Search for the decay $H \to b\bar{b}$ of the standard model Higgs boson produced in association with hadronically decaying top quarks in pp collisions at 8 TeV with the ATLAS detector at the LHC

arXiv:1604.03812

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

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ATLAS EXPERIMENT

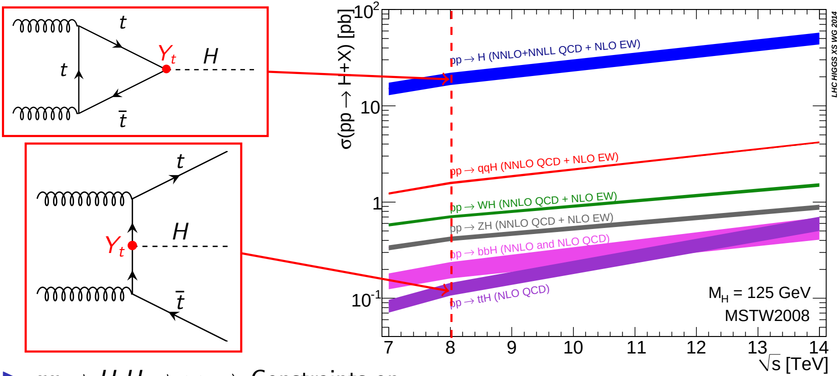
Outline

- Higgs boson phenomenology and top Yukawa coupling
- Search for $t\bar{t}H$ ($H \to b\bar{b}$) in the full hadronic final state
  - Motivations and main characteristics of the analysis
  - Preselection and event categorisation
  - Data-driven multijet background estimation: "$\mathrm{TRF_{MJ}}$ method"
  - Systematic uncertainties
  - Results
- ATLAS Run 1 $t\bar{t}H$ combination
- Conclusions

Yukawa coupling and Higgs boson phenomenology

- New physics could manifest by modifying **top-quark Yukawa coupling Y_{top}**
  - The top-quark is the heaviest SM particle and has the largest coupling $Y_{top} \sim 1$
  - It decays before hadronizing, top observables can be computed and measured

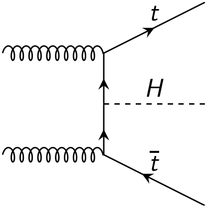
Higgs production modes



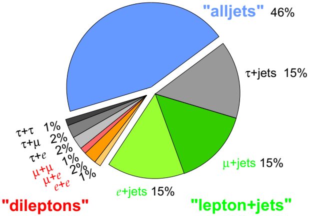
- $gg \to H, H \to \gamma\gamma \Rightarrow$ Constraints on Y_t, no control if new particles participate to the loops
- $t\bar{t}H \Rightarrow$ direct access to Y_t

$t\bar{t}H$ and its backgrounds at LHC $\sqrt{s} = 8$ TeV

Signal: $t\bar{t}H$

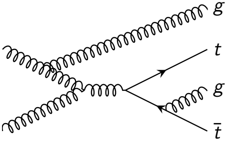


- $\sigma^{\text{NLO}}_{t\bar{t}H} = 0.129 \pm 0.015$ pb
  arXiv:1307.1347
- Exploit all Higgs decay channels
  - $H \to b\bar{b}$: Highest BR, 58%
- Exploit all $t\bar{t}$ decay
  - $t\bar{t} \to$ all-jets : Highest BR

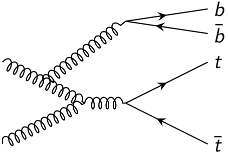


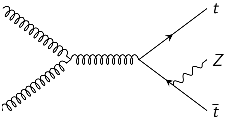
$top + X$ Backgrounds

$t\bar{t}$ + jets

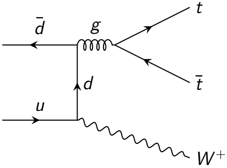


$t\bar{t} + b\bar{b}$





$t\bar{t}V$



$\sigma^{\text{NNLO+ NNLL}}_{t\bar{t}+X} = 246 \pm 10$ pb
arXiv:1303.6254

$\sigma^{\text{NLO}}_{t\bar{t}+b\bar{b}} = 2.638 \pm 0.006$ pb
arXiv:0907.4723

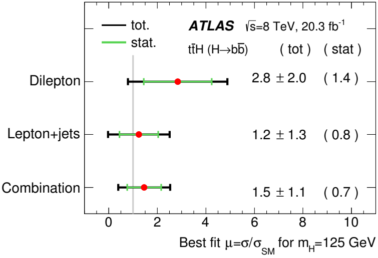
$\sigma^{\text{NLO}}_{t\bar{t}+Z} = 1.121 \pm 0.002$ pb
arXiv:1111.0610

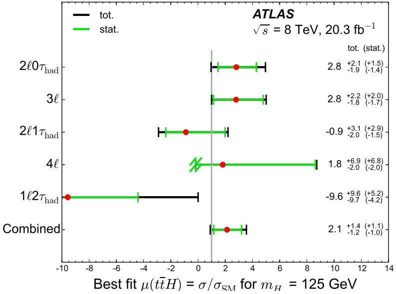
$\sigma^{\text{NLO}}_{t\bar{t}+W+} = 0.161 \pm 0.032$ pb
$\sigma^{\text{NLO}}_{t\bar{t}+W-} = 0.071 \pm 0.014$ pb
arXiv:1204.5678

Previous $t\bar{t}H$ results in ATLAS

Signal strength: $\mu = \frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}}$

- $t\bar{t}H$ ($H \to b\bar{b}$) in the single-lepton and dilepton $t\bar{t}$ decay channel
  Eur. Phys. J. C 75 (2015) 349



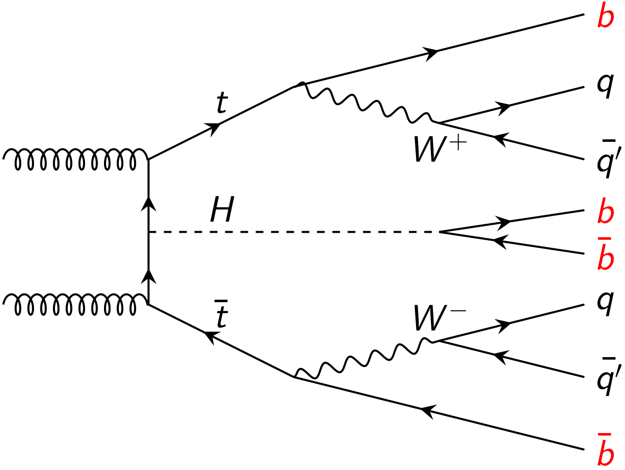


- $t\bar{t}H$ ($H \to WW, H \to ZZ, H \to \tau\tau$) in multi-leptons final states
  Phys. Lett. B 749 (2015) 519541

- $t\bar{t}H$ ($H \to \gamma\gamma$) hadronic and leptonic $t\bar{t}$ decay channels $\quad \mu = 1.2^{+2.6}_{-1.8}$
  Phys. Lett. B 740 (2015) 222

Full hadronic $t\bar{t}H$ $(H \rightarrow b\bar{b})$

- Striking signature $\rightarrow$ High p_T jets and b-jets
- Large statistics available from BR and trigger efficiency
- Sensitive to different systematic uncertainties



Signal

POWHEL NLO + PYTHIA

Background

Multijet:
Data driven

$t\bar{t}$ + jets:
POWHEG NLO + PYTHIA
Reweight applied on top and $t\bar{t}$ p_T

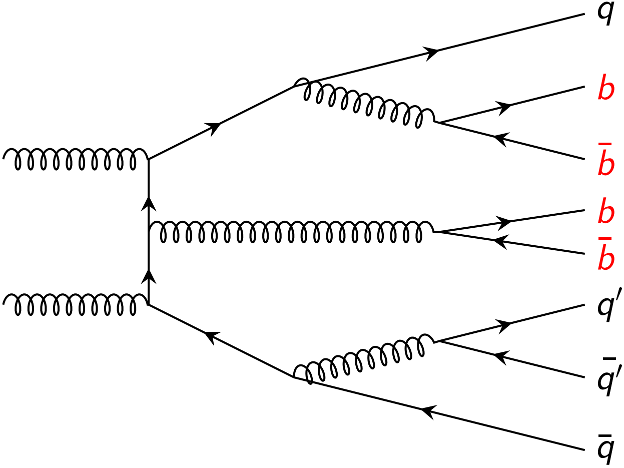
$t\bar{t} + b\bar{b}$:
POWHEG NLO + PYTHIA
Reweight to SHERPA OPENLOOPS NLO

$t\bar{t}V$:
MADGRAPH LO + PYTHIA

Single top:
Wt-channel:
POWHEG NLO + PYTHIA
t-channel:
ACERMC LO + PYTHIA

Full hadronic $t\bar{t}H$ ($H \rightarrow b\bar{b}$)

- Striking signature $\rightarrow$ High p_T jets and b-jets
- Large statistics available from BR and trigger efficiency
- Sensitive to different systematic uncertainties
- Need to fight vs multijet background



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$t\bar{t}V$:
MADGRAPH LO + PYTHIA

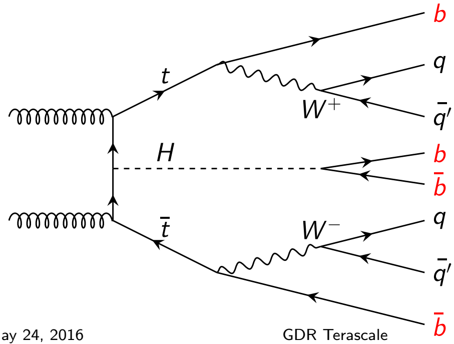
Single top:
Wt-channel:
POWHEG NLO + PYTHIA
t-channel:
ACERMC LO + PYTHIA

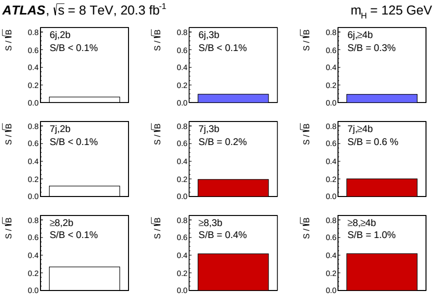
Signal regions and event selection

Preselection:

- Events selected with a **multi-jet trigger** ($L = 20.3$ fb^{-1})
- ≥ 5 jets with $p_T > 55$ GeV and $\eta < 2.5$
- Additional jets with $p_T > 25$ GeV and $\eta < 2.5$
- Lepton veto
  - Assure orthogonality with other $t\bar{t}H$ channels
- b-tagging: MV1 algorithm
  - 60% b-tag efficiency, c-jet rejection ~ 10 and light jet rejection ~ 600

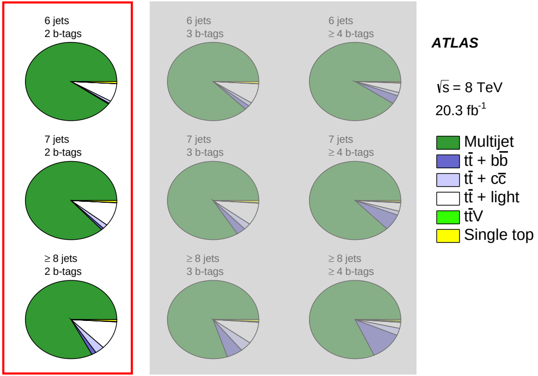
Events categorised according to jet and b-jet multiplicity to maximise sensitivity





Multijet background estimation: TRF_{MJ} method

- **TRF_{MJ} is a data-driven method to describe MultiJet background (MJ)**
- **MJ is extracted** in a region with low *b*-tag multiplicity away from signal region
  - Exactly 2 *b*-tagged jets
  - MJ (2b) = DATA (2b) - $\sum MC_{background}$ (2b)



Multijet background estimation: $\mathrm{TRF}_{\mathrm{MJ}}$ method

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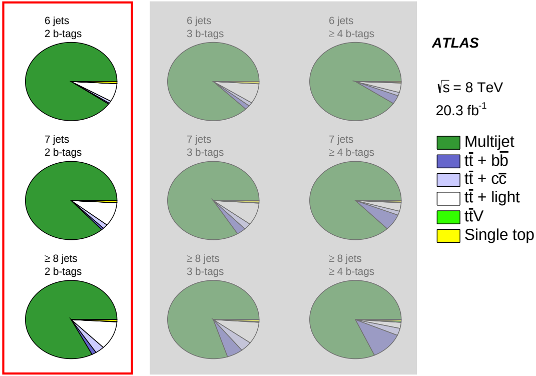
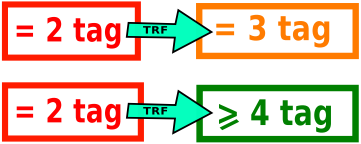
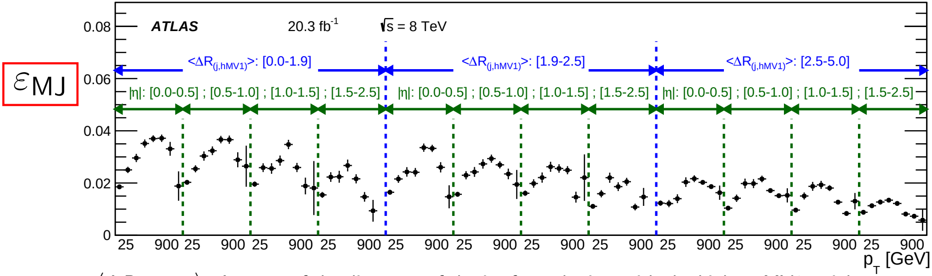




- The amount of MJ in higher *b*-tag multiplicity regions is estimated using the *b*-tagging probability for MJ jets ($\varepsilon_{\mathbf{MJ}}$)

TRF$_{MJ}$ method: ε_{MJ}

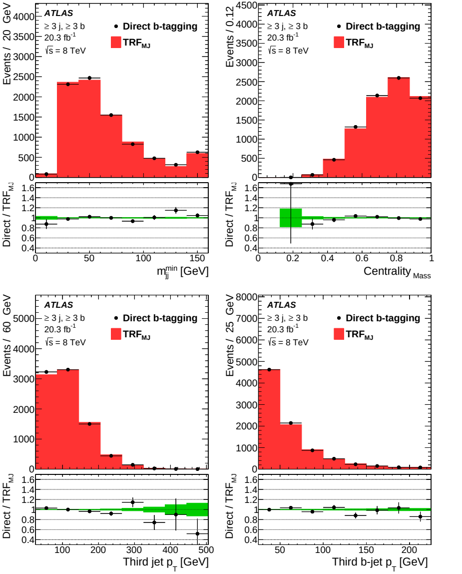
- **ε_{MJ}: probability of tagging a jet once the two jets with the highest MV1 (b-tagging) weight are excluded**
- It is evaluated in data collected by a single jet trigger with $E_T > 360$ GeV
- Parametrised with respect to: p_T, η and $\langle \Delta R_{(j,\mathrm{hMV1})} \rangle$



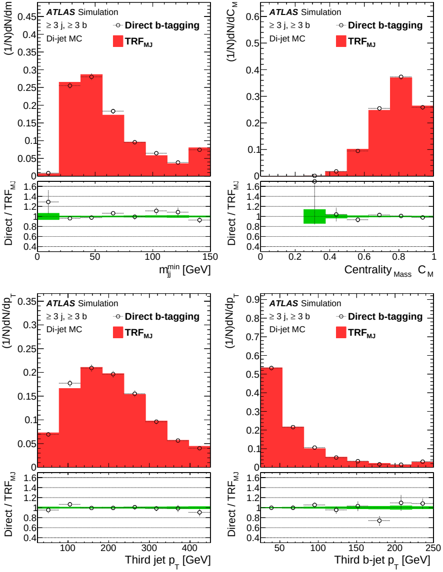
- $\langle \Delta R_{(j,\mathrm{hMV1})} \rangle$: Average of the distances of the jet from the jets with the highest MV1 weight

TRF_{MJ} validation in data and MC

- **Data:** ε_{MJ} **evaluation sample**



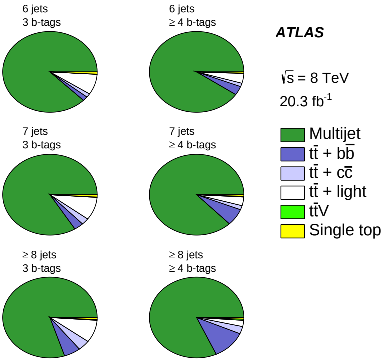
- **MC:** PYTHIA8 di-jet



Event yields in analysis regions

	6j,3b	7j,3b	$\geq$8j,3b
Multijet	16380 $\pm$ 130	12530 $\pm$ 110	10670 $\pm$ 100
$t\bar{t} + b\bar{b}$	330 $\pm$ 180	490 $\pm$ 270	760 $\pm$ 450
$t\bar{t} + c\bar{c}$	280 $\pm$ 180	390 $\pm$ 240	560 $\pm$ 350
$t\bar{t}$+light	1530 $\pm$ 390	1370 $\pm$ 430	1200 $\pm$ 520
$t\bar{t} + V$	14.2 $\pm$ 6.3	22.0 $\pm$ 9.0	40 $\pm$ 15
single top	168 $\pm$ 63	139 $\pm$ 55	110 $\pm$ 49
Total bkg.	18700 $\pm$ 480	14940 $\pm$ 580	13330 $\pm$ 780
$t\bar{t}H$ (125)	14.3 $\pm$ 4.6	23.7 $\pm$ 6.4	48 $\pm$ 11
Data	18508	14741	13131

	6j,$\geq$4b	7j,$\geq$4b	$\geq$8j,$\geq$4b
Multijet	1112 $\pm$ 33	1123 $\pm$ 34	1324 $\pm$ 36
$t\bar{t} + b\bar{b}$	44 $\pm$ 26	87 $\pm$ 51	190 $\pm$ 110
$t\bar{t} + c\bar{c}$	17 $\pm$ 12	21 $\pm$ 15	48 $\pm$ 33
$t\bar{t}$+light	48 $\pm$ 18	45 $\pm$ 18	40 $\pm$ 23
$t\bar{t} + V$	1.8 $\pm$ 1.5	3.5 $\pm$ 2.3	8.0 $\pm$ 4.2
single top	6.0 $\pm$ 3.7	8.3 $\pm$ 4.6	10.6 $\pm$ 5.9
Total bkg.	1229 $\pm$ 48	1288 $\pm$ 66	1620 $\pm$ 130
$t\bar{t}H$ (125)	3.3 $\pm$ 2.1	7.2 $\pm$ 3.3	16.8 $\pm$ 6.1
Data	1545	1402	1587

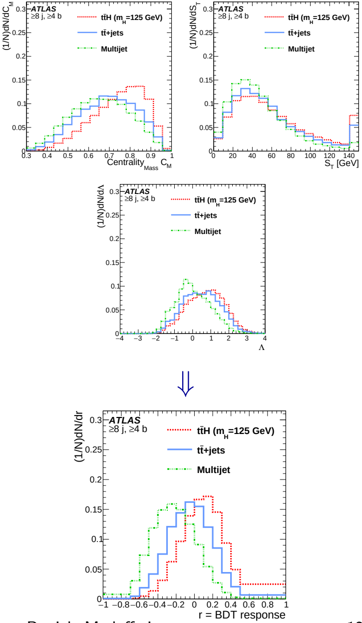


Boosted Decision Tree

- Output of a **Boosted Decision Tree (BDT)** is used as **final discriminant**
- One BDT is trained in each signal region

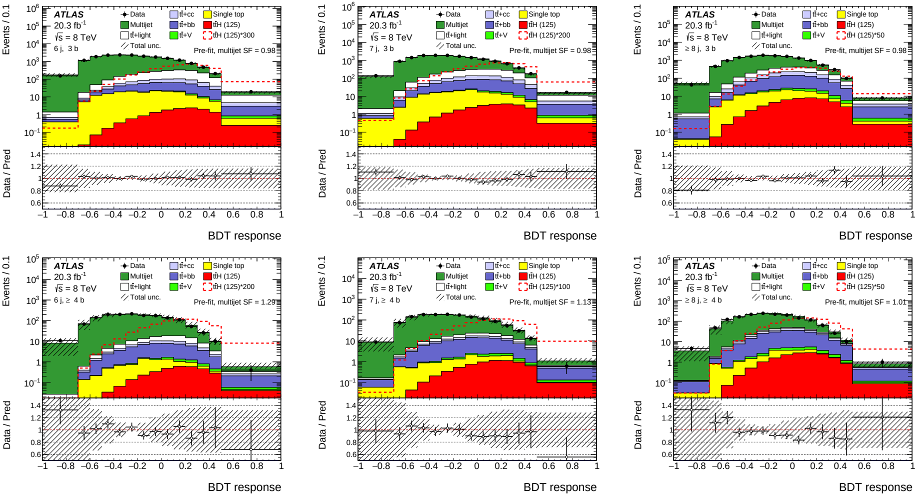
  Signal : $t\bar{t}H$, inclusive in top and Higgs decays

  Background : Multijet + all MC backgrounds
- Input variables selected with an iterative procedure
- List of variables entering in each BDT built to optimise performance
  - On average 11 variables per region
  - Event shape: Aplanarity, centrality
  - Kinematic: H_T, S_T, jet p_T
  - Angular correlations: $\Delta R(b,b)^{p_T^{\max}}$,$\Delta R^{\min}$



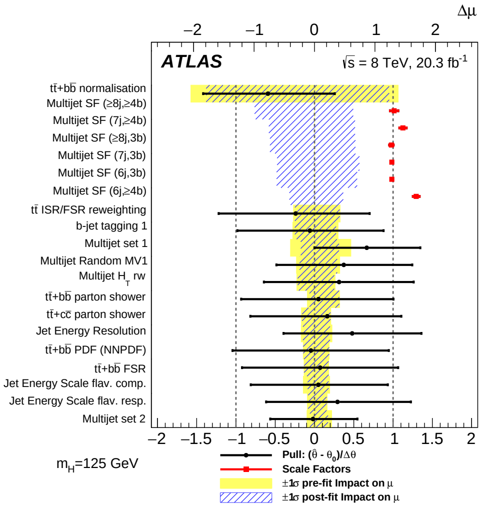
Fitting procedure

- The distributions of the BDT discriminant from each of the six regions are combined as inputs to a **statistical test** to search for the presence of a signal



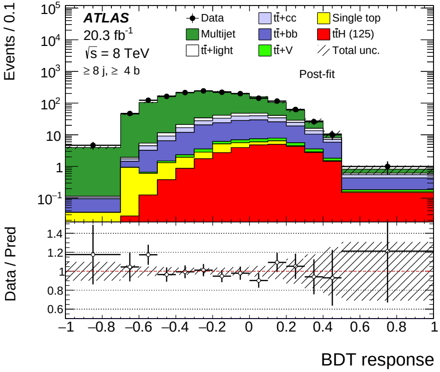
Leading systematic uncertainties — post-fit

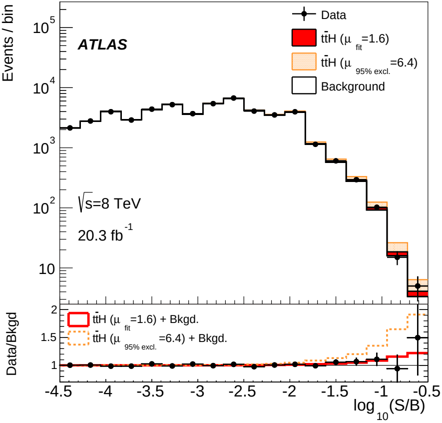
- $t\bar{t} + b\bar{b}$ normalisation 50%
  - Difference between POWHEG+PYTHIA and SHERPAOL
- MJ normalization is free floating independently in each region
- Top and $t\bar{t}$ p_T modeling
  - 9 leading syst. unc. of the $t\bar{t}$ differential cross section from where the reweighting is obtained Phys. Rev. D 90, 072004 (2014)
- Change of showering simulation for $t\bar{t} + b\bar{b}$ and $t\bar{t} + c\bar{c}$
  - Comparison of POWHEG events interfaced to PYTHIA and HERWIG
- $t\bar{t} + b\bar{b}$ modeling
  - Scale variation of SHERPAOL
  - Additional syst. on MPI and FSR, not present in SHERPAOL



Signal strength: $\mu = \frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}}$

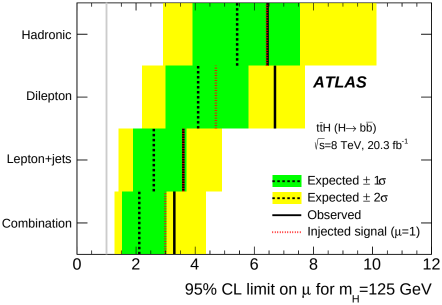
Full hadronic $t\bar{t}H$ ($H \to b\bar{b}$) results

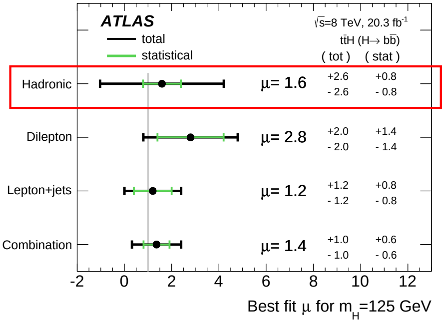




- 95% CL observed (expected) upper limit on $\sigma_{t\bar{t}H}$: 6.4 (5.4) $\times \sigma^{SM}_{t\bar{t}H}$
- Best fit value: $\mu = 1.6 \pm 2.6$

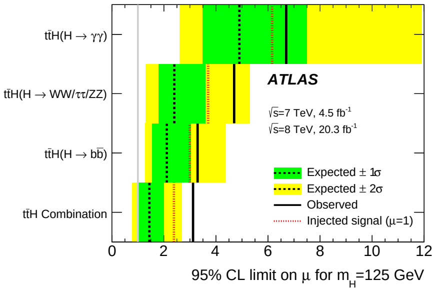
$t\bar{t}H$ ($H \to b\bar{b}$) combination

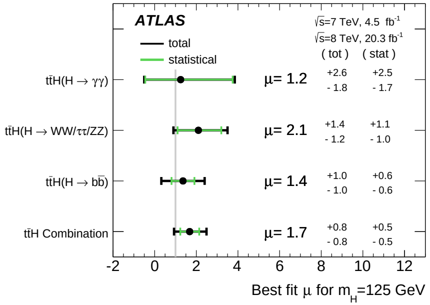




- Fully hadronic channel is actually limited by systematic uncertainties
- Improvement with $t\bar{t}H$ fully hadronic channel
  - Upper limit 3.4 (2.2) $\to$ **3.3 (2.1)** $\times\sigma^{\text{SM}}_{t\bar{t}H}$
- Best fit value $\mu = 1.4 \pm 1$

Run 1 $t\bar{t}H$ combination





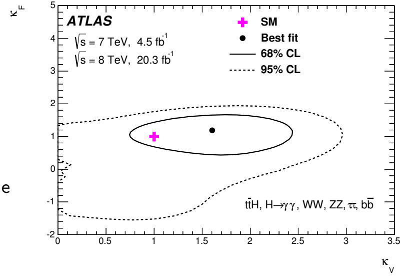
Signal strength and limit:

- 95% CL observed (expected) upper limit on $t\bar{t}H$ cross section 3.1 (1.4) $\times\sigma^{SM}_{t\bar{t}H}$
- Best fit value $\mu = 1.7 \pm 0.8$

Higgs couplings:

- Best-fit of couplings modifiers κ_V and κ_F is compatible with SM prediction within 1 σ

$$\kappa_{V/F} = \frac{\sigma_{V/F}}{\sigma^{SM}_{V/F}} \quad \text{or} \quad \kappa_{V/F} = \frac{\Gamma_{V/F}}{\Gamma^{SM}_{V/F}}$$



Conclusions

First search of $t\bar{t}H$ ($H \rightarrow b\bar{b}$) in the fully hadronic channel @ LHC

- A new method to evaluate SF_{trig} made possible to increase signal efficiency
- Multijet background described by a data-driven method
  - Validation in data and MC
  - Full assessment of systematic uncertainties
- Fully hadronic $t\bar{t}H$ ($H \rightarrow b\bar{b}$) results:
  - Observed (expected) 95% CL UL 6.4 (5.4) $\times\sigma^{SM}_{t\bar{t}H}$; $\mu = 1.6 \pm 2.6$
- Run 1 ATLAS $t\bar{t}H$ combination including full hadronic contribution
  - Observed (expected) 95% CL UL 3.1 (1.4) $\times\sigma^{SM}_{t\bar{t}H}$; $\mu = 1.7 \pm 0.8$

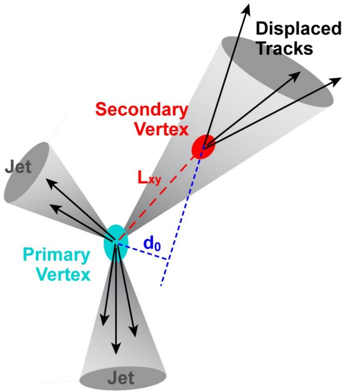
Prospects for Run 2:

- Improved performance *b*-tagging
  - Improved algorithms and addition of IBL
- Improved performance of the trigger
  - Level 1 trigger can select jets in E_T and η
  - *b*-jet trigger can be used to lower the jet threshold
    - On-line *b*-tagging performance close to offline in Run 2

Thanks for your attention

Back-up

Identification of b-jets



- ***b*-tagging :** identification of jets originating from b-quarks (b-jets)
- Relies on the long life-time of b-hadrons: $\tau_b \sim 1.5$ ps
  - They travel several millimetres before decaying
- Presence in the b-jet of a secondary vertex
- Tracks in the b-jet will tend to have an impact parameter $d_0 \neq 0$

Jet trigger efficiency and scale factor

- Events selected with a **multi-jet trigger** ($L = 20.3$ fb^{-1})
  - **4 L1 jets $E_T > 15$ GeV** $\rightarrow$ **5 L2 jets $E_T > 15$ GeV** $\rightarrow$ **5 EF jets $E_T > 55$ GeV**

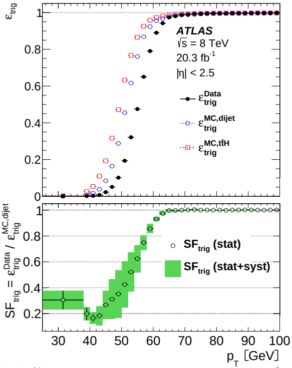
"Single-jet trigger efficiency" $\varepsilon_{\text{trig}}$ with respect to offline jets

$$\varepsilon_{\text{trig}}(p_T, \eta) = \frac{N(p_T,\eta)}{N_{Tot}(p_T,\eta)}$$

- N: Number of offline jets matched to a trigger chain
  - **Trigger chain** is defined as a sequence of L1, L2 and EF jets within $\Delta R < 0.4$
- N_{Tot}: Total number of offline jets

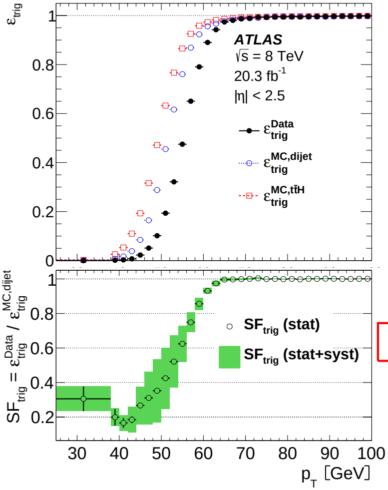
$\varepsilon_{\text{trig}}$ evaluation

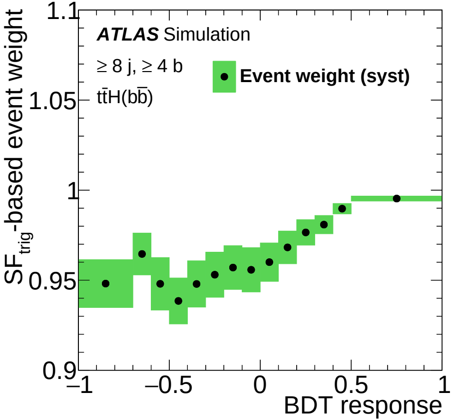
- Single jet trigger with $E_T > 110$ GeV
- At least 1 jet with $p_T > 25$ GeV and $|\eta| < 3.2$
- Veto if ≥ 2 jets with $E_T > 110$ GeV
- $\varepsilon_{\text{trig}}$ evaluated using jets with $\Delta\phi > \pi/2$ from jet firing the trigger
  - Avoid trigger bias
- SF is evaluated comparing **data** and PYTHIA8 **di-jet MC**



Trigger SF systematic uncertainty

- **Systematic uncertainty:** SF sample dependence derived in MC
  - It is maximal in the efficiency turn-on region





Trigger efficiency: algebra

$$P_{\geq 5} = 1 - (P_{=0} + P_{=1} + P_{=2} + P_{=3} + P_{=4})$$

$$P_{=0} = \prod_{i=1} (1 - \varepsilon_i)$$

$$P_{=1} = \sum_{j=1} \left(\varepsilon_j \prod_{i \neq j} (1 - \varepsilon_i) \right)$$

$$P_{=2} = \sum_{j=1} \sum_{l=j+1} \left(\varepsilon_j \varepsilon_l \prod_{i \neq j,l} (1 - \varepsilon_i) \right)$$

$$P_{=3} = \sum_{j=1} \sum_{l=j+1} \sum_{m=l+1} \left(\varepsilon_j \varepsilon_l \varepsilon_m \prod_{i \neq j,l,m} (1 - \varepsilon_i) \right)$$

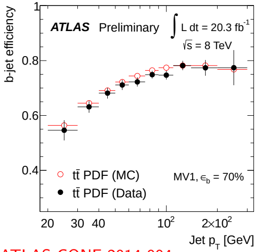
$$P_{=4} = \sum_{j=1} \sum_{l=j+1} \sum_{m=l+1} \sum_{n=m+1} \left(\varepsilon_j \varepsilon_l \varepsilon_m \varepsilon_n \prod_{i \neq j,l,m,n} (1 - \varepsilon_i) \right)$$

ε stands for $\varepsilon_{\mathrm{trig}}(p_T, \eta)$ and indexes i, j, k, l, m, n run over the number of jets in the event

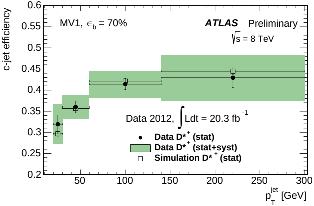
Analysis strategy

nj \ nb	2	3	≥4
6	**multijet (MJ)** background *extraction region.* **MJ** defined here as the difference between data and the MC based top-quark background	TRF_{MJ} → Fit region; TRF_{MJ} →	Fit region
7		TRF_{MJ} → Fit region; TRF_{MJ} →	Fit region
≥8		TRF_{MJ} → Fit region; TRF_{MJ} →	Fit region

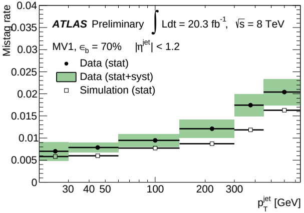
Treatment of MC: TRF_{MC}



ATLAS-CONF-2014-004

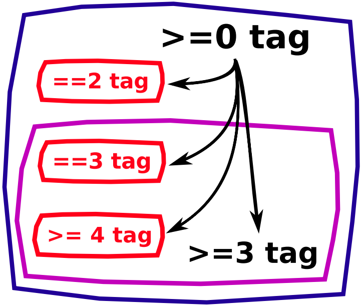


ATLAS-CONF-2014-046



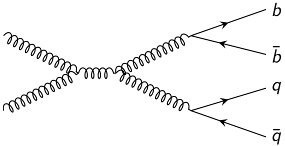
ATLAS-CONF-2014-046

- Requiring a cut on MV1 weight results in a loss statistics available for MC samples
  - Especially for physics processes with large fraction of light jets
- **Using the *b*-tagging efficiency as a probability:** $\varepsilon(p_T, \eta, flavour)$
- **Use full MC data set**

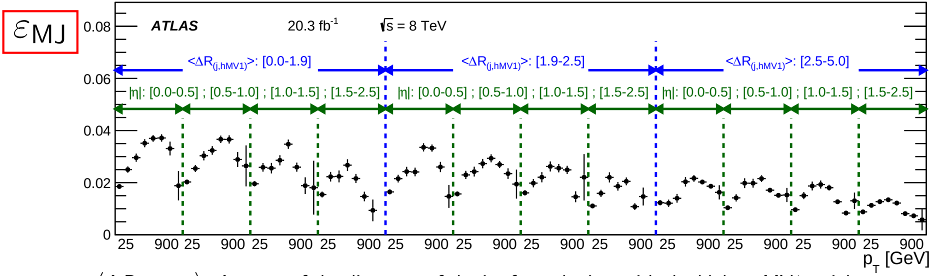


TRF$_{\text{MJ}}$ method: ε_{MJ} evaluation

- Event selection for ε_{MJ} **evaluation sample**
  - Single-jet trigger with $E_T > 360$ GeV
    Low jet multiplicity region **away from signal**
  - At least 3 jets with $p_T > 25$ GeV and $|\eta| < 2.5$ of which at least 2 b-tagged
    Linked to **MJ extraction region** choice
- **ε_{MJ} is the probability of tagging a jet once the two jets with the highest MV1 (b-tagging) weight are excluded**
- Parametrised with respect to: p_T, η and $\langle \Delta R_{(j,\text{hMV1})} \rangle$



- Angular correlation are sensitive to gluon splitting to $b\bar{b}$



- $\langle \Delta R_{(j,\text{hMV1})} \rangle$: Average of the distances of the jet from the jets with the highest MV1 weight

Shape systematic on TRF_{MJ}

Description of ε_{MJ}: **Angular correlations** exist among jets $\rightarrow$ **Cover all of them**
$\Rightarrow$ TRF_{MJ} applied using ε_{MJ} evaluated with **different criteria and parametrisation**

Five parametrisation of ε_{MJ} are considered:

1. p_T, Min $\Delta R_{(j,\mathrm{hMV1})}$, MV1 ΔR
2. p_T, Min $\Delta R_{(j,j)}$, MV1 ΔR
3. p_T, $|\eta|$, Min$\Delta R_{(j,\mathrm{hMV1})}$
4. p_T, $|\eta|$, Min $\Delta R_{(j,\mathrm{hMV1})}$, MV1 ΔR
5. p_T, $\langle \Delta R_{(j,\mathrm{hMV1})} \rangle$, MV1 ΔR

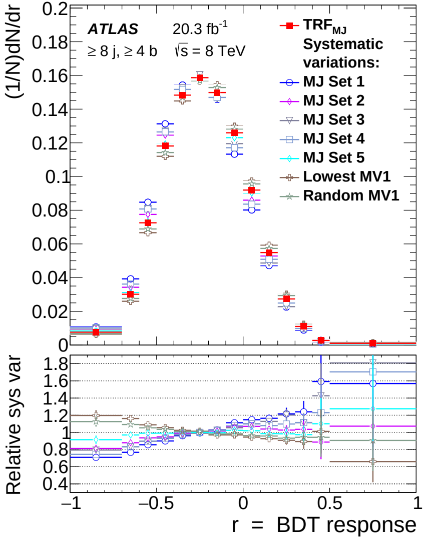
Where:

- Min $\Delta R_{(j,j)}$: Minimum ΔR between the jet and any other jet in the event
- Min $\Delta R_{(j,\mathrm{hMV1})}$: Minimum ΔR between the jet and excluded jets
- MV1 ΔR: ΔR between excluded jets

Two criterion for b-tagged jets exclusion:

- Two jets with **lowest** MV1 value
- Two **random**

Residual mismodeling of H_T and S_T from the ε_{MJ} **evaluation sample** also taken into account



TRF_{MJ} method: mathematics

For any event with $N(\geq 2b)$:

$$P_i(\geq 2 \to 2b+1b) = \sum_{j\neq b_1,b_2}^{n_i} \varepsilon_j^i \cdot \prod_{k\neq j,b_1,b_2}(1-\varepsilon_k^i)$$

The number of events with exactly 3 b-jets is given by:

$$N(2b+1b) = \sum_i^{N(\geq 2b)} P_i(\geq 2 \to 2b+1b)$$

The number of events with at least 4 b-jets is given by:

$$N(\geq 2b+2b) = \sum_i^{N(\geq 2b)} P_i(\geq 2b+1b \to \geq 2b+2b)$$
$$P_i(\geq 2b+1b \to \geq 2b+2b) = 1 - P_i(\geq 2b+1b \to 2b+1b)$$

ε_j^i depends on the relative position of the jet j with the already b-tagged jets in ith the event

The position of the third b-jets has to be predicted for each event to predict $N(2b+mb)$

$$P_i(\geq 2b+1b \to \geq 2b+2b) = \sum_{j\neq b_1,b_2,p}^{n_i} \varepsilon_j^i \cdot \prod_{k\neq j,b_1,b_2,p}(1-\varepsilon_k^i)$$

Application to the sample with 2 b-tags:

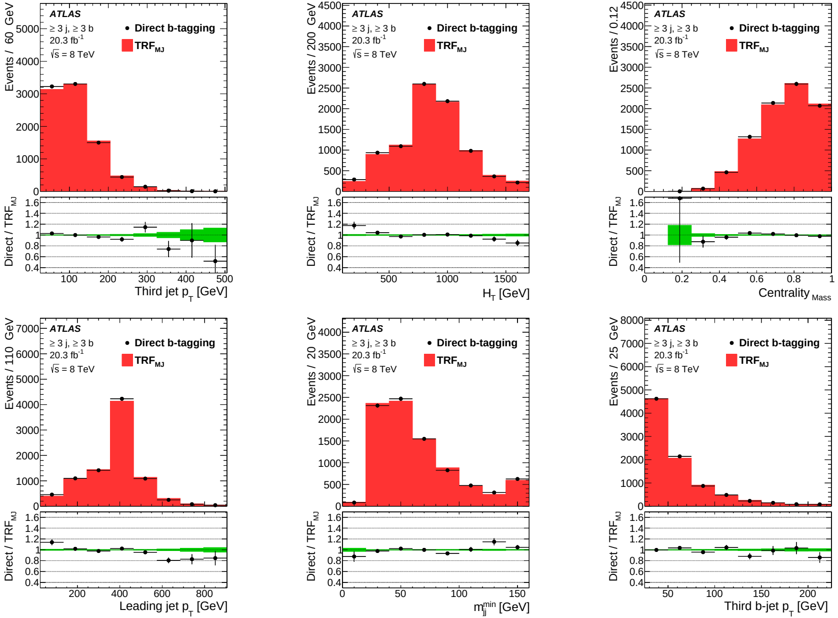
Infer $N(\geq 2b)$ by weighting each of the $N(2b)$ events by the inverse of $P_i(\geq 2b \to 2b)$:

$$P_i(\geq 2b \to 2b) = \prod_{j\neq b_1,b_2}^{n_i}(1-\varepsilon_j) \quad \text{, hence} \quad N(\geq 2b) = \sum_{l=1}^{N(2b)} \frac{1}{P_l(\geq 2b \to 2b)} = \sum_{l=1}^{N(2b)} \frac{1}{\prod_{j\neq b_1,b_2}^{M_l}(1-\varepsilon_j^l)}$$

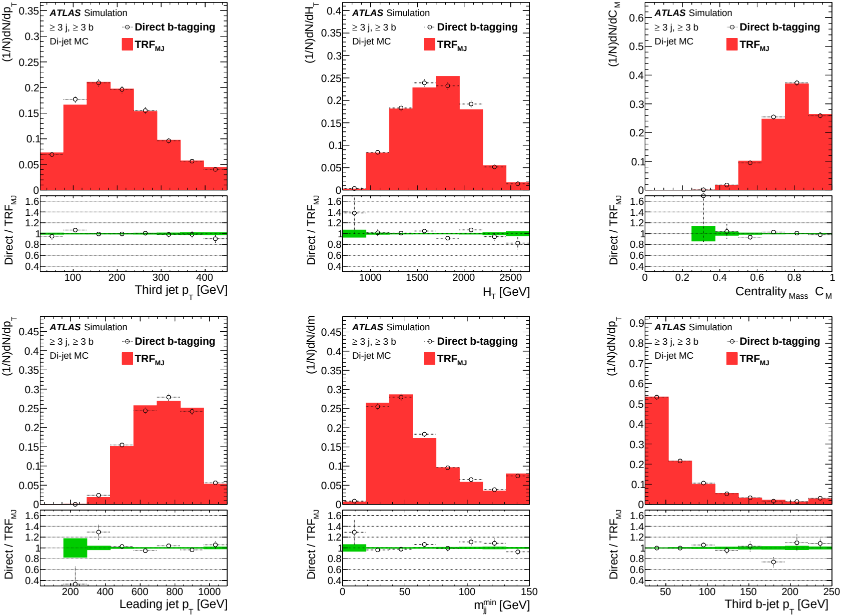
$$\boxed{N(2b+1b)} = \sum_l^{N(2b)} \frac{P_l(\geq 2b \to 2b+1b)}{P_l(\geq 2b \to 2b)} = \boxed{\sum_l^{N(2b)} \frac{P_l(\geq 2b \to 2b+1b)}{P_l(\geq 2b \to 2b)P_l(\geq 2b+1b \to 2b+1b)}}$$

$$\boxed{N(\geq 2b+2b) = \sum_l^{N(2b)} \frac{P_l(\geq 2b \to 2b+1b)P_l(\geq 2b+1b \to \geq 2b+2b)}{P_l(\geq 2b \to 2b)P_l(\geq 2b+1b \to 2b+1b)}}$$

$\mathrm{TRF}_{\mathrm{MJ}}$ validation in data: $\varepsilon_{\mathrm{MJ}}$ evaluation sample



TRF_{MJ} validation in MC: PYTHIA8 di-jet



Boosted Decision Tree

- Boosted Decision Trees (BDT) are trained **one for each fit region**

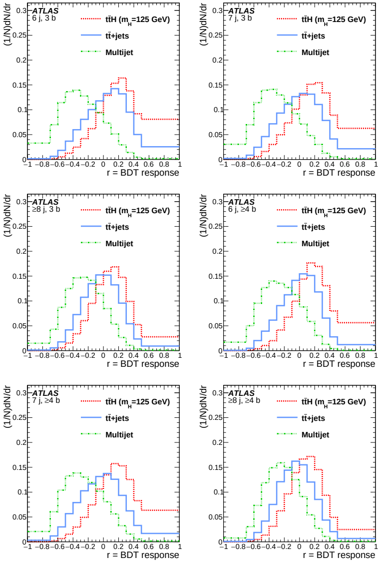
  Signal : $t\bar{t}H$, inclusive in top and Higgs decays

  Background : Multijet + all MC backgrounds

  Input variables selection:

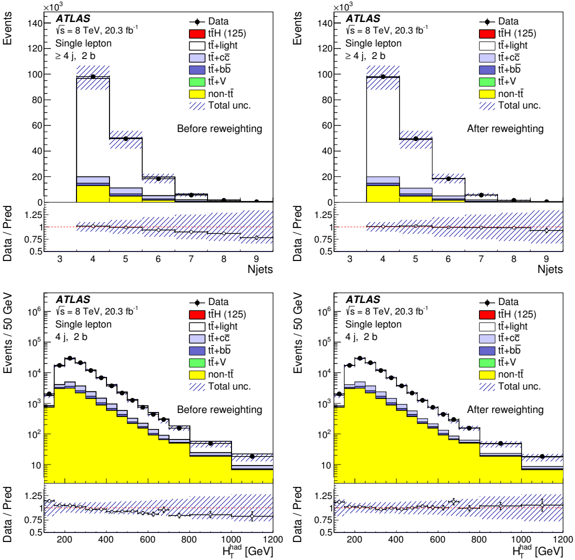
- Start with a pool of interesting variables (~ 35)
- Rank the best variables
  - Iteratively add one variable in the BDT training and select the one giving the best improvement in the discrimination
  - Stop when the addition of more variables does not improve the performance anymore

    - i.e. Reach a plateau in the BDT performance -
  - Roughly 11 variables per region



$t\bar{t}$ modeling – $t\bar{t} + c\bar{c}$ and $t\bar{t}$ + light

- Reweighting function of top-quark p_T and $t\bar{t}$ system p_T
- Based on the ratio of differential cross section at $\sqrt{s} = 7$ TeV in data and simulations
- Common across all $t\bar{t}H$ ($H \to b\bar{b}$) ATLAS analyses



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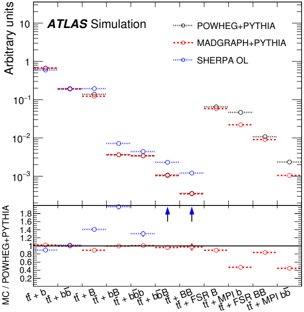
$t\bar{t}$ modeling – $t\bar{t} + b\bar{b}$

- Reweighting of Powheg + Pythia to Sherpa + OpenLoops
- Function of several kinematic variables, like top-quark p_T and p_T of jets not originating from top
- Common across all $t\bar{t}H$ ($H \to b\bar{b}$) ATLAS analyses



Systematic uncertainties:

- Scale variations
- PDF and shower recoil model variations
- Effect of MPI and FSR production mode

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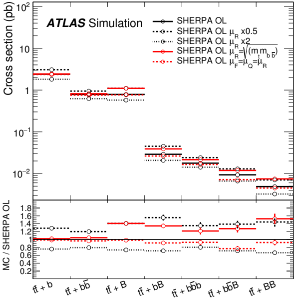
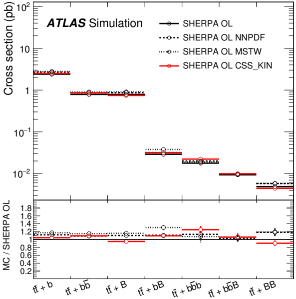




BDT input variables description

Variable	Definition	BDT rank					
		6j, 3b	6j, $\geq$ 4b	7j, 3b	7j, $\geq$ 4b	$\geq$ 8j, 3b	$\geq$ 8j, $\geq$ 4b
$\text{Centrality}_{\text{Mass}}$	Scalar sum of the jet p_{T} divided by the invariant mass of the jets	1	1	1	1	9	6
Aplanarity	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor built with all jets	–	11	–	–	6	–
S_{T}	The modulus of the vector sum of jet p_{T}	2	2	2	4	2	2
$H_{\text{T}\,5}$	Scalar sum of jet p_{T} starting from the fifth jet	8	–	–	7	–	–
m_{jj}^{min}	Smallest invariant mass of any combination of two jets	9	–	6	10	11	12
ΔR^{min}	Minimum ΔR between two jets	6	5	9	–	8	4
$p_{\text{T}}^{\text{softest jet}}$	p_{T} of the softest jet	–	6	10	–	–	10
$\Delta R(b,b)^{p_{\text{T}}^{\text{max}}}$	ΔR between two b-tagged jets with the largest vector sum p_{T}	11	–	7	5	5	3
$m_{bb}^{\Delta R(b,b)^{\text{min}}}$	Invariant mass of the combination of two b-tagged jets with the smallest ΔR	3	3	8	9	3	9
$\frac{E_{\text{T}\,1}+E_{\text{T}\,2}}{\sum E_{\text{T}}^{\text{jets}}}$	Sum of the E_{T} of the two jets with leading E_{T} divided by the sum of the E_{T} of all jets	5	8	4	2	7	5
$m_{2\,\text{jets}}$	The mass of the dijet pair, which, when combined with any b-tagged jet, maximises the magnitude of the vector sum of the p_{T} of the three-jet system	10	–	–	8	–	–
$m_{2\,\text{b-jets}}$	The invariant mass of the two b-tagged jets which are selected by requiring that the invariant mass of all the remaining jets is maximal	12	7	–	6	–	8
$m_{\text{top},1}$	Mass of the reconstructed top quark	13	10	–	–	4	11
$m_{\text{top},2}$	Mass of the reconstructed top quark calculated from the jets not entering $m_{\text{top},1}$	7	9	5	–	10	7
Λ	The logarithm of the ratio of event probabilities under the signal and background hypotheses	4	4	3	3	1	1

List of systematic uncertainties

Systematic uncertainty source	Type	Number of components
Luminosity	N	1
Trigger	SN	1
Physics Objects		
Jet energy scale	SN	21
Jet vertex fraction	SN	1
Jet energy resolution	SN	1
b-tagging efficiency	SN	7
c-tagging efficiency	SN	4
Light-jet tagging efficiency	SN	12
Background MC Model		
$t\bar{t}$ cross section	N	1
$t\bar{t}$ modelling: p_{T} reweighting	SN	9
$t\bar{t}$ modelling: parton shower	SN	3
$t\bar{t}$+heavy-flavour: normalisation	N	2
$t\bar{t}+c\bar{c}$: heavy-flavour reweighting	SN	2
$t\bar{t}+c\bar{c}$: generator	SN	4
$t\bar{t}+b\bar{b}$: NLO Shape	SN	8
$t\bar{t}V$ cross section	N	1
$t\bar{t}V$ modelling	SN	1
Single top cross section	N	1
Data driven background		
Multijet normalisation	N	6
Multijet $\mathrm{TRF}_{\mathrm{MJ}}$ parameterisation	S	6
Multijet H_{T} correction	S	1
Multijet S_{T} correction	S	1
Signal Model		
$t\bar{t}H$ scale	SN	2
$t\bar{t}H$ generator	SN	1
$t\bar{t}H$ hadronisation	SN	1
$t\bar{t}H$ parton shower	SN	1

Impact of systematic uncertainties on μ

Sources of systematic uncertainty	$\pm 1\sigma$ post-fit impact on μ
$t\bar{t}$ normalisation	108%
Multijet normalisation	71%
Multijet shape	60%
Main contributions from $t\bar{t}$ modelling	34%–41%
Flavour tagging	31%
Jet energy scale	27%
Signal modelling	22%
Luminosity+trigger+JVF+JER	18%

- Effect of main systematic uncertainties on the fitted value of $\mu = \frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}}$

Pre- and post-fit event yields

Pre-fit

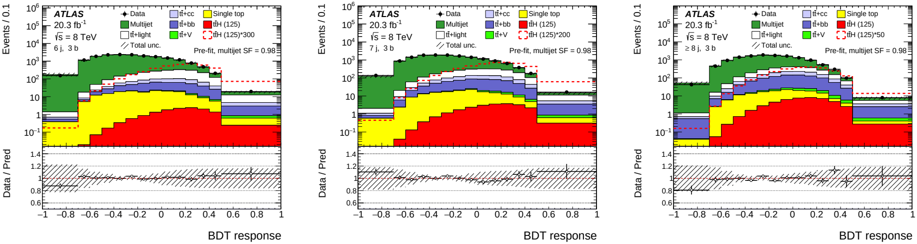
	6j,3b	6j,≥4b	7j,3b	7j,≥4b	≥8j,3b	≥8j,≥4b
Multijet	16380 ± 130	1112 ± 33	12530 ± 110	1123 ± 34	10670 ± 100	1324 ± 36
$t\bar{t}+b\bar{b}$	330 ± 180	44 ± 26	490 ± 270	87 ± 51	760 ± 450	190 ± 110
$t\bar{t}+c\bar{c}$	280 ± 180	17 ± 12	390 ± 240	21 ± 15	560 ± 350	48 ± 33
$t\bar{t}$+light	1530 ± 390	48 ± 18	1370 ± 430	45 ± 18	1200 ± 520	40 ± 23
$t\bar{t}+V$	14.2 ± 6.3	1.8 ± 1.5	22.0 ± 9.0	3.5 ± 2.3	40 ± 15	8.0 ± 4.2
single top	168 ± 63	6.0 ± 3.7	139 ± 55	8.3 ± 4.6	110 ± 49	10.6 ± 5.9
Total bkg.	18700 ± 480	1229 ± 48	14940 ± 580	1288 ± 66	13330 ± 780	1620 ± 130
$t\bar{t}H$ (125)	14.3 ± 4.6	3.3 ± 2.1	23.7 ± 6.4	7.2 ± 3.3	48 ± 11	16.8 ± 6.1
Data	18508	1545	14741	1402	13131	1587

Post-fit

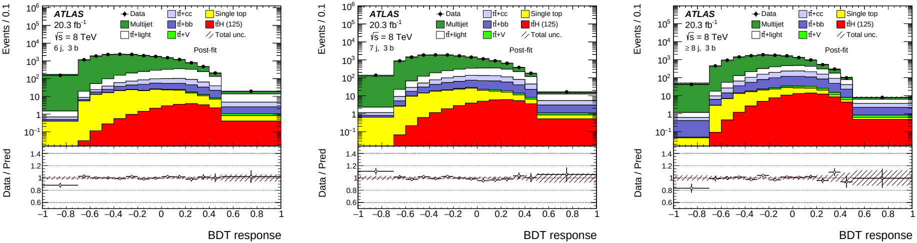
	6j,3b	6j,≥4b	7j,3b	7j,≥4b	≥8j,3b	≥8j,≥4b
Multijet	15940 ± 320	1423 ± 66	12060 ± 350	1233 ± 78	10020 ± 490	1280 ± 100
$t\bar{t}+b\bar{b}$	230 ± 120	31 ± 17	350 ± 190	63 ± 34	560 ± 320	139 ± 75
$t\bar{t}+c\bar{c}$	350 ± 170	22 ± 11	490 ± 240	28 ± 14	750 ± 360	66 ± 33
$t\bar{t}$+light	1750 ± 270	55 ± 13	1650 ± 340	54 ± 15	1550 ± 450	54 ± 21
$t\bar{t}+V$	15.0 ± 6.2	1.9 ± 1.5	23.3 ± 8.9	3.6 ± 2.2	43 ± 15	8.7 ± 4.2
single top	184 ± 59	6.7 ± 3.6	153 ± 52	9.4 ± 4.4	123 ± 48	11.8 ± 5.8
Total bkg.	18470 ± 320	1539 ± 58	14720 ± 320	1391 ± 69	13030 ± 340	1561 ± 63
$t\bar{t}H$ (125)	23.4 ± 6.3	5.6 ± 2.8	39.1 ± 8.9	11.9 ± 4.5	71 ± 15	28.8 ± 8.5
Data	18508	1545	14741	1402	13131	1587

Pre- / post-fit data-bkg agreement – BDT

Pre-fit

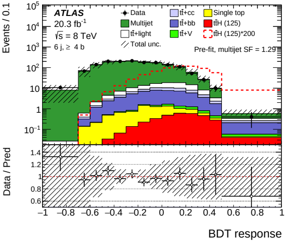


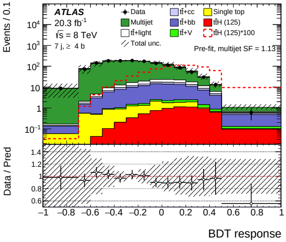
Post-fit

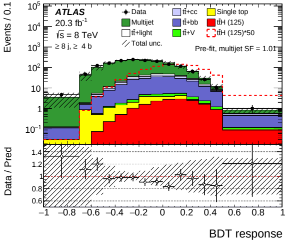


Pre- / post-fit data-bkg agreement – BDT

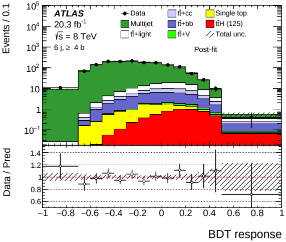
Pre-fit

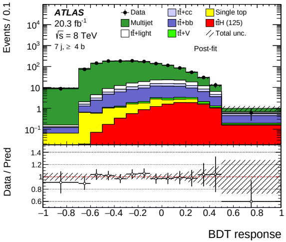


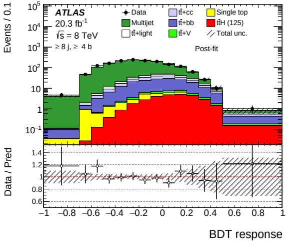




Post-fit

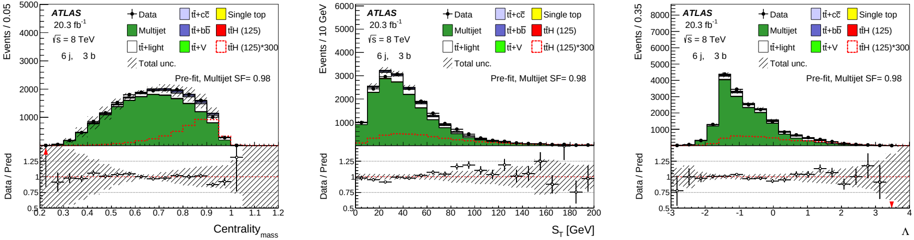




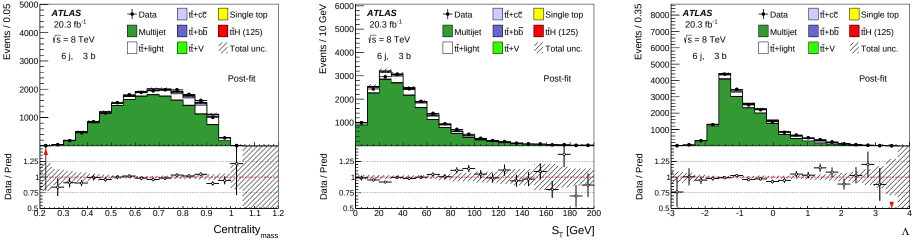


Pre- / Post-fit variables comparison: 6j, 3b

Pre-fit

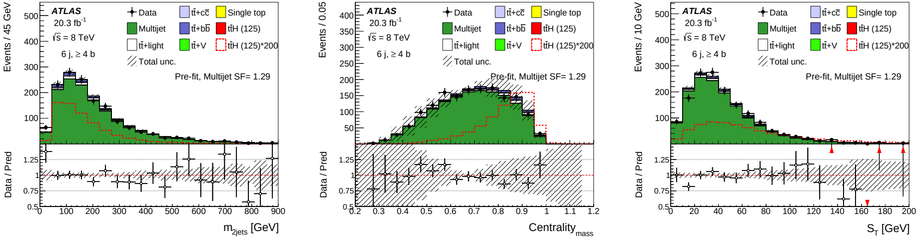


Post-fit

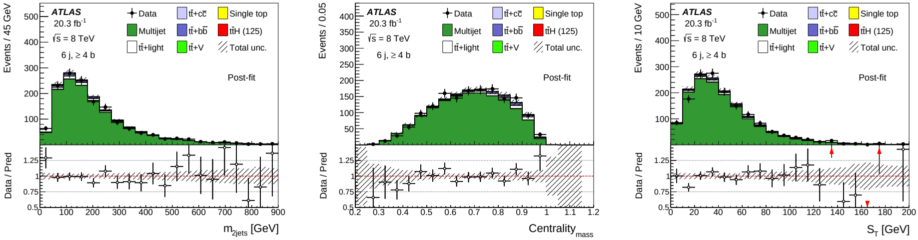


Pre- / Post-fit variables comparison: 6j, ≥4b

Pre-fit

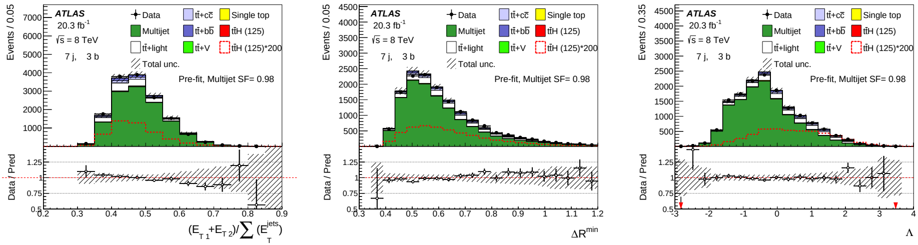


Post-fit

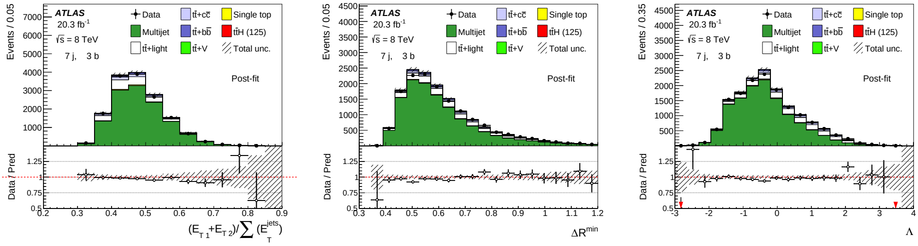


Pre- / Post-fit variables comparison: 7j, 3b

Pre-fit

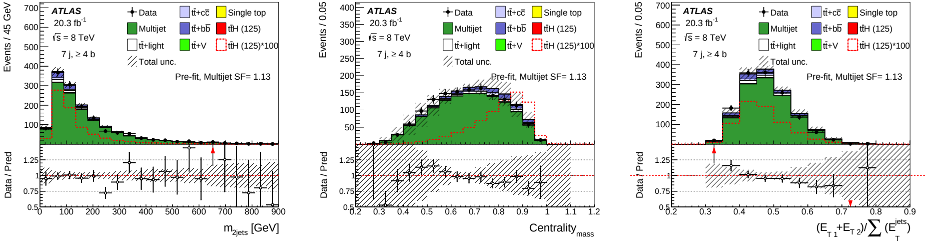


Post-fit

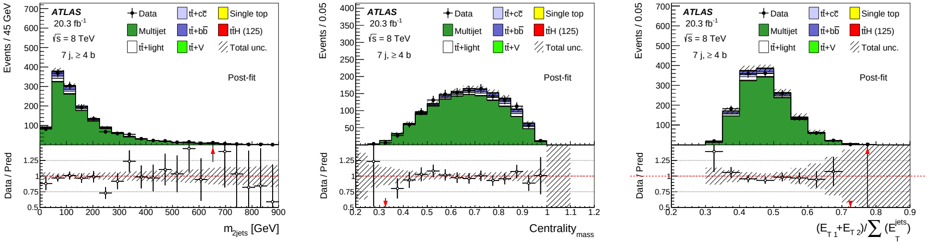


Pre- / Post-fit variables comparison: 7j, ≥4b

Pre-fit

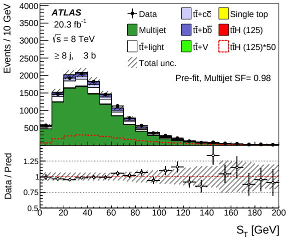


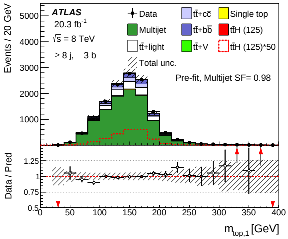
Post-fit

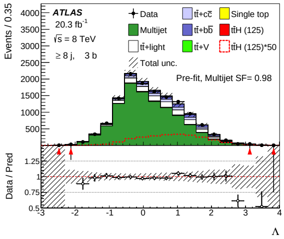


Pre- / Post-fit variables comparison: ≥8j, 3b

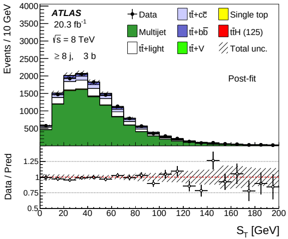
Pre-fit

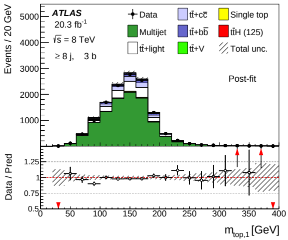


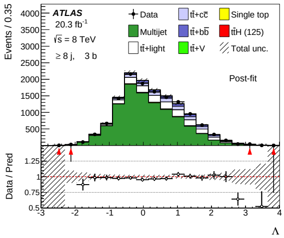




Post-fit

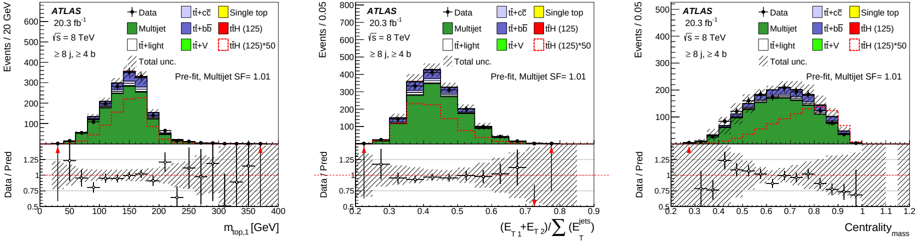






Pre- / Post-fit variables comparison: ≥8j, ≥4b

Pre-fit



Post-fit