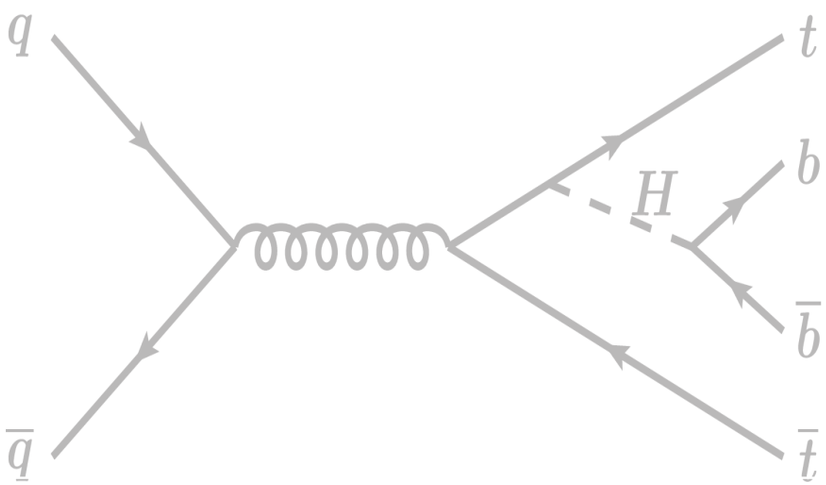
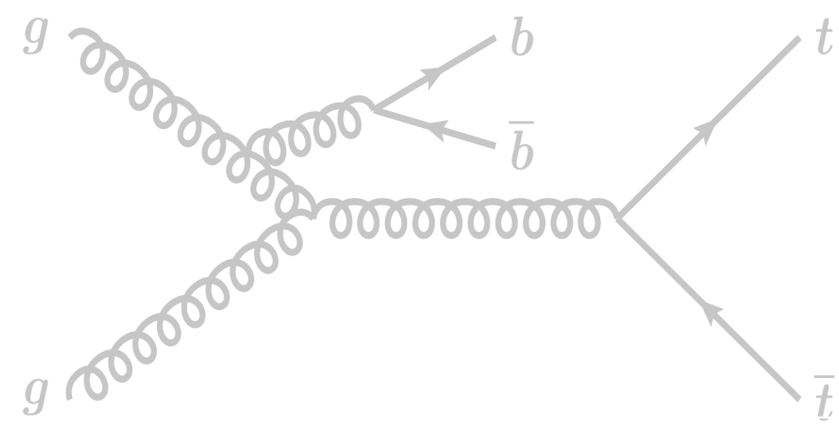
Differential and CP measurements in ttH/tH (H→bb) with ATLAS





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On behalf of ATLAS Collaboration

Higgs Hunting 2022

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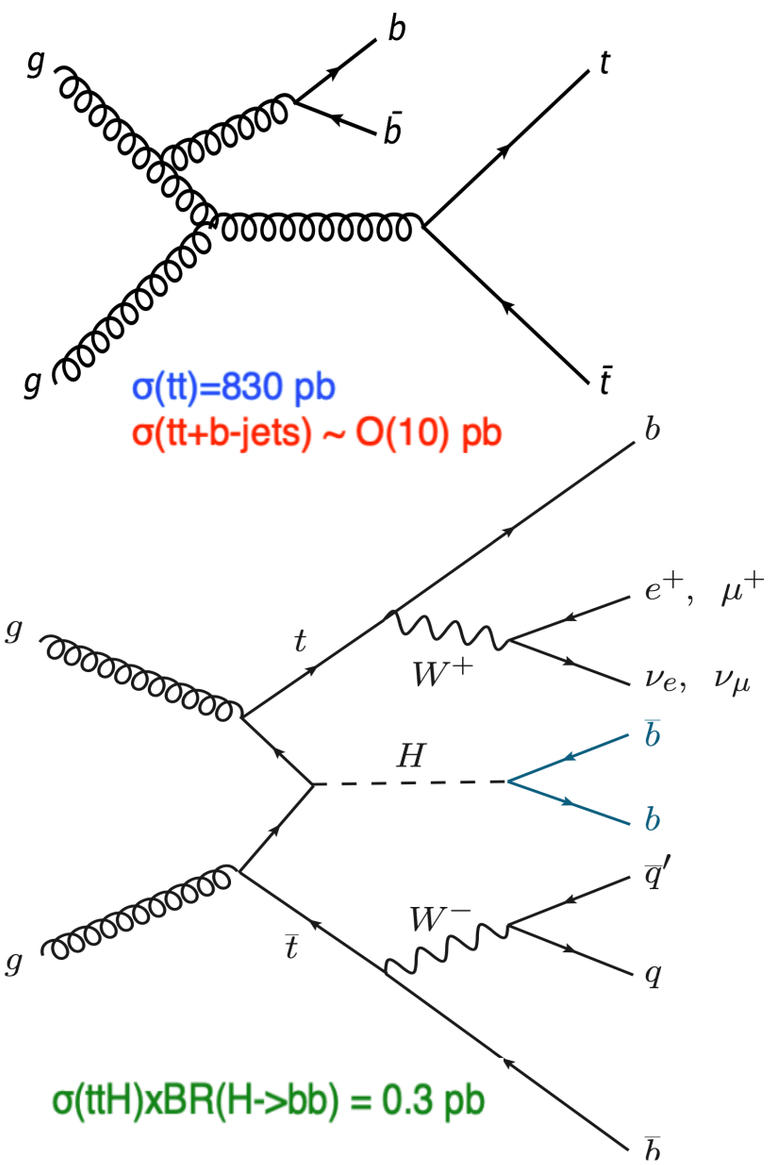
Introduction

Higgs Boson discovery → precision measurements !

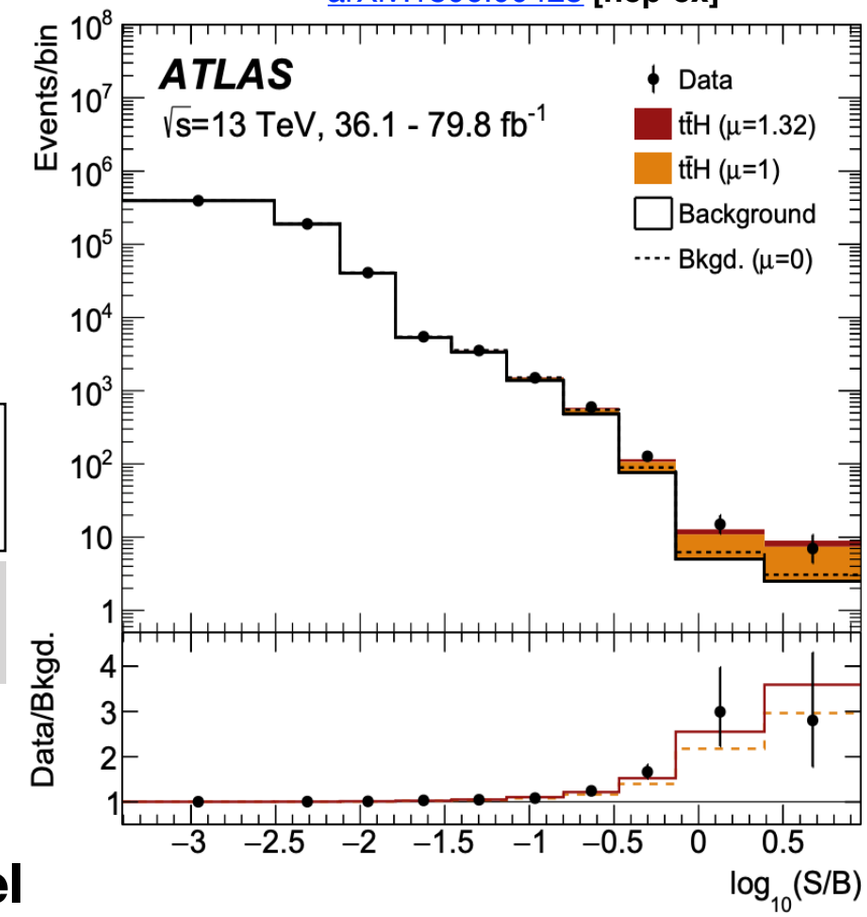
- **ttH production** provides direct access to **top-Higgs Yukawa coupling y_t** ⇒ sensitive to **potential New Physics**
- ttH production also allows to **probe the CP structure** of y_t

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)

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



ttH(H →bb) leptonic channel

- Exploits the **large branching ratio** of H→bb (**58%**) and the **leptonic decays of top quarks** ⇒ distinctive signature
- **Two channels** based on the number of leptons in the final state: **single-lepton** and **di-lepton**

Challenges:

- **Modelling of tt+HF background** due to large irreducible background with big theoretical uncertainty (from tt+bb)
- Higgs boson reconstruction challenging due to **b-jet combinatorics**

ttH/tH(H →bb): CP mixing

Lagrangian can be expressed as a superposition of CP-even and a CP-odd terms

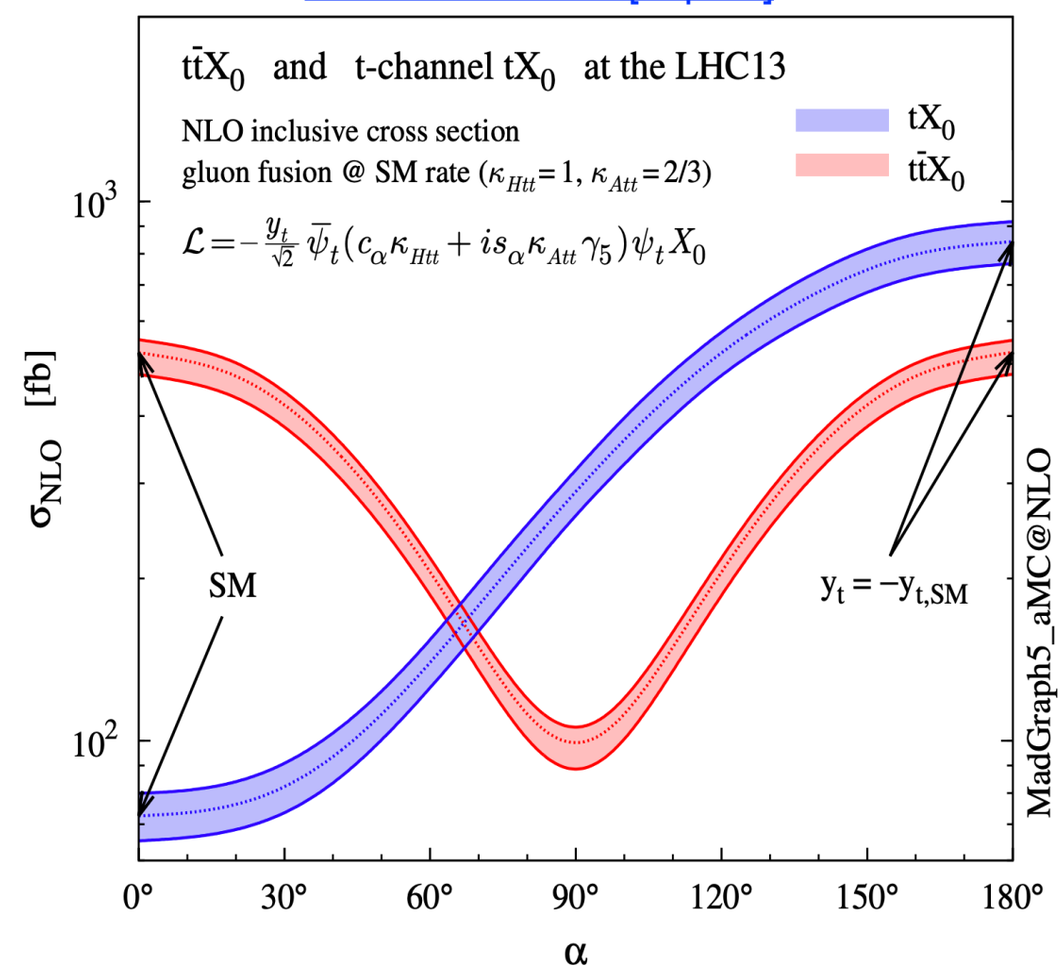
$$\mathcal{L}'_{t\bar{t}H} = -\kappa'_t y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$

Pure CP-even Pure CP-odd

- Admixtures of CP-even and CP-odd are still allowed experimentally.
- **CP mixing** parametrised via mixing angle **α** and **coupling strength modifier κ'$_t$**
- **Choice of** α **and κ'$_t$** → affects the **cross section (XS)** and **kinematical properties** of ttH/tH processes
- **Kinematic differences** between the **pure CP-even** and **pure CP-odd** can be exploited to **discriminate** between them

- **tH production** is also powerful probe → challenging due to low XS but **sensitive to relative sign** of **H-t** and **H-W** interaction

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



- **ttH** process **symmetric** around **pure CP coupling (α = 90°)** → **not sensitive** to **difference** between the **SM (α = 0) and inverse (α = 180°)** coupling

ttH (H→bb): Differential measurement

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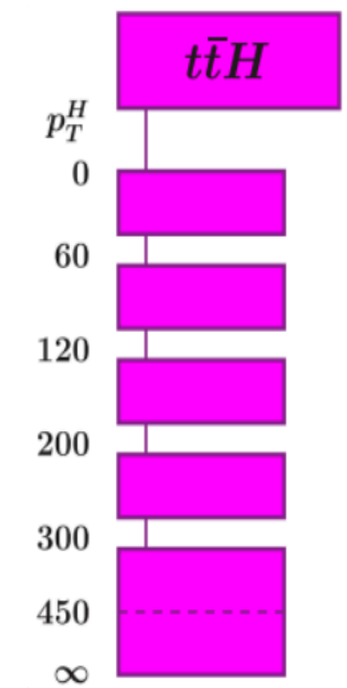
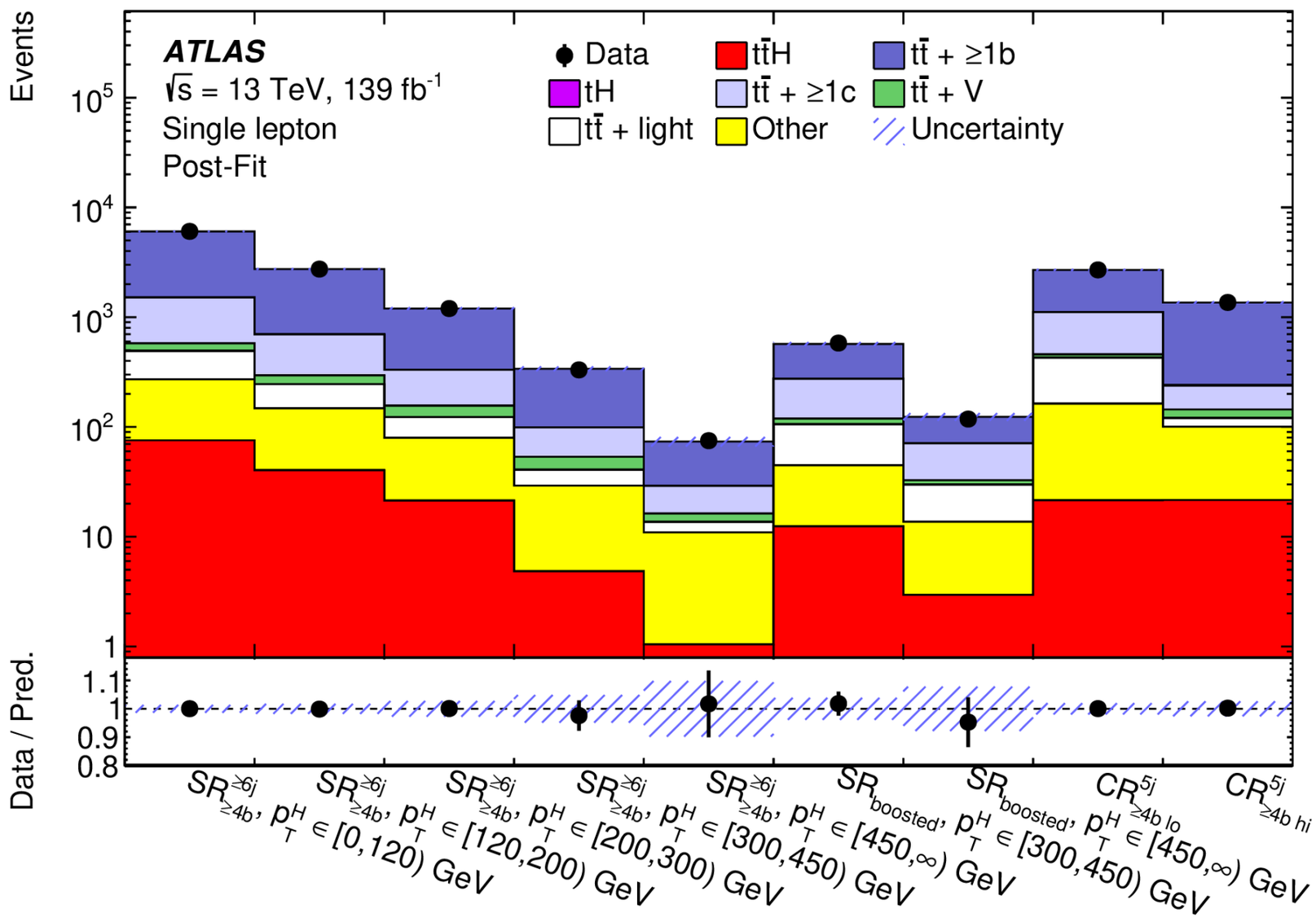
Analysis strategy: Full Run 2 dataset (139 fb^{-1})

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 **p_T^H**



- Events categorised in signal regions (**SRs**) defined by the **#leptons**, **#jets**, **#b-tagged jets** and **#boosted Higgs boson candidates**



- **BDTs** used for **reconstructing Higgs boson candidate** and **signal extraction**

- Control regions (CRs) to **constrain tt+≥1b and tt+≥1c**

ttH (H→bb): Differential measurement

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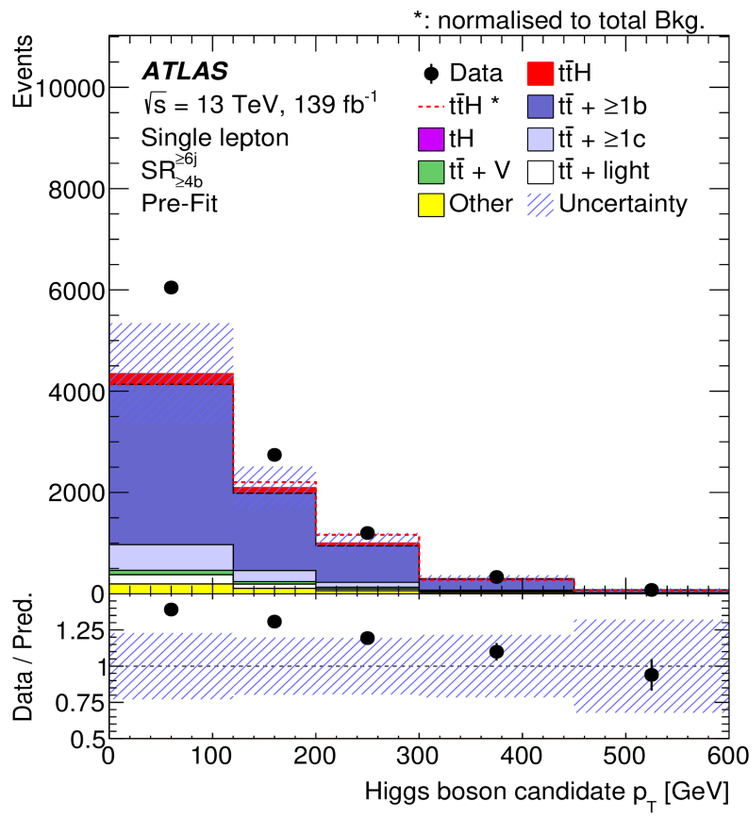
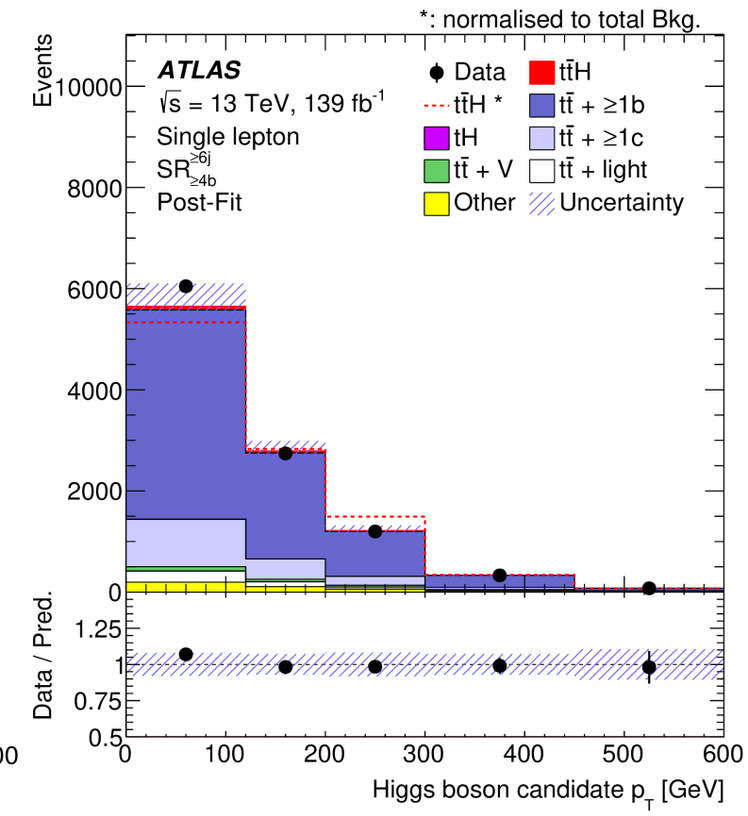
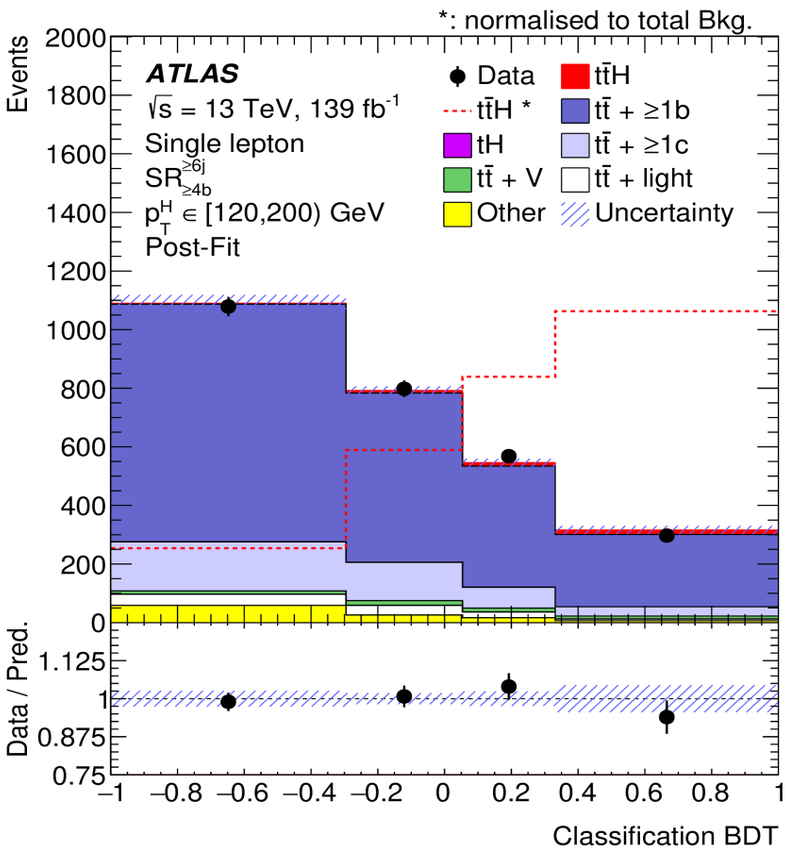
Modelling of tt+bb background

- **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): Differential measurement

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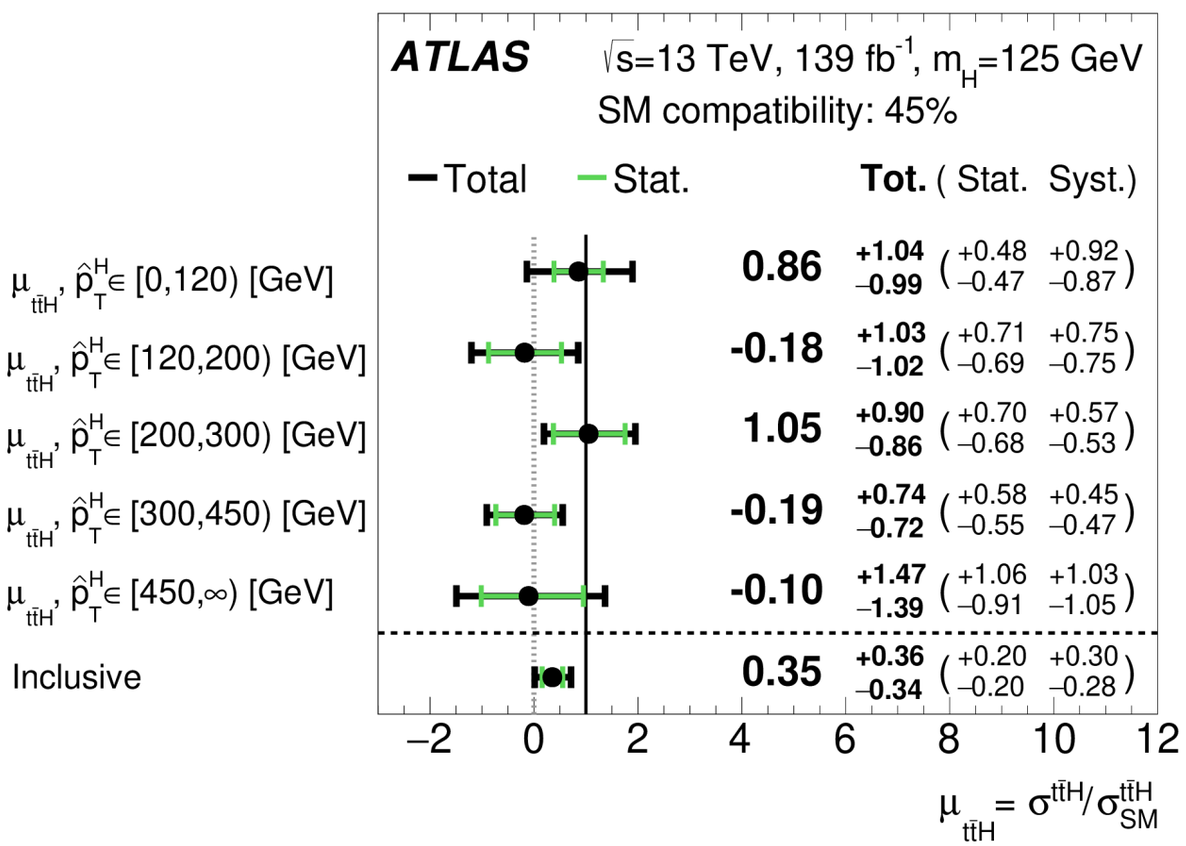
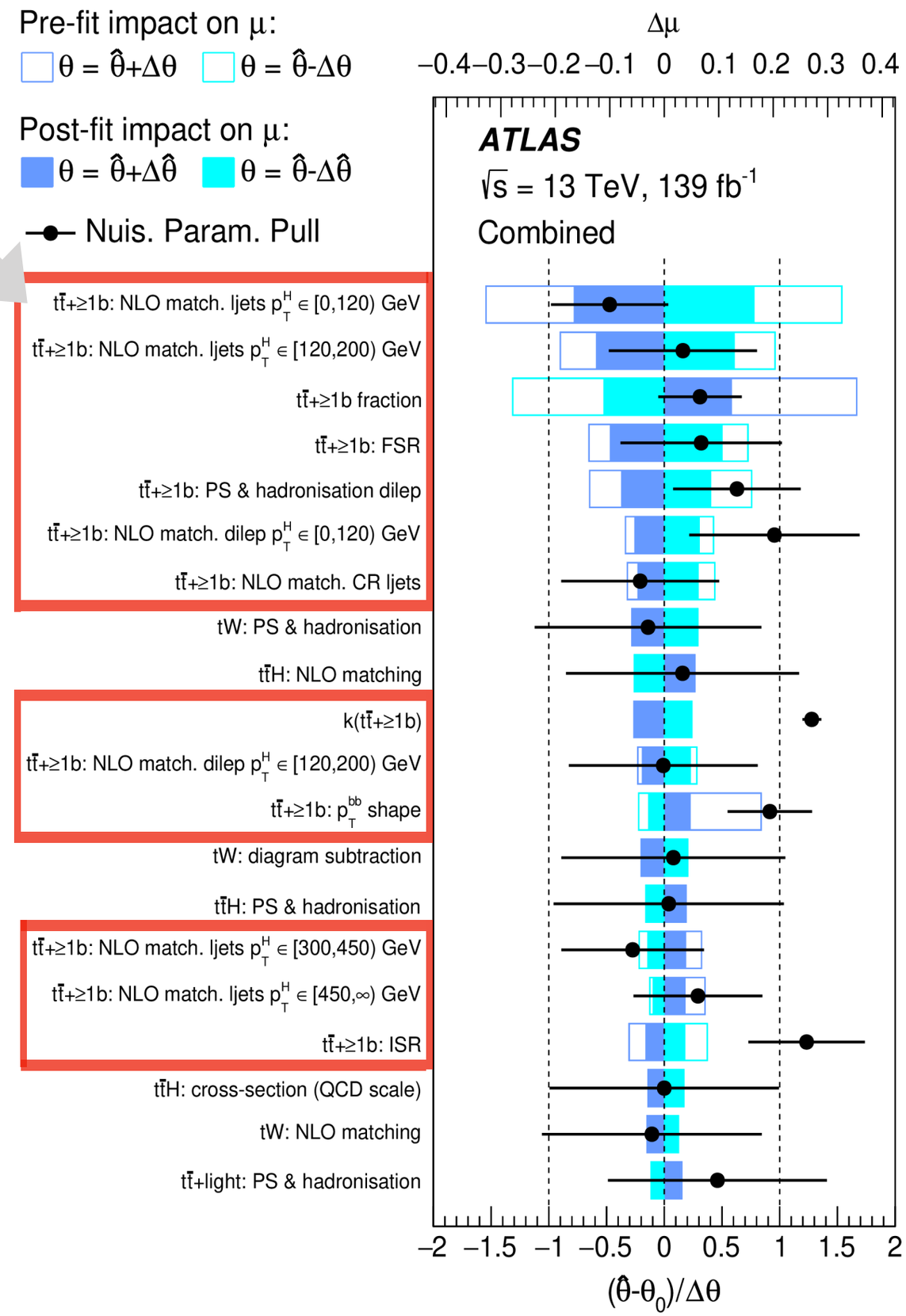
- Measurement **uncertainty** is **dominated** by systematic uncertainties, especially from **tt+≥1b modelling**

- **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 (2.7σ exp.)**





ttH/tH (H→bb): CP measurement

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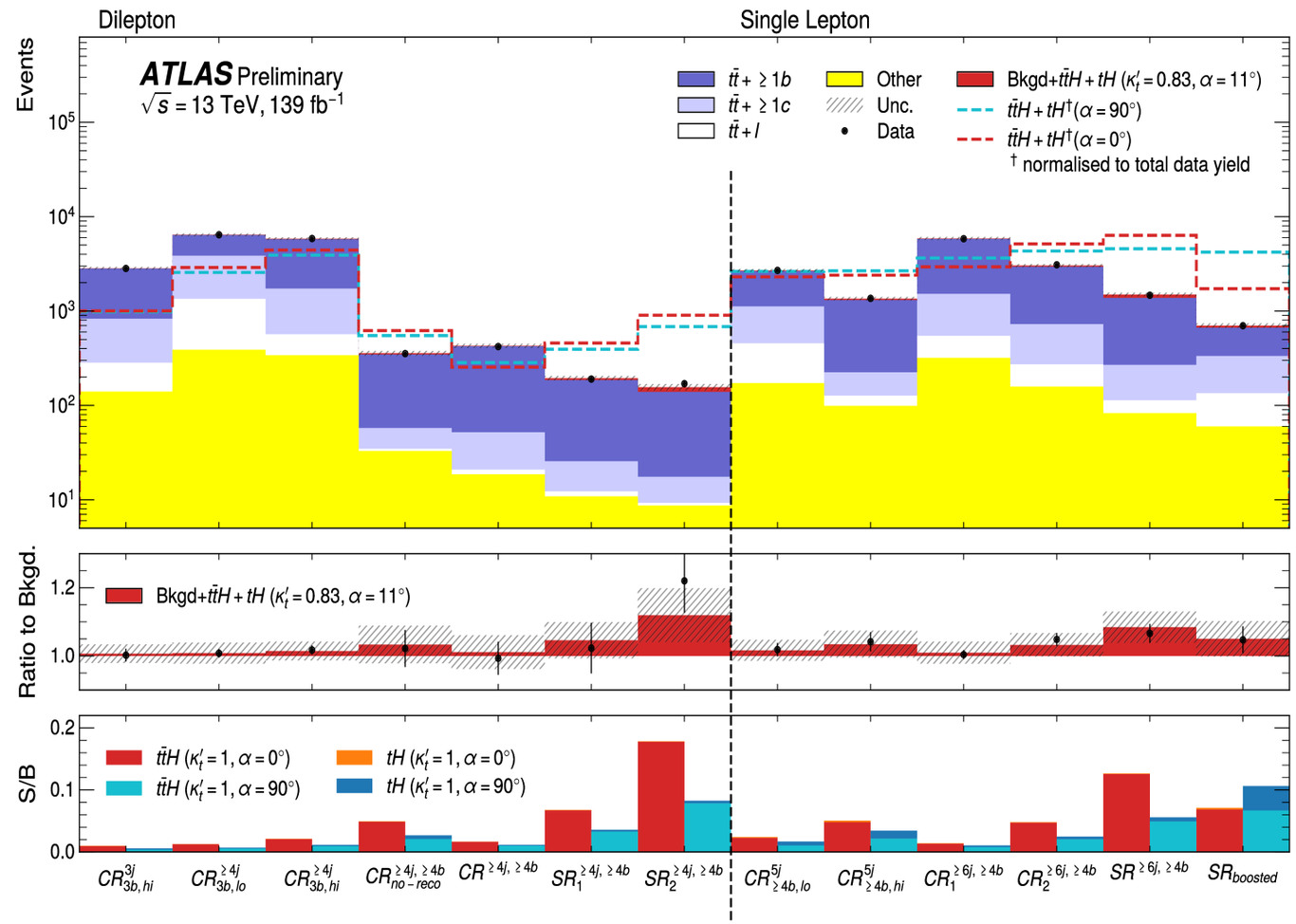
Analysis strategy: Full Run 2 dataset (139 fb^{-1})

First measurement of the CP properties in the H→ bb decay channel

Analysis based on ttH (H→bb) Differential measurement with a few modifications:

- tWH and tHjb considered as signal
- Event categorisation:
  - Step I: CR and **preliminary signal regions (PSR)** defined
  - Step II: **Classification BDT** (ttH vs tt+jets) cut used to define final SR (**ttH-enrich region**) from PSRs
  - **CP sensitive observables** used in PSRs → exploit angular and kinematic differences in events caused by CP effects



Channel (PSR)	Final SRs and CRs	Classification BDT selection	Fitted observable
Dilepton ($PSR^{\geq 4j,\geq 4b}$)	$CR^{\geq 4j,\geq 4b}_{no\text{-}reco}$	–	$\Delta\eta_{\ell\ell}$
	$CR^{\geq 4j,\geq 4b}$	BDT∈ [−1, −0.086)	b_4
	$SR^{\geq 4j,\geq 4b}_{1}$	BDT∈ [−0.086, 0.186)	b_4
	$SR^{\geq 4j,\geq 4b}_{2}$	BDT∈ [0.186, 1]	b_4
ℓ+jets ($PSR^{\geq 6j,\geq 4b}$)	$CR^{\geq 6j,\geq 4b}_{1}$	BDT∈ [−1, −0.128)	b_2
	$CR^{\geq 6j,\geq 4b}_{2}$	BDT∈ [−0.128, 0.249)	b_2
	$SR^{\geq 6j,\geq 4b}$	BDT∈ [0.249, 1]	b_2
ℓ+jets ($PSR_{boosted}$)	$SR_{boosted}$	BDT∈ [−0.05, 1]	Classification BDT score

ttH/tH (H→bb): CP measurement

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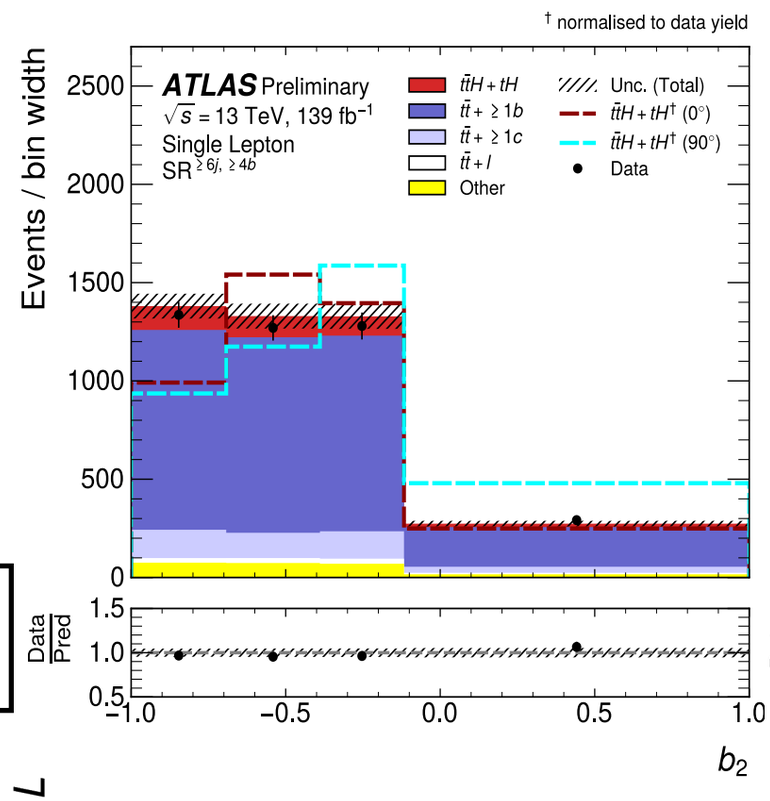
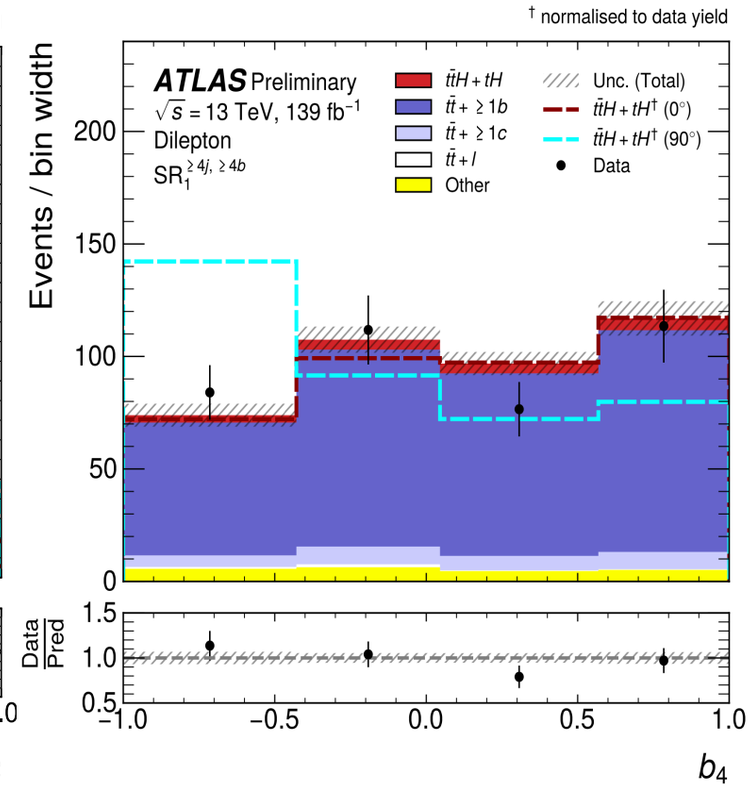
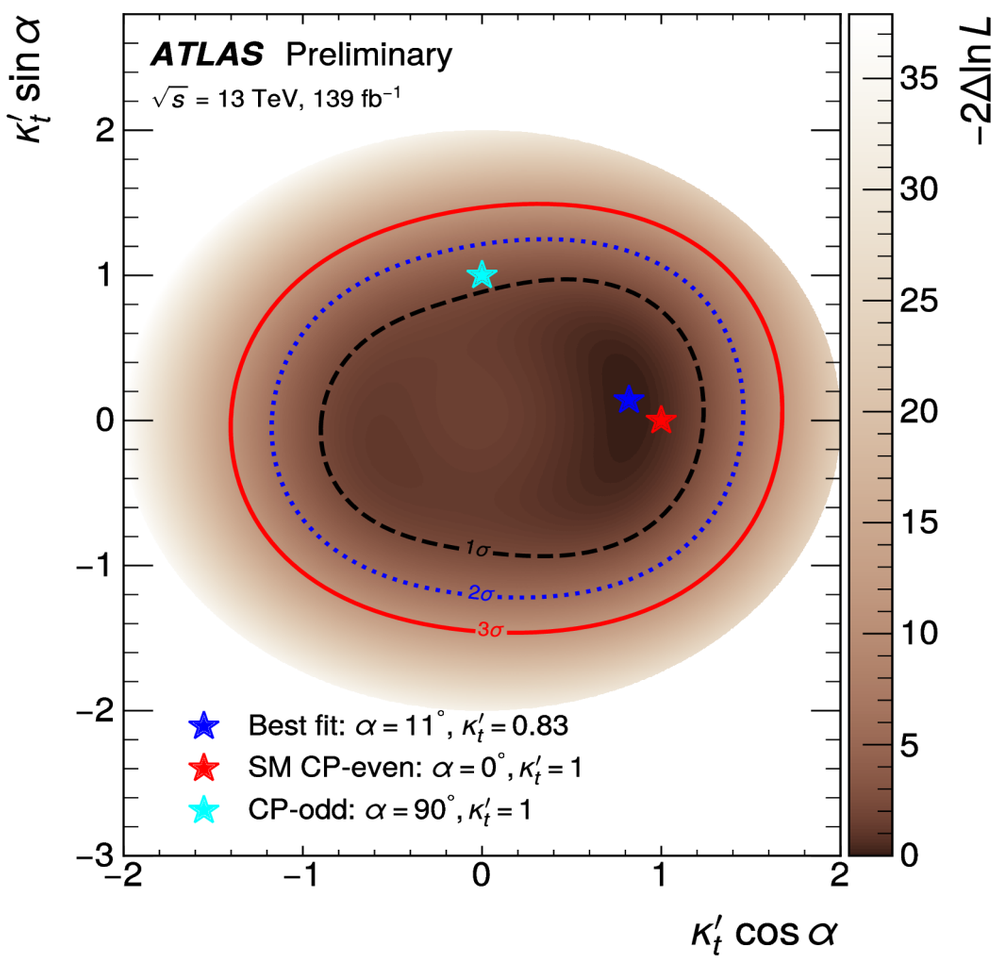
- Sensitivity to α and κ'_t obtained by fitting **CP-sensitive observables: b_4 and b_2** are most sensitive

$$b_2 = \frac{(\vec{p}_1 \times \hat{n}) \cdot (\vec{p}_2 \times \hat{n})}{|\vec{p}_1||\vec{p}_2|}, \quad \text{and} \quad b_4 = \frac{p_1^z p_2^z}{|\vec{p}_1||\vec{p}_2|},$$

CP Mixing angle and coupling strength are extracted from profile likelihood fit







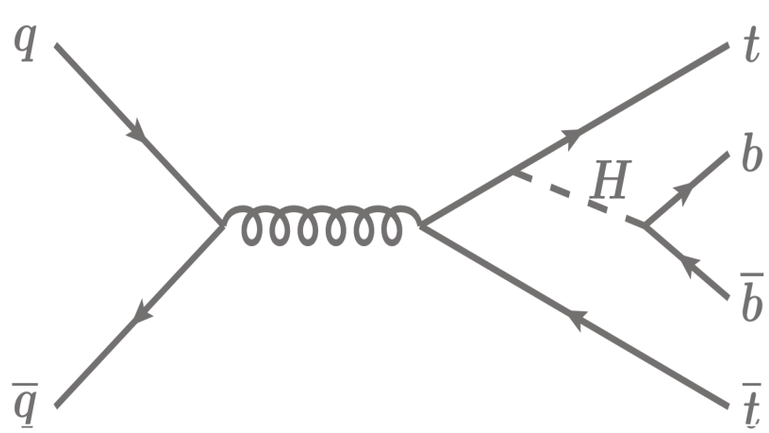
- Implement **4FS vs 5FS systematic** into the fit model: CP sensitive variables being **sensitive to flavour scheme choice**
- Uncertainty in α dominated by tt+≥1b modelling

- The best fit point gives:
  - **mixing angle α = 11° (+56° / -77°)**
  - **coupling strength modifier: κ'_t = 0.83 (+ 0.30 / - 0.46)**
- **Sensitivity to exclude pure CP-odd: 1.2σ**

Conclusion

- The first differential measurement in **ttH (H→bb) was** performed in five STXS using the STXS formalism
- Observed results are compatible with SM expectations within uncertainties → dominated by systematic uncertainties: **tt+ ≥1b modelling**
- **ttH (H→ γγ)** STXS measurement already performed : Statistically limited at higher p_T
- **ttH (H→bb)** benefits from **sensitivity beyond p_T > 300 GeV**

ttH(H → γγ)
STXS: ATLAS-CONF-2020-026
CP: Phys. Rev. Lett. 125, 061802



- First CP measurement of top Yukawa coupling in **ttH/tH (H→bb)** production
- Results complement **previous measurements** obtained from the **ttH/tH(H → γγ) decay** channel and will allow for a future combined measurement of the CP properties of $\mathbf{y_t}$
- In the SM the Higgs boson is a **CP-even** scalar particle, a pure **CP-odd coupling** has been excluded at 95% confidence level

Looking forward to Run 3 and beyond for precision measurements
Expect to profit from latest developments!

Thank you for your time!

Back-up

ttH(H→bb)

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

ttH(H→bb)

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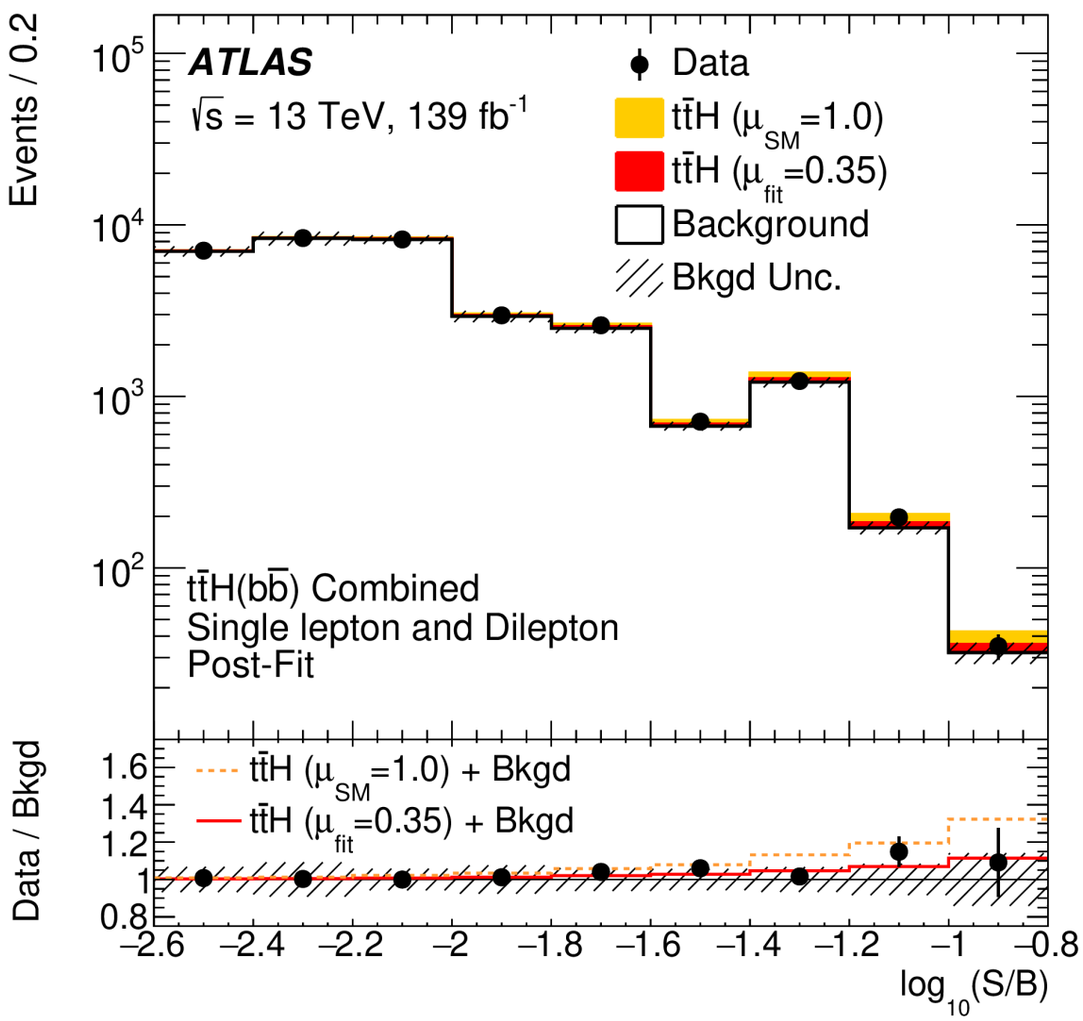

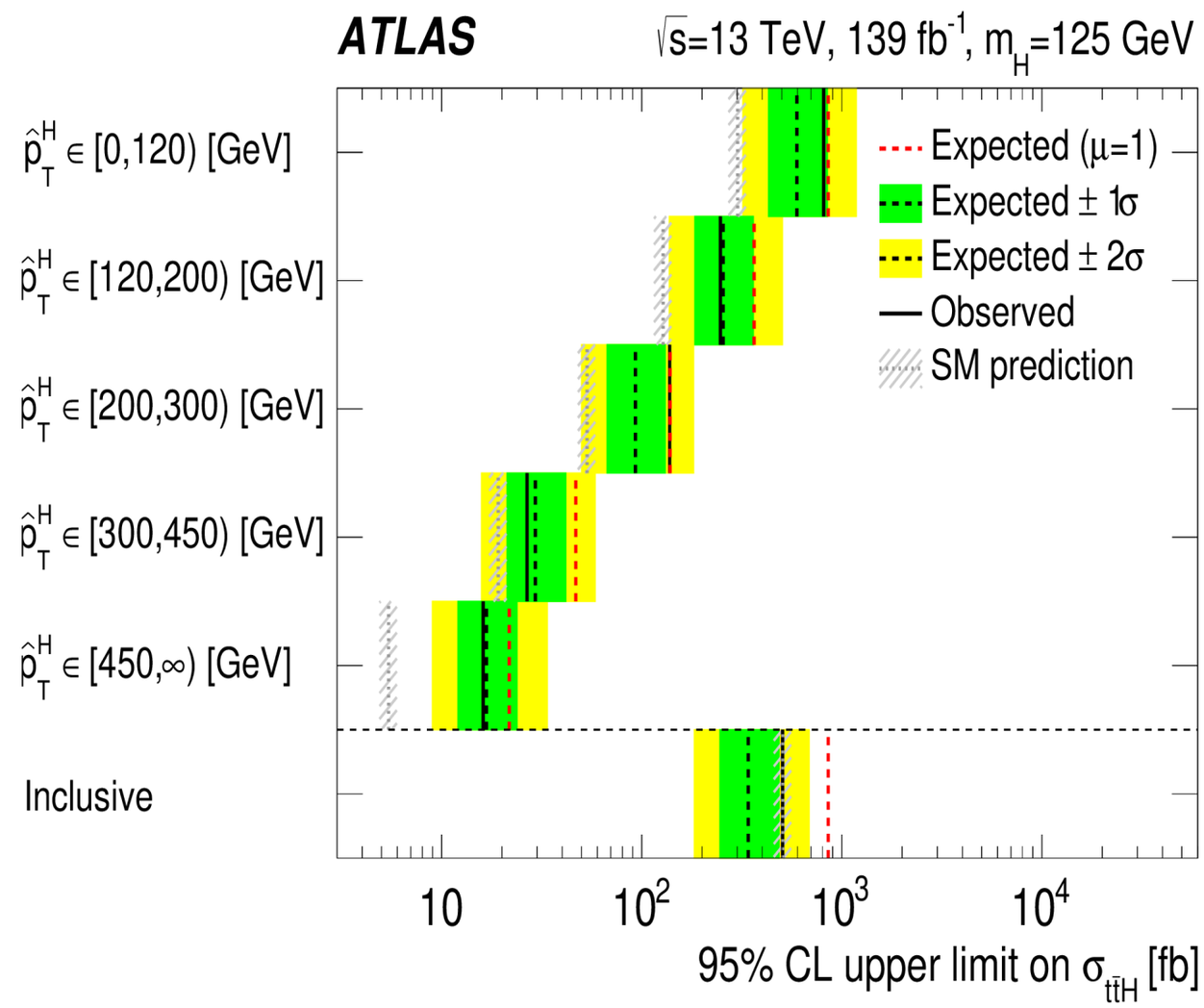

ttH(H→bb)

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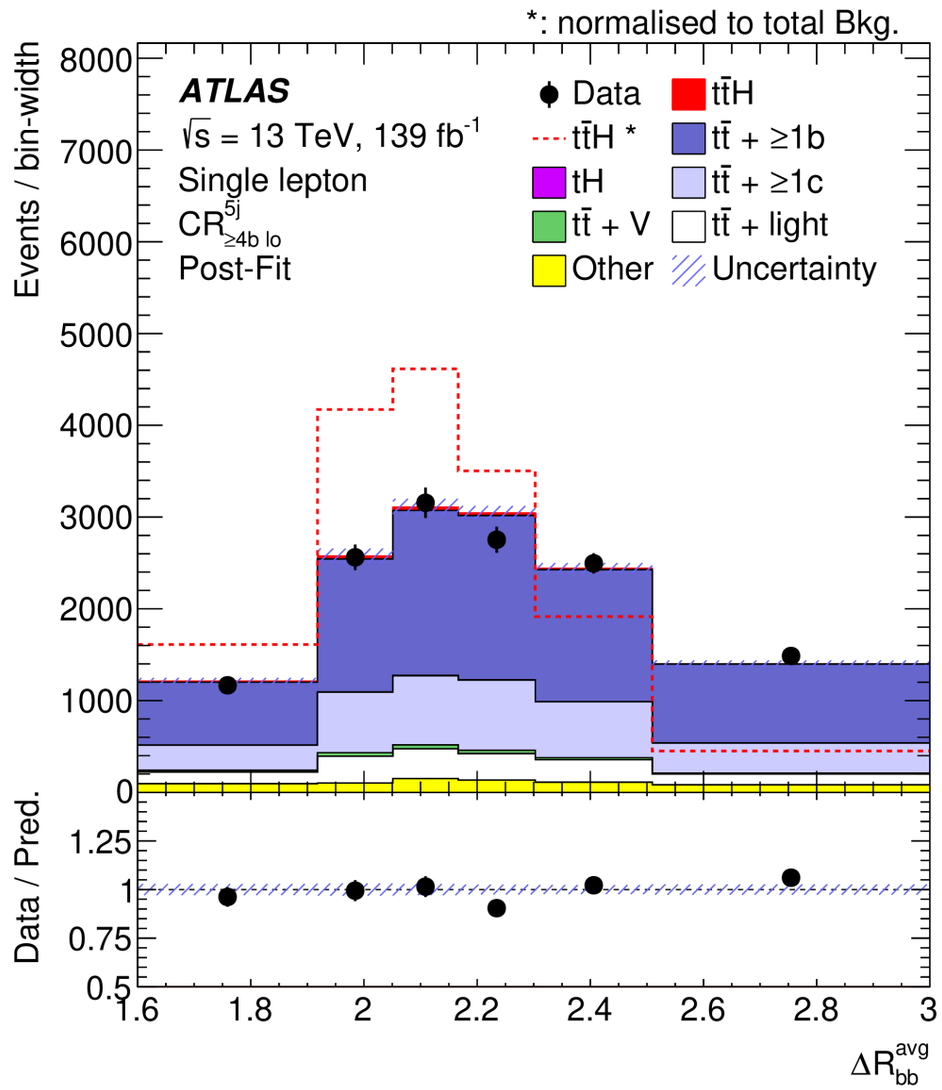

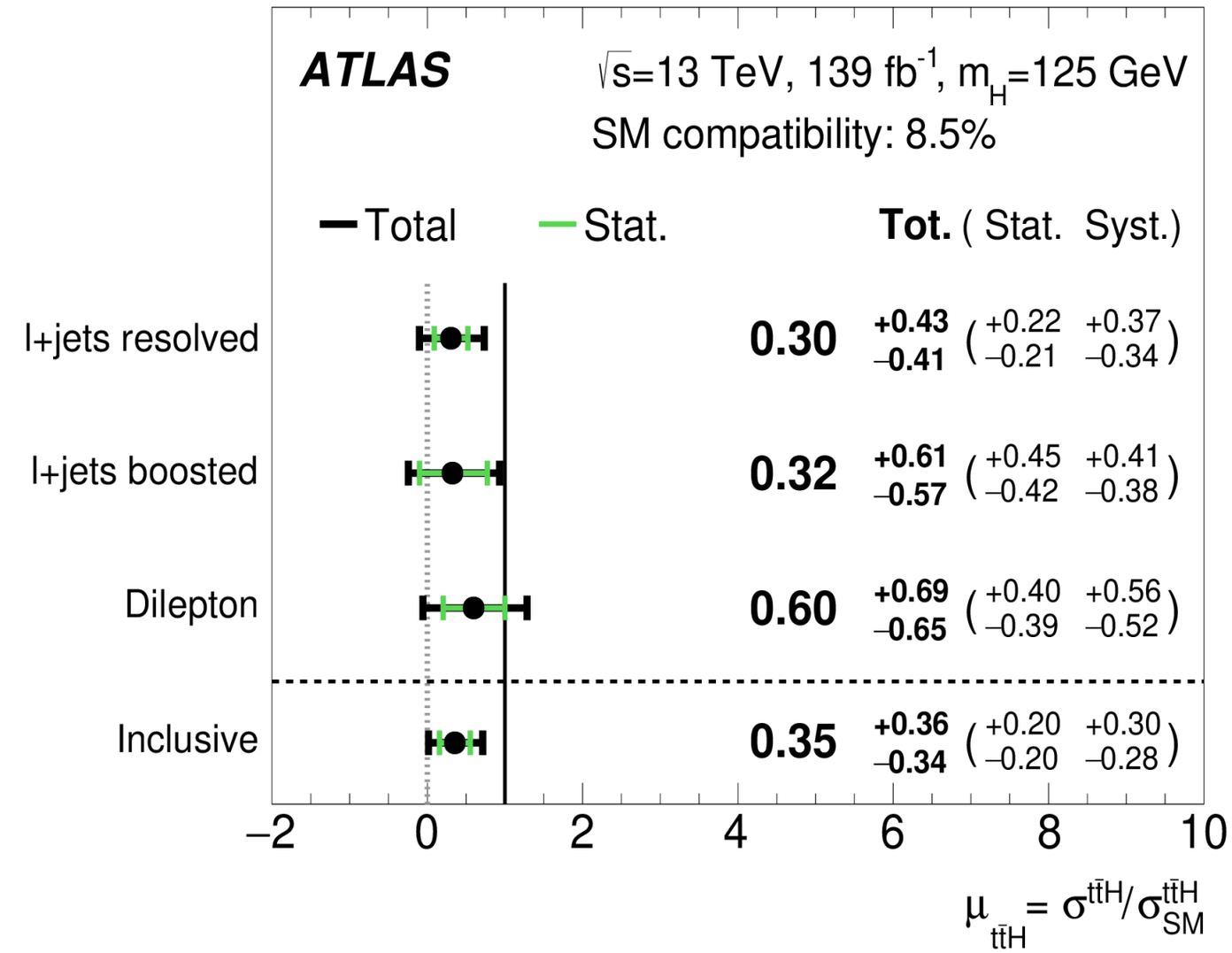

ttH(H→bb): CP

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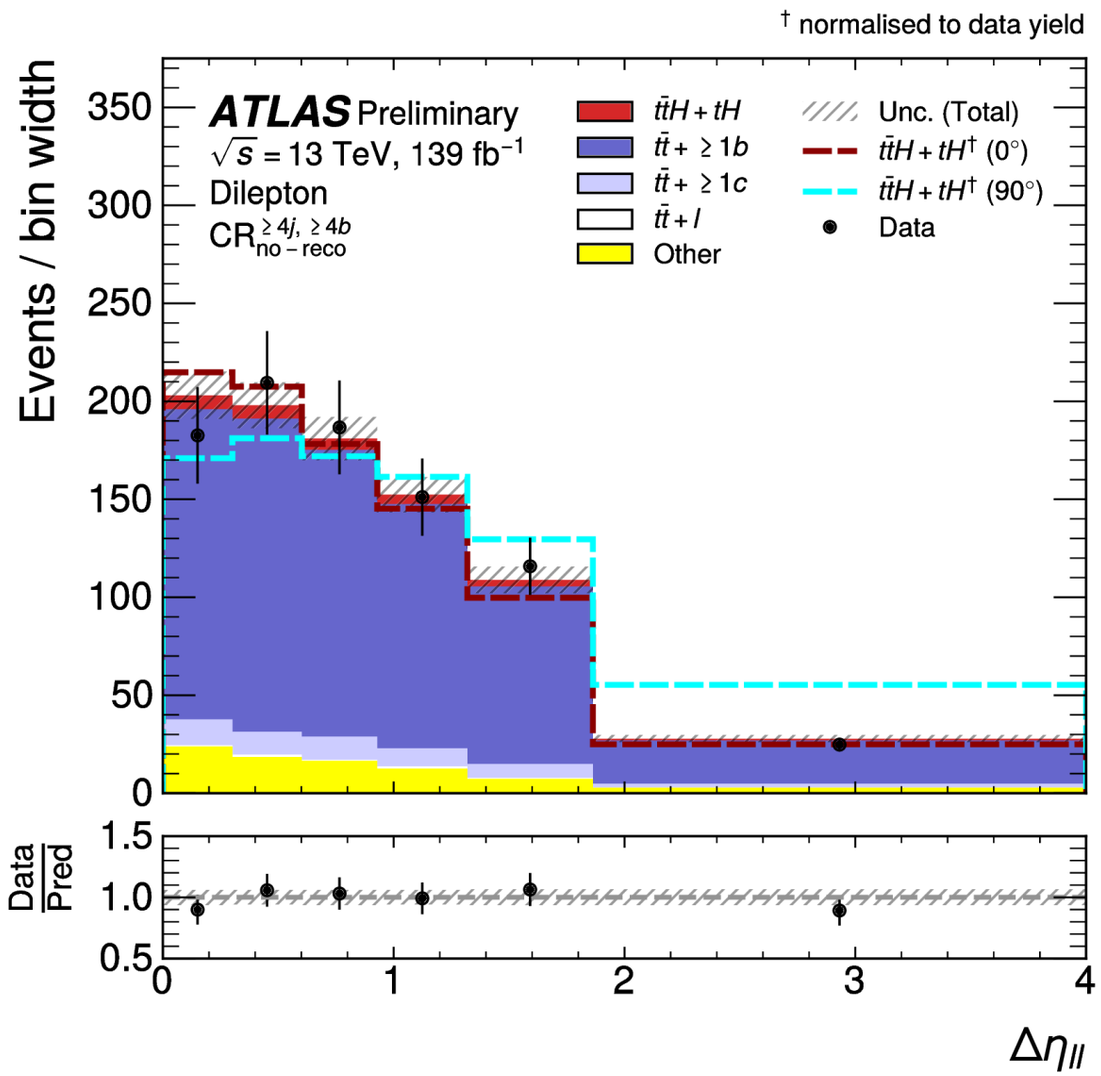

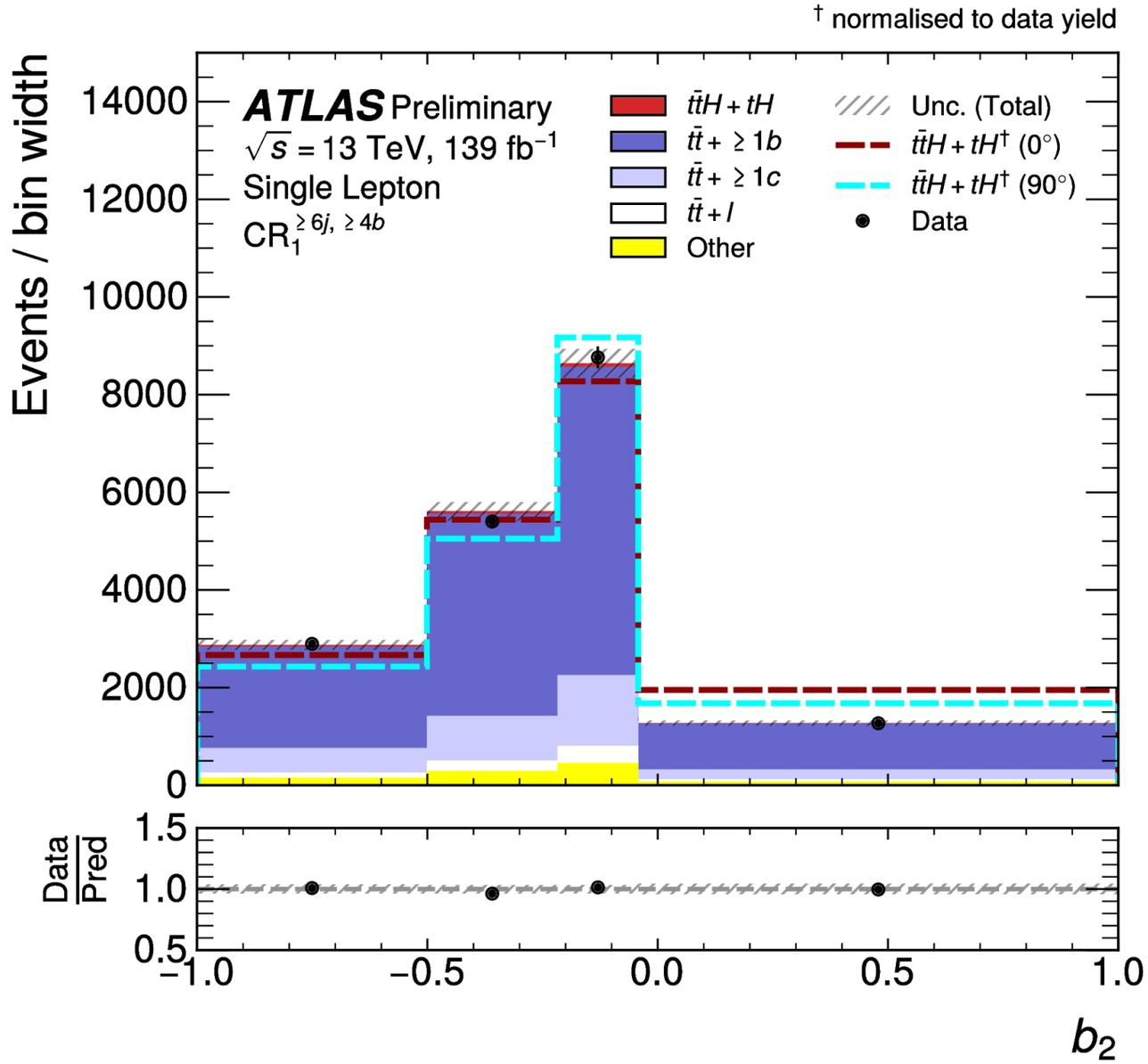

ttH(H→bb): CP

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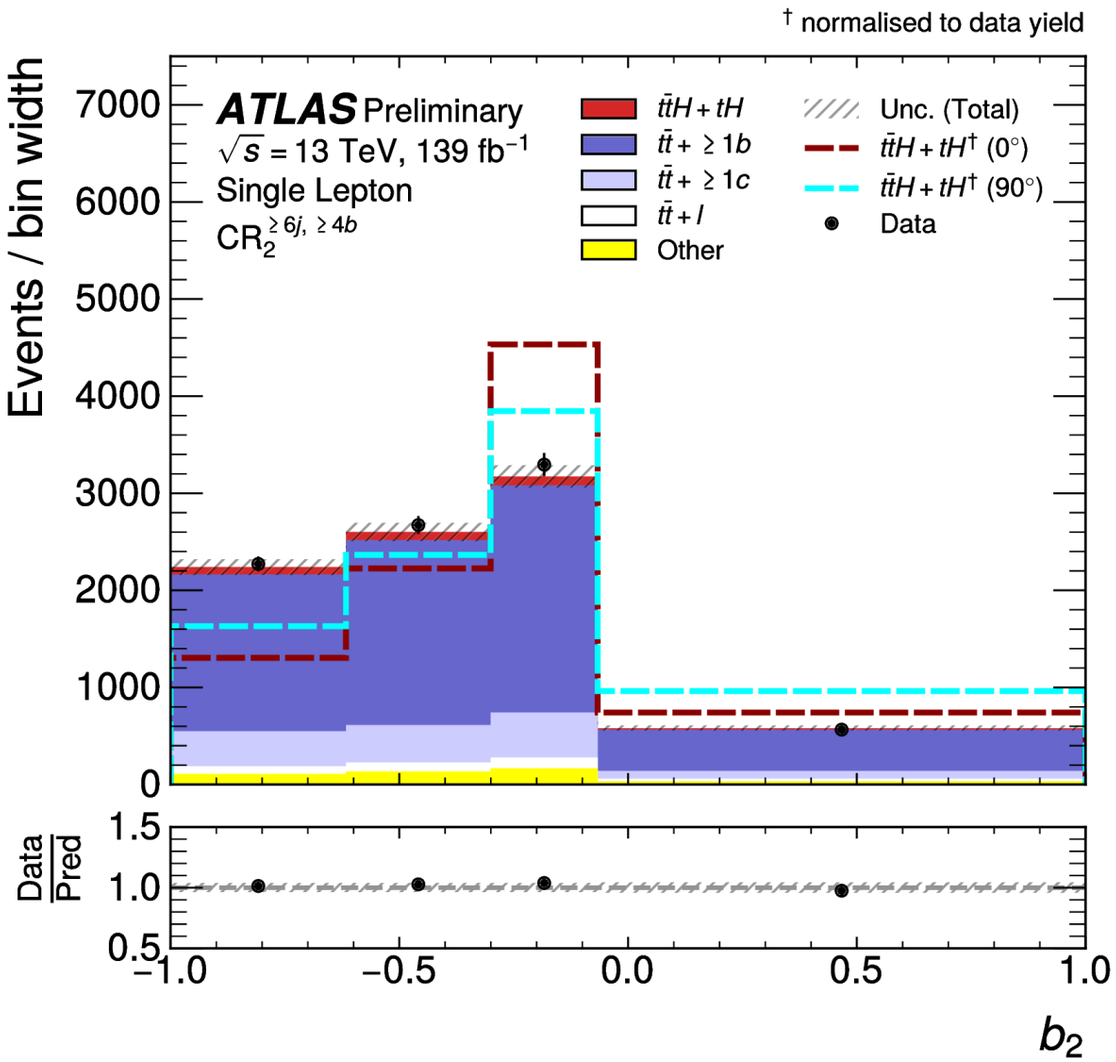

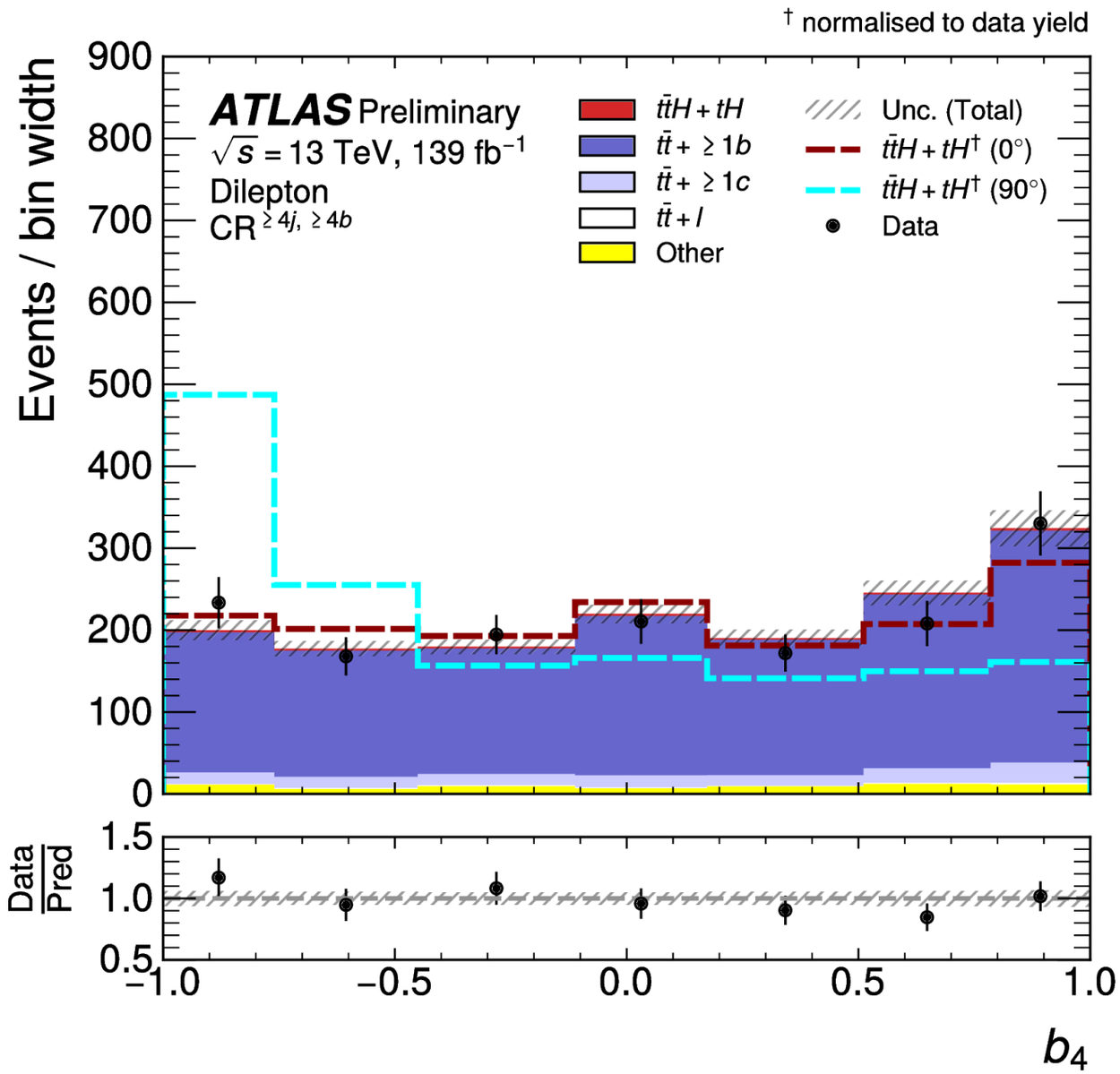

ttH(H→bb): CP

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Uncertainty source	$\Delta\alpha[^\circ]$	
Process modelling		
Signal modelling	+7.9	-13
$t\bar{t}+\geq 1b$ modelling		
$t\bar{t}+\geq 1b$ 4V5 FS	+26	-40
$t\bar{t}+\geq 1b$ NLO matching	+24	-36
$t\bar{t}+\geq 1b$ fractions	+15	-23
$t\bar{t}+\geq 1b$ FSR	+5.2	-9.9
$t\bar{t}+\geq 1b$ PS & hadronisation	+17	-27
$t\bar{t}+\geq 1b$ $p_{\mathrm{T}}^{b\bar{b}}$ shape	+5.7	-5.3
$t\bar{t}+\geq 1b$ ISR	+15	-26
$t\bar{t}+\geq 1c$ modelling	+7.4	-12
$t\bar{t}$ + light modelling	+2.7	-4.8
b-tagging efficiency and mis-tag rates		
b-tagging efficiency	+9.7	-17
c-mis-tag rates	+7.4	-12
l-mis-tag rates	+2.5	-3
Jet energy scale and resolution		
b-jet energy scale	+1.9	-4.2
Jet energy scale (flavour)	+8.8	-13
Jet energy scale (pileup)	+5.9	-9.2
Jet energy scale (remaining)	+9	-15
Jet energy resolution	+6.2	-10
Luminosity	$\leq \pm 1$	
Other sources	+5.4	-8.8
Total systematic uncertainty	+43	-58
$t\bar{t}+\geq 1b$ normalisation	+8.9	-15
κ_t'	+18	-35
Total statistical uncertainty	+34	-51
Total uncertainty	+55	-77

Uncertainty source	$\Delta\kappa_t'$	
Process modelling		
Signal modelling	+0.09	-0.09
$t\bar{t}+\geq 1b$ modelling		
$t\bar{t}+\geq 1b$ 4V5 FS	+0.08	-0.24
$t\bar{t}+\geq 1b$ NLO matching	+0.15	-0.30
$t\bar{t}+\geq 1b$ fractions	+0.09	-0.22
$t\bar{t}+\geq 1b$ FSR	+0.02	-0.02
$t\bar{t}+\geq 1b$ PS & hadronisation	+0.08	-0.20
$t\bar{t}+\geq 1b$ $p_{\mathrm{T}}^{b\bar{b}}$ shape	+0.07	-0.11
$t\bar{t}+\geq 1b$ ISR	+0.06	-0.17
$t\bar{t}+\geq 1c$ modelling	+0.04	-0.10
$t\bar{t}$ + light modelling	+0.01	-0.01
b-tagging efficiency and mis-tag rates		
b-tagging efficiency	+0.06	-0.12
c-mis-tag rates	+0.03	-0.07
l-mis-tag rates	+0.01	-0.03
Jet energy scale and resolution		
b-jet energy scale	+0.02	-0.02
Jet energy scale (flavour)	+0.01	-0.05
Jet energy scale (pileup)	+0.02	-0.05
Jet energy scale (remaining)	+0.04	-0.08
Jet energy resolution	+0.03	-0.09
Luminosity	$\leq \pm 0.01$	
Other sources	+0.03	-0.07
Total systematic uncertainty	+0.29	-0.45
$t\bar{t}+\geq 1b$ normalisation	+0.05	-0.15
α	+0.09	-0.07
Total statistical uncertainty	+0.09	-0.10
Total uncertainty	+0.30	-0.46