Study of the associated production of the Higgs boson with top quarks in the ATLAS experiment at the Large Hadron Collider

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ATLAS Paper

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Search for the production of a Higgs boson in association with a single top quark in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

A search for the production of a Higgs boson in association with a single top quark, tH, is presented. The analysis uses proton–proton collision data corresponding to an integrated luminosity of 140 fb^{-1} at a centre-of-mass energy of 13 TeV, collected by the ATLAS detector at the LHC. The search targets Higgs-boson decays into bb, WW^*, ZZ^*, and $\tau\tau$, accompanied by a lepton (electron or muon) from the top-quark decay. Multivariate techniques are employed to enhance the separation between signal and background processes. The observed signal strength, μ_{tH}, defined as the ratio between the measured cross-section and the predicted Standard Model value, is $\mu_{tH} = 8.1 \pm 2.6$ (stat.) $\pm$ 1.9 (syst.). The corresponding observed (expected) upper limit at the 95% confidence level on the tH cross-section is found to be 13.9 (6.1) times the value predicted by the Standard Model, while it is 2.4 (1.2) under the inverted Yukawa coupling (($y_t = -1$) hypothesis.

ATLAS Note

ANA-HIGG-2020-02-INT2

8th June 2024

Draft version 0.8

Search for associated production of a Higgs boson and a single top quark using pp collisions at 13 TeV with the ATLAS detector in the $H \rightarrow b\bar{b}$ final state.

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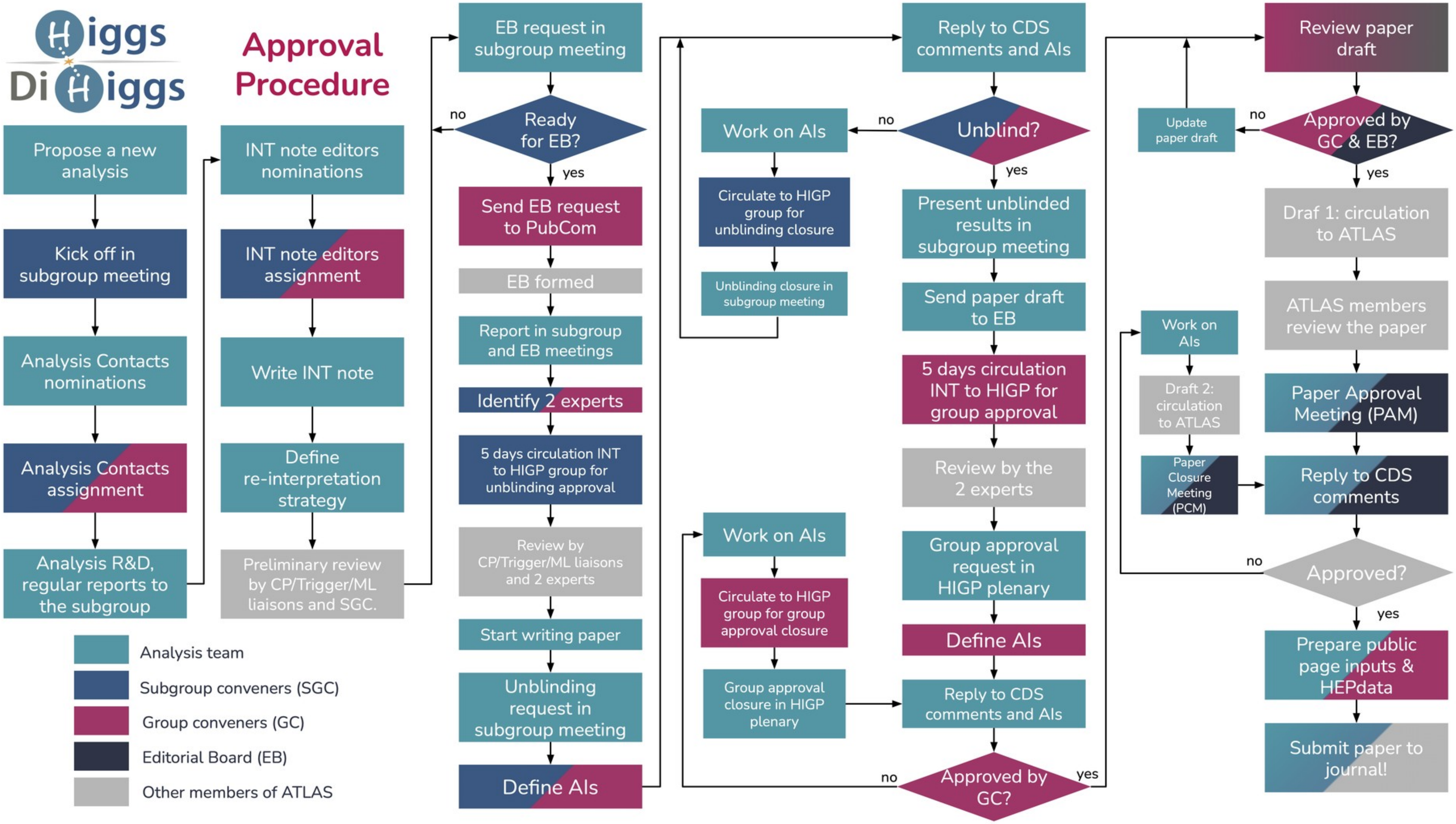
This is a bare bones ATLAS document. Put the abstract for the document here.

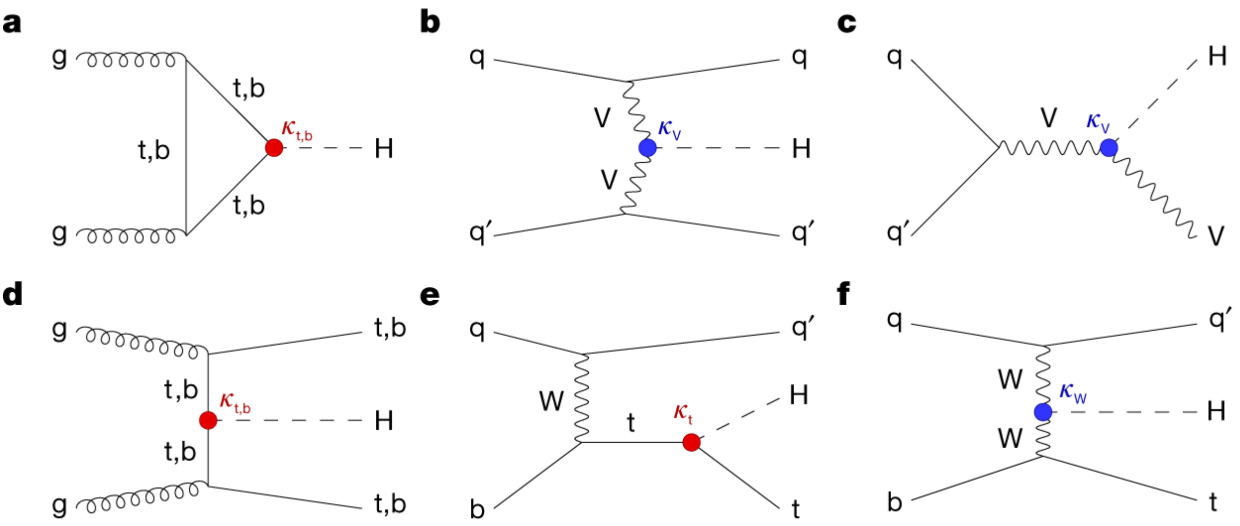
Approval Procedure

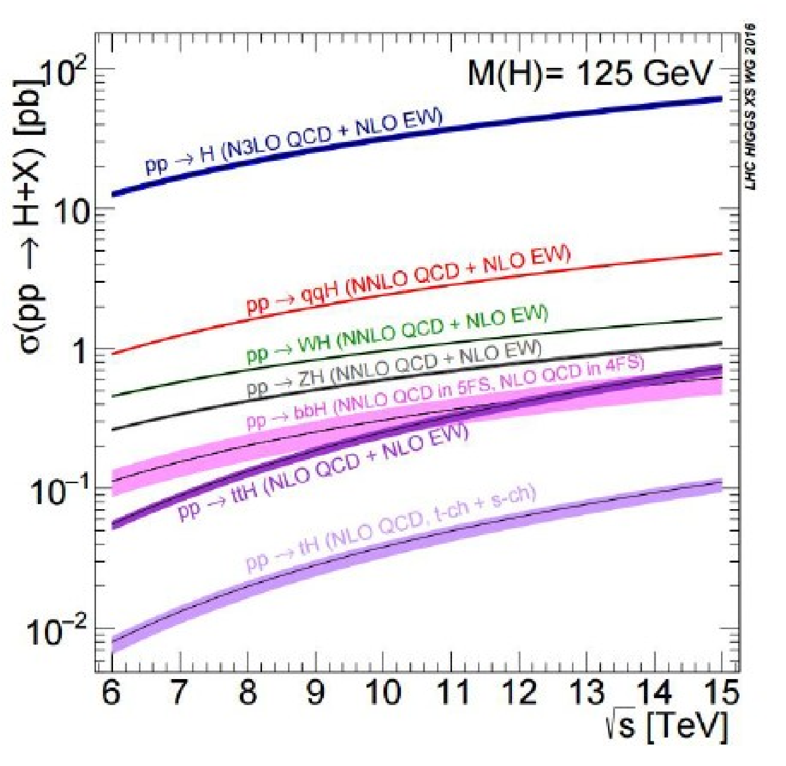


The tH analysis team

Institute	Name	Contribution
Dubna	I. Boyko	BDT variables, C&C Analysis
	A. Didenko	Cross-check neural network implementation and optimization
	N. Huseynov	NTuples Production, C&C Analysis, reco. studies, fakes estimation
	O. Koval	Truth studies, alternative MC generation
	A. Tropina	BDT variables, C&C Analysis, high-pT jets studies
	I. Yelechkich	Cross-check neural network implementation and optimization
Manchester	M. Aly	Fit expert, background studies, BDT variables
	V. Vecchio	Analysis Contact, NTuple Production, fit expert, background studies, BDT variables
	R. Peters	Supervisor
Rome	N. Bruscino	MC Preparation, NTuple Production, BDT developer, Foam developer, fit expert
	S. Gentile	NTuple Production
Prague	M. Patzwahl	Cross-check neural network optimization
	A. Sopczak	Cross-check neural network optimization
Dubna	I. Suslov	C&C Analysis, BDT variables

Higgs boson production modes

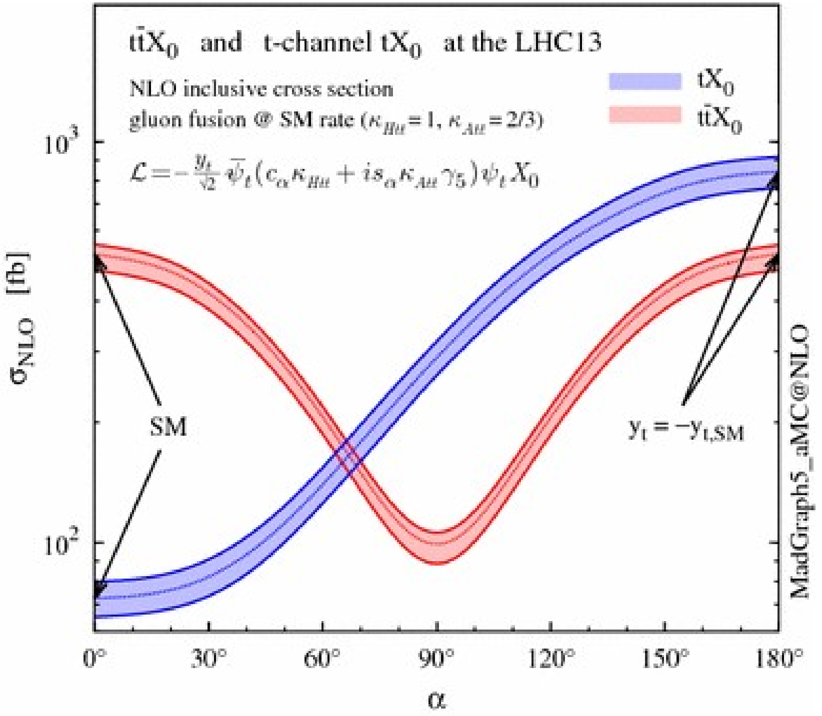




Motivation

[Eur.Phys.J.C(2015)75:267]

- **tH** is sensitive to Top-Higgs and W-Higgs Yukawa couplings
- Direct probe of the **magnitude and sign** of Top-Higgs Yukawa
- Higgs is CP-even (SM).
- For a = 0, interference term destructive
- For a = 180° or **$y_{t,ITC} = - y_{t,SM}$**,
- interference term of (ttH vs WWH) is constructive
- **$\sigma(tH)_{ITC} \approx 11 \bullet \sigma(tH)_{SM}$**



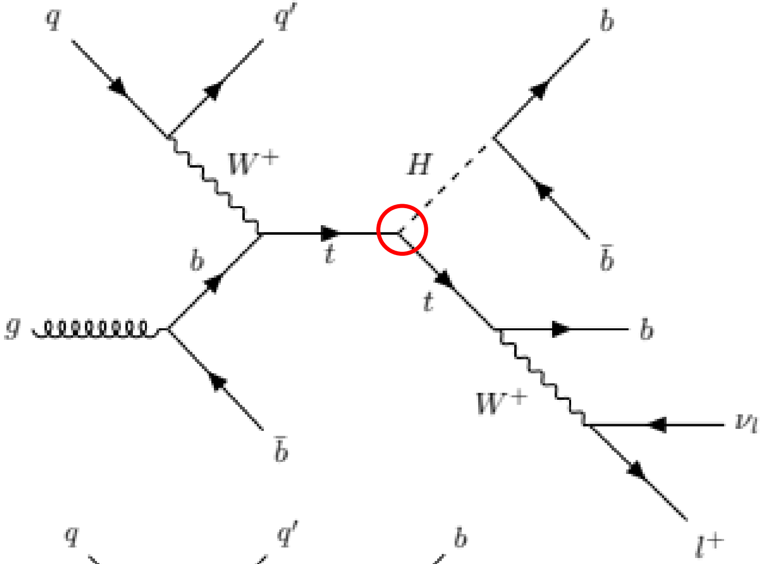
$$\sigma(ttH) \sim |y_t|^2 k^2 \left(A\cos^2\alpha + B\sin^2\alpha\right)$$

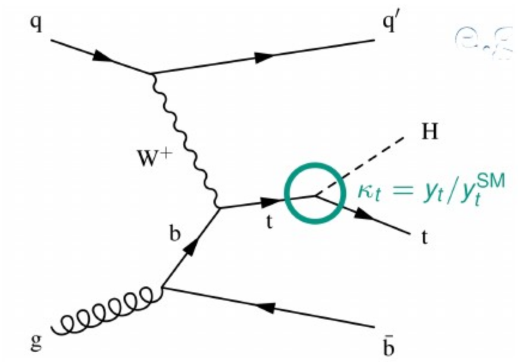
$$\sigma(tH) \sim |y_t^2| k^2 \left(A\cos^2\alpha + B\sin^2\alpha\right) + \boxed{C y_t k \cos\alpha + D y_t k \sin\alpha} + E$$

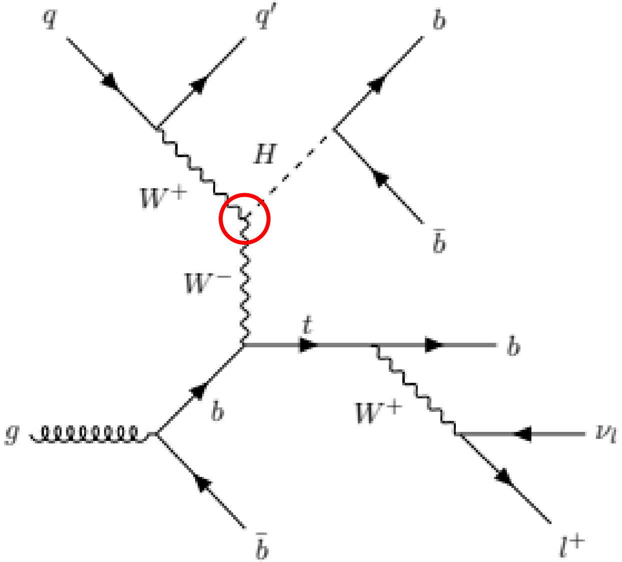
t-H and W-H vertex interference

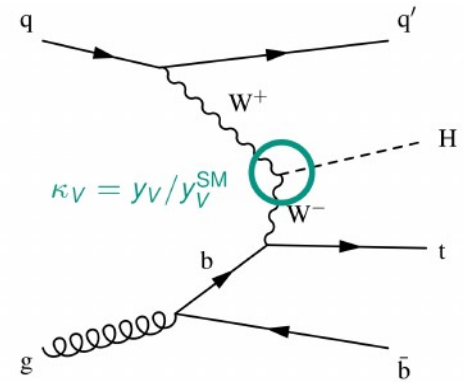
Great probe of new physics !

Motivation: tHqb Feynman diagrams

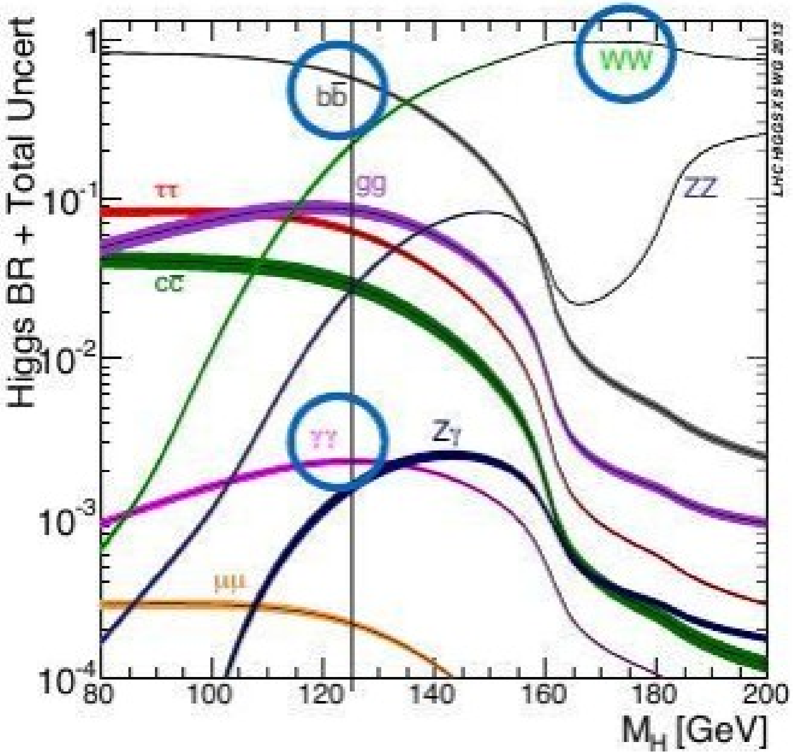




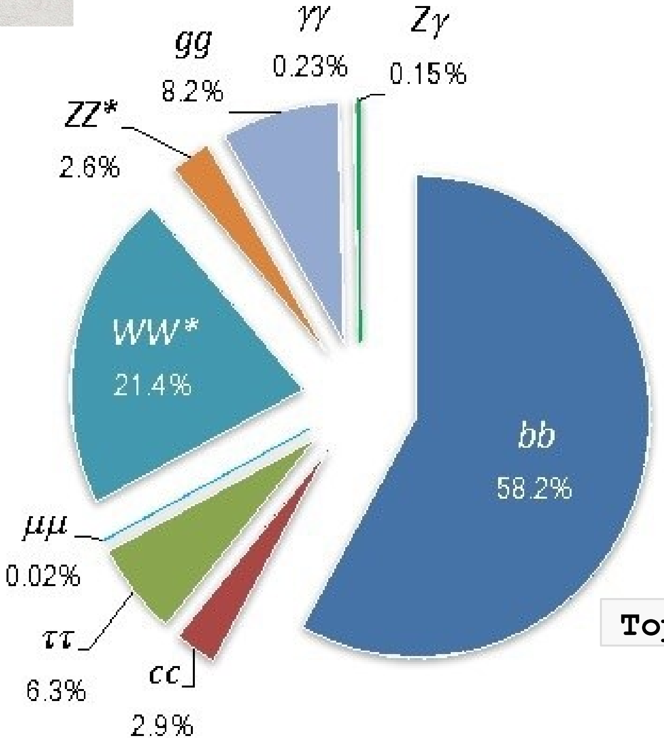




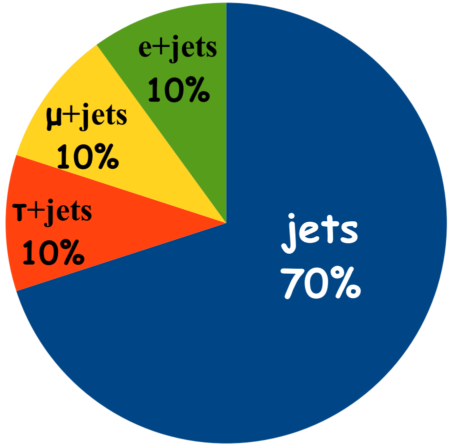
Higgs decays mode



Higgs Branching Fraction



Top quark Branching Fraction



Analysis strategy

- Ntuple production. Skimming.

- Define Preselection Region
- Use obvious cuts to achieve orthogonality with other channels.

- Use Rectangular Cuts
- Apply rectangular cuts (e.g., on variables like lepton multiplicity, jet multiplicity, b- tagging, transverse momentum (pT), etc.) to define the Signal Region (SR) and Control Region (CR).

- Estimate Signal Significance
- Calculate the signal significance to evaluate the potential discovery or exclusion of the signal.

- Estimate Background from Fakes
- Estimate the contribution of fake or misidentified objects (e.g., fake leptons or jets) to the background.

- Use MVA (BDT, NN) for Improved Separation
- Use advanced multivariate analysis techniques, such as Boosted Decision Trees (BDT) or Neural Networks (NN), to enhance the separation between signal and background events.

- Fitting Procedure
- Perform a fitting procedure to model the signal and background distributions and extract relevant parameters.

- Combine Results
- Combine the results from different regions and analyses to obtain a final measurement or limit.

Ntuples and triggers

Using single-lepton ntuples produced with SingleTopAnalysis framework

- from TOPQ1 derivation (ML uses multilepton type)
- sharing same object selections and same MC samples for 1L and ML analyses
- single lepton triggers applied in all channels (trigger matched lepton pT > 27 GeV)

Triggers

Year	Single-electron trigger	Single-muon trigger
2015	HLT_e24_lhmedium_L1EM20VH HLT_e60_lhmedium HLT_e120_lhloose	HLT_mu20_iloose_L1MU15 HLT_mu50
2016–2018	HLT_e26_lhtight_nod0_ivarloose HLT_e60_lhmedium_nod0 HLT_e140_lhloose_nod0	HLT_mu26_ivarmedium HLT_mu50

MC Samples

Process	Generator	Order (scheme)	PDF set	Partor shower	PDF set (tune)
			Signal		
tHq	MadGraph5_aMC@NLO 2.6.2	NLO (4FS)	NNPDF3.0nlo nf4	Pythia 8.230	NNPDF2.3lo (A14 tune)
			Backgrounds		
$t\bar{t}$	Powheg Box v2	NLO (5FS)	NNPDF3.0nlo	Pythia 8.230	NNPDF2.3lo (A14 tune)
V+jets	Sherpa 2.2.1	NLO+LO	NNPDF3.0nnlo	-	-
Diboson	Sherpa 2.2.1-2	NLO+LO	NNPDF3.0nnlo	-	-
Triboson	Sherpa 2.2.2	NLO+LO	NNPDF3.0nnlo	-	-
$t\bar{t}Z$	MadGraph5_aMC@NLO 2.3.3	NLO	NNPDF3.0nlo	Pythia 8.210	NNPDF2.3lo (A14 tune)
$t\bar{t}W$	Sherpa 2.2.10	NLO	NNPDF3.0nnlo	-	-
$t\bar{t}H$	Powheg Box v2	NLO (5FS)	NNPDF3.0nlo	Pythia 8.230	NNPDF2.3lo (A14 tune)
t-channel	Powheg Box v2	NLO (4FS)	NNPDF3.0nlo nf4	Pythia 8.230	NNPDF2.3lo (A14 tune)
tW	Powheg Box v2	NLO (5FS, DR)	NNPDF3.0nlo	Pythia 8.230	NNPDF2.3lo (A14 tune)
s-channel	Powheg Box v2	NLO	NNPDF3.0nlo	Pythia 8.230	NNPDF2.3lo (A14 tune)
tZq	MadGraph5_aMC@NLO 2.3.3	NLO	NNPDF3.0nlo	Pythia 8.230	NNPDF2.3lo (A14 tune)
tWH	MadGraph5_aMC@NLO 2.8.1	NLO (5FS, DR)	NNPDF3.0nlo	Pythia 8.245p3	NNPDF2.3lo (A14 tune)
tWZ	MadGraph5_aMC@NLO 2.3.3	NLO	NNPDF3.0nlo	Pythia 8.212	NNPDF2.3lo (A14 tune)
ttt	MadGraph5_aMC@NLO 2.2.2	NLO	NNPDF3.1nlo	Pythia 8.186	NNPDF2.3lo (A14 tune)
$t\bar{t}t\bar{t}$	MadGraph5_aMC@NLO 2.3.3	NLO	NNPDF3.1nlo	Pythia 8.230	NNPDF2.3lo (A14 tune)
ggH	Powheg Box v2	NLO	CT10	Pythia 8.210	CTEQ6L1 (AZNLO tune)
qqH	Powheg Box v1	NLO	CT10	Pythia 8.186	CTEQ6L1 (AZNLO tune)
WH	Pythia 8.186	LO	NNPDF2.3lo	-	-
ZH	Pythia 8.186	LO	NNPDF2.3lo	-	-

Cross-sections of the MC processes

Standard model cross sections for tH signal as well as for the most relevant background processes estimated from MC simulation. The cross sections are quoted for pp collisions at $\sqrt{s} = 13$ TeV.

JHEP07(2023)092

Process	Cross section [fb]
$t\bar{t}H$	507 [53]
tHq	74.3 [53]
tHW	15.2 [87]
ggH	4.86×10^4 [53]
qqH	3.78×10^3 [53]
WH	1.37×10^3 [53]
ZH	884 [53]
$t\bar{t}Z$	839 [53]
$t\bar{t}W$	650 [53, 69, 70]
$t\bar{t}WW$	6.98 [65]
WZ	4.50×10^4 [88]
ZZ	1.69×10^4 [88]

The Skimming procedure

An Express Tour of the Process

Skimming is a 2-step process

- ✘ **Step 1:** on Grid — O(50) reduction in N-tuple sizes
- ✓ Fully Pythonic code
- ✓ Filter events: >3 b-jets @85%, >3 jets, 1 Loose lepton, MET >25 GeV
- ✓ Filter Truth: >2 b-jets, >0 spectator-jets
- ✓ Filters un-wanted branches
- ✘ **Step 2:** on HT-Condor—O2) reduction in Grid-skimmed sizes
- ✓ ROOT-based code
- ✓ Tighter filter to define pre-selection: >3 b-jets @70%
- ✓ Compute new variables — e.g.
  - ✓ event BDT & Foam score,
  - ✓ Various object containers (leptons, jets, ...) and their kinematics
  - ✓ MC-related factors (k-factor, x-section, ...)
  - ✓ Discriminating reco-level variables
- ✓ Drop branches only needed for new variables

Object selection

Common selection of electron, muons and hadronic taus

- **electrons: p_T > 27 GeV + ID TightLH + PLImprovedTight**
- **muon: p_T > 27 GeV + ID Medium + PLImprovedTight**
- **hadronic's: RNN Medium → veto applied (==1L and ==0 τ_{had})**

LIGHT LEPTONS SELECTION

	Pre-selected electron	Pre-selected muon
Identification	looseAndBLayerLH	medium
Acceptance	$p_T > 10\,\text{GeV}, \lvert\eta^{\text{clust}}\rvert < 2.47$ except $1.37 < \lvert\eta^{\text{clust}}\rvert < 1.52$	$p_T > 10\,\text{GeV}, \lvert\eta\rvert < 2.5$
Impact parameter	$\lvert d_0/\sigma(d_0)\rvert < 5.0$ $\lvert z_0 \sin(\theta)\rvert < 0.5\,\text{mm}$	$\lvert d_0/\sigma(d_0)\rvert < 3.0$ $\lvert z_0 \sin(\theta)\rvert < 0.5\,\text{mm}$
Overlap removal	See Section 5.8	
	Electron	Muon
Identification	tightLH	medium
Isolation	PLImprovedTight	PLImprovedTight

HADRONIC TAUS SELECTION

	τ_{had}
Acceptance	$p_T > 20\,\text{GeV}, \lvert\eta^{\text{clust}}\rvert < 2.5$ except $1.37 < \lvert\eta^{\text{clust}}\rvert < 1.52$
Number of tracks	1 or 3
Identification	RNN Medium (Loose)
Electron veto	electron BDT Loose (Loose)
Overlap removal	See Section 5.8

Object selection

Common selection of jets

EMPFlow (AntiKtEMPFlow) jets $p_T > 20$ GeV and $|\eta| < 4.5$

- **Both JVT and fJVT requirements are applied**
- **DL1r PCBT working point used in all channels**
- **Overlap Removal on loose leptons and jets**

JETS

Pre-selected jet	
Collection	`AntiKt4EMPFlowJets`
Acceptance	$p_T > 20\,\text{GeV}$, $|\eta| < 4.5$
Jet Vertex Tagger	JVT > 0.5 if $|\eta| < 2.4$ and $p_T < 60\,\text{GeV}$
	fJVT < 0.4 if $2.5 < |\eta| < 4.5$ and $p_T < 120\,\text{GeV}$
Overlap removal	See Section 5.8
***b*-tagging jet**	
Acceptance	$p_T > 20\,\text{GeV}$, $|\eta| < 2.5$
b-tagging	DL1r algorithm

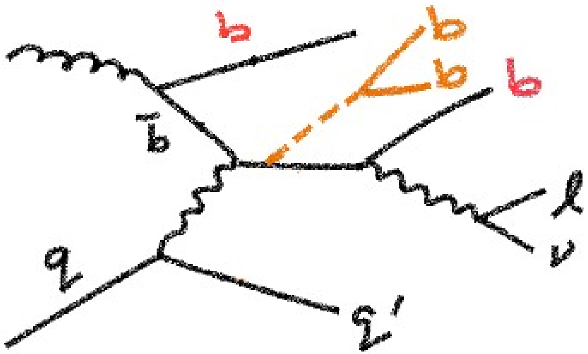
Definition of analysis regions

Preselection region	
Number of leptons (PLIVTight)	1
Number of hadronic taus	0
Number of b-jets (WP 70%)	≥ 3
Missing energy, E^{miss}_{T}	≥25GeV
ttHbb veto	$!(n^{70\%}_{b} \geq 4 \ \&\& \ n_{j} \geq 5)$

	Signal region	Control region
Number of leptons (PLIVTight)	1	1
Number of hadronic taus	0	0
Number of b-jets (WP 70%)	3, 4	• ≥ 2
Missing energy, E^{miss}_{T}	≥25GeV	≥25GeV
ttHbb veto	$!(n^{70\%}_{b\text{-}jets} \geq 4 \ \&\& \ n_{jets} \geq 5)$	$!(n^{70\%}_{b\text{-}jets} \geq 4 \ \&\& \ n_{jets} \geq 5)$
Number of forward jets, n^{fwd}_{jets}	≥ 1	0

Pre-selection region and yields

Processes	Pre-selection
tH	73.80 ± 0.15
tWH	49.62 ± 0.04
tt + ≥1b	60170 ± 50
tt + ≥1c	33585 ± 29
tt + light	106290 ± 90
ttH	1676.9 ± 1.4
ttZ	891.0 ± 0.8
ttW	362.01 ± 0.31
tZq	170.54 ± 0.25
tWZ	2.2157 ± 0.0019
Wt channel	5849± 5
t channel	3223 ± 4
s channel	259.71 ± 0.22
W + jets	4072 ± 4
Z + jets	609.5 ± 0.6
VV	291.79 ± 0.26
other Higgs	25.054 ± 0.023
Rare top	8.936 ± 0.008
Fakes	8028 ± 7
Total	225640 ± 190
Data	244167



Topology-motivated requirements:

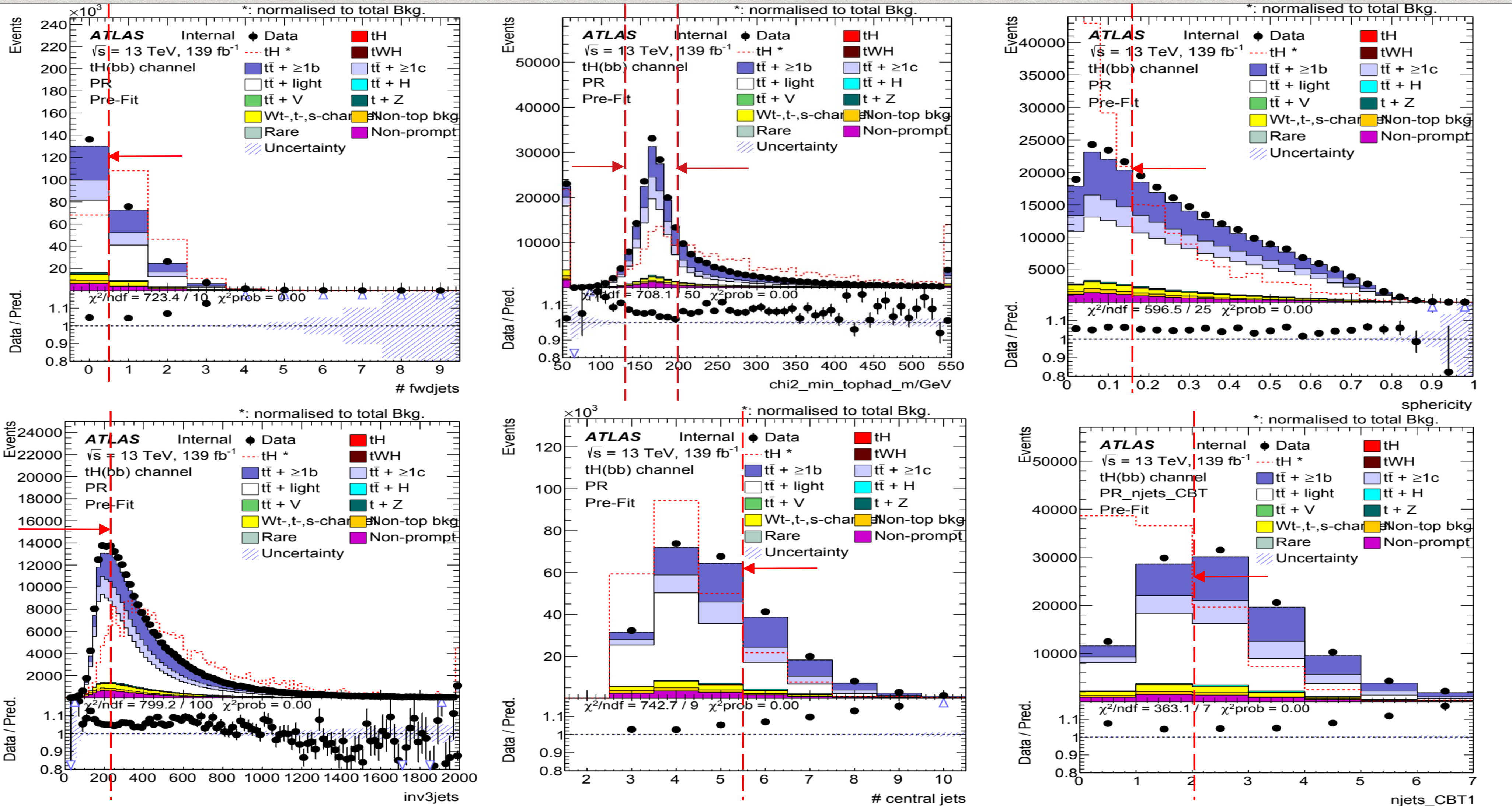
$N^{tight}_{lepton} = 1$ **(PLIV isolation)**

$N^{WP70}_{bjets} \geq 3$

$E^{miss}_{T} > 25$ GeV

!($N_{jets} \geq 5$ && $N_{jets} \geq 4$) - orthogonality condition with ttH(bb)

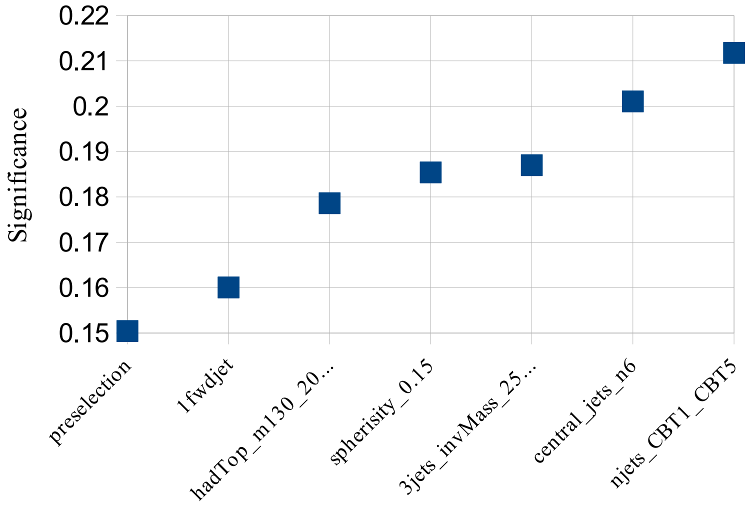
C&C analysis



*: normalised to total Bkg.
ATLAS Internal
√s = 13 TeV, 139 fb-1
tH(bb) channel
PR
PR_njets_CBT
Pre-Fit
Data
tH *
tH
tWH
tt̄ + ≥1b
tt̄ + ≥1c
tt̄ + light
tt̄ + H
tt̄ + V
t + Z
Wt-,t-,s-chan
Non-top bkg
Rare
Non-prompt
Uncertainty
Events
Data / Pred.
χ2/ndf = 723.4 / 10 χ2prob = 0.00
fwdjets
χ2/ndf = 708.1 / 50 χ2prob = 0.00
chi2_min_tophad_m/GeV
χ2/ndf = 596.5 / 25 χ2prob = 0.00
sphericity
χ2/ndf = 799.2 / 100 χ2prob = 0.00
inv3jets
χ2/ndf = 742.7 / 9 χ2prob = 0.00
central jets
χ2/ndf = 363.1 / 7 χ2prob = 0.00
njets_CBT1

C&C analysis: Significance & Limit of tHq(SM)

Preselection Significance = 0.15
Signal Region Significance = 0.21
Improving ≈ 40%



tHq(SM): Significance = 0.21

95% C.L.s upper limit				
-2σ	**-1σ**	**exp.median**	**+1σ**	**+2σ**
5.00	6.71	9.32	12.96	17.38

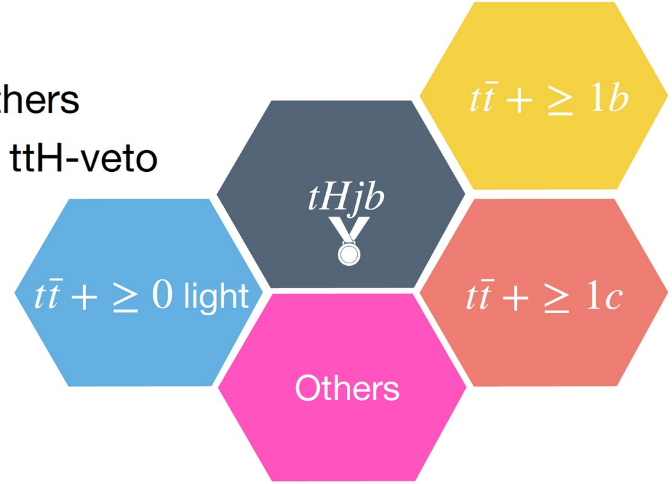
Multidimensional Multivariate Analysis

- Multi-class BDT (Boosted Decision Trees)
- Neural Network

• Multi-class BDT (Boosted Decision Trees)

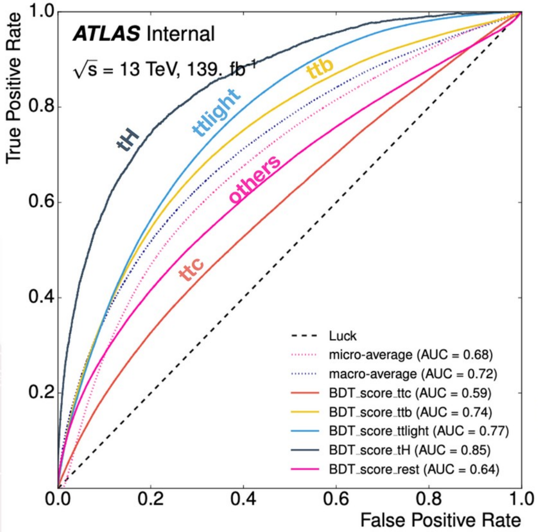
Multi-classification BDT (Gradient) with k-fold method

- 5 *hypothesis:* tH vs. $t\bar{t}$+≥1b vs. $t\bar{t}$+≥1c vs. $t\bar{t}$+light vs. Others
- *pre-selection:* n_L=1 + n_τ=0 + $n_b^{70\%}$≥3 + E_T^{miss}≥25GeV + ttH-veto
- *hyper-parameters:*
  - Folds = 10, nEstimators = ~4k (more details in backup)



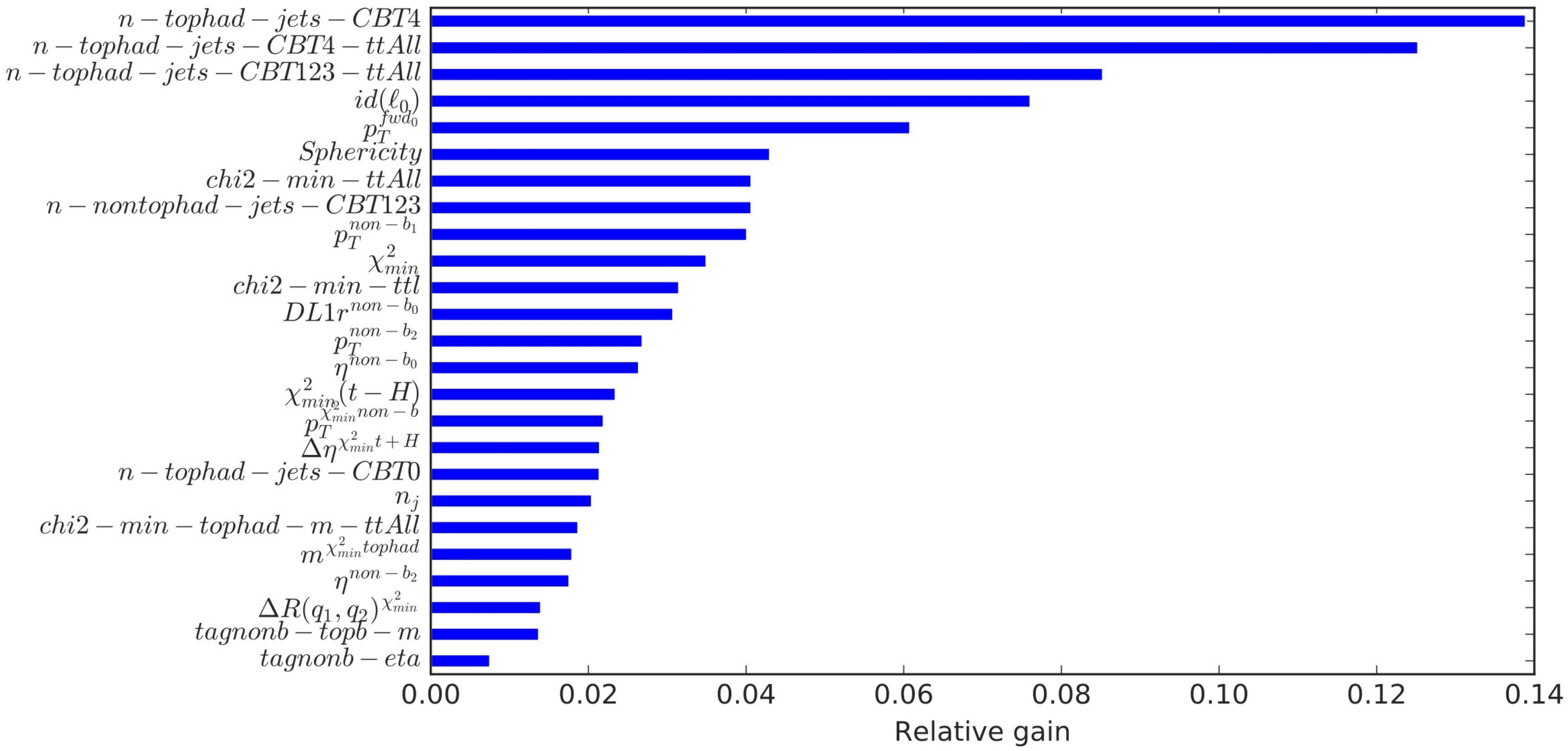
Procedure for the “optimal” set of input variables:

- starting with *119* variables
- → remove less important variables (gain<1%)
- → remove the most correlated ones (|ρ|>75%)
- ending up with *26* variables
- check modelling in pre-selection region
- post-EB#1: remove 3 mis-modelled variables
  - $n_j(CBT-bin4)$, $n_j(CBT-bin5)$ and $m_{3\,jets}$
- post-EB#1: include 2 new variables
  - $M(b_{top}, j_{tag})$ and $|\eta(b_{top}, j_{tag})|$
- ending up with *25* variables
- check post-fit modelling in SR and CR



• Multi-class BDT

Variable ranking (gain) representing the overall gain in the multi-class BDT



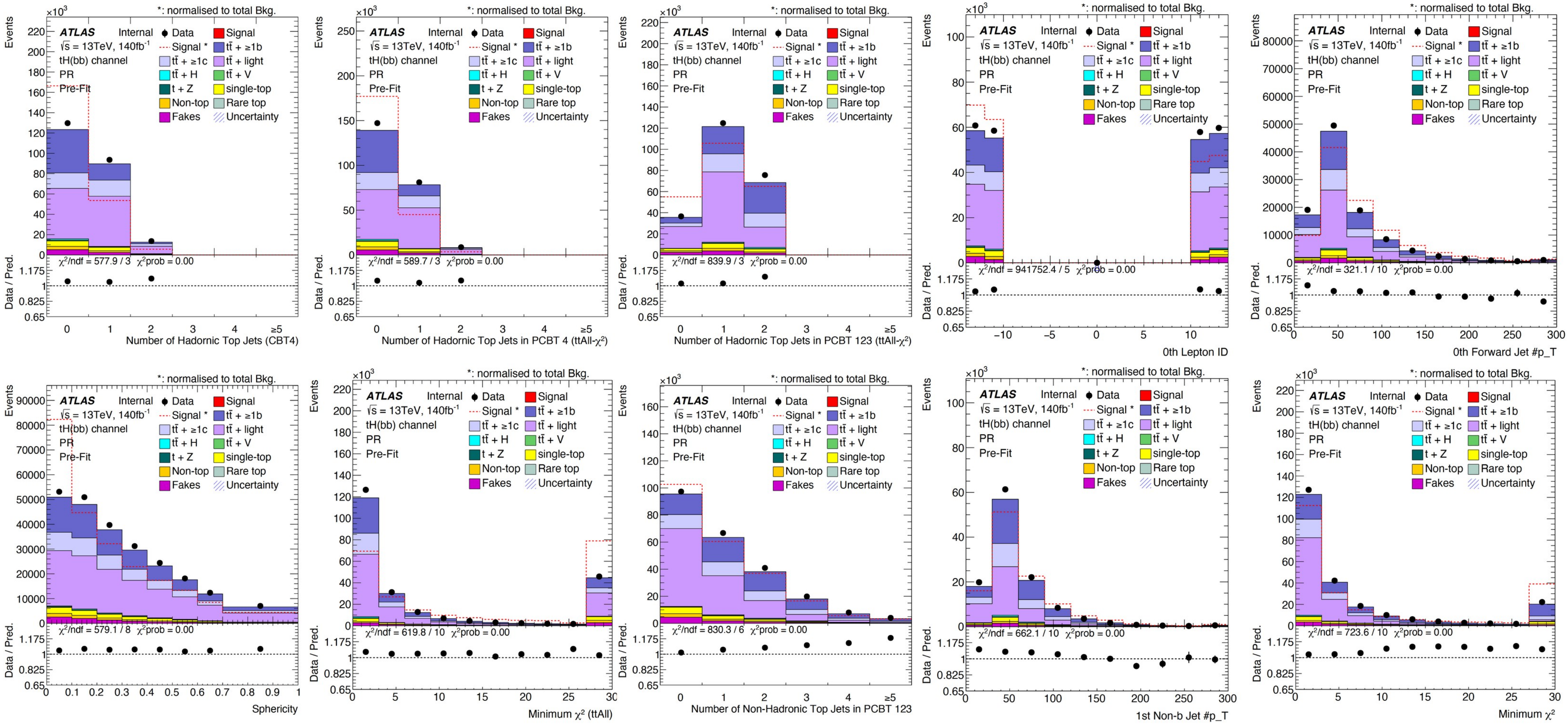
Variables Definitions

Variable	Meaning
$n_{j,t_{\text{had}}}(\chi^2_{\text{min, ttl}}, \text{PCBT-bin } 4)$	number of jets that belong to the hadronic top-quark found from reconstructing $t\bar{t}$ events but allowing only Hypothesis I as described in Appendix A.3 within the 4^{th} PCBT bin
$n_{j,t_{\text{had}}}(\chi^2_{\text{min, ttAll}}, \text{PCBT-bin } 4)$	number of jets that belong to the hadronic top-quark found from reconstructing $t\bar{t}$ events as described in Appendix A.3 within the 4^{th} PCBT bin,
$n_{j,t_{\text{had}}}(\chi^2_{\text{min, ttAll}}, \text{PCBT-bin } \in \{1,2,3\})$	number of jets that belong to the hadronic top-quark found from reconstructing $t\bar{t}$ events as described in Appendix A.3 within the 1^{st}, 2^{nd} or 3^{rd} PCBT bin
$id(\ell_0)$	identification number of the lepton combining charge and flavour information
$p^T_{\text{fwd},0}$	transverse momentum of the leading forward-jet
Sphericity	as defined in [3]
$\chi^2_{\text{min,ttAll}}$	the minimum χ^2 value found from reconstructing $t\bar{t}$ events as described in Appendix A.3
$n_{j,\text{not-}t_{\text{had}}}(\chi^2_{\text{min, ttl}}, \text{PCBT-bin} \in \{1,2,3\})$	number of jets that do not belong to the hadronic top-quark found from reconstructing $t\bar{t}$ events but allowing only Hypothesis I as described in Appendix A.3 within the 1^{st}, 2^{nd} or 3^{rd} PCBT bin
$p^T_{\text{light},1}$	transverse momentum of the 2^{nd} leading jet failing the b-tagging requirement
$\chi^2_{\text{top-higgs}}(M_H = 111.5, M_t = 168)$	the minimum χ^2 value found from reconstructing $tHq(H \to b\bar{b})$ events, where the leptonic W from the top quark decay is reconstructed using the neutrino reconstruction technique described in Appendix A.1
$\chi^2_{\text{min,ttl}}$	the minimum χ^2 value found from reconstructing $t\bar{t}$ events allowing only Hypothesis I as described in Appendix A.3
$\text{DL1r}_{\text{light},0}$	pseudo-continuous b-tagging distribution for the leading jet failing the b-tagging requirement
$p^T_{\text{light},2}$	transverse momentum of the 3^{rd} leading jet failing the b-tagging requirement

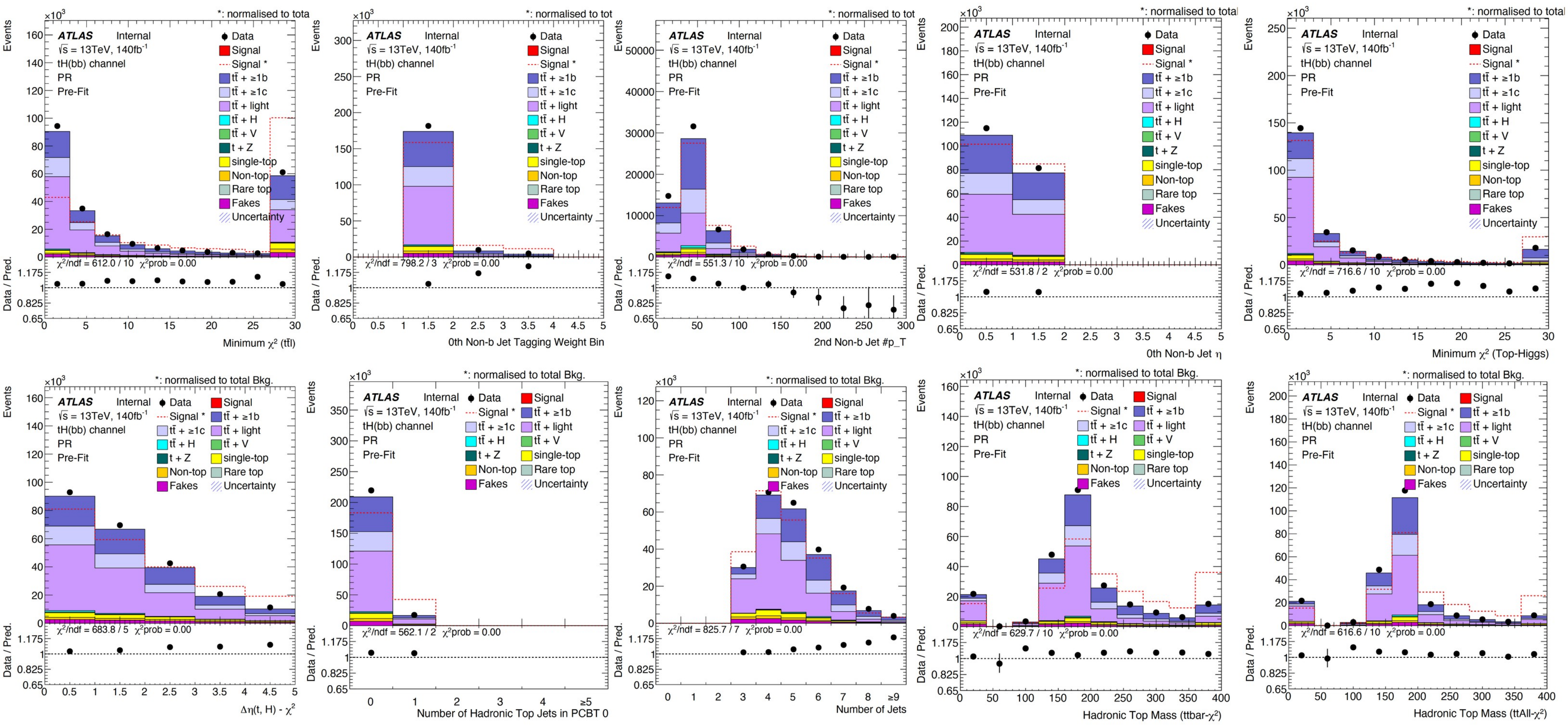
Variables Definitions

$\eta_{\text{light},0}$	pseudo-rapidity of the leading jet failing the b-tagging requirement
$\chi^2_{\text{top-higgs}}(M_H = 113, M_t = 165)$	the minimum χ^2 value found from reconstructing $tHq(H \to b\bar{b})$ events, where the leptonic W from the top quark decay is reconstructed using the neutrino reconstruction technique described in Appendix A.1
$p^T_{\text{light},0}$	transverse momentum of the leading jet failing the b-tagging requirement
$\Delta\eta_{\text{top-higgs}}$	the $\Delta\eta$ between the reconstructed top quark and the reconstructed Higgs boson according to the minimum χ^2 method
$n_{j,t_{\text{had}}}(\chi^2_{\text{min, ttI}}, \text{PCBT-bin 0})$	number of jets that belong to the hadronic top-quark found from reconstructing $t\bar{t}$ events but allowing only Hypothesis I as described in Appendix A.3 within the 0th PCBT bin
n_j	number of jets
$m_{t_{\text{had}}}(\chi^2_{\text{min, ttAll}})$	the mass of the reconstructed hadronic top-quark found from reconstructing $t\bar{t}$ events as described in Appendix A.3
$m_{t_{\text{had}}}(\chi^2_{\text{min, ttI}})$	the mass of the reconstructed hadronic top-quark found from reconstructing $t\bar{t}$ events but allowing only Hypothesis I as described in Appendix A.3
$\eta_{\text{light},2}$	pseudo-rapidity of the 3rd leading jet failing the b-tagging requirement
$\Delta R(q_1^W, q_2^W)$	the minimum ΔR between the two jets assigned to the hadronic W decay from reconstructing $t\bar{t}$ events as described in Appendix A.3
$M(b_{\text{top}}, j_{\text{tag}})$	the invariant mass of the b-jet from top decay found using a reconstruction of $tHq(H \to b\bar{b})$ events and the light-flavour jet most de-correlated from the top quark system. The light jet is chosen such that it maximises the invariant mass $M(b_{\text{top}}, j_{\text{tag}})$
η_{tag}	the η of the light-flavour jet, η_{tag} most de-correlated from the top quark system. The light jet is chosen such that it maximises the invariant mass $M(b_{\text{top}}, j_{\text{tag}})$

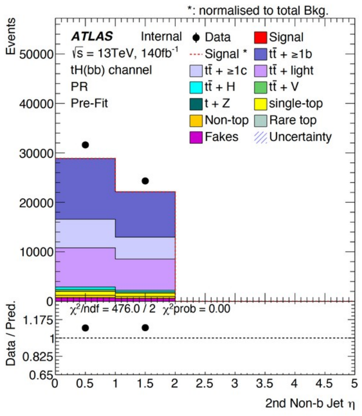
Variables modelling

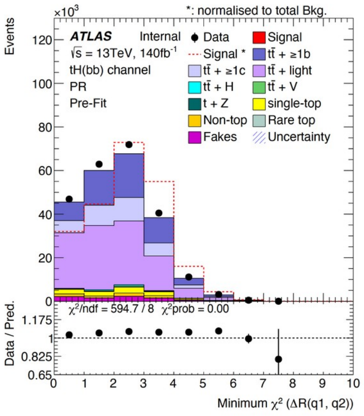


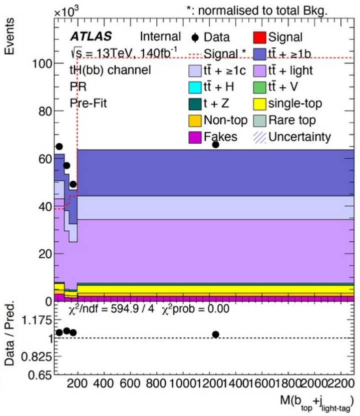
Variables modelling

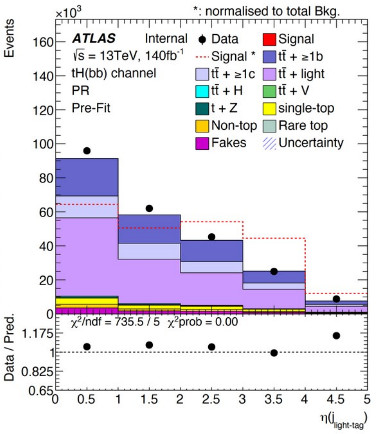


Variables modelling



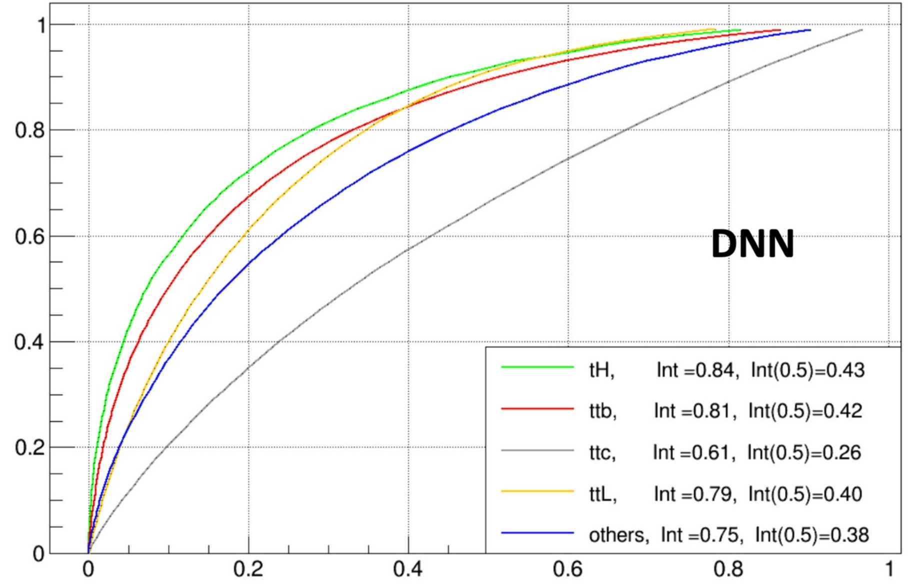


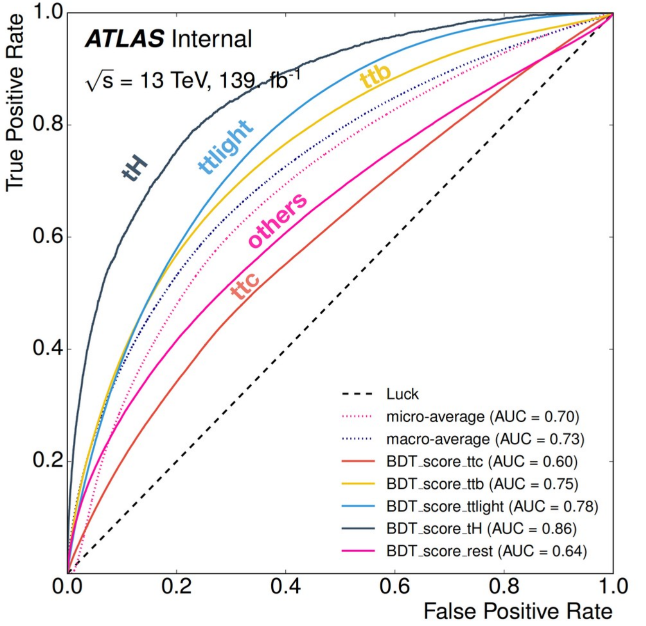




Neural Network

- Deep Neural Network used as tool to classify tH(bb) signal and main backgrounds
  - Multi-classification with five possible output categories
- Employs Keras API to model DNN - 4 hidden layers with [90,90,90,30]
- structure
- Initial results are comparable with the existing MVA
- DNN still in very early stages, big room for improvements in
  - The network structure and setup
  - Implementation of new reco-level variables for training
  - Choice of learning algorithm and performance in data

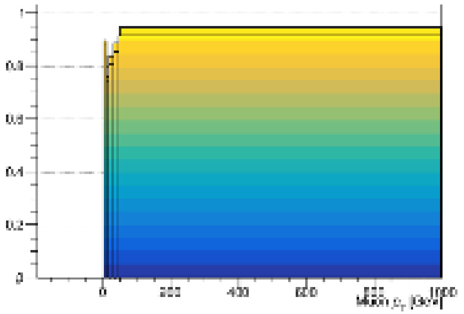




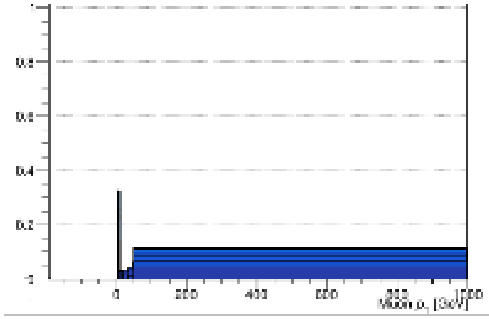
Process	DNN AUC	BDT AUC
tH	0,84	0,86
ttb	0,81	0,75
ttc	0.61	0.60
ttL	0.79	0.78
others	0.75	0.64

Non-prompt backgrounds

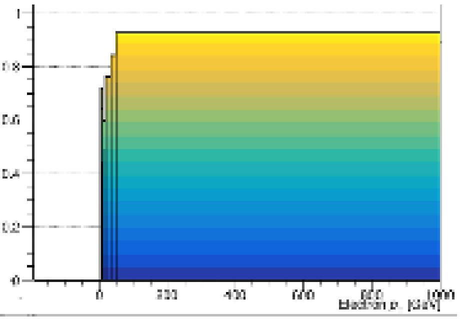
- Non-prompt (fake) lepton background originated by HF/LF jets mis-reconstructed as electron or muons - small (3-5%) but not negligible background
- Fake background by the Matrix Method with IFF prescription
- Performed at the ‘Sklimming’ level using the FakeBkgTools package
- uses FakeEfficiencyTool to extract efficiency maps from data
- Fake and real efficiencies parameterised in p_T-η space
- Estimation performed in “*fake*-enriched” regions
- PLIV Tight efficiency maps used in-line with the ML analyses
- A conservative 50% normalisation uncertainty is used on yields



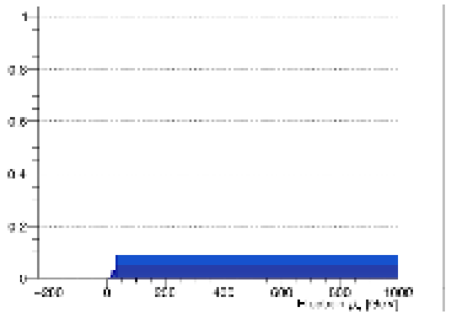
Muon Real Efficiency



Muon Fake Efficiency



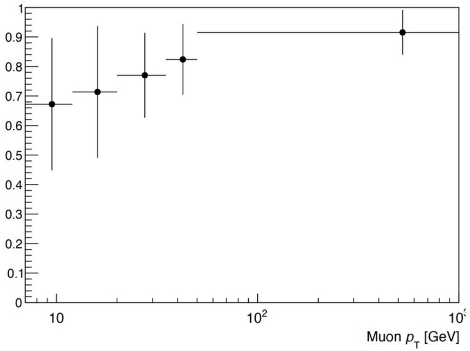
Electron Real Efficiency



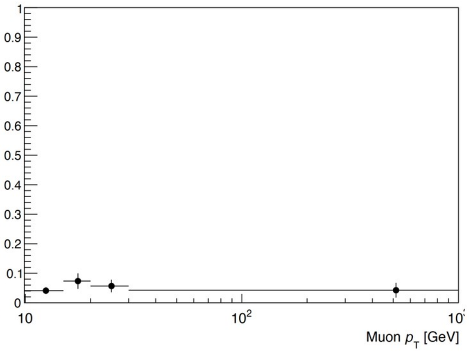
Electron Fake Efficiency

Non-prompt backgrounds

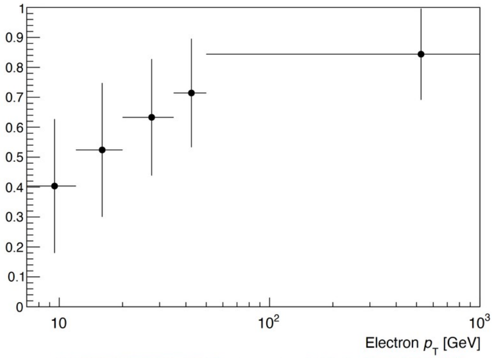
pT



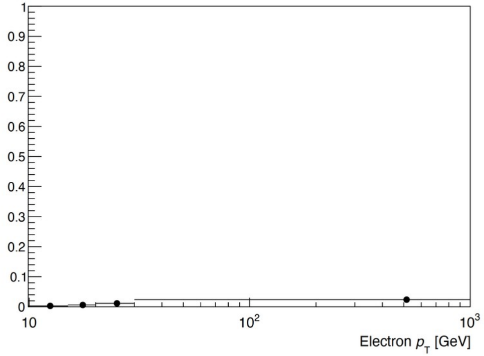
Muon Real Efficiency



Muon Fake Efficiency

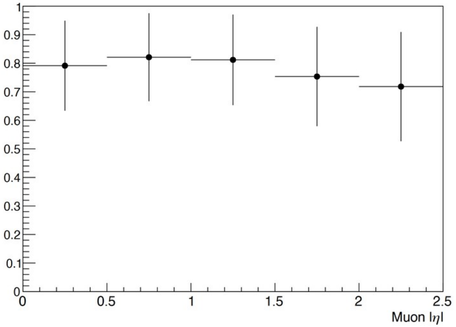


Electron Real Efficiency

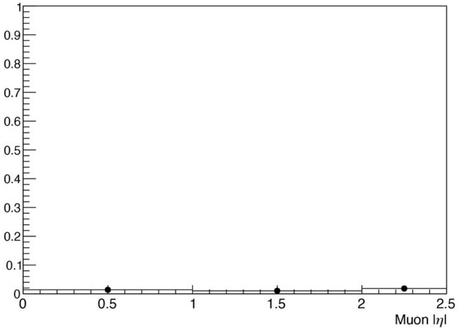


Electron Fake Efficiency

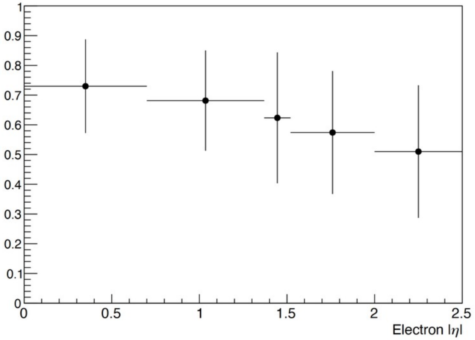
Eta



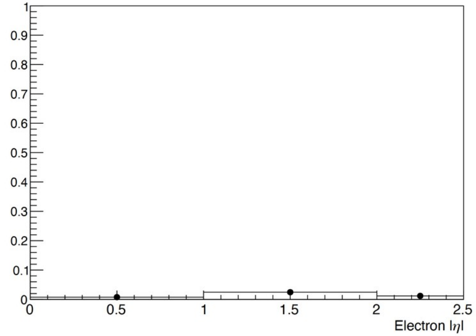
Muon Real Efficiency



Muon Fake Efficiency



Electron Real Efficiency



Electron Fake Efficiency

Fitting

Profile likelihood fit with BDT scores as templates

SM scenario : Yields of the analysis (pre/post fit)

pre-fit

	SR	CR (tt+≥ 1b)
tH	34.7 ± 2.3	7.4±1.2
tWH	4.6 ± 2.6	19 ±10
tt + ≥1b	6800 ± 1100	20 100 ± 2600
tt + ≥1c	4000 ± 2400	11 000 ± 6000
tt + light	19 300 ± 3300	23 100 ± 500
ttH	120 ± 16	680 ± 70
tt + Z	68 ±9	340 ± 40
tt + W	22.8 ±3.4	149 ± 22
tZq	69 ±7	20.4 ± 1.9
tWZ	0.20±0.10	0.9 ± 0.5
Wt channel	970 ± 260	1500 ± 500
t channel	1070 ± 180	350 ± 120
s channel	43 ± 8	40 ± 11
W + jets	740 ± 310	900 ± 400
Z + jets	140 ± 50	100 ± 40
VV	48 ± 25	70 ± 40
other Higgs	6 ± 5	5.3 ± 2.9
Rare top	0	3
Fakes	1700 ± 500	1600 ± 500
Total	35 000 ± 5000	60 000 ±8000
Data	35 869	65 002

post-fit

	SR	CR (tt + ≥ 1b)
tH	249.481±nan	52.45±3.6
tWH	32.7793±nan	135.63±12
tt + ≥1b	8200 ±1000	25 600 ±1900
tt + ≥1c	3800 ±1400	9900 ±3200
tt+ light	18 600 ±1100	23 500 ±2100
ttH	121 ±16	690 ±70
tt + Z	68 ±9	340 ±40
tt + W	22.9 ±3.3	149 ±21
tZq	69 ±6	20.5 ±1.9
tWZ	0.20±0.11	0.9±0.5
Wt channel	980 ±250	1600 ±500
t channel	1060 ±170	350 ±120
s channel	42 ±7	40 ±11
W + jets	750 ±300	900 ±350
Z + jets	140 ±50	100 ±40
VV	47 ±24	70 ±40
other Higgs	6 ±4	5.3±2.9
Rare top	0	3
Fakes	1700 ±500	1600 ±500
Total	35 870 ±230	65 000 ±400
Data	35 869	65 002

ITC scenario : Yields of the analysis (pre/post fit)

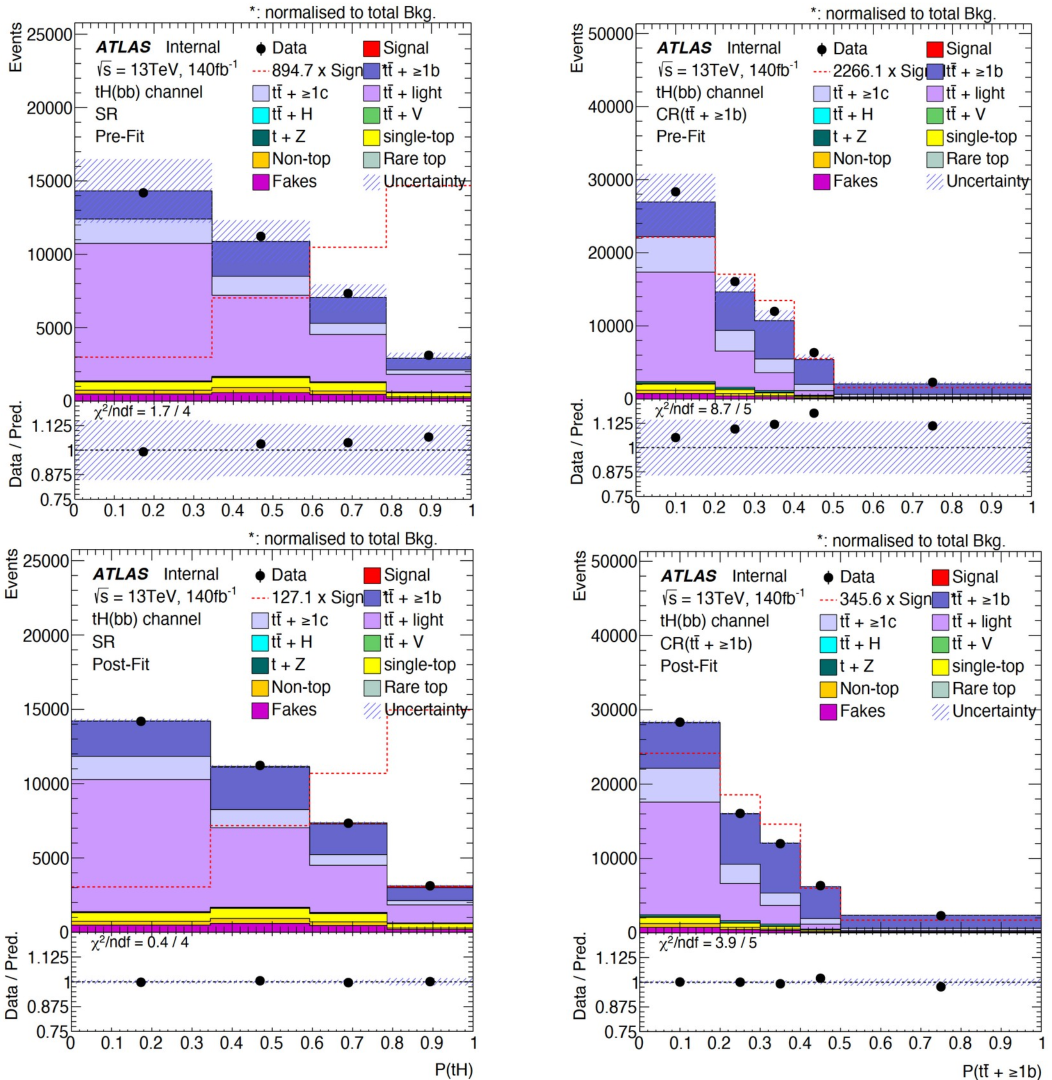
pre-fit

	SR	CR($tt+>1b$)
tH	680 ± 110	106 ± 19
tWH	32 ± 4	114 ± 12
$tt+>1b$	6800 ± 1100	20100 ± 2600
$tt+>1c$	4000 ± 2400	11000 ± 6000
tt + light	19 300 ± 3300	23100 ± 3500
ttH	120 ± 14	683 ± 34
$tt+Z$	68 ± 9	340 ± 40
$tt+W$	20.1 ± 3.0	134 ± 19
tZq	69 ± 7	20.4 ± 1.9
tWZ	0.20 ± 0.10	0.9 ± 0.5
Wt channel	970 ± 260	1500 ± 500
t channel	1070 ± 180	350 ± 120
s channel	43 ± 8	40 ± 11
W + jets	740 ± 310	900 ± 400
Z + jets	140 ± 50	100 ± 40
VV	48 ± 25	70 ± 40
other Higgs	6 ± 5	5.3 ± 2.9
Rare top	0.08 ± 0.04	3.3 ± 1.7
Fakes	1700 ± 500	1600 ± 500
Total	36 000 ± 5000	60 000 ± 8000
Data	35 869	65 002

post-fit

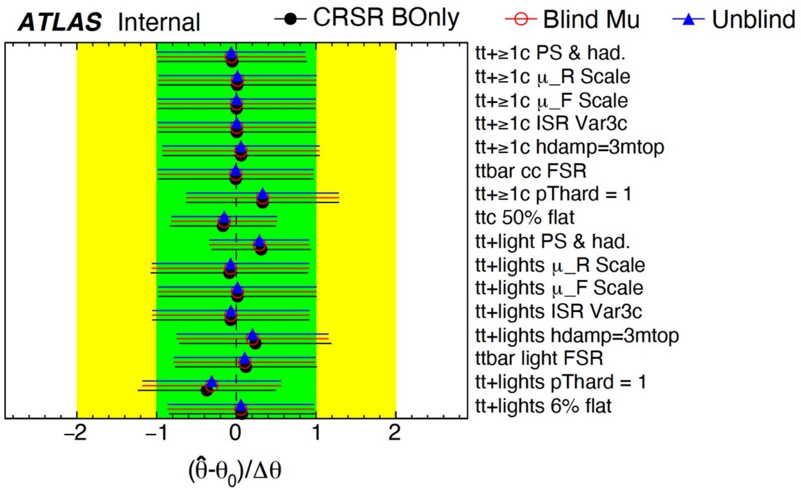
	SR	CR($tt+>1b$)
tH	400 ± 400	70 ± 70
tWH	21 ± 21	80 ± 80
$tt+>1b$	8000 ± 1100	25 600 ± 1900
$tt+>1c$	3800 ± 1500	10100 ± 3300
tt + light	18 600 ± 1100	23 400 ± 2100
ttH	120 ± 16	683 ± 38
$tt+Z$	68 ± 9	340 ± 40
$tt+W$	20.1 ± 2.9	134 ± 19
tZq	69 ± 6	20.5 ± 1.9
tWZ	0.20 ± 0.11	0.9 ± 0.5
Wt channel	980 ± 250	1600 ± 500
t channel	1060 ± 170	350 ± 120
s channel	42 ± 7	40 ± 11
W + jets	740 ± 300	890 ± 350
Z + jets	140 ± 50	100 ± 40
VV	47 ± 24	70 ± 40
other Higgs	6 ± 4	5.3 ± 2.9
Rare top	0.08 ± 0.04	3.3 ± 1.7
Fakes	1700 ± 500	1500 ± 500
Total	35 870 ± 220	65 000 ± 400
Data	35 869	65 002

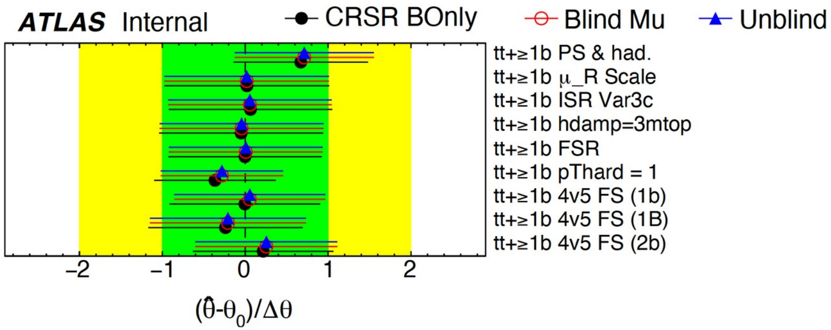
Data/MC comparison



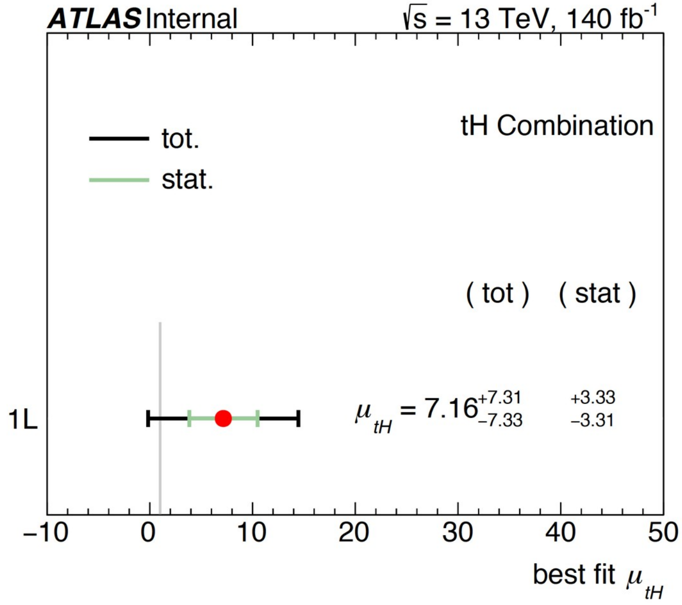
Pulls comparison

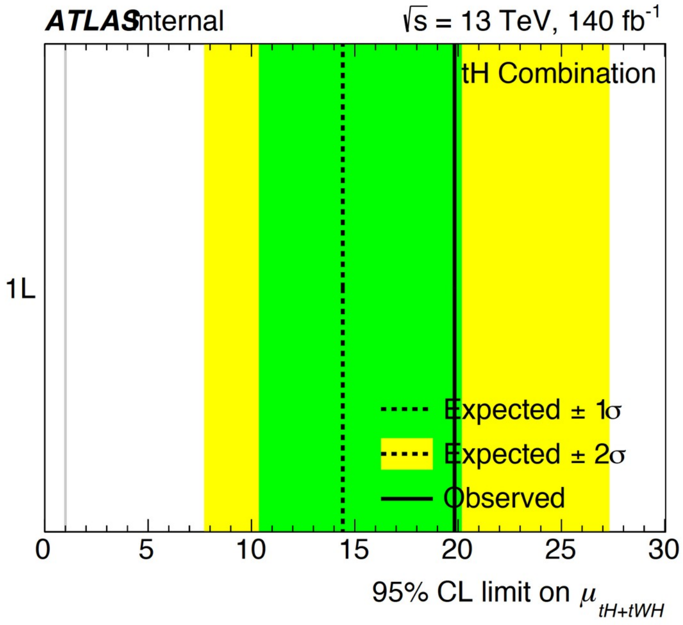
- **Red** and **blue** have to be exactly the same as the only difference between the two is in the fact that we look at the actual value of the signal strength
- Comparison between black and red instead was already shown during unblinding closure



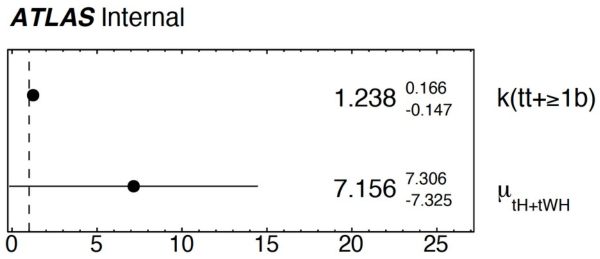


Results: SM tH(bb)



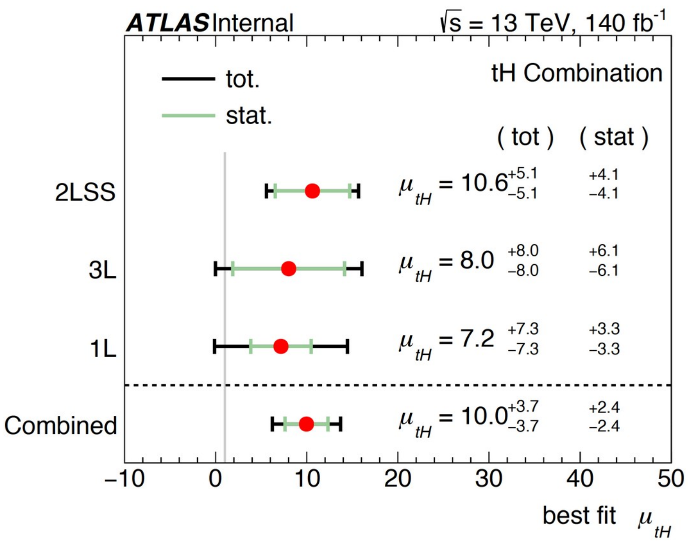


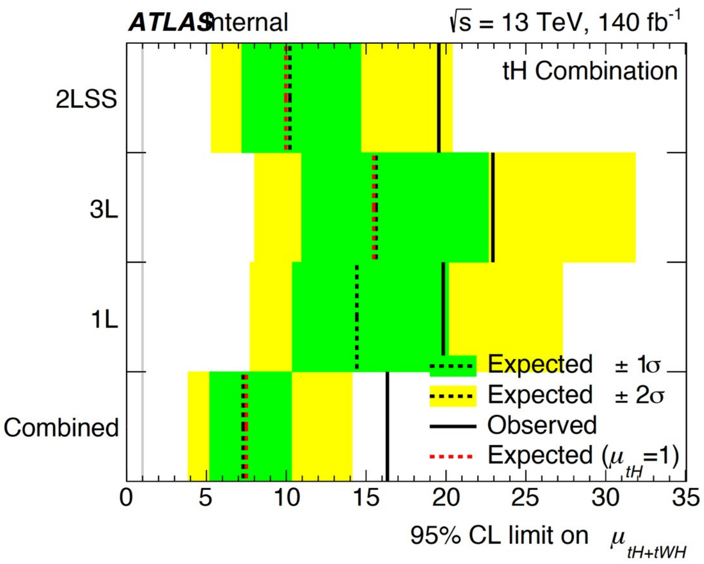
Goodness-of-fit probability: 0.991573



tH(H→γγ) ATLAS: upper limit of 12 times the SM
tH(H→bb) CMS (36/fb): upper limit of 25 to 12 times the SM
tH(H→γγ) CMS: upper limit of 14 times the SM

Combination results: SM tH

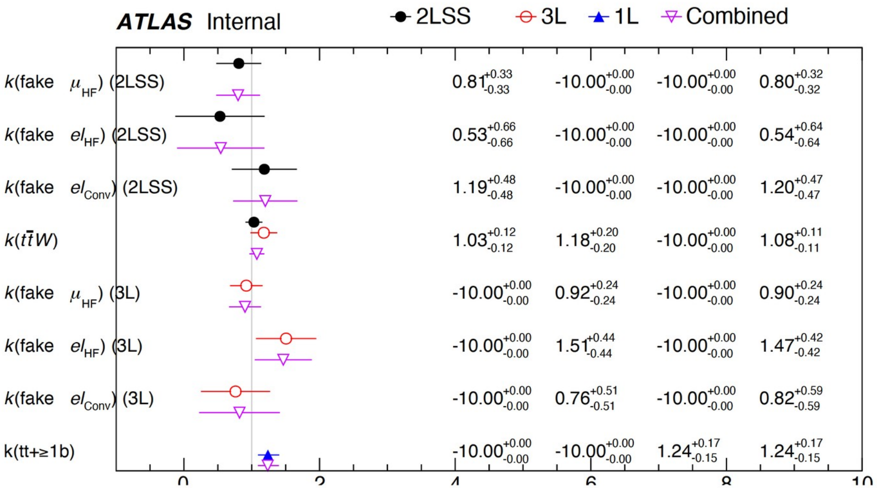


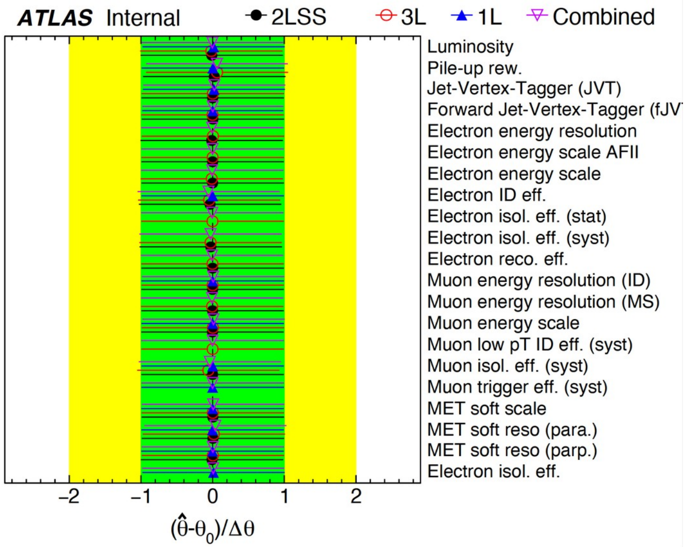


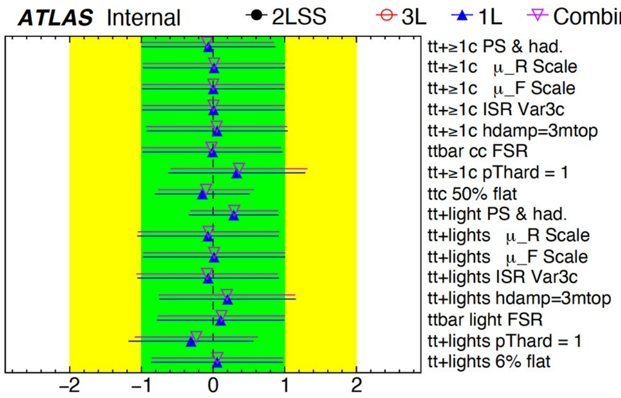
Channel	Expected Significance	Observed Significance
2LSS	0.21	2.25
3L	0.14	1.04
1L	0.14	0.98
Combined	**0.28**	**2.78**

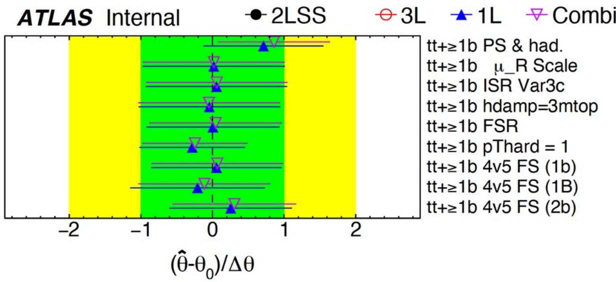
- **Current result use tHq 4FS (60fb) and tWH 5FS DR1(20fb) xsec from MadGraph**
- **YR values tHq 5FS (74fb) and tWH 5FS DR2 (15fb)**
- **Will switch to YR to compare to CMS other ATLAS results**

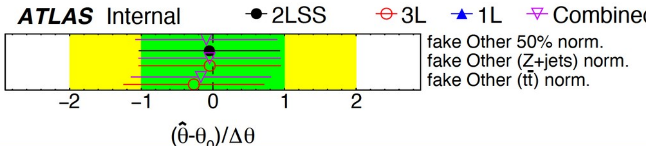
Combination results: SM tH

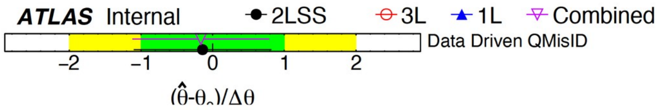












Conclusion

The measurement of the cross section of the associated production of a single to quark to a Higgs boson (tH) is presented. The measurement is based on $\sqrt{s}$ = 13 TeV proton–proton collision data with an integrated luminosity of 140 fb^{-1} , recorded from 2015 to 2018 with the ATLAS detector at the Large Hadron Collider. The signal regions are split into final states with one, two same-sign or three isolated leptons (electrons or muons). Additional background-enriched regions are used in the fit to improve the modelling of several leading backgrounds. The tH signal strength is found to be **μ_{tH}= 7.9 ± 2.6(stat.) ± 1.9(syst.)**, which is consistent with the previous measurement from CMS and other analyses probing the top-Higgs Yukawa coupling. The main source of uncertainty for the this measurement is the one associated with the data available, therefore a better limit can be achieved analysing a larger sample. Despite the analysis being optimised to set the best tH limit under the SM hypothesis, it was possible to also test the inverted Yukawa coupling hypothesis ($y_t = -1$). The signal strenght value in this case is found to be **μ_{tH} ($y_t = -1$) = 1.22 ± 0.42 (stat.) ± 0.50 (syst.).**

Thank you very much for your attention

BackUp Slides

Useful Links

[HTop tH to bb and multilep]

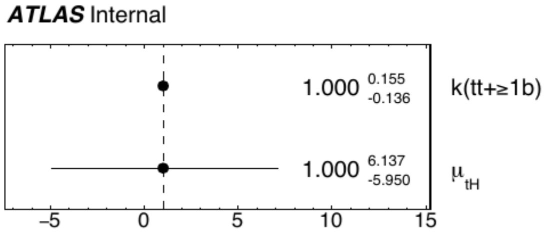
[tHbb unblinded results]

[Unblinding of the ML(0 tau) channels]

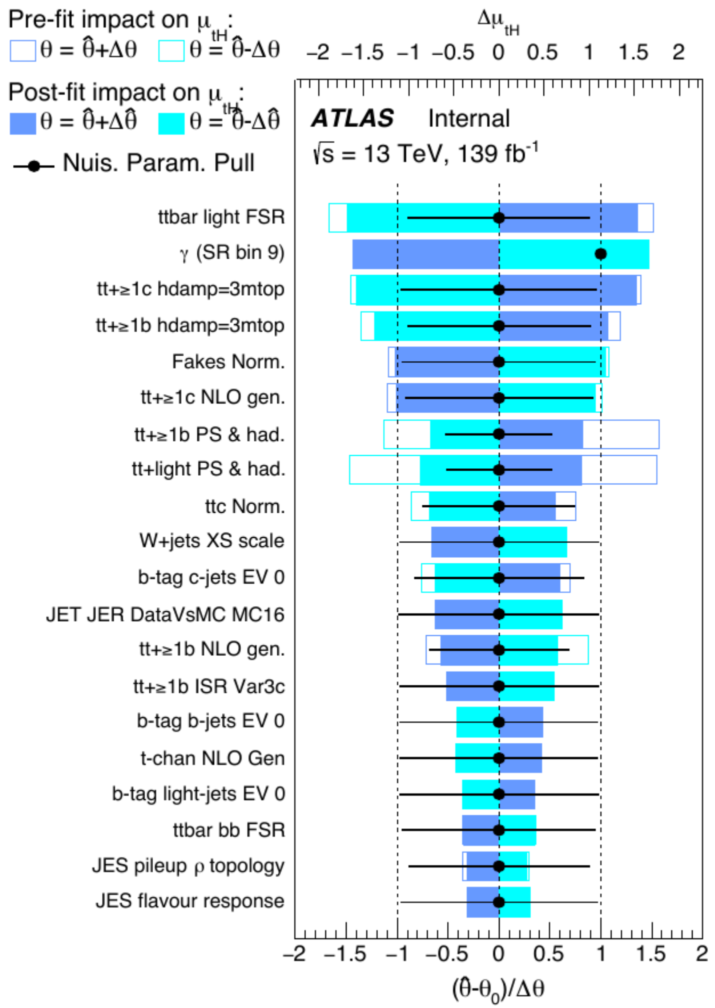
[tH analysis: lessons learnt and plans for Run 3]

[Studies on EB open points]

Asimov Fit — Limits and Ranking Plot



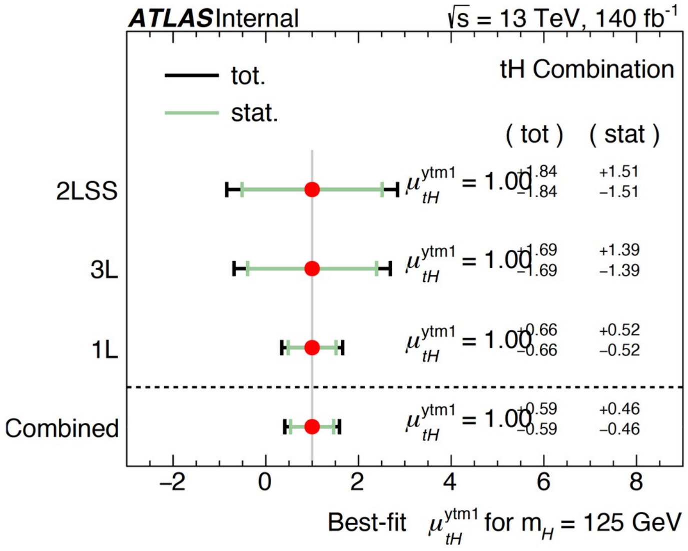
95% C.L.s upper limit				
-2σ	-1σ	exp. median	+1σ	+2σ
6.7	8.9	12.4	17.8	25.1

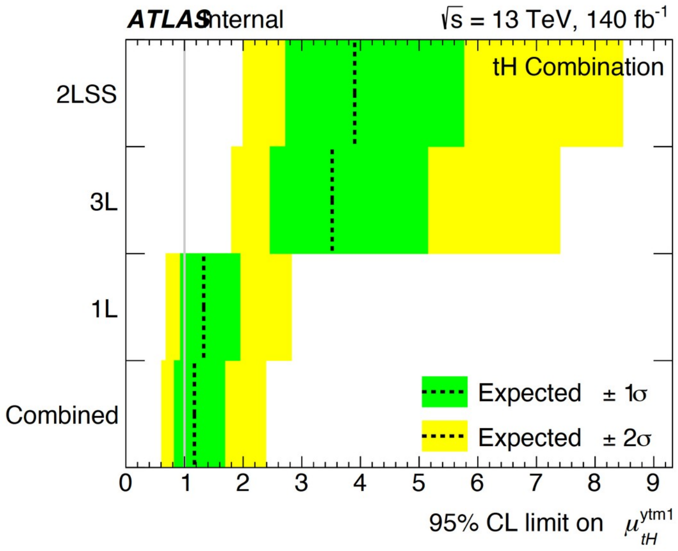


- Mostly $t\bar{t}$ modelling systematics are high-ranked
  - Large statistics and big fluctuations
- The MC Statistics in the last bin of SR also high-ranked
  - Last bin is where tH purity is highest — low background stats expected
- Upper limit at 95% CL stands at $\mu = 12.4$
- Uncertainty on μ ~ ± 6

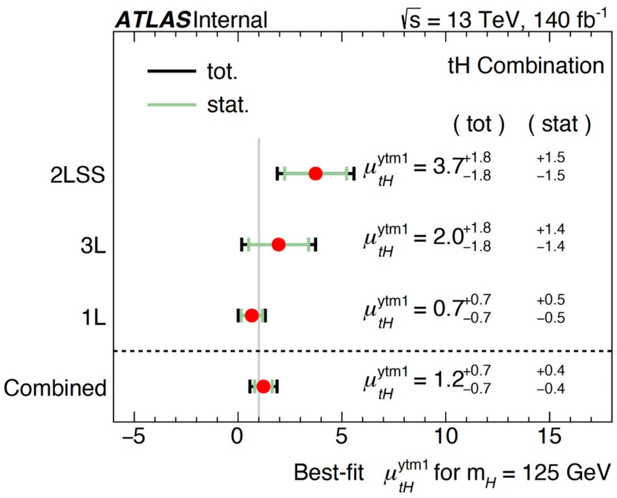
Inverted Coupling(ITC)

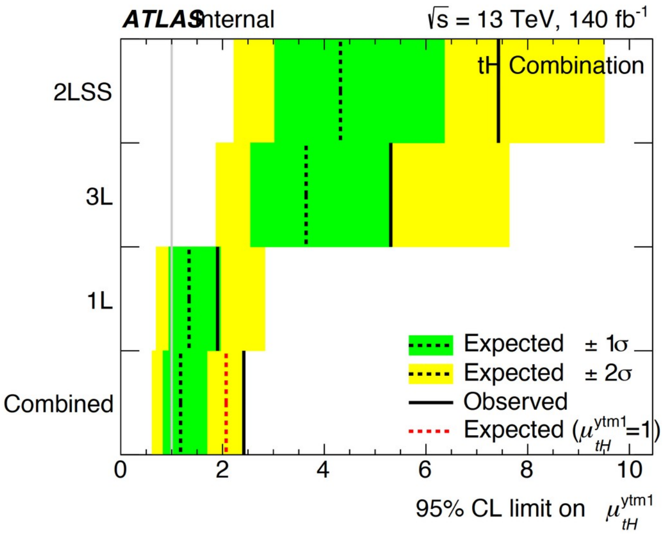
tH (ITC) combination





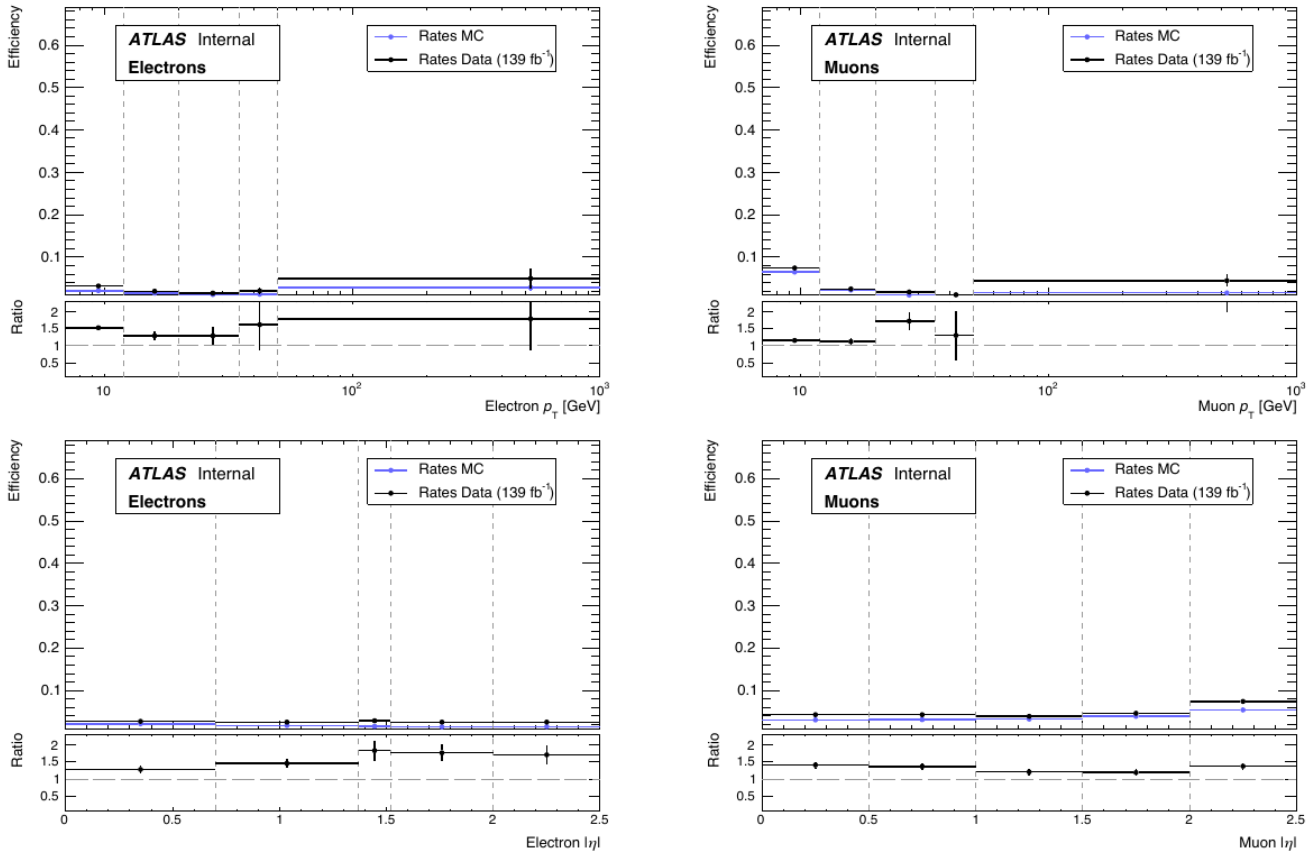
tH (ITC) combination: Unblinded





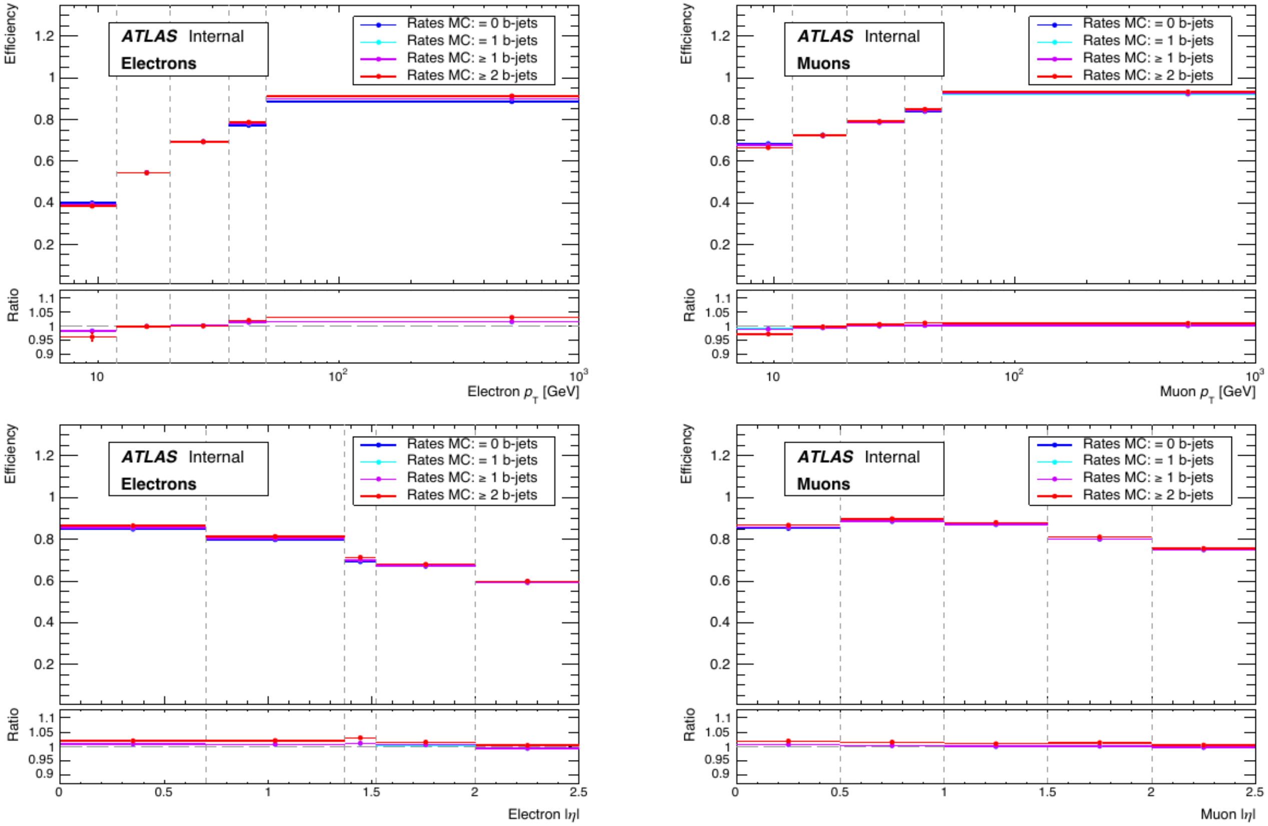
tH(bb): fakes estimation study

Matrix method in 1l: fake efficiencies



Fake efficiencies for electrons (left) and muons (right). Binned in lepton p_T (top) and $|\eta|$ (bottom)

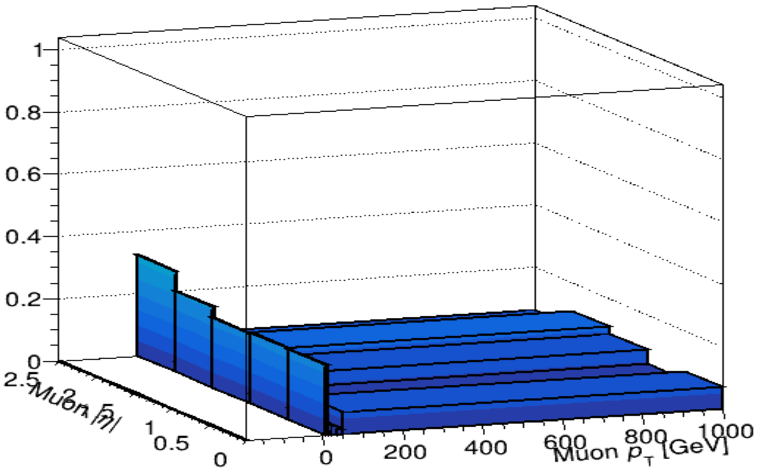
Matrix method in 1l: real efficiencies



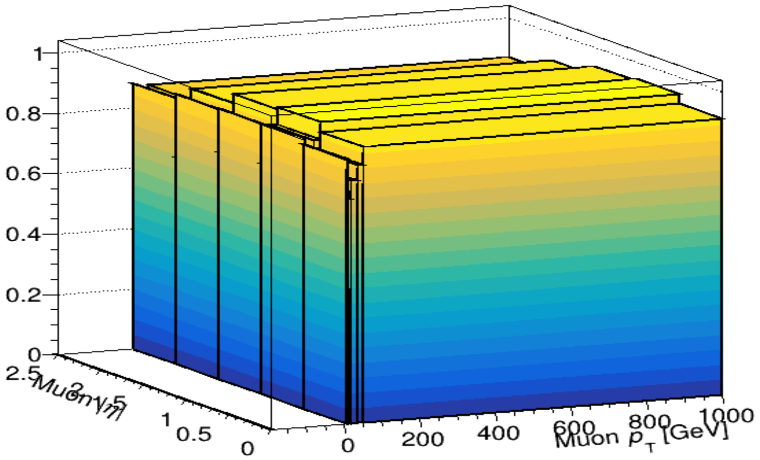
Real efficiencies for electrons (left) and muons (right). Binned in lepton p_T (top) and $|\eta|$ (bottom)

2L efficiency map (Efficiency2D_PLV.root)

FakeEfficiency2D_mu_pt_eta

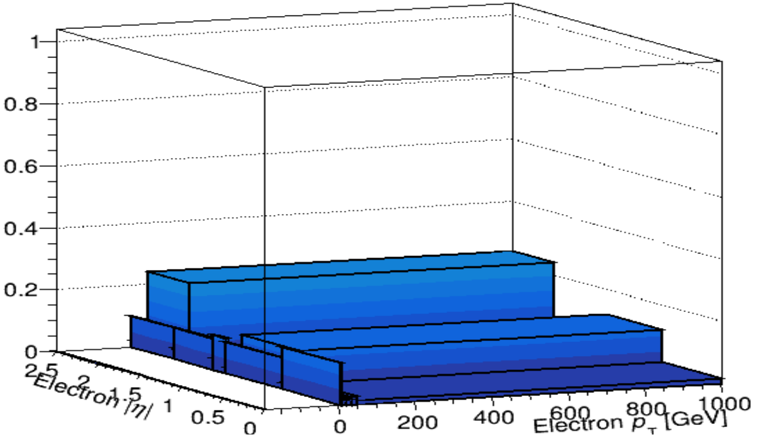


RealEfficiency2D_mu_pt_eta

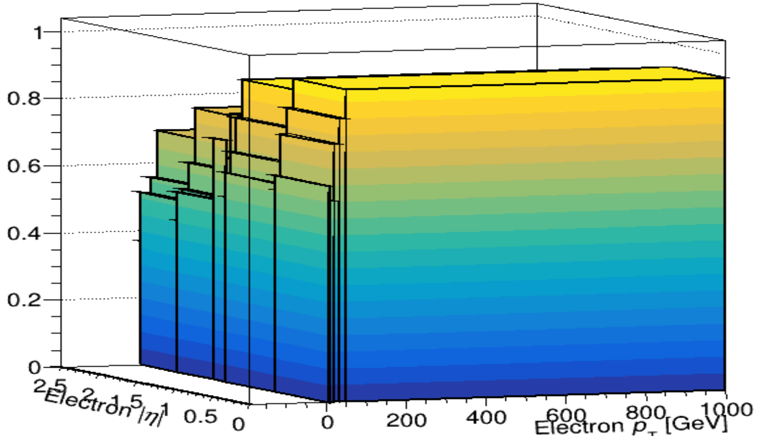


muon

FakeEfficiency2D_el_pt_eta



RealEfficiency2D_el_pt_eta



electron