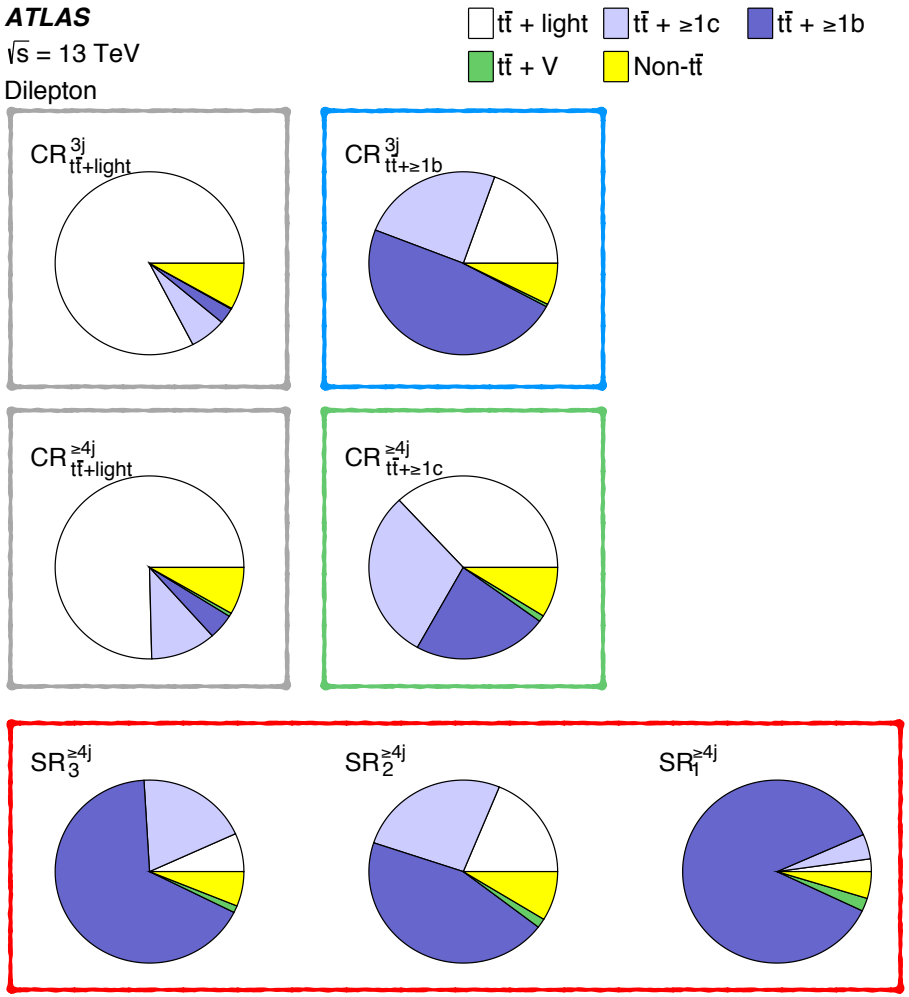
Defined Regions in Dilepton Channel





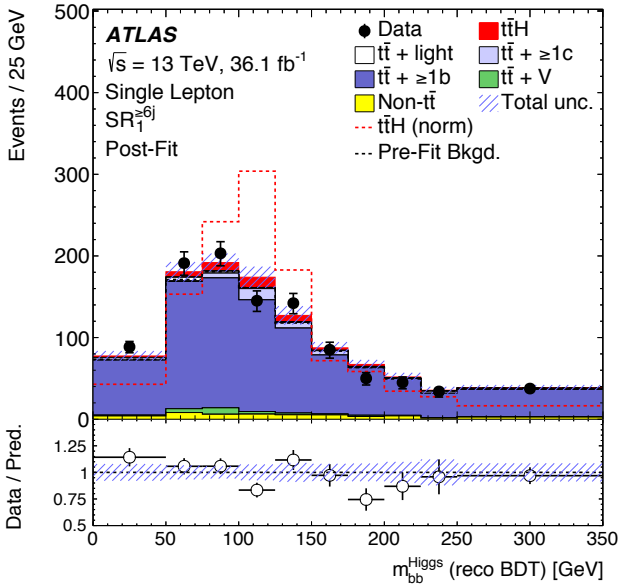
7 regions for single-lepton channel (5jets, ≥6jets)

- two control regions enriched by tt+light ,
- one control regions enriched by tt+≥1c or tt+b
- three signal enriched regions

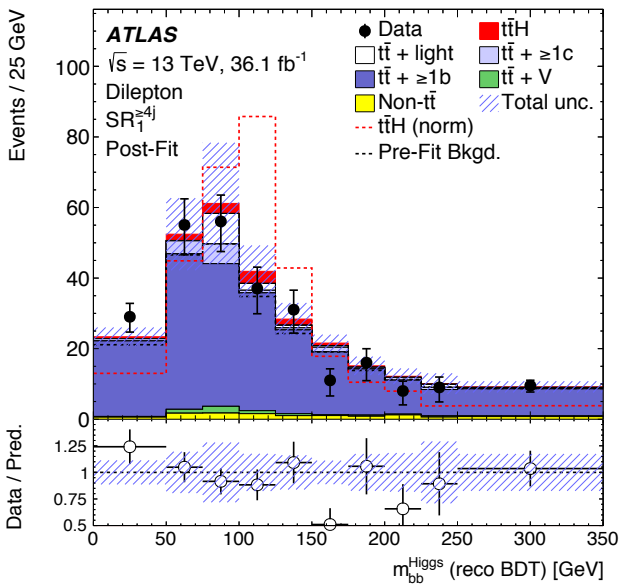


Higgs Mass

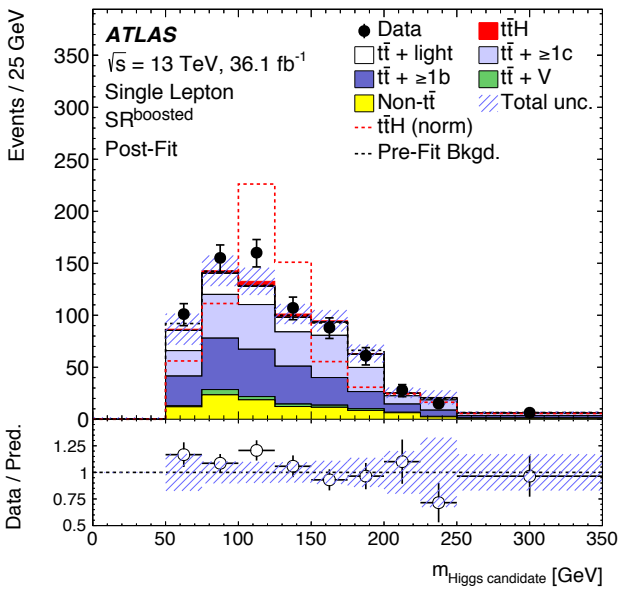
≥6jets, SR1



≥4jets, SR1



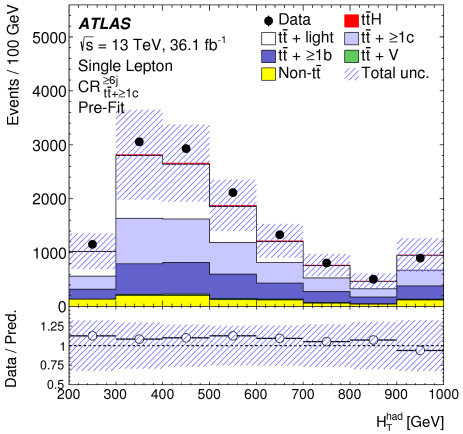
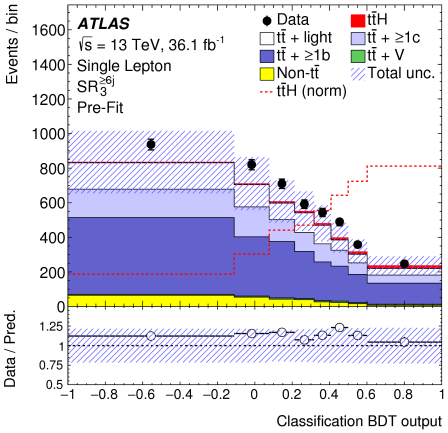
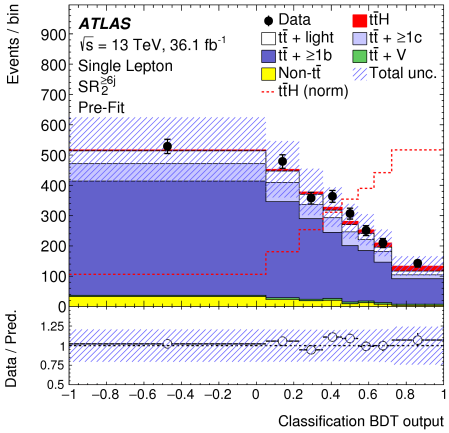
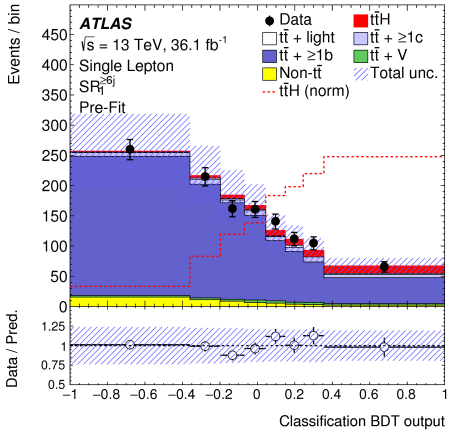
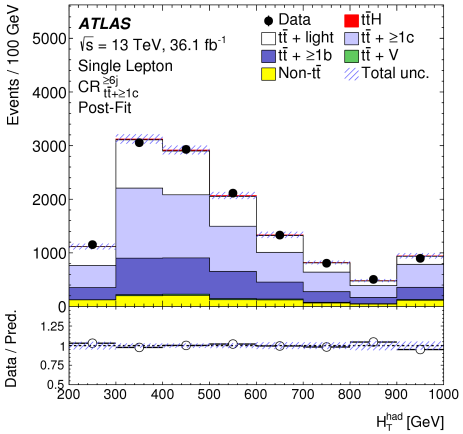
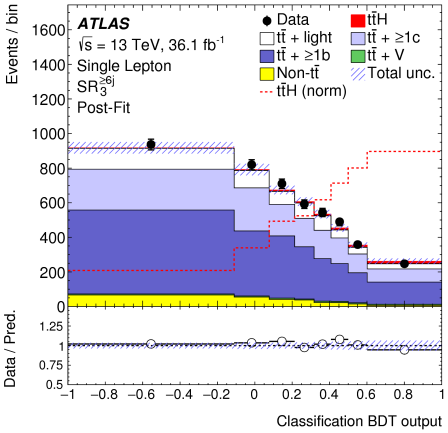
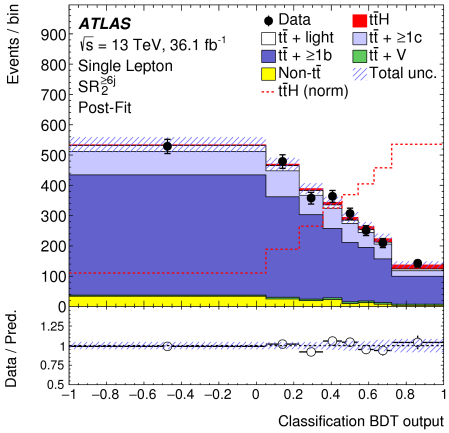
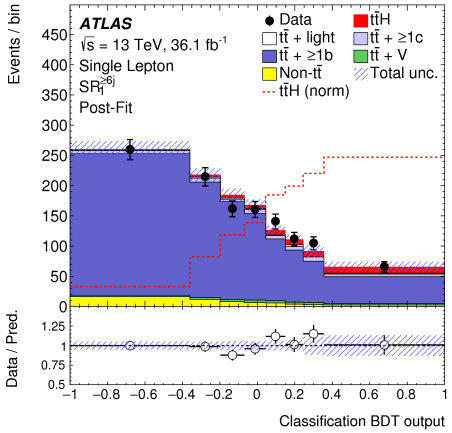
boosted



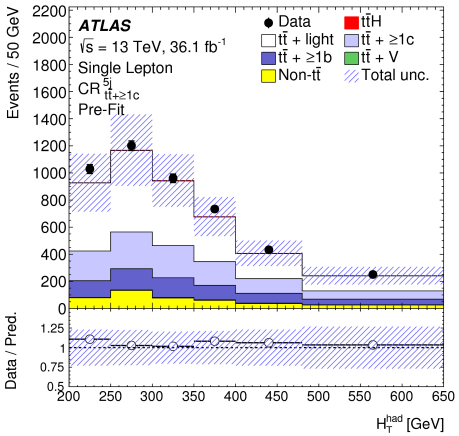
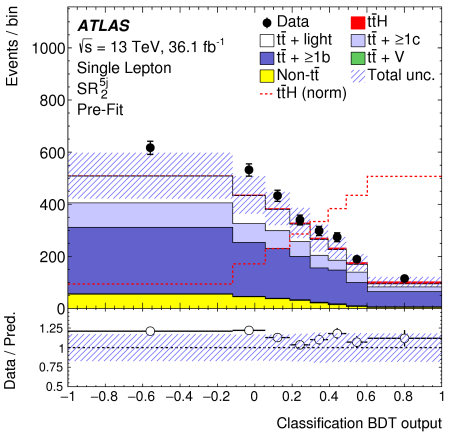
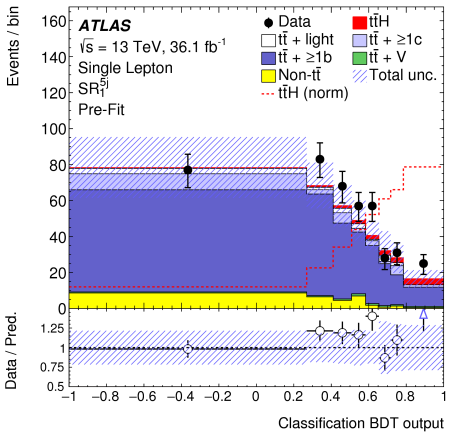
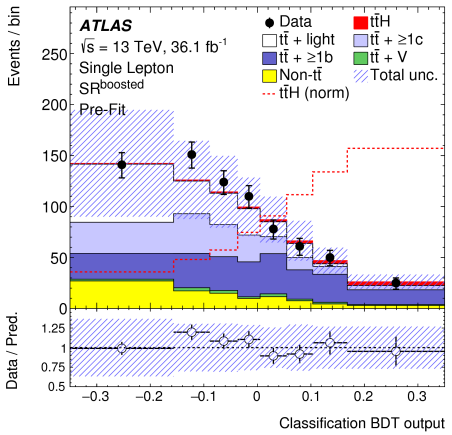
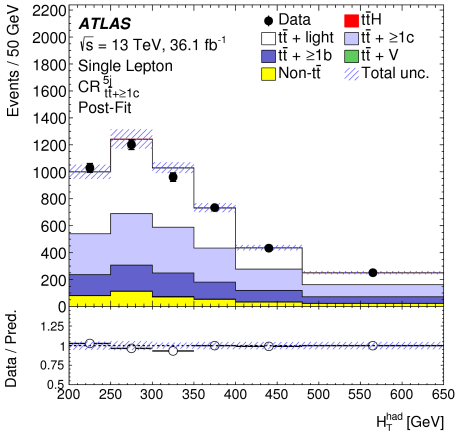
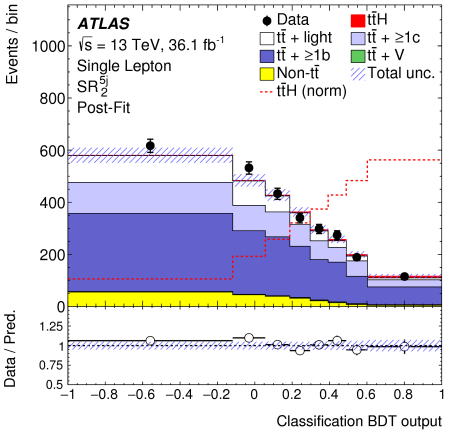
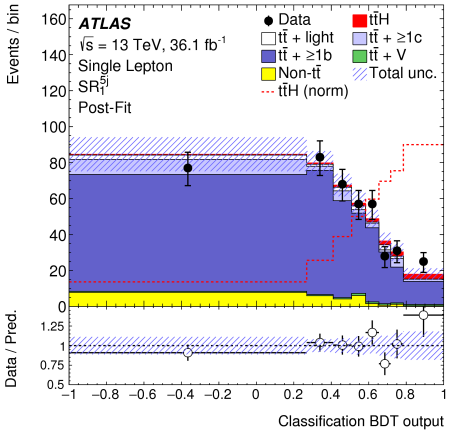
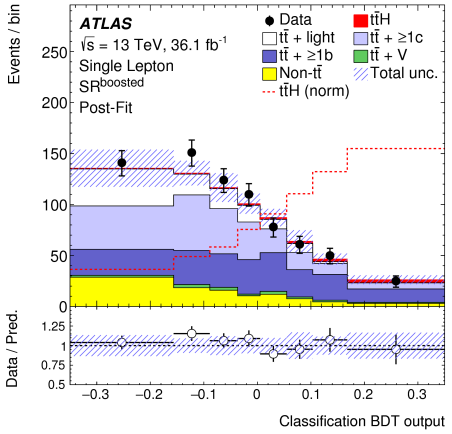
efficiency for correctly Higgs reconstructed:

≥6jets, SR1	≥4jets, SR1	boosted
32%	32%	47%

Single-Lepton Plots

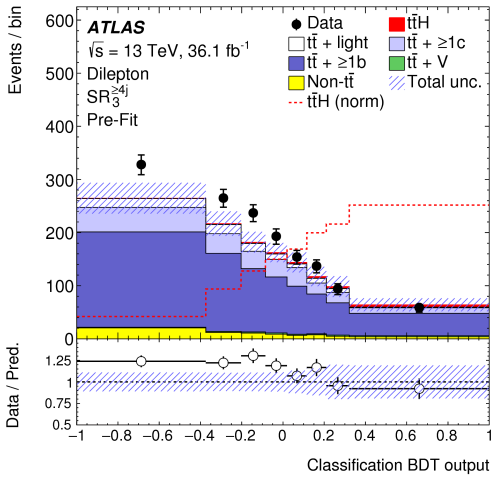
	6jCR(ttc)	6jSR3	6jSR2	6jSR1
Pre-fit				
Post-fit				

Single-Lepton Plots

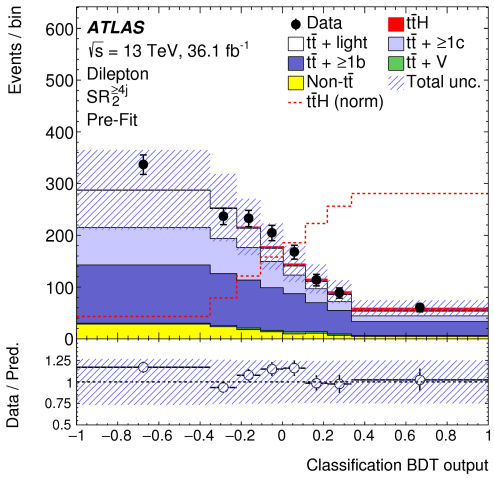
	5jCR(ttc)	5jSR2	5jSR1	Boosted SR
Pre-fit				
Post-fit				

Dilepton Plots

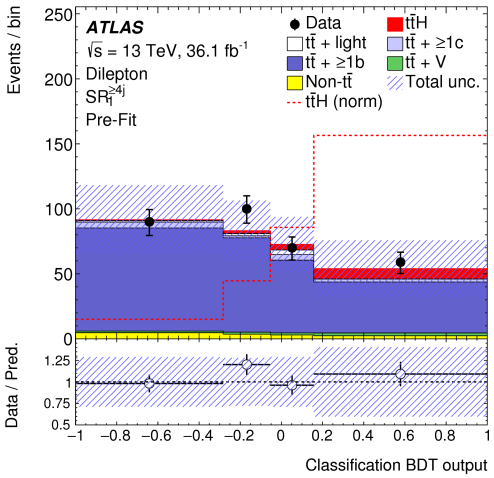
4jSR3



4jSR2

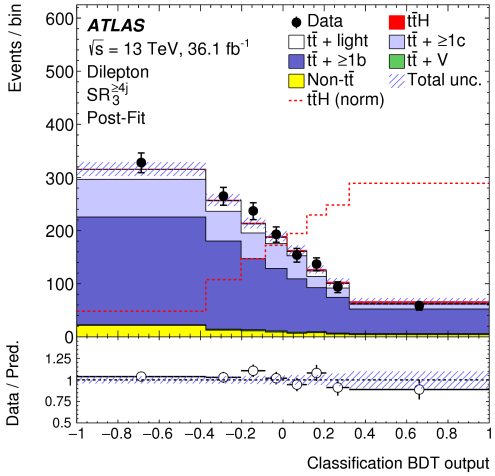


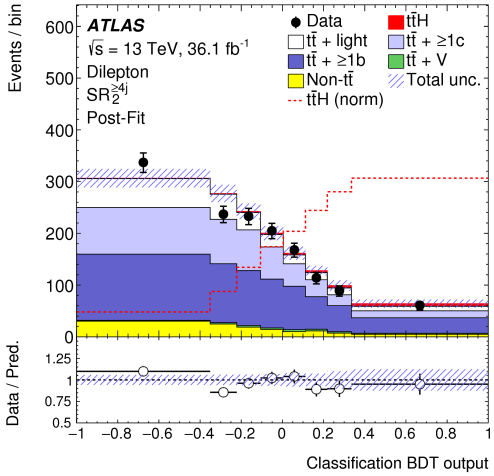
4jSR1

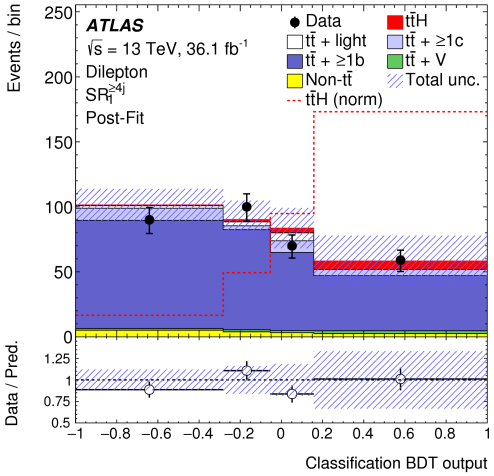


Pre-fit

Post-fit

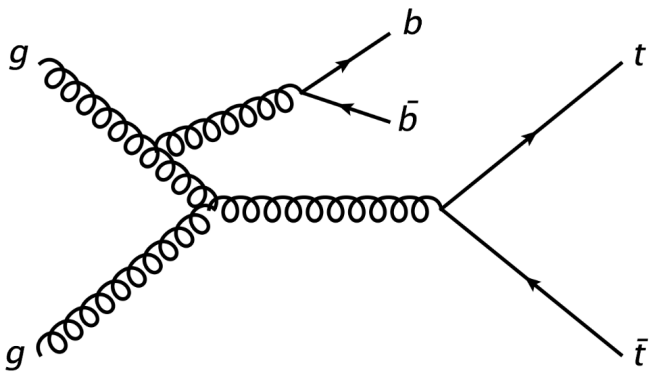


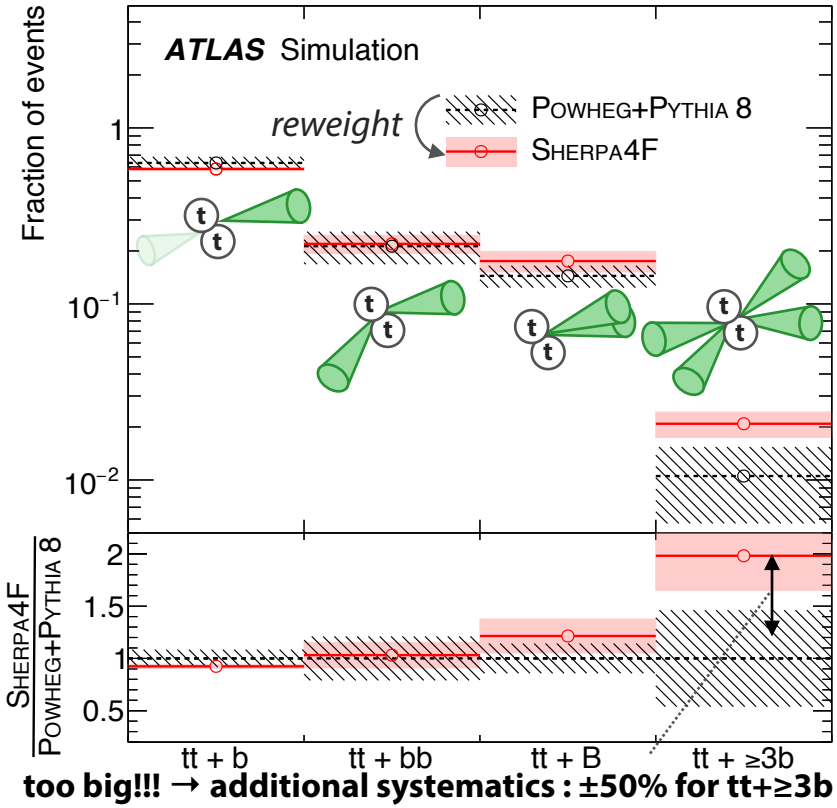




BackGround: Normalization Reweights on tt+≥1b

PowhegPythia8(5FS) reweighted to SherpaOL(4FS)



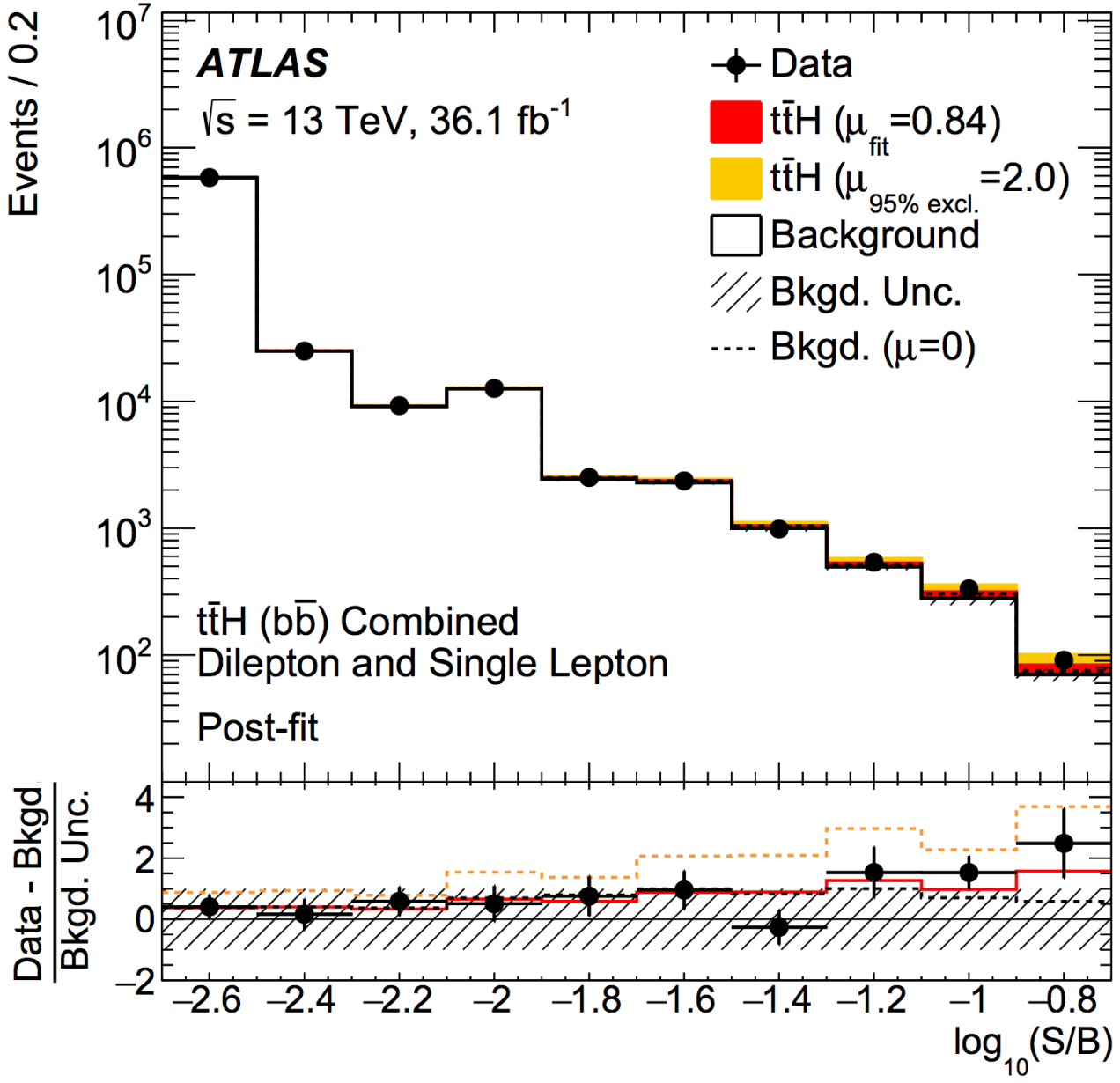


too big!!! → additional systematics : ±50% for tt+≥3b

ttbar Modeling Systematic Unc.

Systematic source	Description	$t\bar{t}$ categories
$t\bar{t}$ cross-section	Up or down by 6%	All, correlated
$k(t\bar{t} + \geq 1c)$	Free-floating $t\bar{t} + \geq 1c$ normalization	$t\bar{t} + \geq 1c$
$k(t\bar{t} + \geq 1b)$	Free-floating $t\bar{t} + \geq 1b$ normalization	$t\bar{t} + \geq 1b$
SHERPA5F vs. nominal	Related to the choice of NLO event generator	All, uncorrelated
PS & hadronization	POWHEG+HERWIG 7 vs. POWHEG+PYTHIA 8	All, uncorrelated
ISR / FSR	Variations of μ_R, μ_F, h_{damp} and A14 Var3c parameters	All, uncorrelated
$t\bar{t} + \geq 1c$ ME vs. inclusive	MG5_aMC@NLO+HERWIG++: ME prediction (3F) vs. incl. (5F)	$t\bar{t} + \geq 1c$
$t\bar{t} + \geq 1b$ SHERPA4F vs. nominal	Comparison of $t\bar{t} + b\bar{b}$ NLO (4F) vs. POWHEG+PYTHIA 8 (5F)	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ renorm. scale	Up or down by a factor of two	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ resumm. scale	Vary μ_Q from $H_T/2$ to μ_{CMMPS}	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ global scales	Set μ_Q, μ_R, and μ_F to μ_{CMMPS}	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ shower recoil scheme	Alternative model scheme	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ PDF (MSTW)	MSTW vs. CT10	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ PDF (NNPDF)	NNPDF vs. CT10	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ UE	Alternative set of tuned parameters for the underlying event	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ MPI	Up or down by 50%	$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 3b$ normalization	Up or down by 50%	$t\bar{t} + \geq 1b$

S/B Sorted Plot



BDT Input Variables

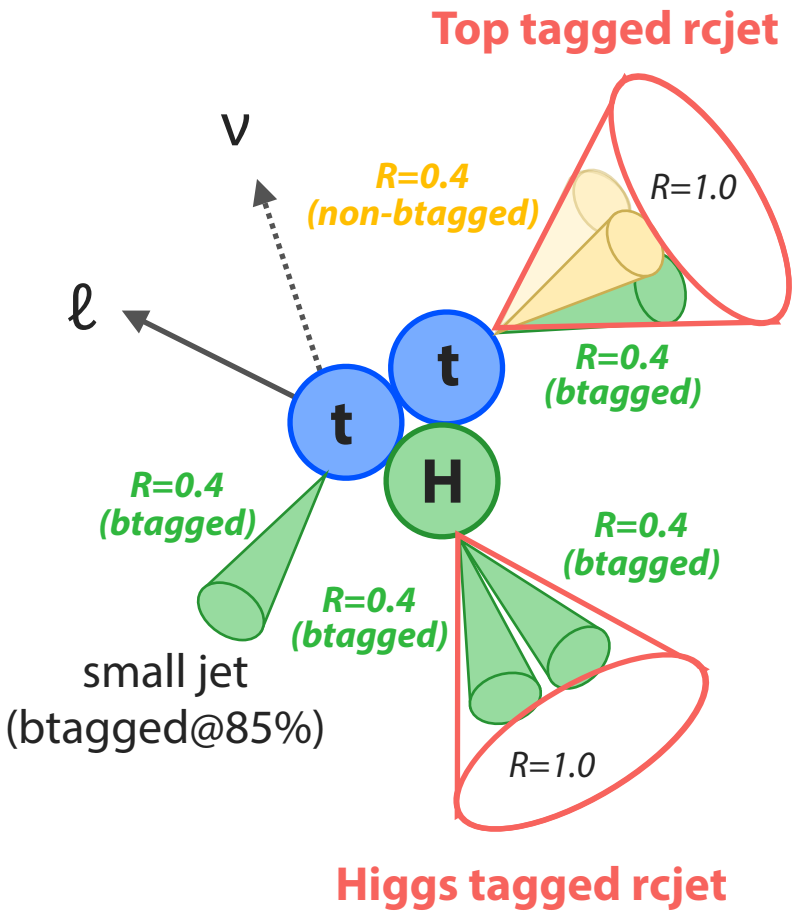
Variable	Definition	$SR^{\geq 6j}_{1,2,3}$	$SR^{5j}_{1,2}$
General kinematic variables			
$\Delta R_{bb}^{\text{avg}}$	Average ΔR for all b-tagged jet pairs	✓	✓
$\Delta R_{bb}^{\text{max } p_{\text{T}}}$	ΔR between the two b-tagged jets with the largest vector sum p_{T}	✓	–
$\Delta\eta_{\text{jj}}^{\text{max}}$	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	✓	–
$m_{\text{jj}}^{\text{min } \Delta R}$	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	✓	✓
$H_{\text{T}}^{\text{had}}$	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 [99] 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	3rd largest jet b-tagging discriminant	✓	✓
B_{jet}^4	4th largest jet b-tagging discriminant	✓	✓
B_{jet}^5	5th largest jet b-tagging discriminant	✓	✓

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 [99] 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	-	✓	-

Boosted Region

ReClustered **Jet**: using calibrated normal (small-R) jets to construct the large-R jet

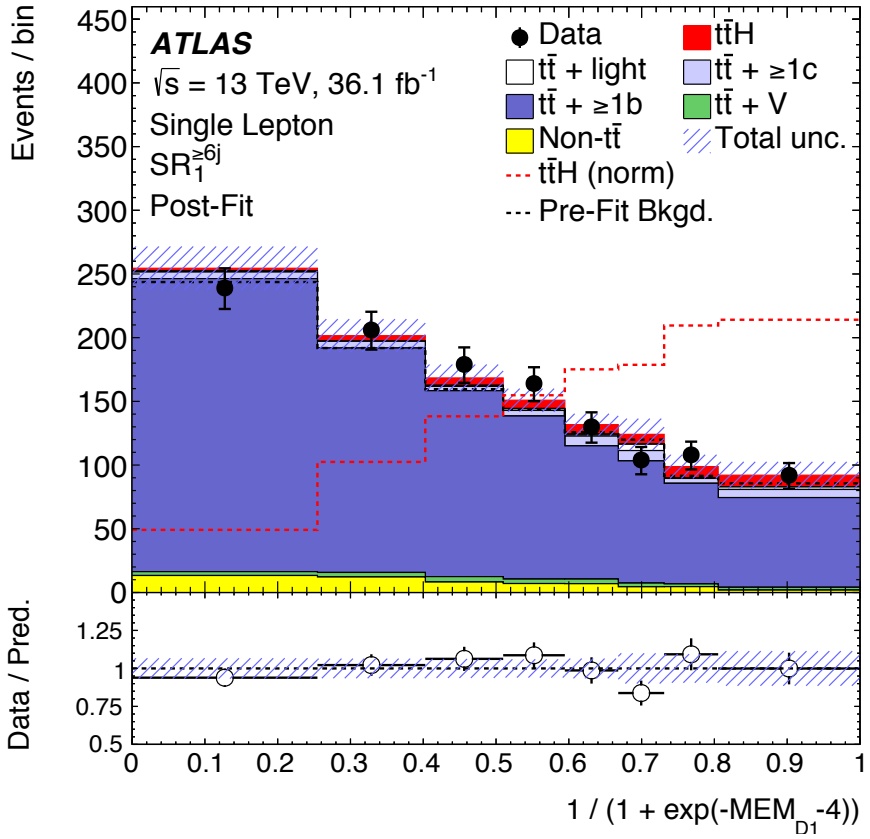
→ High momentum Higgs(→bb) and top(→bjj) objects can be tagged!

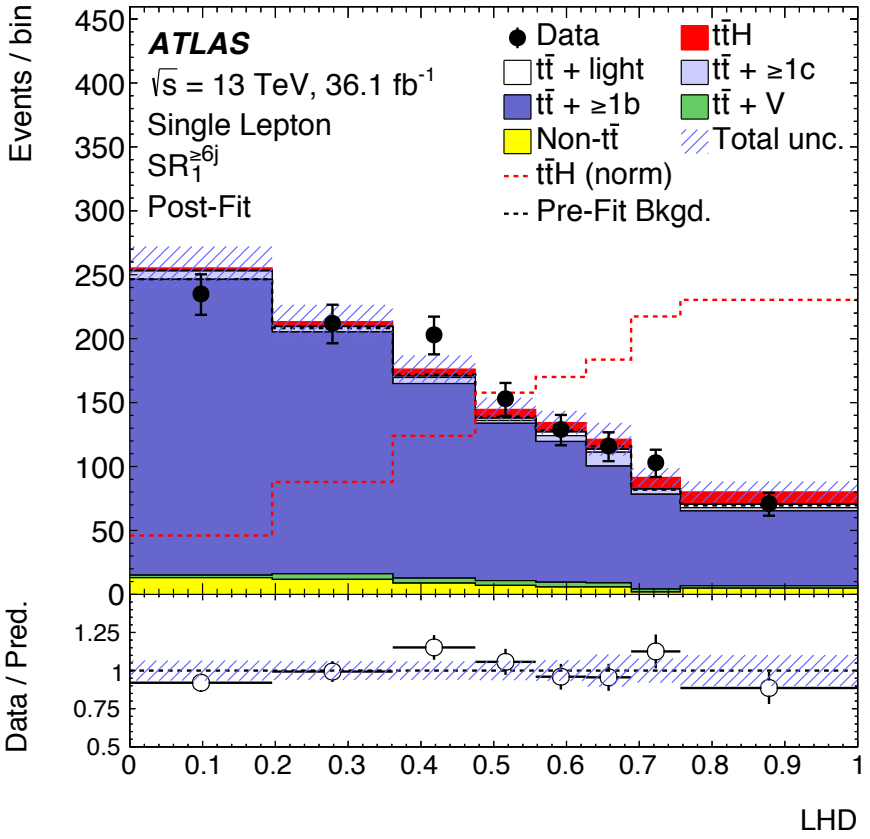


BDT input variables

Variable	Definition
Variables from jet reclustering	
$\Delta R_{H,t}$	ΔR between the Higgs-boson and top-quark candidates
$\Delta R_{t,b^{\text{add}}}$	ΔR between the top-quark candidate and additional b-jet
$\Delta R_{H,b^{\text{add}}}$	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 [100]
Variables from b-tagging	
$w_{b\text{-tag}}$	Sum of b-tagging discriminants of all b-jets
$w^{\text{add}}_{b\text{-tag}}/w_{b\text{-tag}}$	Ratio of sum of b-tagging discriminants of additional b-jets to all b-jets

MEM and LHD


ATLAS
√s = 13 TeV, 36.1 fb-1
Single Lepton
SR1≥6j
Post-Fit
Data
tt̄H
tt̄ + light
tt̄ + ≥1c
tt̄ + ≥1b
tt̄ + V
Non-tt̄
Total unc.
tt̄H (norm)
Pre-Fit Bkgd.
Events / bin
Data / Pred.
1 / (1 + exp(-MEMD1-4))


ATLAS
√s = 13 TeV, 36.1 fb-1
Single Lepton
SR1≥6j
Post-Fit
Data
tt̄H
tt̄ + light
tt̄ + ≥1c
tt̄ + ≥1b
tt̄ + V
Non-tt̄
Total unc.
tt̄H (norm)
Pre-Fit Bkgd.
Events / bin
Data / Pred.
LHD