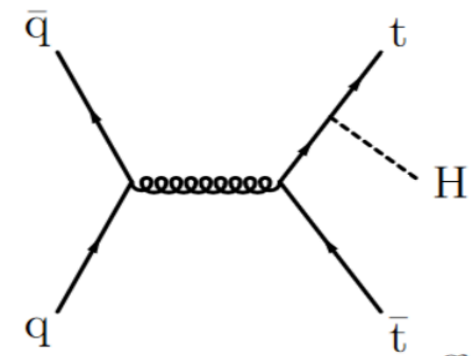
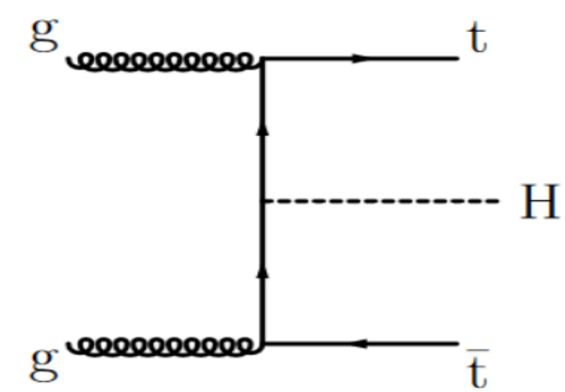
ATLAS and CMS latest results on ttH





Neelam Kumari

TOP-LHC France 2022

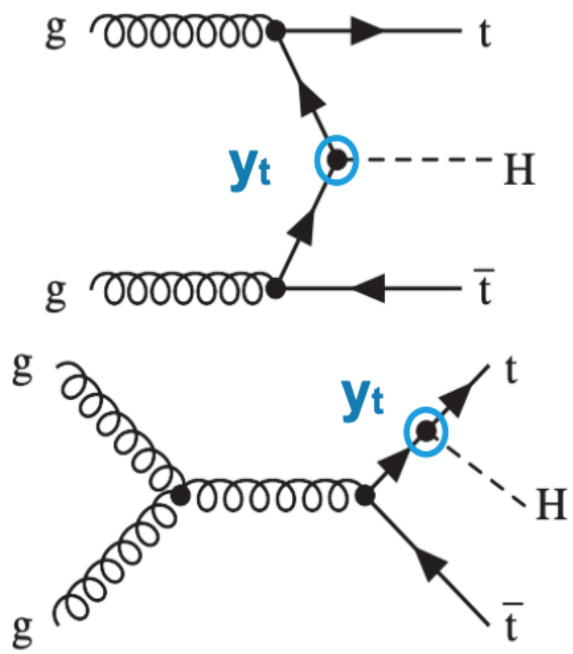
Centre de Physique des Particules de Marseille
Aix-Marseille Université / IN2P3-CNRS

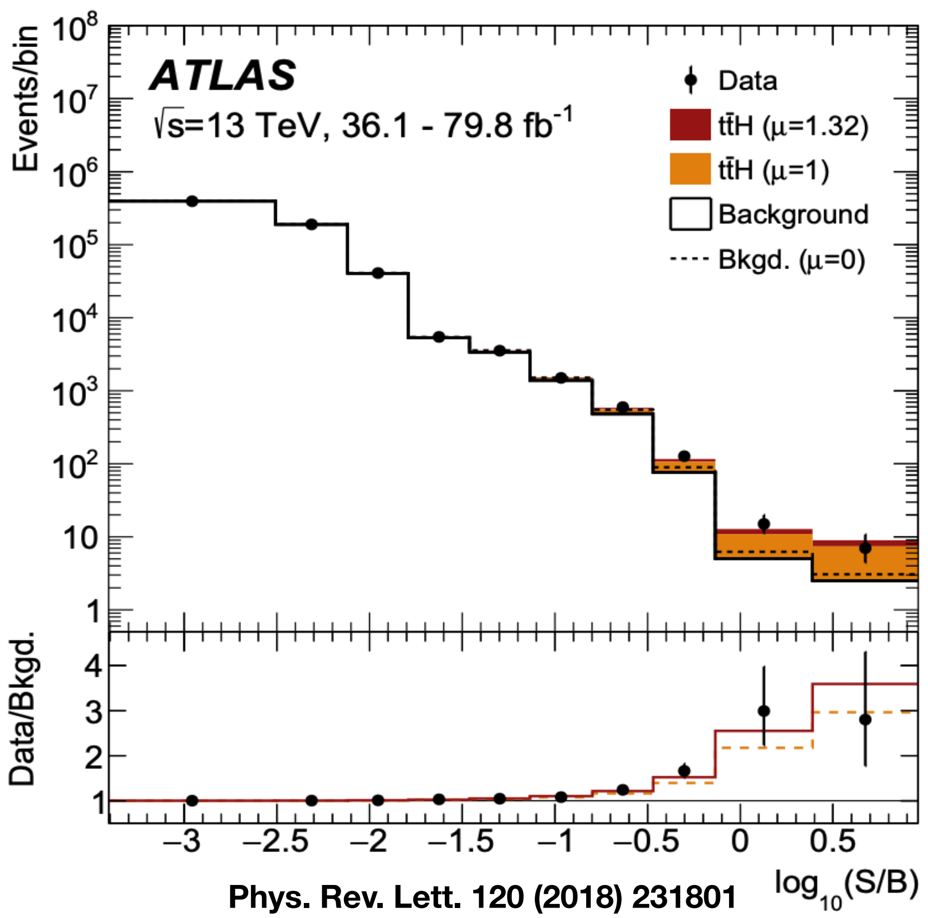
May 10th, 2022

Introduction

Motivation: **Higgs Boson discovery → precision measurements !**

- **ttH production** provides direct access to **top-Higgs Yukawa coupling y_t**
- **Largest** in SM and sensitive to **potential New Physics**
- **ttH~1%** of total Higgs boson production cross section

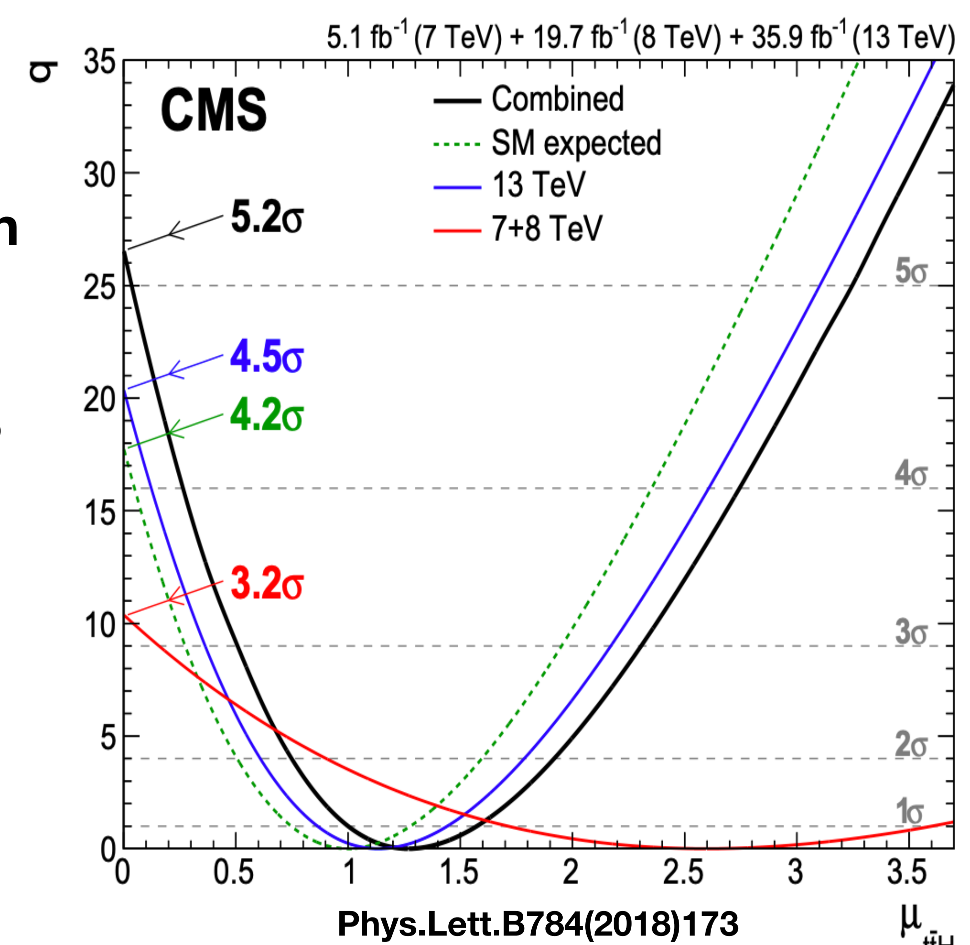




Phys. Rev. Lett. 120 (2018) 231801
arXiv:1804.02610 [hep-ex]

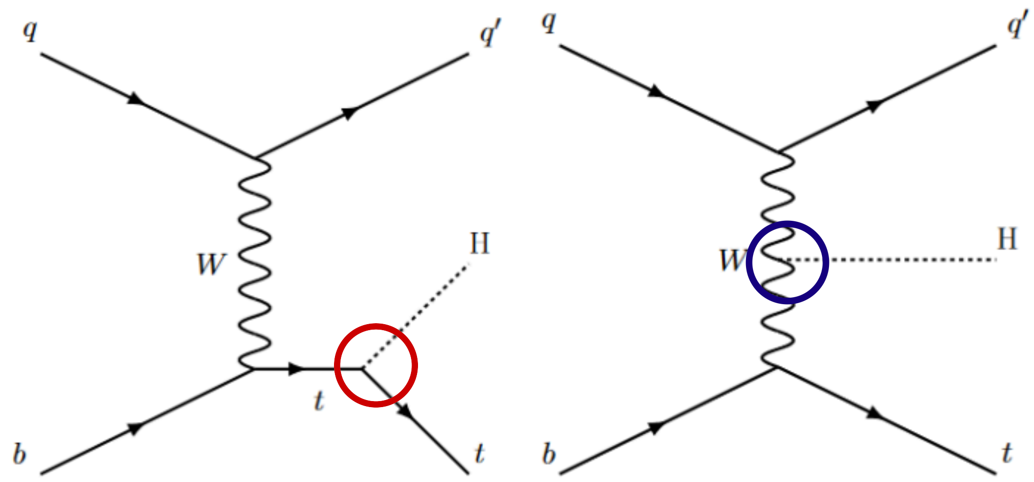
- **Run 2 dataset** offered possibility to probe **Higgs coupling** to **third generation fermions** in more detail
- **First observation** by **ATLAS** and **CMS** of **Higgs+top associated production** in Spring 2018 with partial Run 2 datasets

ATLAS: 6.3σ (5.1σ exp.)
(Run1 + 79.5 fb-1 Run2)
CMS: 5.2σ (4.2σ exp.)
(Run1 + 35.9 fb-1 Run2)



Phys.Lett.B784(2018)173
arXiv:1806.00425 [hep-ex]

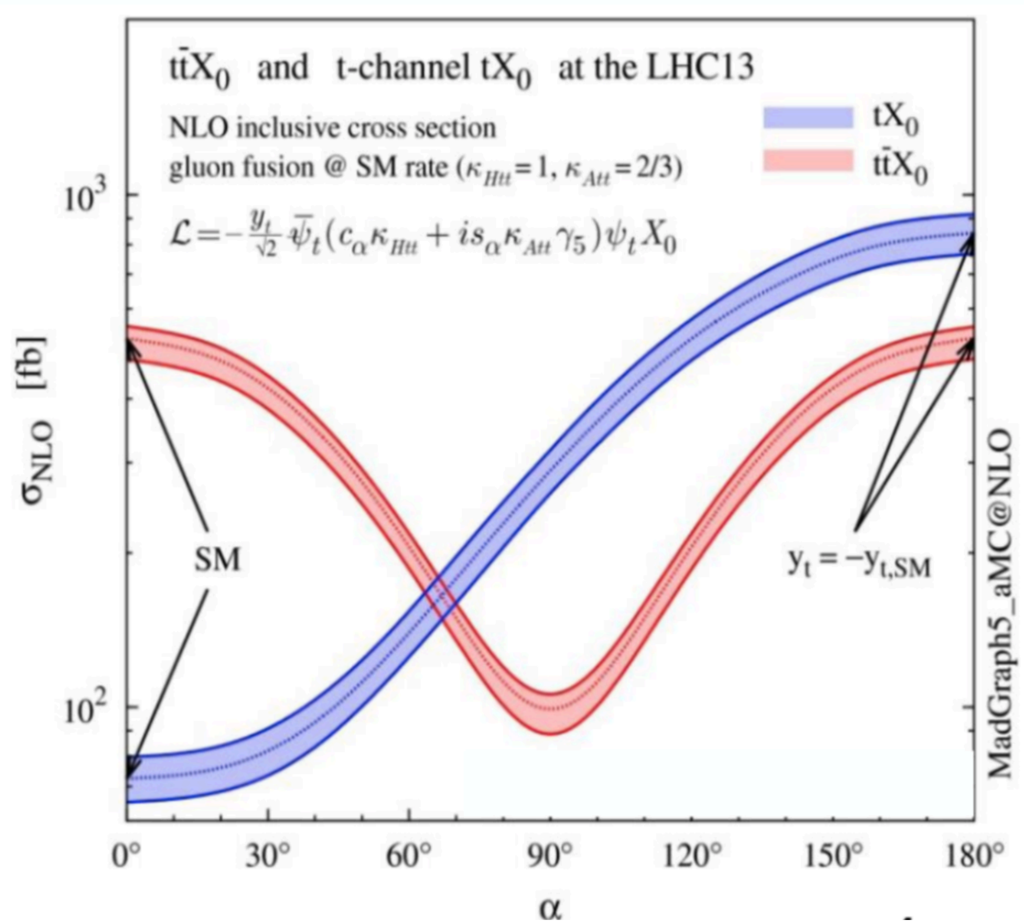
Introduction



Motivation:

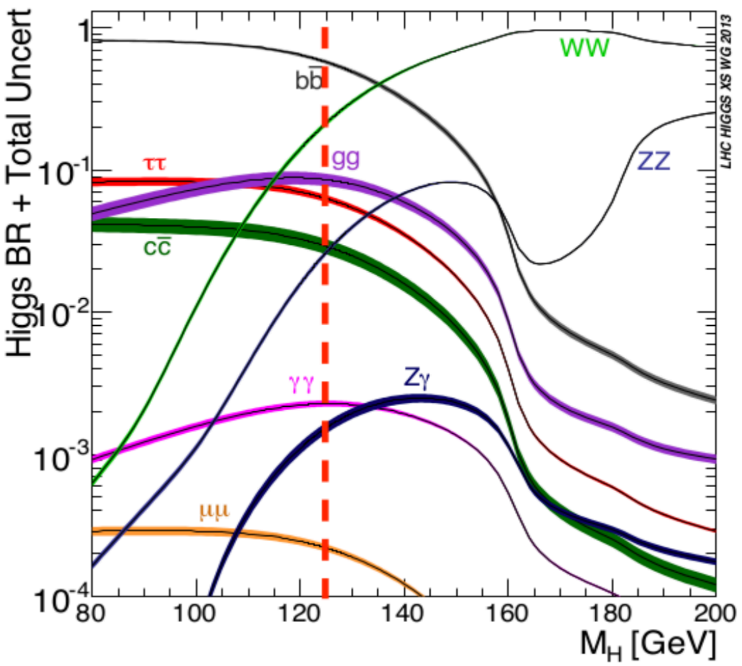
- Not only ttH but also **tH production** is a powerful probe
- tH very challenging due to low cross section but **sensitive to relative sign** of **H-t** and **H-W** interaction
- **σ(t_H)** ≈ 10 × **σ(t_H)SM** if **sign of y_t** is switched

- ttH production also allows to **probe the CP structure** of the top-Higgs coupling (CP measurements discussed in previous [talk by Laurent](#) :
  - Impacts cross-section and kinematics of top + Higgs
  - **CP-odd component:** direct indication of new physics
- Combined analysis of **ttH + tH processes** can be used to lift degeneracy between **α** and **180°-α** hypothese

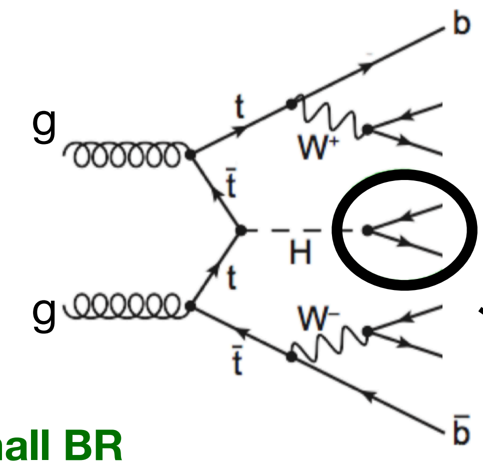


Eur. Phys. J. C 75 (2015) 6, 267
[arXiv:1504.00611 [hep-ex]](#)

ttH Analysis @LHC



Large branching ratio (BR)
Large background



Small BR
Purity & Precision

H→bb
Multi-lepton H→ww/zz/ττ
H→γγ
H→zz→4l

- Target as many **decay modes** as possible to optimally exploit small cross section
- Characterised by **BR** and **signal purity → modelling of the backgrounds** is a key element

Recent highlights from ATLAS and CMS at √s = 13 TeV

Channel	Benefits/Challenges	Latest ATLAS/CMS results	
H→bb	Largest BR / Low purity + combinatorics + large theoretical uncertainties on irreducible tt+bb background	*ATLAS 139 fb^{-1}*	*ATLAS-HIGG-2020-23*
		CMS 77.4 fb^{-1}	*CMS-PAS-HIG-18-030*
Multi-lepton H→ww/zz/ττ	Clean final state with leptons + moderate irreducible background/ Challenging modelling of ttW and reducible backgrounds	*ATLAS 80 fb^{-1}*	*ATLAS-CONF-2019-045*
		CMS 137 fb^{-1}	*Eur. Phys. J. C 81 (2021) 378*
H→γγ	Clean signature + possible to reconstruct all Higgs decay products/ Low BR	*ATLAS 139 fb^{-1}*	*ATLAS-CONF-2020-026* *ATLAS-HIGG-2019-13*
		CMS 137 fb^{-1}	*JHEP 07 (2021) 027*
H→zz→4l	Very clean signature + possible to reconstruct all Higgs decay product + very high purity/ Very low BR	*ATLAS 139 fb^{-1}*	*Eur. Phys. J. C 80 (2020) 957*
		CMS 137 fb^{-1}	*Eur. Phys. J. C 81 (2021) 488*

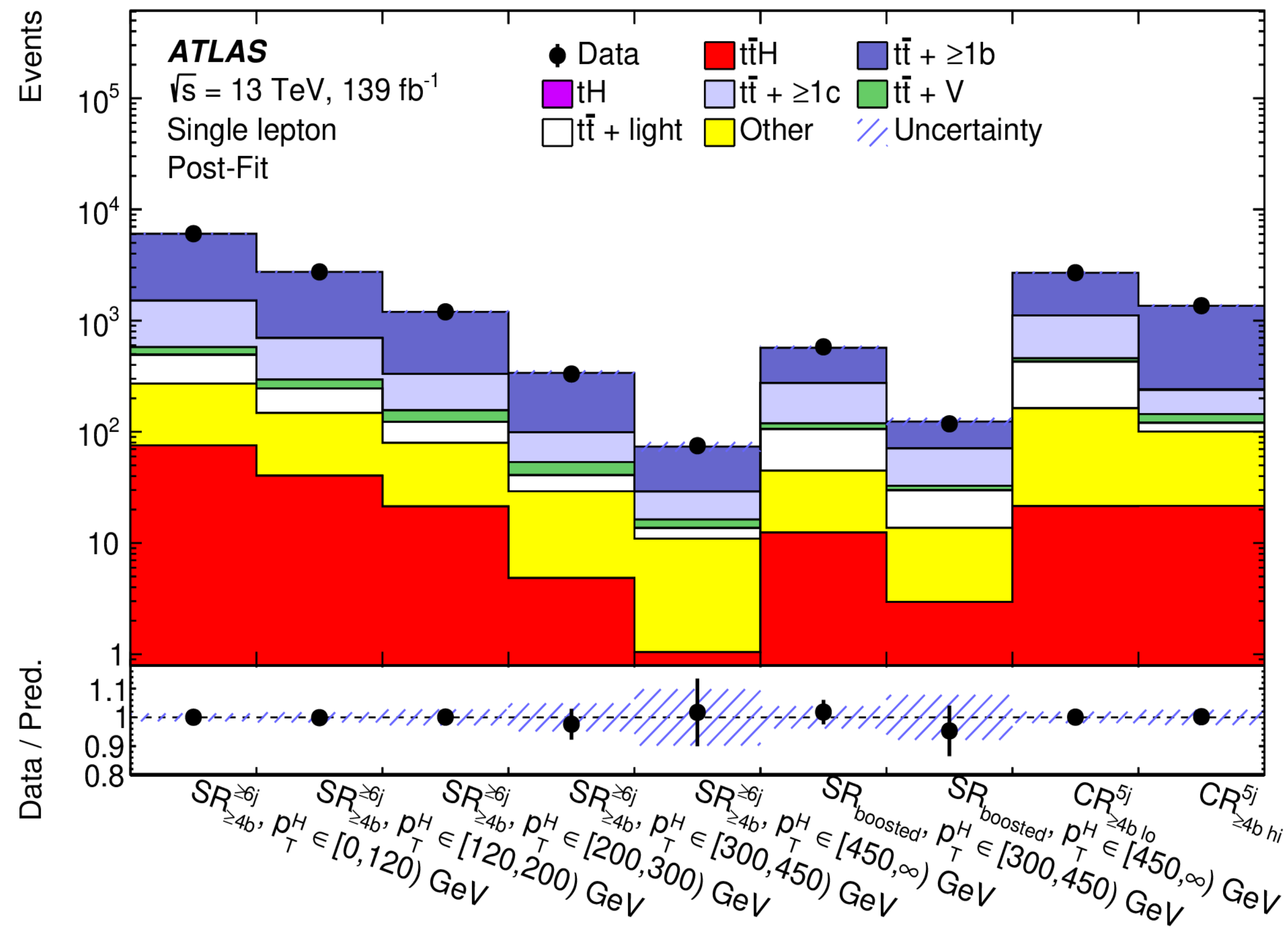
ttH H→bb

ATLAS-HIGG-2020-23 (submitted to JHEP)

Analysis strategy: Full Run 2 dataset (139 fb^{-1})

First differential measurement of ttH (H→bb) decays

- Explored through **Simplified Template Cross Sections** (STXS) formalism where cross-section is measured as a function of the $\mathbf{p_T^H}$
- Events categorised in signal regions (**SRs**) are defined by the **#leptons**, **#jets**, **#b-tagged jets** (4 working points) and **#boosted Higgs boson candidates**
- Includes single-lepton **resolved**, **boosted** and **di-lepton** channels



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

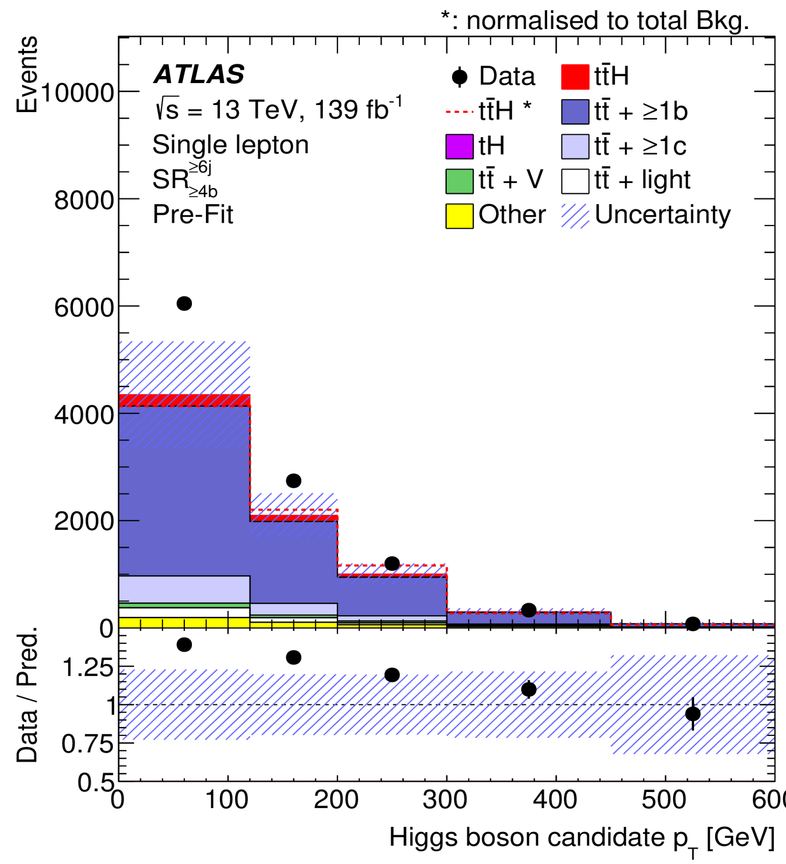
- **BDTs** used for **reconstructing Higgs boson candidate** and **signal extraction**
- Control regions (CRs) to **constrain tt+≥1b and tt+≥1c** exploiting $\mathbf{\Delta R(bb)_{avg}}$ **/ yield** for the fit in single/di-lepton channel

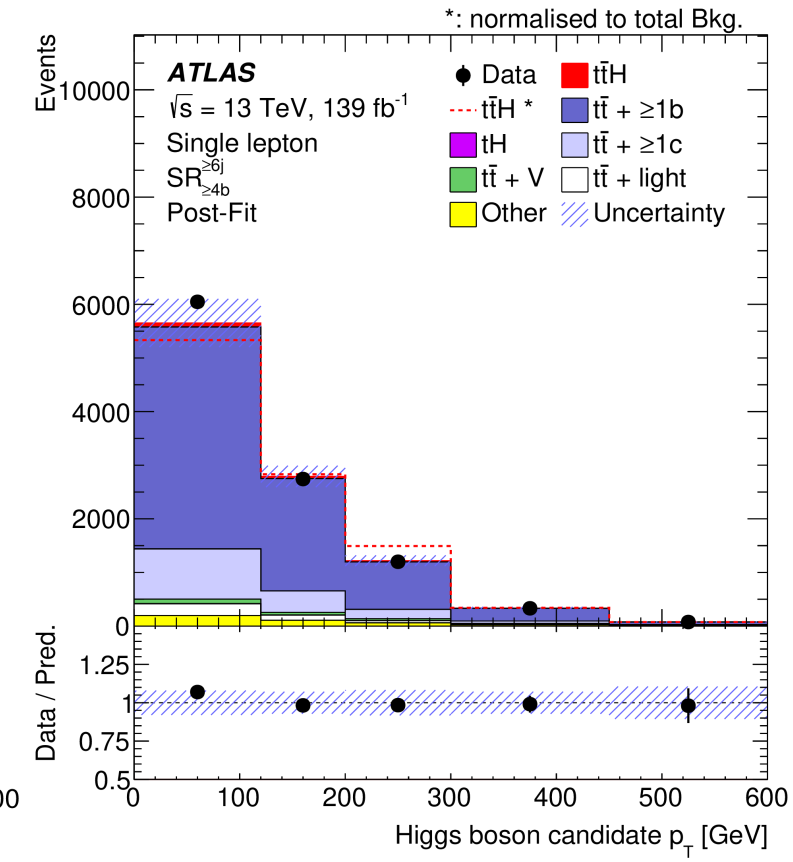
ttH H→bb

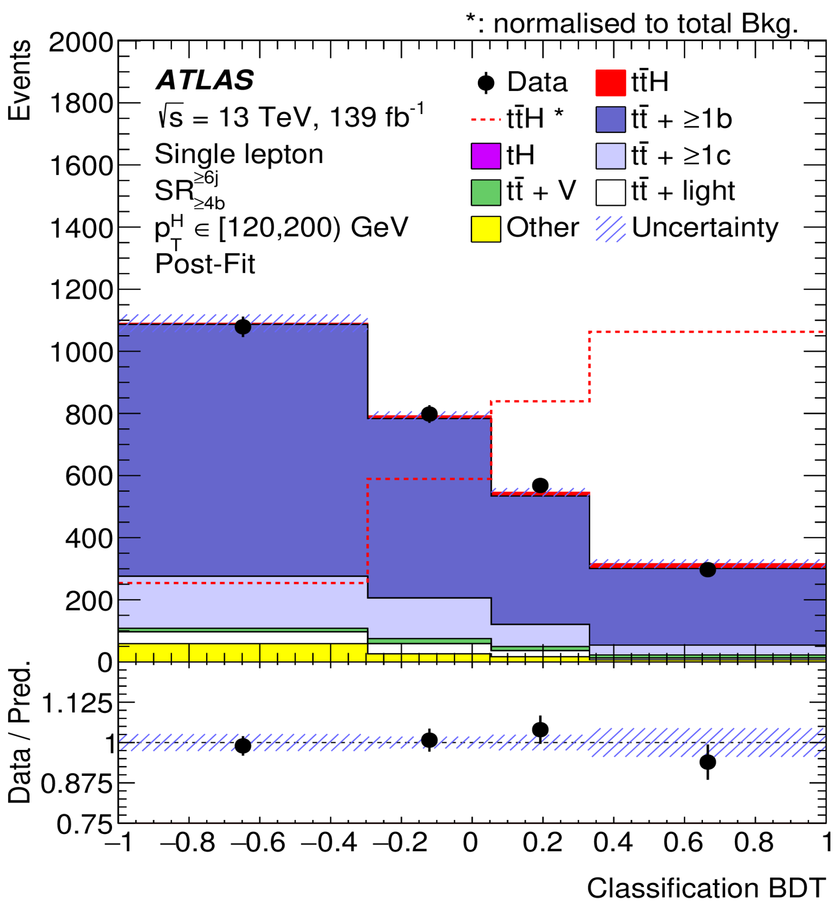
ATLAS-HIGG-2020-23 (submitted to JHEP)

Modelling of tt+bb background

- **Irreducible background:** tt+heavy flavour (hf) jets
- **tt+bb background** modelled with **4FS NLO** simulation with **extra b-jets from ME**
- **Dedicated samples** used to assess dominant shape **systematic uncertainties**:
  - Initial and final state radiations, parton showers, NLO matching
  - Relative fractions of tt+hf components





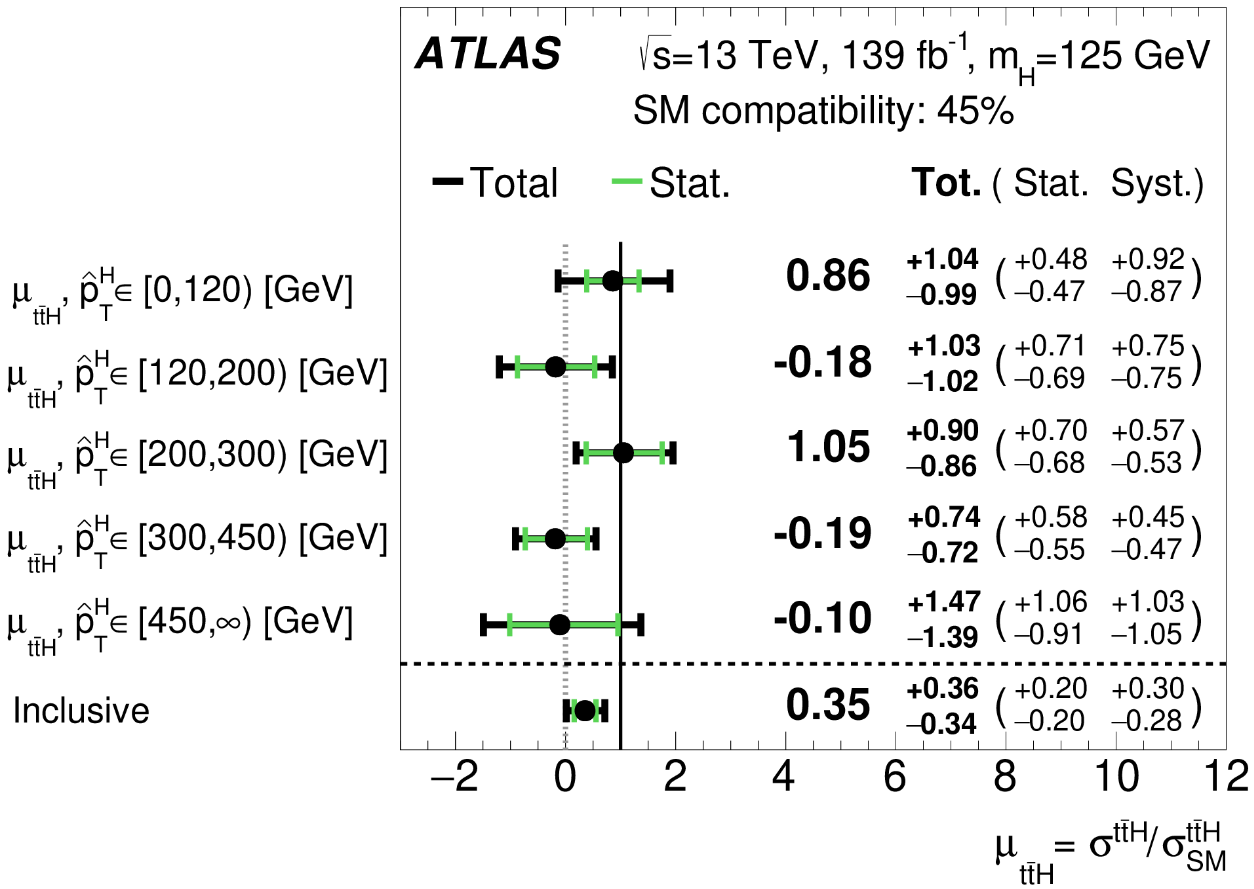


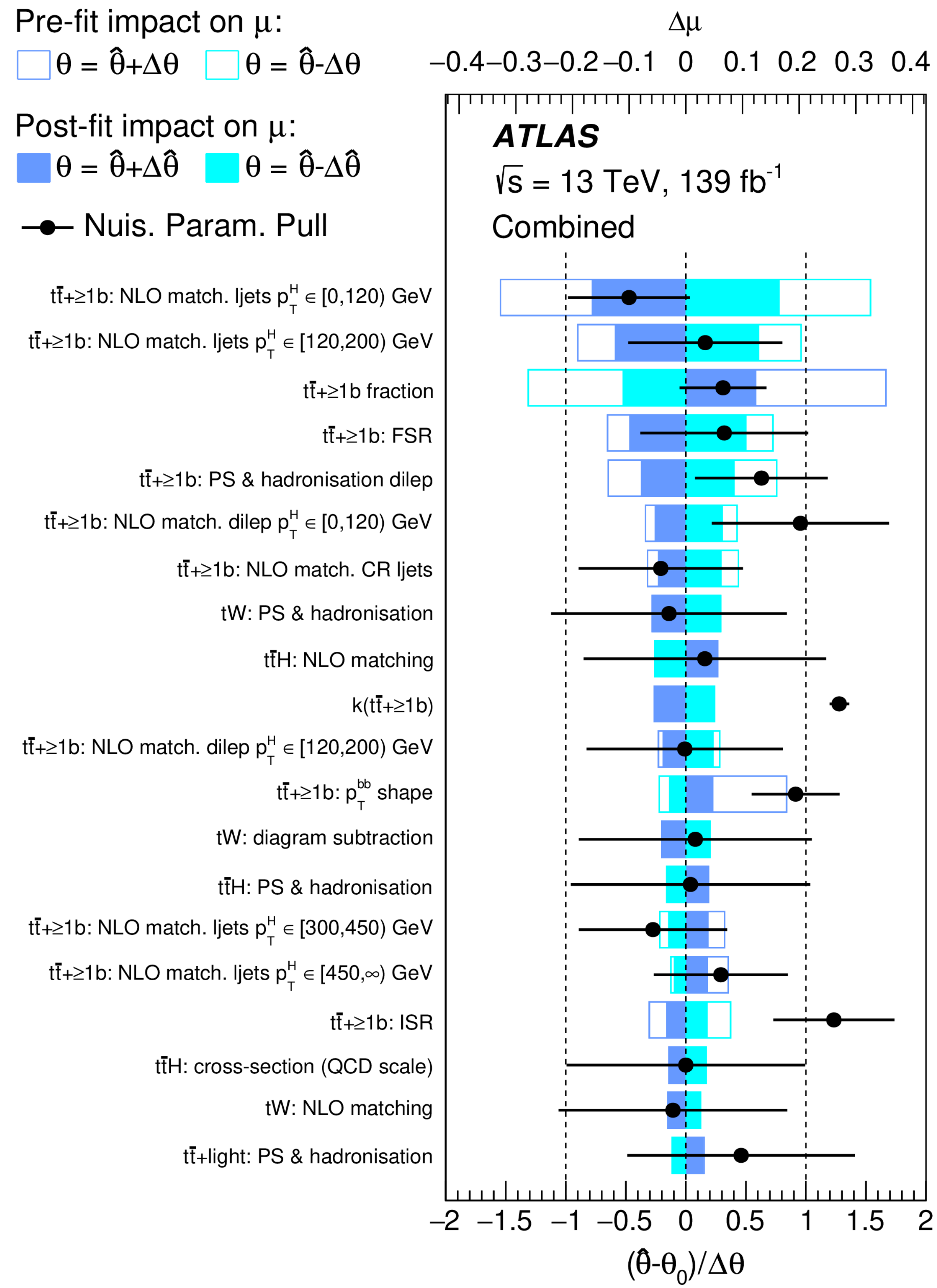
- **Normalisation** of **tt+≥1b** estimated with free-floating parameter in the signal extraction fit to data: **k(tt+bb)=1.26 ± 0.09**
- **tt+cc** 100% normalisation priori uncertainty
- Observed **$p_{T(H)}$ mismodelling** covered by dedicated shape uncertainty on tt+bb
- **Good post-fit agreement** observed, with **uncertainty dominated** by **tt+hf** modelling systematics

ttH H→bb

ATLAS-HIGG-2020-23 (submitted to JHEP)

- Measurement **uncertainty** is **dominated** by systematic uncertainties, especially from **tt+≥1b modelling**





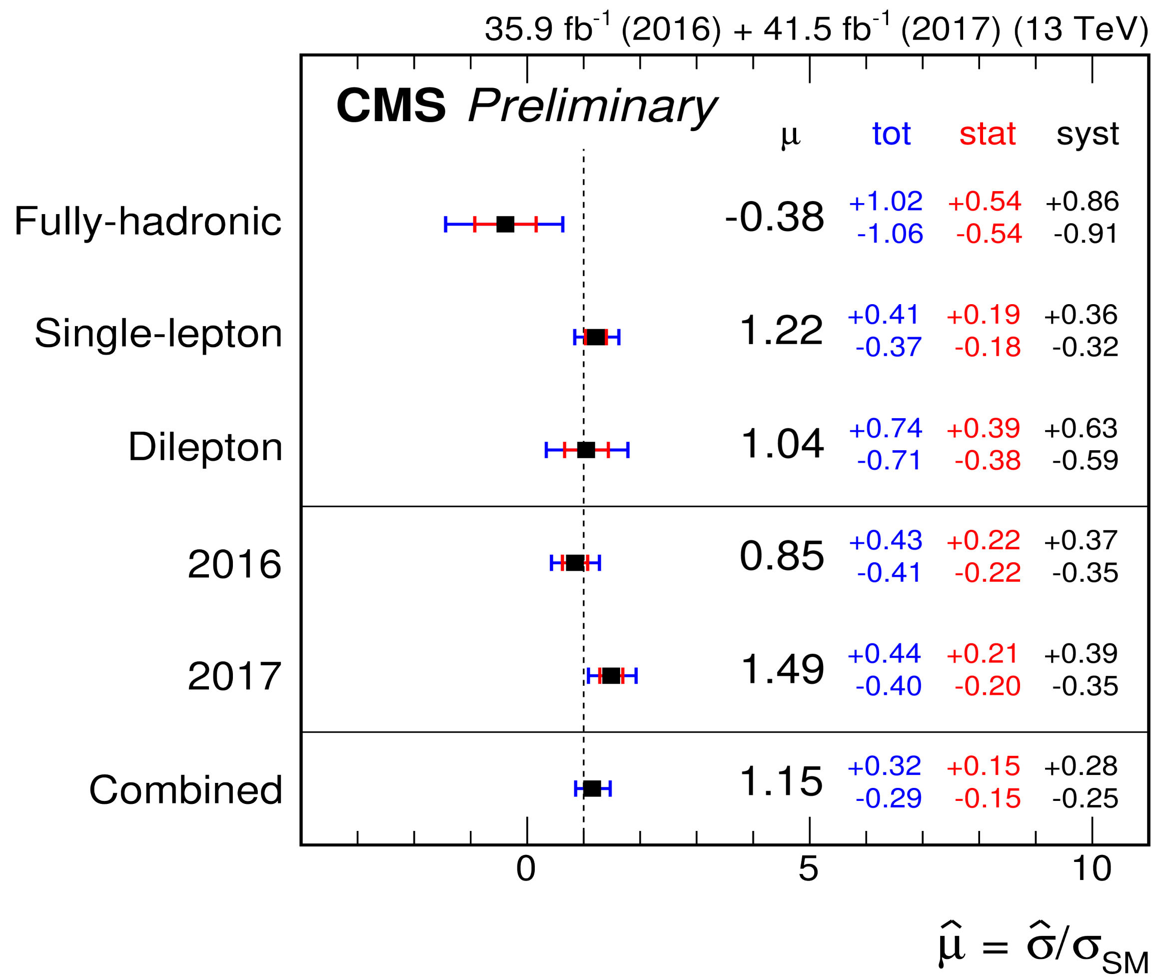
- **Individual STXS** signal strengths **compatible with SM** or μ=0 within **2σ, sensitivity** beyond p_T=300 GeV, **thanks to boosted categories**
- Sensitivity: **1.3σ observed (3.0σ exp.)**

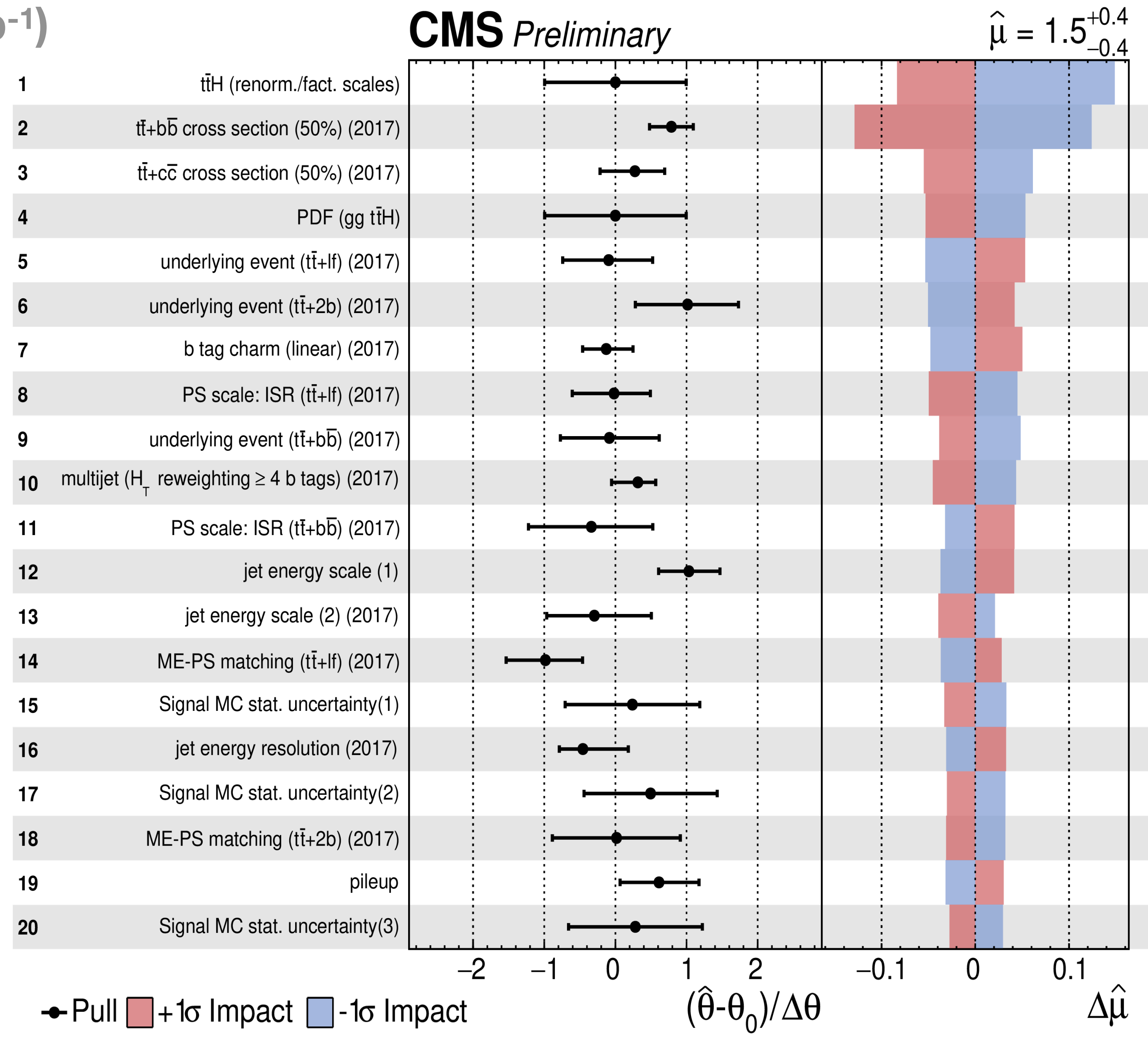
ttH H→bb

CMS-PAS-HIG-18-030

Analysis strategy: Partial Run 2 dataset (77.4 fb^{-1})

- **Single-lepton channel: ANN** used as **multi-classifier** to define background enriched nodes & for signal extraction
- **Di-lepton channel:** BDTs for signal extraction
- **Fully hadronic channel:**
  - **data-driven** multi-jet background estimate
  - **MEM shape** for signal extraction





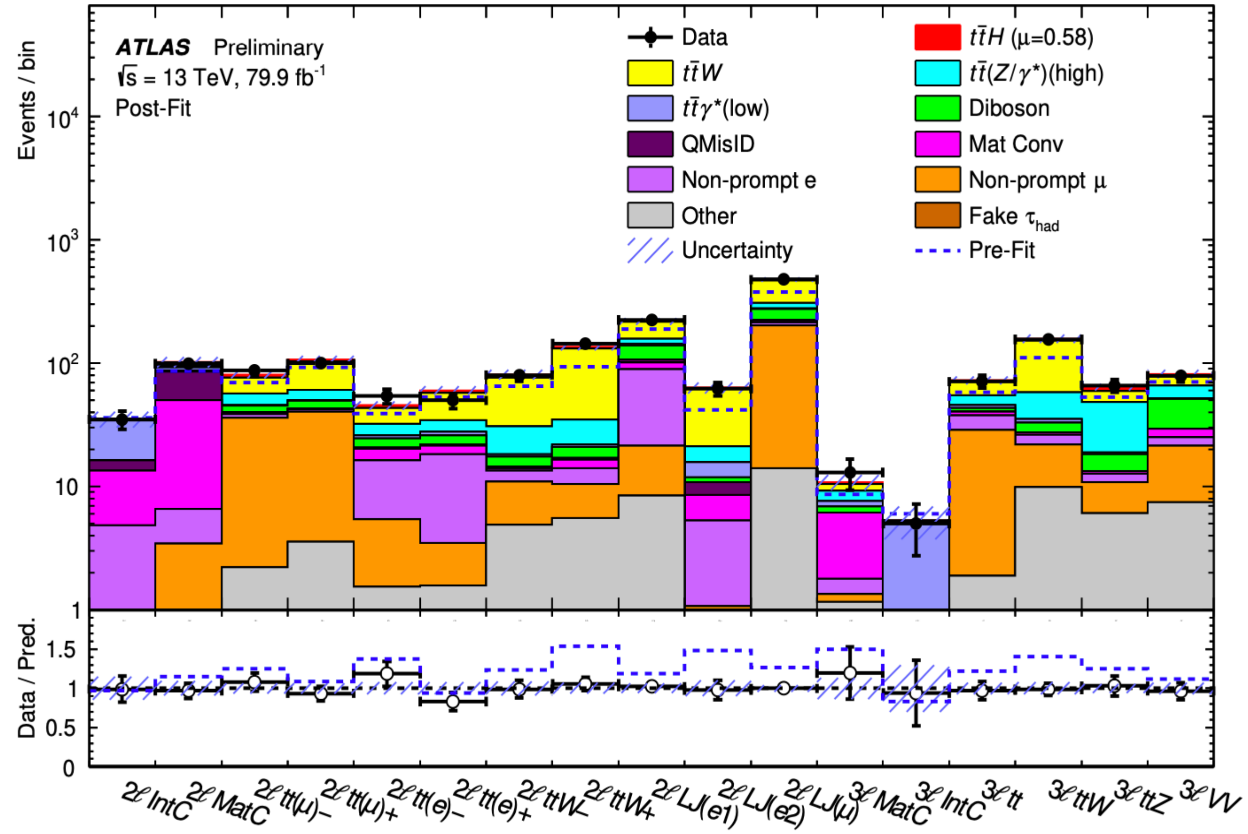
- **Largest impact uncertainties:**
  - cross-sections of signal
  - tt+hf covered by a 50% rate uncertainty
  - b-tagging
  - data-driven multijet background
- Sensitivity: **3.9σ observed (3.5σ expected)**

ttH H→WW/ZZ/ττ (Multi-lepton)

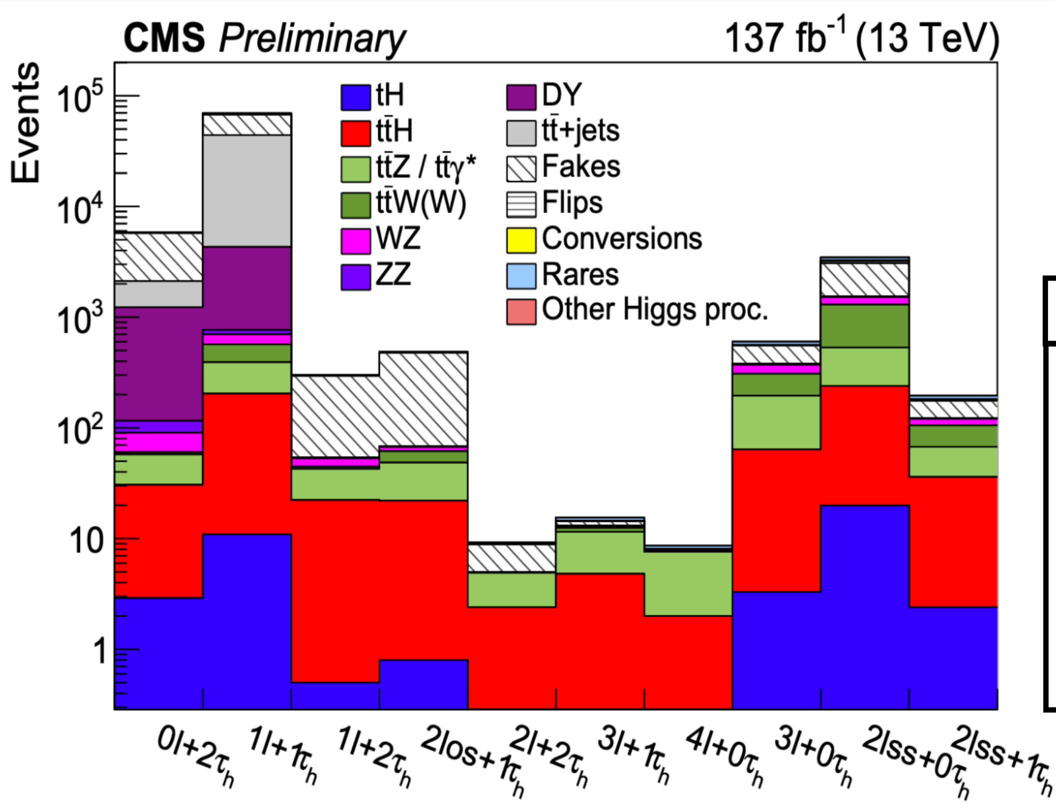
ATLAS-CONF-2019-045
Eur. Phys. J. C 81 (2021) 378
CMS-PAS-HIG-19-008

Analysis strategy: Partial Run 2 dataset (ATLAS 80 fb^{-1}) / Full Run 2 dataset (CMS 137 fb^{-1})

- **10 (CMS) / 8 (ATLAS)** analysis categories based on #**lepton** and #**hadronic tau (τh)**
- **Backgrounds sources**:
  - **Irreducible**: ttW, ttZ, WZ, ZZ
  - **Reducible**: ttbar/QCD + non-prompt leptons (MVA based selections used to separate from prompt leptons), charge mis-ID, fake τh
- Irreducible background shape estimated from **MC simulation**
- **CRs** are defined to constrain **ttZ, WZ** and **ZZ**



ATLAS
- **17 CRs** fitted simultaneously in 8 categories
- Signal extracted from **BDT output**

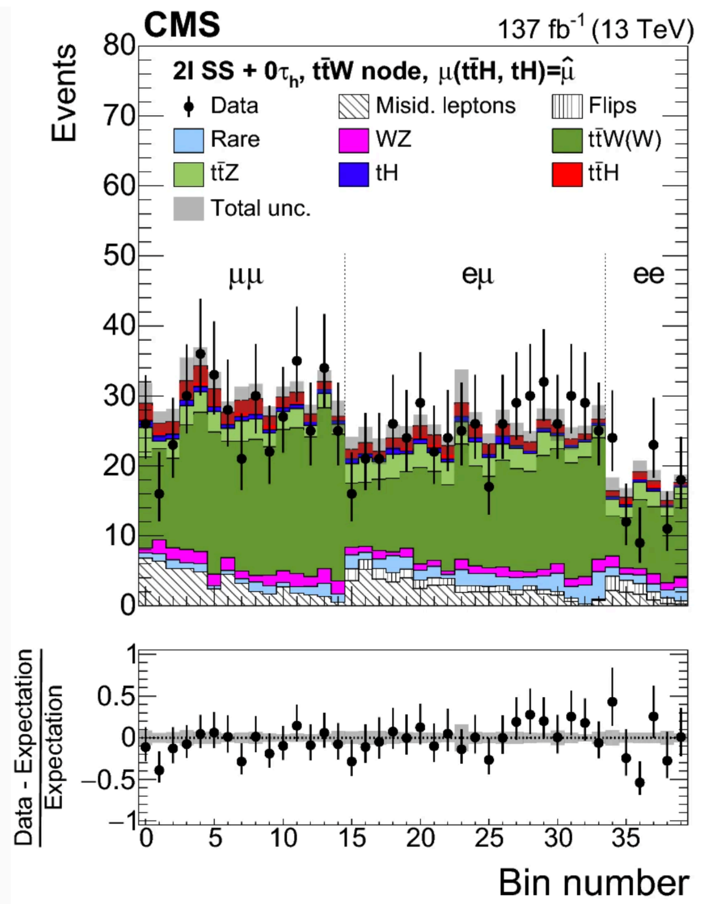


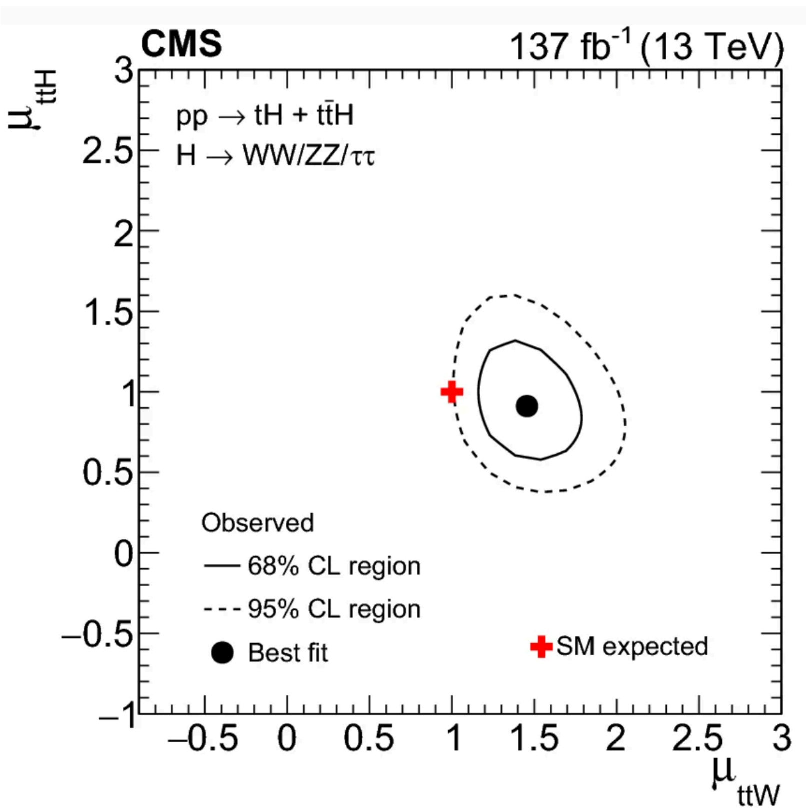
CMS
- **Simultaneous measurement** of **ttH** and **tH**
- **DNN multi-class** to separate ttH, tH and backgrounds in **2ℓSS+0τh** , **3ℓ+0τh** , and **2ℓSS+1τh** channels & rest categories rely on a BDTs

ttH H→WW/ZZ/ττ (Multi-lepton)

ATLAS-CONF-2019-045

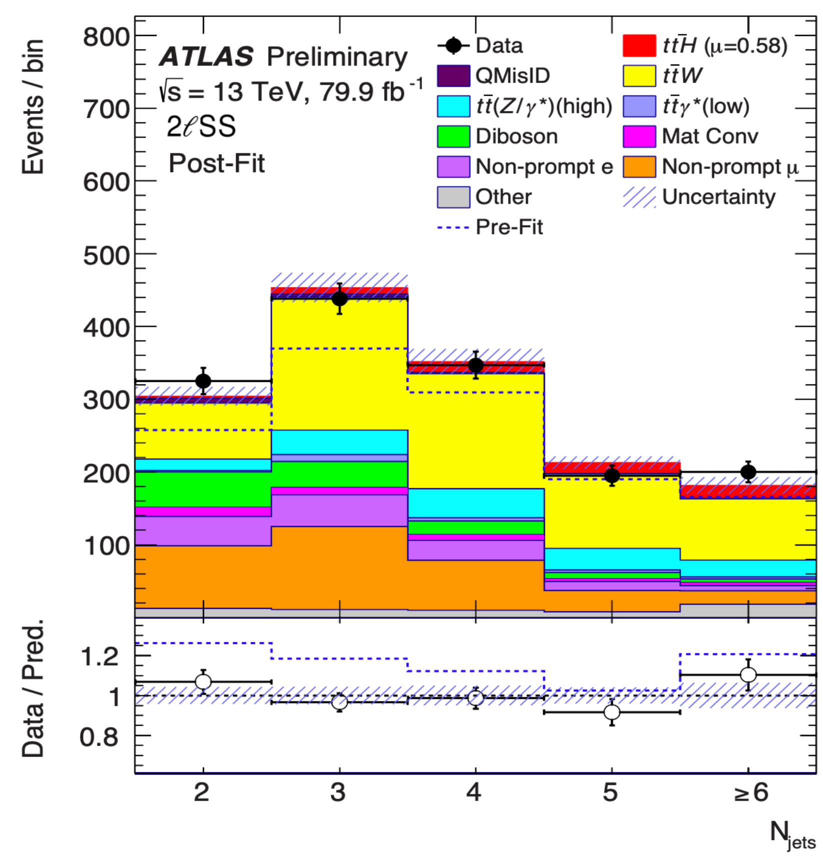
Eur. Phys. J. C 81 (2021) 378





CMS

- **ttW constrained** via dedicated CR using **DNN multi-class** in **2ℓSS+0τ$_h$** channel
- **ttW & ttZ freely floating in fit:** μ_{ttW} = 1.43±0.21, μ_{ttZ} =1.03±0.14)
- **Misidentified lepton background data-driven estimation with misID probability method**: fake rate measured in data, w/ extrapolation correction + uncertainty



ATLAS

- **Dominant ttW** in 2lSS and 3l channels constrain via 3 **freely-floating parameters in fit** (taking into account QCD and EW corrections)**:**

$$\lambda^{2\ell SS, 2\leq n_{jets}\leq 3} = 1.56 \pm 0.29$$

$$\lambda^{2\ell SS, 4\leq n_{jets}} = 1.26 \pm 0.19$$

$$\lambda^{3\ell} = 1.68 \pm 0.29$$

- **Extrapolation uncertainties** for charge asymmetry and b-jet multiplicity

Modelling of the ttW background is the main challenge

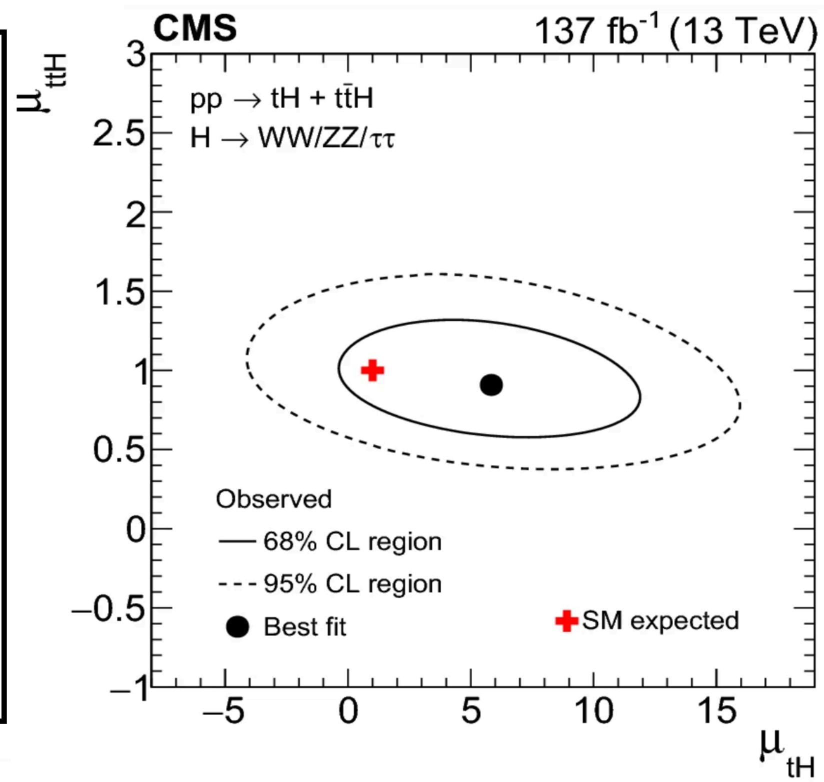
Significant mis-modelling of ttW background

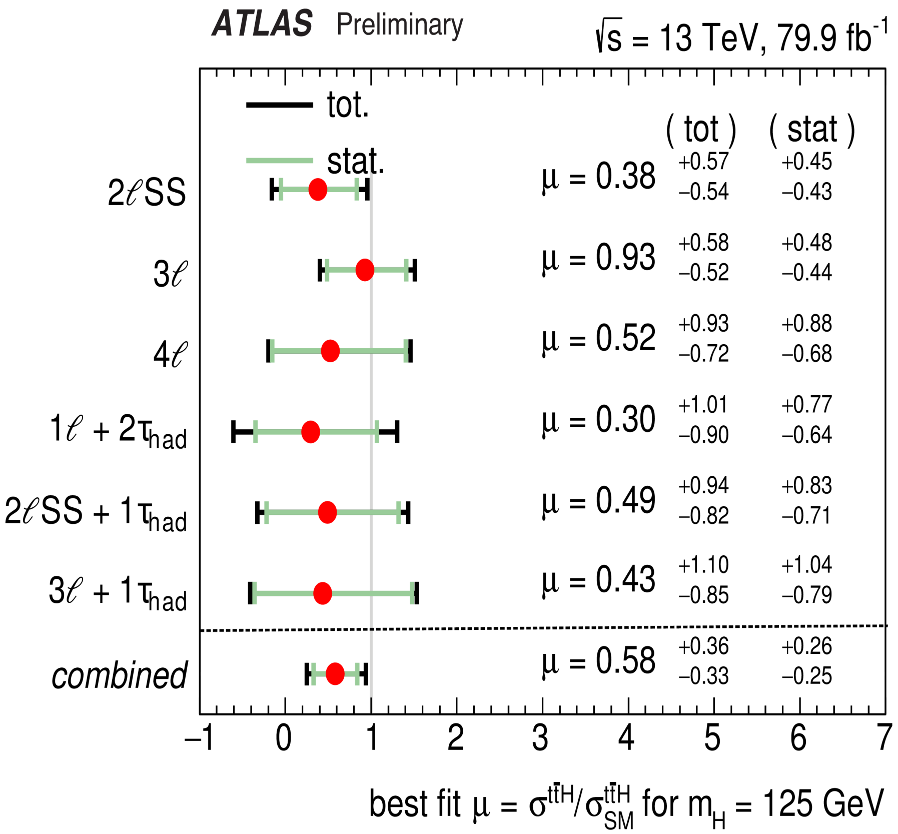
ttH H→WW/ZZ/ττ (Multi-lepton)

ATLAS-CONF-2019-045

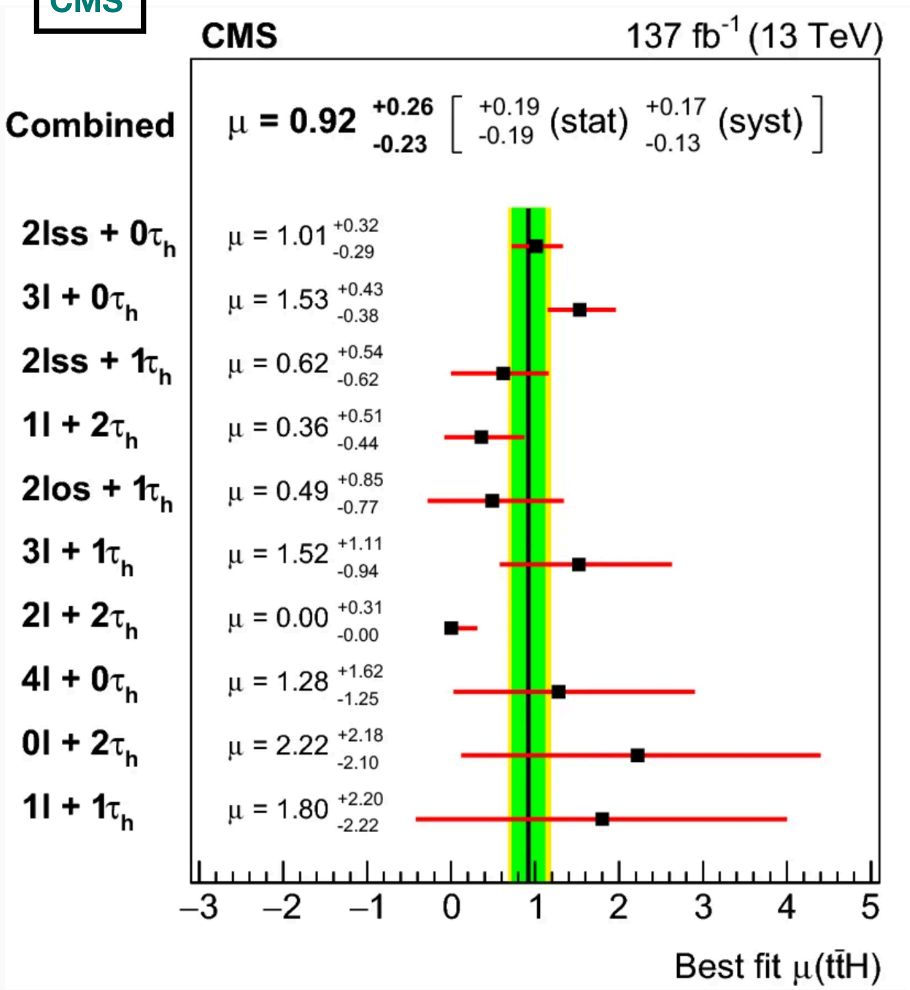
Eur. Phys. J. C 81 (2021) 378

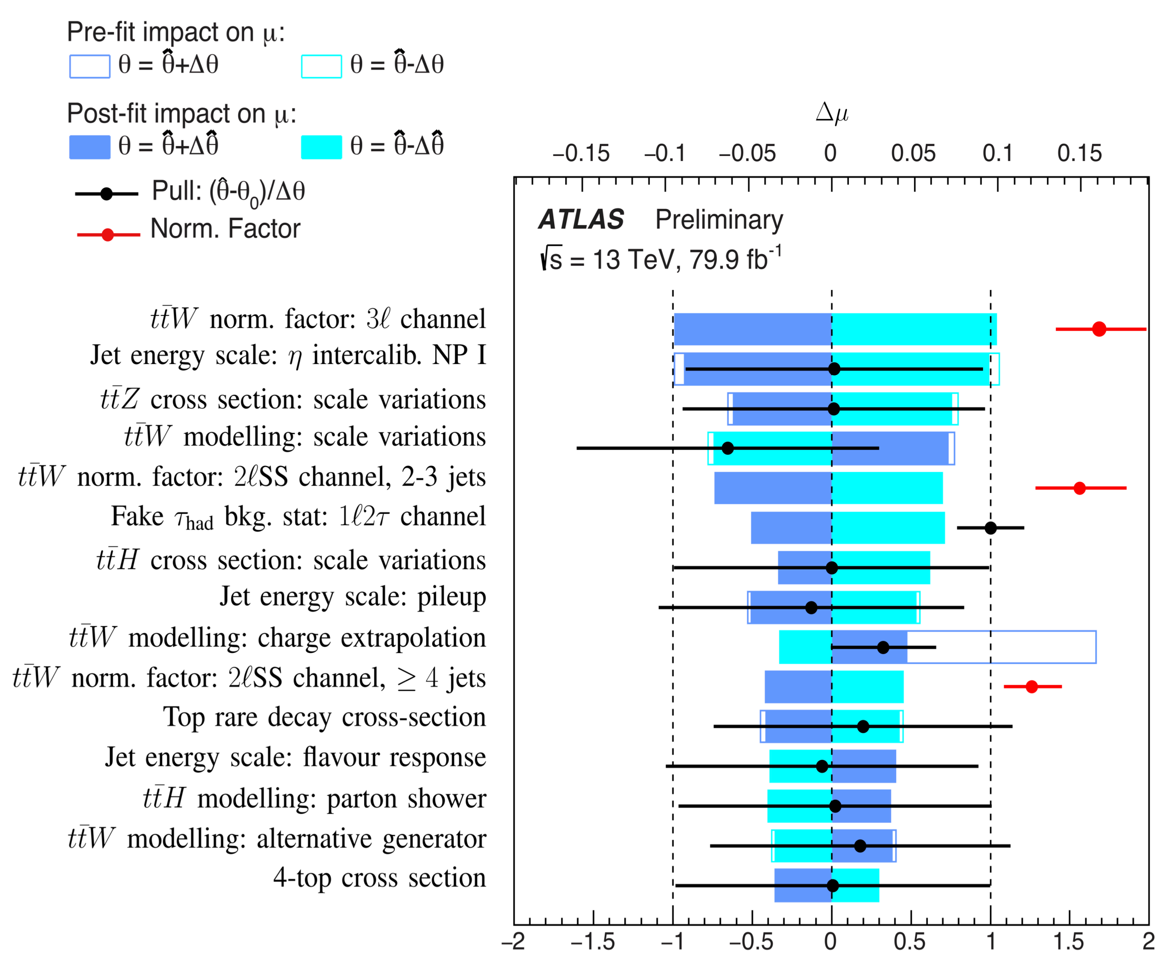
- Signal extraction with **uncorrelated signal strengths** for **ttH, tH, ttW and ttZ**
- **Sensitivity: ttH: 4.7σ (5.2σ exp.) tH: 1.4σ (0.3σ exp.)**
- **tH sensitive to the sign of κt,** constrained within (-0.9,-0.7) or (0.7,1.1) @95% CL





CMS





ATLAS

Systematic uncertainties getting larger than stat. uncertainty:

- **Dominated by ttW** modelling
- Jet energy scale

Sensitivity:
ttH: 1.8σ (3.1σ exp.)

H→γγ

ATLAS-CONF-2020-026
JHEP 07 (2021) 027

Analysis strategy: Full Run 2 dataset (ATLAS 139 fb^{-1}) / (CMS 137 fb^{-1})

ttH H→γγ studied as part of inclusive STXS measurements

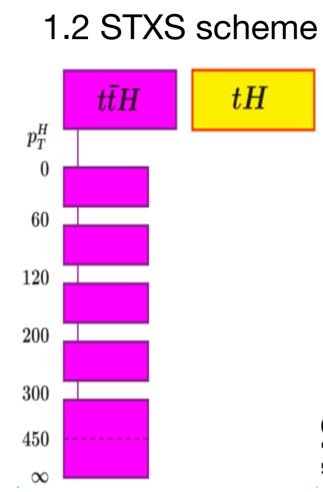
Categorisation via STXS bin assignment

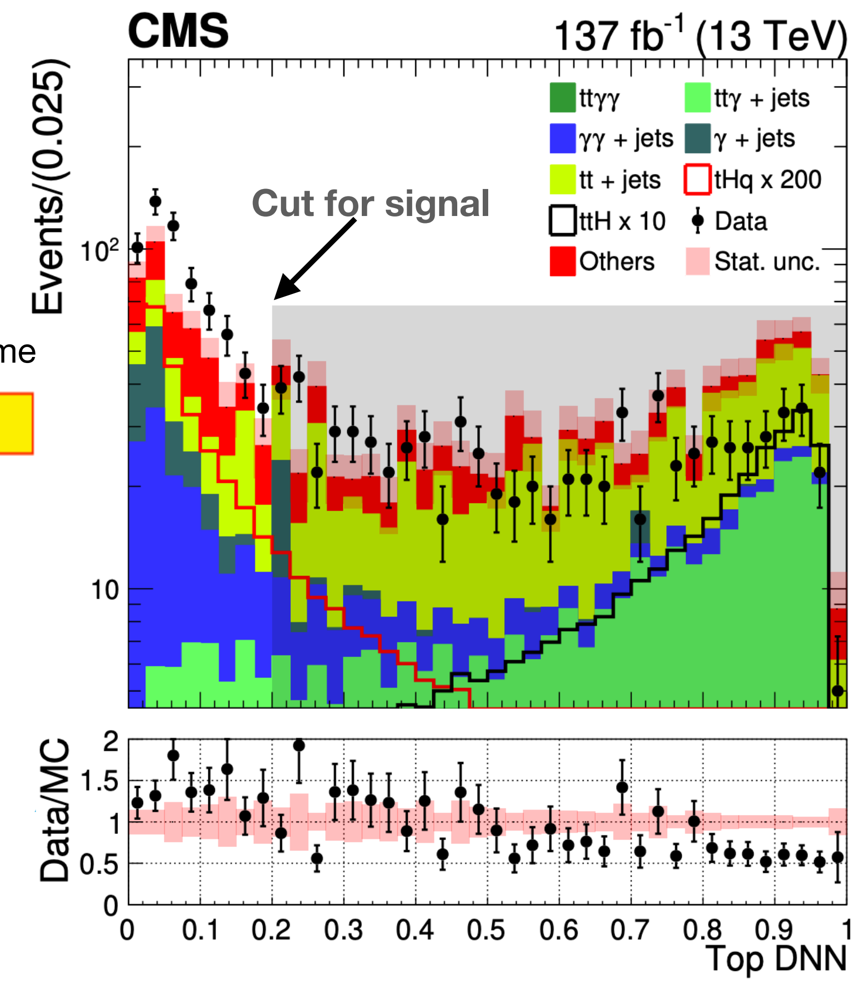
ATLAS

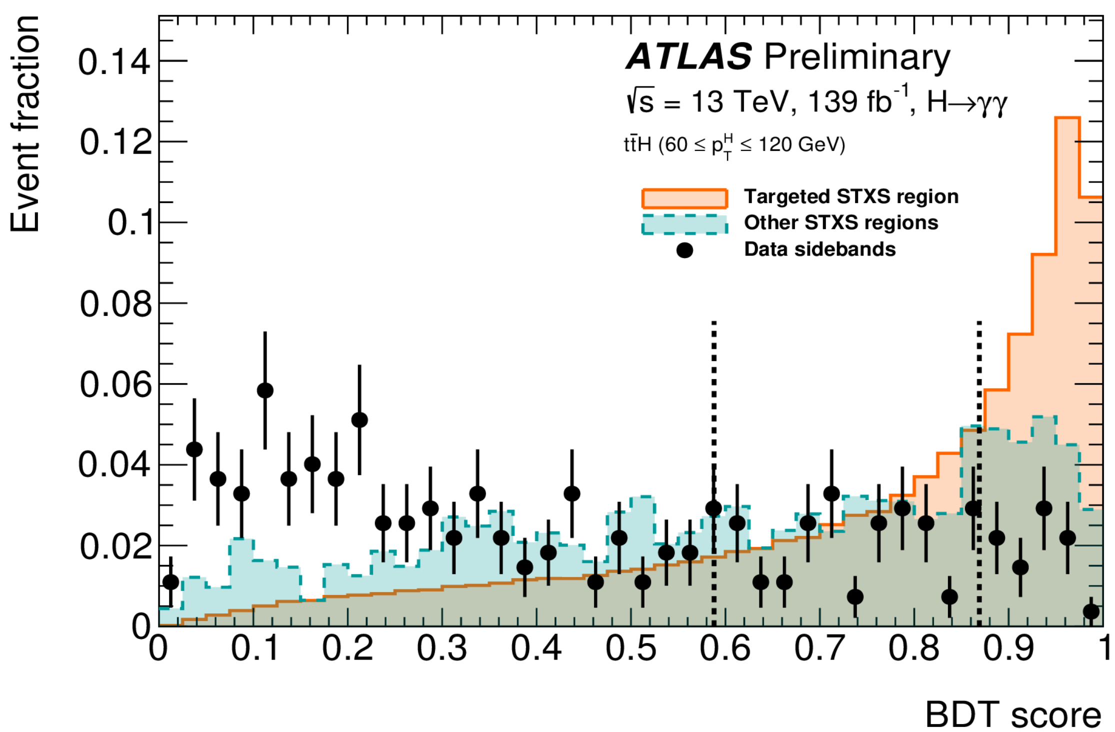
- **Multi-class BDT** targeting **44 STXS classes**
- **Binary BDT** is trained against the continuum background in each class: Rejecting variables **correlated** with **$m_{\gamma\gamma}$**

CMS

- **STXS bin** assigned with **$p_{T\gamma\gamma}$ using ordering categorisation**
- Discrimination between ttH & tH achieved via **DNN**





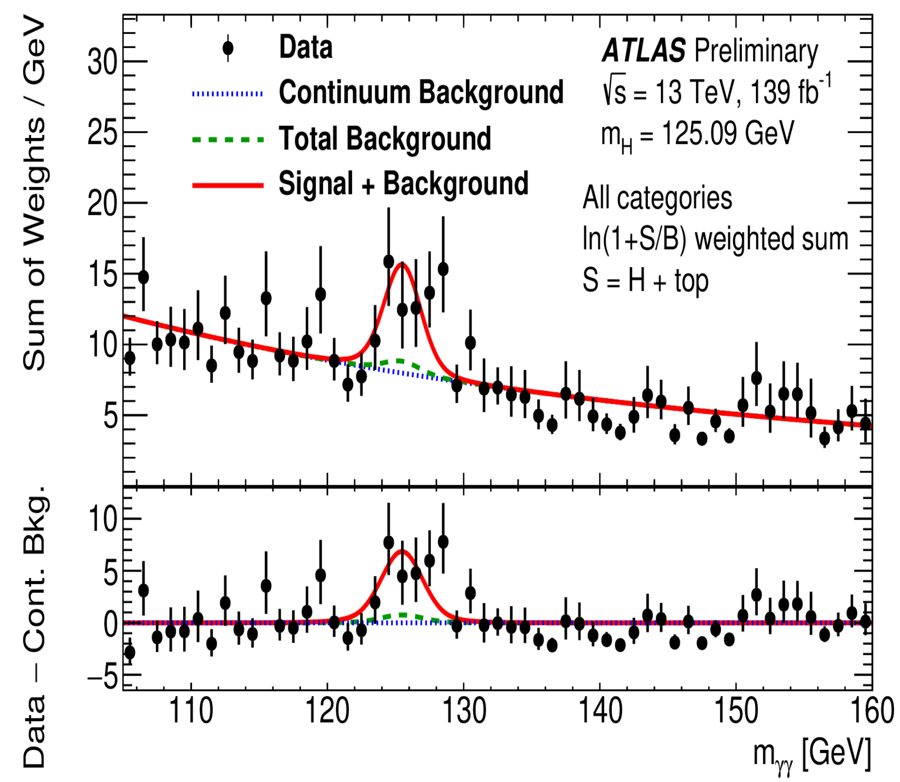


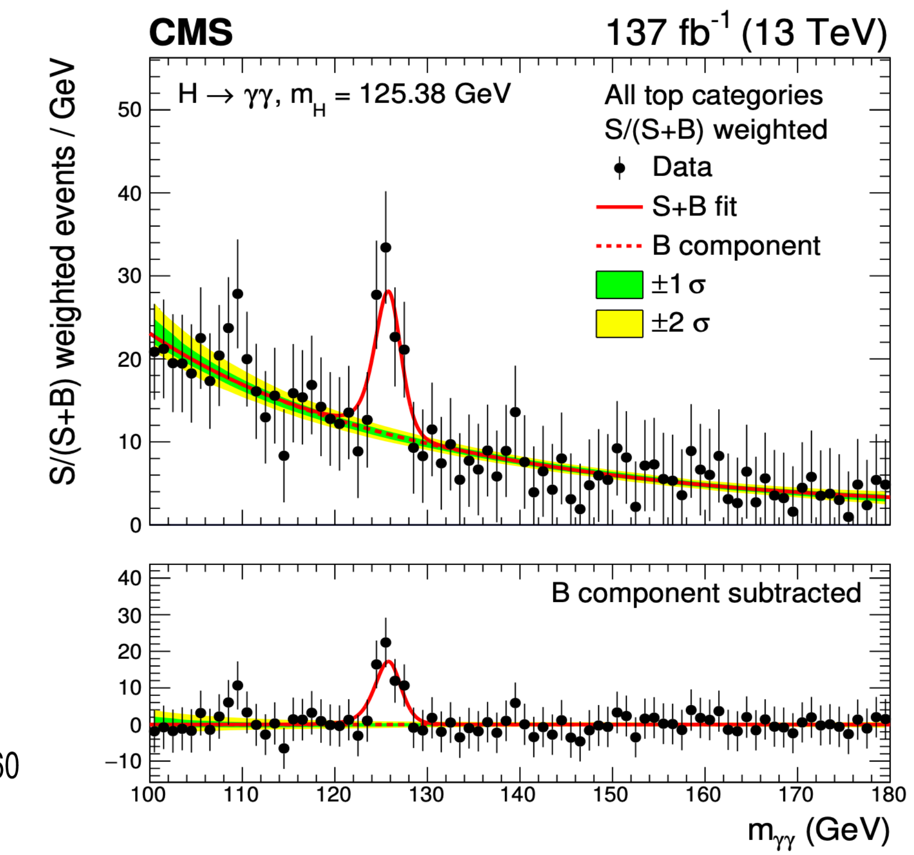
- **Two channels defined:** ttH hadronic and leptonic
- Categories within each class defined based in **background BDT score**
- **Diphoton vertex** identification using **BDT**
- Fit of **$m_{\gamma\gamma}$** used for signal extraction

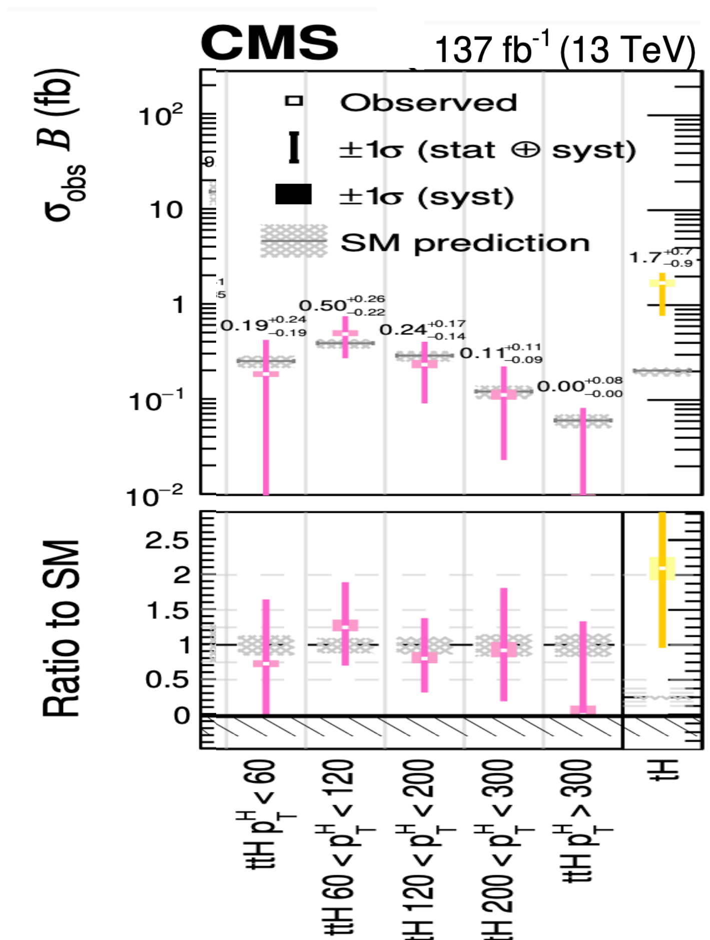
$H \to \gamma\gamma$

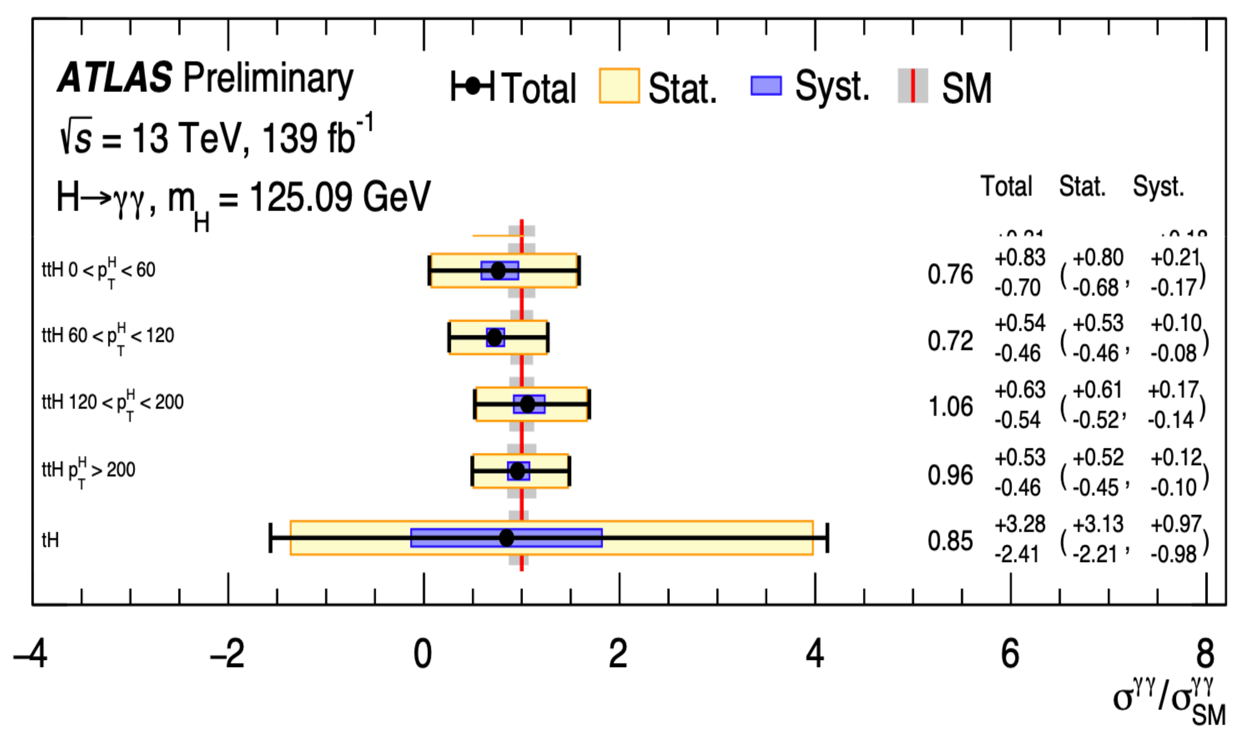
ATLAS-CONF-2020-026
JHEP 07 (2021) 027

- **Signal shape** in each analysis category **modelled from MC**
- ttH differential cross section measured in **4 p_T-bins:** last 3 high-p_T bins of the 1.2 STXS scheme merged into one
- **Background modelling** via **analytic function** to fit the background $m_{\gamma\gamma}$ distribution







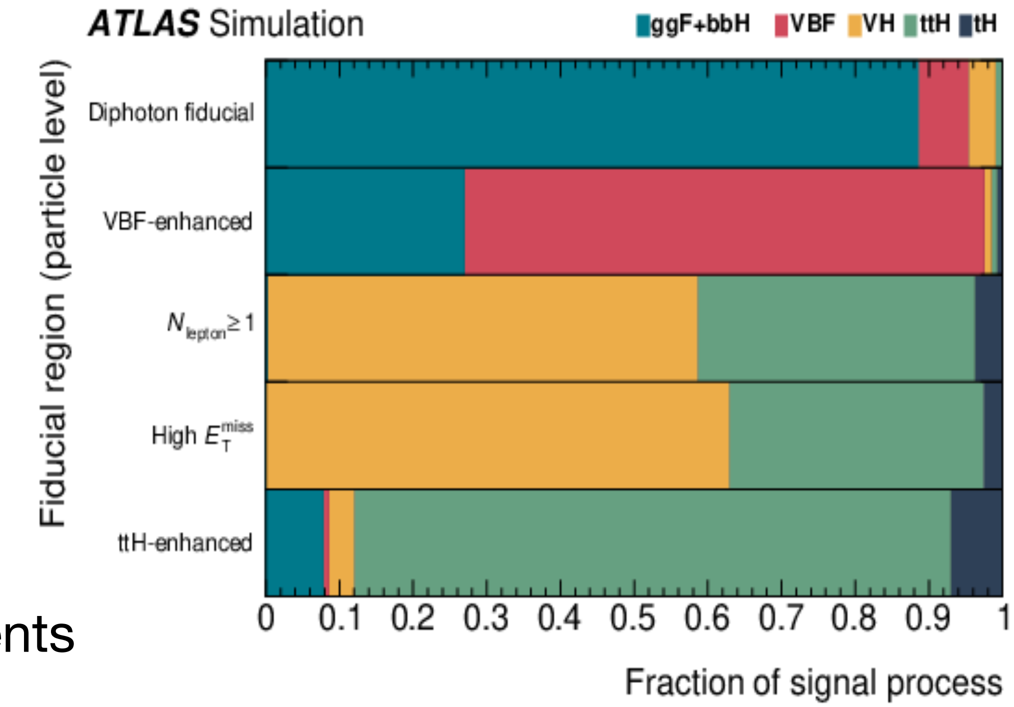


- **Statistically limited**: Uncertainties ~50-100%
- Stat. Limited measurements **in agreement with SM 95% CL upper limit on tH**:
  - ATLAS: 8 X SM
  - CMS: 14 X SM

H→γγ (fiducial differential measurement)   NEW! ATLAS-HIGG-2019-13 (submitted to JHEP)

Analysis strategy: Full Run 2 dataset (139 fb^{-1})

- Dedicated analysis to perform inclusive fiducial differential measurement **instead of STXS**
- Measured in **fiducial phase space** region defined by detector response **(unfolding)**: Reduced **model dependence**
- **Inclusive fiducial** + **20 differential** + **4 double differential** XS measurements



Matches reco selections: Identical to the STXS selections

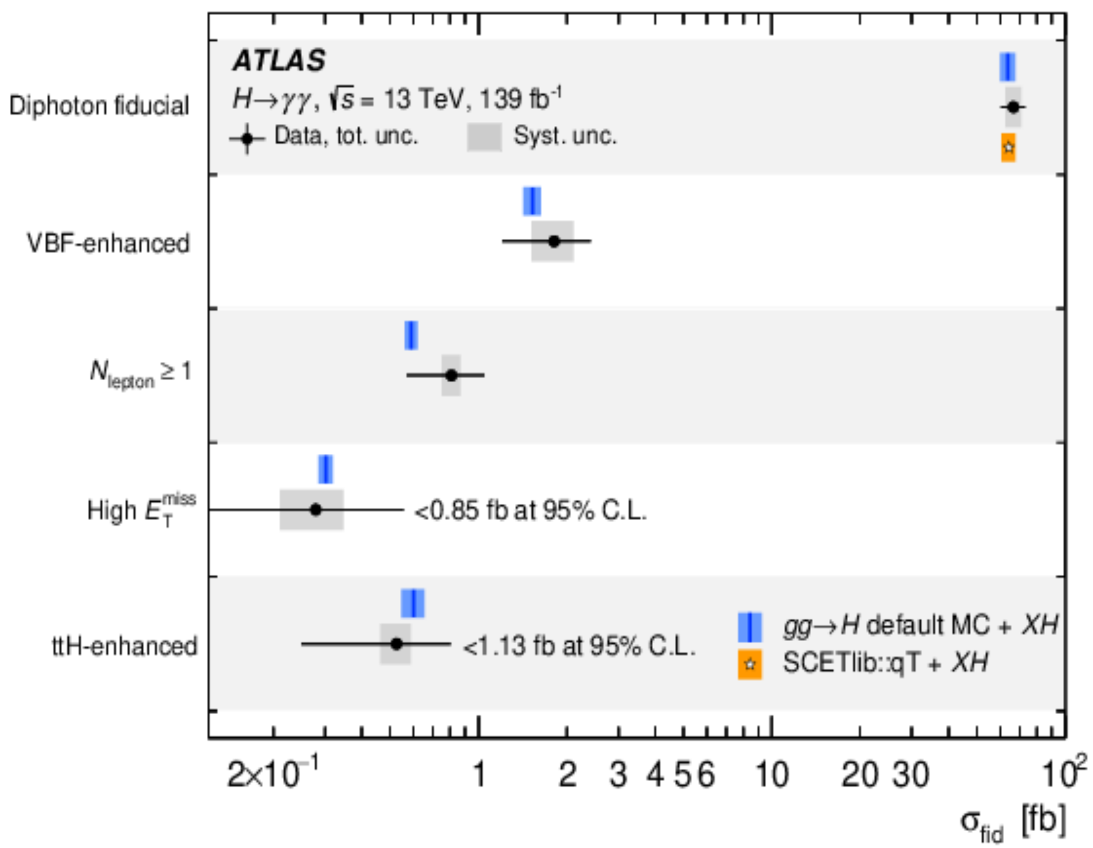
Fiducial region definition	
$p_T^{\gamma_1}/m_{\gamma\gamma}$	> 0.35
$p_T^{\gamma_2}/m_{\gamma\gamma}$	> 0.25
$\sum p_T^i/p_T^\gamma$	< 0.05

Photon isolation $\sum p_T^i$ is sum of the p_T of charged particles within Δr < 0.2 of γ

105 GeV < $m_{\gamma\gamma}$ < 160 GeV

$|\eta|$ < 1.37 or 1.52 < $|\eta|$ < 2.37

ttH enhanced region: ≥1 b-jet, (≥ 4jets & 0ℓ) or (≥3 jets & 1ℓ)



- Background in the Higgs boson signal extraction fit is **modelled analytically**
- Signal extraction via fit to **$m_{\gamma\gamma}$ distribution** in each **fiducial region**
- Dominated by **instrumental uncertainties** (photon and JES)

Observed fiducial **ttH enhanced region** XS: **0.53±0.27(stat)±0.06(sys) fb** compatible with SM **(0.6±0.05)**

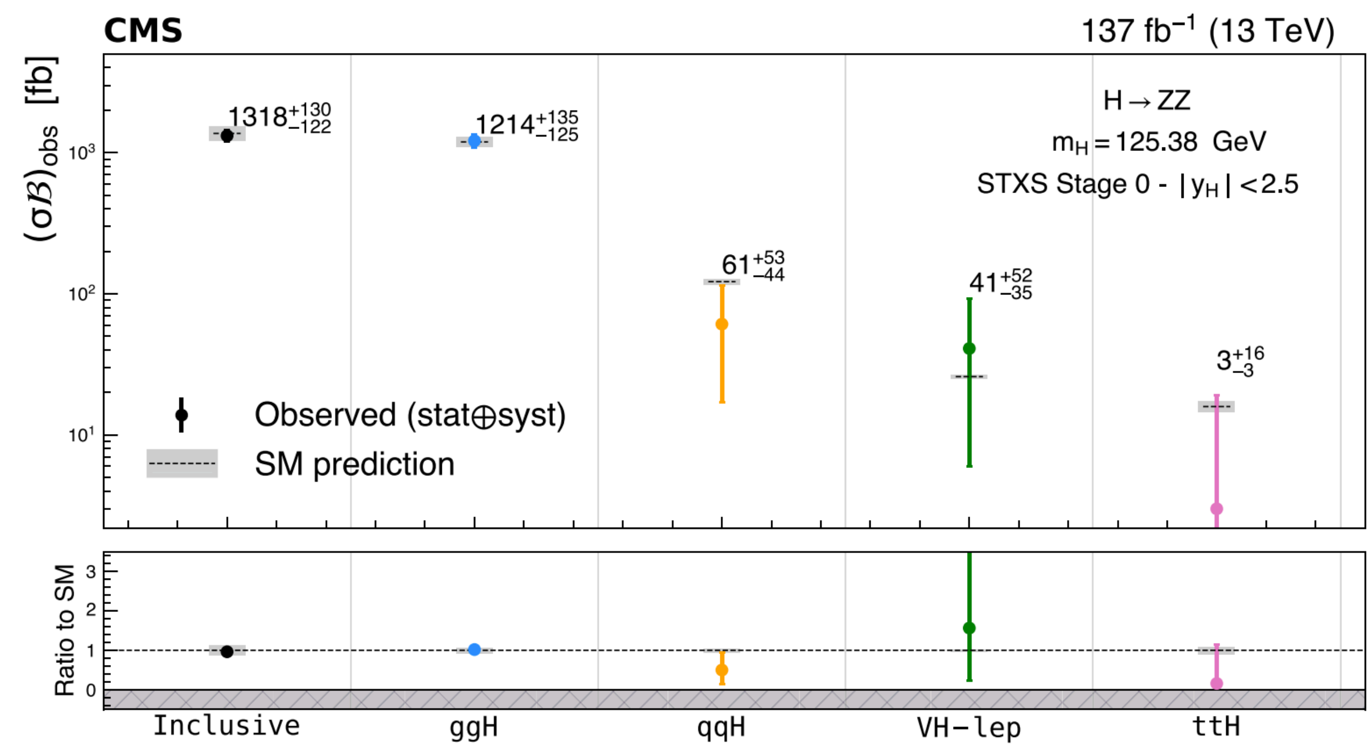
H→zz→4l

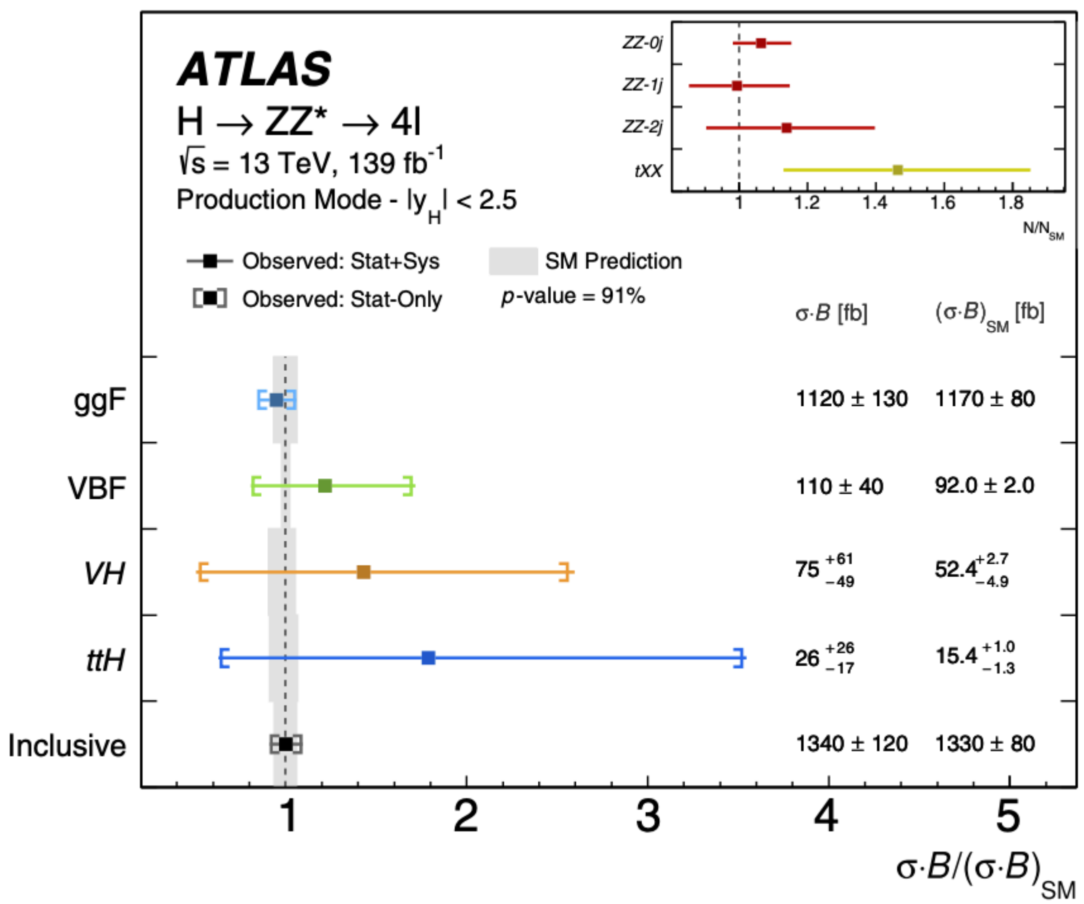
[Eur. Phys. J. C 80 (2020) 957](#)

[Eur. Phys. J. C 81 (2021) 488](#)

Analysis strategy: Full Run 2 dataset (ATLAS 139 fb^{-1}) / (CMS 137 fb^{-1})

- **Reconstruct Higgs boson** decay & **tag production mode** with dedicated categories
- **Two channels defined:** ttH hadronic and leptonic
- **Background sources:**
  - non-prompt leptons: **estimated from CRs**
  - ZZ shape estimated from MC





ATLAS

- **ttH-rich region**: 4ℓ + ≥ 1ℓ + ≥ 2 b-jet OR ≥ 2 jets ≥ 1 b-jet
- Background normalisation by data-driven technique
- **NN discriminants** separates different production modes, and signal and backgrounds

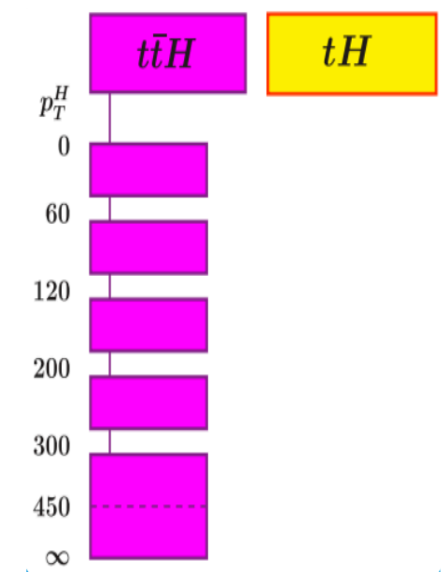
CMS

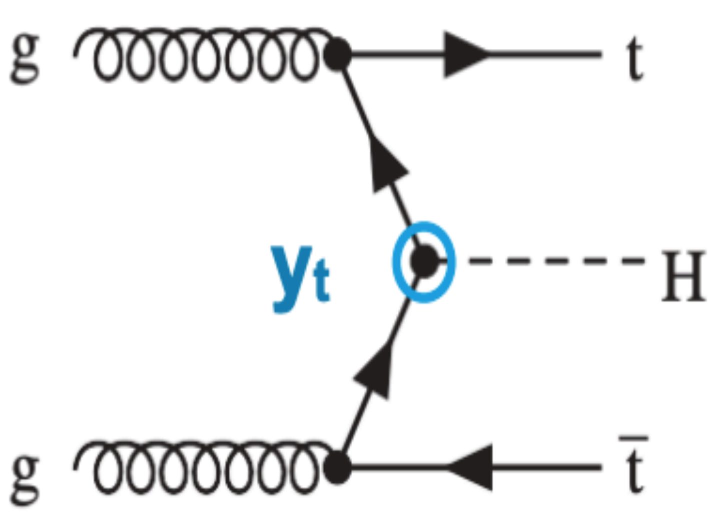
- **ttH-rich region**: 4ℓ + ≥ 1ℓ OR ≥ 4 jets, ≥ 1 b-jet
- Signal extraction in **2D fit $m_{4\ell}$ vs ME** output

Dominated uncertainties: Signal modelling, lepton ID

Conclusion

- **Measurement of ttH (and tH) production** is crucial in determining the Higgs boson's properties
- Experimentally challenging due to **small production cross section**
- Great progress has been made in the measurement of the top-Higgs associated production





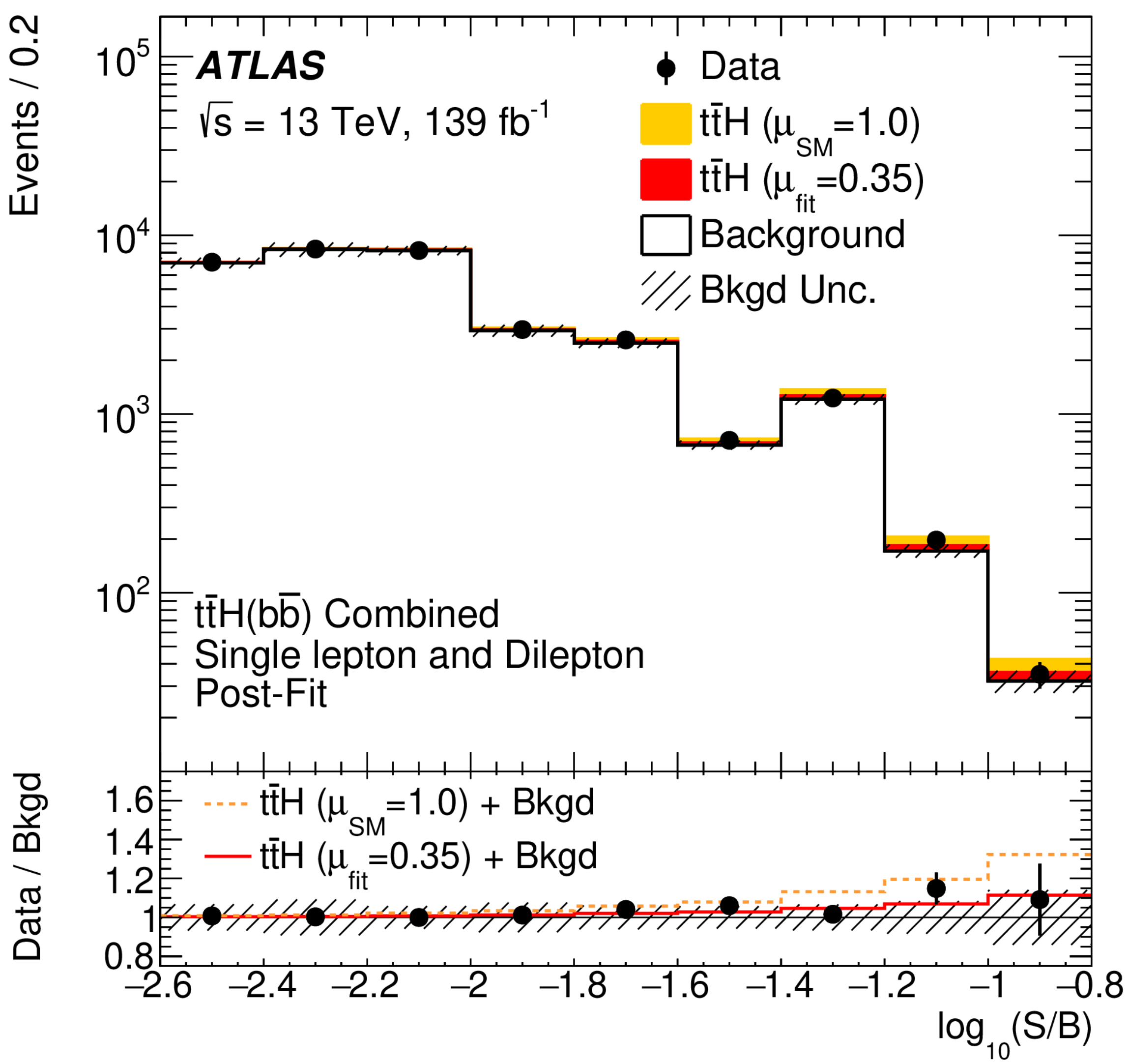
- Several ttH analyses are close to the observation in the single decay modes (multi-lepton, bb): **Improved dedicated measurement of the tt+HF and ttW backgrounds crucial**
- Looking forward to **Run 3** and beyond for precision measurements: Expect to profit from latest developments

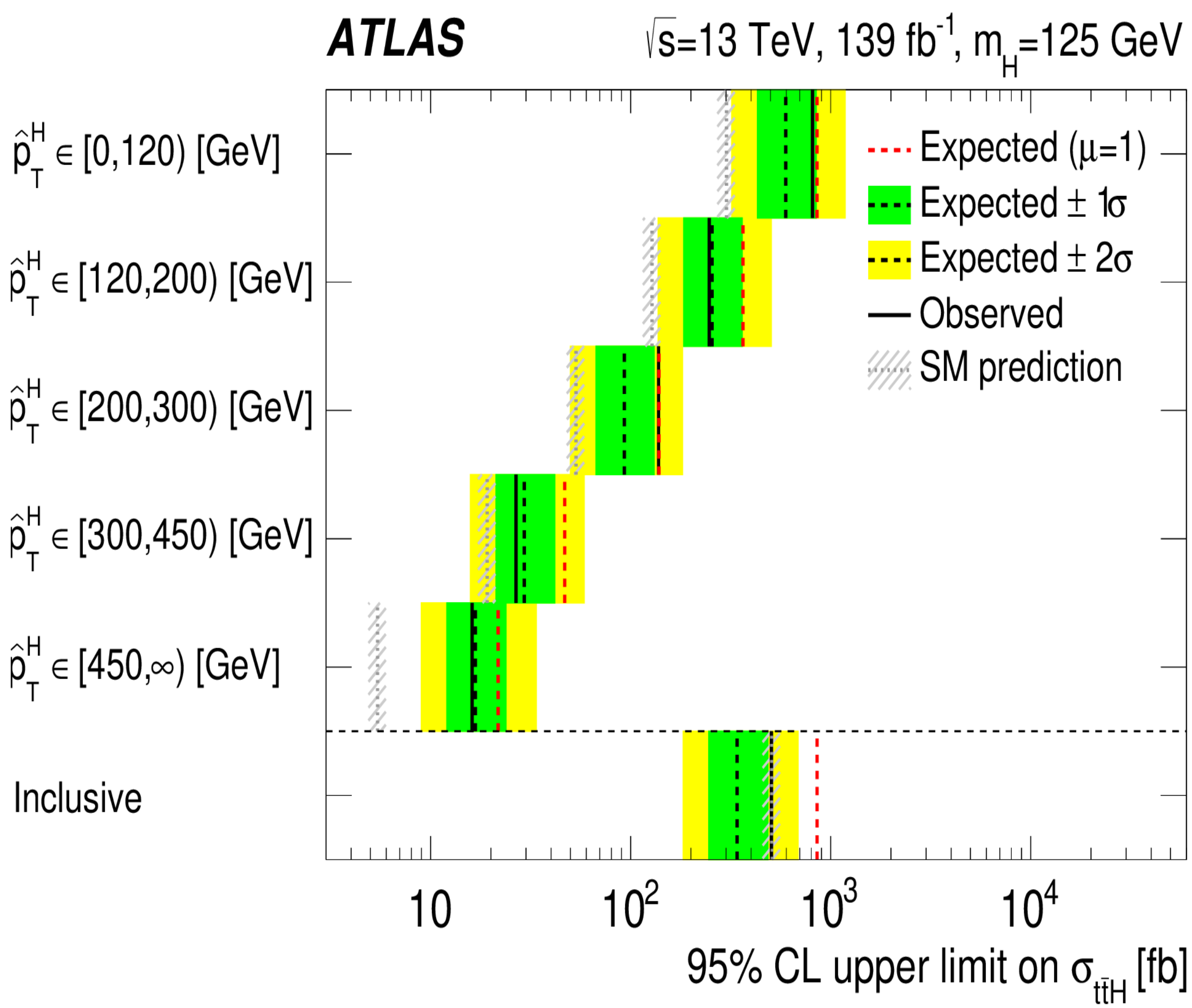
Thank you for your time!

Back-up

H→bb

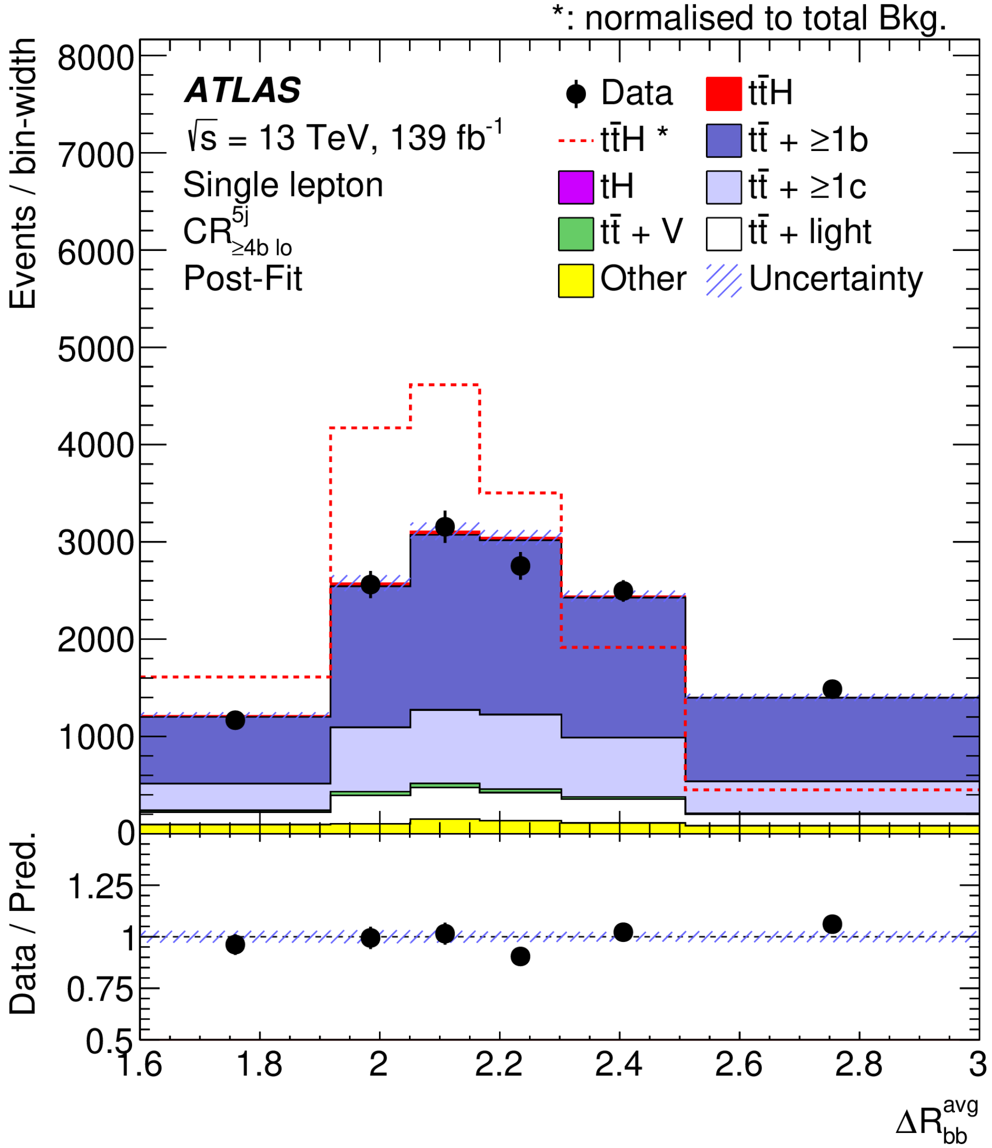
ATLAS-HIGG-2020-23 (submitted to JHEP)

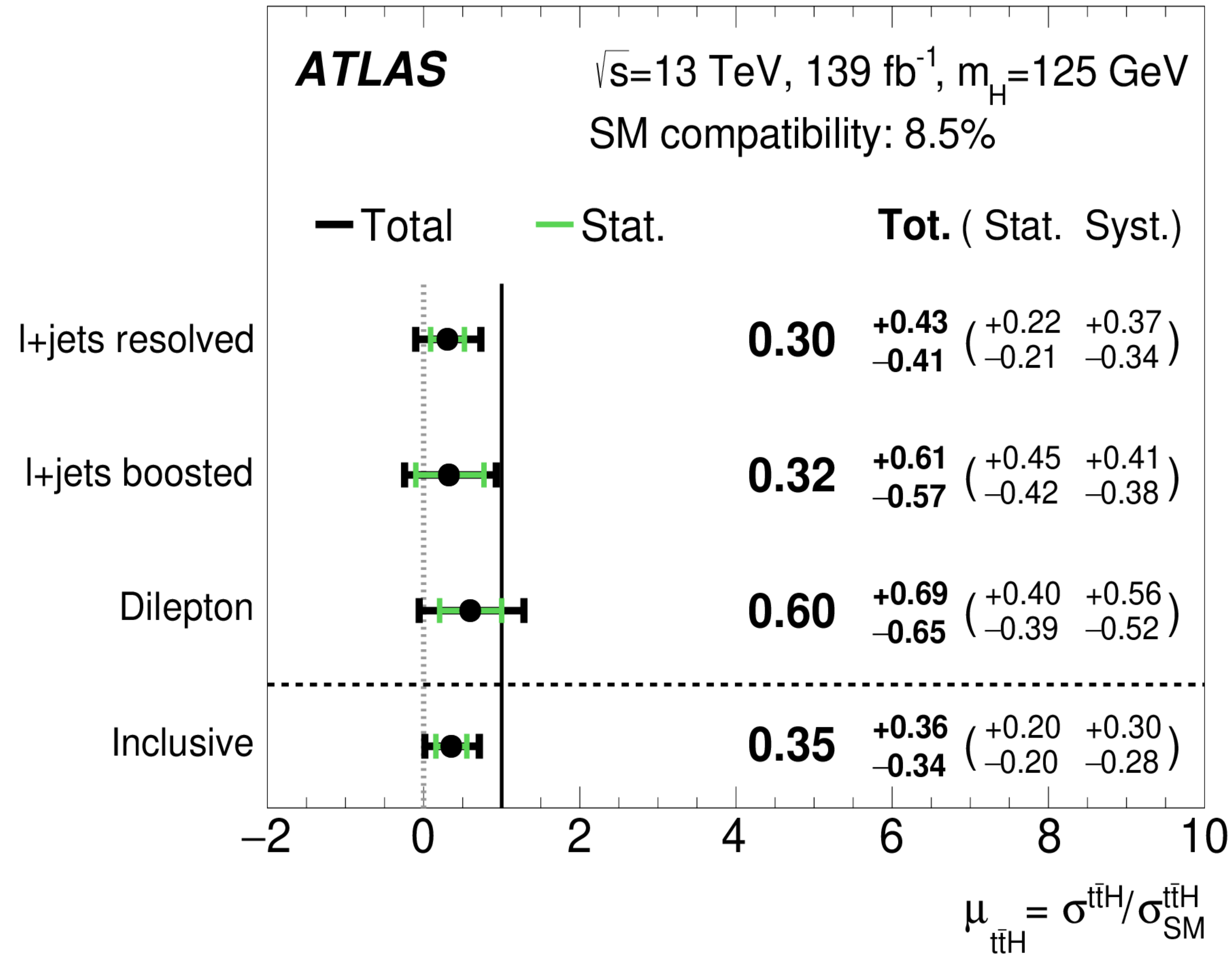




$H \rightarrow bb$

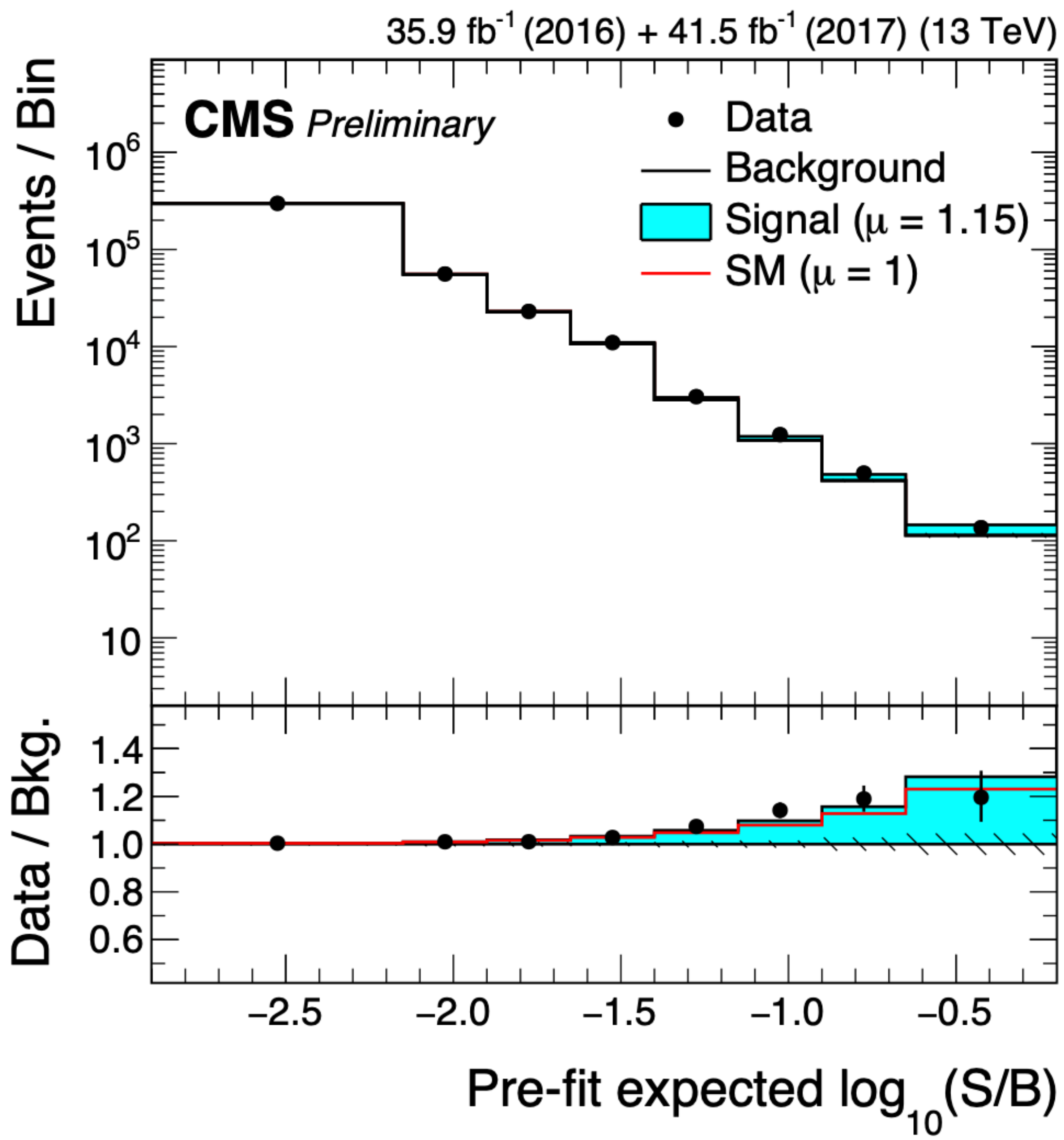
[ATLAS-HIGG-2020-23 (submitted to JHEP)](#)

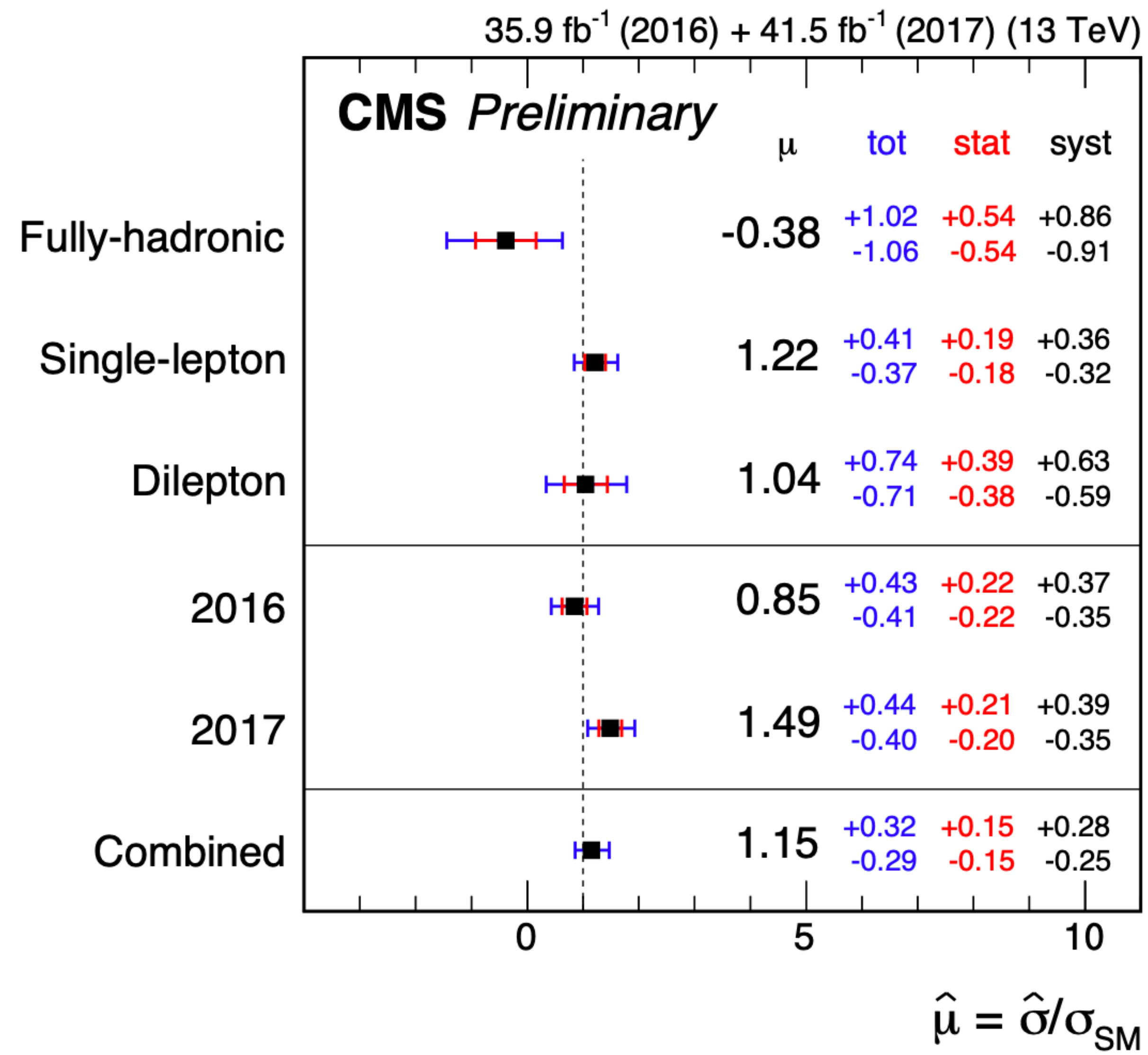




H→bb

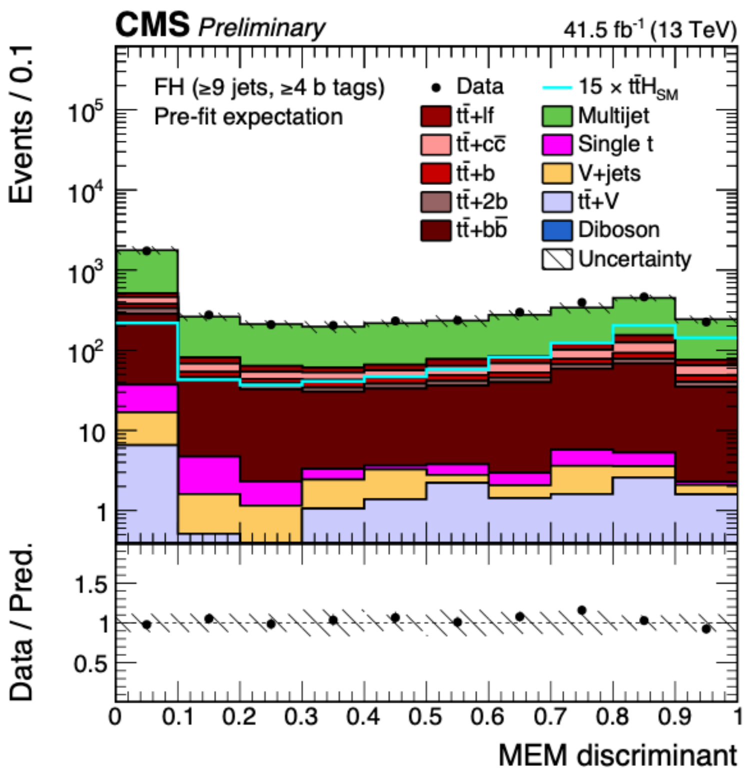
CMS-PAS-HIG-18-030

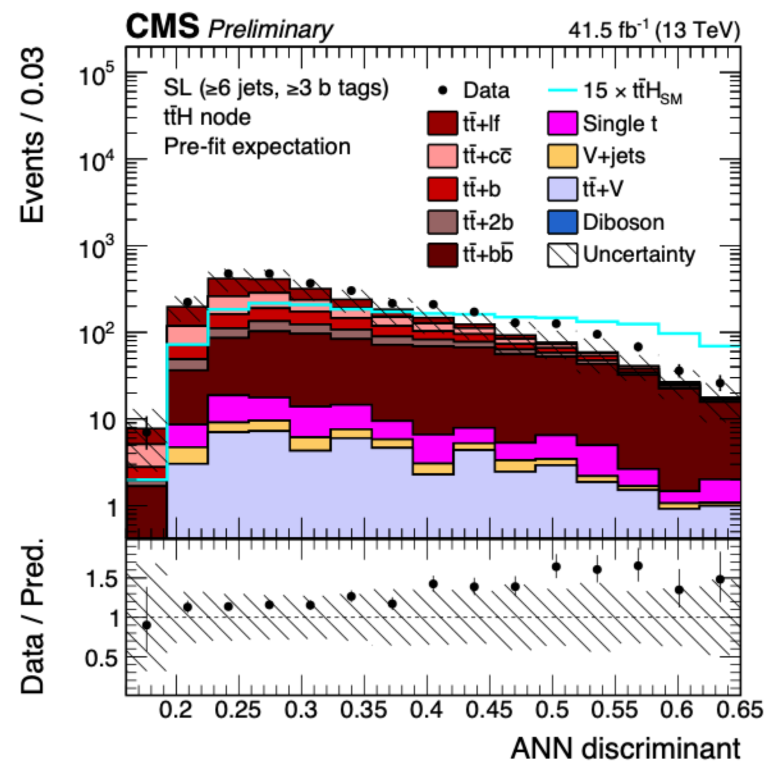


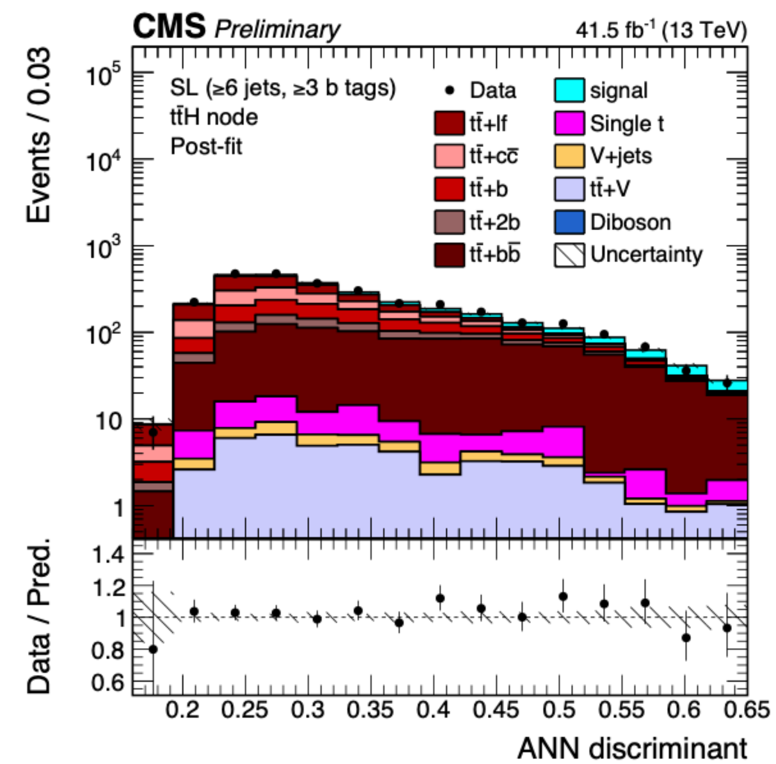


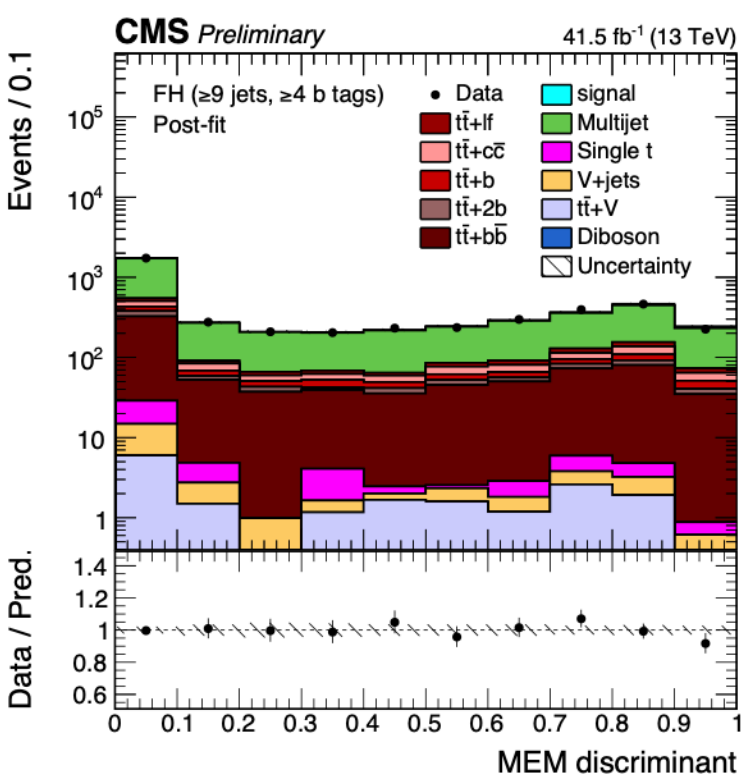
H→bb

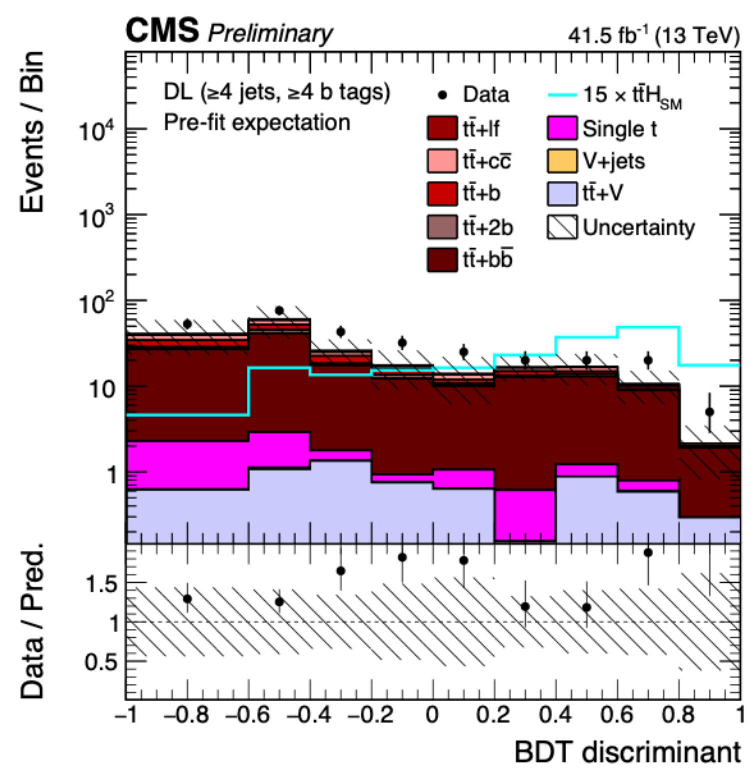
CMS-PAS-HIG-18-030

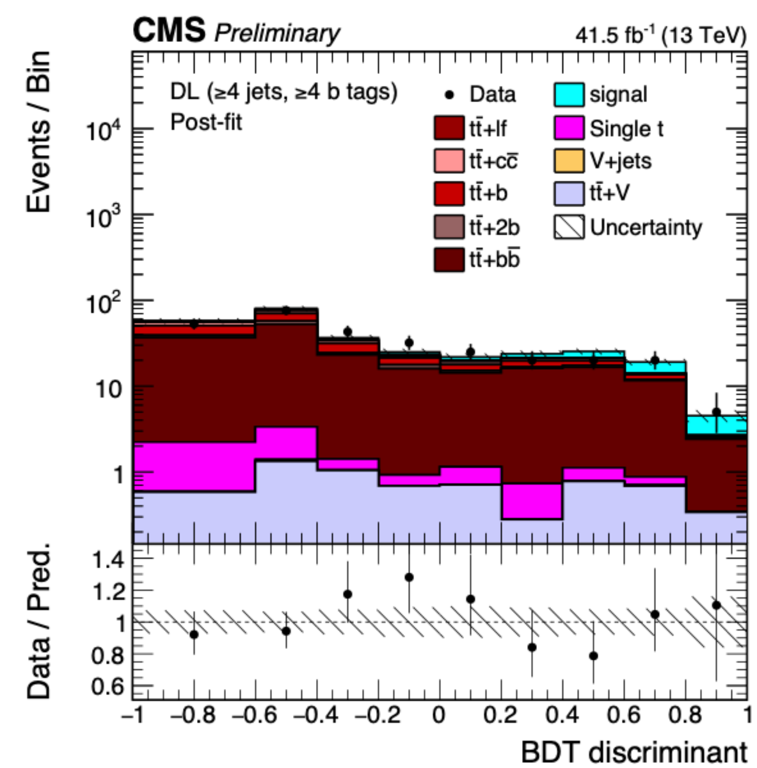






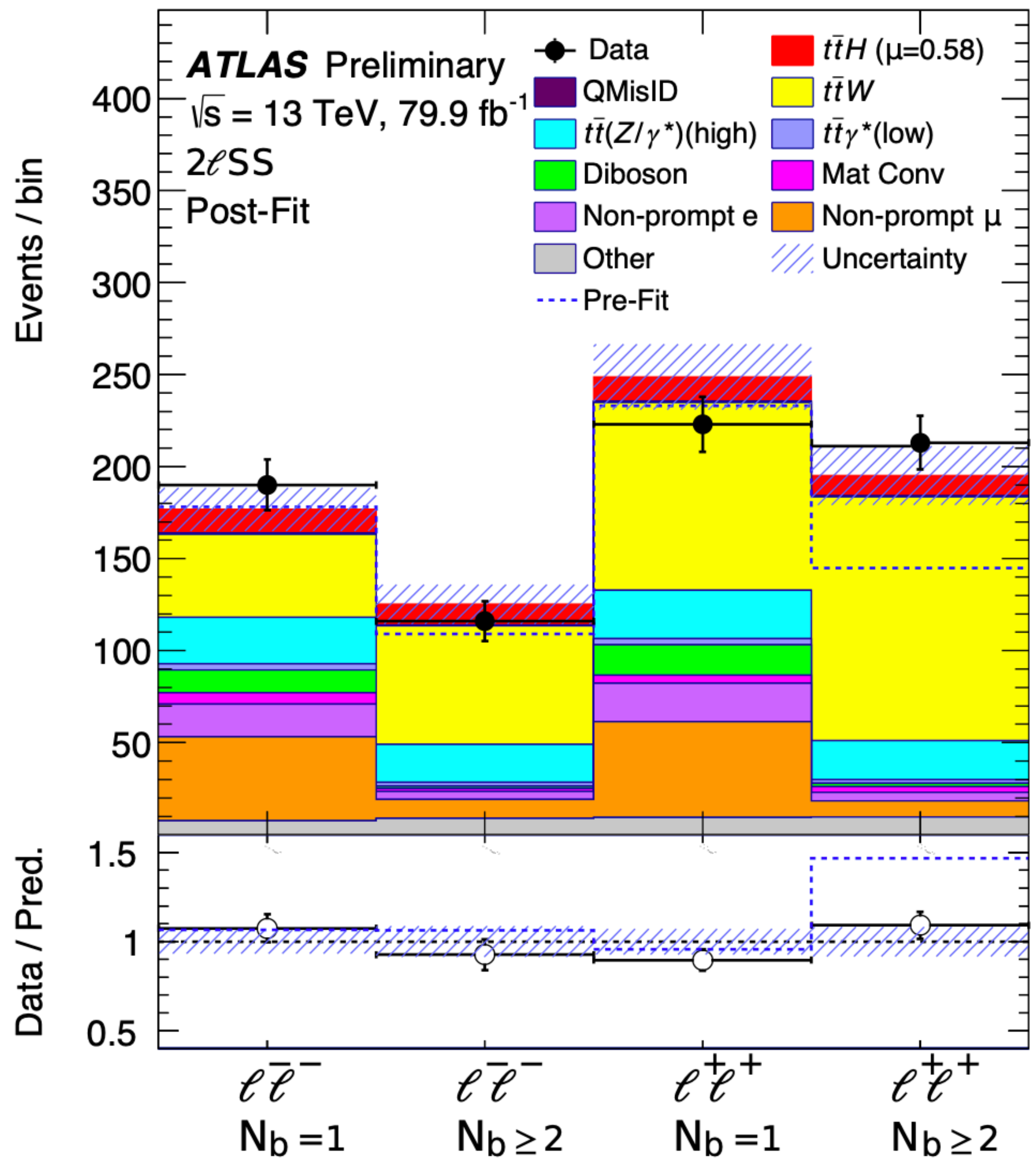


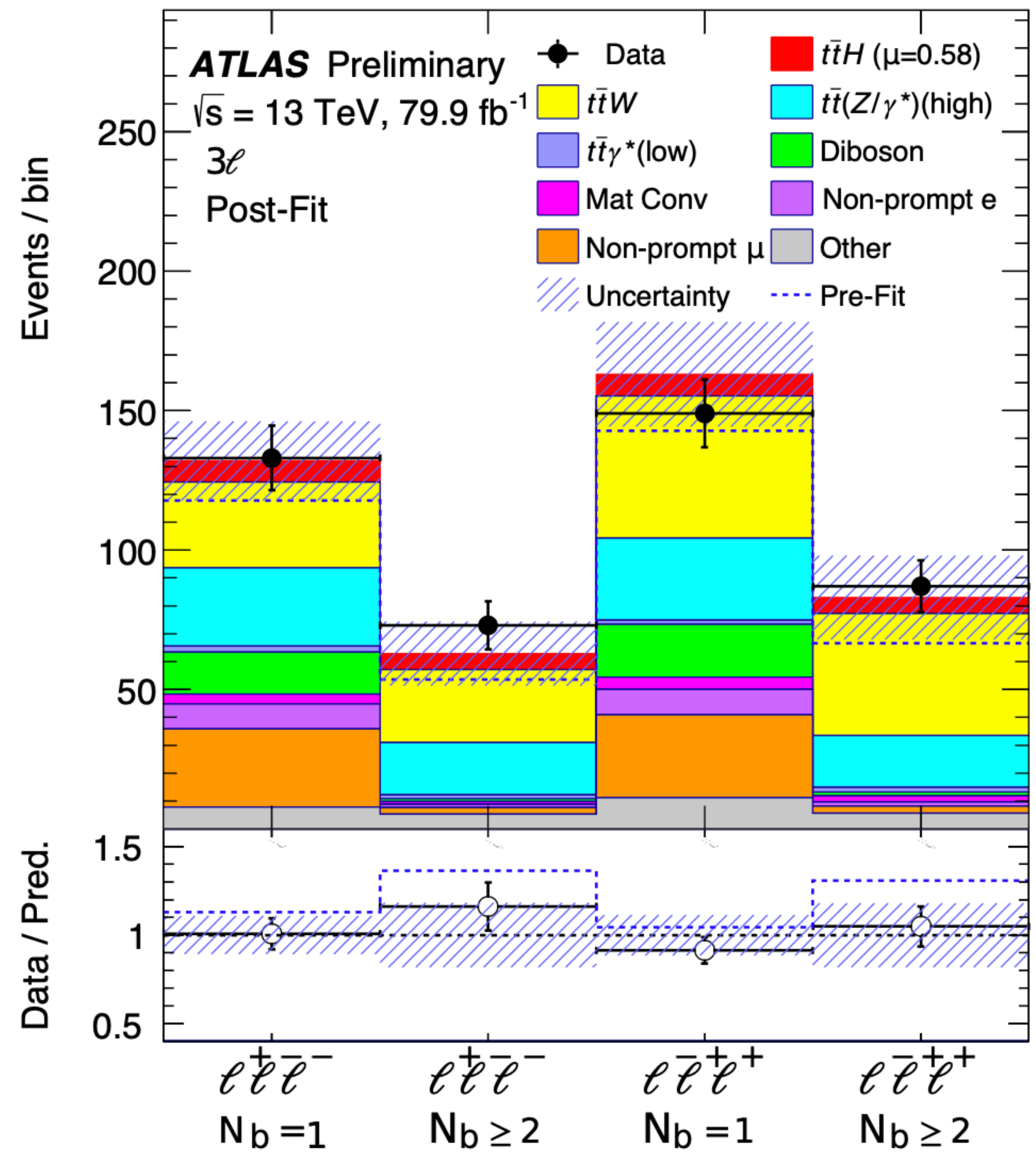




H→Multi-lepton

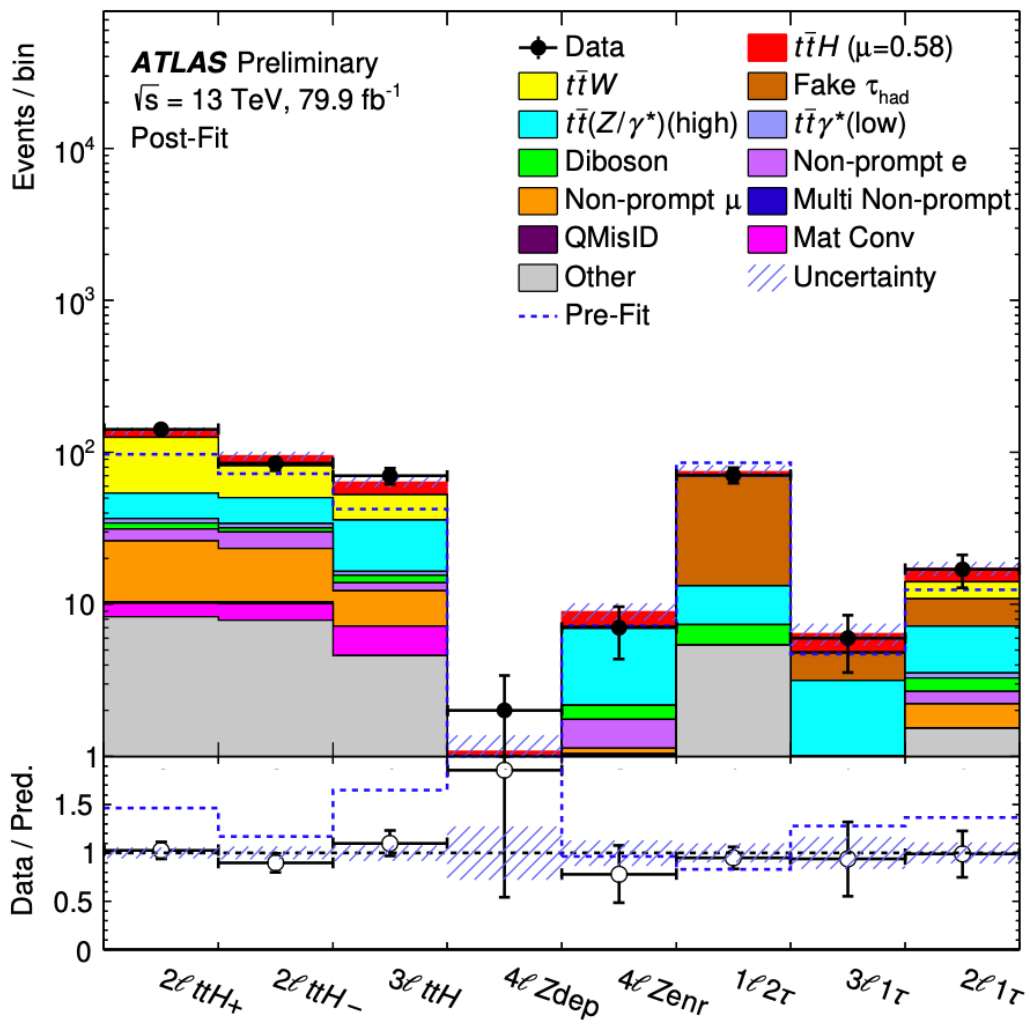
ATLAS-CONF-2019-045

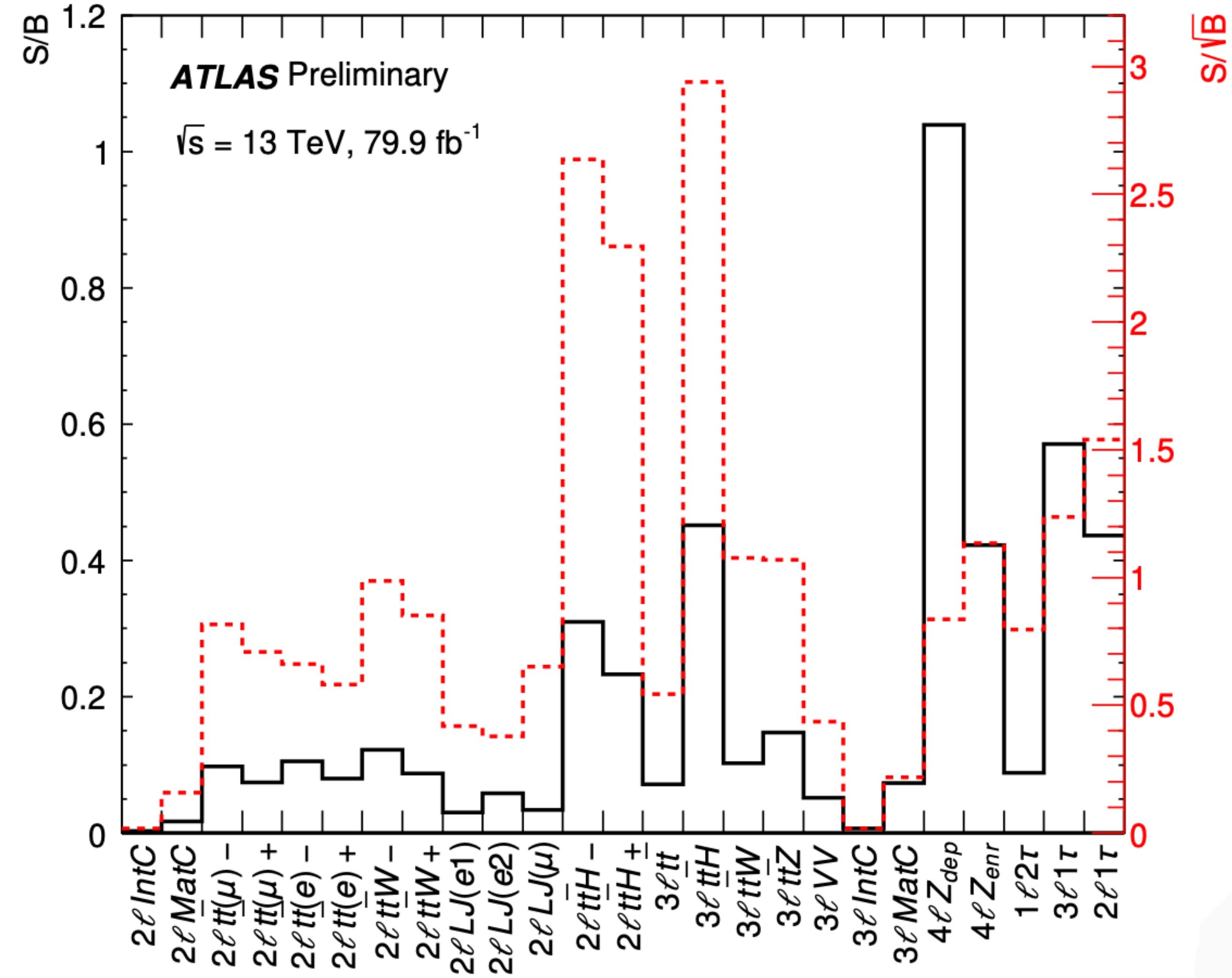




H→Multi-lepton

ATLAS-CONF-2019-045





H→Multi-lepton

ATLAS-CONF-2019-045

Uncertainty source	$\Delta\hat{\mu}$	
Jet energy scale and resolution	+0.13	−0.13
$t\bar{t}(Z/\gamma^*)$ (high mass) modelling	+0.09	−0.09
$t\bar{t}W$ modelling (radiation, generator, PDF)	+0.08	−0.08
Fake τ_{had} background estimate	+0.07	−0.07
$t\bar{t}W$ modelling (extrapolation)	+0.05	−0.05
$t\bar{t}H$ cross section	+0.05	−0.05
Simulation sample size	+0.05	−0.05
$t\bar{t}H$ modelling	+0.04	−0.04
Other background modelling	+0.04	−0.04
Jet flavour tagging and τ_{had} identification	+0.04	−0.04
Other experimental uncertainties	+0.03	−0.03
Luminosity	+0.03	−0.03
Diboson modelling	+0.01	−0.01
$t\bar{t}\gamma^*$ (low mass) modelling	+0.01	−0.01
Charge misassignment	+0.01	−0.01
Template fit (non-prompt leptons)	+0.01	−0.01
Total systematic uncertainty	+0.25	−0.22
Intrinsic statistical uncertainty	+0.23	−0.22
$t\bar{t}W$ normalisation factors	+0.10	−0.10
Non-prompt leptons normalisation factors (HF, material conversions)	+0.05	−0.05
Total statistical uncertainty	+0.26	−0.25
Total uncertainty	+0.36	−0.33

H→Multi-lepton

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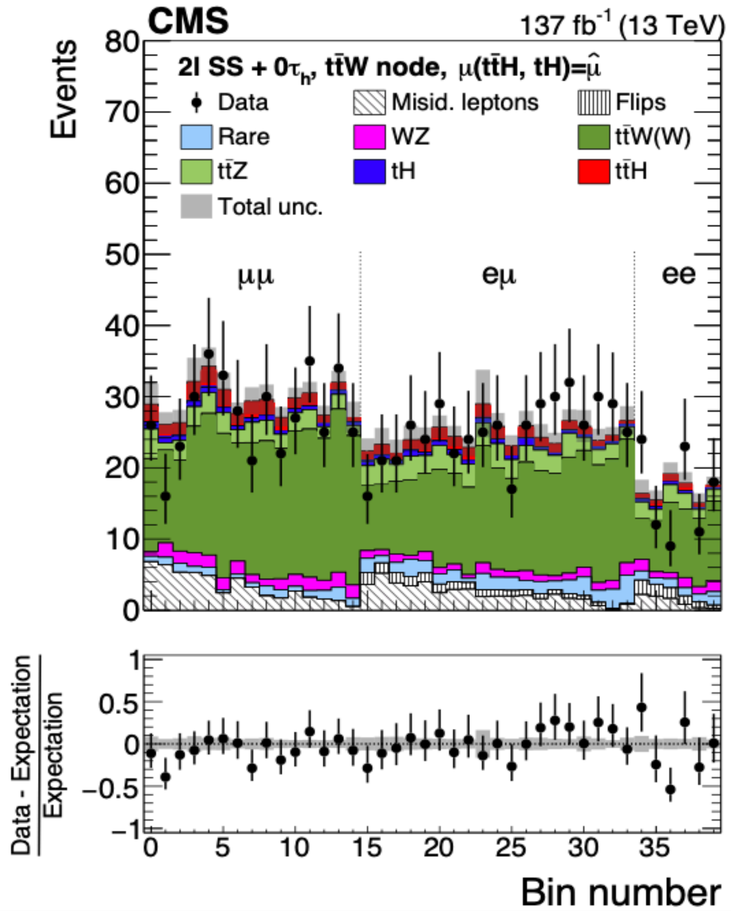

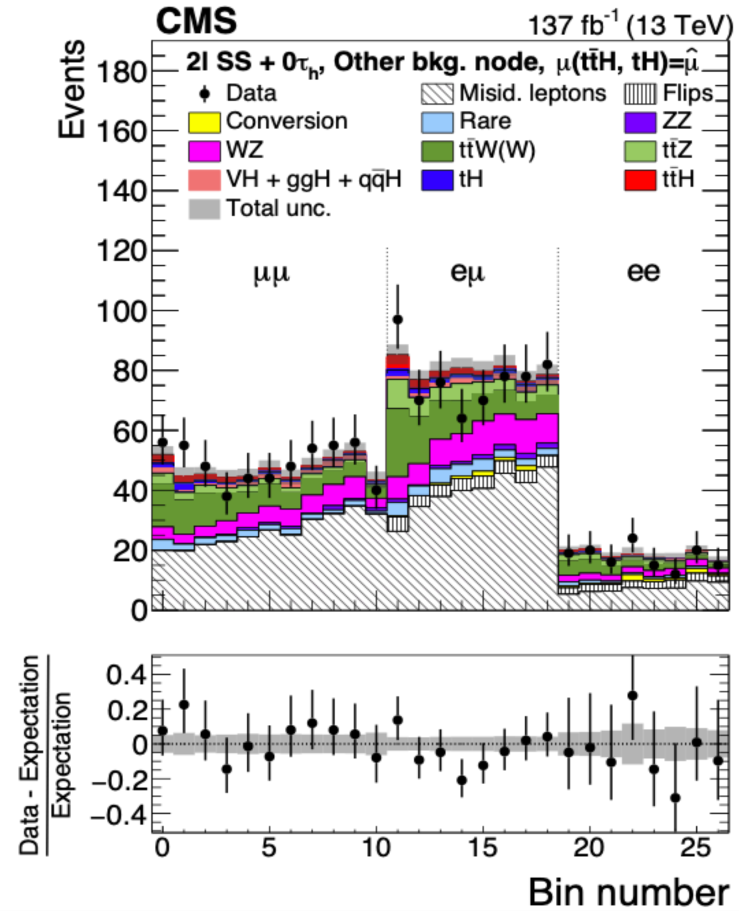

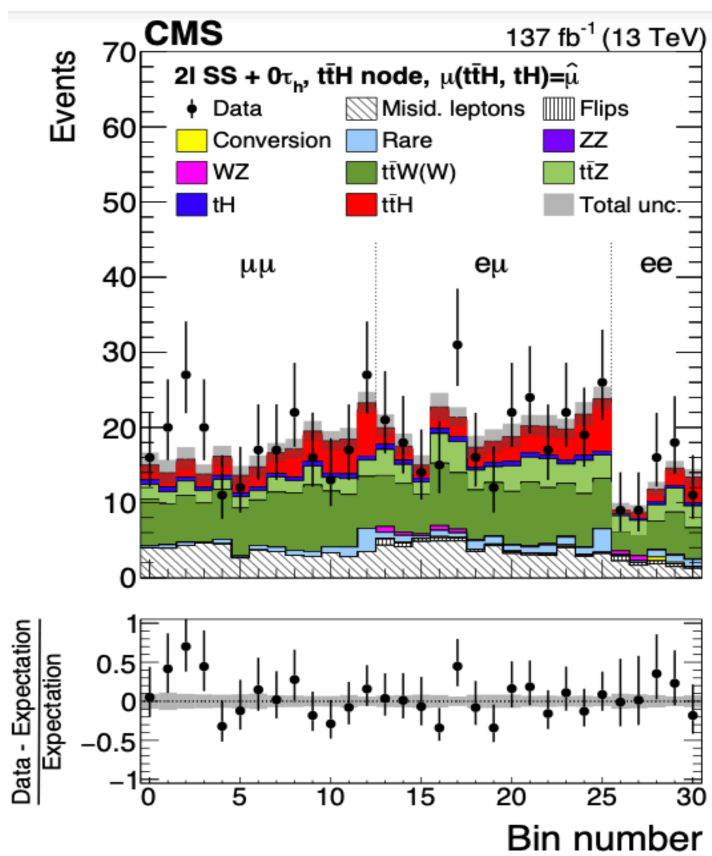

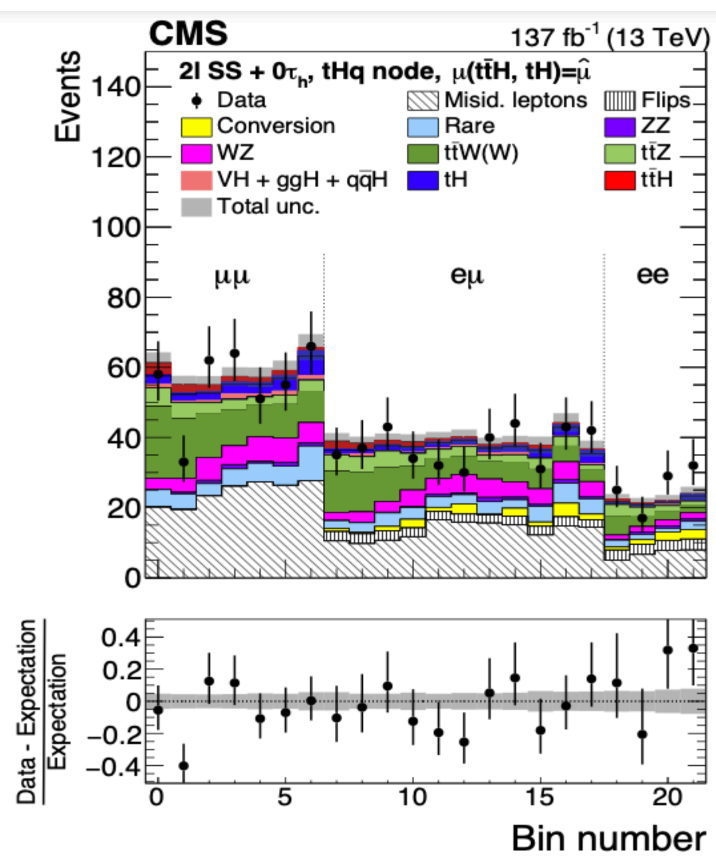

H → Multi-lepton

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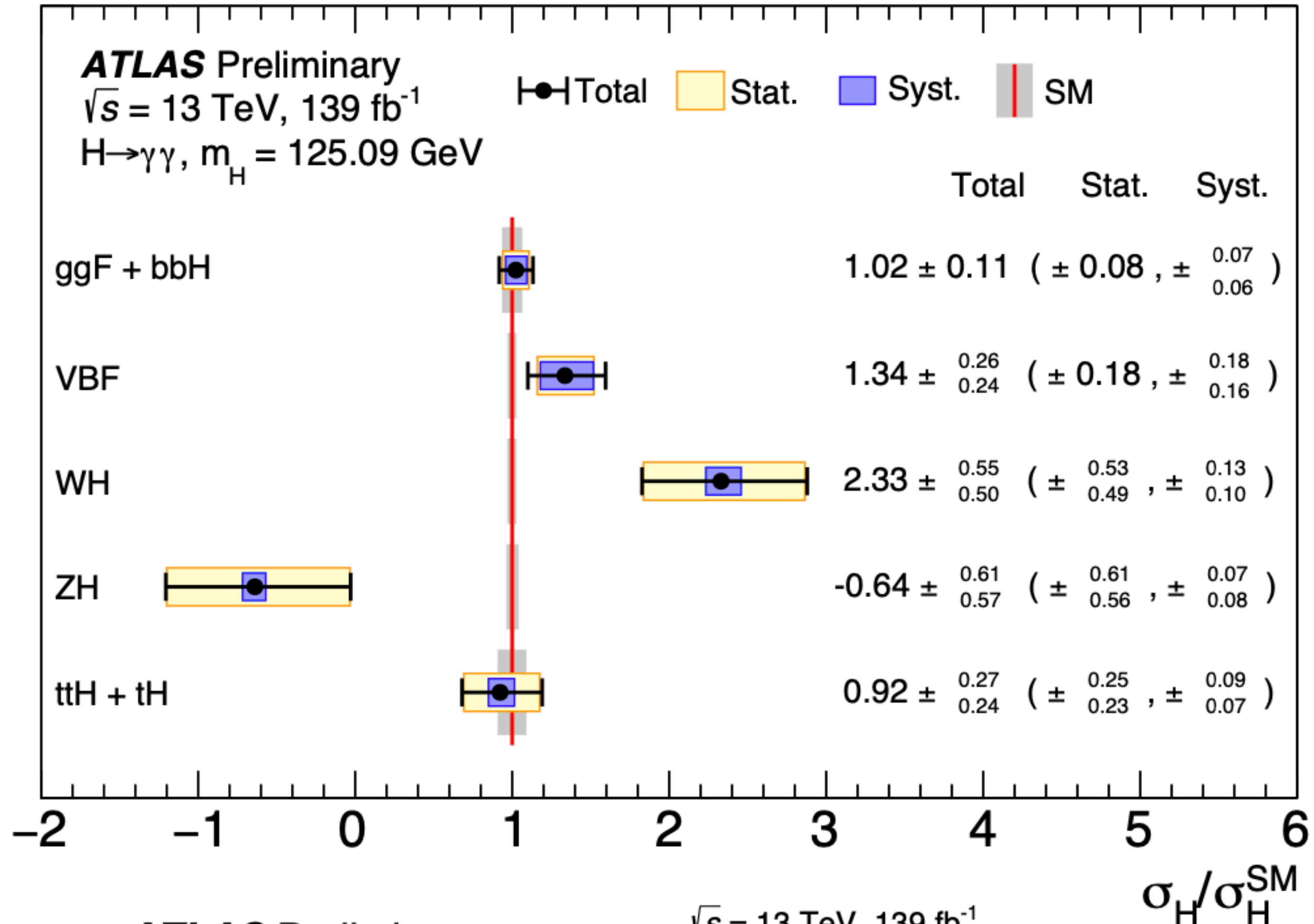
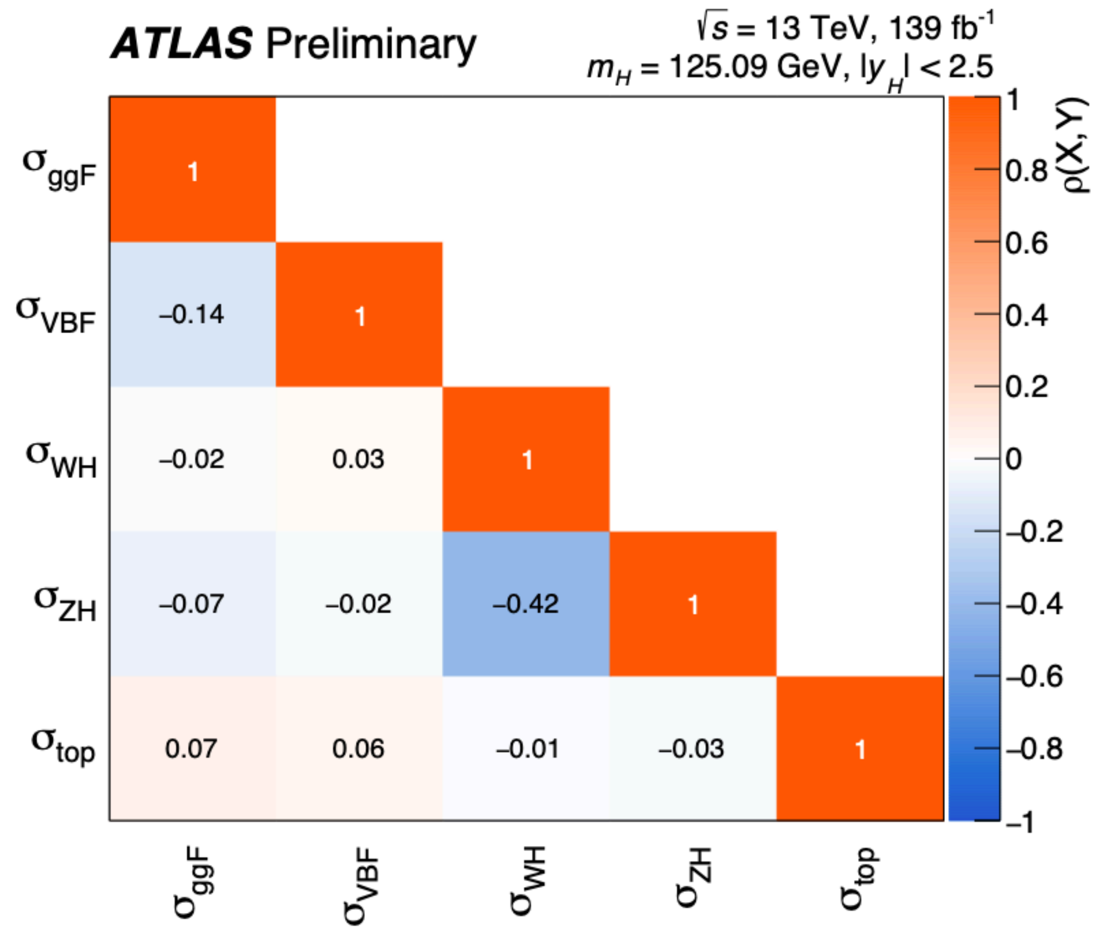
Source	$\Delta\mu_{t\bar{t}H}/\mu_{t\bar{t}H}$ [%]	$\Delta\mu_{tH}/\mu_{tH}$ [%]	$\Delta\mu_{t\bar{t}W}/\mu_{t\bar{t}W}$ [%]	$\Delta\mu_{t\bar{t}Z}/\mu_{t\bar{t}Z}$ [%]
Trigger efficiency	2.3	8.1	1.2	1.9
e, μreconstruction and identification efficiency	2.9	7.1	1.7	3.2
τ_h identification efficiency	4.6	9.1	1.7	1.3
b tagging efficiency and mistag rate	3.6	13.6	1.3	2.9
Misidentified leptons and flips	6.0	36.8	2.6	1.4
Jet energy scale and resolution	3.4	8.3	1.1	1.2
MC sample and sideband statistical uncertainty	7.1	27.2	2.4	2.3
Theory-related sources	4.6	18.2	2.0	4.2
Normalization of MC-estimated processes	13.3	12.3	13.9	11.3
Integrated luminosity	2.2	4.6	1.8	3.1
Statistical uncertainty	20.9	48.0	5.9	5.8

H→ γ γ

ATLAS-CONF-2020-026





H→ γ γ

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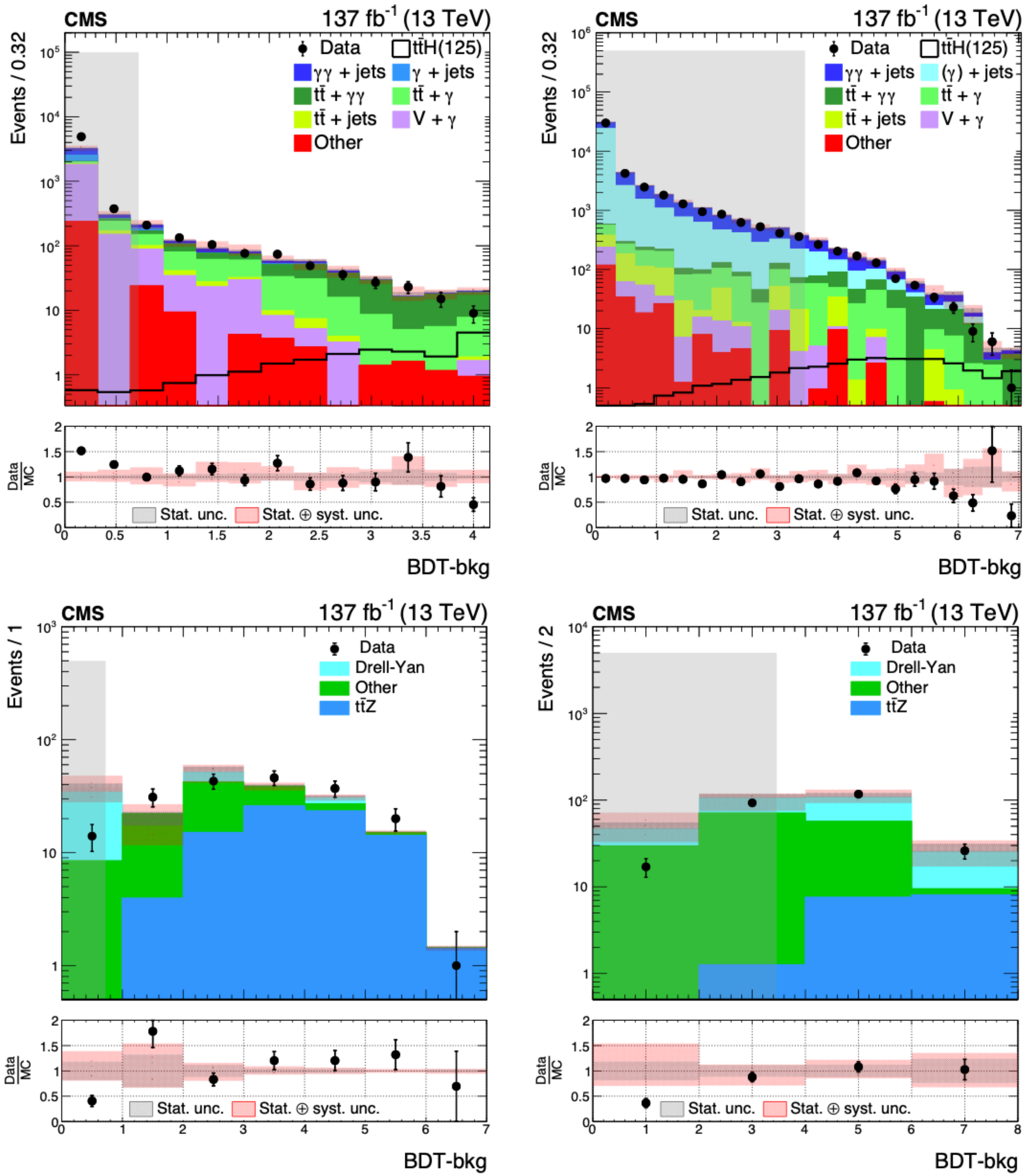

$H \rightarrow ZZ \rightarrow 4l$

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