L. Popova

Higgs boson production in association with top quarks at ATLAS

LHCP 2023 - Belgrade 22-26 May

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ATLAS EXPERIMENT

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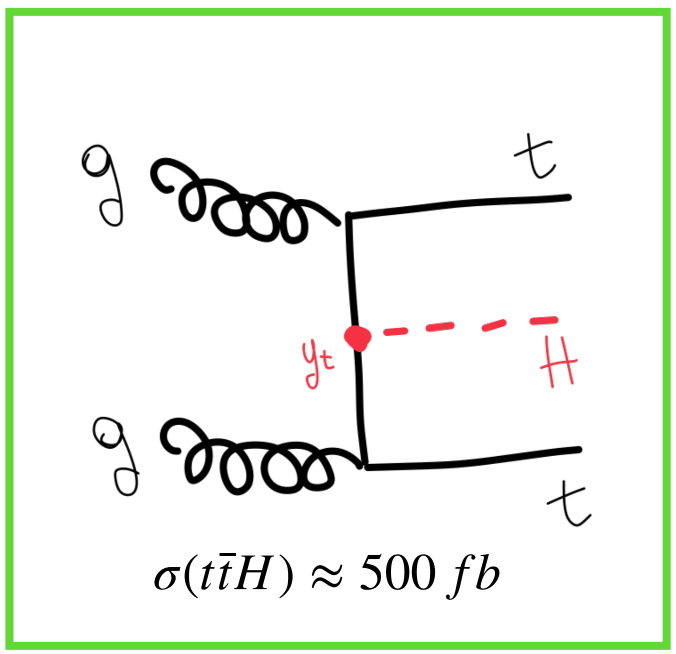
Introduction

Higgs boson
Only scalar particle in the SM
Responsible for EWSB
$J^{CP} = 0^{++} \rightarrow$ CP-even particle

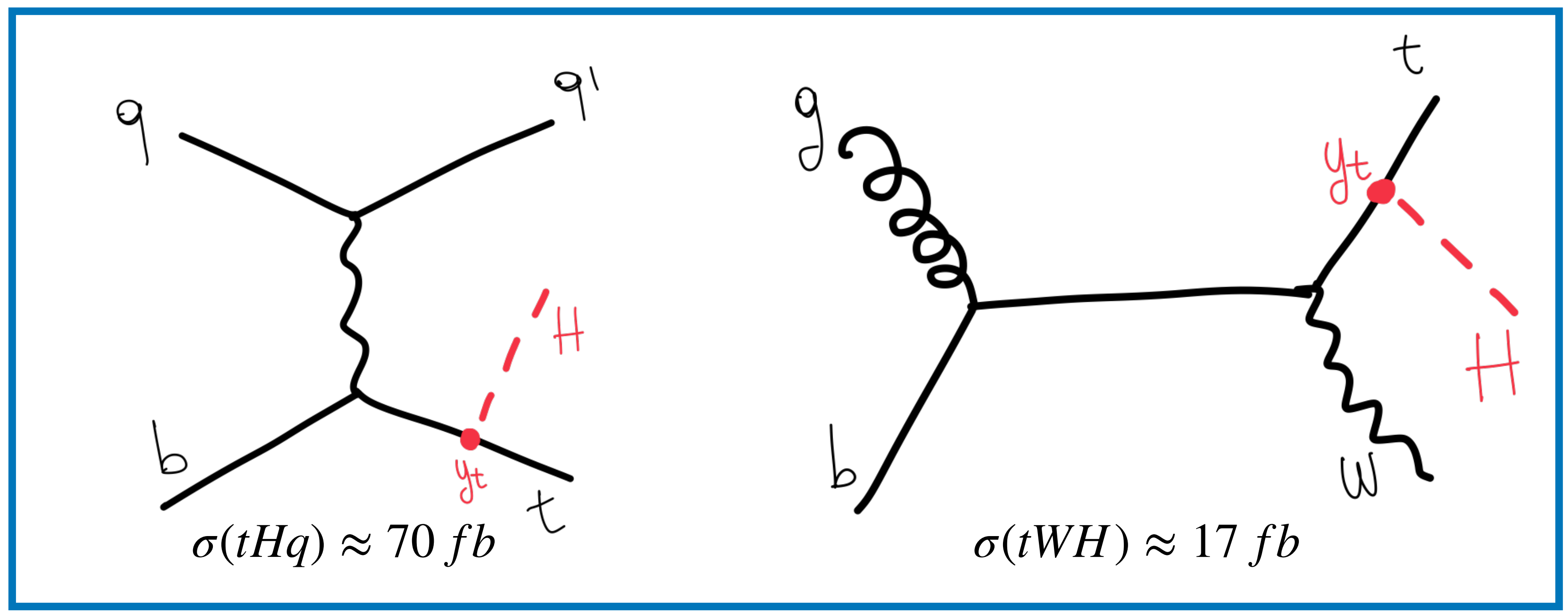
BSM?

Top quark
Heaviest particle in the SM
Does not appear in bound states
Exclusive decay to $W + b$

$t\bar{t}H$



tH — $\sigma(pp \rightarrow H + top)$ prediction for $\sqrt{s} = 13\ TeV$



Associated production of Higgs boson and top quarks is considered a good probe to look for BSM physics:

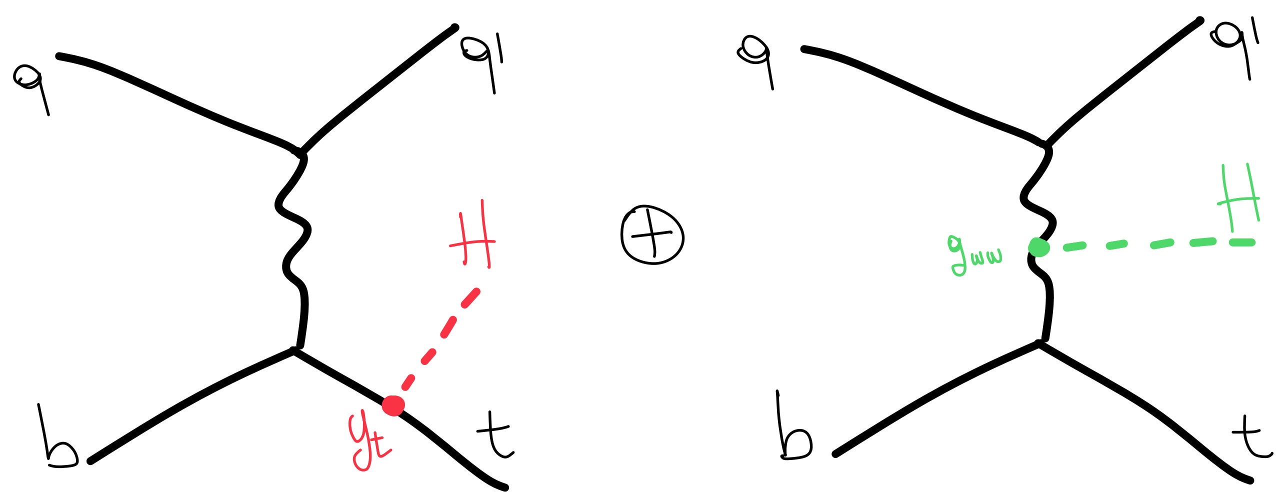
- Extraction of **top Yukawa coupling** $y_{top} = \sqrt{2}M_{top}/v$ through **cross-section measurements**
- Study of **CP nature** of Higgs+top coupling
- p_T(Higgs) linked to BSM effects, Higgs self-coupling through **STXS measurement**

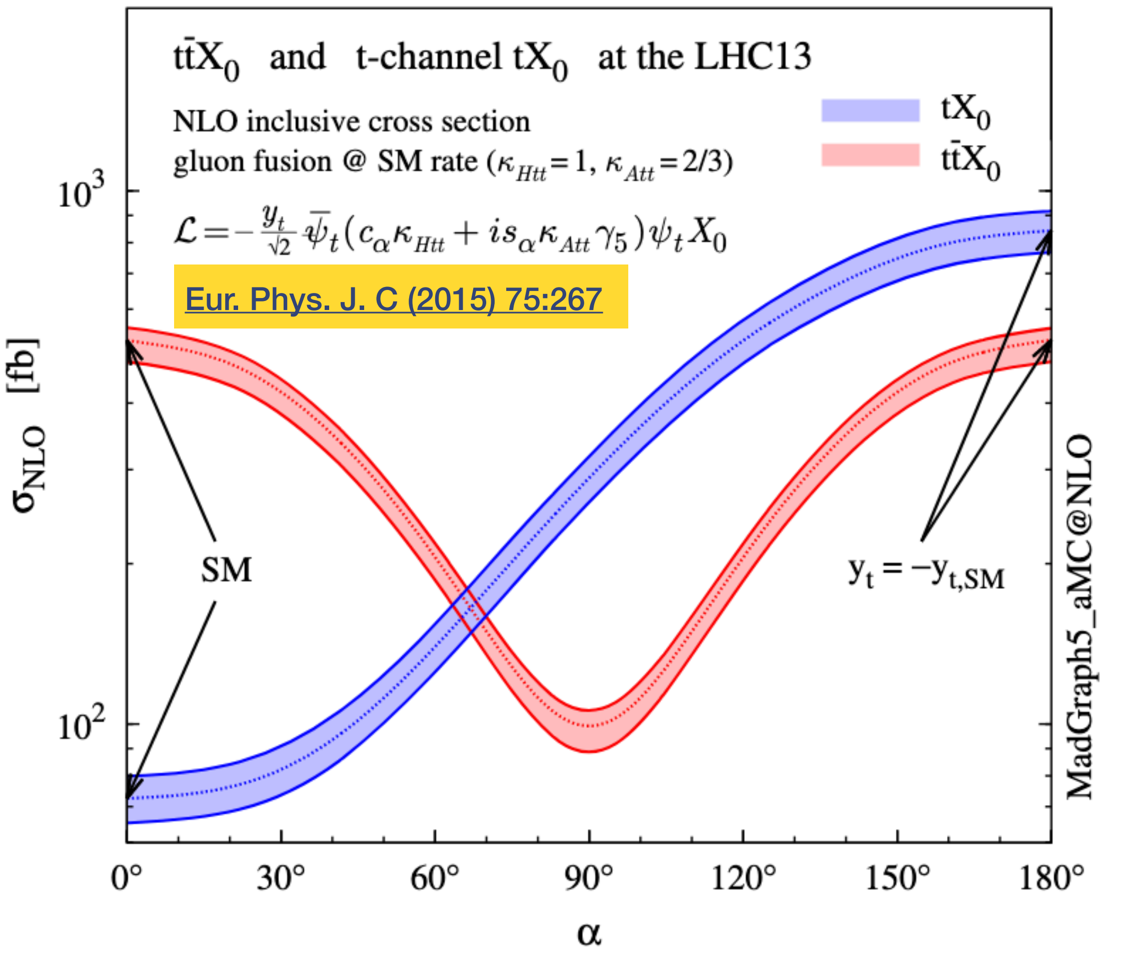
Coupling modifier

$$\mathscr{L}_{y_{top}} = -\frac{y_{top}}{\sqrt{2}} \boxed{k_t} \bar{\psi}_t (\cos \boxed{\alpha} + i\gamma_5 \sin\alpha)\psi_t \phi$$

CP mixing angle

- k_t affects overall cross section while α differential distributions
- Pure **CP-even scenario** $\rightarrow k_t = 1$ and $\alpha = 0^{\circ}$
- Pure **CP-odd scenario** $\rightarrow \alpha = 90^{\circ}$
- Interesting case of $\alpha = 180^{\circ}$ where tHq cross section is enhanced by almost a factor ten due to constructive interference of diagrams

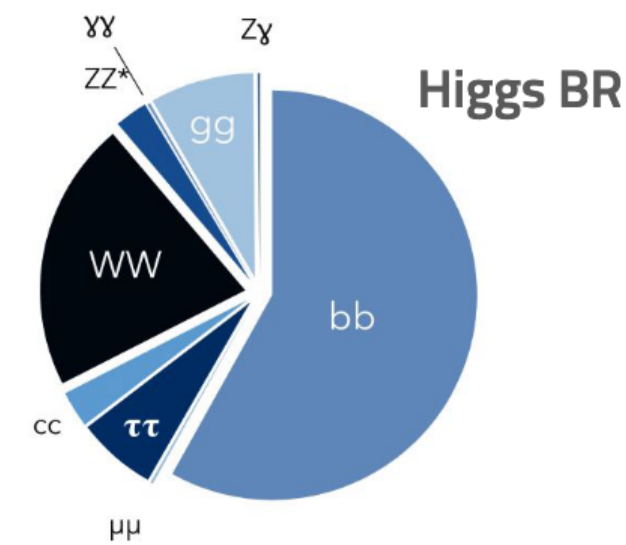


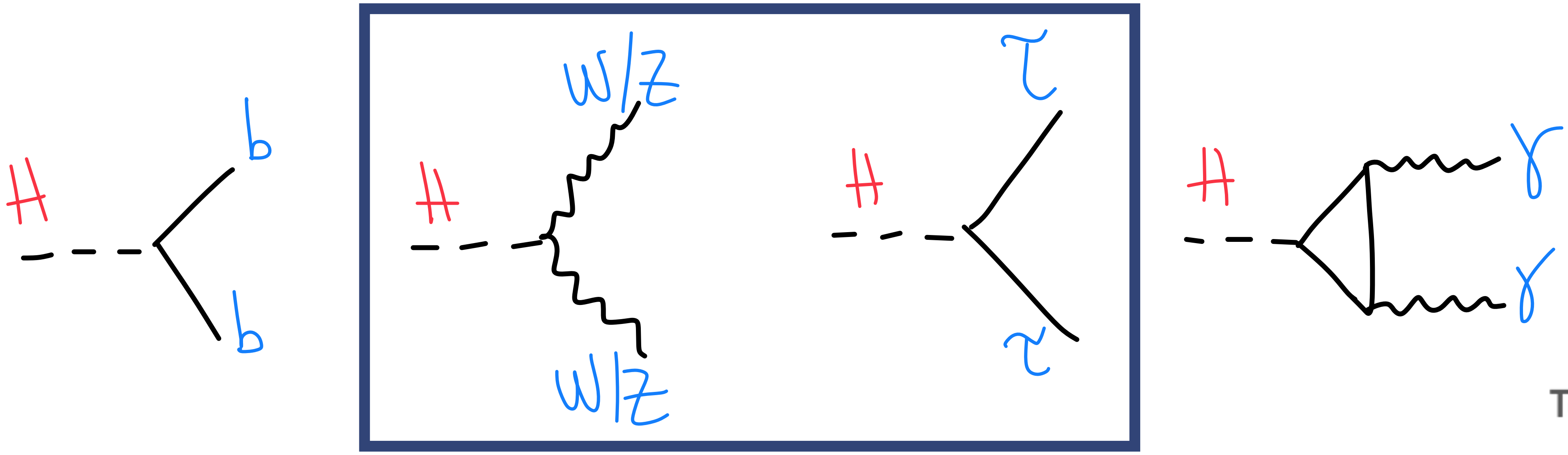


Strategy

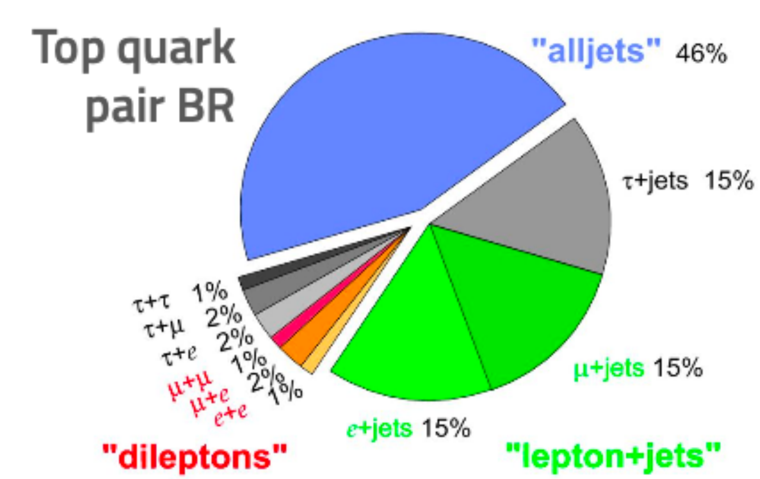
Small cross-section ($\approx 1\,\%$ of Higgs production at LHC!) with many particles in the final state:

- Split the phase space depending on the H decay mode
- Optimise every single channel and understand the different backgrounds
- Combine results from single channels





Typically explored in the so-called "Multilepton" final states with at least one W, Z or τ decaying leptonically



NB: Sensibility to y_t also in 4 tops production not covered in this talk [See J. Raine's talk]

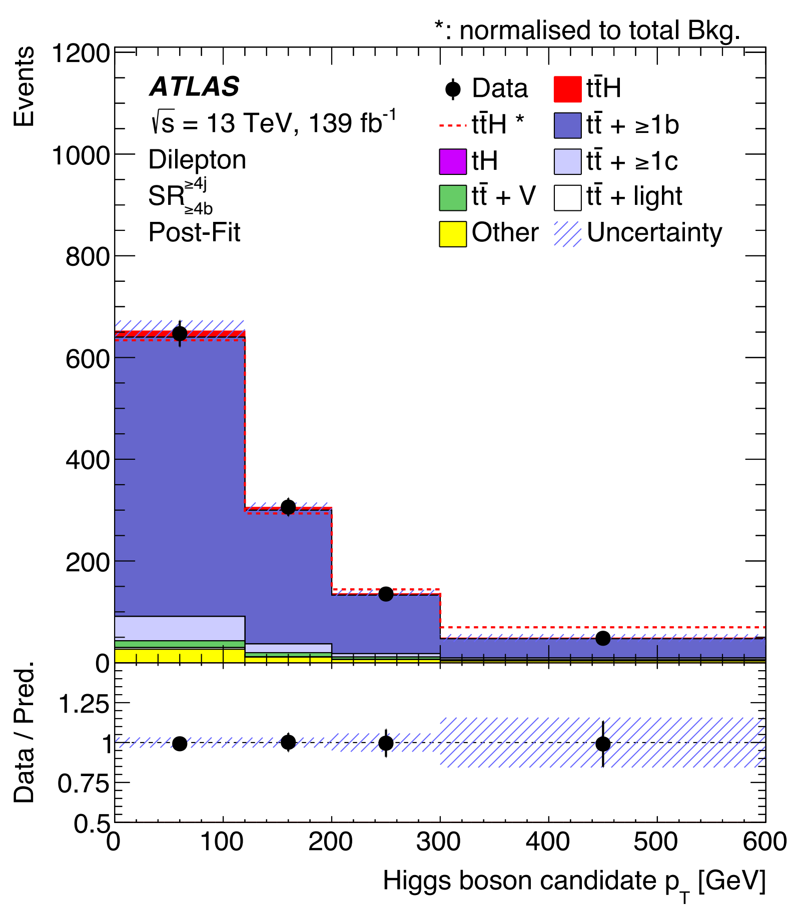
Cross-section and STXS measurements

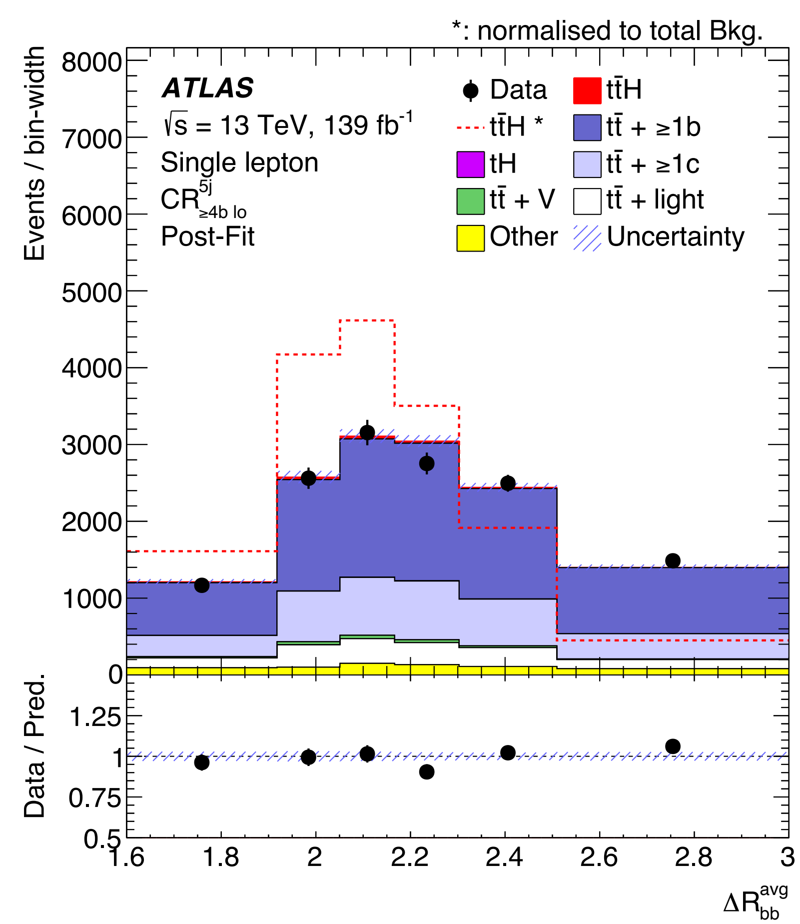
$t\bar{t}H(\rightarrow b\bar{b})$

SM interpretation analysis using 139/fb JHEP06(2022)097

- Single light lepton (e/μ) triggers
- MVA algorithms to identify Higgs boson and classify $t\bar{t}H$ events
  - BDT in resolved channels
  - DNN in boosted Higgs channel ($p_T(H) > 300\ GeV$)
- Major and most challenging background from $t\bar{t} + jets$ background
  - **$t\bar{t} + \geq 1b$ background rescaled by a factor 1.28 ± 0.08**

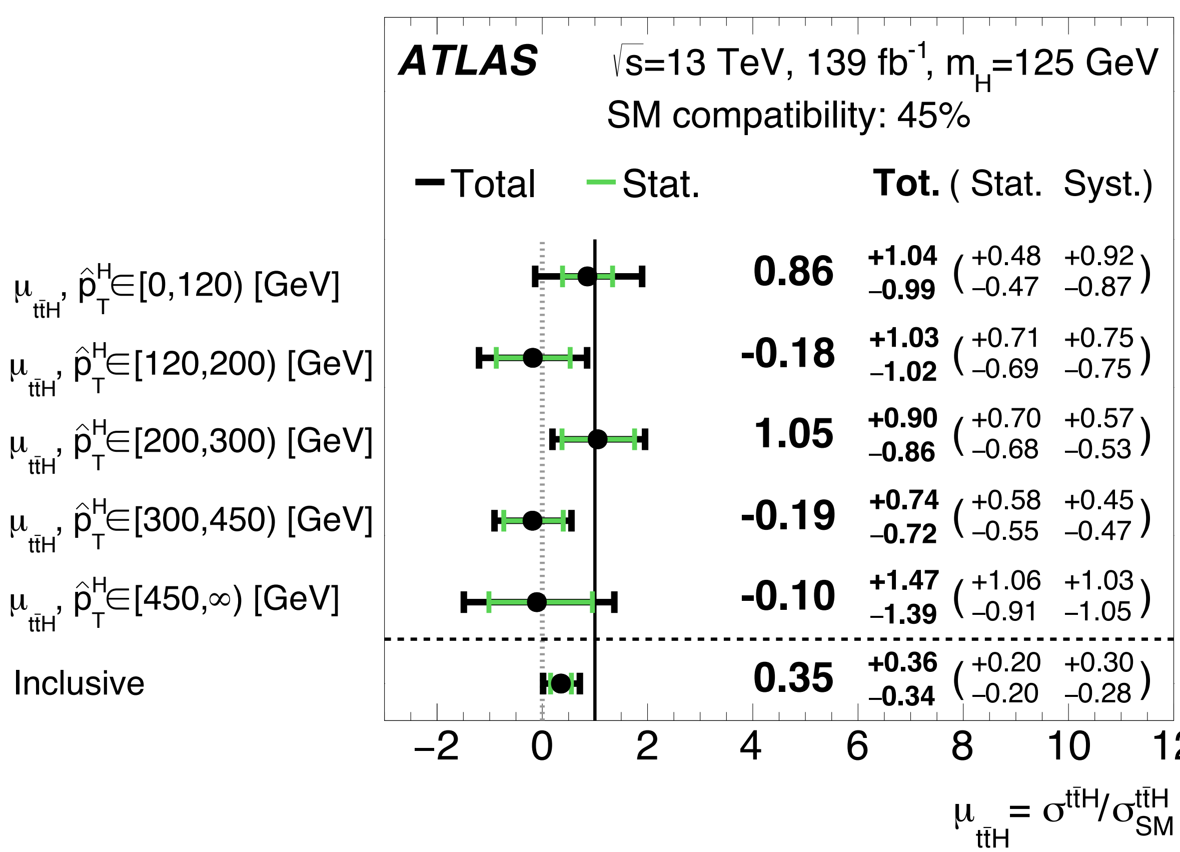
Region		Dilepton $SR^{\geq 4j}_{\geq 4b}$	Dilepton $CR^{\geq 4j}_{3b\ hi}$	Dilepton $CR^{\geq 4j}_{3b\ lo}$	Dilepton $CR^{3j}_{3b\ hi}$	Single-lepton $SR^{\geq 6j}_{\geq 4b}$	Single-lepton $CR^{5j}_{\geq 4b\ hi}$	Single-lepton $CR^{5j}_{\geq 4b\ lo}$	Single-lepton $SR_{boosted}$
#leptons		$= 2$				$= 1$			
#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

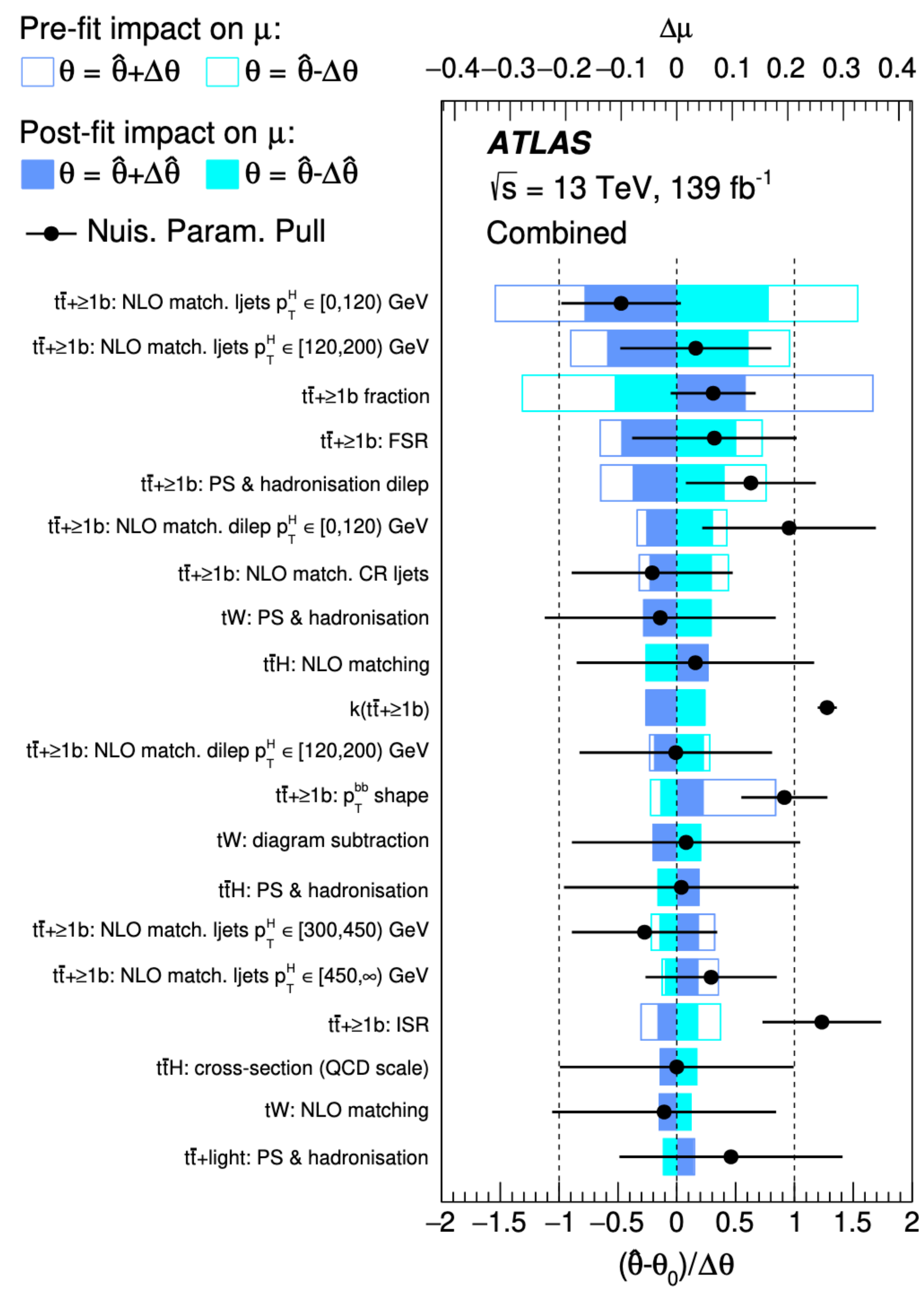




SM interpretation analysis using 139/fb JHEP06(2022)097

Uncertainty source	Description		Components
$t\bar{t}$ cross-section	$\pm 6\%$		$t\bar{t}+$ light
$t\bar{t}+\geq 1b$ normalisation	Free-floating		$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1c$ normalisation	$\pm 100\%$		$t\bar{t}+\geq 1c$
NLO matching	MadGraph5_aMC@NLO + Pythia 8 vs Powheg Box + Pythia 8		All
PS & hadronisation	Powheg Box + Herwig 7 vs Powheg Box + Pythia 8		All
ISR	Varying α_s^{ISR} (PS), μ_r & μ_f (ME)	in Powheg Box Res + Pythia 8	$t\bar{t}+\geq 1b$
		in Powheg Box + Pythia 8	$t\bar{t}+\geq 1c$, $t\bar{t}+$ light
FSR	Varying α_s^{FSR} (PS)	in Powheg Box Res + Pythia 8	$t\bar{t}+\geq 1b$
		in Powheg Box + Pythia 8	$t\bar{t}+\geq 1c$, $t\bar{t}+$ light
$t\bar{t}+\geq 1b$ fractions	Powheg Box + Herwig 7 vs Powheg Box + Pythia 8		$t\bar{t}+1b$, $t\bar{t}+\geq 2b$
p_T^{bb} shape	Shape mismodelling measured from data		$t\bar{t}+\geq 1b$





Leading contribution to systematic uncertainty is $t\bar{t}+\geq 1b$ modelling

Multilepton analysis

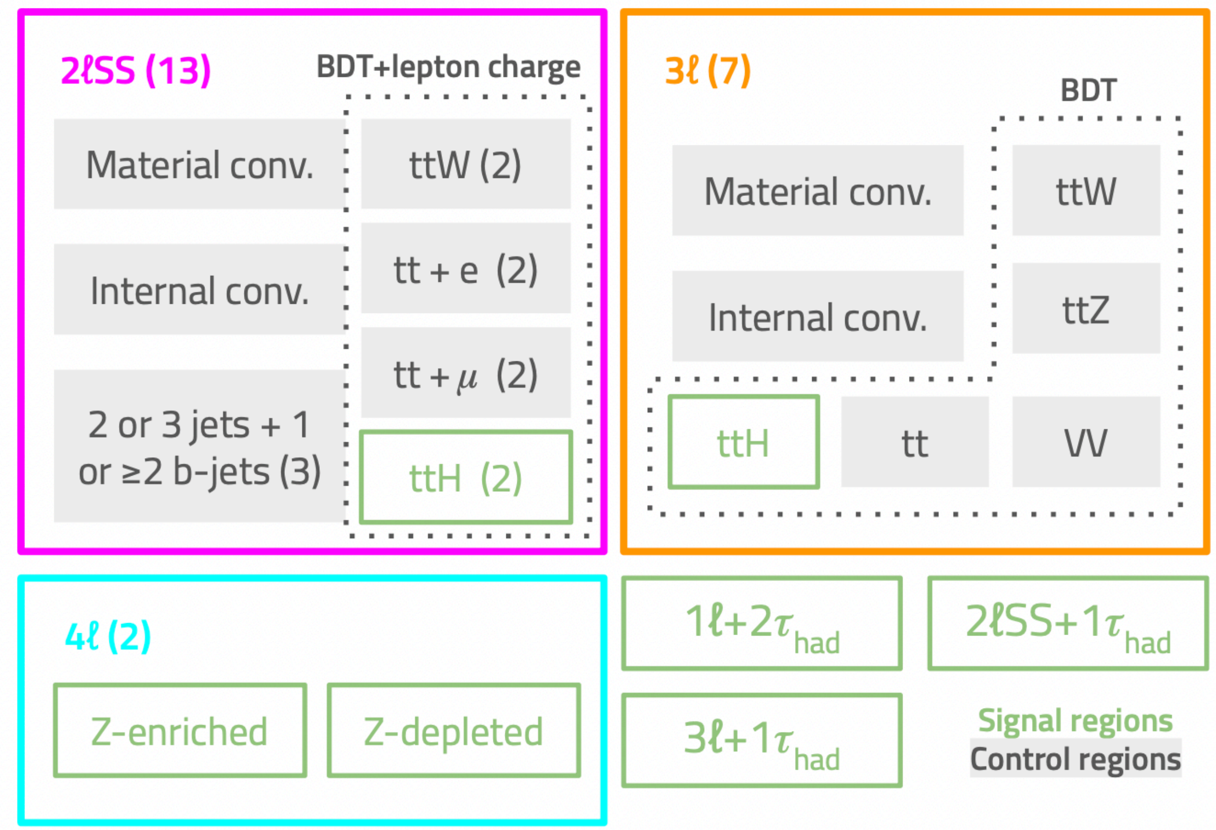
SM interpretation analysis using 80/fb ATLAS-CONF-2019-045

Targeting Higgs boson decays to $H \to WW^*/ZZ^*/\tau^+\tau^-$ and $t \to W(\to \ell\nu) + b$

Non prompt (e/μ) background estimation

- Muons and electrons from heavy flavour decays
- Electrons from material γ conversion
- Mainly from $t\bar{t}$, $Z+$jets and single top
- Using MC prediction with data driven correction

$$k_{\mu}^{HF} = 1.20 \pm 0.18,\ k_{e}^{HF} = 1.12 \pm 0.38,\ k_{e}^{\mathrm{MatC}} = 1.61 \pm 0.48$$



Electron charge flip

- Charge of electron flipped as an effect of mis-measurement of track bending of hard bremsstrahlung $e^{\pm} \to e^{\pm}\gamma \to e^{\pm}e^{+}e^{-}$
- Rates derived from data in $Z \to e^+e^-$ events ad function of electron kinematics
- Mainly from $t\bar{t}$ events

Hadronic τ fakes

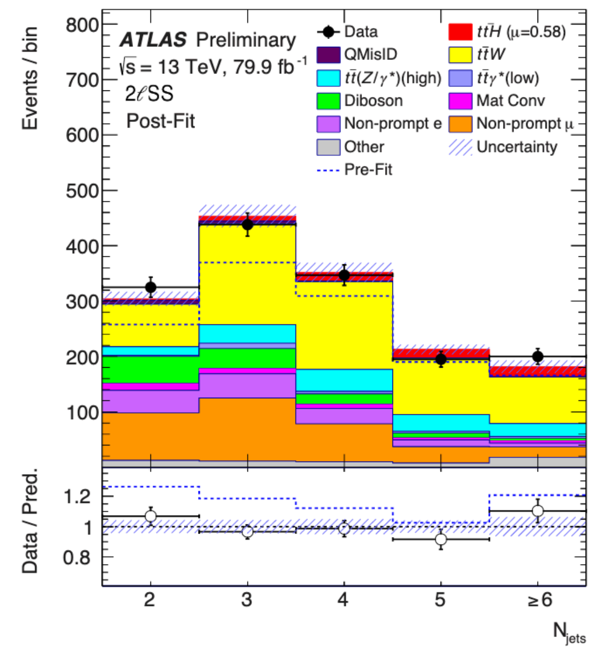
- Jets faking a hadronic tau
- Mainly from $t\bar{t}$ and $t\bar{t}V$ events
- Measuring one prong and three prong correction factor from CR as a function of p_T

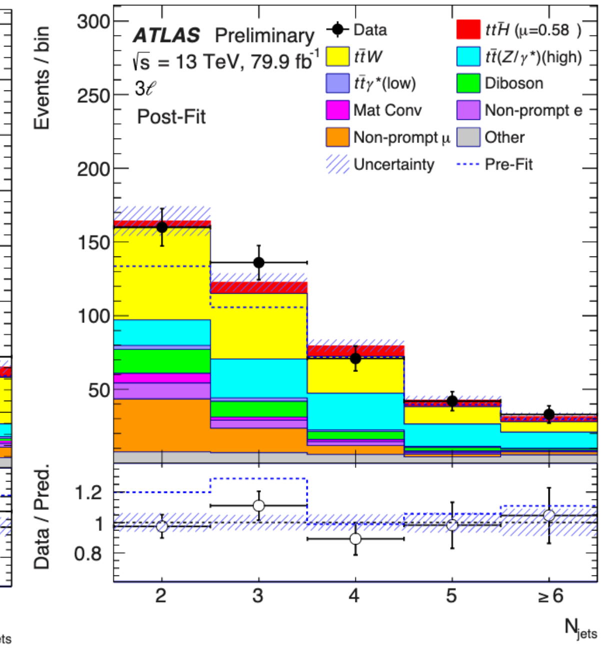
Multilepton analysis

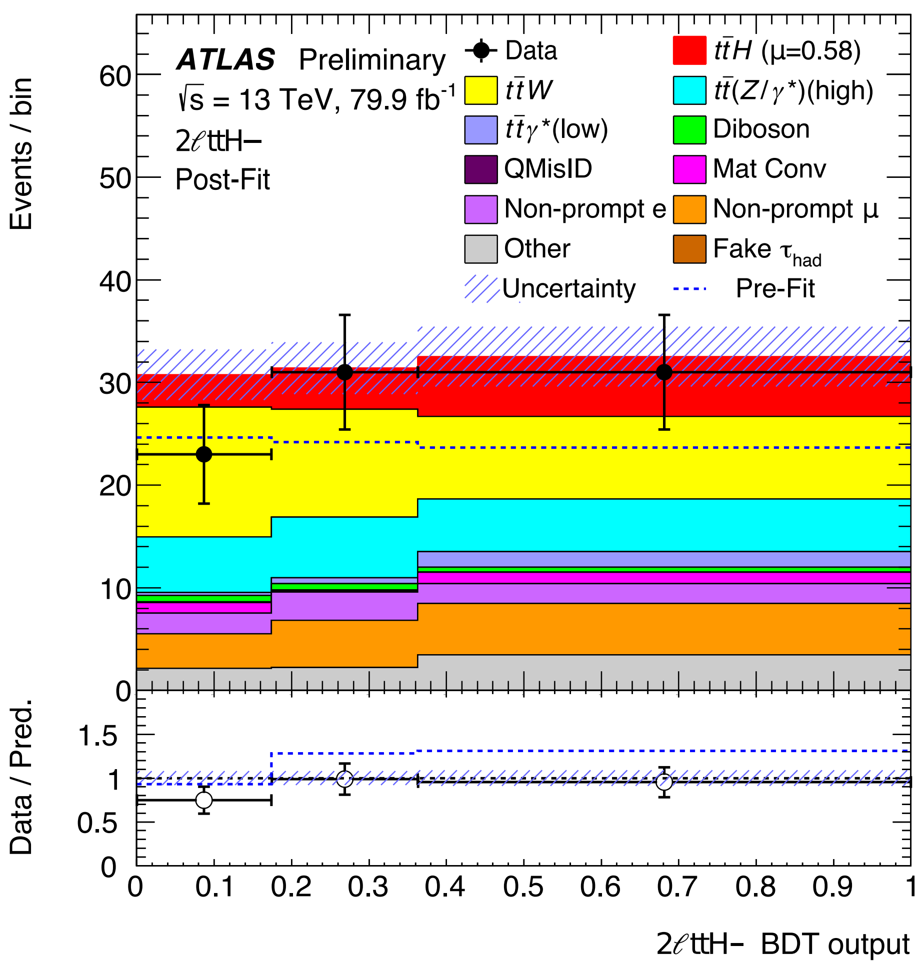
SM interpretation analysis using 80/fb **ATLAS-CONF-2019-045**

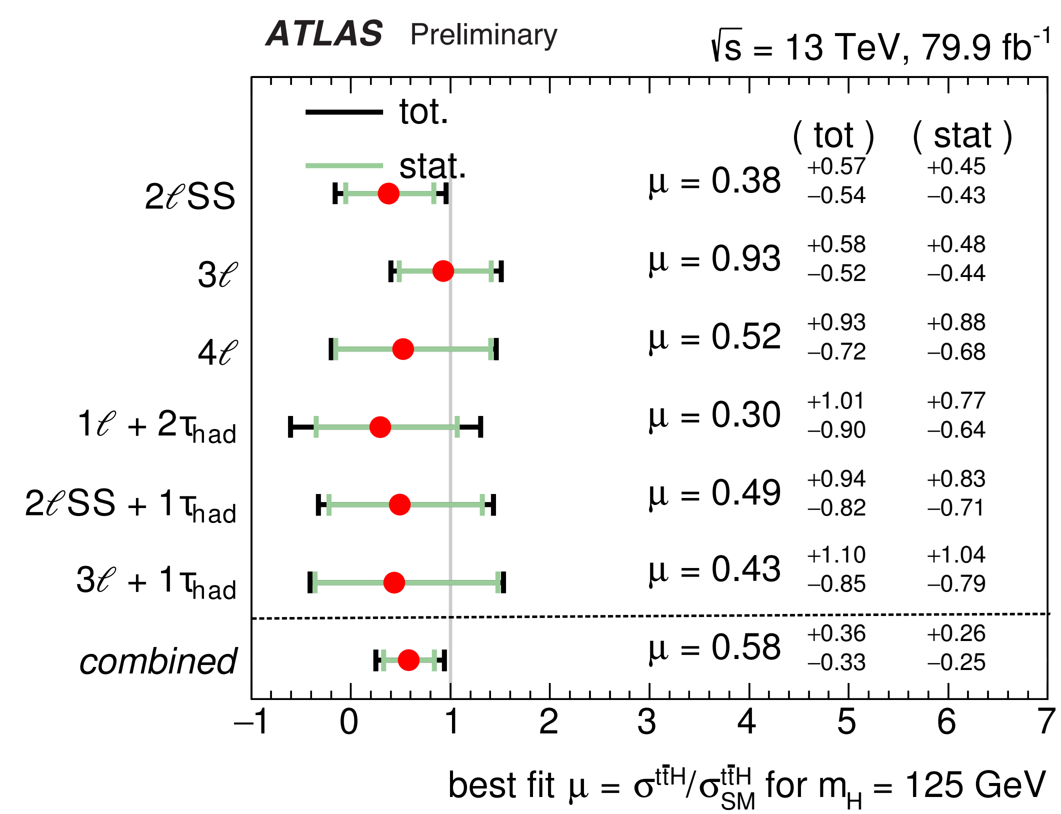
Main **irreducible backgrounds** from $t\bar{t}Z$, $t\bar{t}W$ and VV

- Normalisation of $t\bar{t}W$ estimated from enriched control regions
- $k^{2\ell LJ}_{t\bar{t}W} = 1.56^{+0.30}_{-0.28}$, $k^{2\ell HJ}_{t\bar{t}W} = 1.26^{+0.19}_{-0.18}$, $k^{3\ell}_{t\bar{t}W} = 1.68^{+0.30}_{-0.28}$
- Now better understanding of $t\bar{t}W$ [see S. Kazakos's talk]









$H \to ZZ^* \to 4\ell$

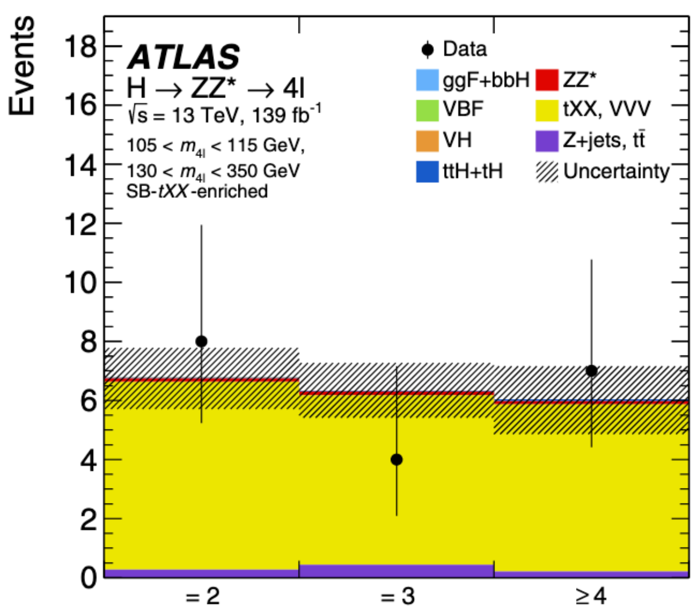
SM interpretation analysis using 139/fb

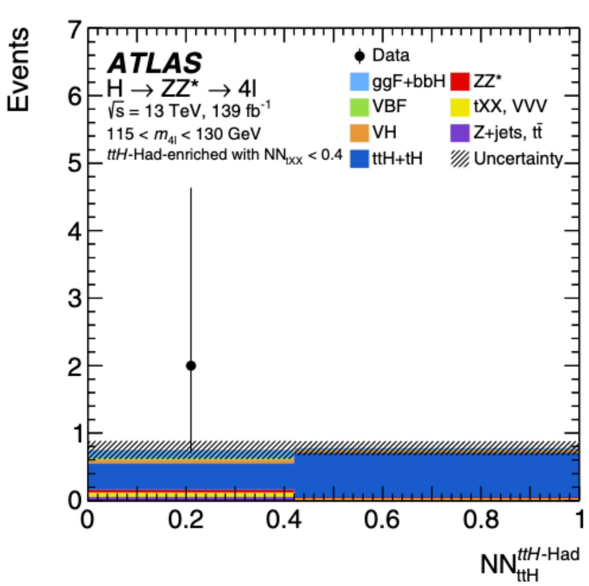
Eur. Phys. J. C 80 (2020) 957

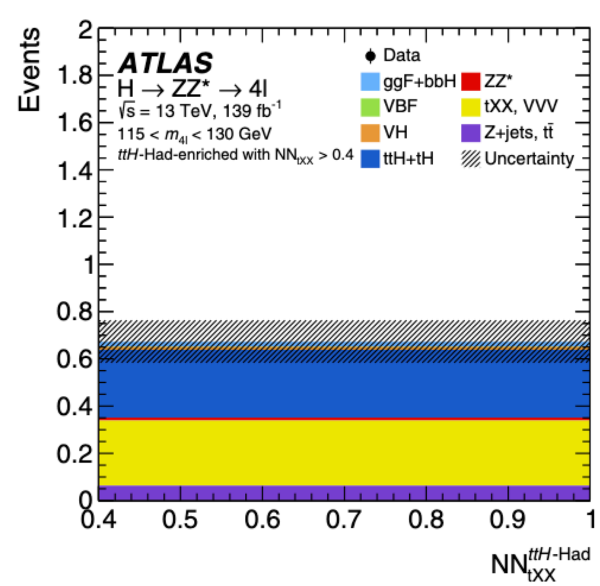
- $t\bar{t}H$ enriched regions with dominant backgrounds being $t\bar{t}$ and VV
- In other regions the main background is the non-resonant production of Z-pairs
- Non prompt-lepton background has smaller contribution
- $t\bar{t}H$ and tH classified together

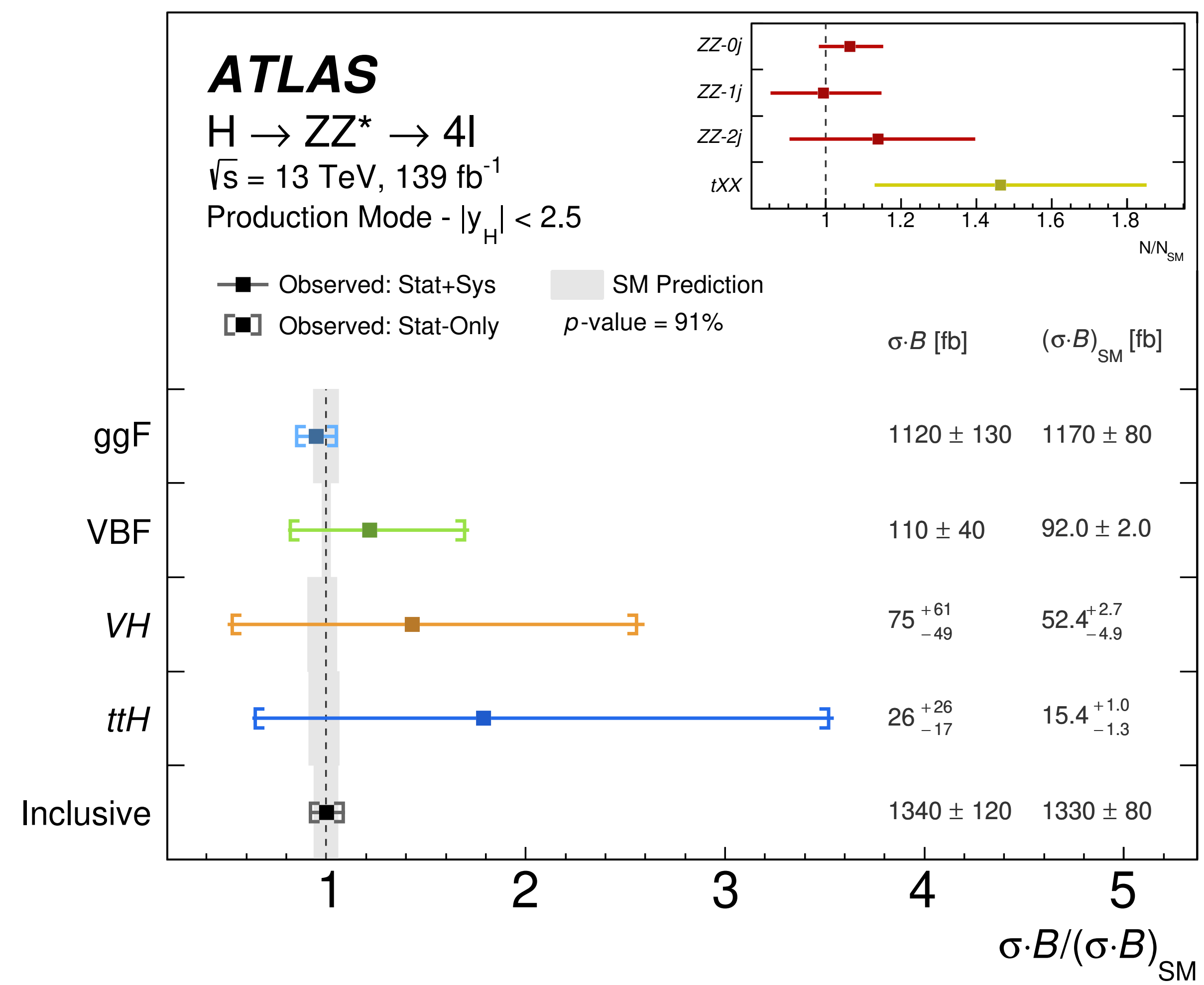
RESULT

Observed $\mu(t\bar{t}H) = 1.7^{+1.7}_{-1.2}$
Dominant contribution from statistical uncertainty





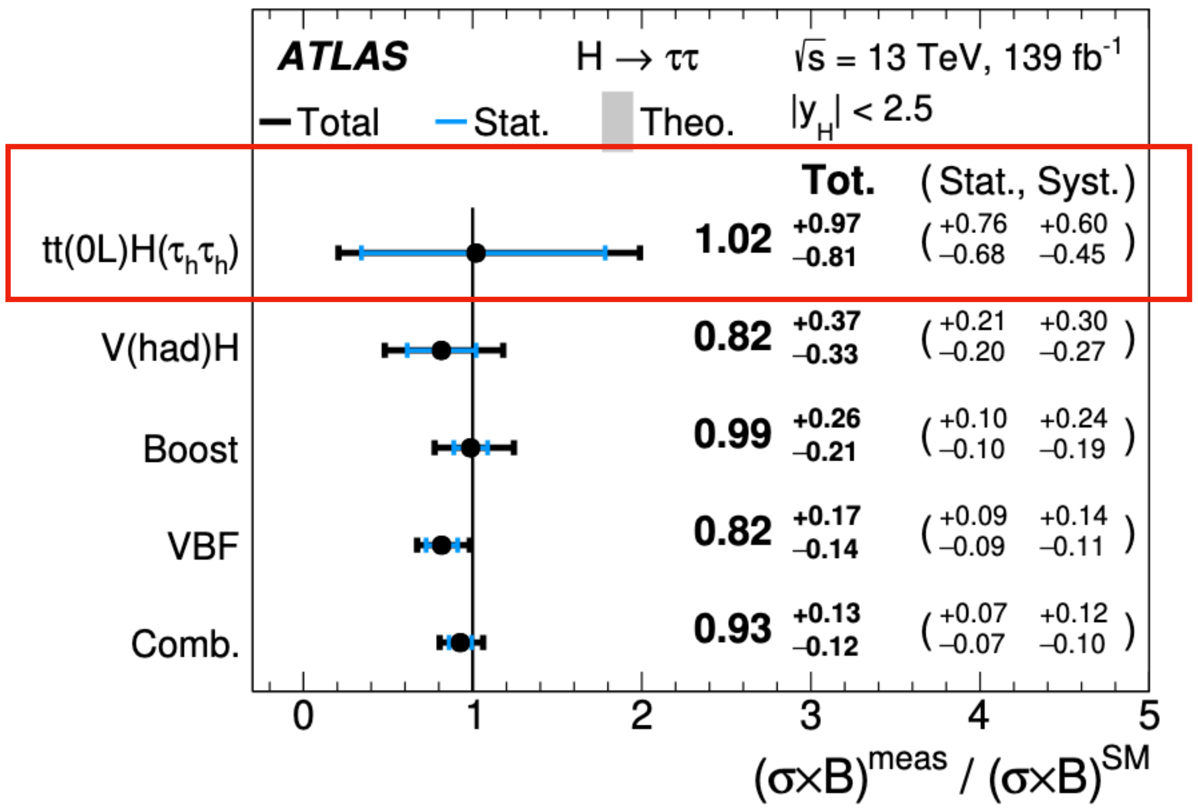


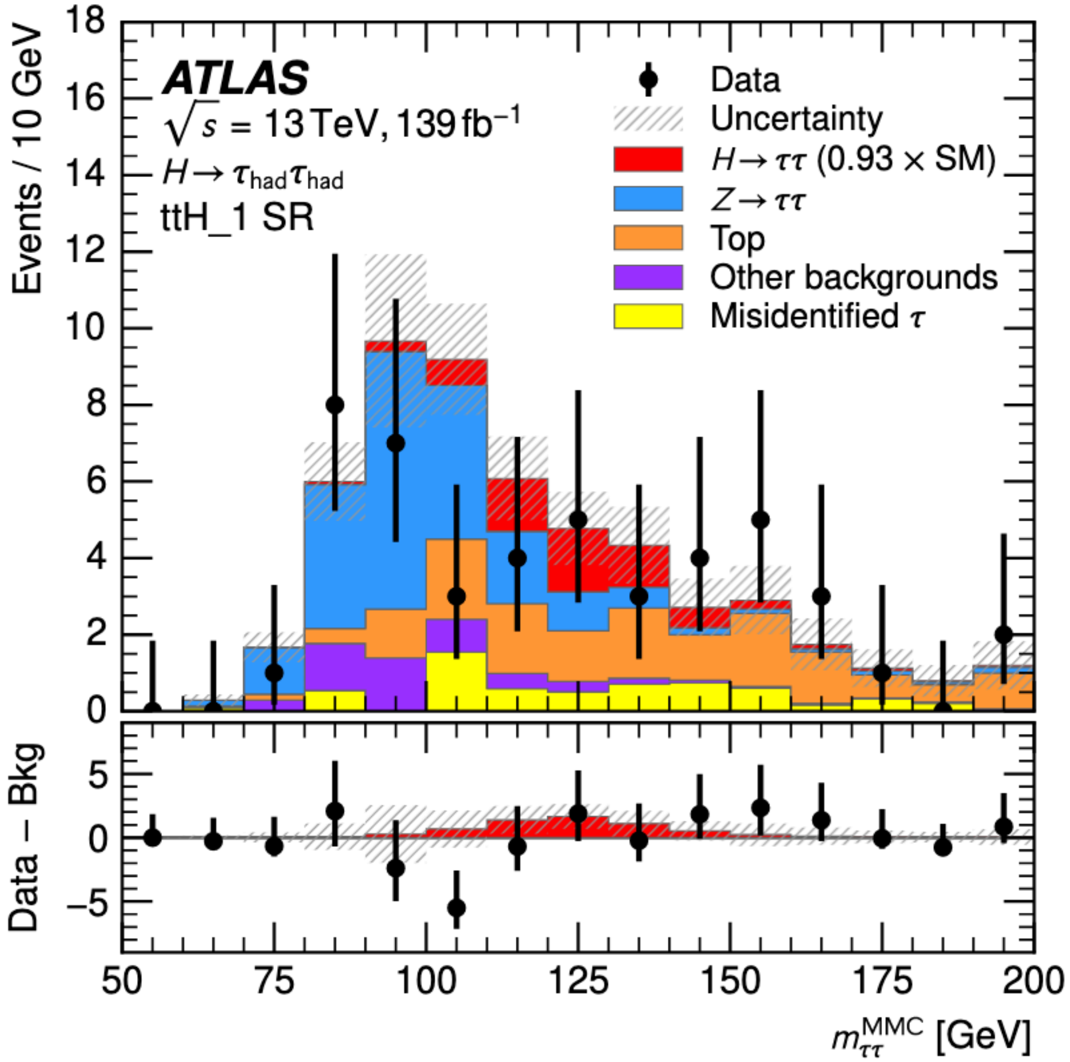


$H \to \tau\tau$

SM interpretation analysis using 139/fb JHEP08(2022)175

- Part of a wider effort to measure $H \to \tau_{\rm had}\tau_{\rm had}$ in several production modes
- Fully hadronic decay from top pair and triggering on $\tau\tau$ pair
- Two BDTs to distinguish $t\bar{t}H$ from $Z \to \tau\tau$ and $t\bar{t}$
- Two signal regions defined depending on $N_{\rm jets}$ and $N_{\rm b-jets}$



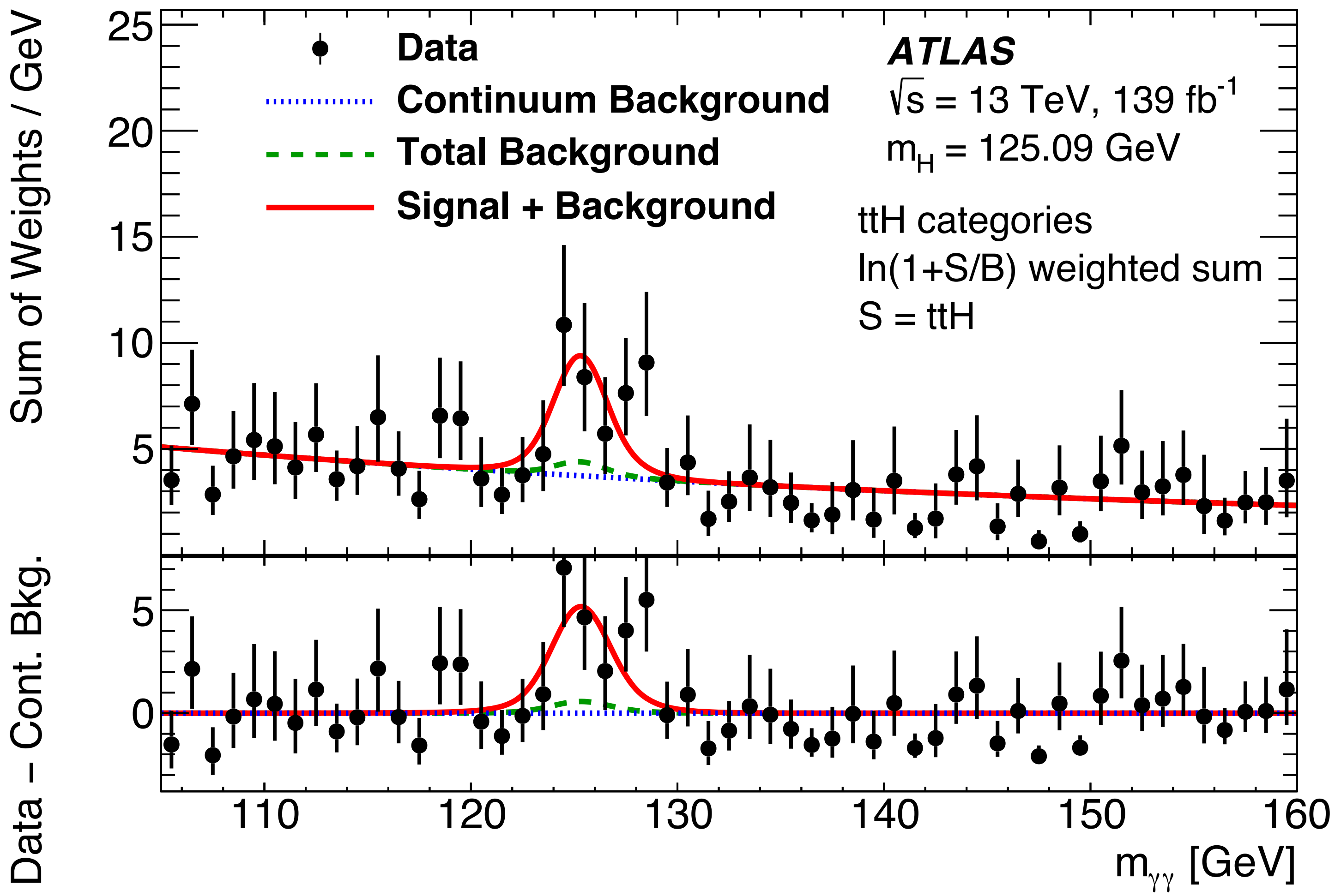


Missing Mass Calculator (MMC) is an algorithm for the calculation of the **Higgs mass** using the τ lepton decay products and $\vec{E}_T^{\rm miss}$ together with additional jets informations

$t\bar{t}H$ and tH with $H \rightarrow \gamma\gamma$

SM interpretation analysis using 139/fb ATLAS-CONF-2020-026

- Targeting $t\bar{t}H$ and tH and STXS framework
- Diphoton selection in combination with NN vertex finder
- BDTs trained to disentangle signal from background, derive STXS categories and identify three production modes: $t\bar{t}H$, tHq and tWH (tH optimised for $y_t = -1$)
- From BDT training removed variables correlated to $m_{\gamma\gamma}$



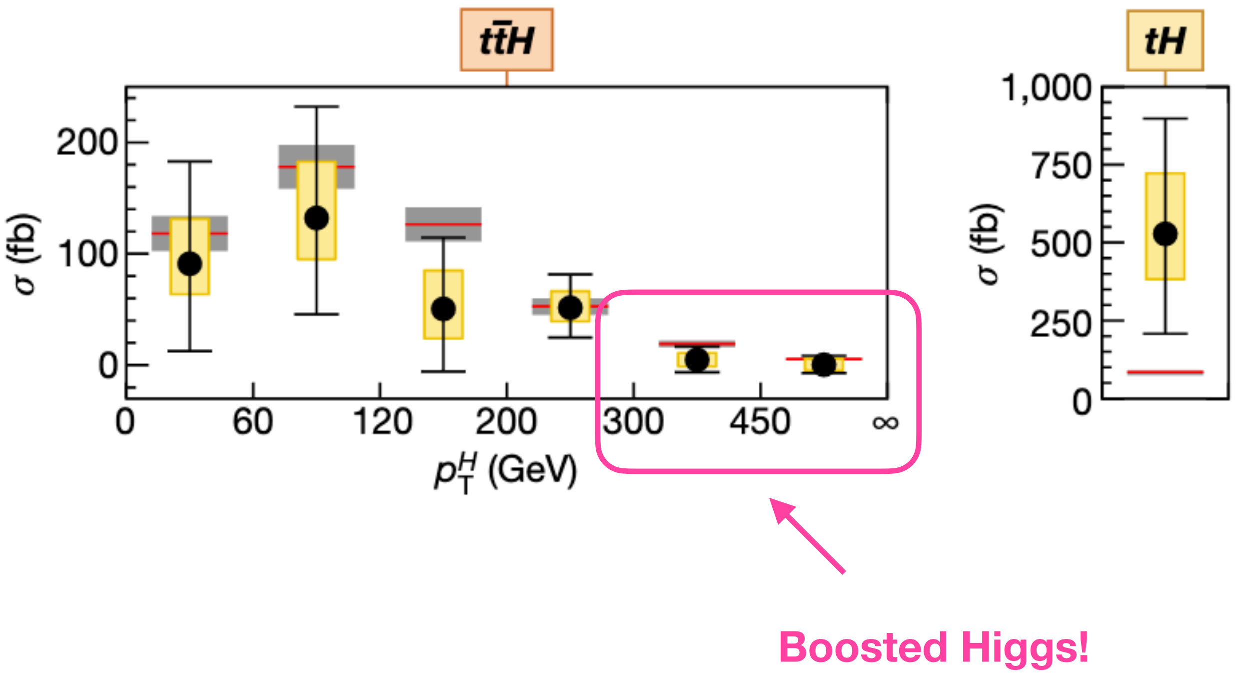
- Signal modelled with **double sided Crystal Ball**
- Background function optimised looking at **spurious signal**

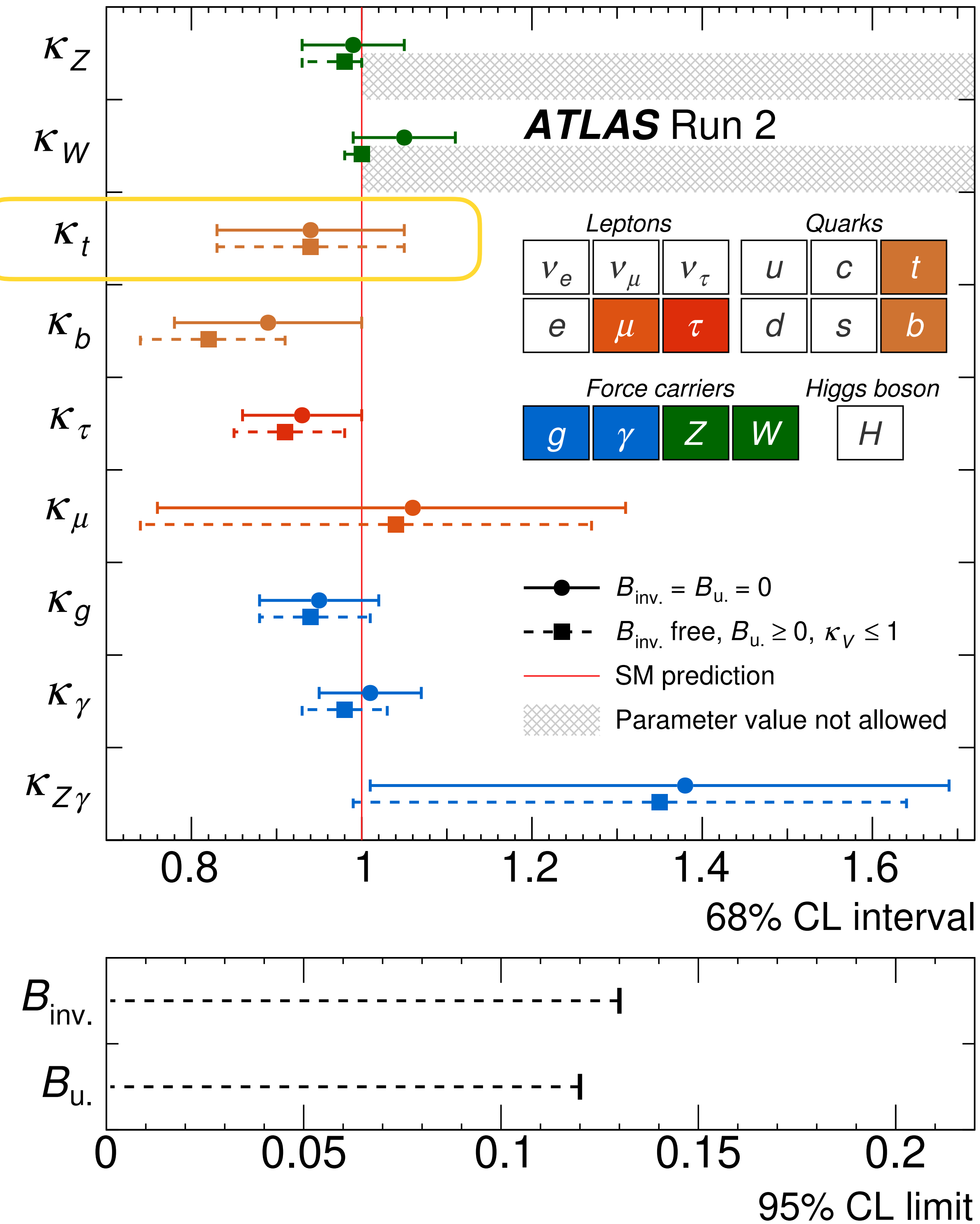
RESULT

$t\bar{t}H + tH$ significance of 4.7σ
Measured $\mu(t\bar{t}H + tH) = 0.92^{+0.27}_{-0.24}$
Upper limit on $tHq + tWH$ at 95% LC is $8 \times$ SM
Leading uncertainty is statistical followed by photon energy resolution

Combination of Higgs measurements [Nature 607(2022)]

- Combination of Higgs measurement to extract interactions with SM particles
- Both inclusive cross-section and STXS on $p_T(H)$
- $t\bar{t}H$ and tH distinction from $H \to \gamma\gamma$ analysis
- Included as well $t\bar{t}H$ with $H \to b\bar{b}$, $H \to ZZ^* \to 4\ell$, $H \to \tau\tau$ and multi lepton analysis
- Results compatible with SM expectation
- $t\bar{t}H + tH$ observed sensitivity 6.4σ





Top Yukawa CP properties

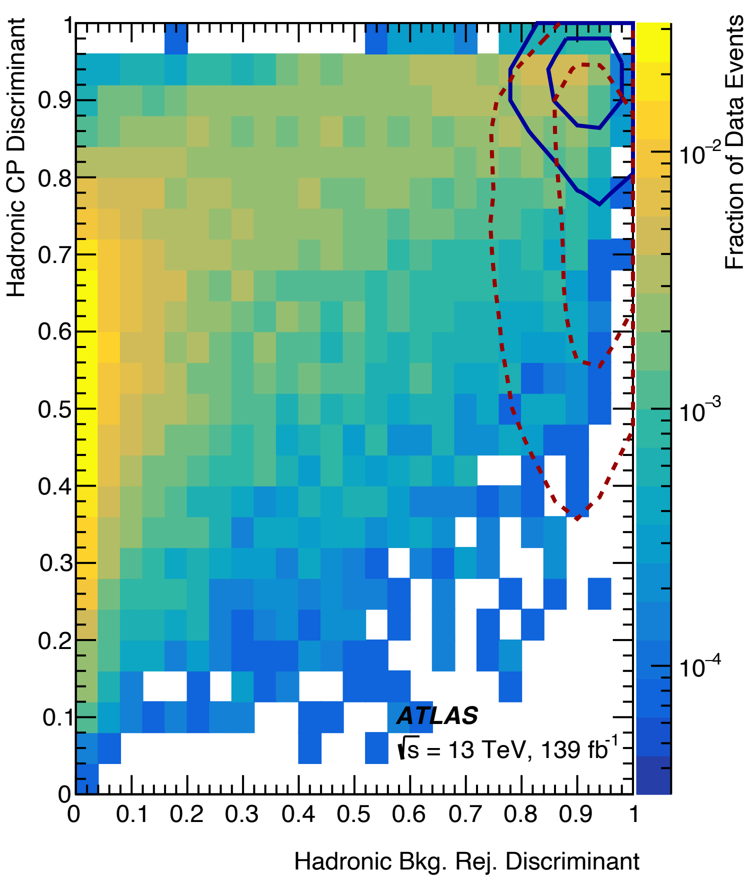
$t\bar{t}H$ and tH with $H \to \gamma\gamma$

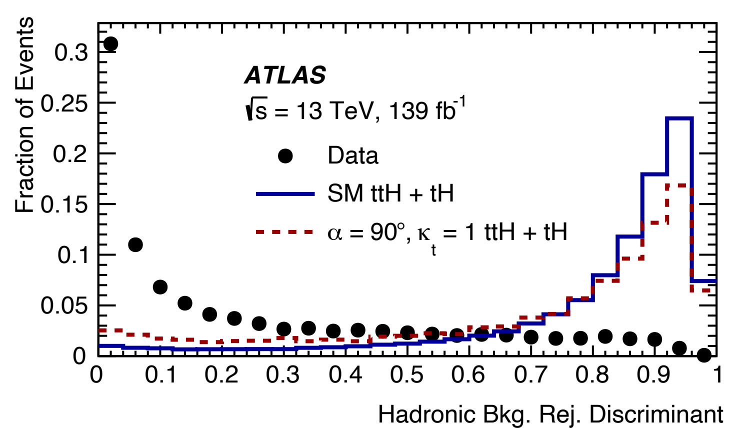
CP interpretation analysis using 139/fb

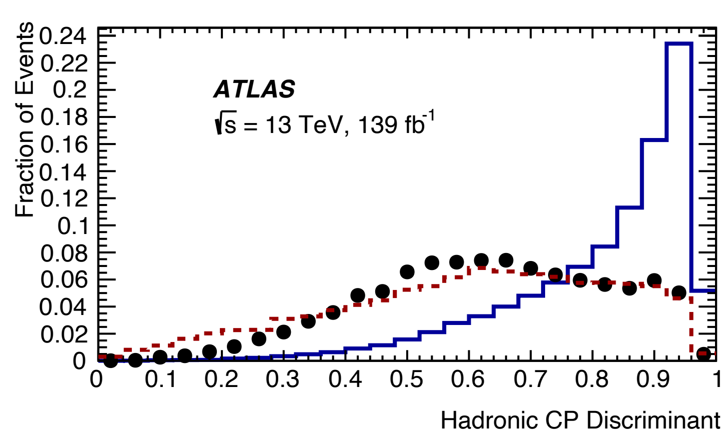
PhysRevLett.125.061802

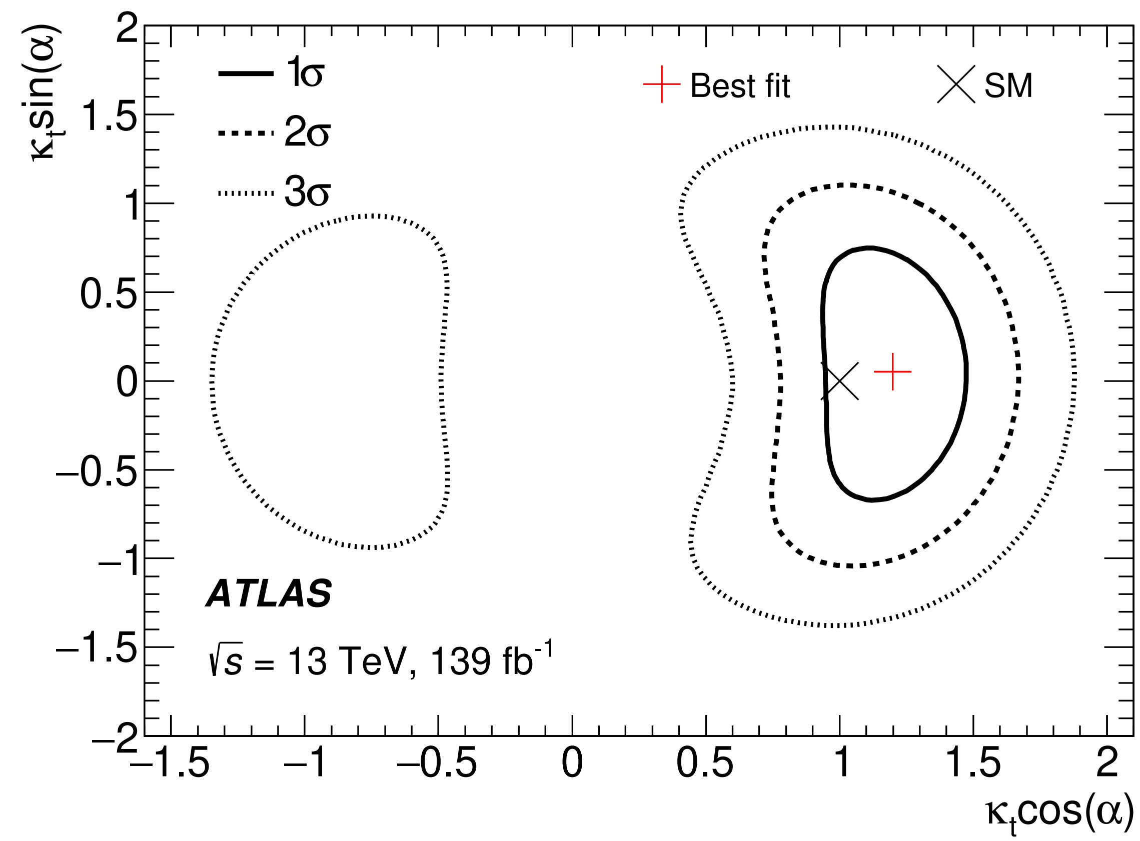
Targets both leptonic and fully hadronic $t\bar{t}$ pair decays

- BDT to distinguish $t\bar{t}H$ from background and CP even/odd $t\bar{t}H + tH$ production
- 20 analysis categories defined looking at 2D BDT space
- Fitting on $m_{\gamma\gamma}$ as in SM analysis case









RESULT

$|\alpha| > 43^{\circ}$ excluded at 95% CL

Pure CP-odd excluded at 3.9σ

$t\bar{t}H$ and tH with $H \to b\bar{b}$

CP interpretation analysis using 139/fb

arXiv:2303.05974v1

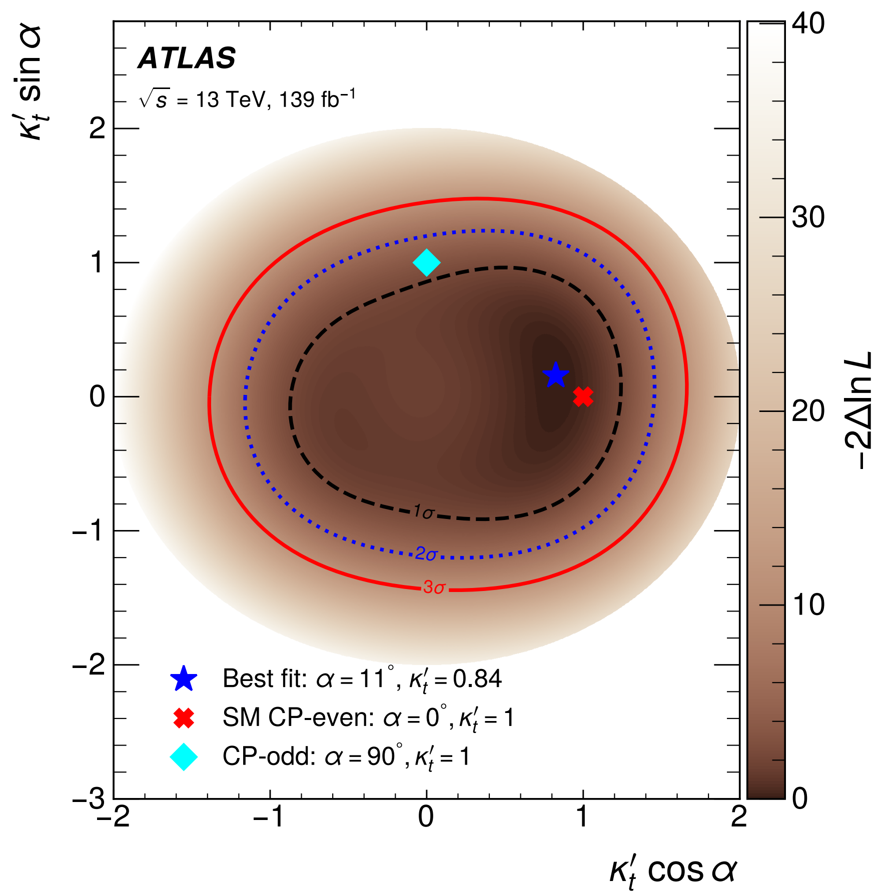
- Using same selections and background estimation as SM interpretation analysis
- CP interpretation via parametrisation of $t\bar{t}H$ and tH to simultaneously extract k_t and α
- Fit on CP sensitive variables in signal enriched regions
  - Defined $\vec{p}_{1,2}$ the momentum three-vectors of the two top quarks and $\hat{z}$ unity vector in the beam line direction

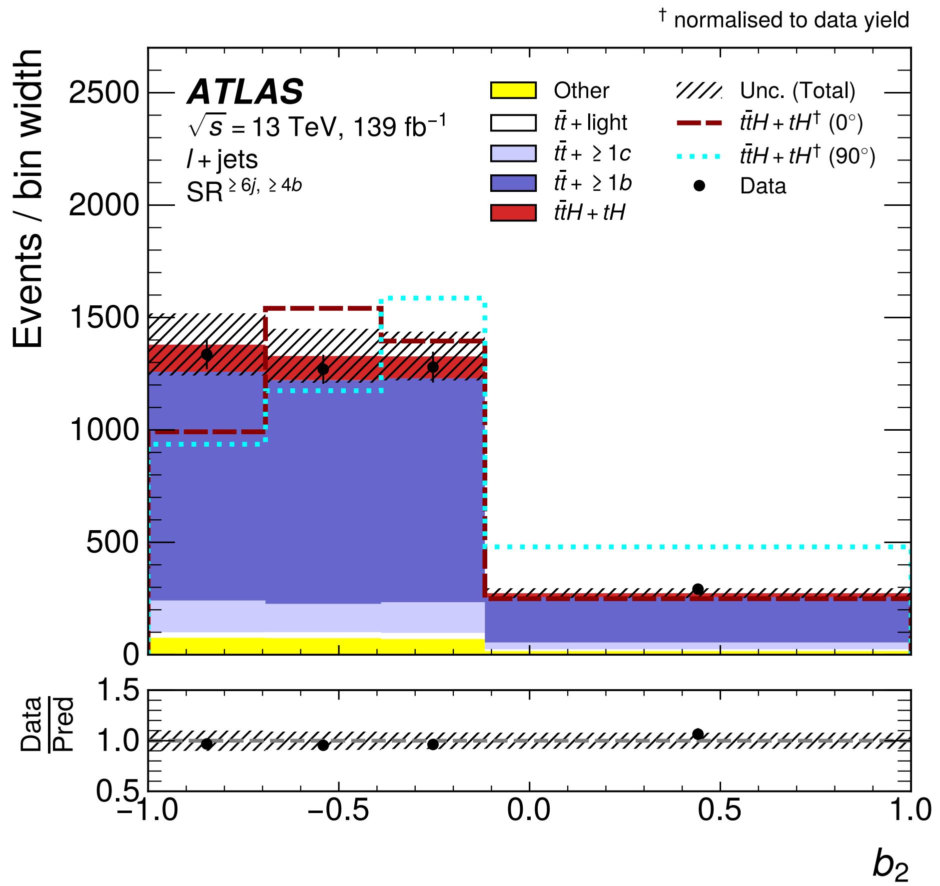
$$b_2 = \frac{(\vec{p}_1 \times \hat{z}) \cdot (\vec{p}_2 \times \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$

l+jets channel

$$b_4 = \frac{(\vec{p}_1 \cdot \hat{z}) \cdot (\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$

dilepton channel





RESULT

Best fit $\alpha = 11^\circ\,^{+56^\circ}_{-77^\circ}$ $k_t = 0.84^{+0.30}_{-0.46}$

Pure CP odd excluded at 1.2σ

Conclusions

- Increasing statistics delivered by LHC Run 2 allowed to observe $t\bar{t}H$, start studying tH
- Challenging modelling of some backgrounds such as $t\bar{t} + \geq 1b$ and $t\bar{t}W$ posed a big challenge
  - But we can now say we know our predictions better and better!
- A lot of interesting physics worth exploring in differential cross-sections, boosted regimes and tH production

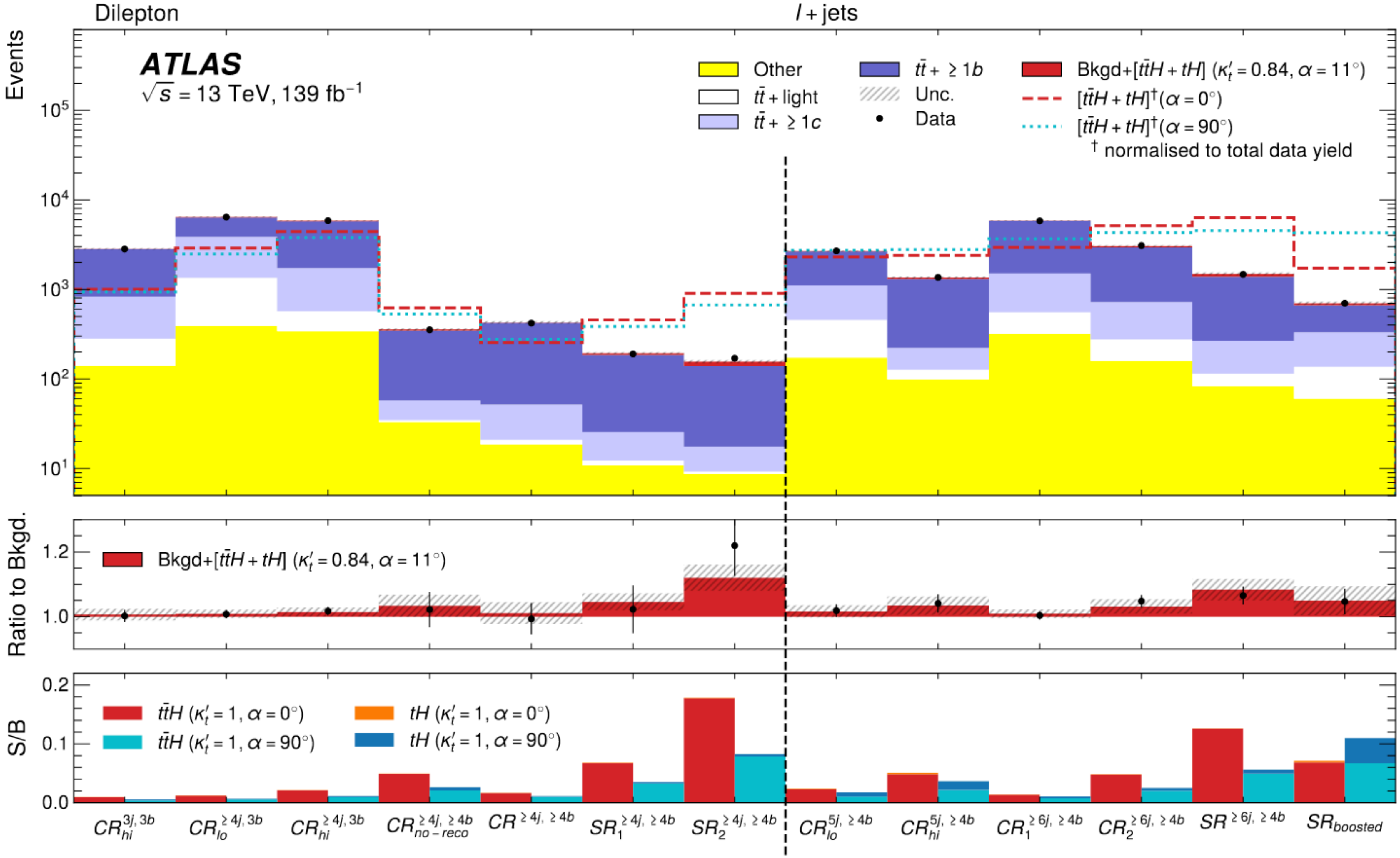
THANKS FOR YOUR ATTENTION!

L. Popova

BACKUP

$t\bar{t}H$ and tH with $H \to b\bar{b}$

CP interpretation analysis using 139/fb arXiv:2303.05974v1



Combination