ATLAS measurement of $t\bar{t}H$ in multilepton final state

arXiv:2510.23755

Gianna Loeschcke Centeno
gianna.loeschcke.centeno@cern.ch

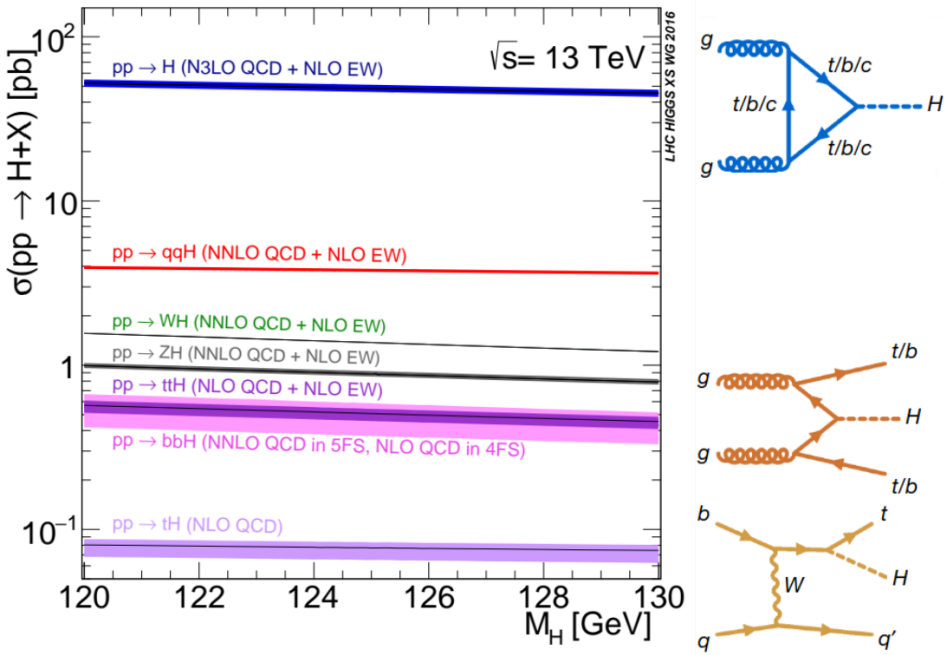
LAPP

21.04.2026

Motivation for $t\bar{t}H$

Top-Higgs coupling

- Top quark is the heaviest fermion in SM: top Higgs Yukawa coupling of O(1)
- Interesting place to study Yukawa coupling and potential deviations from the SM expectations



- Many H production modes are sensitive to y_t through loops
- Cross-section of $t\bar{t}H$ and $tHqb$ few orders of magnitude smaller than ggF
- But: $t\bar{t}H$ and $tHqb$ probe t-H coupling in direct way
- $tHqb$ also probes the sign of y_t in a direct way

$t\bar{t}H$ in multi-lepton final state

Higgs decay modes

- $t\bar{t}H$ measurements in several decay modes by ATLAS: $\gamma\gamma$, bb, ZZ, $\tau\tau$
- $\gamma\gamma$: clean channel but low statistics
- bb: high statistics but complicated backgrounds (tt+HF)
- ML: middleground

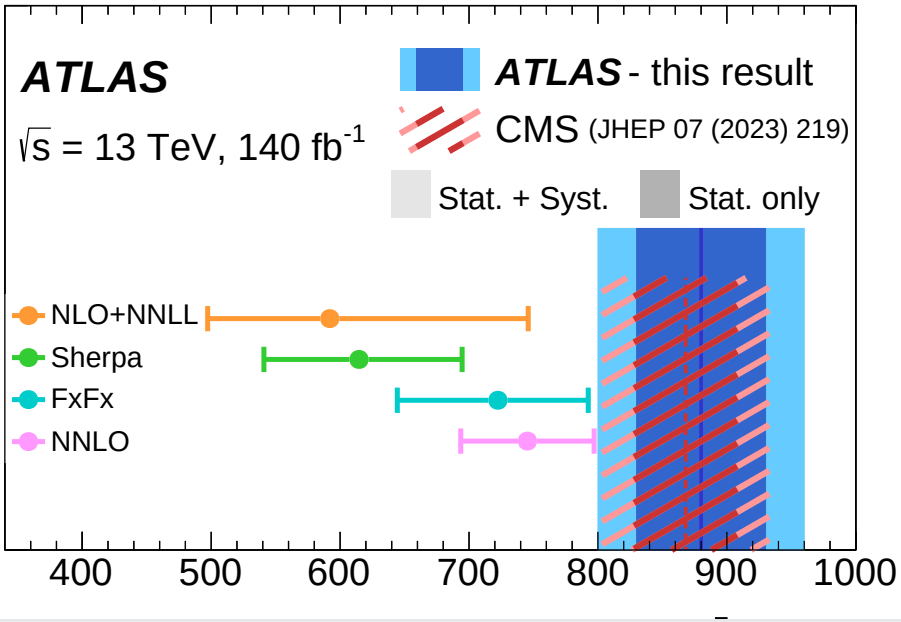
ATLAS $t\bar{t}H$ ML measurement

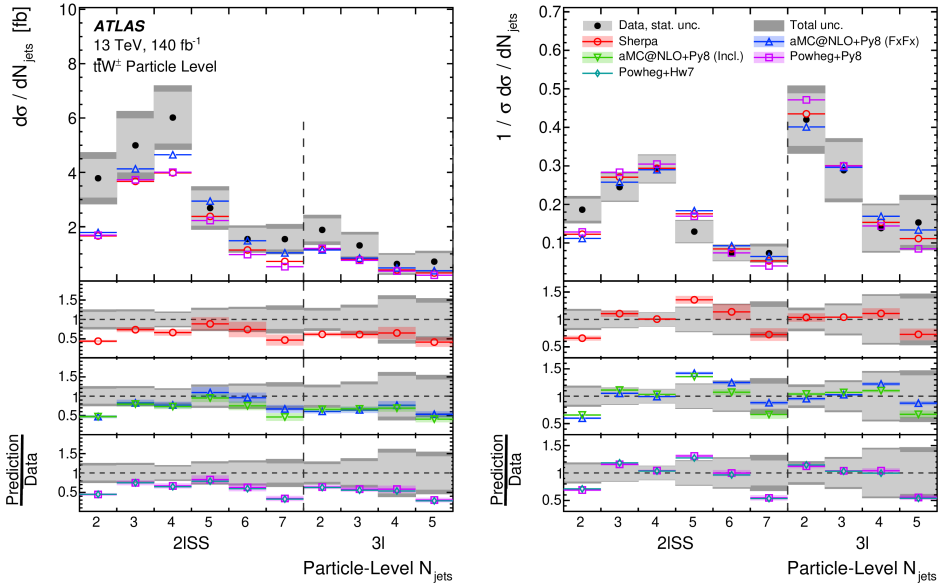
- Full Run2 data set ($140\,\text{fb}^{-1}$)
- Improves with respect to ▸ ATLAS-CONF-2019-045:
  - Higher statistics
  - Improved flavour-tagging and lepton identification
  - Improved understanding of $t\bar{t}W$
  - STXS measurement
  - CP interpretation

$t\bar{t}W$ background

Complicated SM process

- Quark antiquark induced process (charge asymmetry)
- Large higher-order QCD and EW corrections
- Dedicated inclusive and differential measurements ▸ JHEP05(2024)131
- New cross-section calculations from theory community ▸ PhysRevLett.131.231901



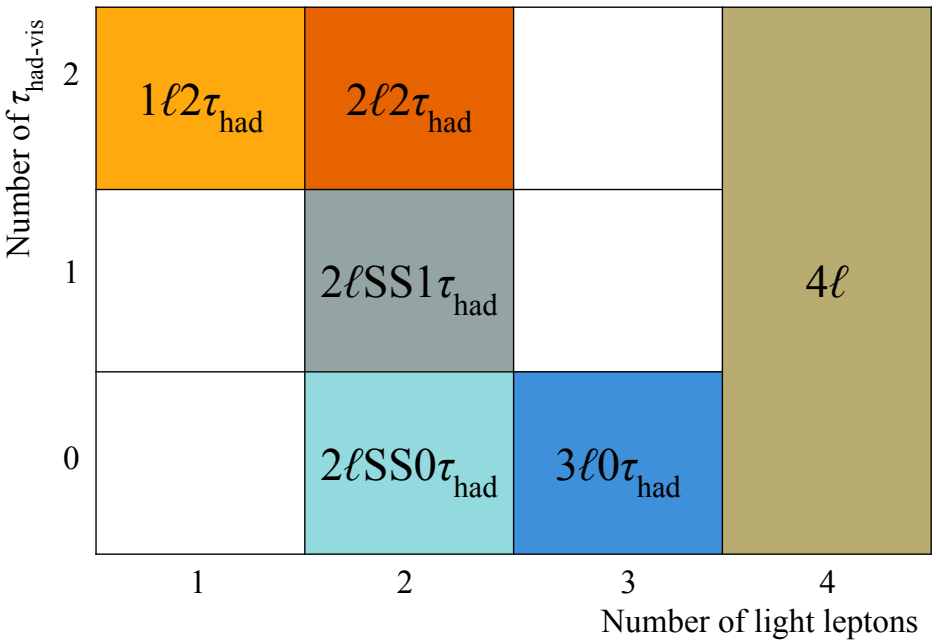


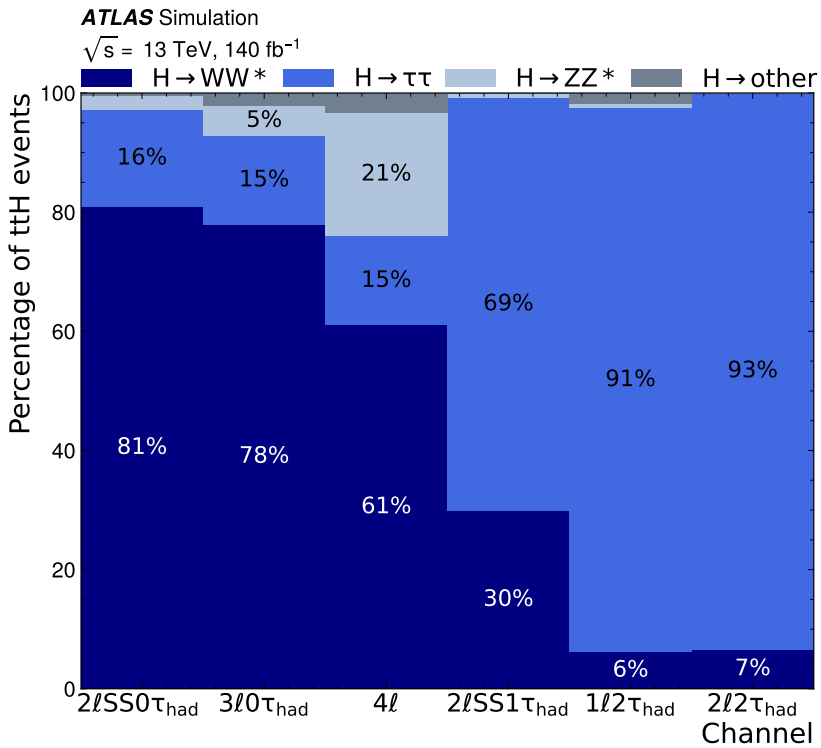
- $t\bar{t}H$ ML analysis closely follows methods developed for $t\bar{t}W$ analysis

Overview of analysis

Selected Higgs decay modes

- Target process with several leptons in final state
- $0\tau_{had}$ channels: highest statistics
- Selection targets different Higgs decay modes: WW, $\tau\tau$, ZZ
- Dominant decay mode dependent on channel





Event categorisation

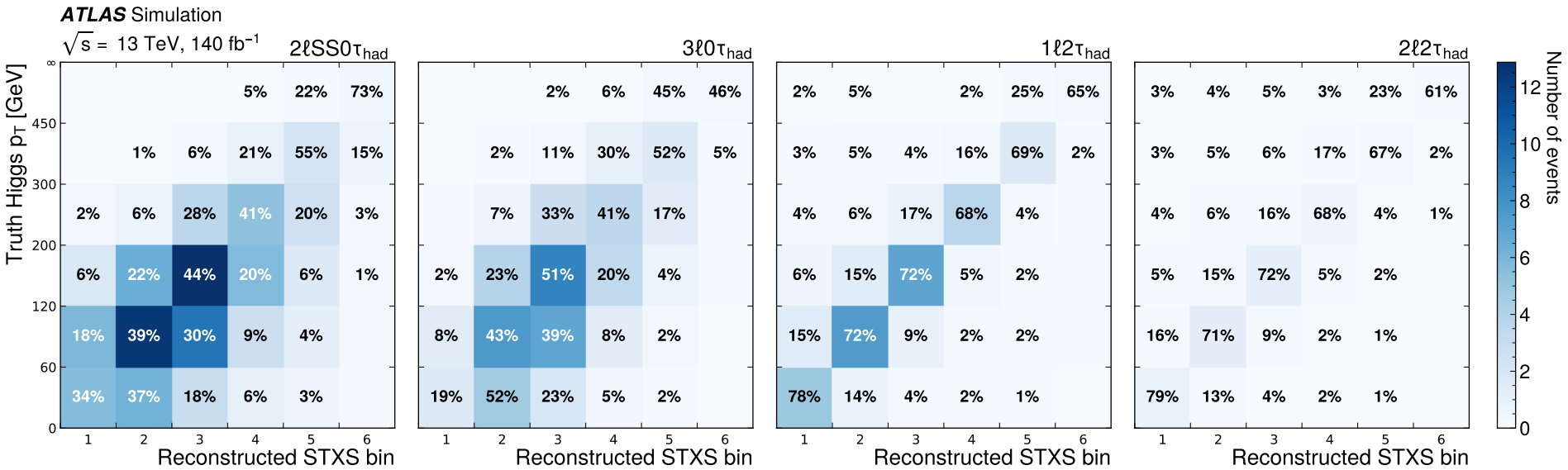
- In $0\tau_{had}$ and $2\tau_{had}$ channels: Higgs p_T reconstruction

$0\tau_{had}$

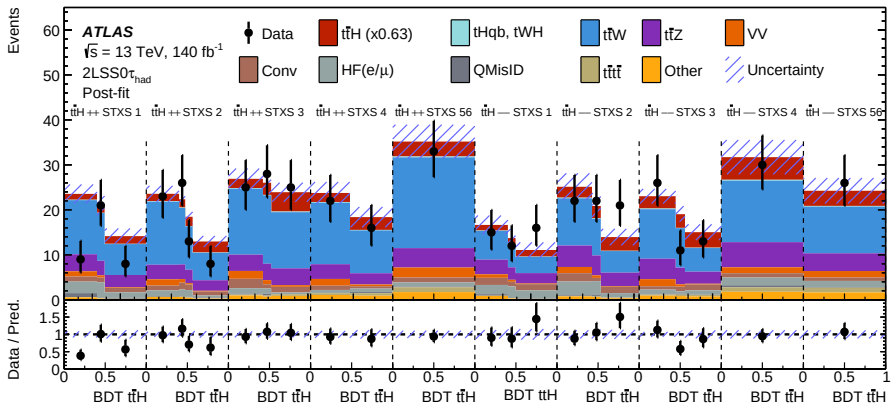
- GNN
- large migrations because of neutrinos and soft jets out of acceptance

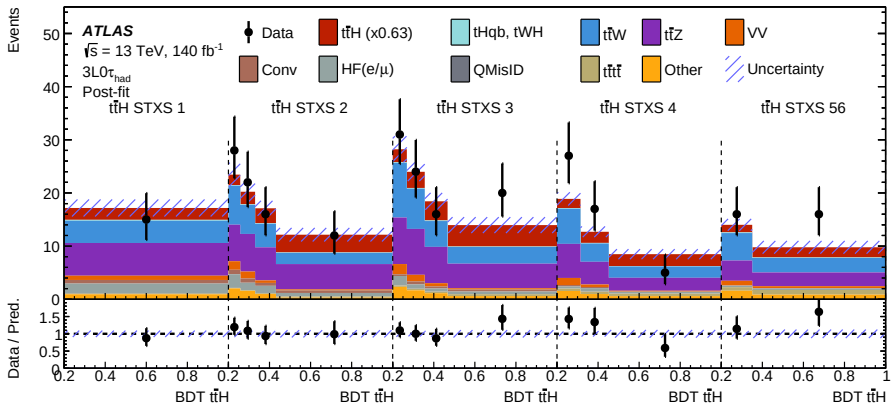
$2\tau_{had}$

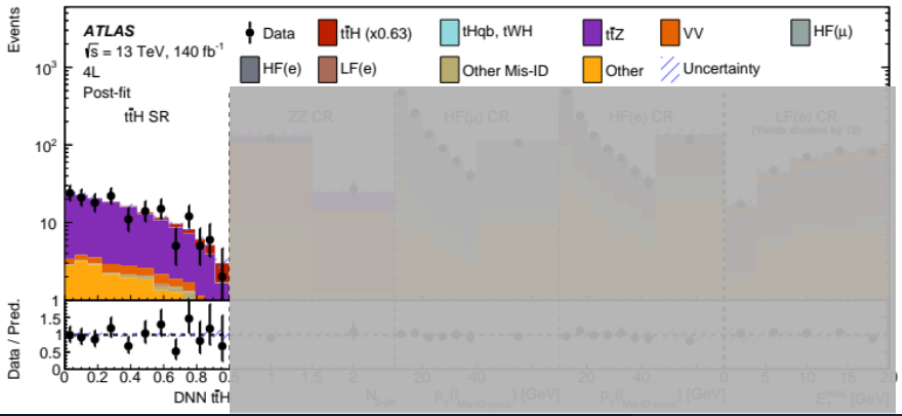
- BDT
- more diagonality in $H \to \tau_{had}\tau_{had}$



Event categorisation: $0\tau_{had} + 4L$ channels







2LSS

- 4dim BDT: $t\bar{t}H$, $tHqb$, $t\bar{t}W$ and Other
- Dominant background: $t\bar{t}W$
- Make use of charge asymmetry of $t\bar{t}W$ to decouple from $t\bar{t}W$

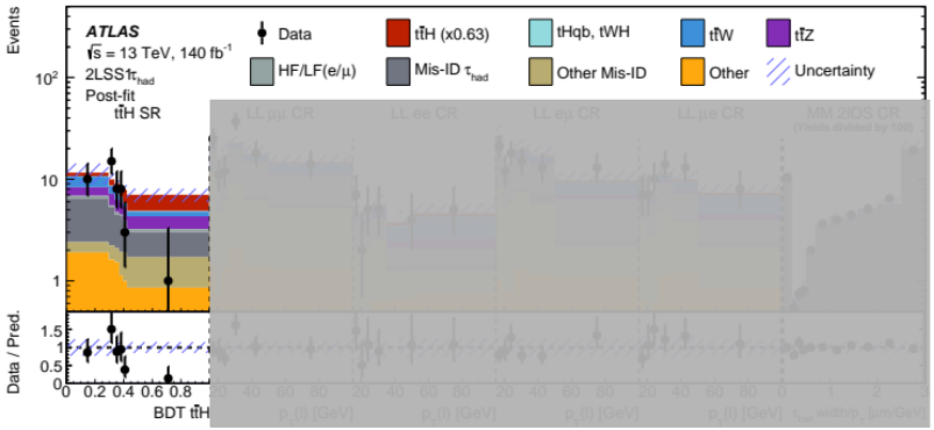
3L

- 6dim BDT: $t\bar{t}H$, $tHqb$, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}$, VV and Other
- Dominant background: $t\bar{t}W$ and $t\bar{t}Z$

4L

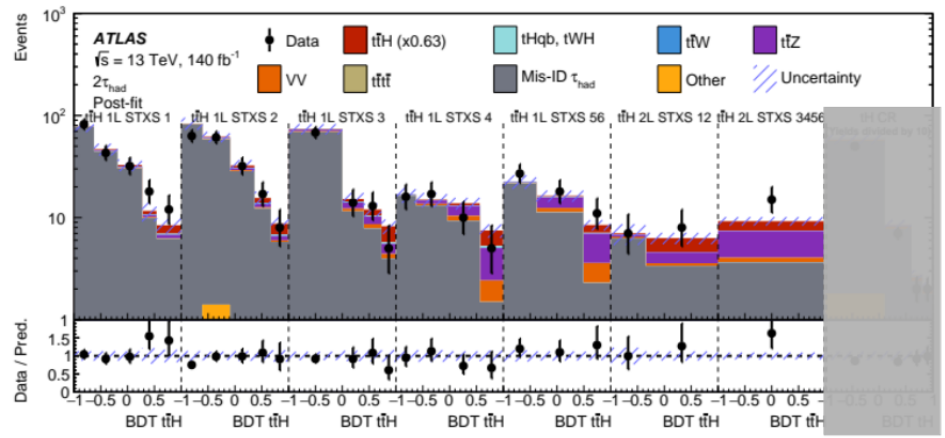
- 3dim DNN: $t\bar{t}H$, $t\bar{t}Z$, ZZ
- Dominant background: $t\bar{t}Z$

Event categorisation: τ_{had} channels



$2LSS1\tau_{had}$

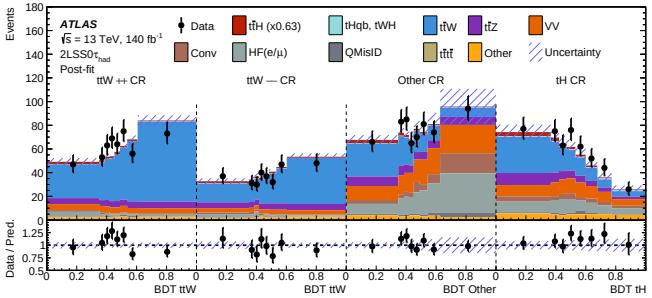
- 3dim BDT: $t\bar{t}H$, $t\bar{t}W$ and $t\bar{t}$
- Dominant backgrounds: non-prompt

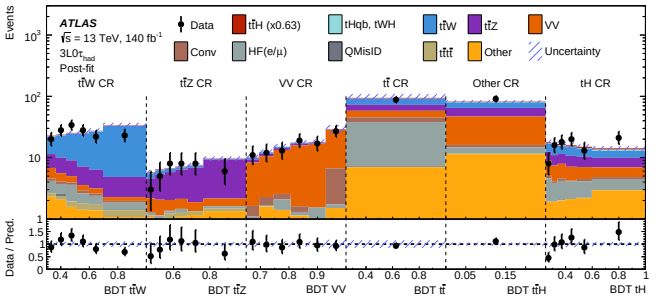


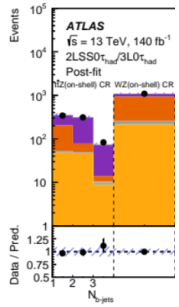
$2\tau_{had}$

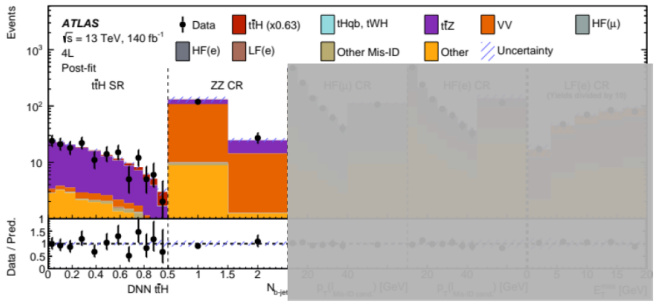
- 1L and 2L regions
- $t\bar{t}H$ and $tHqb$ split via njets
- Binary BDT as discriminant variable
- Fully dominated by non-prompt τ_{had}

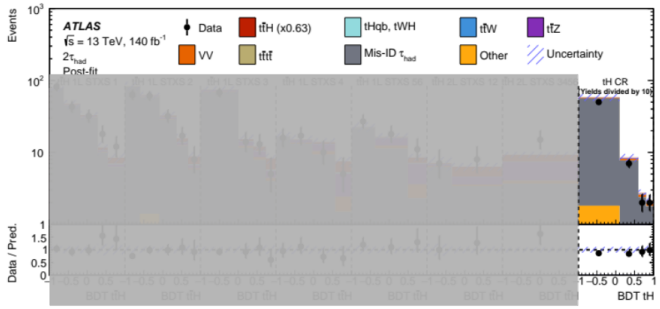
Irreducible backgrounds



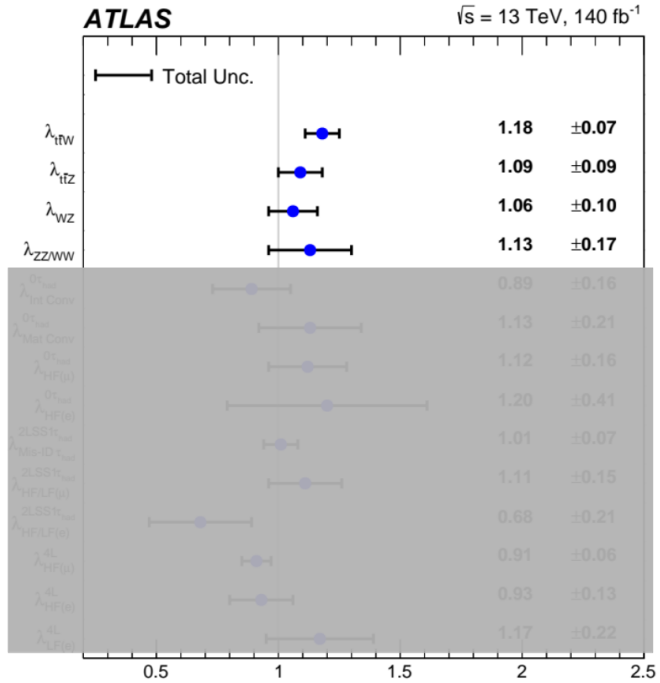




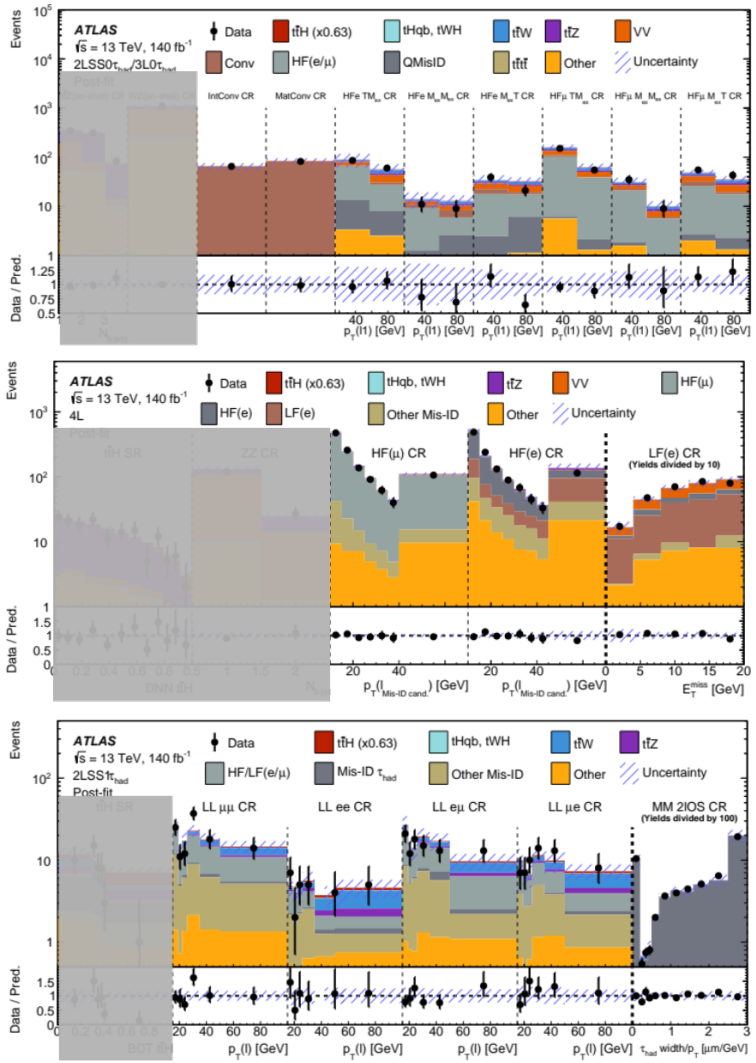




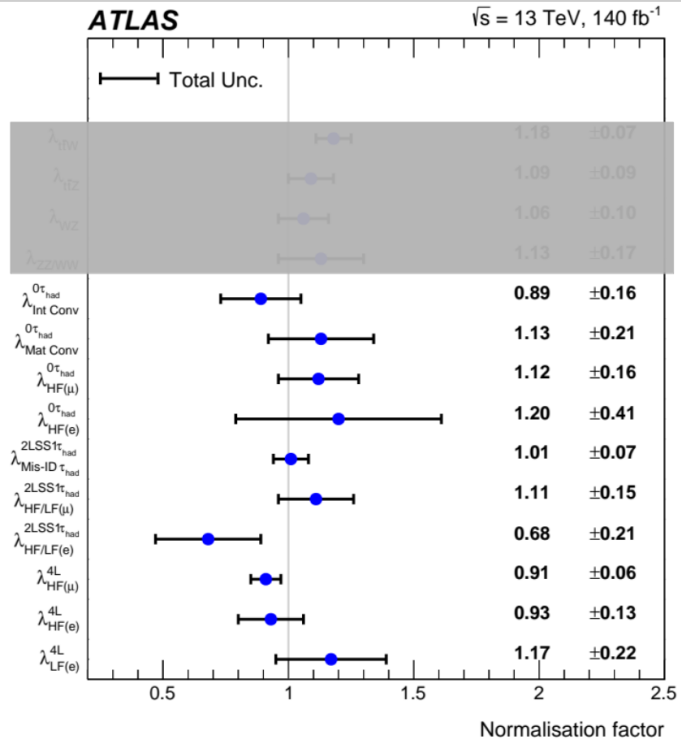
- Dedicated *tHqb* categories for simmultaneous measurement
- Constrain normalisation of dominant backgrounds: NFs fully correlated across channels
- $t\bar{t}W$ NF consistent with ATLAS $t\bar{t}W$ measurement



Reducible backgrounds

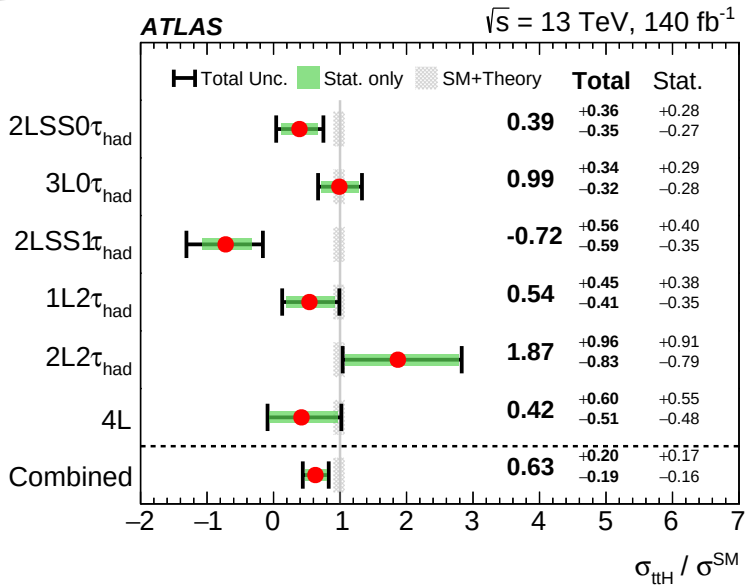


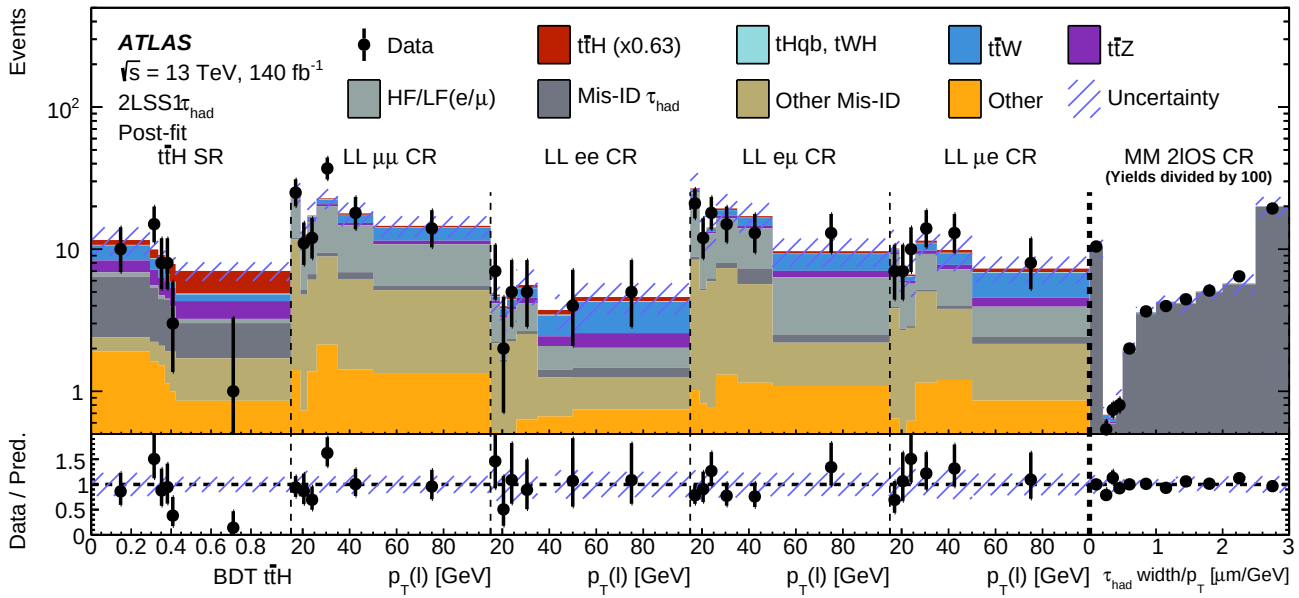
- Non-prompt leptons (mainly $t\bar{t}$): HF and LF hadron decays, conversions, mis-ID τ_{had}
- Constrain normalisation with data
- Uncorrelated between channels, as use different lepton working points
- Fully data-driven fake factor method in $2\tau_{had}$ channel



Results: inclusive cross-section

- Simultaneous fit of signal and backgrounds
- $tHqb$ fixed to SM
- $\sigma_{t\bar{t}H} = 321^{+102}_{-99}$ fb
- 7.2 % compatibility with SM
- Measure $t\bar{t}H$ with significance of 3.3σ (5.3σ expected)
- Down fluctuation in $2LSS1\tau_{had}$
- 6 channels compatible at 12.4 %





Results: inclusive cross-section

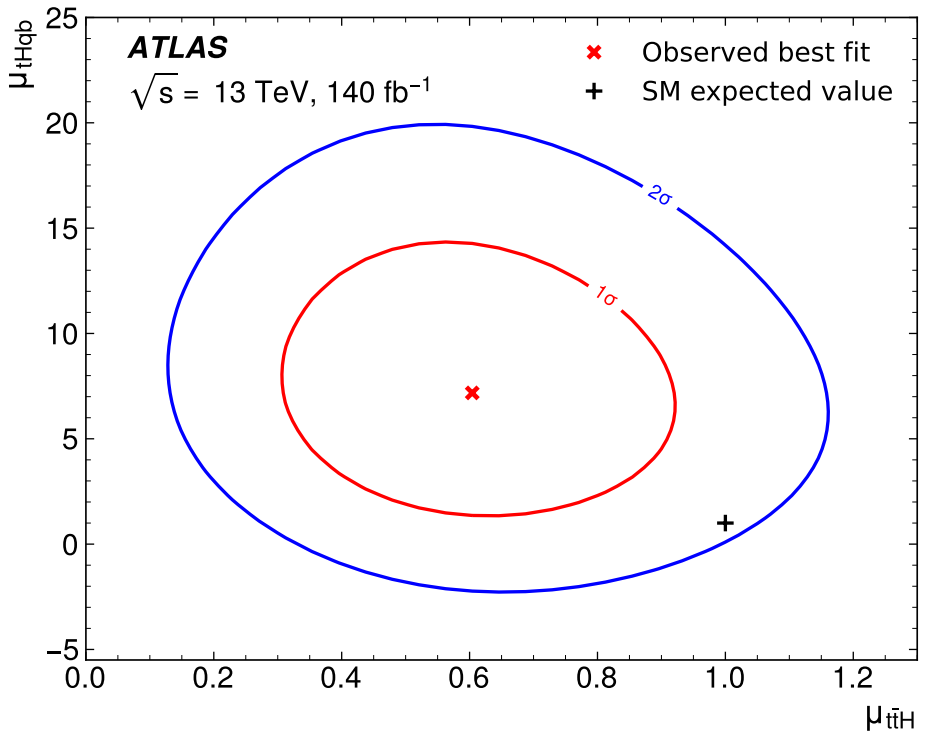
Impact of uncertainties

- Similar statistical and systematical impact
- $t\bar{t}W$ normalisation and modelling still major uncertainty (ME, PS, μ_R)

	$\Delta\sigma_{t\bar{t}H}/\sigma^{\mathrm{SM}}$
Total uncertainty	$+0.20\ -0.19$
Statistical uncertainty	$+0.13\ -0.12$
Total systematic uncertainty	± 0.15
ttH modelling	$+0.03\ -0.02$
$t\bar{t}W$ modelling	± 0.05
$t\bar{t}$ modelling	± 0.04
$t\bar{t}t\bar{t}$ modelling	± 0.03
$t\bar{t}Z$ modelling	± 0.01
Diboson modelling	± 0.01
Other backgrounds modelling	± 0.03
$t\bar{t}W$ normalisation	$+0.07\ -0.06$
$t\bar{t}Z$ normalisation	$+0.05\ -0.05$
Non-prompt normalisation	$+0.02\ -0.02$
Diboson normalisation	$+0.01\ -0.01$
MC samples size	± 0.04
Electrons, muons and $\tau_{\text{had-vis}}$	$+0.04\ -0.03$
Jets	$+0.04\ -0.03$
Flavour tagging	< 0.01
$E_{\mathrm{T}}^{\mathrm{miss}}$	± 0.01
Misidentified τ-lepton background	± 0.03
Luminosity	< 0.01

Results: simultaneous measurement of $t\bar{t}H$ and $tHqb$

- Dedicated $tHqb$ category to reduce correlations
- $\mu_{ttH} = 0.59^{+0.22}_{-0.20}$
- $\mu_{tHqb} = 7.2^{+4.6}_{-4.0}$
- Correlation of $-11\,\%$

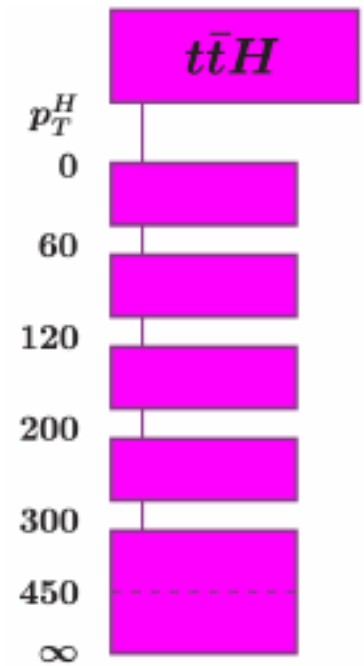


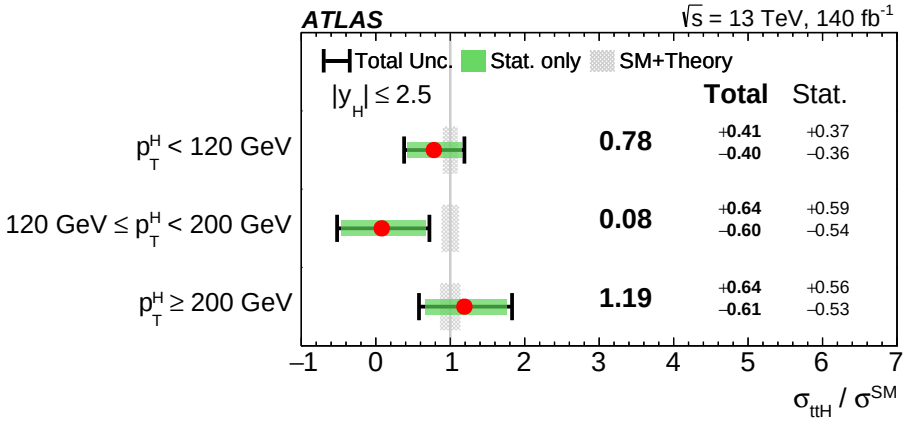
- Result consistent with ATLAS $tHqb$ (bb, ML) measurements ▸ JHEP10(2025)093: $\mu_{tHqb} = 8.1^{+3.3}_{-3.3}$

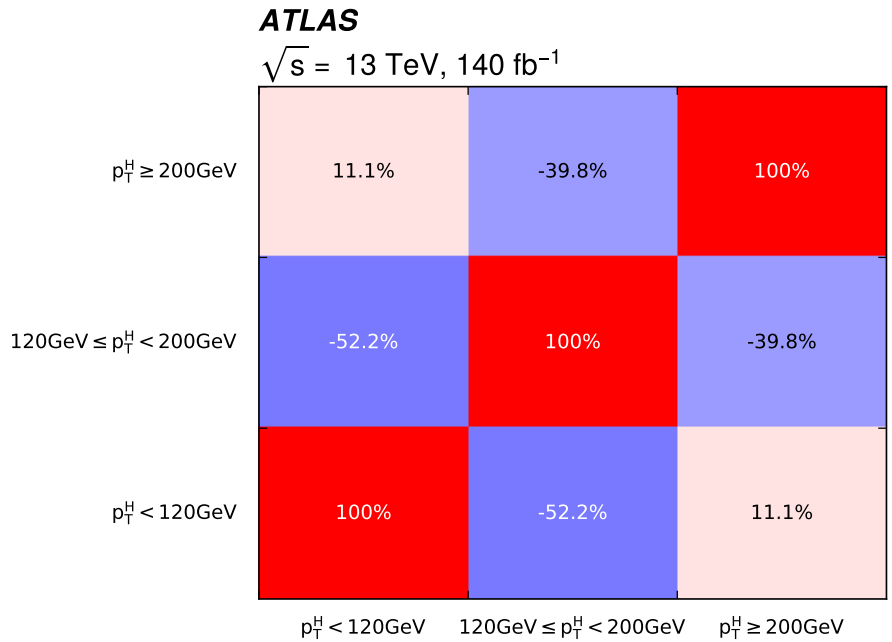
Results: STXS measurement

Differential measurement in p_T^H

- Low cross-section in central STXS bin, but high correlation
- 28 % compatible with SM prediction
- 55 % compatible with inclusive measurement

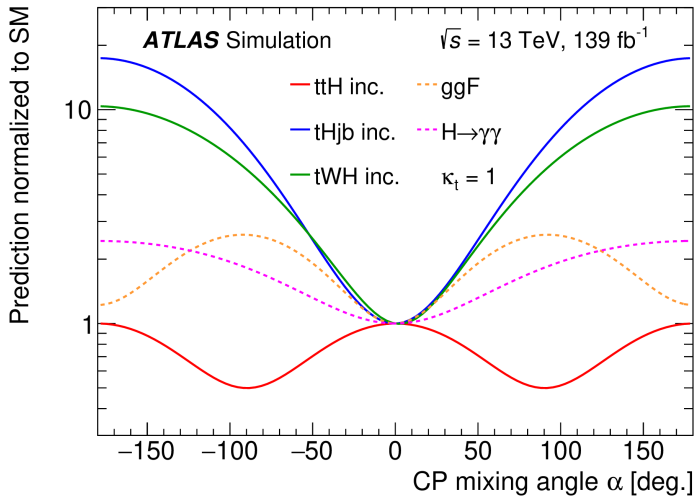






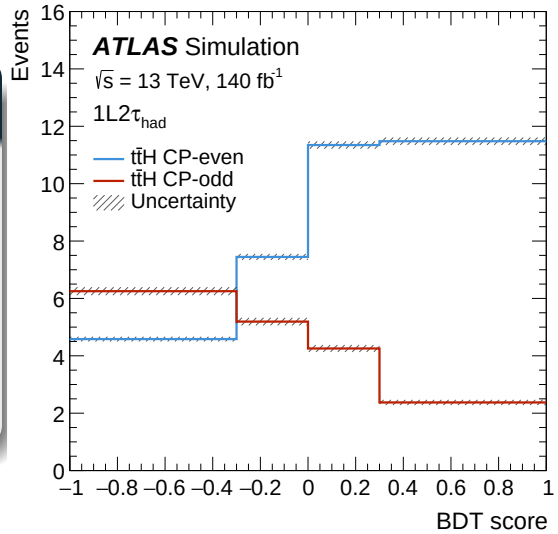
CP Interpretation

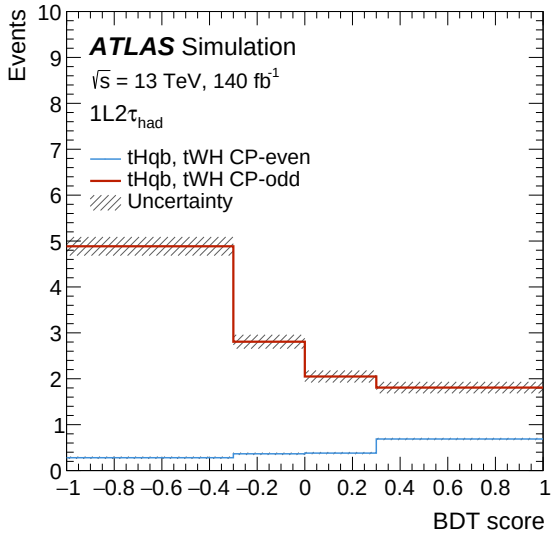
- CP violation in top Yukawa coupling would impact $t\bar{t}H$ and tH production rates and differential distributions
- Effective Lagrangian:
  $\mathcal{L} = -\frac{m_t}{\nu}\{\bar{\psi}_t \kappa'_t[\cos(\alpha) + i\sin(\alpha)]\psi_t\}H$
  - κ'_t: coupling modifier (SM: $\kappa'_t = 1$)
  - α: CP-mixing angle (SM: $\alpha = 0$; CP-odd: $\alpha = 90°$)
- Parametrise $t\bar{t}H$ and $tHqb$ signal yields with α and κ'_t



Setup

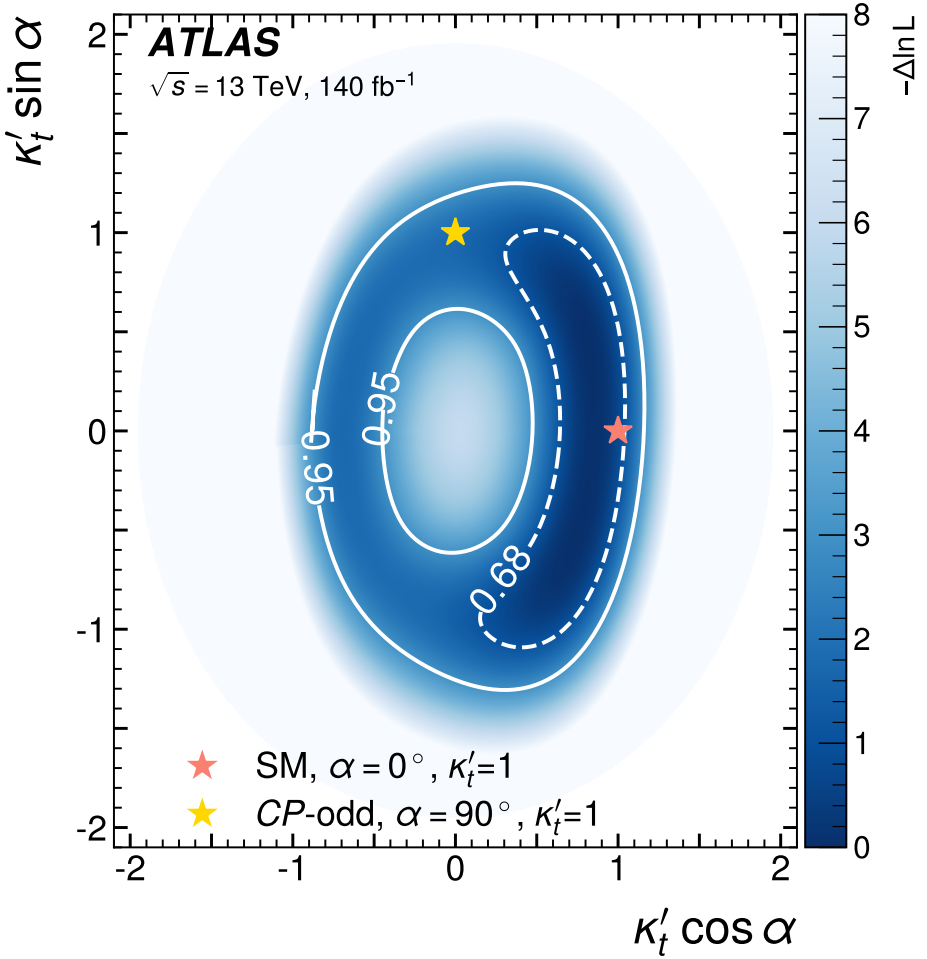
- Use STXS setup for $0\tau_{had}$ channels
- Dedicated CP BDT for $2\tau_{had}$ channels





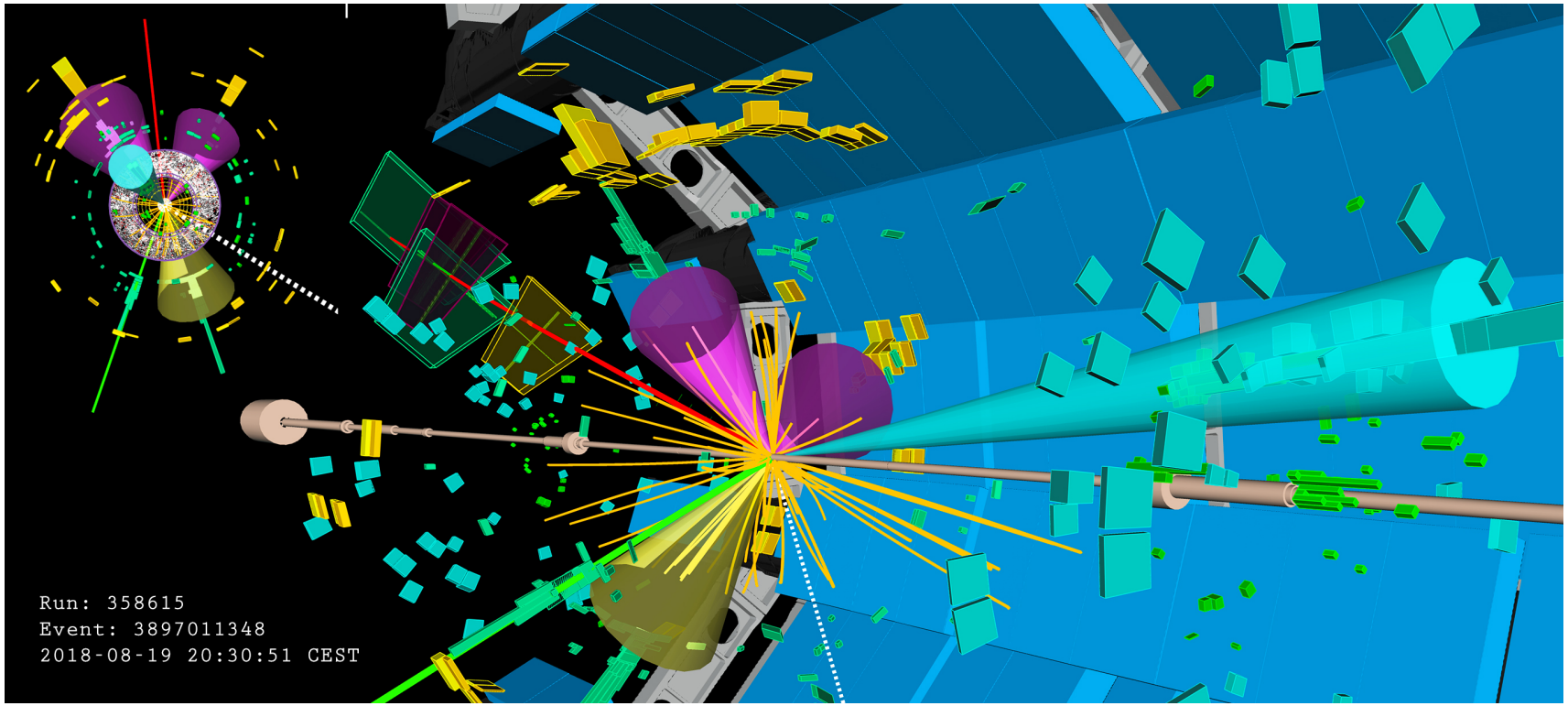
CP Interpretation

- Results compatible with SM expectation: $|\alpha| < 62^\circ$ at 68 % exclusion limit
- Exclusion of pure CP-odd hypothesis at 1.8σ (3.1σ expected)
- $0\tau_{had}$ and $2\tau_{had}$ channels compatible at 34 %



Summary

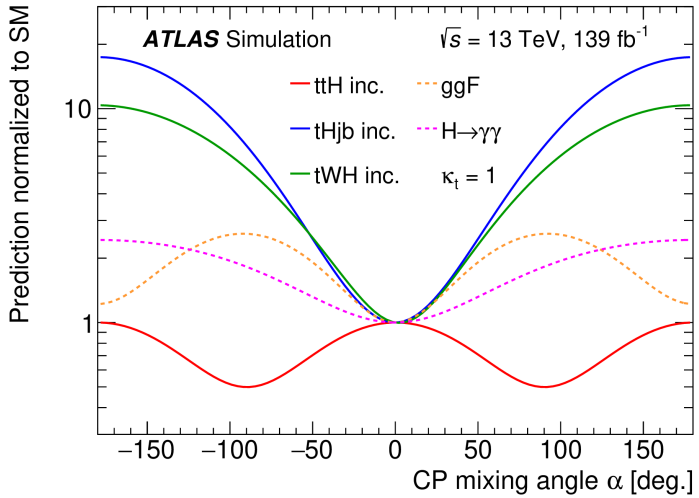
- Full Run 2 measurement of $t\bar{t}H$ in multilepton final state
- Included inclusive and STXS measurement and CP interpretation
- All results compatible with SM: but $t\bar{t}H$ normalisation slightly low while $tHqb$ slightly high
- CMS results ▸ EPJC 81 (2021) 378: $\mu_{t\bar{t}H} = 0.92^{+0.26}_{-0.23}$, $\mu_{tH} = 5.7^{+4.1}_{-4.0}$
- Stays an interesting channel for Run 3 and beyond

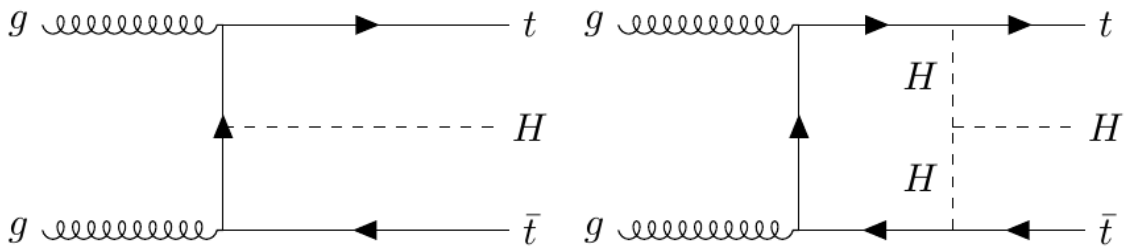


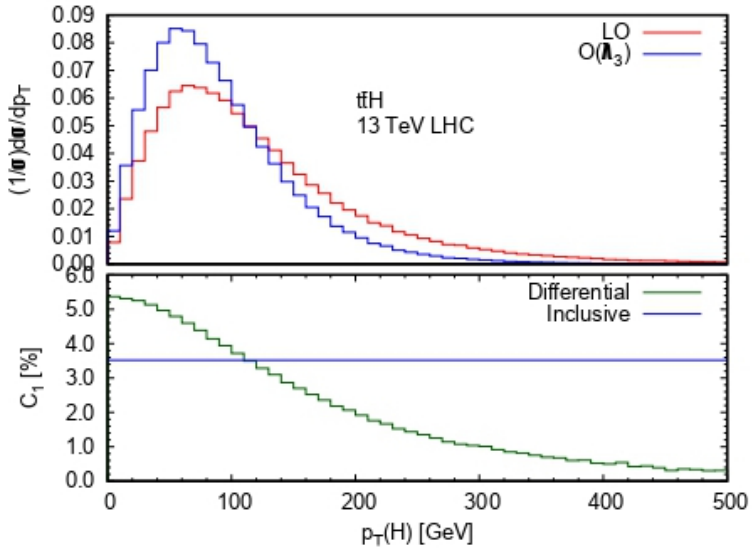
Backup

Interpretations of $t\bar{t}H$ measurements

- Inclusive and differential cross-section measurements give access to several Higgs properties
  - CP structure of the Higgs
  - Higgs self-coupling
  - EFT interpretation







MC samples

Physics process	Event generator	Matrix element order	Parton shower	PDF set	Tune
$t\bar{t}H$	Powheg Box	NLO	Pythia 8	NNPDF3.0nlo	A14
$t\bar{t}H$ (CP interpretation)	MadGraph5_aMC@NLO	NLO	Pythia 8	NNPDF3.0nnlo	A14
$tHqb$	MadGraph5_aMC@NLO	NLO	Pythia 8	NNPDF3.0nnlo	A14
tHW	MadGraph5_aMC@NLO	NLO	Pythia 8	NNPDF3.0nnlo	A14
$t\bar{t}$	Powheg Box	NLO	Pythia 8	NNPDF3.0nlo	A14
$t\bar{t}W$	Sherpa 2.2.10	MEPS@NLO	Sherpa	NNPDF3.0nnlo	Sherpa default
$t\bar{t}W$ (EWK)	Sherpa 2.2.10	LO	Sherpa	NNPDF3.0nnlo	Sherpa default
$t\bar{t}Z/\gamma^*$	MadGraph5_aMC@NLO	NLO	Pythia 8	NNPDF3.0nlo	A14
$t\bar{t}Z/\gamma^*$ (rad. decay)	MadGraph5_aMC@NLO	LO	Pythia 8	NNPDF3.0lo	A14
$t\bar{t}t\bar{t}$	MadGraph5_aMC@NLO	NLO	Pythia 8	NNPDF3.1nlo	A14
$t\bar{t}t$	MadGraph5_aMC@NLO	LO	Pythia 8	NNPDF2.3lo [49]	A14
VV, $qqVV$, VVV	Sherpa 2.2.2(1)	MEPS@NLO	Sherpa	NNPDF3.0nnlo	Sherpa default
Single top (t-, Wt-, s-channel)	Powheg Box	NLO	Pythia 8	NNPDF3.0nlo	A14
$Z \to \ell^+\ell^-$	Sherpa 2.2.1	MEPS@NLO	Sherpa	NNPDF3.0nnlo	Sherpa default
$Z \to \ell^+\ell^-(\gamma \to e^+e^-)$	Powheg Box	NLO	Pythia 8	CTEQ6L1nlo [50]	A14
$Z \to \ell^+\ell^-(\gamma* \to e^+e^-)$	Powheg Box	NLO	Pythia 8	CTEQ6L1nlo	A14
$t\bar{t}WW$	MadGraph5_aMC@NLO	LO	Pythia 8	NNPDF2.3lo	A14
tZ, tWZ	MadGraph5_aMC@NLO	NLO	Pythia 8	NNPDF3.0nlo	A14

Lepton working points

	Electron					Muon				
Lepton definition	L	L'	M	M_{ex}	T	L	L'	M	M_{ex}	T
Identification	*Loose*	*Tight*				*Loose*	*Medium*			
Transverse impact parameter significance $\lvert d_0\rvert/\sigma_{d_0}$	< 5					< 3				
Longitudinal impact parameter z_0	$\lvert z_0 \sin\theta\rvert < 0.5$ mm									
Isolation	Yes					Yes				
Non-prompt lepton WP	–		*Tight*	*Tight–not-VeryTight*	*VeryTight*	–		*Tight*	*Tight–not-VeryTight*	*VeryTight*
Electron charge-misassignment veto	–	Yes				–				
Electron conversion candidate veto	–	Yes (except e^*)				–				

Channel selection criteria

	$2\ell\text{SS}0\tau_{\text{had}}$	$3\ell 0\tau_{\text{had}}$	4ℓ	$2\ell\text{SS}1\tau_{\text{had}}$	$1\ell 2\tau_{\text{had}}$	$2\ell 2\tau_{\text{had}}$
Light leptons						
N_ℓ	2	3	4	2	1	2
Lepton definition	T	ℓ_0, ℓ_1, ℓ_2: L,T,T	L	M	L	L
Lepton p_{T} [GeV]	> 15	ℓ_0, ℓ_1, ℓ_2: > 10, 15, 15	> 10	> 15	> 27	> 10
$\sum q_\ell$	± 2	± 1	0	± 2	± 1	0
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV]	–	> 10 (SFOS)	–	> 10 (SF)	–	> 10
$m_{\ell\ell}$ [GeV]	–	> 12 (SFOS)	> 12 (SFOS)	–	–	> 12
$m(4\ell)$ [GeV]	–	–	¡115 or ¿130	–	–	–
$\tau_{\text{had-vis}}$ and jets						
$N_{\tau_{\text{had-vis}}}$	0	0	–	1	2	2
$\sum q_{\tau_{\text{had-vis}}}$	–	–	–	± 1	0	0
N_{jets}	≥ 3	≥ 2	≥ 2	≥ 4	≥ 1	≥ 1
$N_{b^{85\%}}$	≥ 1	≥ 1	≥ 1	≥ 1	–	–
$N_{b^{77\%}}$	–	–	–	–	≥ 1	≥ 1
Number of categories	14	11	2	1	6	2

Channel selection criteria

	2ℓSS0τ_{had} and $3\ell0\tau_{\text{had}}$ channels				4ℓ channel	
Region	3ℓVV	$3\ell t\bar{t}Z$	3ℓIntC, 3ℓMatC	$2\ell\text{tt(e)}_{TM_{\text{ex}}}$, $2\ell\text{tt(e)}_{M_{\text{ex}}T}$, $2\ell\text{tt}(\mu)_{TM_{\text{ex}}}$, $2\ell\text{tt}(\mu)_{M_{\text{ex}}T}$, $2\ell\text{tt(e)}_{M_{\text{ex}}M_{\text{ex}}}$, $2\ell\text{tt}(\mu)_{M_{\text{ex}}M_{\text{ex}}}$	3ℓ μ HF, 3ℓ e HF	3ℓ e LF
Lepton requirement	3ℓ		$\mu\mu e^*$	2ℓSS	$e^\mp\mu^\pm\mu^\pm$, $\mu^\mp e^\pm e^\pm$	$\mu^\pm\mu^\mp e^\mp$
Lepton definition	$(L$ or $L', M, M)$		(L, M, M)	(T, M_{ex}) or (M_{ex}, T) or $(M_{\text{ex}}, M_{\text{ex}})$	L	
Lepton p_{T} [GeV]	(10, 15, 15)			(15, 15)	(10,10,10)	
$\lvert m^{\text{SF}}_{\ell^+\ell^-} - m_Z\rvert$ [GeV]	< 10		> 10	–	–	< 10
$\lvert m_{\ell\ell\ell} - m_Z\rvert$ [GeV]	> 10		< 10	–	–	> 15
$m_{\text{T}}(\ell_0, E_{\text{T}}^{\text{miss}})$ [GeV]	–			< 250 for TM_{ex} and $M_{\text{ex}}T$ pairs	–	
$E_{\text{T}}^{\text{miss}}$ [GeV]	–			–	–	< 20
N_{jets}	2 or 3	≥ 4	–	≥ 2	≥ 1	
$N_{b\text{-jets}}$	1 $b^{85\%}$	≥ 1 $b^{85\%}$	0 $b^{85\%}$	1 $b^{85\%}$	≥ 1 $b^{85\%}$	0 $b^{85\%}$
$\tau_{\text{had-vis}}$ candidates	0			0	–	
$3\ell0\tau_{\text{had}}$ channel veto	–			–	Yes	
Region split	–	–	internal, material	sub-leading e/μ $\times$ (TM_{ex}, $M_{\text{ex}}T$, $M_{\text{ex}}M_{\text{ex}}$)	$e^\mp\mu^\pm\mu^\pm$, $\mu^\mp e^\pm e^\pm$	–

Channel selection criteria

	2ℓSS$1\tau_{\text{had}}$ channel			$1\ell 2\tau_{\text{had}}$ and $2\ell 2\tau_{\text{had}}$ channels			
Region	CR-OS	CR-SS	$\text{VR}_{1\tau_{\text{had}}}$	FF-Z	FF-tt	$\text{VR}^{1\ell}_{2\tau_{\text{had}}}$	$\text{VR}^{2\ell}_{2\tau_{\text{had}}}$
Lepton requirement	2, OS	2, SS	2, OS	2, OS	2, OS	1	2, OS
Lepton definition	M	L'	M	L	L	L	L
$\tau_{\text{had-vis}}$ requirement	1	1	1	2, OS	2, OS	2, SS	2, SS
$\tau_{\text{had-vis}}$ definition	M	M	M	VL	VL	M	M
$\lvert m^{\text{SF}}_{\ell^+\ell^-} - m_Z\rvert$ [GeV]	–	–	–	< 10	> 10	–	–
N_{jets}	2 or 3	2 or 3	≥ 4	≥ 1	≥ 1	≥ 1	≥ 1
$N_{b\text{-jets}}$	$\geq 1\ b^{85\%}$	$\geq 1\ b^{85\%}$	$\geq 1\ b^{85\%}$	$0\ b^{77\%}$	$\geq 1\ b^{77\%}$	$\geq 1\ b^{77\%}$	$\geq 1\ b^{77\%}$
Region split	–	ee, $e\mu$, μe, $\mu\mu$	–	–	–	–	–