$t\bar{t}t\bar{t}$ interpretations and future plans

Abhishek Sharma

for ATLAS and CMS

Top2023, 25th September 2023

ATLAS EXPERIMENT

THE UNIVERSITY OF BRITISH COLUMBIA

CMS

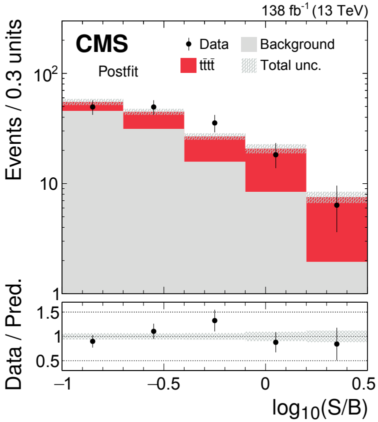
Outline

- SM result
- Interpretations
  - $t\bar{t}t\bar{t}$ and ttt
  - Top Yukawa
  - Higgs oblique
  - BSM models
  - EFT
- Future work
  - Run 3
  - Addressing current limitations
  - HL-LHC

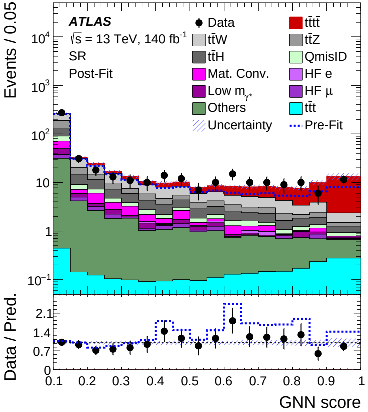
I'll largely be referring to arXiv:2305.13439 (submitted to PLB) and EPJ C 80 (2020) 75 for CMS results, and EPJ C 83 (2023) 496 for the ATLAS result. Other references will be inline.

In case you weren't paying attention...

- Both CMS & ATLAS observed $t\bar{t}t\bar{t}$ in the $2\ell SS/3\ell/4\ell$ channels
- Thanks to Niels for the thorough explanation of the main analyses!



$\sigma(t\bar{t}t\bar{t}) = 17.7^{+4.4}_{-4.0}$ fb
Obs. (exp.) sig. 5.6 (4.9)

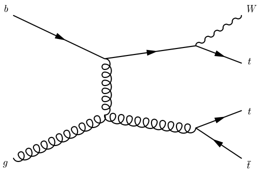


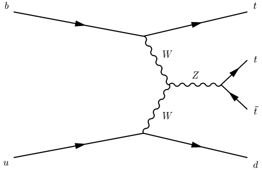
$\sigma(t\bar{t}t\bar{t}) = 22.5^{+6.6}_{-5.5}$ fb
Obs. (exp.) sig. 6.1 (4.3)

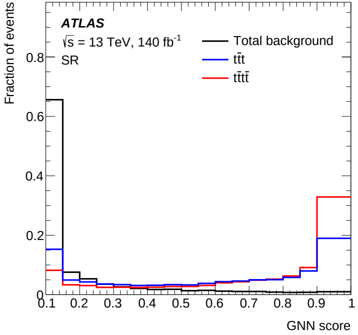
Interpretations

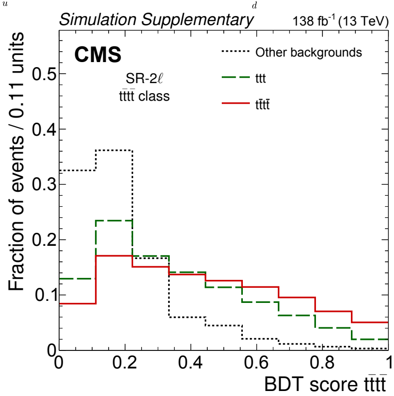
$t\bar{t}t\bar{t}$ v. ttt

- ttt is produced with either an extra q or W $\rightarrow$ looks much like $t\bar{t}t\bar{t}$
- Nominal σ(ttt):
  - 1.67 fb (LO QCD, NLO norm.) for ATLAS,
  - and 2 fb (LO QCD, NLO QCD and LO EW norm.) for CMS
- Machine learning classifiers struggle to separate the two processes
- Perform simultaneous measurement of $t\bar{t}t\bar{t}$ and ttt







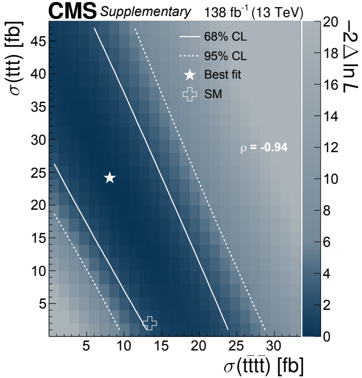


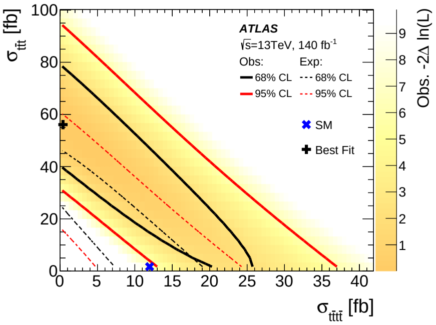
ttt encompasses all permutations of $t\bar{t}t$ and $\bar{t}t\bar{t}$ with extra q or W. Diagrams from PLB 687:70-74 (2010)

$t\bar{t}t\bar{t}$ v. ttt cont.

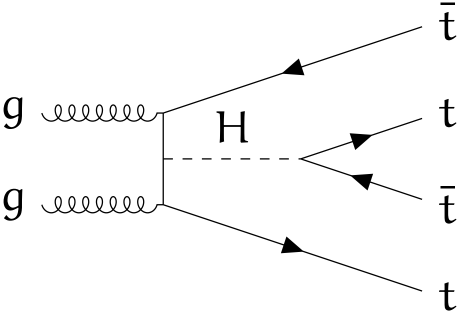
- Both collaborations see similar results, with ttt being poorly constrained
- Strong negative correlation between the two processes
- ATLAS result also splits ttt into $+q$ and $+W$ states

Processes	95% CL cross section interval [fb]	
	$\mu_{t\bar{t}t\bar{t}} = 1$	$\mu_{t\bar{t}t\bar{t}} = 1.9$
ttt	[4.7, 60]	[0, 41]
$tttW$	[3.1, 43]	[0, 30]
$tttq$	[0, 144]	[0, 100]





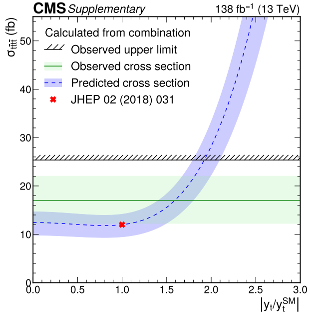
Testing Higgs properties with $t\bar{t}t\bar{t}$



- Some $t\bar{t}t\bar{t}$ production processes contain Higgs propagator
- We can use $t\bar{t}t\bar{t}$ to constrain Higgs properties
- Top Yukawa coupling y_t, including CP properties: complementary to existing measurements
- Higgs oblique parameter: $t\bar{t}t\bar{t}$ is most sensitive process (JHEP 09 (2019) 41)
- Care must be taken with $t\bar{t}H$, as it is a background process to $t\bar{t}t\bar{t}$

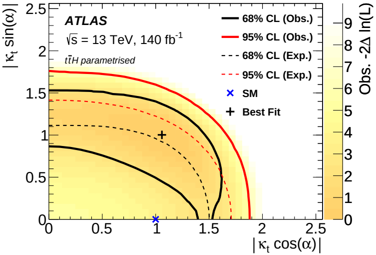
Top Yukawa coupling

- The $t\bar{t}t\bar{t}$ cross section can be parametrised in terms of the Yukawa coupling strength
- ATLAS splits CP-odd and -even components, and tests effect of parametrising the $t\bar{t}H$ contribution in the same way as $t\bar{t}t\bar{t}$

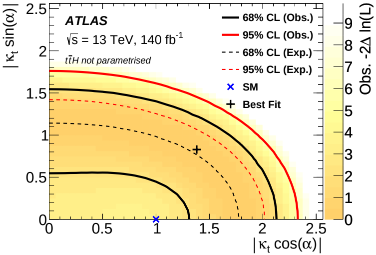


From PLB 844 (2023) 138076

$t\bar{t}t\bar{t}$ combination



$t\bar{t}H$ parametrised

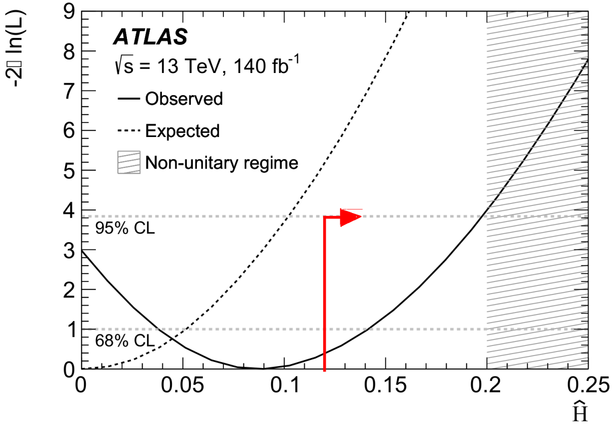


$t\bar{t}H$ not parametrised

A higher measured cross section → a less stringent limit than expected

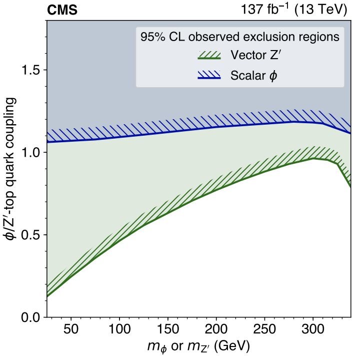
Higgs oblique parameter

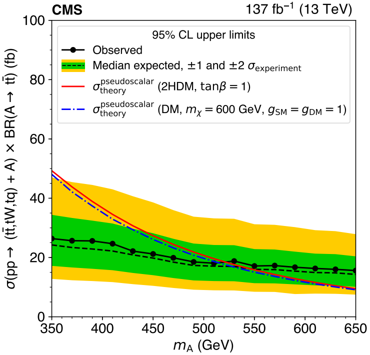
- $t\bar{t}t\bar{t}$ can also probe the Higgs oblique parameter $\hat{H}$, which modifies the Higgs propagator
- $\hat{H} \neq 0$ variations included as EFT operators
- Since $t\bar{t}H$ is also affected $\mu_{t\bar{t}H} = 1 - \hat{H}$ is needed
- CMS reported $\hat{H} < 0.12$ at 95%

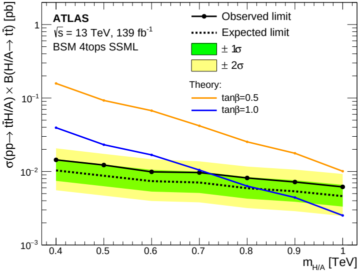


BSM models

- Many BSM models couple to top, $t\bar{t}t\bar{t}$ is heavy $\rightarrow$ good process to constrain new physics
- ATLAS and CMS test simple heavy scalars/vectors, to 2HDMs(+a), dark matter, etc







From JHEP 07 (2023) 203

More BSM on Wednesday!

EFT

- Standard Model effective field theory provides a neat way to introduce new physics without explicit models
- Restrict to heavy fermion operators: O^1_{tt}, O^1_{QQ}, O^1_{Qt} and O^8_{Qt} [1]
- Measure linear (interference between EFT and SM) and quadratic (EFT) effects on the $t\bar{t}t\bar{t}$ yield
- Individual limits for each operator, assuming others are zero

ATLAS 2ℓSS/3ℓ full Run 2

Operators	Expected C_i/Λ^2 [TeV^{-2}]	Observed C_i/Λ^2 [TeV^{-2}]
$\mathcal{O}^1_{QQ}$	[-2.4, 3.0]	[-3.5, 4.1]
$\mathcal{O}^1_{Qt}$	[-2.5, 2.0]	[-3.5, 3.0]
$\mathcal{O}^1_{tt}$	[-1.1, 1.3]	[-1.7, 1.9]
$\mathcal{O}^8_{Qt}$	[-4.2, 4.8]	[-6.2, 6.9]

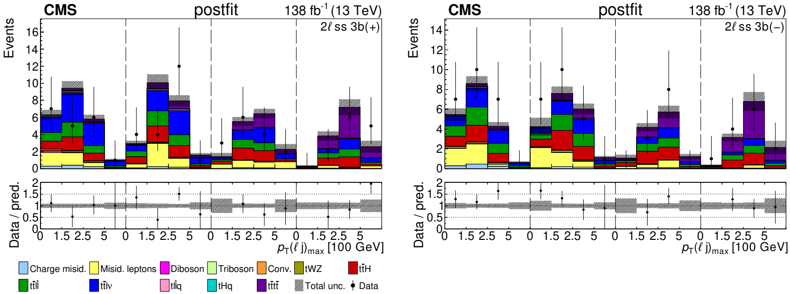
JHEP 11 (2019) 082: CMS $1\ell/2\ell$OS 35.8 fb^{-1}

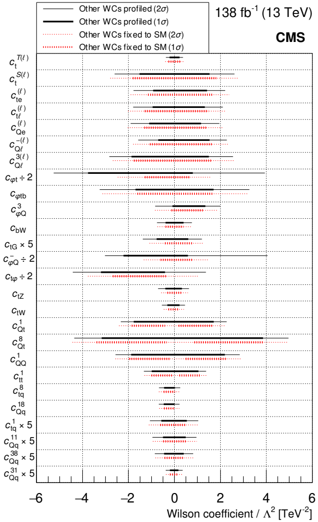
Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{tt}$	$[-2.0, 1.8]$	$[-2.1, 2.0]$
$\mathcal{O}^1_{QQ}$	$[-2.0, 1.8]$	$[-2.2, 2.0]$
$\mathcal{O}^1_{Qt}$	$[-3.3, 3.2]$	$[-3.5, 3.5]$
$\mathcal{O}^8_{Qt}$	$[-7.3, 6.1]$	$[-7.9, 6.6]$

1- Another operator is redundant in this case: $O^8_{QQ} = \frac{1}{3} O^1_{QQ}$

EFT cont.

- $t\bar{t}t\bar{t}$ is affected by more EFT operators than the four mentioned so far
- Major backgrounds like $t\bar{t}W$ and $t\bar{t}Z$ are also affected
- CMS (arXiv:2307.15761) did an EFT search for new physics with 26 operators
- $t\bar{t}t\bar{t}$ features prominently, especially in 2ℓSS regions



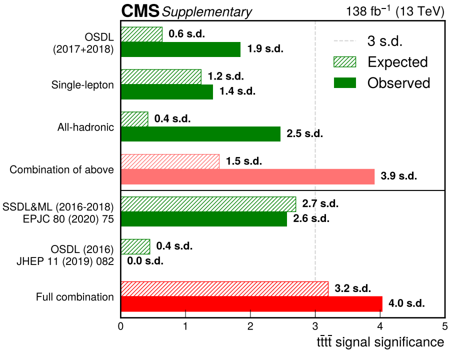


More EFT talks tomorrow!

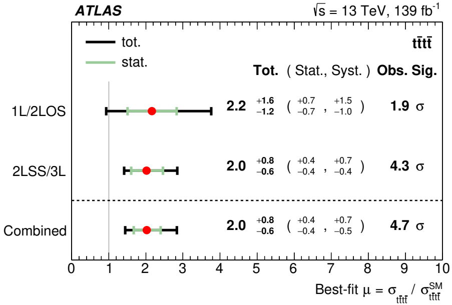
The future of $t\bar{t}t\bar{t}$

Prognosis for Run 3

- $t\bar{t}t\bar{t}$ is ∼20% more abundant at 13.6 TeV while backgrounds don't scale quite so much
- Expect 300 fb^{-1} in Run 3
- $t\bar{t}t\bar{t}$ observation in 2ℓSS/3ℓ channels, plenty of opportunity to revisit others



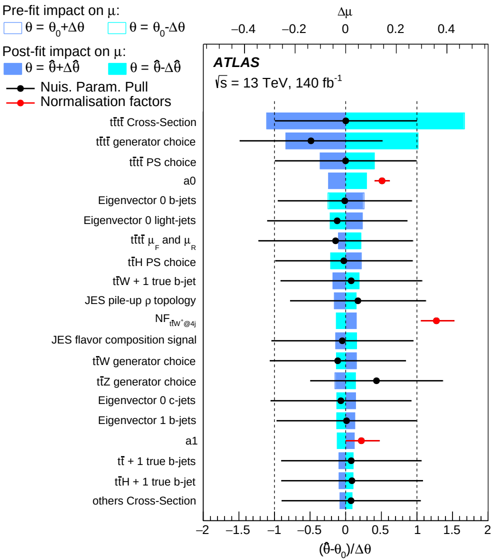
PLB 844 (2023) 138076



JHEP 11 (2021) 118

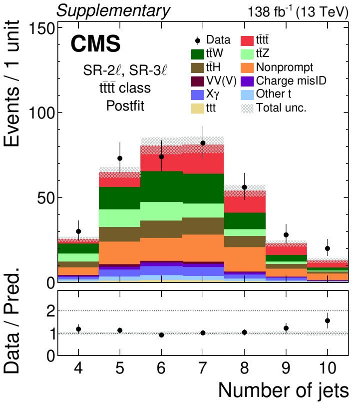
Technical challenges

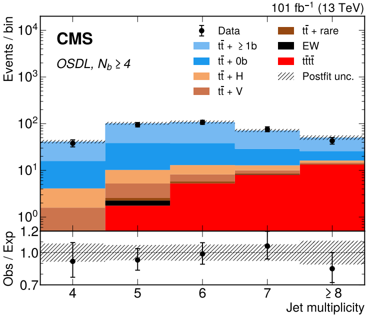
- Signal modelling uncertainties were dominant in the ATLAS result, and important for CMS too
- Improvements in matrix element and parton shower matching will have big impact
- Given ttt v. $t\bar{t}t\bar{t}$ results, improvements in ttt simulation such moving to NLO MC will help
- Improving ttt discrimination in machine learning, eg. a dedicated category in multiclass classifiers, will also aid in decoupling the two processes

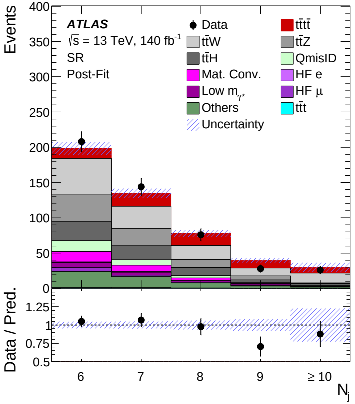


Technical challenges cont.

- Background processes are also in extreme regimes with extra radiation
  - $t\bar{t}W$+jets necessitates data driven methods or large normalisation uncertainty
  - $t\bar{t}$+HF will have a similar impact in hadronic, 1ℓ, 2ℓOS

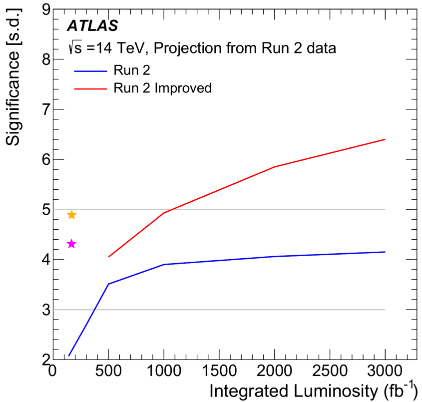






HL-LHC

- Looking back at a conservative projection from the previous ATLAS $2\ell SS/3\ell$ ATL-PHYS-PUB-2022-004
- "Run 2 Improved" scenario calls for:
  - halving of some uncertainties, like $t\bar{t}t\bar{t}$ and $t\bar{t}V$ theory, flavour tagging,
  - and lumi scaling of others, like additional jet modelling, jet experimental uncertainties
  - and a naive H_T fit, expected 5 σ with 1000 fb^{-1}
- We're well beyond that (orange star for CMS, magenta star for ATLAS), thanks to improved background estimates and more sophisticated sig/bkg separation
- Bodes well for the future!



Conclusion

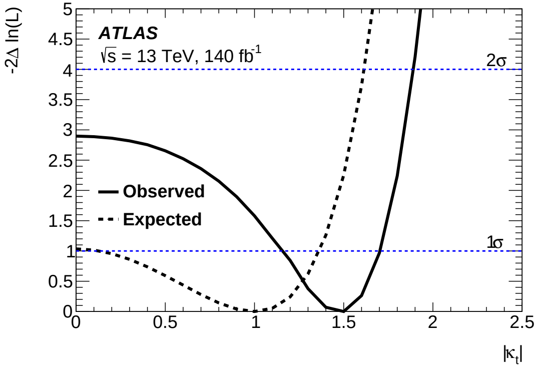
- A huge effort to measure $t\bar{t}t\bar{t}$, now time to make the most of it!
- Interpretations:
  - $t\bar{t}t\bar{t}$ versus ttt
  - Top Yukawa coupling
  - Higgs oblique parameter
  - Explicit BSM models
  - EFT
- Many directions for future work, including:
  - Hadronic, 1ℓ, 2ℓOS channels
  - Combinations
  - More EFT operators
  - Stuff we haven't even thought of yet
- Plenty of work yet to be done!

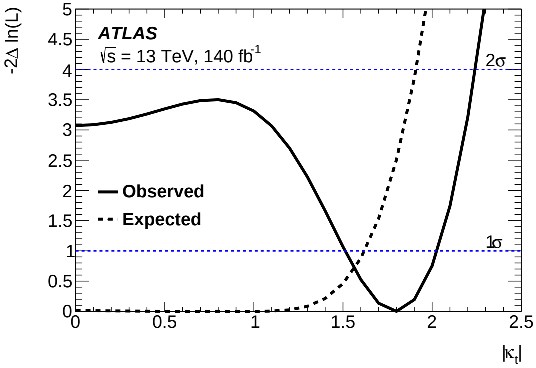
Thanks for listening!

Backup material

EPJ C. 83 (2023) 496

Top Yukawa

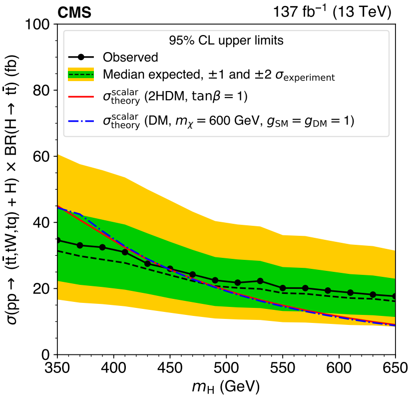


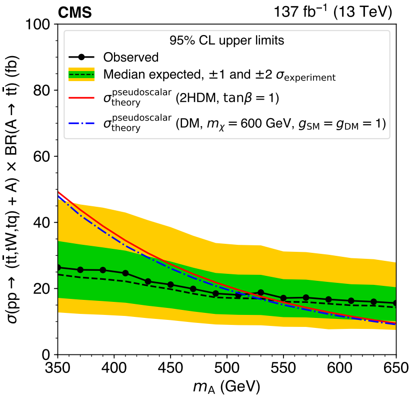


Log-likelihood with $t\bar{t}H$ parametrised or not.

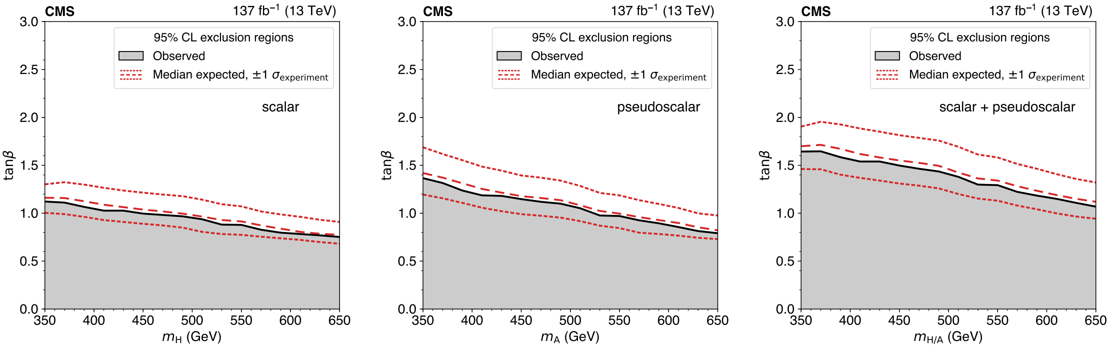
EPJ C 80 (2020) 75

Heavy (pseudo)scalar

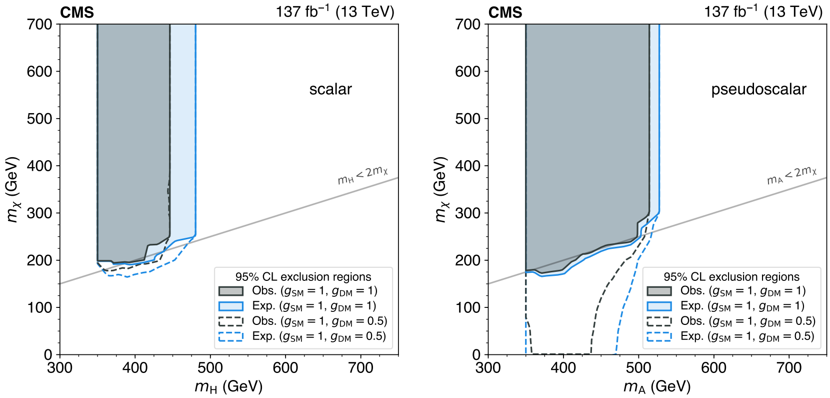




2HDM


CMS
137 fb⁻¹ (13 TeV)
95% CL exclusion regions
Observed
Median expected, ±1 σexperiment
scalar
tanβ
mH (GeV)
CMS
137 fb⁻¹ (13 TeV)
95% CL exclusion regions
Observed
Median expected, ±1 σexperiment
pseudoscalar
tanβ
mA (GeV)
CMS
137 fb⁻¹ (13 TeV)
95% CL exclusion regions
Observed
Median expected, ±1 σexperiment
scalar + pseudoscalar
tanβ
mH/A (GeV)

Dark matter + heavy (pseudo)scalar



JHEP 11 (2019) 082 $1\ell/2\ell$OS partial Run 2

EFT

Operator	$\sigma_k^{(1)}$	$\mathcal{O}^1_{\text{tt}}$	$\mathcal{O}^1_{\text{QQ}}$	$\sigma_{j,k}^{(2)}$ $\mathcal{O}^1_{\text{Qt}}$	$\mathcal{O}^8_{\text{Qt}}$
$\mathcal{O}^1_{\text{tt}}$	0.39	5.59	0.36	−0.39	0.3
$\mathcal{O}^1_{\text{QQ}}$	0.47		5.49	−0.45	0.13
$\mathcal{O}^1_{\text{Qt}}$	0.03			1.9	−0.08
$\mathcal{O}^8_{\text{Qt}}$	0.28				0.45

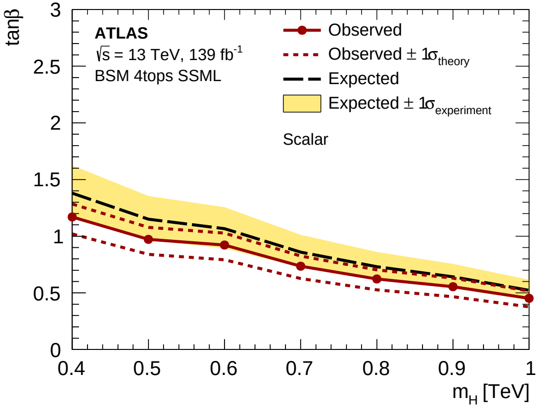
Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{\text{tt}}$	[−2.0, 1.8]	[−2.1, 2.0]
$\mathcal{O}^1_{\text{QQ}}$	[−2.0, 1.8]	[−2.2, 2.0]
$\mathcal{O}^1_{\text{Qt}}$	[−3.3, 3.2]	[−3.5, 3.5]
$\mathcal{O}^8_{\text{Qt}}$	[−7.3, 6.1]	[−7.9, 6.6]

Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{\text{tt}}$	[−2.0, 1.9]	[−2.2, 2.1]
$\mathcal{O}^1_{\text{QQ}}$	[−2.0, 1.9]	[−2.2, 2.0]
$\mathcal{O}^1_{\text{Qt}}$	[−3.4, 3.3]	[−3.7, 3.5]
$\mathcal{O}^8_{\text{Qt}}$	[−7.4, 6.3]	[−8.0, 6.8]

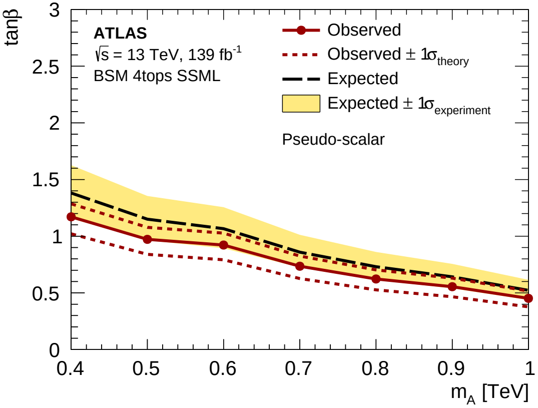
Linear and quadratic parametrisation coeffs, 95% CL for individual operators, and 95% CL for operators when others are marginalised.

JHEP 07 (2023) 203

2HDM



ATLAS
√s = 13 TeV, 139 fb-1
BSM 4tops SSML
Observed
Observed ± 1σtheory
Expected
Expected ± 1σexperiment
Scalar
tanβ
mH [TeV]



ATLAS
√s = 13 TeV, 139 fb-1
BSM 4tops SSML
Observed
Observed ± 1σtheory
Expected
Expected ± 1σexperiment
Pseudo-scalar
tanβ
mA [TeV]

ATLAS-PHYS-PUB-2022-004

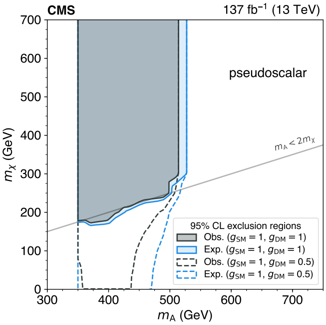
Extrapolation

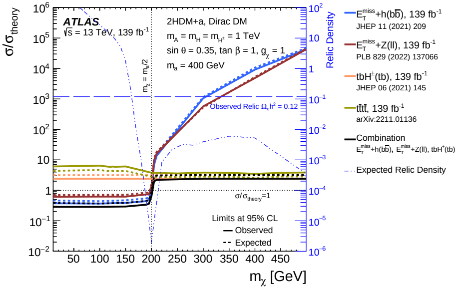
Uncertainty source	Treatment in the "Run 2 Improved" model
Signal modelling	
$t\bar{t}t\bar{t}$ cross section	Half of Run 2
$t\bar{t}t\bar{t}$ modelling	Half of Run 2
Background modelling	
$t\bar{t}W$+jets modelling	
Renormalisation and factorisation scales	Half of Run 2
Generator	Half of Run 2
Jets multiplicity modelling	Scaled by Run 2 pulls
Additional heavy flavour jets	Scaled by luminosity
$t\bar{t}t$ modelling	
Cross section	Half of Run 2
Additional heavy flavour jets	Scaled by luminosity
Non-prompt leptons modelling	Scaled by luminosity
$t\bar{t}H$+jets and $t\bar{t}Z$+jets modelling	
Cross section	Half of Run 2
Renormalisation and factorisation scales	Half of Run 2
Generator	Half of Run 2
PDF	Half of Run 2
Additional heavy flavour jets	Scaled by luminosity
Other background modelling	
Cross section	Half of Run 2
Additional heavy flavour jets	Scaled by luminosity
Charge misassignment	Same as Run 2
Template fit shape uncertainties	
Mat. Conv., γ^*, and HF non-prompt leptons	Scaled by luminosity
Other fake leptons	Half of Run 2
Additional heavy flavour jets	Half of Run 2
Instrumental	
Jet uncertainties	Same as Run 2
Jet flavour tagging (light-flavour jets)	Half of Run 2
Luminosity	Same as Run 2
Jet flavour tagging (b-jets)	Half of Run 2
Jet flavour tagging (c-jets)	Half of Run 2
Other experimental uncertainties	Same as Run 2

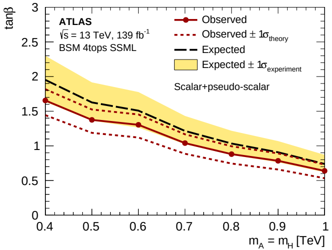
Uncertainty source	$\Delta\mu$	
Signal modelling		
$t\bar{t}t\bar{t}$ cross section	$+0.12$	-0.08
$t\bar{t}t\bar{t}$ modelling	$+0.01$	-0.01
Background modelling		
$t\bar{t}W$+jets modelling	$+0.05$	-0.05
$t\bar{t}t$ modelling	$+0.03$	-0.03
Non-prompt leptons modelling	$+0.03$	-0.03
$t\bar{t}H$+jets modelling	$+0.01$	-0.01
$t\bar{t}Z$+jets modelling	$+0.01$	-0.01
Other background modelling	$+0.01$	-0.01
Charge misassignment	$< \pm 0.01$	
Instrumental		
Jet uncertainties	$+0.05$	-0.04
Jet flavour tagging (light-flavour jets)	$+0.07$	-0.09
Luminosity	$+0.02$	-0.02
Jet flavour tagging (c-jets)	$+0.03$	-0.02
Jet flavour tagging (b-jets)	$+0.01$	-0.01
Other experimental uncertainties	$+0.02$	-0.02
Total systematic uncertainty	$+0.17$	-0.16
Statistical	$+0.07$	-0.07
Non-prompt leptons normalisation (HF, Mat. Conv., Low m_{γ^*})	$+0.03$	-0.05
$t\bar{t}W$ normalisation	$+0.03$	-0.04
Total uncertainty	$+0.19$	-0.17

BSM models 2HDMs

- $t\bar{t}t\bar{t}$ provides extra sensitivity in certain areas of parameter space, complementing dedicated searches
- ATLAS-PUB-2023-018 includes BSM $t\bar{t}t\bar{t}$ in 2HDM+a summaries







From JHEP 07 (2023) 203