Measurement of the production of four-top-quark production with the ATLAS experiment at the LHC

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XXVIII International Workshop on Deep-Inelastic Scattering and Related Subject

April 15th, 2021
Stony Brook University, New York - USA (Online)

$t\bar{t}t\bar{t}$ Production at the LHC

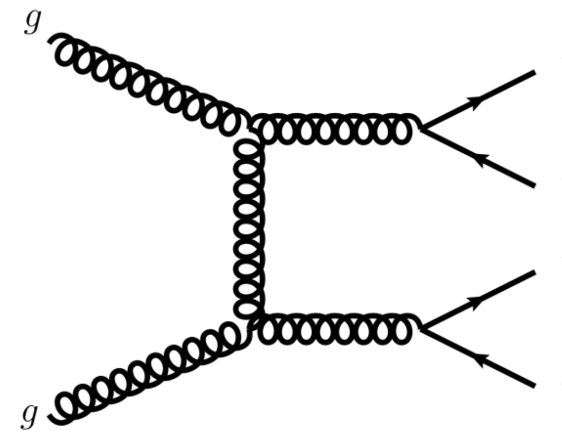
[1] JHEP 02 (2018) 031

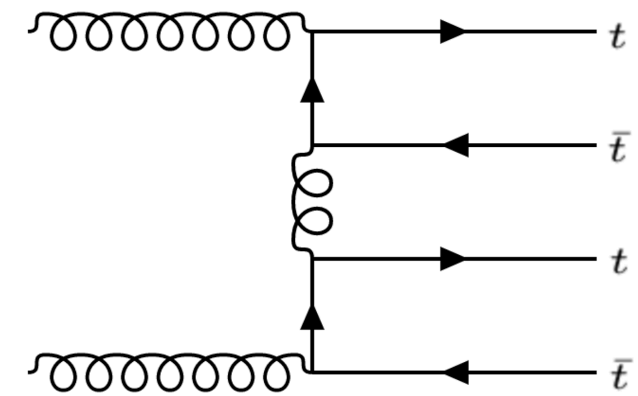
Standard Model cross-section

$\sigma(pp \rightarrow t\bar{t}t\bar{t}) = 12 \pm 2.4$ fb (NLO QCD + EW @ 13TeV) [1]

1 Lepton or 2 Opposite-Sign Leptons (1L/2LOS)
Higher Branching ratio, lower signal purity

2 Same-sign leptons or at least 3 Leptons (SS2L/3L)
Lower Branching ratio, higher signal purity





All-hadronic	1L/2LOS		SS2L/3L		
Channel = 0L Branching Ratio = 31%	1L 42%	2LOS 15%	2LSS 7%	3L 5%	4L 0.5%

Best Previous Measurements by ATLAS & CMS

- ATLAS (Combined): 2.8 σ (Expected: 1.0 σ)
- CMS (2LSS/3L) : 2.6 σ (Expected: 2.7 σ)

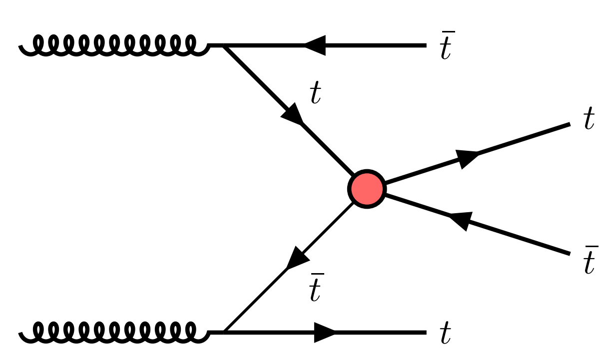
Today: Two ATLAS analyses in two channels

1L/2LOS: *ATLAS-CONF-2021-013* NEW!

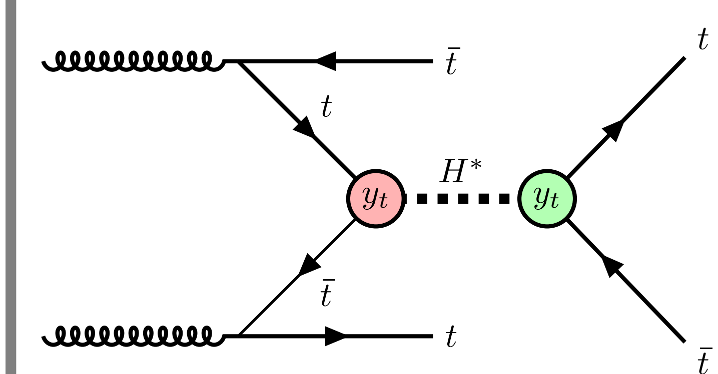
SS2L/3L: *Eur. Phys. J. C 80 (2020) 1085*

And their combination! NEW!

Four-top Contact Interaction



Sensitivity to y_t



Object Definitions

- Full LHC Run 2 dataset, Lumi = 139.0 ± 2.4 fb^{-1}
- Single e/μ trigger (both) or dilepton trigger (SS2L/3L only)
- Anti-k_t algorithm is used for jet clustering
  - Default radius R=0.4
  - Large radius R=1.0 (LR-jet)
- Lepton = e or μ including ones decaying from τ
- $H_T = \Sigma\, p_T$ of leptons and jets

	Electrons	Muons	Jets	*b*-jets
p_T [GeV]	> 10 (1L/2LOS) > 28 (SS2L/3L)		> 25	> 25
$\lvert\eta\rvert$	<1.37 OR 1.52-2.47	< 2.5	< 2.5	< 2.5

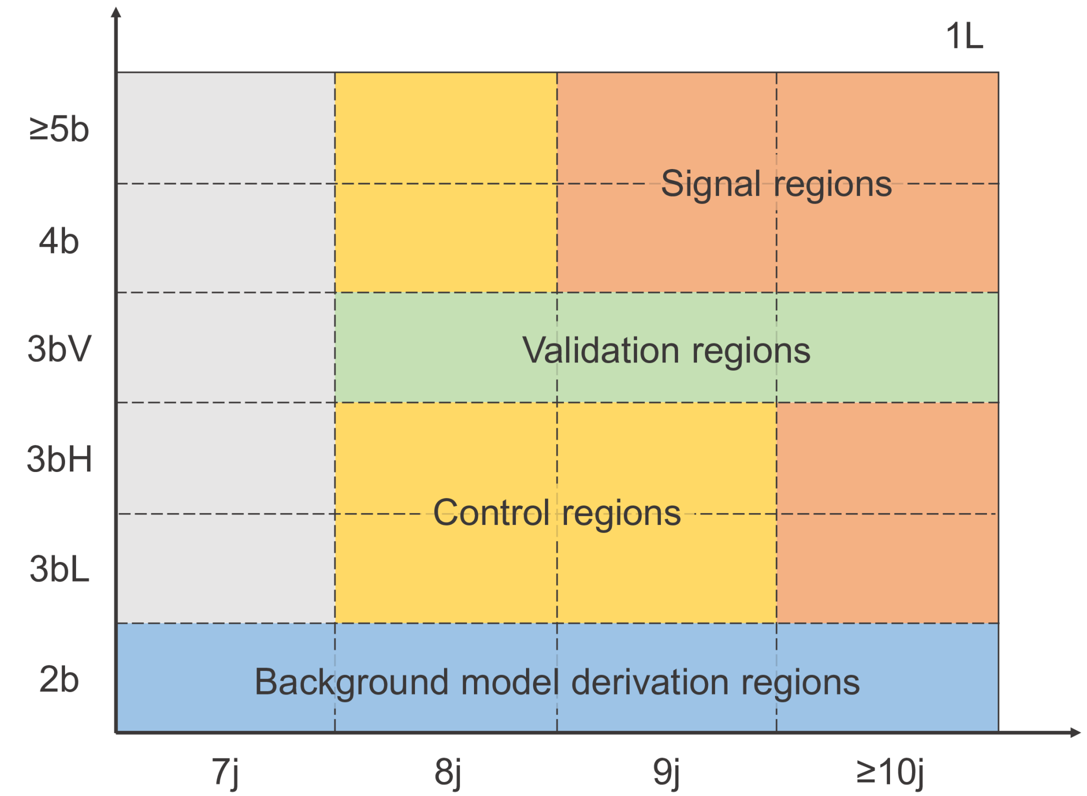
Most signal discrimination comes from b-tagging information:
MV2c10 is an MVA based *b*-tagging tool

- Calibrated for 5 different operating points (OP) based on b-tagging efficiencies
- Sum b-tag score
  - In increasing efficiency, each of OPs are assigned a number 1-5
  - All jets in an event are binned according to the OP range they fall into

b-tagging OP efficiency %	0-60	60-70	70-77	77-85	85-100
Bin Number	1	2	3	4	5
Sum b-tag score = Σ (Bin Number) x (nJets in the bin)					

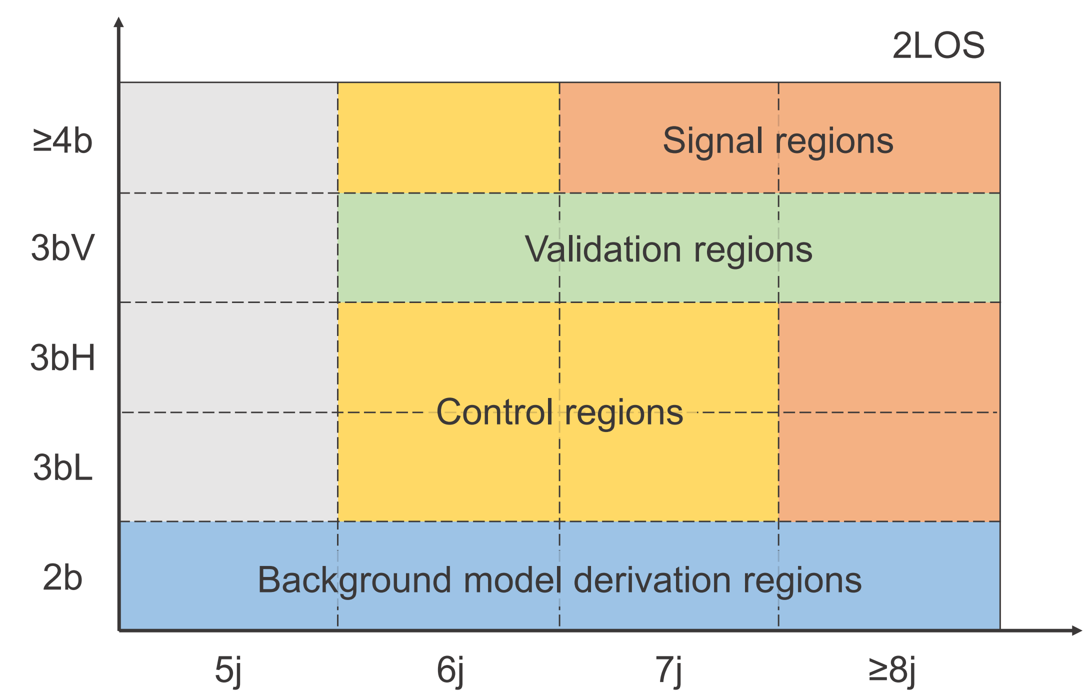
Final state is characterised by high jet & *b*-jet multiplicities

- Main challenge is mismodelled $t\bar{t}$+jets background
  - Data-driven correction methods
- Signal discrimination with Boosted Decision Trees (BDTs)
- Pre-selection
  - 1L : $N_{jets} \geq 7$ && $N_{b\text{-}jets} \geq 2$ && 1L
  - 2LOS: $N_{jets} \geq 5$ && $N_{b\text{-}jets} \geq 2$ && 2LOS



Event categorisation based on different *b*-tagging requirements

Analysis Regions		
Regions	$N_{Regions}$	Distribution
Signal Region (SR)	10	BDT
Control Region (SR)	12	H_T
Validation Region (VR)	6	Various



1L/2LOS - Background Composition

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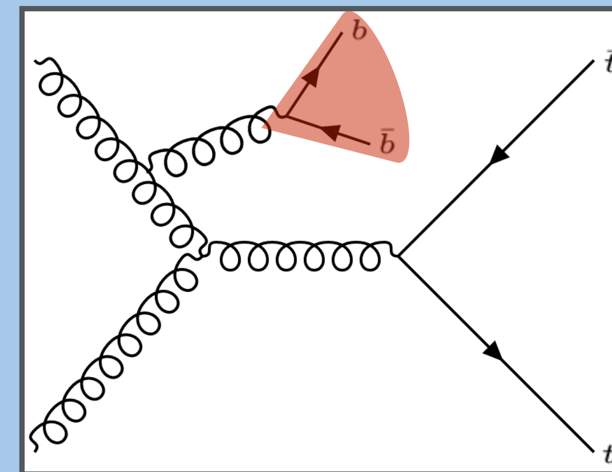
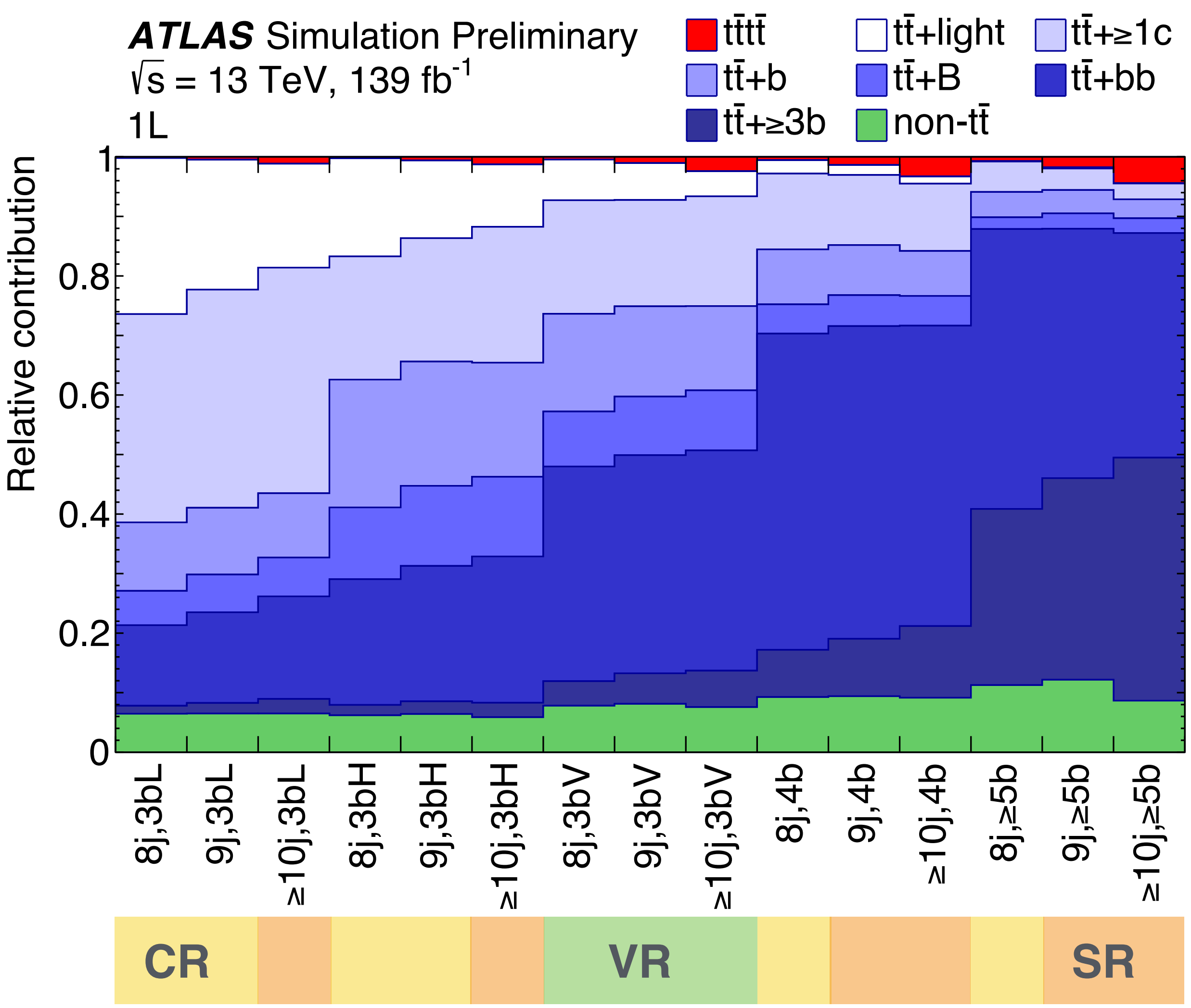
$t\bar{t}$+jets ~ 90% of total background (non-$t\bar{t}$ ~ 10%)

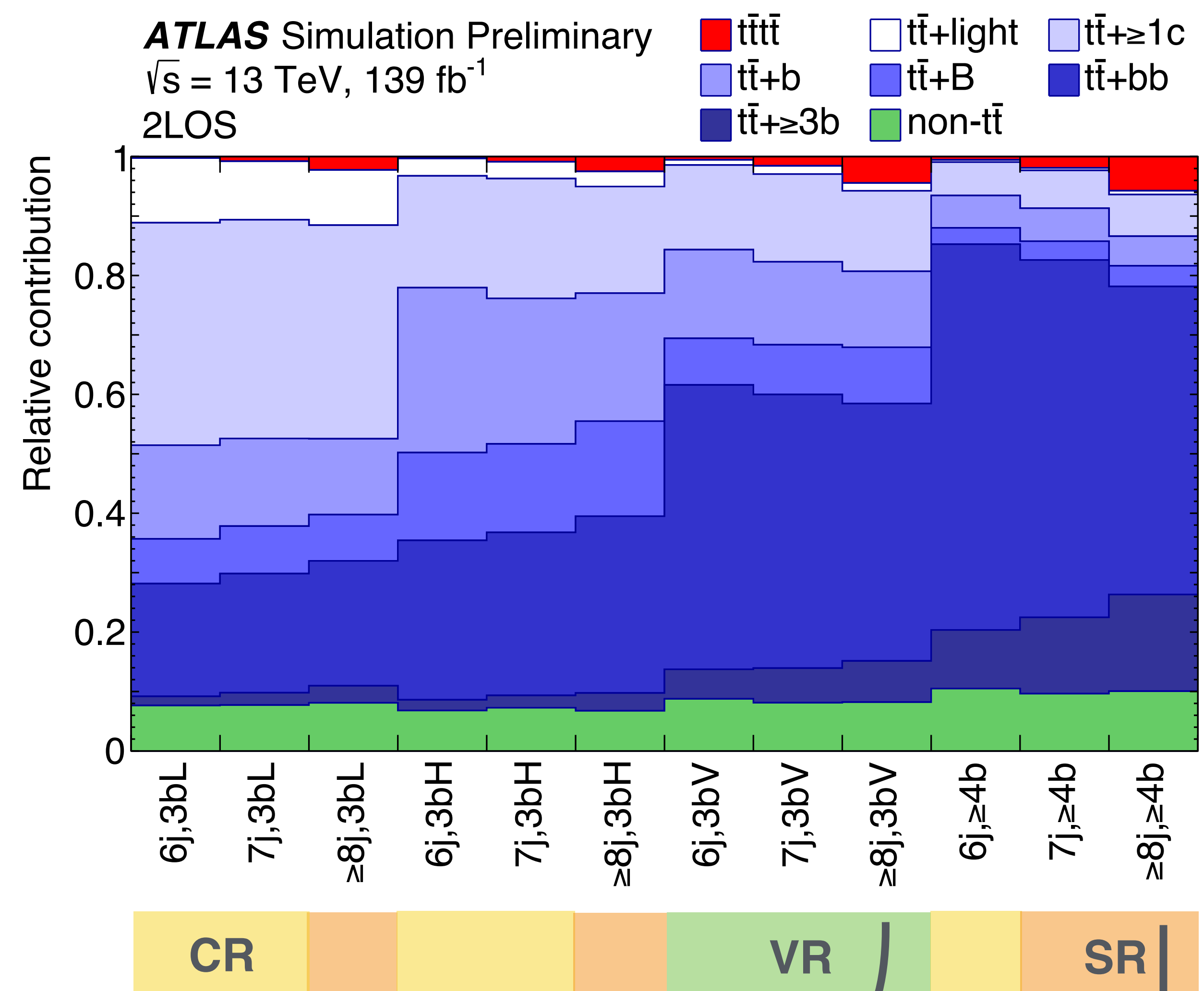
$t\bar{t}$+jets separated into subprocesses based on true additional jets

Jets not from $t\bar{t}$ decays



Number of Jets matched to b/c hadrons	Category
1 → 1b	$t\bar{t}$+b
1 → 2b	$t\bar{t}$+B
1+1 → 1b + 1b	$t\bar{t}$+bb
≥ 2b → ≥ 2b	$t\bar{t}$+≥3b
≥ 1 → ≥ 1c	$t\bar{t}$+≥1c
Others	$t\bar{t}$+≥light





VR with Max(S/B) ~ 4.4%

SR with Max(S/B) ~ 6.6%

1L/2LOS - $t\bar{t}$+jets Flavour Rescaling

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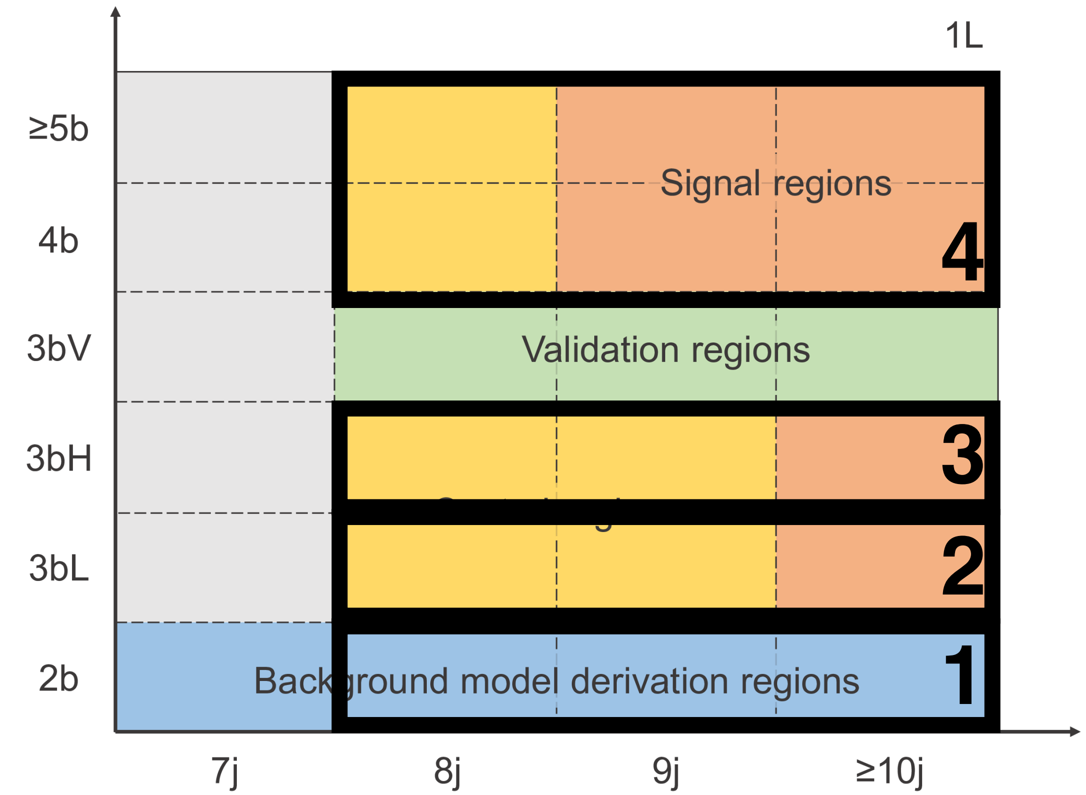
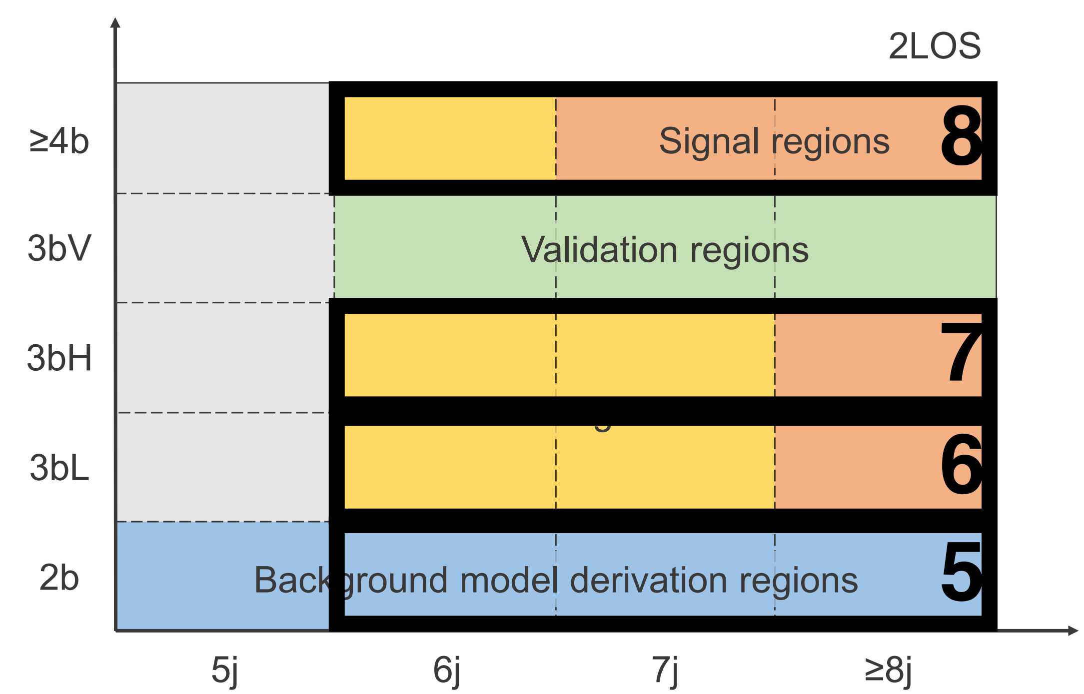
Data-driven estimate of $t\bar{t}$+jets rescaling factors

- $t\bar{t}$+jets flavour fractions are underestimated in MC
- Profile likelihood fit to data in 8 regions
  - 1L, ≥ 8jets for 4 different b-tag selections
  - 2LOS, ≥ 6jets for 4 different b-tag selections
  - Max(Signal/Background) ~ 2.5%
  - Yields are fitted
- Rescaled factors are applied to all $t\bar{t}$+jets MC





Parameter	Fitted Value
$t\bar{t}$+light	1.0 ± 0.1
$t\bar{t}$+≥1c	1.6 ± 0.2
$t\bar{t}$+≥1b	1.3 ± 0.1

1L/2LOS - $t\bar{t}$+jets Kinematic Reweighting

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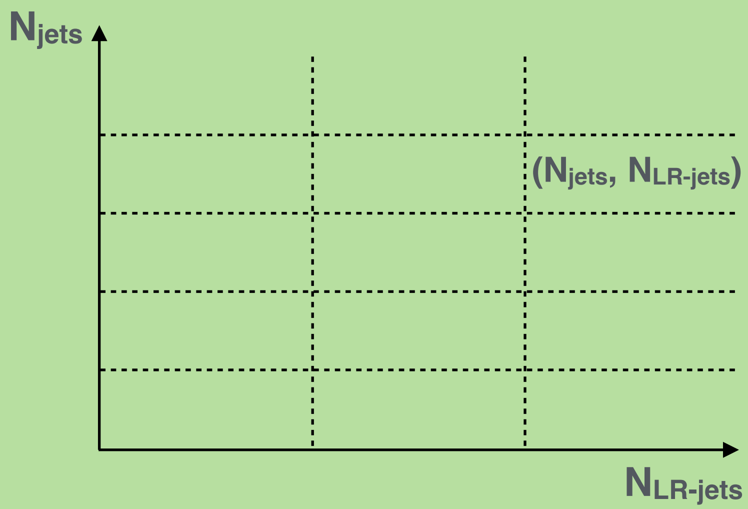
Problem
Kinematic mismodelling in

N_{jets}, H_T, $\Delta R(j,j)_{avg.}$, $N_{LR\text{-}jets}$

Method
Match MC & Data in 2b regions ⟶ reweighting factors ⟶ apply to events in ≥3*b* regions

Done in 3 steps, separately for both channels

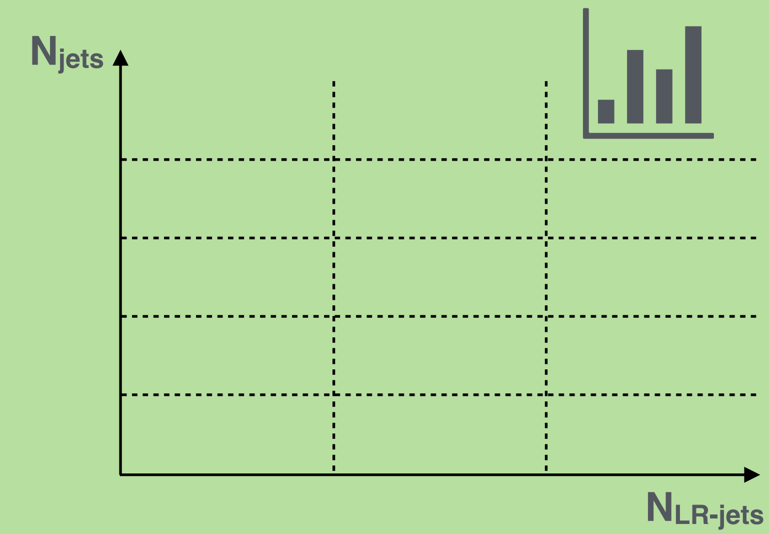
Step 1, reweight in each 2D bin



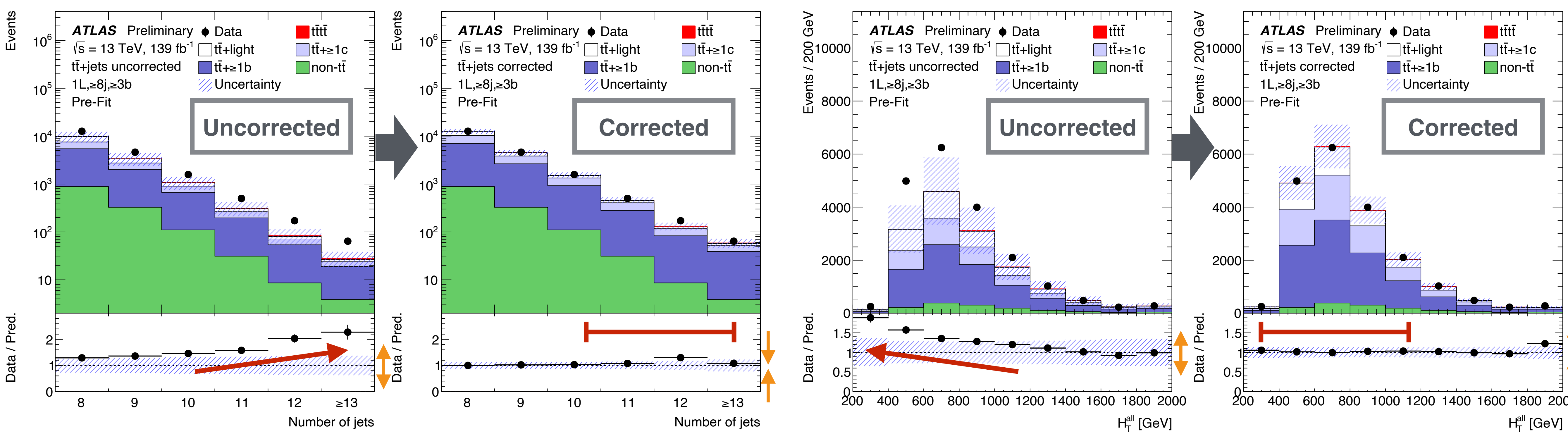
Step 2, reweight $f(H_T)$ in bins

$f(H_T)$ = functional form of H_T

Step 3, reweight $\Delta R(j,j)_{avg.}$ in each 2D bin



Examples of combined effect of $t\bar{t}$+jets flavour rescaling and kinematic reweighting



1L/2LOS - Signal Discrimination

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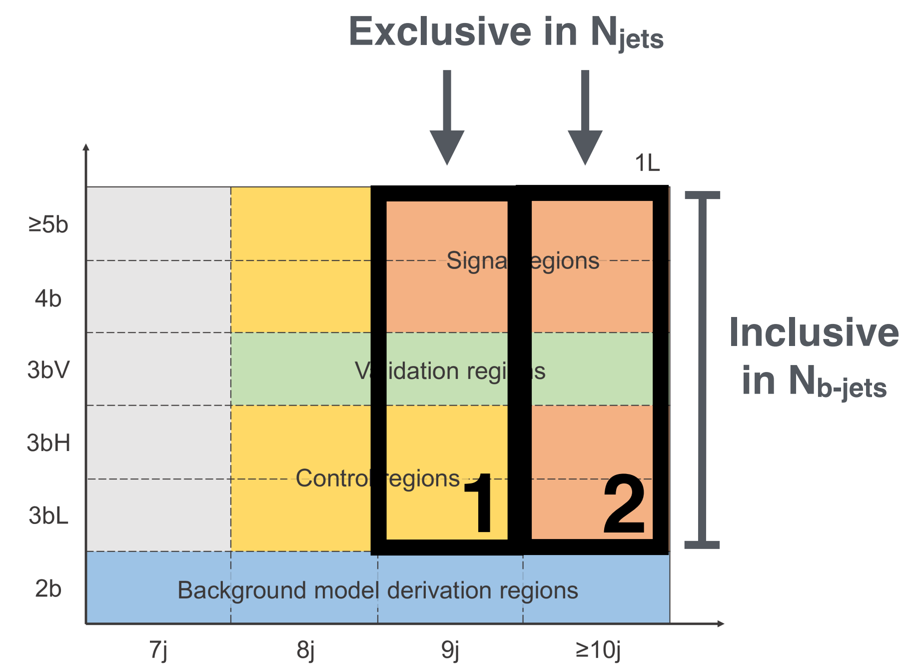
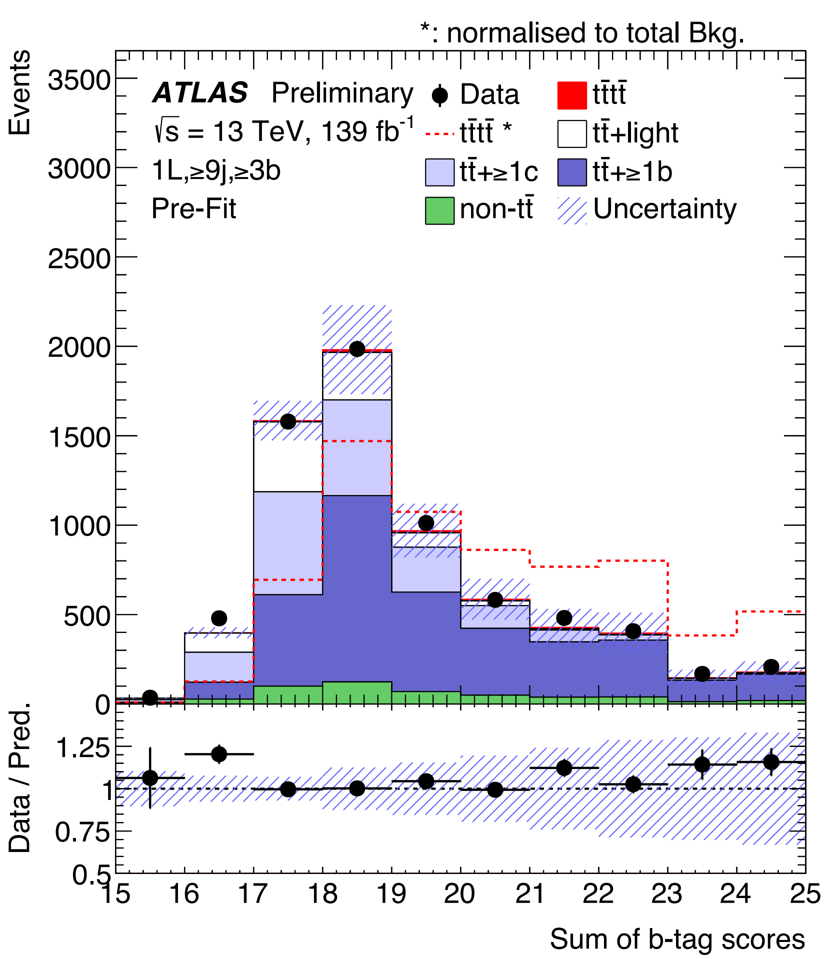
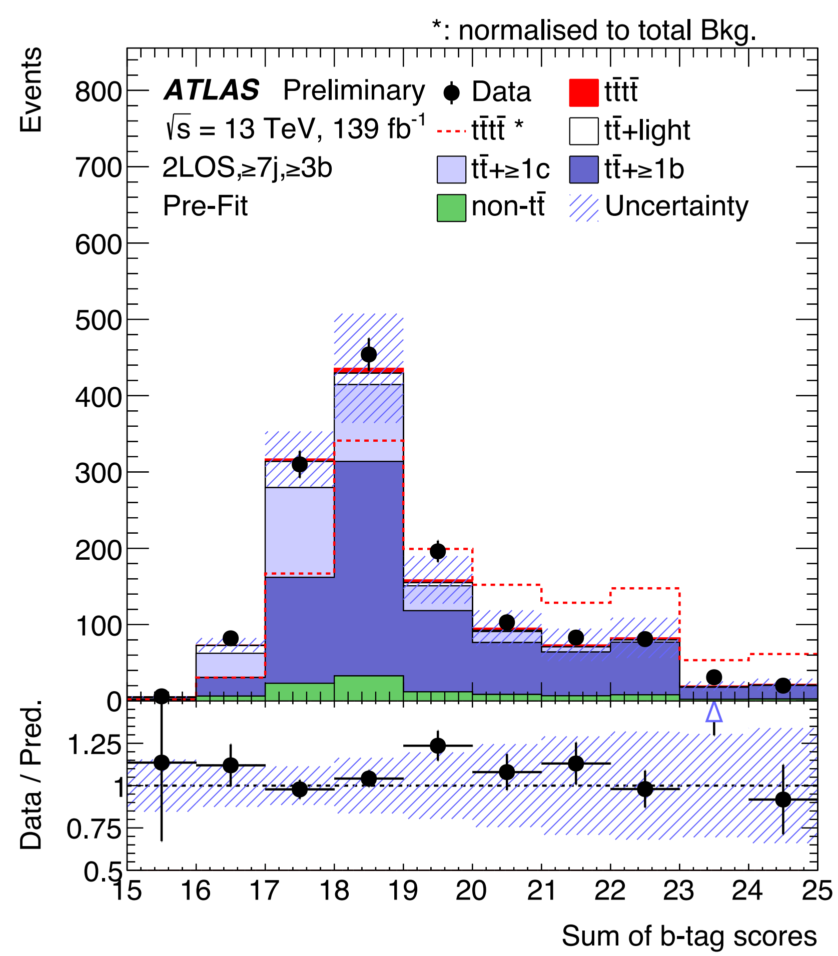
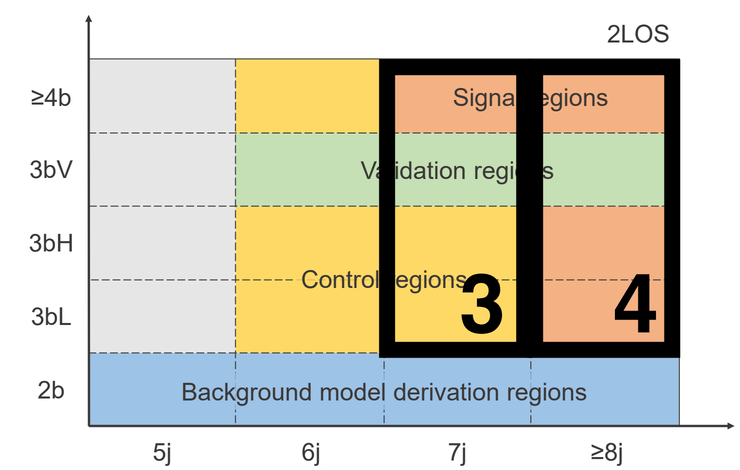
Individual BDTs are trained in 4 inclusive regions

- LO $t\bar{t}t\bar{t}$ signal trained against corrected $t\bar{t}$+jets background
- 14 input training variables
  - b-tagging information, E^{miss}_T
  - Lepton/jet information and their various combinations
- BDTs are optimised so as to maximise the ROC curve value
- 3-fold cross validation: overtraining/discrimination power checks
- Input variables' modelling are checked for pre- and post-fit cases









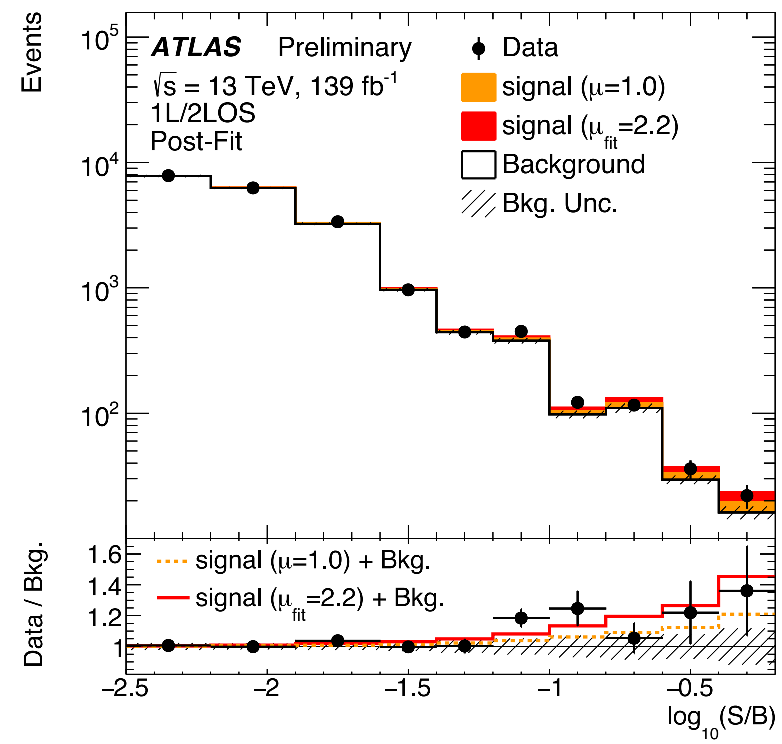
Profile likelihood fit to all CRs (H_T) + SRs (BDT)

- $\mu = 2.2 \pm 0.7\ \text{(stat)}\ ^{+1.5}_{-1.0}\ \text{(syst.)} = 2.2^{+1.6}_{-1.2}$
- $\mu_{1L} = 2.9\ ^{+1.8}_{-1.5}$, $\mu_{2LOS} = 1.3\ ^{+1.7}_{-1.5}$

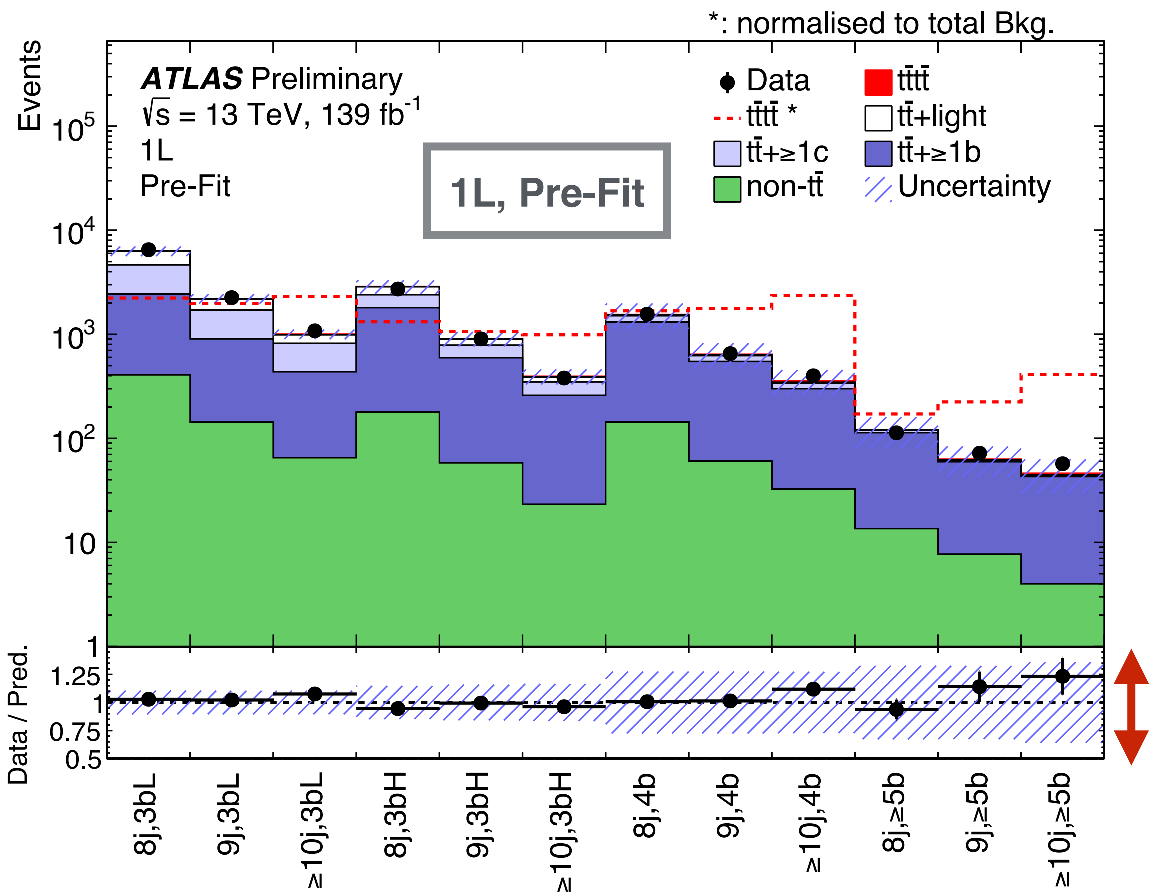
$\sigma_{t\bar{t}t\bar{t}} = 26\ ^{+17}_{-15}$ fb

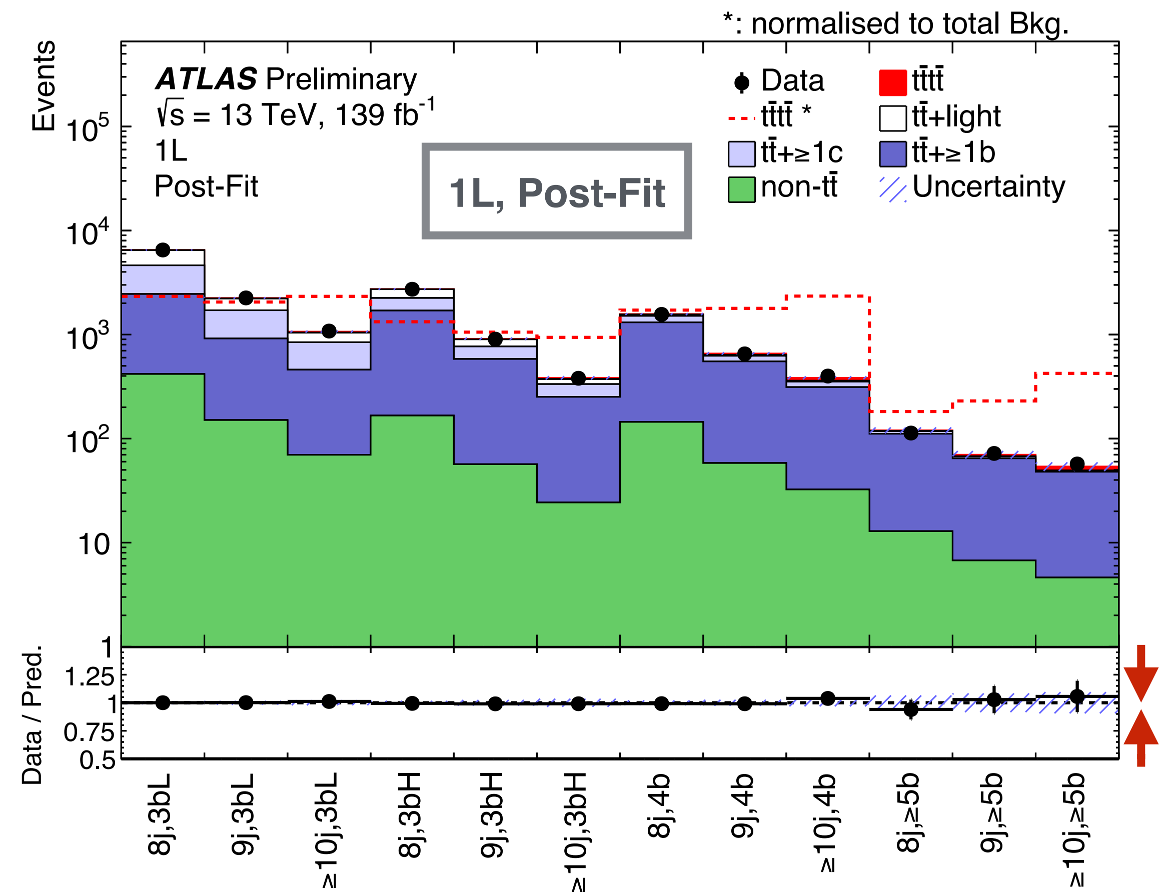
1.9 σ Obs. Sig. (1.0 σ Expected)

- Leading systematic uncertainty:
  - $t\bar{t}$+HF background modelling



Signal-like Data Excess





1L/2LOS - Systematic Uncertainties

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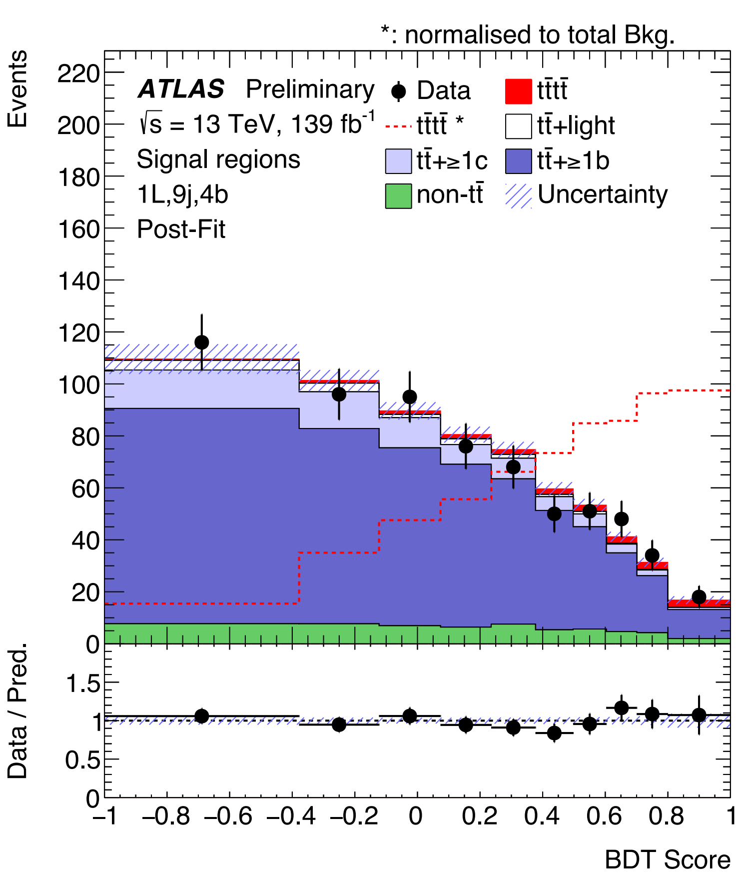
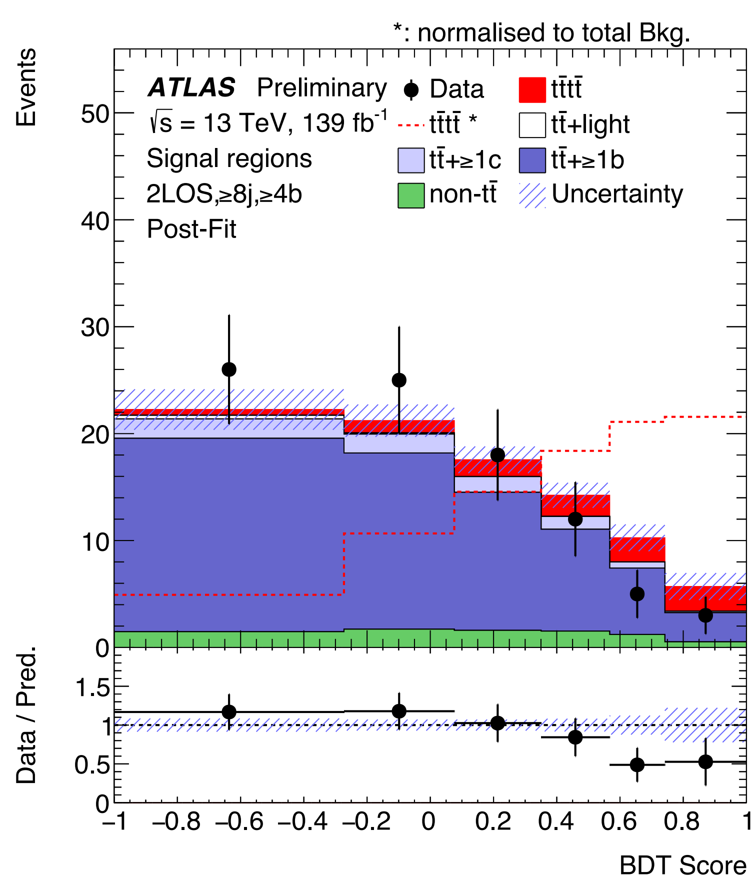
- Renormalisation/Factorisation scales, PDF, parton shower and hadronisation model
- 50% normalisation uncertainty on flavour components
- Uncertainty on non-$t\bar{t}$ processes in 2b regions (~ 5%)
- Uncertainties on limited Data/MC in kinematic fit regions (~ 1%)
- Comparison of f(H_T) vs. Another parametrisation of H_T (~ 5%)
- Statistical uncertainty

Uncertainty source	$\Delta\sigma_{t\bar{t}t\bar{t}}$ [fb]	
Signal Modelling		
$t\bar{t}t\bar{t}$ modelling	+8	-3
Background Modelling		
$t\bar{t}+\geq 1b$ modelling	+8	-7
$t\bar{t}+\geq 1c$ modelling	+5	-4
$t\bar{t}$+jets reweighting	+4	-3
Other background modelling	+4	-3
$t\bar{t}$+light modelling	+2	-2
Experimental		
Jet energy scale and resolution	+6	-4
b-tagging efficiency and mis-tag rates	+4	-3
MC statistical uncertainties	+2	-2
Luminosity	< 1	
Other uncertainties	< 1	
Total systematic uncertainty	+15	-12
Statistical uncertainty	+8	-8
Total uncertainty	+17	-15





SS2L/3L - Analysis Strategy

Process characterised by leptonic signatures creating a cleaner signal

- Main challenge is handling of dominant $t\bar{t}W$+jets background
  - Mismodelled at high jet multiplicities
  - Dedicated CR and VR for proper $t\bar{t}W$+jets estimation
- Further CRs for Fake/Non-prompt lepton background estimations
- Data-driven charge misassignment background estimation
- 1 inclusive SR with a BDT distribution

Pre-selection requires either SS2L or at least 3L with different conditions on lepton channels

- Two same-sign electrons: $|M_{ee} - 91\ \text{GeV}| < 10$ GeV && $M_{ee} > 15$ GeV
- At least three leptons: $|M_{ee} - 91\ \text{GeV}| < 10$ GeV for all opposite-sign same-flavour lepton pairs
- Inclusive jets selection: $N_{jets} \geq 4$ && $N_{b\text{-}jets} \geq 1$

SS2L/3L - Irreducible Backgrounds

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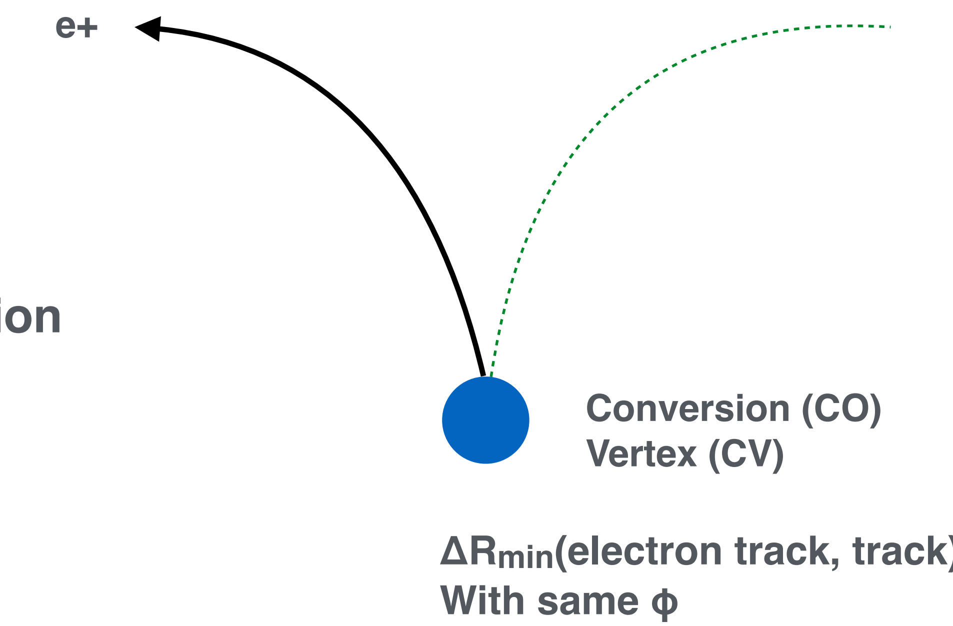
Irreducible backgrounds ~ 80%

Major: $t\bar{t}W$ (~40%), $t\bar{t}Z$ (~20%), $t\bar{t}H$ (~15%),
Minor: tWZ, tZq, single-top, V+jets, 3tops, $t\bar{t}VV$, VV, VVV with V=W,Z

All irreducible backgrounds except $t\bar{t}W$ are estimated from MC prediction



Template Fit Method

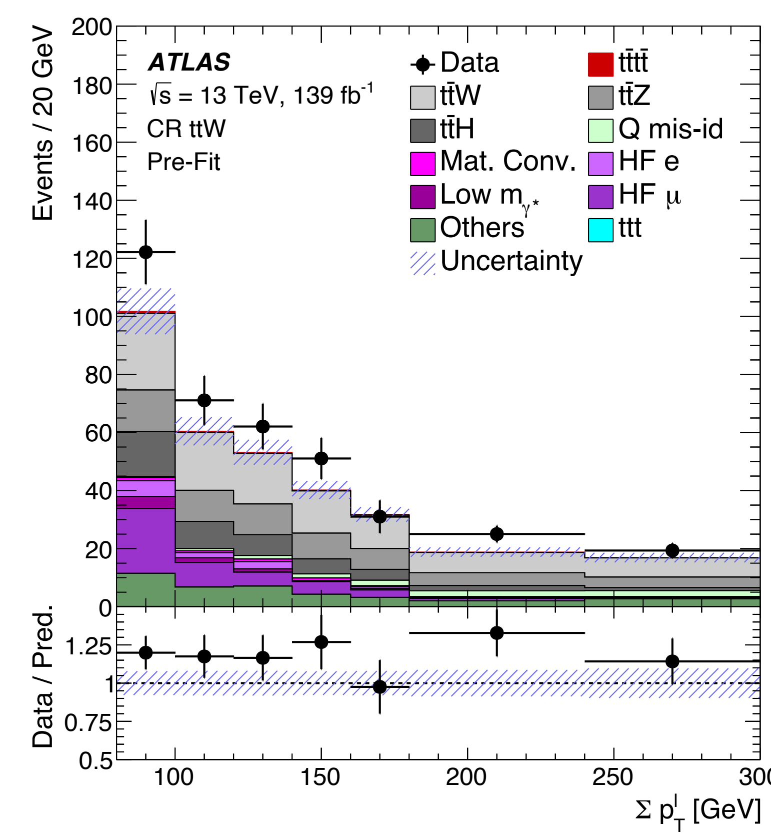
- Rely on MC description for the shape of the distribution
- Normalization Factors (NFs) are estimated from fit to data
- Dedicated systematic uncertainties for templates

Template Example: $t\bar{t}W$ Control Region

- MC prediction for $t\bar{t}W$ cross-section is known to be underestimated
- Dedicated CR to constrain the free floating normalisation parameter

Region	Channel	N_{jets}	$N_{b\text{-}jets}$	Other
CR $t\bar{t}W$	SSeμ + SSμμ	≥ 4	≥ 2	M_{ee}@CV > 0.1GeV, $\lvert\eta(e)\rvert < 1.5$ For $N_{b\text{-}jets} = 2$, $H_T < 500$ GeV or $N_{jets} < 6$ For $N_{b\text{-}jets} \geq 3$, $H_T < 500$ GeV

M_{ee}@CV: Invariant mass of the system formed by the electron track and the closest track at the conversion vertex



Charge Mis-Identification (Qmis-id) ~5%

Fully Data-driven estimation in two steps

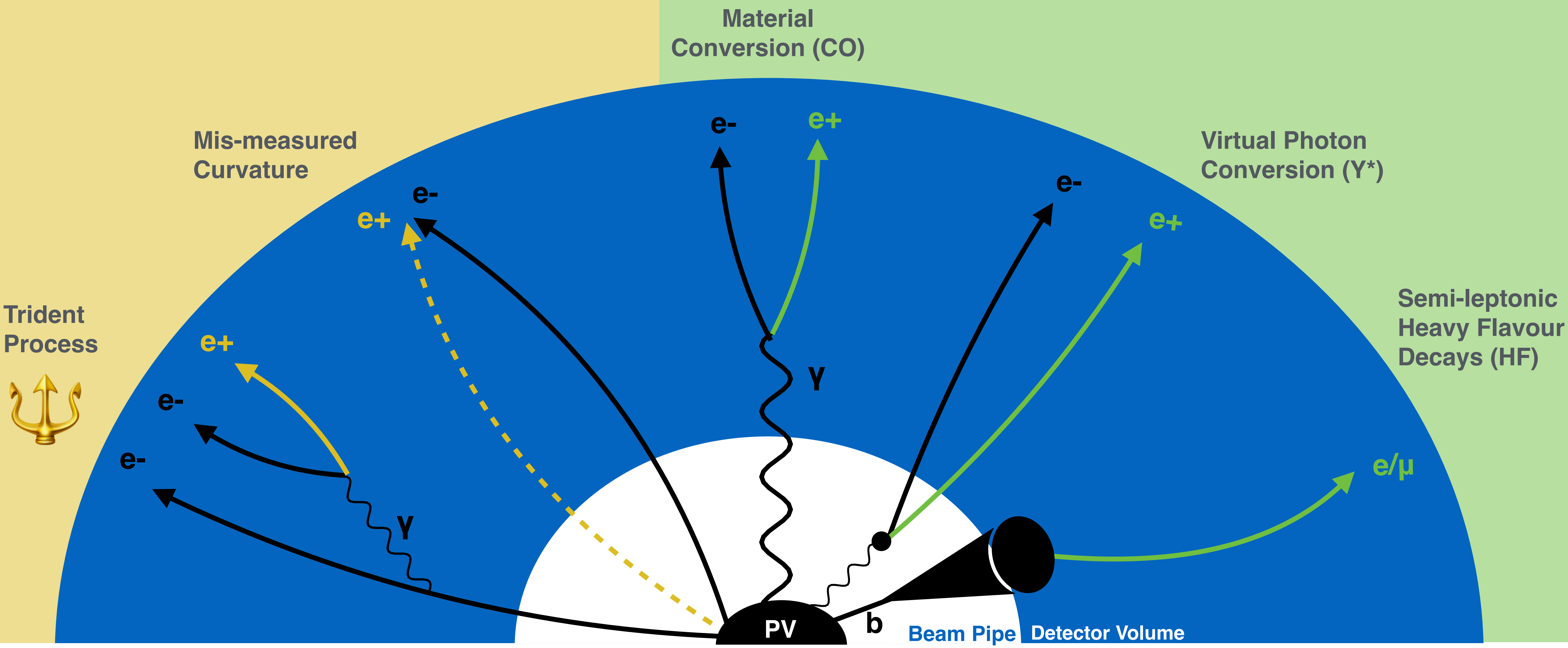
1) Derive Qmis-id rates $\varepsilon(p_T,\eta)$
   $Z \longrightarrow ee$ samples with SR selection
   $|M_{ee} - 91\ \mathrm{GeV}| < 10$ GeV required

2) Apply ε to events in Data samples with SS2L SR selection but with OS requirement instead

Fake and Non-prompt Leptons ~15%

Dedicated CRs to constrain NFs via Template Method

Region	Lepton Selection	N_{jets}	$N_{b\text{-}jets}$	Fitted Variable	Constrained NF
CR $t\bar{t}$ CO	SSee + SSeμ M_{ee}@CV < 0.1GeV	$6 \geq N_j \geq 4$	≥ 1	M_{ee} @ PV	NF CO, NF γ*
CR 1b3Le	eee + eeμ	≥ 4	1	Counting	NF HF_e
CR 1b3Lm	eμμ + μμμ	≥ 4	1	Counting	NF HF_μ



SS2L/3L - $t\bar{t}W$ Validation Region

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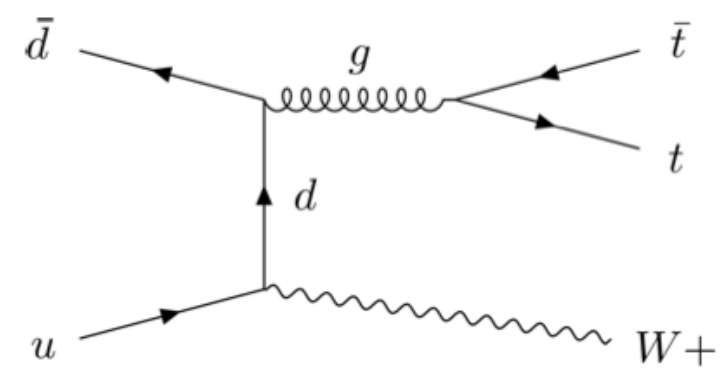
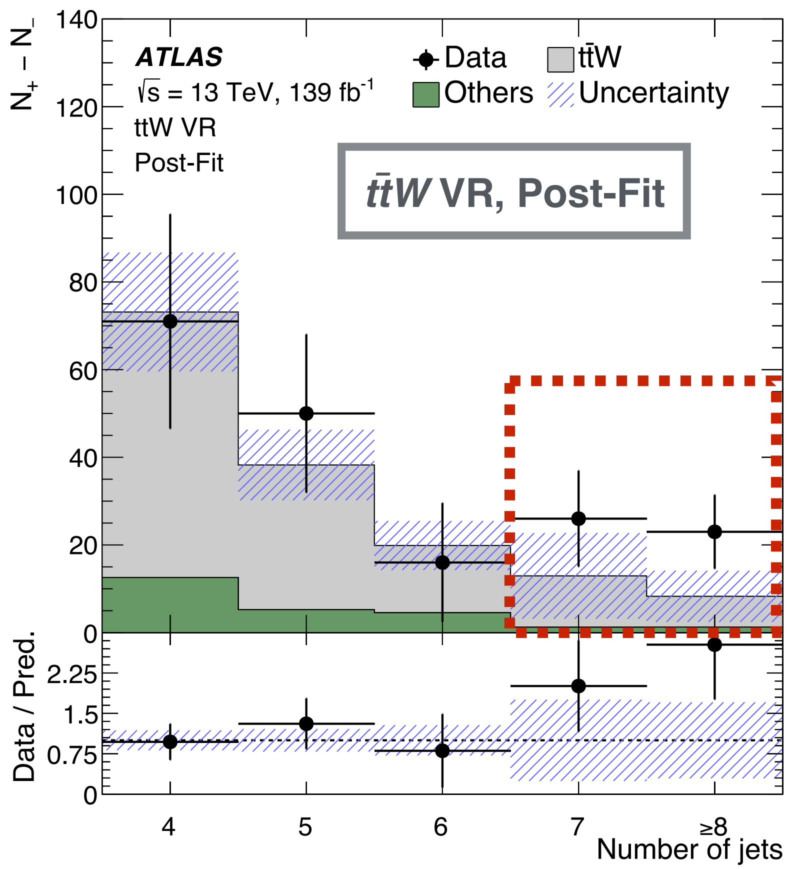
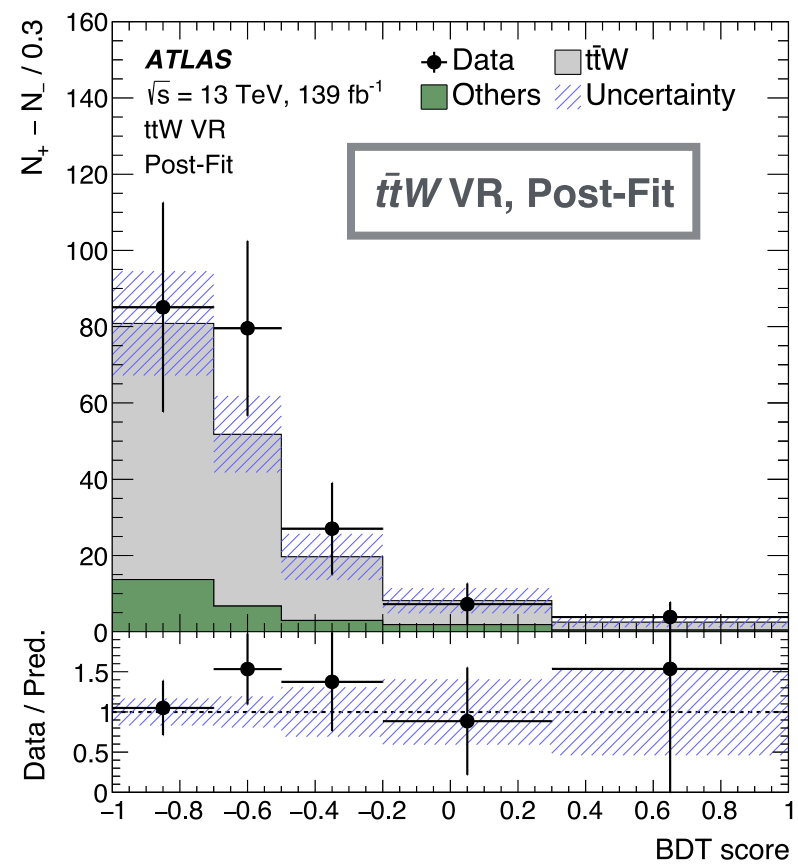
$t\bar{t}W$ process is poorly modelled in high jet multiplicities

- $t\bar{t}W$ VR region based on charge asymmetry of $t\bar{t}W$ process
  - 2:1 ratio favouring positively charged events
  - Removes charge symmetric processes
  - VR Selection: SS2L/3L && $N_{jets} \geq 4$ && $N_{b\text{-}jets} \geq 2$



- Additional systematic uncertainties to account for mismodelling
  - 125% for nJets = 7
  - 300% for nJets ≥ 8





SS2L/3L - Signal Discrimination

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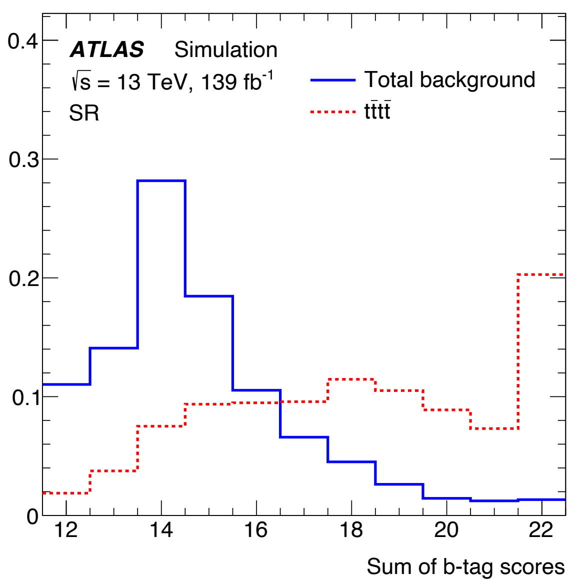
BDT Training in SR pre-selection: $N_{jets} \geq 6$ && $H_T > 500$ GeV && $N_{b\text{-}jets} \geq 2$

- LO $t\bar{t}t\bar{t}$ signal trained against all backgrounds
- Hyper-parameters & input variables are selected so as to maximize the ROC curve
- Checks: Input variable modelling, overtraining, performance validation on unused 20% of samples



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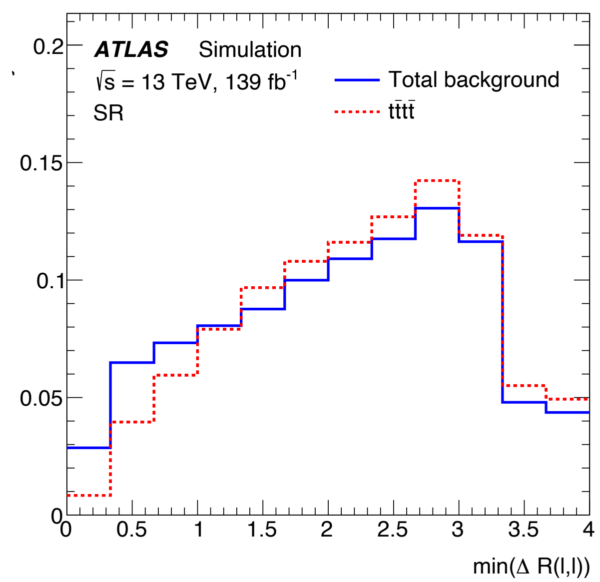

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- Leading jet p_T
- Leading b-jet p_T
- Leading lepton p_T
- E^{miss}_T
- $\Sigma\Delta R(\ell,\ell)_{min}$
- H_T (no lead jet)
- $\Delta R(\ell,b)_{max}$
- 6th leading jet p_T
- $\Delta R(j,b)_{min}$
- Sub-leading jet p_T

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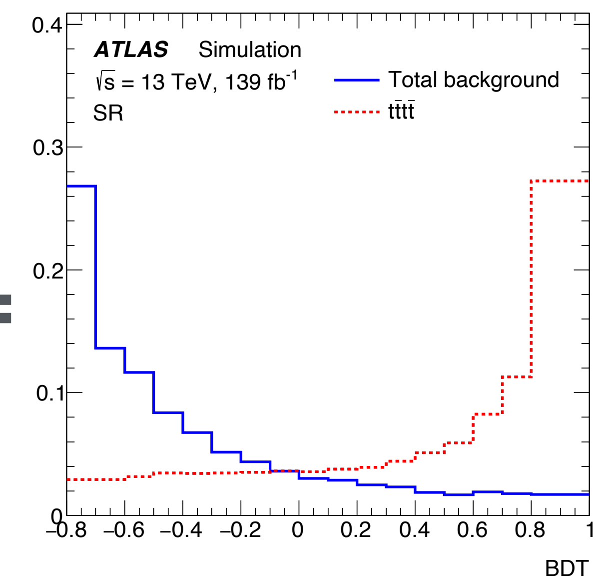
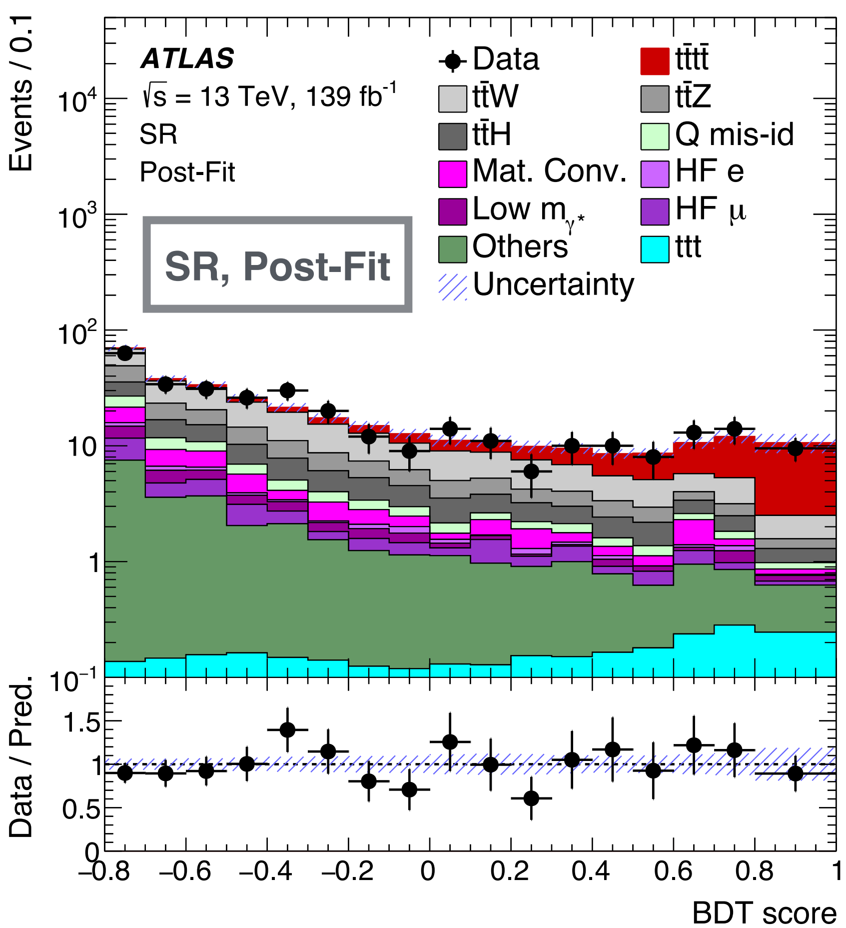


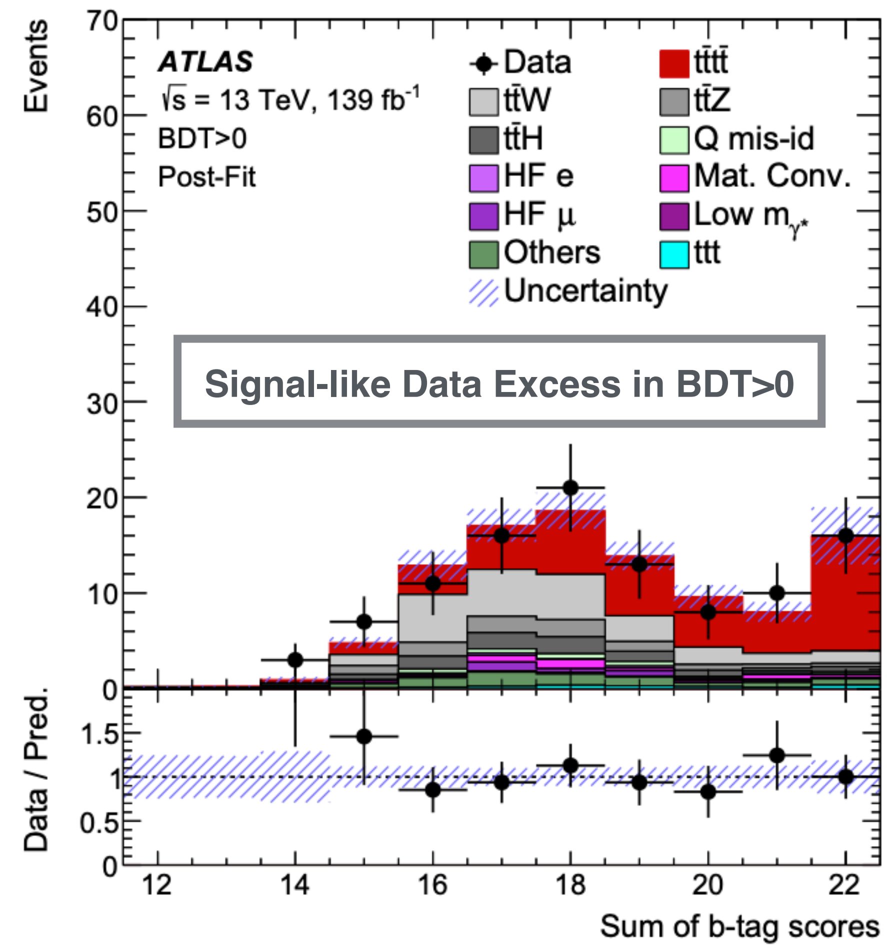
Profile likelihood fit to all CRs + SR

- 330 data events in SR
- $\mu = 2.0 \pm 0.4\,(\text{stat})\,^{+0.7}_{-0.4}\,(\text{syst.}) = 2.0^{+0.8}_{-0.6}$
- $\sigma_{t\bar{t}t\bar{t}} = 24\,^{+7}_{-6}$ fb
- Significance 4.3 σ observed (2.4 σ Expected)
- CMS result: 2.6 σ observed (2.7 σ Expected)
- Leading systematic uncertainty:
  - $t\bar{t}W \geq$ 8jets

Parameter	Fitted Values (Normalised to Pre-fit)
NF $t\bar{t}W$	1.6 ± 0.3
NF Mat. CO.	1.6 ± 0.5
NF γ^*	0.9 ± 0.4
NF HF_e	0.8 ± 0.4
NF HF_μ	1.0 ± 0.4

Consistent with ATLAS $t\bar{t}H$(ML) [1]





SS2L/3L - Systematic Uncertainties

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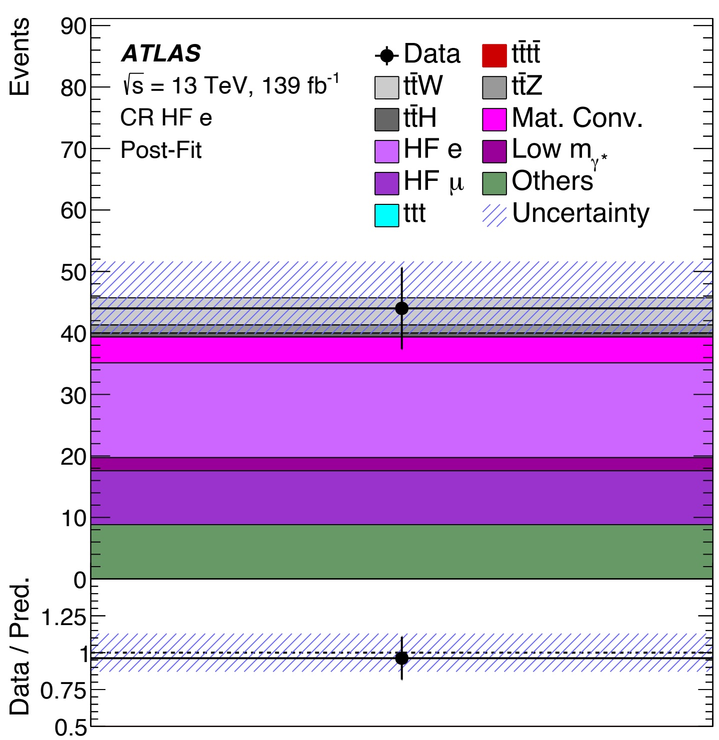
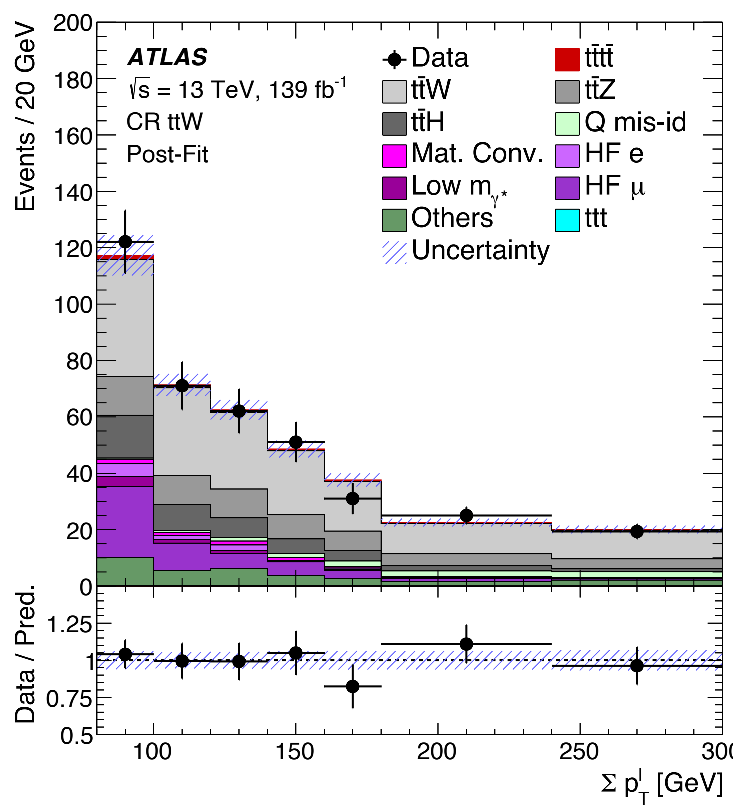
- Renormalisation/Factorisation scales, PDF, parton shower and hadronisation model
- *$t\bar{t}W$*+jets modelling uncertainties
- *$t\bar{t}t$*: 100% cross section +
  50% for events with generator-level $N_{b\text{-jets}} = 4$
- Primarily jet energy scale & resolution uncertainties
- Statistical uncertainty





Uncertainty source	$\Delta\mu$	
Signal modelling		
$t\bar{t}t\bar{t}$ cross section	+0.56	−0.31
$t\bar{t}t\bar{t}$ modelling	+0.15	−0.09
Background modelling		
$t\bar{t}W$+jets modelling	+0.26	−0.27
$t\bar{t}t$ modelling	+0.10	−0.07
Non-prompt leptons modelling	+0.05	−0.04
$t\bar{t}H$+jets modelling	+0.04	−0.01
$t\bar{t}Z$+jets modelling	+0.02	−0.04
Other background modelling	+0.03	−0.02
Charge misassignment	+0.01	−0.02
Instrumental		
Jet uncertainties	+0.12	−0.08
Jet flavour tagging (light-flavour jets)	+0.11	−0.06
Simulation sample size	+0.06	−0.06
Luminosity	+0.05	−0.03
Jet flavour tagging (b-jets)	+0.04	−0.02
Jet flavour tagging (c-jets)	+0.03	−0.01
Other experimental uncertainties	+0.03	−0.01
Total systematic uncertainty	+0.70	−0.44
Statistical	+0.42	−0.39
Non-prompt leptons normalisation (HF, Mat. Conv., Low m_{γ^*})	+0.05	−0.04
$t\bar{t}W$ normalisation	+0.04	−0.04
Total uncertainty	+0.83	−0.60

Summary and the Combination of Channels

1L/2LOS

Main challenge: $t\bar{t}$+jets background
Multiple separate BDT SRs

Dominant Systematic Uncertainty:
$t\bar{t}$+HF background modelling

$\sigma_{1L/2LOS} = 26^{+17}_{-15}$ fb

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SS2L/3L

Main challenge: $t\bar{t}W$+jets background
Single inclusive BDT SR

Dominant Systematic Uncertainty:
$t\bar{t}W \geq 8$ Jets

$\sigma_{SS2L/3L} = 24^{+7}_{-6}$ fb

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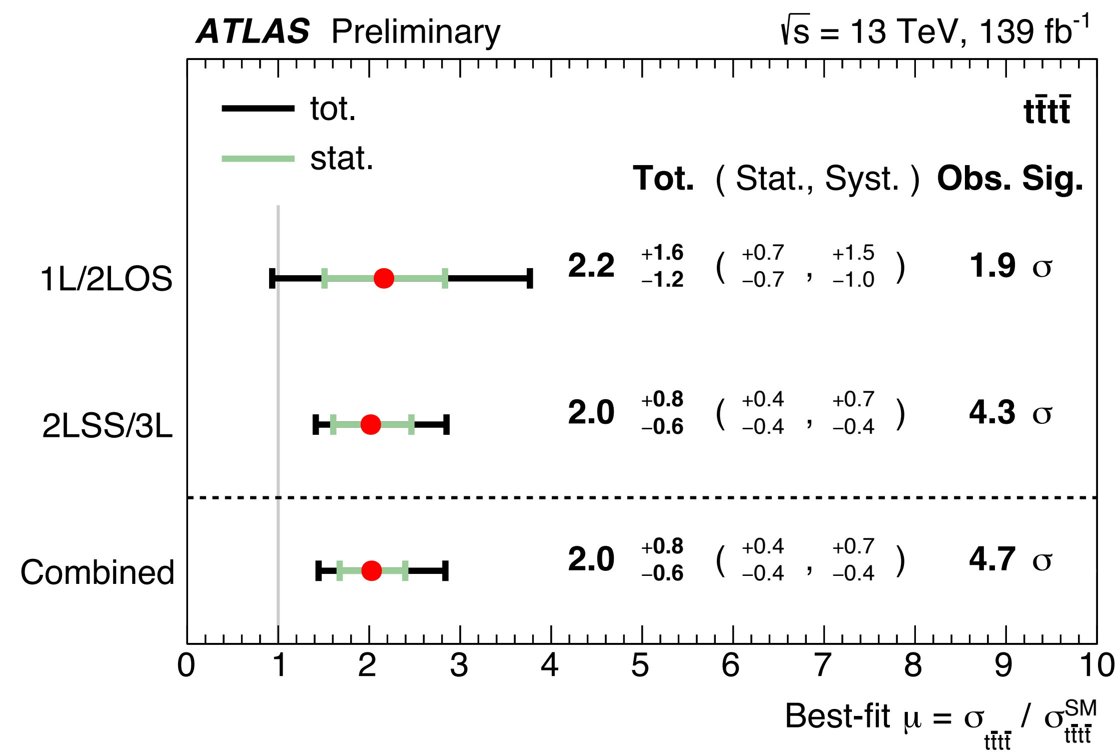
Simultaneous fit to all regions of both channels

$\sigma_{combined} = 25^{+7}_{-6}$ fb   Combined Obs. Sig. = 4.7 σ

Uncertainty	Correlated	Comment
Theoretical		
$t\bar{t}t\bar{t}$	Yes	
$t\bar{t}W$	No	Special treatment in 2LSS/3L, smaller in 1L/2LOS
$t\bar{t}$+jets	No	Special treatment in 1L/2LOS, smaller in 2LSS/3L
Other backgrounds	Yes	
Experimental	Yes	Same objects and dataset
Instrumental Backgrounds	No	Fake & Non-prompt lepton estimations
Data-Driven Corrections	No	Qmis-id in SS2L/3L & $t\bar{t}$+jets in 1L/2LOS

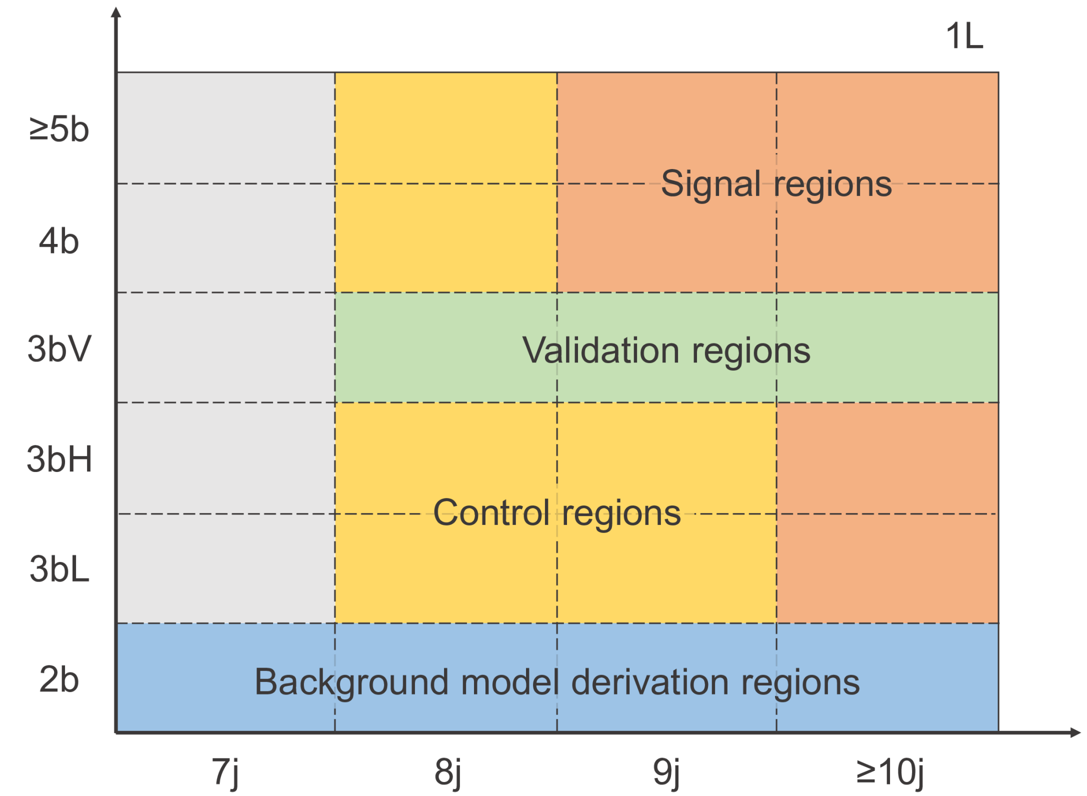


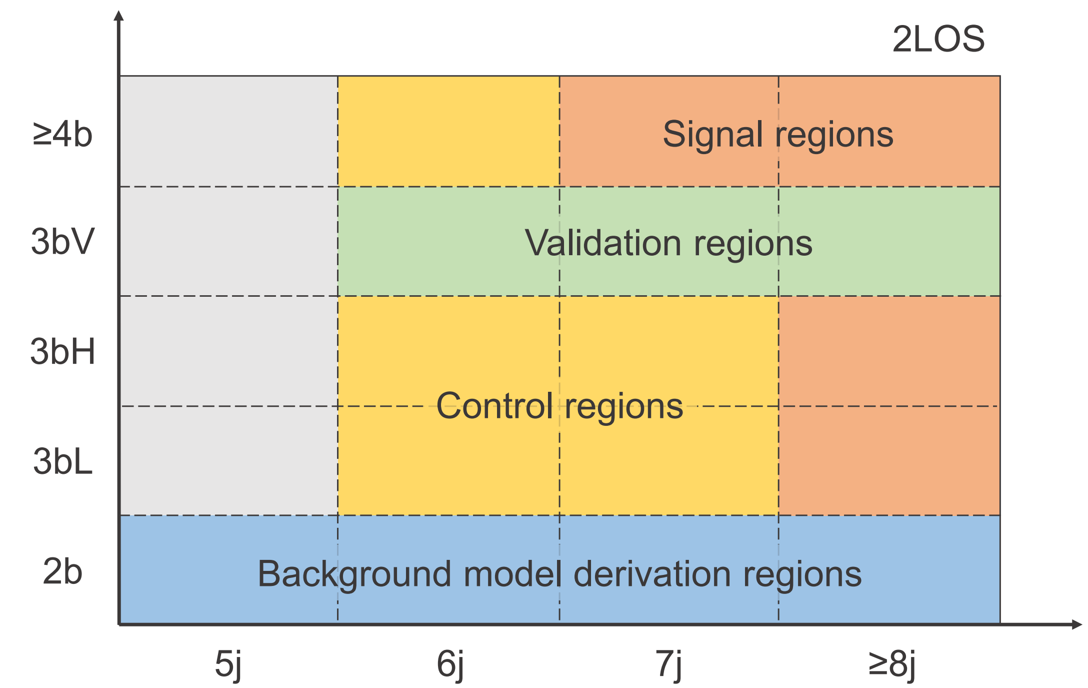
Backup

1l/2LOS Further Region Definitions

Detailed b-jet based region classification table

Name	$N_b^{60\%}$	$N_b^{70\%}$	$N_b^{85\%}$
2b	-	$= 2$	-
3bL	≤ 2	$= 3$	-
3bH	$= 3$	$= 3$	$= 3$
3bV	$= 3$	$= 3$	≥ 4
$\geq$4b (2LOS)	-	≥ 4	-
4b (1L)	-	$= 4$	-
$\geq$5b (1L)	-	≥ 5	-





1L/2LOS - Selected BDT SRs

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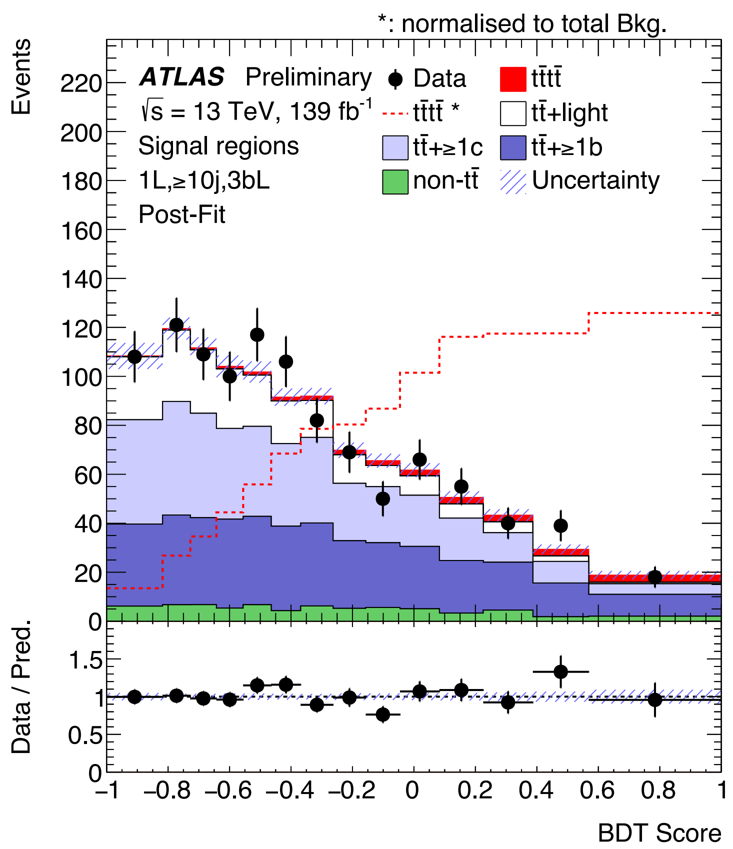

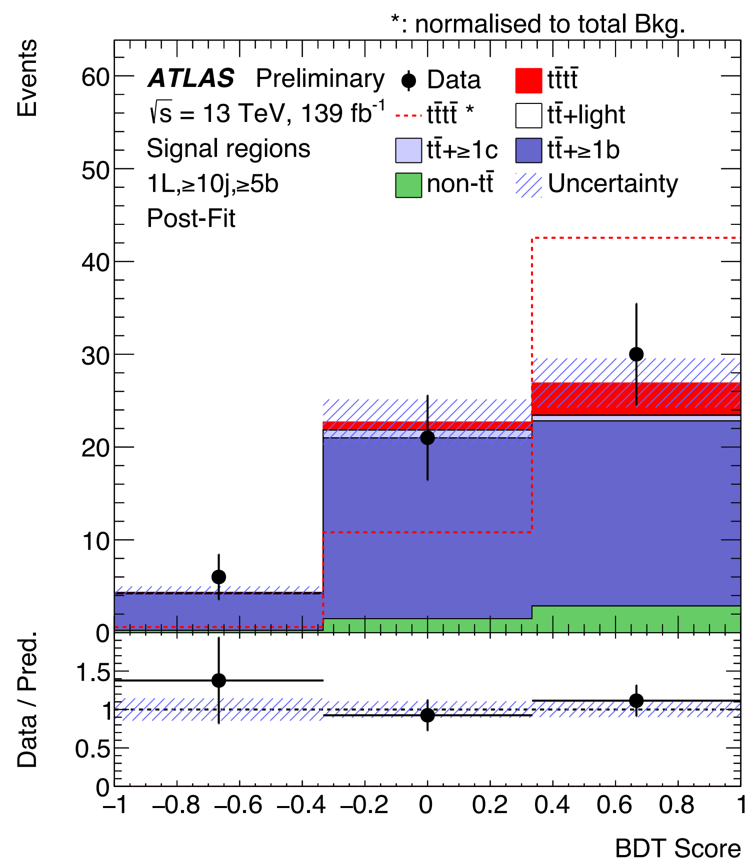

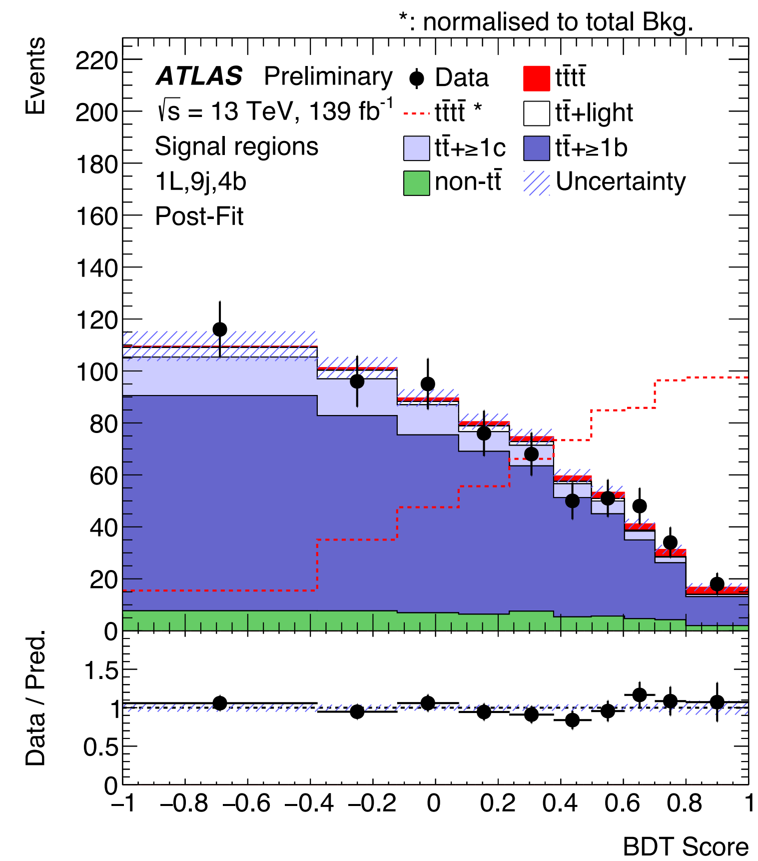

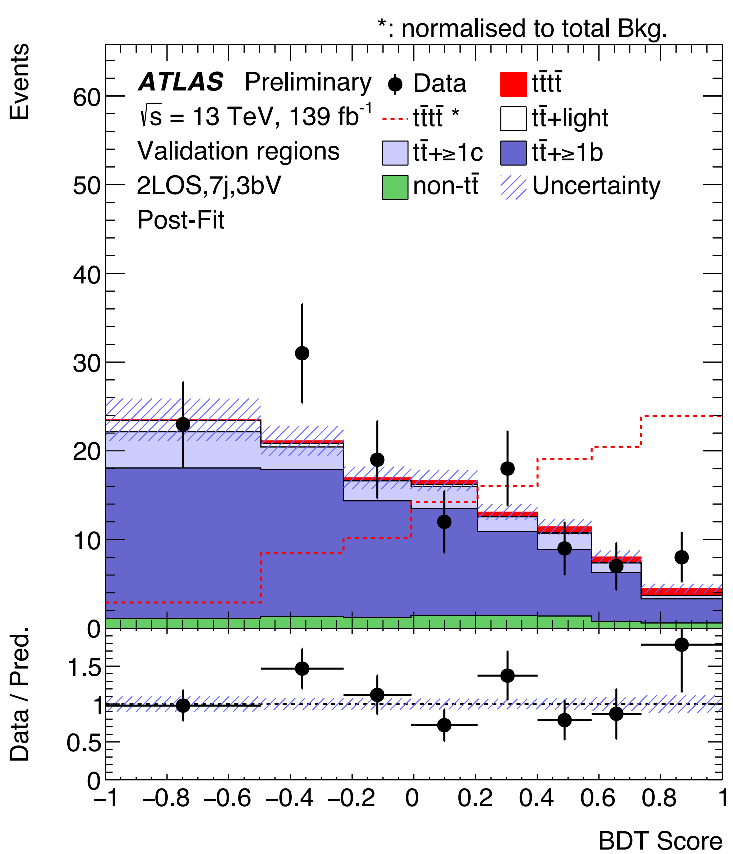

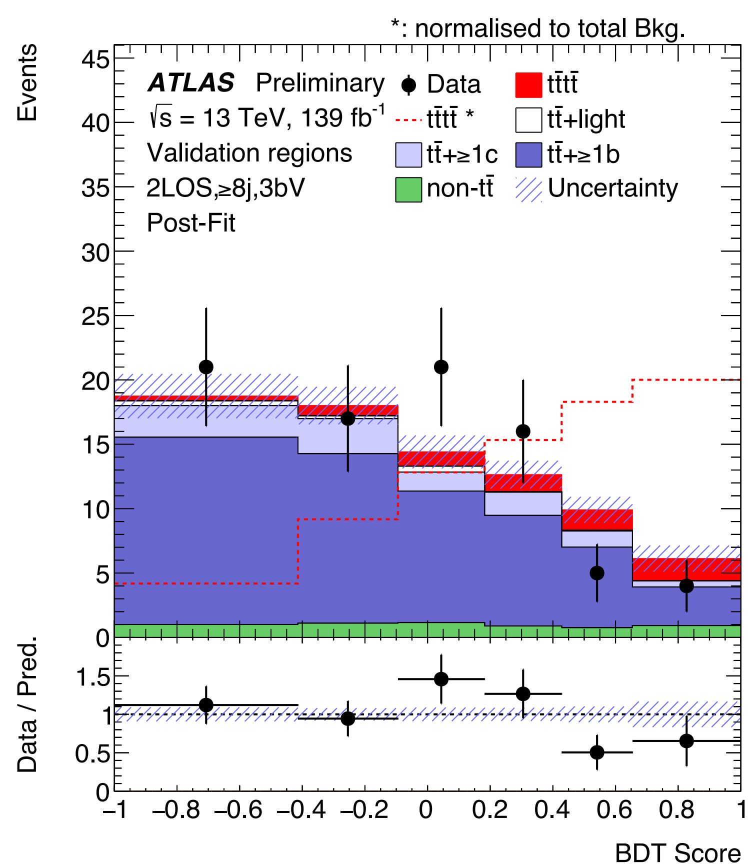

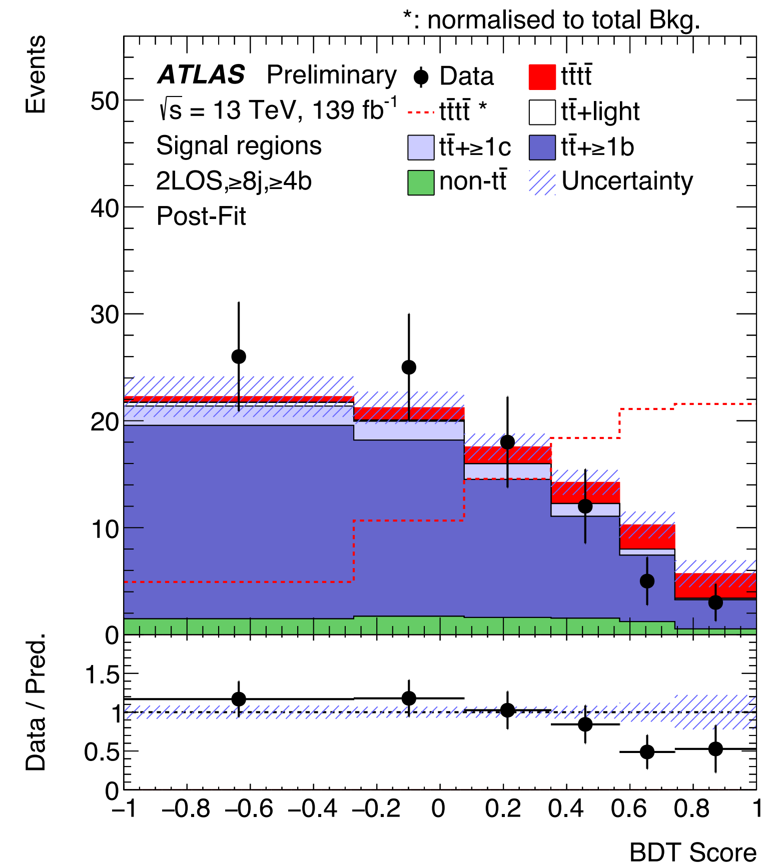

SS2L/3L - Control Region Plots 1/2

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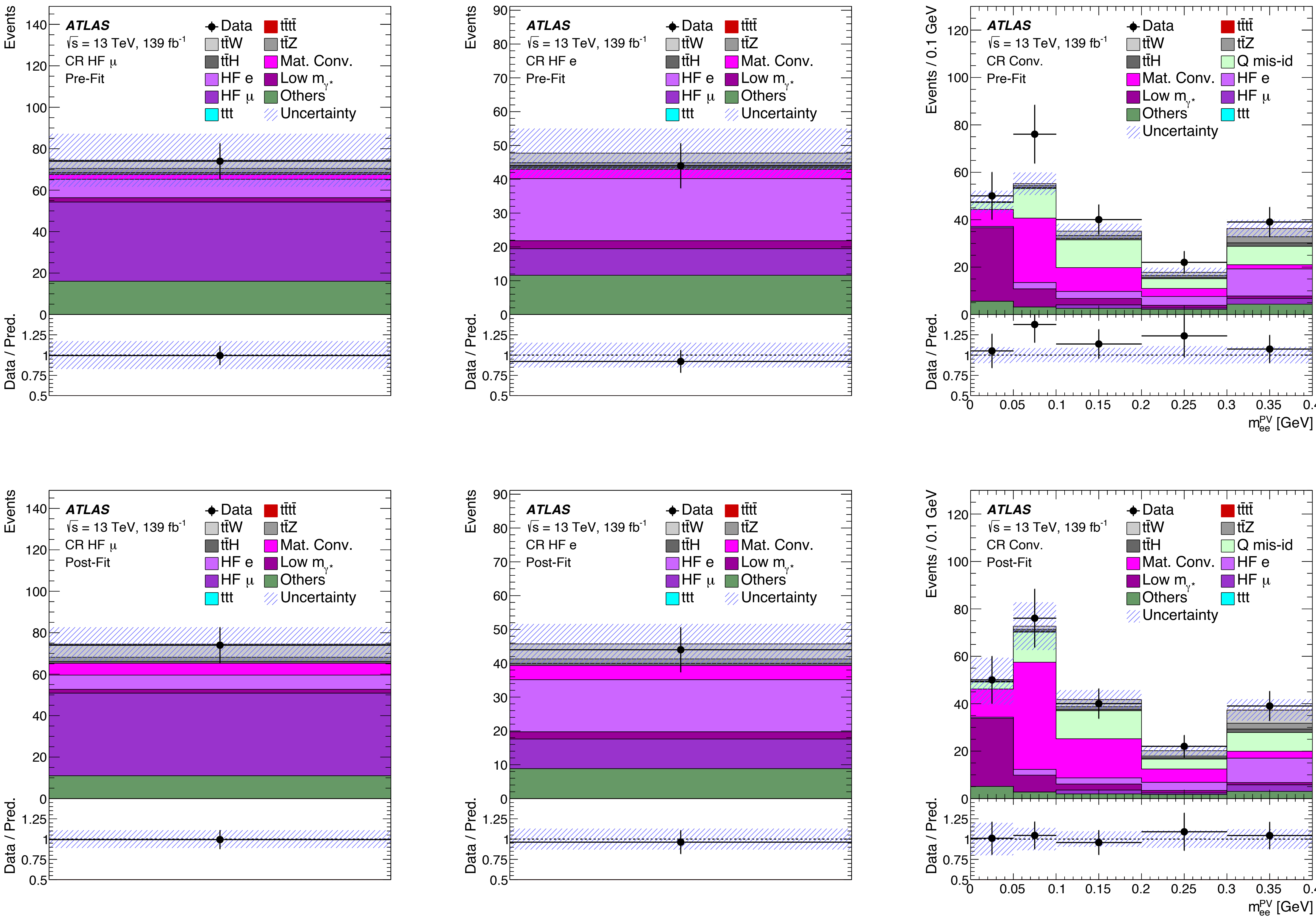

SS2L/3L - Control Region Plots 2/2

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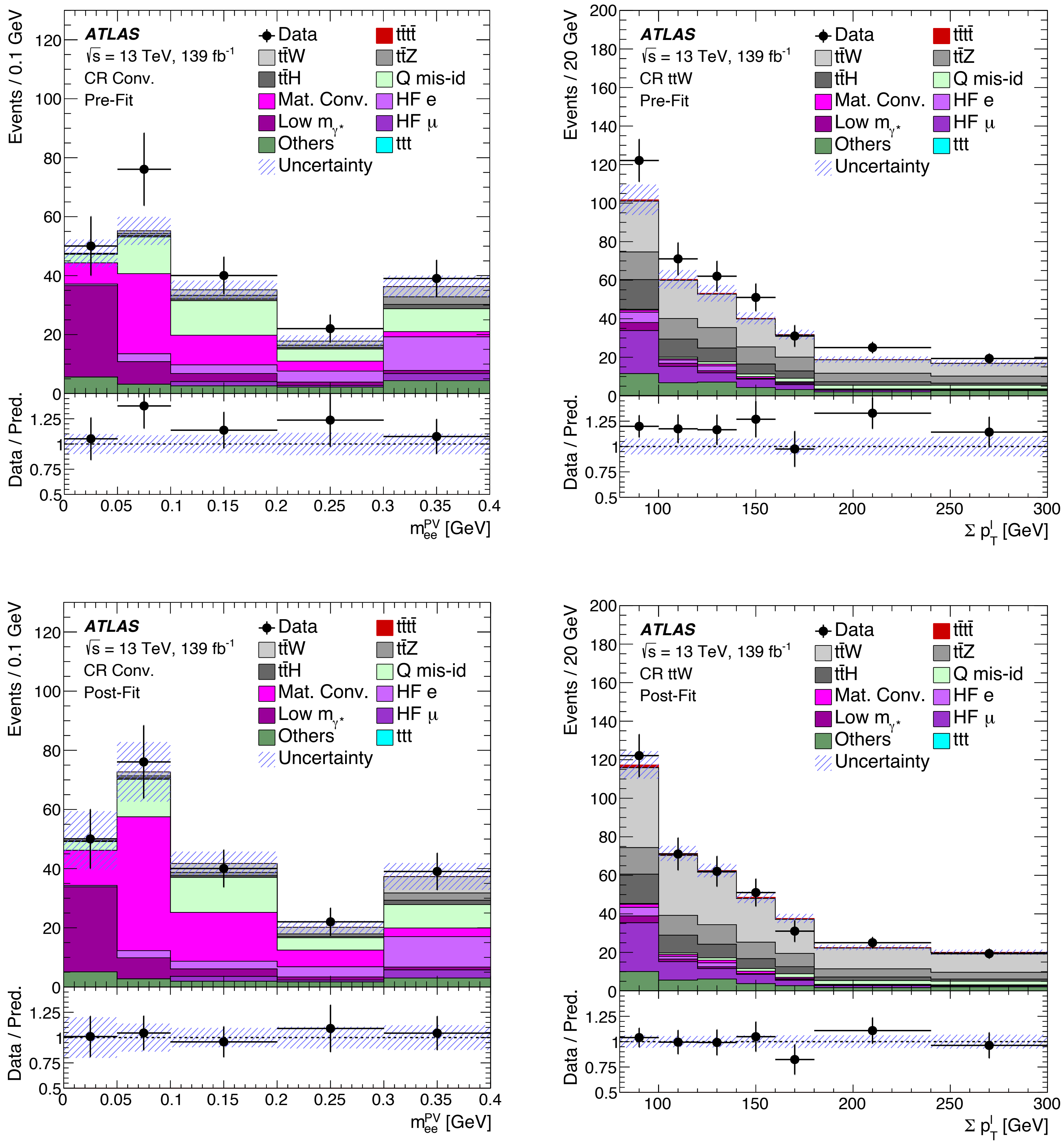
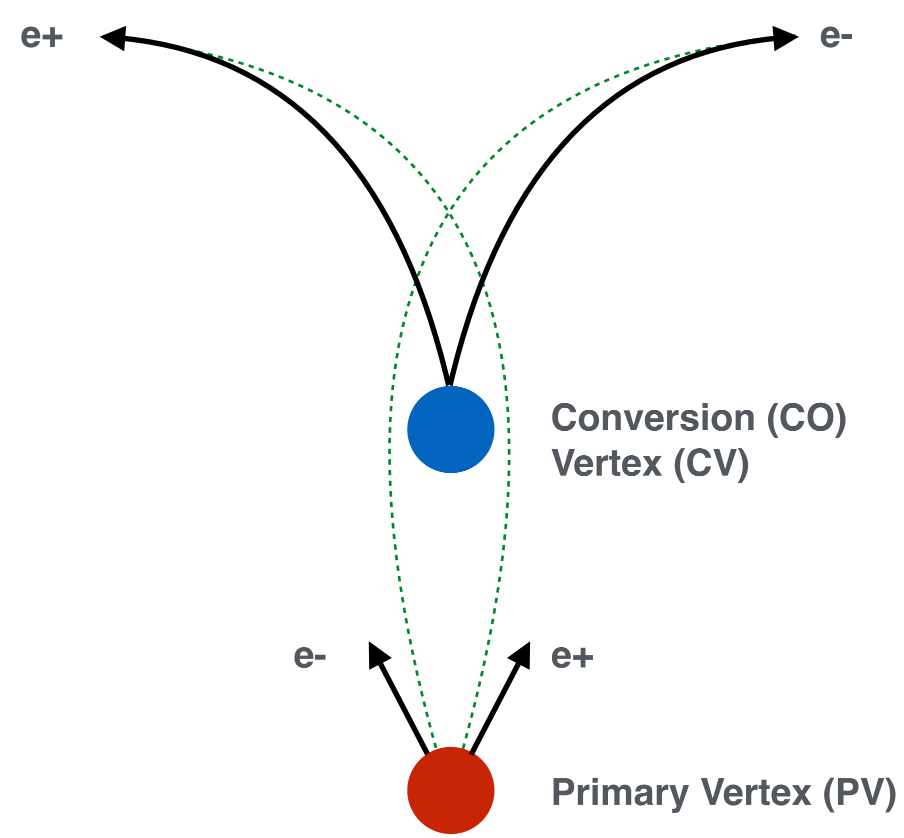
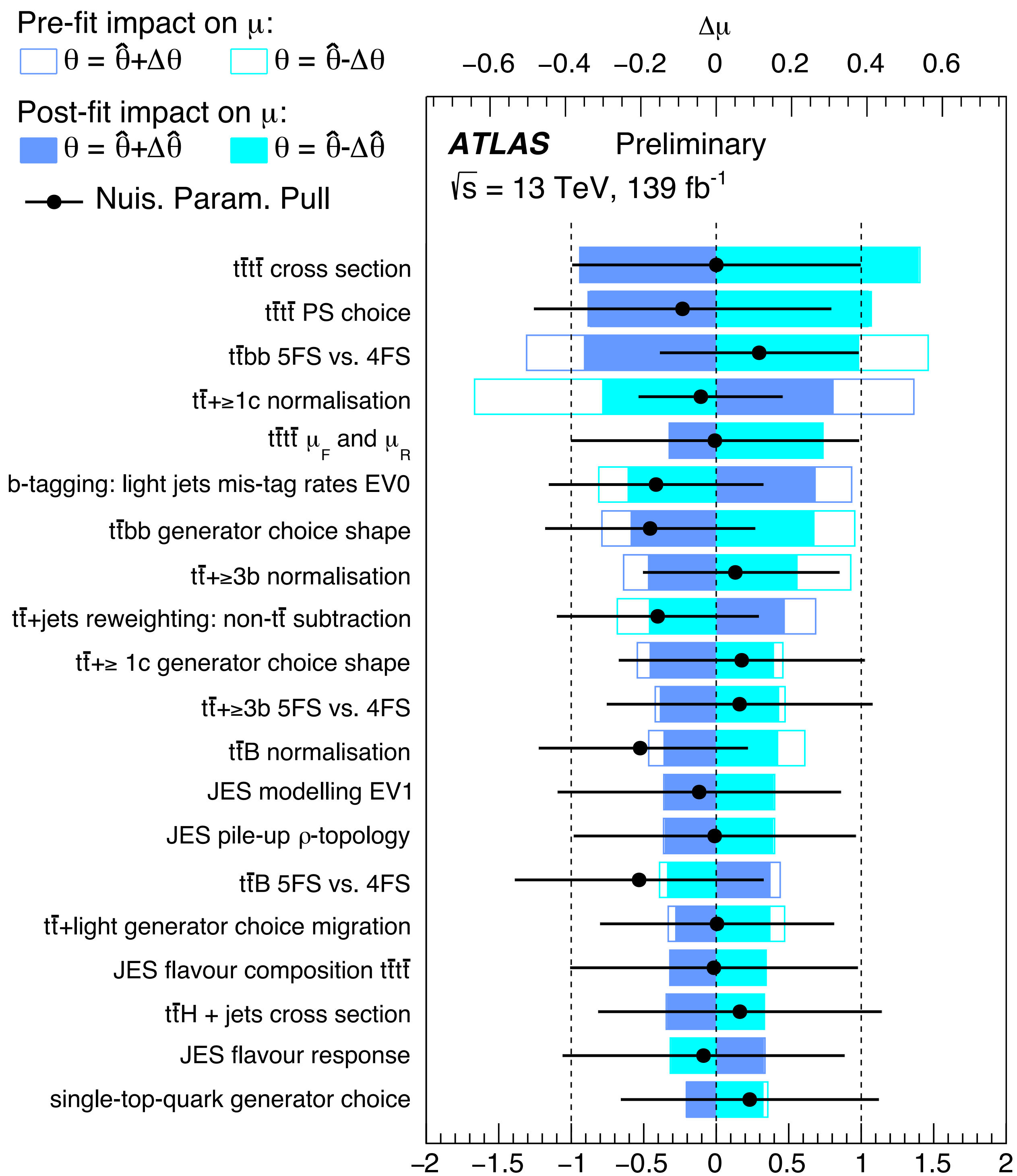




Leading Systematical Uncertainties

1L/2LOS



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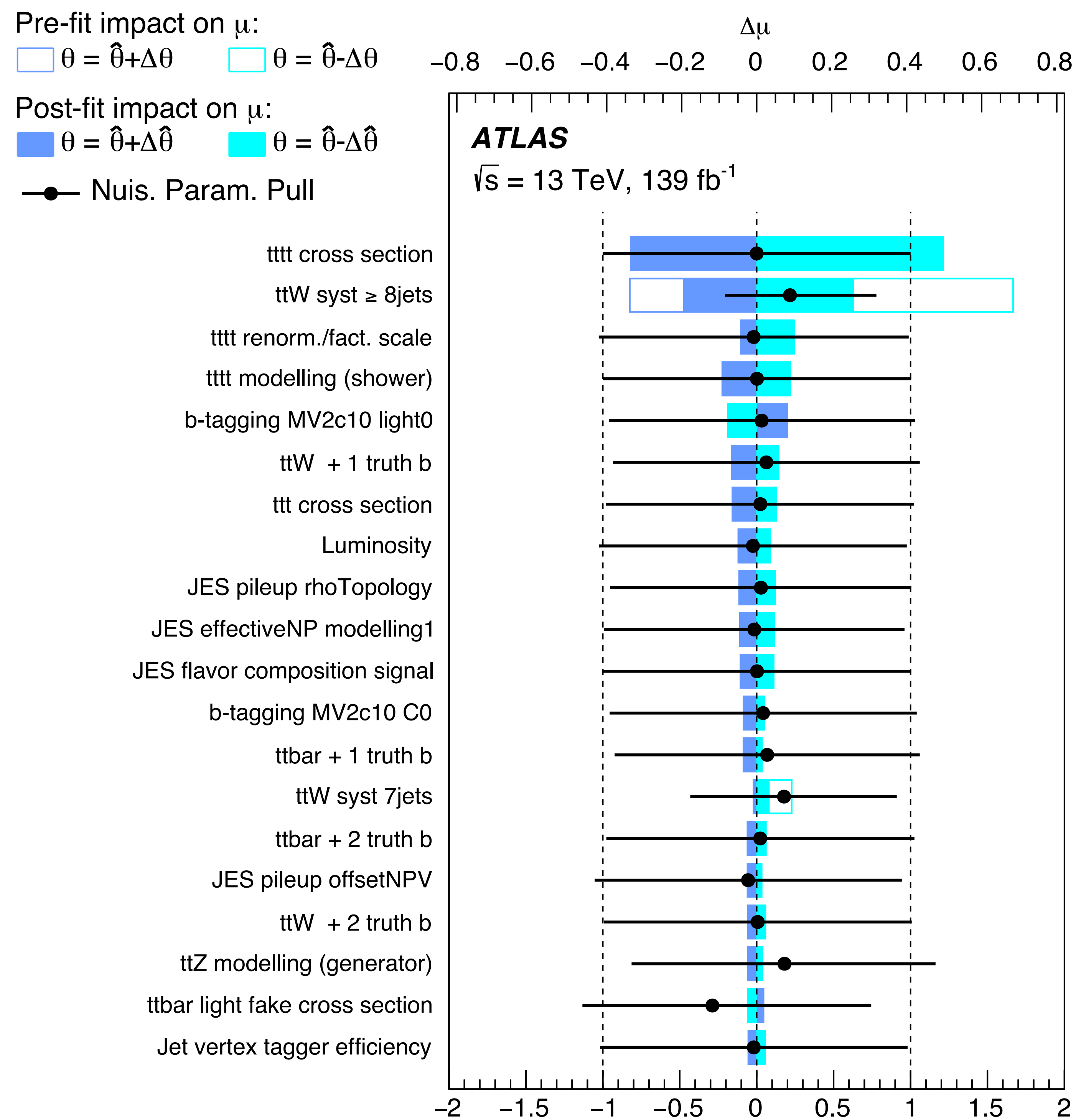
2LSS/3L



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Categorised Tables of Systematical Uncertainties

1L/2LOS

Uncertainty source	$\Delta\sigma_{t\bar{t}t\bar{t}}$ [fb]	
Signal Modelling		
$t\bar{t}t\bar{t}$ modelling	+8	-3
Background Modelling		
$t\bar{t}+\geq1b$ modelling	+8	-7
$t\bar{t}+\geq1c$ modelling	+5	-4
$t\bar{t}$+jets reweighting	+4	-3
Other background modelling	+4	-3
$t\bar{t}$+light modelling	+2	-2
Experimental		
Jet energy scale and resolution	+6	-4
b-tagging efficiency and mis-tag rates	+4	-3
MC statistical uncertainties	+2	-2
Luminosity	< 1	
Other uncertainties	< 1	
Total systematic uncertainty	+15	-12
Statistical uncertainty	+8	-8
Total uncertainty	+17	-15

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2LSS/3L

Uncertainty source	$\Delta\mu$	
Signal modelling		
$t\bar{t}t\bar{t}$ cross section	+0.56	−0.31
$t\bar{t}t\bar{t}$ modelling	+0.15	−0.09
Background modelling		
$t\bar{t}W$+jets modelling	+0.26	−0.27
$t\bar{t}t$ modelling	+0.10	−0.07
Non-prompt leptons modelling	+0.05	−0.04
$t\bar{t}H$+jets modelling	+0.04	−0.01
$t\bar{t}Z$+jets modelling	+0.02	−0.04
Other background modelling	+0.03	−0.02
Charge misassignment	+0.01	−0.02
Instrumental		
Jet uncertainties	+0.12	−0.08
Jet flavour tagging (light-flavour jets)	+0.11	−0.06
Simulation sample size	+0.06	−0.06
Luminosity	+0.05	−0.03
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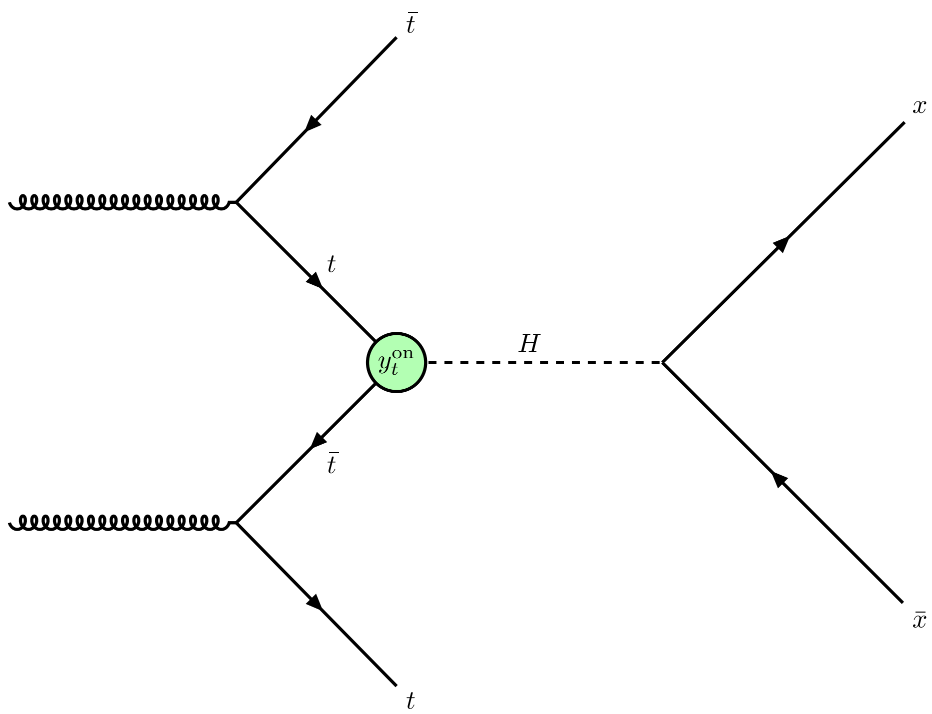
Measuring y_t from $t\bar{t}H$

One on-shell yukawa coupling vertex

- Two assumptions are needed
- On-shell Higgs cannot decay into top



$x = b, \mu, ..$

$$\kappa_t = \frac{y_t}{y_t^{\mathrm{SM}}} \qquad \kappa_x = \frac{y_x}{y_x^{\mathrm{SM}}}$$

$$\sigma = \sigma(gg \to ttH)\frac{\Gamma(H \to X)}{\Gamma_H} = \frac{\kappa_t^2 \kappa_x^2}{\Gamma_H / \Gamma_H^{\mathrm{SM}}} \sigma_{\mathrm{SM}}$$

$$\mu = \frac{\sigma}{\sigma_{SM}} = \frac{\kappa_t^2 \kappa_x^2}{\Gamma_H / \Gamma_H^{\mathrm{SM}}}$$

$\boxed{\Gamma_H = \Gamma_H^{\mathrm{SM}}}$ Good for rare decay modes (Ex: μ) Modification to rare decays won't affect total width dramatically

$\boxed{\kappa_x = 1}$ Good for dominant decay modes (Ex: b)

$$\mu = \kappa_t^2$$

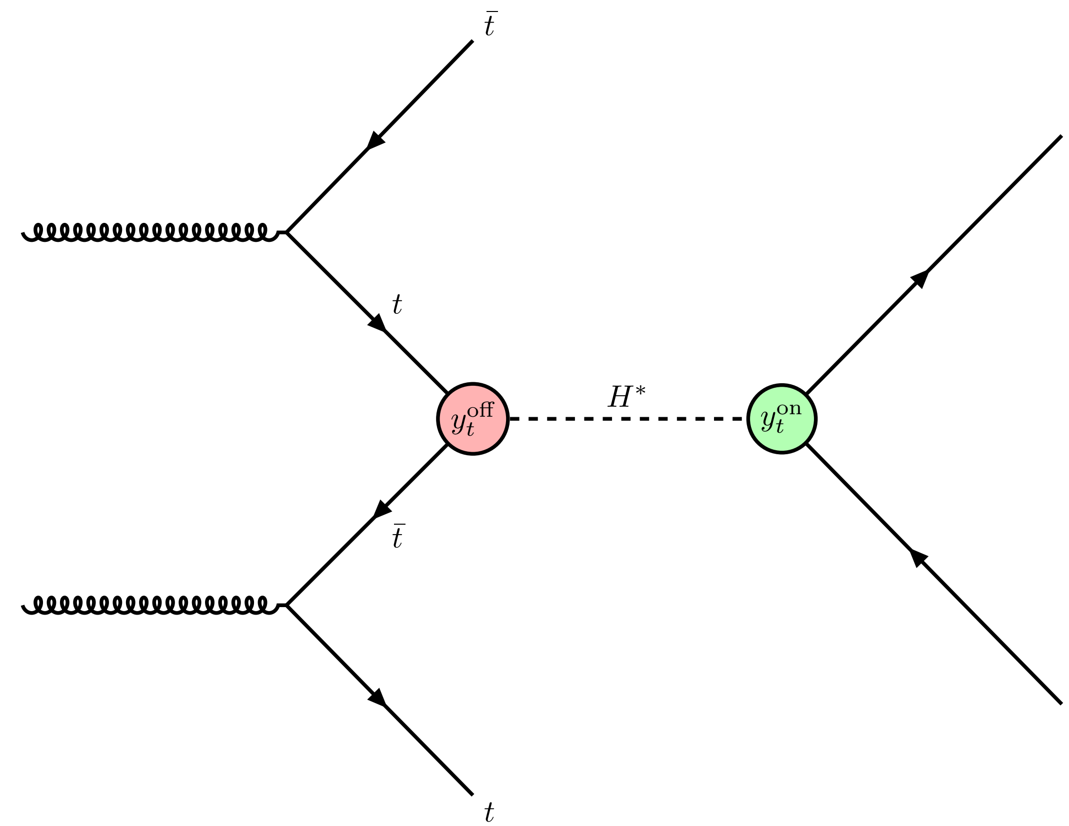
Measuring y_t from $t\bar{t}t\bar{t}$

Assumption free access to y_t!

- Assumptions are not needed
  - Higgs Width: Can be ignored in H*

$$\frac{1}{(s-M_x^2)+\cancel{M_x\Gamma_x}}$$

  - K_x: It is also top, so only y_t
- Can further constraint $t\bar{t}H$ based limits



$\propto |y_t|^4$

$$\boxed{\Gamma_H = \Gamma_H^{\text{SM}}}$$

Not needed because H* is off-shell, cross-section is independent of width

$$\boxed{\kappa_x = 1}$$

Not needed because no x dependence since x=top

Important because Higgs width is O(2) smaller than the detector resolution