

Search for $t\bar{t}(H \rightarrow b\bar{b})$ using the ATLAS detector at 8 TeV

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on behalf of the ATLAS collaboration

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Motivation, Strategy & Introduction

Overview: $t\bar{t}(H \rightarrow b\bar{b})$ leptonic analysis

Summary & Outlook

GEFÖRDERT VOM

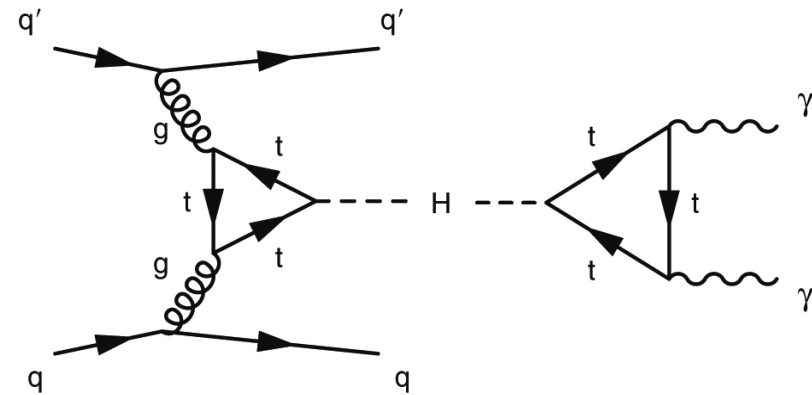
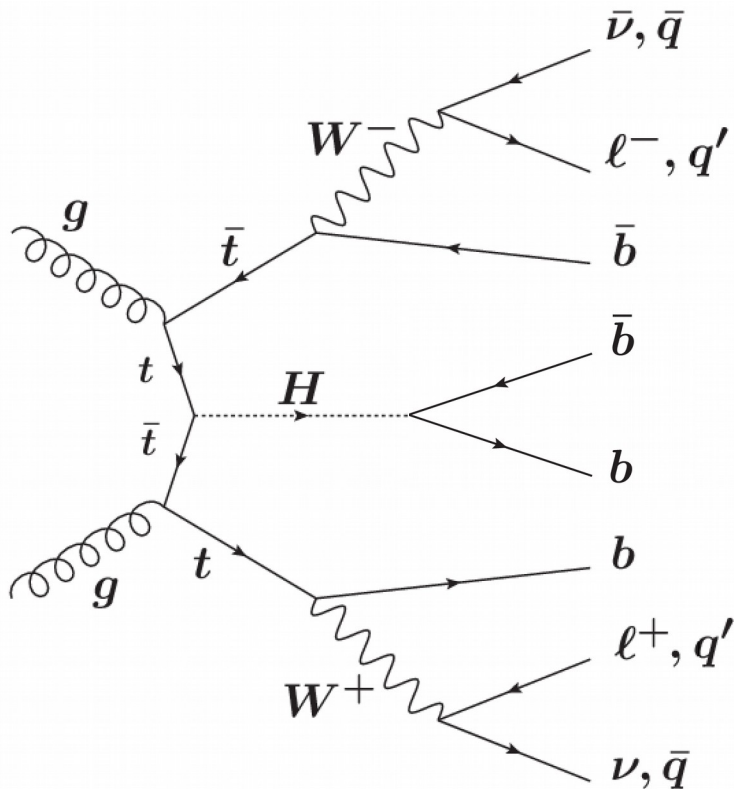


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Questions after Higgs boson discovery

- Part of the SM? Coupling to fermions?
- Top quark Yukawa coupling $y_t \sim 1$?
- Is there new physics?



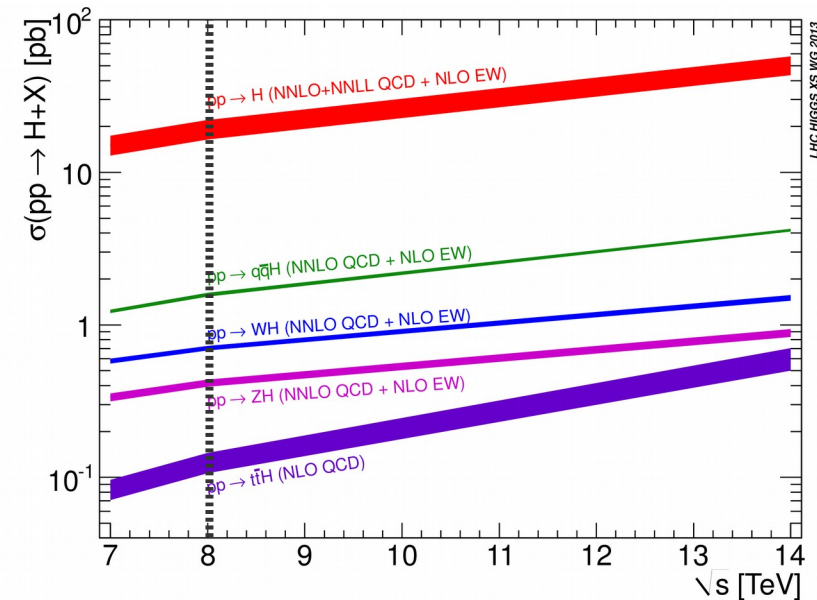
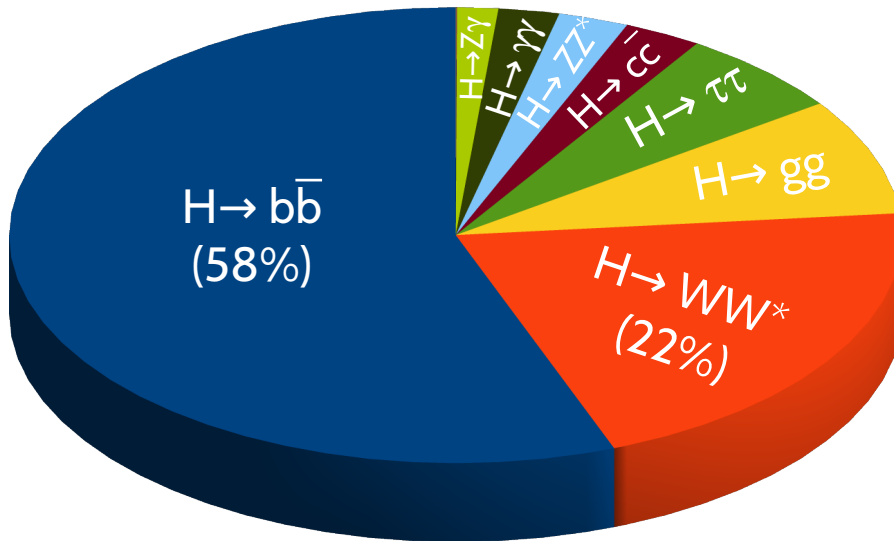
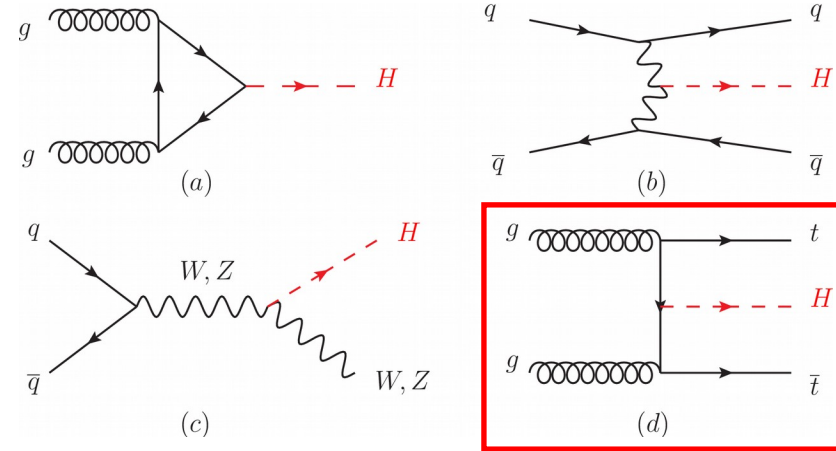
Answers in $t\bar{t}H$ search

- Observe $t\bar{t}H$ production and $H \rightarrow b\bar{b}$
- Most direct measurement of y_t ($\sigma \sim y_t^2$)
- Comparison to indirect y_t measurements

Focus of analysis

- Single lepton or dilepton $t\bar{t}$ decay
- Optimized for $H \rightarrow b\bar{b}$ decay

- Higgs boson production at the LHC
 - Four production mechanisms
 - Dominated by gg , $t\bar{t}H$ suppressed
- Higgs boson decay at 125 GeV
 - Dominated by $b\bar{b}$



- Selection: single lepton (dilepton)

= 1 (2) isolated lepton

≥ 4 (2) high p_T jets ($p_T > 25$ GeV)

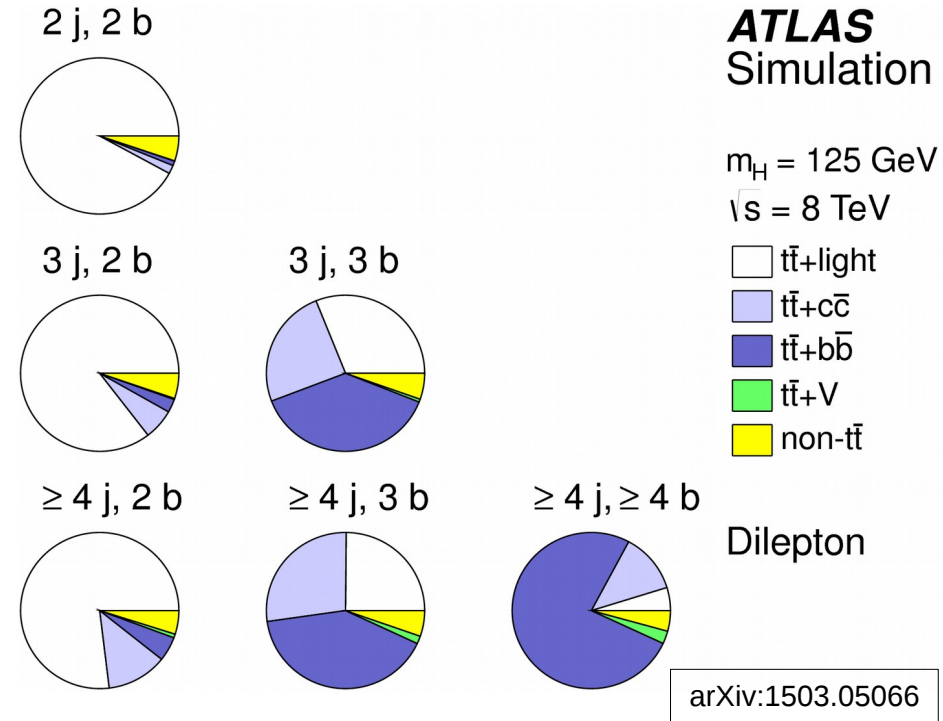
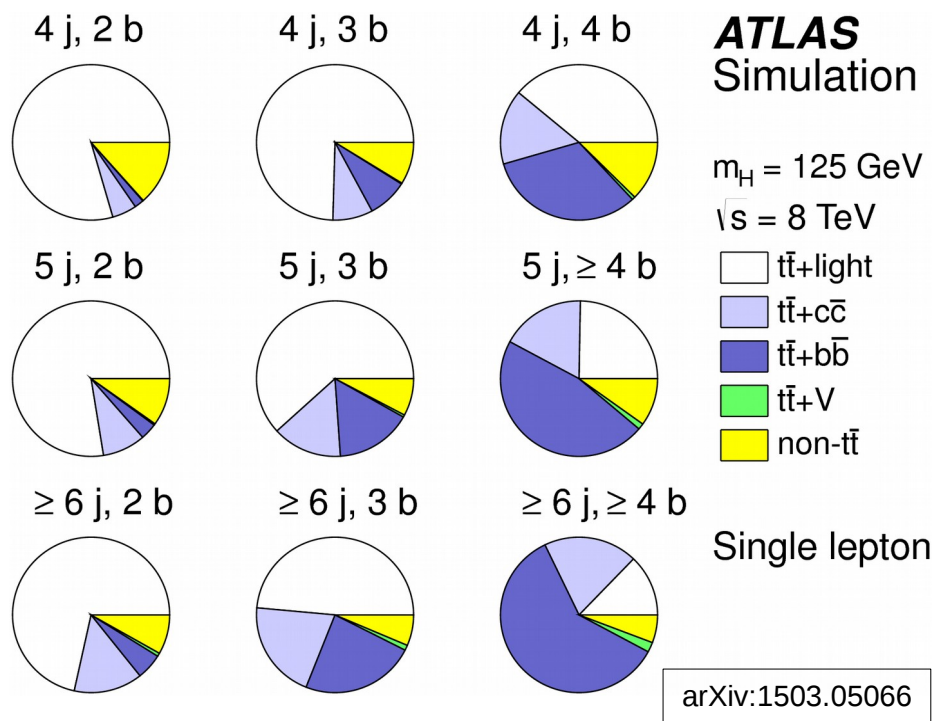
≥ 2 (2) b-tagged jets

- Classification of events:

- jet number & b-tag number

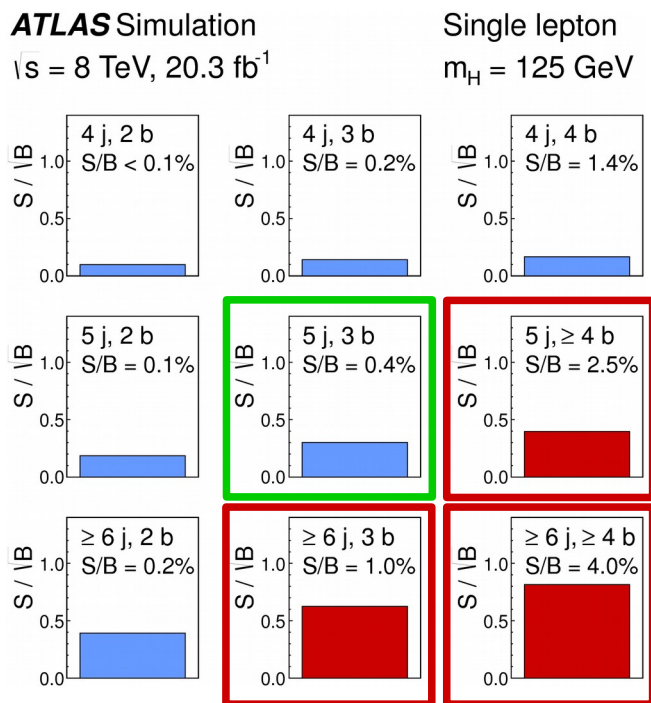
→ different BG compositions

→ dominated by $t\bar{t}$ +jets ($2000 \times \sigma_{t\bar{t}H}$)

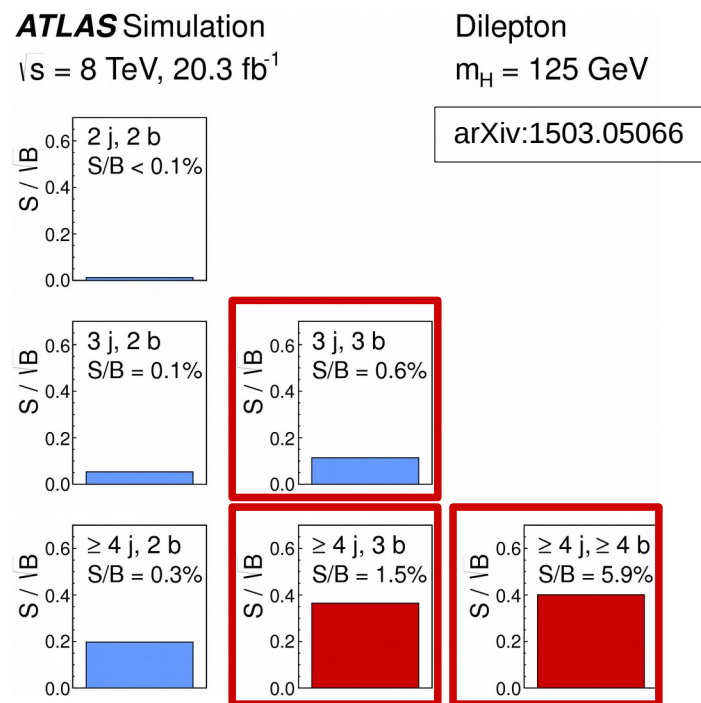


- Analysis regions by S/B
 - signal regions ($S/B > 1\%$ & $S/\sqrt{B} > 0.3$)
 - background regions
- Matrix Element Method (SL ≥ 6 jets)
 - Maximize $t\bar{t}H$ vs $t\bar{t}b\bar{b}$ separation

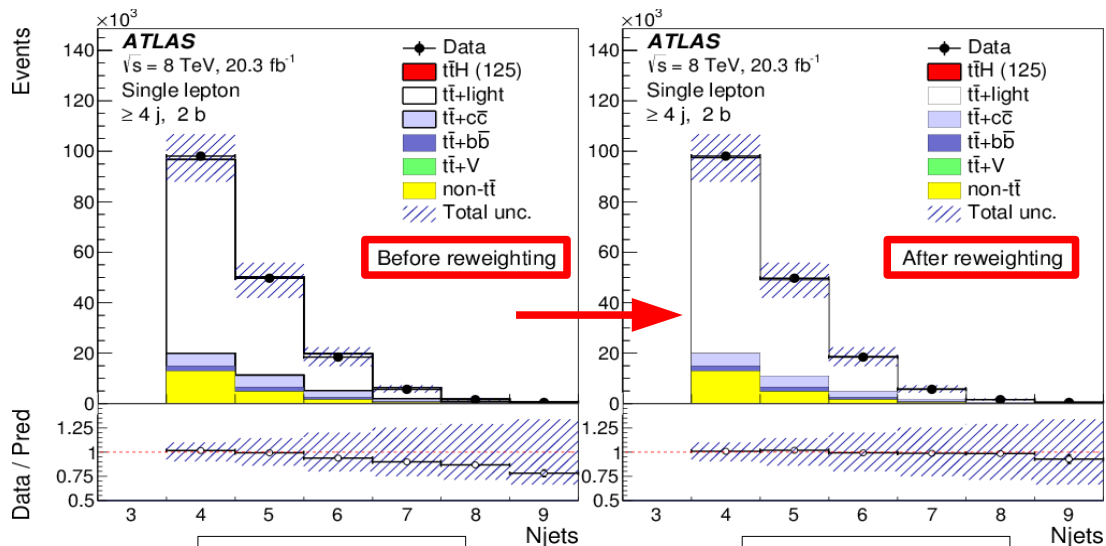
arXiv:1503.05066



- Artificial neural network
 - Signal regions: $t\bar{t}H$ vs BG (NN)
 - SL 5j, 3b: $t\bar{t}HF$ vs $t\bar{t}LF$ (NNHF)
- Profile Likelihood fit
 - Input: NN output or H_T
 - Extract μ & constrain systematics

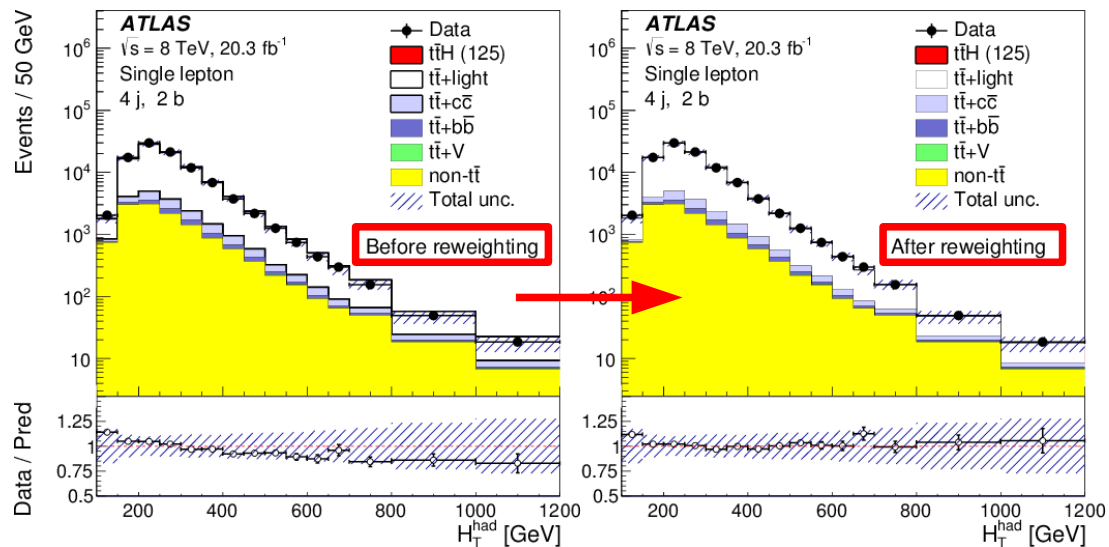


- PowHeg+Pythia (NLO+PS)
 - $t\bar{t}$ +light, $t\bar{t}$ + $c\bar{c}$, $t\bar{t}$ + $b\bar{b}$
- Observed disagreement
 - $t\bar{t}$ system p_T
 - top quark p_T
- Sequential p_T reweighting
 - 7 TeV differential xsecs
 - $t\bar{t}$ +light, $t\bar{t}$ + $c\bar{c}$
 - Parton level
- $t\bar{t}$ + $b\bar{b}$ modeling
 - HF only by parton shower
 - Split in truth categories
 - Reweight to SherpaOL



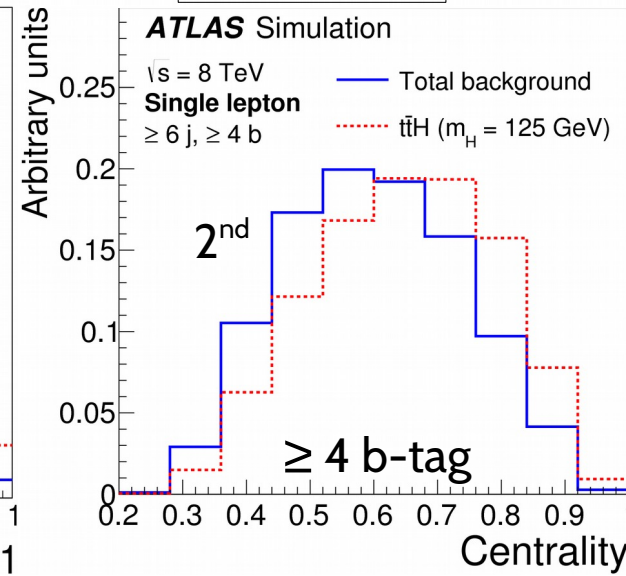
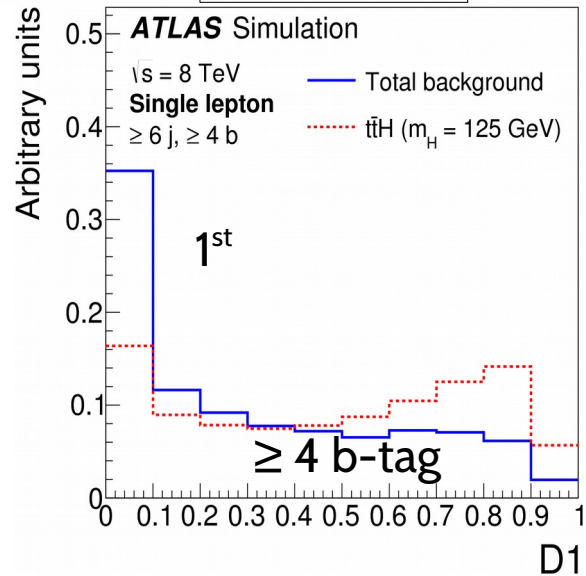
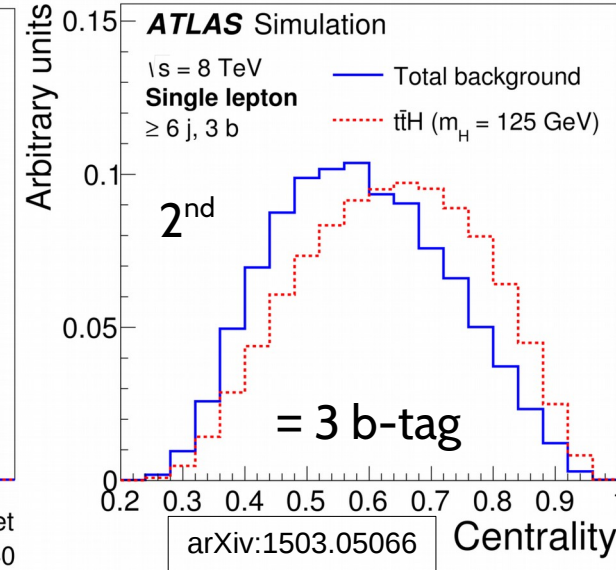
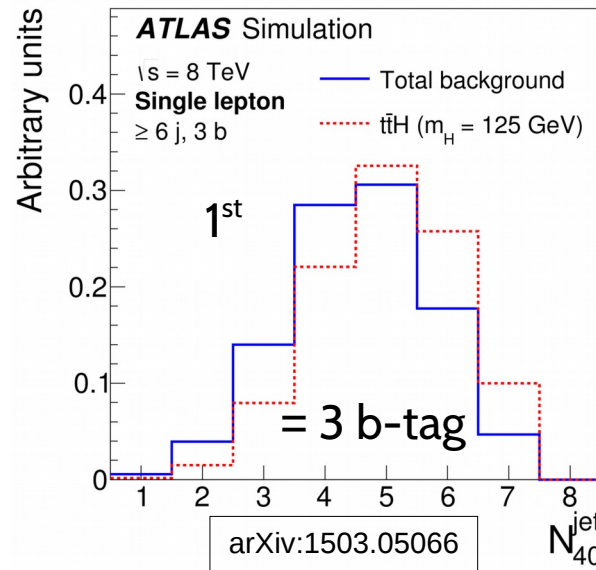
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- Single lepton
- 10 kinematic variable:
 - event shape
 - object pair properties
- 2 MEM (≥ 6 jets):
 - D1, SSLL

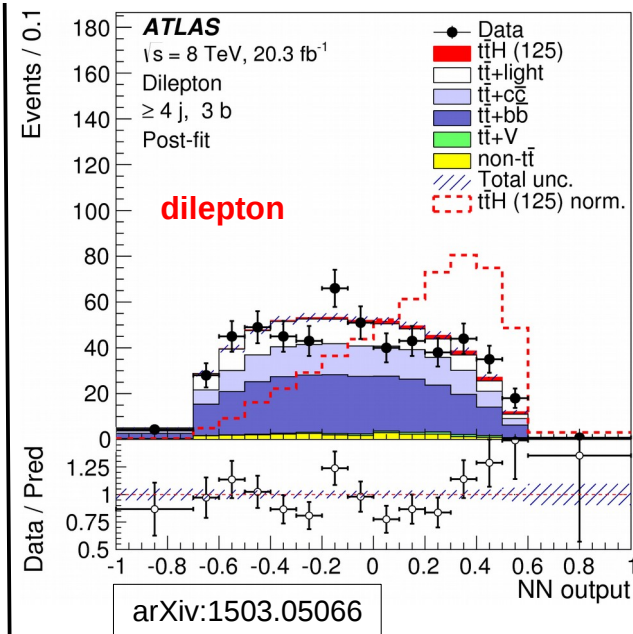
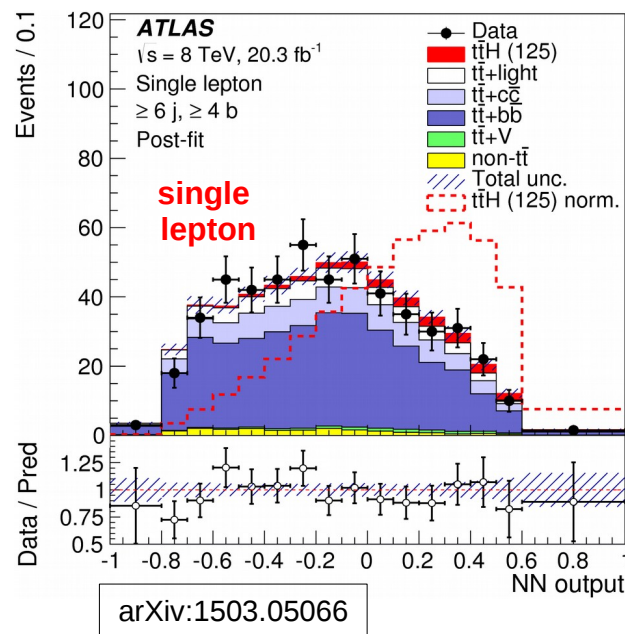
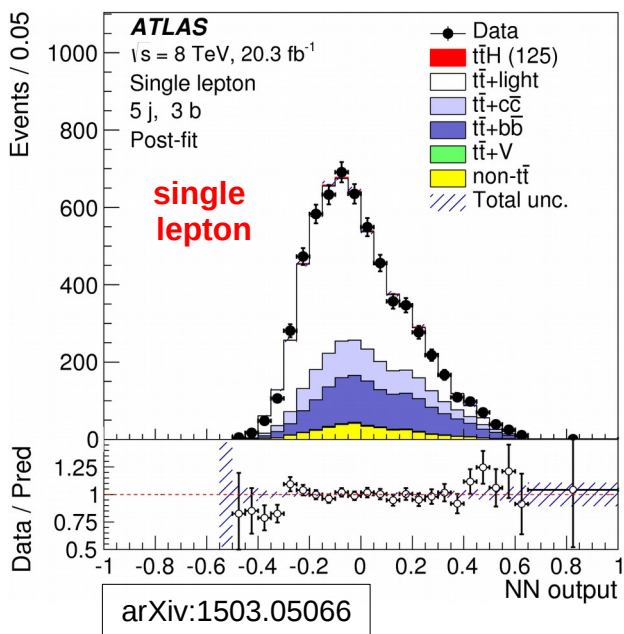
Variable	($\geq 6j, \geq 4b$)	($\geq 6j, 3b$)
<i>D1</i>	1	10
Centrality	2	2
p_T^{jet5}	3	7
<i>H1</i>	4	3
$\Delta R_{bb}^{\text{avg}}$	5	6
<i>SSLL</i>	6	4
$m_{bb}^{\text{min}} \Delta R$	7	12
$m_{bj}^{\text{max}} p_T$	8	8
$\Delta R_{bb}^{\text{max}} p_T$	9	-
$\Delta R_{lep-bb}^{\text{min}} \Delta R$	10	11
$m_{uu}^{\text{min}} \Delta R$	11	9
Aplanarity _{b-jet}	12	-



- Profile Likelihood Fit Input
 - Signal enriched: NN for ttH vs tt +jets
 - SL 5j, 3b: NNHF for tt +HF vs tt +LF
 - BG dominated: H_T to constrain systematics
- Good agreement of data & predictions

single lep	2 b-tags	3 b-tags	≥ 4 b-tags
4 jets	H_T^{had}	H_T^{had}	H_T^{had}
5 jets	H_T^{had}	NN	NN
≥ 6 jets	H_T^{had}	NN	NN

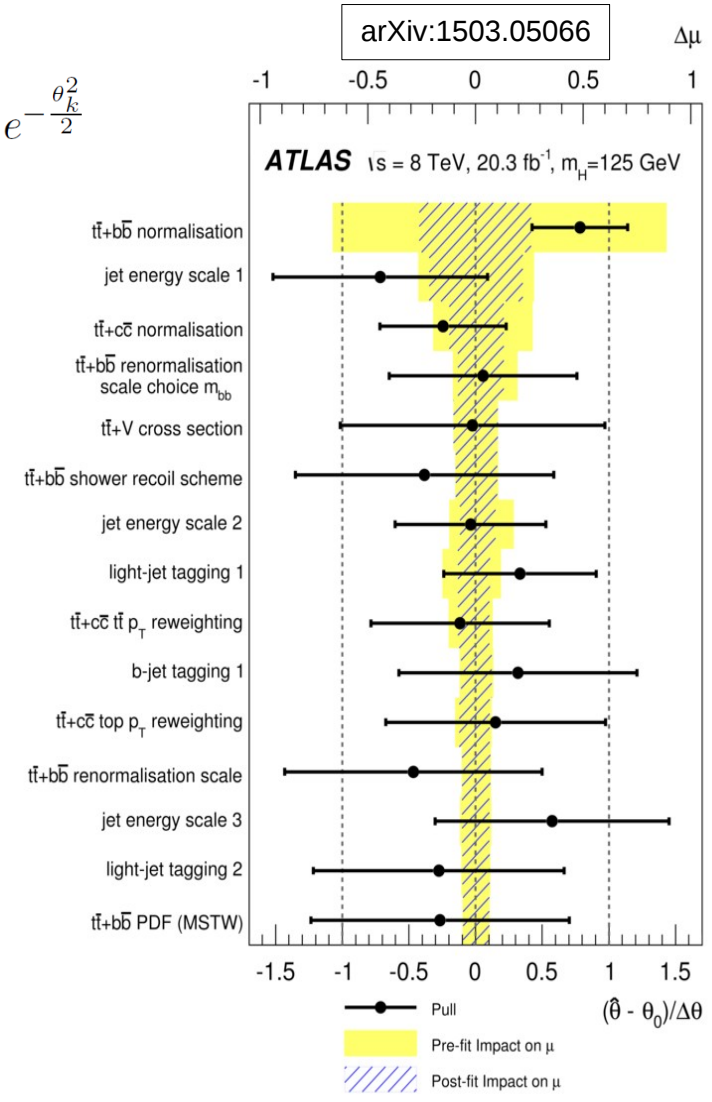
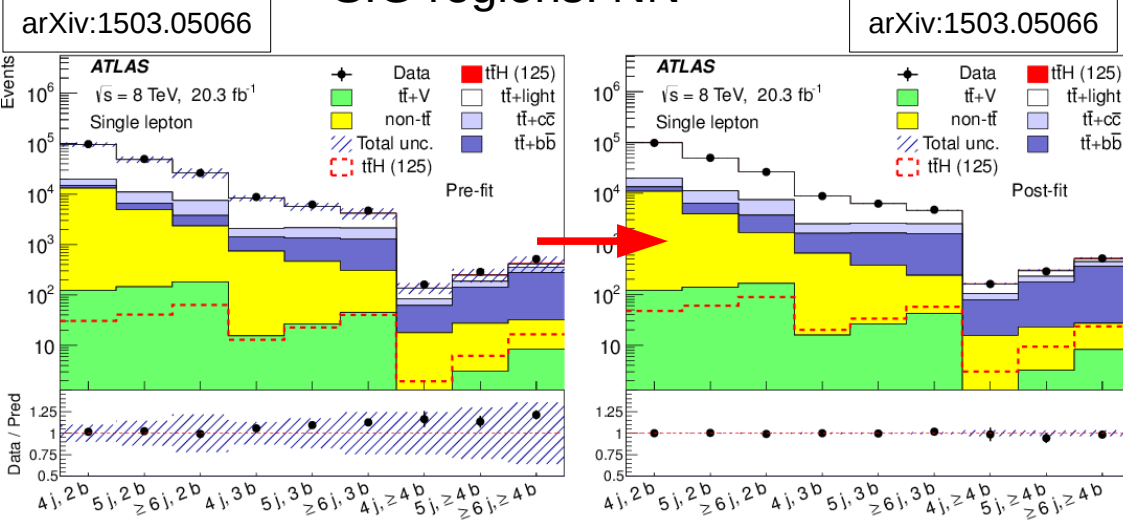
dilepton	2 b-tags	3 b-tags	≥ 4 b-tags
2 jets	H_T		
3 jets	H_T	NN	
≥ 4 jets	H_T	NN	NN



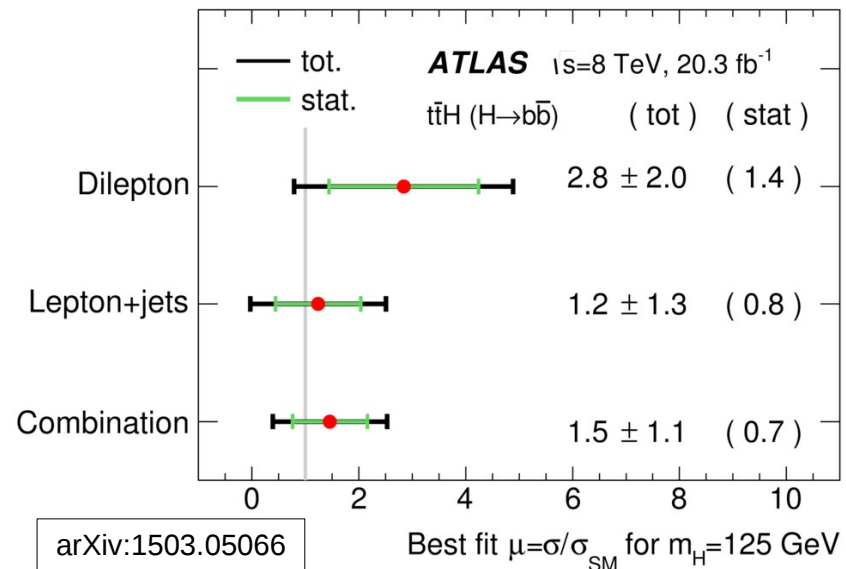
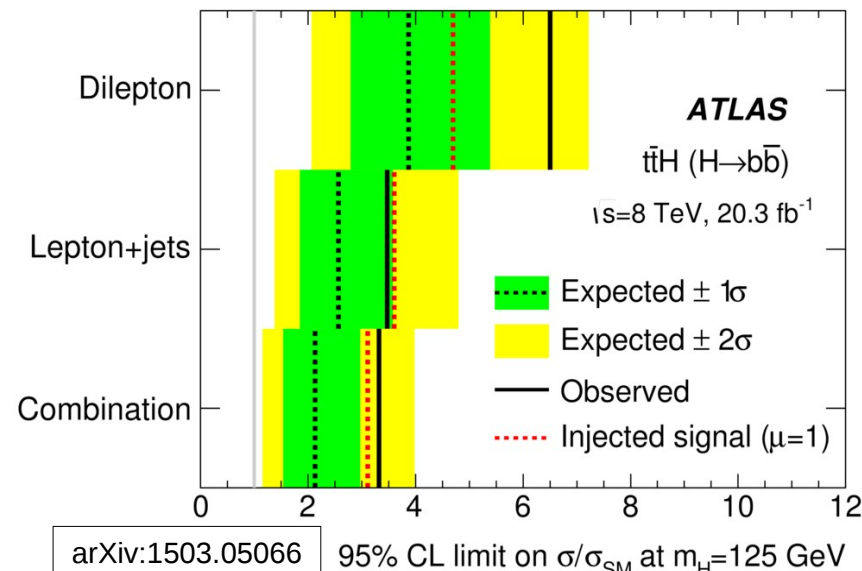
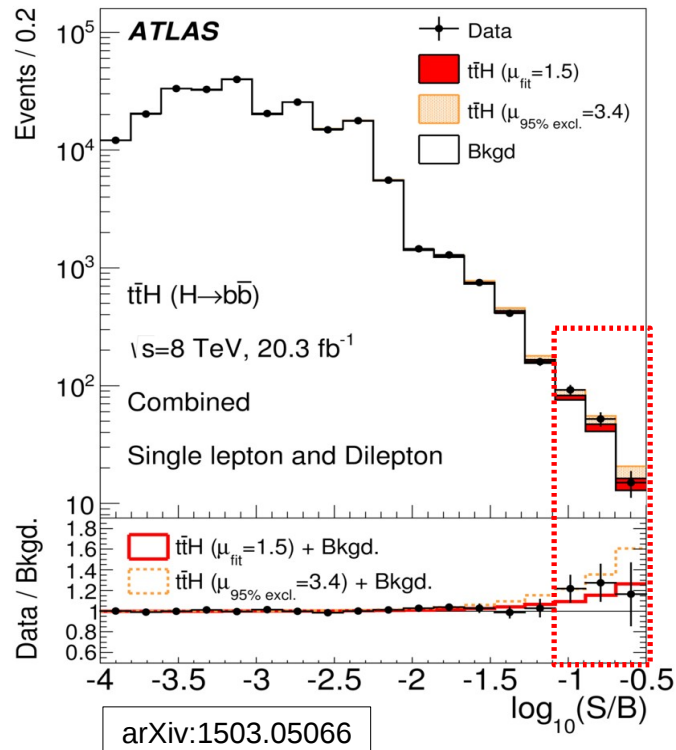
- Binned profile likelihood fit:

$$\mathcal{L}(\mu, \theta) = \prod_{i=0}^{N_{\text{bins}}} \frac{(\mu s_i(\theta) + b_i(\theta))^{n_i}}{n_i!} e^{-(\mu s_i(\theta) + b_i(\theta))} \prod_{k=0}^{N_{\text{syst}}} \frac{1}{\sqrt{2\pi}} e^{-\frac{\theta_k^2}{2}}$$

- signal strength $\mu = \sigma_{\text{obs}} / \sigma_{\text{SM}}$
- nuisance parameters θ
- Combine regions statistically
 - BG regions: H_T or NNHF
 - SIG regions: NN



- Combined results
 - Observed (expected) limit at 95% CL:
 - **3.4 (2.2)** x SM for $m_H = 125$ GeV
 - Best fit signal strength:
 - **$\mu_{t\bar{t}H} = 1.5 \pm 1.1$**



Higgs Decay	Channel	Expected (Observed) Limit	
		ATLAS	CMS
$H \rightarrow b\bar{b}$	single lepton	2.6 (3.6)	4.2 (5.5)*
	dilepton	4.1 (6.7)	6.7 (7.0)
	combined	2.2 (3.4)	3.5 (4.1)
$H \rightarrow \gamma\gamma$	leptonic	6.6 (10.7)	6.8 (8.2)
	hadronic	10.1 (9.0)	10.7 (8.0)
	combined	4.9 (6.7)	4.7 (7.4)
$H \rightarrow WW/ZZ/\tau\tau$	2ℓ	3.9 (6.7)	3.4 (9.0)
	3ℓ	3.8 (6.8)	4.1 (7.5)
	4ℓ	15 (18)	8.8 (6.8)
	$2\tau_{\text{had}}$	18 (13)	14.2 (13.0)
	$2\ell 1\tau_{\text{had}}$	8.4 (7.5)	-
	combined	2.4 (4.7)	2.4 (6.6)
Combination		1.4 (3.2)	1.7 (4.5)

→ highly competitive

→ most sensitive Higgs decay

→ large contribution to ATLAS combination

ATLAS and CMS working on LHC combination

→ Expected to be close to SM sensitivity

Summary

- Sophisticated search for $t\bar{t}H(bb)$ [accepted by Eur. Phys. J. C: arXiv:1503.05066]
 - Many analysis regions, Matrix Element Method, Neural Network, Profiled Likelihood
 - **Matrix Element Method** improves expected limit by **16%**
- Good background modeling crucial
 - Correct $t\bar{t}+LF/c\bar{c}$ to 7 TeV data, $t\bar{t}+HF$ to improved MC simulation
 - Further improve predictions by profile likelihood fit
- Combined Results
 - Signal strength: $\mu_{t\bar{t}H} = 1.5 \pm 1.1$
 - Observed (expected) limit: $\mu_{t\bar{t}H} < 3.4 (2.2)$
 - single **most sensitive** search
- $t\bar{t}H$ production not yet discovered at the LHC
 - ATLAS (2.4σ) and CMS (3.4σ) close to SM sensitivity (combination expected)
 - **Discovery of $t\bar{t}H$ is expected in Run II of the LHC**



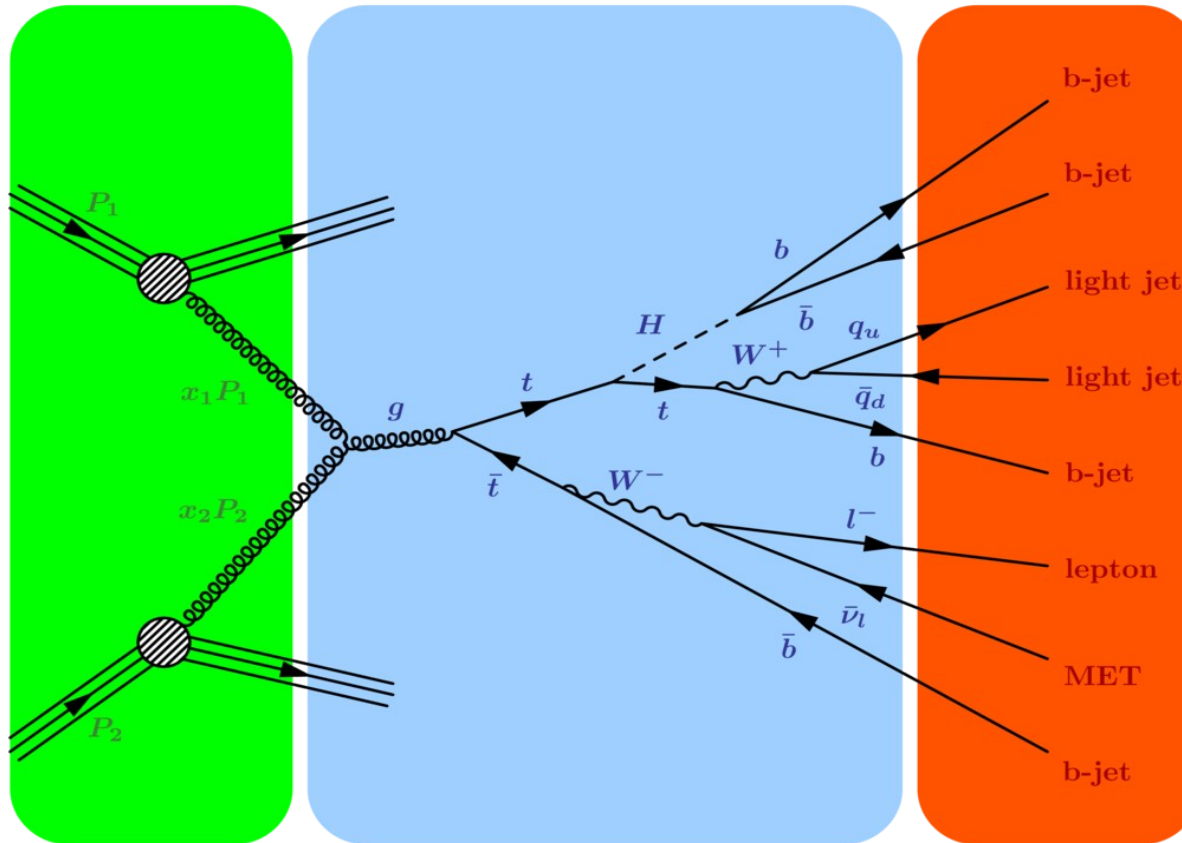
BACKUP



Systematic uncertainty	Type	Components
Luminosity	N	1
Physics Objects		
Electron	SN	5
Muon	SN	6
Jet reconstruction	SN	1
Jet energy scale	SN	22
Jet vertex fraction	SN	1
Jet energy resolution	SN	1
<i>b</i> -tagging efficiency	SN	6
<i>c</i> -tagging efficiency	SN	4
Light-jet tagging efficiency	SN	12
High- p_T tagging efficiency	SN	1
Background Model		
$t\bar{t}$ cross section	N	1
$t\bar{t}$ modelling: parton shower	SN	3
$t\bar{t}$ modelling: p_T reweighting	SN	9
$t\bar{t}+c\bar{c}$: p_T reweighting	SN	2
$t\bar{t}$ +heavy-flavour: normalisation	N	2
$t\bar{t}+b\bar{b}$: NLO Shape	SN	8
$t\bar{t}+c\bar{c}$: generator	SN	4
<i>W</i> +jets normalisation	N	3
<i>W</i> p_T reweighting	SN	1
<i>Z</i> +jets normalisation	N	3
<i>Z</i> p_T reweighting	SN	1
Diboson+jets normalisation	N	3
Lepton misID normalisation	N	2
Lepton misID shape	S	2
Single top cross section	N	1
Single top model	SN	1
$t\bar{t}V$ cross section	N	1
$t\bar{t}V$ model	SN	1
Signal Model		
$t\bar{t}H$ scale	SN	2
$t\bar{t}H$ generator	SN	1
$t\bar{t}H$ hadronisation	SN	1
$t\bar{t}H$ PDF	SN	1

- Luminosity (3%)
- Physics Objects
 - Lepton (2%)
 - Jet: ID, JVF, JER (4%), JES (10%),
 - Tagging (5-20%)
- Background Model
 - $t\bar{t}$ +jets
 - Cross section (6%)
 - $t\bar{t}$ +jj/cc p_T reweighting (6%)
 - Parton shower (10-15%)
 - $t\bar{t}+b\bar{b}/c\bar{c}$ modelling (10-15%)
 - $t\bar{t}+b\bar{b}/c\bar{c}$ normalisation (50%)
 - Small backgrounds
- Signal Model
 - Scale, generator, hadronisation, PDF (3%)





$$\underbrace{P_{t\bar{t}H}(\vec{x}_{\text{Detector}}, m_H)}_{\text{probability}} = \frac{1}{\underbrace{\sigma_{t\bar{t}H}(m_H)}_{\text{normalization}}} \int \underbrace{dp_{g1} dp_{g2} f(p_{g1}) f(p_{g2})}_{\text{parton density function}} \underbrace{d\sigma_{t\bar{t}H}(\tilde{x}_{\text{Parton}}, m_H)}_{\text{differential cross section}} \underbrace{W(\vec{x}_{\text{Parton}}, \vec{x}_{\text{Detector}})}_{\text{transfer functions}}$$



Signal Likelihood

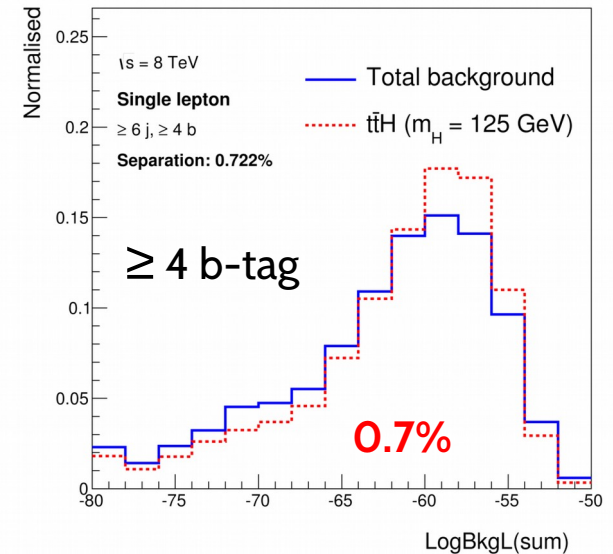
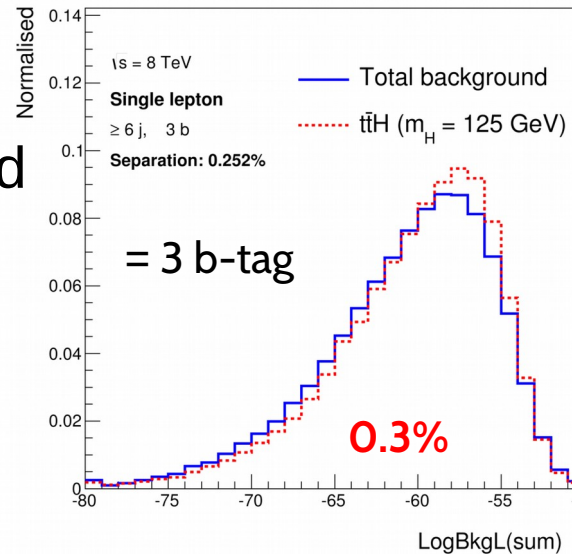
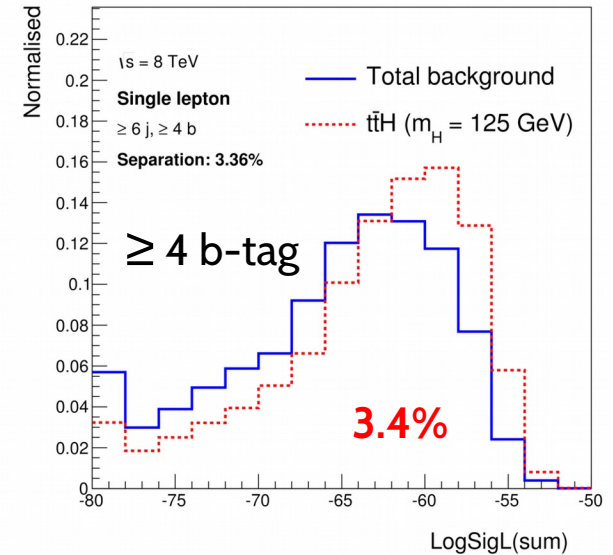
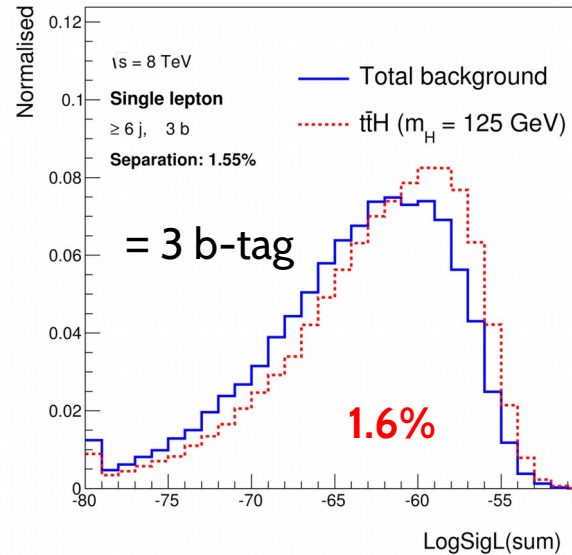
- $t\bar{t}H$ hypothesis

Separation:

$$\langle s^2 \rangle = \frac{1}{2} \int_{-\infty}^{\infty} \frac{(S(x) - B(x))^2}{S(x) + B(x)} dx$$

Background Likelihood

- $t\bar{t}b\bar{b}$ hypothesis

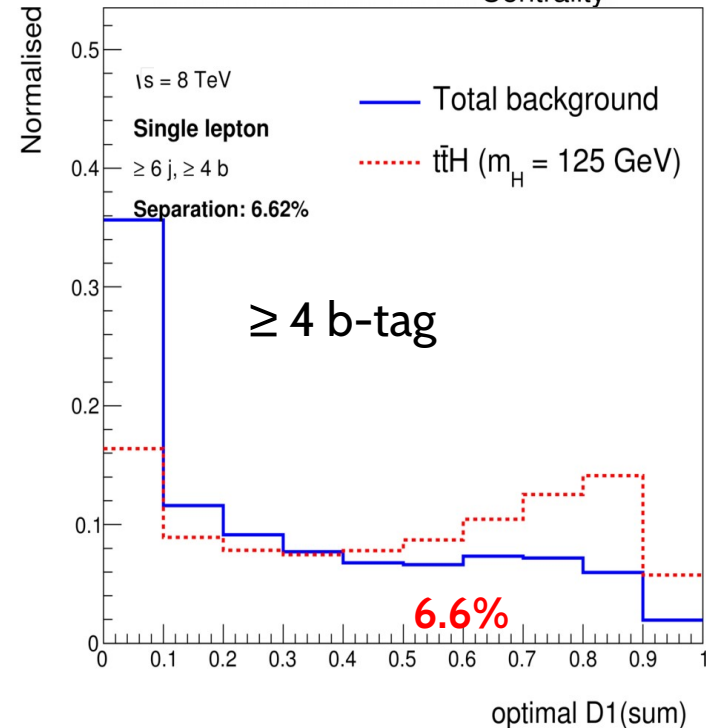
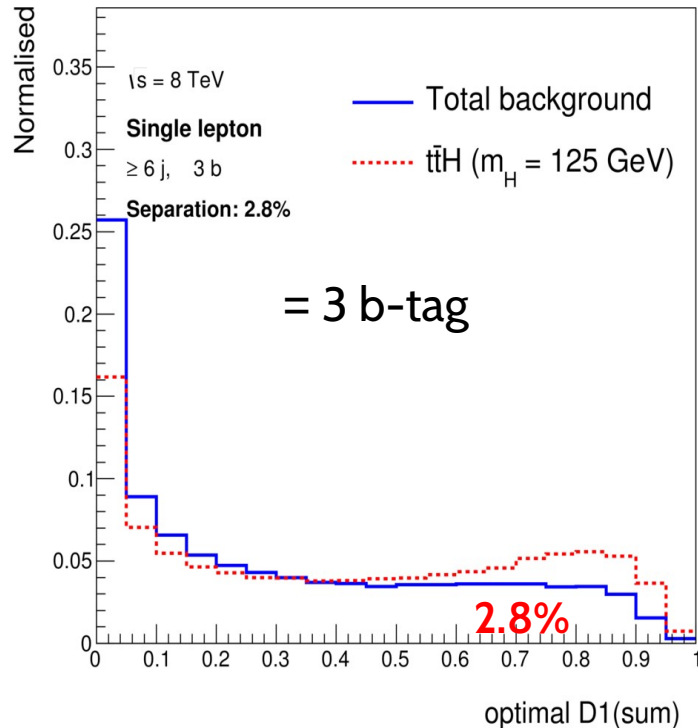
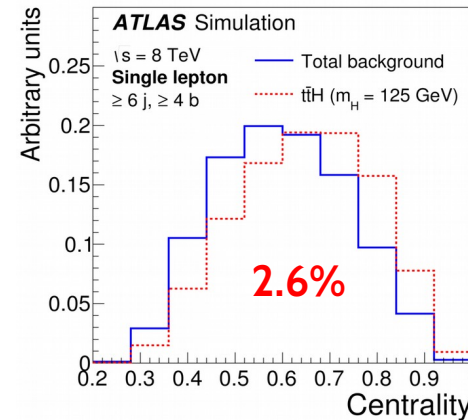


- Neyman-Pearson Likelihood Ratio

$$D1 = \frac{\mathcal{L}_{t\bar{t}H}^{\text{sum}}}{\mathcal{L}_{t\bar{t}H}^{\text{sum}} + \alpha \cdot \mathcal{L}_{t\bar{t}+b\bar{b}}^{\text{sum}}}$$

- Optimal normalization

- $\alpha = 0.23$



Event Reconstruction

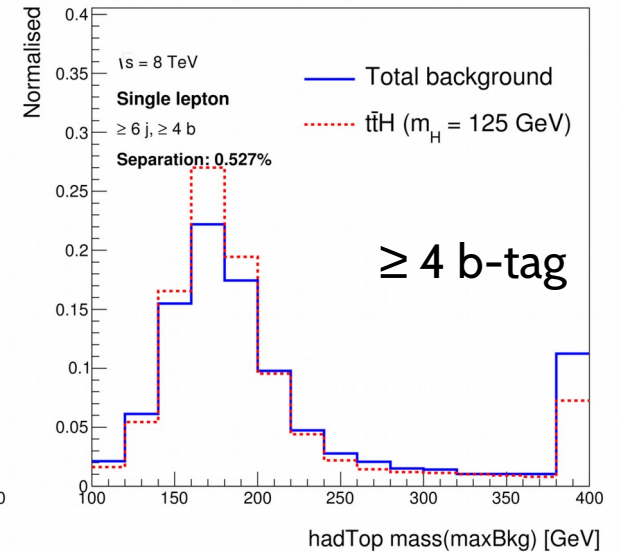
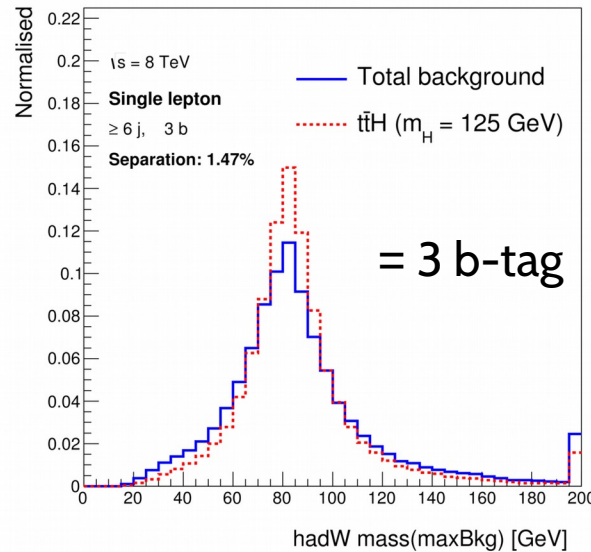
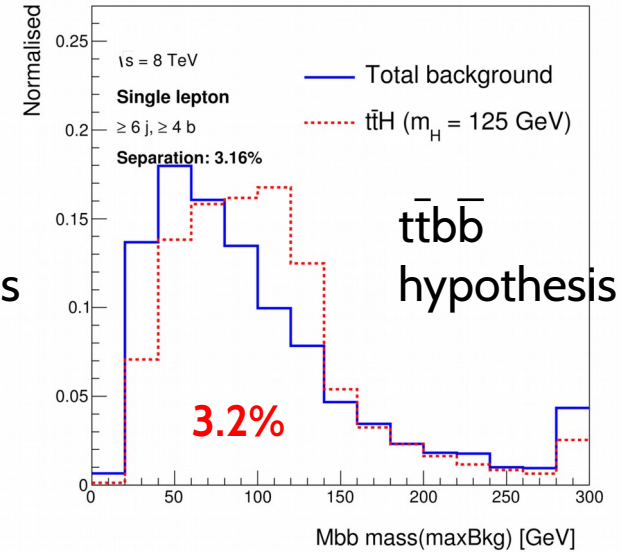
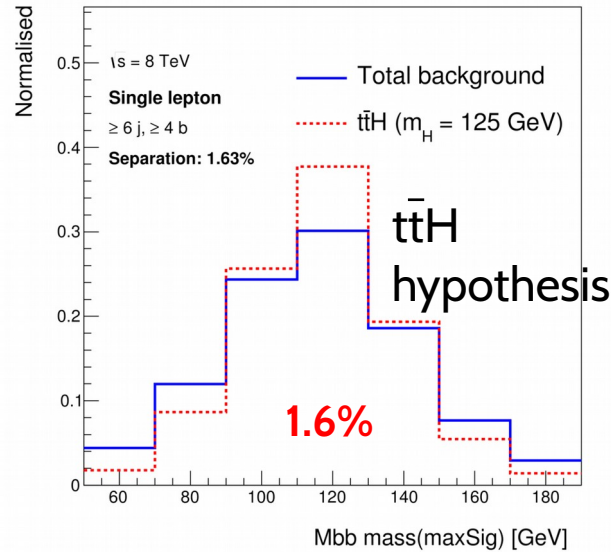
- jet parton assignment
- highest likelihood
- $t\bar{t}H$ or $t\bar{t}b\bar{b}$

Invariant mass m_{bb}

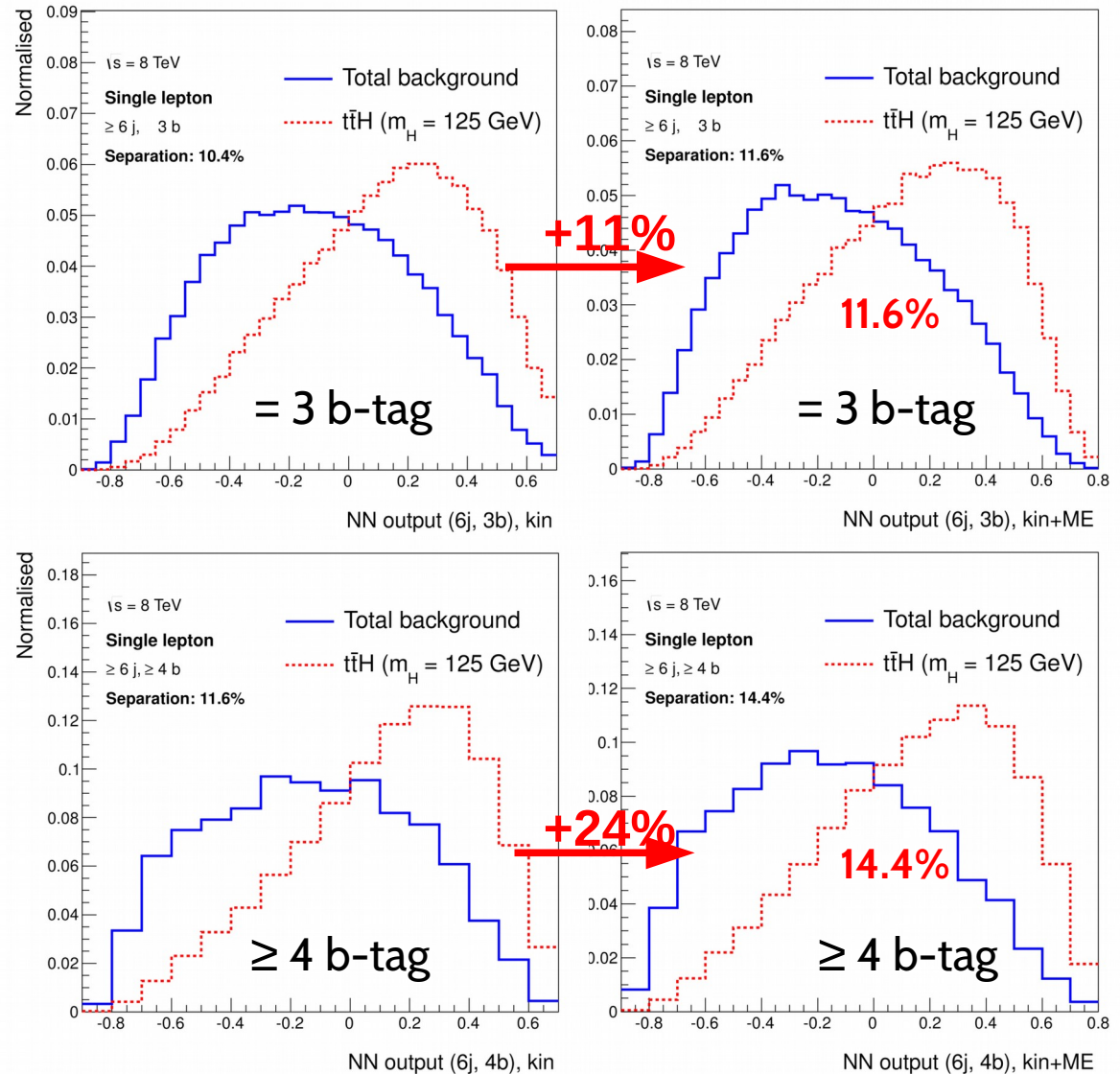
- non- $t\bar{t}$ jets

Hadronic W mass

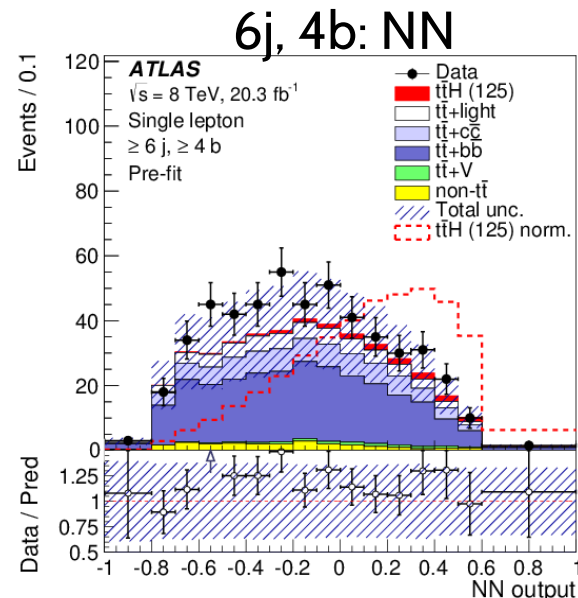
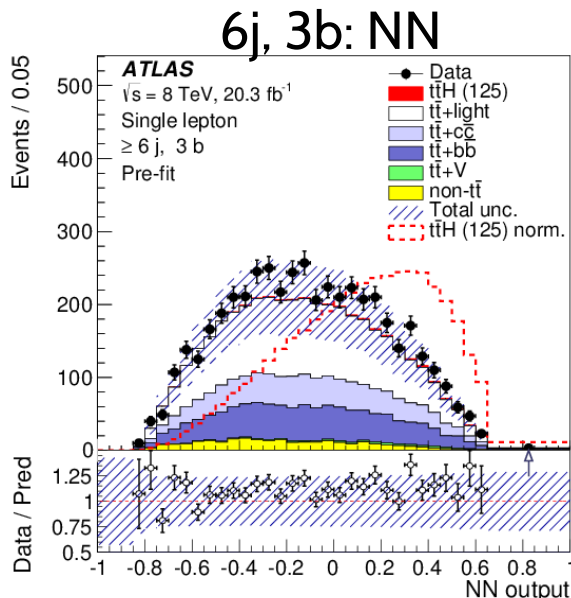
Hadronic top mass



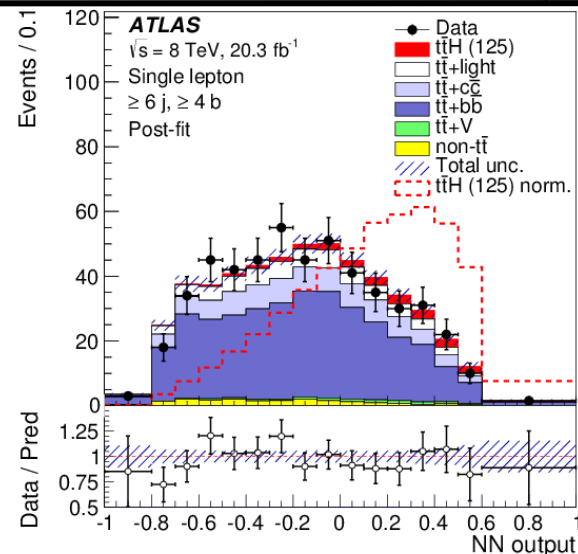
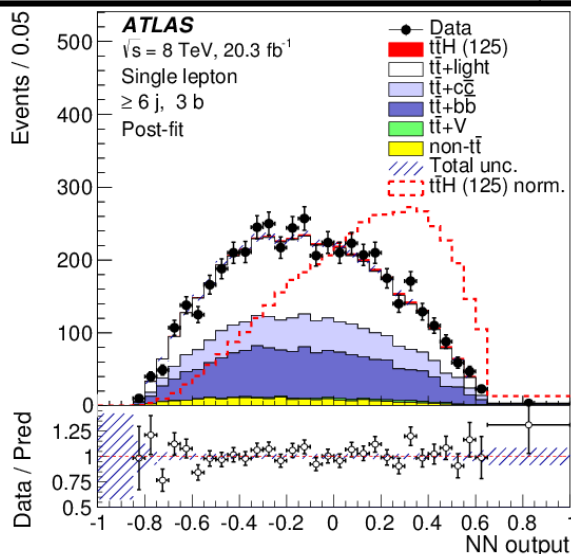
- NN Separation (≥ 6 jets)
 - 3 b-tags: + 11%
 - 4 b-tags: + 24%
- Large improvement
- Better constrain systematics



- Pre-fit

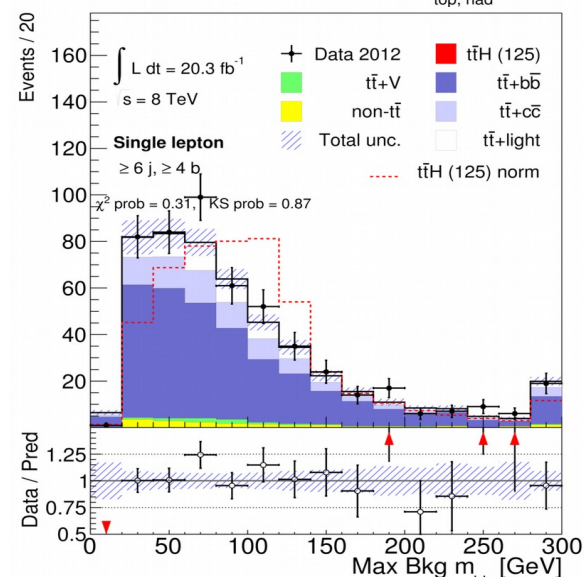
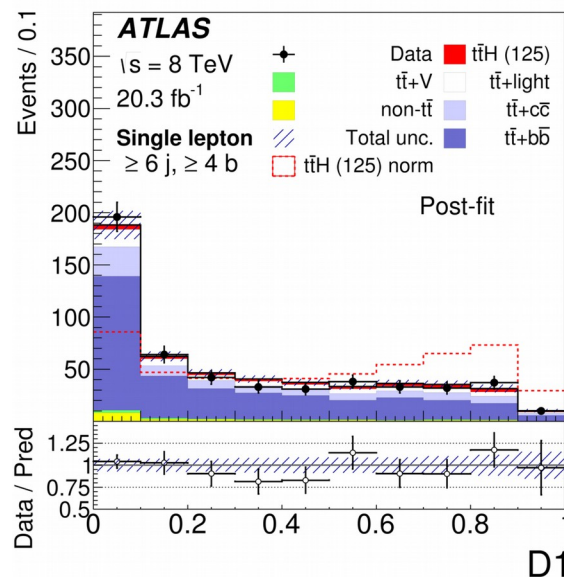
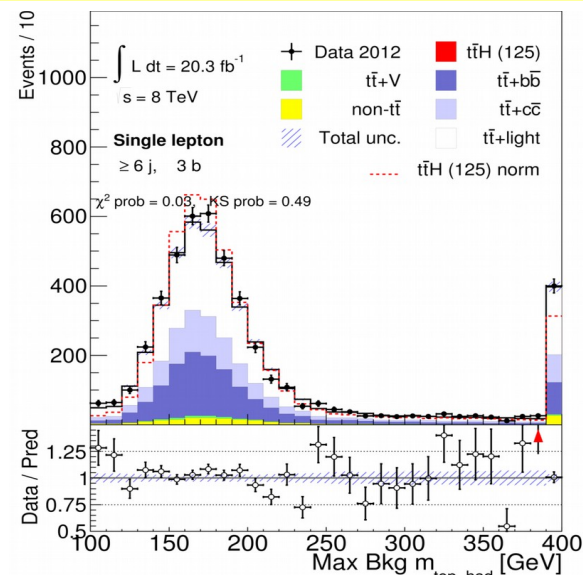
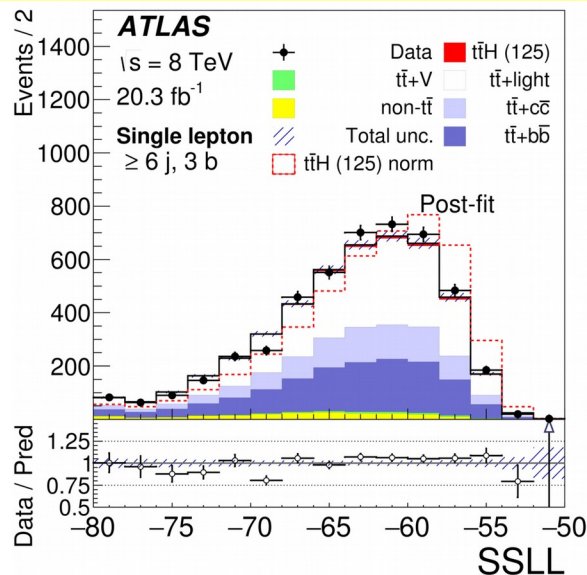


- Post-fit

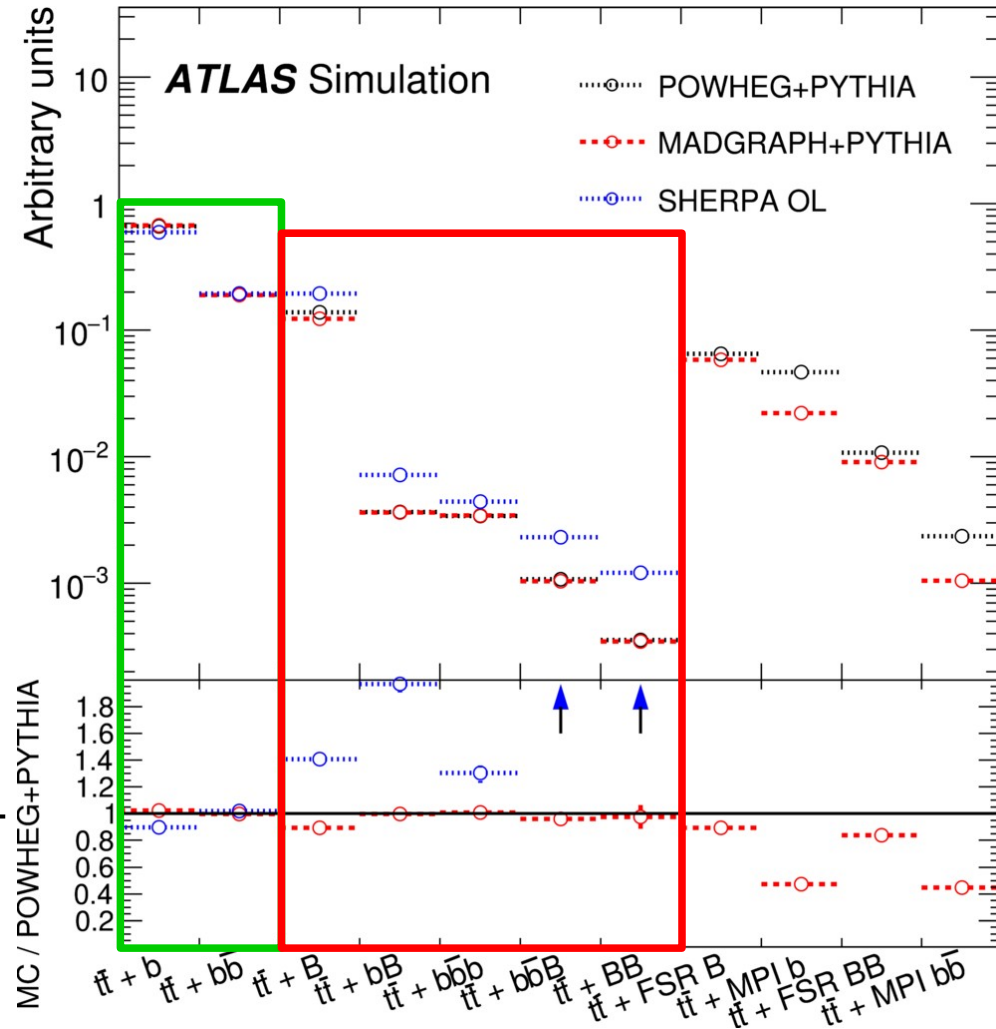


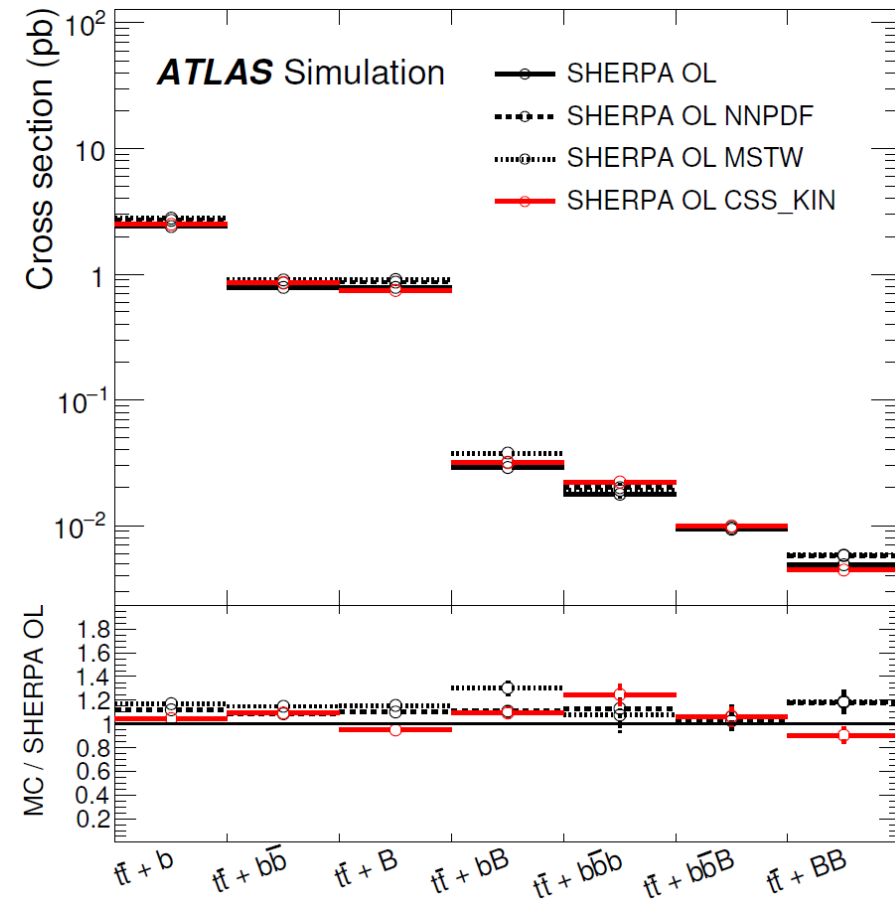
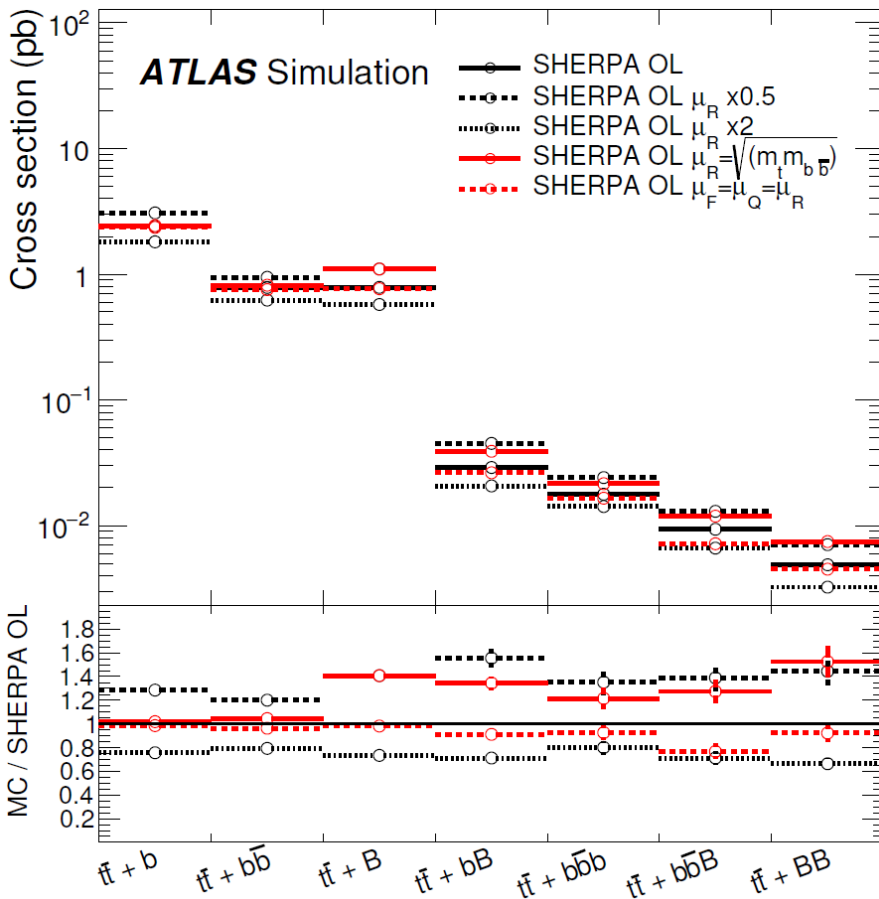
- 6j, 3b
- Signal Likelihood
- Hadronic top mass

- 6j, 4b
- Likelihood ratio D1
- Invariant m_{bb}



- Key aspect to understand $t\bar{t}+b\bar{b}$
- $t\bar{t}+HF$ only by parton shower
- Compare to other generators
 - Sherpa OpenLoops (4F NLO)
 - Madgraph+Pythia (5F LO+PS)
- Categorize
 - Resolved: $t\bar{t}+b$, $t\bar{t}+b\bar{b}$
 - Unresolved: $t\bar{t}+B$, $t\bar{t}+BB$
- Reweight categories to Sherpa OL
 - Parton level
 - Kinematic distributions





Process	ME Generator	PDF	Parton Shower	Normalisation
$t\bar{t}H$	HELAC-Oneloop	CT10	Pythia 8.1	NLO
$t\bar{t} + \text{jets}$	Powheg	CT10	Pythia 6.425	NNLO+NNLL
Single top (s-chan., Wt)	Powheg	CT10	Pythia 6.426	aNNLO
Single top (t-chan.)	Powheg	CT10	Pythia 6.427	aNNLO
$t\bar{t}V$	Madgraph	CTEQ6L1	Pythia 6.425	NLO
$W + \text{jets}$	Alpgen	CTEQ6L1	Pythia 6.426	NLO
$Z + \text{jets}$	Alpgen	CTEQ6L1	Pythia 6.426	NLO
Diboson	Alpgen	CTEQ6L1	Herwig 6.520	NLO

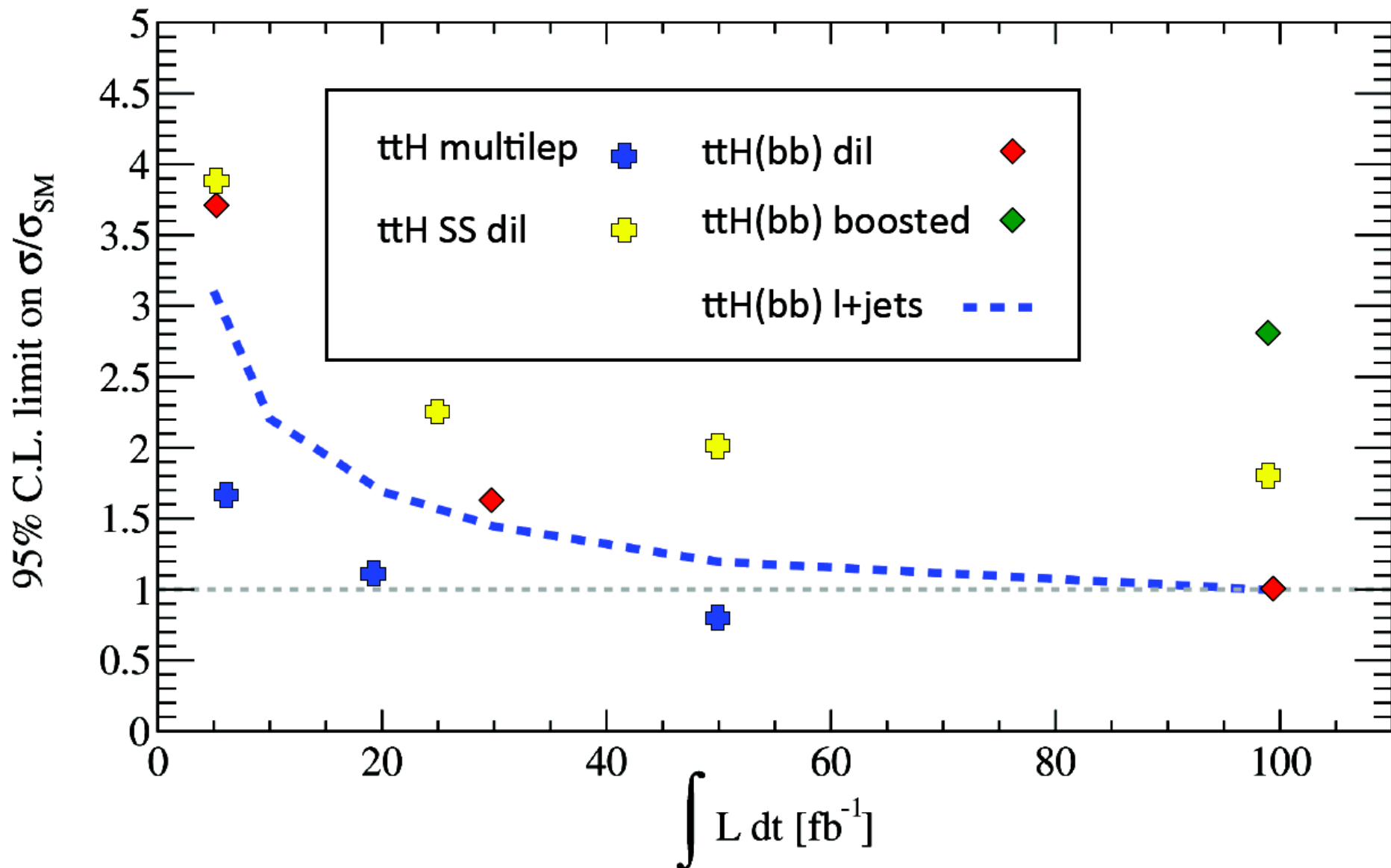


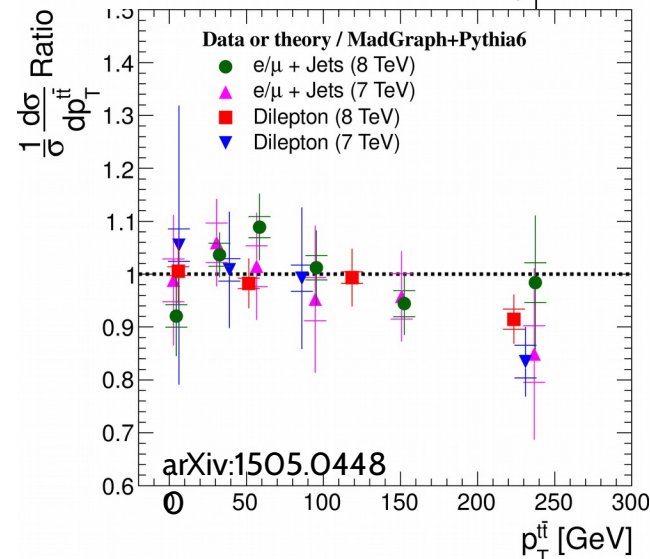
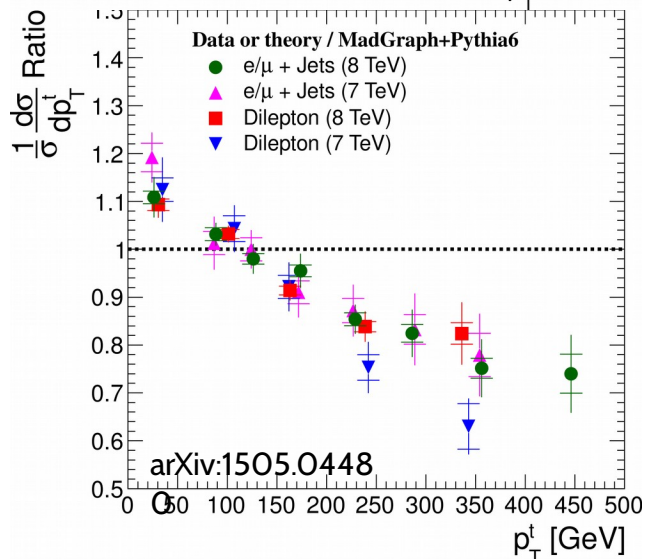
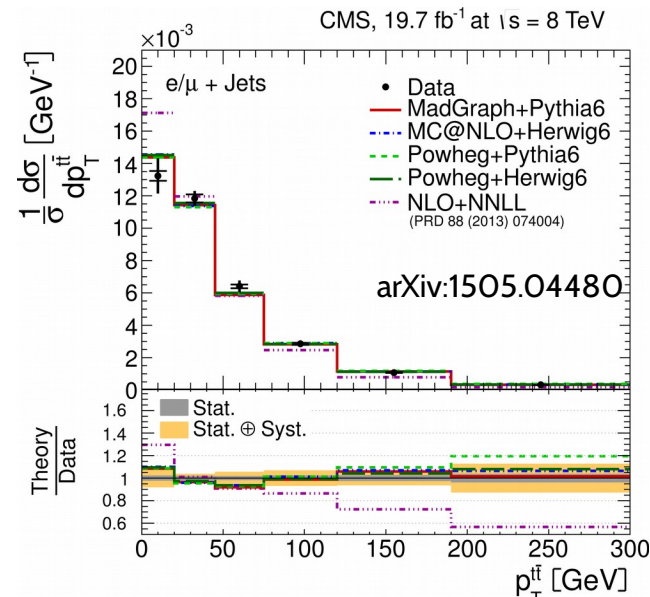
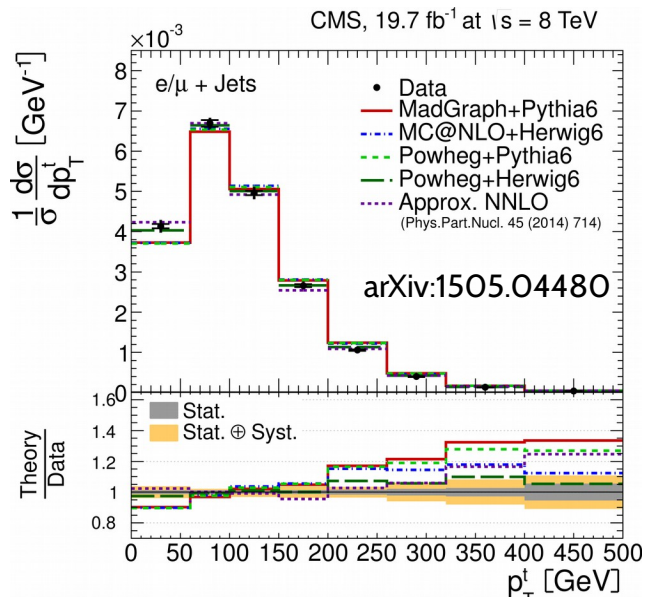
Variable	Definition	Neural Network Rank			
		$\geq 6j, \geq 4b$	$\geq 6j, 3b$	$5j, \geq 4b$	$5j, 3b$
$D1$	Neyman–Pearson MEM discriminant	1	10	-	-
Centrality	Scalar sum of the p_T divided by sum of the E for all jets and the lepton	2	2	1	-
p_T^{jet5}	p_T of the fifth leading jet	3	7	-	-
$H1$	Second Fox–Wolfram moment [220, 221] computed using all jets and the lepton	4	3	2	-
$\Delta R_{bb}^{\text{avg}}$	Average ΔR for all b -tagged jet pairs	5	6	5	-
$\ln \mathcal{L}_{t\bar{t}H}^{\text{sum}}$	Logarithm of the summed signal likelihoods	6	4	-	-
$m_{bb}^{\text{min } \Delta R}$	Mass of the combination of the two b -tagged jets with the smallest ΔR	7	12	4	4
$m_{bj}^{\text{max } p_T}$	Mass of the combination of a b -tagged jet and any jet with the largest vector sum p_T	8	8	-	-
$\Delta R_{bb}^{\text{max } p_T}$	ΔR between the two b -tagged jets with the largest vector sum p_T	9	-	-	-
$\Delta R_{\text{lep-bb}}^{\text{min } \Delta R}$	ΔR between the lepton and the combination of the two b -tagged jets with the smallest ΔR	10	11	10	-
$m_{uu}^{\text{min } \Delta R}$	Mass of the combination of the two untagged jets with the smallest ΔR	11	9	-	2
$A_{\text{plan}_{b\text{-jet}}}$	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor [222] built with only b -tagged jets	12	-	8	-
N_{40}^{jet}	Number of jets with $p_T \geq 40$ GeV	-	1	3	-
$m_{bj}^{\text{min } \Delta R}$	Mass of the combination of a b -tagged jet and any jet with the smallest ΔR	-	5	-	-
$m_{jj}^{\text{max } p_T}$	Mass of the combination of any two jets with the largest vector sum p_T	-	-	6	-
H_T^{had}	Scalar sum of jet p_T	-	-	7	-
$m_{jj}^{\text{min } \Delta R}$	Mass of the combination of any two jets with the smallest ΔR	-	-	9	-
$m_{bb}^{\text{max } p_T}$	Mass of the combination of the two b -tagged jets with the largest vector sum p_T	-	-	-	1
$p_{T,uu}^{\text{min } \Delta R}$	Scalar sum of the p_T of the pair of untagged jets with the smallest ΔR	-	-	-	3
$m_{bb}^{\text{max } m}$	Mass of the combination of the two b -tagged jets with the largest invariant mass	-	-	-	5
$\Delta R_{uu}^{\text{min } \Delta R}$	Minimum ΔR between the two untagged jets	-	-	-	6
m_{jjj}	Mass of the jet triplet with the largest vector sum p_T	-	-	-	7



	Pre-fit				Post-fit			
	$t\bar{t}H$ (125)	$t\bar{t} + \text{light}$	$t\bar{t} + c\bar{c}$	$t\bar{t} + b\bar{b}$	$t\bar{t}H$ (125)	$t\bar{t} + \text{light}$	$t\bar{t} + c\bar{c}$	$t\bar{t} + b\bar{b}$
Luminosity	± 2.8	± 2.8	± 2.8	± 2.8	± 2.6	± 2.6	± 2.6	± 2.6
Lepton efficiencies	± 1.4	± 1.4	± 1.4	± 1.5	± 1.3	± 1.3	± 1.3	± 1.3
Jet energy scale	± 6.4	± 13	± 11	± 9.2	± 2.3	± 5.3	± 4.7	± 3.6
Jet efficiencies	± 1.7	± 5.2	± 2.7	± 2.5	± 0.7	± 2.3	± 1.2	± 1.1
Jet energy resolution	± 0.1	± 4.4	± 2.5	± 1.6	± 0.1	± 2.3	± 1.3	± 0.8
b -tagging efficiency	± 9.2	± 5.6	± 5.1	± 9.3	± 5.0	± 3.1	± 2.9	± 5.0
c -tagging efficiency	± 1.7	± 6.0	± 12	± 2.4	± 1.4	± 5.1	± 10	± 2.1
l -tagging efficiency	± 1.0	± 19	± 5.2	± 2.1	± 0.6	± 11	± 3.0	± 1.1
High p_T tagging efficiency	± 0.6	–	± 0.7	± 0.6	± 0.3	–	± 0.4	± 0.3
$t\bar{t}$: p_T reweighting	–	± 12	± 13	–	–	± 5.1	± 5.8	–
$t\bar{t}$: parton shower	–	± 13	± 16	± 11	–	± 3.6	± 10	± 6.0
$t\bar{t}$ +HF: normalisation	–	–	± 50	± 50	–	–	± 28	± 14
$t\bar{t}$ +HF: modelling	–	–	± 11	± 8.3	–	–	± 8.1	± 7.1
Theoretical cross sections	–	± 6.3	± 6.3	± 6.3	–	± 4.1	± 4.1	± 4.1
$t\bar{t}H$ modelling	± 2.7	–	–	–	± 2.6	–	–	–
Total	± 12	± 32	± 59	± 54	± 6.9	± 9.2	± 23	± 12







- Combined results
 - Observed (expected) limit at 95% CL:
 - **4.1 (2.6)** x SM for $m_H = 125$ GeV
 - Best fit signal strength:
 - **$\mu_{ttH} = 1.7 \pm 1.4$**

