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THE ROYAL SOCIETY

ttH/tH subgroup Experimental update

LHC Higgs WG

1/12/2021

Josh McFayden (ATLAS),
Sergio Sanchez Cruz (CMS)
on behalf of the ATLAS and CMS Collaborations

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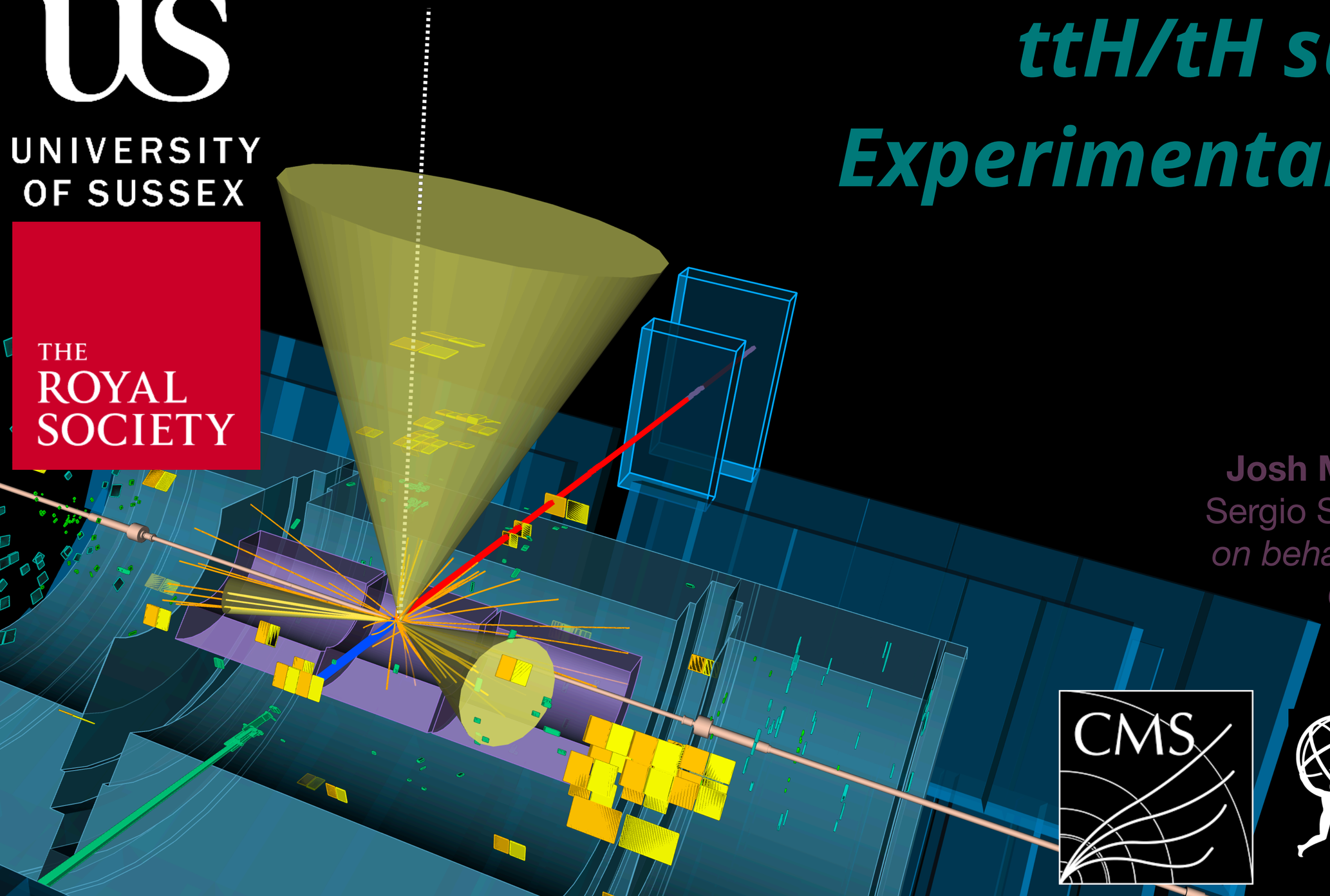

CMS

ATLAS EXPERIMENT

Overview

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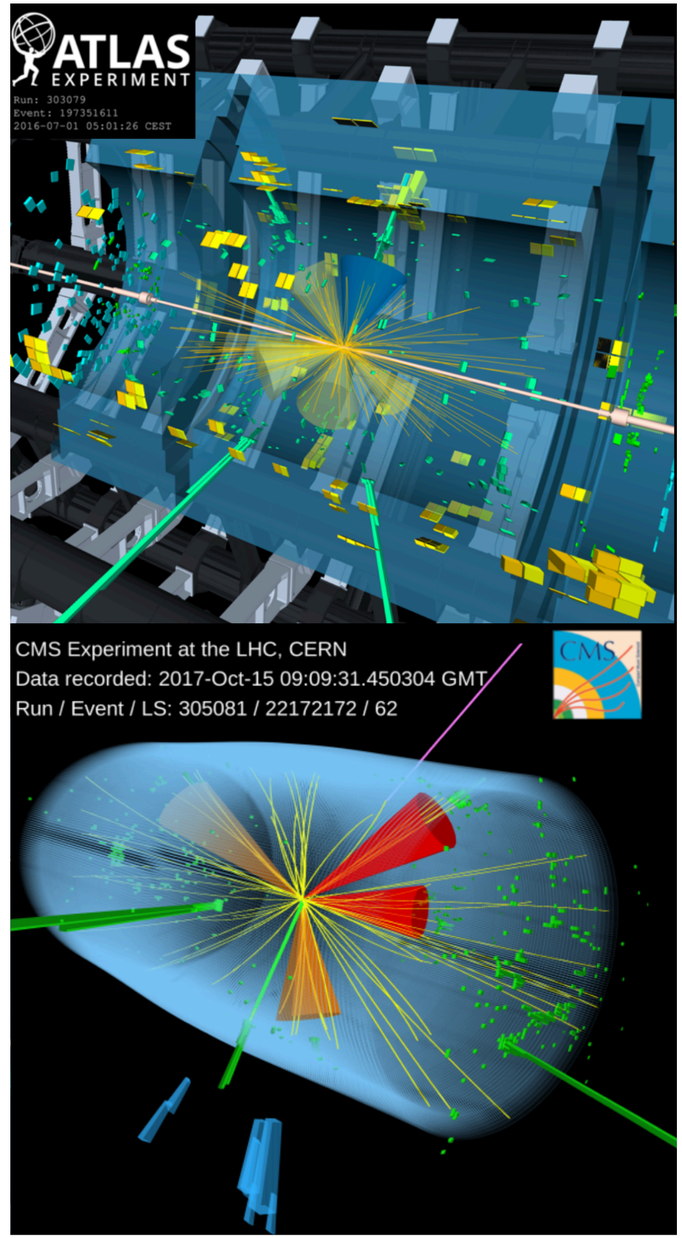
- Overview of most recent results since last Workshop
  - Including most recent results
    - ATLAS ttHbb, CMS ttH→γγ, CMS ttH→γγ+4ℓ CP
- Reminder of main limitations in those measurements relevant to the WG
  - Motivation of the theoretical activity that Laura will discuss in more detail
    - Primarily tt+bb and tt+W modelling
    - Signal modelling also becoming increasingly important



New ATLAS ttH→bb result

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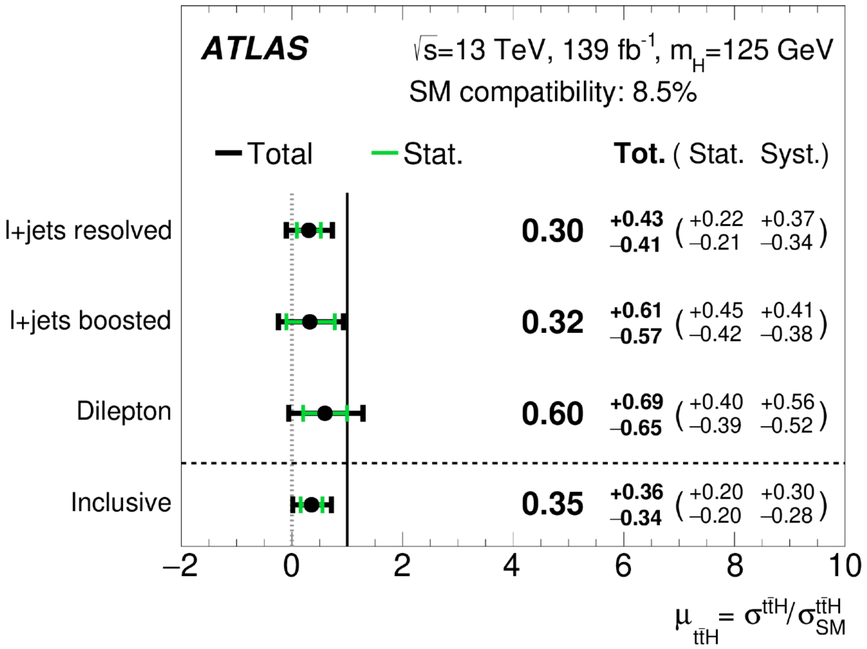
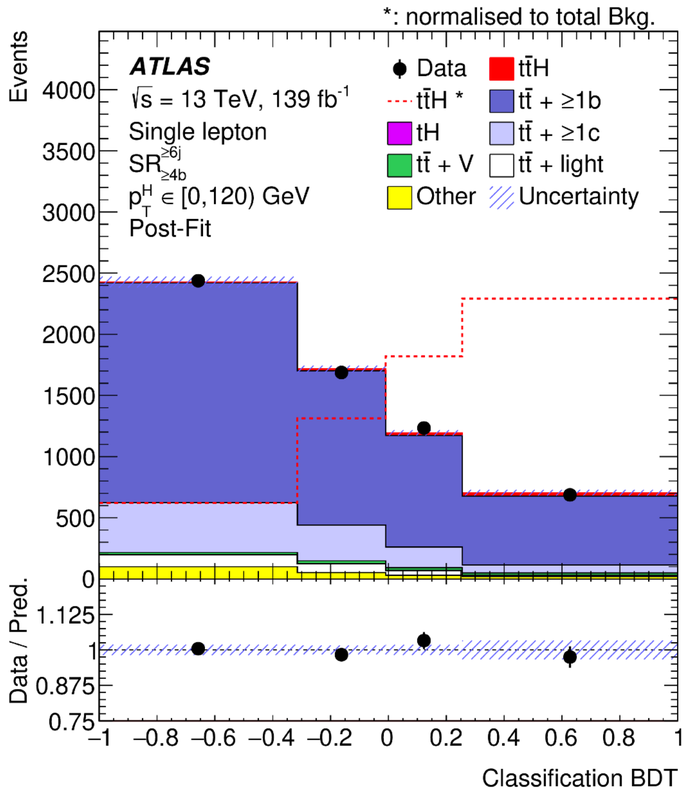
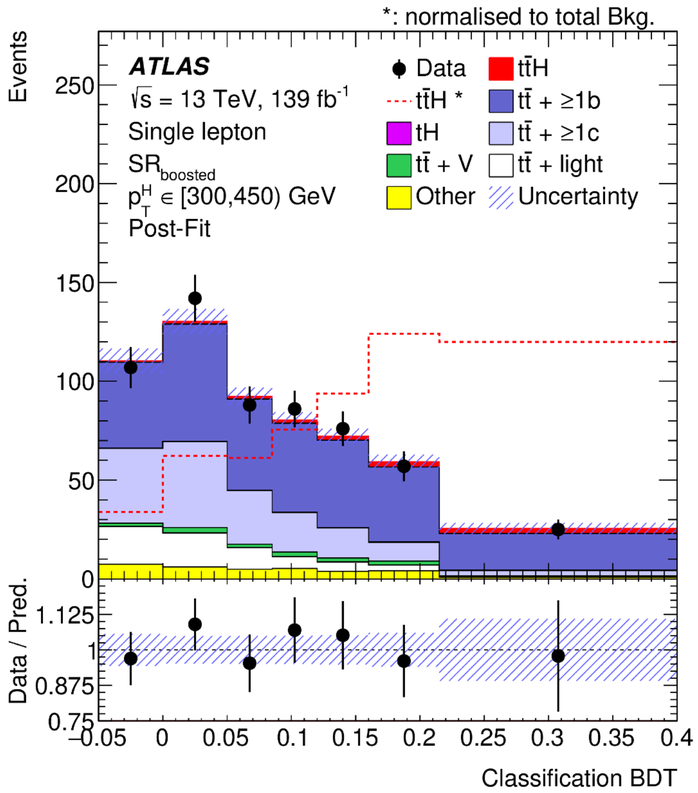
- New ATLAS result! HIGG-2020-23 *(submitted to JHEP)*
- Full Run 2 analysis
  - Lepton+jets and di-lepton channels
  - Boosted l+jets included
  - STXS $p_T(H)$ interpretation



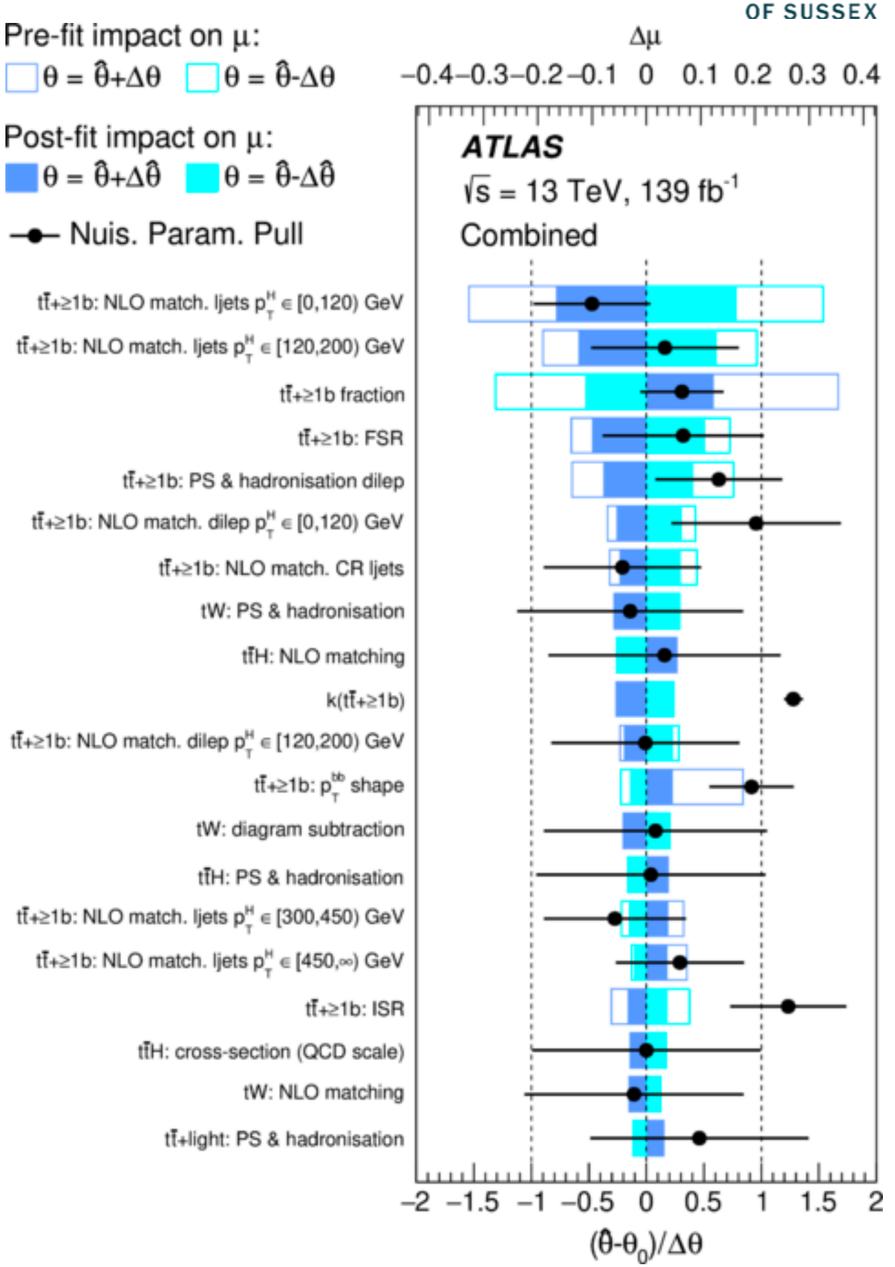




New ATLAS ttH→bb result

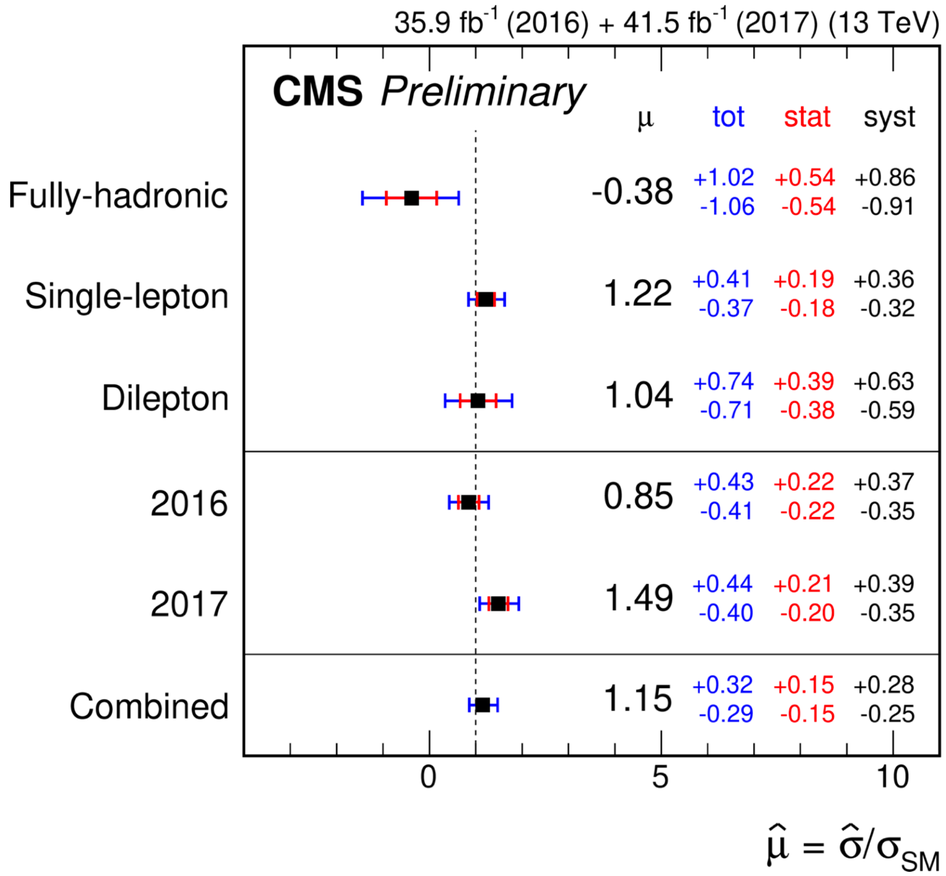
- Impact of systematic uncertainties has been reduced by about a factor of two.
  - Main improvements:
    - Improved theoretical knowledge in tt + ≥1b modelling
    - Much larger size of simulated event samples
    - refined b-tagging scale factors and jet energy scale and resolution measurements.

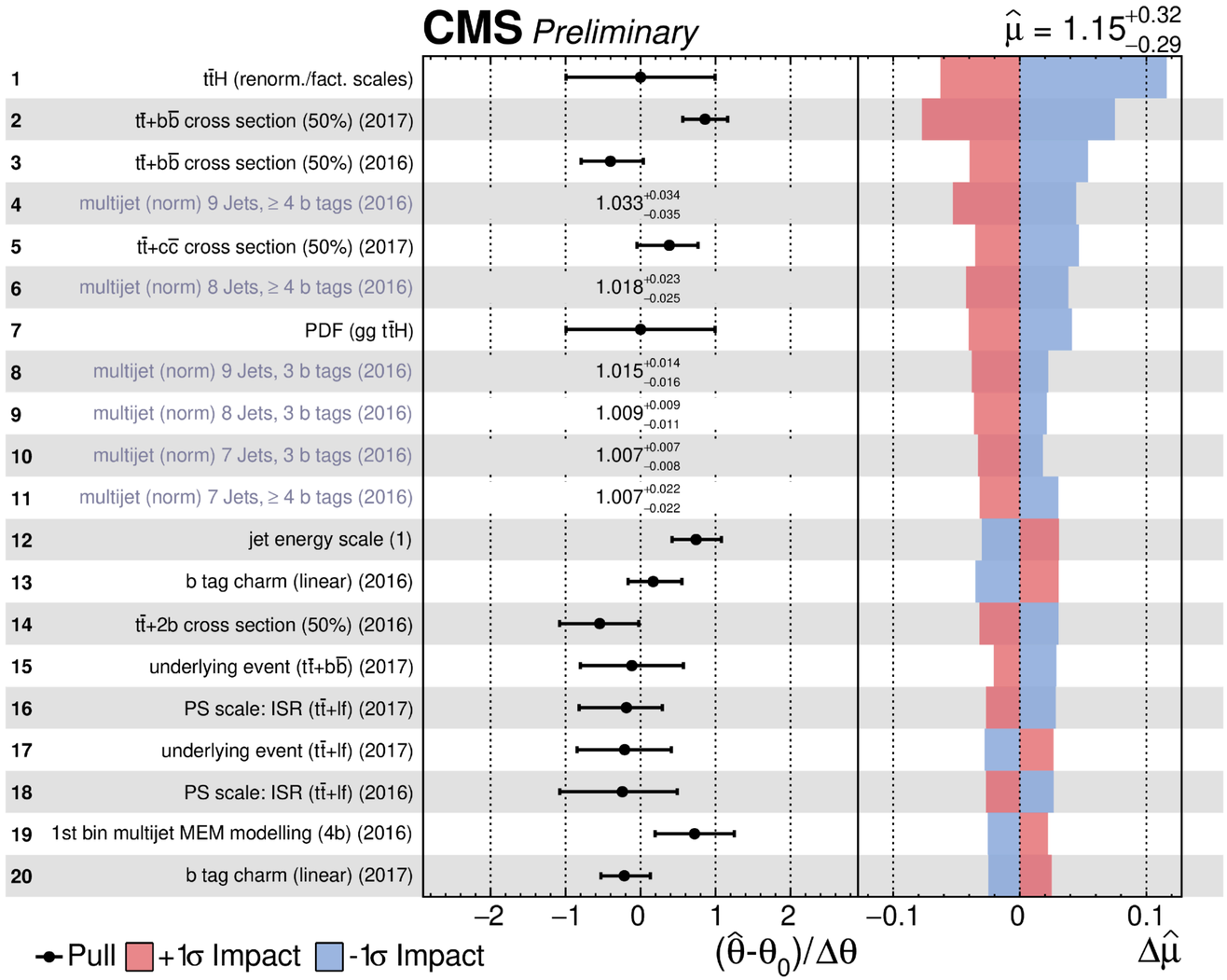
- Sensitivity still very much dominated by tt+bb modelling uncertainties
  - Not yet using most recent recommendations from ttH/tH subgroup MC studies
  - More on this later…



CMS ttH→bb result

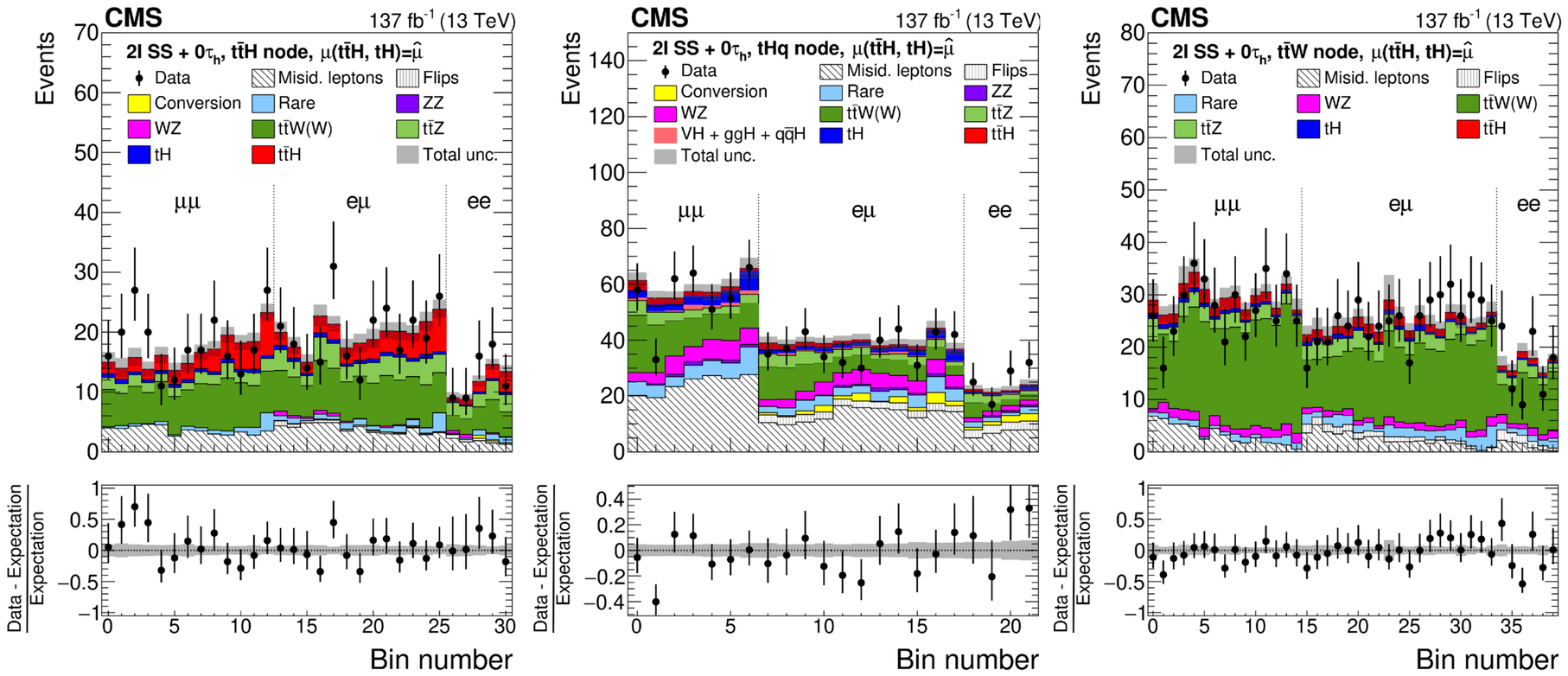
- Latest CMS ttHbb result: CMS-PAS-HIG-18-030
  - Also very sensitive to tt+bb modelling systematics





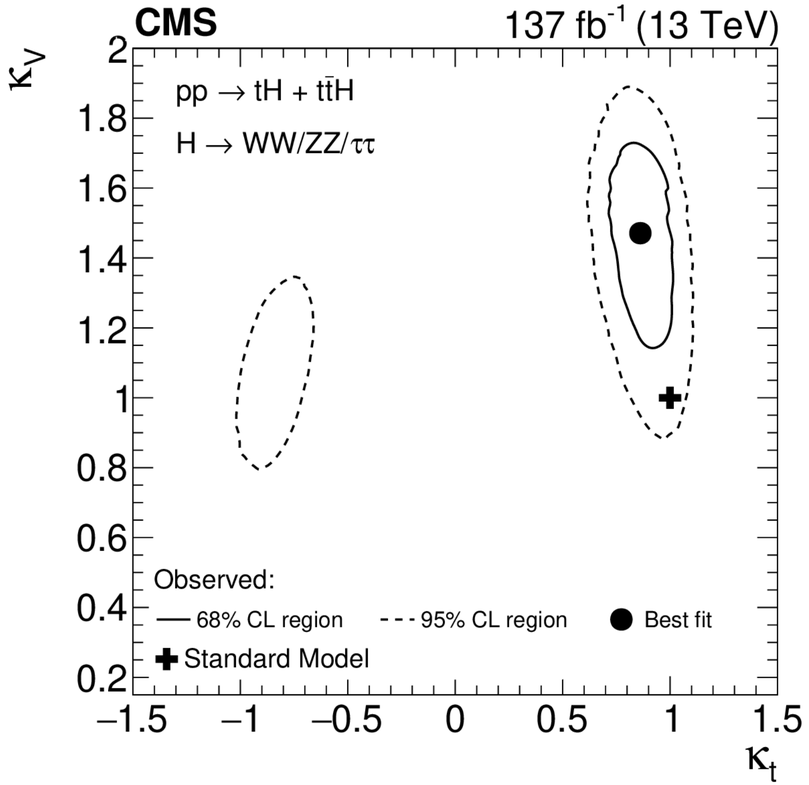
CMS ttH→multi-leptons

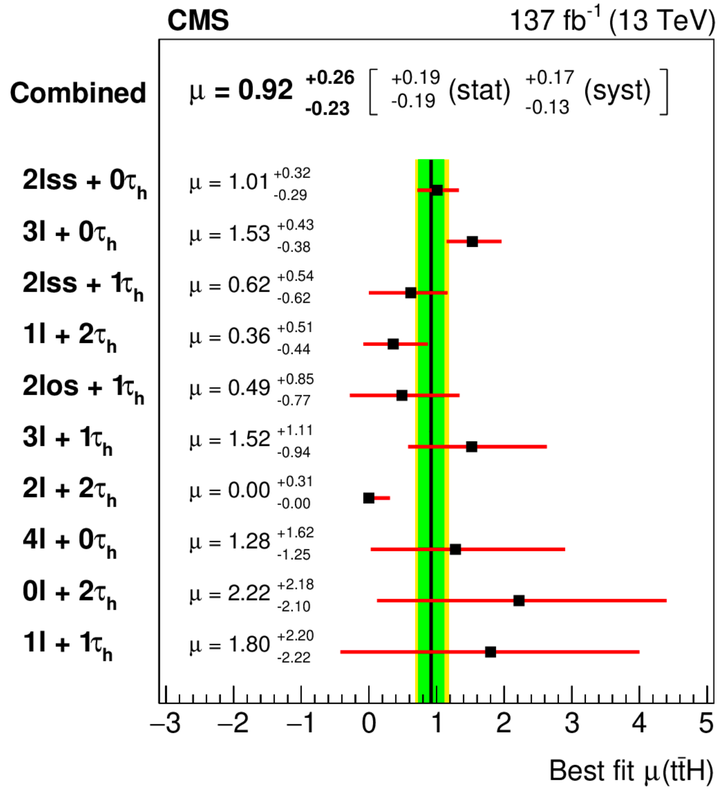
- ttH and tH production in e, μ, τ_{had} final state: Eur. Phys. J. C 81 (2021) 378
  - Nice that so much is combined into a single coherent analysis:
    - ttH, tH, ttW, ttZ and correlations
    - Kappa framework
  - Complex categorisation strategy

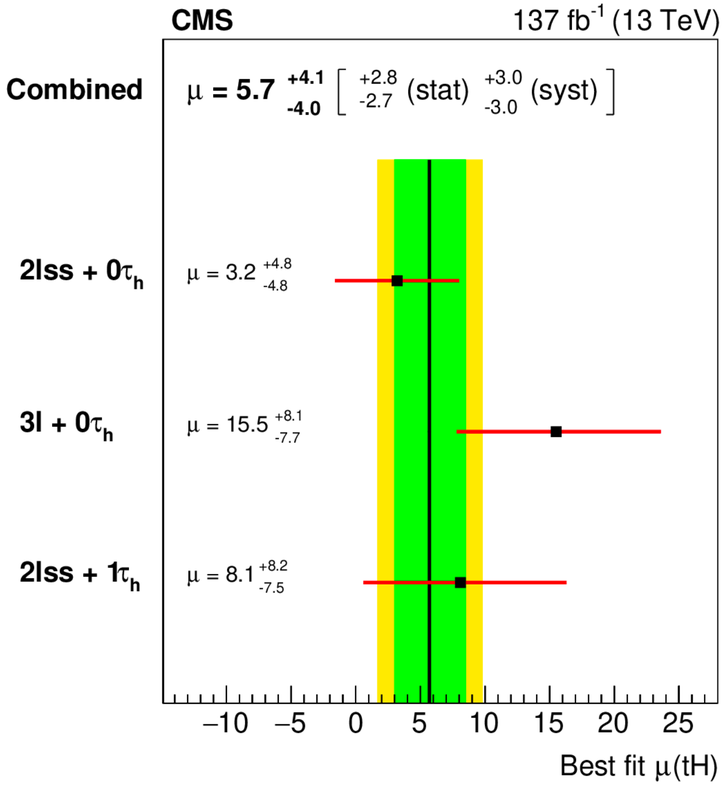


CMS ttH→multi-leptons

- ttH and tH production in e, μ, τ_{had} final state: Eur. Phys. J. C 81 (2021) 378
  - tH signal strength not yet verv precise (as expected).
  - But has some power to distinguish sign of κt.

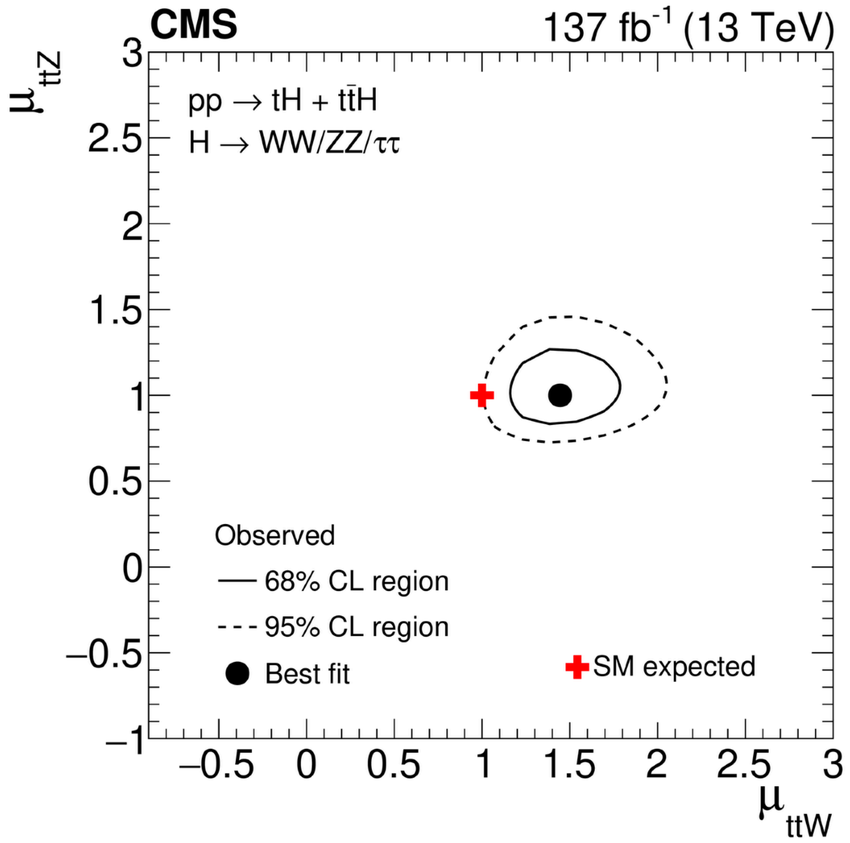






CMS ttH→multi-leptons

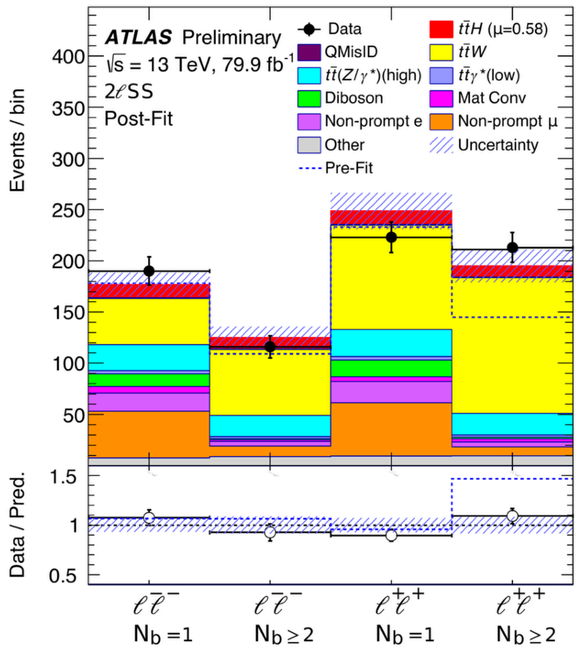
- ttH and tH production in e, μ, τ_{had} final state: Eur. Phys. J. C 81 (2021) 378
  - ttW extraction very important for analysis sensitivity
  - Fitted ttW normalisation higher than SM prediction

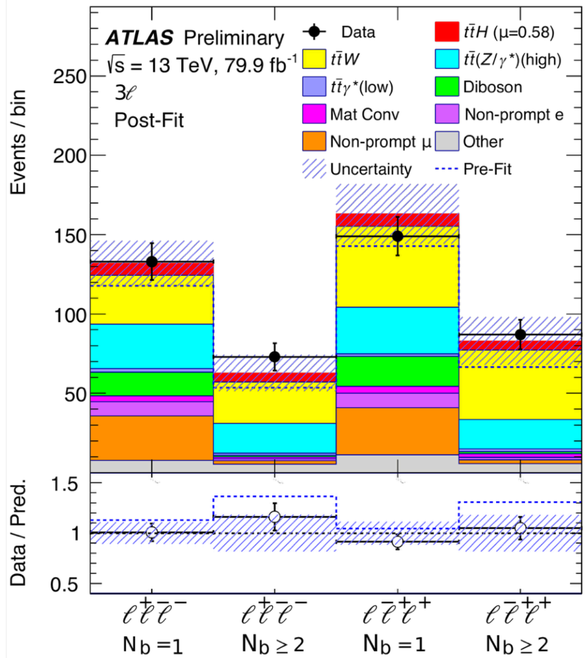


Source	$\Delta\mu_{t\bar{t}H}/\mu_{t\bar{t}H}$ [%]	$\Delta\mu_{tH}/\mu_{tH}$ [%]	$\Delta\mu_{t\bar{t}W}/\mu_{t\bar{t}W}$ [%]	$\Delta\mu_{t\bar{t}Z}/\mu_{t\bar{t}Z}$ [%]
Trigger efficiency	2.3	8.1	1.2	1.9
e, μreconstruction and identification efficiency	2.9	7.1	1.7	3.2
τ_h identification efficiency	4.6	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 affecting acceptance and shape of distributions	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

ATLAS ttH→multi-leptons

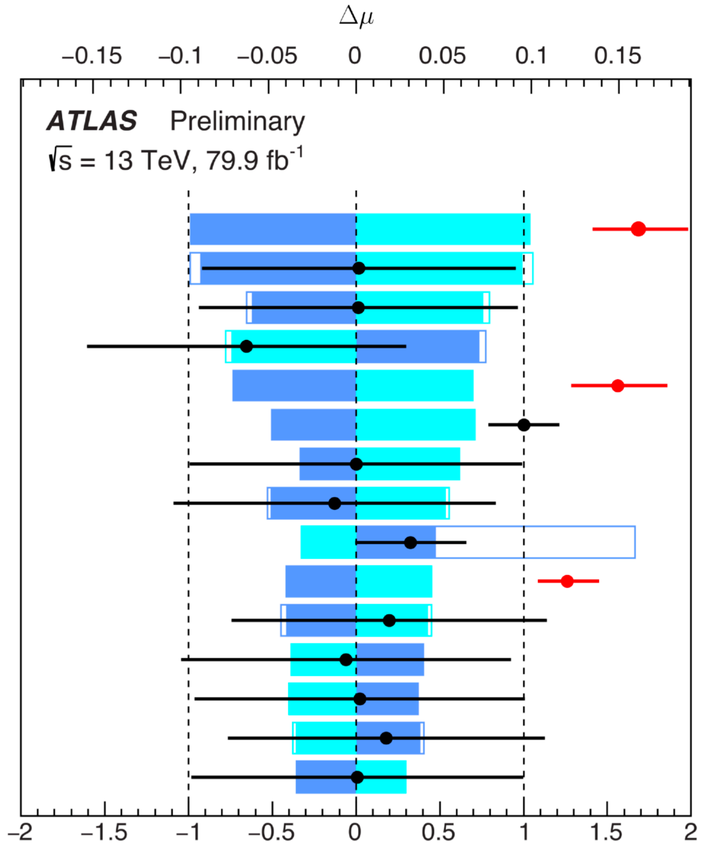
- ATLAS ttHML CONF note (80 fb^{-1}): ATLAS-CONF-2019-045
  - Observed significant mismodelling attributed to ttW background
    - Need ttW+2j for 2LSS region
  - Very important for overall sensitivity





Pre-fit impact on μ:
$\theta = \hat{\theta}+\Delta\theta$ $\theta = \hat{\theta}-\Delta\theta$
Post-fit impact on μ:
$\theta = \hat{\theta}+\Delta\hat{\theta}$ $\theta = \hat{\theta}-\Delta\hat{\theta}$
Pull: $(\hat{\theta}-\theta_0)/\Delta\theta$
Norm. Factor

$t\bar{t}W$ norm. factor: 3ℓ channel
Jet energy scale: η intercalib. NP I
$t\bar{t}Z$ cross section: scale variations
$t\bar{t}W$ modelling: scale variations
$t\bar{t}W$ norm. factor: 2ℓSS channel, 2-3 jets
Fake τ_{had} bkg. stat: $1\ell 2\tau$ channel
$t\bar{t}H$ cross section: scale variations
Jet energy scale: pileup
$t\bar{t}W$ modelling: charge extrapolation
$t\bar{t}W$ norm. factor: 2ℓSS channel, ≥ 4 jets
Top rare decay cross-section
Jet energy scale: flavour response
$t\bar{t}H$ modelling: parton shower
$t\bar{t}W$ modelling: alternative generator
4-top cross section



ttH→multi-leptons

- Comparing ATLAS and CMS extracted normalisation factors for ttHML analyses
  - Quite comparable fitted ttW normalisations (both ~40% high when considering a single parameter in the fit).

	CMS	ATLAS (single NF)	ATLAS (multiple NFs)
ttW	1.43±0.21	1.39±0.17	LJ ttW = 1.56 ± 0.29 HJ ttW = 1.26 ± 0.19 3L ttW = 1.68 ± 0.29
ttZ	1.03±0.14	(1.00±0.13)	

  - ttW+2j is not a trivial process to simulate - these results triggered significant work in the theory community
    - See Laura's talk for most recent developments

ttH Summary

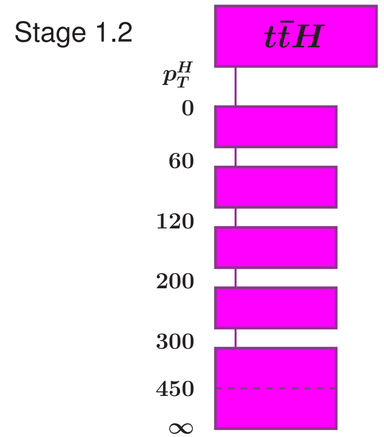
- Inclusive signal strength measurements show that all channels apart from H→4l have similar sensitivities

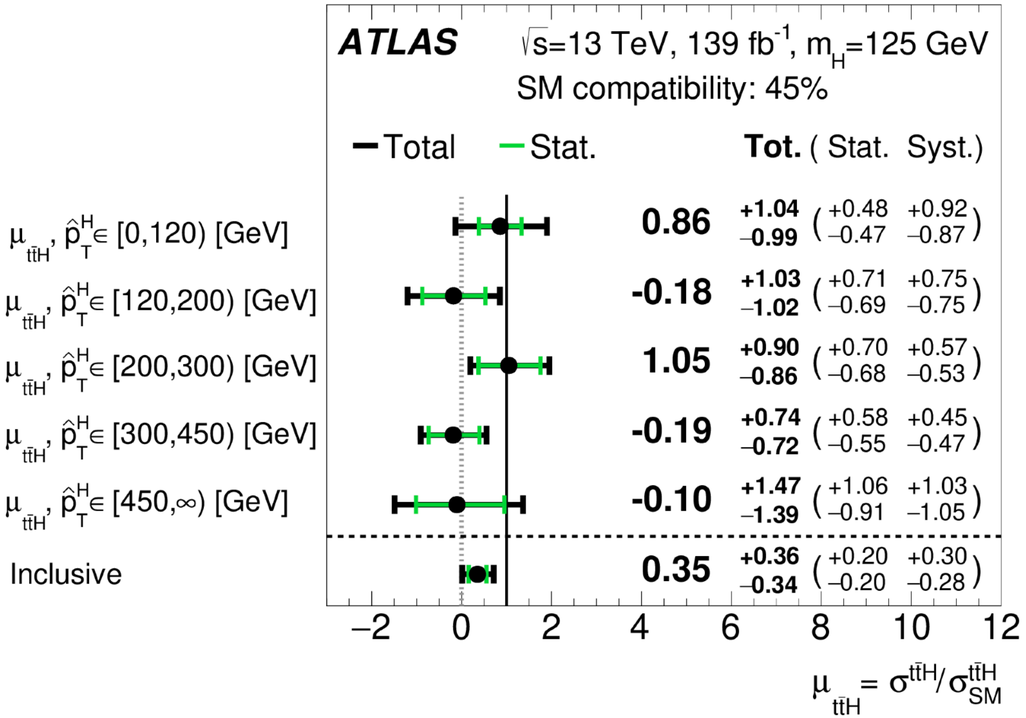
- Most channels now moving focus to: **differential, CP and EFT interpretations.**

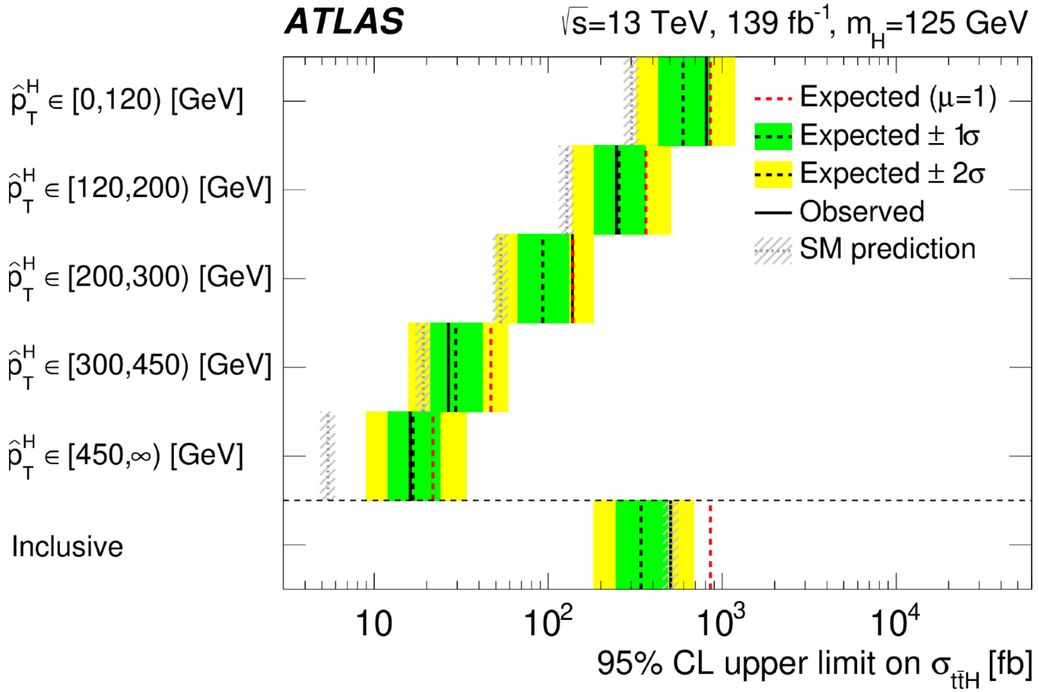
	ATLAS	CMS
H→bb	$0.35^{+0.36}_{-0.34}$ HIGG-2020-23	$1.15^{+0.32}_{-0.29}$ CMS-PAS-HIG-18-030
H→multilep	$0.58^{+0.36}_{-0.33}$ ATLAS-CONF-2020-026 (80 fb^{-1})	$0.93^{+0.26}_{-0.23}$ Eur. Phys. J. C 81 (2021) 378
H→4l	$1.6^{+1.7}_{-1.1}$ Eur. Phys. J. C 80 (2020) 957	$0.04^{+0.76}_{-0.04}$ Phys. Rev. D 104 (2021) 052004
H→yy	$0.92^{+0.27}_{-0.24}$ ATLAS-CONF-2020-026	$1.35^{+0.34}_{-0.28}$ JHEP 07 (2021) 027

Differential | ATLAS ttHbb

- STXS interpretation
  - Following STXS Stage 1.2 prescription
  - Special selection for boosted Higgs for p_T > 300 GeV
    - Significant improvements wrt previous result



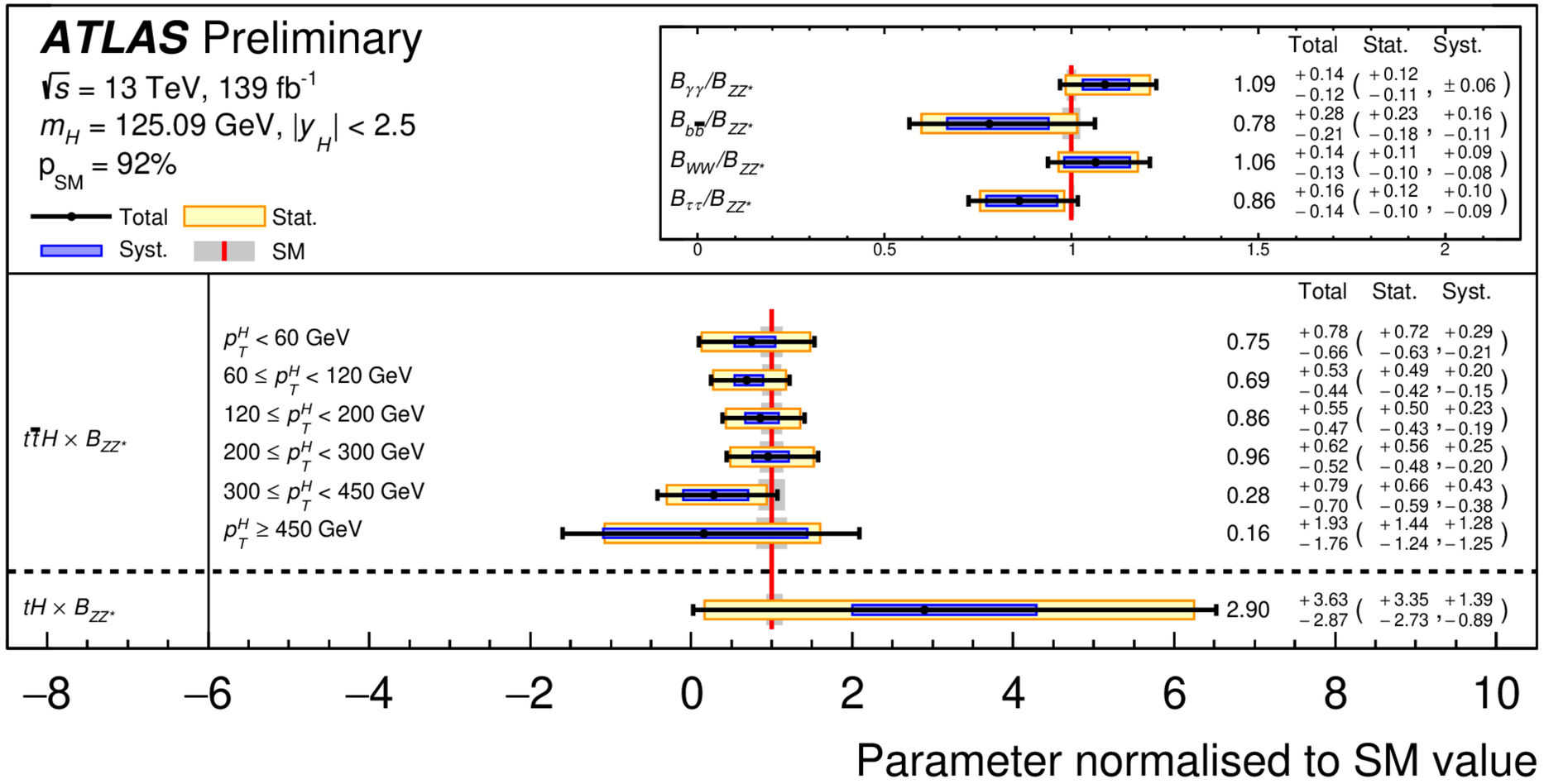




Differential | ATLAS Higgs combination

- ATLAS ttHbb result also included in combination: ATLAS-CONF-2021-053

- Very much still statistics-limited in general
- Large systematics also in highest pT bin

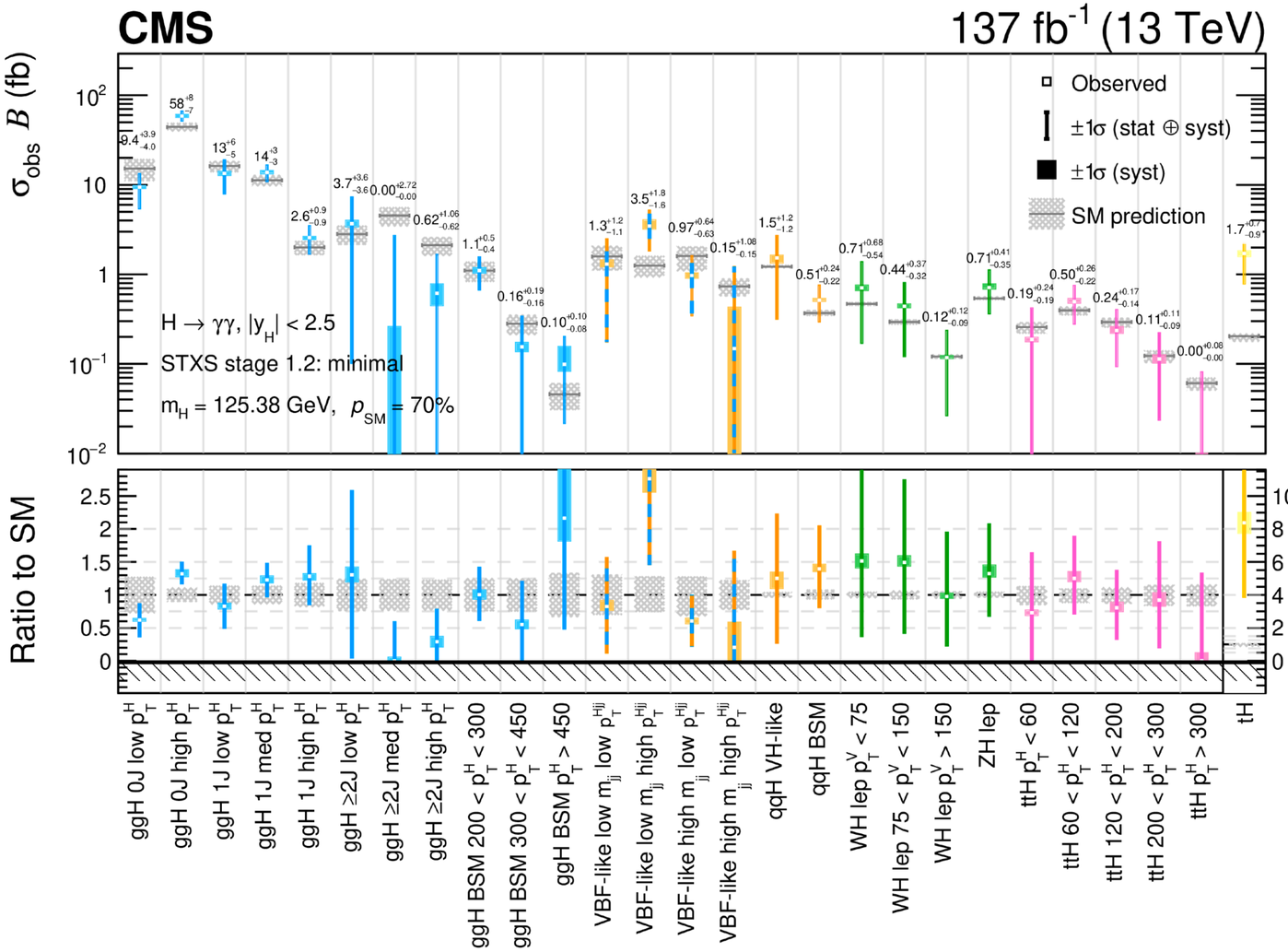


Differential | CMS H→γγ

- CMS H→γγ cross sections and couplings: JHEP 07 (2021) 027

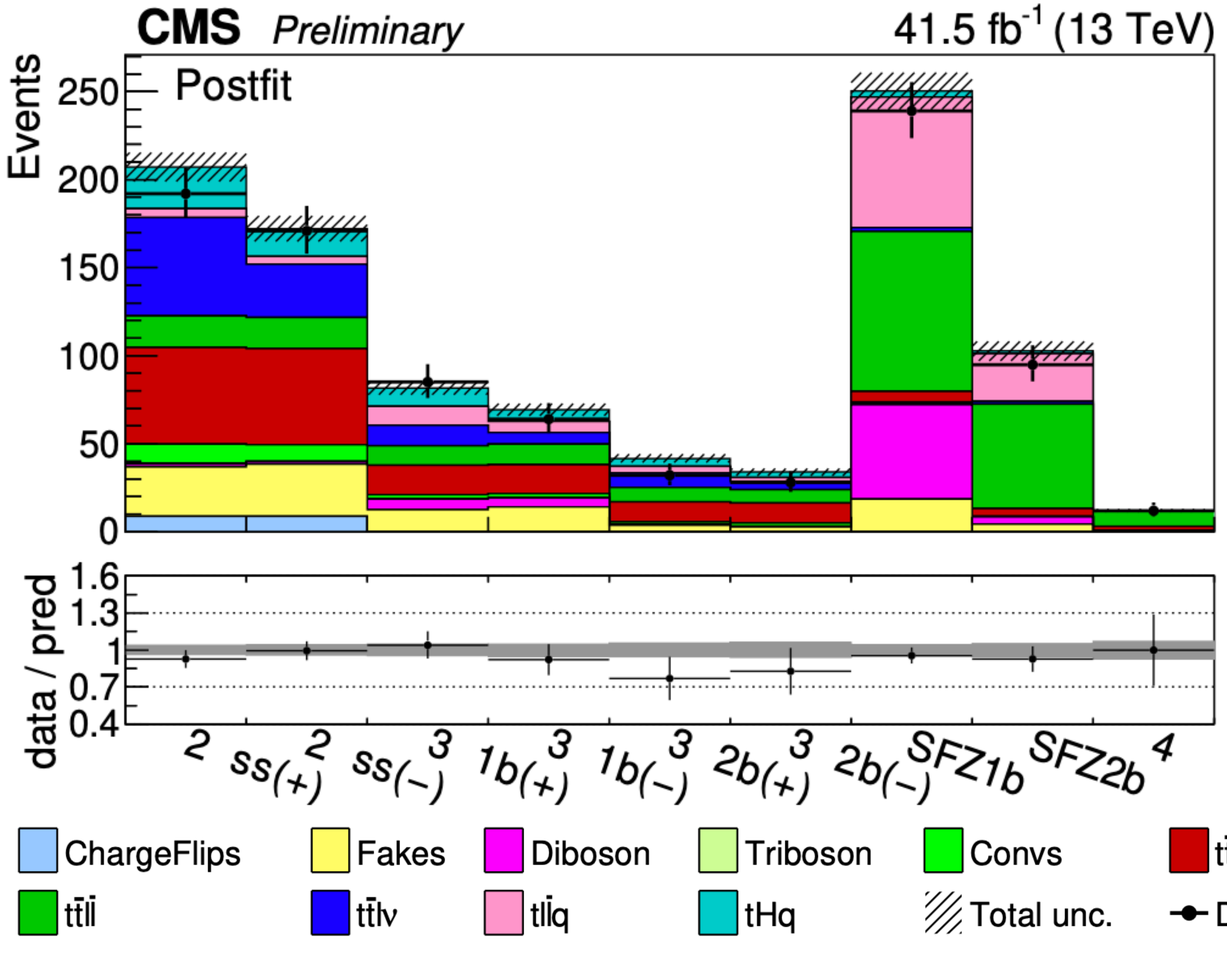
  - Also using Stage 1.2 ttH STXS bins
    - first binned pT(H) measurement of ttH

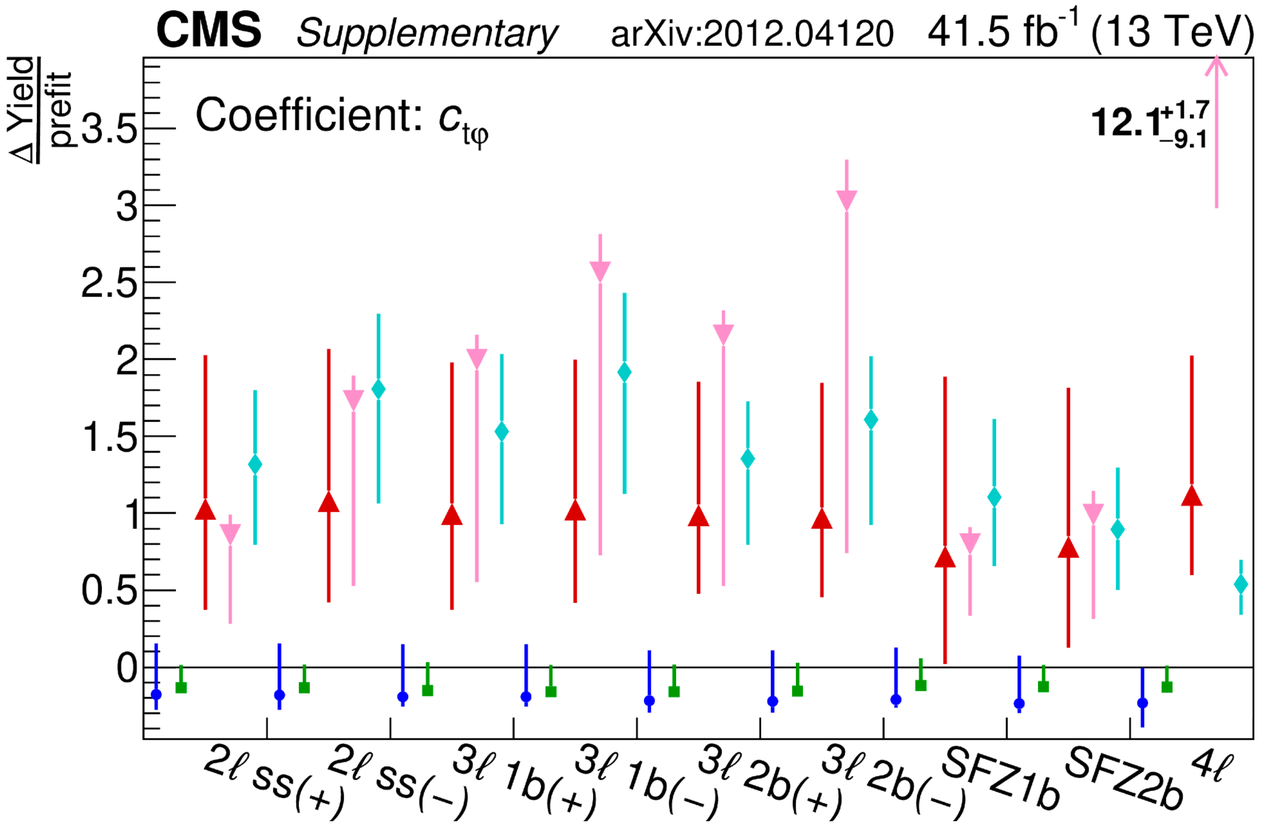
  - Largest uncertainties come from migrations due to scale variations



EFT | CMS top+X multi-leptons

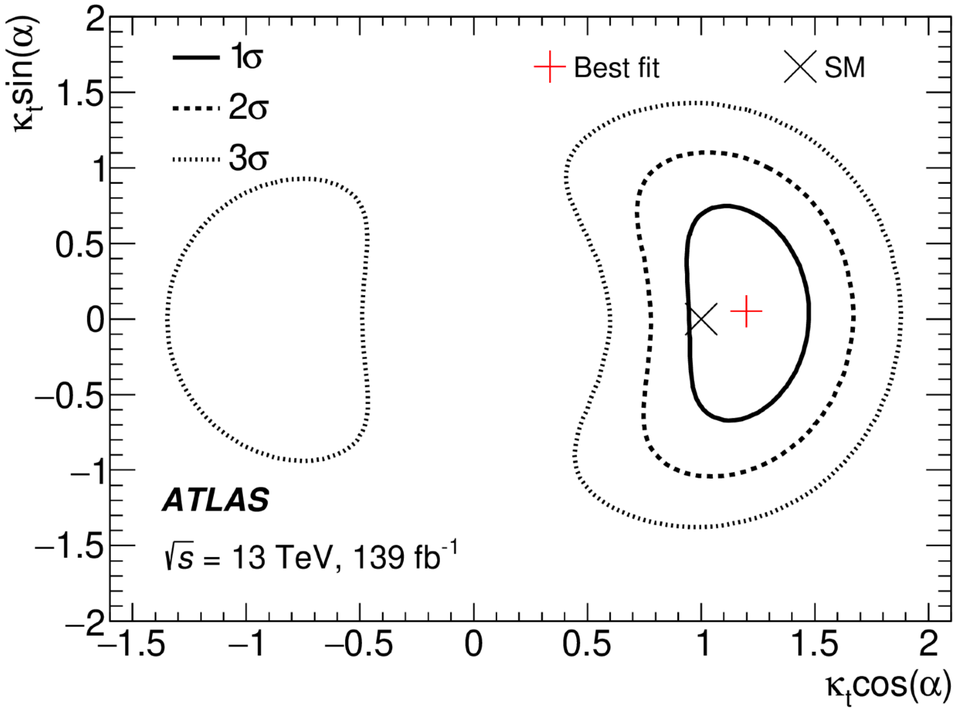
- CMS top+X multi-lepton EFT fit: JHEP 2103 (2021) 095
  - Top+X “global” EFT fit
  - Interpretation in several EFT operators

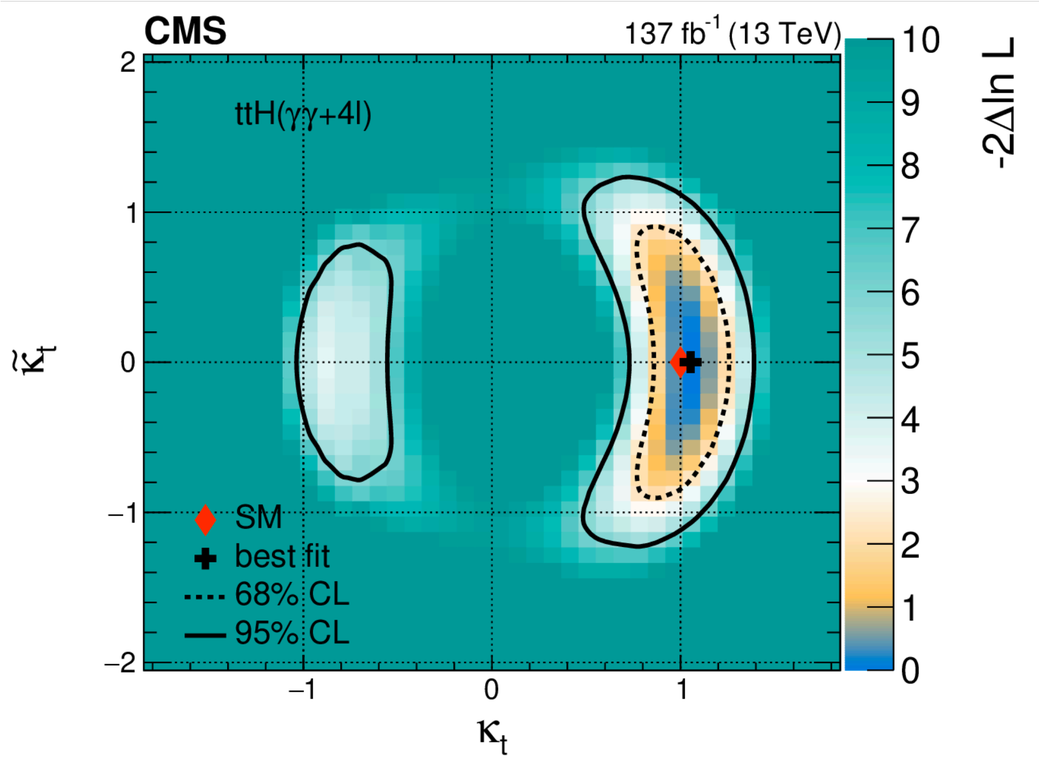




Higgs CP | ttH

- ATLAS H→γγ: HIGG-2019-01, CMS H→γγ+H→4ℓ: HIG-19-013
- Results:
  - Overall similar sensitivities
  - Mainly limited by data statistics
  - Pure CP-odd coupling excluded at 3.9σ/3.2σ





Modelling uncertainties

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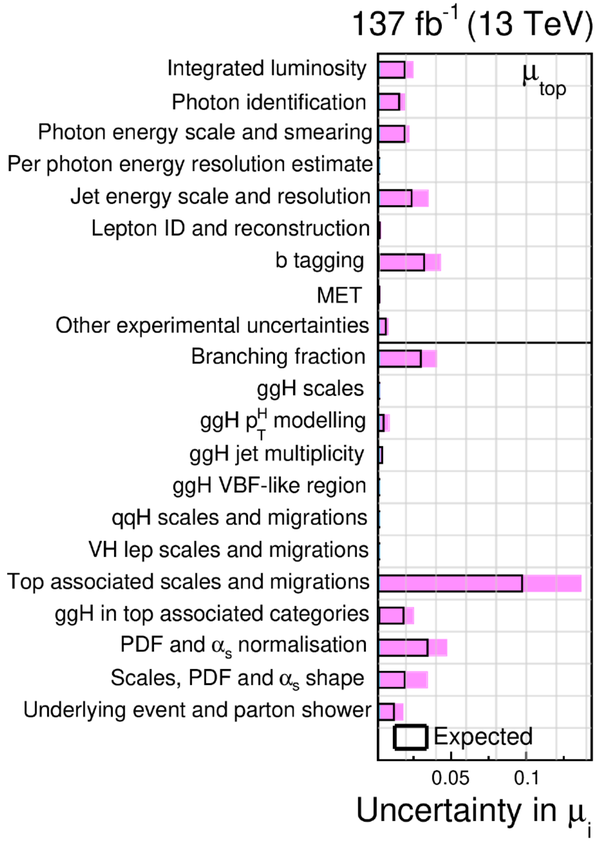
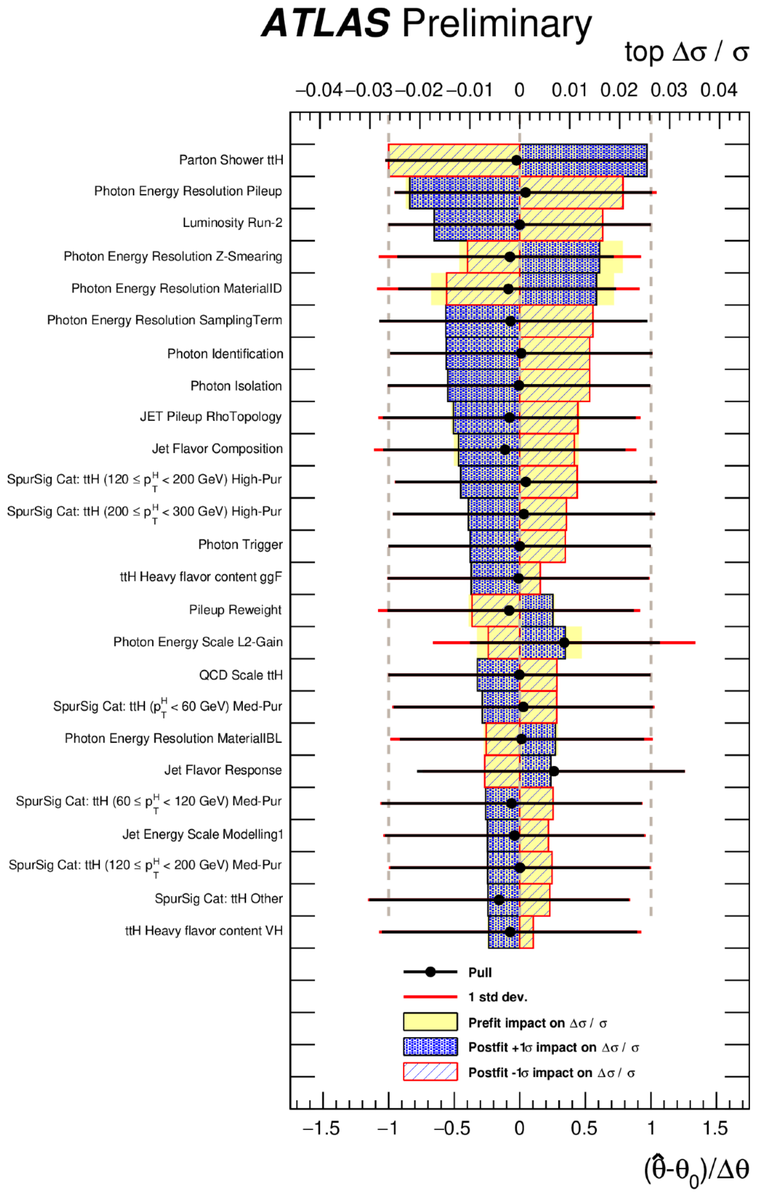
- Ttbb
  - ATLAS looking at tt+bb MC models using settings from LHC Higgs WG studies
    - Initial signs are that predictions are much closer than in the past - PUB note in progress
  - ATLAS+CMS note in preparation
    - Cross-check of parameter settings are work towards a common systematic uncertainty recipe

- ttW
  - Looking at implementation of recent predictions e.g. modified MG5_aMC+Py8 FxFx
  - ATLAS has new STA with Malgorzata and others designed to improve EXP<=>TH interactions on ttW modelling

Modelling uncertainties

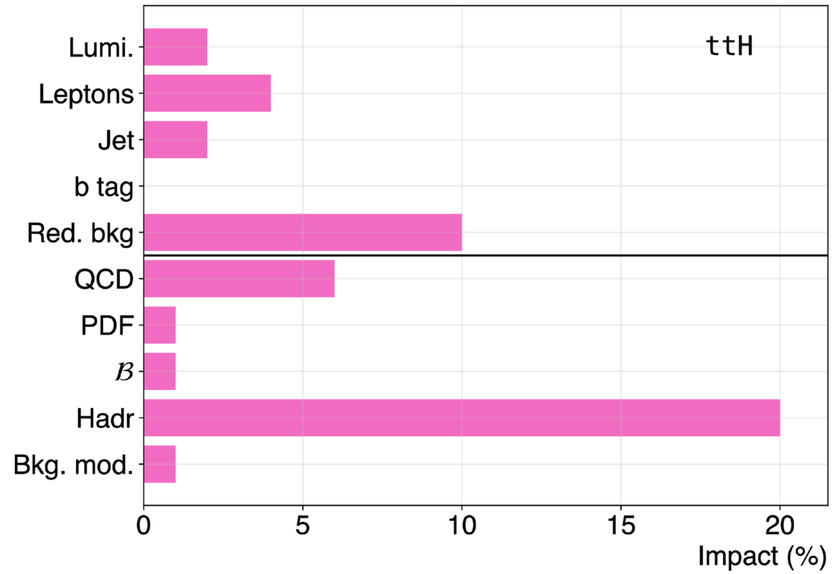
- ttH signal
  - Signal model scale and UEPS uncertainties dominant for H→γγ





Modelling uncertainties

- ttH signal
  - Signal model scale and UEPS uncertainties dominant for H→γγ and H→4l



- Much more on all these theoretical details from Laura next!

Measurement	Experimental uncertainties [%]				Theory uncertainties [%]				
	Lumi.	e, μ, pile-up	Jets, flav. tag	Reducible bkg	Background ZZ^*	Background tXX	Signal PDF	Signal QCD	Signal Shower
Inclusive cross-section									
	1.7	2.5	0.5	< 0.5	1	< 0.5	< 0.5	1	2
Production mode cross-sections									
ggF	1.7	2.5	1	< 0.5	1.5	< 0.5	0.5	1	2
VBF	1.7	2	4	< 0.5	1.5	< 0.5	1	5	7
VH	1.9	2	4	1	6	< 0.5	2	13.5	7.5
ttH	1.7	2	6	< 0.5	1	0.5	0.5	12.5	4

Summary

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- ttH/tH remains a very challenging final state but were significant progress is being made
- Very much now in the realm of differential measurements and more complicated interpretations
- Particular issues on modelling and associated theoretical uncertainties
  - Especially for ttH→bb and ttH→multi-leptons backgrounds
  - Increasingly on signal modelling for ttH→γγ/H→4ℓ
    - **More on this from Laura next!**

Back-ups

ATLAS ttHbb modelling

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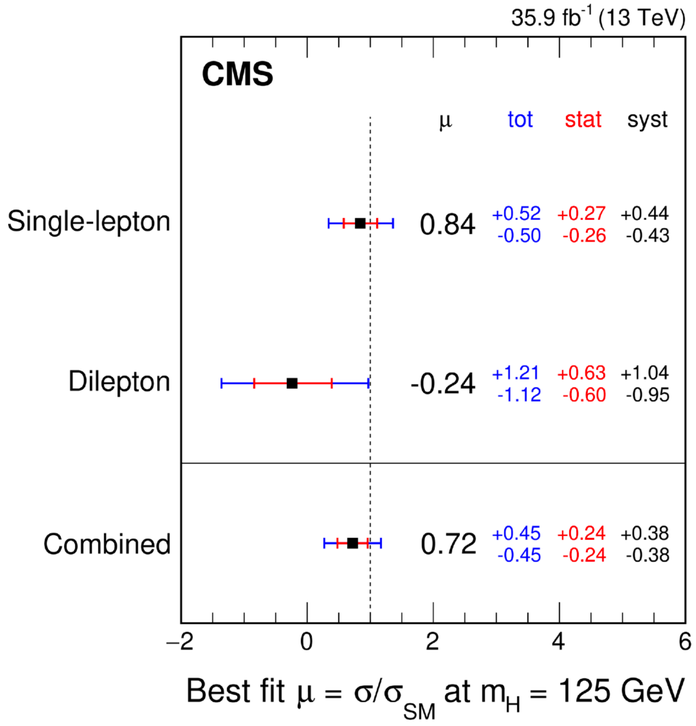
- tt+>=1b model
  - PowhegBoxRes+Py8
    - Factorisation scale: $\frac{1}{2}\Sigma_{i=t,\bar{t},b,\bar{b},j} m_{\mathrm{T},i}$
    - Renormalisation scale: $\sqrt[4]{m_{\mathrm{T}}(t)\cdot m_{\mathrm{T}}(\bar{t})\cdot m_{\mathrm{T}}(b)\cdot m_{\mathrm{T}}(\bar{b})}$
    - hdamp scale: $\frac{1}{2}\Sigma_{i=t,\bar{t},b,\bar{b},j} m_{\mathrm{T},i}$

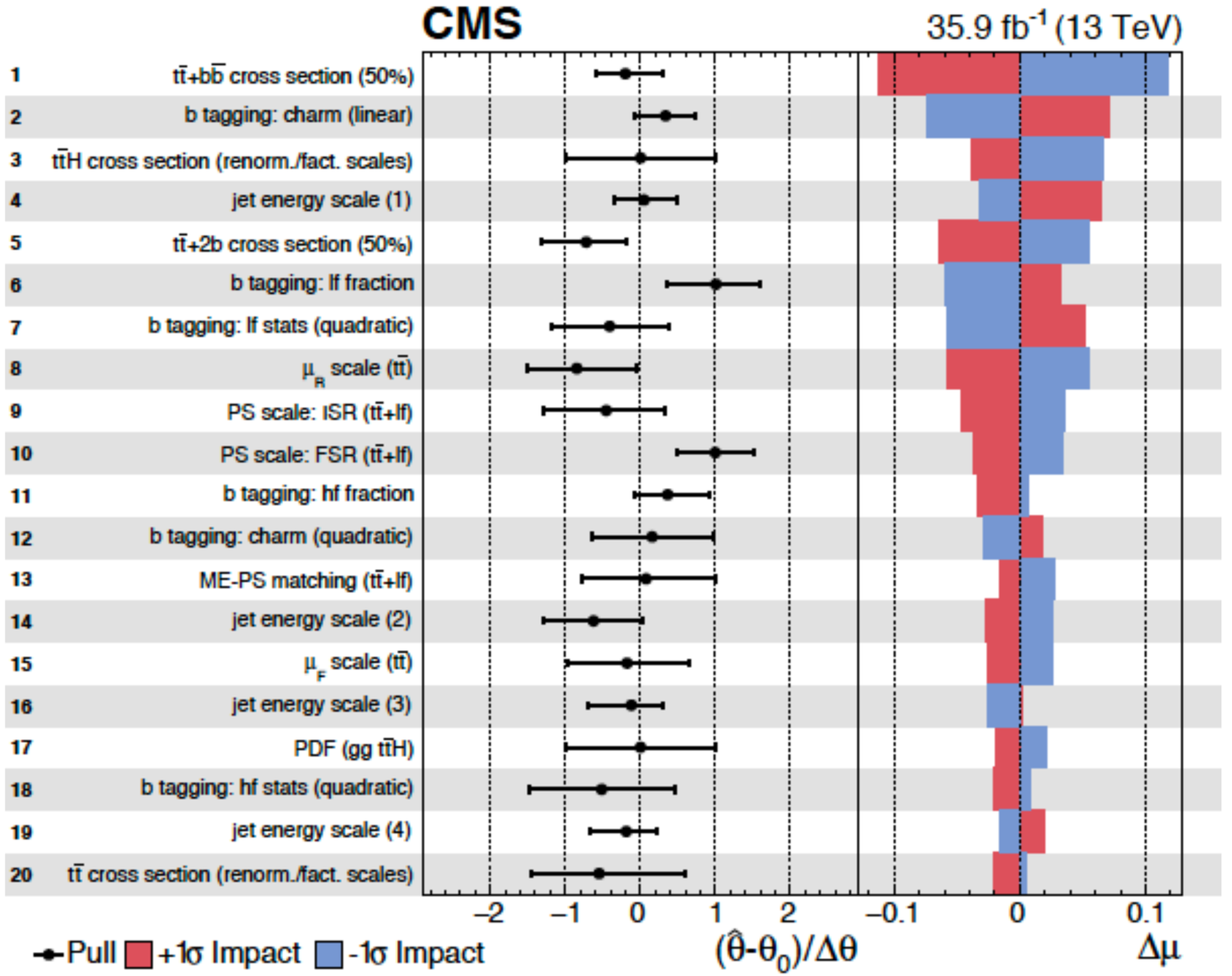
Uncertainty source	Description		Components
$t\bar{t}$ cross-section	Up or down by 6%		$t\bar{t}$ + light
$t\bar{t}$ + ≥1b normalisation	Free-floating		$t\bar{t}$ + ≥1b
$t\bar{t}$ + ≥1c normalisation	Up or down by 100%		$t\bar{t}$ + ≥1c
ISR	Varying $\mu_{\mathrm{R}}^{\mathrm{ISR}}$ (PS), μ_{R}&μ_{F} (ME)	in PowhegBox+Pythia8 $t\bar{t}b\bar{b}$ (4FS)	$t\bar{t}$ + ≥1b
		in PowhegBox+Pythia8 $t\bar{t}$ (5FS)	$t\bar{t}$ + ≥1c, $t\bar{t}$ + light
FSR	Varying $\mu_{\mathrm{R}}^{\mathrm{FSR}}$ (PS)	in PowhegBox+Pythia8 $t\bar{t}b\bar{b}$ (4FS)	$t\bar{t}$ + ≥1b
		in PowhegBox+Pythia8 $t\bar{t}$ (5FS)	$t\bar{t}$ + ≥1c, $t\bar{t}$ + light
NLO matching	MadGraph5_aMC@NLO +Pythia8 $t\bar{t}$ (5FS)	vs. PowhegBox+Pythia8 $t\bar{t}$ (5FS)	All
PS & hadronisation	PowhegBox+Herwig7 $t\bar{t}$ (5FS)	vs. PowhegBox+Pythia8 $t\bar{t}$ (5FS)	All
$p_{\mathrm{T}}^{b\bar{b}}$ shape	Correction from data of $p_{\mathrm{T}}^{b\bar{b}}$ shape in signal regions		$t\bar{t}$ + ≥1b
$t\bar{t}$ + ≥1b fractions	Variation of the relative fractions of $t\bar{t}$ + ≥2b and $t\bar{t}$ + 1b/1B		$t\bar{t}$ + ≥1b

Uncertainty source	$\Delta\mu$	
Process modelling		
$t\bar{t}H$ modelling	+0.13	−0.05
$t\bar{t}$ + ≥1b modelling		
$t\bar{t}$ + ≥1b NLO matching	+0.21	−0.20
$t\bar{t}$ + ≥1b fractions	+0.12	−0.12
$t\bar{t}$ + ≥1b FSR	+0.10	−0.11
$t\bar{t}$ + ≥1b PS & hadronisation	+0.09	−0.08
$t\bar{t}$ + ≥1b p_{T}^{bb} shape	+0.04	−0.04
$t\bar{t}$ + ≥1b ISR	+0.04	−0.04
$t\bar{t}$ + ≥1c modelling	+0.03	−0.04
$t\bar{t}$ + light modelling	+0.03	−0.03
tW modelling	+0.08	−0.07
Background-model statistical uncertainty	+0.04	−0.05
b-tagging efficiency and mis-tag rates		
b-tagging efficiency	+0.03	−0.02
c-mis-tag rates	+0.03	−0.03
l-mis-tag rates	+0.02	−0.02
Jet energy scale and resolution		
b-jet energy scale	+0.00	−0.01
Jet energy scale (flavour)	+0.01	−0.01
Jet energy scale (pile-up)	+0.00	−0.01
Jet energy scale (remaining)	+0.01	−0.01
Jet energy resolution	+0.02	−0.02
Luminosity	+0.01	−0.00
Other sources	+0.03	−0.03
Total systematic uncertainty	+0.30	−0.28
$t\bar{t}$ + ≥1b normalisation	+0.04	−0.07
Total statistical uncertainty	+0.20	−0.20
Total uncertainty	+0.36	−0.34

CMS ttHbb result 36 ifb

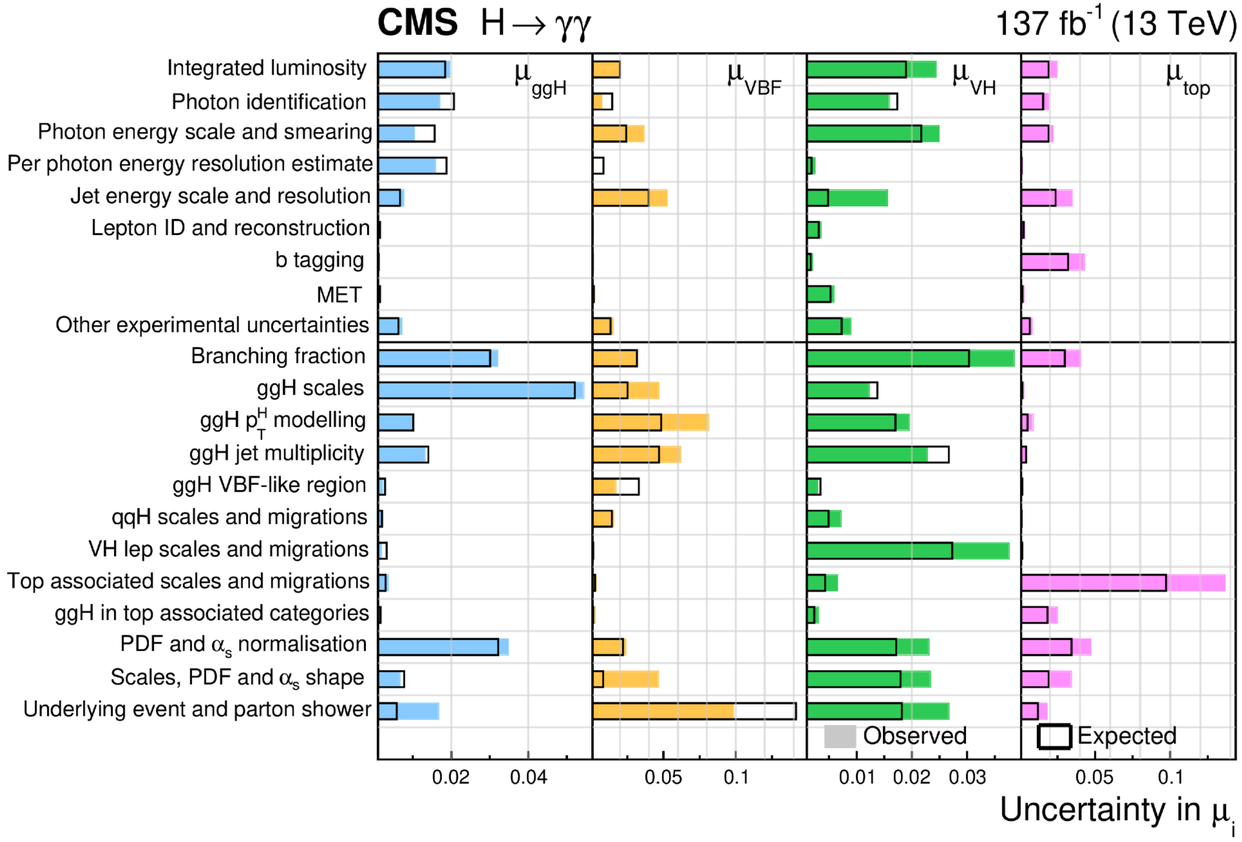
- JHEP 03 (2019) 026

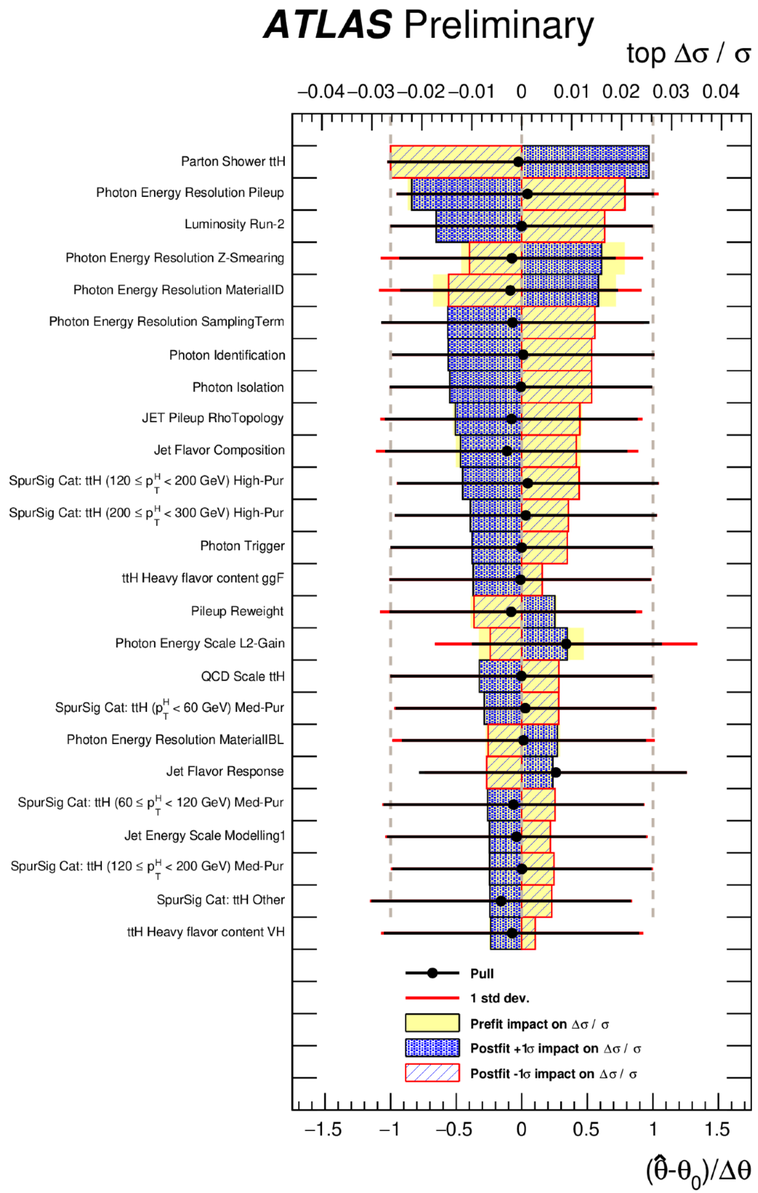




Hyy

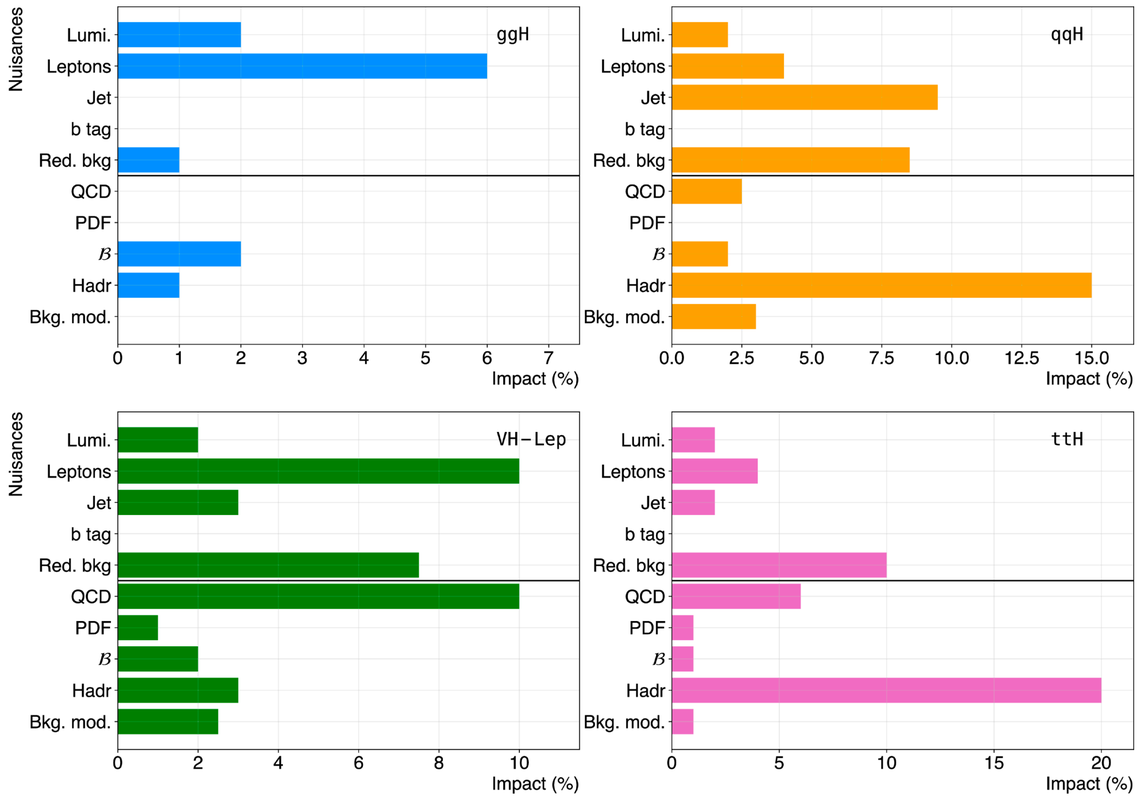
- https://atlas.web.cern.ch/Atlas/GROUPS/PHYCONF-2020-026/
- http://cms-results.web.cern.ch/cms-results/pHIG-19-015/index.html





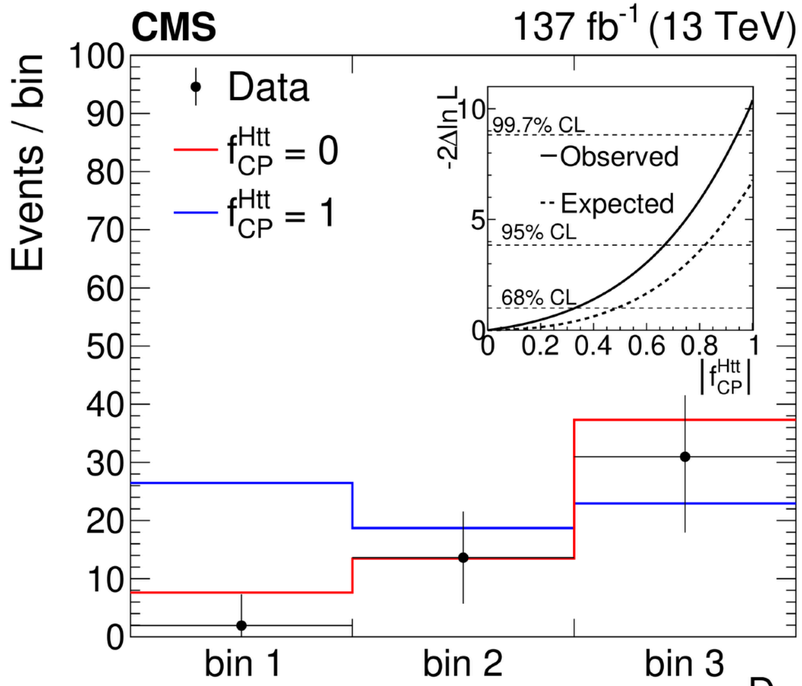
CMS ttHbb result 36 ifb

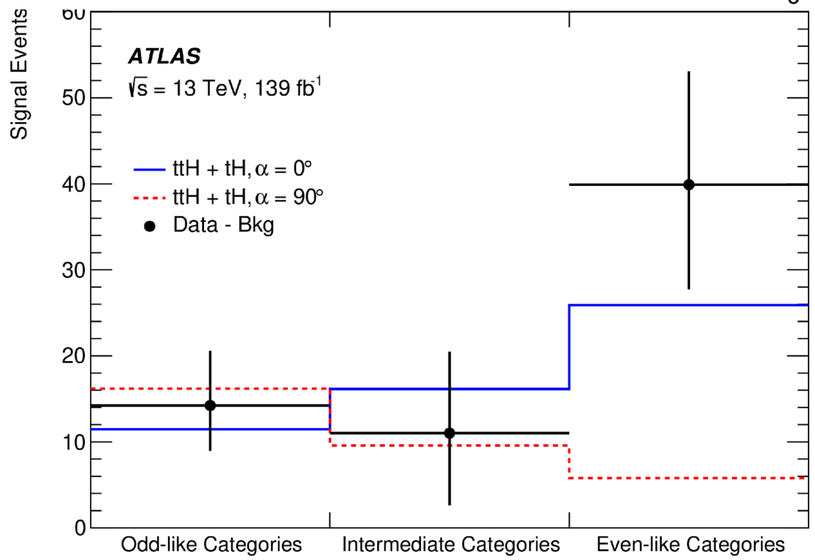
- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2018-28/
- http://cms-results.web.cern.ch/cms
  HIG-19-001/



Measurement	Experimental uncertainties [%]				Theory uncertainties [%]				
	Lumi.	e, μ, pile-up	Jets, flav. tag	Reducible bkg	Background ZZ^*	Background tXX	Signal PDF	Signal QCD	Signal Shower
Inclusive cross-section									
	1.7	2.5	0.5	< 0.5	1	< 0.5	< 0.5	1	2
Production mode cross-sections									
ggF	1.7	2.5	1	< 0.5	1.5	< 0.5	0.5	1	2
VBF	1.7	2	4	< 0.5	1.5	< 0.5	1	5	7
VH	1.9	2	4	1	6	< 0.5	2	13.5	7.5
ttH	1.7	2	6	< 0.5	1	0.5	0.5	12.5	4
Reduced Stage-1.1 production bin cross-sections									
gg2H-0j-p_{T}^{H}-Low	1.7	3	1.5	0.5	6.5	< 0.5	< 0.5	1	1.5
gg2H-0j-p_{T}^{H}-High	1.7	3	5	< 0.5	3	< 0.5	< 0.5	0.5	5.5
gg2H-1j-p_{T}^{H}-Low	1.7	2.5	12	0.5	7	< 0.5	< 0.5	1	6
gg2H-1j-p_{T}^{H}-Med	1.7	3	7.5	< 0.5	1	< 0.5	< 0.5	1.5	5.5
gg2H-1j-p_{T}^{H}-High	1.7	3	11	0.5	2	< 0.5	< 0.5	2	7.5
gg2H-2j	1.7	2.5	16.5	1	12.5	0.5	< 0.5	2.5	10.5
gg2H-p_{T}^{H}-High	1.7	1.5	3	0.5	3.5	< 0.5	< 0.5	2	3.5
qq2Hqq-VH	1.8	4	17	1	4	1	0.5	5.5	8
qq2Hqq-VBF	1.7	2	3.5	< 0.5	5	< 0.5	< 0.5	6	10.5
qq2Hqq-BSM	1.7	2	4	< 0.5	2.5	< 0.5	< 0.5	3	8
VH-Lep	1.8	2.5	2	1	2	0.5	< 0.5	1.5	3
ttH	1.7	2.5	5	0.5	1	0.5	< 0.5	11	3

Higgs CP





From Haichen Wang

CMS

$$\mathcal{A}(\mathrm{Htt}) = -\frac{m_t}{v}\bar{\psi}_t\left(\kappa_t + i\tilde{\kappa}_t\gamma_5\right)\psi_t$$

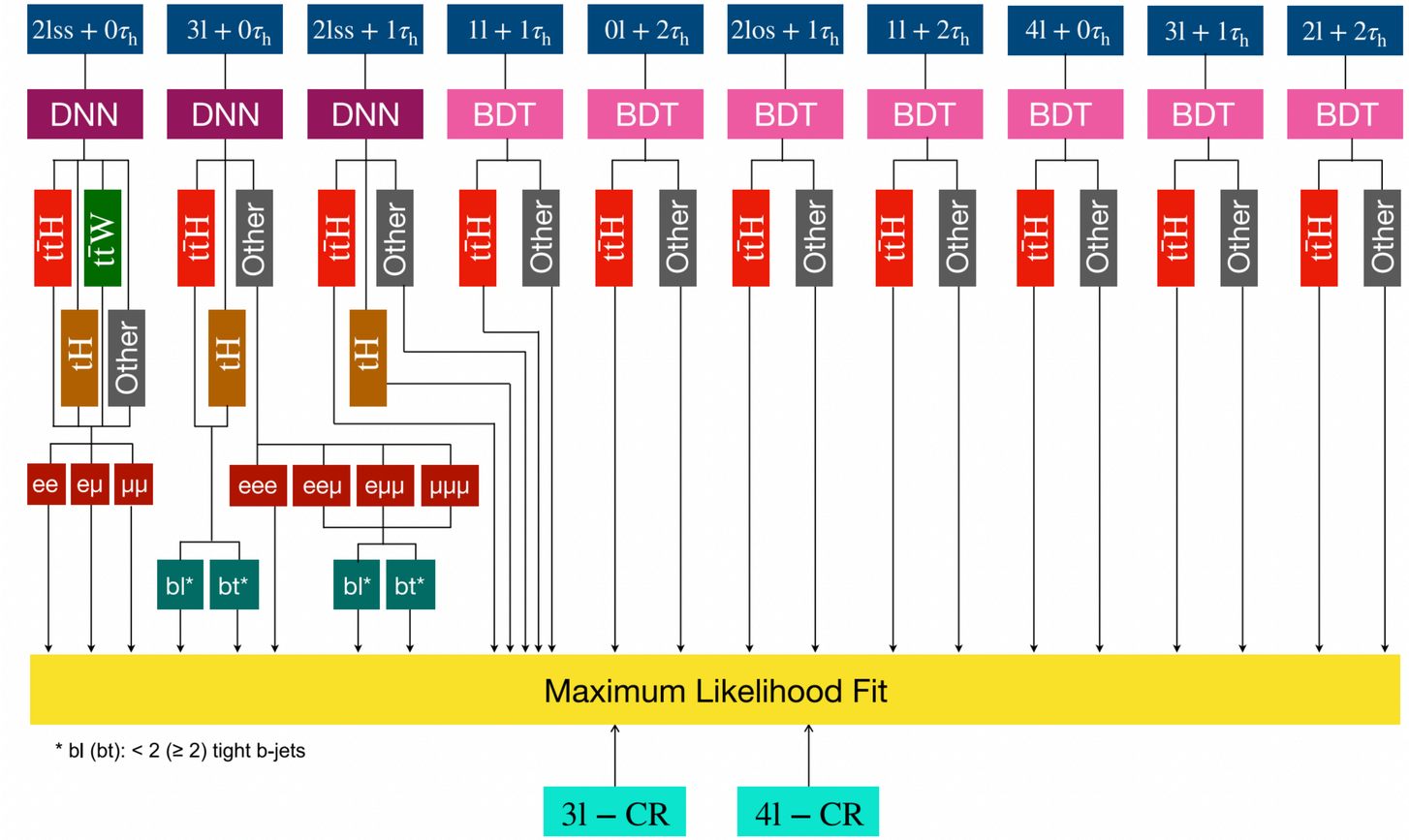
ATLAS

$$\mathcal{L} = -\frac{\sqrt{2}m_t}{v}(\bar{\psi}_t\kappa_t\,(\cos(\alpha) + i\sin(\alpha)\gamma_5)\,\psi_t)H$$

CMS		ATLAS
κ_t	$\Leftrightarrow$	$\kappa_t\cos\alpha$
$\tilde{\kappa}_t$	$\Leftrightarrow$	$\kappa_t\sin\alpha$
$\kappa_t > 0$	$\Rightarrow$	$-90° < \alpha < 90°$
$\lvert f_{CP}^{Htt}\rvert = \frac{\lvert\tilde{\kappa}_t\rvert^2}{\lvert\tilde{\kappa}_t\rvert^2+\lvert\kappa_t\rvert^2}$	$\Leftrightarrow$	$\sin^2\alpha$
μ_{ttH}	$\Leftrightarrow$	κ_t^2

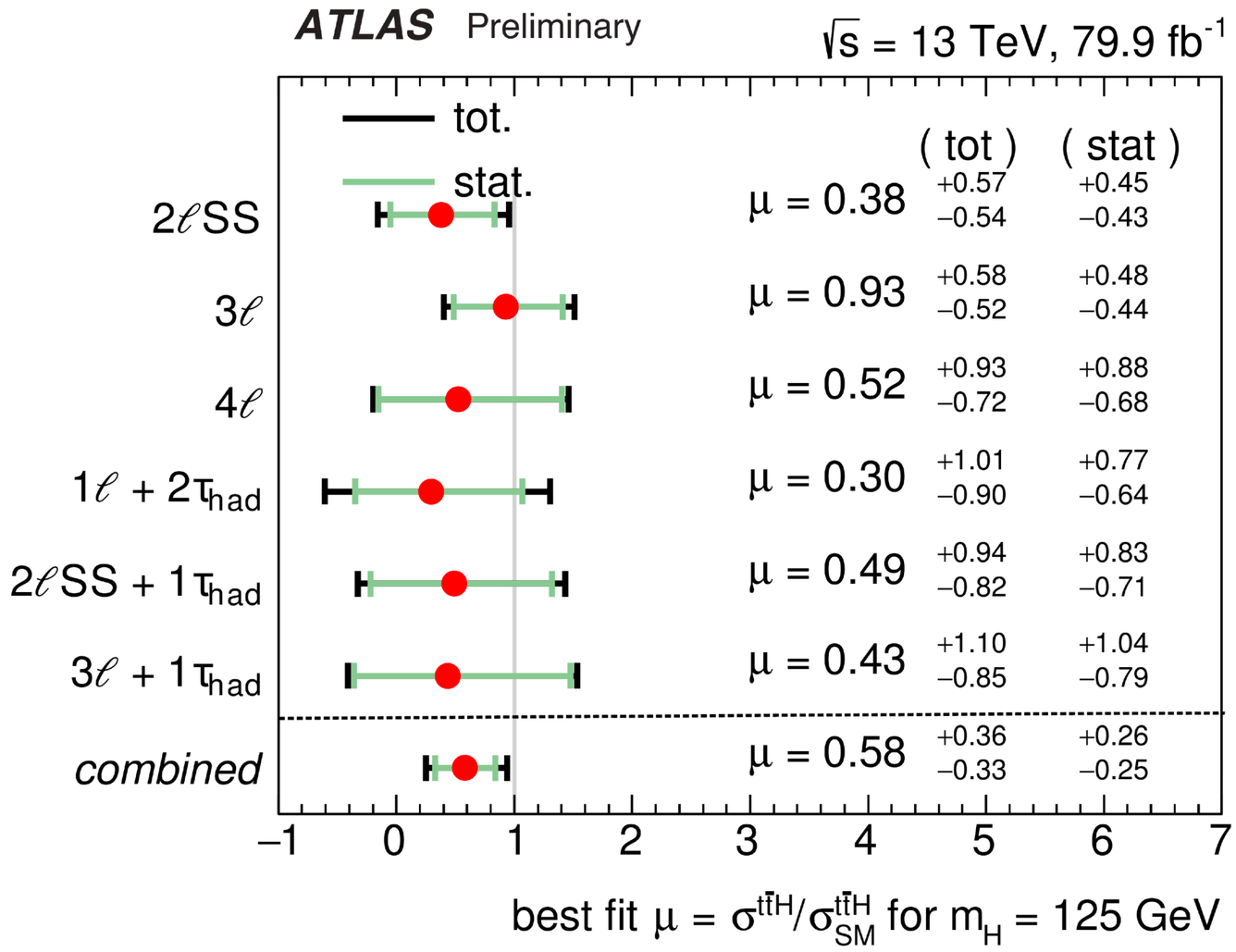
CMS ttH→multi-leptons

- ttH and tH production in e, μ, τ_{had} final state: Eur. Phys. J. C 81 (2021) 378
  - Nice that so much is combined into a single coherent analysis:
    - ttH, tH, ttW, ttZ and correlations
    - Kappa framework
  - Complex categorisation strategy

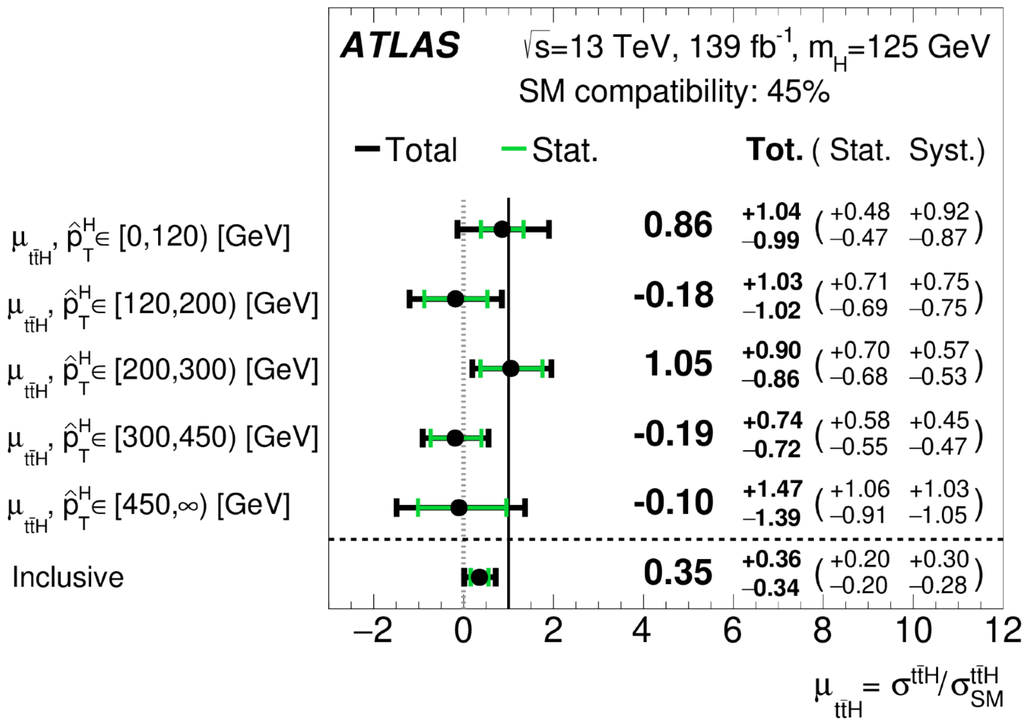


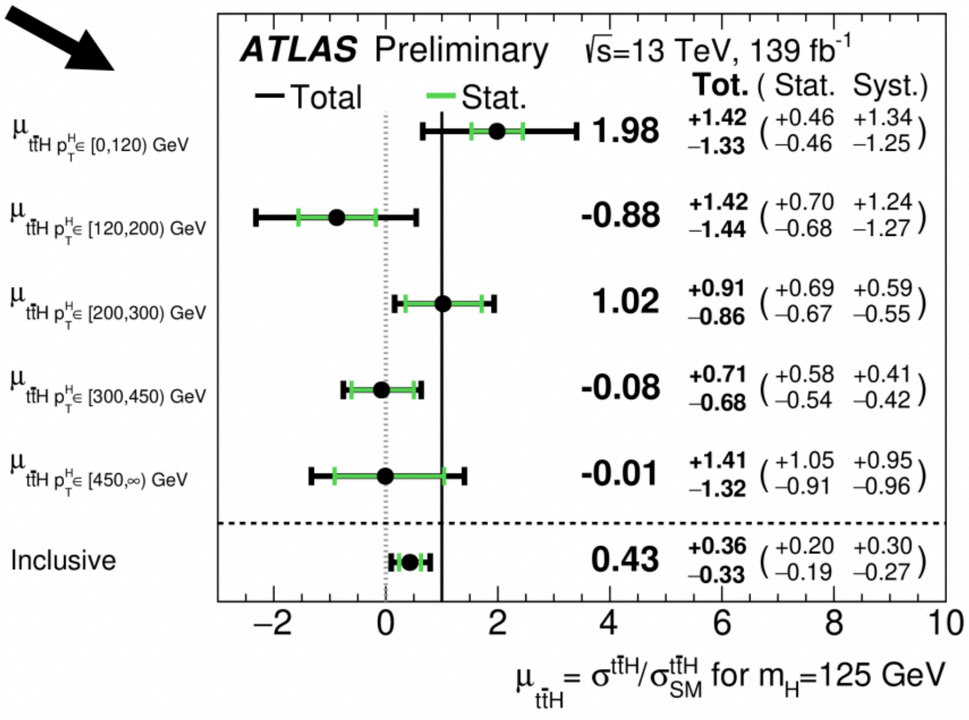
ATLAS ttH→multi-leptons

- ATLAS ttHML CONF note (80 fb^{-1}): ATLAS-CONF-2019-045
  - Observed significant mismodelling attributed to ttW background
    - Need ttW+2j for 2LSS region
  - Very important for overall sensitivity



ATLAS ttHbb


ATLAS √s=13 TeV, 139 fb-1, mH=125 GeV
SM compatibility: 45%
Total
Stat.
Tot. (Stat. Syst.)
μttH, p̂TH∈ [0,120) [GeV]
0.86 +1.04 −0.99 (+0.48 −0.47 +0.92 −0.87)
μttH, p̂TH∈ [120,200) [GeV]
-0.18 +1.03 −1.02 (+0.71 −0.69 +0.75 −0.75)
μttH, p̂TH∈ [200,300) [GeV]
1.05 +0.90 −0.86 (+0.70 −0.68 +0.57 −0.53)
μttH, p̂TH∈ [300,450) [GeV]
-0.19 +0.74 −0.72 (+0.58 −0.55 +0.45 −0.47)
μttH, p̂TH∈ [450,∞) [GeV]
-0.10 +1.47 −1.39 (+1.06 −0.91 +1.03 −1.05)
Inclusive
0.35 +0.36 −0.34 (+0.20 −0.20 +0.30 −0.28)
−2 0 2 4 6 8 10 12
μttH = σttH/σttHSM


ATLAS Preliminary √s=13 TeV, 139 fb-1
Total
Stat.
Tot. (Stat. Syst.)
μttH pTH∈ [0,120) GeV
1.98 +1.42 −1.33 (+0.46 −0.46 +1.34 −1.25)
μttH pTH∈ [120,200) GeV
-0.88 +1.42 −1.44 (+0.70 −0.68 +1.24 −1.27)
μttH pTH∈ [200,300) GeV
1.02 +0.91 −0.86 (+0.69 −0.67 +0.59 −0.55)
μttH pTH∈ [300,450) GeV
-0.08 +0.71 −0.68 (+0.58 −0.54 +0.41 −0.42)
μttH pTH∈ [450,∞) GeV
-0.01 +1.41 −1.32 (+1.05 −0.91 +0.95 −0.96)
Inclusive
0.43 +0.36 −0.33 (+0.20 −0.19 +0.30 −0.27)
−2 0 2 4 6 8 10
μttH = σttH/σttHSM for mH=125 GeV

ATLAS ttH combination

- https://atlas.web.cern.ch/Atlas/GROUPS/P[illegible]S-CONF-2021-053/