Search for the Higgs boson in the ttH production channel using the ATLAS detector

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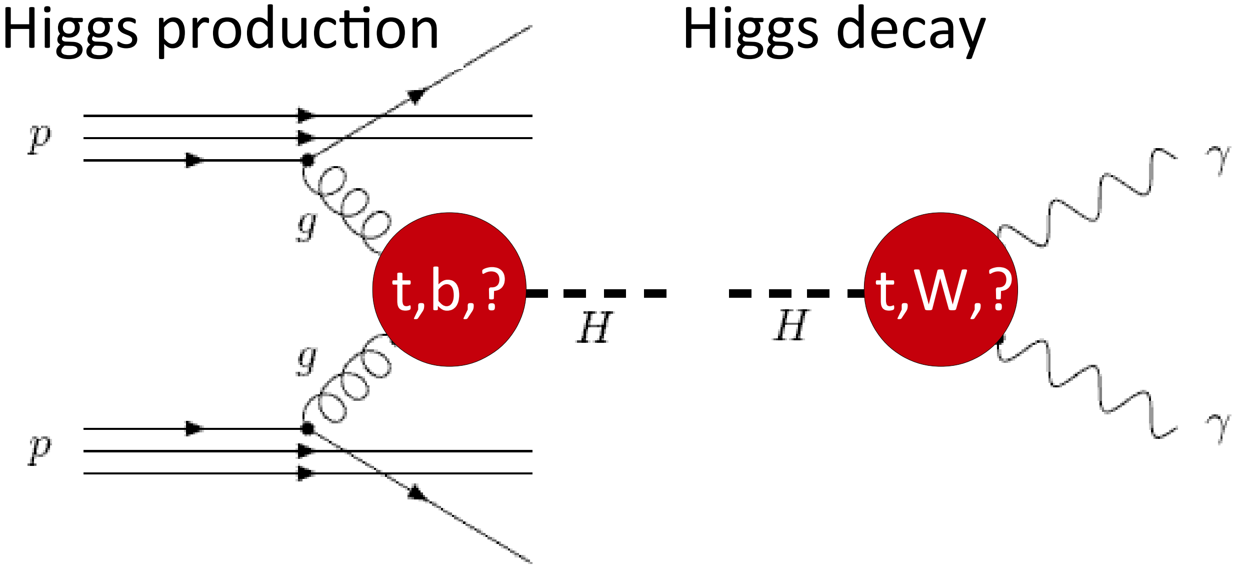
IFAE, Barcelona

YSF, La Thuile 2015

Motivation

- After the Higgs discovery the main focus is on the measurement of its properties
  - couplings to fermions and gauge bosons
- Top quark is the most strongly-coupled SM particle with **Y_t** ~ 1

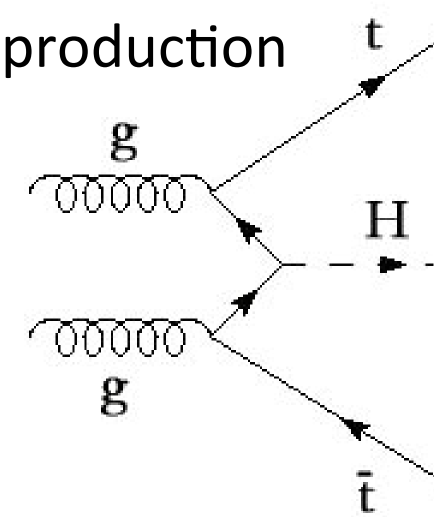
Higgs production Higgs decay



- Already indirect constraints on the top-Higgs Yukawa coupling
  - assumes no new particles in the loop

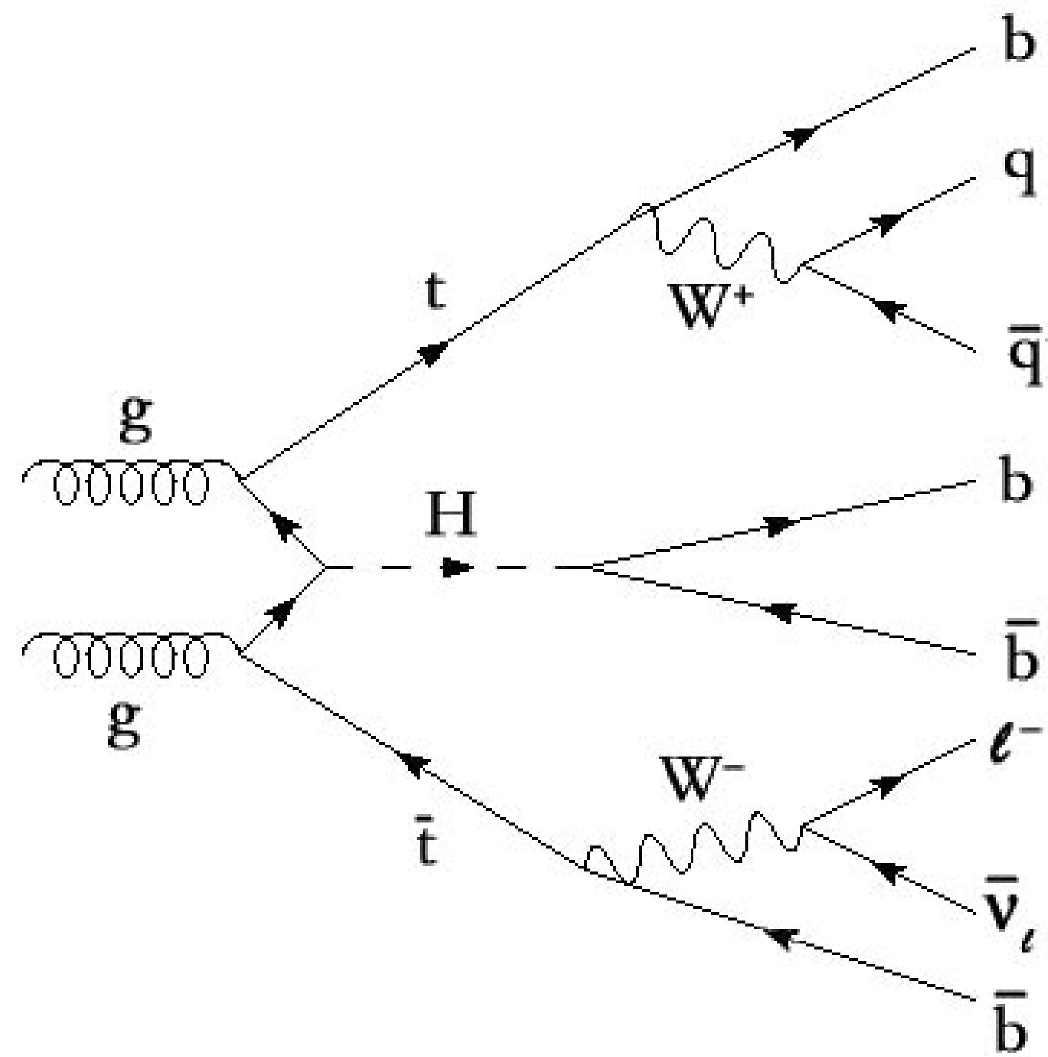
- Direct measurement of **Y_t** in ttH production
  - allows probing new physics in ggH and γγH effective vertices

ttH production



$$\sigma(\mathbf{t\bar{t}H}) \propto \mathbf{g^2_{ttH}}$$

ttH production

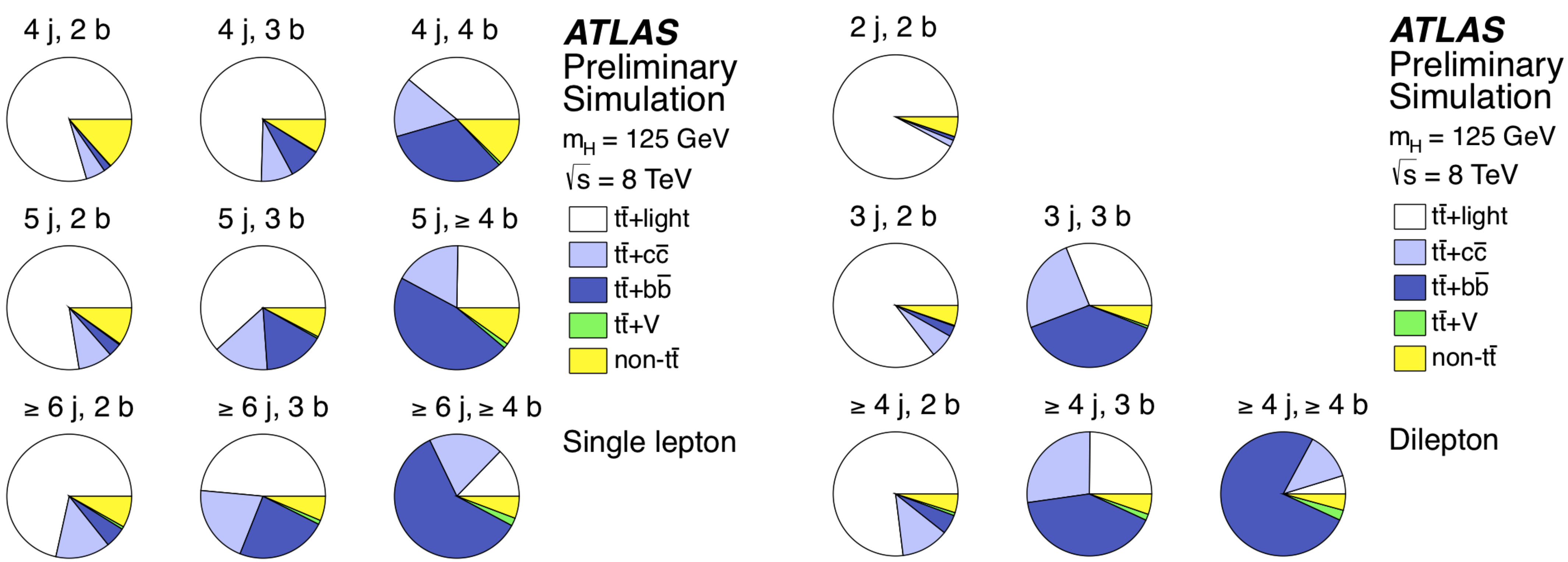


- **Production**
  - σ(ttH) is known at NLO QCD
  - suppressed compared to other Higgs production modes
  - ≈ 2600 events in 20.3 fb^{-1} at 8 TeV
- **Decay**
  - Focusing on the decay H → bb
  - Highest branching ratio (58%) but large backgrounds
- **Main background**
  - tt+X, 2000 times higher cross section
  - Very challenging final state, with high jet and b-tag multiplicity, large systematic uncertainties, both theoretical and experimental
- **Search for ttH focusing on the decay H → bb in the lepton+jets and dilepton channels**

HIGG-2013-27

Analysis strategy

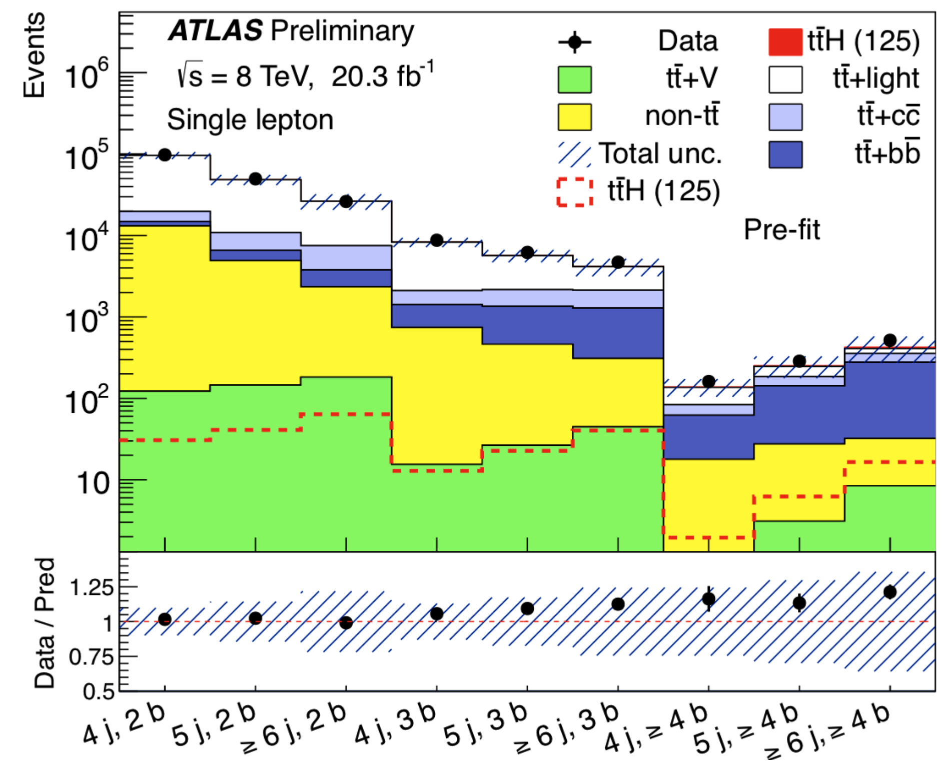
- ttH, H→bb signal produces 1 or 2 leptons and 6 or 4 jets, 4 of them b-jets
- Very challenging final state affected by large systematics:
  - tt+jets, tt+heavy flavor modeling, b-tagging, JES
- Analysis relies on a **profiled likelihood fit**, in order to constrain in-situ the leading systematics
- Analysis channels defined splitting in jet and b-tag multiplicities
- Signal-depleted channels play a key role constraining systematic uncertainties

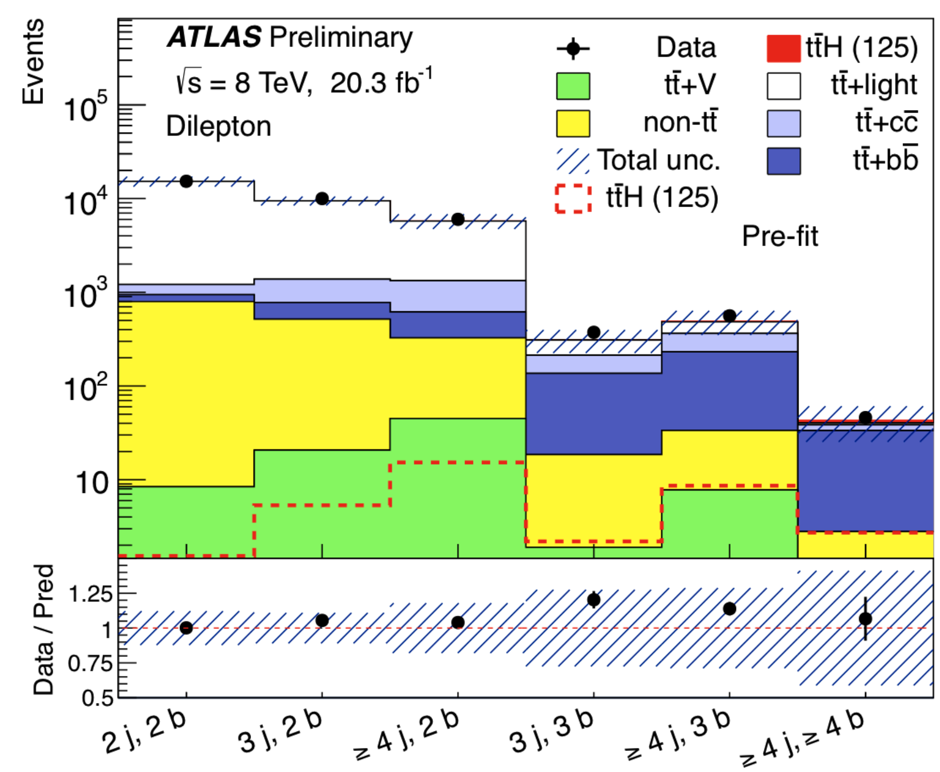


Modeling

- Modeling of the tt+jets and tt+HF backgrounds across multiple jet and b-tag multiplicities is a critical aspect for this analysis
- Powheg+Pythia used as baseline MC, NLO description of inclusive tt production
  - **tt+jets**: Corrections to MC derived from differential cross section measurement
  - **tt+bb**: Only parton shower accuracy, but prediction at NLO available in Sherpa+OpenLoops: reweight MC to NLO prediction
- ttH modeling at NLO, using PowHel
- MC prediction for minor backgrounds: V+jets, single top, diboson, tt+V
- Data driven template for fake lepton backgrounds

Prefit data/MC yields per channel





tt+light jets modeling

- Enough statistics in data to validate the modeling
- Correct tt and top p_T spectra to the differential cross section measurement
- Clear improvement in the modeling after the reweighting
- Assign uncertainties from the measurement to this correction

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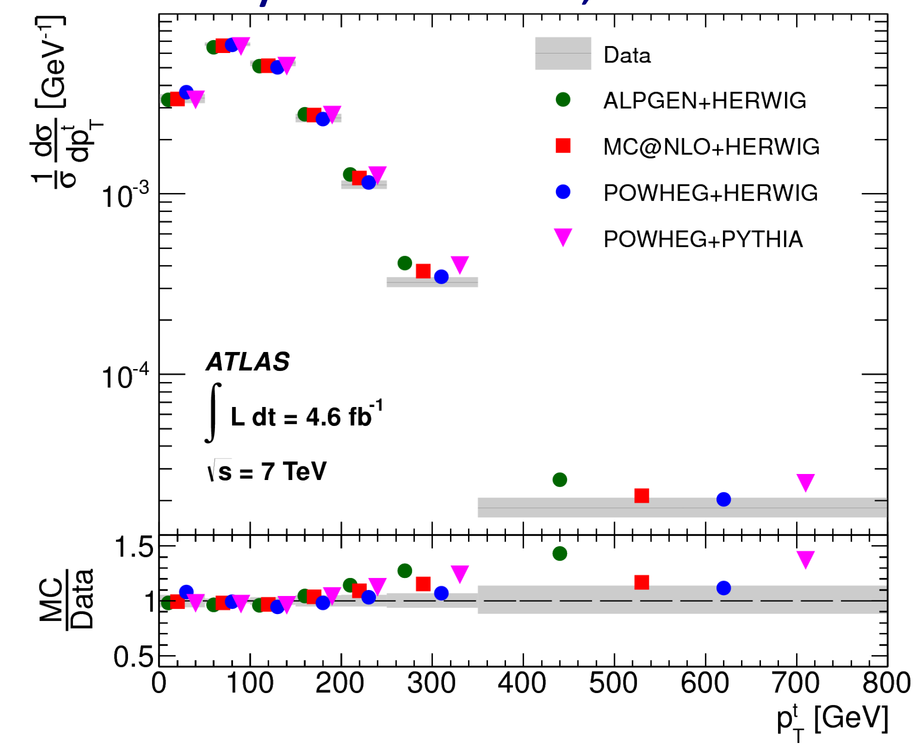
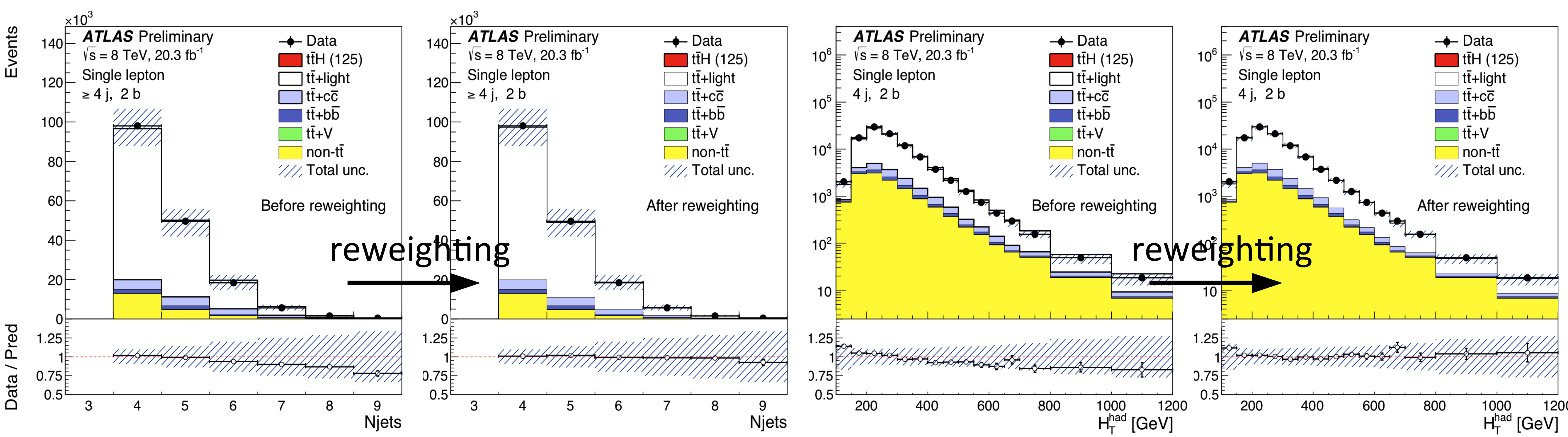
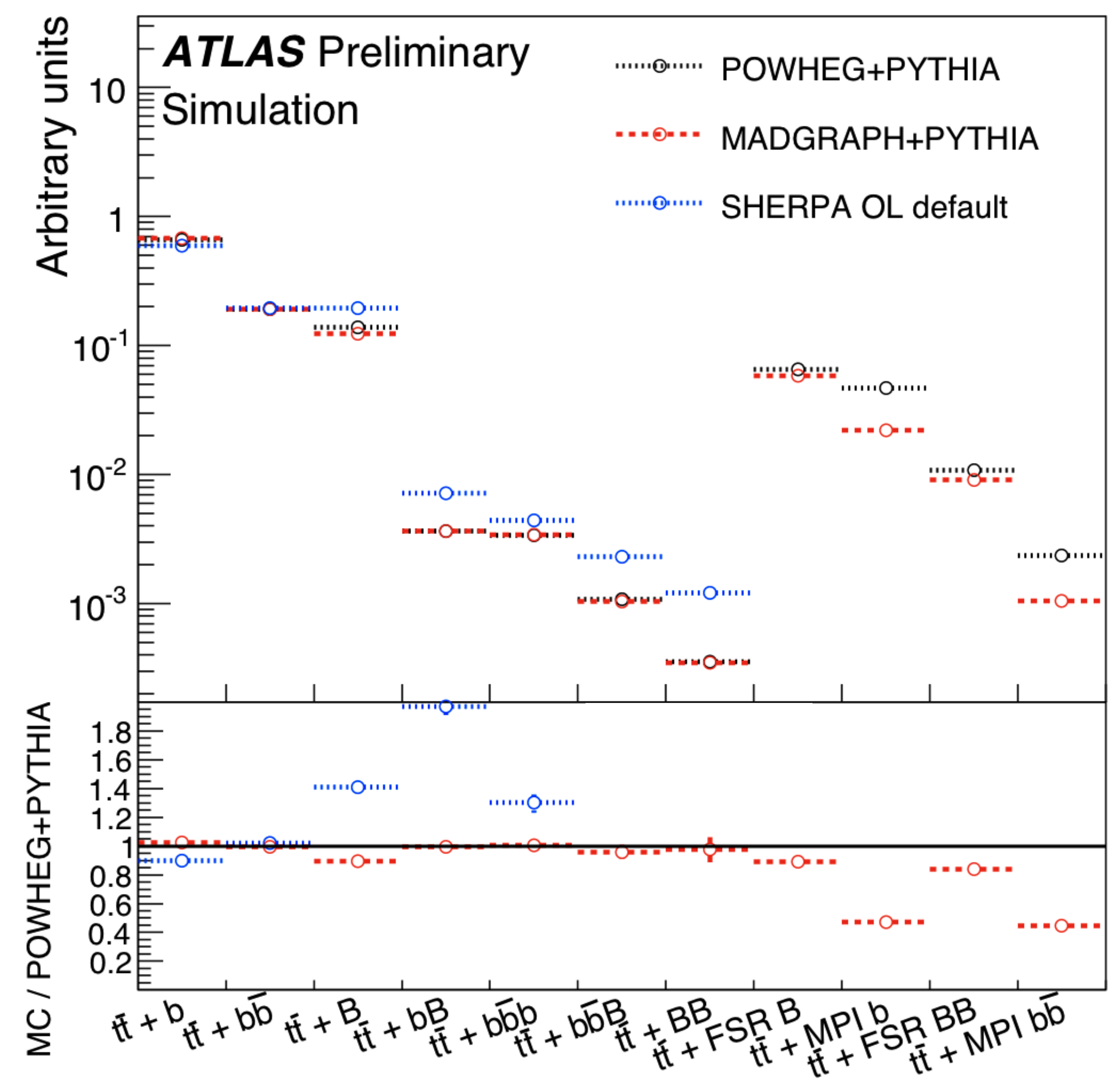




ttbb modeling

- tt+HF classification based on truth level jets, no matching to reconstructed jets
- Find particle jets containing B/C hadrons not originated from top decays
- Count number of B/C hadrons inside the jet, allows to identify unresolved g → bb splitting (labelled tt+B)
- **Allows comparison of the ttbb prediction among generators**
  - ttbb prediction in Sherpa+OpenLoops, massive b's, 4 flavor pdf, S-MC@NLO



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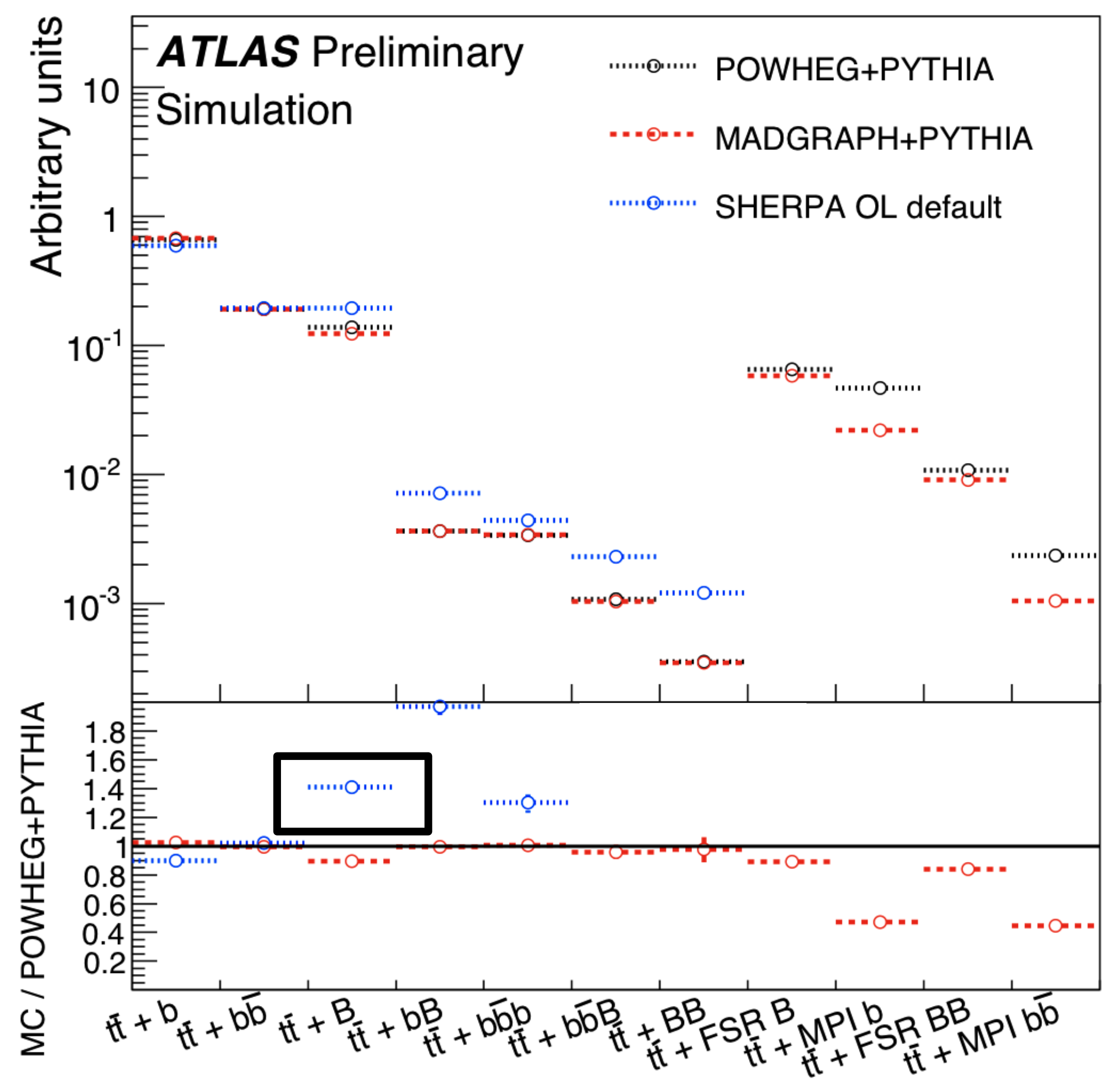
  - ttbb prediction in Sherpa+OpenLoops, massive b's, 4 flavor pdf, S-MC@NLO
  - Minor corrections to the kinematics: top and tt p_T, bb p_T and dR
  - Sizeable correction in the normalization of the tt+B category (unresolved g → bb)



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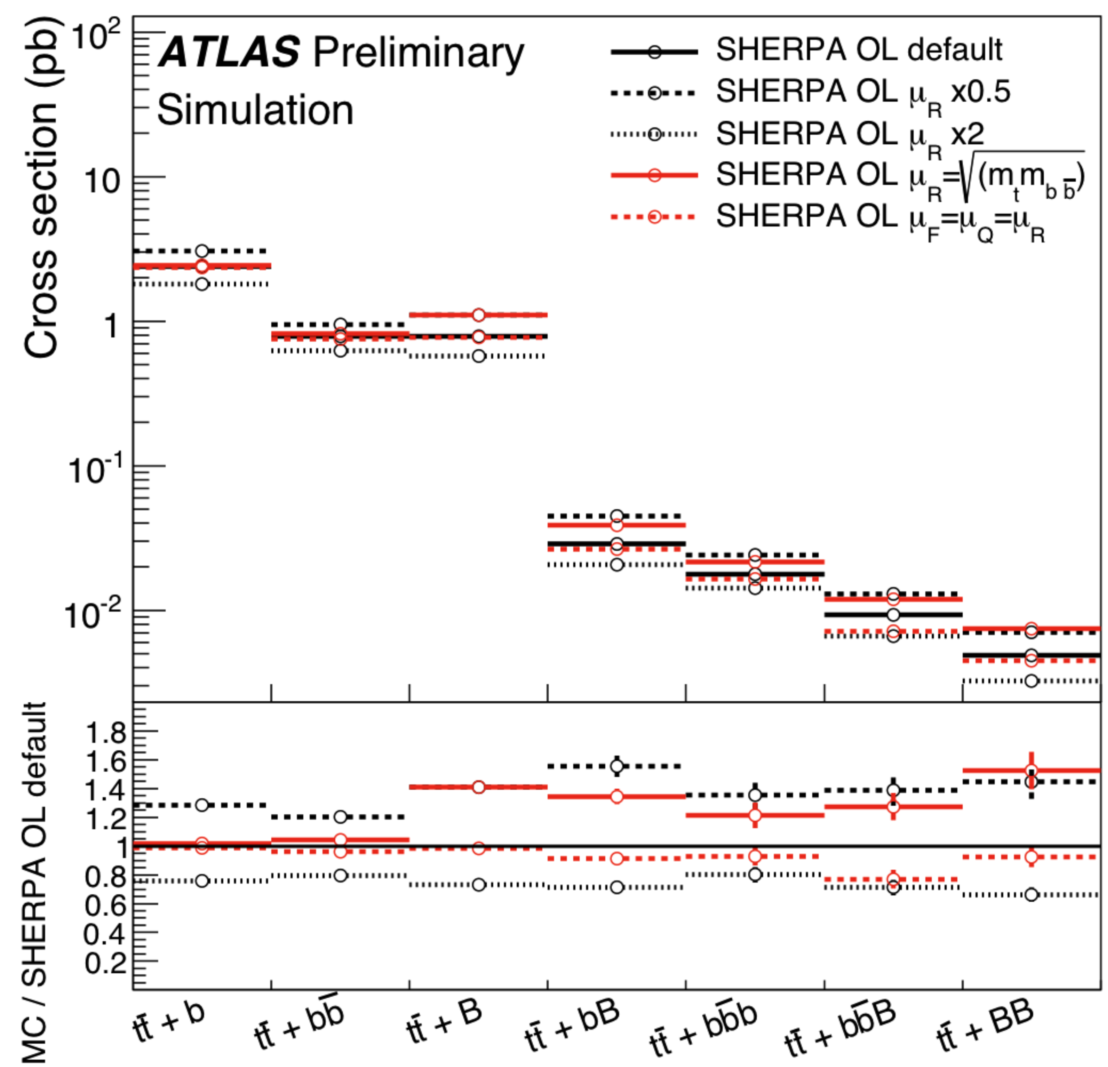
- **ttbb modeling systematics at NLO**
  - Factorisation scale up/down, different functional forms for the factorisation, renormalisation and resummation scales
  - PDF variations (MSTW, NNPDF) and shower recoil scheme variation



Analysis strategy

Lepton+jets

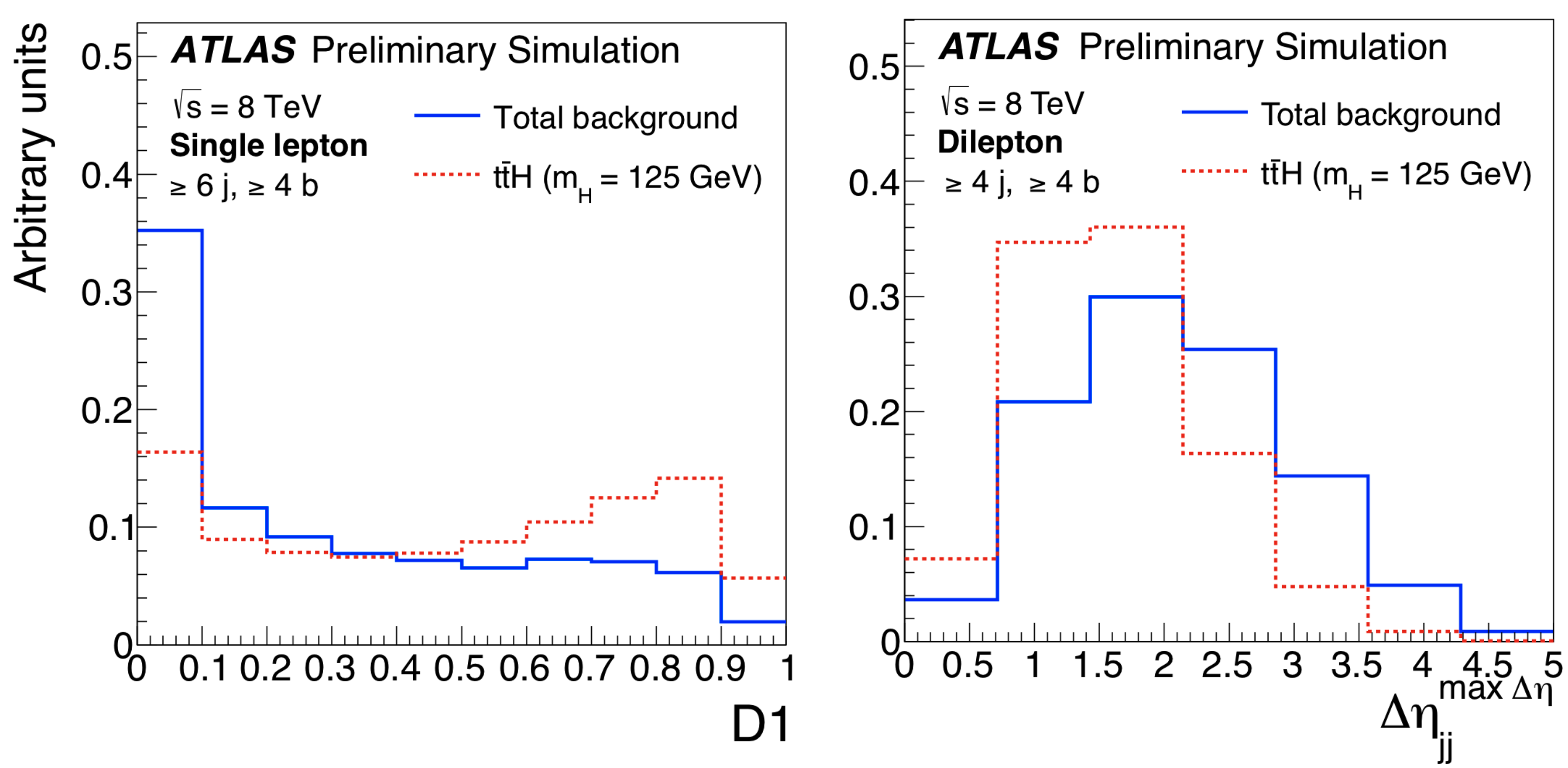
	2 b-tags	3 b-tags	4 b-tags
4 jets	H_T^{had}	H_T^{had}	H_T^{had}
5 jets	H_T^{had}	NN*	NN
6 jets	H_T^{had}	NN	NN

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

- Signal-rich regions: neural network (NN) trained to separate ttH from tt+jets. Several types of variables:
  - Event shape: centrality
  - Object pair properties: $\Delta\eta_{jj}^{\max\Delta\eta}$
  - Object kinematics: p_T^{jet5}
  - Event kinematics: H_T
  - Matrix element method: D1
- Dedicated NN in single lepton channel with 5 jets, 3 b-jets to separate tt+bb/cc from tt+light

Example of input variables to the NN



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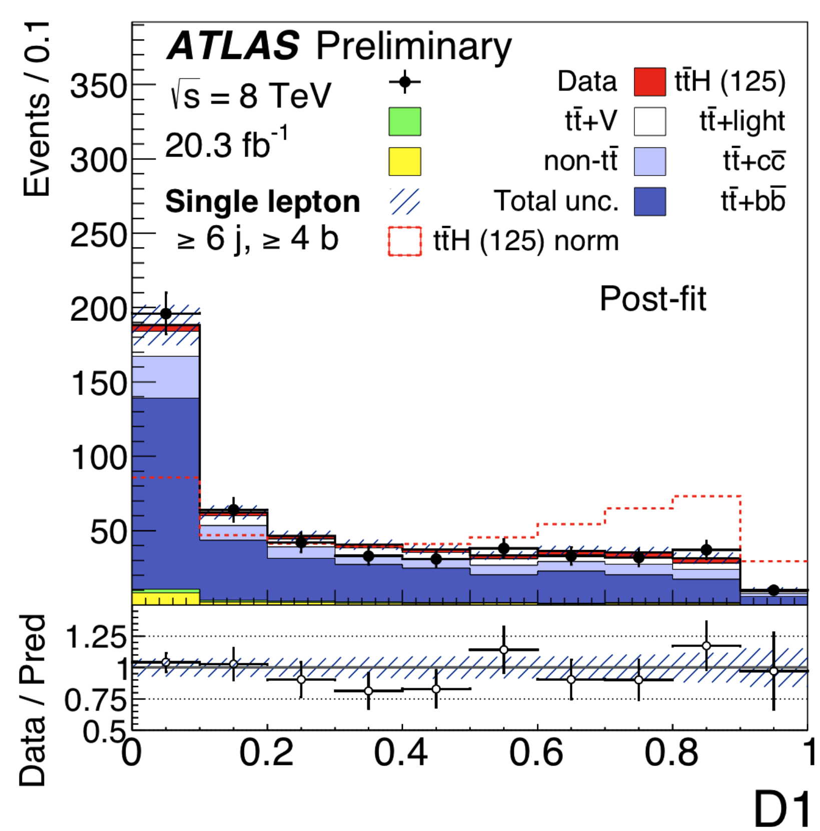
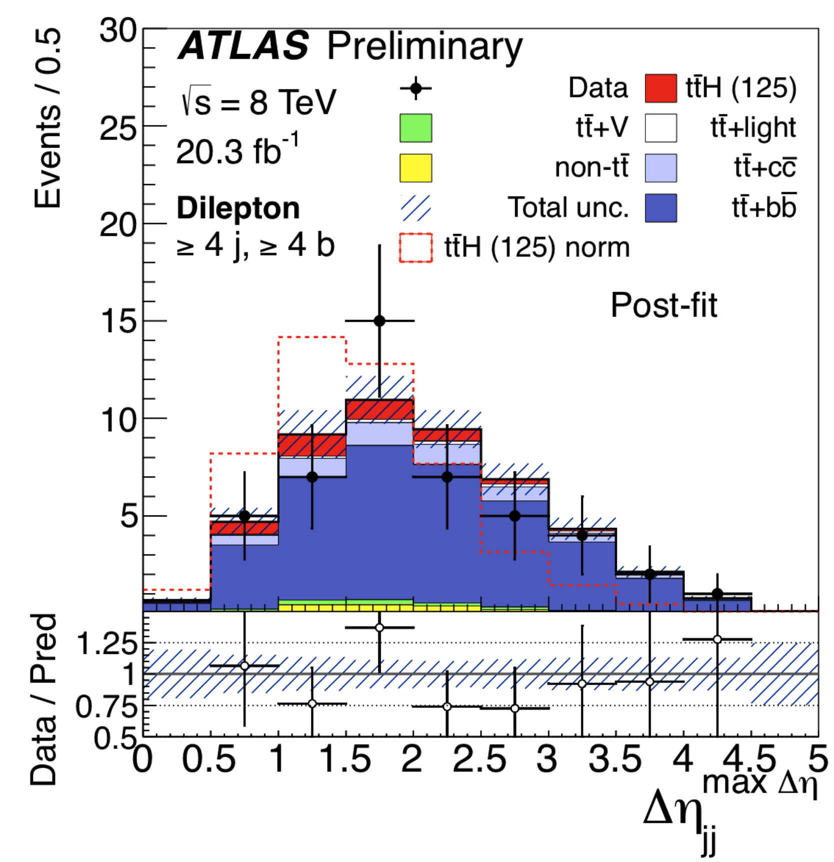




Matrix element method

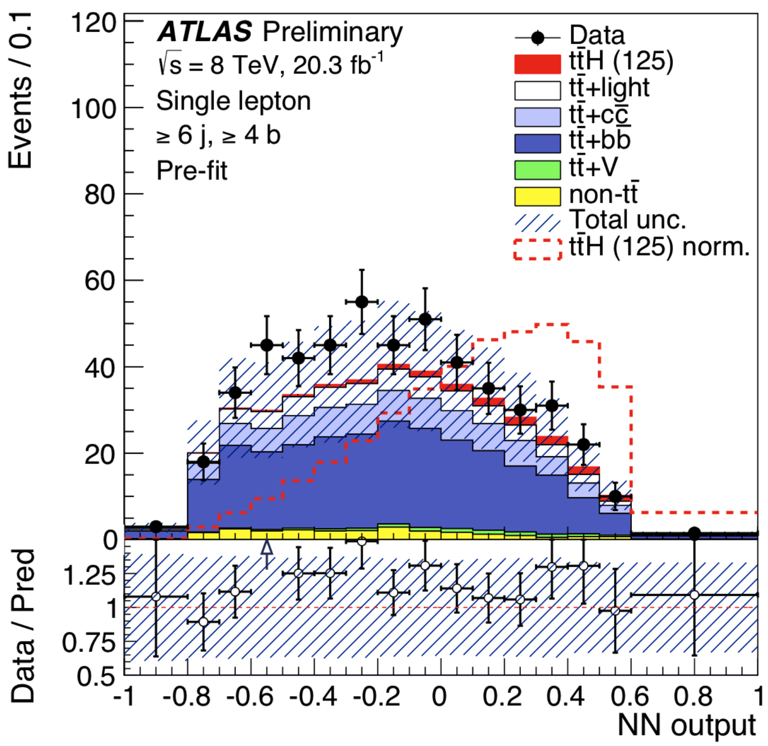
- The Matrix Element Method (MEM) is used to compute the likelihood for an event to be originated from a certain theoretical hypothesis.
- Compute the likelihood respect to the ttH or ttbb hypothesis

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

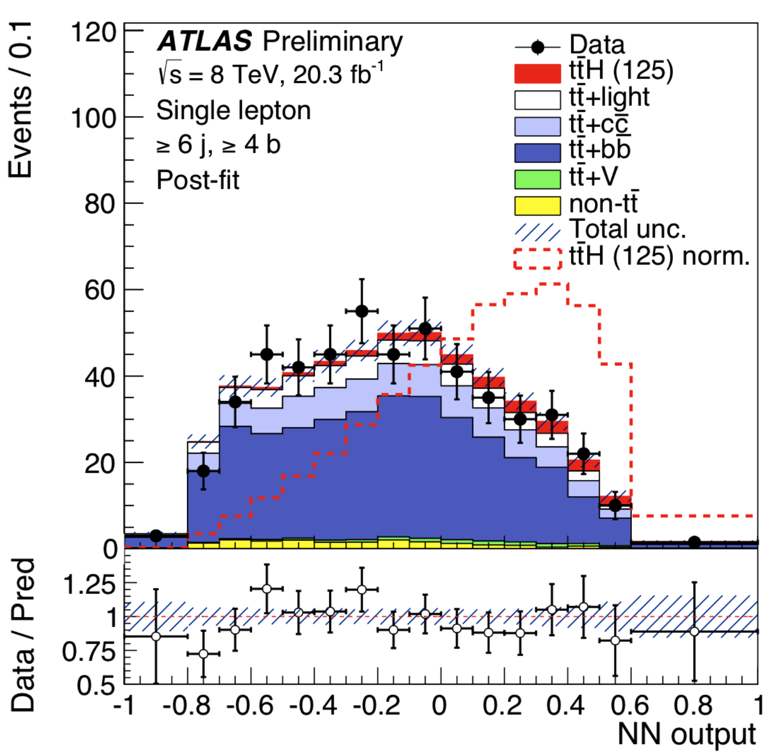
  - PDFs account for production mechanism
  - Differential cross section proportional to $|M|^2$, consider only LO ME. Test ttbb and ttH hypothesis
  - Transfer functions map detector response to parton level
- Likelihood ratio of ttH/ttbb (**D1**) is the most discriminating variable against ttbb in 6j4b.
- Sum of likelihood under signal hypothesis (**SSLL**) is discriminating against the rest of the backgrounds

Profiling in action

Prefit 6j4b lepton+jets



Postfit 6j4b lepton+jets



- Signal extracted via binned likelihood fit to 6 signal and 9 control regions under S+B hypothesis
- Many systematic uncertainties, both theoretical and experimental.

≥ 6 j, ≥ 4 b

	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
Light jet-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
$t\bar{t}$ modelling: p_T reweighting	–	±5.4	±6.1	–	–	±4.7	±5.4	–
$t\bar{t}$ modelling: parton shower	–	±13	±16	±11	–	±3.6	±10	±6.0
$t\bar{t}$ heavy-flavour: normalisation	–	–	±50	±50	–	–	±28	±14
$t\bar{t}$ heavy-flavour: modelling	–	±11	±16	±8.3	–	±3.6	±9.1	±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

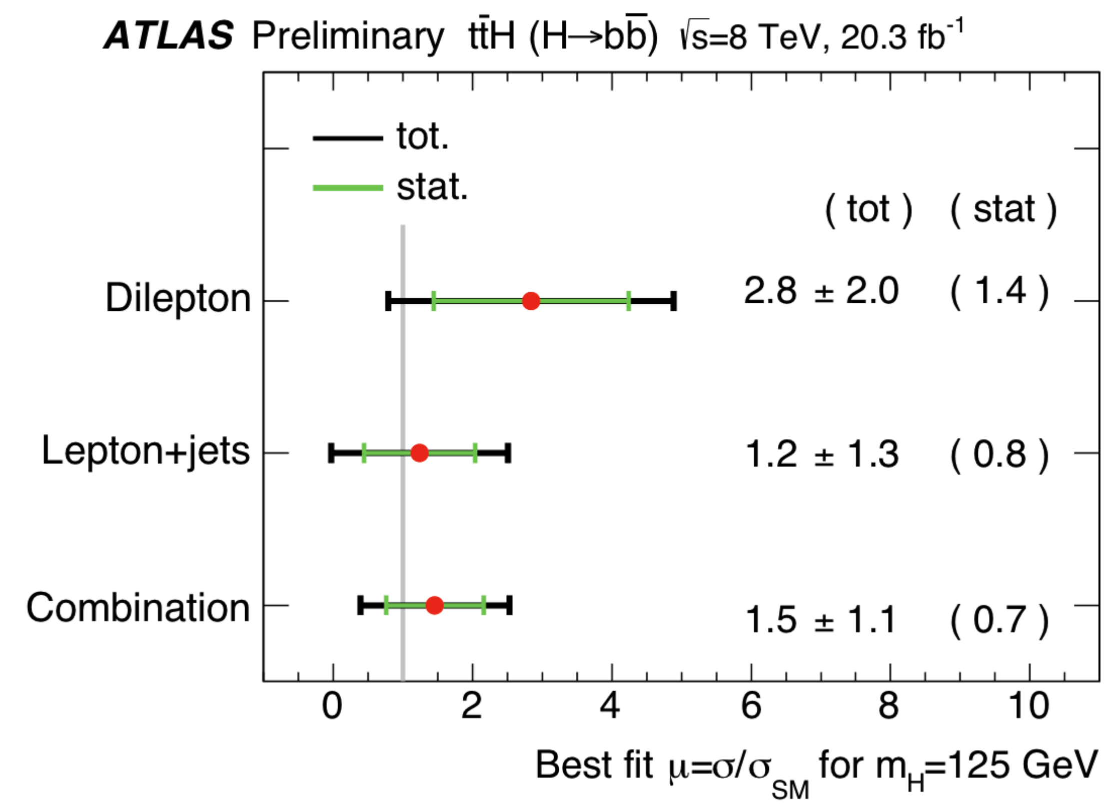
ttbb normalization uncertainty is greatly reduced

Results

- **Fitted signal strength:**

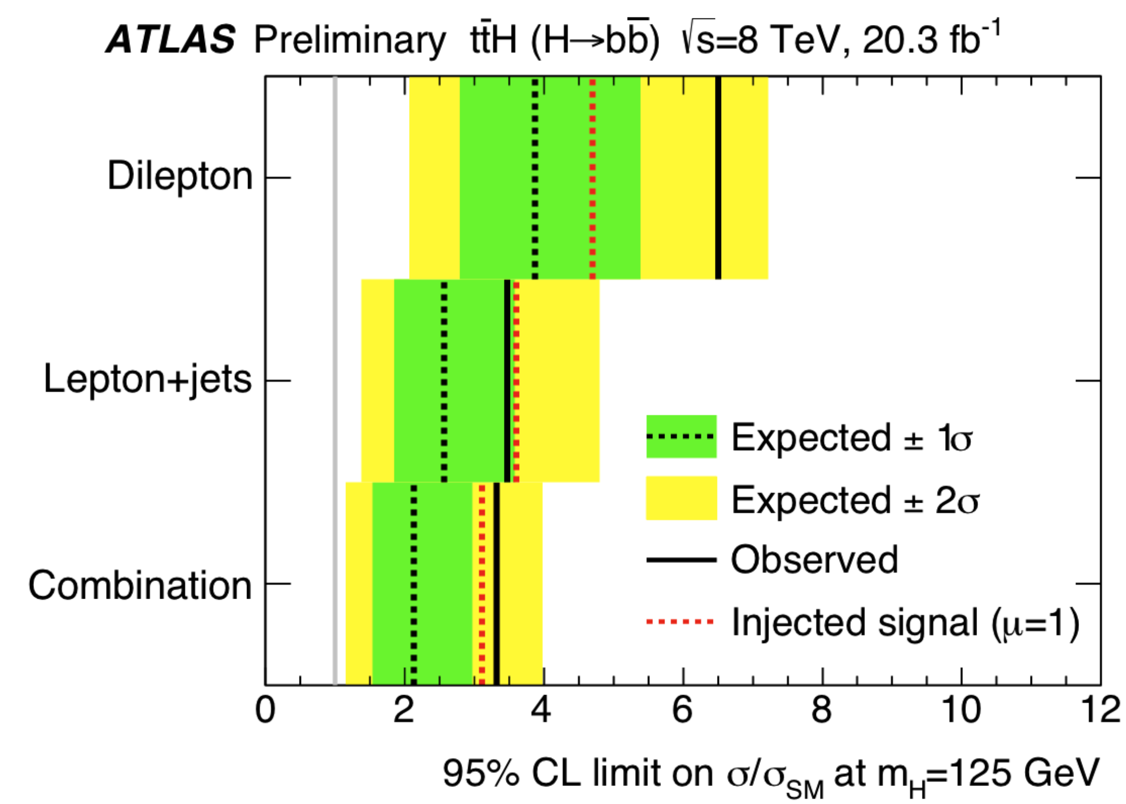
  $\mu = 1.5 \pm 1.1$

- In agreement with SM expectation



- **Observed (expected) exclusion limits:**

  $\sigma/\sigma_{SM} < 3.4\ (2.2)$



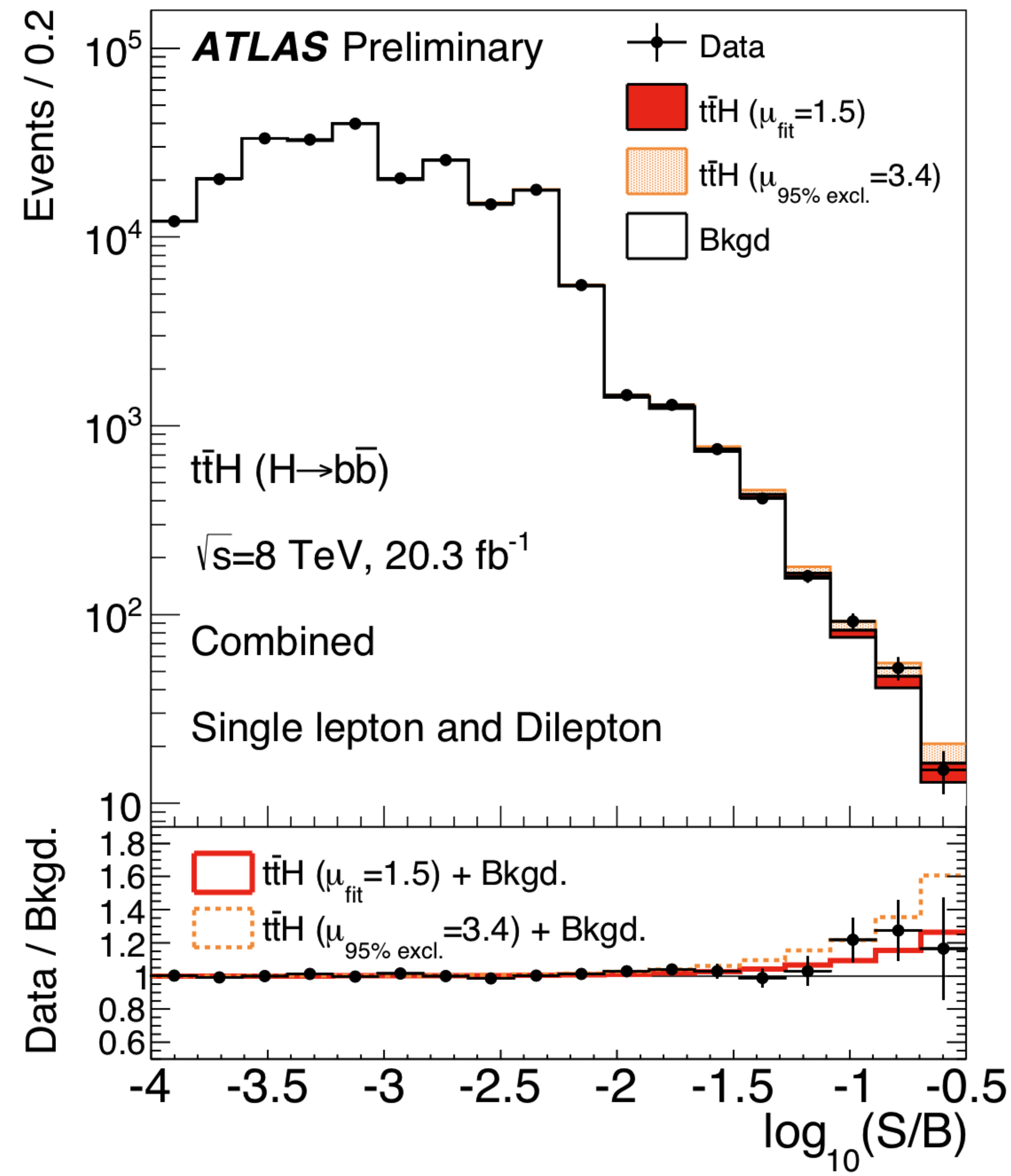
Summary

- Presented a search for the Higgs boson in the ttH, H→bb channel

  μ = 1.5 ± 1.1

  σ/σ_{SM} < 3.4 (2.2)

- Single most sensitive analysis for ttH
- Two key aspects introduced since the preliminary result:
  - **ttbb modeling at NLO:** MC calibrated to the NLO prediction in Sherpa+OpenLoops
  - **Matrix element method:** Introduced in the lepton+jets channel, provided the most discriminating variable in the 6j4b channel



- On the way for a measurement of the top Yukawa coupling, stay tuned for run II :)

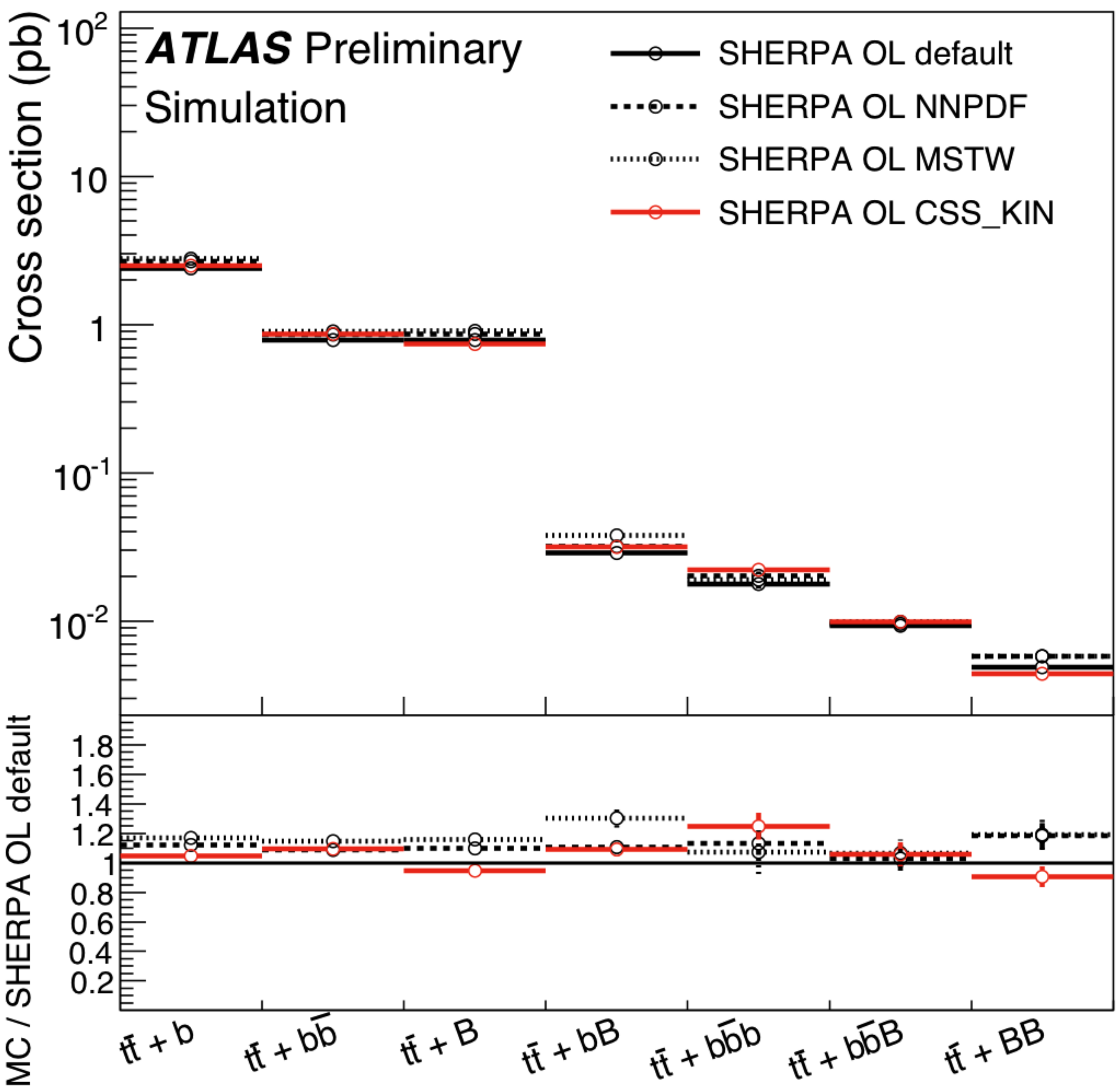
Backup

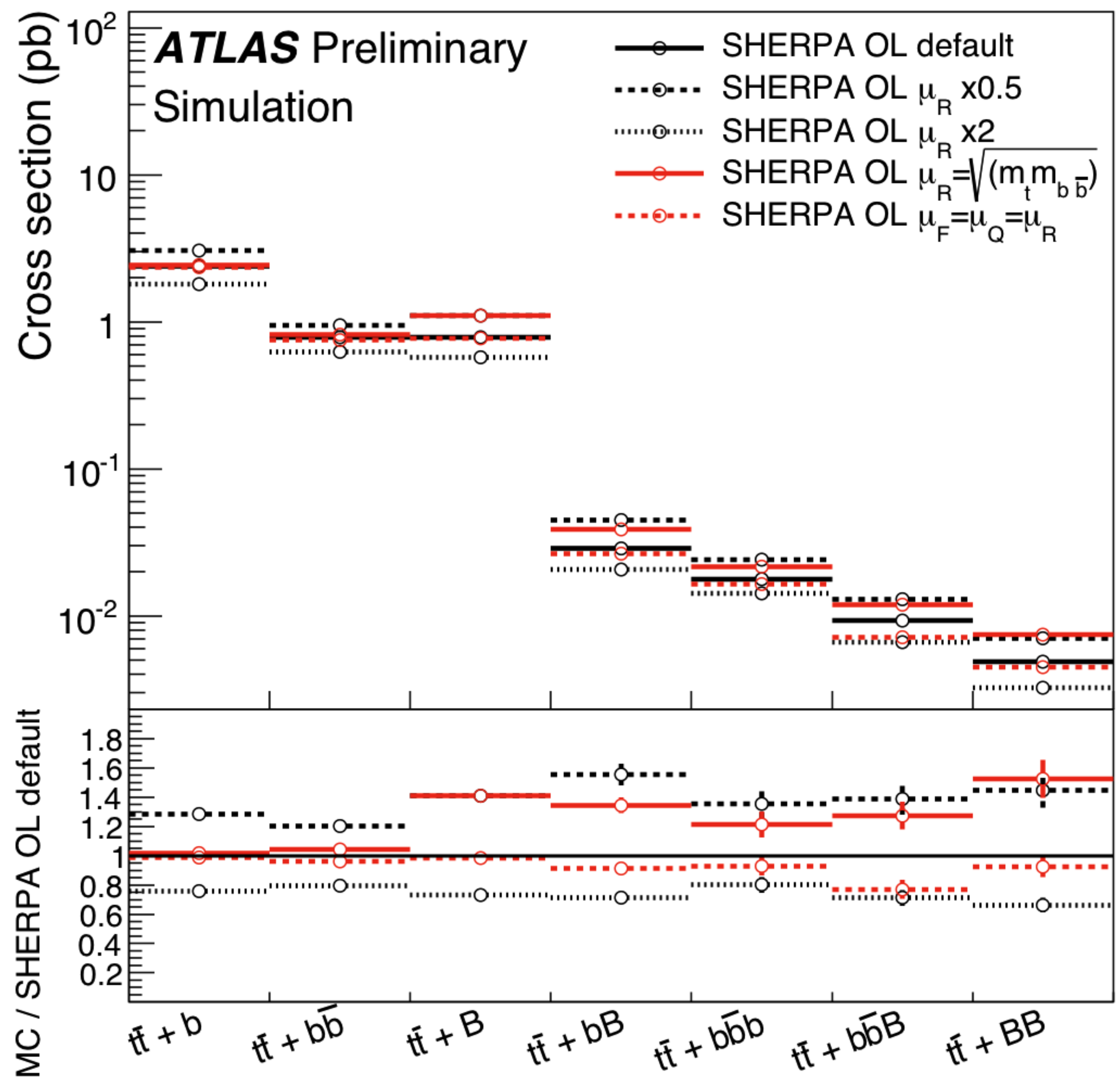
HF definition

- We define tt+HF at truth level, in order to compare generators and extract information from the NLO prediction
- **Truth jets**: jets built from stable particles, excluding muons and neutrinos, using the anti-kt algorithm with radius R=0.4
- **HF jet**: jet containing a B/D hadron with pT > 5 GeV, not originated from another hadron decay
- **tt+HF event:** event with at least one HF jet with pT > 15 GeV, |eta| < 2.5, where the HF jet is not originated from a top decay
  - Resolved HF (tt+b): the additional HF jet contains exactly one heavy flavor hadron
  - Merged HF (tt+B): the additional HF jet contains more than one heavy hadron. No pT requirement is performed on the second hadron

ttbb systematics

- Systematics for ttbb modeling derived from scale, pdf and shower recoil scheme variations in the Sherpa+OpenLoops sample





Nuisance parameter ranking

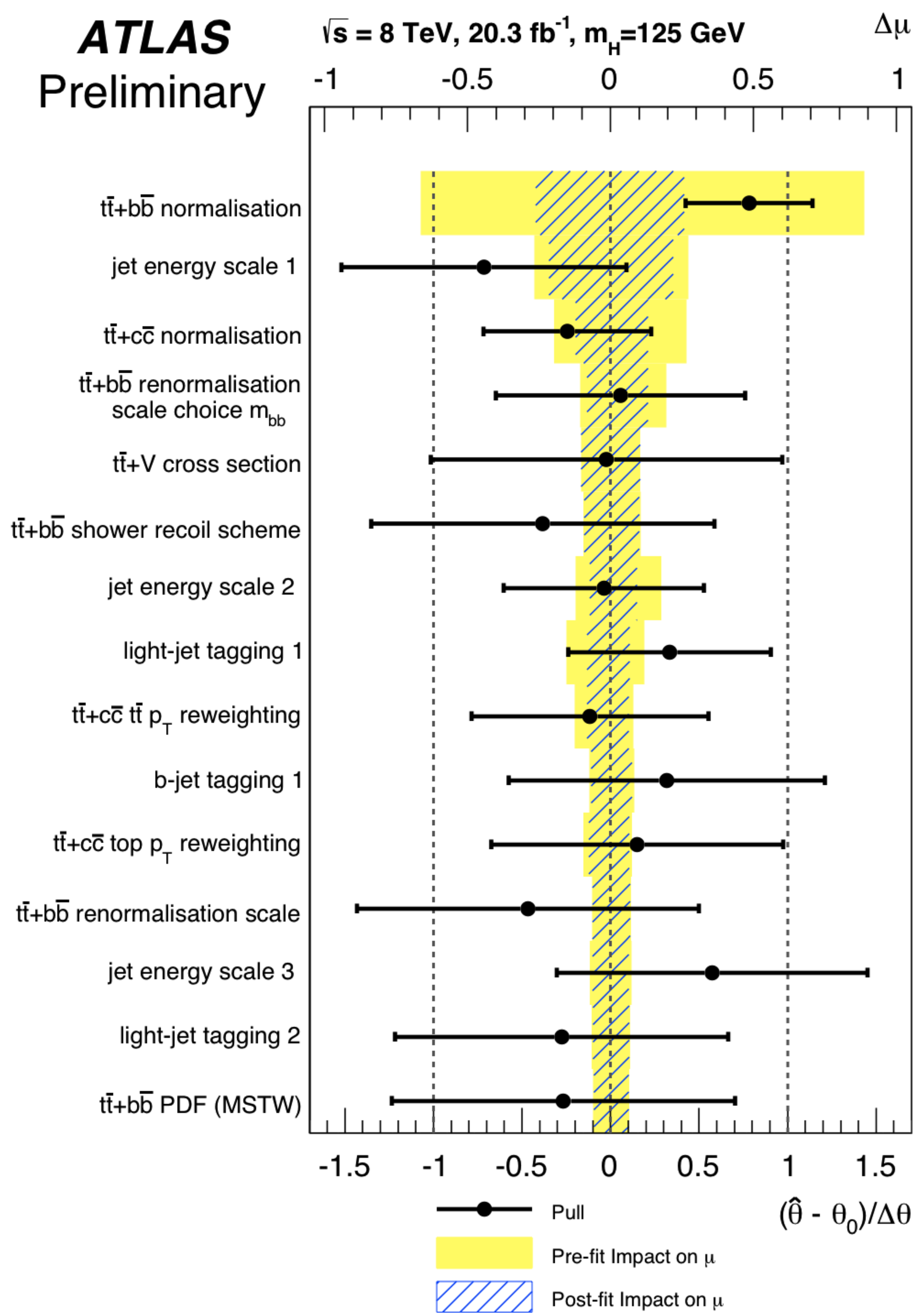


Fig. 18 The fitted values of the most important nuisance parameters and their impact on the measured signal strength. The points, which are drawn obeying the scale of the bottom axis, show the deviation of each of the fitted nuisance parameters, $\hat{\theta}$, from θ_0, which is the nominal value of that nuisance parameter, in units of the pre-fit standard deviation $\Delta\theta$. The error bars show the post-fit errors, σ_θ, which are close to 1 if these data do not provide any further constraint on that uncertainty. Conversely, a value of σ_θ much smaller than 1 indicates a significant reduction with respect to the original uncertainty. The nuisance parameters are sorted according to the post-fit effect of each on μ (hashed blue area), with those with the largest impact at the top. The post-fit effect on μ, shown obeying the scale of the top axis, is calculated by fixing the corresponding nuisance parameter at $\hat{\theta} \pm \sigma_\theta$ and redoing the fit. The difference between the default and the modified μ, $\Delta\mu$, represents the effect on μ of this particular systematic uncertainty.

Neural network variables, lepton+jets

Variable	Definition
$D1$	Newman-Pearson MEM discriminant
$SSLL$	Signal summed log-likelihoood
Centrality	Sum of the p_{T} divided by sum of the E for all jets and the lepton
H1	Second Fox-Wolfram moment computed using all jets and the lepton
$m_{\mathrm{bb}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of two b-tagged jets with the smallest ΔR
N_{40}^{jet}	Number of jets with $p_{\mathrm{T}} \geq 40$ GeV
$\Delta R_{\mathrm{bb}}^{\mathrm{avg}}$	Average ΔR for all b-tagged jet pairs
$m_{\mathrm{jj}}^{\mathrm{max}\ p_{\mathrm{T}}}$	Mass of the combination of any two jets with the largest vector sum p_{T}
$\mathrm{Aplanarity}_{b\mathrm{-jet}}$	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor built with only b-tagged jets
$H_{\mathrm{T}}^{\mathrm{had}}$	Scalar sum of jet p_{T}
$m_{\mathrm{jj}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of any two jets with the smallest ΔR
$\Delta R_{\mathrm{lep-bb}}^{\mathrm{min}\ \Delta\mathrm{R}}$	ΔR between the lepton and the combination of two b-tagged jets with the smallest ΔR
$m_{\mathrm{bj}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of a b-tagged jet and any jet with the smallest ΔR
$m_{\mathrm{bj}}^{\mathrm{max}\ p_{\mathrm{T}}}$	Mass of the combination of a b-tagged jet and any jet with the largest vector sum p_{T}
$m_{\mathrm{uu}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of two untagged jets with the smallest ΔR
$p_{\mathrm{T}}^{\mathrm{jet5}}$	Fifth leading jet p_{T}
$\Delta R_{\mathrm{bb}}^{\mathrm{max}\ p_{\mathrm{T}}}$	ΔR between two b-tagged jets with the largest vector sum p_{T}
$m_{\mathrm{bb}}^{\mathrm{max}\ \mathrm{m}}$	Mass of the combination of two b-tagged jets with the largest invariant mass
$p_{T,\mathrm{uu}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Scalar sum of the p_{T}'s of the pair of untagged jets with the smallest ΔR
m_{jjj}	Mass of the jet triplet with the largest vector sum p_{T}
$\Delta R_{\mathrm{uu}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Minimum ΔR between two untagged jets
$m_{\mathrm{bb}}^{\mathrm{max}\ p_{\mathrm{T}}}$	Mass of the combination of two b-tagged jets with the largest vector sum p_{T}

Neural network variables, lepton+jets

Variable	$(\geq 6j, \geq 4b)$	$(\geq 6j, 3b)$	$(5j, \geq 4b)$	$(5j, 3b)$
$D1$	1	10	-	-
Centrality	2	2	1	-
$p_{\mathrm{T}}^{\mathrm{jet5}}$	3	7	-	-
$H1$	4	3	2	-
$\Delta R_{\mathrm{bb}}^{\mathrm{avg}}$	5	6	5	-
$SSLL$	6	4	-	-
$m_{\mathrm{bb}}^{\mathrm{min}\ \Delta\mathrm{R}}$	7	12	4	4
$m_{\mathrm{bj}}^{\mathrm{max}\ \mathrm{p_T}}$	8	8	-	-
$\Delta R_{\mathrm{bb}}^{\mathrm{max}\ \mathrm{p_T}}$	9	-	-	-
$\Delta R_{\mathrm{lep-bb}}^{\mathrm{min}\ \Delta\mathrm{R}}$	10	11	10	-
$m_{\mathrm{uu}}^{\mathrm{min}\ \Delta\mathrm{R}}$	11	9	-	2
$\mathrm{Aplanarity}_{\mathrm{b-jet}}$	12	-	8	-
N_{40}^{jet}	-	1	3	-
$m_{\mathrm{bj}}^{\mathrm{min}\ \Delta\mathrm{R}}$	-	5	-	-
$m_{\mathrm{jj}}^{\mathrm{max}\ \mathrm{p_T}}$	-	-	6	-
$H_{\mathrm{T}}^{\mathrm{had}}$	-	-	7	-
$m_{\mathrm{jj}}^{\mathrm{min}\ \Delta\mathrm{R}}$	-	-	9	-
$m_{\mathrm{bb}}^{\mathrm{max}\ \mathrm{p_T}}$	-	-	-	1
$p_{T,\mathrm{uu}}^{\mathrm{min}\ \Delta\mathrm{R}}$	-	-	-	3
$m_{\mathrm{bb}}^{\mathrm{max}\ \mathrm{m}}$	-	-	-	5
$\Delta R_{\mathrm{uu}}^{\mathrm{min}\ \Delta\mathrm{R}}$	-	-	-	6
m_{jjj}	-	-	-	7

Neural network variables, dilepton

Variable	Definition
$m_{b\bar{b}}$	Mass of the two b jets from the Higgs candidate system
H_{T}	Scalar sum of jet p_{T} and lepton p_{T}
$p_{\mathrm{T}}^{\mathrm{jet3}}$	3rd Leading jet p_{T}
Centrality	Sum of p_{T} divided by sum of E for all jets
Aplanarity$_{\mathrm{jet}}$	$1.5\lambda_2$ (Second eigenvalue of the momentum tensor constructed from jets)
$H4$	Fifth Fox-Wolfram Moment
$\Delta R_{\mathrm{hl}}^{\mathrm{max}\ \Delta R}$	Maximum ΔR between the Higgs candidate and the two leptons
$\Delta R_{\mathrm{hl}}^{\mathrm{min}\ \Delta R}$	Minimum ΔR between the Higgs candidate and the two leptons
NHiggs 30	Number of Higgs candidates within 30 GeV of the defined Higgs mass (e.g. 125 GeV)
$m_{\mathrm{jj}}^{\mathrm{closest}}$	Dijet mass closest to the defined Higgs mass
$\Delta\eta_{\mathrm{jj}}^{\mathrm{max}\ \Delta\eta}$	Maximum $\Delta\eta$ between two jets in the event
$m_{\mathrm{jj}}^{\mathrm{min\ m}}$	Minimum di-jet mass
$m_{\mathrm{jj}}^{\mathrm{max}\ p_{\mathrm{T}}}$	Mass of the two jet system with maximum p_{T} in the event
$m_{\mathrm{bb}}^{\mathrm{min}\ \Delta R}$	Mass of the two b-jet system with minimum ΔR in the event
$\Delta R_{\mathrm{lj}}^{\mathrm{min}\ \Delta R}$	Minimum ΔR between leptons and untagged jets
$\Delta R_{\mathrm{bb}}^{\mathrm{max}\ p_{\mathrm{T}}}$	ΔR between the b-jet pair with maximum p_{T} in the event
$\Delta R_{\mathrm{bb}}^{\mathrm{max\ m}}$	ΔR between the b-jet pair with maximum mass in the event

Neural network variables, dilepton

Variable	($\geq$ 4j, $\geq$ 4b)	($\geq$ 4j, 3b)	(3j, 3b)
$\Delta\eta_{\mathrm{jj}}^{\mathrm{max}\ \Delta\eta}$	1	1	1
$m_{\mathrm{jj}}^{\mathrm{min\ m}}$	2	2	2
NHiggs30	3	5	4
$\Delta R_{\mathrm{hl}}^{\mathrm{min}\ \Delta\mathrm{R}}$	4	4	-
$m_{b\bar{b}}$	5	-	-
$\Delta R_{\mathrm{bb}}^{\mathrm{max\ p_T}}$	6	3	8
$\mathrm{Aplanarity}_{\mathrm{jet}}$	7	9	-
$m_{\mathrm{jj}}^{\mathrm{closest}}$	8	-	9
$m_{\mathrm{bb}}^{\mathrm{min}\ \Delta\mathrm{R}}$	9	8	-
$\Delta R_{\mathrm{hl}}^{\mathrm{max}\ \Delta\mathrm{R}}$	10	-	-
H_{T}	-	6	3
$\Delta R_{\mathrm{bb}}^{\mathrm{max\ m}}$	-	7	-
$\Delta R_{\mathrm{lj}}^{\mathrm{min}\ \Delta\mathrm{R}}$	-	10	-
$p_{\mathrm{T}}^{\mathrm{jet3}}$	-	-	5
$H4$	-	-	6
Centrality	-	-	7
$m_{\mathrm{jj}}^{\mathrm{max\ p_T}}$	-	-	10

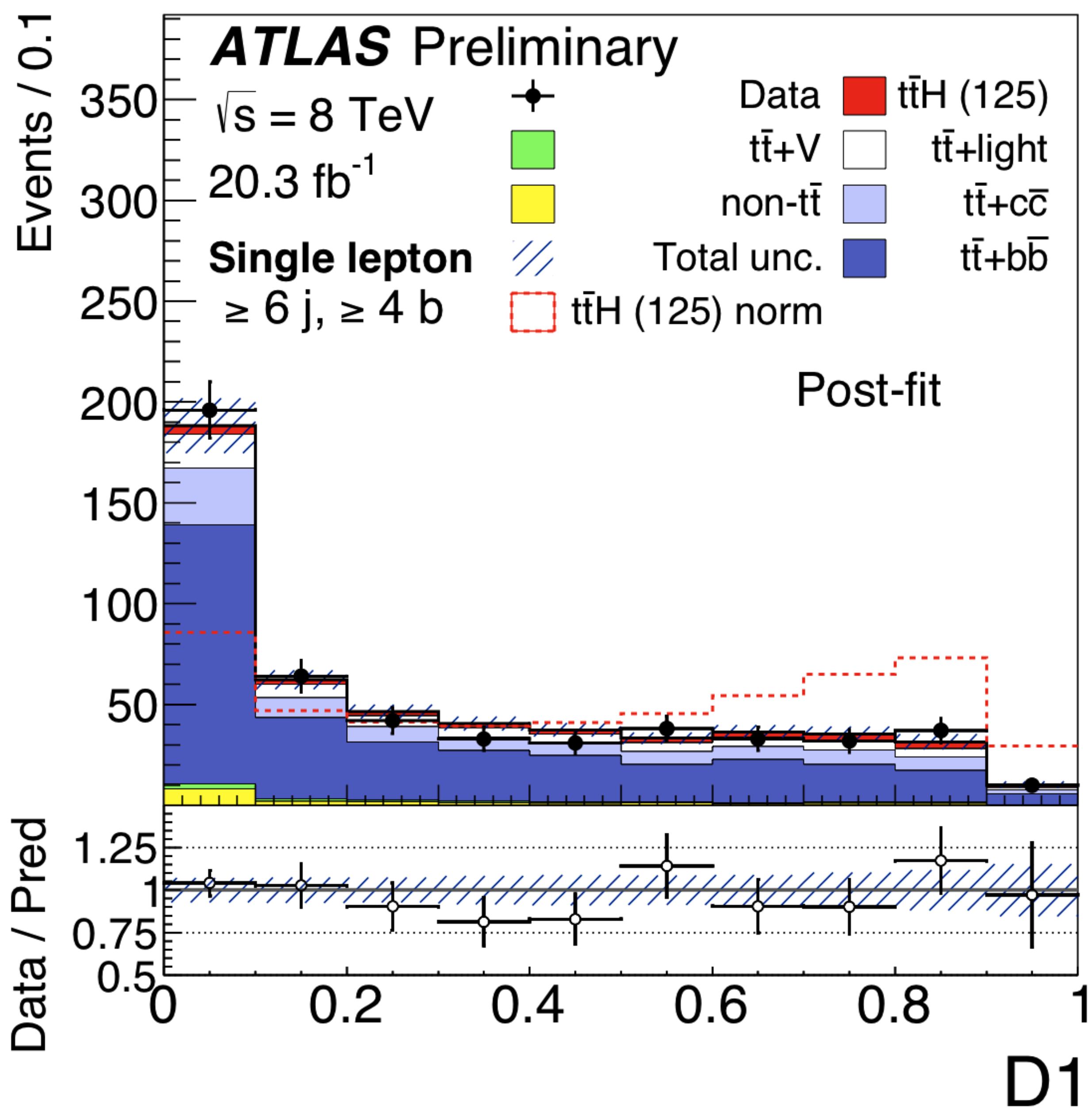
Matrix element method

- Integration via the GSL 1.16 implementation of the VEGAS technique.
- PDFs with LHAPDF 5.9.1 using the CTEQ6 parametrization
- Matrix elements generated by MadGraph 5
- Delta function detector response for the objects eta/phi and lepton 4-momentum
  - 6 jet energies + neutrino pz
- Integration variables:
  - bb mass, leading b energy
  - Hadronic W mass, leading q energy
  - 2 b's from top
  - Solve neutrino pz imposing W mass
- Choose pair of untagged jets closest to W mass
- 12 possible permutations in 6j4b, 36 permutations in 6j3b

Matrix element method

- Good modeling of MEM variables and good separation power, especially in D1

D1, 1st ranked variable in 6j4b



SSLL, 4th ranked variable in 6j3b