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

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FSP 101 ATLAS

Motivation, Strategy & Introduction

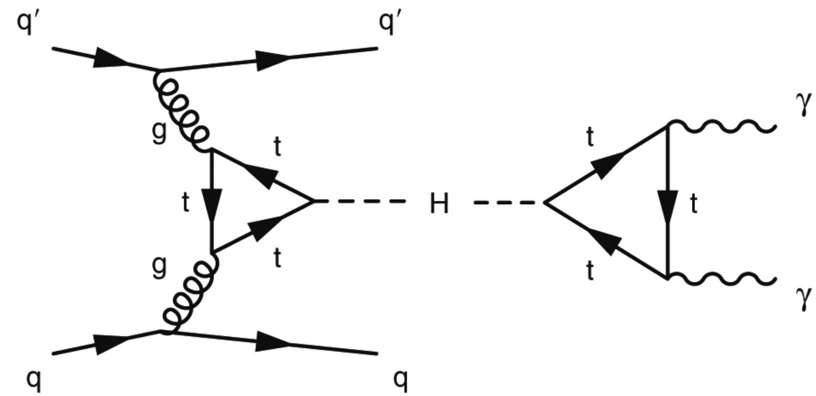
Overview: $t\bar{t}(H\rightarrow b\bar{b})$ leptonic analysis

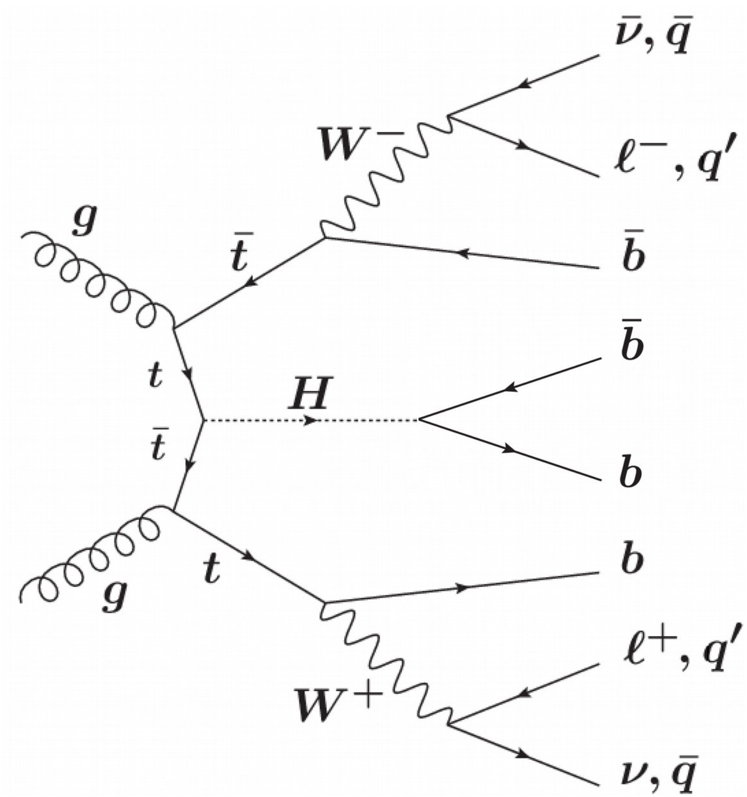
Summary & Outlook

Motivation

Questions after Higgs boson discovery

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





Answers in $t\bar{t}H(b\bar{b})$ search

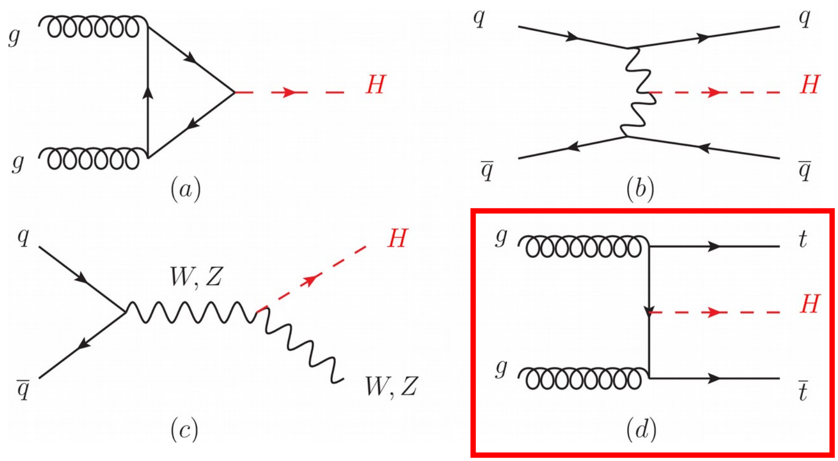
- Observe ttH production and H → $b\bar{b}$
- Most direct measurement of y_t ($\sigma \sim y_t^2$)
- Comparison to indirect y_t measurements

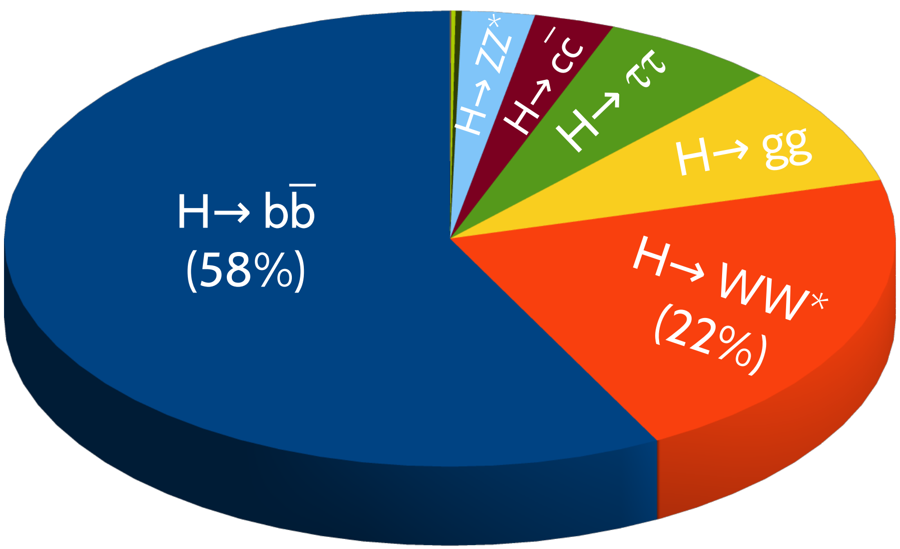
Focus of analysis

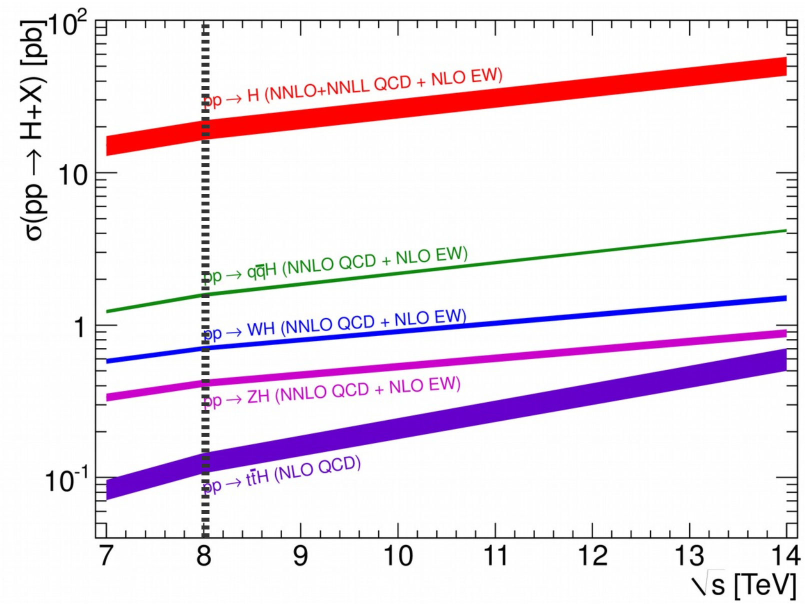
- Single lepton or dilepton $t\bar{t}$ decay
- Optimized for H → $b\bar{b}$ decay

Higgs Production and Decay

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



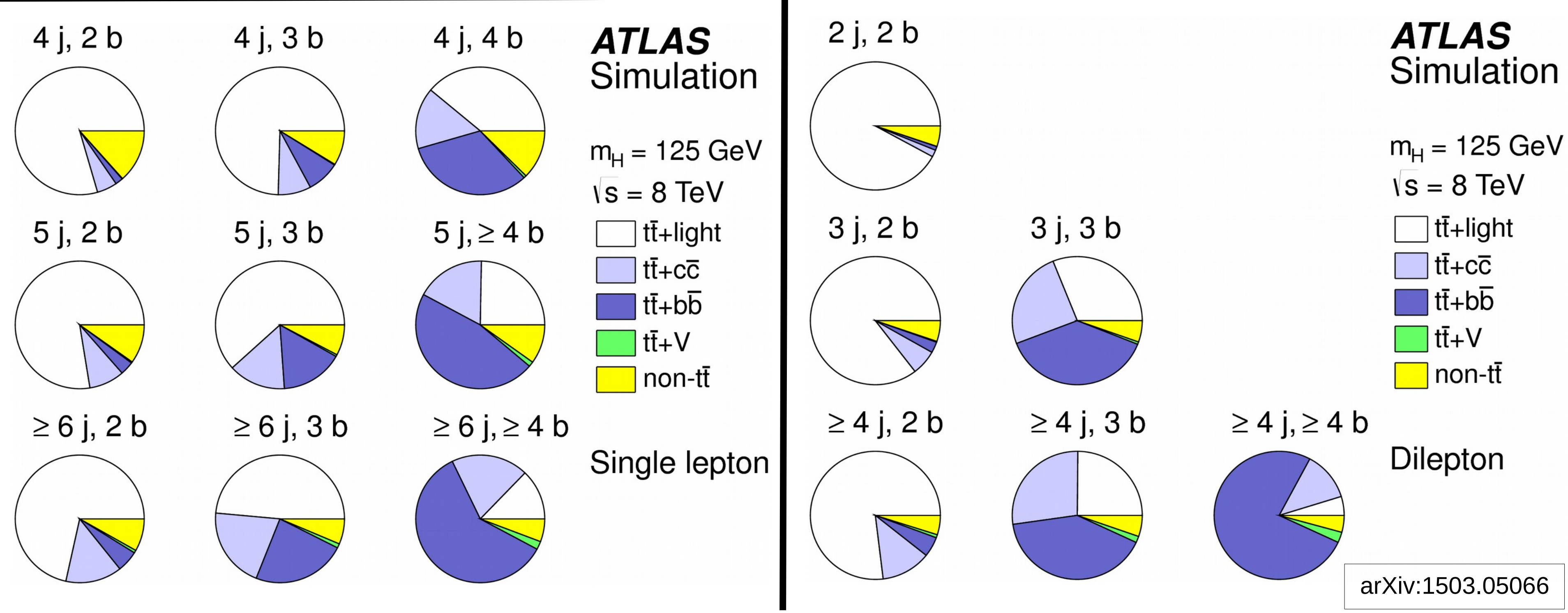




Selection & Classification

- Selection: single lepton (dilepton)
  - = 1 (2) isolated lepton
  - ≥ 4 (2) high p_T jets (p_T > 25 GeV)
  - ≥ 2 (2) b-tagged jets

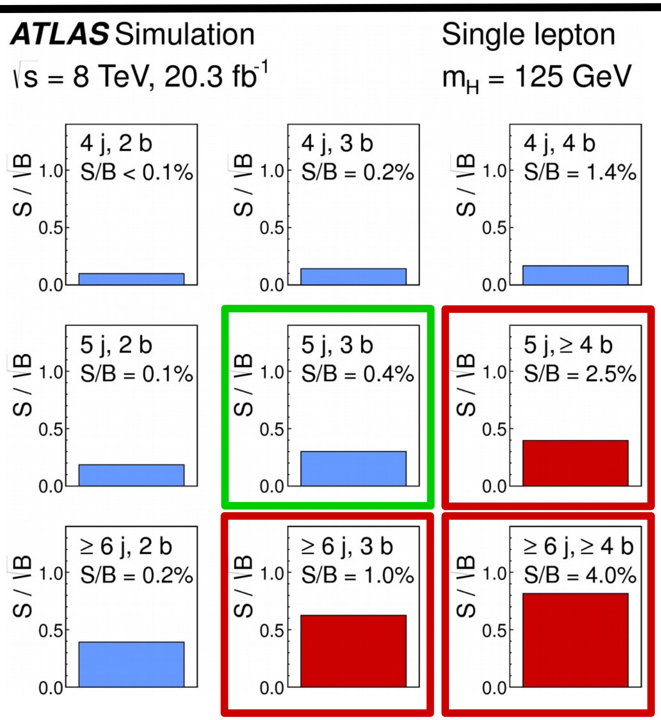
- Classification of events:
  - jet number & b-tag number
  - → different BG compositions
  - → dominated by $t\bar{t}$+jets (2000 x $\sigma_{t\bar{t}H}$)

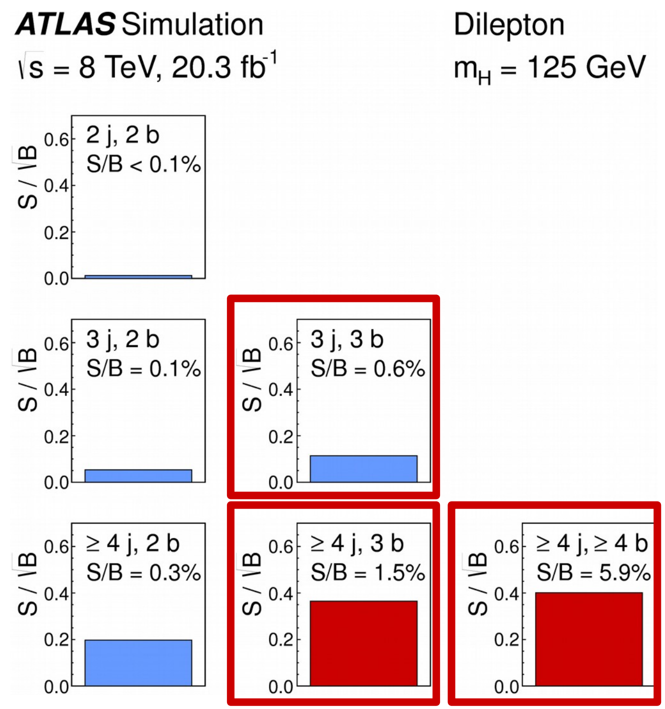


arXiv:1503.05066

Analysis Strategy

- Analysis regions by S/B
  - signal regions (S/B > 1% & S/√B > 0.3)
  - background regions
- Matrix Element Method (1ℓ, ≥ 6 jets)
  - Maximize $t\bar{t}H$ vs $t\bar{t}b\bar{b}$ separation
- Artificial neural network
  - Signal regions: $t\bar{t}H$ vs BG (NN)
  - 1ℓ, 5j, 3b: $t\bar{t}$HF vs $t\bar{t}$LF (NNHF)
- Profile Likelihood fit
  - Input: NN discriminant and H_T
  - Extract μ & constrain systematics

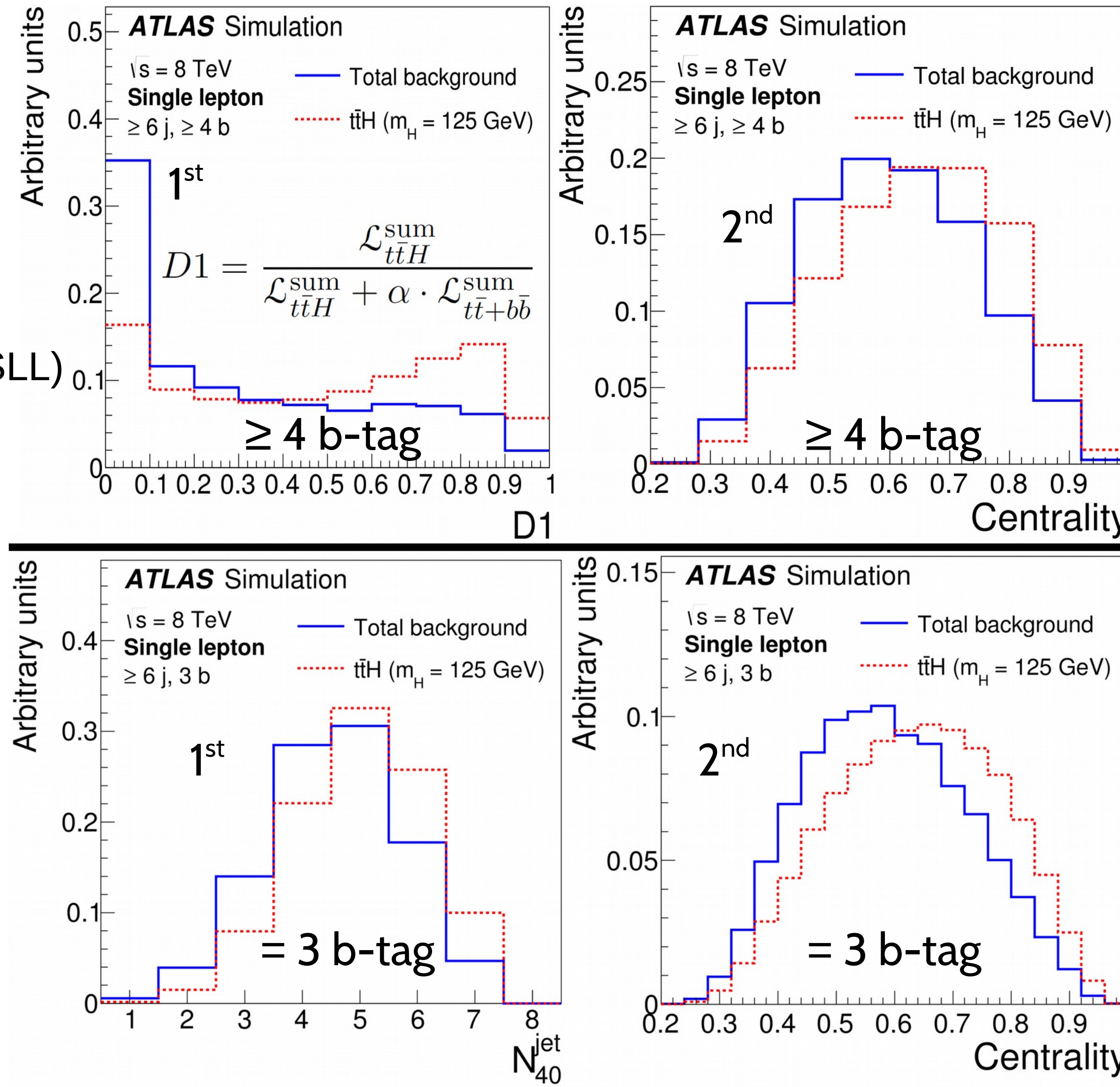




Neural Network Input

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

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

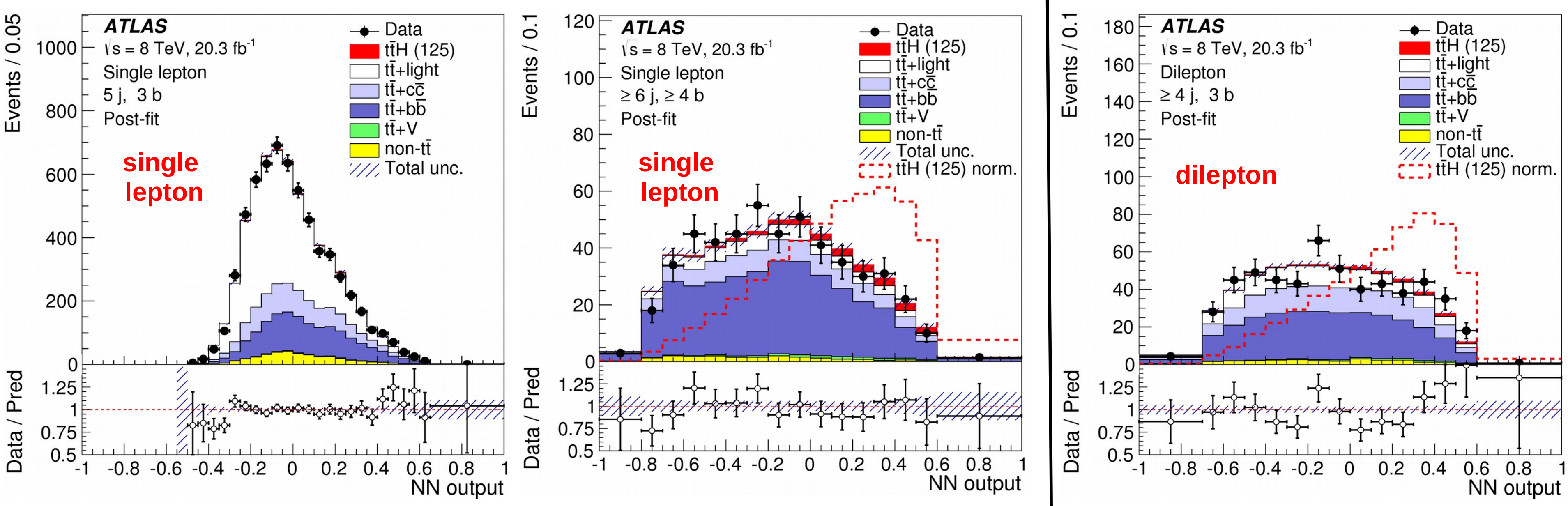


Neural Network Output

- Profile Likelihood Fit Input
  - Signal enriched: NN for ttH vs BG
  - 1ℓ, 5j, 3b: NNHF for tt+HF vs tt+LF
  - BG dominated: H_T to constrain systematics
- Good agreement of data & predictions

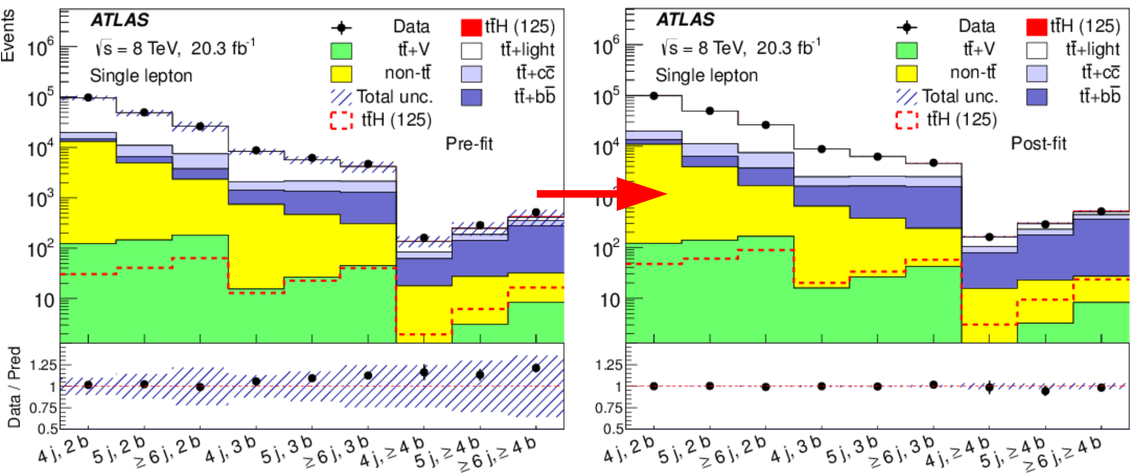
single lep	2 b-tags	3 b-tags	≥ 4 b-tags
4 jets	H_T^{had}	H_T^{had}	H_T^{had}
5 jets	H_T^{had}	NN	NN
≥ 6 jets	H_T^{had}	NN	NN

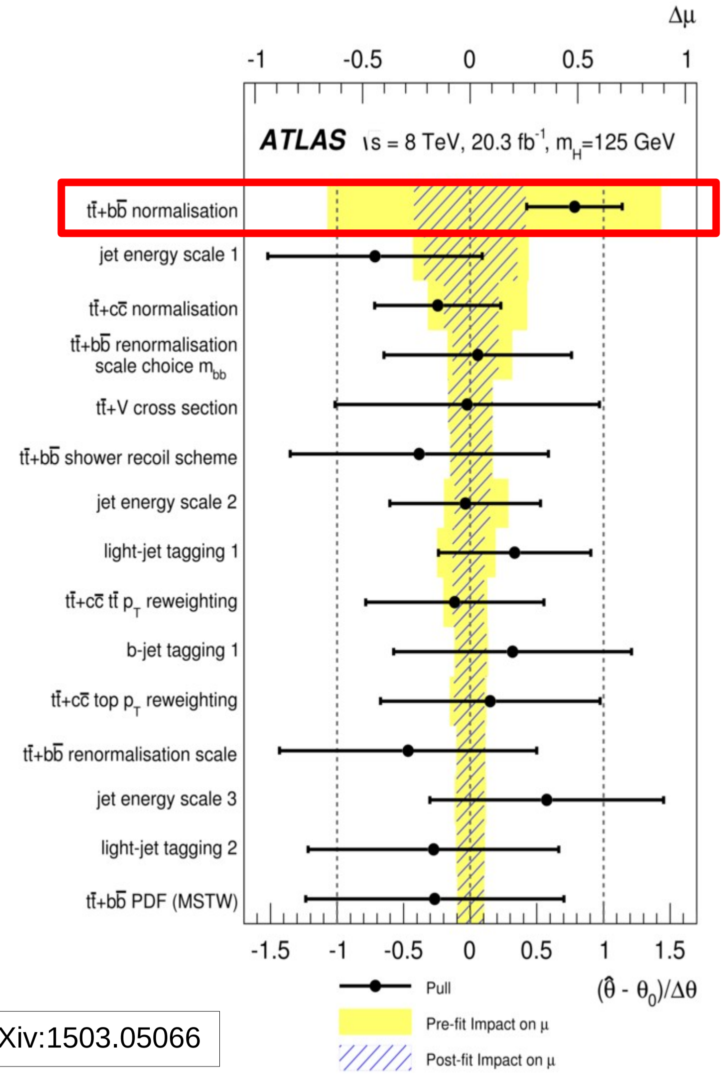
dilepton	2 b-tags	3 b-tags	≥ 4 b-tags
2 jets	H_T		
3 jets	H_T	NN	
≥ 4 jets	H_T	NN	NN



Profile Likelihood Fit

- Binned profile likelihood fit:
  - signal strength $\mu = \sigma_{obs} / \sigma_{SM}$
  - nuisance parameters θ
- Simultaneously fit all regions
- Dominant systematic uncertainties
  - tt+bb/cc normalization, JES

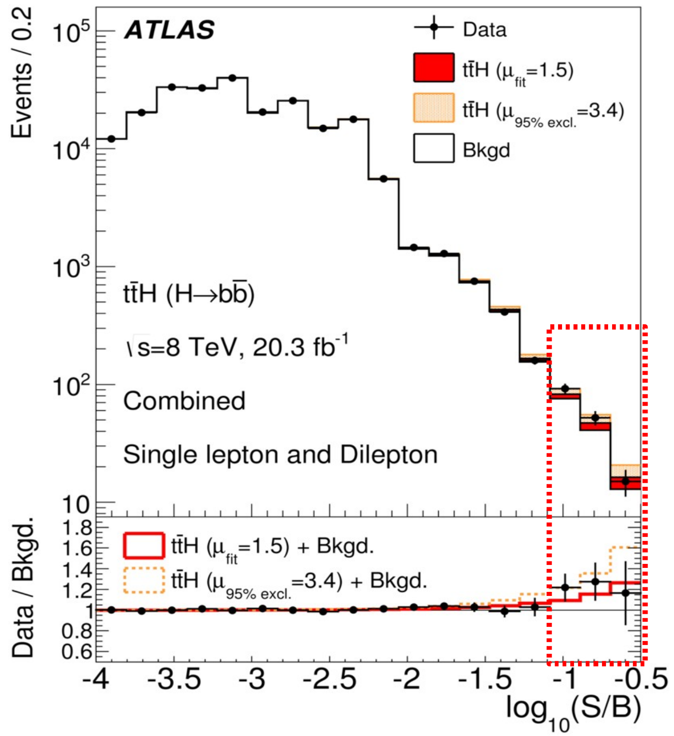


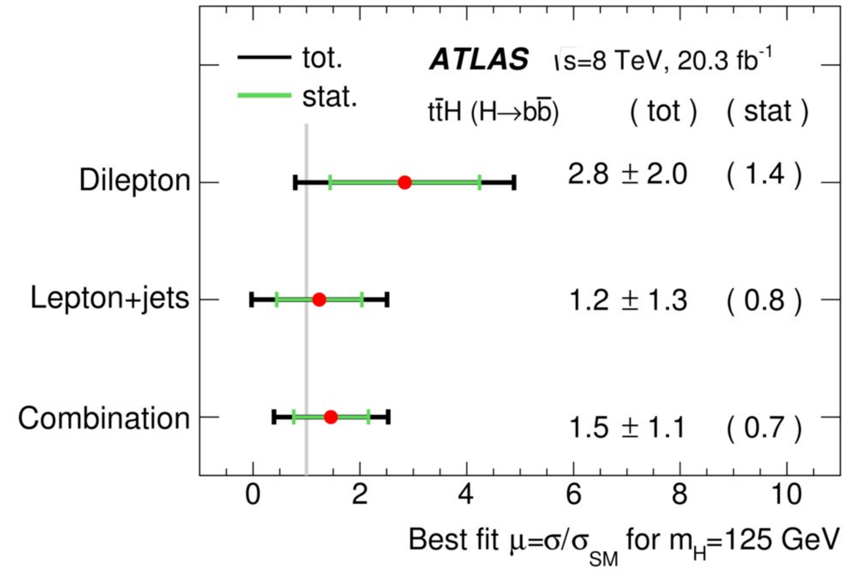


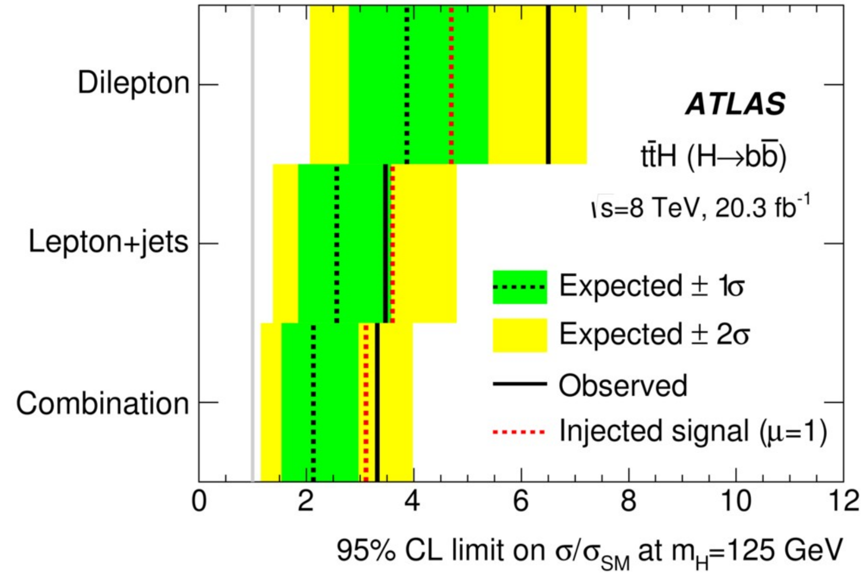
arXiv:1503.05066

Results

- Combined results
  - Best fit signal strength:
    - **μ_{ttH} = 1.5 ± 1.1**
  - Observed (expected) limit at 95% CL:
    - **3.4 (2.2)** x SM for m_H = 125 GeV







Comparison: $t\bar{t}H$ searches

Higgs Decay	Channel	Expected (Observed) Limit ATLAS	Expected (Observed) Limit CMS
$H \to b\bar{b}$	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)
$H \to \gamma\gamma$	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)
$H \to WW/ZZ/\tau\tau$	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 exclusion 1x SM cross section

arXiv:1503.05066, 1408.1682, 1507.04548, 1506.05988, 1409.3122, 1502.02485

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 $t\bar{t}H(b\bar{b})$ results
  - Signal strength: $\mu_{ttH} = 1.5 \pm 1.1$
  - Observed (expected) limit: $\mu_{ttH} < 3.4$ (2.2)

  → single **most sensitive** search
- $t\bar{t}H$ production not yet discovered at the LHC
  - ATLAS (2.4 σ) and CMS (3.4 σ) close to SM sensitivity (combination expected)

  → **Observation of $t\bar{t}H$ likely in Run II of the LHC**

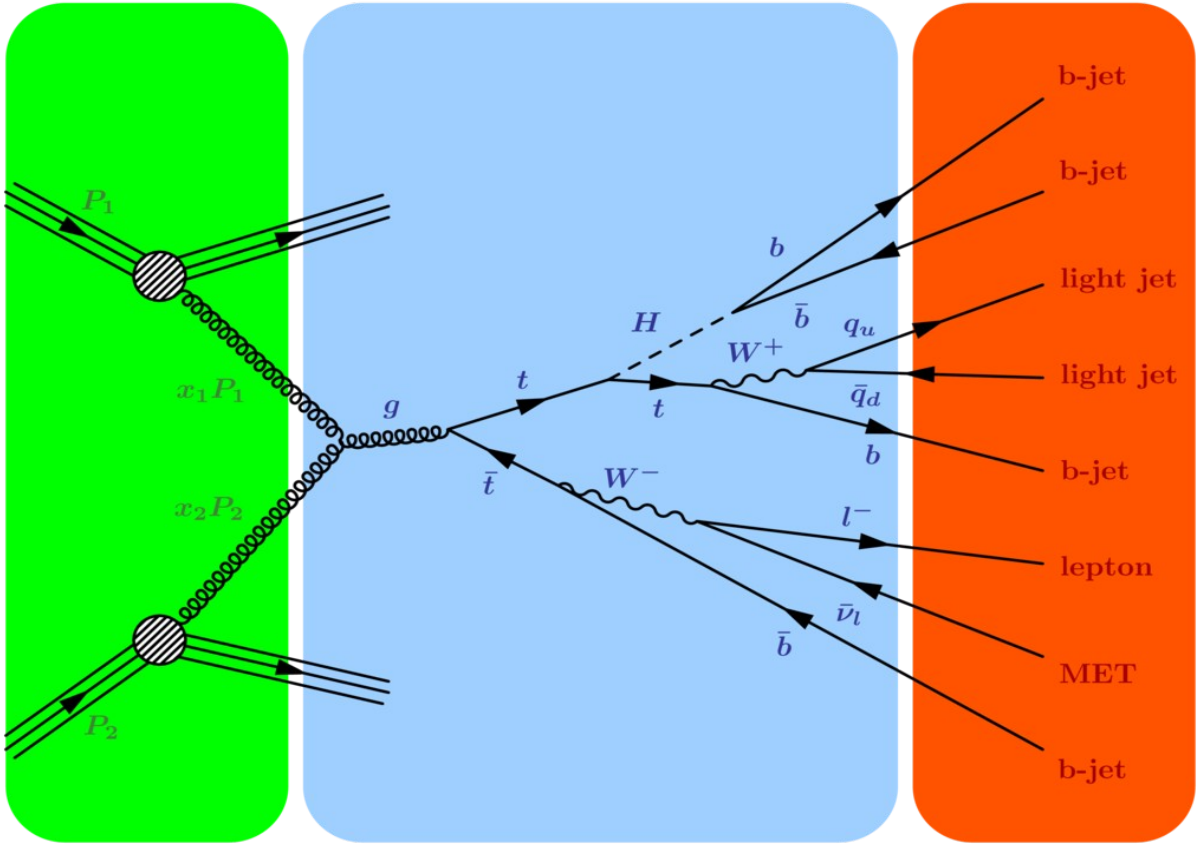
BACKUP

Systematic Uncertainties

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
b-tagging efficiency	SN	6
c-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
W+jets normalisation	N	3
W p_T reweighting	SN	1
Z+jets normalisation	N	3
Z 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%)
    - tt+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%)

Matrix Element Method



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

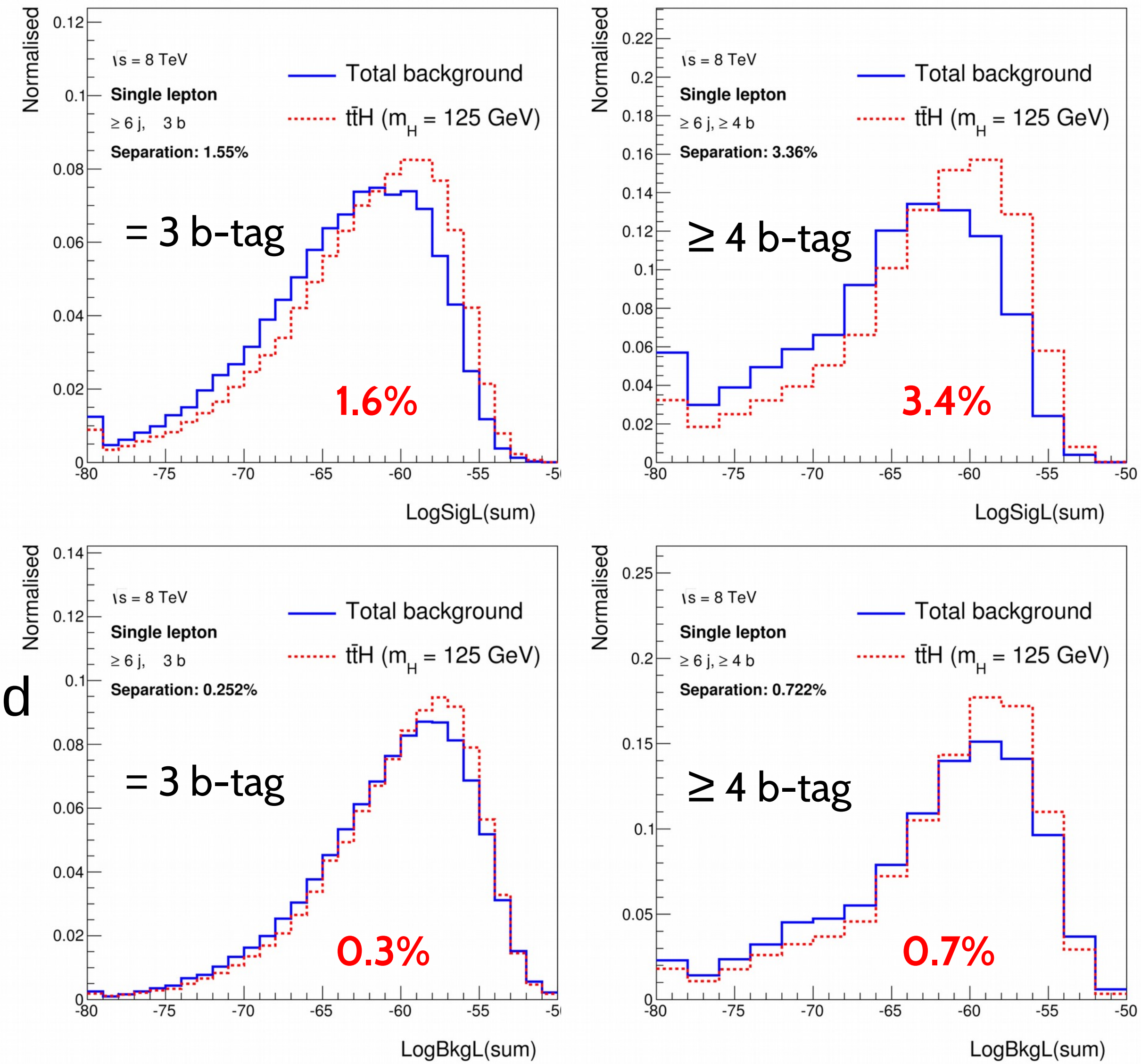
Likelihood Functions

- Signal Likelihood
  - $t\bar{t}H$ hypothesis

Separation:

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

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

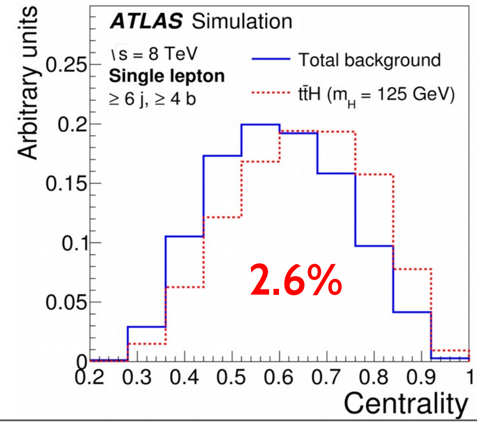


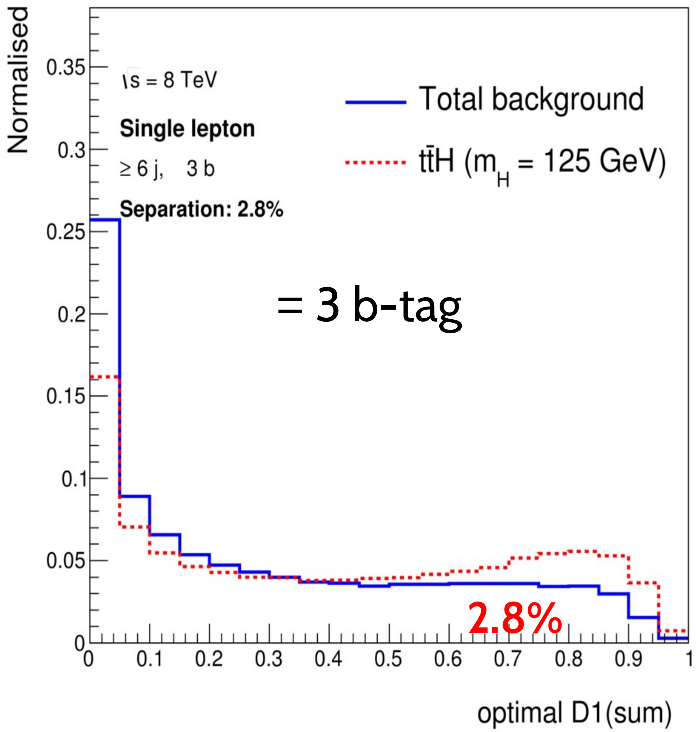
Likelihood Ratios

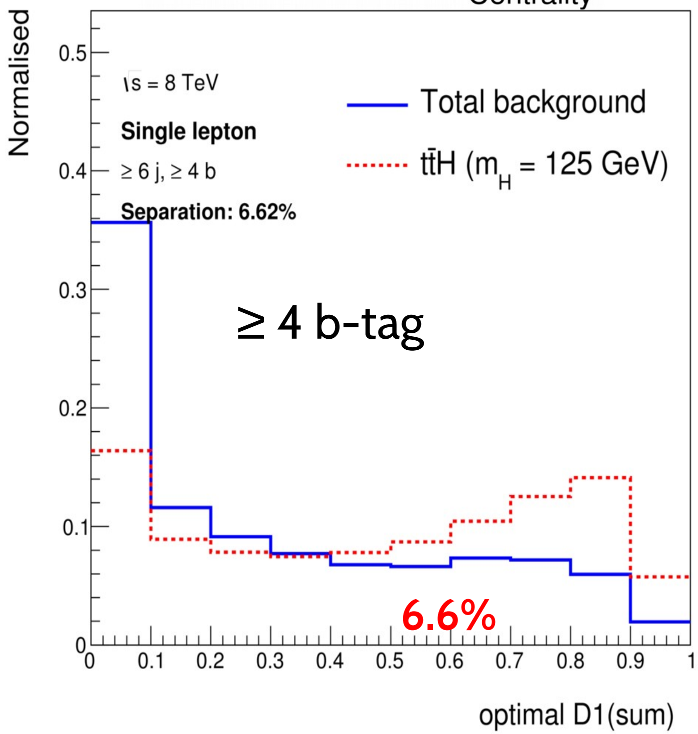
- Neyman-Pearson Likelihood Ratio

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

- Optimal normalization
  - $\alpha = 0.23$

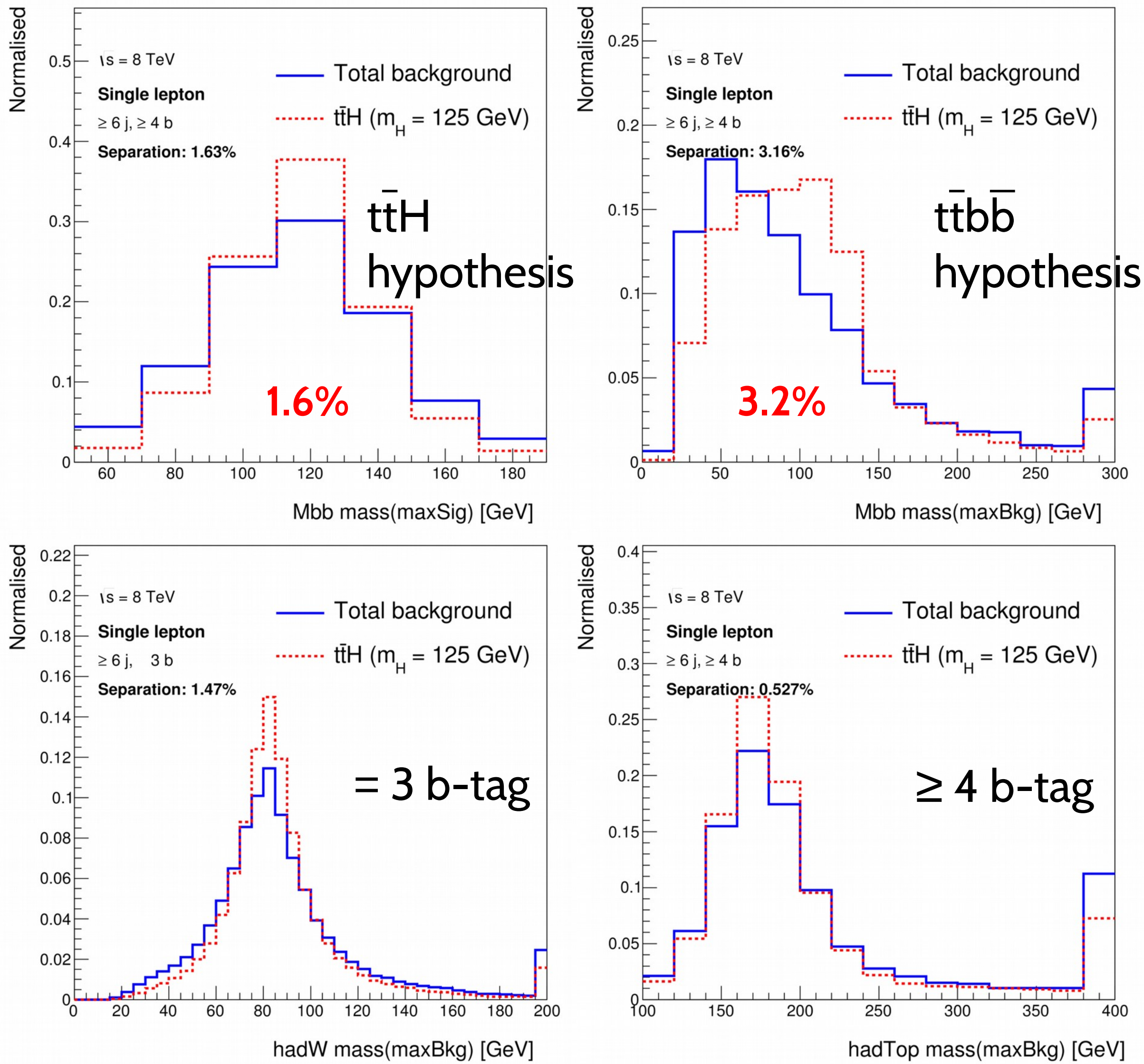






Event Reconstruction

- 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

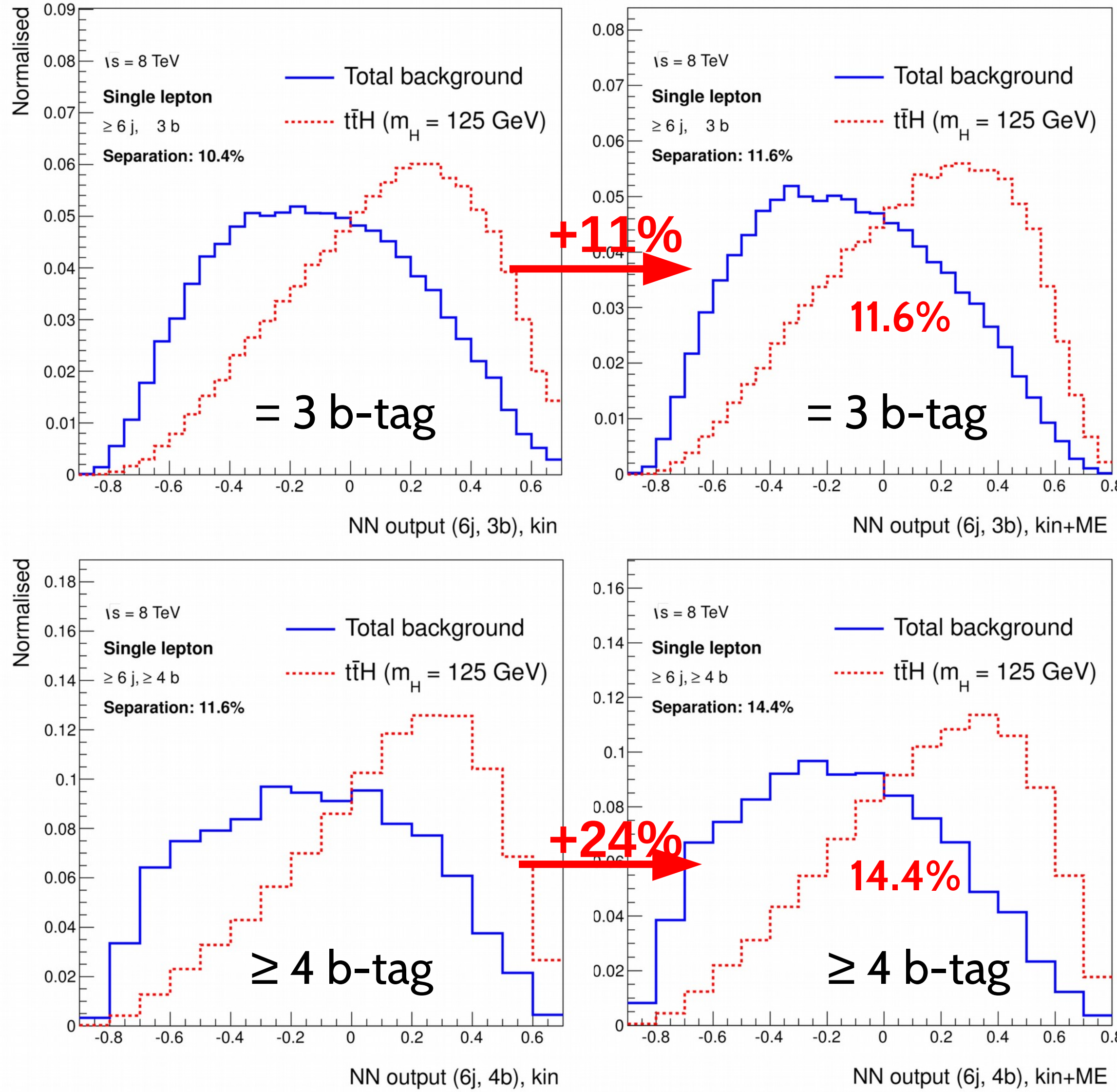


Neural Network Output with MEM

- NN Separation (≥ 6 jets)
  - 3 b-tags: + 11%
  - 4 b-tags: + 24%

→ Large improvement

→ Better constrain systematics

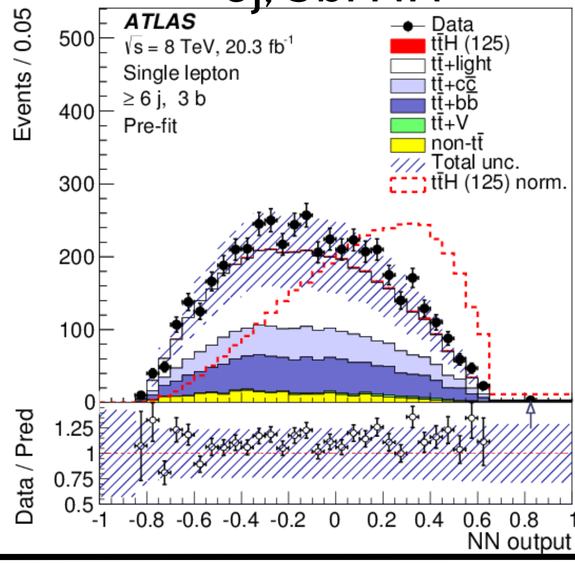


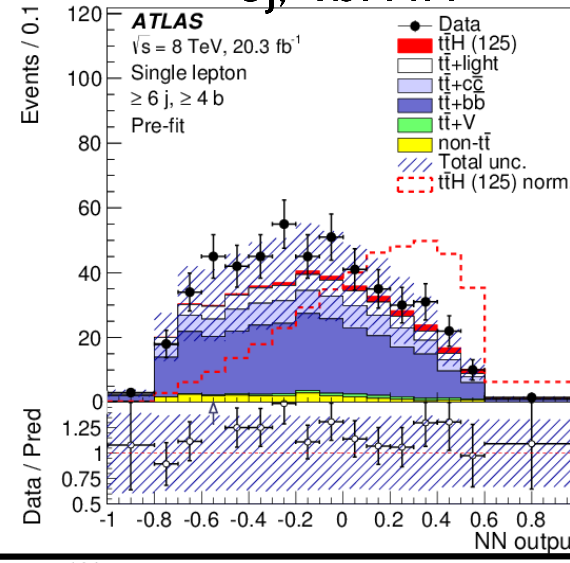
Profile Likelihood Fit: 6j, 3b / 6j, 4b

6j, 3b: NN

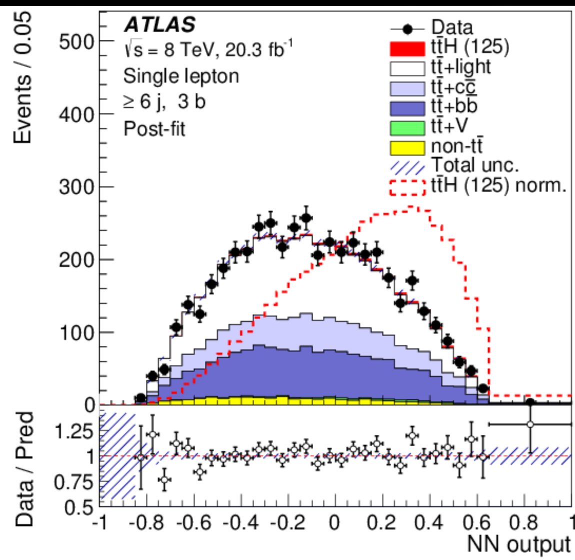
6j, 4b: NN

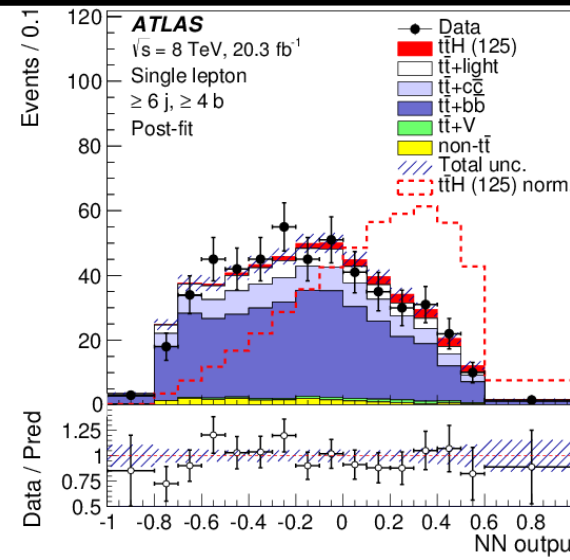
- Pre-fit





- Post-fit

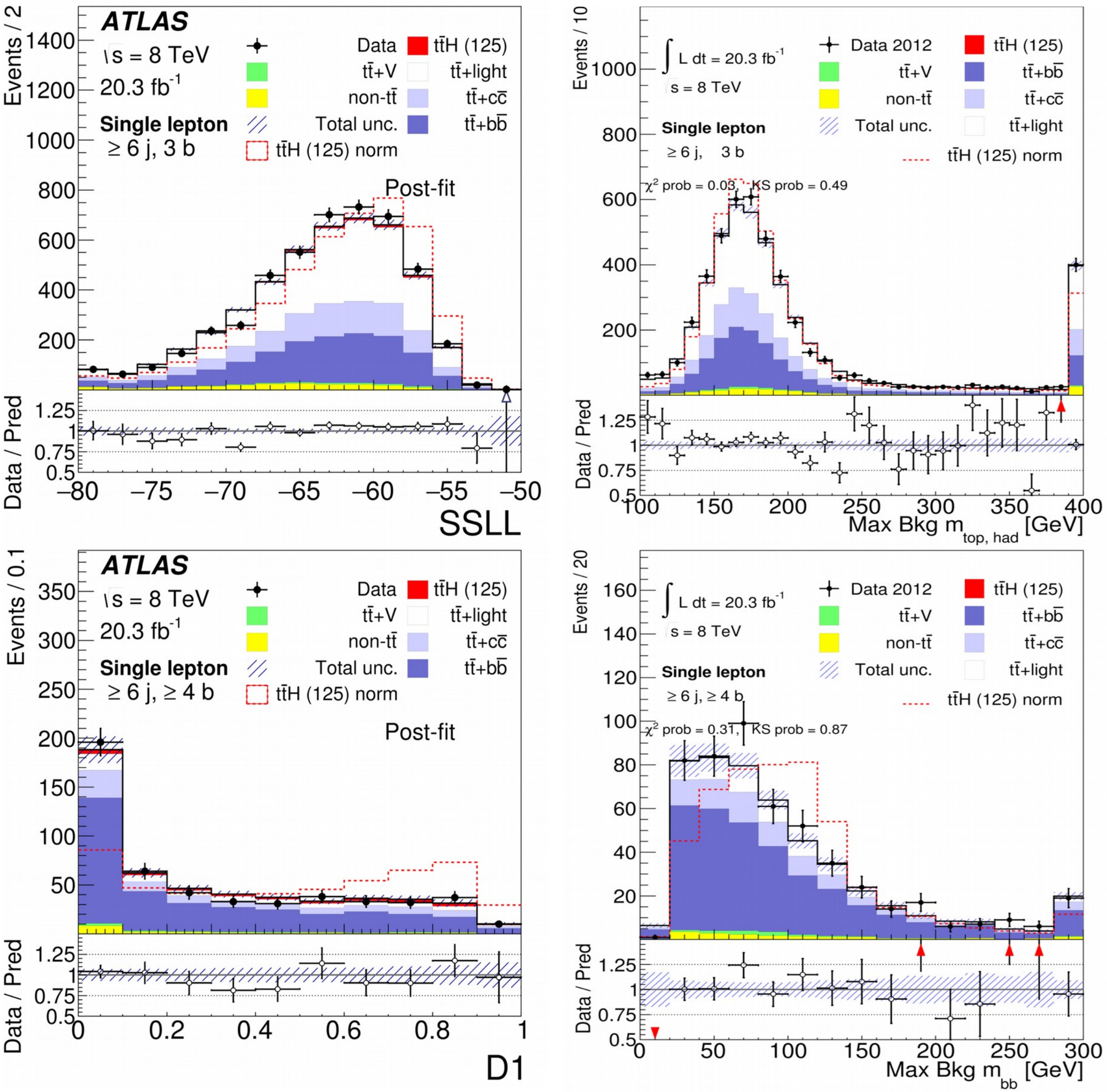




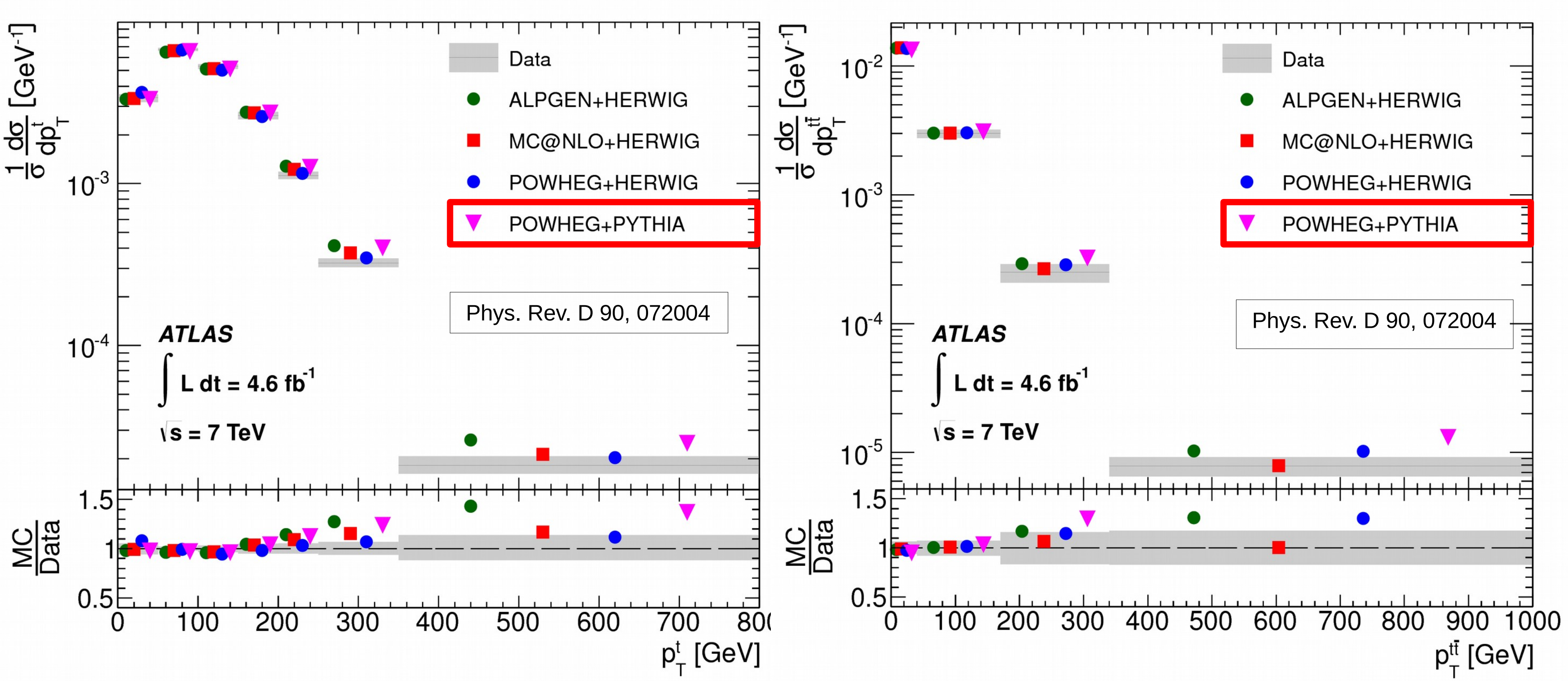
MEM Validation Postfit

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

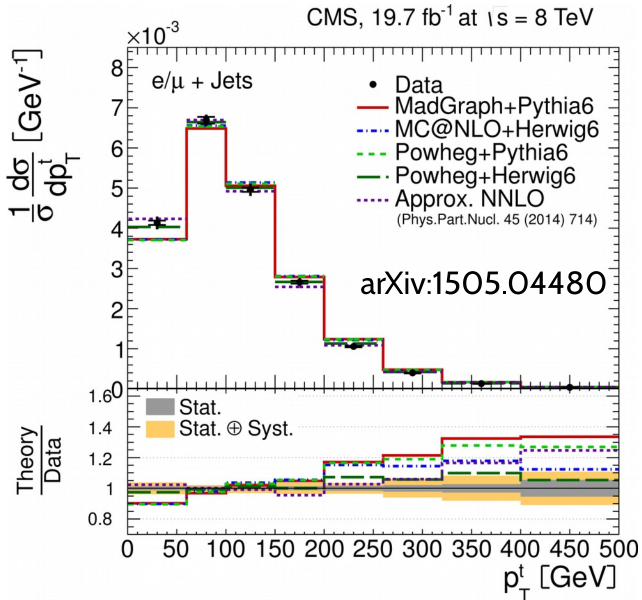
- 6j, 4b
  - Likelihood ratio D1
  - Invariant m_{bb}

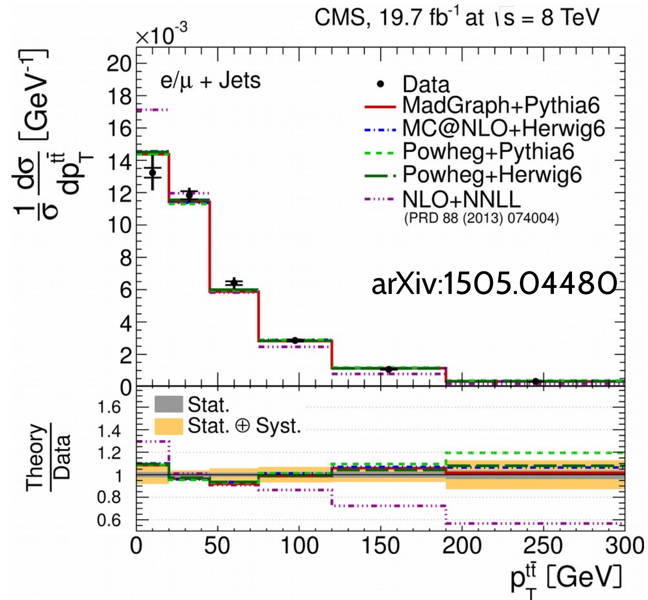


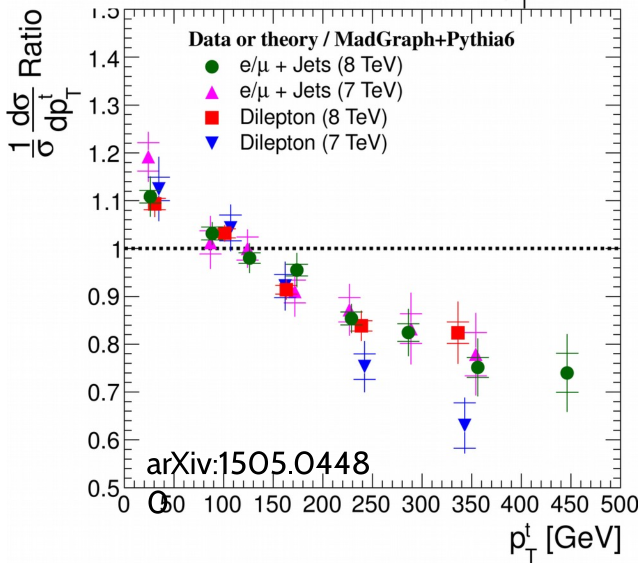
7 TeV Differential Cross Section

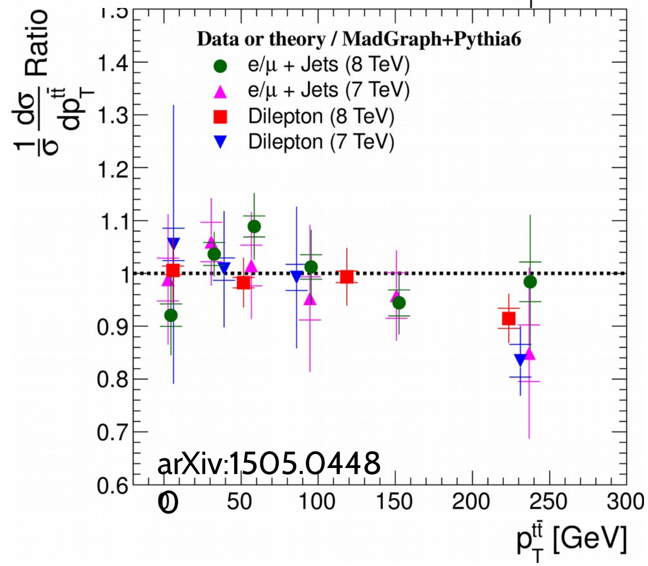


CMS Differential Cross Section Measurement at 8 TeV



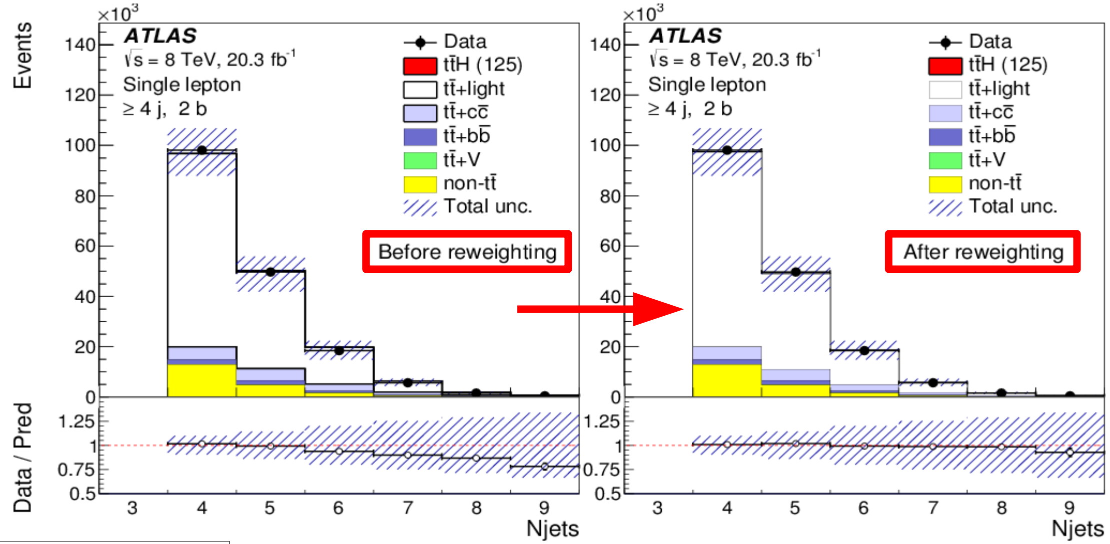




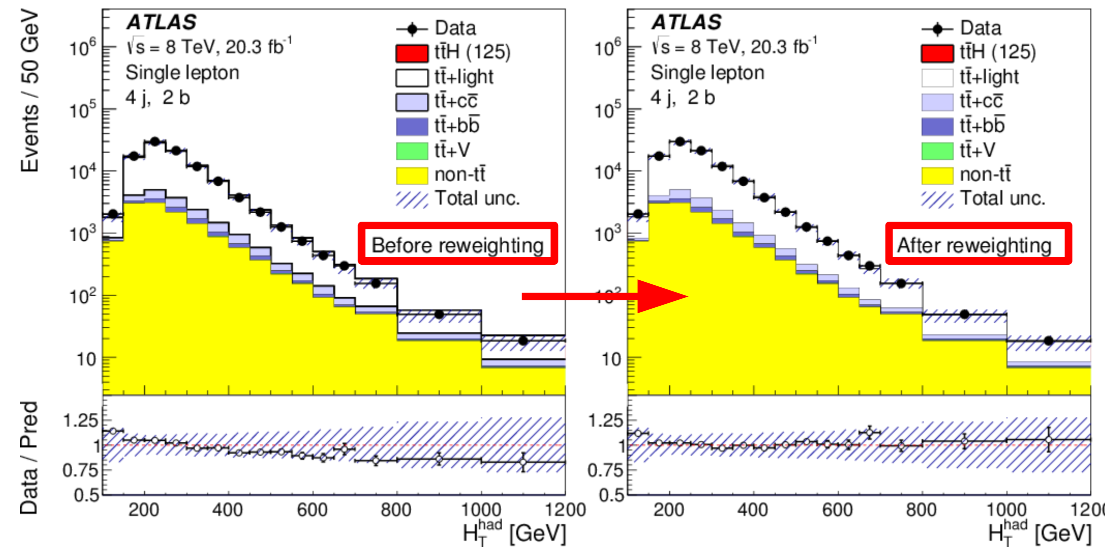


$t\bar{t}$+jets Modeling

- 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 Sherpa OpenLoops

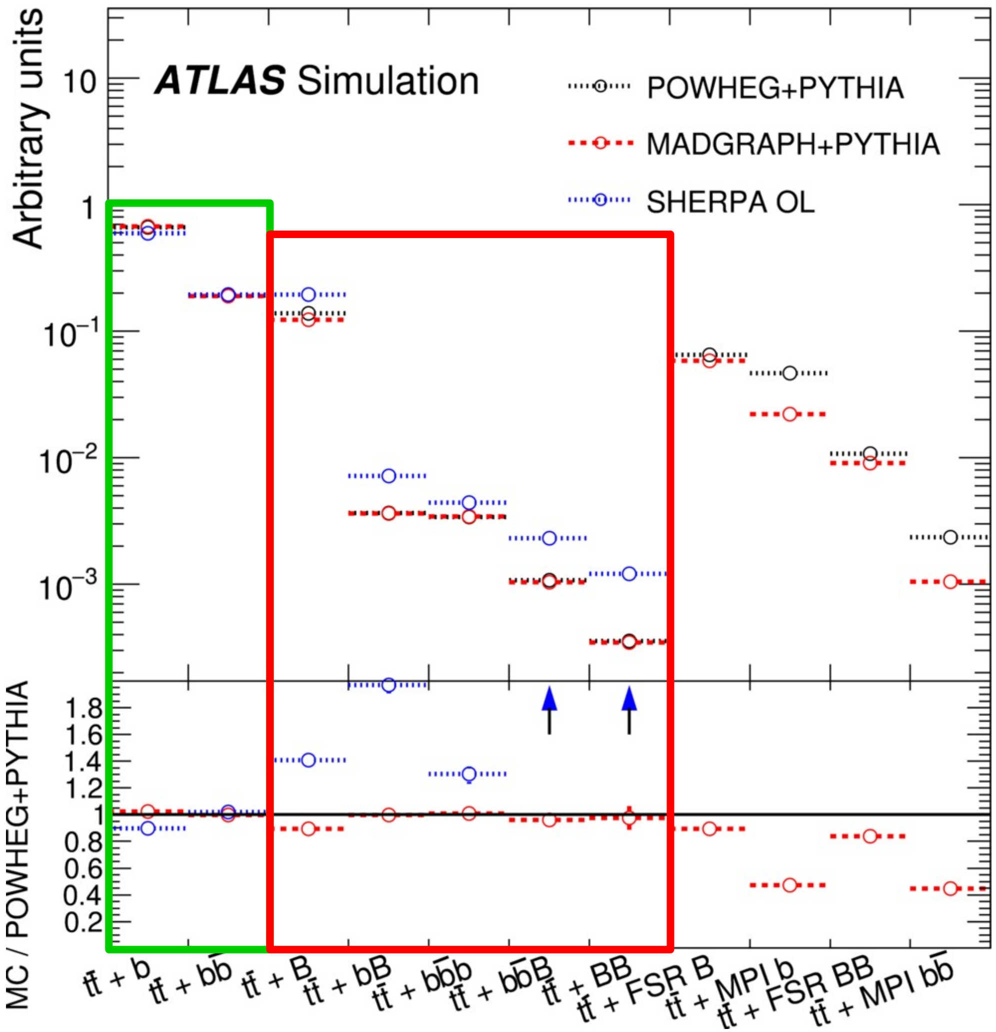


Phys. Rev. D 90, 072004

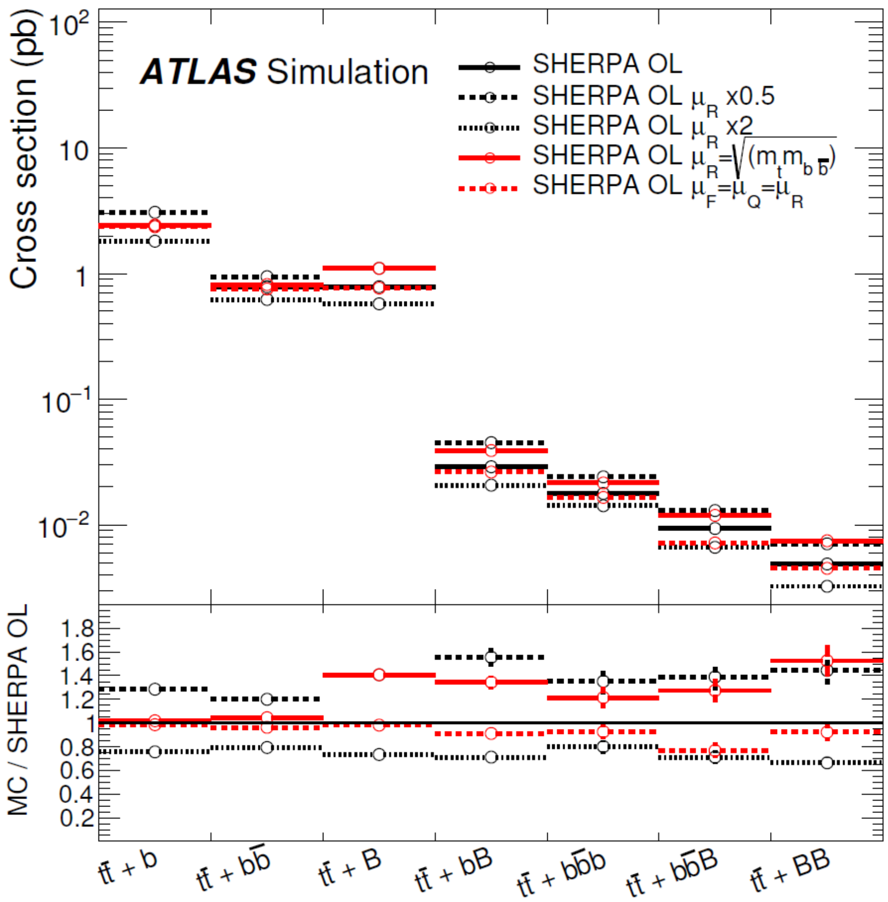


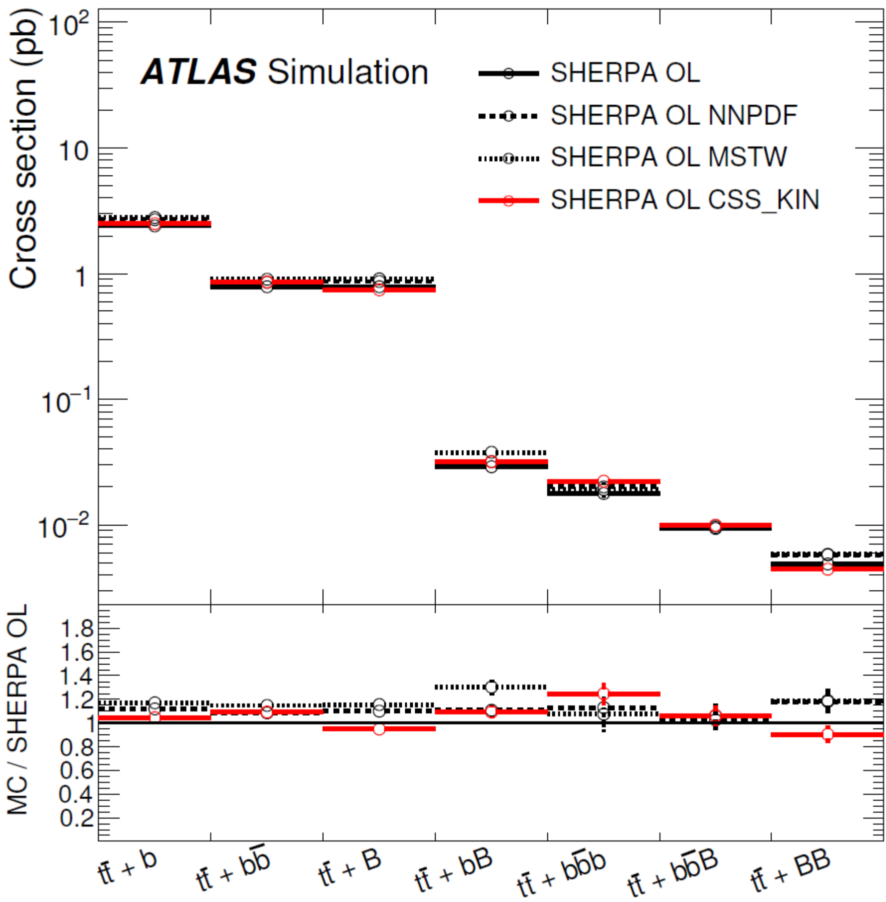
tt+bb Modeling

- 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: tt+b, tt+bb
  - Unresolved: tt+B, tt+BB
- Reweight categories to Sherpa OL
  - Parton level
  - Kinematic distributions



tt+bb Modeling uncertainties





Summary of MC simulation

Process	ME Generator	PDF	Parton Shower	Normalisation
$t\bar{t}H$	HELAC-Oneloop	CT10	Pythia 8.1	NLO
$t\bar{t}$ + 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 + jets	Alpgen	CTEQ6L1	Pythia 6.426	NLO
Z + jets	Alpgen	CTEQ6L1	Pythia 6.426	NLO
Diboson	Alpgen	CTEQ6L1	Herwig 6.520	NLO

NN Variables and Ranking

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	-
$p_{\mathrm{T}}^{\mathrm{jet5}}$	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	-
$\Delta R_{\mathrm{bb}}^{\mathrm{avg}}$	Average ΔR for all b-tagged jet pairs	5	6	5	-
$\ln \mathcal{L}_{t\bar{t}H}^{\mathrm{sum}}$	Logarithm of the summed signal likelihoods	6	4	-	-
$m_{\mathrm{bb}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of the two b-tagged jets with the smallest ΔR	7	12	4	4
$m_{\mathrm{bj}}^{\mathrm{max}\ p_{\mathrm{T}}}$	Mass of the combination of a b-tagged jet and any jet with the largest vector sum p_{T}	8	8	-	-
$\Delta R_{\mathrm{bb}}^{\mathrm{max}\ p_{\mathrm{T}}}$	ΔR between the two b-tagged jets with the largest vector sum p_{T}	9	-	-	-
$\Delta R_{\mathrm{lep-bb}}^{\mathrm{min}\ \Delta\mathrm{R}}$	ΔR between the lepton and the combination of the two b-tagged jets with the smallest ΔR	10	11	10	-
$m_{\mathrm{uu}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of the two untagged jets with the smallest ΔR	11	9	-	2
$\mathrm{Aplan}_{b-\mathrm{jet}}$	$1.5\lambda_2$, 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 $p_{\mathrm{T}} \geq 40$ GeV	-	1	3	-
$m_{\mathrm{bj}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of a b-tagged jet and any jet with the smallest ΔR	-	5	-	-
$m_{\mathrm{jj}}^{\mathrm{max}\ p_{\mathrm{T}}}$	Mass of the combination of any two jets with the largest vector sum p_{T}	-	-	6	-
$H_{\mathrm{T}}^{\mathrm{had}}$	Scalar sum of jet p_{T}	-	-	7	-
$m_{\mathrm{jj}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of any two jets with the smallest ΔR	-	-	9	-
$m_{\mathrm{bb}}^{\mathrm{max}\ p_{\mathrm{T}}}$	Mass of the combination of the two b-tagged jets with the largest vector sum p_{T}	-	-	-	1
$p_{\mathrm{T,uu}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Scalar sum of the p_{T} of the pair of untagged jets with the smallest ΔR	-	-	-	3
$m_{\mathrm{bb}}^{\mathrm{max}\ \mathrm{m}}$	Mass of the combination of the two b-tagged jets with the largest invariant mass	-	-	-	5
$\Delta R_{\mathrm{uu}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Minimum ΔR between the two untagged jets	-	-	-	6
m_{jjj}	Mass of the jet triplet with the largest vector sum p_{T}	-	-	-	7

Systematic Uncertainties: Pre-fit / Post-fit (6j, 4b)

	Pre-fit				Post-fit			
	$t\bar{t}H$ (125)	$t\bar{t}$ + light	$t\bar{t}+c\bar{c}$	$t\bar{t}+b\bar{b}$	$t\bar{t}H$ (125)	$t\bar{t}$ + 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

CONF Note Results

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