Application of the matrix element method in the search for ttH, H→bb in the lepton+jets channel, using the ATLAS detector

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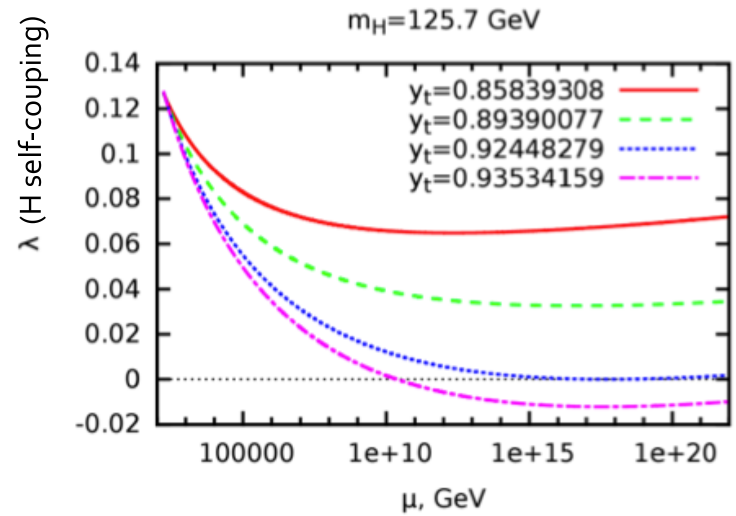
Theoretical Motivation

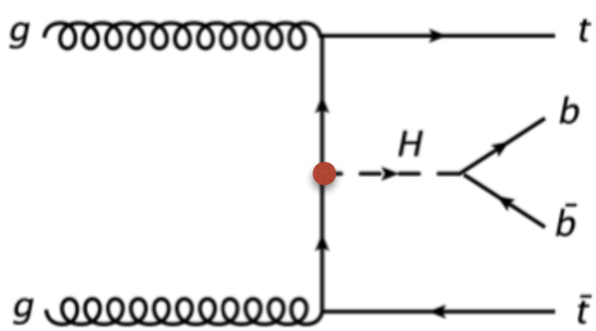
[J.Exp.Theor.Phys. 120 (2015) 3, 335-343; ZhETF 147 (2015) 3, 389]

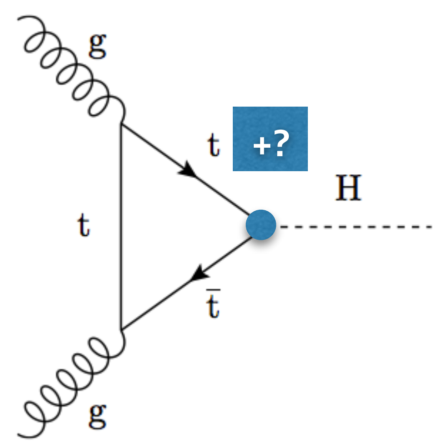
Why ttH?

- Measurement of Higgs properties.
- The top Yukawa coupling (**Y_t**) is approximately unity.
  - EW vacuum stability in SM.
  - Probing this value can provide information of the scale of New Physics.



- This search provides a direct measurement of **Y_t**.
  - Leading order tree diagram.
  - $\boldsymbol{\sigma}_{ttH} \propto |\mathbf{Y_t}|^2$
  - Required to constrain NP contributions in indirect searches (ggF, H→γγ) in a model-independent way.

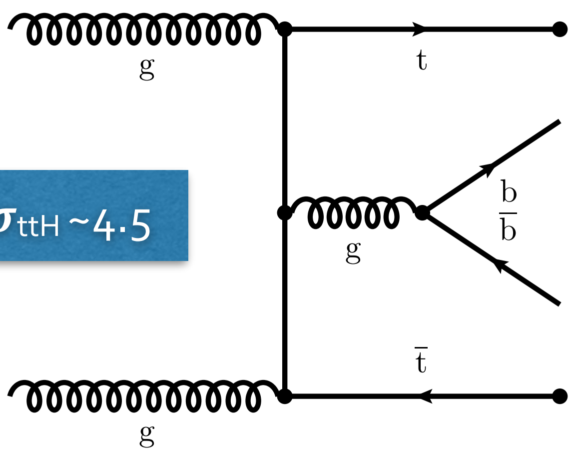




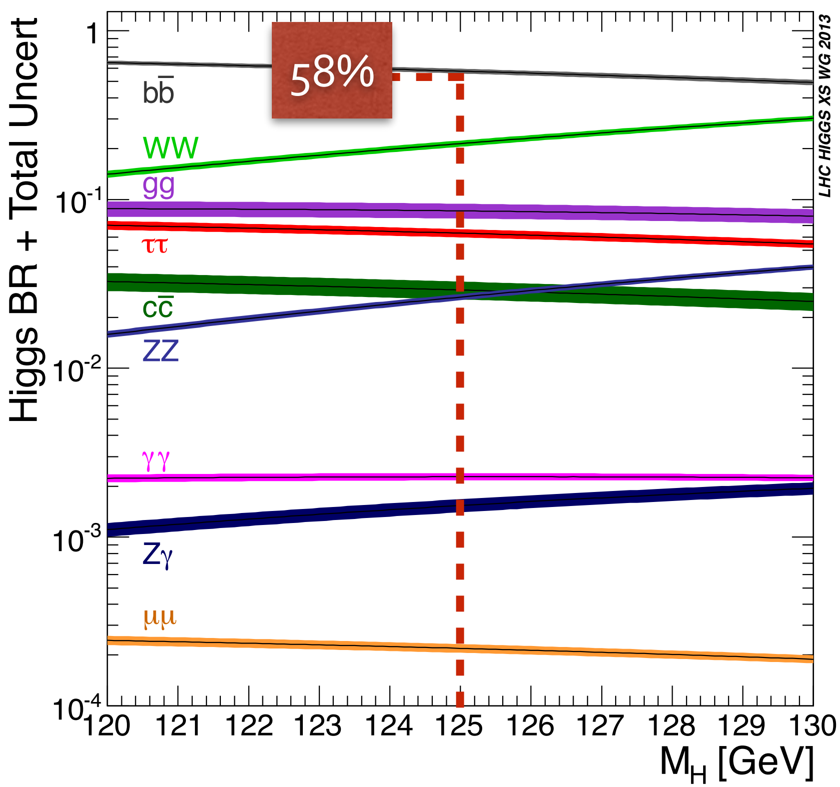
Theoretical Motivation

Why H→bb?

- ttH is largely suppressed at the LHC compared to alternative production modes
  - 129.3 fb @ 8 TeV (5.8% of total Higgs cross-section).
  - Expected ~2600 events in 8 TeV dataset.
- Largest BR of m_H = 125 GeV Higgs is H→bb
  - Provides the most events for single decay signature.
- tt+X provides dominant background processes.
  - ~2000 times larger cross-section.



$\sigma_{tt+bb}/\sigma_{ttH}$ ~4.5



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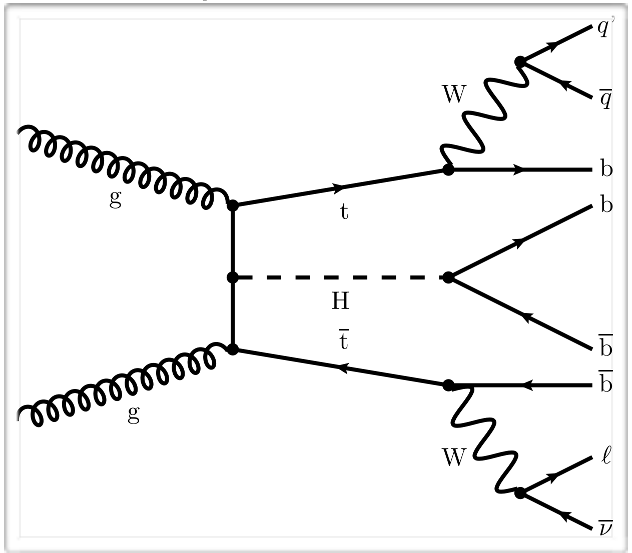
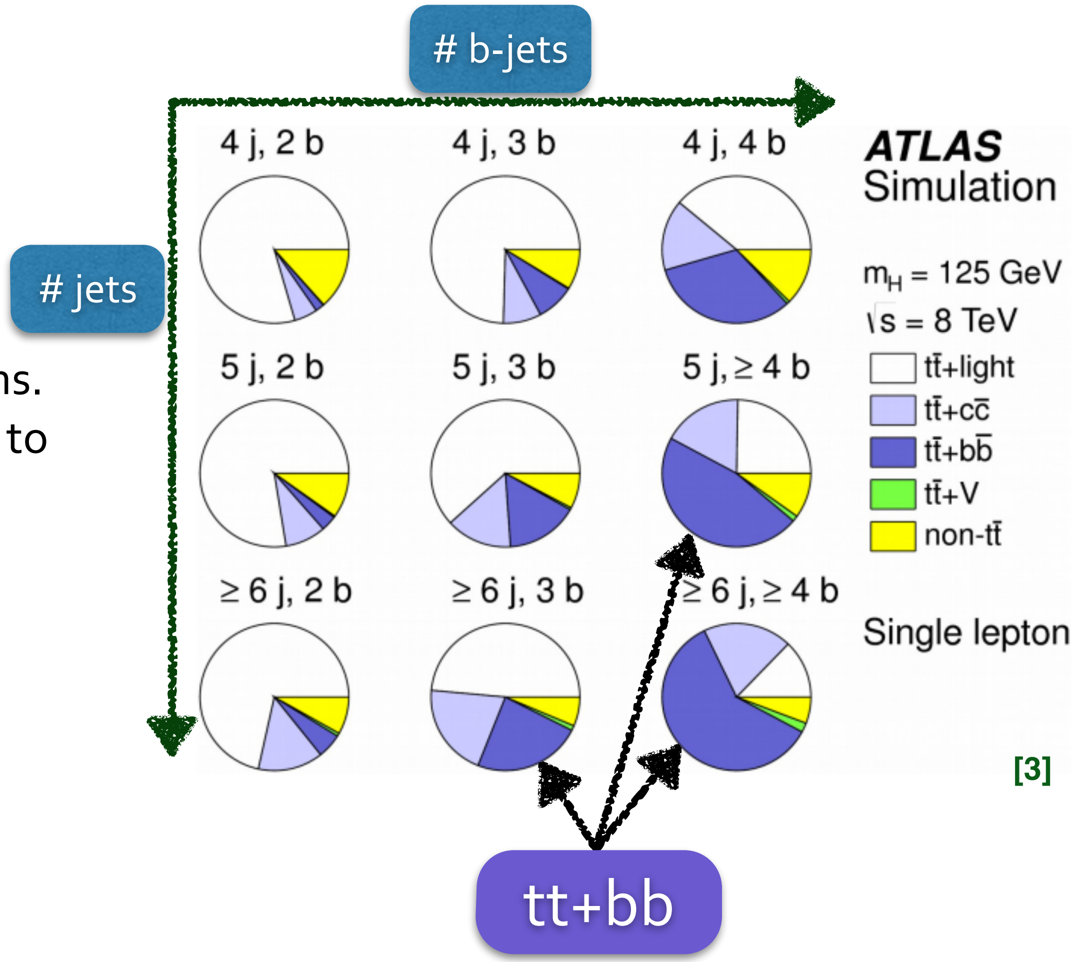
Analysis Overview

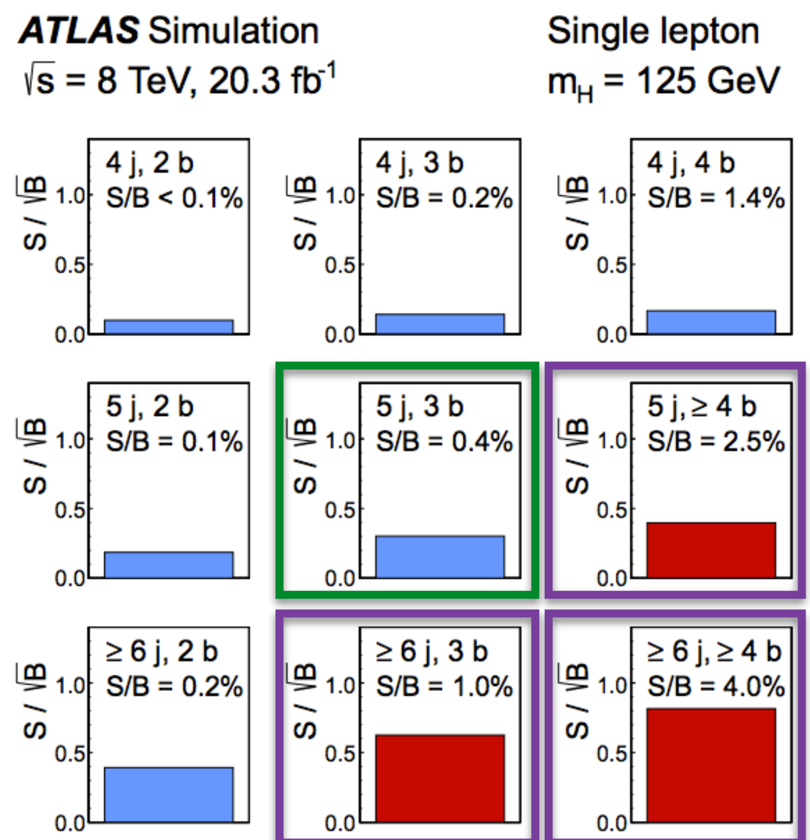
- Event selection
  - 1 isolated lepton (pT > 25 GeV)
  - at least 4 jets (pT > 25 GeV)
  - at least 2 b-tagged jets

- Events are categorised by the number of jets and the number of b-jets.
  - Different background compositions.
  - Profiled likelihood fit to data used to contain systematic uncertainties.





- Signal-rich regions
  - S/B > 1% and S/√B > 0.3
  - Large tt+bb background in these regions
- Neural networks trained to separate signal and background processes.
  - Additional network used to separate tt+heavy flavour from tt+light flavour.



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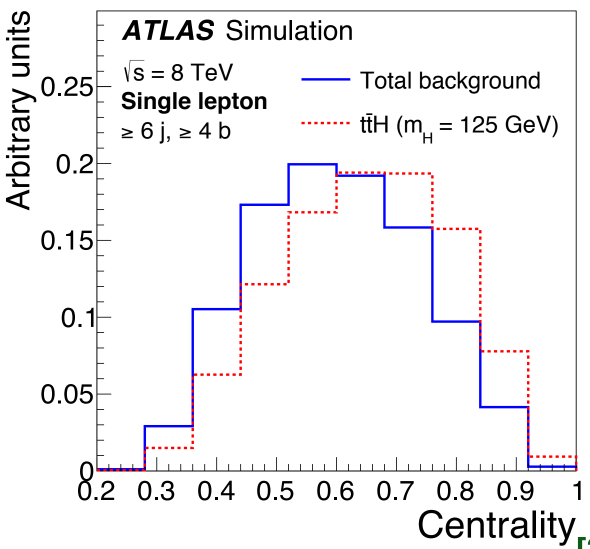
Event and object kinematic variables used to discriminate ttH from tt+jets.



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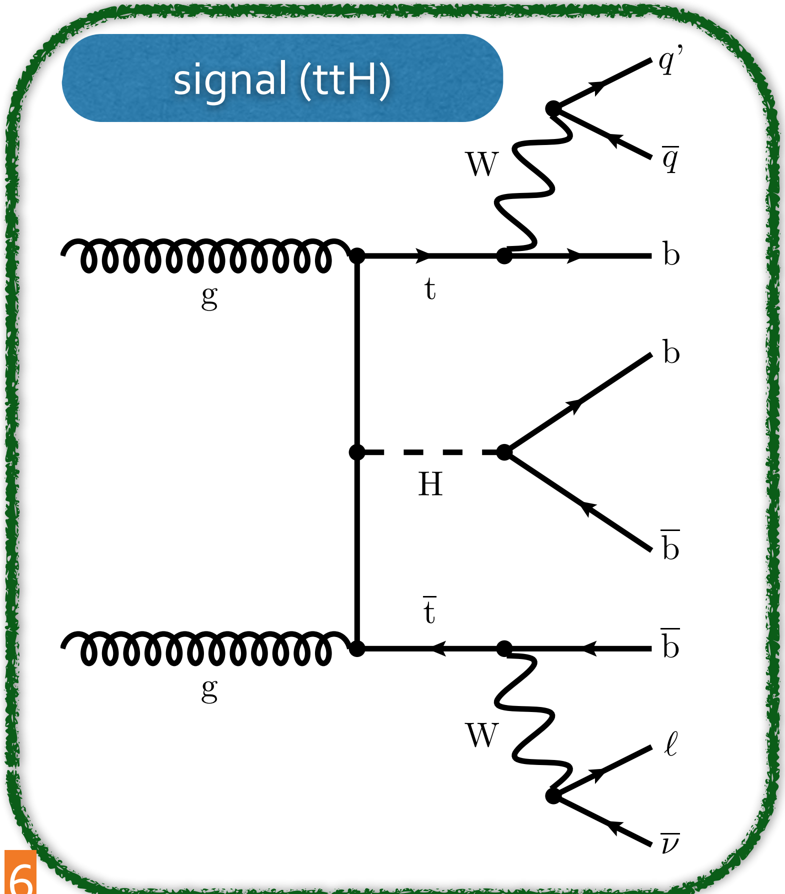
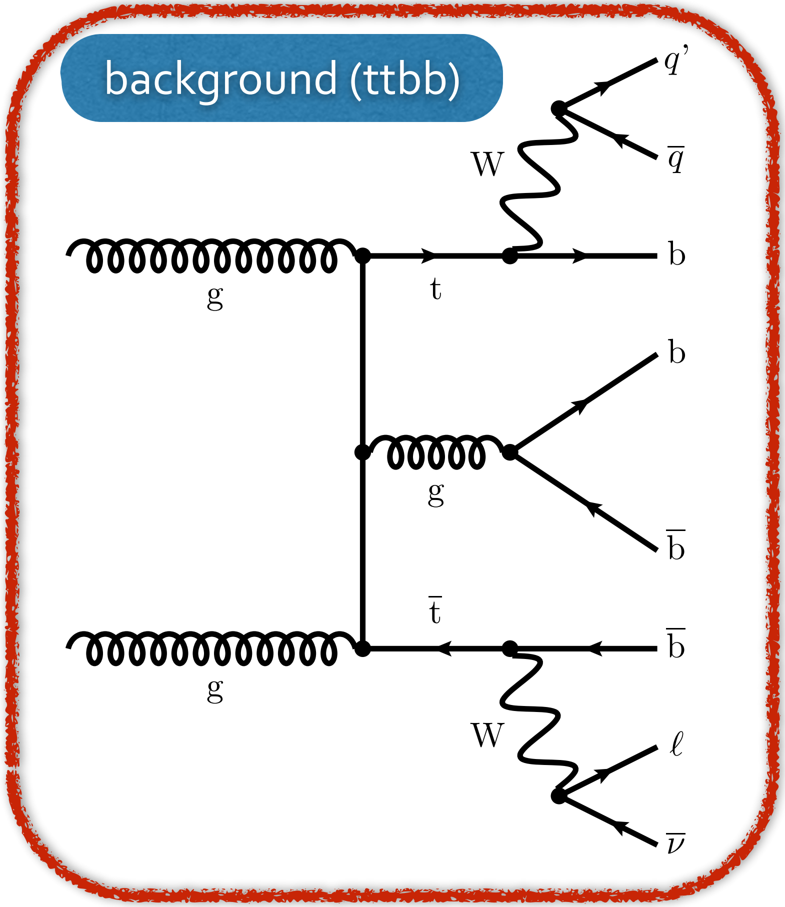
The Matrix Element Method

- Determines the probability of the data under a hypothesis.
  - Test two hypotheses (H) : ttH (signal) and ttbb (background).





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- Determines the probability of the data under a hypothesis.
  - Test two hypotheses (H) : ttH (signal) and ttbb (background).
- The matrix element method links a set of measured quantities (**x**, e.g. b-jet energy) with a set of unobservable partonic objects (**y**, e.g. b-quark energy) associated to a hypothesised process.
  - **α** parameterises the theoretical model.

$$P(\boldsymbol{x}|H,\boldsymbol{\alpha}) = \underbrace{\frac{(2\pi)^4}{\sigma_i^{\exp(\boldsymbol{\alpha})}}}_{\text{Normalisation}} \int \underbrace{dp_A(\boldsymbol{y})\,dp_B(\boldsymbol{y})\,f(p_A)\,f(p_B)}_{\text{PDFs}} \underbrace{\frac{|\mathcal{M}(\boldsymbol{y}|H,\boldsymbol{\alpha})|^2}{\mathcal{F}}}_{\text{Transition matrix element}} \underbrace{W(\boldsymbol{x}|\boldsymbol{y})}_{\text{Transfer functions (TF)}} \underbrace{d\Phi_N(\boldsymbol{y})}_{\text{Phase space volume element}}$$

Integration Strategy

$$P(\mathbf{x}|H,\boldsymbol{\alpha}) = \frac{(2\pi)^4}{\sigma_i^{\exp(\boldsymbol{\alpha})}} \int dp_A(\mathbf{y})\,dp_B(\mathbf{y})\, f(p_A) f(p_B) \frac{|\mathcal{M}(\mathbf{y}|H,\boldsymbol{\alpha})|^2}{\mathcal{F}} W(\mathbf{x}|\mathbf{y})\, d\Phi_N(\mathbf{y})$$

2 partons

4 b-quarks
2 light quarks
1 lepton
1 neutrino

- Each object contributes three degrees of freedom.
  - Nominally 30-dimensional integration
- Approximations used to reduce this to an 6-dimensional integration.
  - Analytic initial state kinematics.
  - Jet directions are well-measured (TF = delta function).
  - Lepton four-vectors are well-measured (TF = delta function).
  - MET interpreted as neutrino p_T measurement.

Integration Strategy

$$P(\mathbf{x}|H,\boldsymbol{\alpha}) = \frac{(2\pi)^4}{\sigma_i^{\exp(\boldsymbol{\alpha})}} \int dp_A(\mathbf{y})\,dp_B(\mathbf{y})\,f(p_A)\,f(p_B)\,\frac{|\mathcal{M}(\mathbf{y}|H,\boldsymbol{\alpha})|^2}{\mathcal{F}}\,W(\mathbf{x}|\mathbf{y})\,d\Phi_N(\mathbf{y})$$

- Integration strategy :

Dijet pair	bb mass	leading b-quark energy
Top decays	b-quark energy	b-quark energy
Hadronic W	W mass	leading light-quark
Leptonic W	Neutrino p	

- Indistinguishable objects in **x** are permuted with their counterparts in **y**.
  - ≥ 6j, ≥ 4b - 12 permutations.
  - ≥ 6j, 3b - 36 permutations.

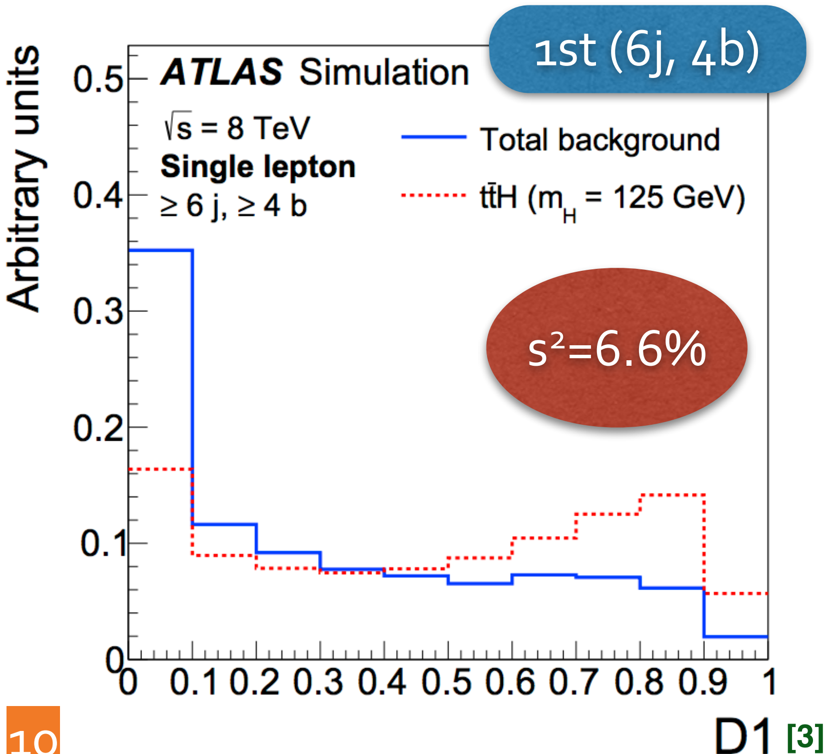
- Per-event integration time : O(1-2 minutes).
  - Feasible for large, complex analysis such as ttH.

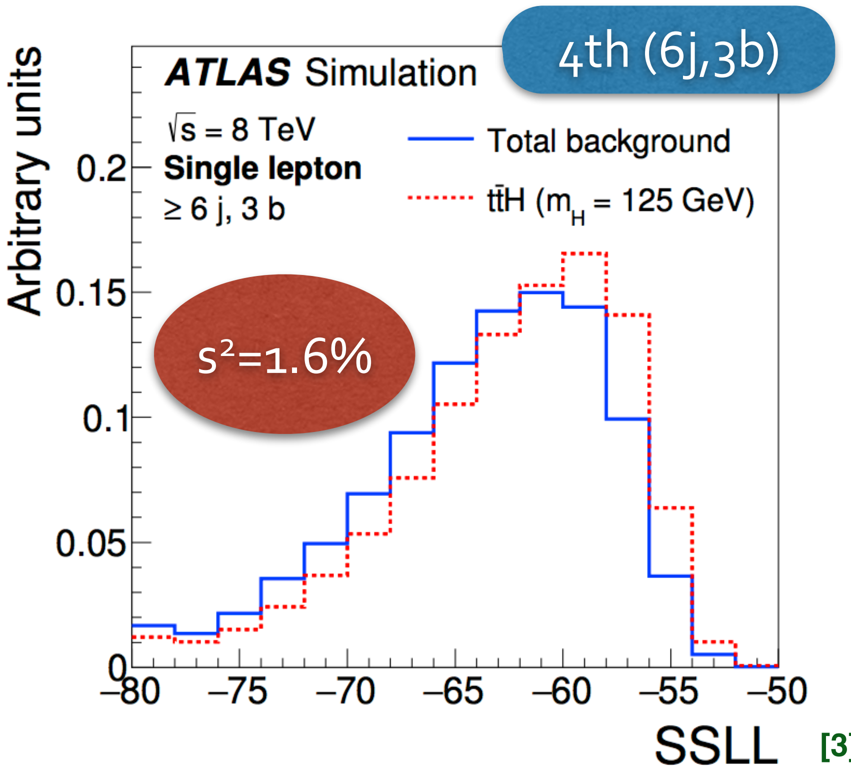
- Two variables constructed using matrix element method.
  - **D1** : Monotonic Neyman-Pearson likelihood ratio.
  - **SSLL** : Logarithm of **Σ**P(**x**|S).

$$D_1 = \frac{P(\mathbf{x}|\mathrm{S})}{P(\mathbf{x}|\mathrm{S}) + \alpha P(\mathbf{x}|\mathrm{B})}$$

- Included in the set of neural network input variables.
  - Very discriminating and ranked highly by NN training.

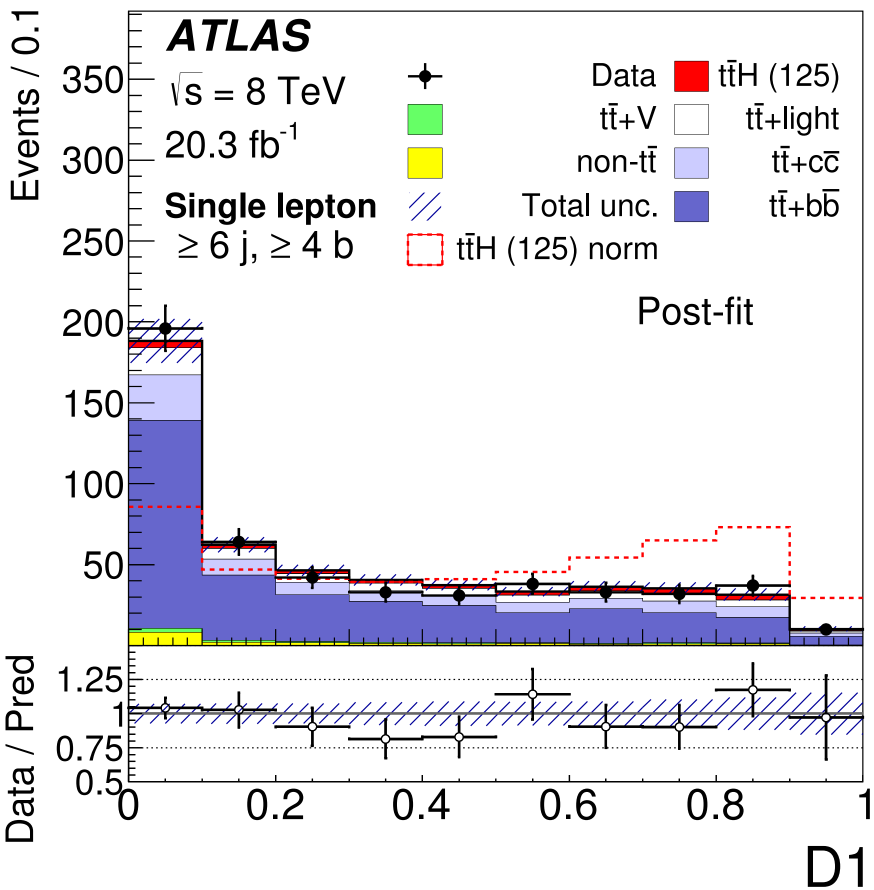
$$\langle s^2 \rangle = \frac{1}{2} \int_{-\infty}^{\infty} \frac{(S(x) - B(x))^2}{S(x) + B(x)} \mathrm{d}x$$

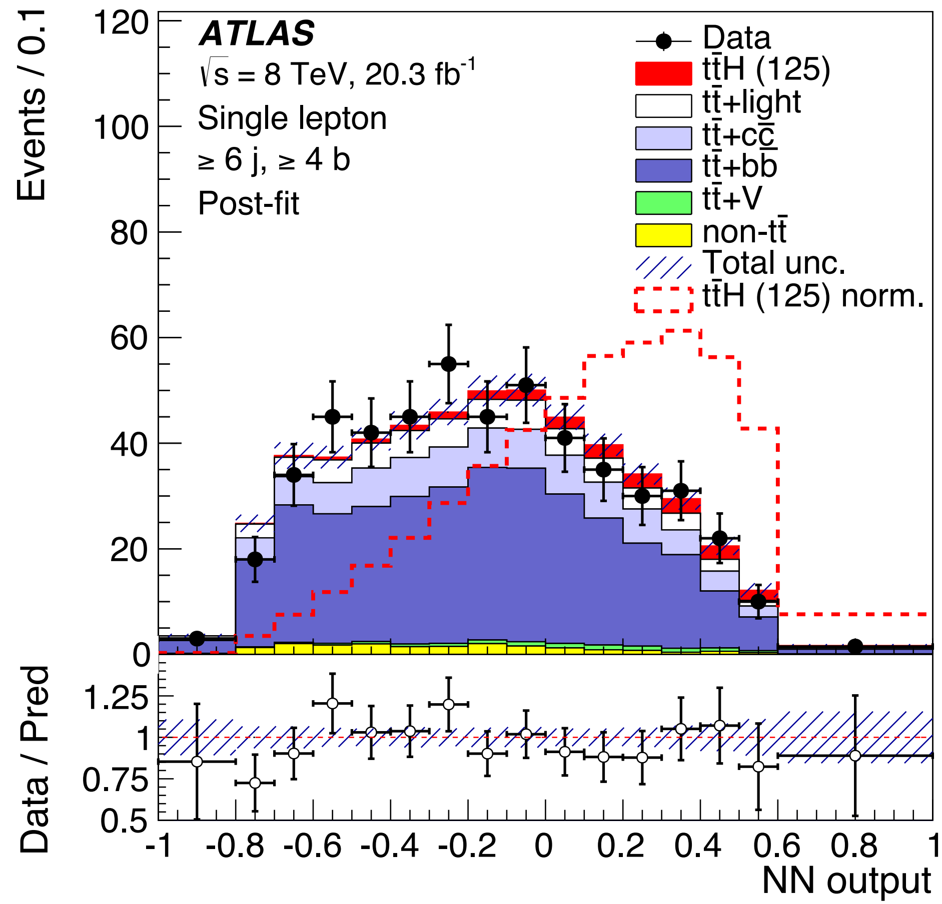




Post-Fit Neural Network

Well-modelled MEM variables and final NN output after fitting to data.

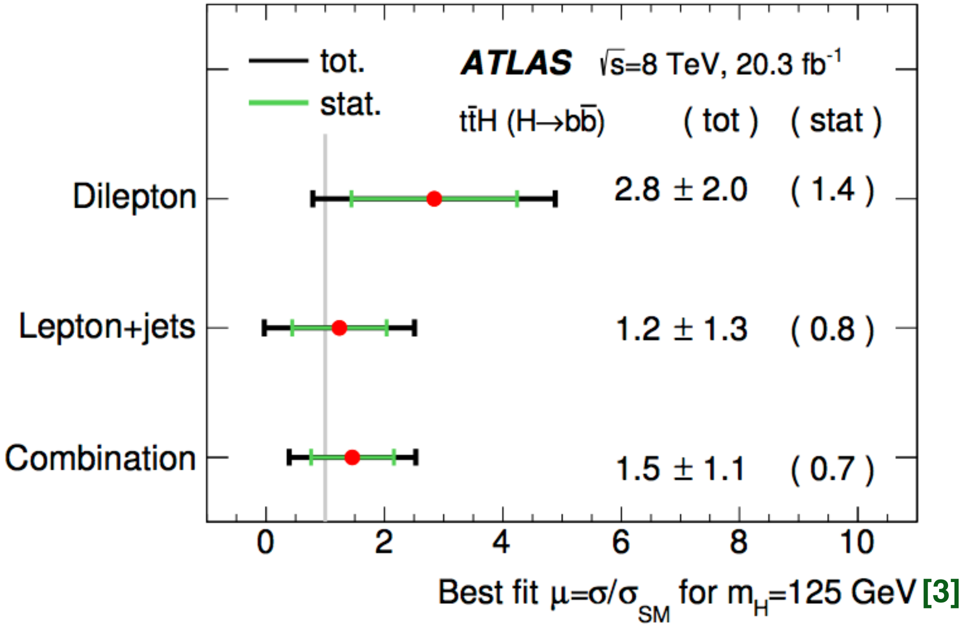


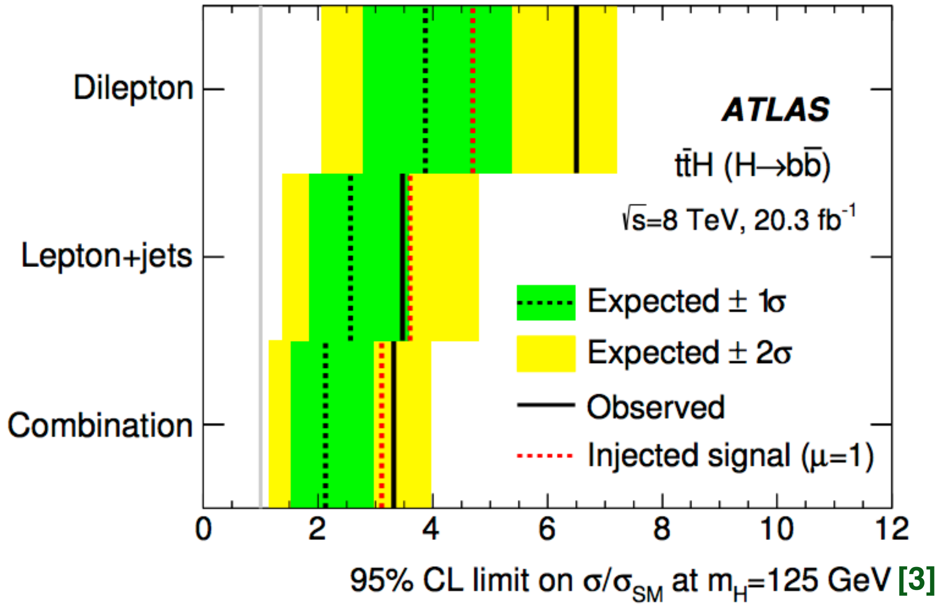


Analysis Results

- Statistical combination of the lepton+jets and dilepton analyses.
  - Approaching SM sensitivity.

$\mu = \sigma/\sigma_{SM}$





Summary

- Successful Run 1 results
  - $\boldsymbol{\mu_{obs} = 1.5 \pm 1.1}$.
  - Exclude $\boldsymbol{\mu > 3.4}$ (2.2 expected) at 95% CL_S.
  - Included in ATLAS Higgs coupling combination.

- A highly complex analysis has been carried out in the search for ttH($H \rightarrow bb$).
  - Many advanced data-analysis techniques used - focussed here on MEM.
    - Success of the analysis highly dependent on modelling ttbar processes.
  - Statistical combination of single lepton and dilepton channels.
  - Inclusion of MEM improved expected limit by **16%**.
    - Studies indicate similar performance gain possible in dilepton analysis.

- Looking at Run 2
  - Enough data to make an observation?
    - Sophisticated techniques like MEM required to maximise performance.
      - Work is on-going for MEM in Run 2.
  - Hopefully reach SM sensitivity!

References

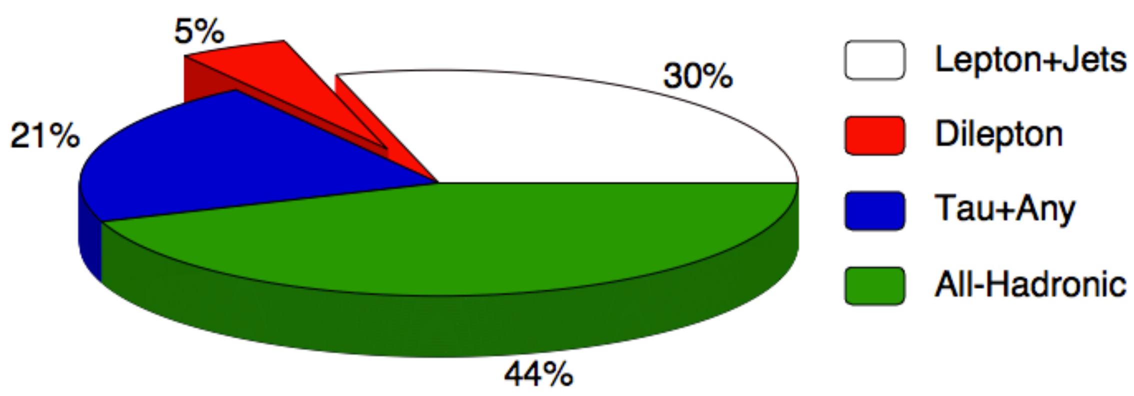
(1) [J.Exp.Theor.Phys. 120 (2015) 3, 335-343; ZhETF 147 (2015) 3, 389]
(2) [LHCHXSWG]
(3) [Eur. Phys. J. C (2015) 75:349]
(4) [ATLAS-CONF-2014-011]

Backup

Theoretical Motivation

ttH events can also be categorised by the top-quark pair decay.

- Leptonic (e/μ) decays provide clean/ well-understood trigger objects.
    - ~450 expected signal events in 8 TeV dataset.

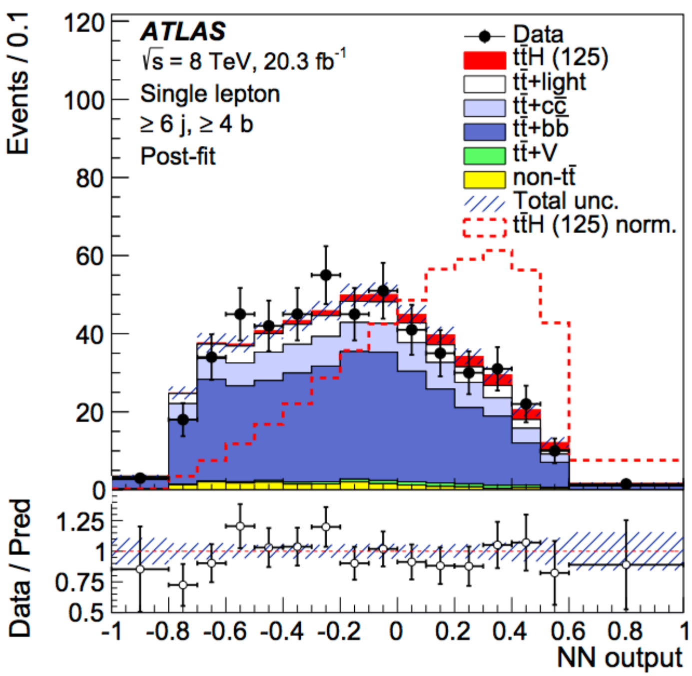


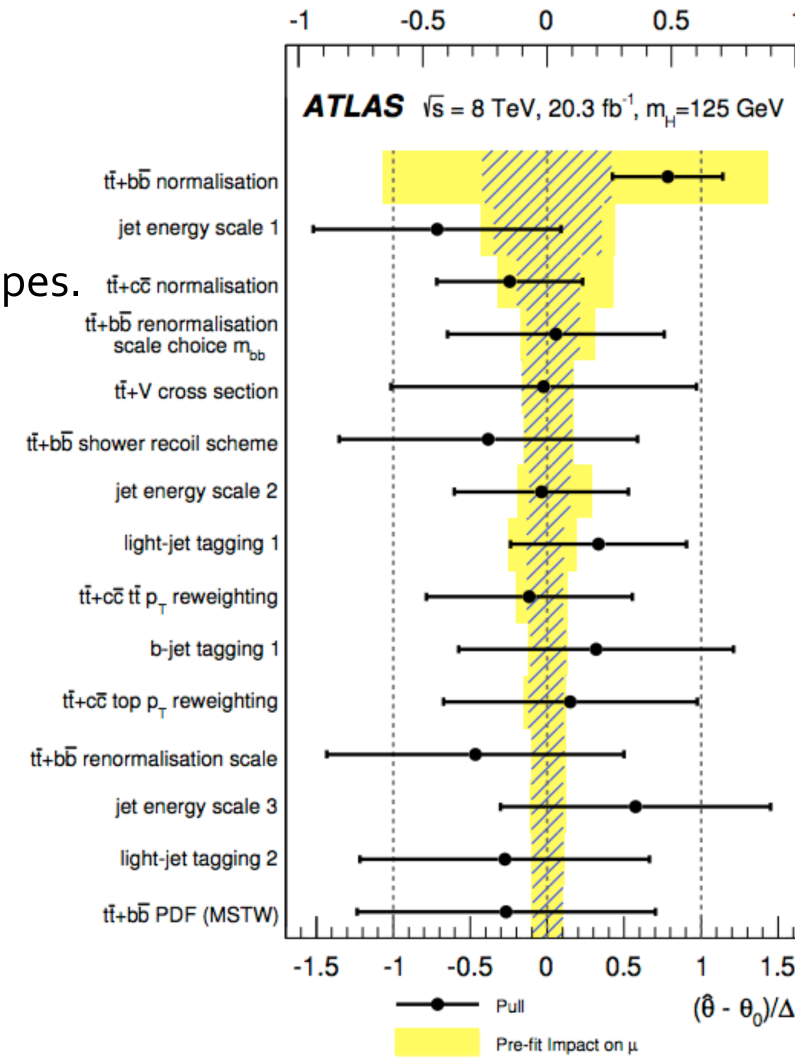
MEM Details

- MEMTool
  - Modular design to allow user flexibility
  - ME generated by MadGraph 5 (standalone, C++)
  - Numerical integration performed by VEGAS (GSL 1.16)
  - PDFs from LHAPDF 5.9.1 (CTEQ 6 parameterisation)

Simultaneous Fit

- Binned profiled likelihood fit used to constrain systematic uncertainties (θ).
- Parameter of interest : $\mu = \boldsymbol{\sigma}_{obs} / \boldsymbol{\sigma}_{ttH}$
- Simultaneous fit over all analysis categories.
  - Requires good modelling of background shapes.
  - Requires background-only regions to fit dominant backgrounds to data.





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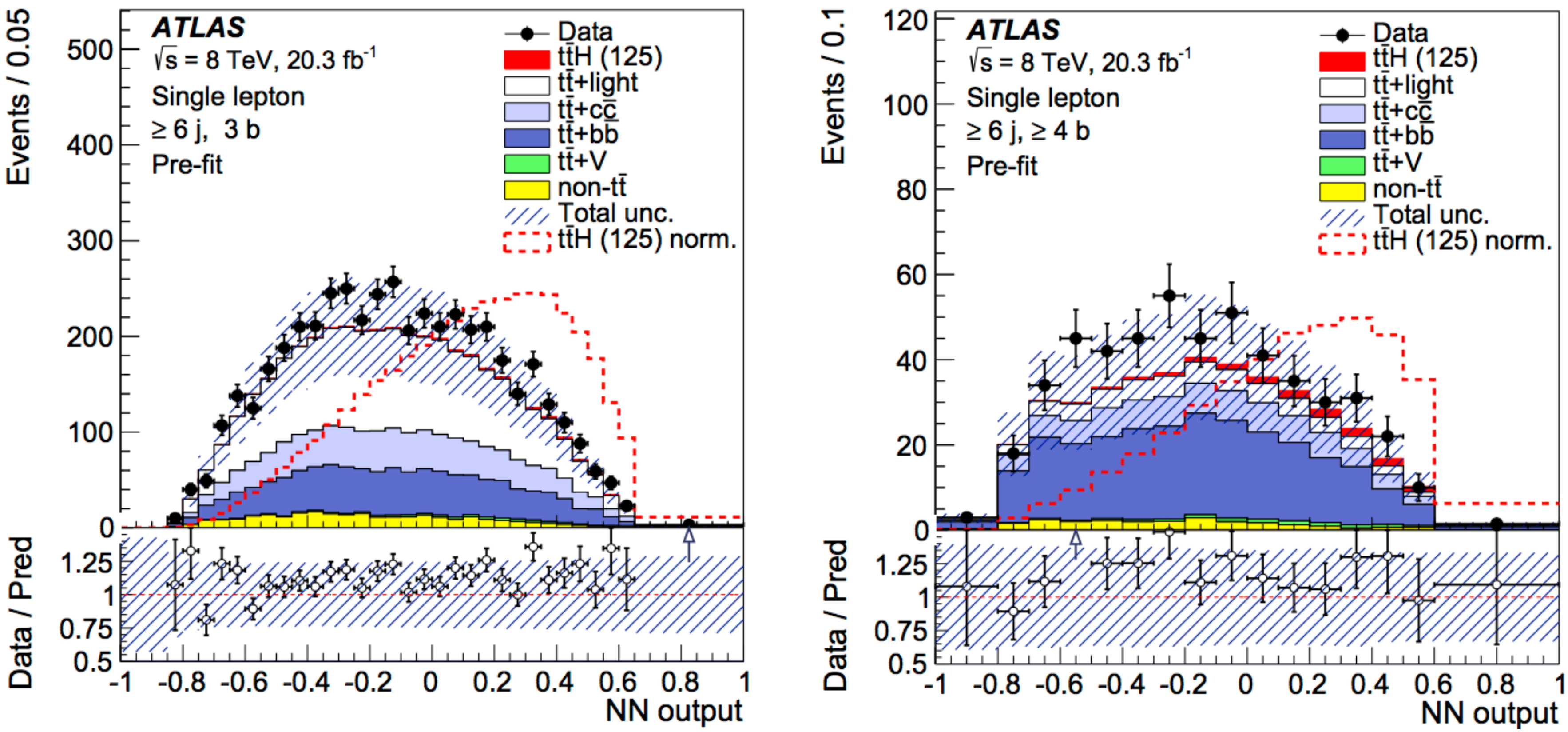
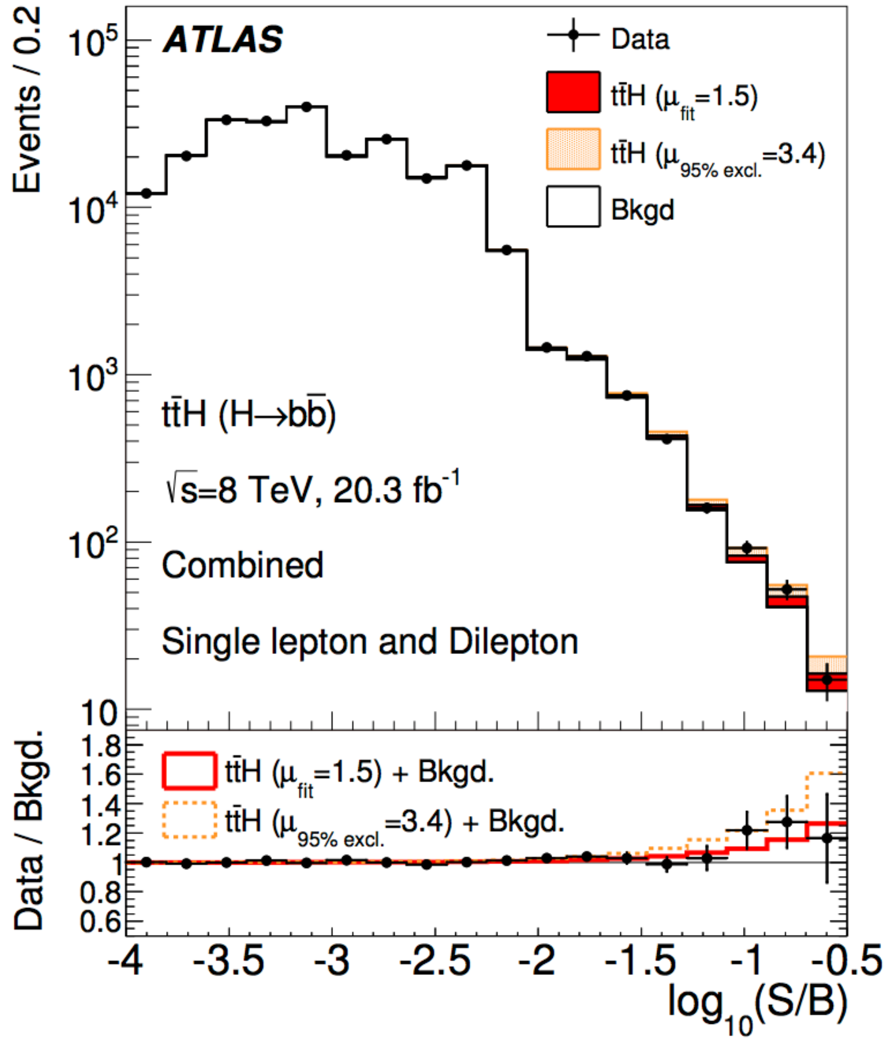

ATLAS
√s = 8 TeV, 20.3 fb-1
Single lepton
≥ 6 j, 3 b
Pre-fit
Data
tt̄H (125)
tt̄+light
tt̄+cc̄
tt̄+bb̄
tt̄+V
non-tt̄
Total unc.
tt̄H (125) norm.
Events / 0.05
Data / Pred
NN output
ATLAS
√s = 8 TeV, 20.3 fb-1
Single lepton
≥ 6 j, ≥ 4 b
Pre-fit
Events / 0.1
Data / Pred
NN output

[3]

Analysis Results



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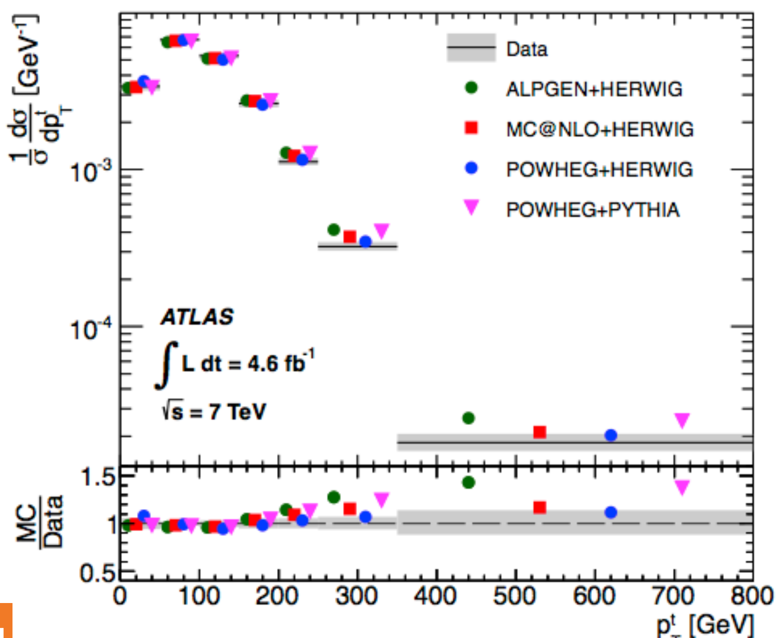
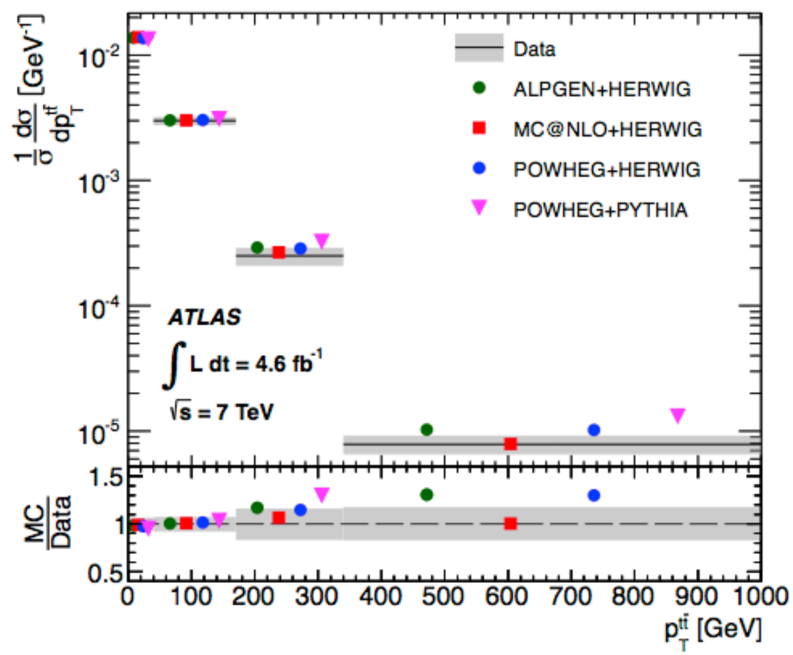
Signal and Background Modelling

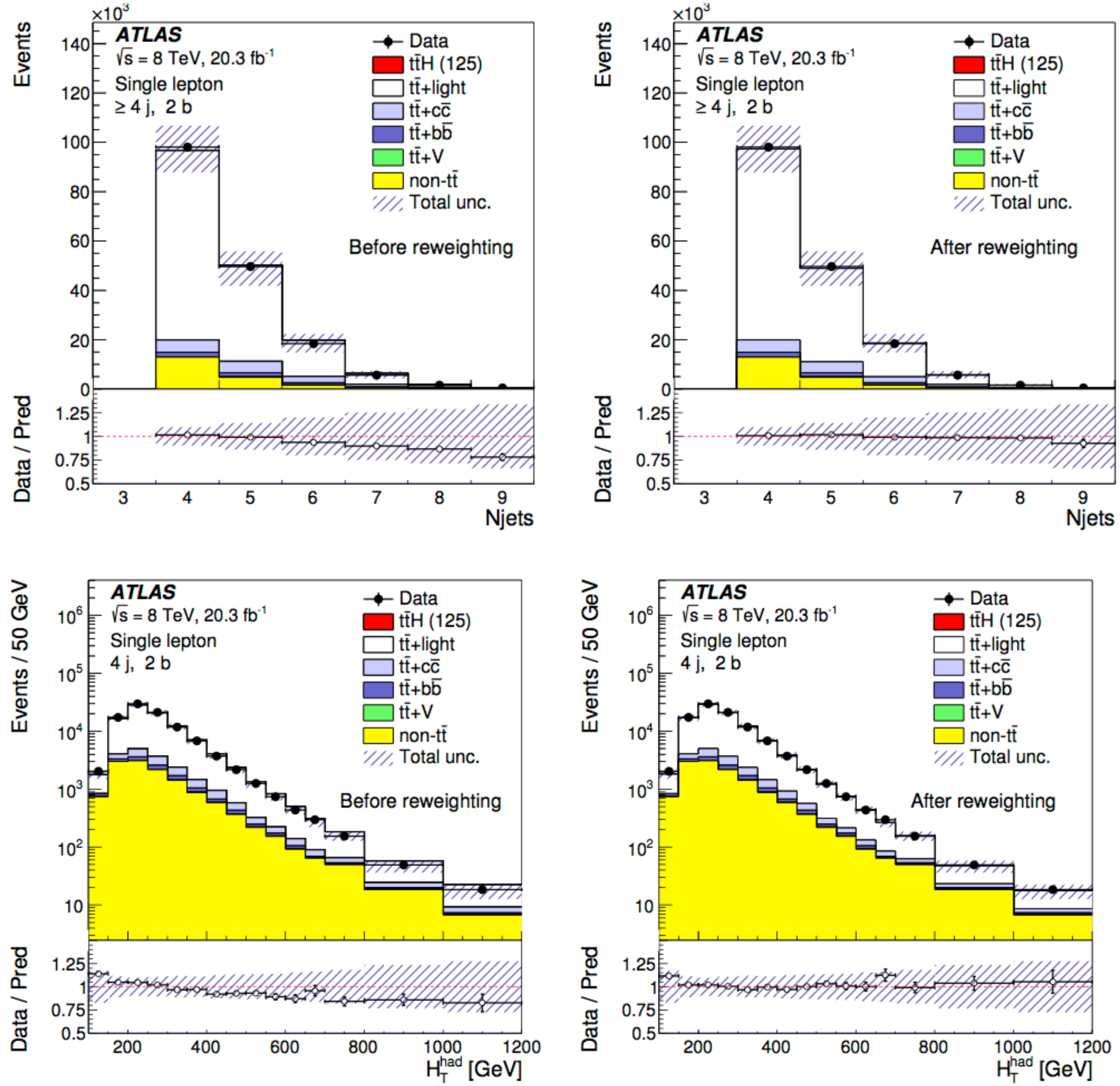
- Important to have the best possible modelling for background processes to prevent any mismodelling being interpreted as signal.
- NLO samples used for signal and dominant backgrounds.
  - tt (inclusive) normalised to NNLO+NNLL (QCD).
  - tt+bb modelling benefitted from recent NLO simulation
- tt sample reweighted to 7 TeV unfolded XS analysis to correct top-quark kinematic modelling.





Top System Modelling

- Reweighting tt p_T improved number of jets beyond LO diagrams.
- Reweighting top p_T improved the hadronic summed p_T distributions.



Heavy Flavour Modelling (tt+HF)

- Large difference in tt + unresolved g→bb events comparing parton-shower modelling with NLO event generation.