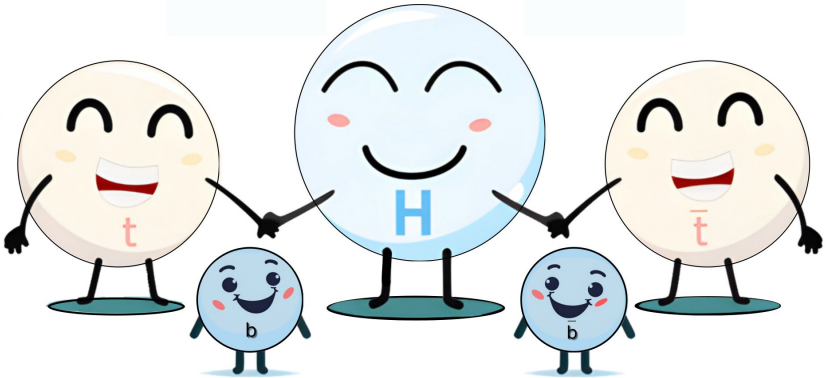
Associated $t\bar{t}H$ Production in the $H \to b\bar{b}$ Decay Channel (arXiv:2407.10904)

Chris Scheulen (he/him) on behalf of the ATLAS Collaboration

LHC Top WG Meeting

2024-11-11



Introduction

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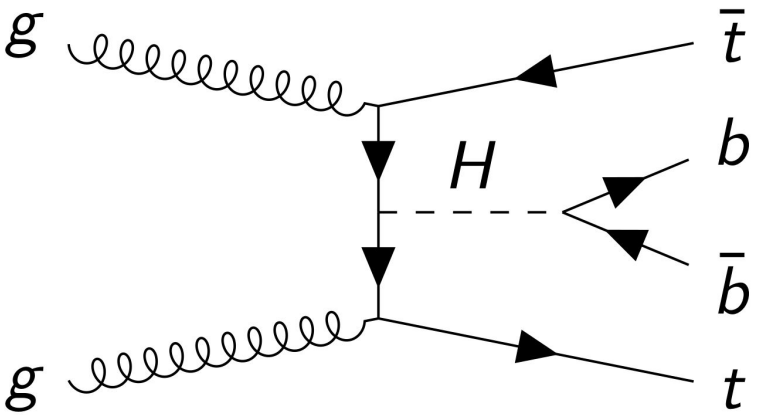
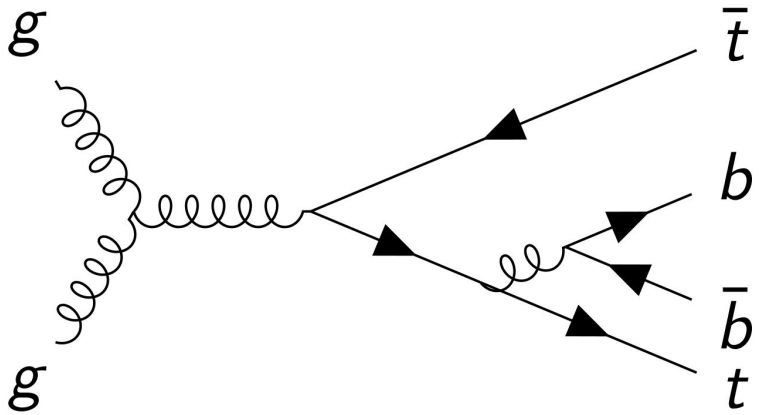
ttH(bb̄) signal



tt̄ + bb̄ background



- ttH provides direct probe of top Yukawa coupling
- H → bb̄ adds sensitivity to high Higgs boson p_T region in differential measurements
- Challenging dominant irreducible tt̄ + bb̄ background
  - ➥ Dedicated systematics studies for ATLAS legacy analysis (ATL-PHYS-PUB-2022-006)
  - ➥ Comparison with CMS samples in LHC Higgs WG note (LHCHWG-2022-003)

First Full Run 2 ATLAS Measurement

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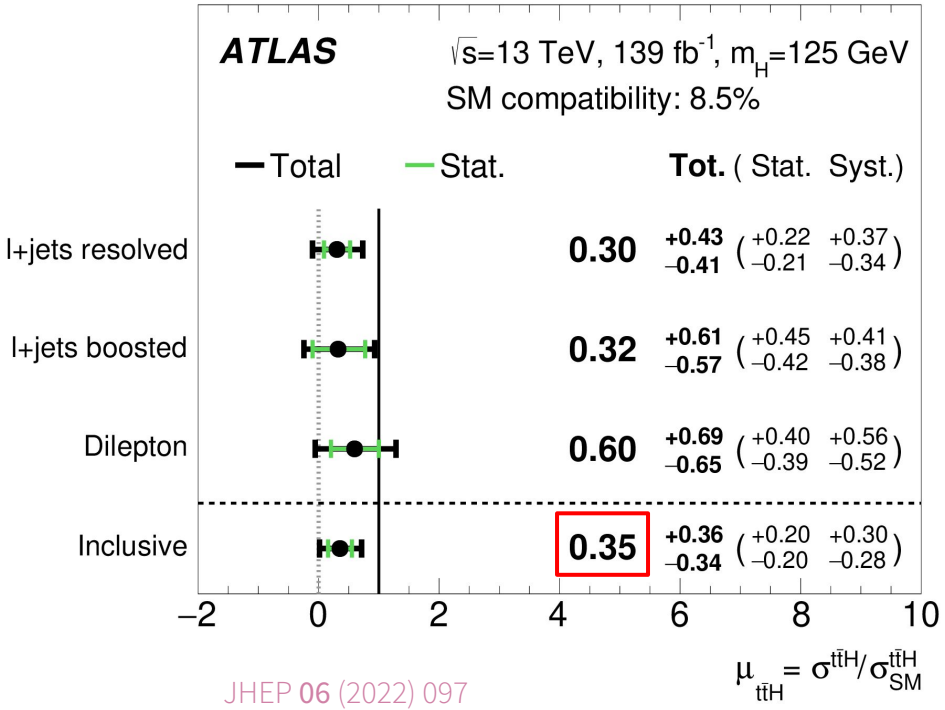
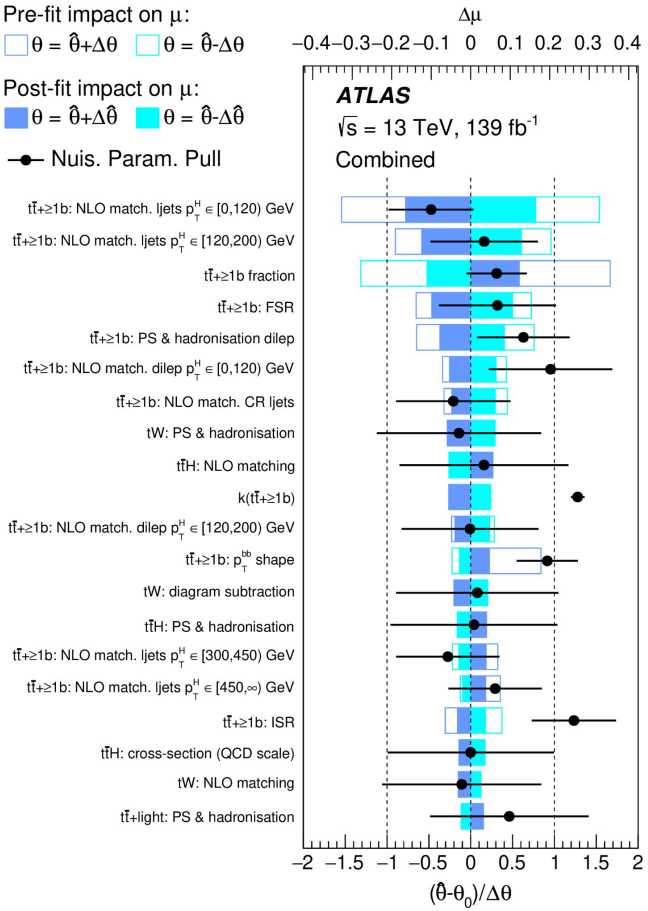
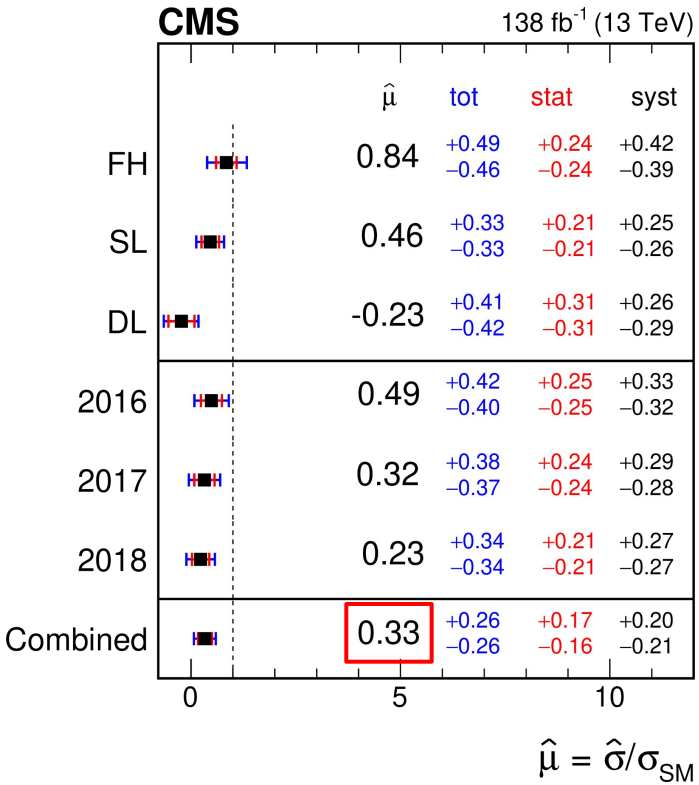
- Low inclusive signal strength
- Systematics dominated by $t\bar{t}$ + ≥ 1b modelling



JHEP 06 (2022) 097



Full Run 2 CMS Measurement



CMS-HIG-19-011

Overall story analogous to first full Run 2 ATLAS analysis

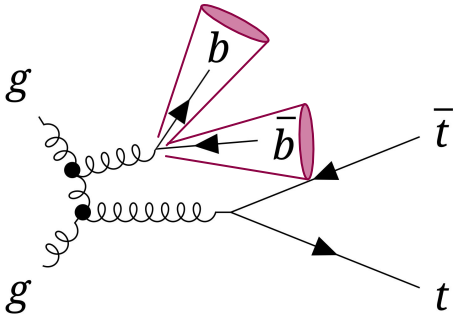
ATLAS Run 2 Legacy Analysis Motivation

- Re-analysis of full Run 2 dataset
- Inclusive & differential measurement
  - Inclusive cross-section and signal strength
  - Full STXS stage 1.2 scheme for Higgs boson p_T
- Leptonic top decay channels targeted
- Major updates incorporated into analysis:
  - Analysis model with consolidated ATLAS Run 2 object recommendations
  - Consistent $t\bar{t}$ + $b\bar{b}$ systematics model in 4-flavour scheme
  - Overhauled event classification & Higgs boson p_T reconstruction:
    Attention-based Transformers using basic particle information
    ➥ Split $t\bar{t}$ + ≥ 1b background into three components with individual normalisation factors
  - Kinematic pre-selection loosened after improved classification
    ➥ Increase in $t\bar{t}H(H \to b\bar{b})$ acceptance by a factor of 3 to 6.3%

tt̄ + Jets Classification Scheme

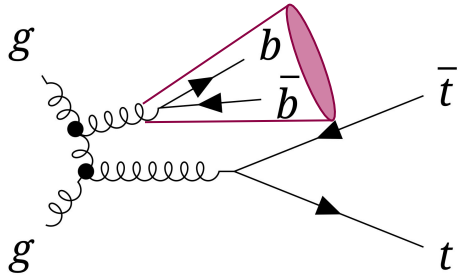
- Classification via matching particle-level non-tt̄ jets to b-/c-hadrons
- 4FS tt̄ + ≥ 1b components classified into 3 categories:

tt̄ + ≥ 2b



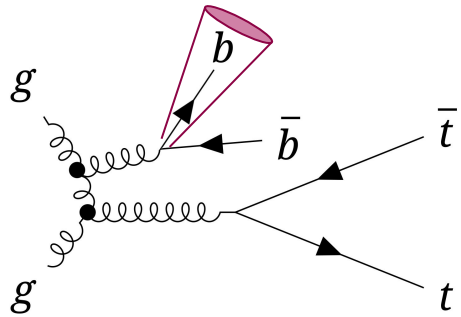
Multiple non-tt̄ jets matched to one or more b-hadrons

tt̄ + 1B



Exactly one non-tt̄ jet matched to multiple b-hadrons

tt̄ + 1b



Exactly one non-tt̄ jet matched to exactly one b-hadron

➥ Dominated by acceptance effects

- 5FS tt̄ components classified into
  - tt̄ + ≥ 1c: one or more non-tt̄ jet matched to c-hadrons, no non-tt̄ jets matched to b-hadrons
  - tt̄ + light: no non-tt̄ jets matched to b-/c-hadrons

$t\bar{t}b\bar{b}$ Samples – ATLAS/CMS Comparison

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Parameter	ATLAS First Full Run 2	ATLAS Run 2 Legacy	CMS Full Run 2
μ_F	$\frac{1}{2} \sum_{i = t, \bar{t}, b, \bar{b}, g} m_T(i)$		$\frac{1}{4} \sum_{i = t, \bar{t}, b, \bar{b}, g} m_T(i)$
μ_R	$\sqrt[4]{(\prod_{i = t, \bar{t}, b, \bar{b}} m_T(i))}$	$\frac{1}{2} \sqrt[4]{(\prod_{i = t, \bar{t}, b, \bar{b}} m_T(i))}$	
h_{damp}	$H_T / 2$		$1.379\ m_t$
$h_{bornzerodamp}$	5		

- ATLAS legacy & CMS parameters follow dedicated studies summarised in ATL-PHYS-PUB-2022-006, LHCHWG-2022-003
- Nominal $t\bar{t}b\bar{b}$ process simulated with PowhegBoxRes+Pythia8 in 4-flavour scheme (m_t = 172.5 GeV, m_b = 4.75 GeV for CMS, and m_b = 4.95 GeV for ATLAS)
- h_{damp} & $h_{bornzerodamp}$ control NLO gluon emission in Powheg, negligible impact observed in studies

ATLAS $t\bar{t}$ + Jets Systematics Model

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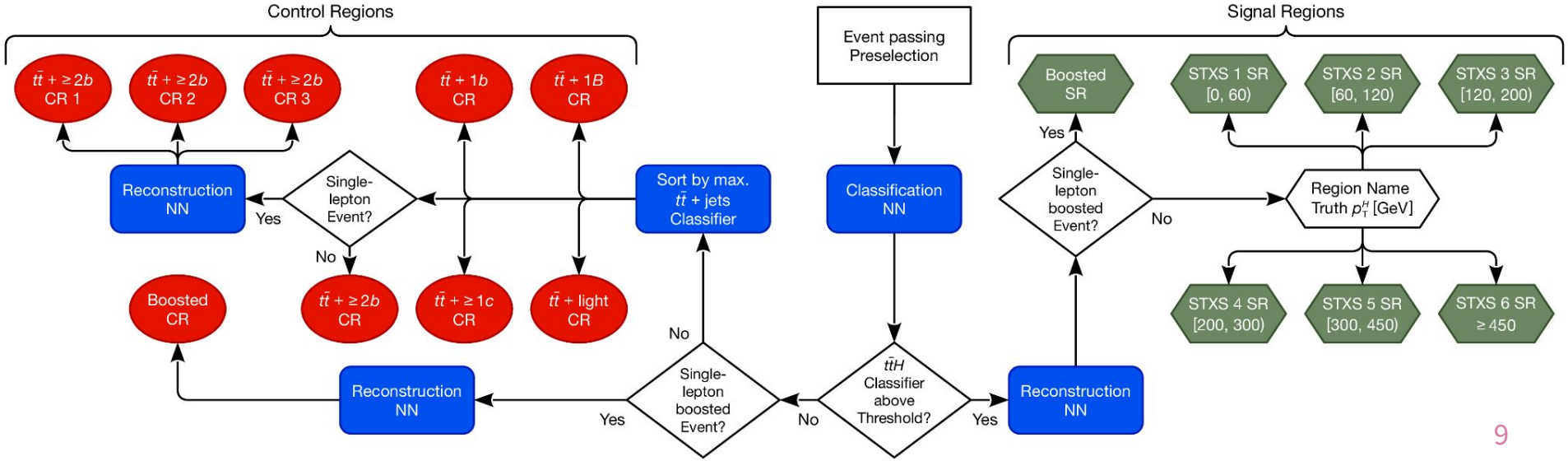
Systematic	ATLAS First Full Run 2	ATLAS Run 2 Legacy
ME Scale	–	independent ME μ_R, μ_F variations
ISR	Var3c and ME μ_R, μ_F variations	A14 tune Var3c variations
FSR	PS FSR μ_R variations	
Parton Shower & Hadronisation	Powheg + Herwig7 alternative (5FS only)	Powheg + Herwig7 alternative (5FS and 4FS)
NLO Matching	MG5_aMC@NLO + Pythia8 (5FS only)	PP8 p_T-hard = 1 alternative (5FS and 4FS)
ISR Recoil	–	PP8 dipole recoil alternative ($t\bar{t}$ + ≥ 1b only)
h_{damp} variation	–	h_{damp} up-variation alternative ($t\bar{t}$ + ≥ 1c/light only)

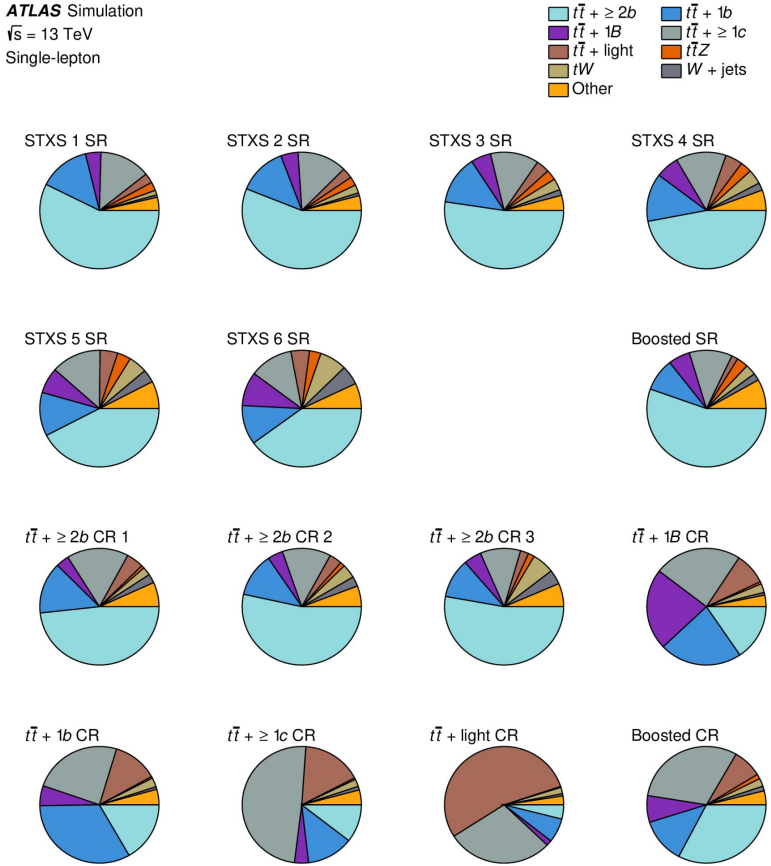
- Floating normalisation factors in legacy analysis
- First full Run 2 analysis: 6% (100%) cross-section uncertainties for $t\bar{t}$ + light ($t\bar{t}$ + ≥ 1c), single $t\bar{t}$ + ≥ 1b normalisation factor with uncertainties on component fractions

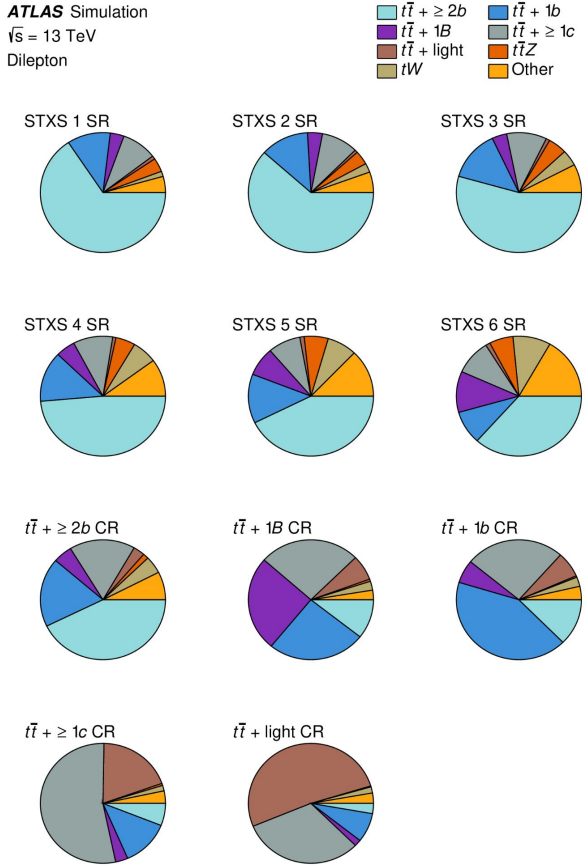
Overall Legacy Analysis Strategy

- $t\bar{t}$ + jets backgrounds split in 5 categories by event classification Transformer
  - ➥ Constraint of each category in simultaneous fit
- SRs split by reconstruction Transformer Higgs boson p_T
- Additional split of single-lepton $t\bar{t}$ + ≥ 2b component
- First full Run 2 ATLAS & CMS: Primary region split based on jet multiplicity



Pre-Fit Background Compositions

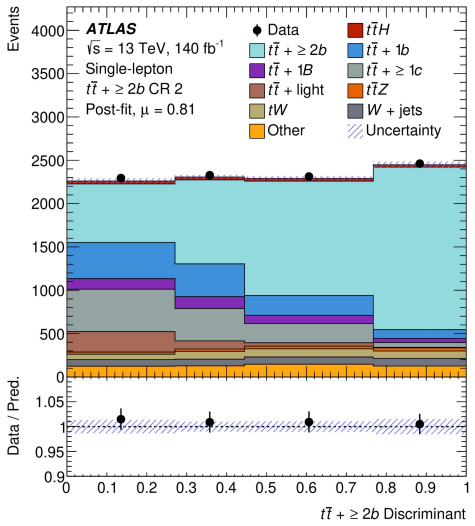


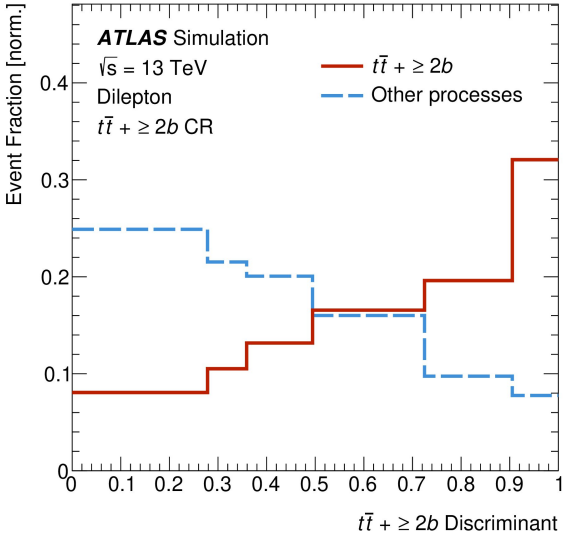


Transformer Performance

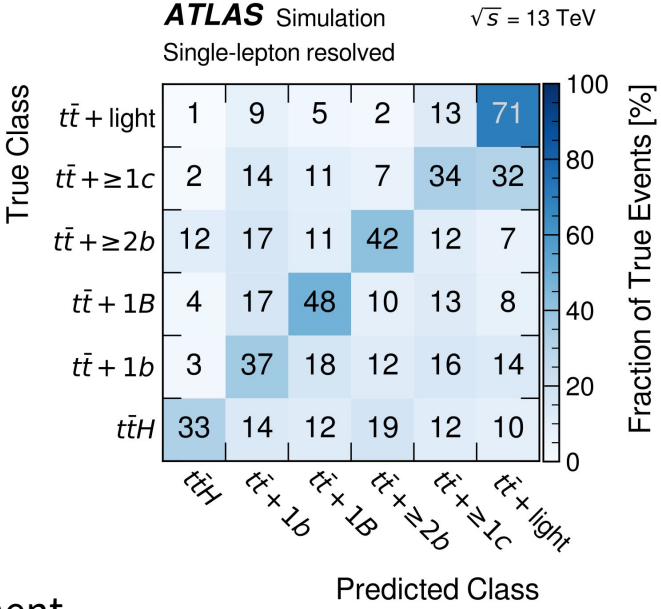
Classification

Single-lepton tt̄ + ≥ 2b CR 2 Separation





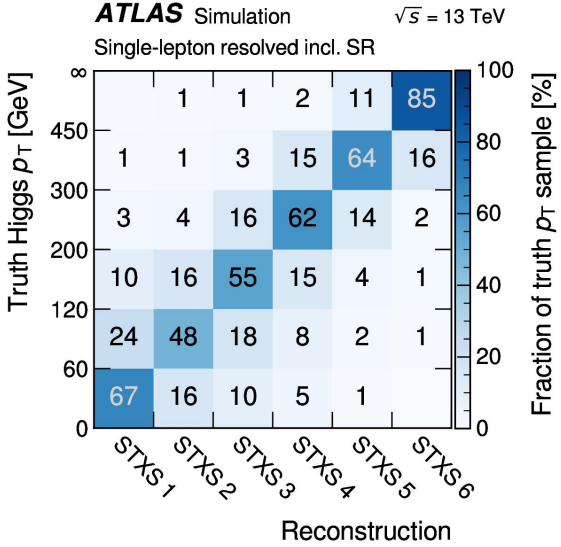
Single-lepton Confusion Matrix

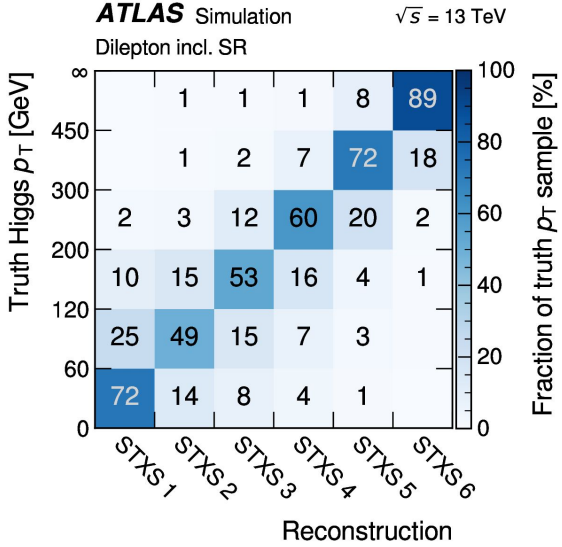


- Good separation power of discriminants after region assignment
  - ➥ Classification discriminants used as fit variables

Transformer Performance

Reconstruction





- Good Higgs boson p_T reconstruction performance observed
- Bin edges of SRs optimised for responses of $t\bar{t}H$ truth Higgs boson p_T

Channel	STXS Bin Edges [GeV]						
Stage 1.2 STXS	0	60	120	200	300	450	∞
Single Lepton Resolved Dilepton	0	60	114	192 186	282 270	408 402	∞

$t\bar{t}$ + Jets H_T Reweighting

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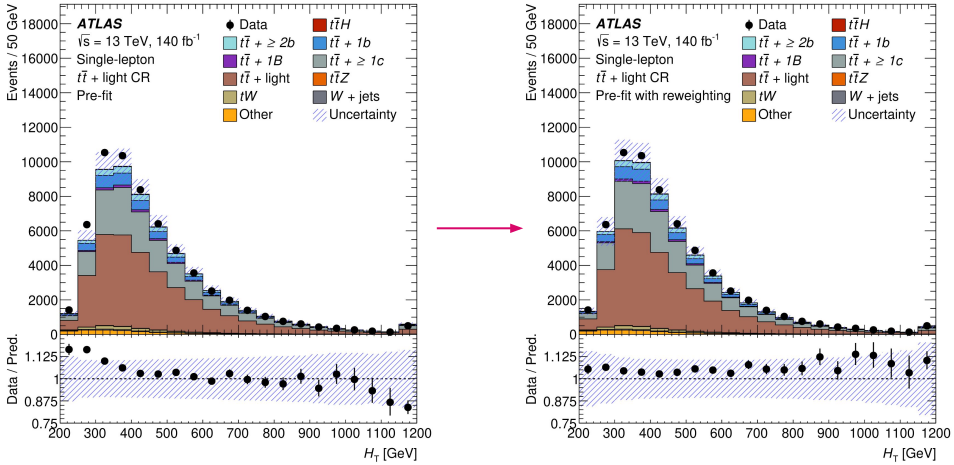
- Mismodelling observed in pre-fit H_T distributions of ATLAS legacy analysis
  - ➥ Per-channel reweighting performed for $t\bar{t}$ + ≥ 1c/light components
- Derivation in orthogonal region after subtraction of other processes
  - Same jet multiplicity requirements, looser b-tagging requirements for $t\bar{t}$ + ≥ 1c/light enrichment
- Correction factors derived for jet multiplicity bins of N_{jet} = 5 to N_{jet} ≥ 8 in single-lepton channel, N_{jet} = 3 to N_{jet} ≥ 6 in dilepton channel
- Separate correction factors derived for systematic variations



Inclusive Results

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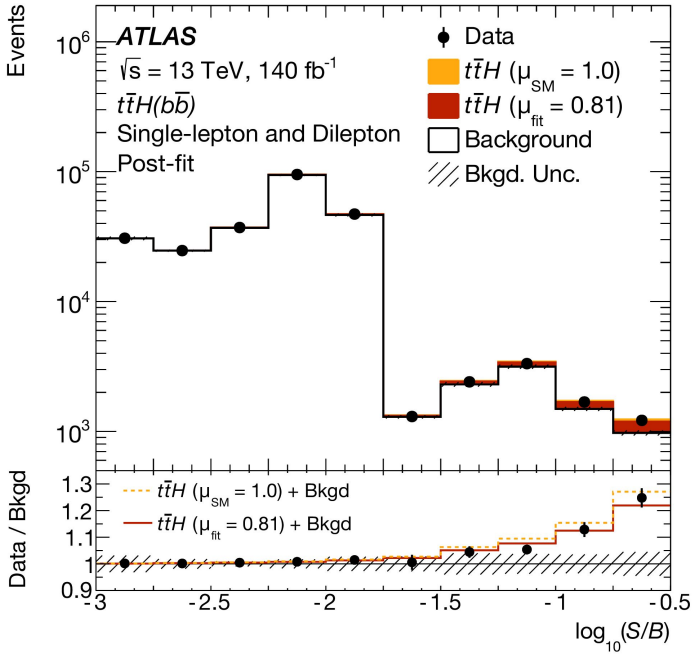
Inclusive cross-section:

$\sigma(t\bar{t}H) = 411\ ^{+101}_{-92}$ fb $= 411 \pm 54$ (stat.) $^{+85}_{-75}$ (syst.) fb (SM prediction: $507\ ^{+35}_{-50}$ fb at NLO QCD+EW)

Observed (expected) significance: 4.6 (5.4) σ



Combined Signal Strength:

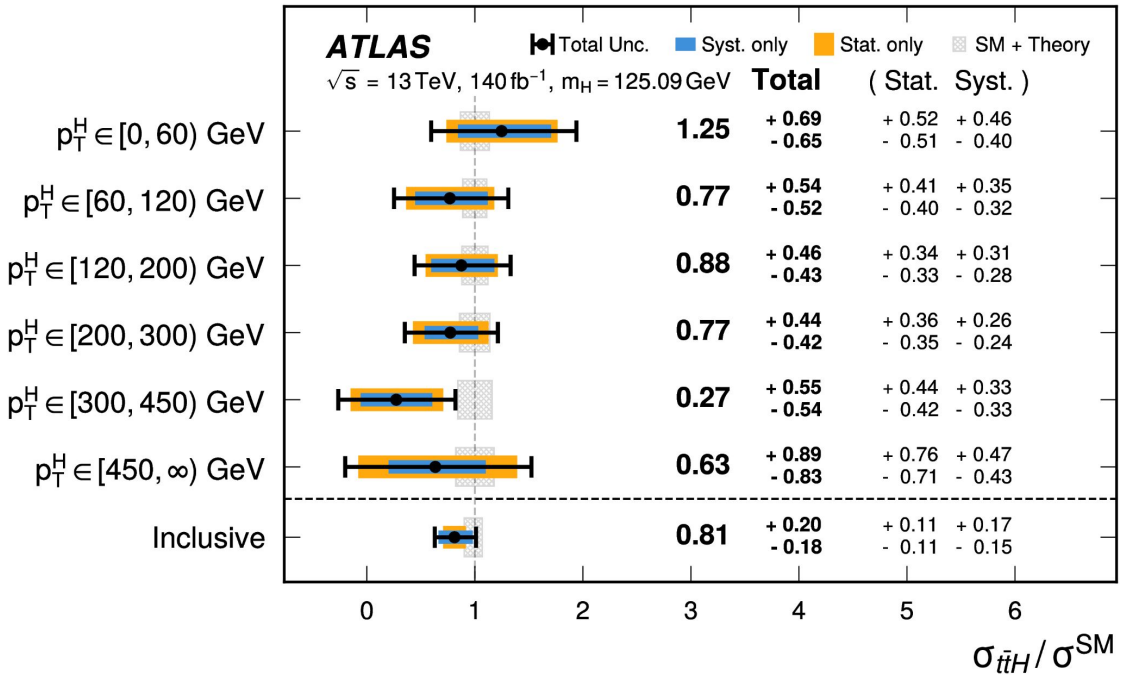
$\mu(t\bar{t}H) = 0.81\ ^{+0.22}_{-0.19} = 0.81 \pm 0.11$ (stat.) $^{+0.20}_{-0.16}$ (syst.)

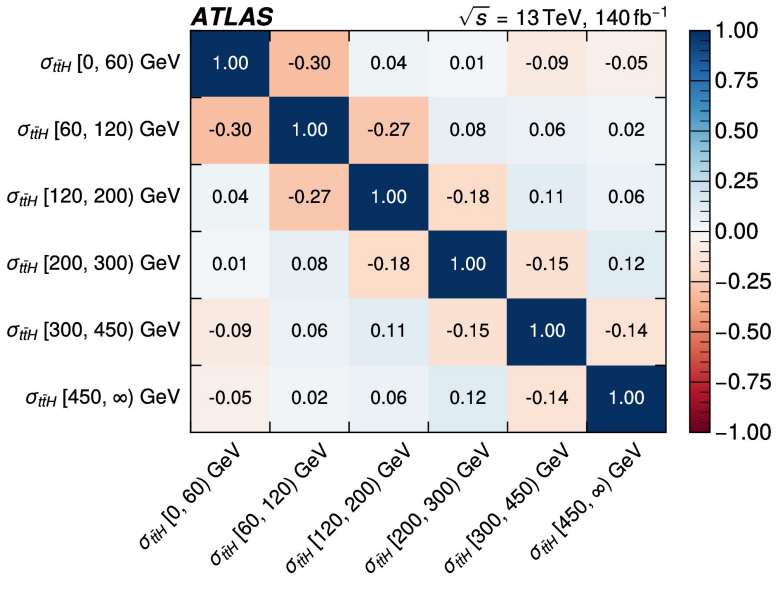
Normalisation factor	$t\bar{t}$ + light	$t\bar{t}$ + ≥ 1c	$t\bar{t}$ + 1b	$t\bar{t}$ + 1B	$t\bar{t}$ + ≥ 2b
Single-lepton	$0.78^{+0.08}_{-0.08}$	$1.51^{+0.19}_{-0.18}$	$1.06^{+0.10}_{-0.10}$	$1.15^{+0.15}_{-0.14}$	$0.94^{+0.08}_{-0.08}$
Dilepton	$0.88^{+0.11}_{-0.10}$	$1.36^{+0.10}_{-0.10}$	$1.24^{+0.09}_{-0.09}$		

Differences between post-fit tt̄ + ≥ 1b norm factors!

ATLAS first full Run 2: k(tt̄ + ≥ 1b) = 1.28 ± 0.08

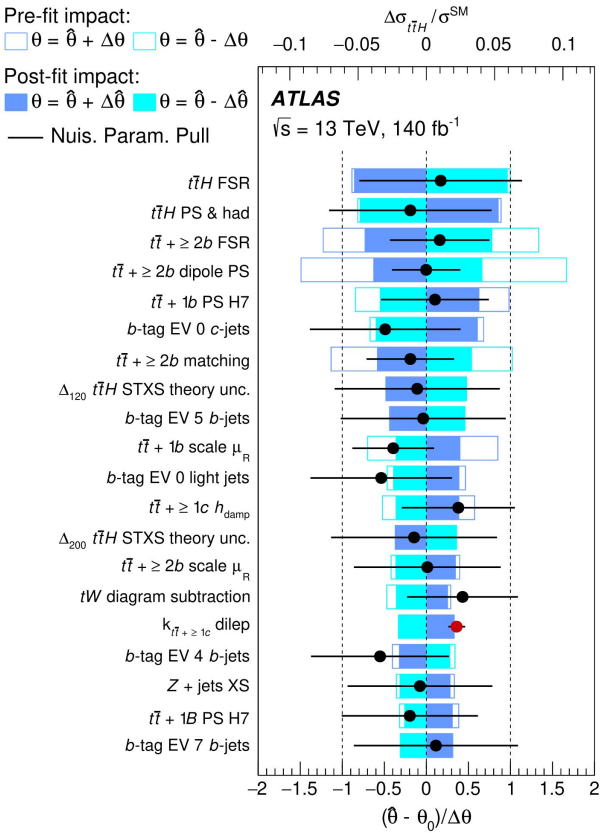
Differential STXS Results





- STXS measurement compatible with SM with p-value of 89%
- Correlations between per-bin cross-sections do not exceed 30%

Systematics Rankings & Grouped Impact



Uncertainty source	$\Delta\sigma_{t\bar{t}H}$ (fb)		$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ (%)	
Process modelling				
$t\bar{t}H$ modelling				
$t\bar{t}H$ radiation	+35	−21	+9	−5
$t\bar{t}H$ parton shower	+32	−19	+8	−5
$t\bar{t}H$ matching	<0.1	−0.3	<0.1	−0.1
$t\bar{t}H$ theory	+25	−17	+6	−4
$t\bar{t}+\geq 1b$ modelling				
$t\bar{t}+\geq 1b$ radiation	±31		±8	
$t\bar{t}+\geq 1b$ parton shower	±29		±7	
$t\bar{t}+\geq 1b$ matching	±19		±5	
$t\bar{t}+\geq 1c$ modelling	±18		±4	
$t\bar{t}$ + light modelling	±5		±1	
tW modelling	±16		±4	
Minor background modelling	±19		±5	
Flavour tagging	±36		±9	
Jet modelling	±22		±5	
Monte-Carlo statistics	±17		±4	
Other instrumental	±10		±2	
Total systematic uncertainty	+85	−75	+21	−18
Normalisation factors	±21		±5	
Total statistical uncertainty	±54		±13	
Total uncertainty	+101	−92	+25	−22

- Uncertainties dominated by signal modelling, tt̄ + ≥ 1b modelling, flavour tagging

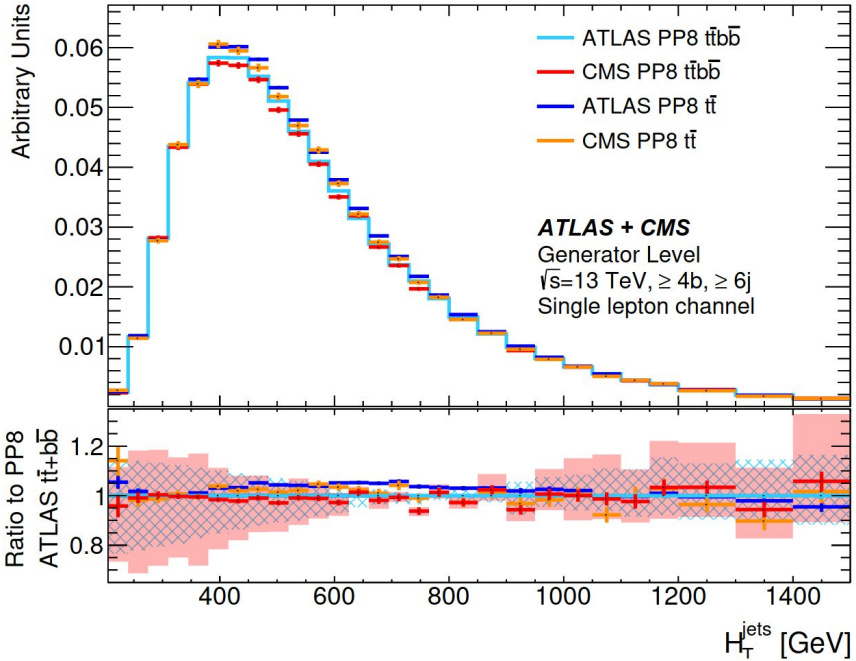
Summary

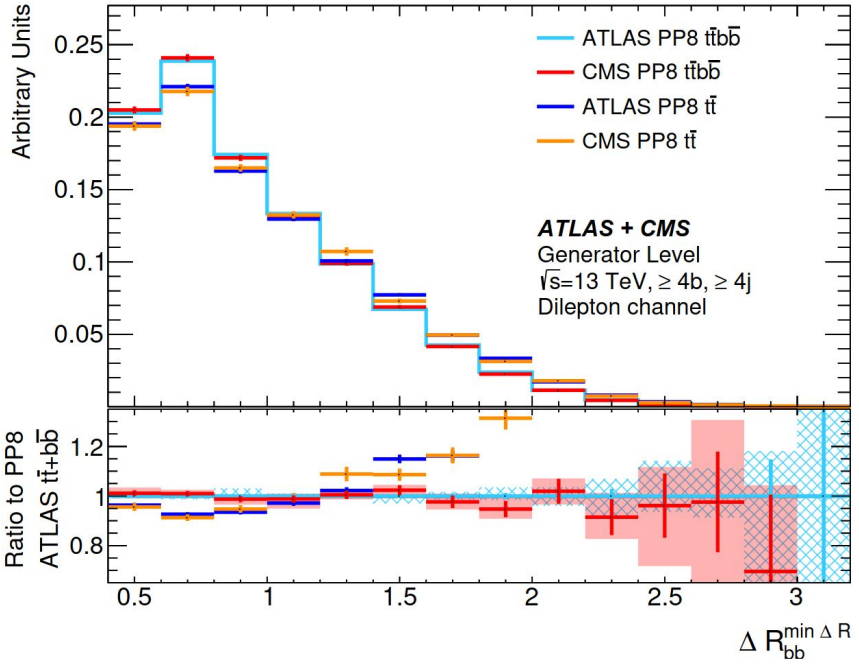
- Low $t\bar{t}H$ signal strengths measured by first ATLAS full Run 2 & CMS full Run 2 analyses
- $t\bar{t}$ + ≥ 1b modelling dominant for both analyses
- ATLAS Run 2 legacy analysis measures higher signal strength
  - Better control over $t\bar{t}$ + ≥ 1b via improved classification strategy
  - Improved $t\bar{t}$ + ≥ 1b systematics model compared to first ATLAS full Run 2
  - Signal modelling now dominant

➤ Good control on individual $t\bar{t}$ + ≥ 1b components seems important in $t\bar{t}H$ phase space!

Backup

$t\bar{t}b\bar{b}$ Samples – A Comparison





- Comparison of samples used in ATLAS Run 2 legacy & CMS in LHCHWG-2022-003
  - Fiducial volume of ≥ 4 b-jets, ≥ 6 jets, 1 lepton and ≥ 4 b-jets, ≥ 4 jets, 2 leptons
- Comparison also to 5-flavour scheme $t\bar{t}$ + jets samples
- Uncertainty bands from stats & QCD scale variations

Object & Event Selection

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- Focus on leptonic top pair decay channels: single lepton (ℓ + jets) & dilepton
- Select leading lepton at $p_T > 27$ GeV, sub-leading lepton at $p_T > 10$ GeV (15 GeV in e^+e^- channel)
  - Lowest unprescaled single-lepton triggers used
  - Same-flavour dilepton channel: $m_{\ell\ell} > 15$ GeV, veto around $m_Z \pm 8$ GeV
- Select small-R jets at $p_T > 25$ GeV, $|\eta| < 2.5$
  - b-tagging with RNN-based DL1r tagger
- Additional single-lepton boosted channel with boosted Higgs candidate
  - R = 1.0 reclustered jet with 100 GeV < m < 140 GeV, $p_T > 300$ GeV
  - ≥ 2 sub-jets, exactly 2 sub-jets b-tagged @ 85%, ≥ 2 non-sub-jets b-tagged @ 77%
  - Analysis-developed boosted DNN tagger to discriminate Higgs candidates and top quarks
- Hadronic tau lepton veto for orthogonality with $t\bar{t}H$(ML) in combinations
- Separate non-isolated muons correct b-tagged jet kinematics in MVA inputs

Channel	# Jets	# DL1r b-Tags @ 70 %	@ 77 %	@ 85 %	# e/μ	# τ_{had}	# Boosted Higgs Candidates
Dilepton	≥ 3	≥ 2	–	≥ 3	2	0	n/a
ℓ + Jets Resolved	≥ 5	≥ 3	–	–	1	≤ 1	–
ℓ + Jets Boosted	≥ 4	–	≥ 2	≥ 4	1	≤ 1	≥ 1

Nominal MC Samples

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Process	Generator	Comments
$t\bar{t}H$	PowhegBox+Pythia8	–
$t\bar{t}$ + ≥ 1b	PowhegBoxRes+Pythia8	4-flavour scheme
$t\bar{t}$ + c/light	PowhegBox+Pythia8	5-flavour scheme
tWH, tHjb, $t\bar{t}Z$, $t\bar{t}t\bar{t}$, tZq, tWZ	MG5_aMC@NLO+Pythia8	4-flavour scheme for tHjb & tZq
Single top (s-, t-channel, Wt)	PowhegBox+Pythia8	4-flavour scheme for t-channel
$t\bar{t}W$	Sherpa 2.2	–
V + jets	Sherpa 2.2	–
Diboson	Sherpa 2.2	–

Non $t\bar{t}$ + Jets Systematics

- Individual nuisance parameters of $t\bar{t}$ + jets modelling systematics for each component
- Yields of $t\bar{t}$ + jets systematics rescaled to nominal due to free-floating normalisation factors
- Modelling and normalisation uncertainties of other processes included
- Experimental systematics follow current ATLAS recommendations
  - Including high-p_T flavour tagging extrapolation uncertainties & muons correcting b-tagged jets
- HT reweighting systematics applied per channel
  - Variation of $t\bar{t}$ + c/light normalisation factors within uncertainties
  - Distributions with reweighting switched off per jet multiplicity used as additional uncertainties
- Single-lepton fake uncertainties estimated via alternative parametrisation scheme
- Individual 50% normalisation uncertainties for single-lepton and dilepton fakes

Fake Estimation

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- Different fake estimation techniques in single-lepton and dilepton channels
- Single-lepton channel fakes determined via data-driven fake factor method (JINST **18** (2023) T11004)
  - Factors parametrised by lepton $|\eta|$ and leading jet p_T
  - Factor derivation performed in region with a single loose lepton,
    ≥ 2 jets, ≥ 2 jets b-tagged @ 70%, $(E_{T,\,miss} + m_{W,\,T}) < 60$ GeV
- Fakes in dilepton channel determined via truth record in MC simulations

Transformer Architecture

Jets, Leptons, MET as input objects
- Agnostic to object number & ordering
- Features: 4-vectors, b-tag scores, object types

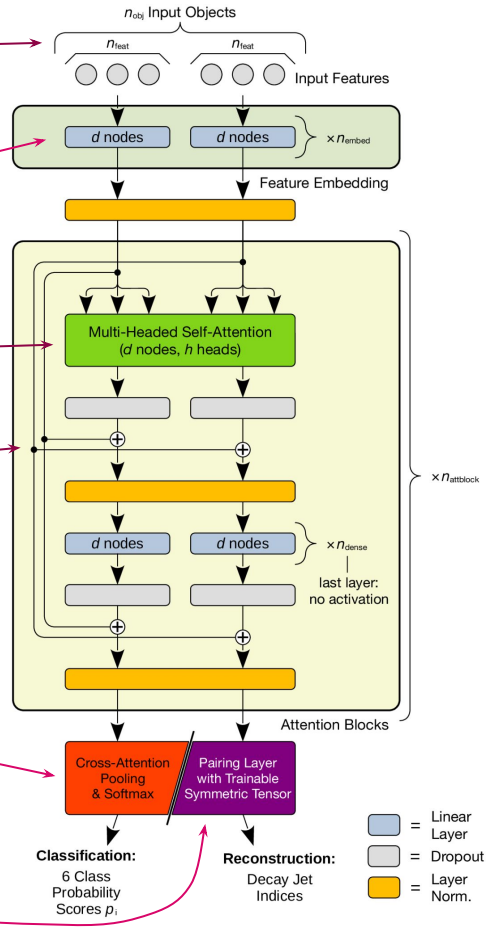
Fully-connected layers applied consistently to all objects

Self-Attention Mechanism for pair-wise object interactions
(generates linear object combinations)

Residual connections to improve training
➥ Improved scheme with respect to original Transformer architecture

Classification layer via pooling of latent features

Pairing Layer to reconstruct 2 most likely b-jets from Higgs boson
(à la tensor attention in SPANet (Phys. Rev. D **105** (2022) 112008))



Transformer Input Features

Feature	Description	Feature Transformations
p_x	Object momentum in x-direction.	Re-scaled to $\mu = 0, \sigma = 1$.
p_y	Object momentum in y-direction.	Re-scaled to $\mu = 0, \sigma = 1$.
p_z	Object momentum in z-direction.	Re-scaled to $\mu = 0, \sigma = 1$.
energy	Object energy.	Re-scaled to $\mu = 0, \sigma = 1$.
p_{T}	Object transverse momentum.	Re-scaled to $\mu = 0, \sigma = 1$.
mass	Object mass.	Re-scaled to $\mu = 0, \sigma = 1$.
η	Object pseudo-rapidity.	Re-scaled to $\mu = 0, \sigma = 1$.
ϕ	Object azimuthal angle.	Re-scaled to $\mu = 0, \sigma = 1$.
$\cos\phi$	Sine of object azimuthal angle.	Re-scaled to $\mu = 0, \sigma = 1$.
$\sin\phi$	Cosine of object azimuthal angle.	Re-scaled to $\mu = 0, \sigma = 1$.
PCBT bin	DL1r pseudo-continuous b-tagging bin assigned to jets in the following manner. Set to 0 for leptons and $E_{\mathrm{T}}^{\mathrm{miss}}$. $\text{feature} = \begin{cases} 1, & \text{if un-tagged} \\ 2, & \text{if tagged at } [85\%, 77\%) \\ 3, & \text{if tagged at } [77\%, 70\%) \\ 4, & \text{if tagged at } [70\%, 60\%) \\ 5, & \text{if tagged at } 60\%. \end{cases}$	None.
lepton type	Lepton type of input objects. Set to 1 for electrons, 2 for muons, and 0 for jets and $E_{\mathrm{T}}^{\mathrm{miss}}$.	None.
lepton charge	Charge of lepton objects in units of e. Set to 0 for jets and $E_{\mathrm{T}}^{\mathrm{miss}}$.	Re-scaled to $\mu = 0, \sigma = 1$.
$E_{\mathrm{T}}^{\mathrm{miss}}$ flag	Whether input object is $E_{\mathrm{T}}^{\mathrm{miss}}$ (value of 1) or not (value of 0).	None.

Some redundancy in input features, as seen to improve Transformer performance

tt̄ + Jets Normalisation Factors & Discriminant Classifiers

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- Class probabilities converted into discriminants to take process yields into account:

Discriminant classifier

$$d_i = \frac{p_i}{\sum_{j \neq i} p_j \cdot \hat{N}_{ij}}$$

Target class probability

$$\hat{N}_{ij} = N_j / \sum_{k \neq i} N_k$$

Average of other probabilities weighted by process yield fractions

- SR ttH discriminant thresholds optimise S / √B
- Choice of discriminant classifiers motivated via fits to Sherpa tt̄ + jets pseudo-data samples
- Discriminants rescaled to [0, 1) in post-fit plots via logistic functions
  - Purely visual as done after region assignment
- Realistic tt̄ + jets normalisation factors required for discriminant yields, H_T reweighting, fakes
  - ➥ Per-channel factors derived via preliminary background-only fit with full systematics
  - Normalisation factors similar those determined in unblinded simultaneous fit to data

Transformer Performance

Classification

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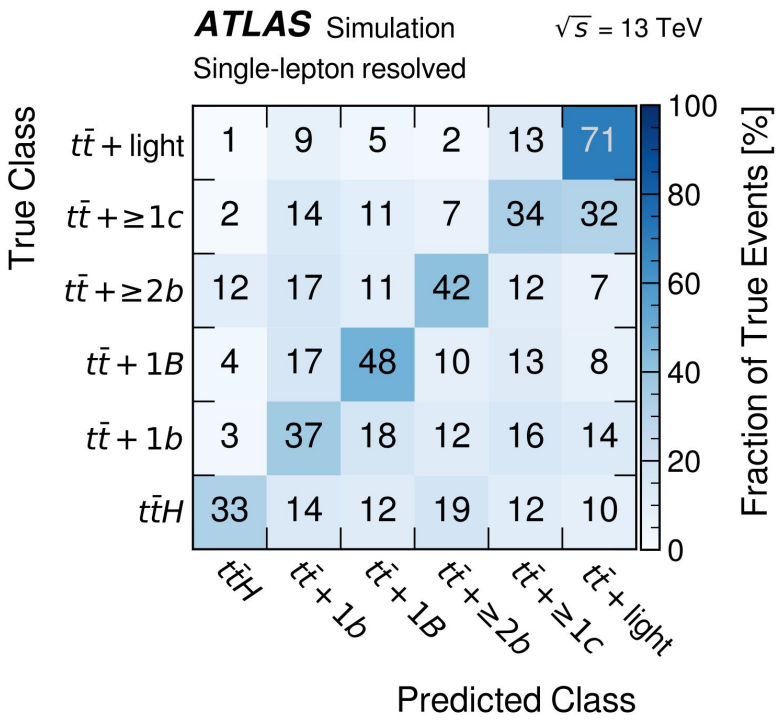
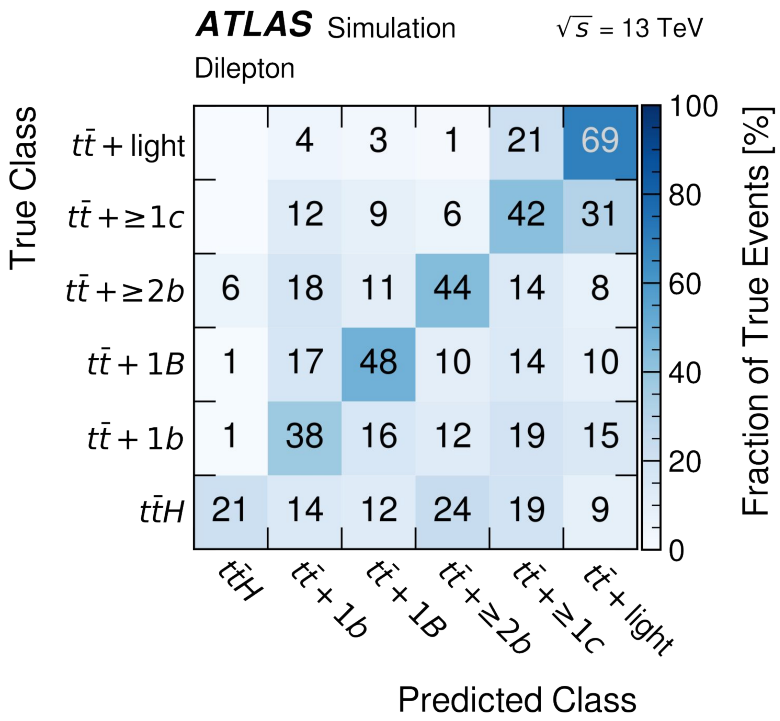
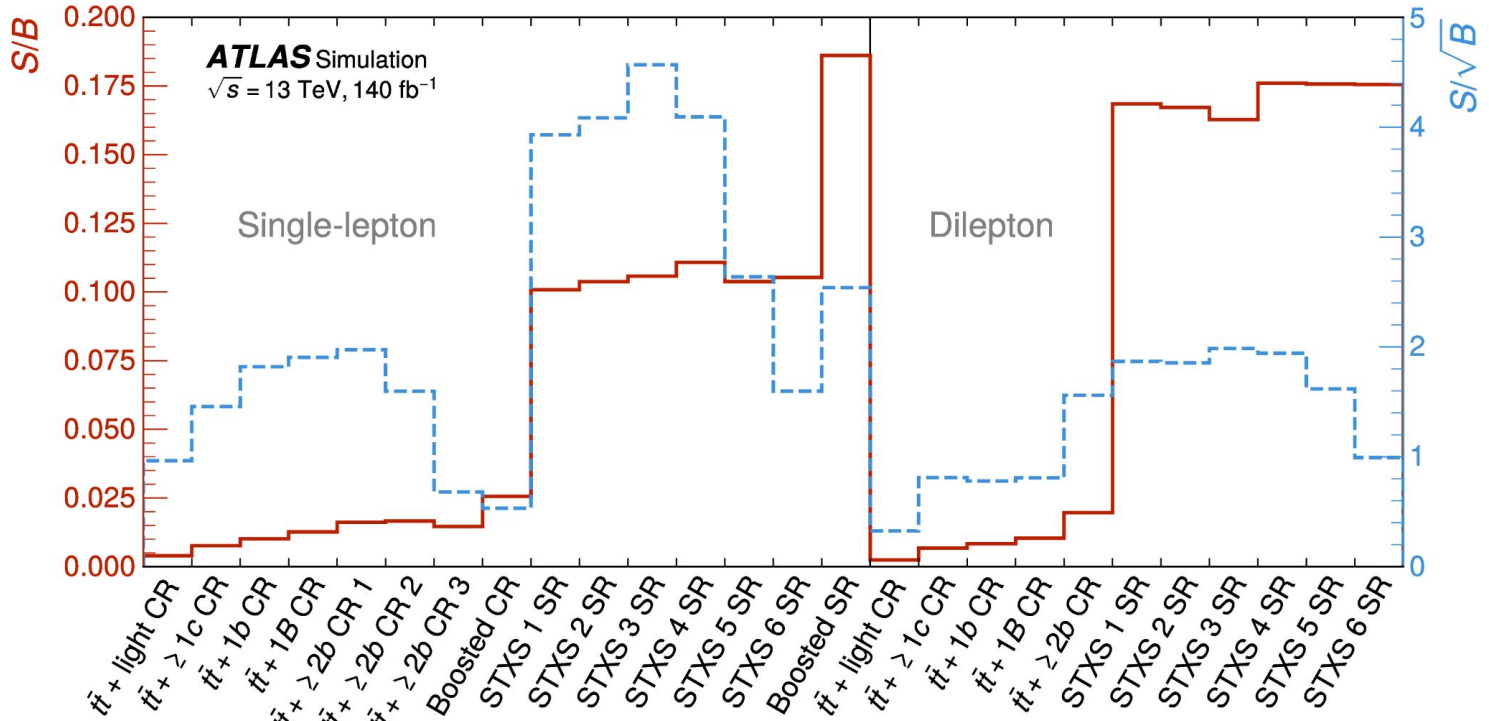
Single-lepton



Dilepton



Pre-Fit Signal/Background Ratios



- Classification Transformers give S/B of ~10% (~17%) in single-lepton resolved (dilepton) SRs
  - ➥ Improvement compared to first full Run 2: ~5% (~7%) in single-lepton resolved (dilepton) SRs

Post-Fit Region Overview

Signal Regions

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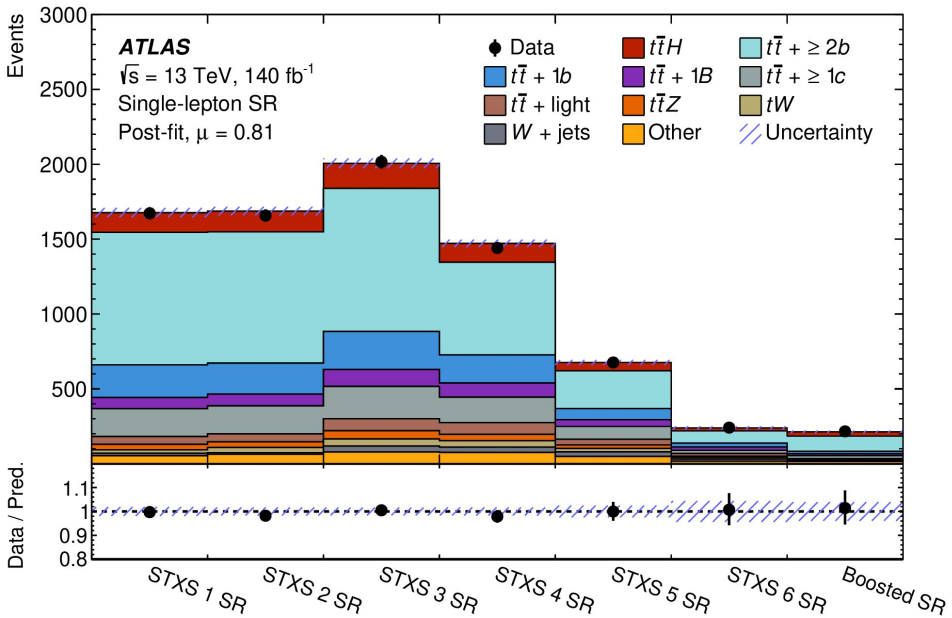
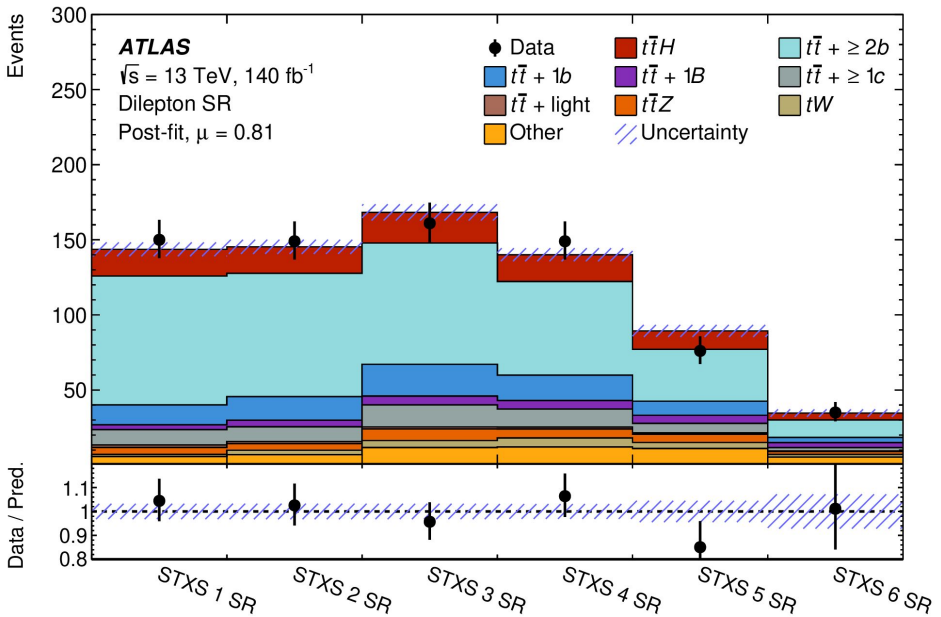
Single-Lepton



Dilepton



Post-Fit Region Overview

Control Regions

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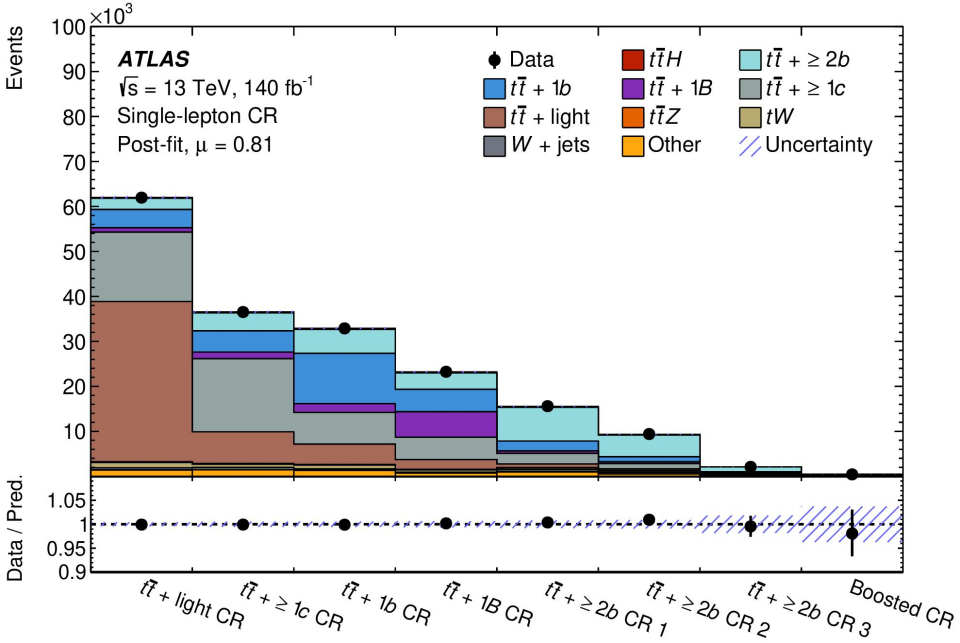
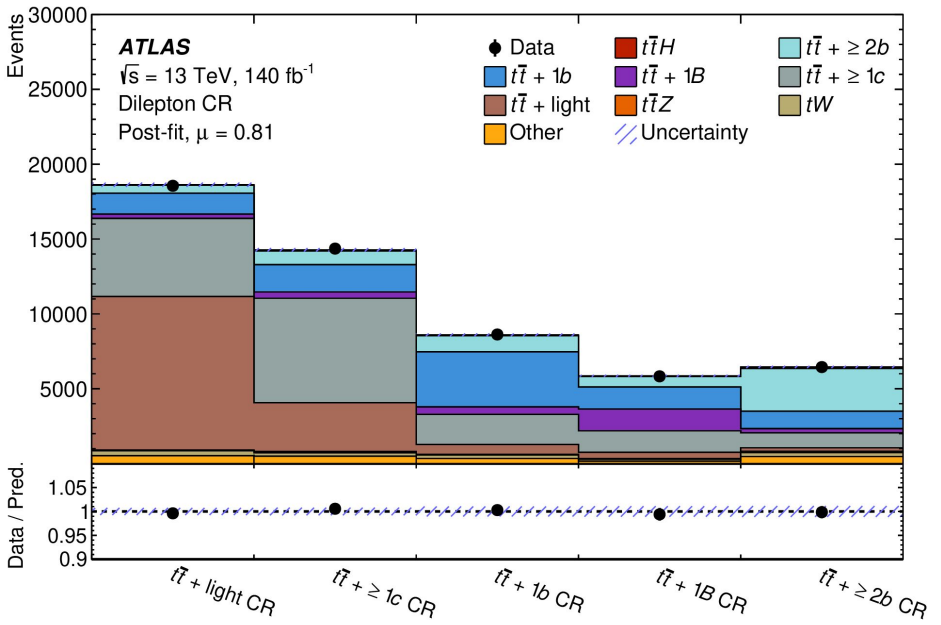
Single-Lepton

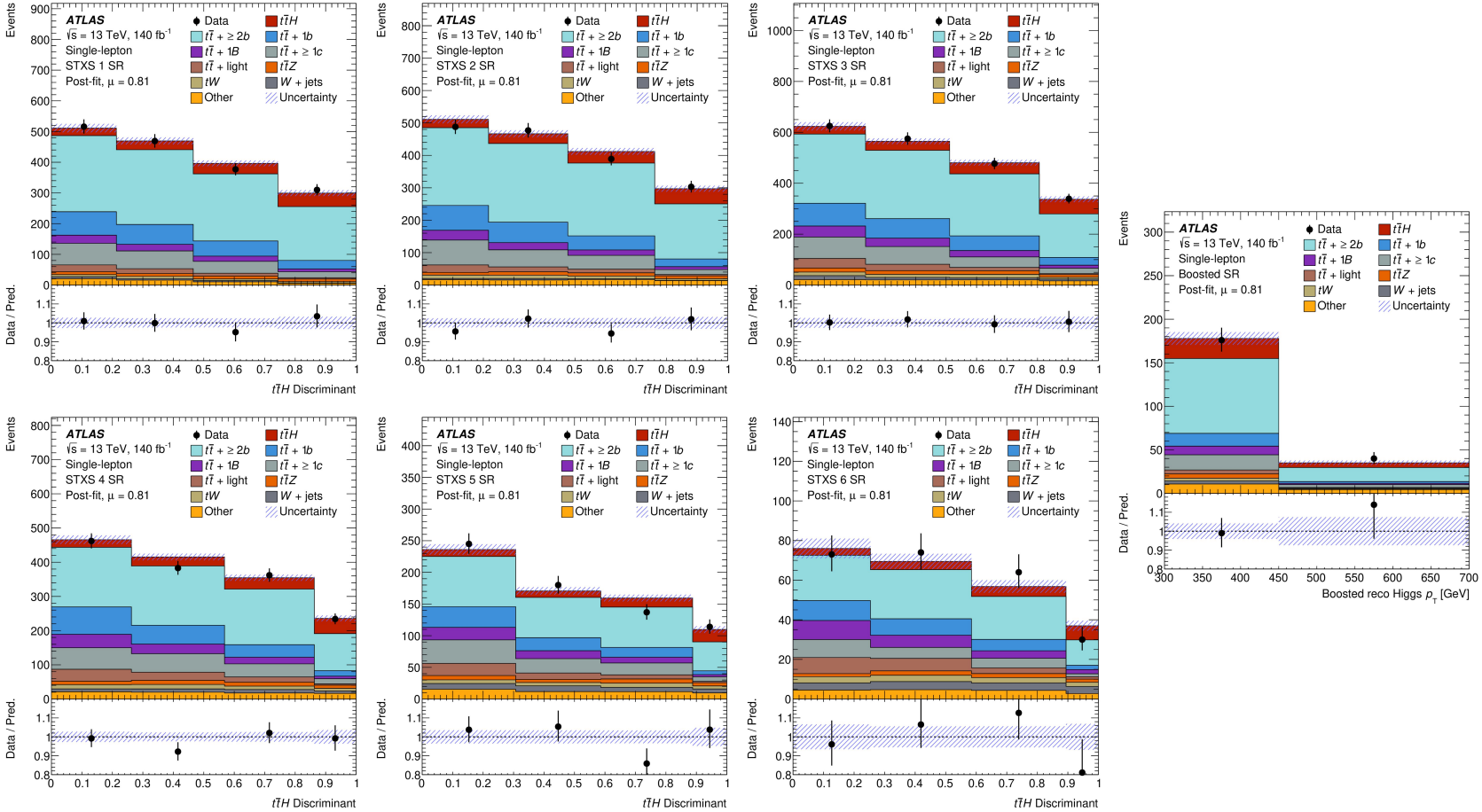


Dilepton



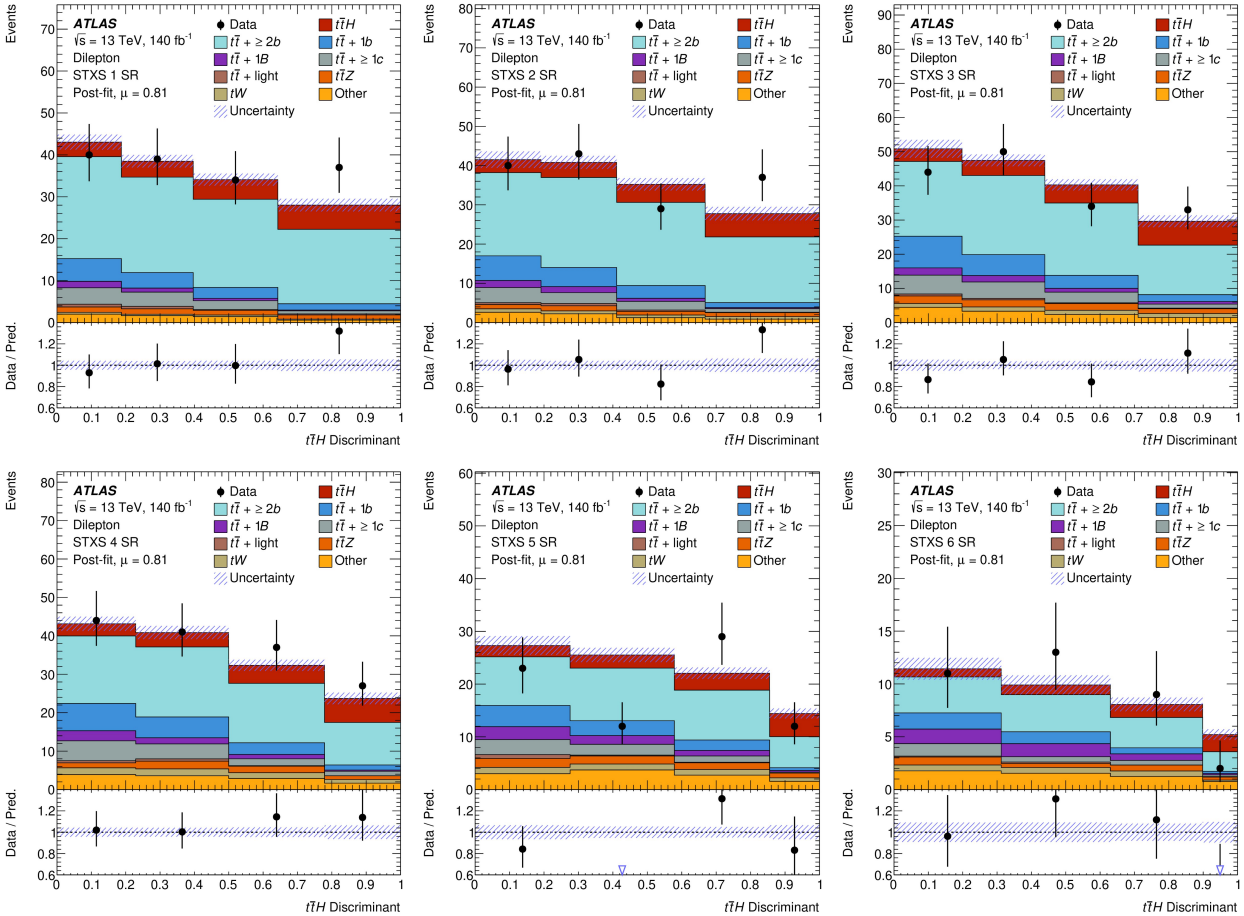
Post-Fit Distributions

Single-Lepton SRs



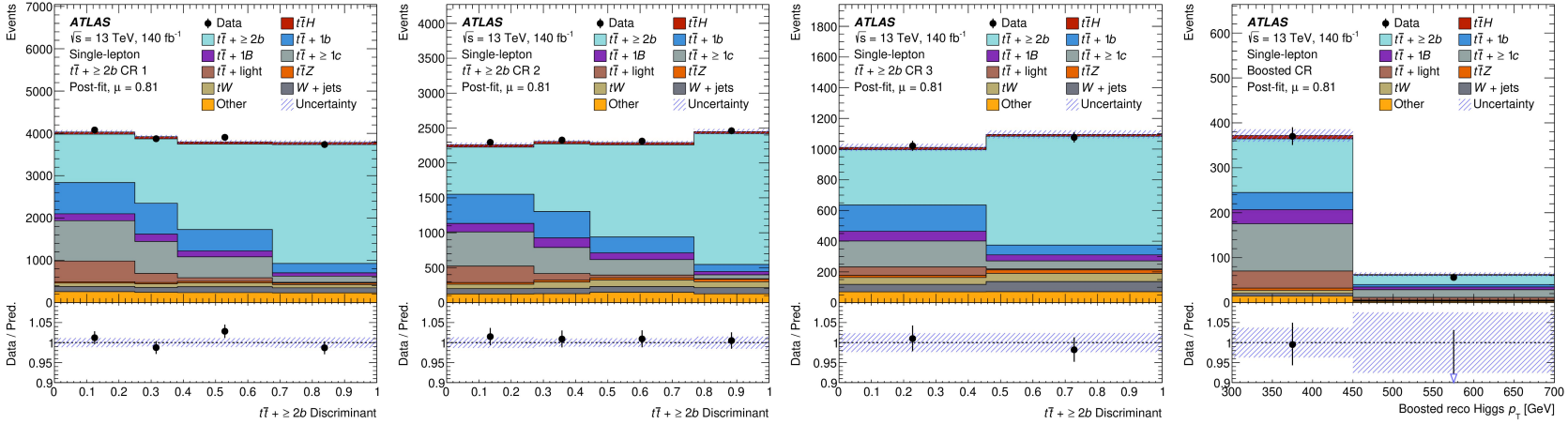
Post-Fit Distributions

Dilepton SRs



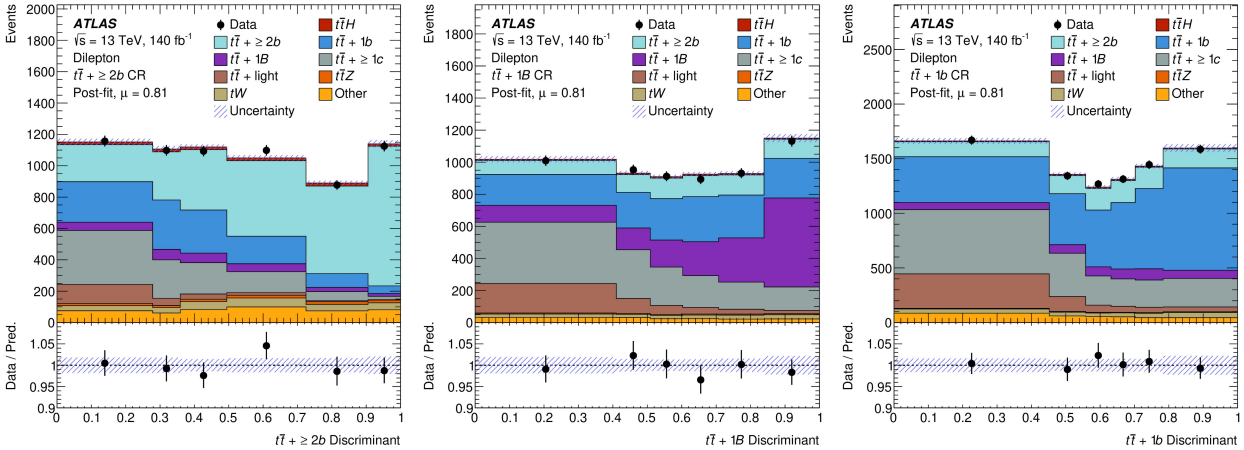
Post-Fit Distributions

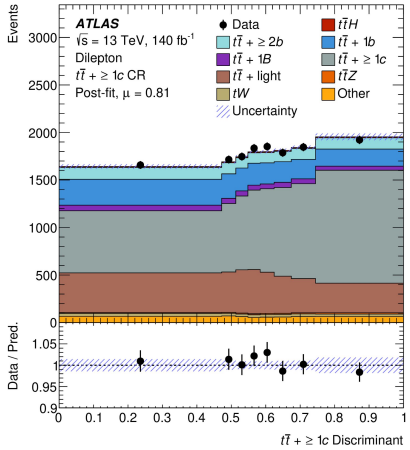
Single-Lepton CRs

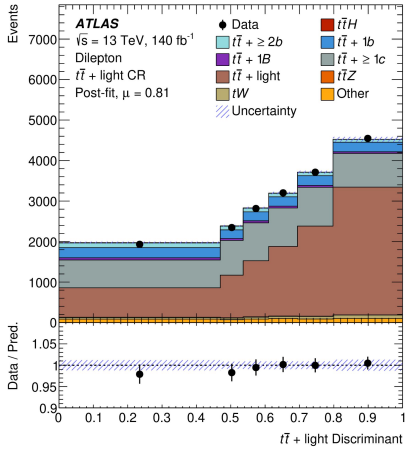


Post-Fit Distributions

Single-Lepton SRs







Single-Channel STXS Fits

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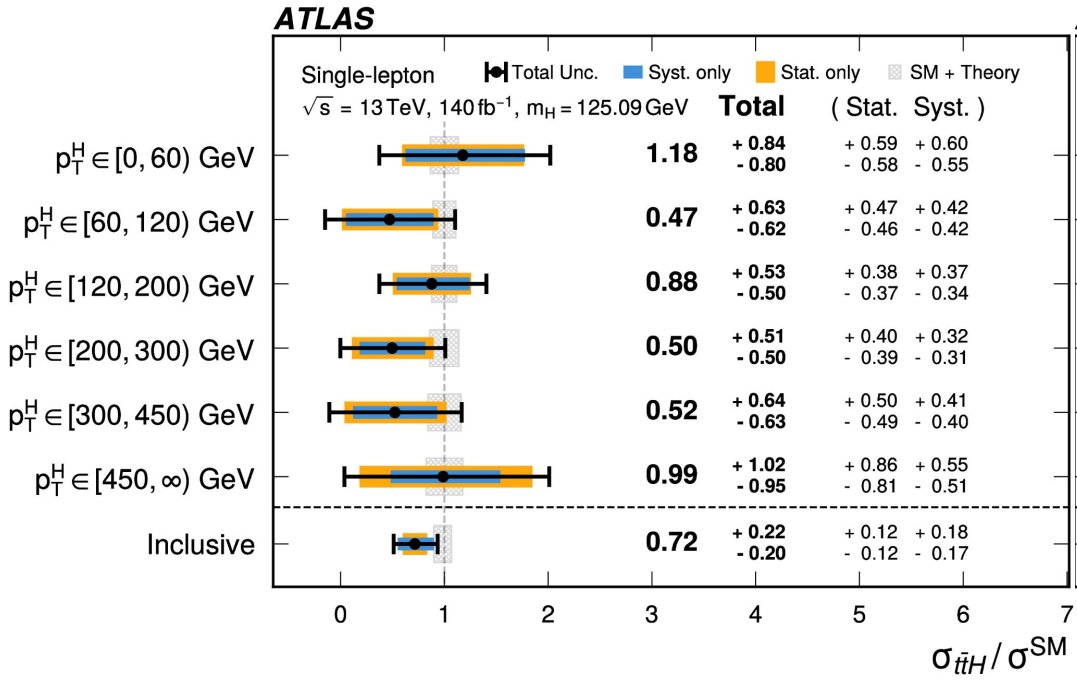
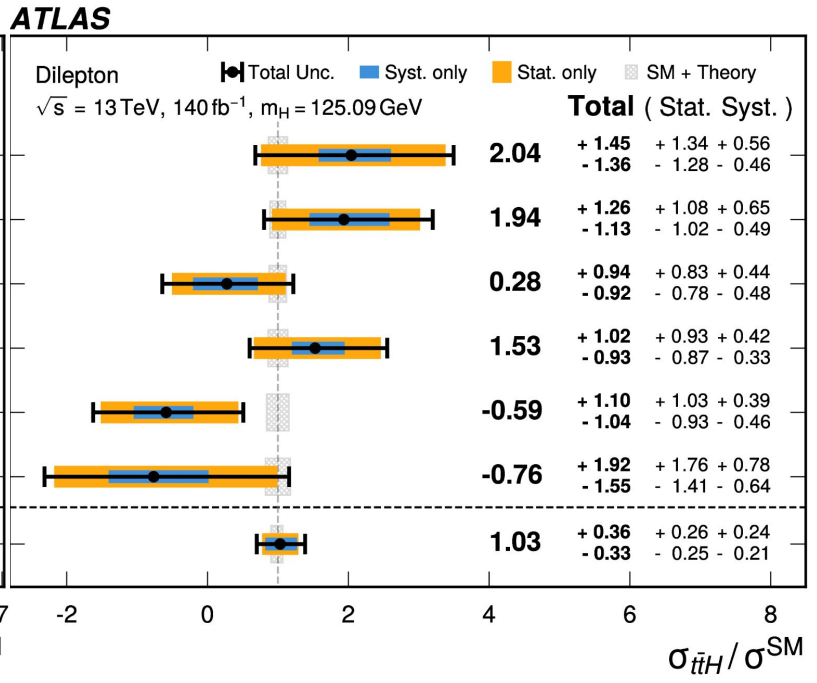
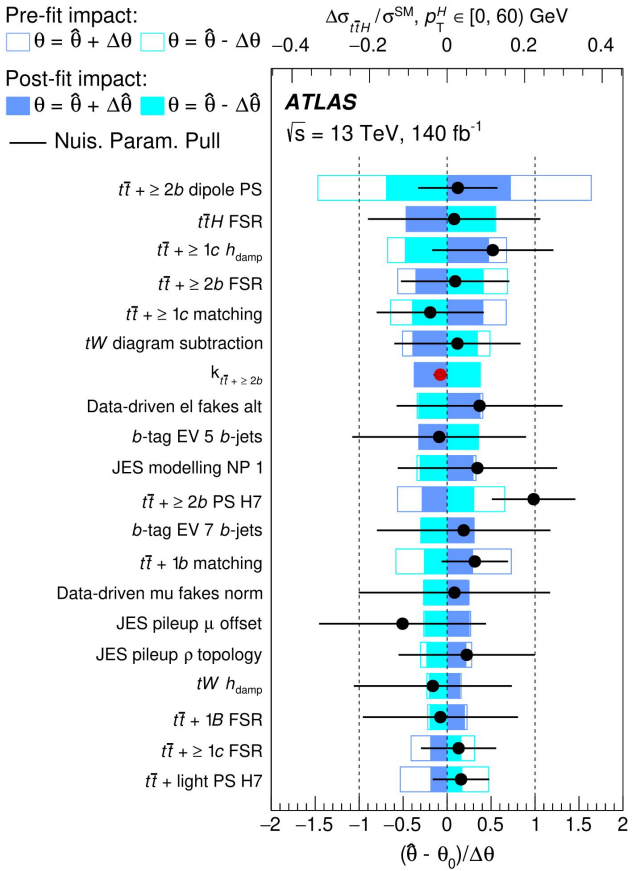
Single-Lepton

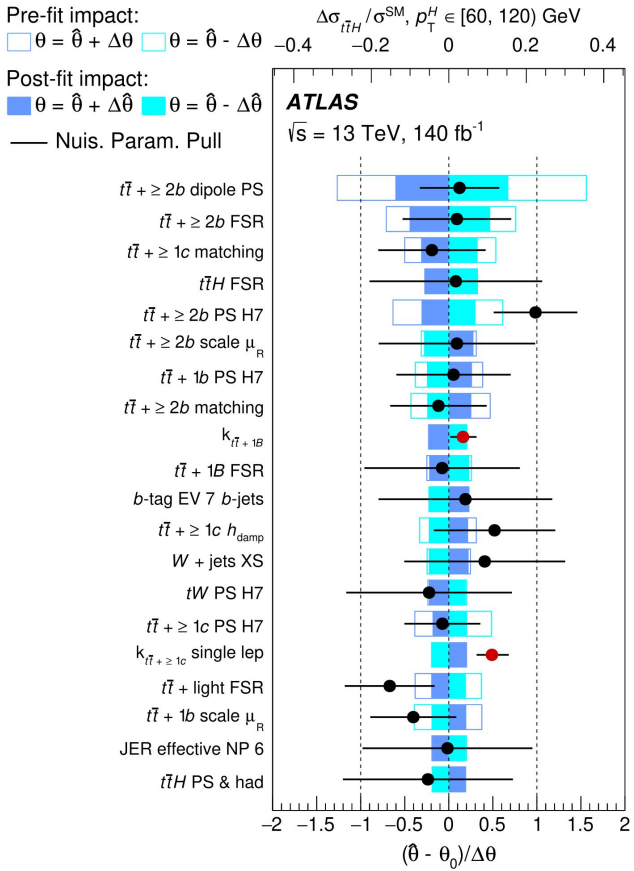


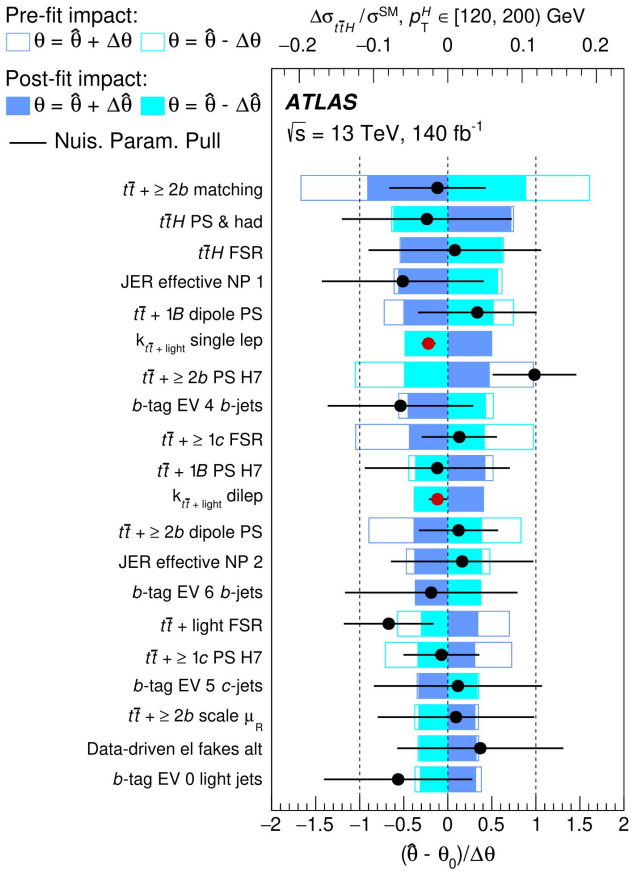
Dilepton



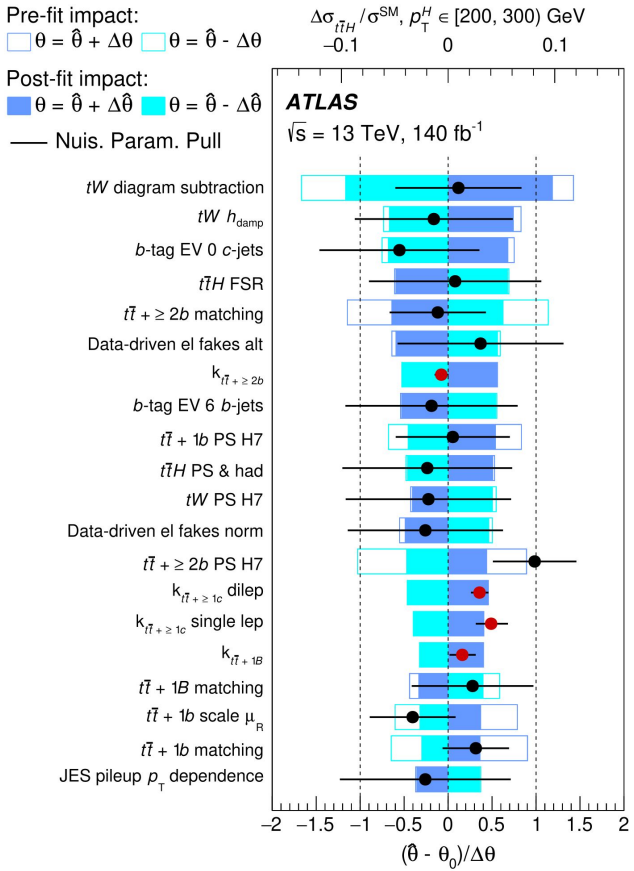
STXS Rankings I/II

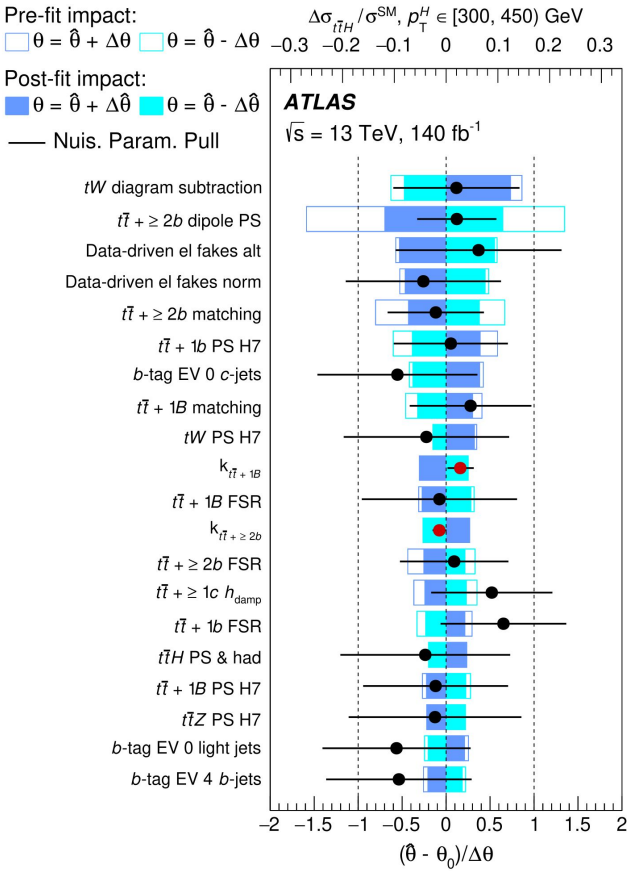


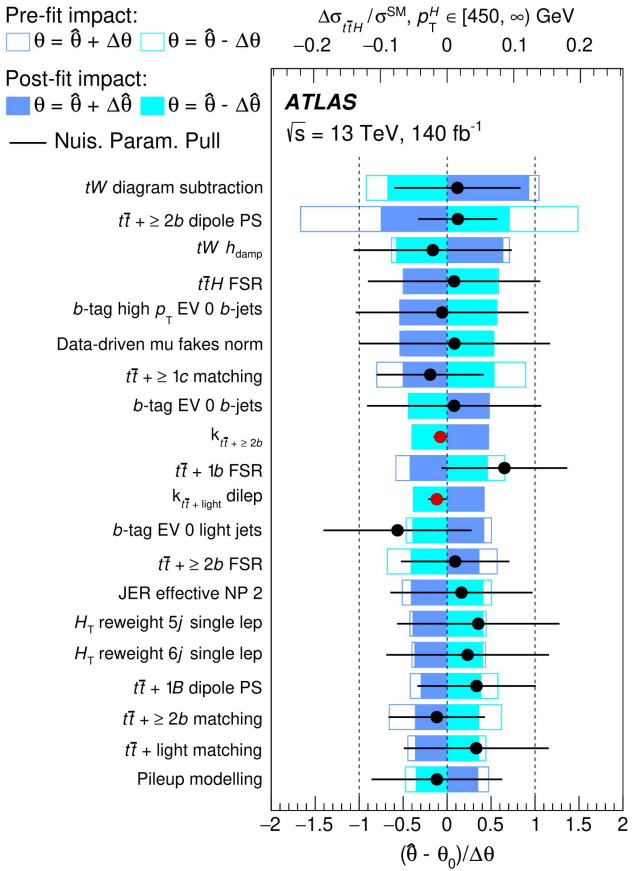




STXS Rankings II/II

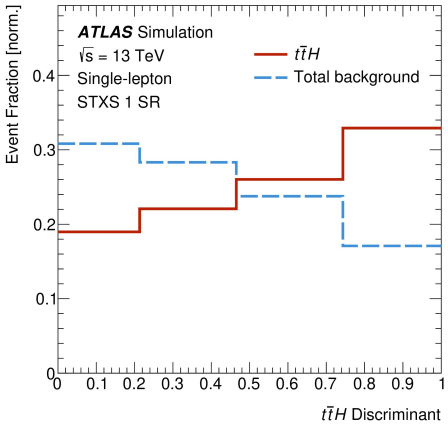


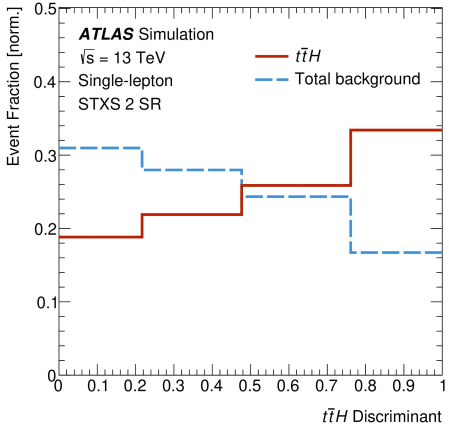


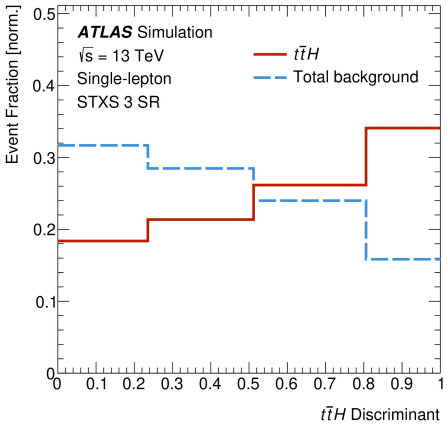


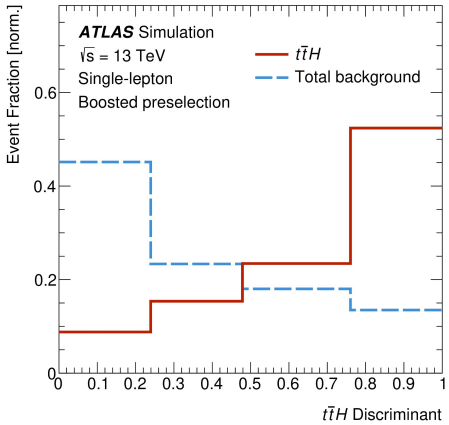
Separation Plots

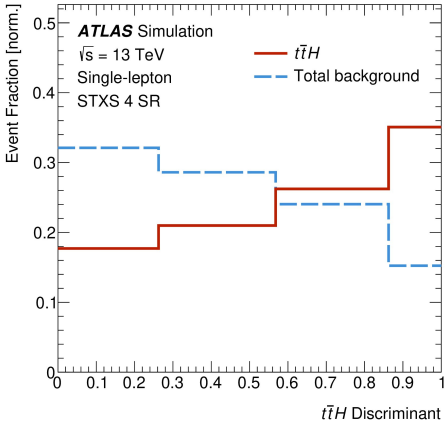
Single-Lepton SRs

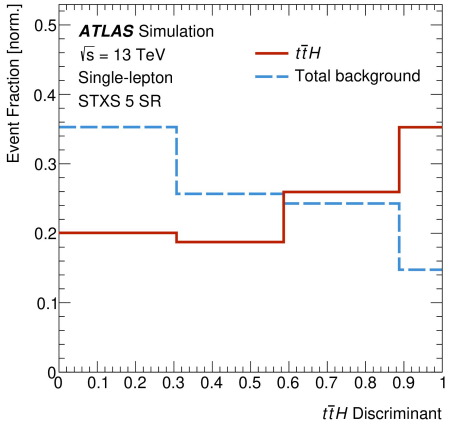


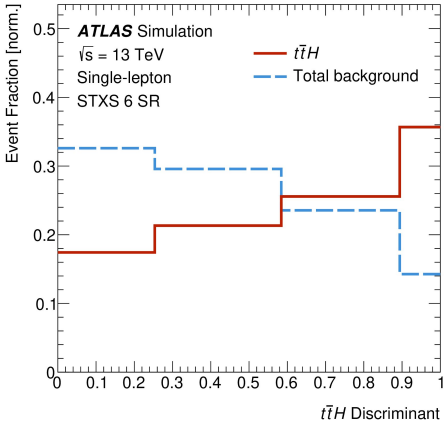






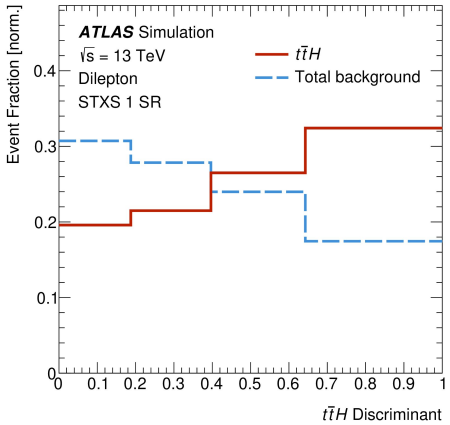


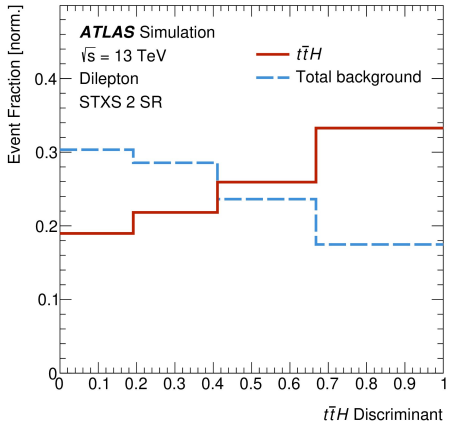


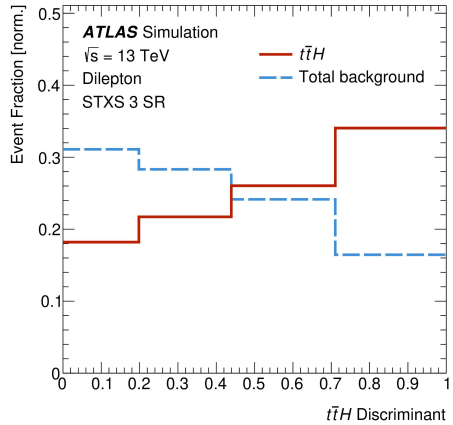


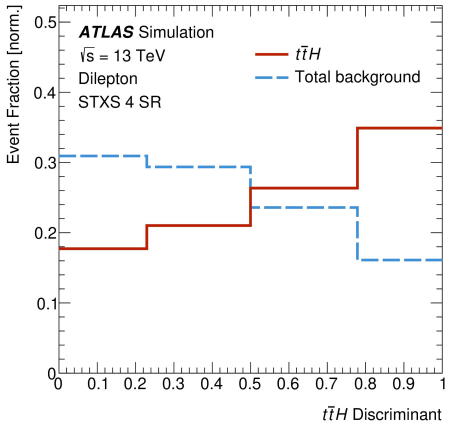
Separation Plots

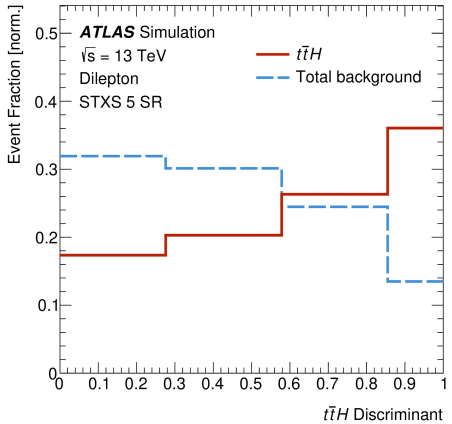
Dilepton SRs

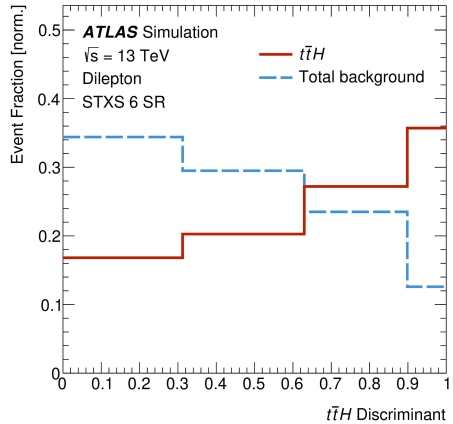






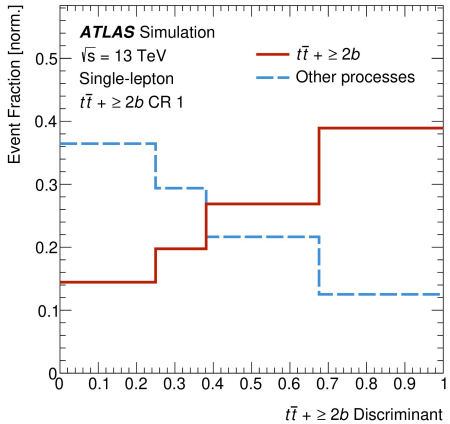


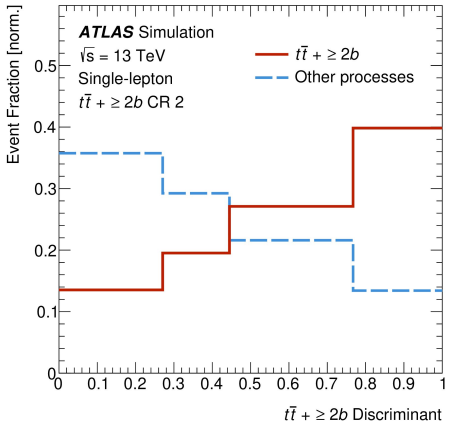


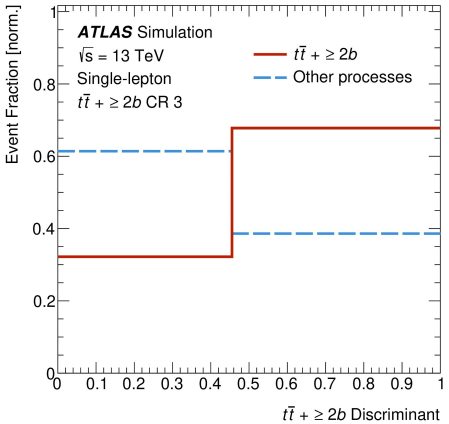


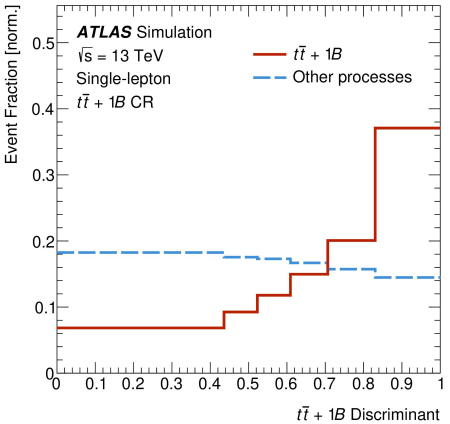
Separation Plots

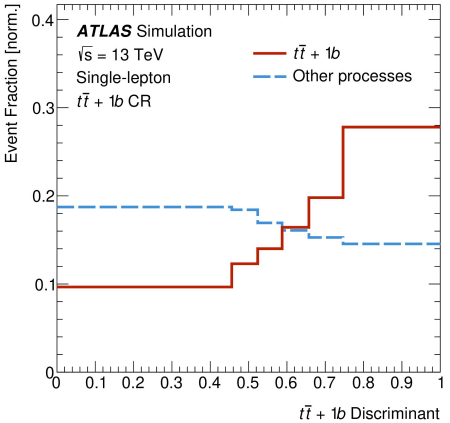
Single-Lepton CRs

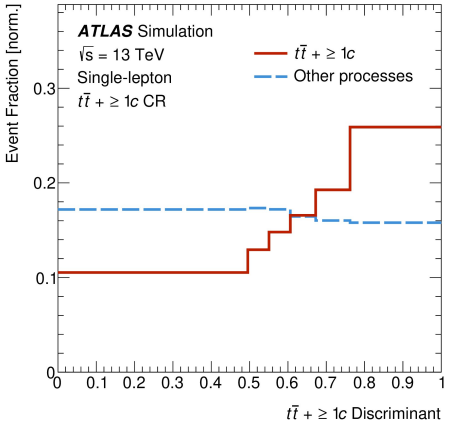


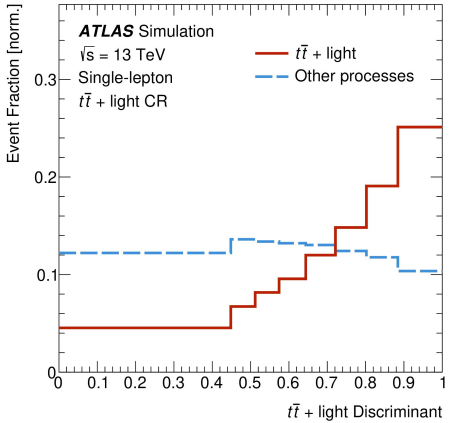






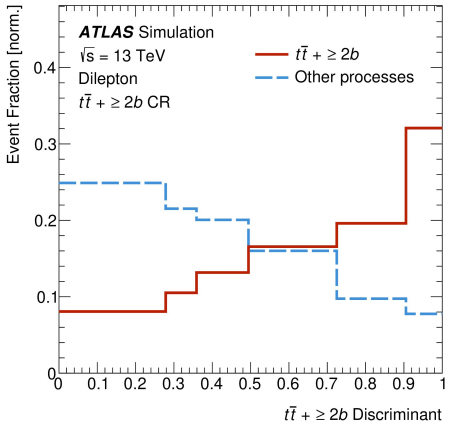


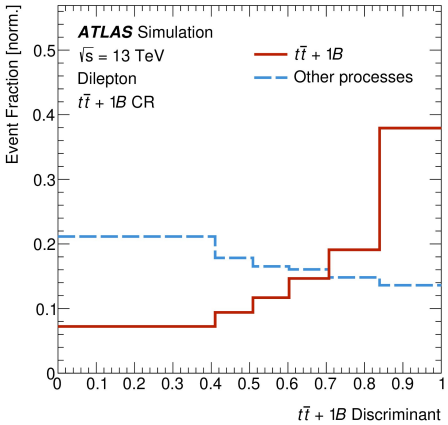


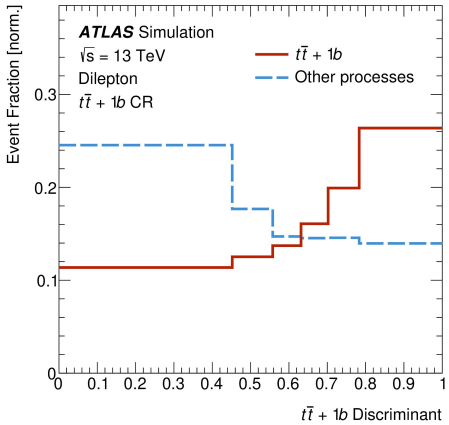


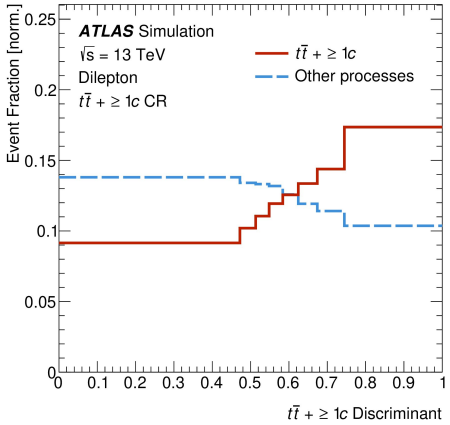
Separation Plots

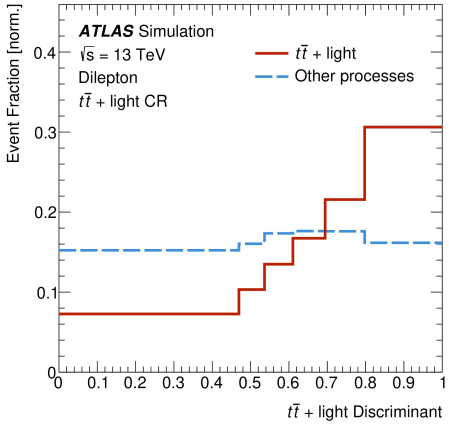
Dilepton CRs











Post-Fit Control Plots

H_T

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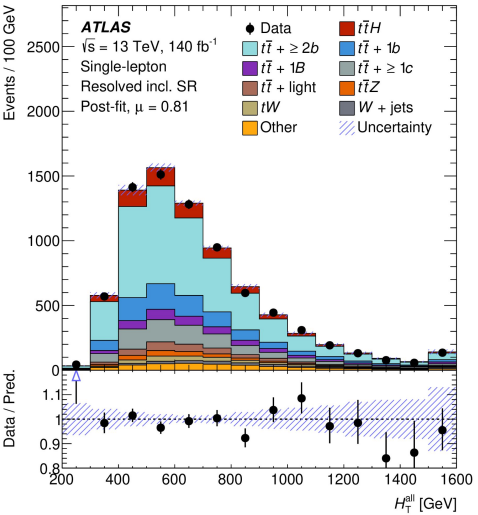
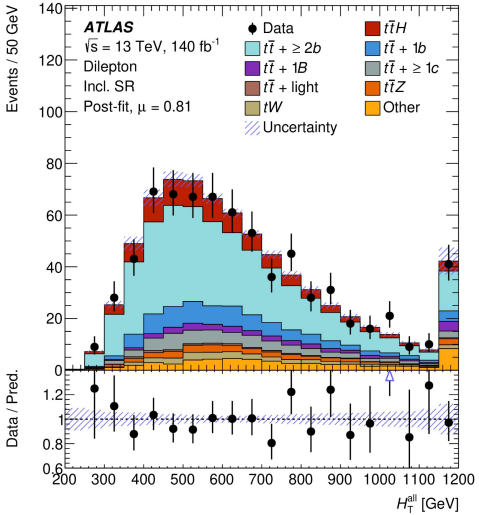
Single-Lepton

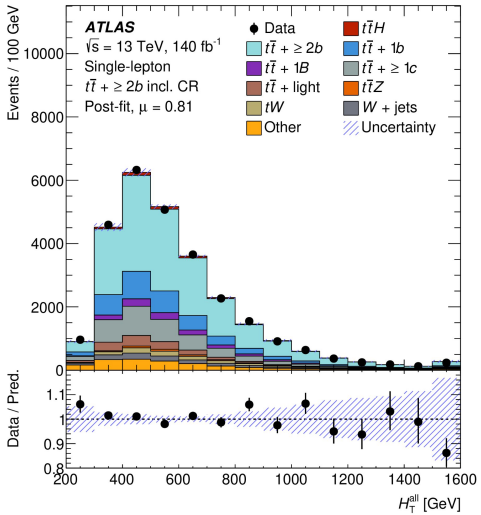


Dilepton

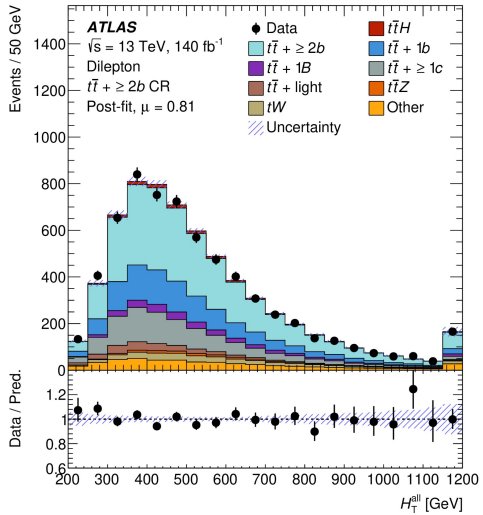


tt̄ + ≥ 2b CR

Single-Lepton



Dilepton



Post-Fit Control Plots

Jet Multiplicity

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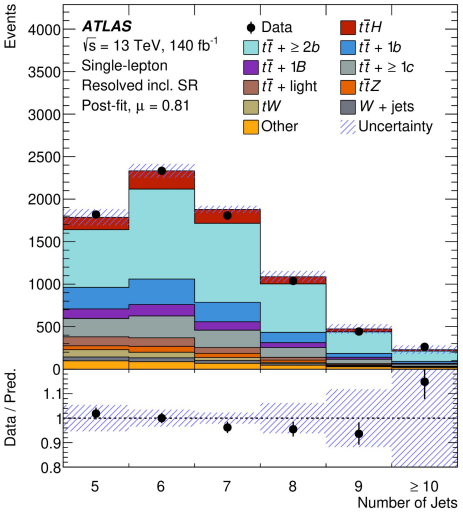
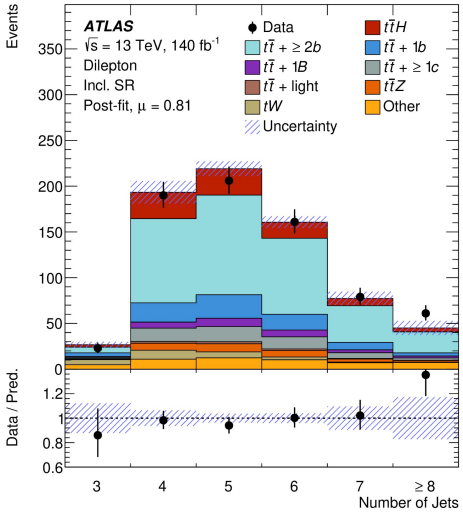
Single-Lepton

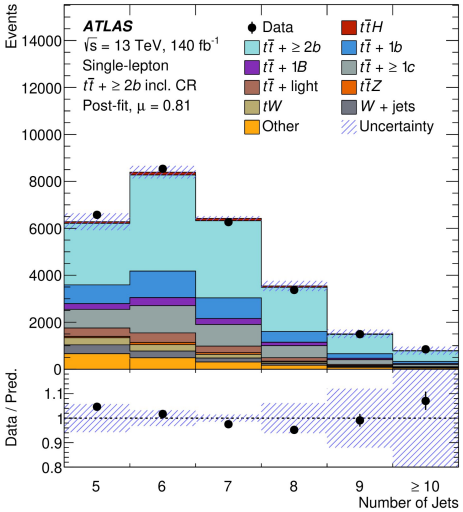


Dilepton

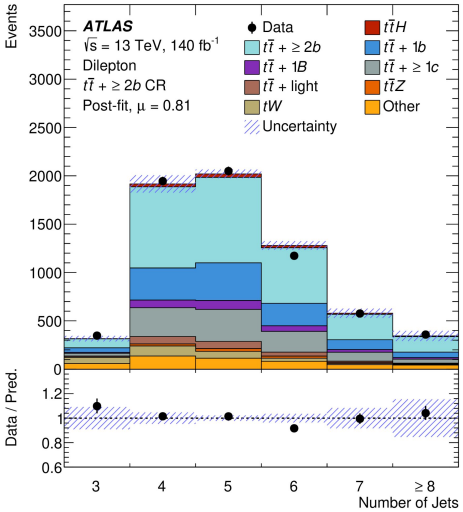


tt̄ + ≥ 2b CR

Single-Lepton



Dilepton



Post-Fit Control Plots

Reco Higgs Boson p_T

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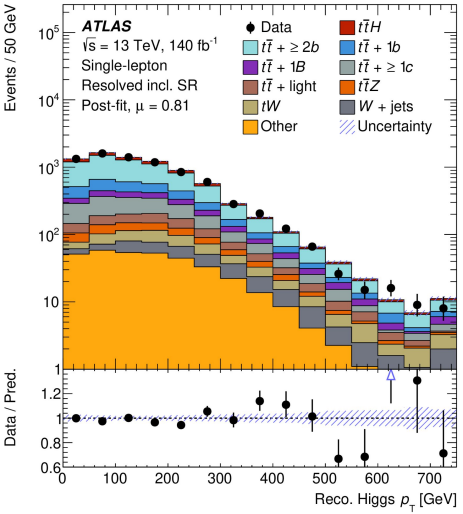
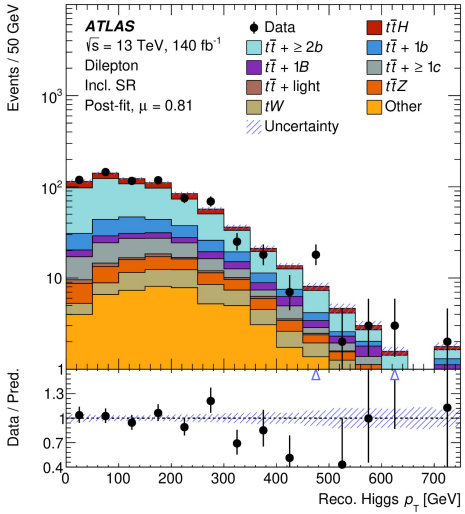
SR

Single-Lepton

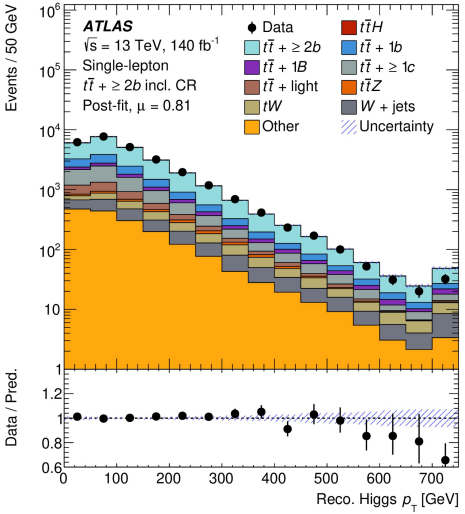


Dilepton

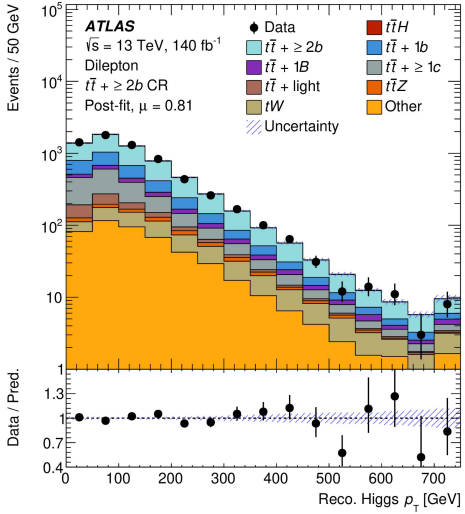


tt̄ + ≥ 2b CR

Single-Lepton



Dilepton



Pre-Fit Yield Tables

Single-Lepton Signal Regions

	STXS 1 SR	STXS 2 SR	STXS 3 SR	STXS 4 SR	STXS 5 SR	STXS 6 SR	Boosted SR
$t\bar{t}H$ truth p_{T}^{H} 0 – 60 GeV	77 ± 12	18.7 ± 3.2	11.1 ± 2.3	5.7 ± 1.0	1.66 ± 0.2	0.42 ± 0.09	0.58 ± 0.13
$t\bar{t}H$ truth p_{T}^{H} 60 – 120 GeV	49 ± 5	99 ± 13	37 ± 6	15.5 ± 2.2	4.4 ± 0.5	1.25 ± 0.19	1.54 ± 0.25
$t\bar{t}H$ truth p_{T}^{H} 120 – 200 GeV	22.7 ± 2.2	37 ± 4	125 ± 16	34 ± 5	8.1 ± 1.3	2.0 ± 0.4	2.31 ± 0.28
$t\bar{t}H$ truth p_{T}^{H} 200 – 300 GeV	4.0 ± 0.5	5.5 ± 0.7	22.5 ± 2.9	88 ± 12	19.4 ± 3.0	2.7 ± 0.4	3.3 ± 0.6
$t\bar{t}H$ truth p_{T}^{H} 300 – 450 GeV	0.39 ± 0.11	0.64 ± 0.16	1.4 ± 0.4	7.6 ± 1.3	32 ± 5	8.0 ± 1.3	20 ± 3
$t\bar{t}H$ truth p_{T}^{H} ≥ 450 GeV	<0.1	<0.1	0.14 ± 0.06	0.21 ± 0.09	1.30 ± 0.31	9.8 ± 1.8	6.9 ± 1.3
$t\bar{t}H$ $\lvert y\rvert > 2.5$	0.16 ± 0.06	0.10 ± 0.04	<0.1	<0.1	<0.1	<0.1	<0.1
$t\bar{t}$ + ≥ 2b	870 ± 80	870 ± 90	980 ± 100	640 ± 60	270 ± 40	92 ± 21	103 ± 8
$t\bar{t}$ + 1b	210 ± 60	210 ± 50	250 ± 80	180 ± 60	78 ± 28	25 ± 9	17 ± 5
$t\bar{t}$ + 1B	64 ± 19	73 ± 24	100 ± 40	87 ± 30	46 ± 19	22 ± 11	11 ± 4
$t\bar{t}$ + ≥ 1c	210 ± 50	210 ± 50	250 ± 50	190 ± 50	88 ± 24	27 ± 13	22 ± 8
$t\bar{t}$ + light	42 ± 16	45 ± 12	68 ± 22	64 ± 19	31 ± 11	12 ± 11	3.2 ± 3
$t\bar{t}Z$	36 ± 6	38 ± 6	53 ± 8	43 ± 8	24 ± 5	7.2 ± 1.1	5.8 ± 1.2
tW	20 ± 8	35 ± 12	60 ± 33	55 ± 32	33 ± 25	17 ± 15	5 ± 4
W + jets	10 ± 6	12 ± 8	30 ± 15	29 ± 14	23 ± 12	12 ± 6	3.7 ± 1.9
$t\bar{t}W$	4.2 ± 0.5	5.9 ± 0.8	9.8 ± 1.6	8.9 ± 1.9	5.6 ± 0.7	3.2 ± 0.5	1.06 ± 0.26
Z + jets	2.5 ± 1.1	5.1 ± 2	6.5 ± 2.6	7.4 ± 2.7	3.1 ± 1.1	1.7 ± 0.6	0.5 ± 0.2
Diboson	1.3 ± 0.8	2.5 ± 1.40	4.4 ± 2.3	4.7 ± 2.7	3.1 ± 1.6	1.4 ± 0.7	0.7 ± 0.4
$t\bar{t}t\bar{t}$	5.1 ± 2.2	6.7 ± 3	11 ± 5	9 ± 4	4.8 ± 2.1	2.5 ± 1.1	1.1 ± 0.5
$tHjb$	0.77 ± 0.22	1.06 ± 0.21	1.61 ± 0.32	1.58 ± 0.28	1.11 ± 0.30	0.26 ± 0.12	0.72 ± 0.14
tWH	1.68 ± 0.23	2.16 ± 0.27	3.8 ± 0.4	4.1 ± 0.5	2.22 ± 0.25	1.03 ± 0.12	1.01 ± 0.11
Other	11.3 ± 1.2	11 ± 1.5	14.4 ± 2	11.9 ± 1.5	7.3 ± 1.1	2.43 ± 0.35	2.2 ± 0.6
Fakes	29 ± 12	29 ± 15	27 ± 12	31 ± 19	22 ± 13	3.8 ± 2.5	8 ± 5
Total	1670 ± 160	1710 ± 170	2060 ± 210	1520 ± 150	710 ± 80	250 ± 40	221 ± 19
Data	1672	1657	2016	1441	676	241	216

Pre-Fit Yield Tables

Dilepton Signal Regions

	STXS 1 SR	STXS 2 SR	STXS 3 SR	STXS 4 SR	STXS 5 SR	STXS 6 SR
$t\bar{t}H$ truth p_{T}^{H} 0–60 GeV	10.6 ± 1.5	2.03 ± 0.31	1.14 ± 0.17	0.63 ± 0.11	0.19 ± 0.07	0.046 ± 0.023
$t\bar{t}H$ truth p_{T}^{H} 60–120 GeV	6.5 ± 0.7	13.0 ± 1.8	4.1 ± 0.7	1.9 ± 0.4	0.7 ± 0.11	0.13 ± 0.07
$t\bar{t}H$ truth p_{T}^{H} 120–200 GeV	3.06 ± 0.34	4.7 ± 0.5	16.3 ± 2.0	5.0 ± 0.7	1.36 ± 0.19	0.24 ± 0.07
$t\bar{t}H$ truth p_{T}^{H} 200–300 GeV	0.5 ± 0.07	0.72 ± 0.08	2.5 ± 0.29	13.0 ± 1.7	4.4 ± 0.6	0.41 ± 0.06
$t\bar{t}H$ truth p_{T}^{H} 300–450 GeV	<0.1	<0.1	0.197 ± 0.033	0.82 ± 0.18	8.0 ± 1.1	1.98 ± 0.32
$t\bar{t}H$ truth p_{T}^{H} ≥ 450 GeV	<0.1	<0.1	<0.1	<0.1	0.26 ± 0.08	2.8 ± 0.5
$t\bar{t}H$ $\|y\| > 2.5$	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
$t\bar{t}$ + ≥ 2b	81 ± 8	76 ± 7	81 ± 13	59 ± 4	36.2 ± 3.0	11.7 ± 2.1
$t\bar{t}$ + 1b	14 ± 5	15 ± 6	20 ± 9	17 ± 5	11 ± 6	2.9 ± 1.9
$t\bar{t}$ + 1B	4.4 ± 2.6	4.8 ± 3.2	5.7 ± 2.3	6.2 ± 1.9	6.6 ± 2.9	3.5 ± 2.3
$t\bar{t}$ + ≥ 1c	11.3 ± 2.4	11.7 ± 2.6	15.4 ± 3.4	12.5 ± 2.6	7.1 ± 2.6	3.0 ± 1.7
$t\bar{t}$ + light	1.1 ± 0.7	0.9 ± 0.5	1.4 ± 0.8	1.0 ± 0.5	1.0 ± 0.4	0.37 ± 0.30
$t\bar{t}Z$	4.6 ± 0.7	4.6 ± 1.1	7.2 ± 1.1	6.2 ± 1.3	5.3 ± 1.1	2 ± 0.6
tW	1.7 ± 0.8	3± 1.8	6 ± 4	8 ± 5	7 ± 5	3.1 ± 2.9
$t\bar{t}W$	0.65 ± 0.11	1.18 ± 0.15	2.1 ± 0.23	2.64 ± 0.3	2.7 ± 0.4	1.2 ± 0.5
Z + jets	1.8 ± 0.9	1.9 ± 0.9	3.4 ± 1.3	3.8 ± 1.4	3.3 ± 1.2	1.8 ± 0.7
$t\bar{t}t\bar{t}$	0.9 ± 0.4	1.1 ± 0.5	1.8 ± 0.7	1.7 ± 0.7	1.3 ± 0.6	0.65 ± 0.28
tWH	0.23 ± 0.04	0.31 ± 0.04	0.57 ± 0.07	0.7 ± 0.08	0.66 ± 0.07	0.24 ± 0.03
Other	<0.1	<0.1	0.28 ± 0.14	0.42 ± 0.19	0.23 ± 0.08	0.29 ± 0.13
Fakes	1.7 ± 0.9	2.2 ± 1.1	3.2 ± 1.6	2.9 ± 1.5	2.6 ± 1.3	1.1 ± 0.6
Total	144 ± 13	144 ± 13	173 ± 20	143 ± 12	100 ± 11	38 ± 6
Data	150	149	161	149	76	35

Pre-Fit Yield Tables

Single-Lepton Control Regions

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	$t\bar{t}$ + light CR	$t\bar{t}$ + ≥ 1c CR	$t\bar{t}$ + 1b CR	$t\bar{t}$ + 1B CR	$t\bar{t}$ + ≥ 2b CR 1	$t\bar{t}$ + ≥ 2b CR 2	$t\bar{t}$ + ≥ 2b CR 3	Boosted CR
$t\bar{t}H$ truth p_T^H 0 – 60 GeV	56 ± 6	59 ± 7	89 ± 11	46 ± 6	80 ± 10	12.5 ± 1.7	2.09 ± 0.26	0.54 ± 0.14
$t\bar{t}H$ truth p_T^H 60 – 120 GeV	86 ± 5	98 ± 8	133 ± 12	92 ± 13	112 ± 11	33 ± 5	4.5 ± 0.9	1.15 ± 0.23
$t\bar{t}H$ truth p_T^H 120 – 200 GeV	59 ± 4	76 ± 7	76 ± 8	88 ± 11	41 ± 4	68 ± 8	5.4 ± 1.1	1.36 ± 0.28
$t\bar{t}H$ truth p_T^H 200 – 300 GeV	23 ± 2.5	31.9 ± 3.5	21.2 ± 3.1	41 ± 5	7.3 ± 1.1	34 ± 4	6.7 ± 1.1	1.42 ± 0.32
$t\bar{t}H$ truth p_T^H 300 – 450 GeV	7.7 ± 1.0	10 ± 1.5	4.7 ± 0.8	14.3 ± 2	1.12 ± 0.27	4.4 ± 0.8	9.8 ± 1.5	4.8 ± 0.7
$t\bar{t}H$ truth p_T^H ≥ 450 GeV	1.67 ± 0.27	2.4 ± 0.5	0.78 ± 0.19	4.1 ± 0.7	0.18 ± 0.05	0.35 ± 0.12	3 ± 0.7	1.75 ± 0.32
$t\bar{t}H$ $\|y\| > 2.5$	0.98 ± 0.08	0.72 ± 0.17	1.38 ± 0.22	0.57 ± 0.15	0.37 ± 0.05	0.188 ± 0.029	<0.1	<0.1
$t\bar{t}$ + ≥ 2b	2320 ± 280	3800 ± 400	5400 ± 600	3500 ± 400	7200 ± 600	4900 ± 500	1140 ± 170	141 ± 10
$t\bar{t}$ + 1b	3900 ± 400	4600 ± 700	10600 ± 1700	5100 ± 600	2100 ± 500	1120 ± 320	230 ± 100	54 ± 19
$t\bar{t}$ + 1B	890 ± 80	1390 ± 270	1780 ± 270	5100 ± 400	530 ± 190	380 ± 140	100 ± 50	32 ± 7
$t\bar{t}$ + ≥ 1c	17000 ± 3300	17900 ± 2600	7800 ± 1000	5400 ± 1300	2500 ± 500	1220 ± 270	240 ± 70	133 ± 35
$t\bar{t}$ + light	31800 ± 3500	5900 ± 1100	4000 ± 600	2000 ± 500	700 ± 180	320 ± 110	49 ± 26	34 ± 8
$t\bar{t}Z$	152 ± 20	171 ± 25	151 ± 21	146 ± 22	122 ± 18	117 ± 15	36 ± 5	5.7 ± 0.9
tW	1040 ± 200	750 ± 220	820 ± 240	560 ± 190	350 ± 140	360 ± 150	130 ± 90	10 ± 6
W + jets	370 ± 180	370 ± 180	230 ± 120	170 ± 80	370 ± 190	250 ± 130	90 ± 40	5.6 ± 2.9
$t\bar{t}W$	100 ± 12	114 ± 17	43 ± 7	44 ± 5	25.6 ± 3.5	26 ± 5	10.5 ± 1.6	1.97 ± 0.33
Z + jets	110 ± 40	110 ± 40	110 ± 40	64 ± 23	100 ± 40	55 ± 20	16 ± 6	0.9 ± 0.4
Diboson	37 ± 19	39 ± 20	23 ± 12	21 ± 11	24 ± 13	23 ± 12	10 ± 5	1.1 ± 0.7
$t\bar{t}t\bar{t}$	2.9 ± 1.2	24 ± 10	7.1 ± 3	19 ± 8	21 ± 9	33 ± 14	17 ± 7	1.4 ± 0.6
$tHjb$	8.2 ± 1.4	5.4 ± 0.9	8.1 ± 1.6	3.5 ± 0.6	5.4 ± 1.1	3.6 ± 0.7	0.53 ± 0.15	0.65 ± 0.20
tWH	7.1 ± 0.7	6.7 ± 0.7	9.6 ± 1	5.7 ± 0.6	5.4 ± 0.6	5.8 ± 0.7	1.78 ± 0.2	0.44 ± 0.07
Other	370 ± 40	370 ± 40	303 ± 35	228 ± 22	179 ± 22	111 ± 12	27.4 ± 2.8	3.9 ± 0.9
Fakes	810 ± 300	800 ± 400	880 ± 350	340 ± 140	660 ± 300	280 ± 130	57 ± 32	6.3 ± 3.3
Total	59000 ± 6000	37000 ± 4000	32500 ± 2900	22900 ± 2200	15200 ± 1700	9400 ± 1000	2190 ± 270	440 ± 50
Data	61954	36528	32887	23245	15595	9397	2097	426

Pre-Fit Yield Tables

Dilepton Control Regions

	$t\bar{t}$ + light CR	$t\bar{t}$ + ≥ 1c CR	$t\bar{t}$ + 1b CR	$t\bar{t}$ + 1B CR	$t\bar{t}$ + ≥ 2b CR
$t\bar{t}H$ truth p_{T}^{H} 0 – 60 GeV	11.9 ± 1.4	19.7 ± 2.3	19.8 ± 2.3	9.9 ± 1.4	26.0 ± 3.0
$t\bar{t}H$ truth p_{T}^{H} 60 – 120 GeV	17.0 ± 1.3	34.5 ± 2.9	29.5 ± 3.0	20.4 ± 2.5	42.0 ± 4.0
$t\bar{t}H$ truth p_{T}^{H} 120 – 200 GeV	10.0 ± 0.9	27.1 ± 2.7	17.0 ± 2.1	19.2 ± 2.4	34.0 ± 3.5
$t\bar{t}H$ truth p_{T}^{H} 200 – 300 GeV	3.1 ± 0.35	11.1 ± 1.3	4.6 ± 0.7	9.2 ± 1.2	14.9 ± 1.9
$t\bar{t}H$ truth p_{T}^{H} 300 – 450 GeV	0.94 ± 0.15	3.5 ± 0.5	0.94 ± 0.19	3.3 ± 0.5	5.4 ± 0.8
$t\bar{t}H$ truth p_{T}^{H} ≥ 450 GeV	0.33 ± 0.07	0.65 ± 0.12	0.116 ± 0.033	0.97 ± 0.15	1.33 ± 0.26
$t\bar{t}H$ $\lvert y\rvert > 2.5$	0.31 ± 0.05	0.25 ± 0.04	0.4 ± 0.05	0.127 ± 0.028	0.166 ± 0.018
$t\bar{t}$ + ≥ 2b	495 ± 35	860 ± 60	1080 ± 200	650 ± 100	2700 ± 200
$t\bar{t}$ + 1b	1410 ± 130	1790 ± 230	3600 ± 700	1540± 180	1200 ± 400
$t\bar{t}$ + 1B	310 ± 40	460 ± 40	540± 210	1560 ± 230	310 ± 110
$t\bar{t}$ + ≥ 1c	5600 ± 500	7700 ± 600	2210 ± 280	1590 ± 330	1070 ± 170
$t\bar{t}$ + light	9200 ± 1500	2800 ± 400	590 ± 130	410 ± 90	190 ± 70
$t\bar{t}Z$	43 ± 6	81 ± 12	35 ± 6	36 ± 5	92 ± 12
tW	300 ± 60	210 ± 50	220 ± 70	150 ± 50	300 ± 140
$t\bar{t}W$	37 ± 5	72 ± 7	12.1 ± 1.3	14.3 ± 3.3	29.8 ± 3.5
Z + jets	340 ± 130	260 ± 100	250 ± 90	93 ± 34	320 ± 120
$t\bar{t}t\bar{t}$	1.6 ± 0.7	10± 4	1± 0.4	4.8 ± 2	28 ± 12
tWH	0.98 ± 0.11	2.24 ± 0.22	2.69 ± 0.29	1.42 ± 0.14	4.0 ± 0.4
Other	5.6 ± 2.4	8.1 ± 3.1	4.4 ± 2.0	2.1 ± 0.7	12 ± 5
Fakes	110 ± 50	120 ± 60	40 ± 20	40 ± 20	80 ± 40
Total	18000 ± 2000	14400 ± 1100	8700 ± 900	6200 ± 500	6400 ± 700
Data	18557	14361	8624	5830	6448