Federal Ministry of Education and Research

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Search for the Standard Model Higgs boson produced in association with top quarks and decaying into a pair of b-quarks with the ATLAS detector

UNI FREIBURG

Manuel Guth on behalf of the ATLAS collaboration

11.03.2021 - La Thuile 21 - Les Rencontres de Physique de la Vallée d’Aoste

ATLAS EXPERIMENT

Masse und Symmetrien nach der Entdeckung des Higgs-Teilchens am LHC GRK 2044

Irfu

DE LA RECHERCHE À L'INDUSTRIE cea SACLAY

université PARIS-SACLAY

Motivation for $t\bar{t}H\,(H \to b\bar{b})$ Measurement

- Small cross section compared to other Higgs production (~ 1% total XS modes) but ~ 7 times larger cross section than tH

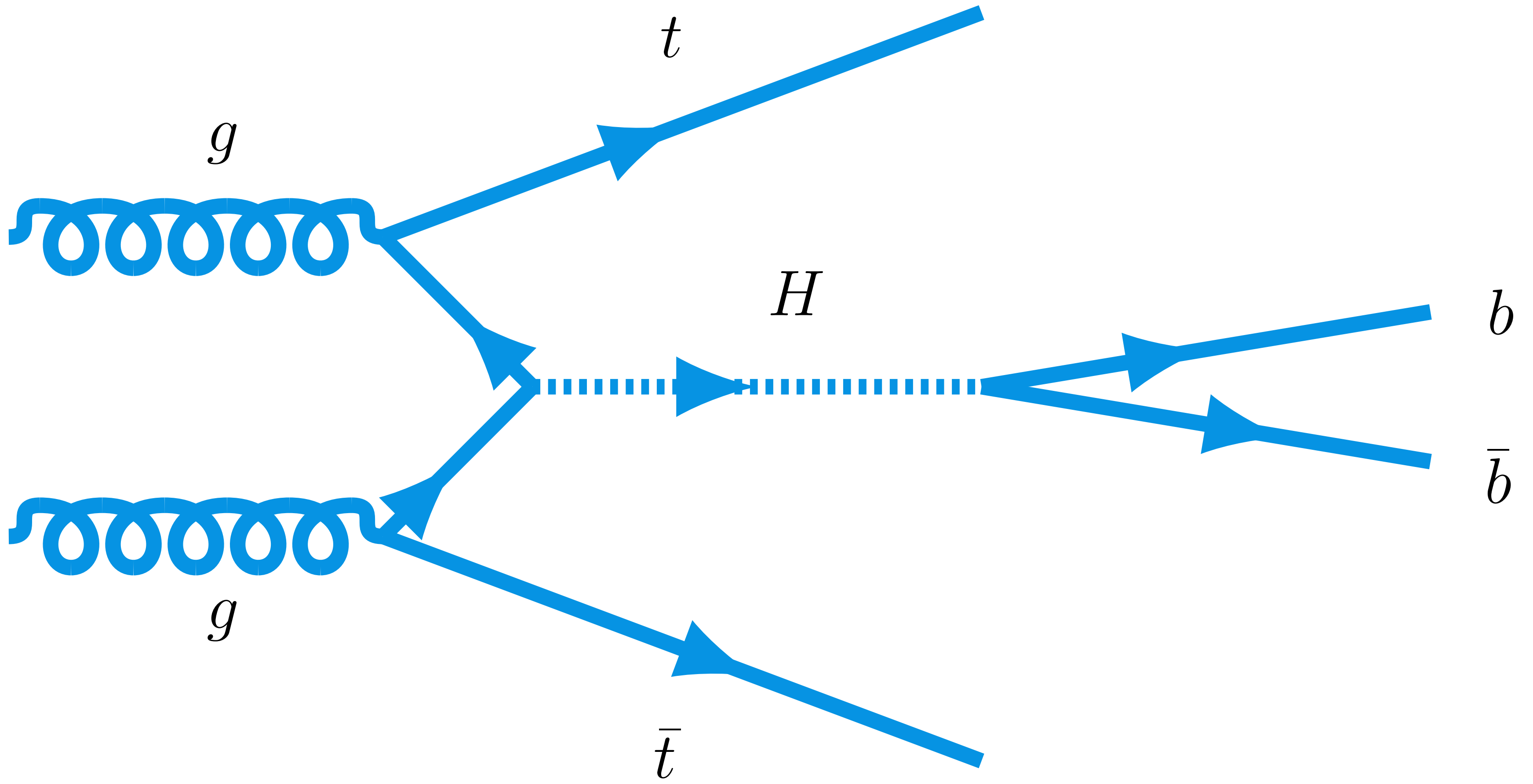
- Top-Yukawa coupling is strongest fermion-Higgs coupling in SM

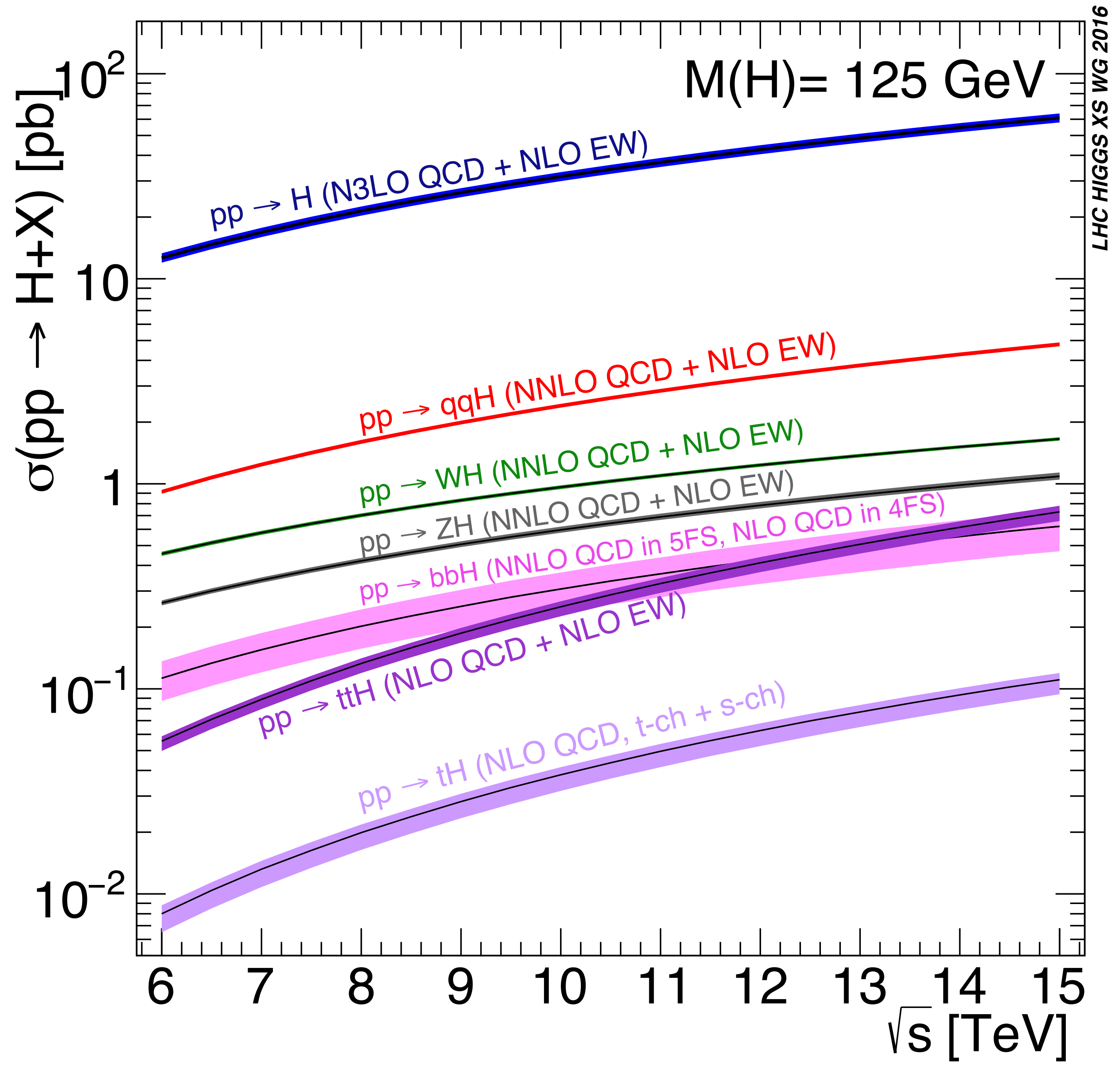
$$y_f = \frac{m_f \cdot \sqrt{2}}{\text{vev}} \approx 1$$

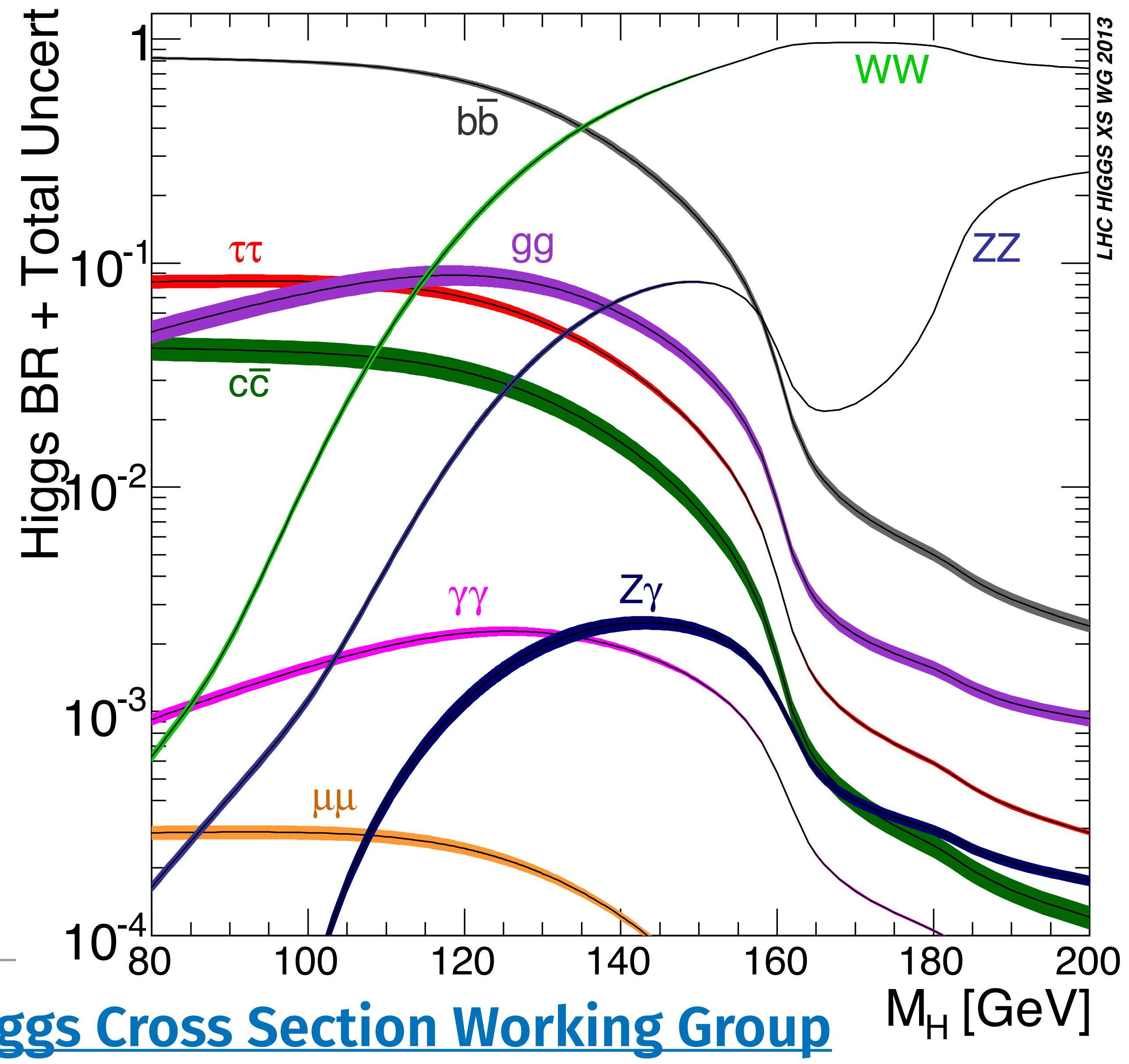
  - Can give hints to the stability of the electroweak vacuum

- **Most favourable production mode for direct measurement of Yukawa coupling to top quark**

- Branching fraction of Higgs decaying to 2 *b*-quarks ~ 58%



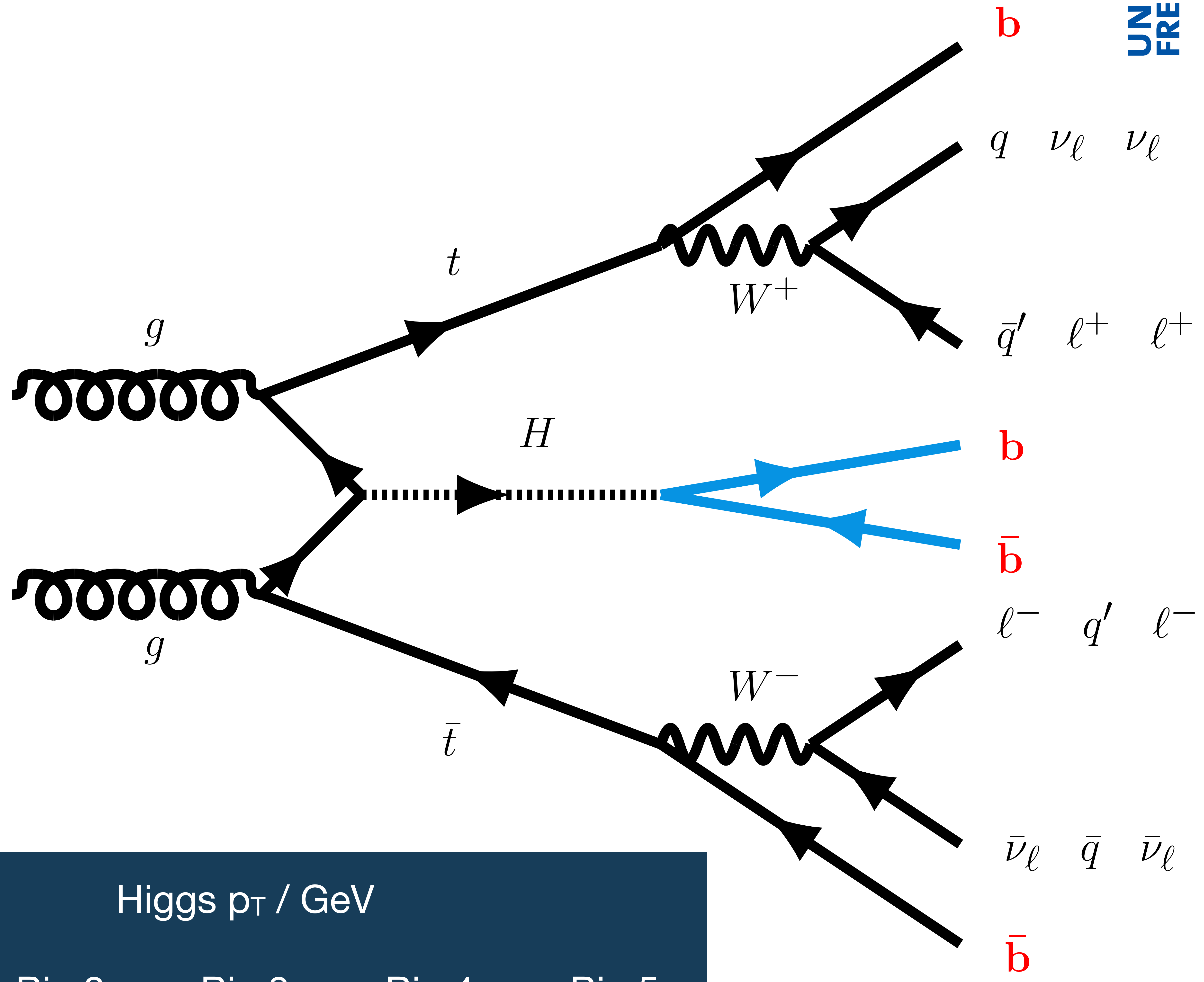


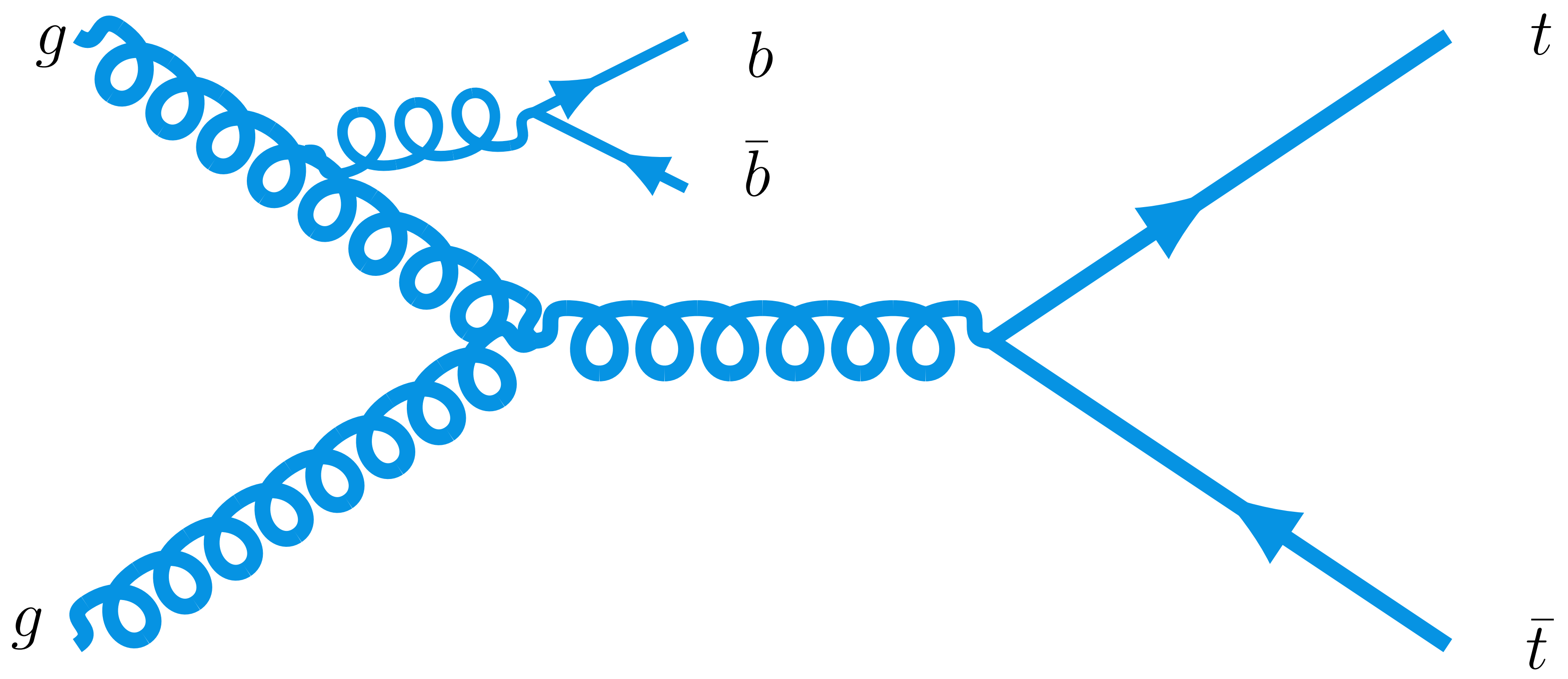


[LHC Higgs Cross Section Working Group](#)

Signature of $t\bar{t}H\,(H \rightarrow b\bar{b})$ Process

- Latest measurements: ATLAS $36\,fb^{-1}$ and CMS $77.4\,fb^{-1}$
- Semi-leptonic or fully leptonic decay of W-bosons considered
- Full RUN II dataset with $139\,fb^{-1}$ recorded with ATLAS @ $\sqrt{s} = 13$ TeV (ATLAS-CONF-2020-058)
- Analysis regions optimised for Simplified Template Cross Section (STXS) measurement in bins of p_T^H
- Dominant background $t\bar{t} + b\bar{b}$ (irreducible)





Higgs p_T / GeV				
Bin 1	Bin 2	Bin 3	Bin 4	Bin 5
0-120	120-200	200-300	300-450	450 - ∞

Analysis Strategy

ATLAS-CONF-2020-058

Dilepton

lepton+jets resolved

veto

lepton+jets boosted

Categorisation/Selection by number of jets & number of *b*-tags

BDT

BDT

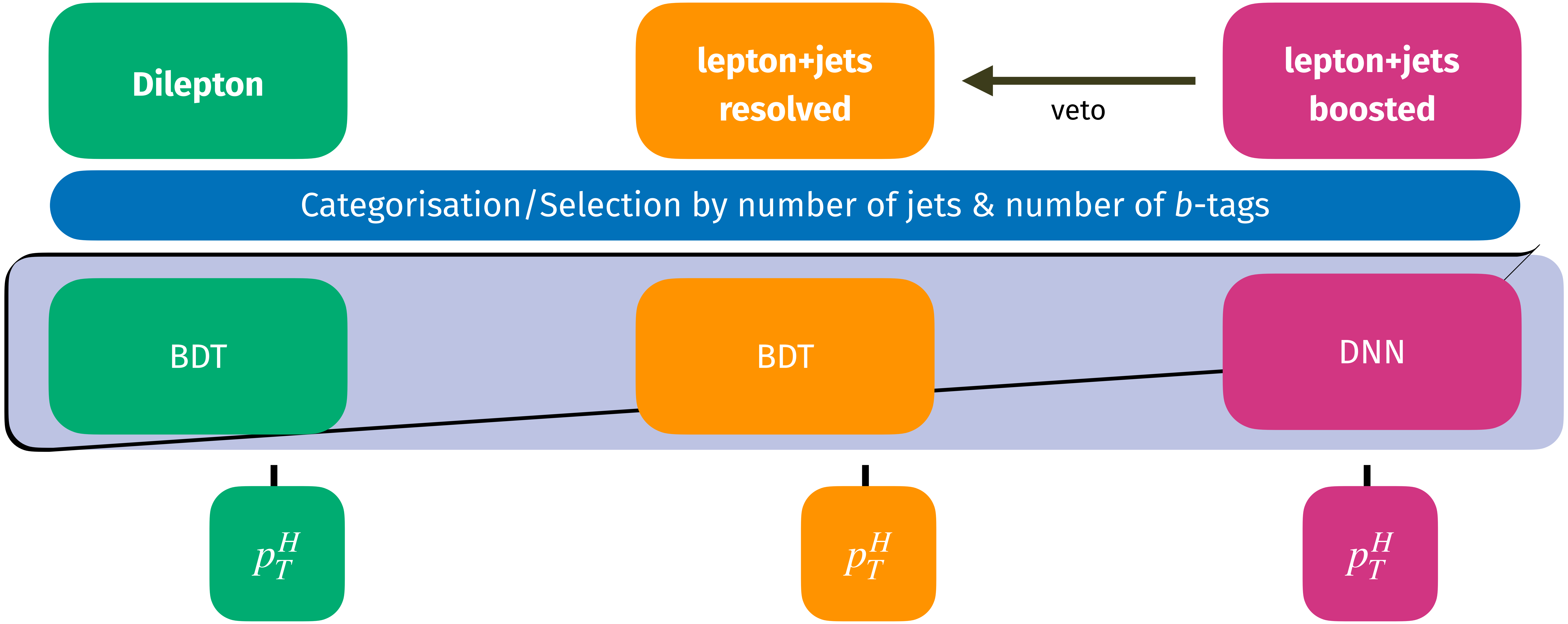
DNN

Event reconstruction (solving combinatorics)

Reconstruction BDT: Matching jets to partons emitted from top-quark and Higgs decay

New Deep Neural Network trained to classify reclustered jets as
Higgs, Top or QCD

Analysis Strategy



Event reconstruction (solving combinatorics)

$p_T^H \in$

Dilepton	lepton+jets resolved	lepton+jets boosted
[0,120) GeV	[0,120) GeV	
[120,200) GeV	[120,200) GeV	
[200,300) GeV	[200,300) GeV	
[300,∞) GeV	[300,450) GeV	[300,450) GeV
	[450,∞) GeV	[450,∞) GeV

Events split by p_T^H

Analysis Strategy

ATLAS-CONF-2020-058

Dilepton | **lepton+jets resolved** ← veto — **lepton+jets boosted**

Categorisation/Selection by number of jets & number of *b*-tags

BDT | BDT | DNN

Event reconstruction (solving combinatorics)

p_T^H | p_T^H | p_T^H

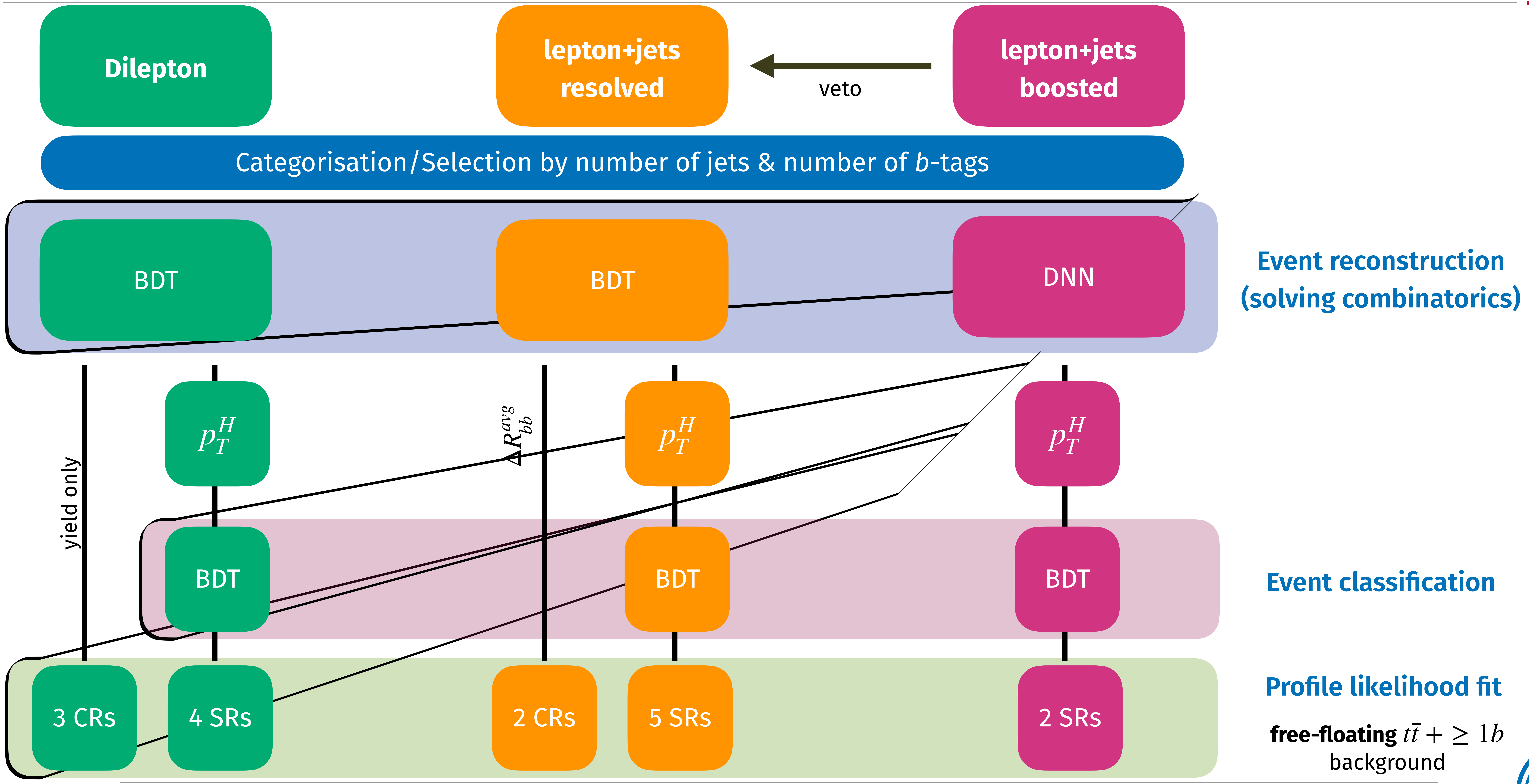
BDT | BDT | BDT

Event classification

(classification) BDTs trained to discriminate between $t\bar{t}H$ signal and background processes (depending on channel)

Analysis Strategy

ATLAS-CONF-2020-058



SR: signal region, CR: control region (for background handling)

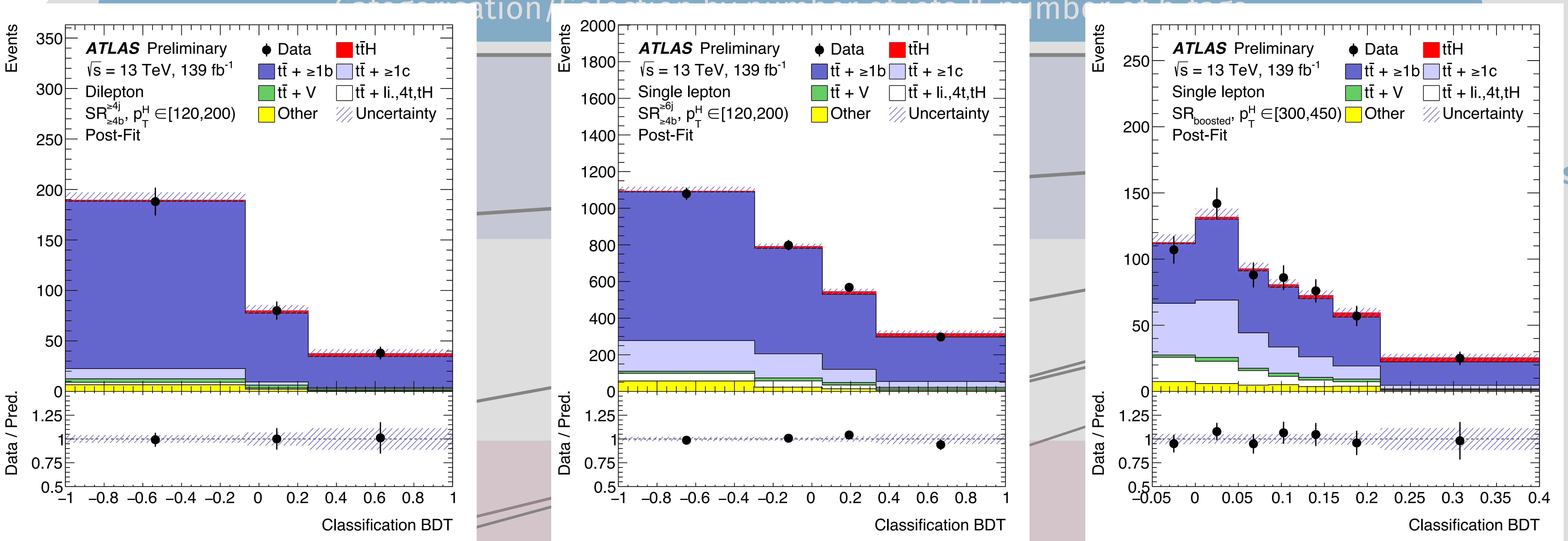
Analysis Strategy

ATLAS-CONF-2020-058

Dilepton

lepton+jets resolved ← veto — **lepton+jets boosted**

Categorization/Selection by number of jets & number of b-tags



Event reconstruction (solving combinatorics)

Event classification

3 CRs | 4 SRs | 2 CRs | 5 SRs | 2 SRs

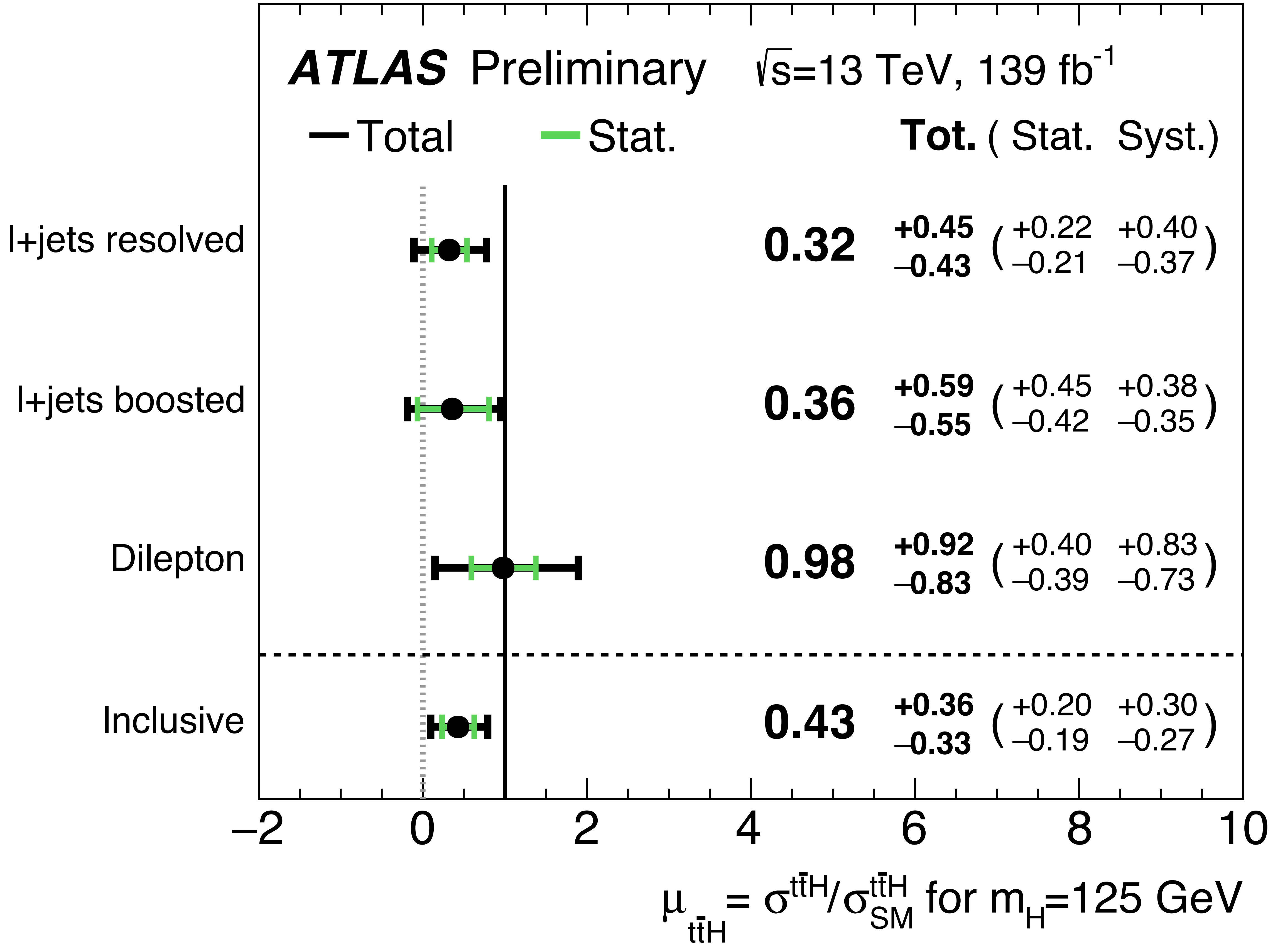
Profile likelihood fit

free-floating $t\bar{t} + \geq 1b$ background

SR: signal region, CR: control region (for background handling)

Results - Signal Strength

ATLAS-CONF-2020-058



- Observed (expected) significance of 1.3 (3.0) standard deviations

$$\mu = 0.43^{+0.20}_{-0.19}(stat.)^{+0.30}_{-0.27}(syst.) = 0.43^{+0.36}_{-0.33}$$

- Measured $t\bar{t} + \geq 1b$ normalisation

$$k(t\bar{t} + \geq 1b) = 1.26 \pm 0.09$$

- Uncertainty improved by almost a factor 2 compared to previous ($36\,fb^{-1}$) analysis (Phys. Rev. D 97, 072016)

Results - Systematic Uncertainties

ATLAS-CONF-2020-058

Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modelling	+0.25	–0.24
$t\bar{t}H$ modelling	+0.14	–0.06
tW modelling	+0.08	–0.08
b-tagging efficiency and mis-tag rates	+0.05	–0.05
Background-model statistical uncertainty	+0.05	–0.05
Jet energy scale and resolution	+0.03	–0.03
$t\bar{t} + \geq 1c$ modelling	+0.03	–0.03
$t\bar{t}$ + light modelling	+0.02	–0.02
Luminosity	+0.01	–0.00
Other sources	+0.03	–0.03
Total systematic uncertainty	+0.30	–0.27
$t\bar{t} + \geq 1b$ normalisation	+0.03	–0.05
Total statistical uncertainty	+0.20	–0.19
Total uncertainty	+0.36	–0.33

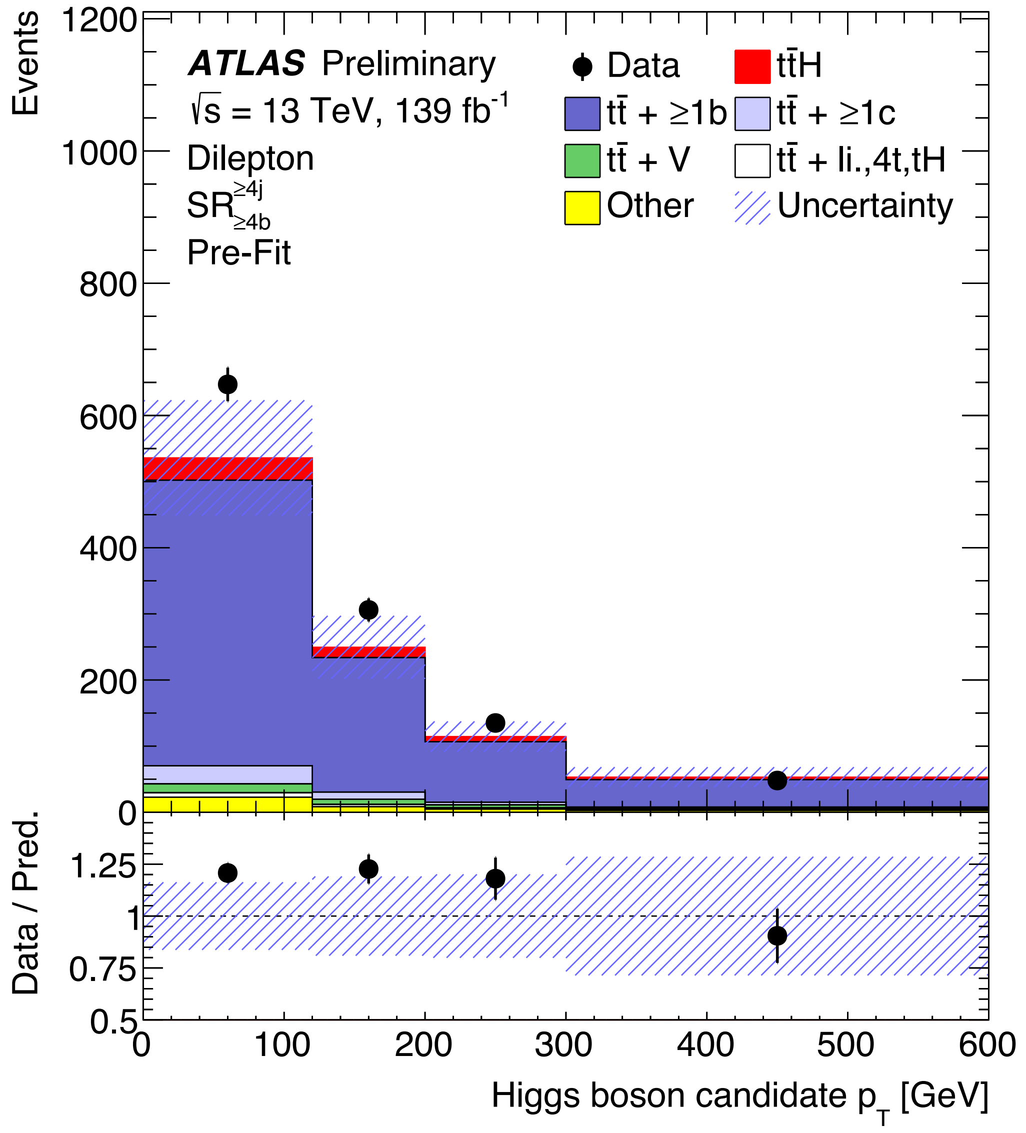
- $t\bar{t} + \geq 1b$ **and** $t\bar{t}H$ **modelling** systematics have the largest impact on μ
- **Experimental** uncertainty with largest impact is related to **b-tagging**

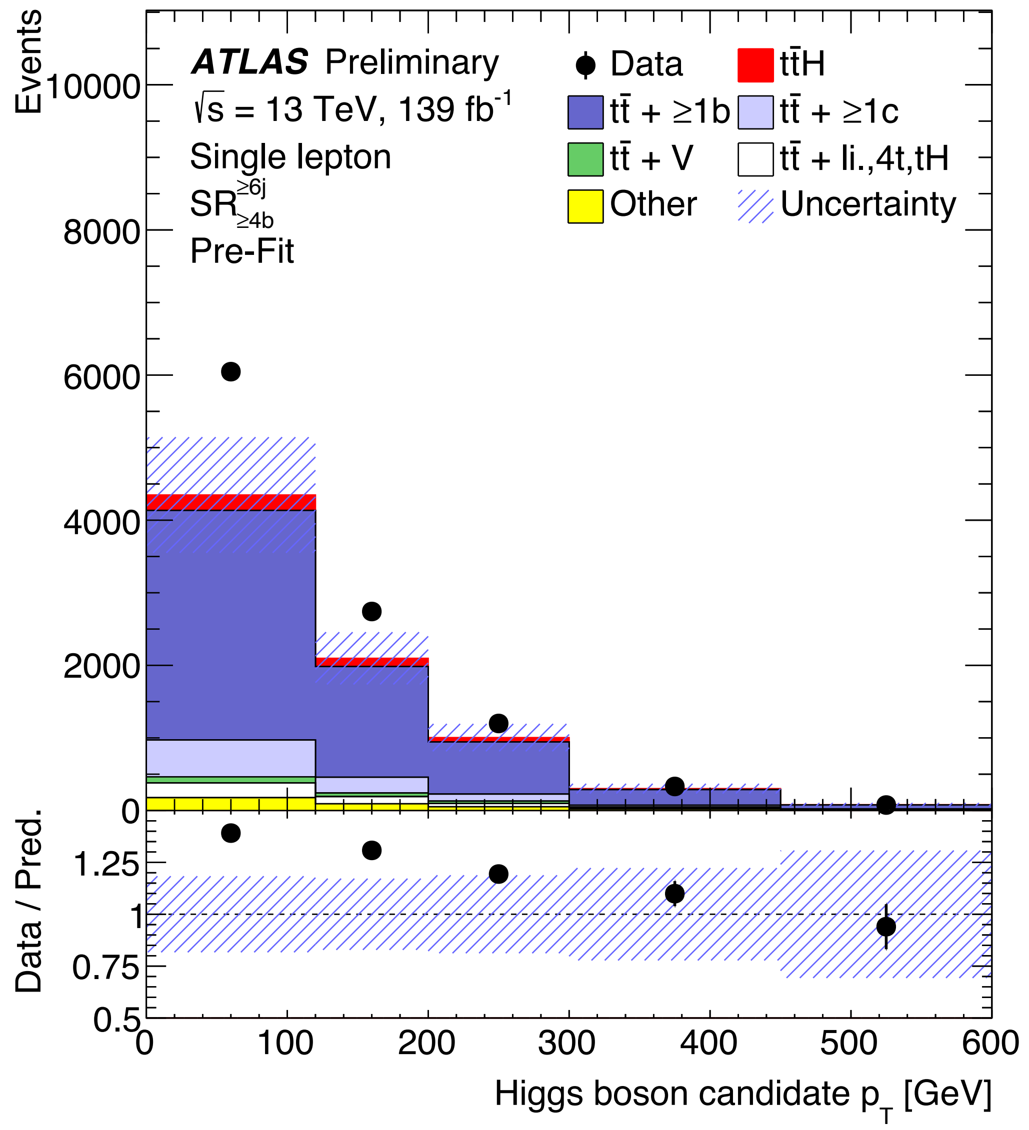
Measurement dominated by signal and background modelling uncertainties

Modelling of $t\bar{t} + \geq 1b$

ATLAS-CONF-2020-058

- Modelling of $t\bar{t} + \geq 1b$ with 4 flavour scheme (no b-quarks in proton PDFs)
- Systematic uncertainties to cover missing higher order terms, initial and final state radiation effects, parton shower & hadronisation etc.
- Additional uncertainty derived to cover the Higgs candidate p_T mis-modelling, assigned entirely to $t\bar{t} + \geq 1b$ background
  - Only shape effect considered (normalisation effects removed)





Results - Pulls and Ranking

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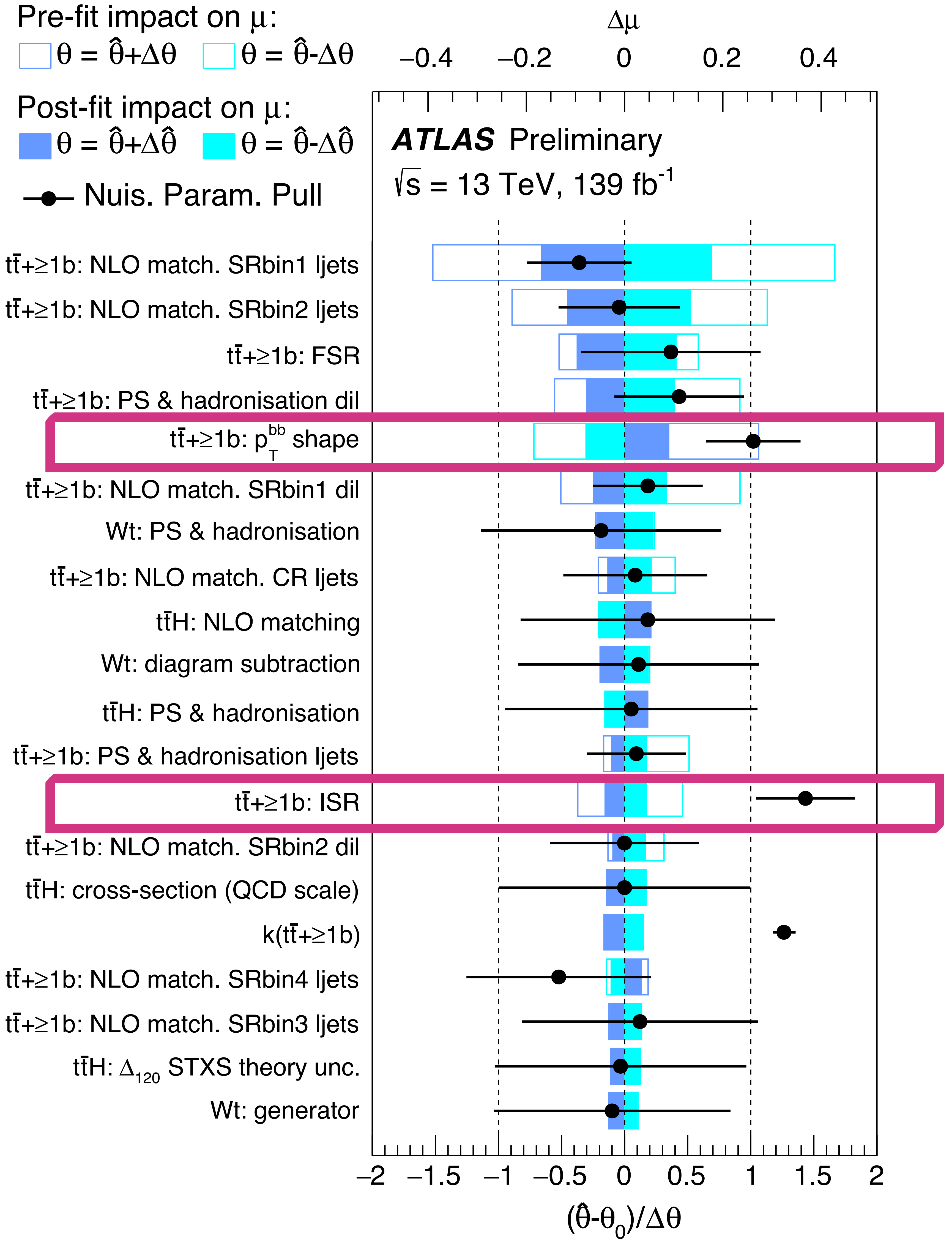
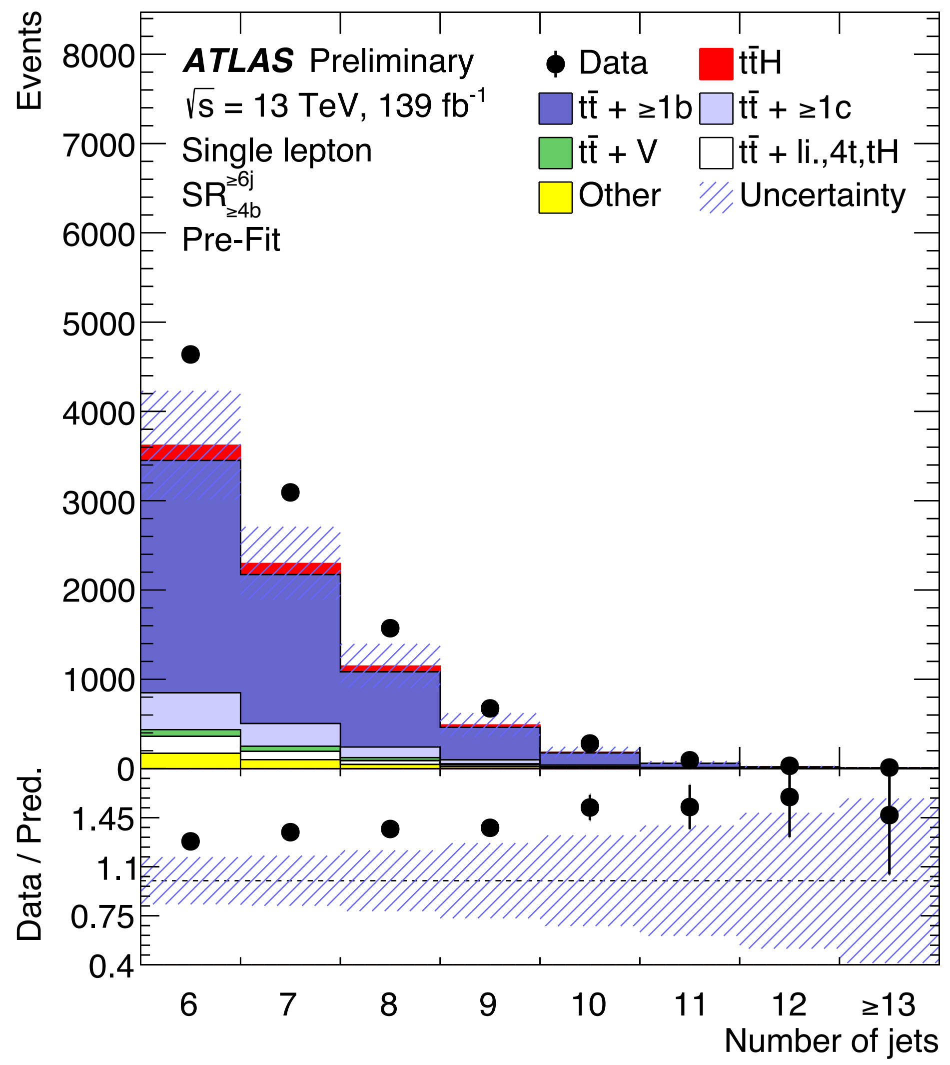
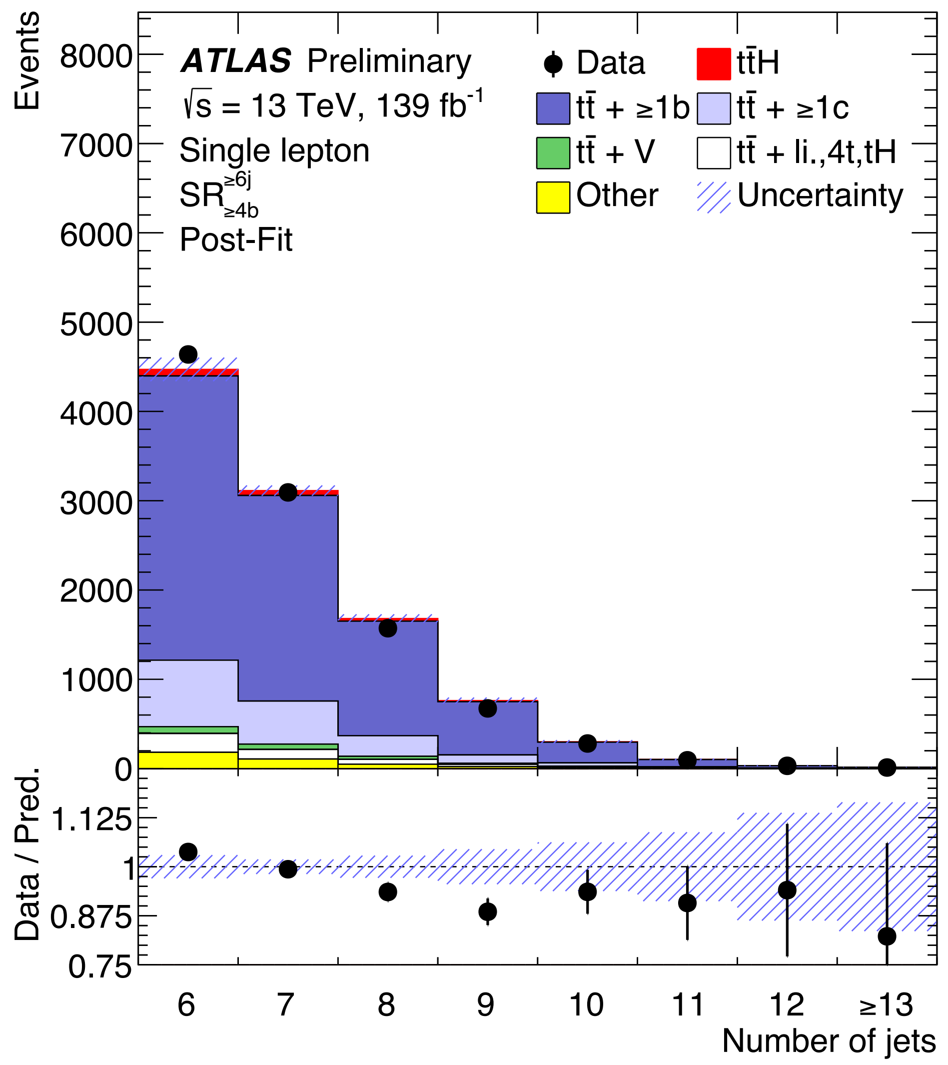


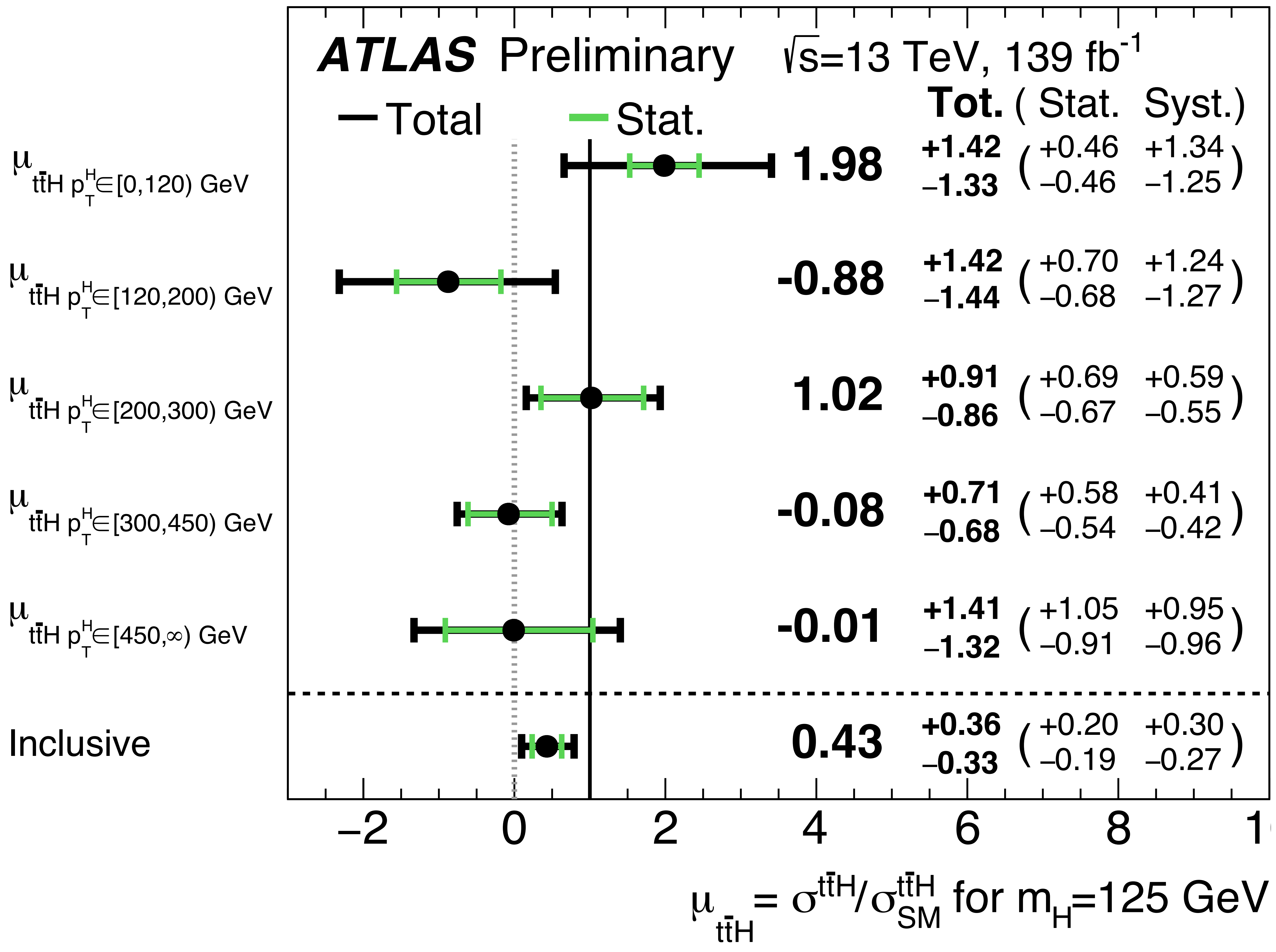
- Second largest pull is on Higgs p_T shape systematics, as expected from pre-fit modelling
- Largest observed pull on $t\bar{t}+\geq 1b$ ISR systematic (~1.4σ)
  - Corrects N_{jets} distribution
- $t\bar{t}+\geq 1b$ NLO matching has highest impact on μ





Results - Signal Strength

ATLAS-CONF-2020-058



- First STXS measurement in bins of p_T^H using $t\bar{t}H(b\bar{b})$
  - Only measurement so far accessing high p_T^H in $t\bar{t}H$
- In general fairly large uncertainties
- 1st & 2nd bins dominated by systematic uncertainties
- 3rd - 5th bins dominated by statistical uncertainty

Summary

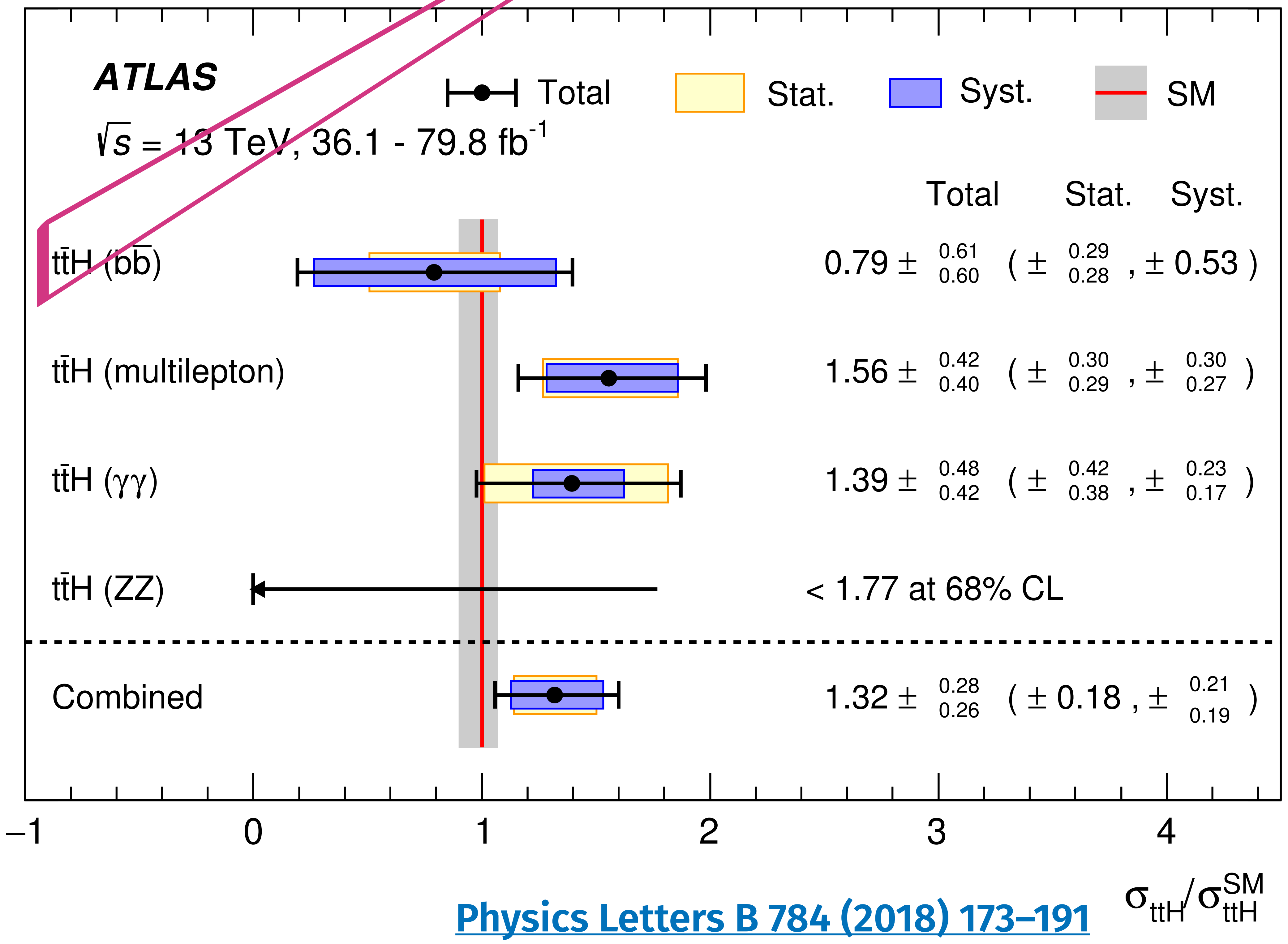
- Measurements of $t\bar{t}H$ production with $H \rightarrow b\bar{b}$ are performed using the full Run-2 dataset of pp collision collected at √s = 13 TeV and corresponding to an integrated luminosity of $139\,fb^{-1}$
- Event selection targets lepton+jets and dilepton channel
- Dominant background is ttbar production with additional heavy-flavour jets
- An excess of events over the expected SM background is found with an observed (expected) significance of 1.3 (3.0) standard deviations
- Measured signal strength: $0.43^{+0.36}_{-0.33}$
- Systematics dominated measurement, particularly modelling of $t\bar{t} + \geq 1b$ background
- First signal strength measurement performed in Higgs p_T bins in STXS framework
    - Observed results are in agreement with SM within large uncertainties

Backup

Latest Results with 36 fb^{-1}

- Latest ATLAS publication (Phys. Rev. D 97 (2018) 072016)
- $1.4\ (1.6)\ \sigma$ excess above the expected background is observed (expected)
- Obtained signal strength $\mu = 0.84^{+0.64}_{-0.61}$
- Analysis mainly dominated by systematic uncertainties
  - Especially modelling of $t\bar{t} + \geq 1b$ background is a big issue
    - Group is working at that also in cooperation with CMS and HiggsXsecWG

Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modeling	+0.46	−0.46
Background-model statistical uncertainty	+0.29	−0.31
b-tagging efficiency and mis-tag rates	+0.16	−0.16



Physics Letters B 784 (2018) 173–191

- $t\bar{t}H$ production discovered in the combination with other channels ($6.3\ \sigma$)

Higgs nth & tH production cross sections

$t\bar{t}H$ and tH production

- Cross sections for $t\bar{t}H$ are calculated at NLO QCD and NLO EW while for $\bar{t}H$ they are at NLO QCD

* $t\bar{t}H$

√s (TeV)	σ	+δ(scale)	-δ(scale)	Δ_{α_s}	Δ_{PDF}	$\Delta_{PDF+\alpha_s}$
14	612.8 fb	6.0%	9.2%	±1.9%	±2.9%	±3.5%
27	2860 fb	7.8%	9.0%	±1.8%	±2.1%	±2.8%

* tH+ $\bar{t}H$

√s (TeV)	σ	+δ(scale)	-δ(scale)	Δ_{α_s}	Δ_{PDF}	$\Delta_{PDF+\alpha_s}$
14	90.12 fb	6.4%	14.7%	±1.2%	±3.4%	±3.6%
27	417.9 fb	5.0%	12.5%	±1.3%	±2.6%	±2.9%

LHC Higgs Cross Section Working Group

Yukawa Coupling Top

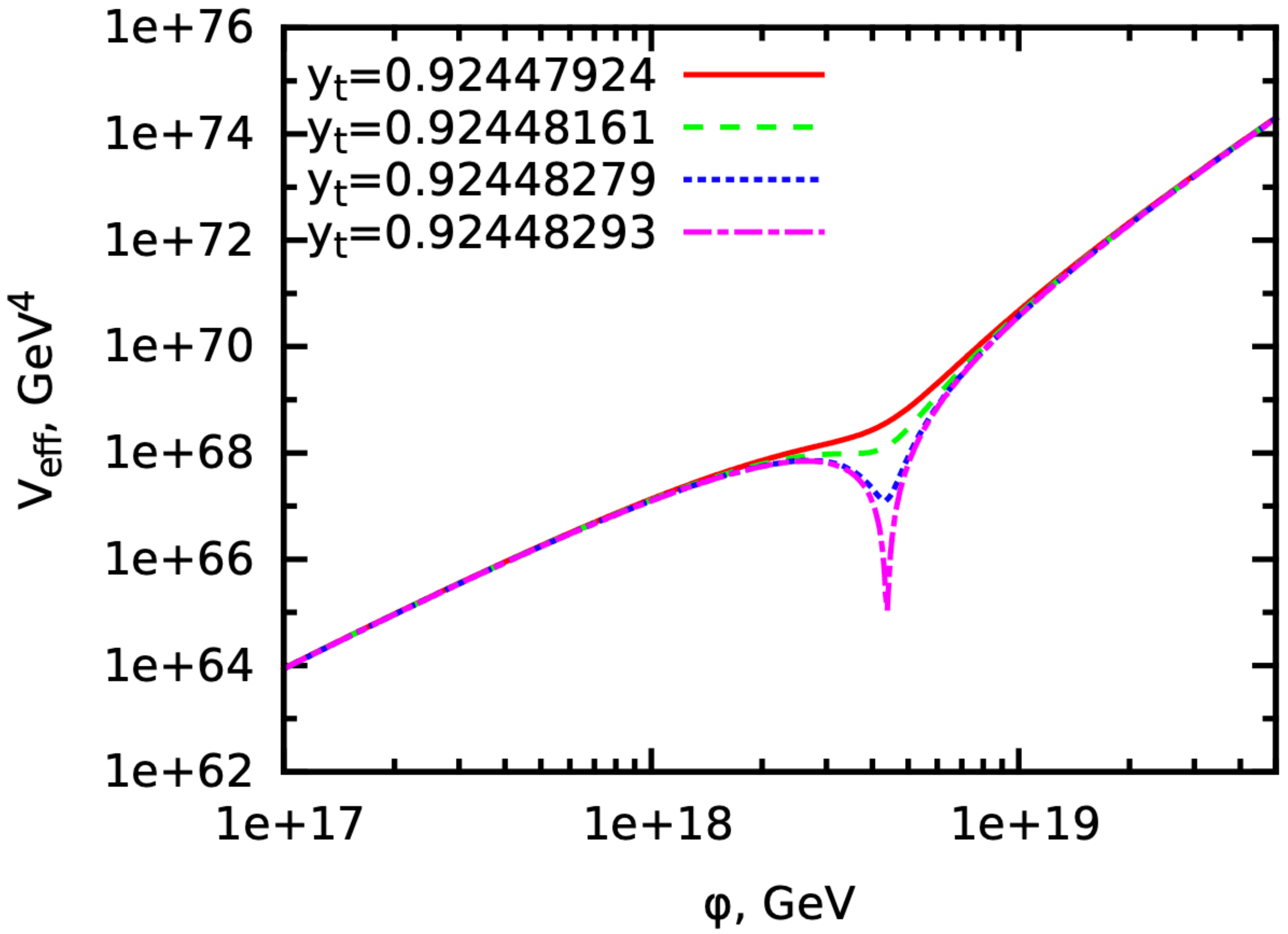


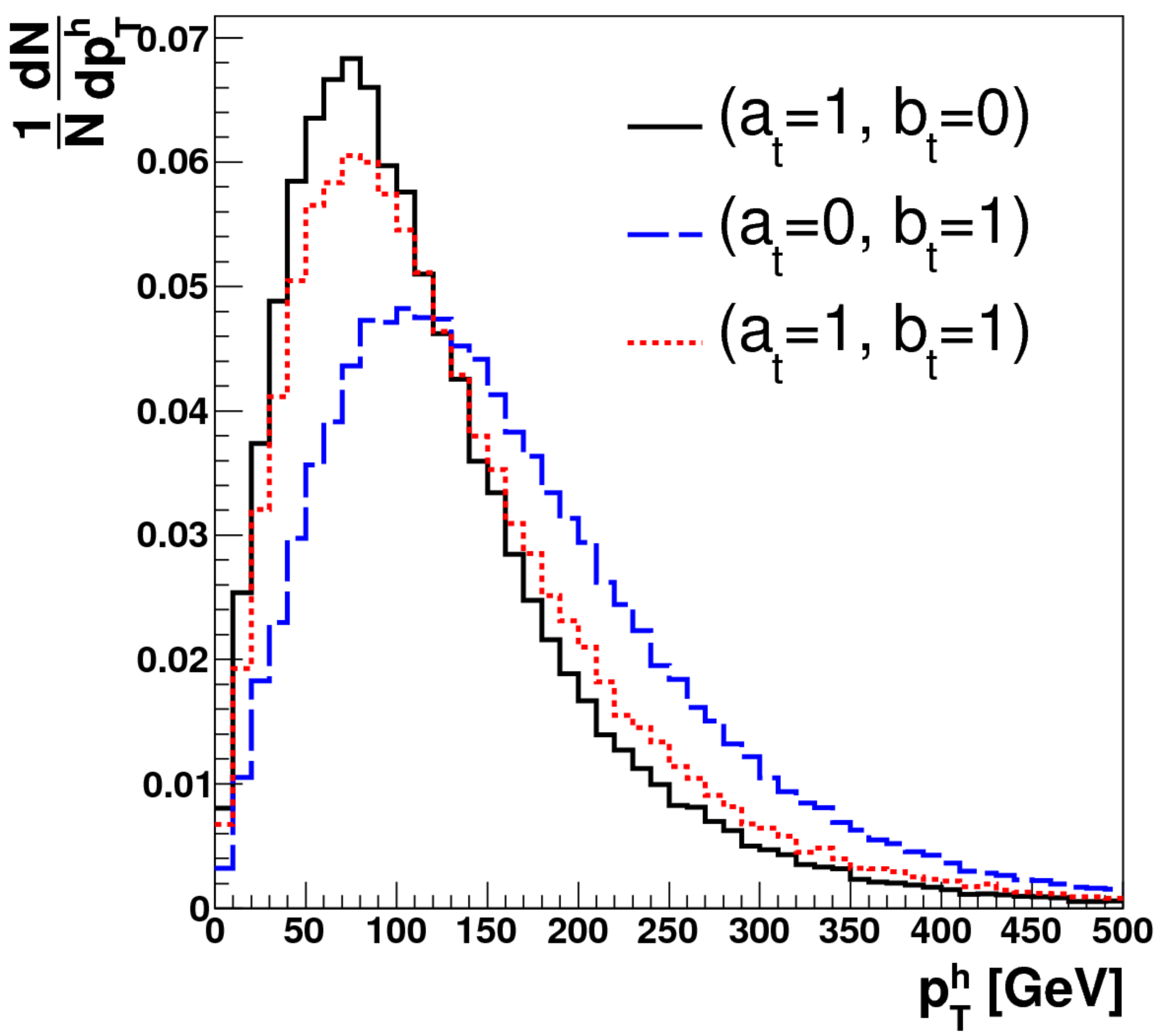
FIG. 2. A very small change in the top Yukawa coupling y_t (taken at scale $\mu = 173.2$ GeV) converts the monotonic behaviour of the effective potential for the Higgs field to that with an extra minimum at large values of the Higgs field.

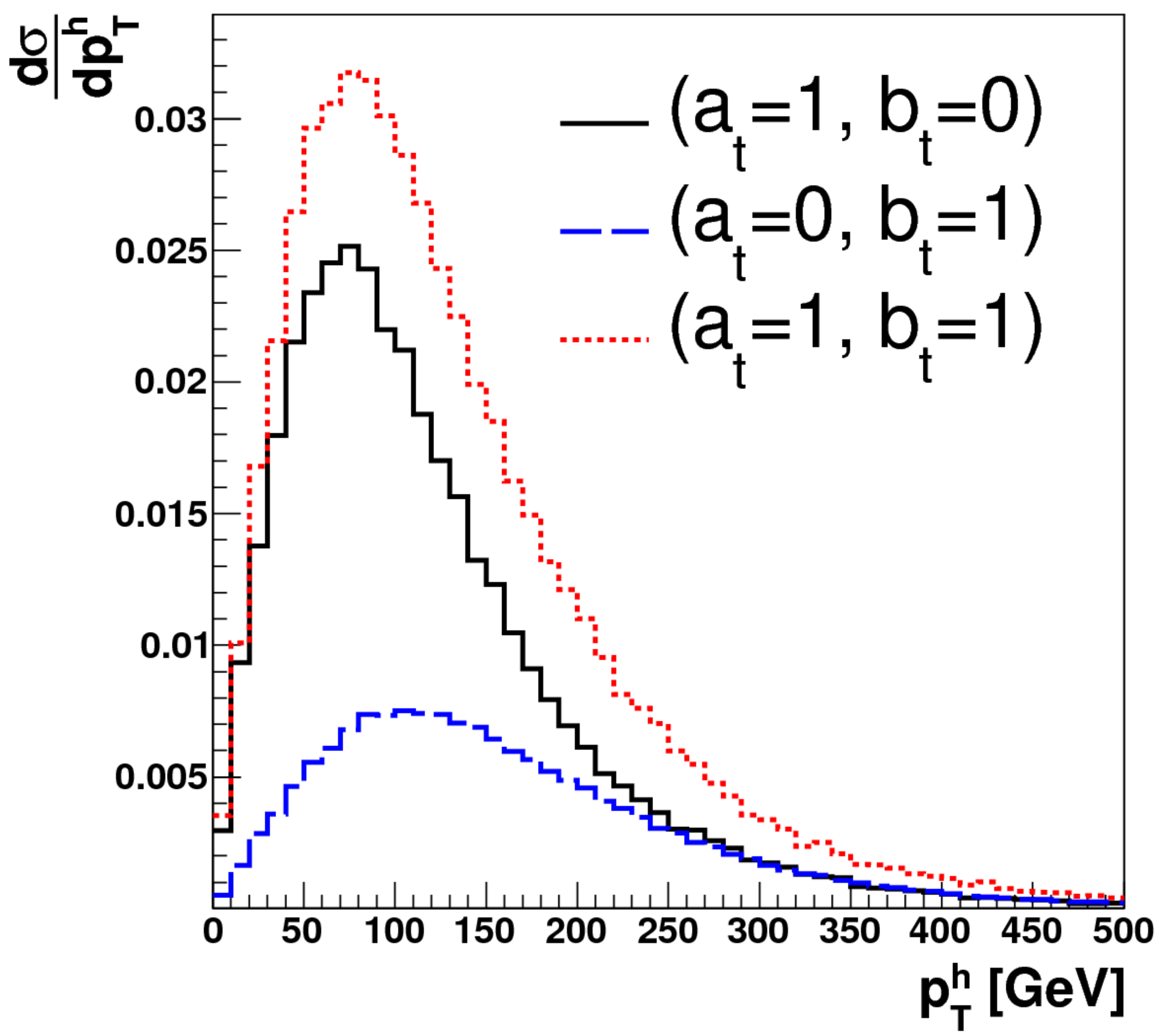
https://cds.cern.ch/record/1968356/files/arXiv:1411.1923.pdf

Theory Motivation Simplified Template Cross Sections (STXS)

- Probing CP structure of Higgs-top coupling
  - Strong dependency on Higgs p_T

- Measuring Higgs pT in STXS bins can exclude CP-odd hypothesis





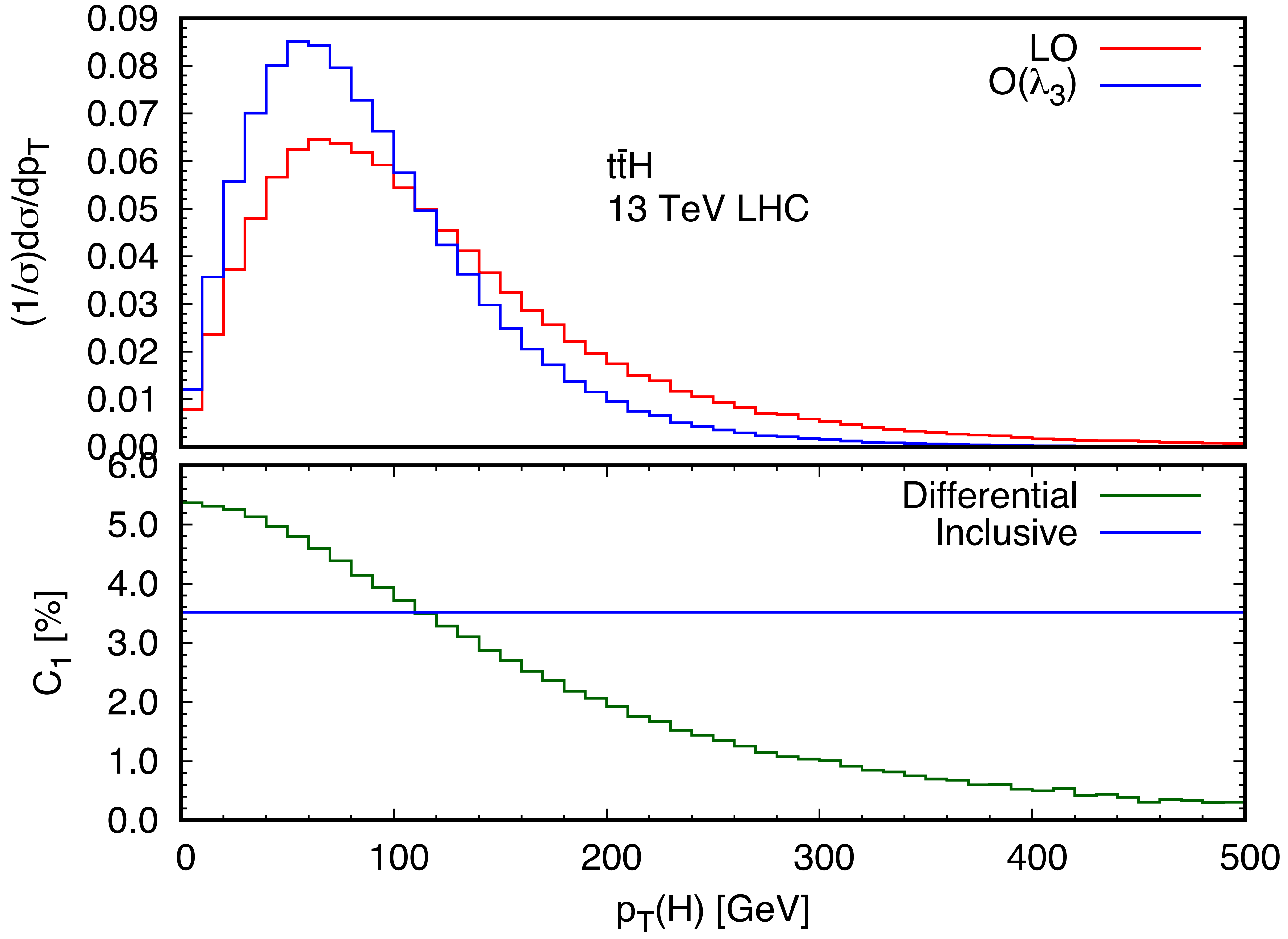
SM distribution $(a_t = 1, b_t = 0)$
Pseudo-scalar case $(a_t = 0, b_t = 1)$
CP violation $(a_t = 1, b_t = 1)$

arXiv: 1501.03157

Simplified Cross Section (STXS) Strategy

- Differential measurement in bins of Higgs p_T
- Analysis regions were optimised for STXS
- The Higgs p_T binning was optimised and also discussed with CMS and theorists to facilitate future combinations
- Sensitive to CP-structure of Higgs and anomalous Higgs self-coupling

Scenario	Higgs p_T / GeV Bin 1	Bin 2	Bin 3	Bin 4	Bin 5
Dilepton	0-120	120-200	200-300	300 - ∞	-
Single lepton	0-120	120-200	200-300	300-450	450 - ∞



[Maltoni, Pagani, Shivaji, Zhao, 1709:08649]

Theory Motivation Simplified Template Cross Sections (STXS)

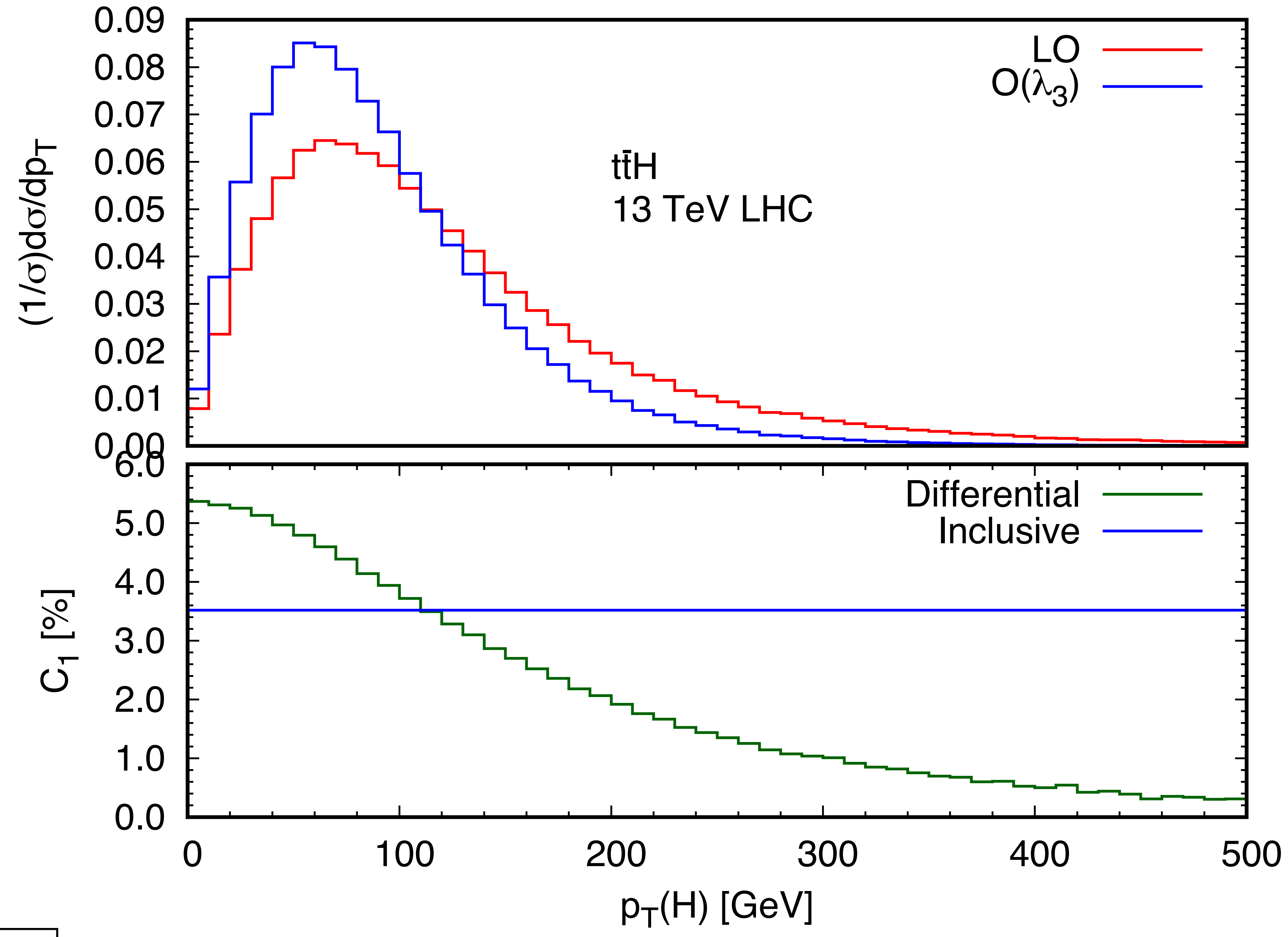
- Potential of Higgs scalar field

$$V(H) = \frac{1}{2}m_H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4 + \mathcal{O}(H^5), \quad \text{with } \lambda_3^{SM} = \lambda_4^{SM}$$

- Introducing anomalous coupling $\lambda_3 = \kappa_3 \lambda_3^{SM}$

$$d\sigma(\kappa_3) = \sigma_{LO}\frac{1}{1-(\kappa_3-1)\delta Z_H}(1+\kappa_3 C_1 + \delta Z_H + \delta_{EW}|_{\lambda_3=0}), \quad \delta Z_H \approx -1.5\cdot 10^{-3}$$

  - δZ_H Higgs wave function correction -> universal but small
  - C_1 process and kinematic dependent
    - If κ_3 small -> C_1 dominant sensitivity



Channels	ggF	VBF	ZH	WH	$t\bar{t}H$	tHj	$H \to 4\ell$
$C_1(\%)$	0.66	0.63	1.19	1.03	3.52	0.91	0.82

➥ **Possible to put limits on Higgs self-coupling**

[Maltoni, Pagani, Shivaji, Zhao, 1709:08649] and F. Tackmann

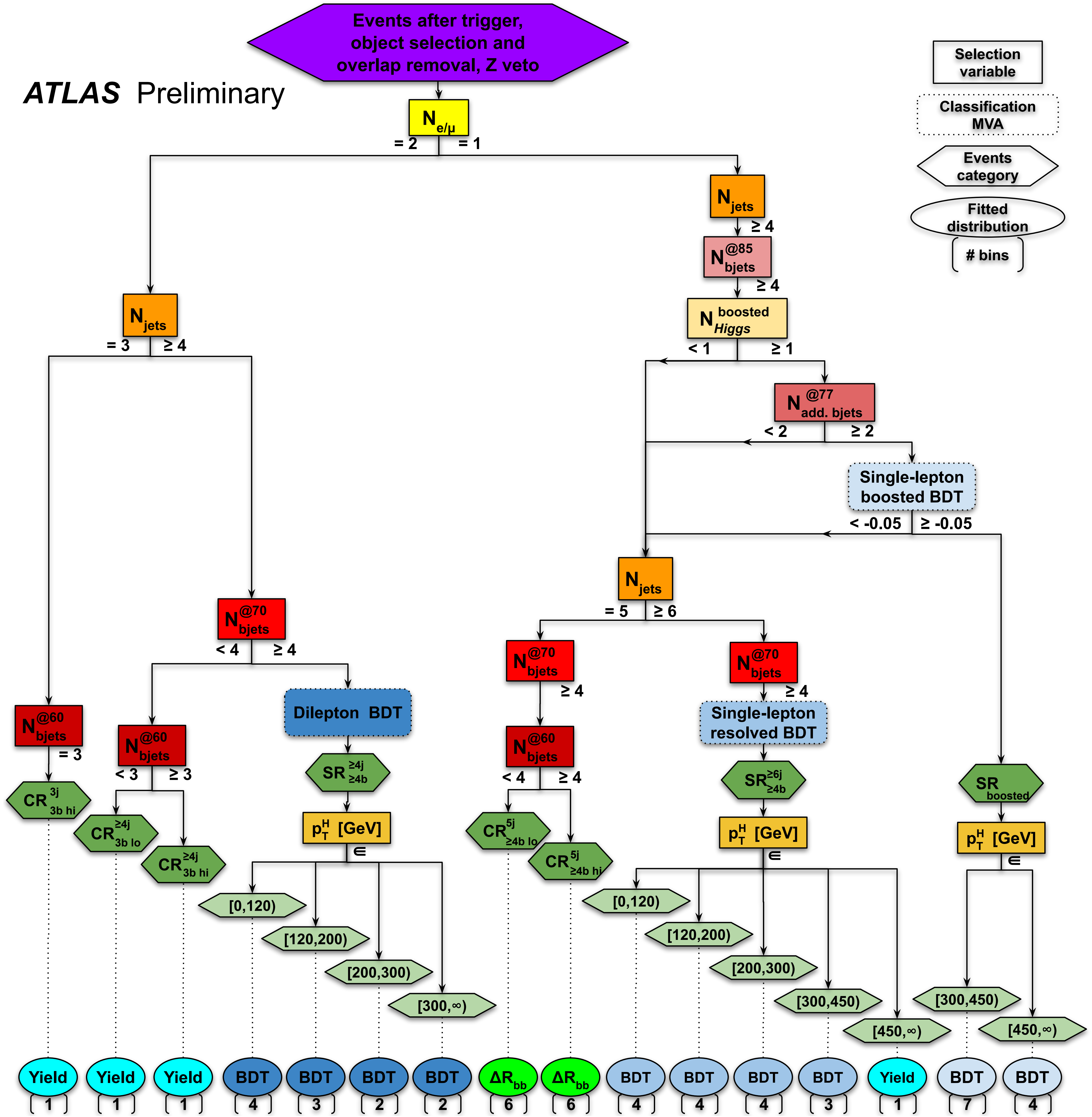
Analysis Region Definition

ATLAS-CONF-2020-058

<table>
<tr><th rowspan="2" colspan="2">Region</th><th colspan="4">Dilepton</th><th colspan="4">Single-lepton</th></tr>
<tr><th>$SR^{\geq 4j}_{\geq 4b}$</th><th>$CR^{\geq 4j}_{3b\ hi}$</th><th>$CR^{\geq 4j}_{3b\ lo}$</th><th>$CR^{3j}_{3b\ hi}$</th><th>$SR^{\geq 6j}_{\geq 4b}$</th><th>$CR^{5j}_{\geq 4b\ hi}$</th><th>$CR^{5j}_{\geq 4b\ lo}$</th><th>$SR_{boosted}$</th></tr>
<tr><td colspan="2">#leptons</td><td colspan="4">$= 2$</td><td colspan="4">$= 1$</td></tr>
<tr><td colspan="2">#jets</td><td colspan="3">≥ 4</td><td>$= 3$</td><td>≥ 6</td><td colspan="2">$= 5$</td><td>≥ 4</td></tr>
<tr><td rowspan="4">#b-tag</td><td>@85%</td><td colspan="4">–</td><td colspan="4">≥ 4</td></tr>
<tr><td>@77%</td><td colspan="4">–</td><td colspan="3">–</td><td>$\geq 2^{\dagger}$</td></tr>
<tr><td>@70%</td><td>≥ 4</td><td colspan="3">$= 3$</td><td colspan="3">≥ 4</td><td>–</td></tr>
<tr><td>@60%</td><td>–</td><td>$= 3$</td><td>< 3</td><td>$= 3$</td><td>–</td><td>≥ 4</td><td>< 4</td><td>–</td></tr>
<tr><td colspan="2">#boosted cand.</td><td colspan="4">–</td><td colspan="3">0</td><td>≥ 1</td></tr>
<tr><td colspan="2">Fit input</td><td>BDT</td><td colspan="3">Yield</td><td>BDT/Yield</td><td colspan="2">ΔR^{avg}_{bb}</td><td>BDT</td></tr>
</table>

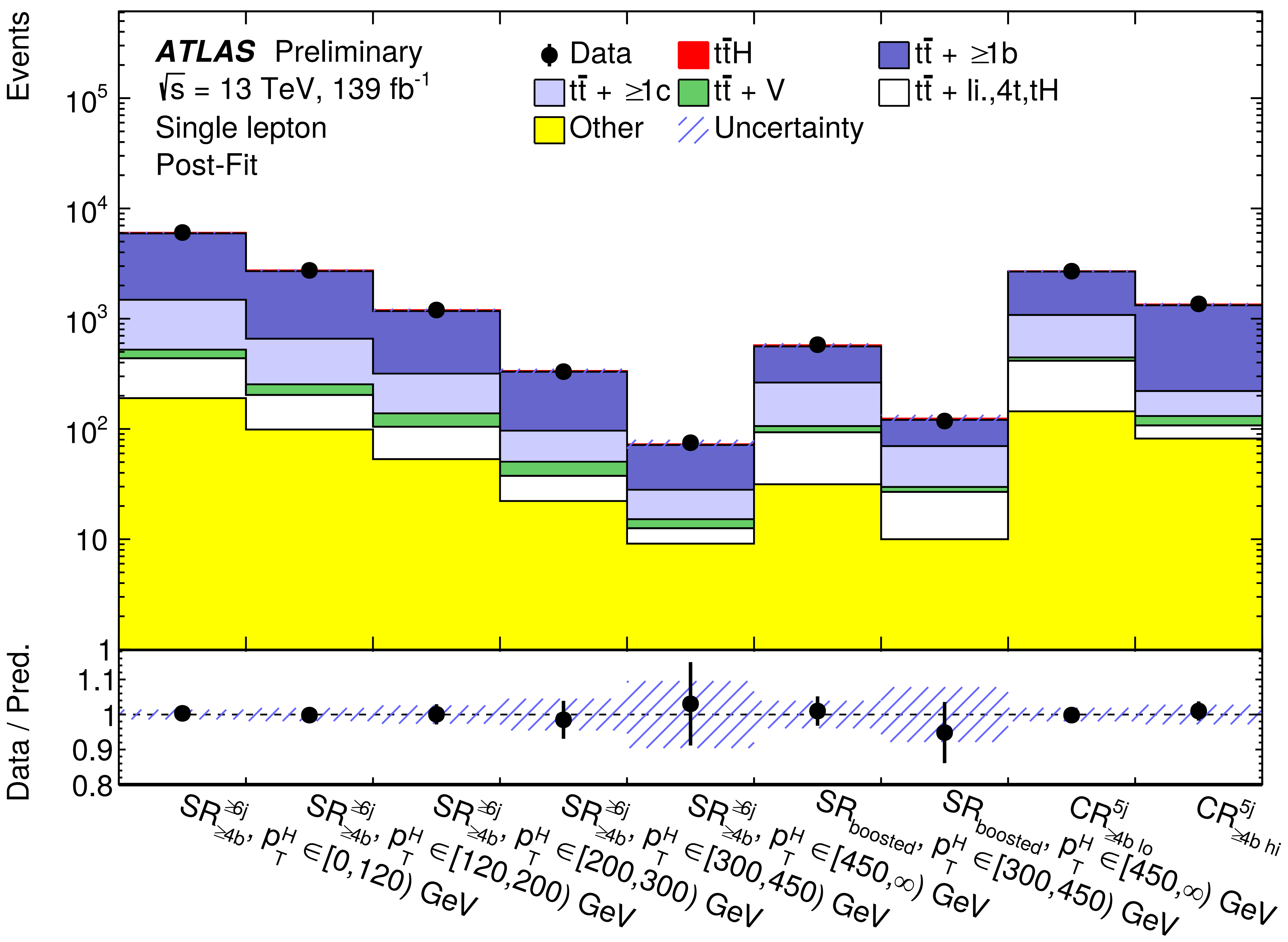
Region Definition

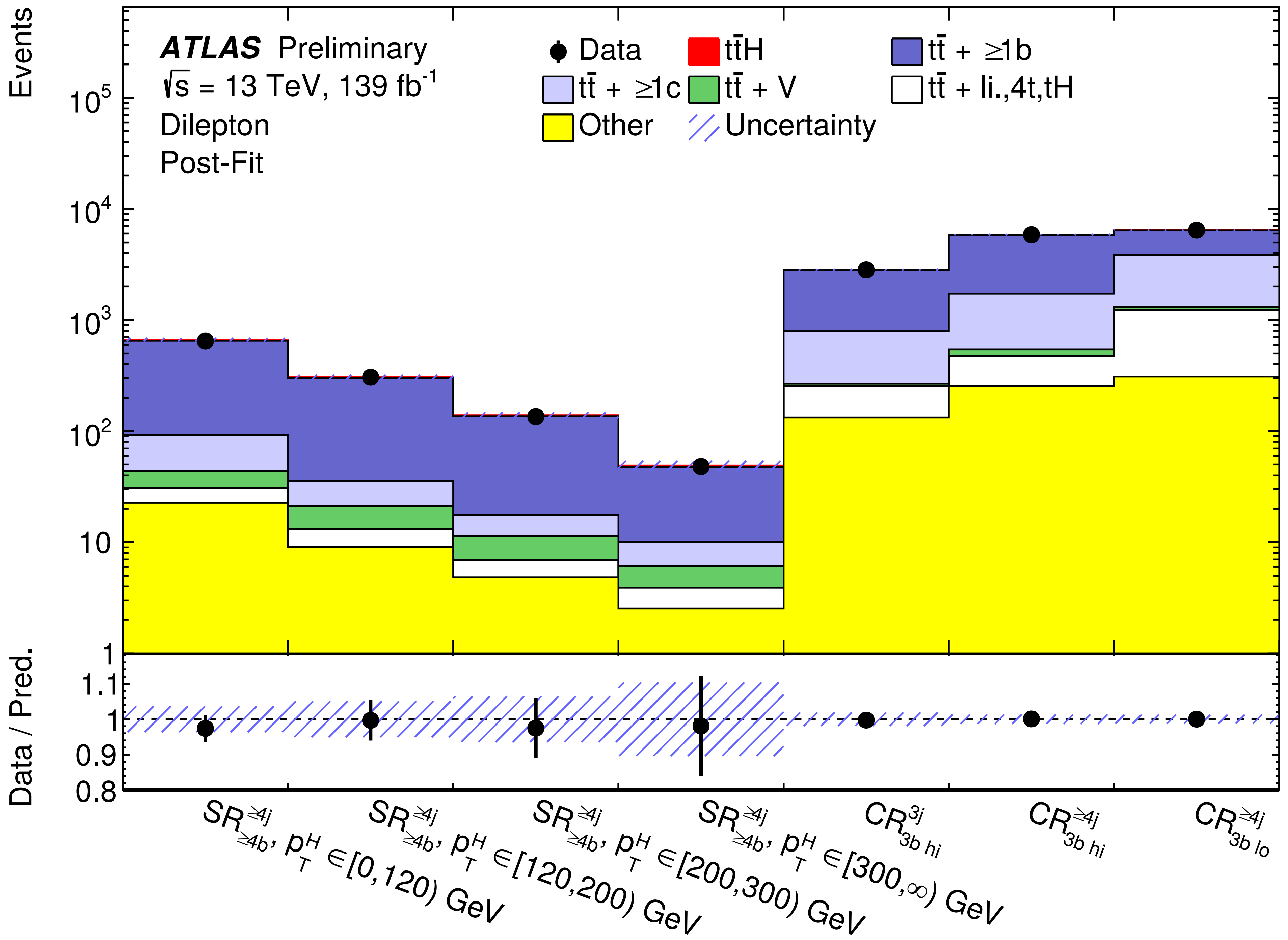
ATLAS-CONF-2020-058



Results - Postfit Modelling

ATLAS-CONF-2020-058





Results - Postfit Modelling - Dilepton SRs

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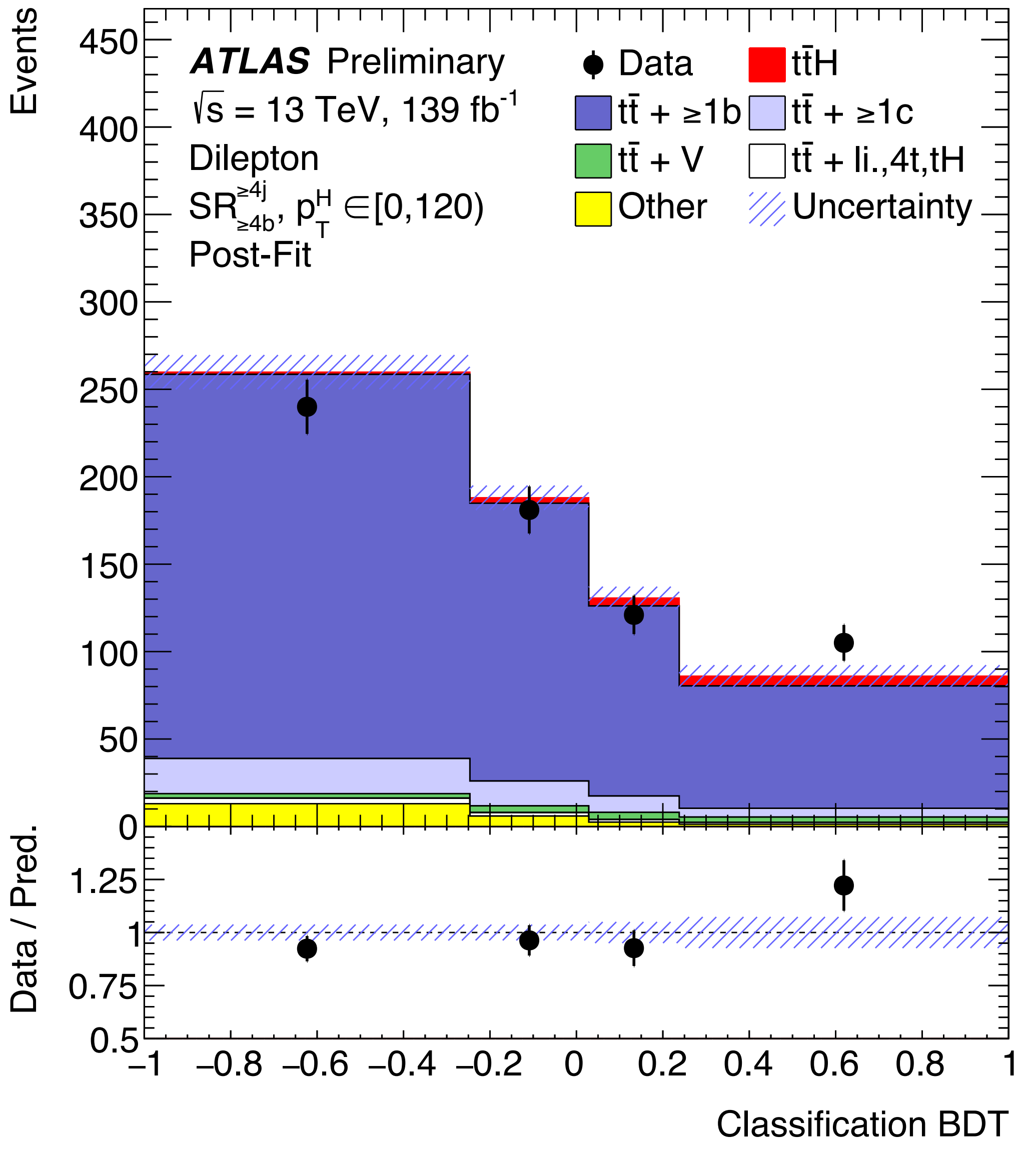
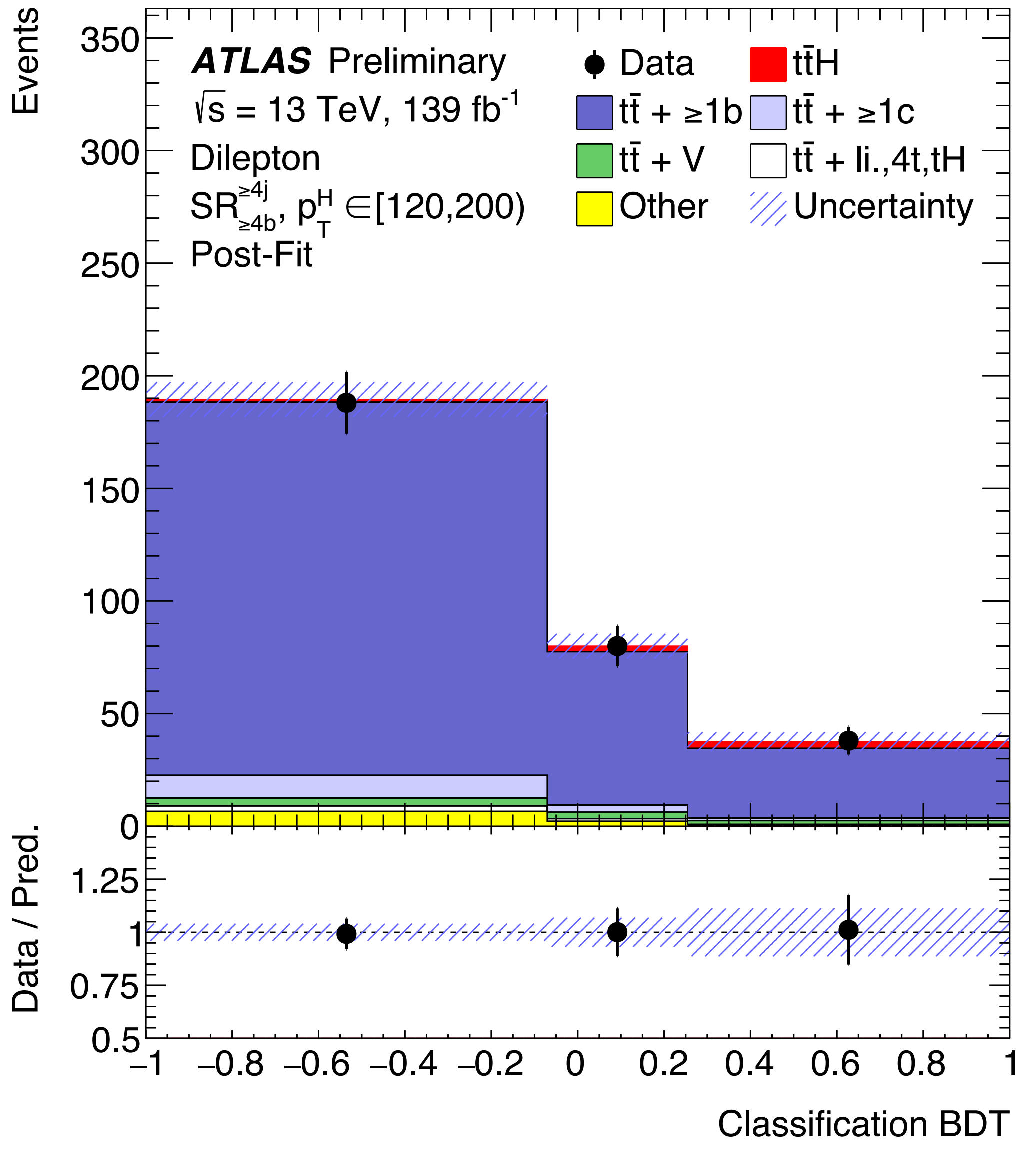
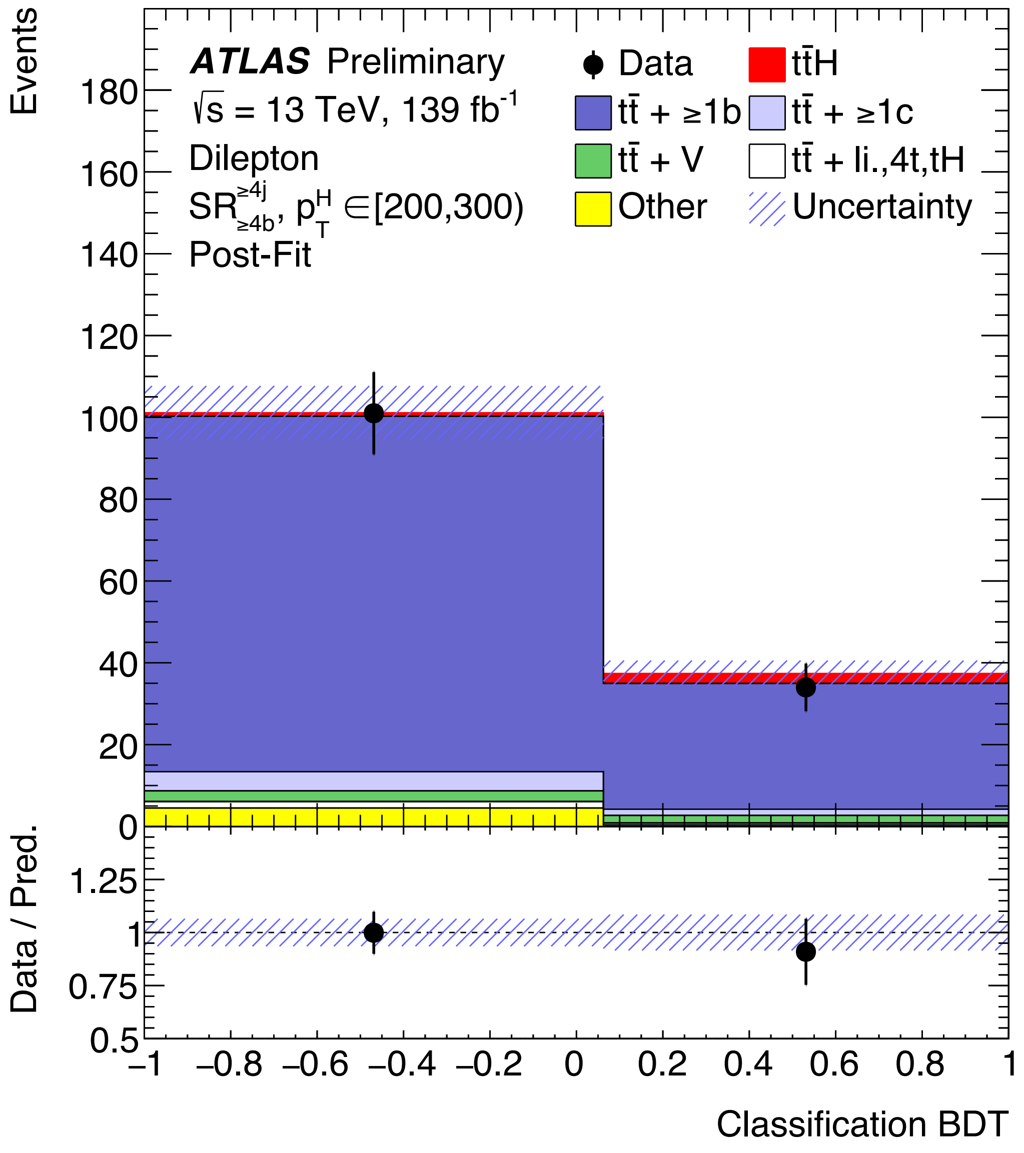
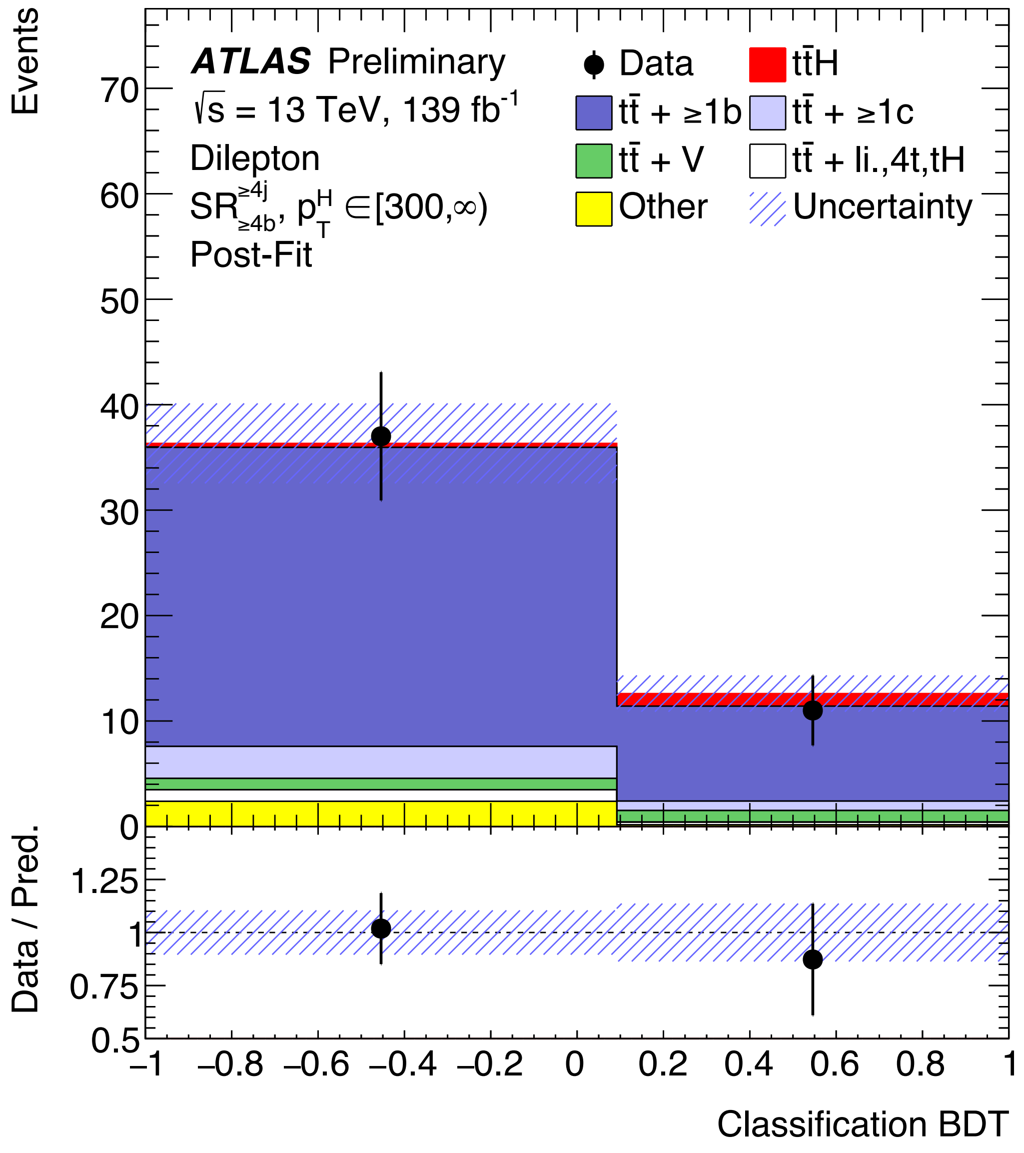


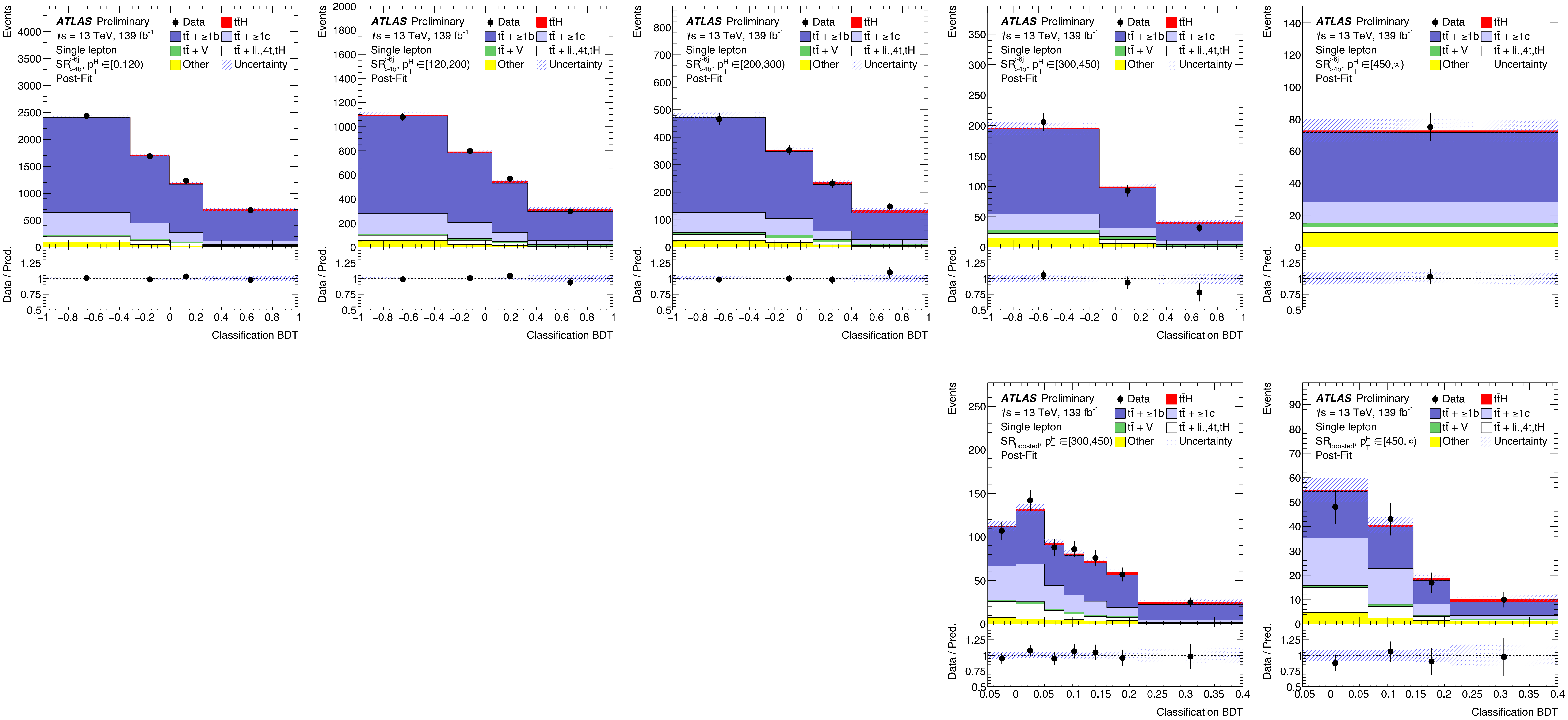






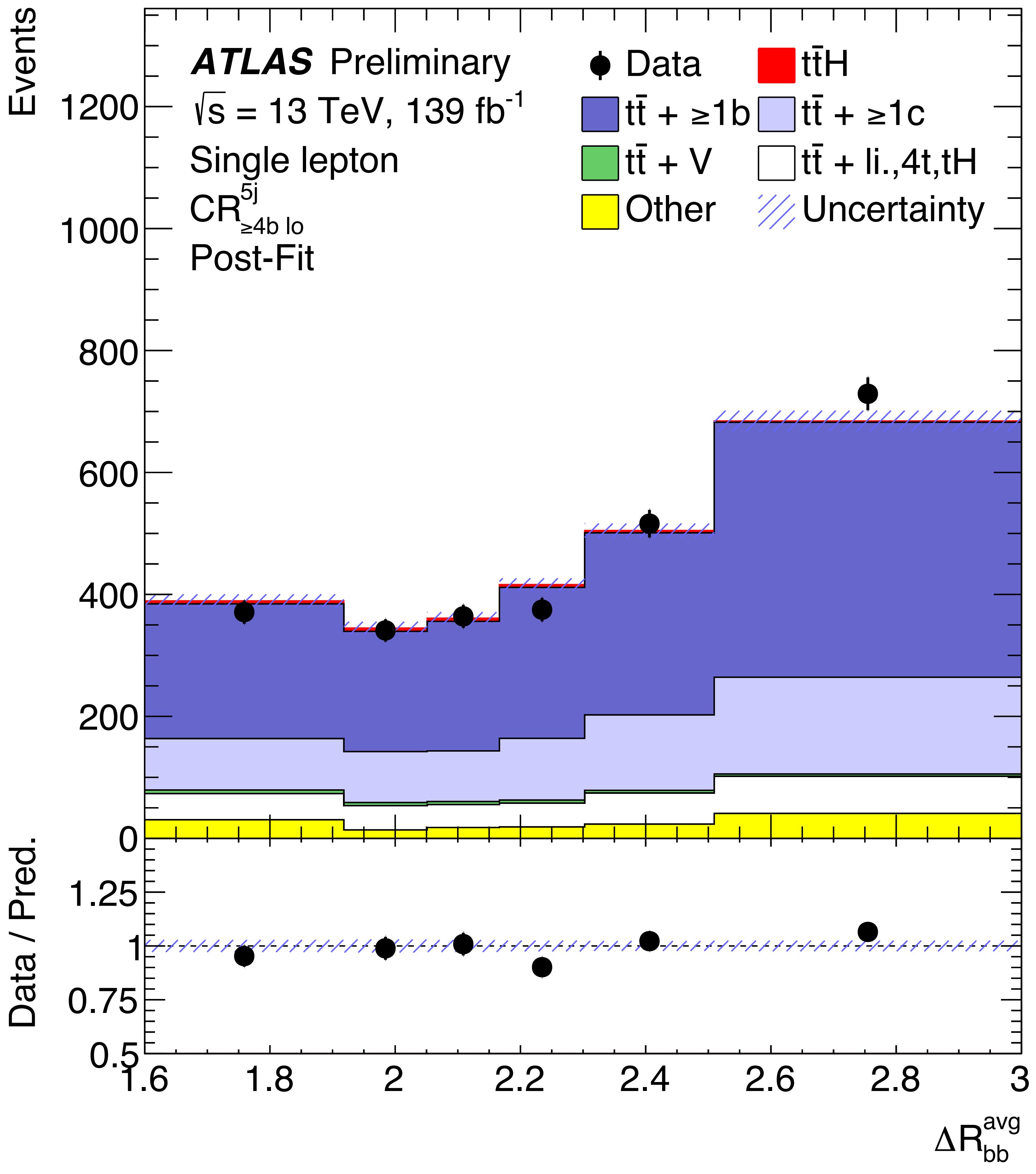
Results - Postfit Modelling - l+jets SRs

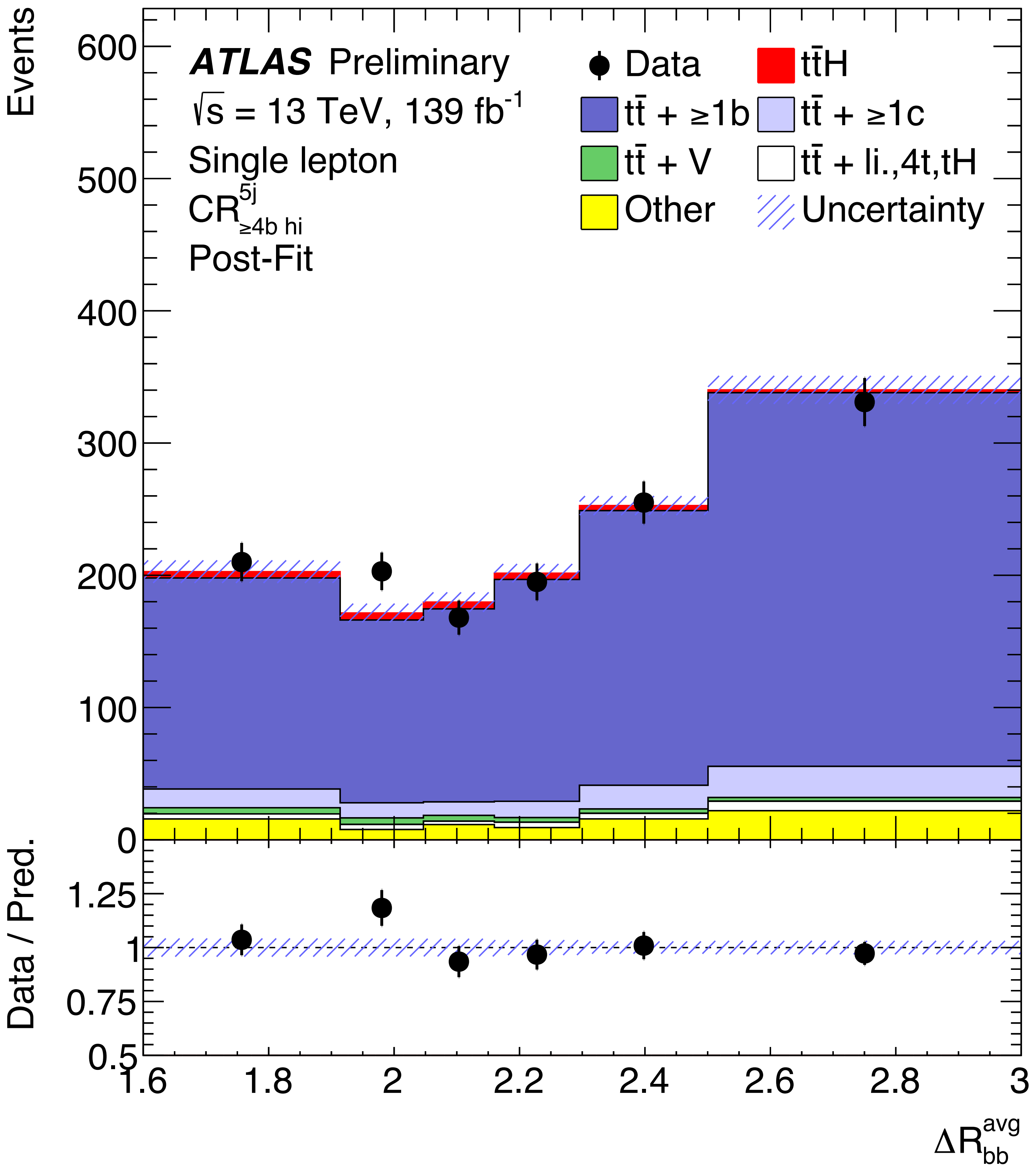
ATLAS-CONF-2020-058



Results - Postfit Modelling - l+jets CRs

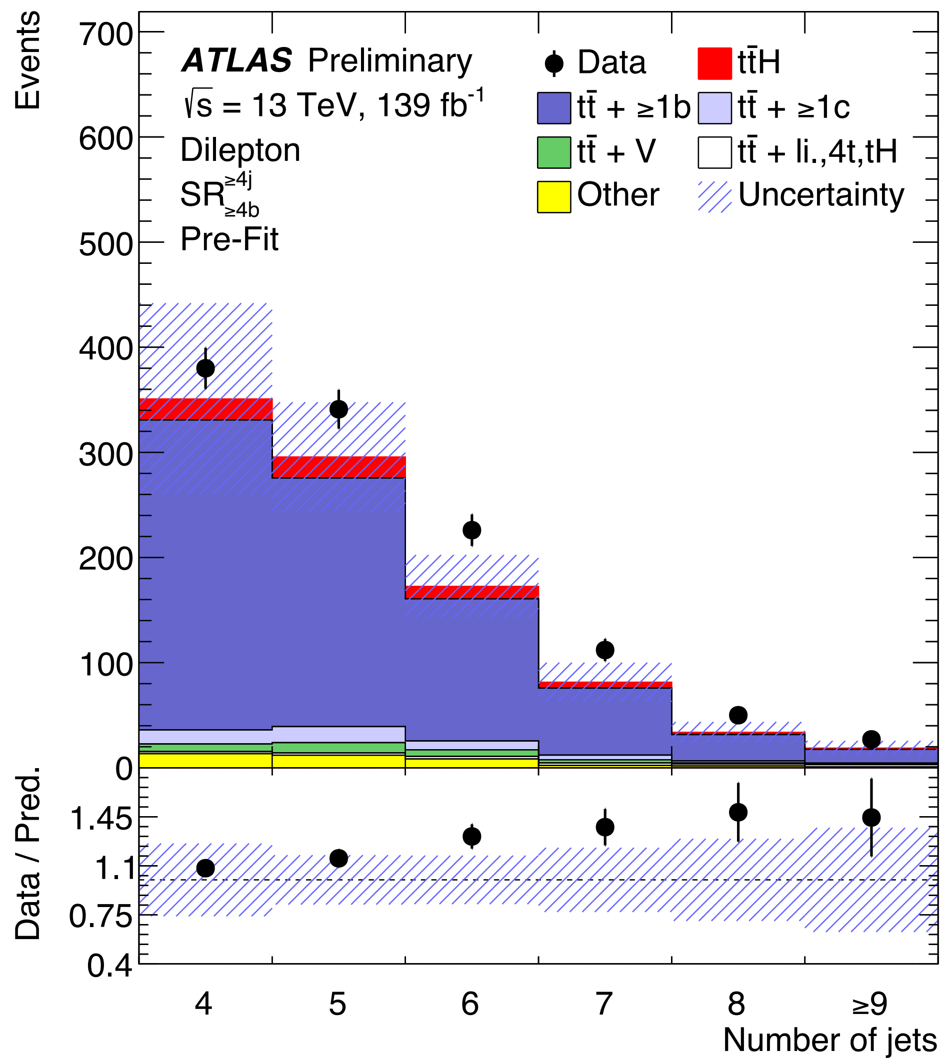
ATLAS-CONF-2020-058

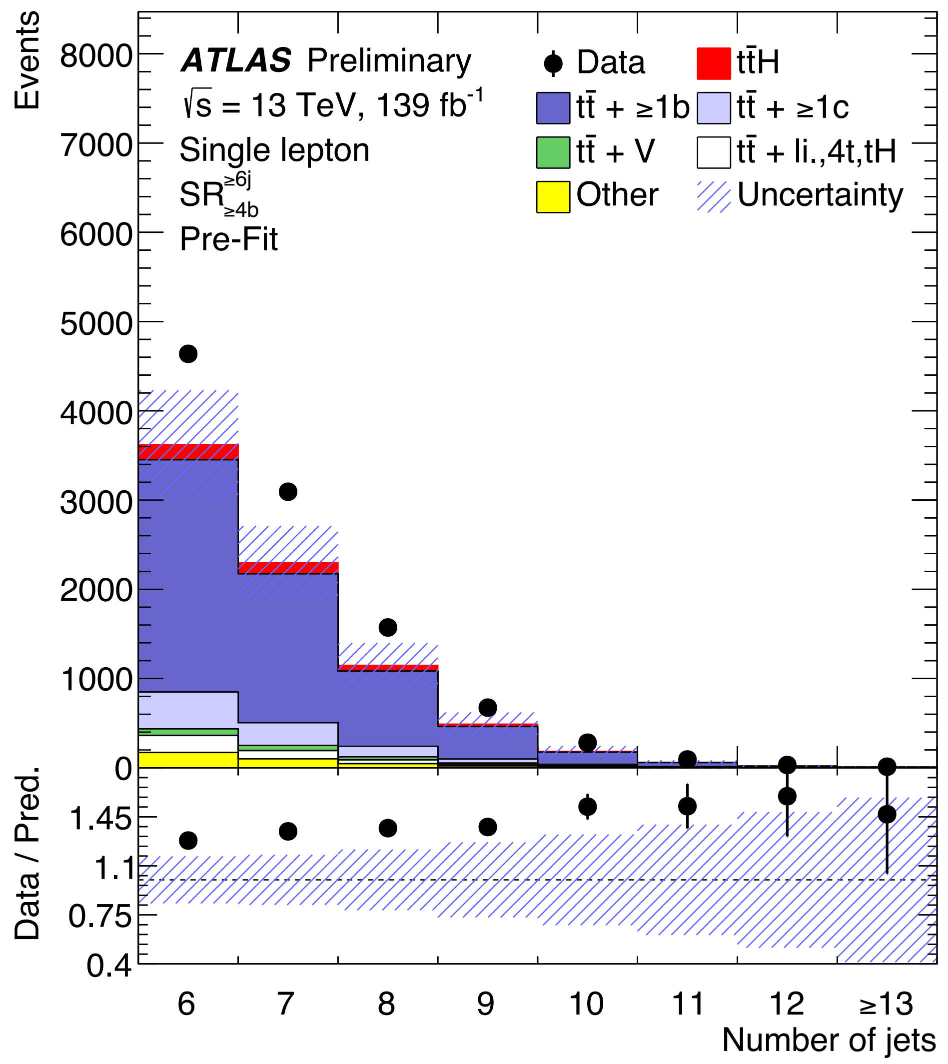


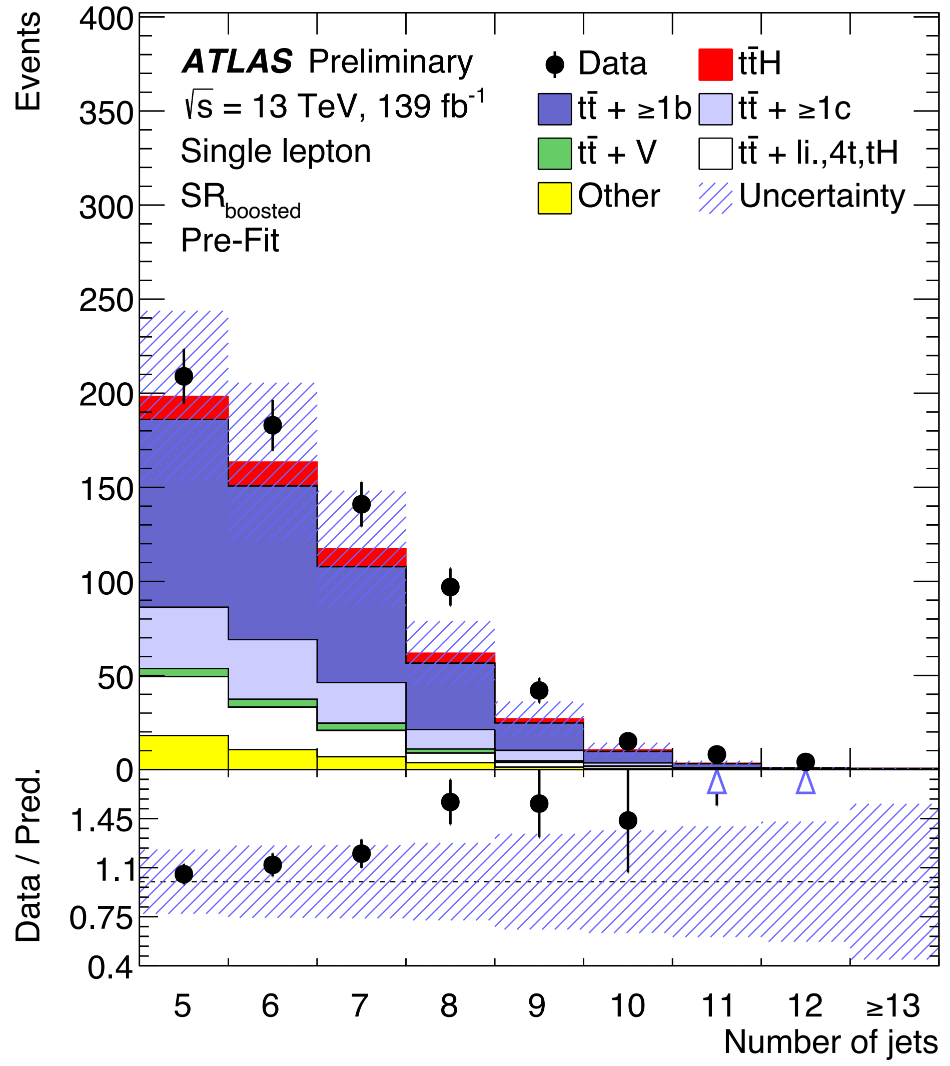


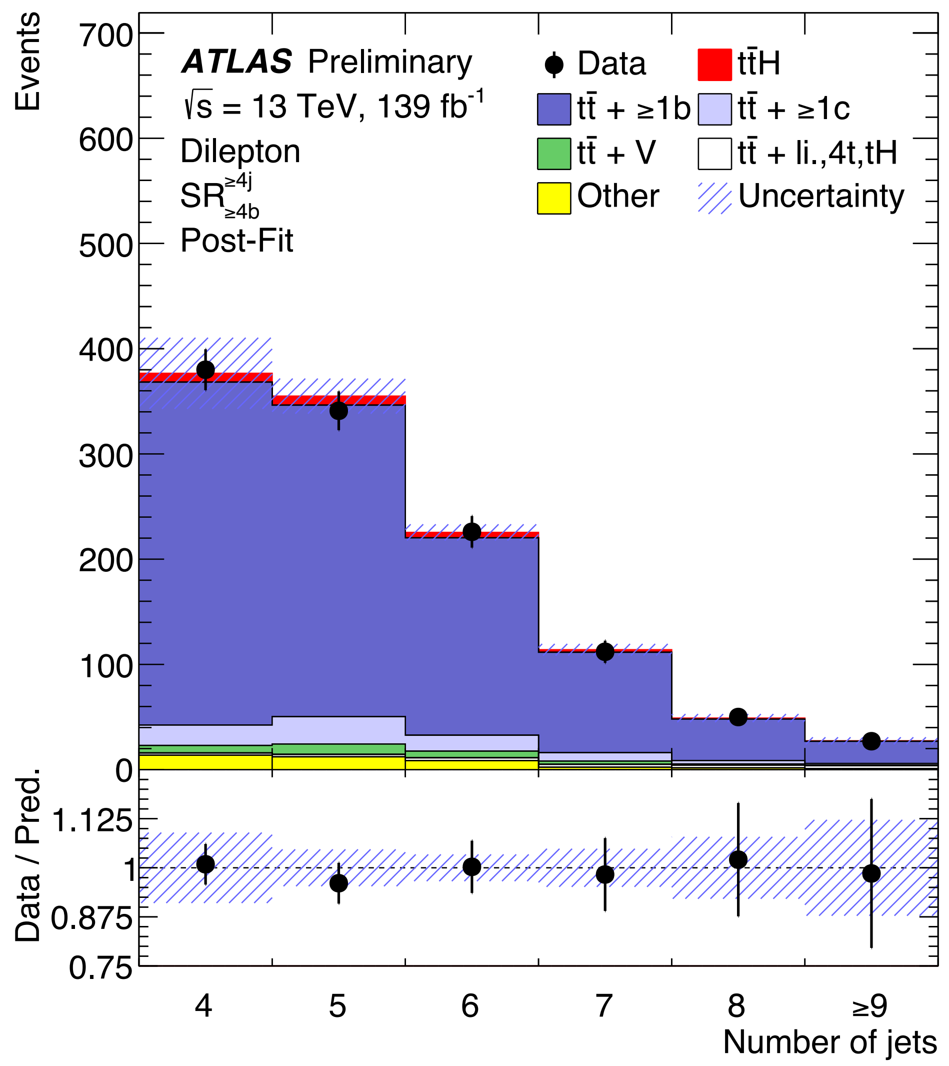
Results - Postfit Modelling - Njet

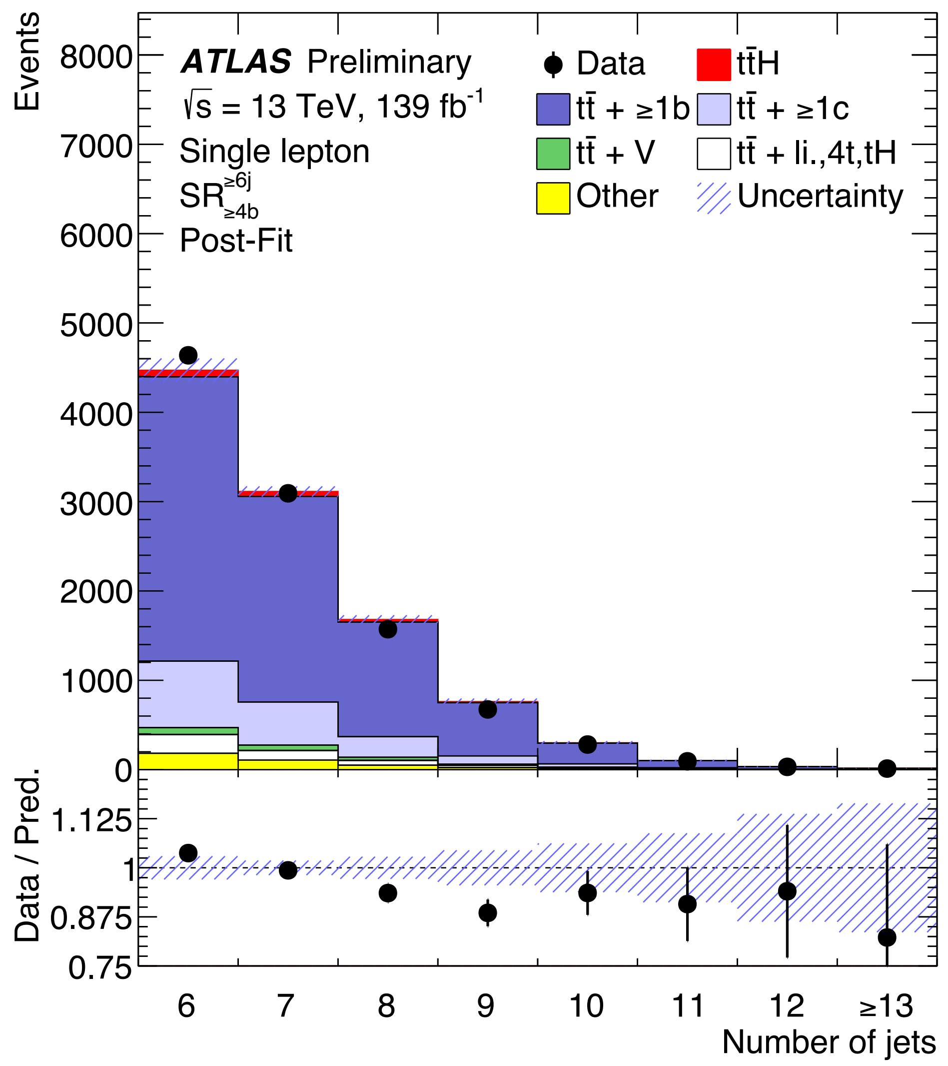
ATLAS-CONF-2020-058

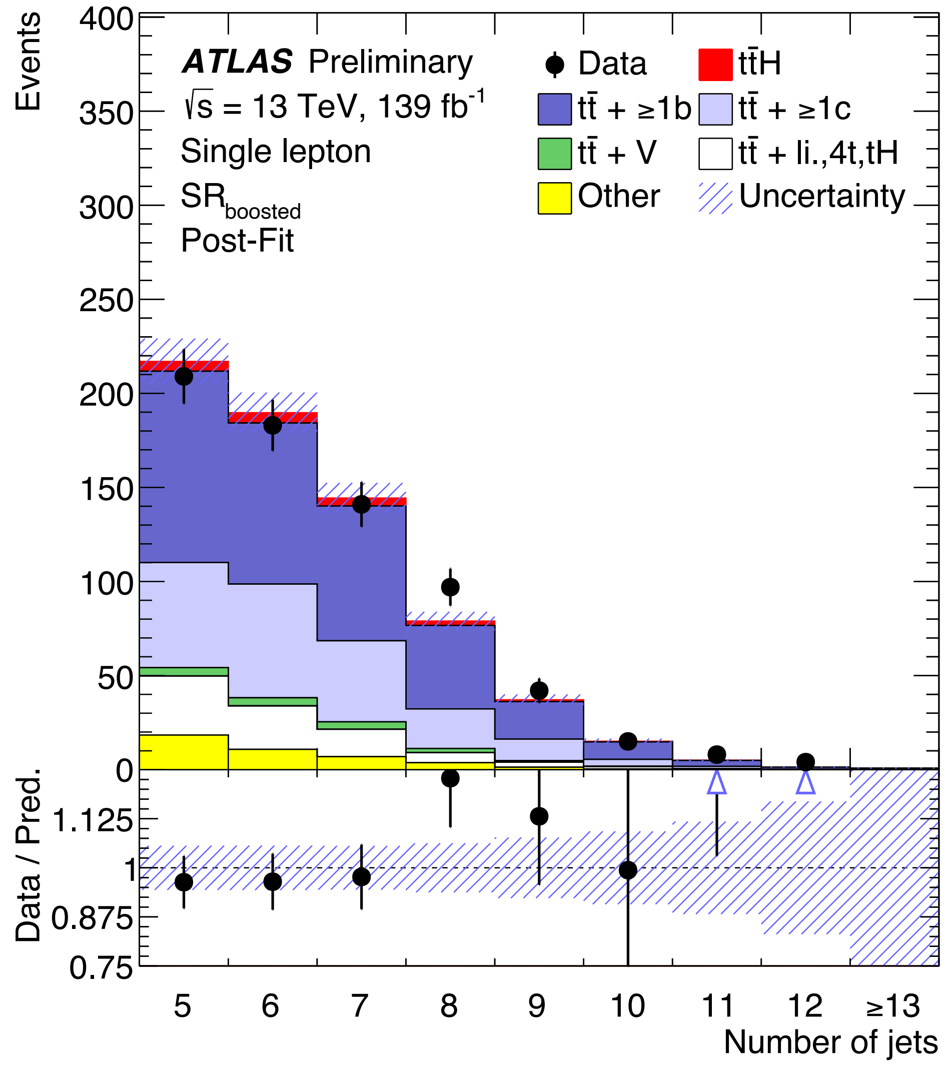






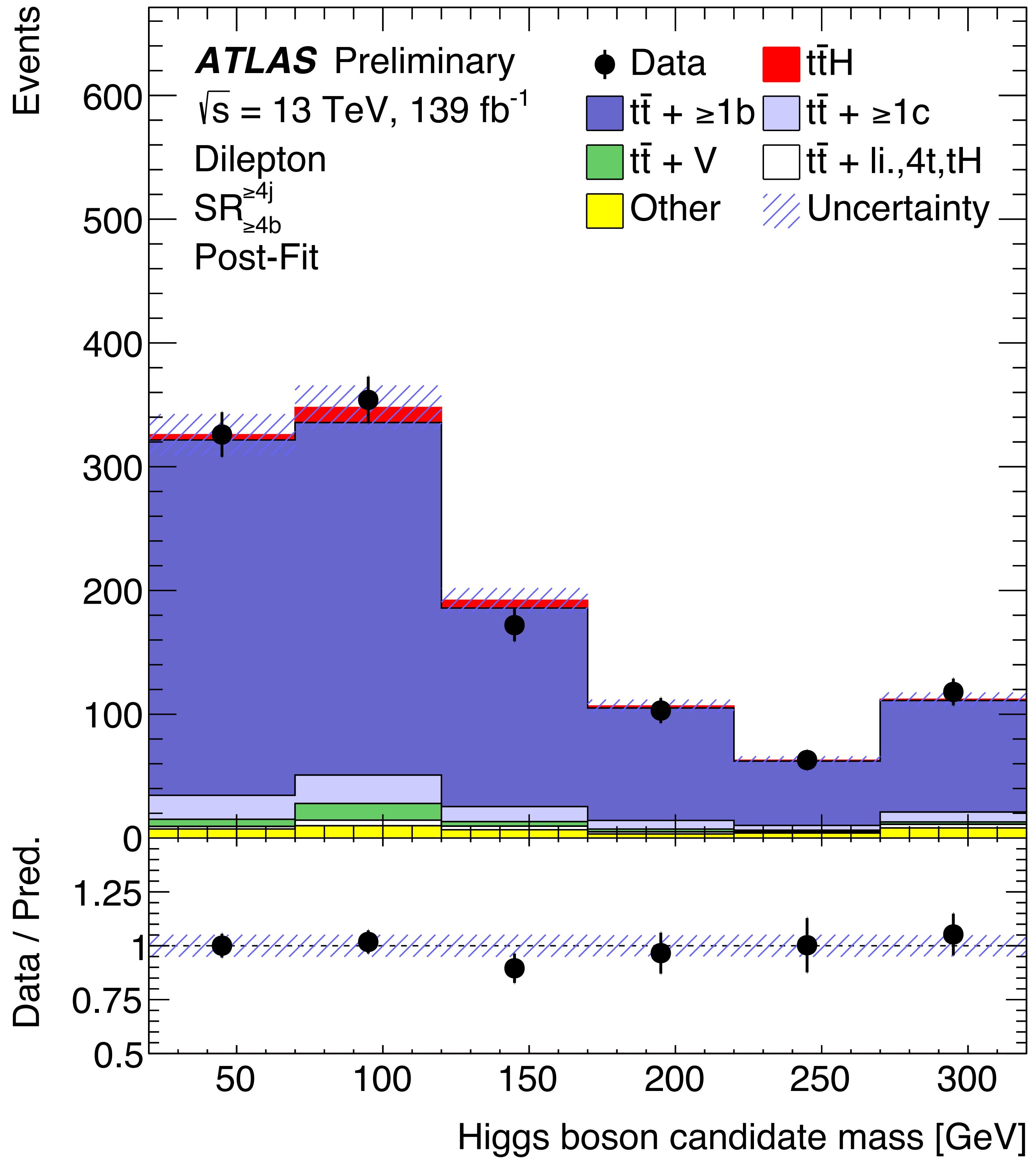


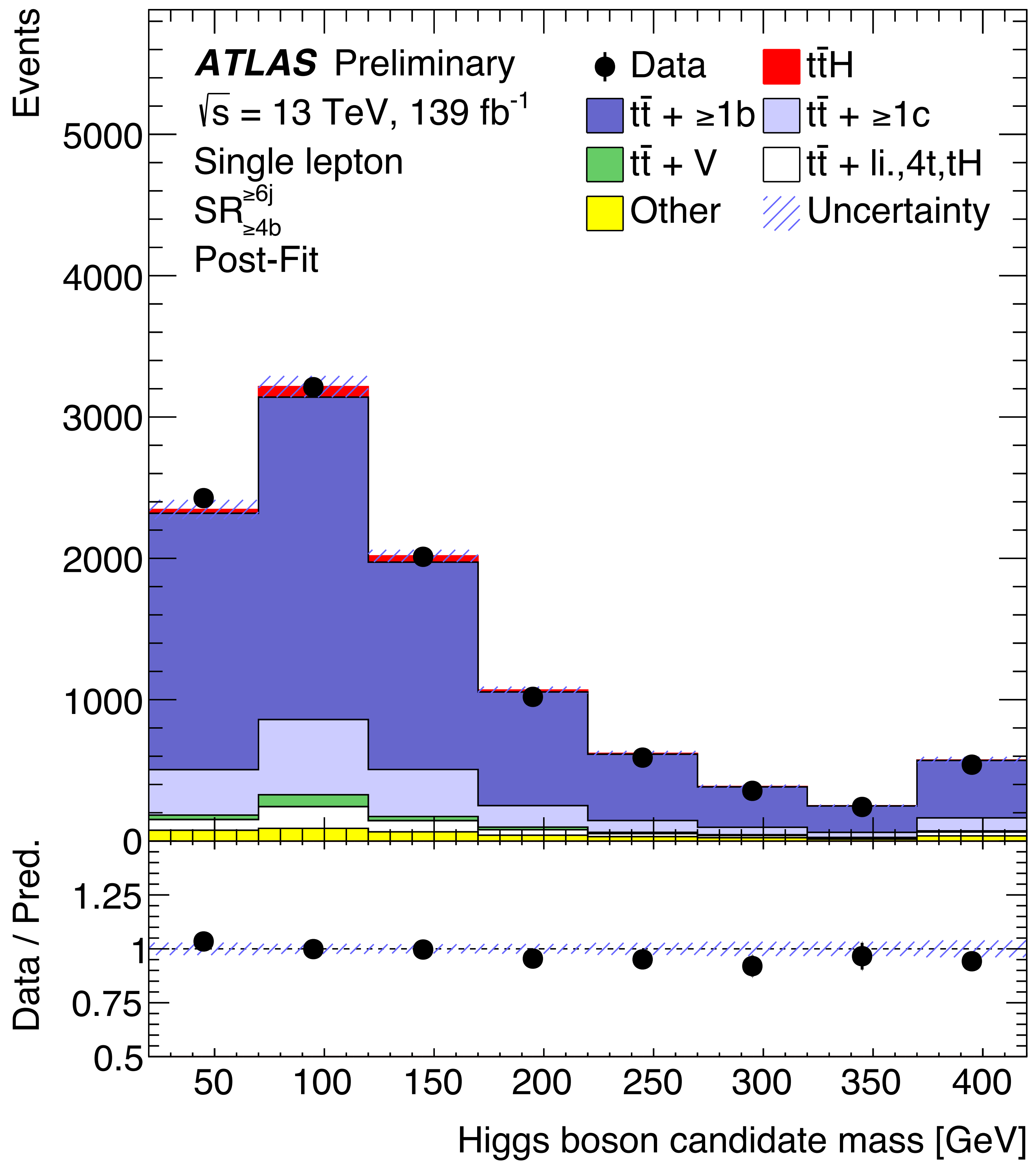


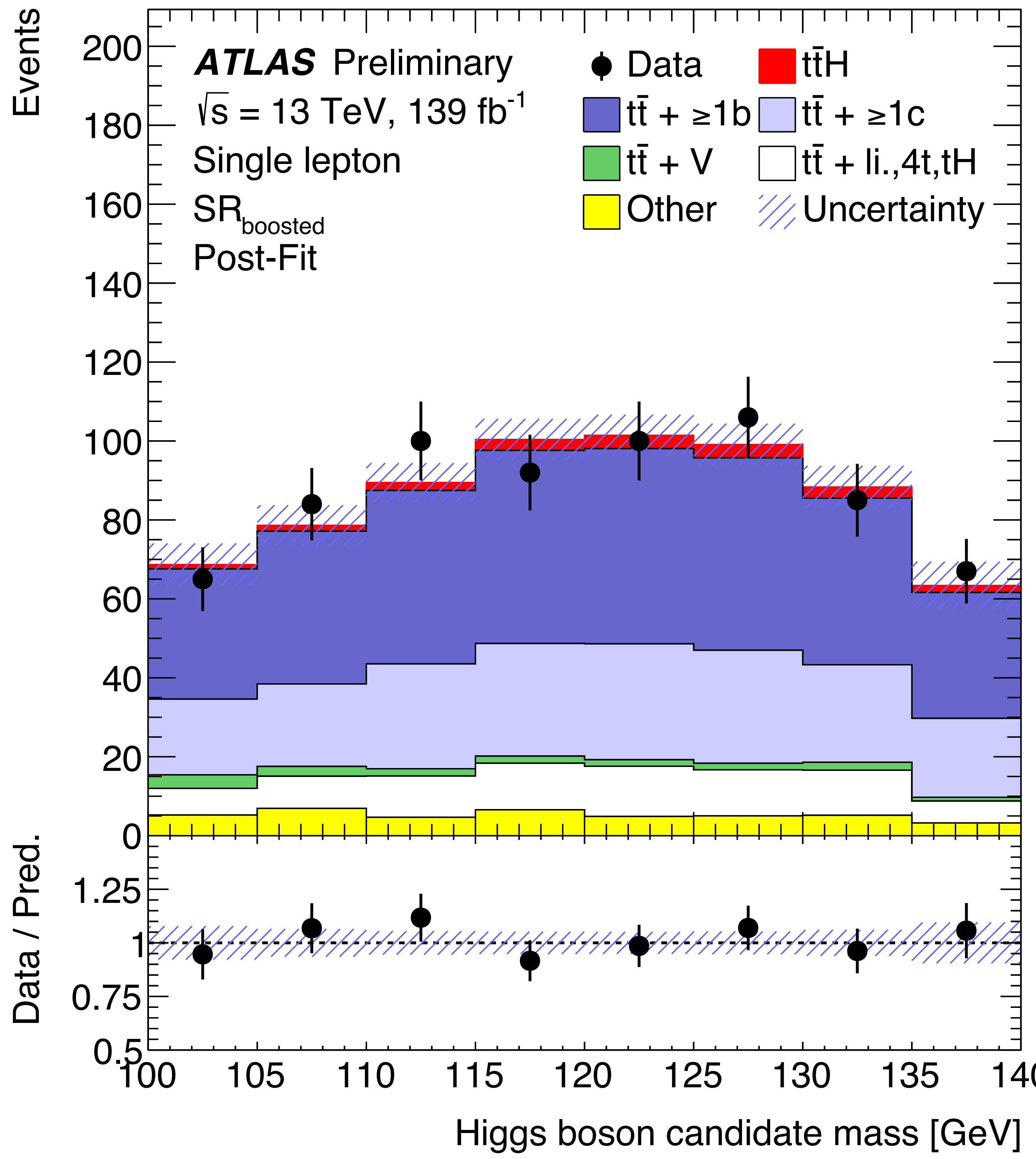


Results - Postfit Modelling - m(H)

ATLAS-CONF-2020-058

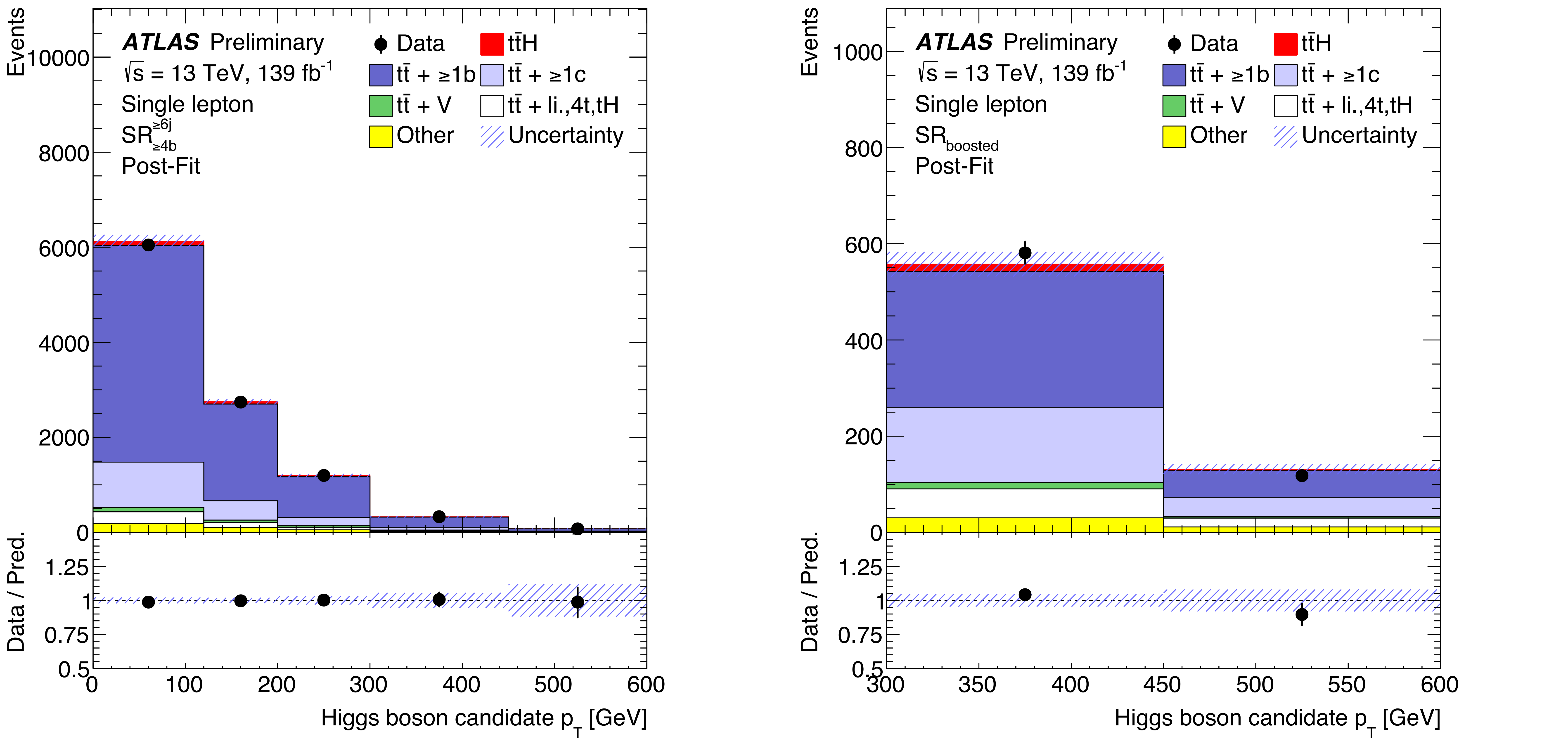






Results - Postfit Modelling

ATLAS-CONF-2020-058



Results

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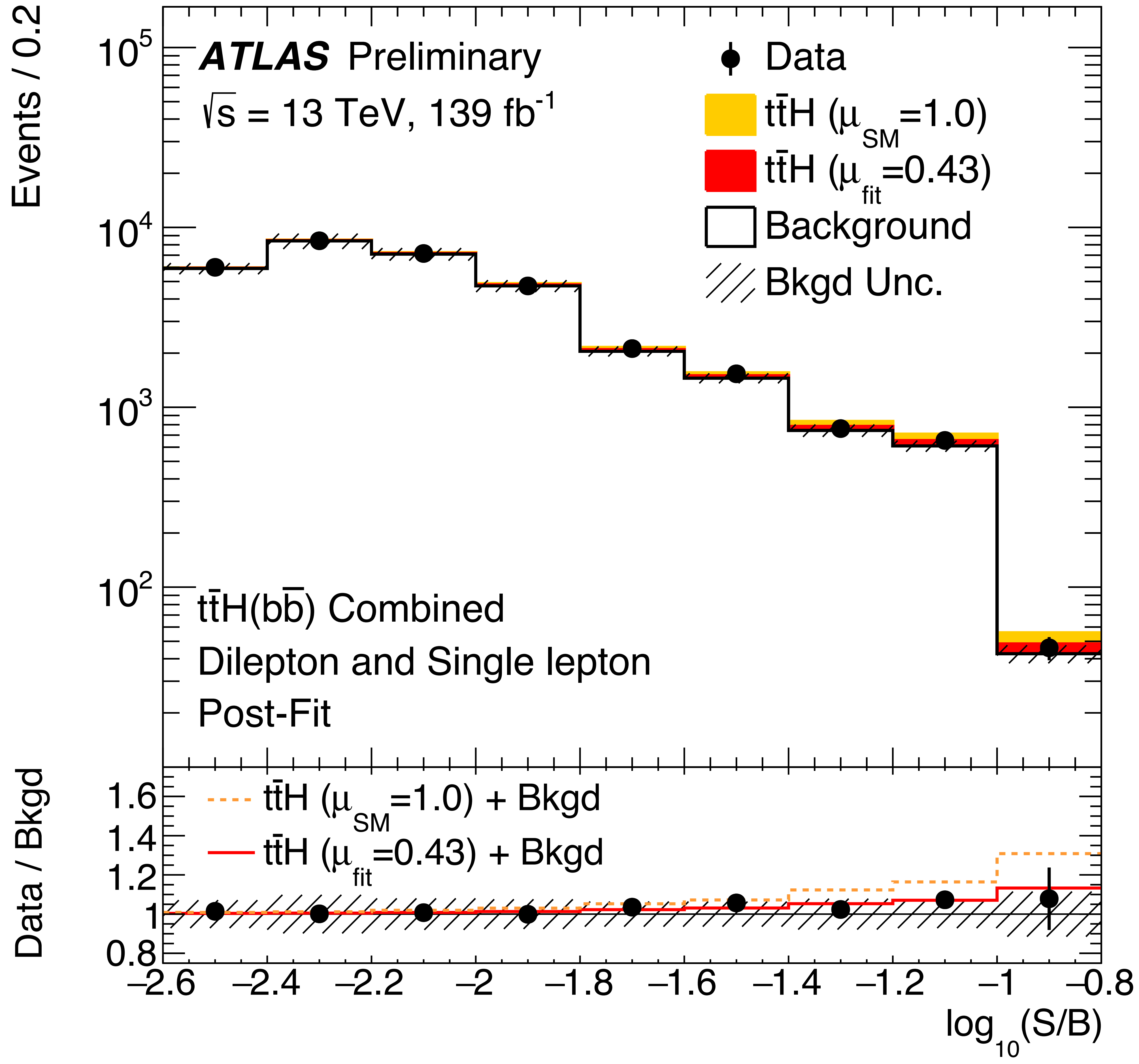

- Final-discriminant bins in all analysis regions combined into bins of log(S/B)
- **Signal normalised to SM prediction** used for calculation of S/B
- **Signal normalised to best-fit value** also shown
- Lower pad shows ratio data/background, ttH(μ_{SM}=1.0)/background and ttH(μ_{fit}=0.43)/background

Results - STXS Rankings

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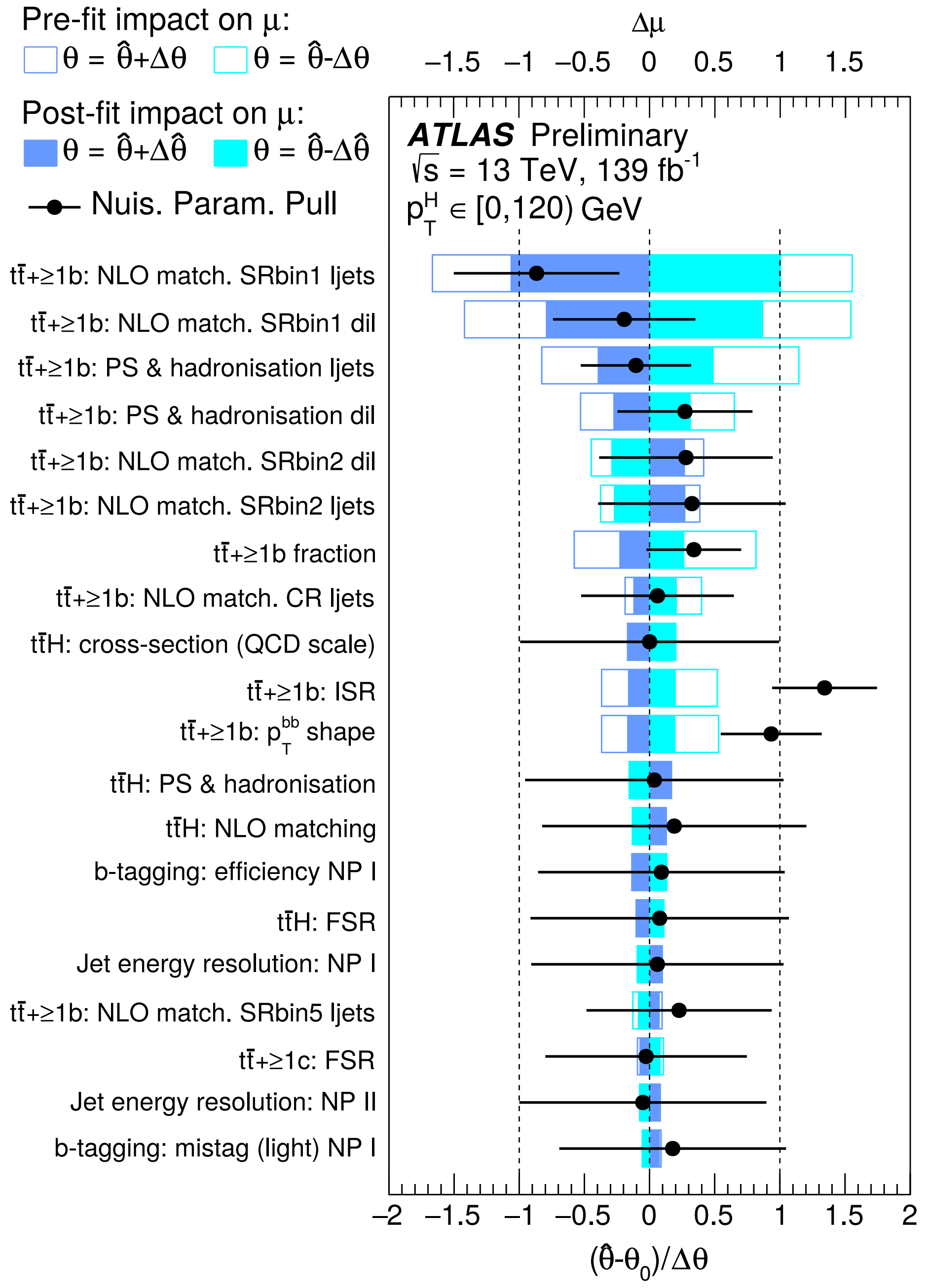

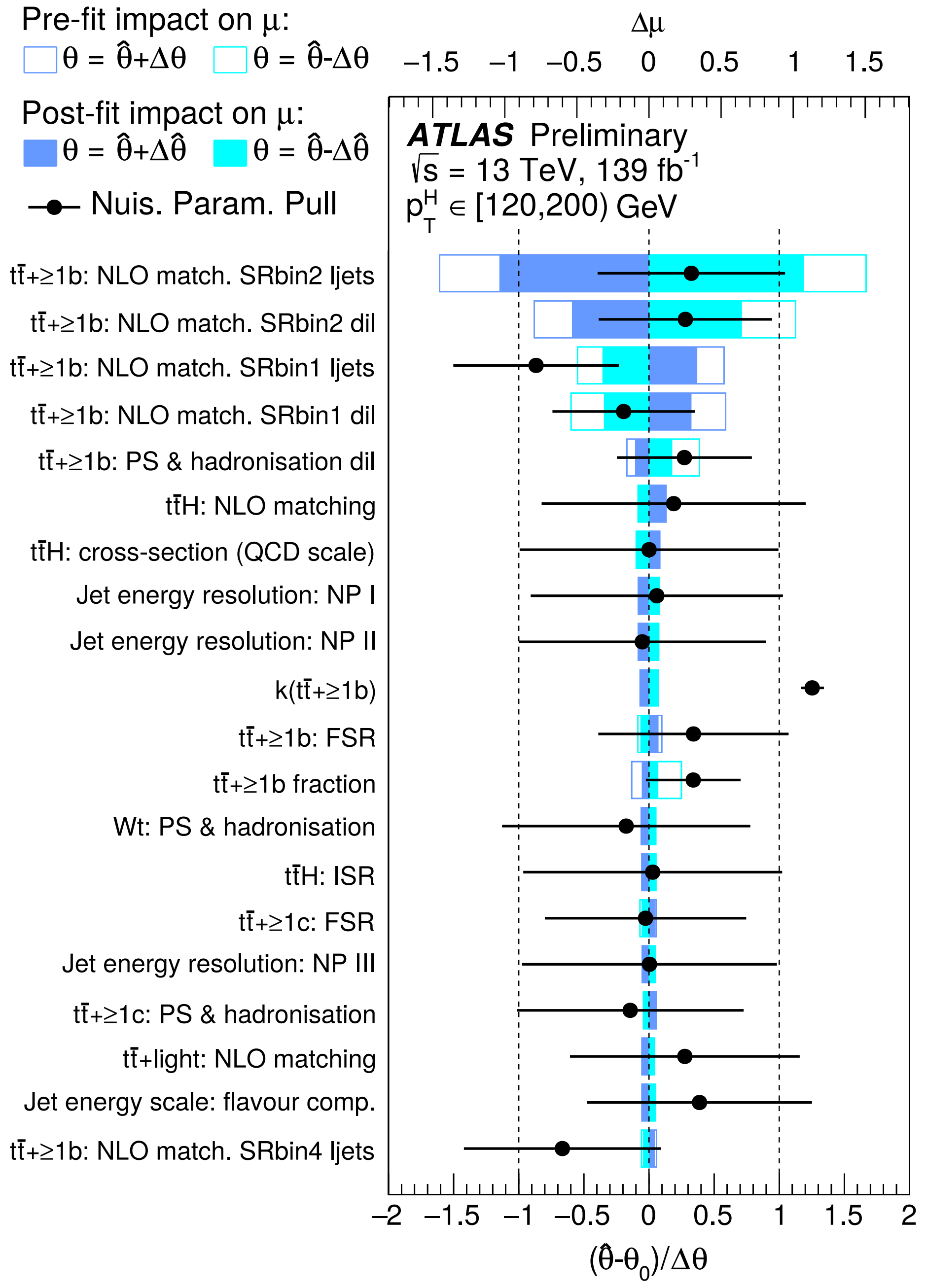

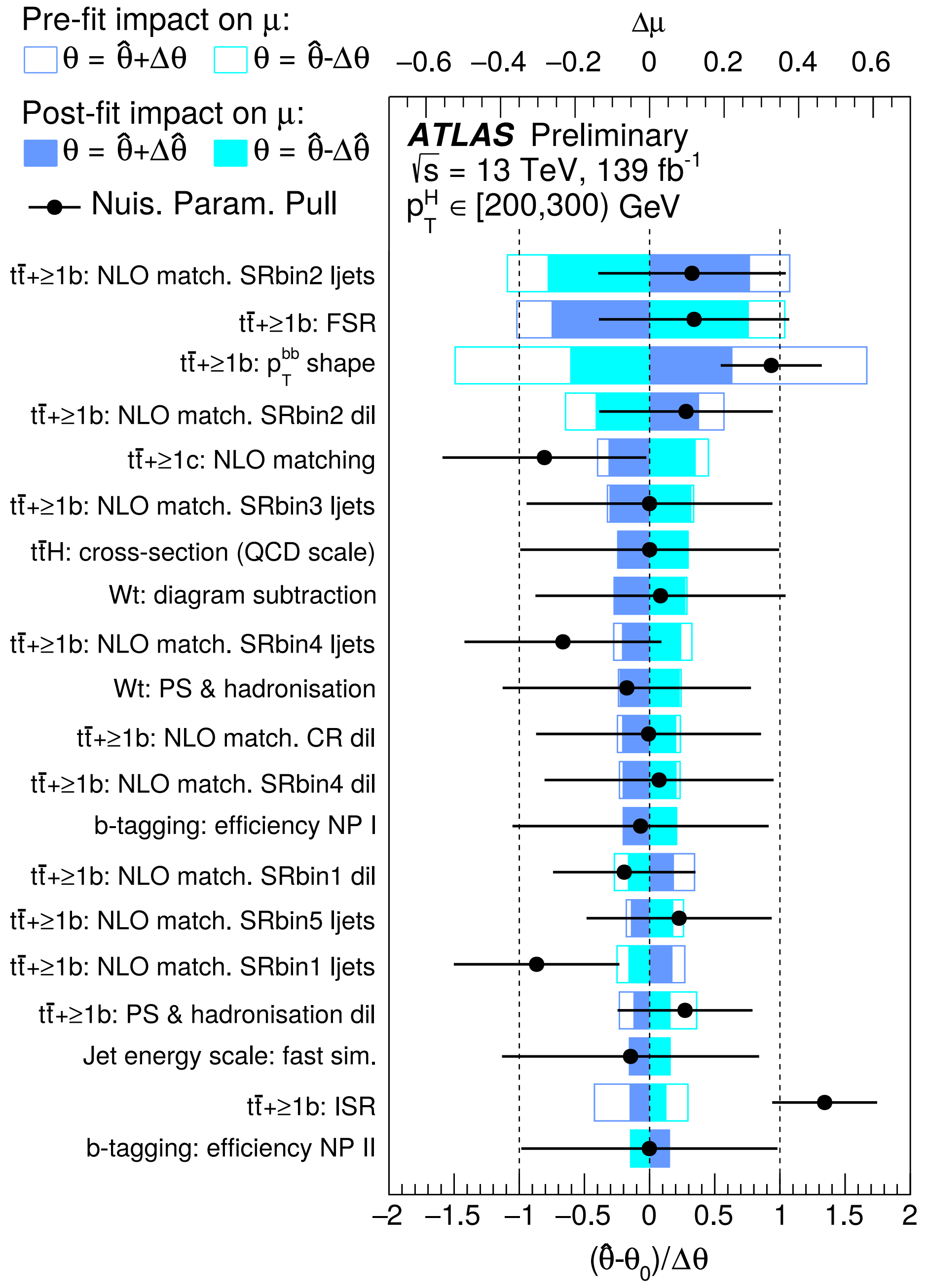

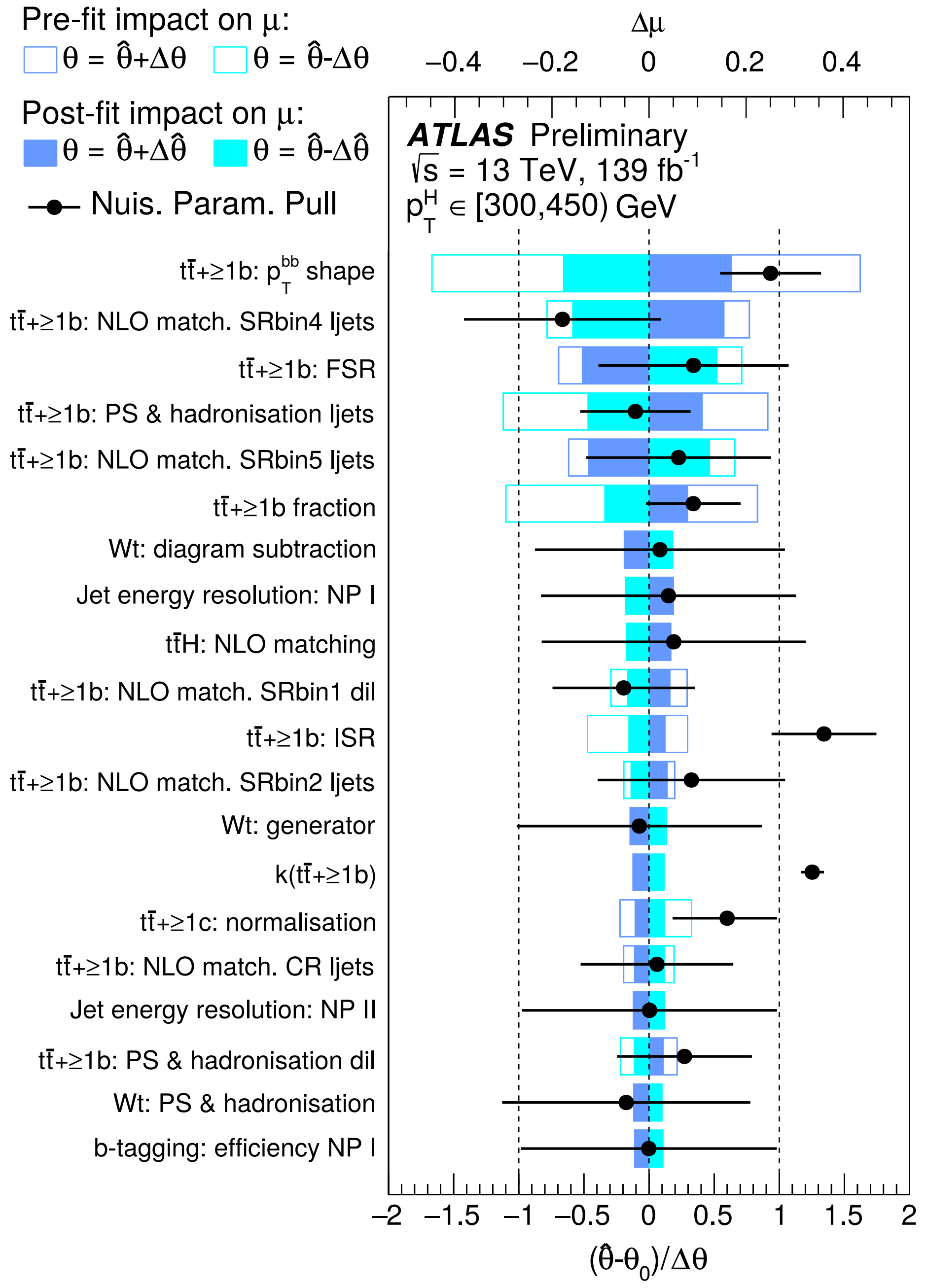

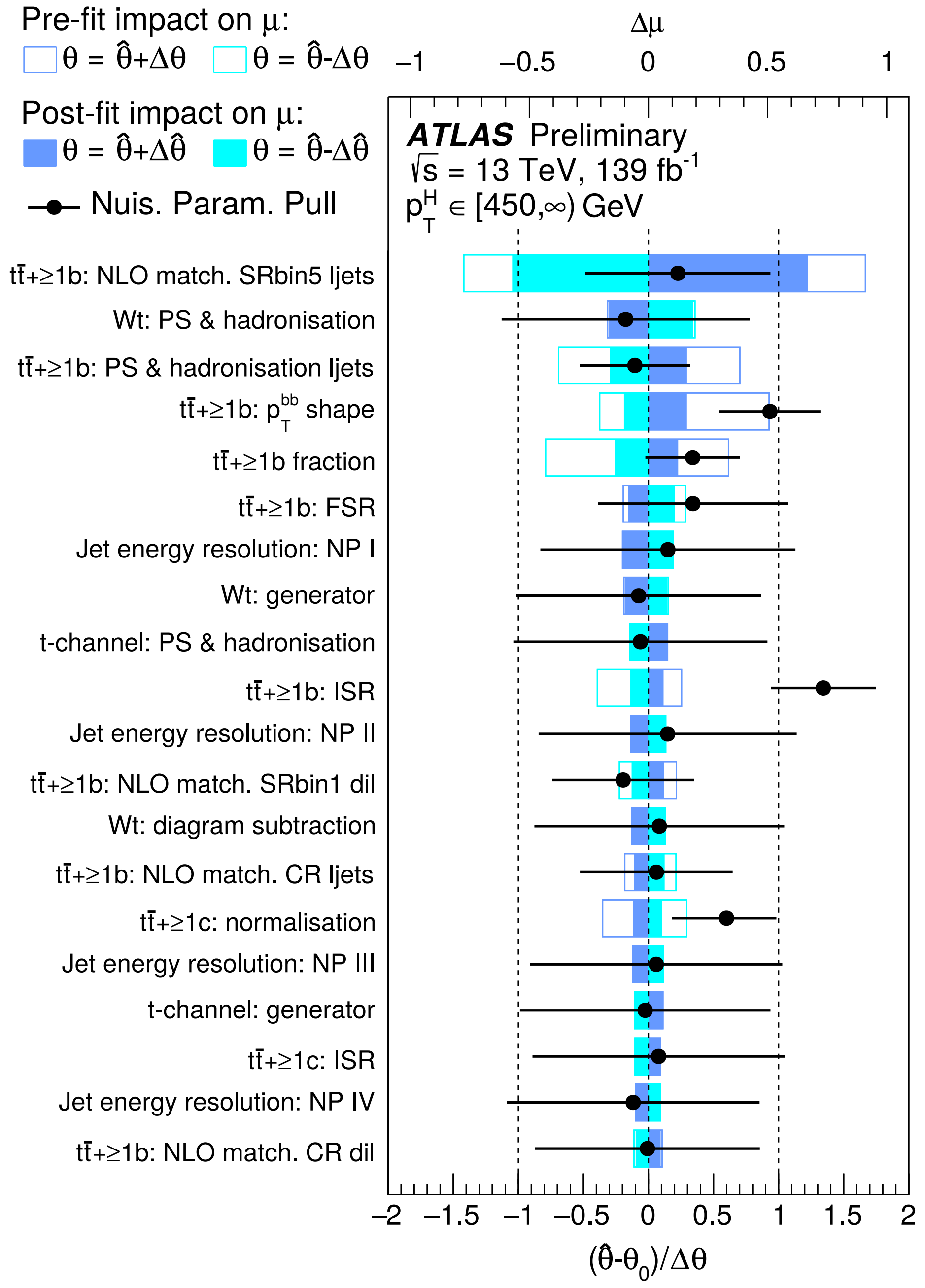

ttbb Modelling

Process	Generator	ME order	Parton shower	PDF	Tune
$t\bar{t}$	PowHeg v2	NLO	Pythia 8	5FS NNPDF3.0 NLO	A14
$t\bar{t}+b\bar{b}$	Powheg-Box-Res	NLO	Pythia 8	4FS NNPDF30_nlo_as_0118_nf_4	A14
$t\bar{t}+b\bar{b}$	Sherpa 2.2.1	NLO	Sherpa	4FS NNPDF30_nlo_as_0118_nf_4	Sherpa default
$t\bar{t}$	Sherpa 2.2.1	tt+0,1NLO+2,3,4@LO	Sherpa	5FS NNPDF3.0 NNLO	Sherpa default

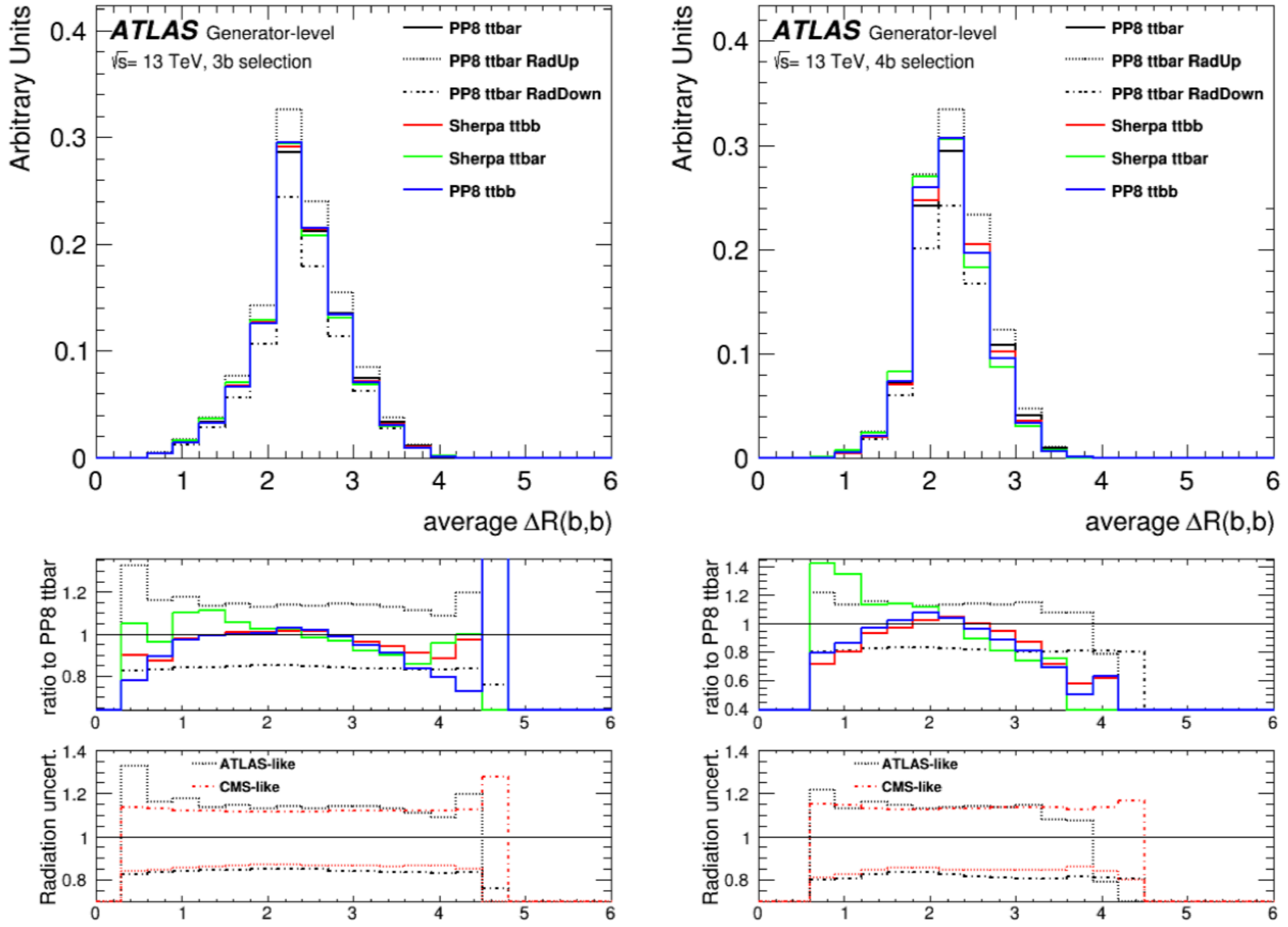

Figure 2: Distribution of the average opening angle between two b-jets, for the 3b selection (left) and the 4b-jet selection (right). The central value of the PP8 $t\bar{t}$ and the other three generators are normalised to 1. The first ratio shows the different curves divided by PP8 $t\bar{t}$. The second ratio plot shows the relative uncertainty of the radiation variations divided by the nominal PP8 $t\bar{t}$ following the above description of simultaneous variations (black) and as the sum of individual variations following the CMS approach (red).

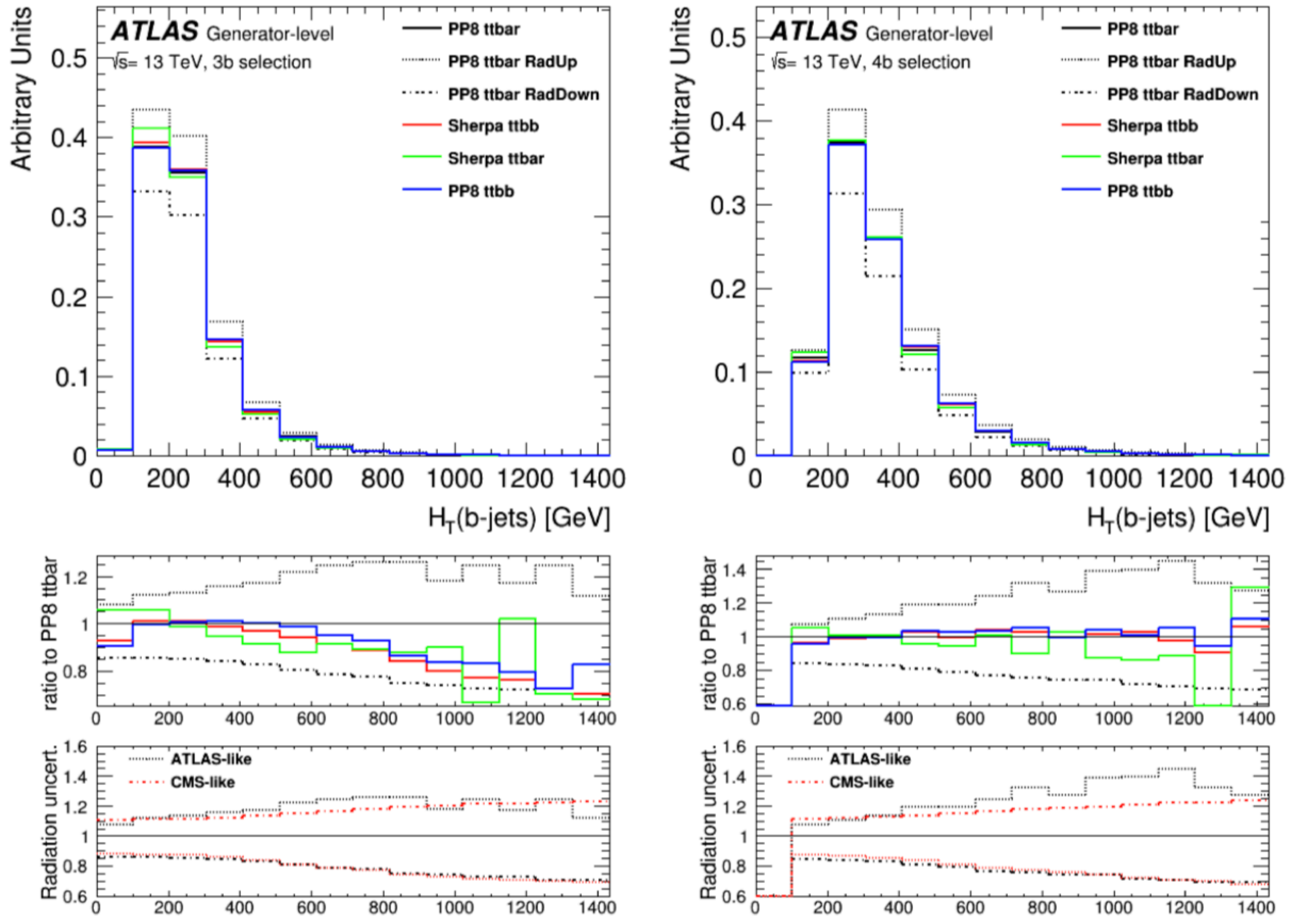

Figure 6: Sum of b-jet transverse momenta in GeV, for the 3b selection (left) and the 4b-jet selection (right). The central value of the PP8 $t\bar{t}$ and the other three generators are normalised to 1. The first ratio shows the different curves divided by PP8 $t\bar{t}$. The second ratio plot shows the relative uncertainty of the radiation variations divided by the nominal PP8 $t\bar{t}$ following the above description of simultaneous variations (black) and as the sum of individual variations following the CMS approach (red).

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ttbb Modelling

Process	Generator	ME order	Parton shower	PDF	Tune
$t\bar{t}$	PowHeg v2	NLO	Pythia 8	5FS NNPDF3.0 NLO	A14
$t\bar{t}+b\bar{b}$	Powheg-Box-Res	NLO	Pythia 8	4FS NNPDF30_nlo_as_0118_nf_4	A14
$t\bar{t}+b\bar{b}$	Sherpa 2.2.1	NLO	Sherpa	4FS NNPDF30_nlo_as_0118_nf_4	Sherpa default
$t\bar{t}$	Sherpa 2.2.1	tt+0,1NLO+2,3,4@LO	Sherpa	5FS NNPDF3.0 NNLO	Sherpa default

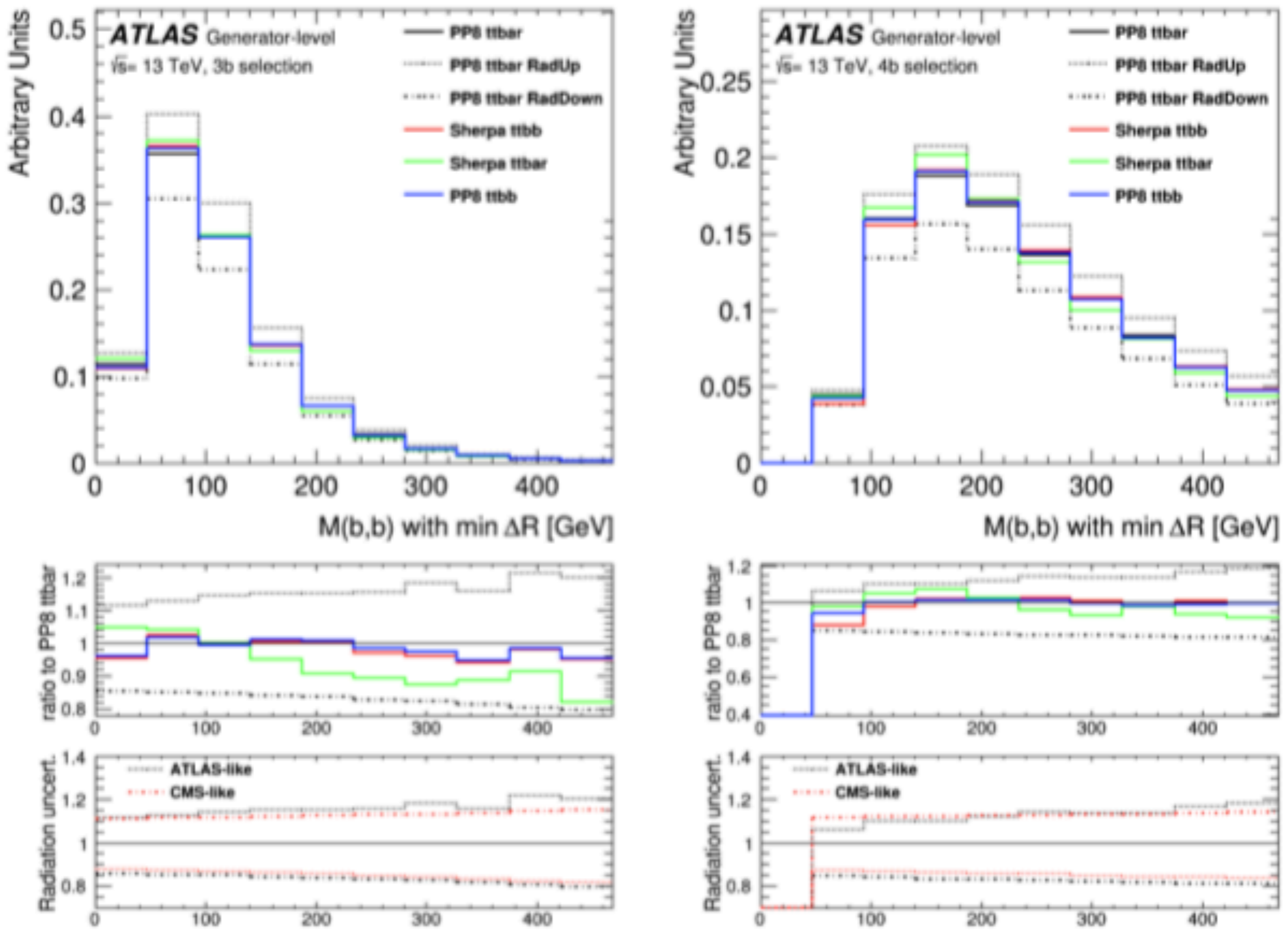

Figure 5: Distribution of the invariant mass in GeV of the two b-jets with the smallest opening angle, for the 3b selection (left) and the 4b-jet selection (right). The central value of the PP8 $t\bar{t}$ and the other three generators are normalised to 1. The first ratio shows the different curves divided by PP8 $t\bar{t}$. The second ratio plot shows the relative uncertainty of the radiation variations divided by the nominal PP8 $t\bar{t}$ following the above description of simultaneous variations (black) and as the sum of individual variations following the CMS approach (red).