Top Yukawa

ttH and tH

$\gamma\gamma$ and bb

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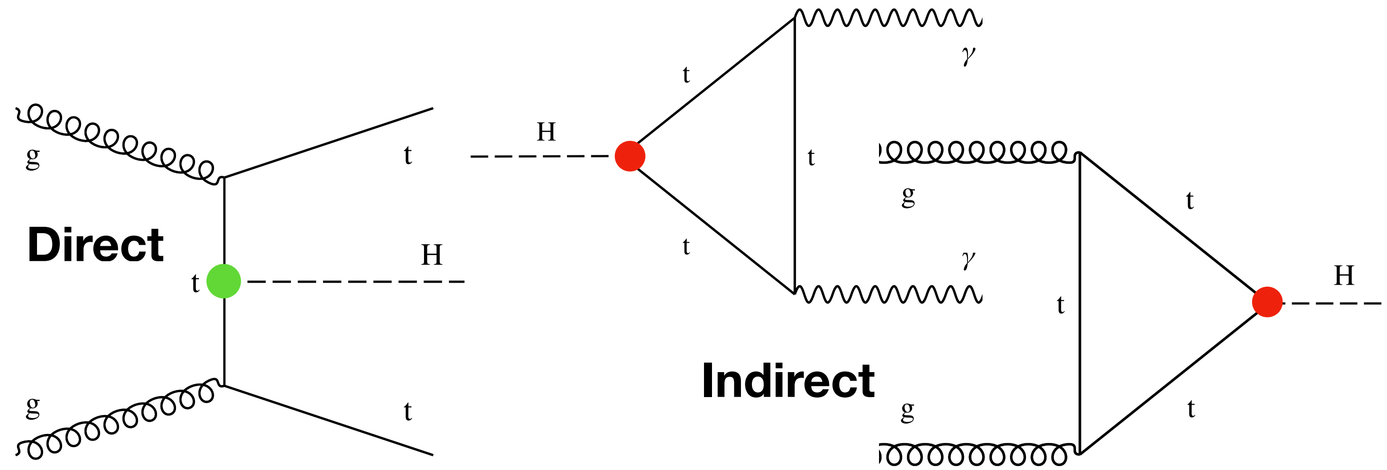
On behalf of the ATLAS and CMS Collaborations

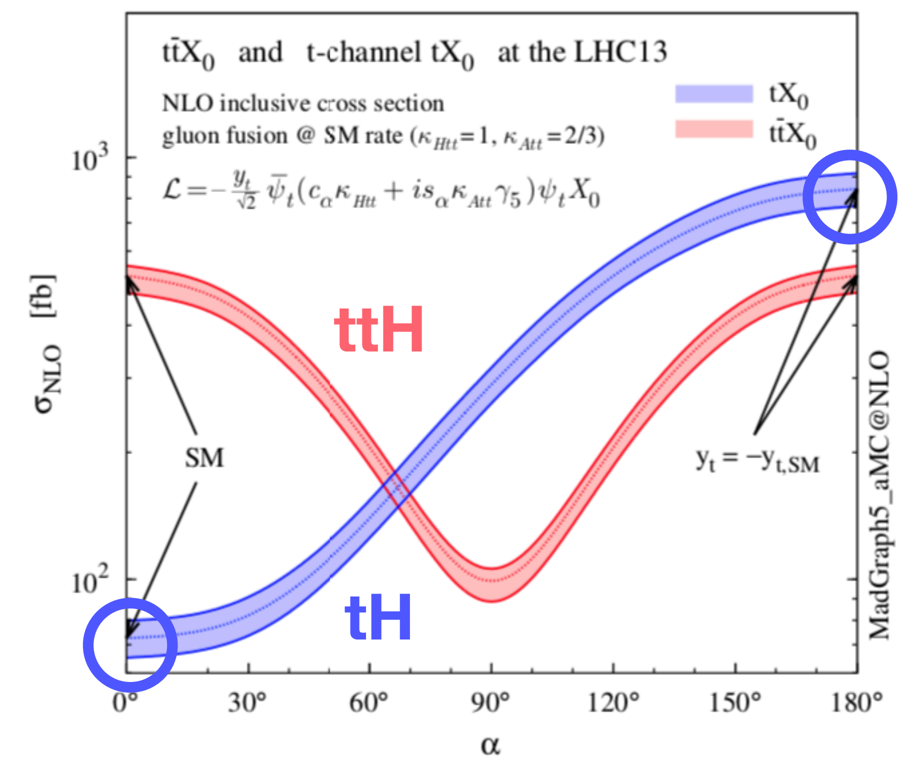
Higgs Coupling 2020

29th October 2020

Exploring the Top Yukawa coupling

- The Yukawa couplings are proportional to fermion masses
  - Leads to Top Yukawa coupling being the most "natural" : O(1)
  - But also leads to large correction terms to the Higgs mass
- Can be sensitive to BSM effects which can be explored through differential measurements (STXS) and EFT interpretations
- ttH not sensitive to sign of Y_t
- Due to interference between W and top couplings, tH *is* sensitive
- The CP properties of the Higgs-Top Yukawa coupling can be probed in ttH and tH production





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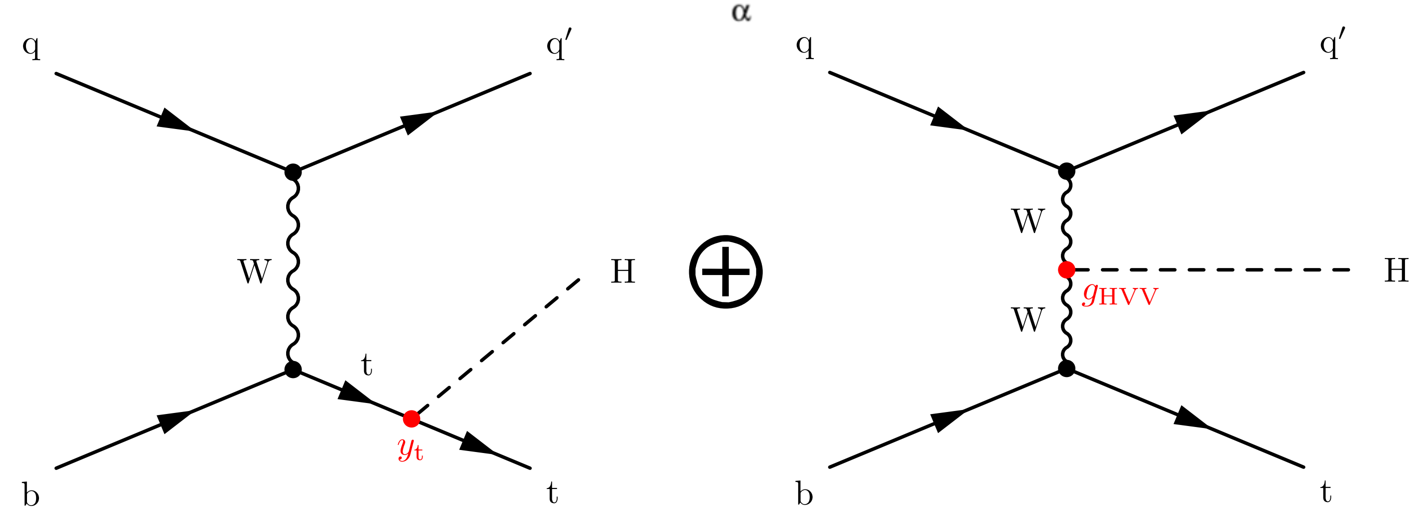


Top-associated Higgs production measurements

Channel		ATLAS				CMS			
ttH	$\gamma\gamma$	PRL 125 (2020) 061802	139	σ	α_{CP}	PRL 125 (2020) 061801	137	σ	f_{CP}
		ATLAS-CONF-2020-026	139	STXS		CMS-PAS-HIG-19-015	137	STXS	
		ATLAS-CONF-2019-004	139	σ					
	bb	ATLAS-CONF-2020-058	139	STXS		CMS-PAS-HIG-18-030	77.4	σ	
tH	$\gamma\gamma$	PRL 125 (2020) 061802	139	σ	α_{CP}	PRD 99 (2019) 092005	35.9	σ	κ_t
						CMS-PAS-HIG-19-015	137	σ	
	bb					PRD 99 (2019) 092005	35.9	σ	κ_t

For more details on STXS measurements by ATLAS+CMS, see D. Mungo talk

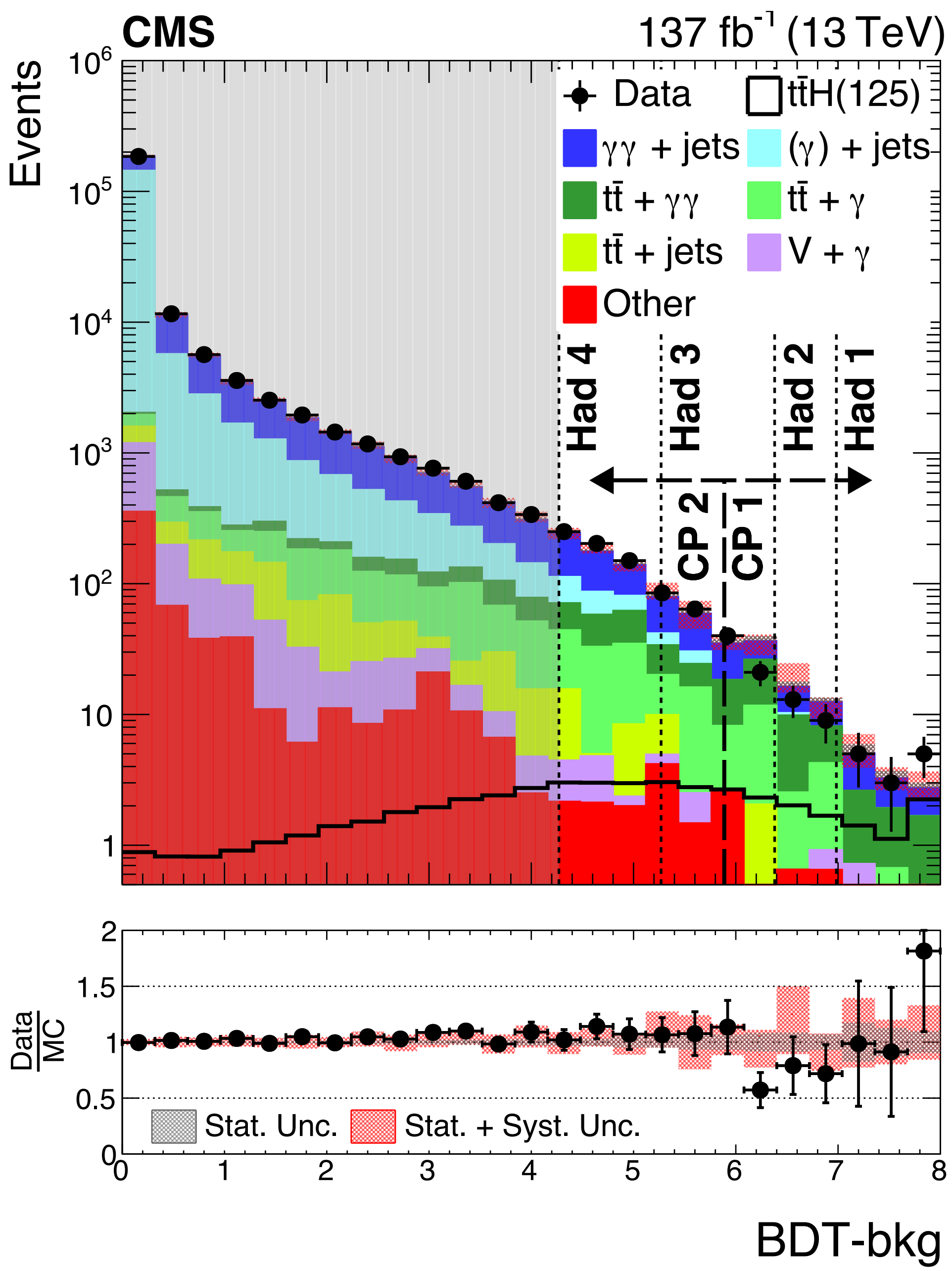
CMS ttH $\gamma\gamma$

PRL 125 061801

137 fb^{-1}

- Measurement of ttH($\gamma\gamma$)
  - Categorised using hadronic and leptonic top decays
  - CP measurement of Htt coupling
- Photon properties in MC such as shower shape and isolation variables are corrected with a BDT regression method to improve the photon ID BDT discriminant modelling
- Diphoton + jet selection (17,18/16):
  - Leading p_T > 35/25 GeV
  - Subleading p_T > 30/20 GeV
  - 100 ≤ m($\gamma\gamma$) ≤ 180 GeV
  - At least one jet pT > 25 GeV
- Loose top decay categorisation
  - Lep : e (μ) pT > 10 (5) GeV
  - Had : At least 1 b-tagged jet, at least 3 jets

- BDT used to discriminate signal and background



CMS ttH $\gamma\gamma$

PRL 125 061801 | 137 fb^{-1}

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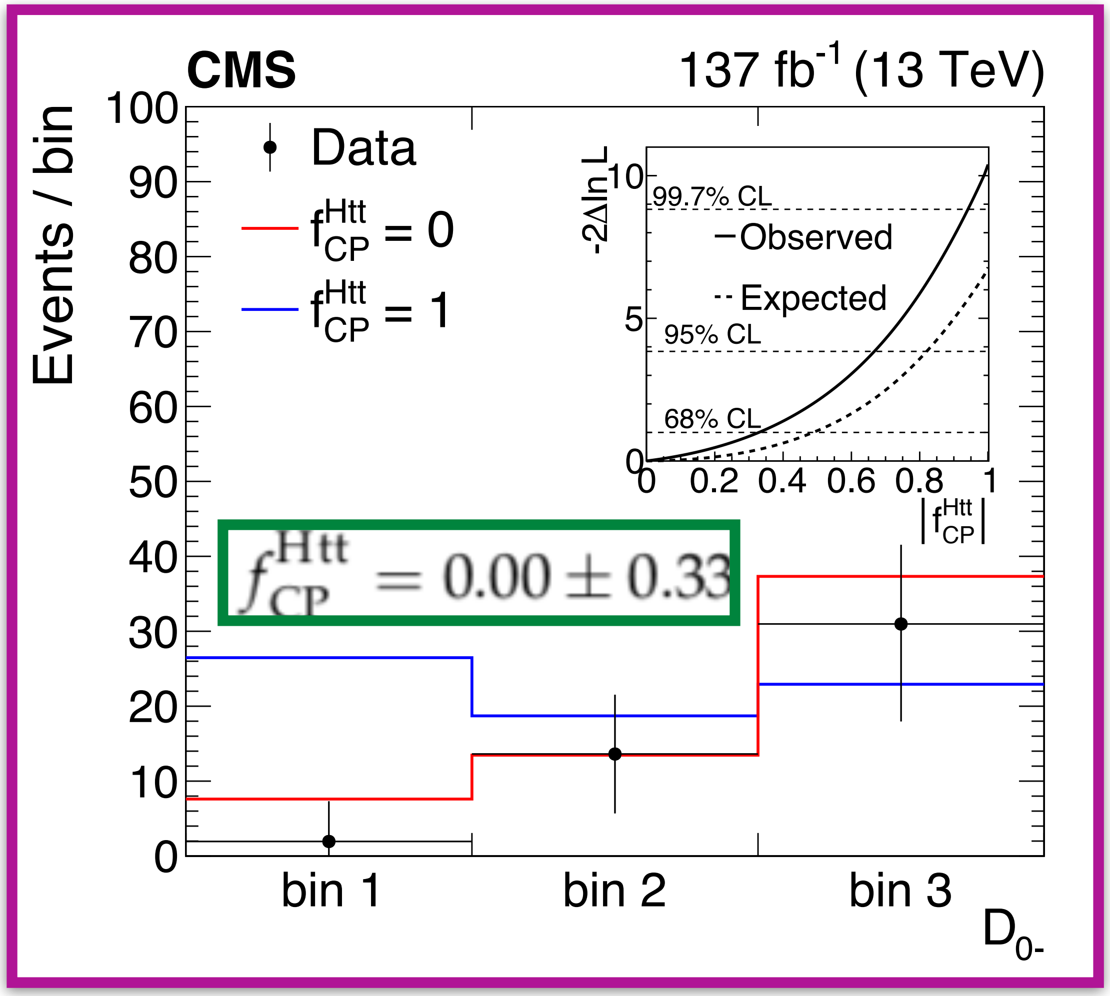
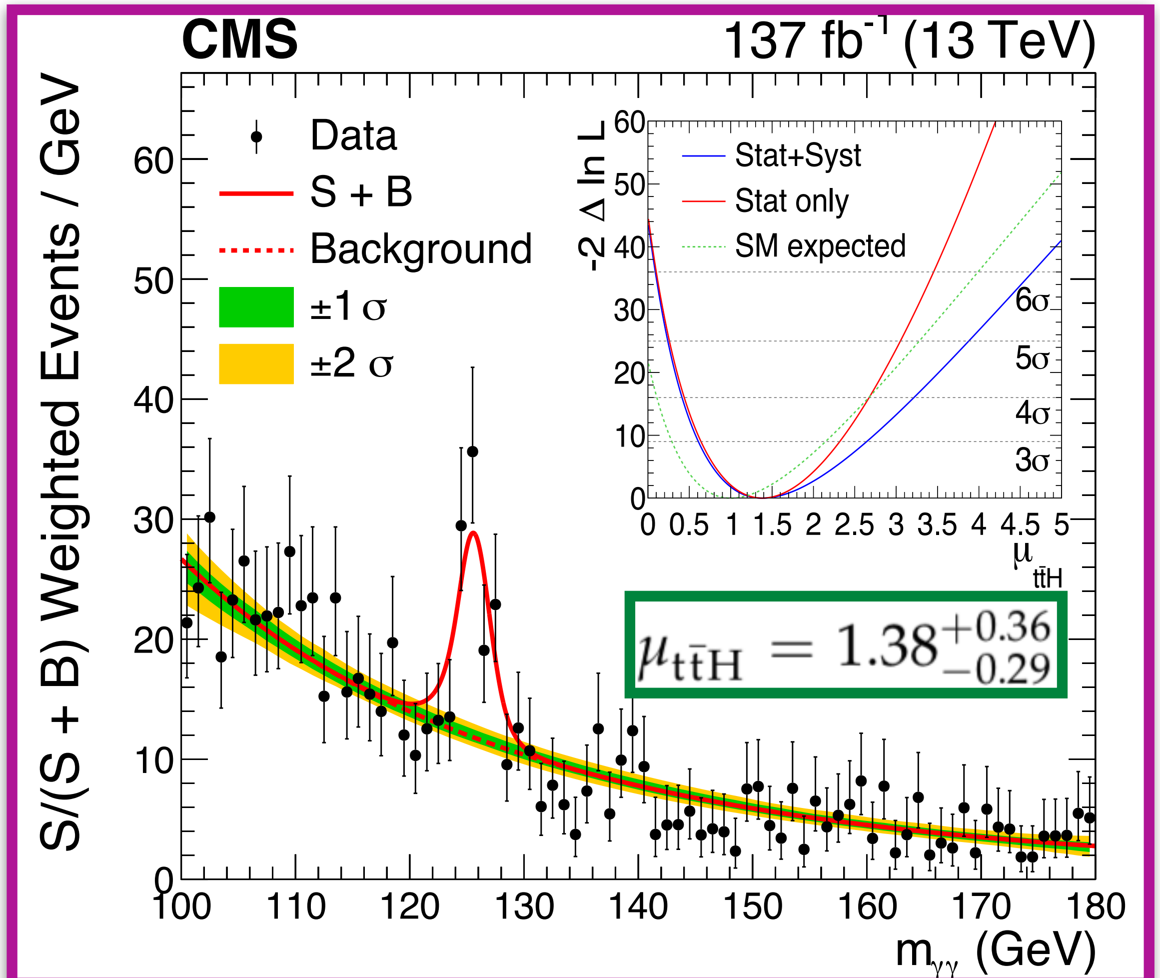
- Profiled-likelihood fit to m($\gamma\gamma$) distributions
- Inclusive cross-section uses 8 regions
- Expected significance : **4.7σ**
- Observed significance : **6.6σ**





- D_{0-} is built using BDT trained to discriminate between CP-even and CP-odd signals
  - Each CP region contributes three bins
- f_{CP} is measured as the absolute fraction of CP states
  - **Exclude f_{CP} > 0.67 at 95%**
  - Pure CP-odd excluded: **3.2σ**

CMS tH ($\gamma\gamma$ + bb)

PRD 99 092005

35.9 fb^{-1}

University of Glasgow

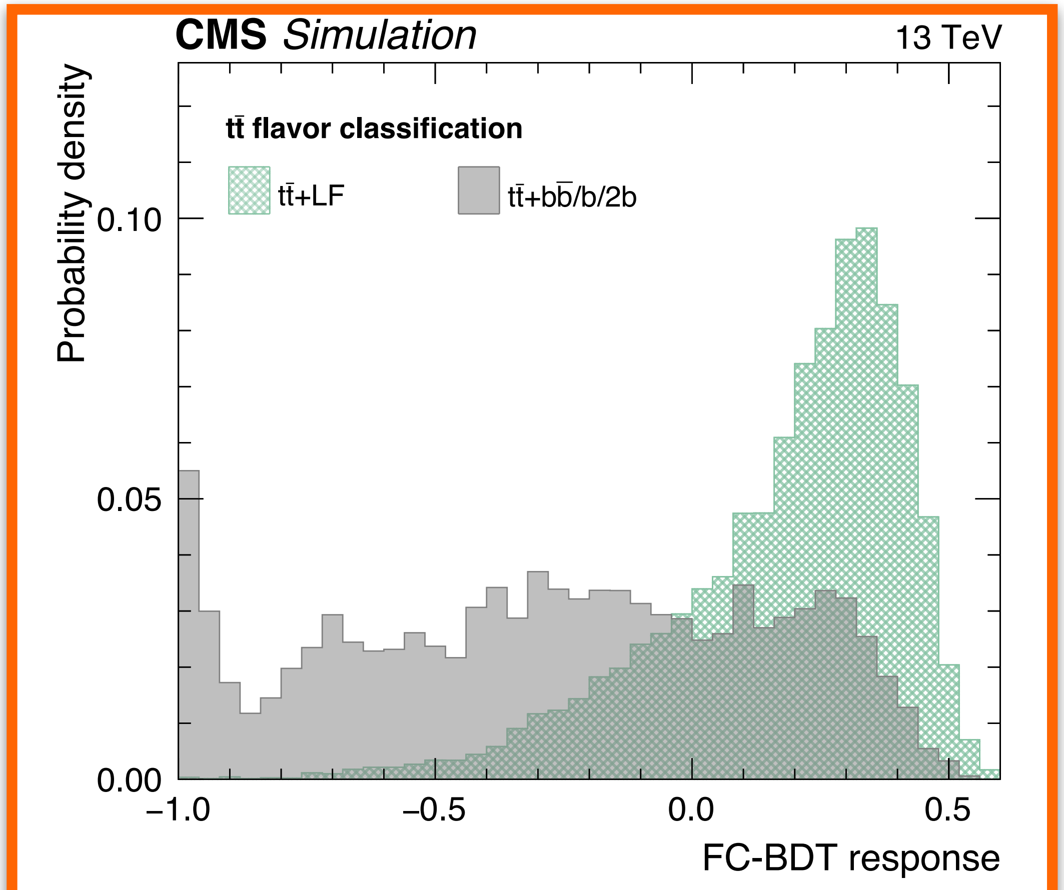
- Combination of multi-lepton (H→WW, ZZ, $\tau\tau$) and single-lepton (H→bb) final-states with a reinterpretation of ttH($\gamma\gamma$)
- The kappa framework is applied to examine hypotheses of $-6.0 \leq \kappa_t \leq 6.0$, with $\kappa_V = 1.0$

$$\sigma_{\mathrm{tHq}} = (2.63\,\kappa_t^2 + 3.58\,\kappa_V^2 - 5.21\,\kappa_t\kappa_V)\sigma^{\mathrm{SM}}_{\mathrm{tHq}},$$
$$\sigma_{\mathrm{tHW}} = (2.91\,\kappa_t^2 + 2.31\,\kappa_V^2 - 4.22\,\kappa_t\kappa_V)\sigma^{\mathrm{SM}}_{\mathrm{tHW}}.$$

- tH(bb) analysis expects three or four central b-tagged jets and at least one additional light jet (central or forward)
- Missing-ET requirements suppress QCD multi-jet events

	p_T	η
Muon (Electron)	27 (35)	2.4 (2.1)
Central-Jet	30	2.4
Forward-Jet	40	2.4 - 4.7

- Dilepton control region defined to constrain tt+jets events with at least three b-tagged jets



CMS tH ($\gamma\gamma$ + bb)

PRD 99 092005

35.9 fb^{-1}

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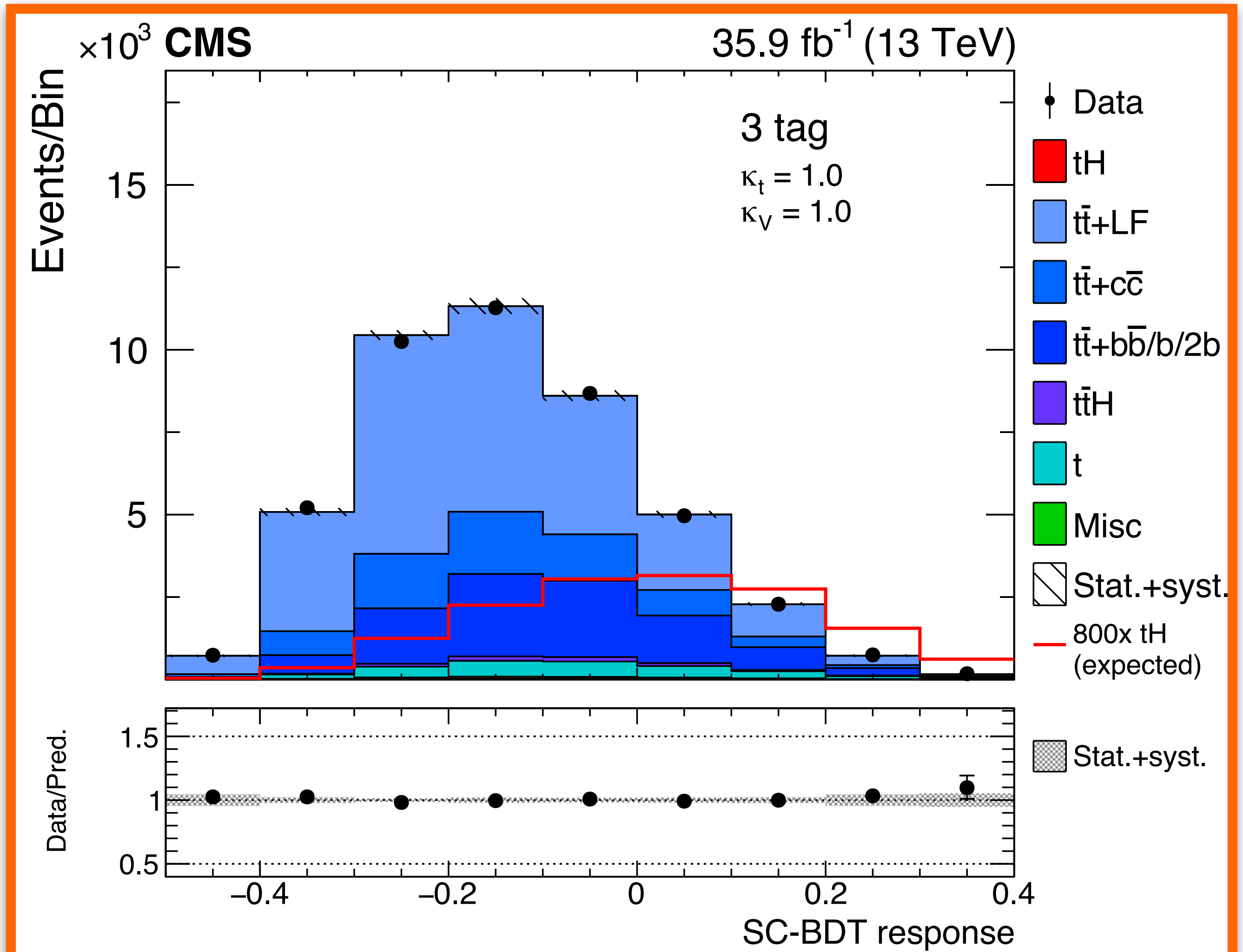
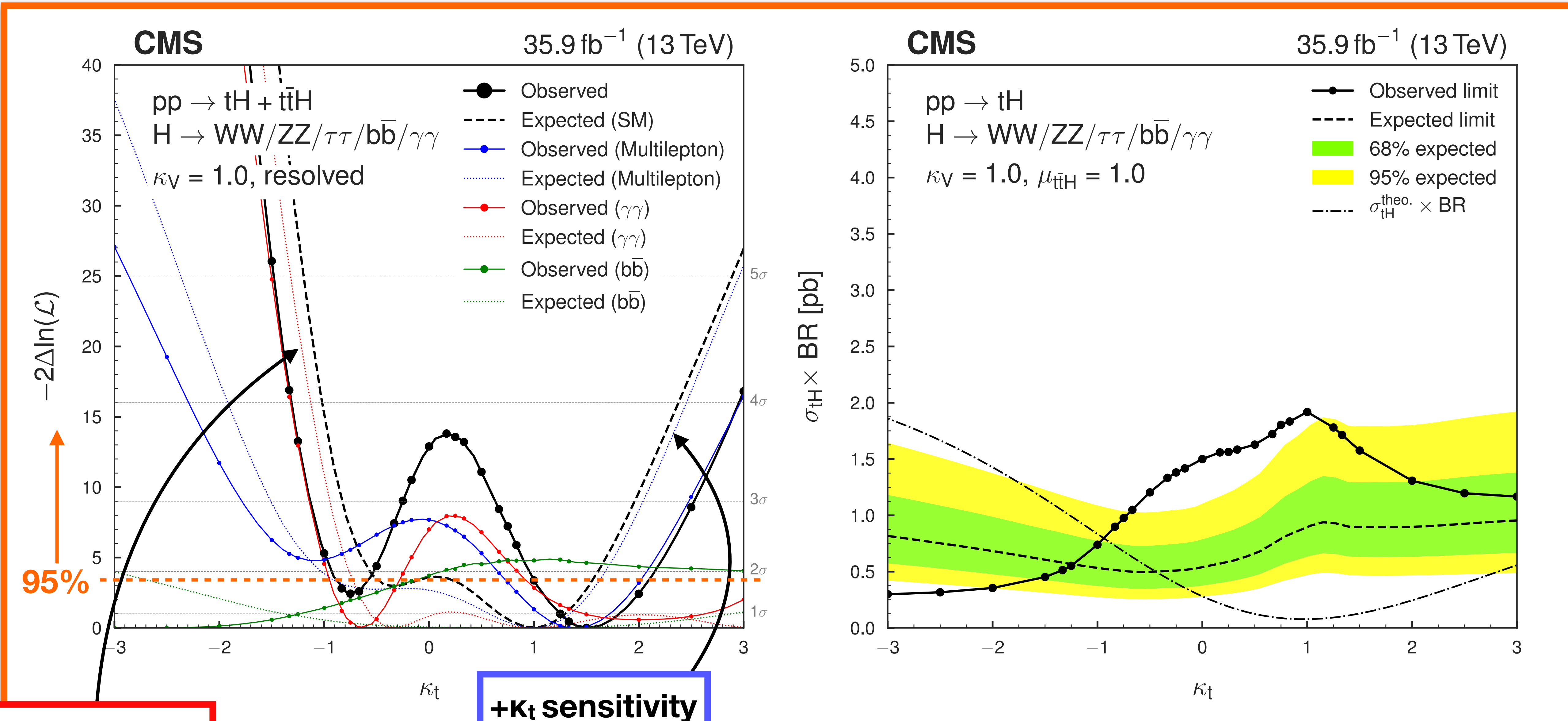
- Signal extraction is performed with multiple MVAs
- *Jet-to-Parton-Assignment-BDT*
  - Three assignment hypotheses : tHq, tHW, tt+jets
  - Highest BDT score is used for jet assignment
- *Signal-Classification-BDT*
  - Uses assignment-dependent and global variables
  - Trained to separate tH from tt+jets events
- Simultaneous profiled-likelihood fit performed using SC-BDT in signal regions and FC-BDT in control region
  - Dominant uncertainties from tH scale, tt+HF normalisation (50%) and jet energy corrections

Reconstruction efficiency

Events	tHq	tHW	tt+jets
3 tag	58%	38%	58%
4 tag	45%	29%	31%





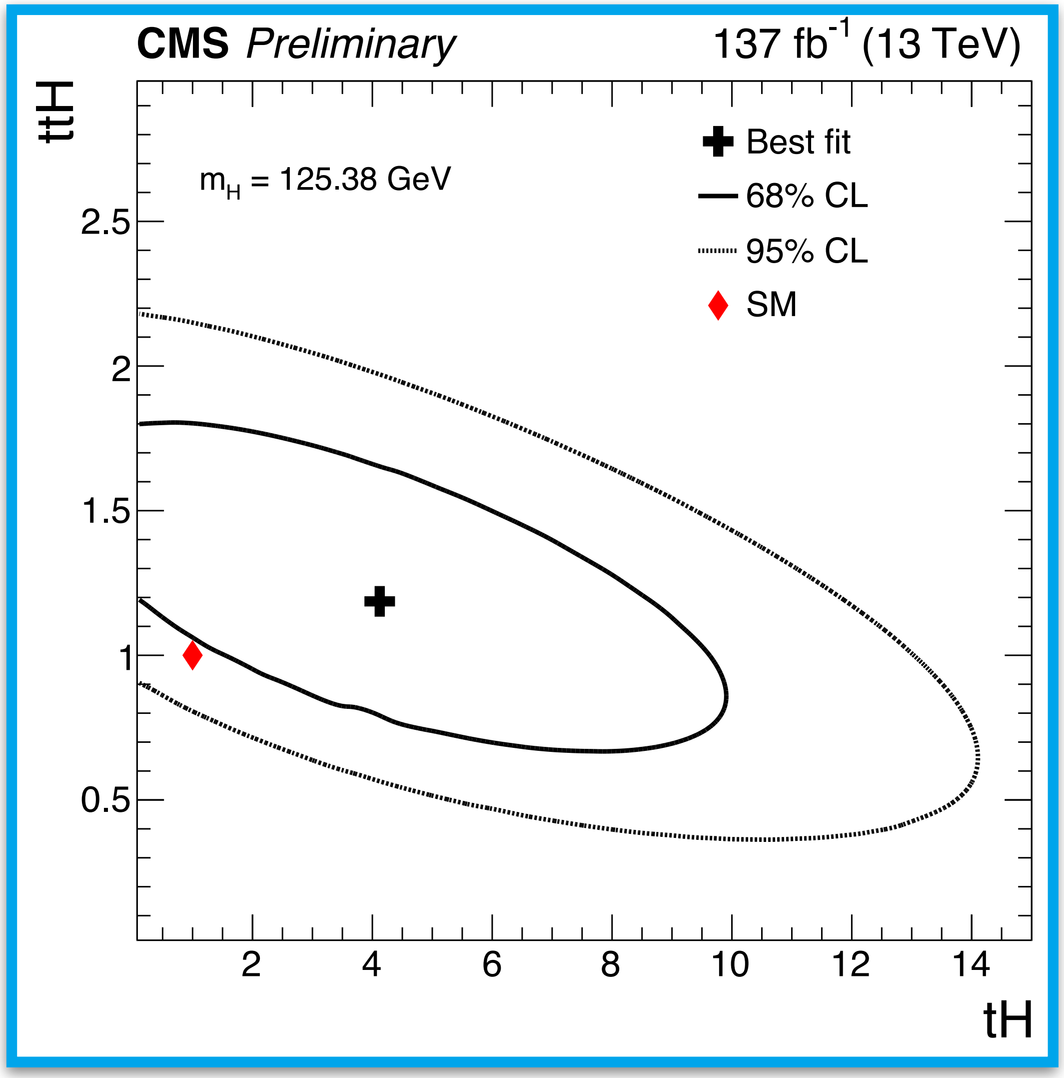
-κt sensitivity driven by $\gamma\gamma$

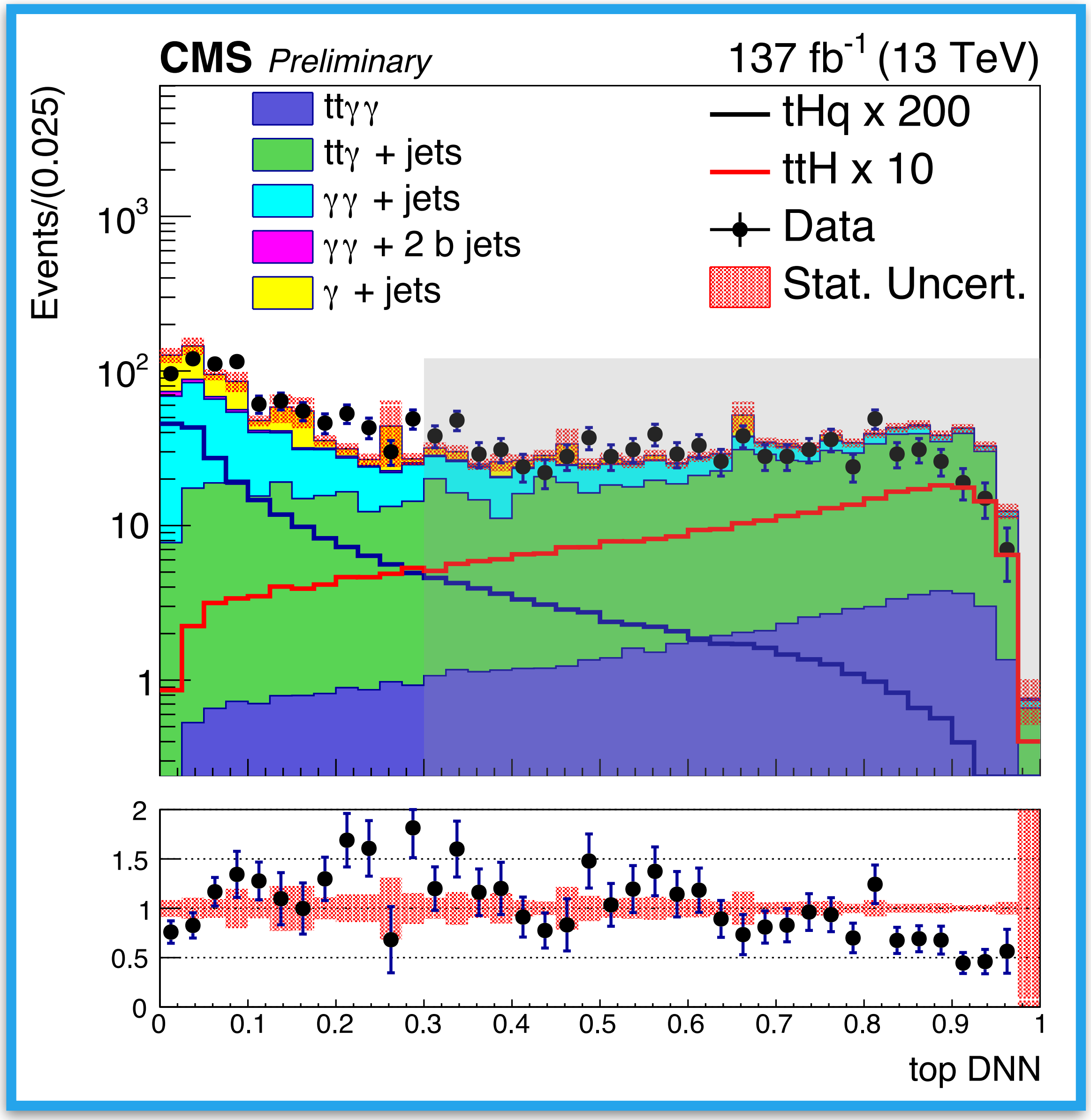
+κt sensitivity driven by ML

tHq and tHW inputs are taken from the ttH($\gamma\gamma$) analysis where the signal diphoton mass is found to be independent of κ_t/κ_V

- Exclude at 95% :
  $\kappa_t < -0.9$, $-0.5 < \kappa_t < 1.0$, $\kappa_t > 2.1$
- Limit on tH (95%) : **25 x SM**

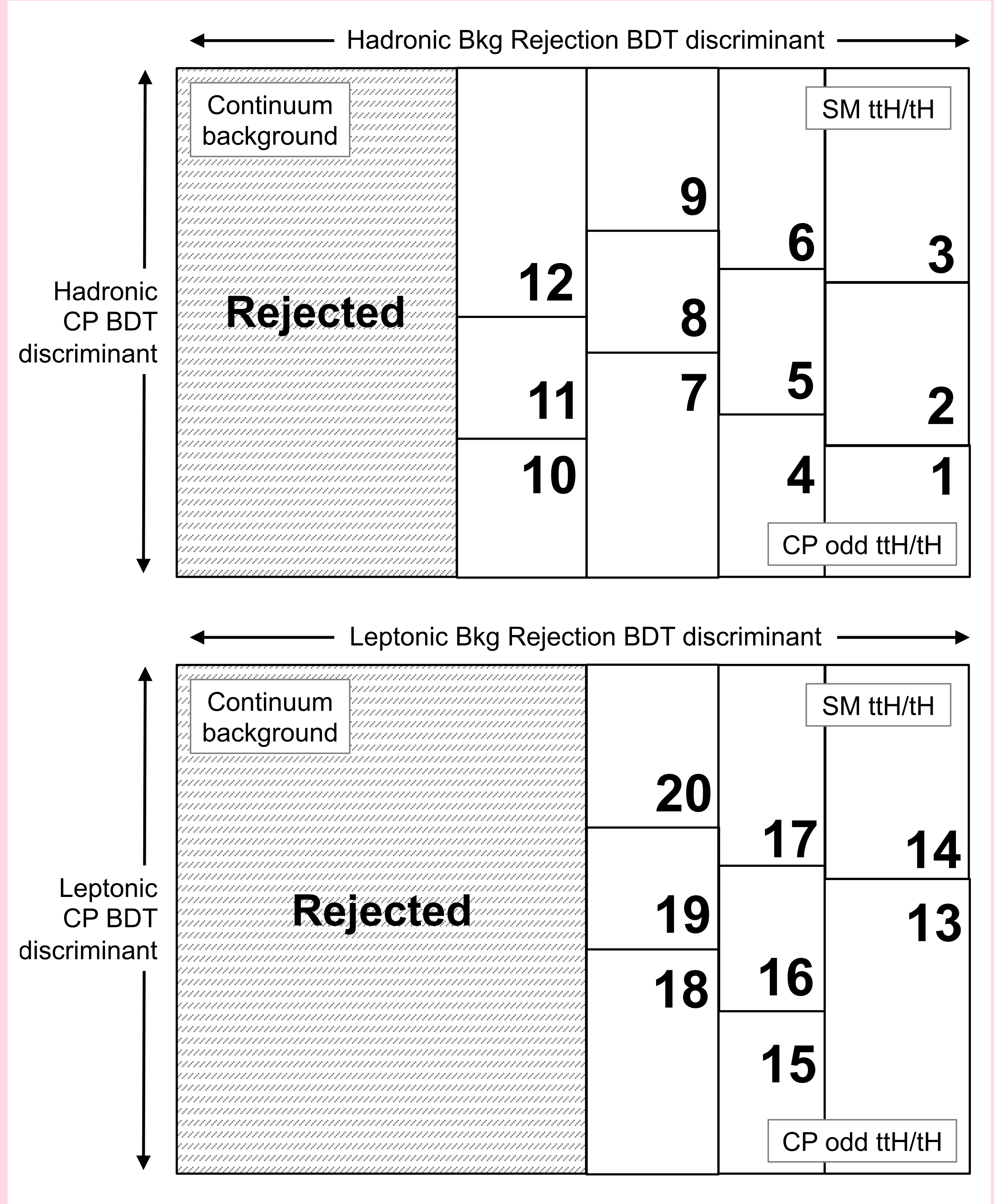
- Combined STXS measurement of all Higgs production modes has been performed
  - ttH strategy updated to target STXS p_T bins
  - ttH channel: 4 bins, tH channel: 1 bin



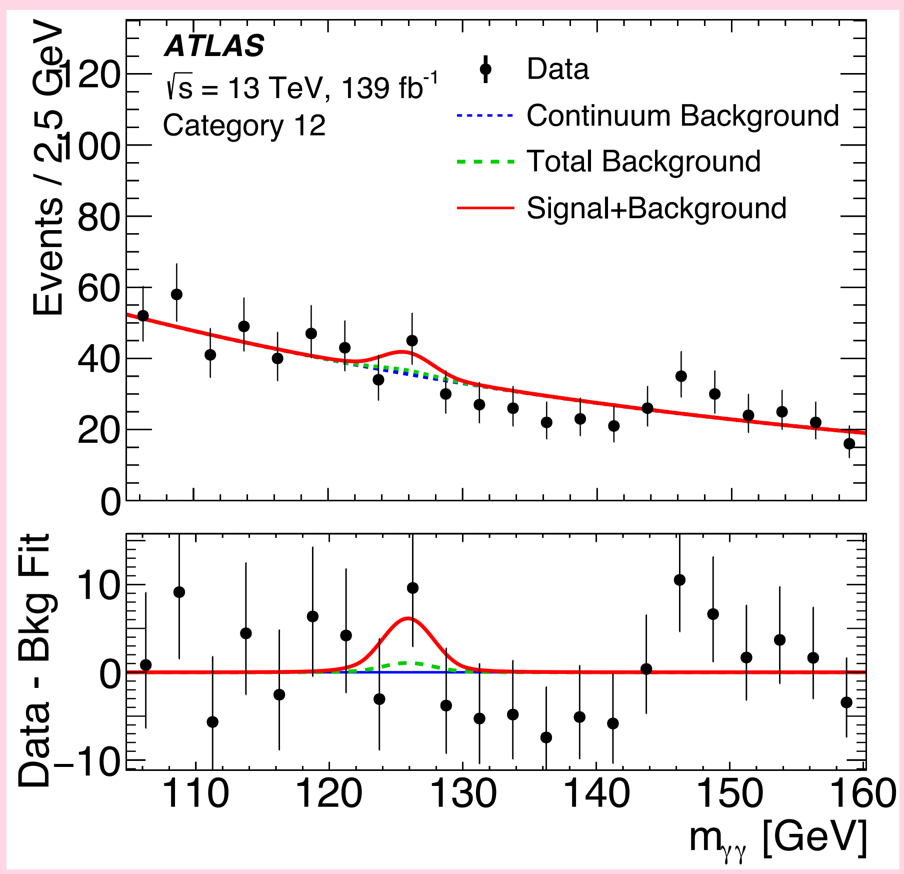


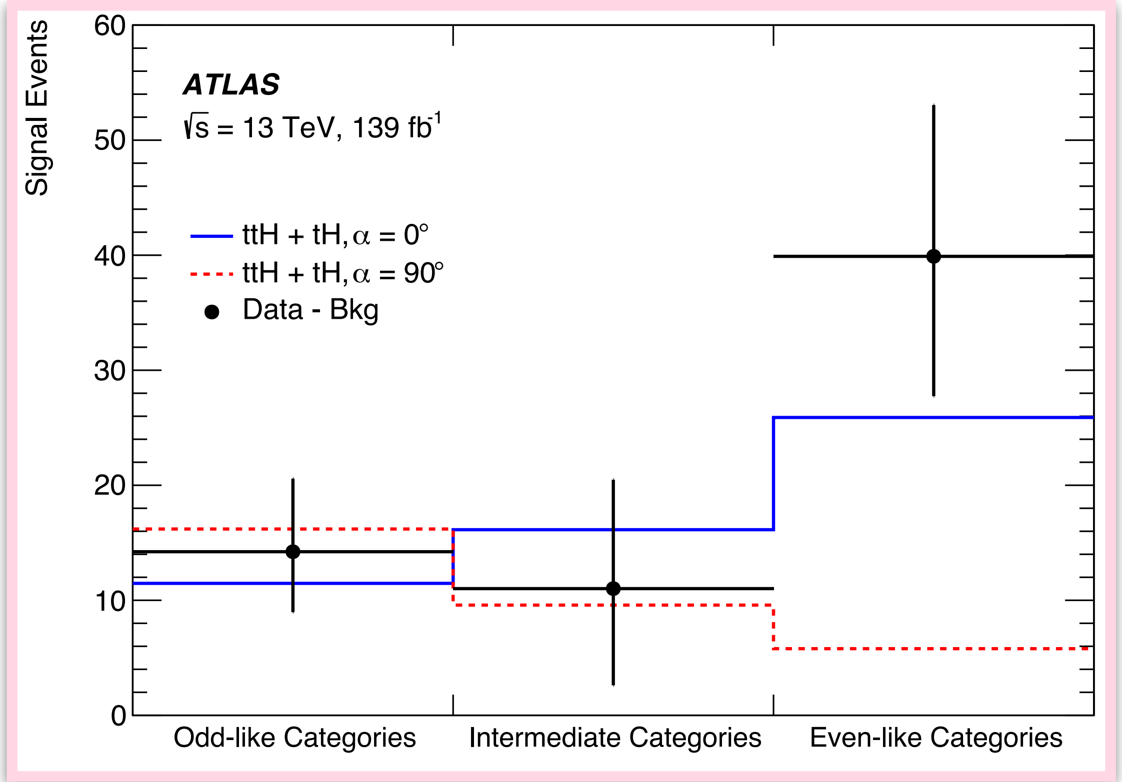
- The tH sensitivity is improved through using DNN to separate ttH and tHq
- Precision improved through combination
  - Expected limit : **9 x SM**
  - Limit on tH (95%) : **12 x SM**

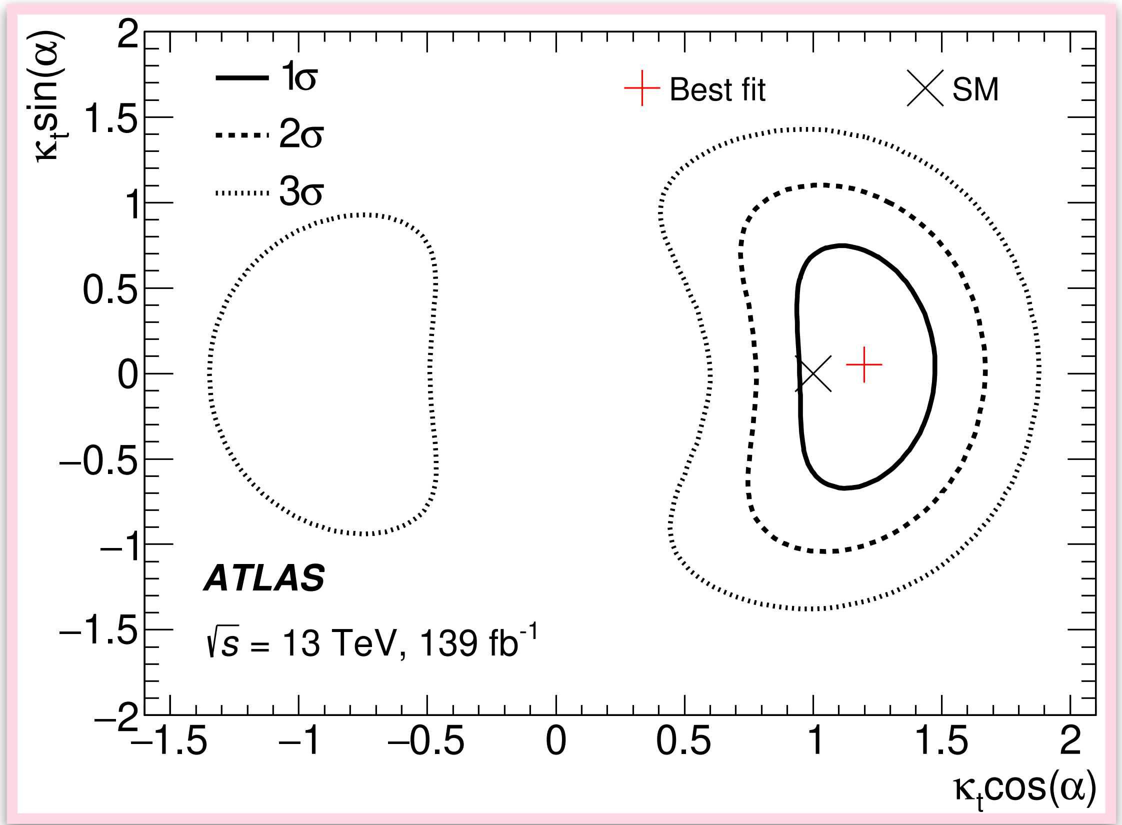
- Combined search for $H\rightarrow\gamma\gamma$ in tH and ttH production modes
  - Analysis optimised for ttH sensitivity and CP measurement of Y_t
- Diphoton + b-jet selection
  - γ : pT > 35 GeV, pT > 25 GeV
  - 105 ≤ m($\gamma\gamma$) ≤ 160 GeV
  - At least one b-jet pT > 25 GeV
- Loose top decay categorisation
  - Lep : at least one lepton pT > 15 GeV
  - Had : at least two jets pT > 25 GeV
- BDT used for top-reconstruction
- BDT used for background rejection (resonant vs non-resonant) and CP discrimination



- Profiled-likelihood fit performed in diphoton mass in all 20 categories







- Expected significance : **4.4σ**
- Observed significance : **5.2σ**
- Limit on tH (95%) : **12 x SM**
- Pure CP-odd excluded : **3.9σ**
- **|α| > 43° excluded at 95%**

CMS ttH bb

CMS-PAS-HIG-18-030 | **77.4 fb^{-1}**

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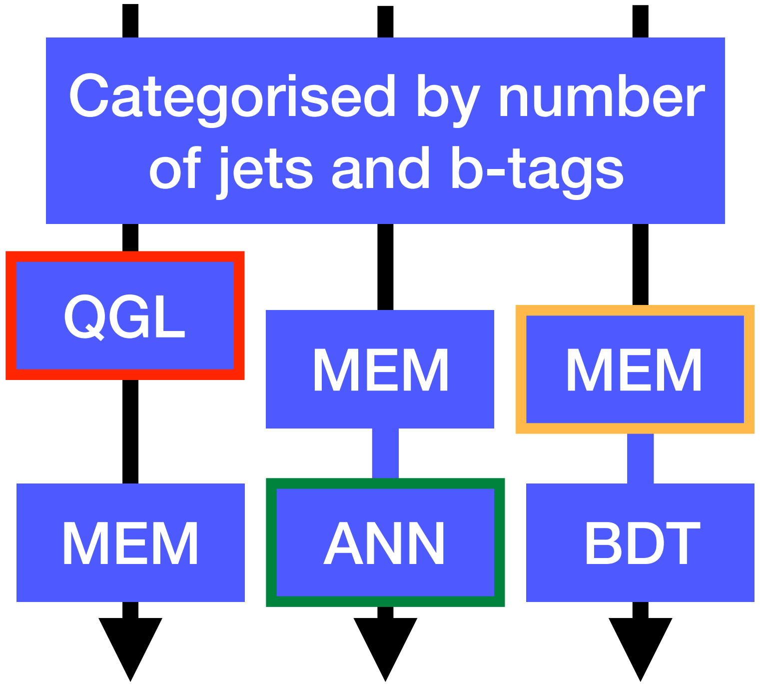
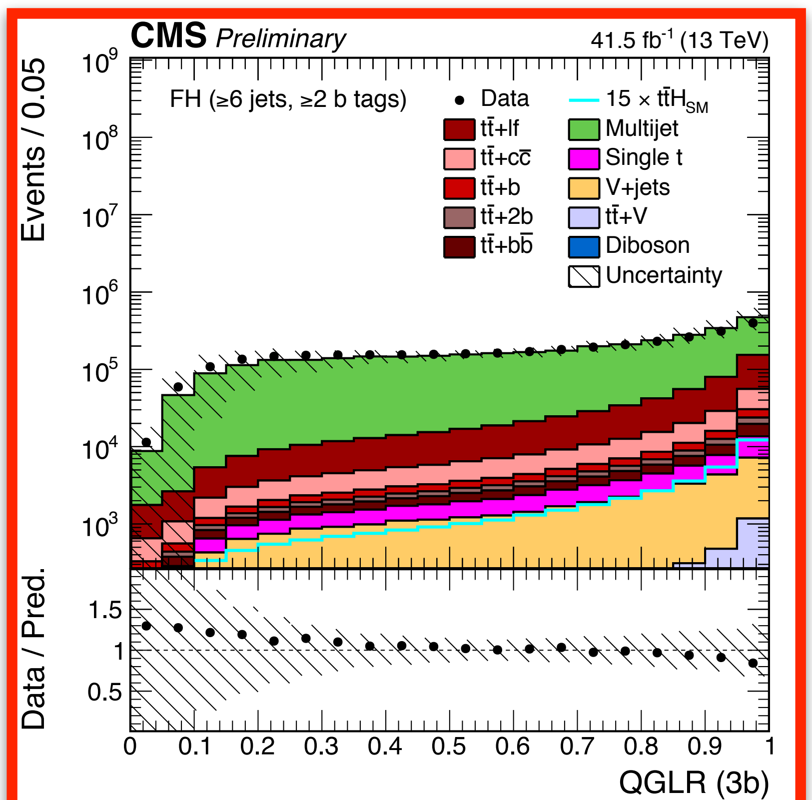
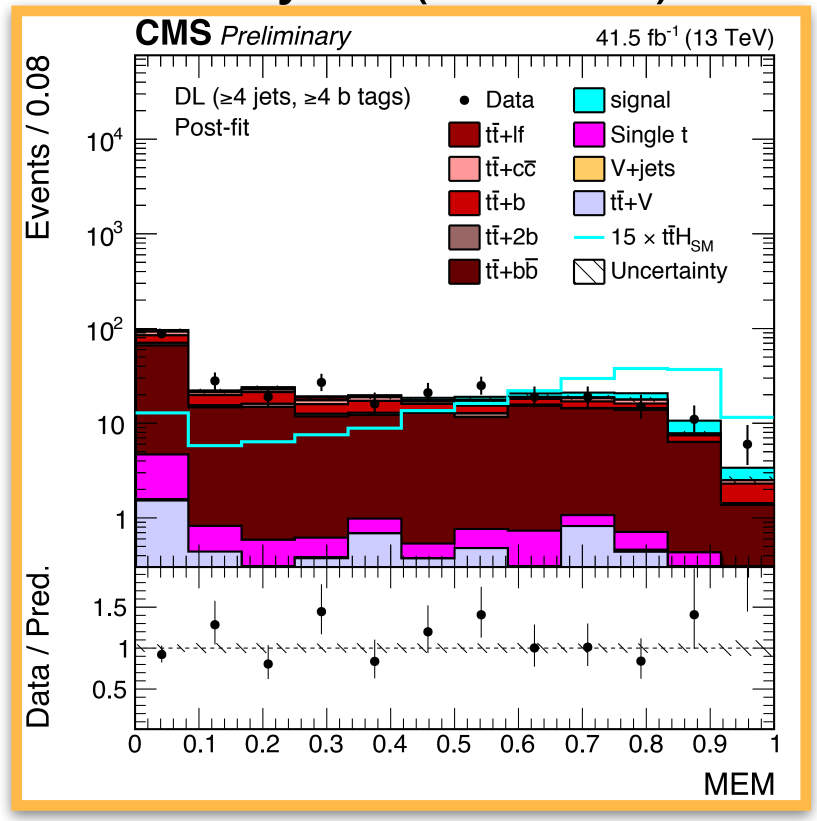
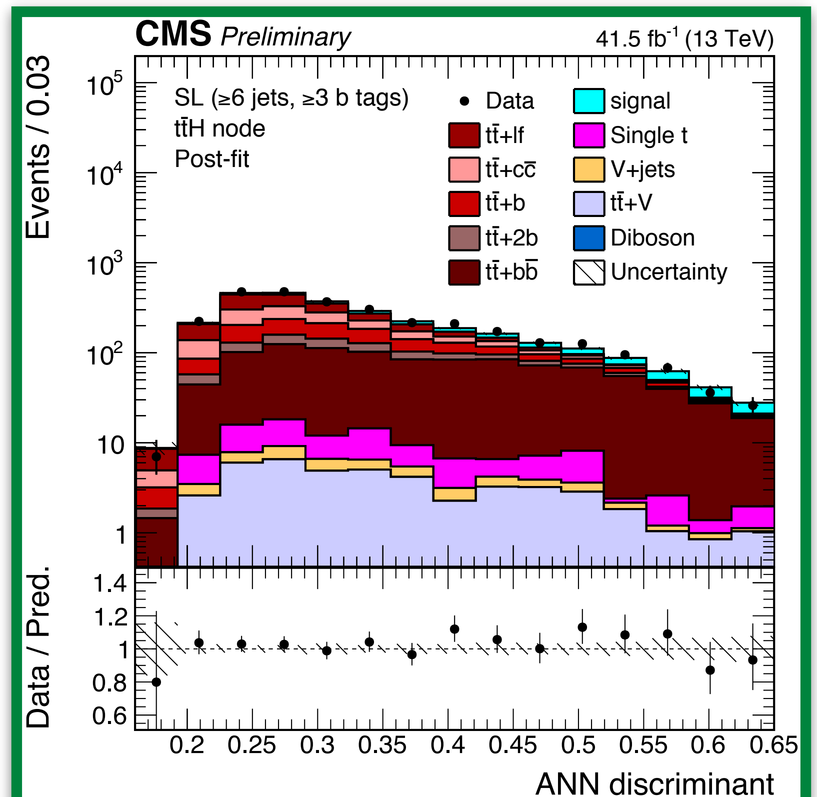
- Analysis uses 2017 data (41.5fb^{-1}) and combined with 2016 data analysis (35.9fb^{-1})
- All tt final states are used with various MVA techniques

	FH channel	SL channel	DL channel
Number of leptons	0	1	2
p_T of leptons (e/μ) [GeV]	—	$> 30/29$	$> 25/25$ GeV
p_T of additional leptons [GeV]	< 15	< 15	< 15
$\lvert\eta\rvert$ of leptons	< 2.4	< 2.4	< 2.4
Number of jets	≥ 6	≥ 4	≥ 2
p_T of jets [GeV]	> 40	> 30	$> 30, 30, 20$
$\lvert\eta\rvert$ of jets	< 2.4	< 2.4	< 2.4
Number of b-tagged jets	≥ 2	≥ 2	≥ 1
p_T^{miss}	—	> 20 GeV	> 40 GeV









ANN is trained to classify events into ttH or 5 tt+jets categories

CMS ttH bb

CMS-PAS-HIG-18-030

77.4 fb^{-1}

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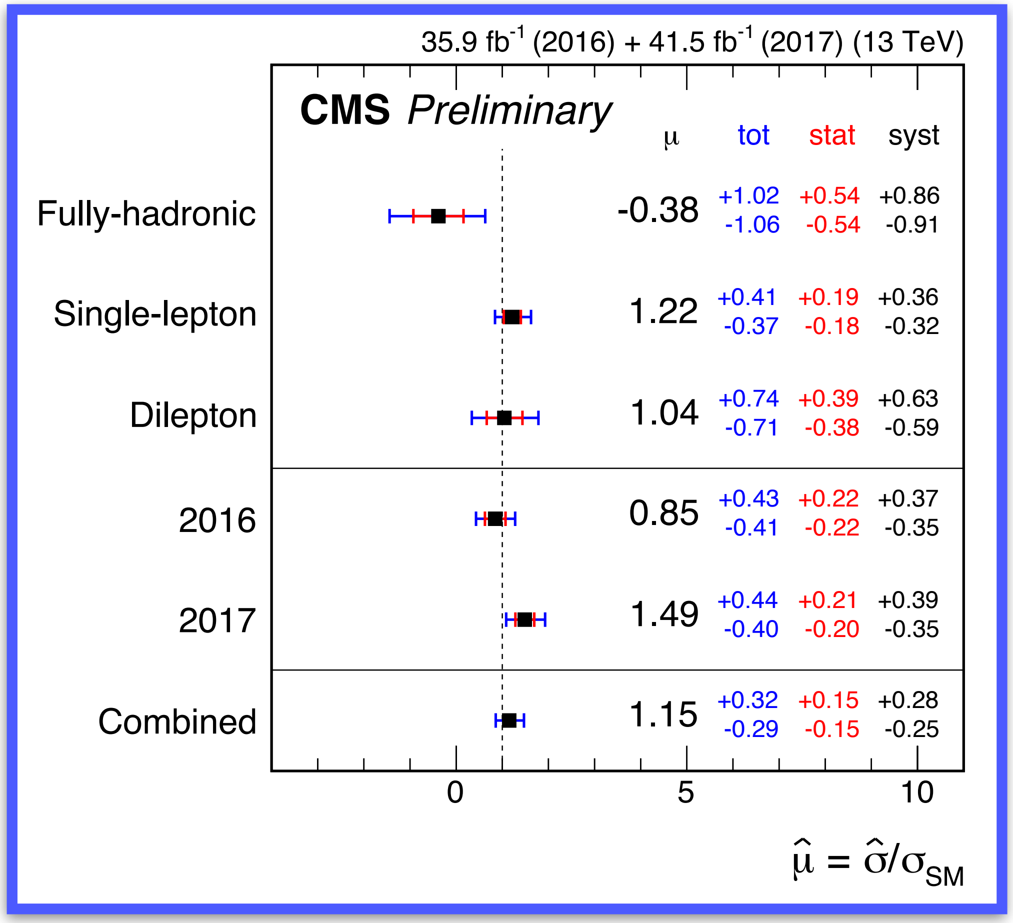

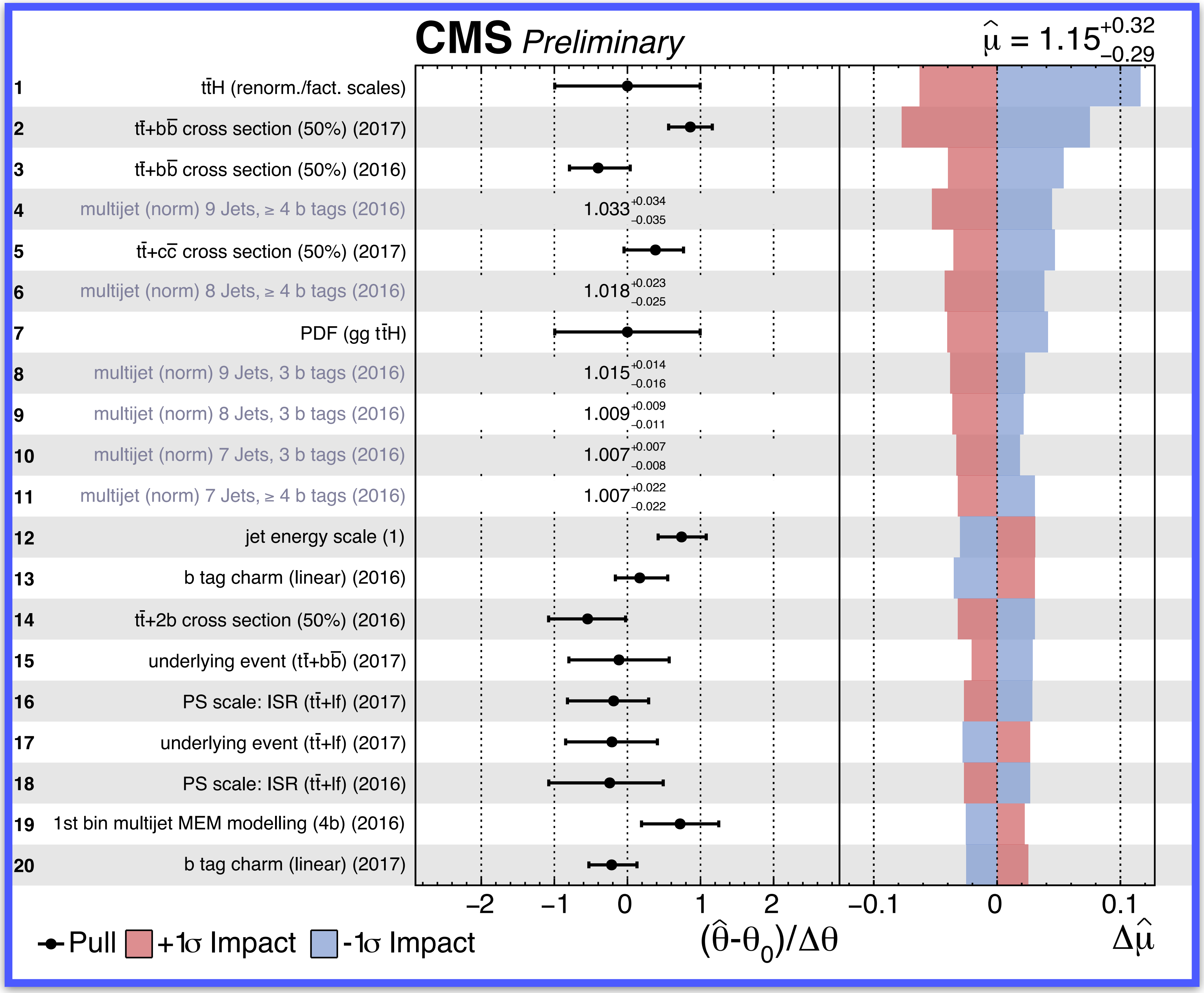

- Dominant uncertainties : ttH and tt+HF theory
- Sensitivity driven by single-lepton channel
- Expected significance : **3.5σ**
- Observed significance : **3.9σ**

ATLAS-CONF-2020-058 | 139 fb^{-1}

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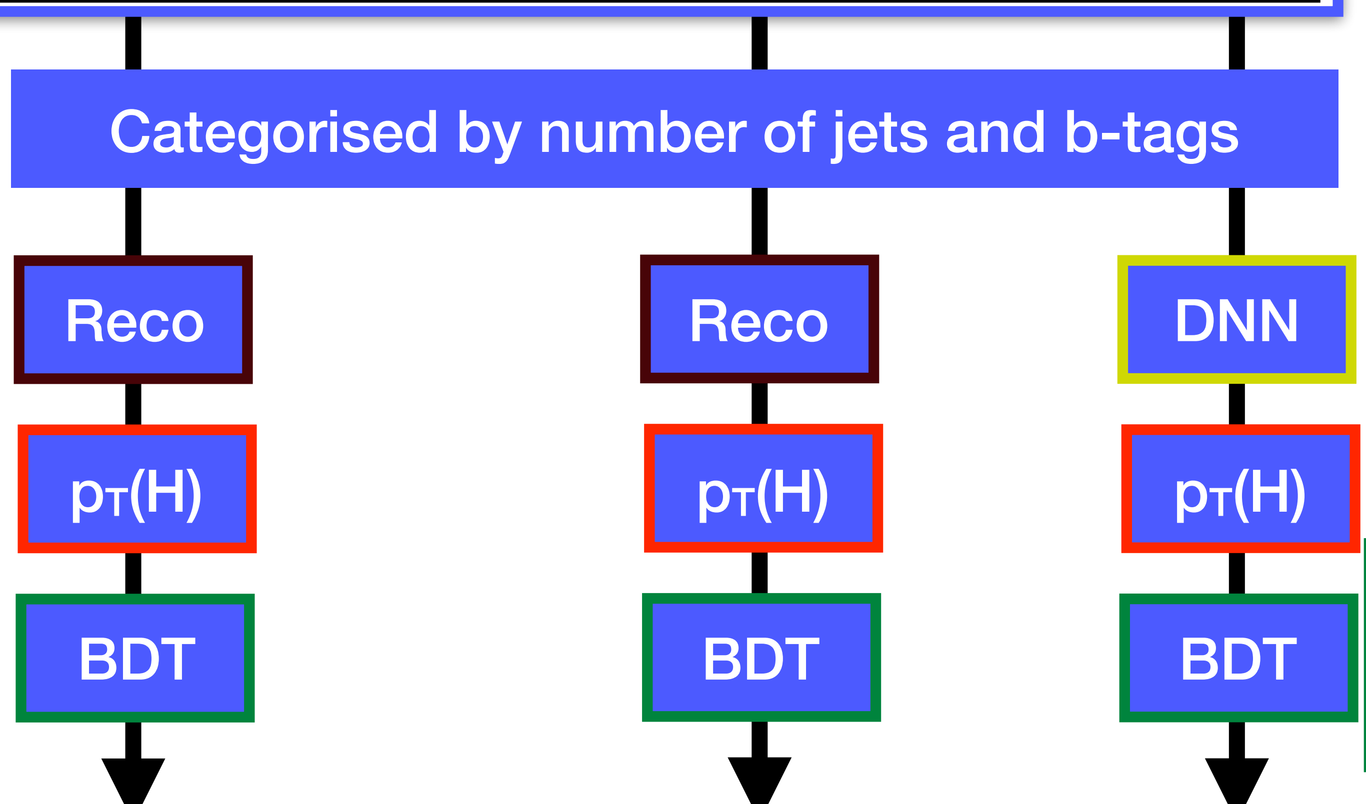
New

- Full Run-2 measurement with ttH(bb) events with at 1 or 2 leptons (e/μ)
  - Similar analysis to 36.1 fb^{-1} but updated strategy targeting STXS
  - Three channels with tightened selection dominated by tt+≥1b with negligible tt+light

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			
#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

- Single-lepton - 5 STXS bins
- Dilepton - 4 STXS bins
- Boosted - 2 STXS bins

New DNN trained to classify RC jet as Higgs/Top/QCD in ttH



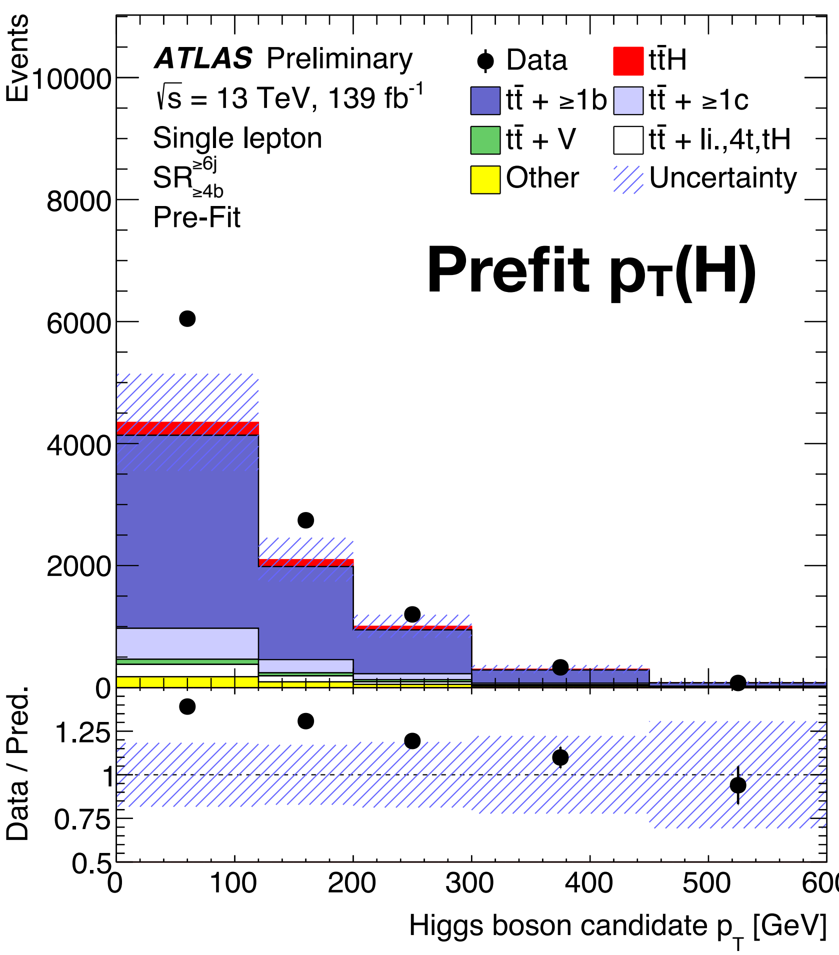
Reconstruction BDT trained to give jet-parton assignment for ttH

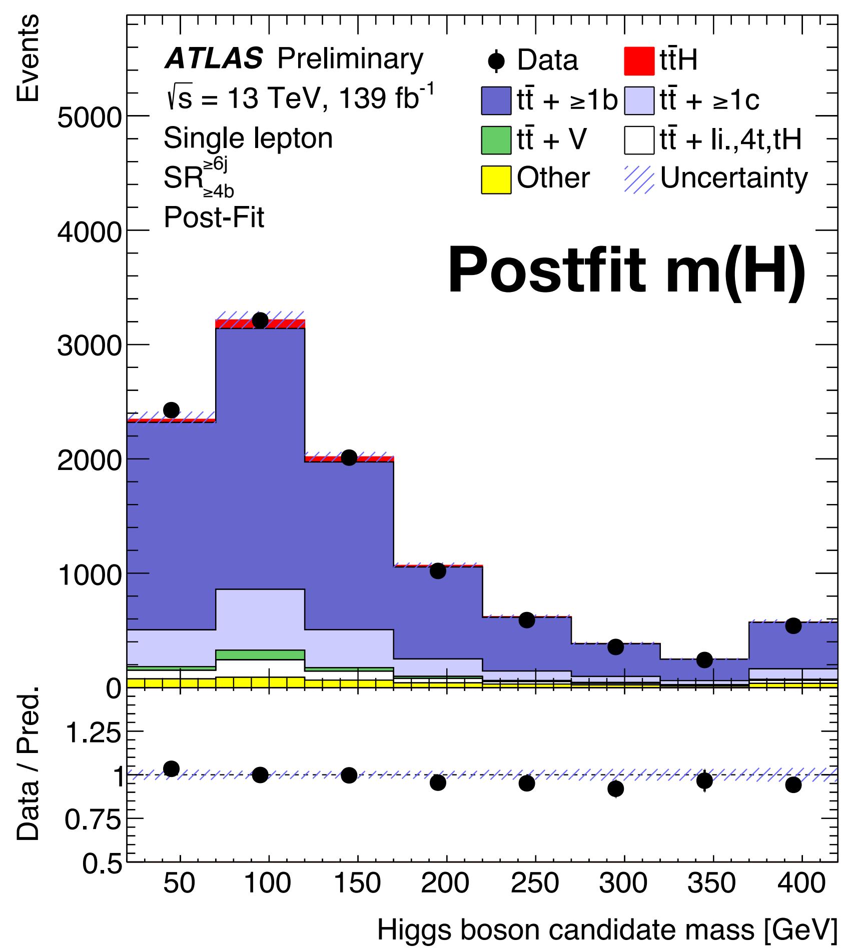
Events split by p_T(H):
0-120
120-200
200-300
300-450
>450

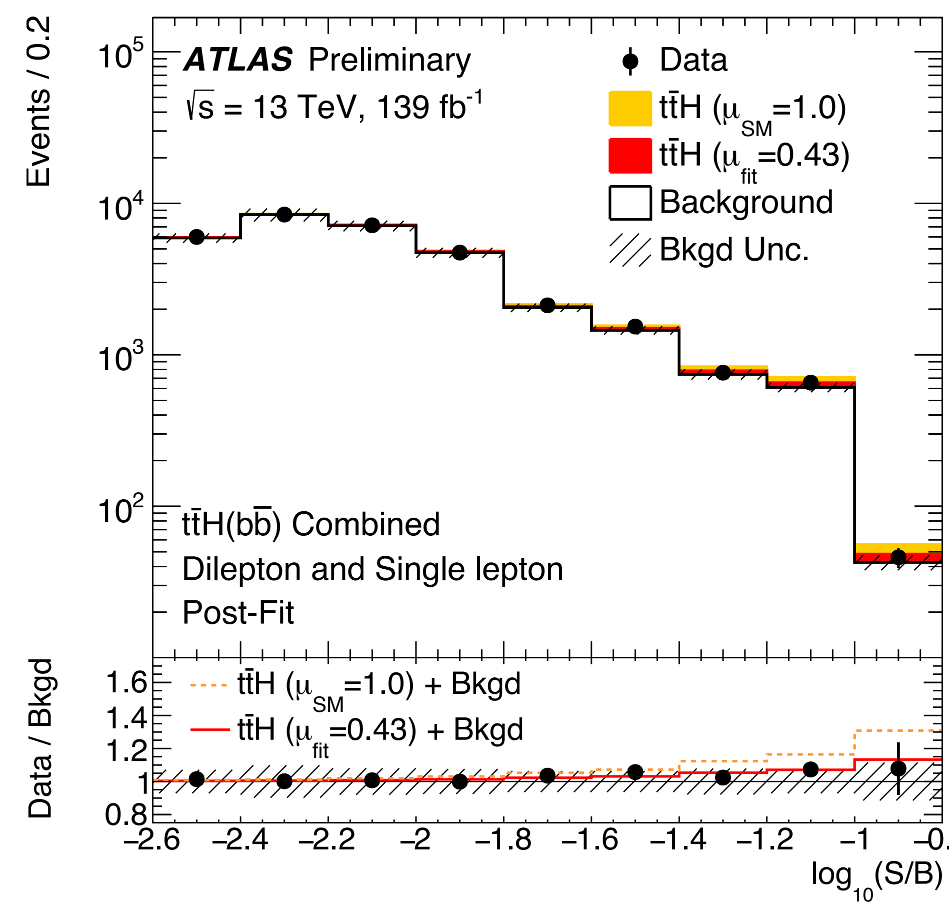
Classification BDT trained to discriminate ttH from backgrounds depending on channel

New

- tt+≥1b modelled with 4FS NLO generator for first time
  - Uncertainties scaled to remove acceptance effects and ensure free-floating k(tt+bb) fits normalisation of this prediction
- tt+≥1c given 100% prior uncertainty
- Focus on modelling Higgs candidate p_T with additional uncertainties
  - Data/MC uncertainty derived from inclusive single-lepton and dilepton regions to correct $p_T(H)$ shape in the fit





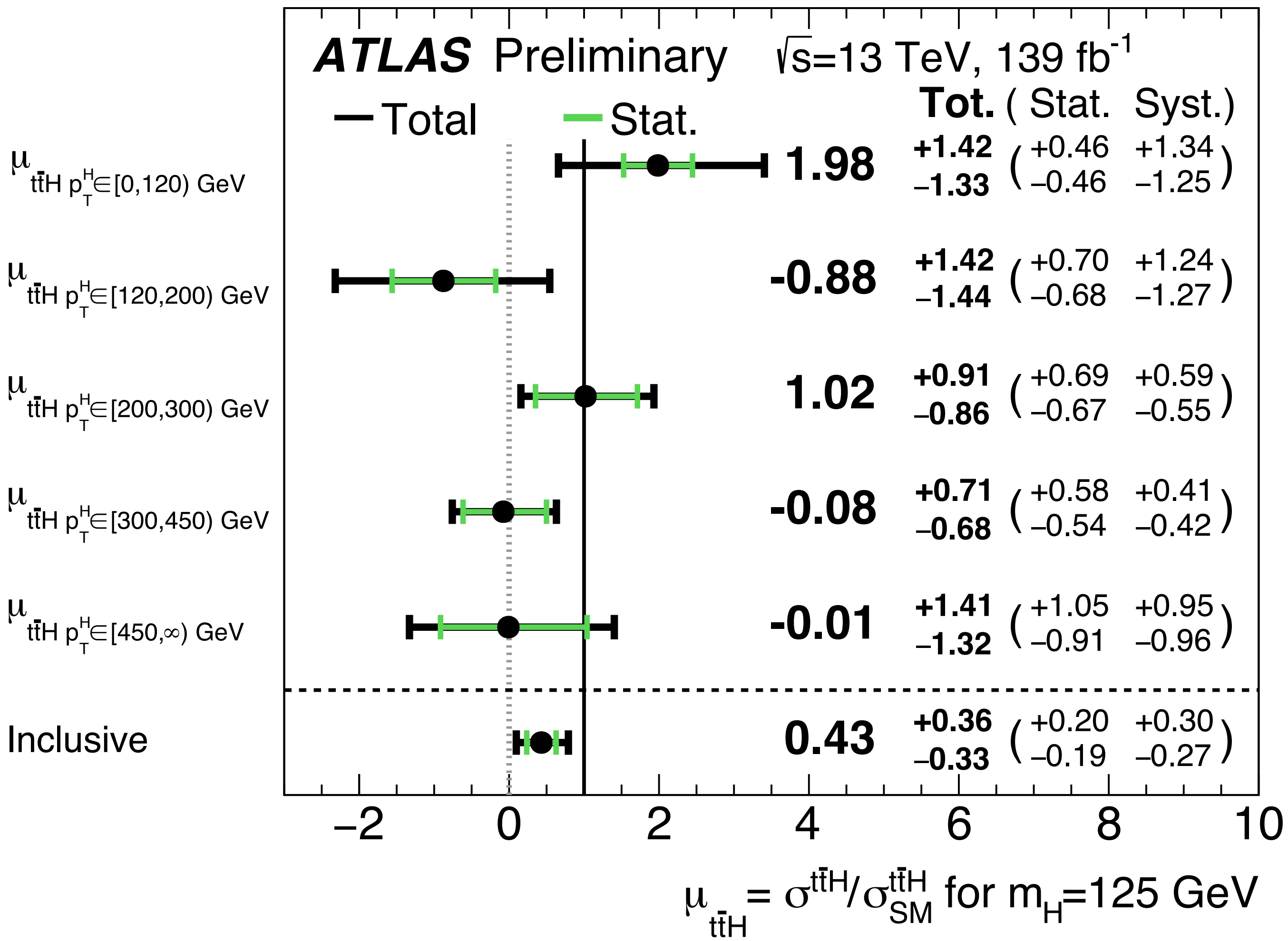


ATLAS ttH bb

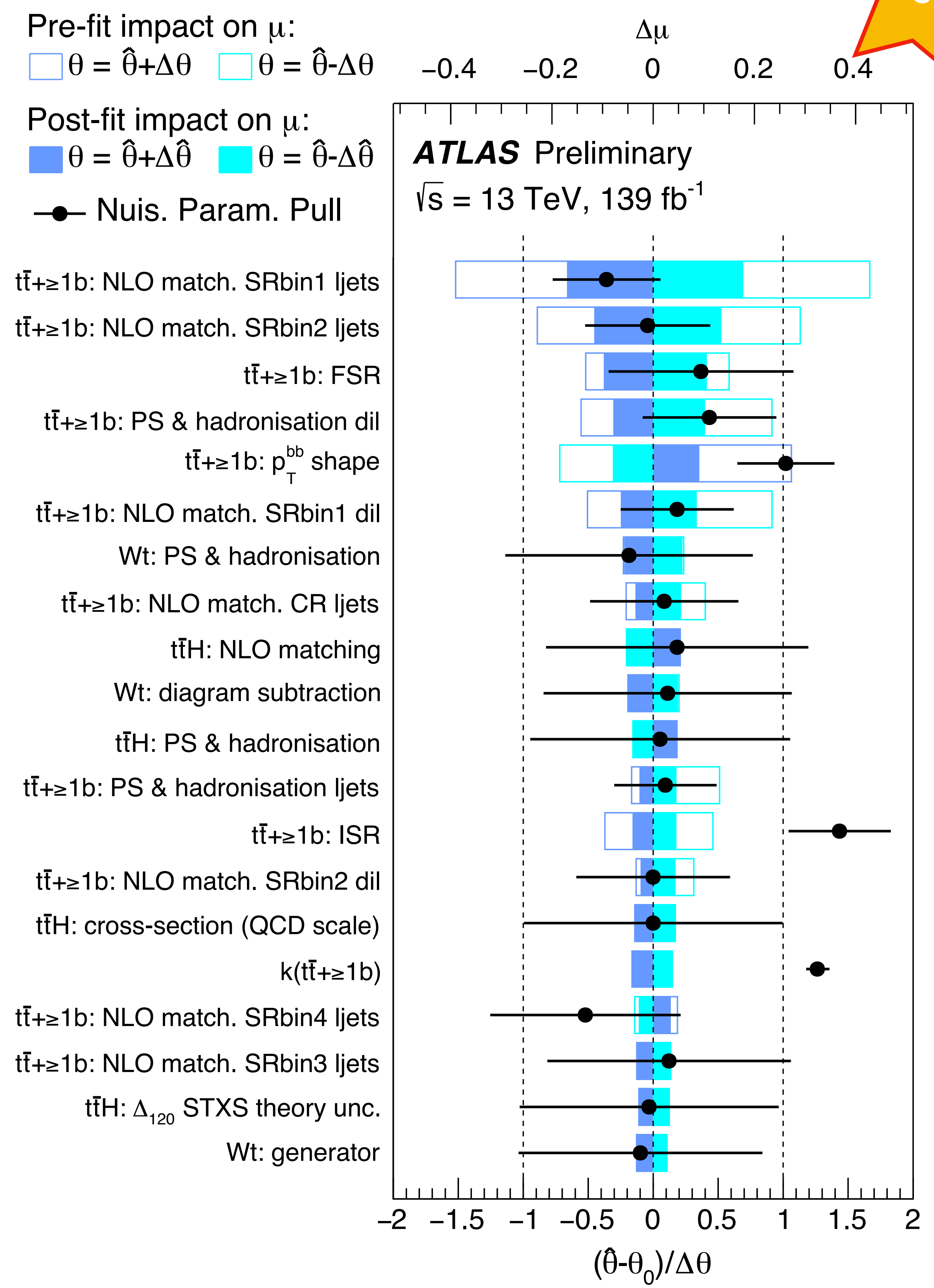
ATLAS-CONF-2020-058

139 fb^{-1}

New



- k(tt+≥1b) = 1.25 ± 0.09
- tt+≥1c pulled to 0.58
- Dominant uncertainties : tt+bb and ttH modelling
- Expected significance : **3.0σ**
- Observed significance : **1.3σ**



Summary

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- Many analyses performed by ATLAS and CMS spanning the Run-2 dataset
  - Not all analyses covered in this talk
  - Full Run-2 results starting to become available
    - New ATLAS ttH(bb) result
  - Consistent results between two experiments
- Consistent limits also being placed on Top Yukawa CP properties (at 95% CL)
  - ATLAS - tH+ttH($\gamma\gamma$) : $|\alpha| > 43°$ excluded
  - CMS - ttH($\gamma\gamma$) : $f_{CP} > 0.67$ excluded
    - ATLAS→CMS : $f_{CP} \gtrsim 0.53$ excluded
- Consistent limits set on negative Y_t
  - CMS : Exclude $\kappa_t < -0.9$, $-0.5 < \kappa_t < 1.0$
  - ATLAS†: Exclude $\kappa_t < 0$ at 2.9σ

Channel		ATLAS		CMS	
ttH	$\gamma\gamma$	5.2σ (4.4σ)	139	6.6σ (4.7σ)	137
	bb	1.3σ (3.0σ)	139	3.9σ (3.5σ)	77.4
tH	$\gamma\gamma$	8 x SM*		12 x SM	
	bb	-		25 x SM	

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

$$f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\mathrm{sign}(\tilde{\kappa}_t/\kappa_t)$$

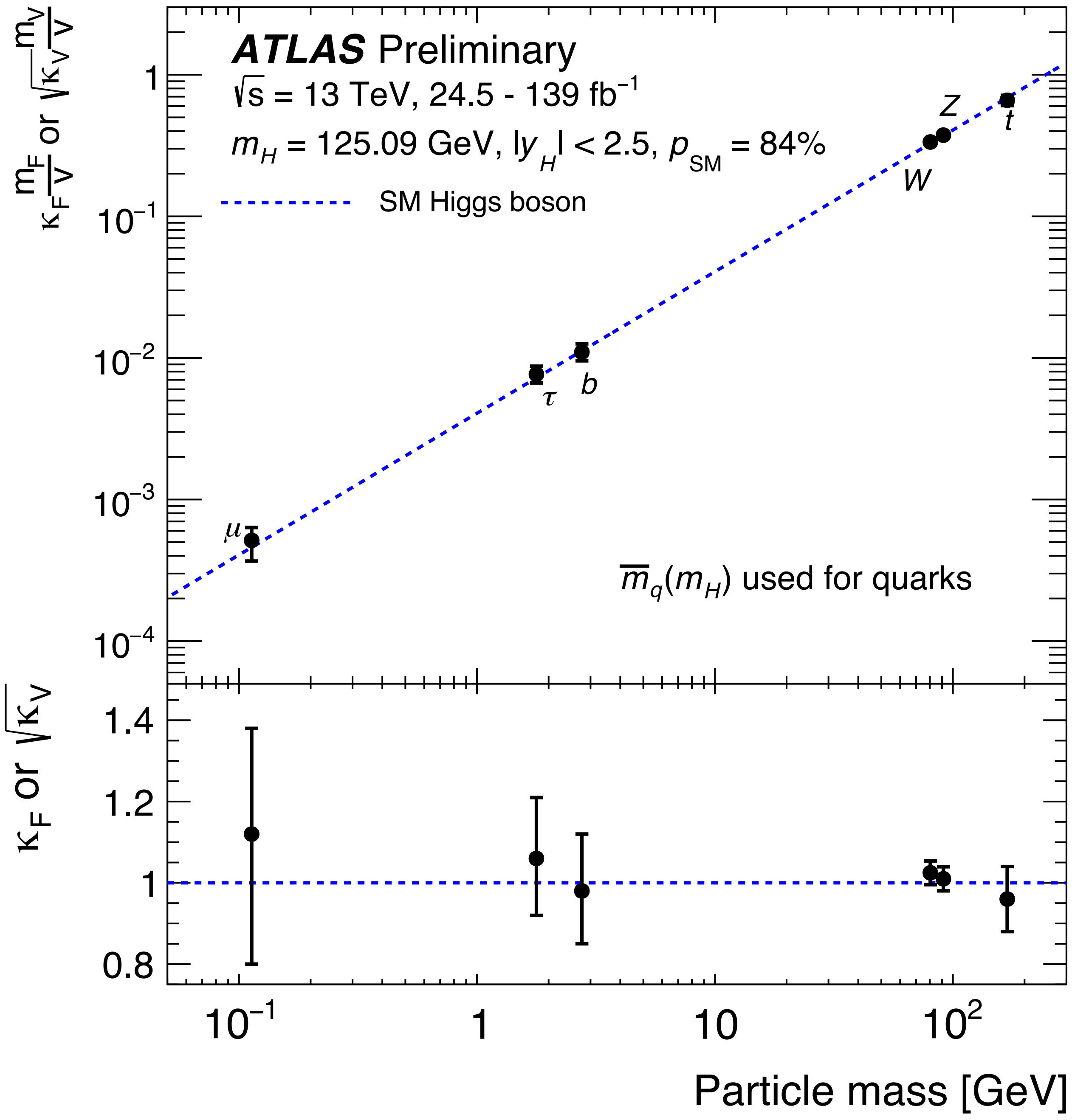
$$\mathcal{L} = -\frac{m_t}{v}\{\bar{\psi}_t\kappa_t[\cos(\alpha) + i\sin(\alpha)\gamma_5]\psi_t\}H$$

* ATLAS-CONF-2020-026 : limit from combined analysis of H($\gamma\gamma$), optimised for STXS

† ATLAS-CONF-2020-027 : latest Higgs combination constrains negative Y_t using tH and ggF

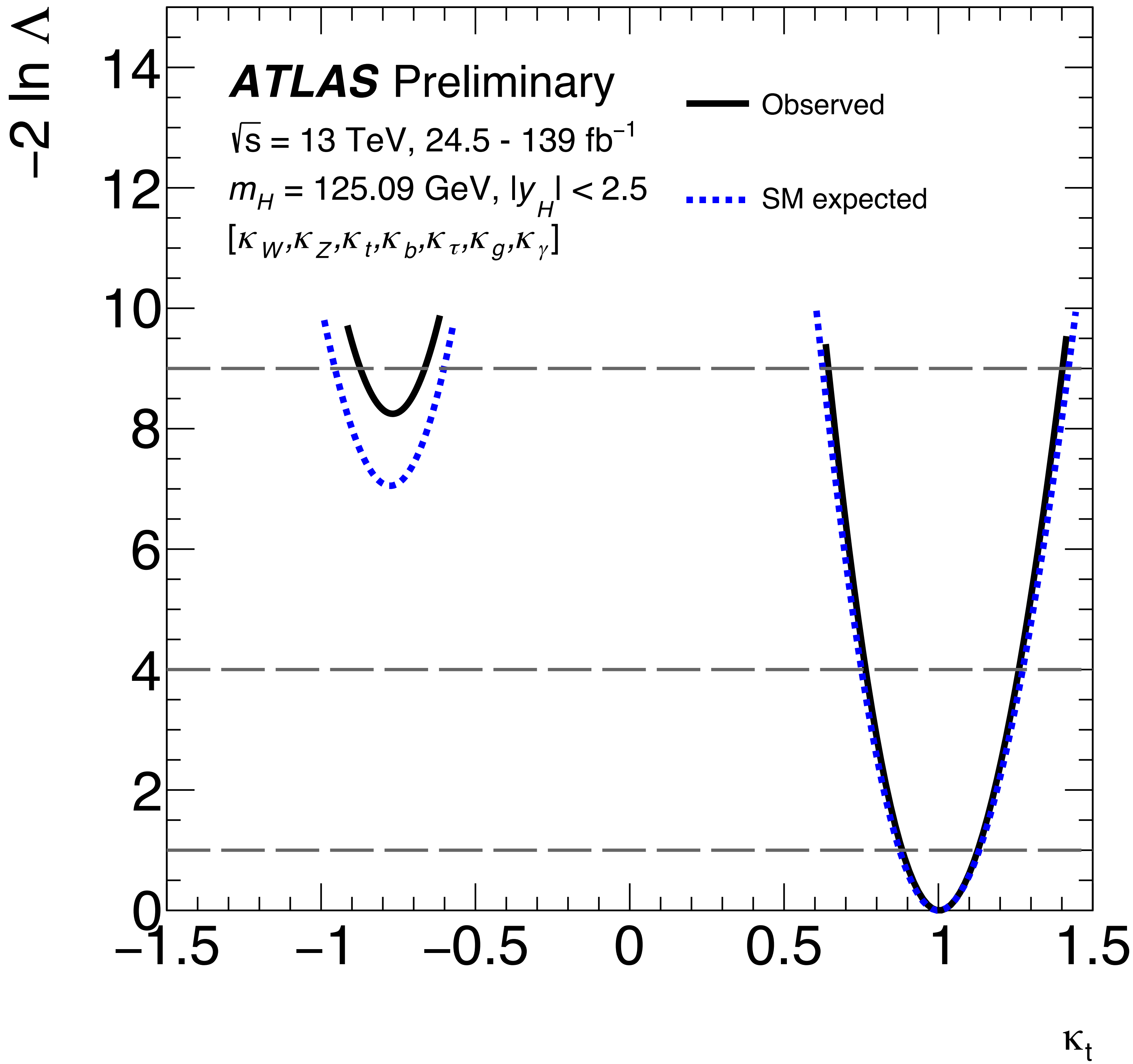
Backup

ATLAS Combination - CONF-2020-027



Parameter	Result
κ_Z	1.02 ± 0.06
κ_W	1.05 ± 0.06
κ_b	$0.98 ^{+0.14}_{-0.13}$
κ_t	0.96 ± 0.08
κ_τ	$1.06 ^{+0.15}_{-0.14}$
κ_μ	$1.12 ^{+0.26}_{-0.32}$

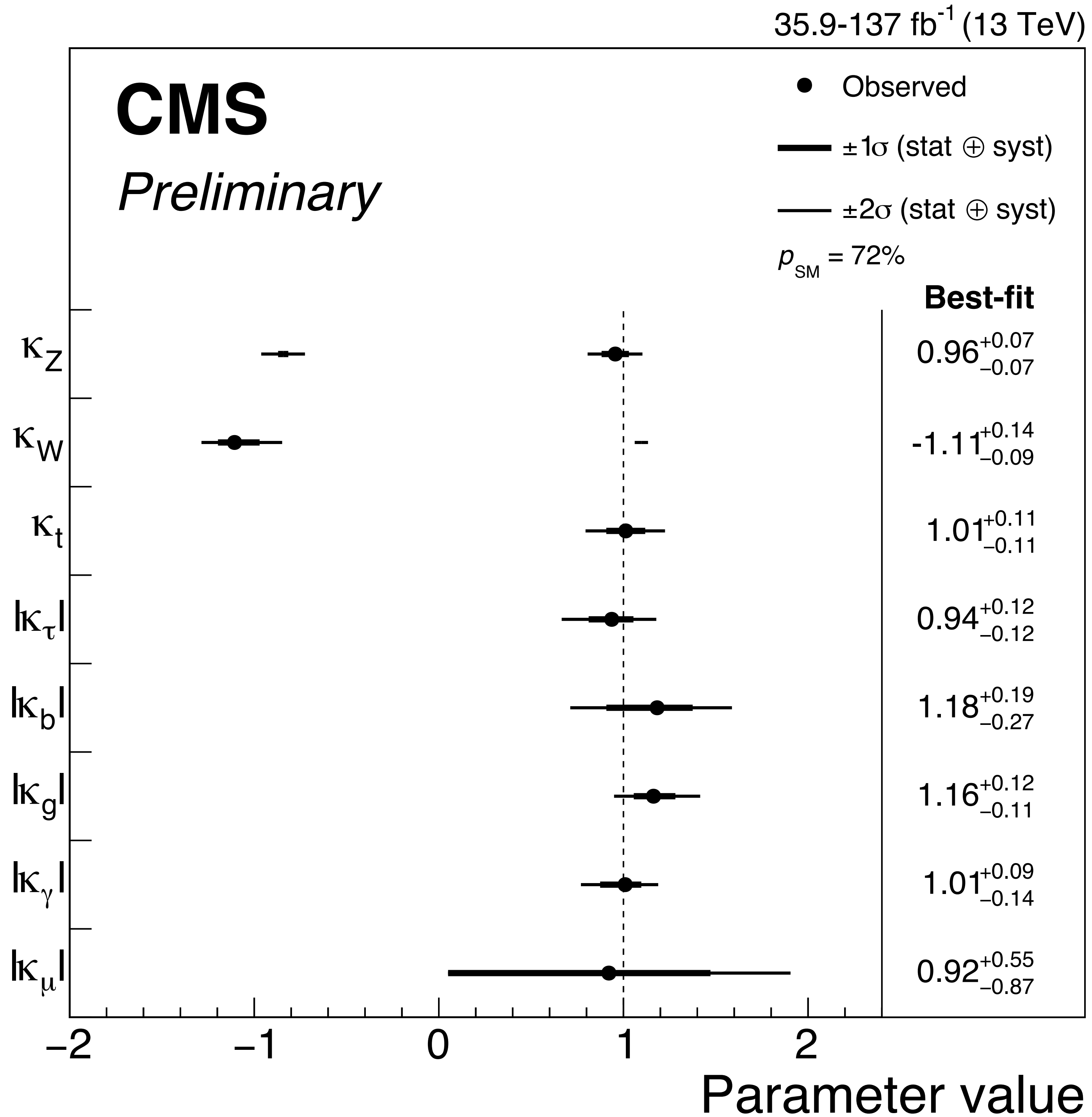
ATLAS Combination - CONF-2020-027



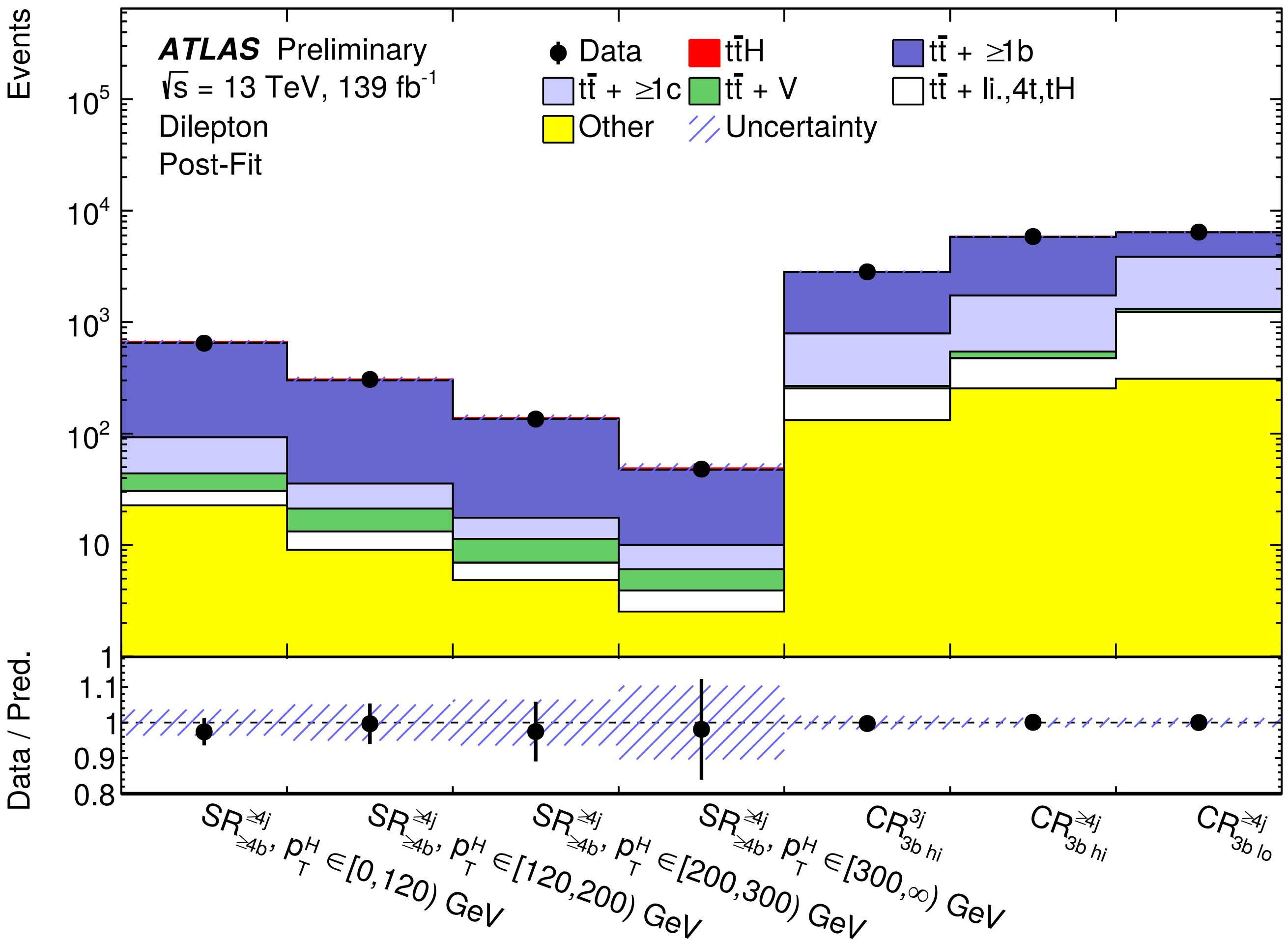
CMS Combination - HIG-19-005

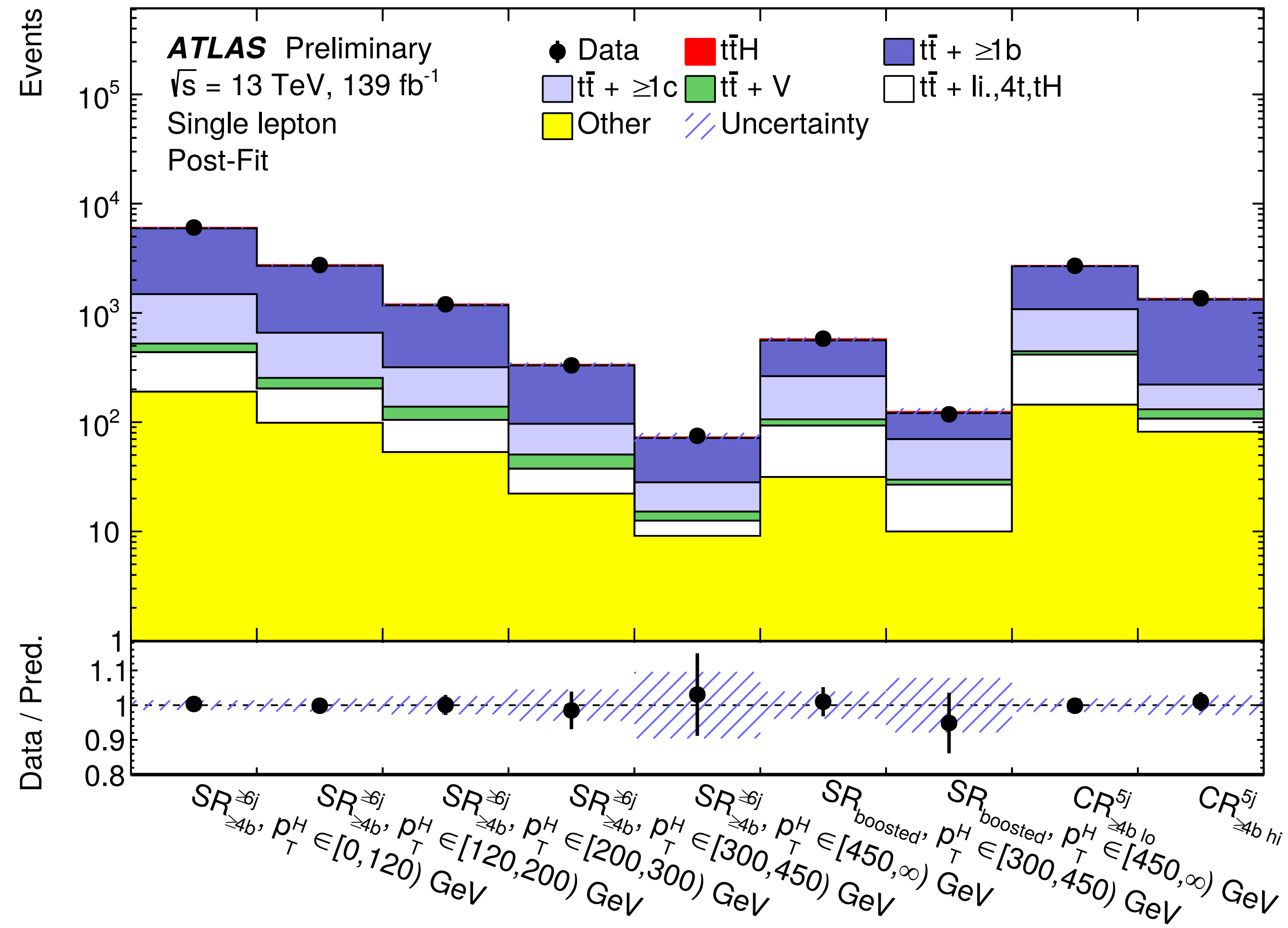
Coupling modifiers κ_i

Parameters	Best-fit	Uncertainty Stat.	Uncertainty Syst.
κ_Z	$0.96^{+0.07}_{-0.07}$ $\binom{+0.08}{-0.08}$	$^{+0.06}_{-0.06}$ $\binom{+0.06}{-0.06}$	$^{+0.04}_{-0.05}$ $\binom{+0.05}{-0.05}$
κ_W	$-1.11^{+0.14}_{-0.09}$ $\binom{+0.09}{-0.09}$	$^{+0.13}_{-0.07}$ $\binom{+0.07}{-0.07}$	$^{+0.05}_{-0.06}$ $\binom{+0.06}{-0.06}$
κ_t	$1.01^{+0.11}_{-0.11}$ $\binom{+0.10}{-0.10}$	$^{+0.06}_{-0.06}$ $\binom{+0.06}{-0.06}$	$^{+0.09}_{-0.08}$ $\binom{+0.08}{-0.08}$
κ_τ	$0.94^{+0.12}_{-0.12}$ $\binom{+0.12}{-0.11}$	$^{+0.08}_{-0.11}$ $\binom{+0.08}{-0.07}$	$^{+0.09}_{-0.06}$ $\binom{+0.09}{-0.08}$
κ_b	$1.18^{+0.19}_{-0.27}$ $\binom{+0.17}{-0.16}$	$^{+0.14}_{-0.13}$ $\binom{+0.13}{-0.12}$	$^{+0.13}_{-0.24}$ $\binom{+0.11}{-0.11}$
κ_g	$1.16^{+0.12}_{-0.11}$ $\binom{+0.11}{-0.10}$	$^{+0.08}_{-0.08}$ $\binom{+0.07}{-0.07}$	$^{+0.08}_{-0.08}$ $\binom{+0.08}{-0.07}$
κ_γ	$1.01^{+0.09}_{-0.14}$ $\binom{+0.09}{-0.08}$	$^{+0.07}_{-0.07}$ $\binom{+0.07}{-0.07}$	$^{+0.06}_{-0.12}$ $\binom{+0.05}{-0.05}$
κ_μ	$0.92^{+0.55}_{-0.87}$ $\binom{+0.52}{-0.96}$	$^{+0.54}_{-0.87}$ $\binom{+0.51}{-0.95}$	$^{+0.10}_{-0.01}$ $\binom{+0.08}{-0.08}$



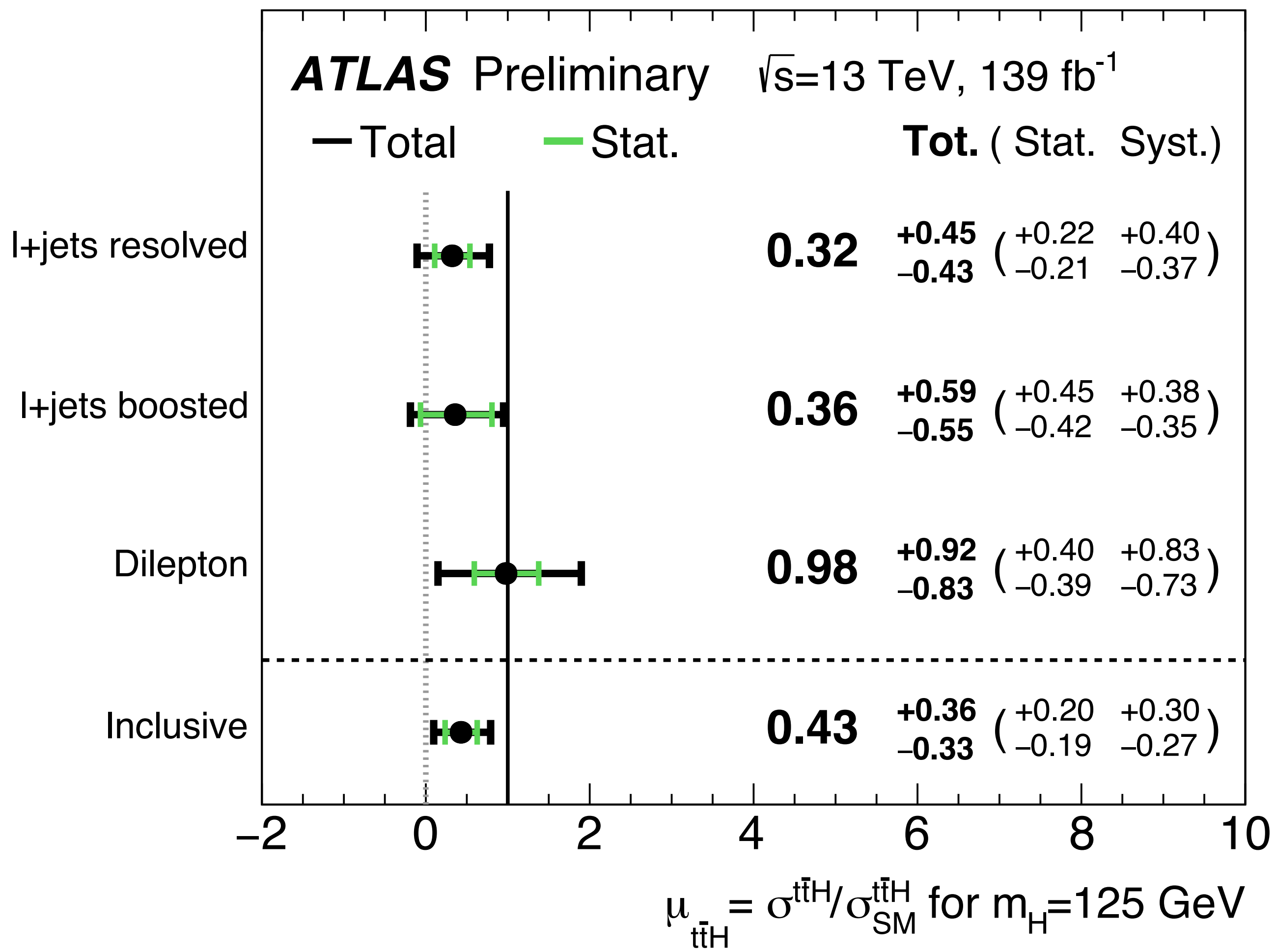
Yield Summary

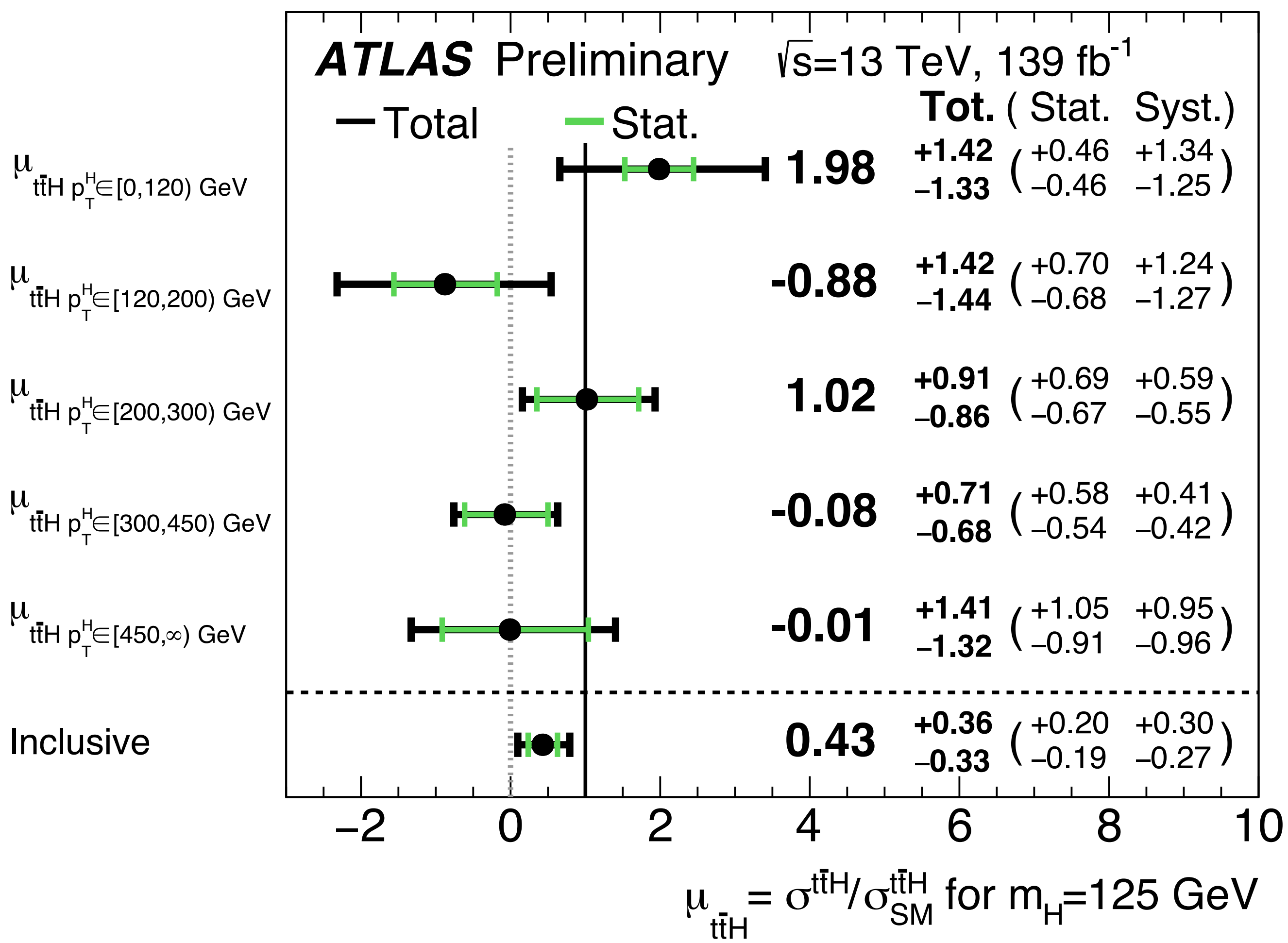




ATLAS ttH bb

Inclusive and STXS

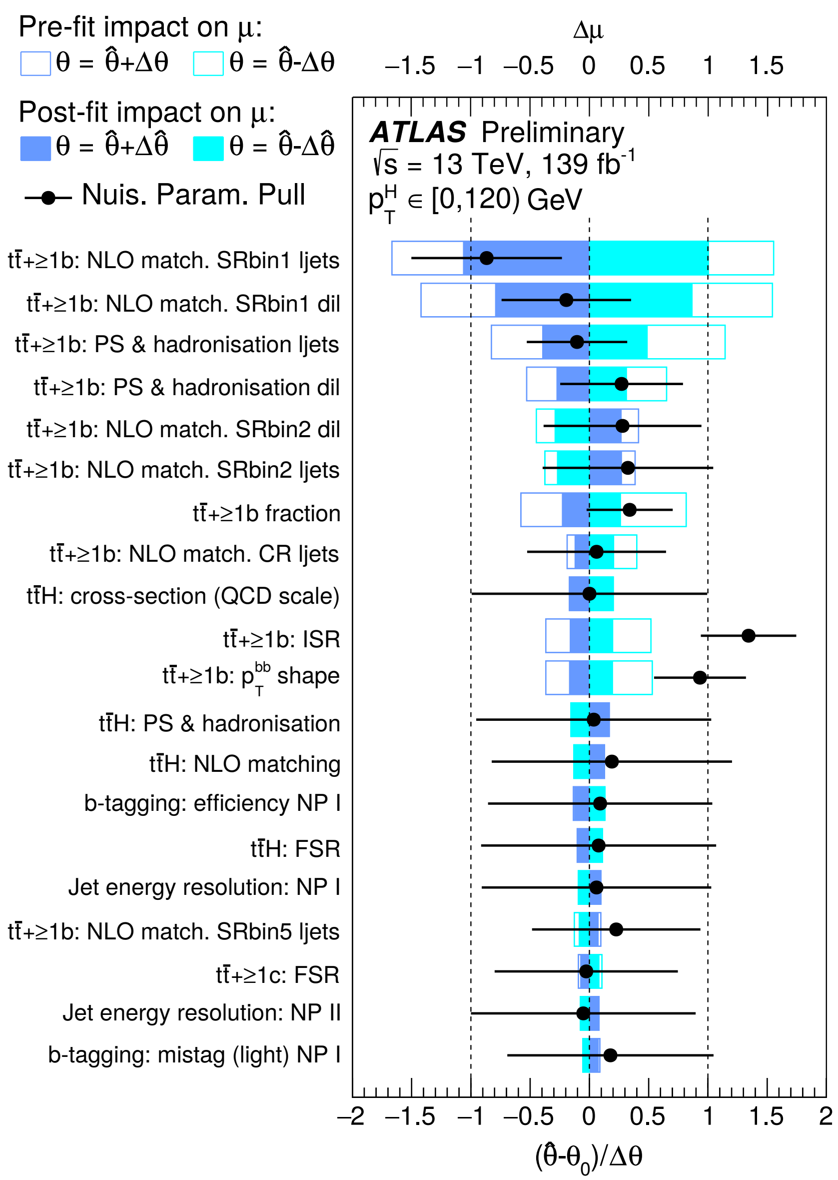


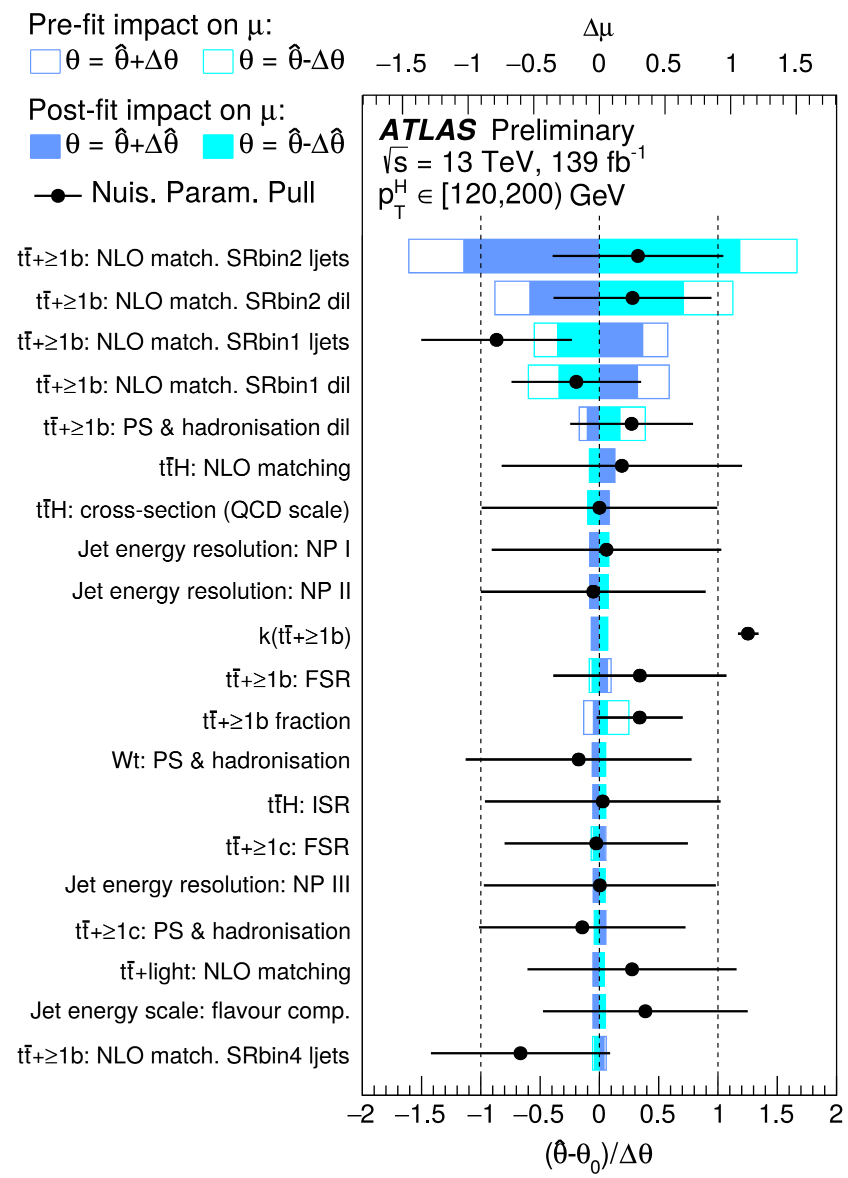


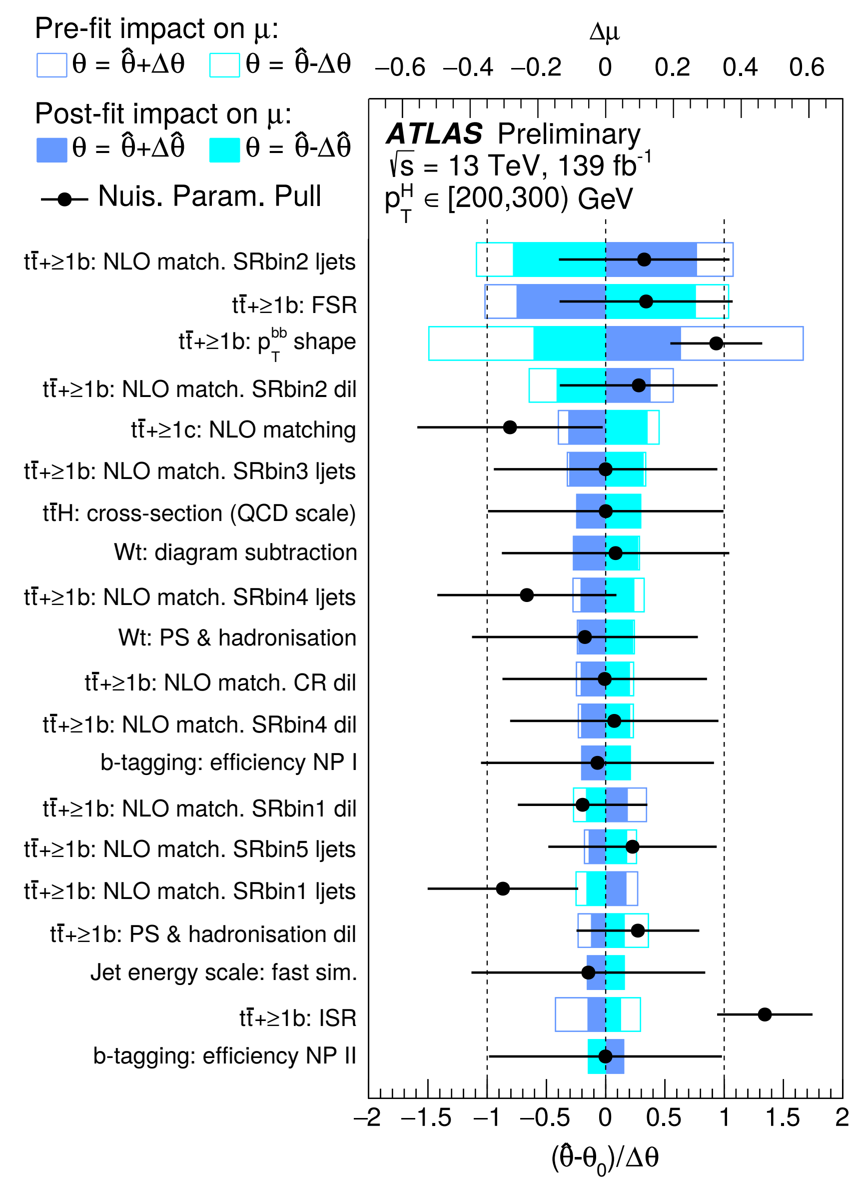
ATLAS ttH bb

New

STXS ranking



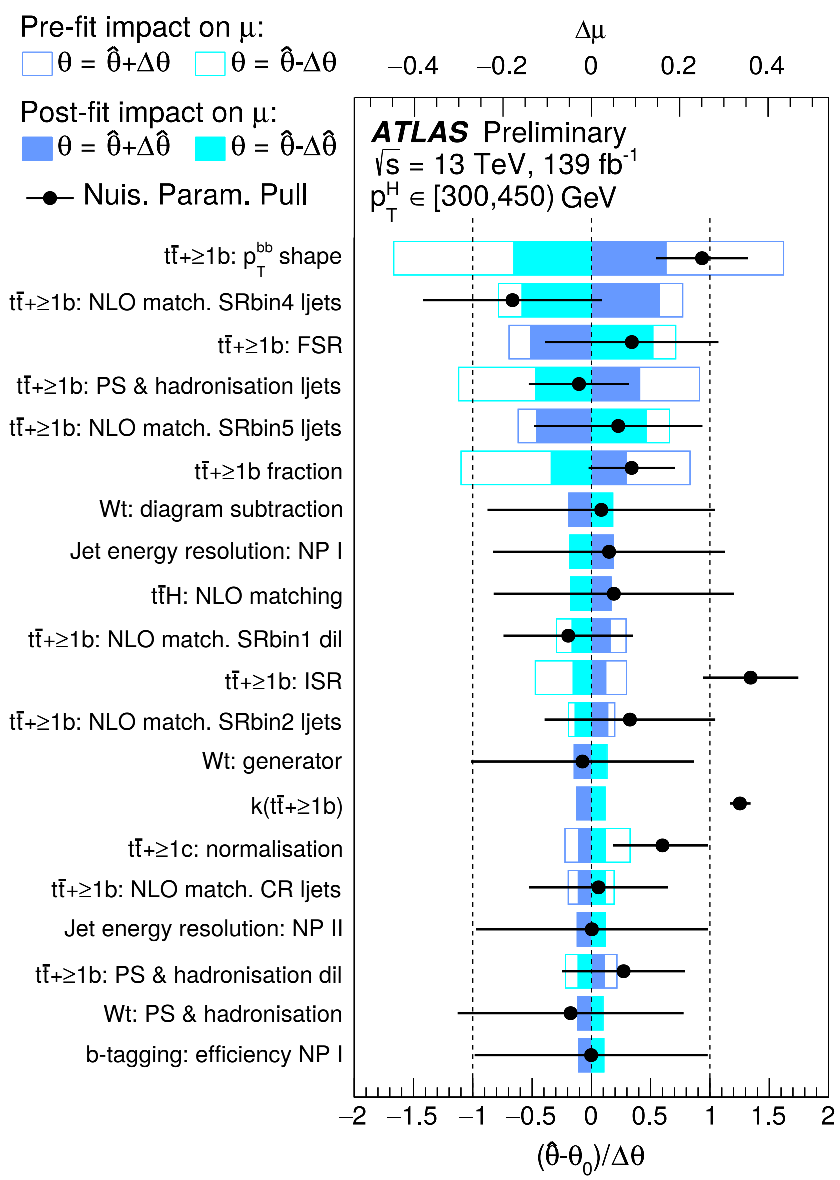


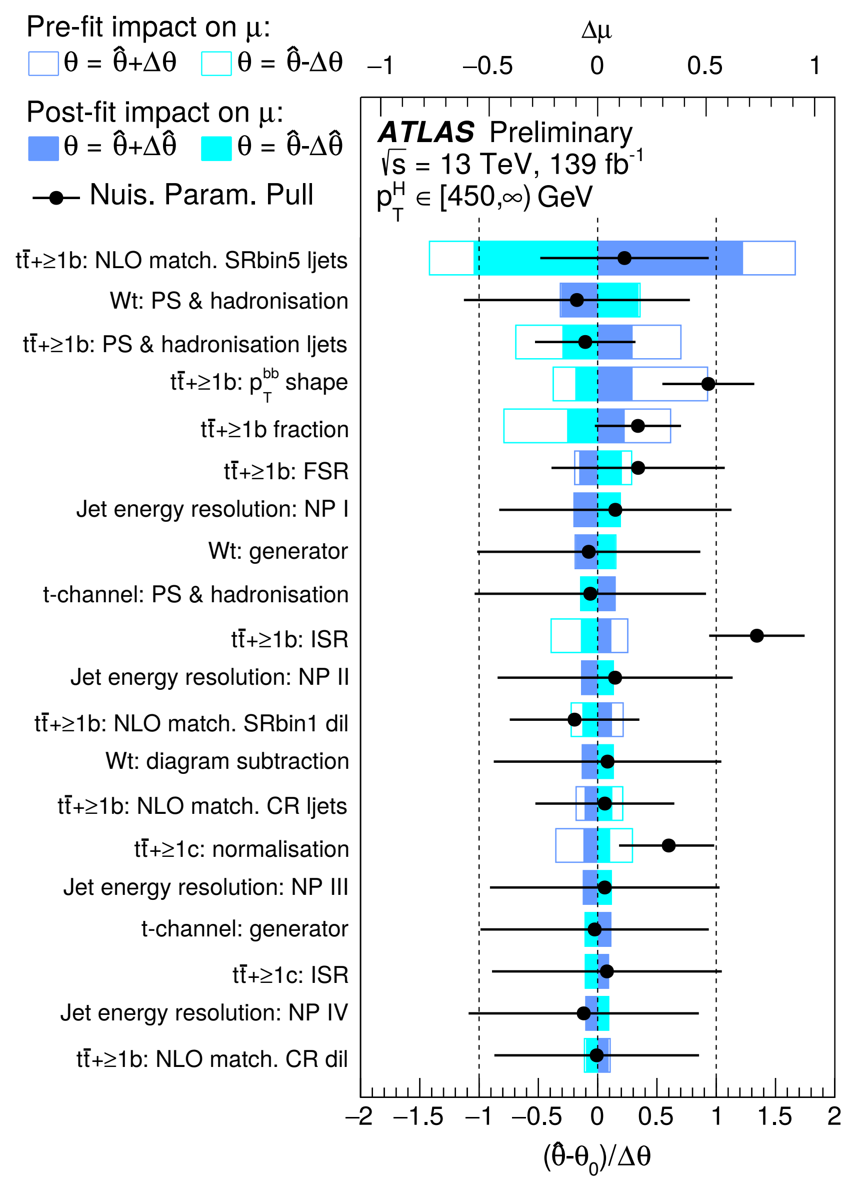


ATLAS ttH bb

STXS ranking

New





ATLAS ttH bb

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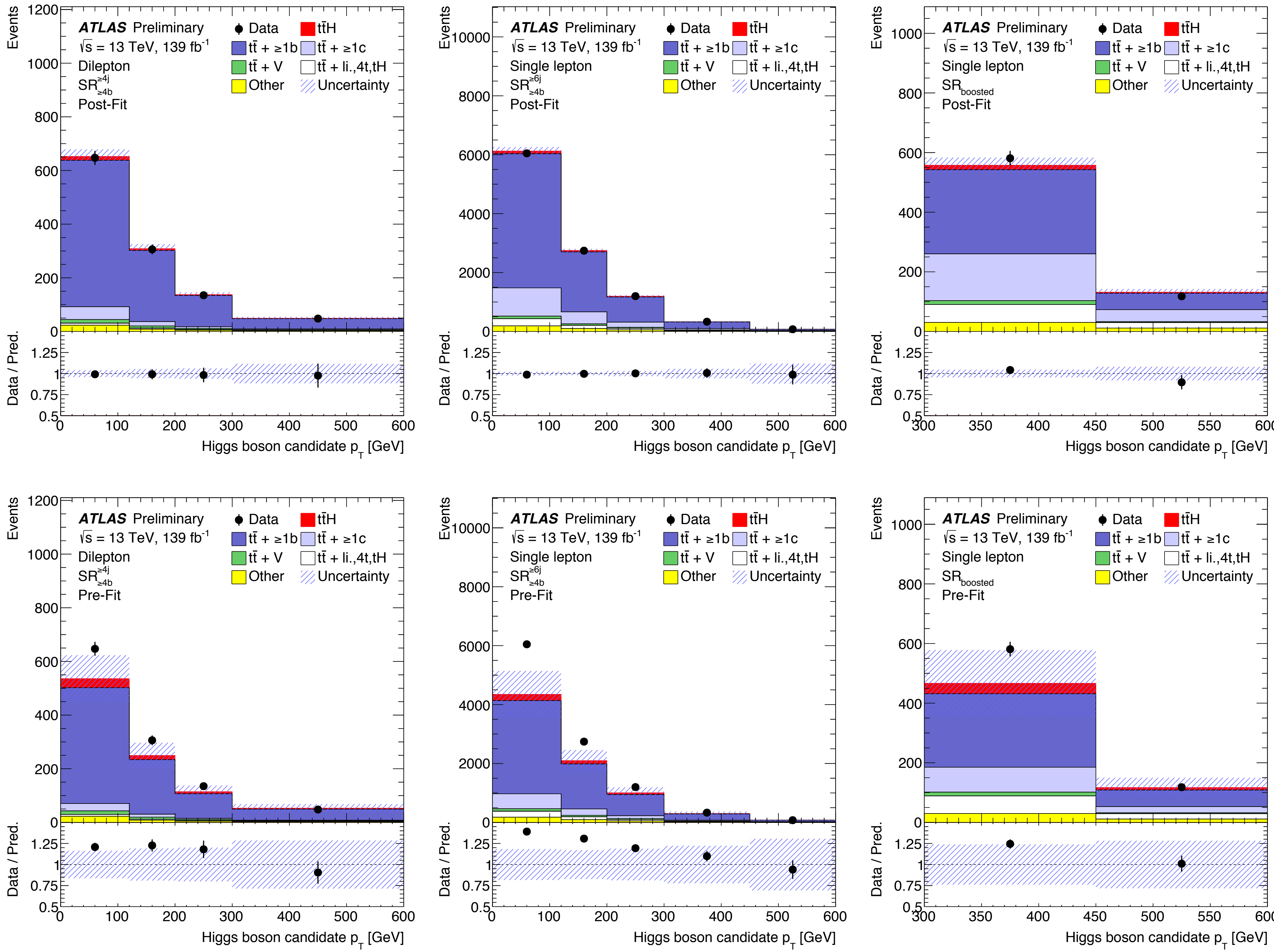
New

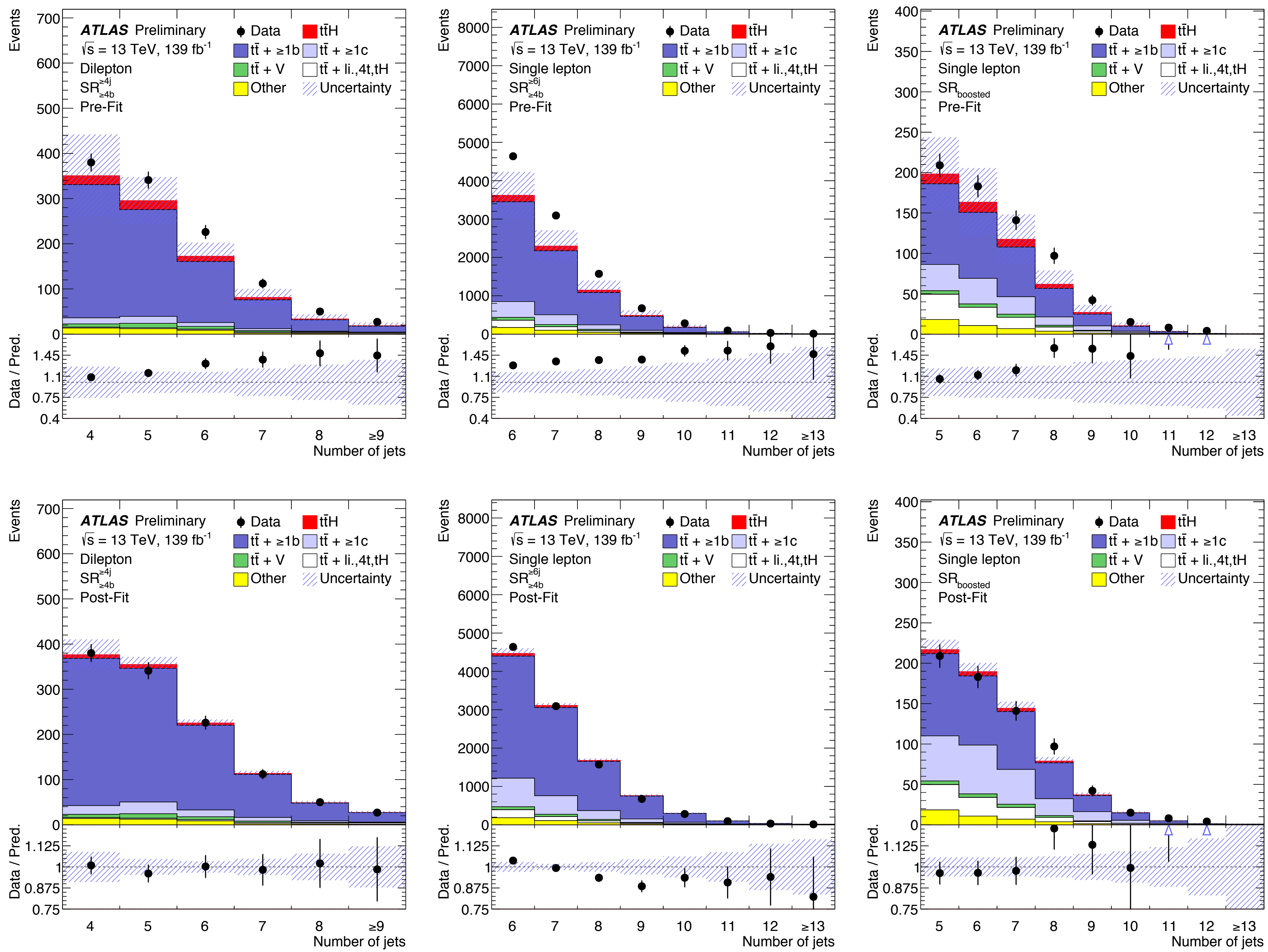
Higgs p_T



ATLAS ttH bb

New

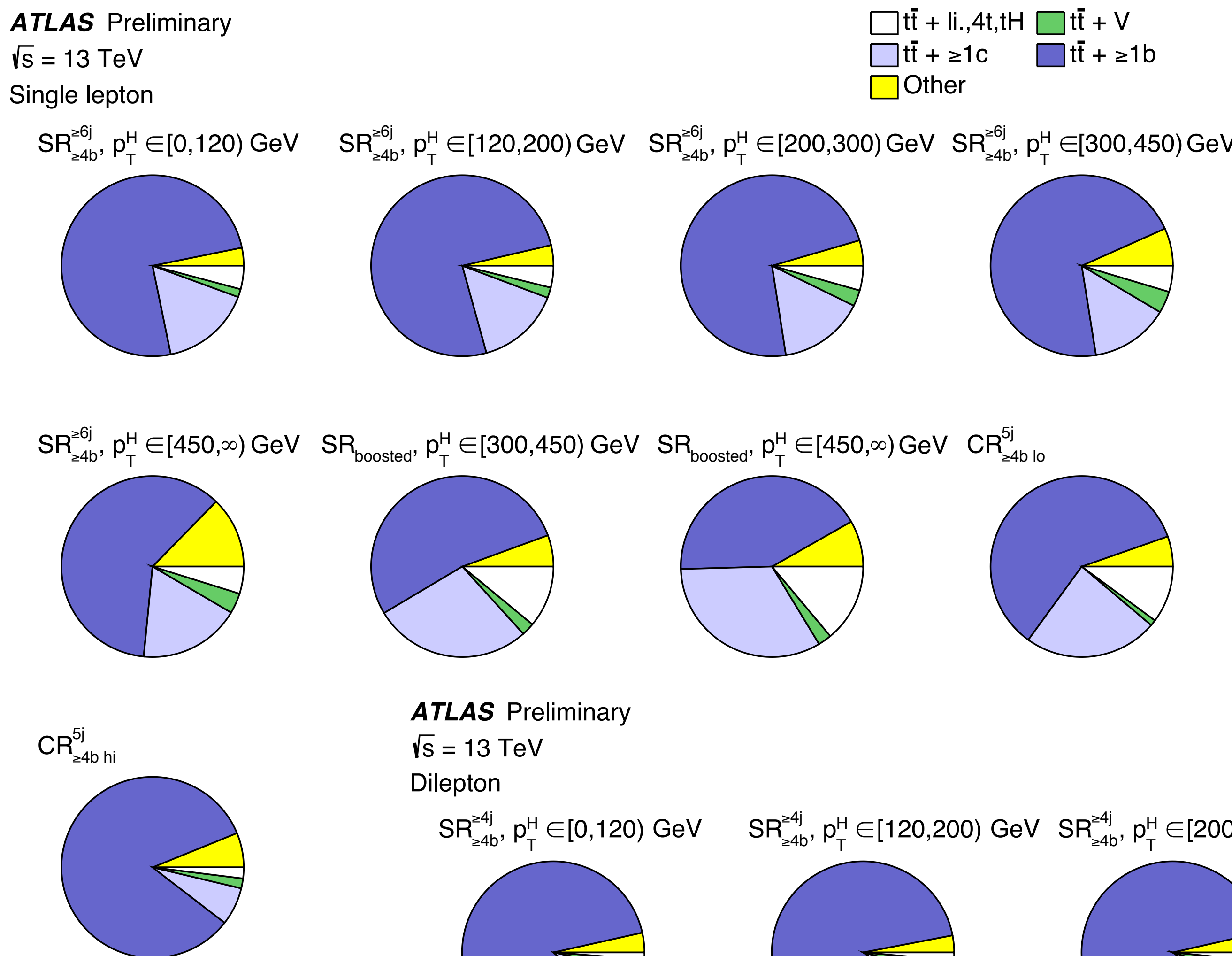
Number of jets

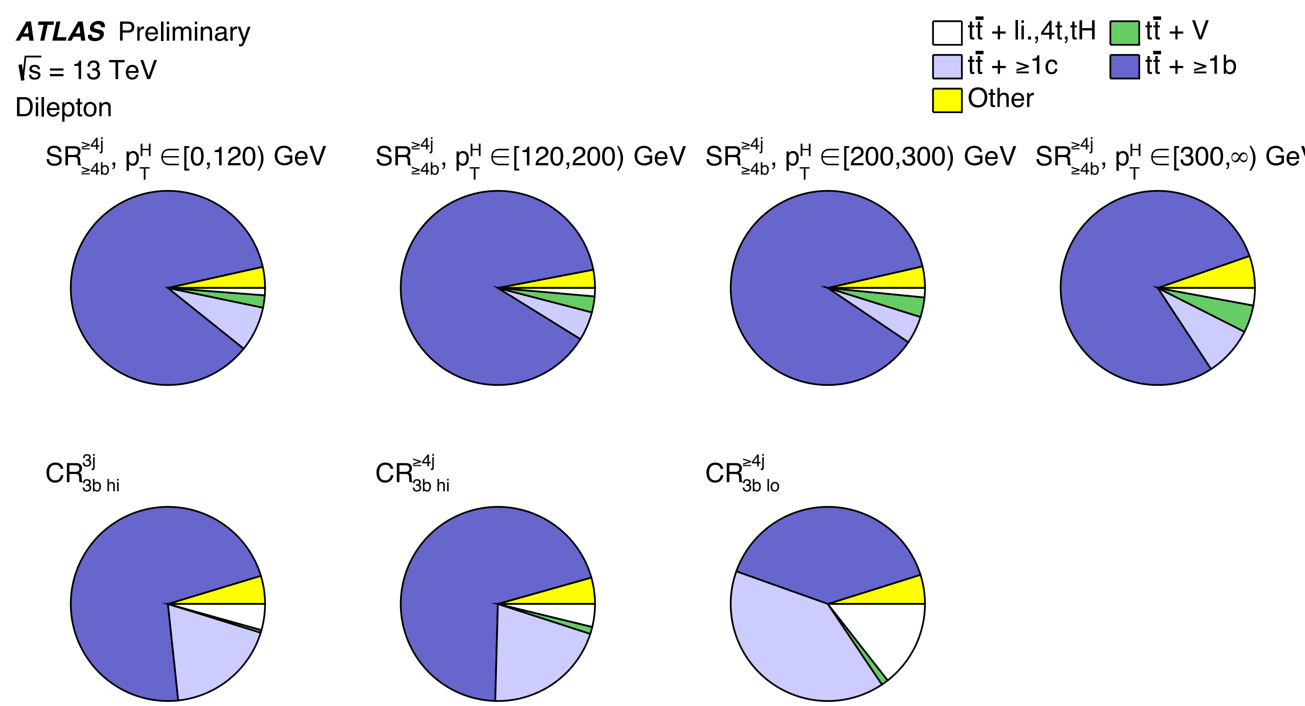


ATLAS ttH bb

New

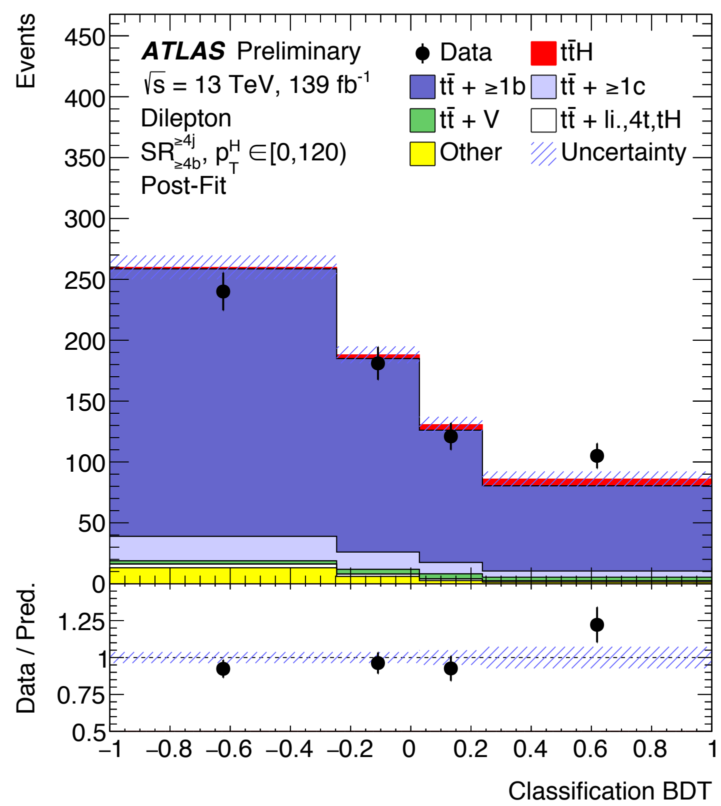
Background composition

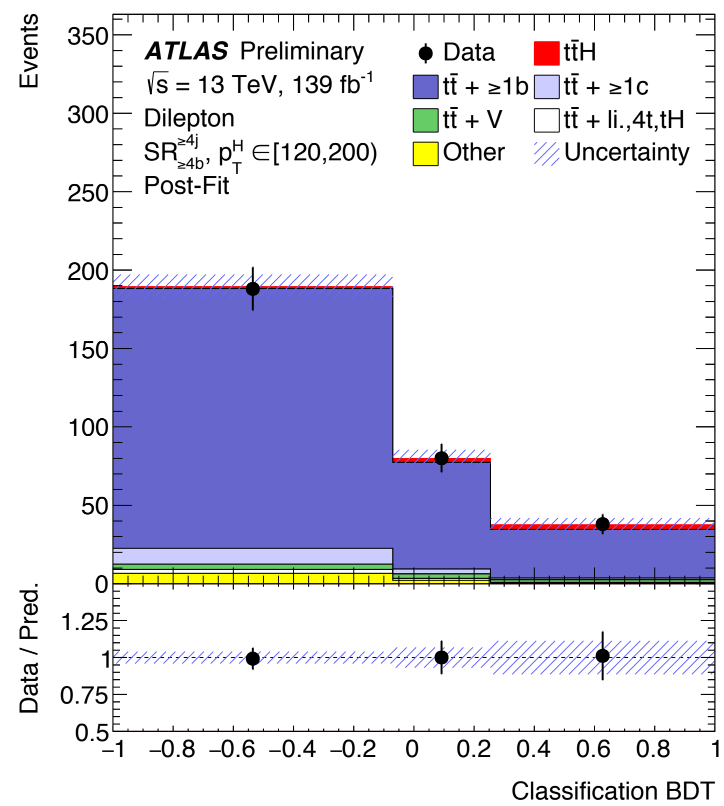


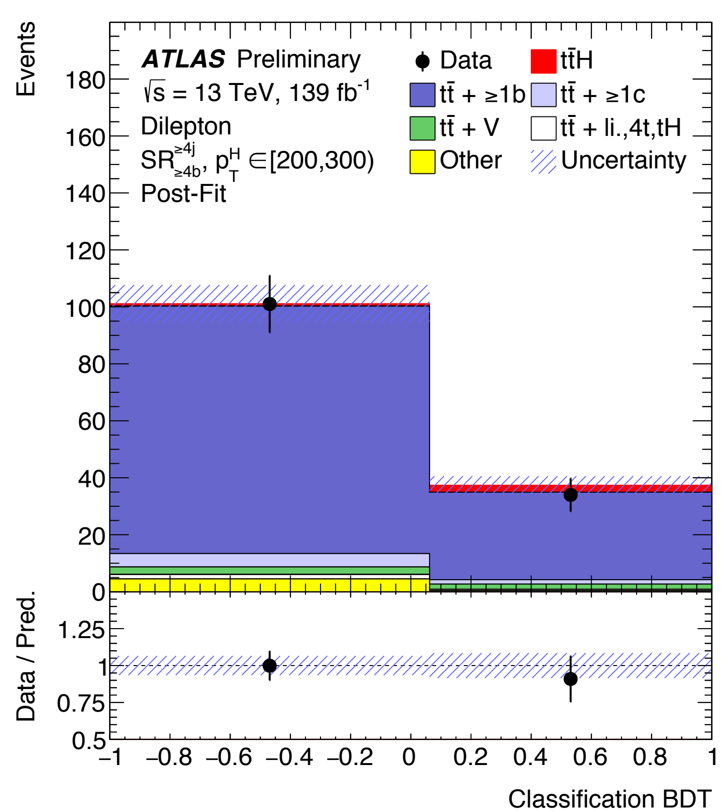


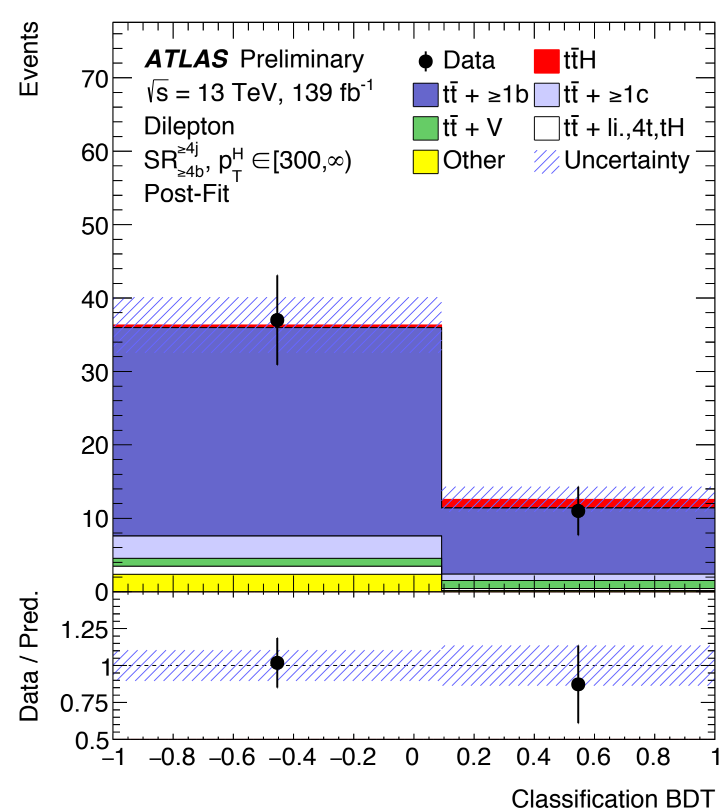
ATLAS ttH bb

Signal variables





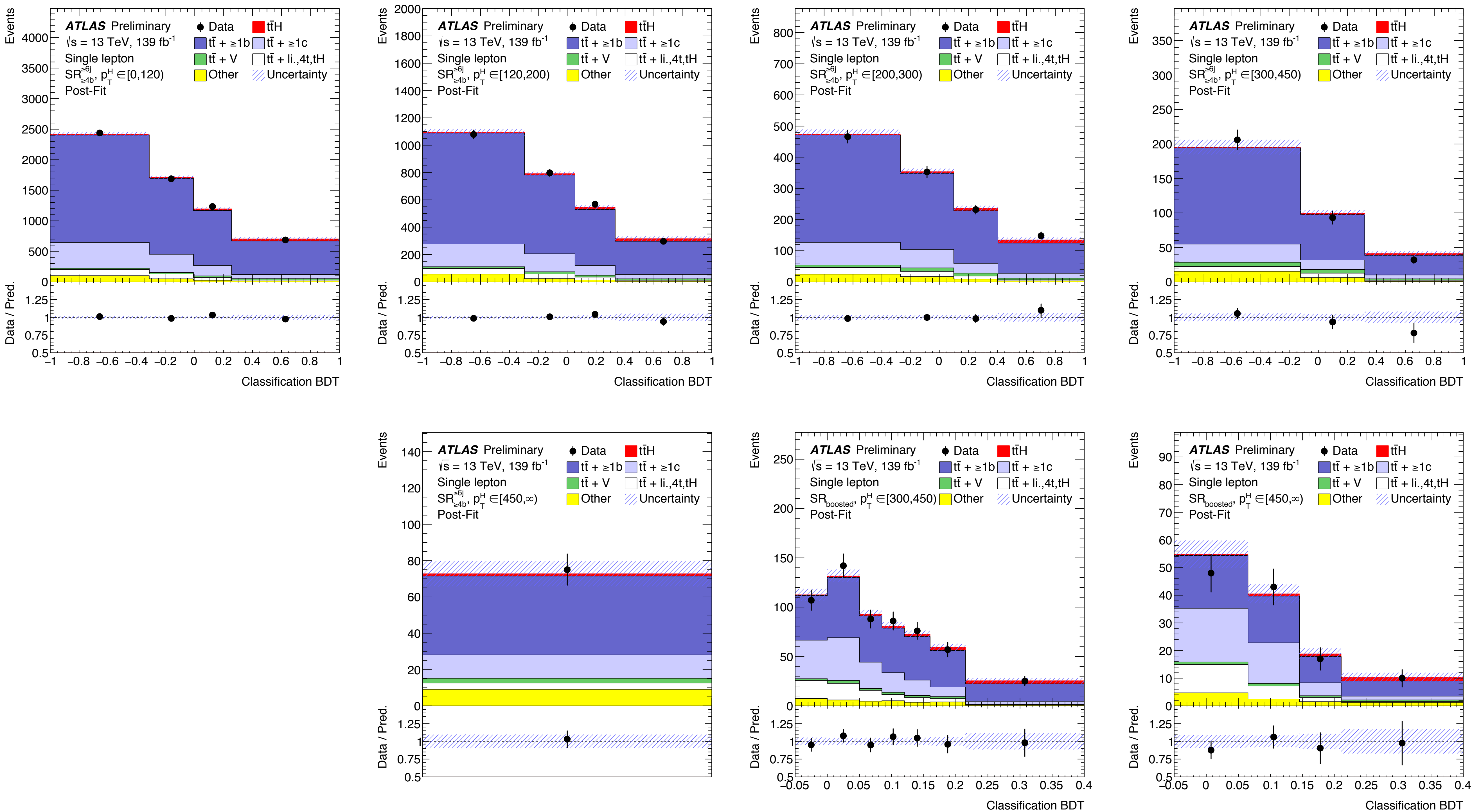




ATLAS ttH bb

New

Signal variables



ATLAS ttH bb

New

Uncertainty source	Description		Components
$t\bar{t}$ cross-section	±6%		$t\bar{t}+$ light
$t\bar{t}+\geq 1b$ normalisation	Free-floating		$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1c$ normalisation	±100%		$t\bar{t}+\geq 1c$
NLO matching	MadGraph5_aMC@NLO+Pythia8 vs. PowhegBox+Pythia8		All
PS & hadronisation	PowhegBox+Herwig7 vs. PowhegBox+Pythia8		All
ISR	Varying α_S^{ISR} (PS), μ_{R}&μ_{F} (ME)	in PowhegBoxRes+Pythia8	$t\bar{t}+\geq 1b$
		in PowhegBox+Pythia8	$t\bar{t}+\geq 1c$, $t\bar{t}+$ light
FSR	Varying α_S^{FSR} (PS)	in PowhegBoxRes+Pythia8	$t\bar{t}+\geq 1b$
		in PowhegBox+Pythia8	$t\bar{t}+\geq 1c$, $t\bar{t}+$ light
$t\bar{t}+\geq 1b$ fractions	PowhegBox+Herwig7 vs. PowhegBox+Pythia8		$t\bar{t}+1b/1B$, $t\bar{t}+\geq 2b$
p_{T}^{bb} shape	Shape mismodelling measured from data		$t\bar{t}+\geq 1b$

Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.25	−0.24
$t\bar{t}H$ modelling	+0.14	−0.06
tW modelling	+0.08	−0.08
b-tagging efficiency and mis-tag rates	+0.05	−0.05
Background-model statistical uncertainty	+0.05	−0.05
Jet energy scale and resolution	+0.03	−0.03
$t\bar{t}+\geq 1c$ modelling	+0.03	−0.03
$t\bar{t}+$ light modelling	+0.02	−0.02
Luminosity	+0.01	−0.00
Other sources	+0.03	−0.03
Total systematic uncertainty	+0.30	−0.27
$t\bar{t}+\geq 1b$ normalisation	+0.03	−0.05
Total statistical uncertainty	+0.20	−0.19
Total uncertainty	+0.36	−0.33

ttH(bb) ATLAS/CMS

ATLAS

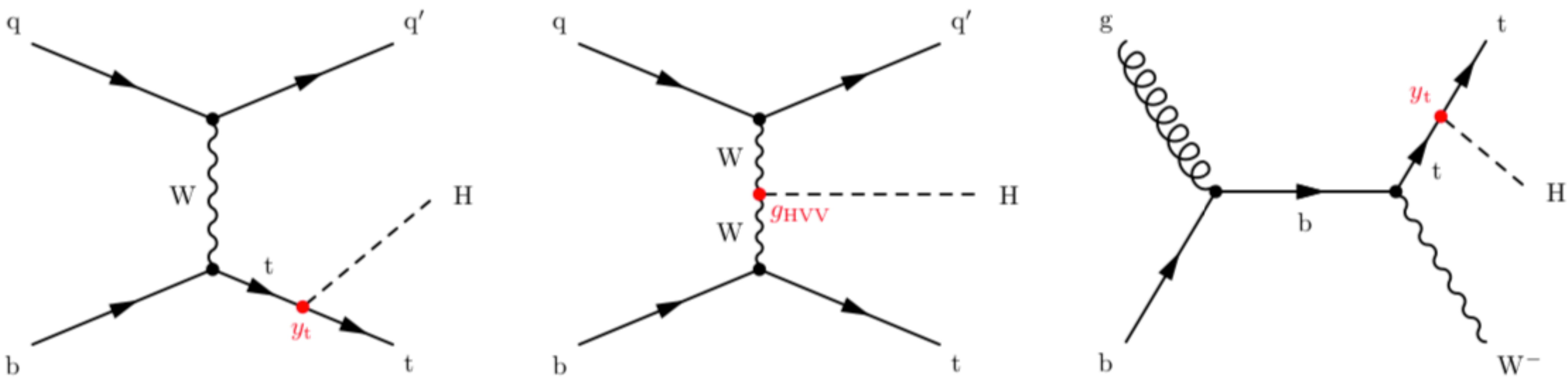
Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.25	−0.24
$t\bar{t}H$ modelling	+0.14	−0.06
tW modelling	+0.08	−0.08
b-tagging efficiency and mis-tag rates	+0.05	−0.05
Background-model statistical uncertainty	+0.05	−0.05
Jet energy scale and resolution	+0.03	−0.03
$t\bar{t}+\geq 1c$ modelling	+0.03	−0.03
$t\bar{t}+$ light modelling	+0.02	−0.02
Luminosity	+0.01	−0.00
Other sources	+0.03	−0.03
Total systematic uncertainty	+0.30	−0.27
$t\bar{t}+\geq 1b$ normalisation	+0.03	−0.05
Total statistical uncertainty	+0.20	−0.19
Total uncertainty	+0.36	−0.33

CMS

Uncertainty source	$\Delta\hat{\mu}$
Total experimental	+0.15/−0.13
b tagging	+0.08/−0.07
jet energy scale and resolution	+0.05/−0.04
Total theory	+0.23/−0.19
signal	+0.15/−0.06
$t\bar{t}$+hf modelling	+0.14/−0.15
QCD background prediction	+0.10/−0.08
Size of simulated samples	+0.10/−0.10
Total systematic	+0.28/−0.25
Statistical	+0.15/−0.15
Total	+0.32/−0.29

Top + Higgs

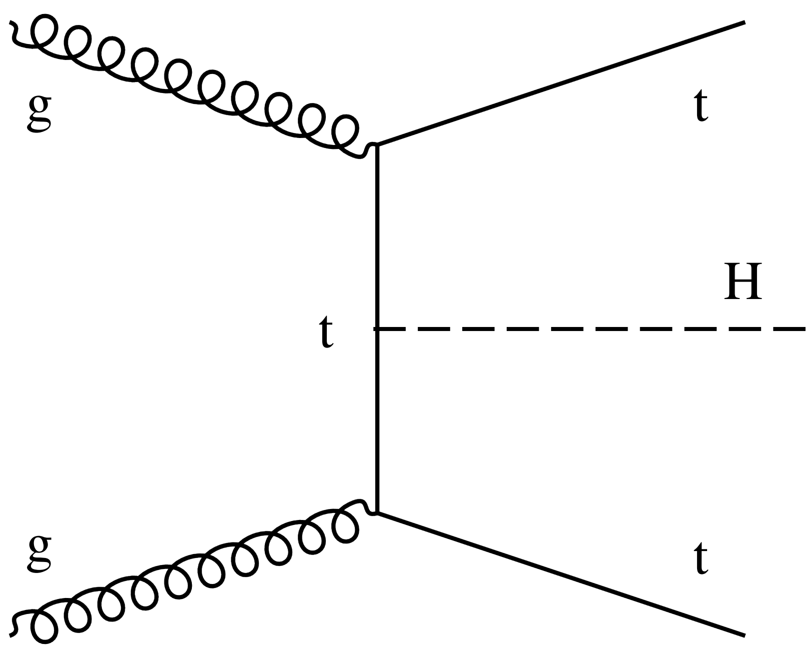
- Two production modes : tHq and tHW
  - tHq : characterised by forward q+b
  - tHW : three heavy central objects
- Rare cross-section : ~90 fb
  - Can be enhanced by sign-flipped y_t or BSM models (eg 2HDM)



- Two decay channels covered here: bb and $\gamma\gamma$
  - bb : dominated by tt+jets background
  - $\gamma\gamma$: clean trigger signal with mainly Higgs background

Top-Pair + Higgs

- ttH final state classified by top-pair decay modes
  - Single lepton, dilepton, all-hadronic
- Rare decay mode : ~500 fb



- Two decay channels covered here: bb and $\gamma\gamma$
  - bb : dominated by tt+jets background
  - $\gamma\gamma$: clean trigger signal and mass peak

CMS tH

University of Glasgow

Signal region	
One muon (electron) with $p_T > 27(35)$ GeV	
No additional loose leptons	
Three or four medium b-tagged jets	
$p_T > 30$ GeV and $\|\eta\| < 2.4$	
One or more untagged jets	
$p_T > 30$ GeV for $\|\eta\| < 2.4$ or	
$p_T > 40$ GeV for $\|\eta\| \geq 2.4$	
$p_T^{miss} > 35(45)$ GeV for muons (electrons)	
Control region	
Two leptons: $p_T > 20/20$ GeV ($\mu^{\pm}\mu^{\mp}$)	
or $p_T > 20/15$ GeV ($e^{\pm}e^{\mp}/\mu^{\pm}e^{\mp}$)	
No additional loose leptons	
Two medium b-tagged jets	
$p_T > 30$ GeV and $\|\eta\| < 2.4$	
One or more additional loose b-tagged jets	
$p_T > 30$ GeV and $\|\eta\| < 2.4$	
$p_T^{miss} > 40$ GeV	

Process	3 tags	4 tags	Dilepton
$t\bar{t}$+LF	24100 ± 5800	320 ± 180	5300 ± 1000
$t\bar{t}+c\bar{c}$	8500 ± 4900	340 ± 260	2100 ± 1200
$t\bar{t}+b\bar{b}$	4100 ± 2300	780 ± 430	750 ± 440
$t\bar{t}$+b	4000 ± 2100	180 ± 110	770 ± 430
$t\bar{t}$+2b	2300 ± 1200	138 ± 88	400 ± 230
Single top	1980 ± 350	78 ± 26	285 ± 37
$t\bar{t}$Z	202 ± 30	32.0 ± 6.6	54.8 ± 7.3
$t\bar{t}$W	90 ± 23	4.2 ± 2.8	31.4 ± 5.9
tZq	28.3 ± 5.7	2.9 ± 2.3	—
Z+jets	—	—	69 ± 32
Total background	45300 ± 8300	1880 ± 550	9700 ± 1700
$t\bar{t}$H	268 ± 31	62.0 ± 9.9	48.9 ± 5.9
tHq (SM)	11.1 ± 3.3	1.3 ± 0.3	0.31 ± 0.08
tHW (SM)	7.6 ± 1.1	1.1 ± 0.3	1.4 ± 0.2
Total SM	45700 ± 8300	1940 ± 550	9700 ± 1700
tHq ($\kappa_V = 1 = -\kappa_t$)	160 ± 38	19.1 ± 5.2	3.9 ± 1.0
tHW ($\kappa_V = 1 = -\kappa_t$)	92 ± 12	13.7 ± 2.3	17.6 ± 2.2
Data	44311	2035	9065

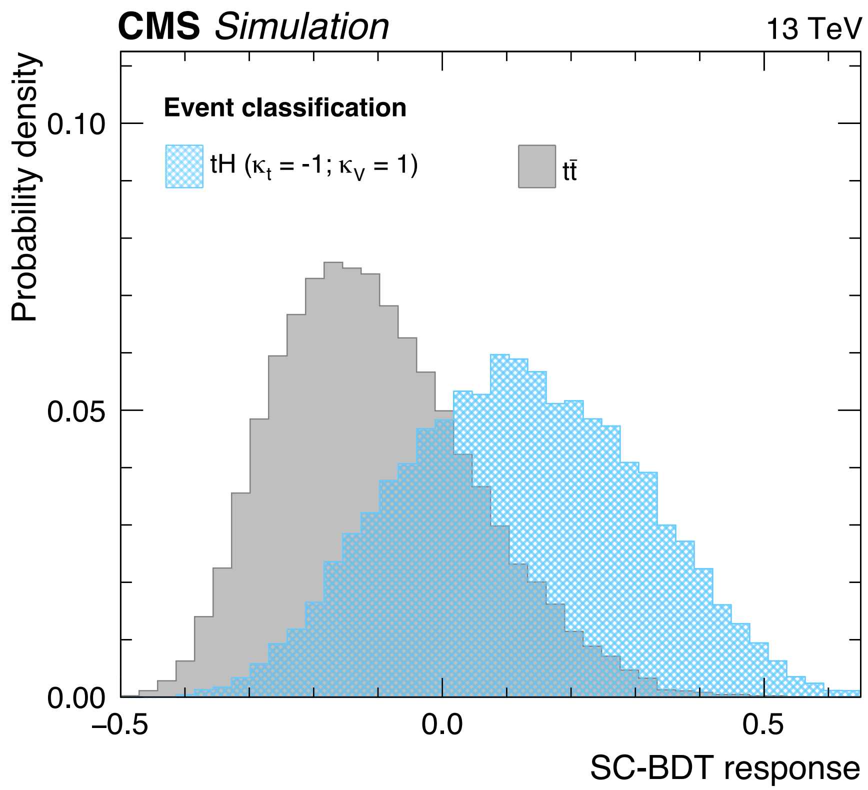
CMS tH

Variable	Description
Event variables	
ln m_3	Invariant mass of three hardest jets in the event
Aplanarity	Aplanarity of the event [?]
Fox–Wolfram #1	First Fox–Wolfram moment [?] of the event
$q(\ell)$	Electric charge of the lepton
$\mathrm{t\bar{t}}$ jet assignment variables	
ln $m(\mathrm{t_{had}})$	Invariant mass of the reconstructed hadronically decaying top quark
CSV($\mathrm{W_{had}}$ jet 1)	Output of the b tagging discriminant for the first jet assigned to the hadronically decaying W boson
CSV($\mathrm{W_{had}}$ jet 2)	Output of the b tagging discriminant for the second jet assigned to the hadronically decaying W boson
ΔR($\mathrm{W_{had}}$ jets)	ΔR between the two light jets assigned to the hadronically decaying W boson
tHq jet assignment variables	
ln p_T(H)	Transverse momentum of the reconstructed Higgs boson candidate
$\lvert\eta$(light-flavor jet)$\rvert$	Absolute pseudorapidity of light-flavor forward jet
ln m(H)	Invariant mass of the reconstructed Higgs boson candidate
CSV(H jet 1)	Output of the b tagging discriminant for the first jet assigned to the Higgs boson candidate
CSV(H jet 2)	Output of the b tagging discriminant for the second jet assigned to the Higgs boson candidate
$\cos\theta(\mathrm{b_t}, \ell)$	Cosine of the angle between the b-tagged jet from the top quark decay and the lepton
$\cos\theta^*$	Cosine of the angle between the light-flavor forward jet and the lepton in the top quark rest frame
$\lvert\eta(\mathrm{t}) - \eta(\mathrm{H})\rvert$	Absolute pseudorapidity difference of reconstructed Higgs boson and top quark
ln p_T(light jet)	Transverse momentum of the light-flavor forward jet
tHW jet assignment variable	
JA-BDT response	Best output of the tHW JA-BDT

SC-BDT

Variable	Description
CSV(bjet 3)	Output of the b tagging discriminant for the b-tagged jet with the third-highest b tagging value in the event
n_jets(tight)	Number of jets in the event passing the tight working point of the b tagging algorithm
CvsL(jet p_T 3)	Output of the charm *vs.* light-flavor tagging algorithm for the jet with the third-highest transverse momentum in the event
CSV(b-tagged jet 2)	Output of the b tagging discriminant for the b-tagged jet with the second-highest b tagging value in the event
CvsL(jet p_T 4)	Output of the charm *vs.* light-flavor tagging algorithm for the jet with the fourth-highest transverse momentum in the event
CvsB(jet p_T 3)	Output of the charm *vs.* bottom flavor tagging algorithm for the jet with the third-highest transverse momentum in the event
CSV(b-tagged jet 4)	Output of the b tagging discriminant for the b-tagged jet with the fourth-highest b tagging value in the event
n_jets(loose)	Number of jets in the event passing the loose working point of the b tagging algorithm

FC-BDT



CMS ttH

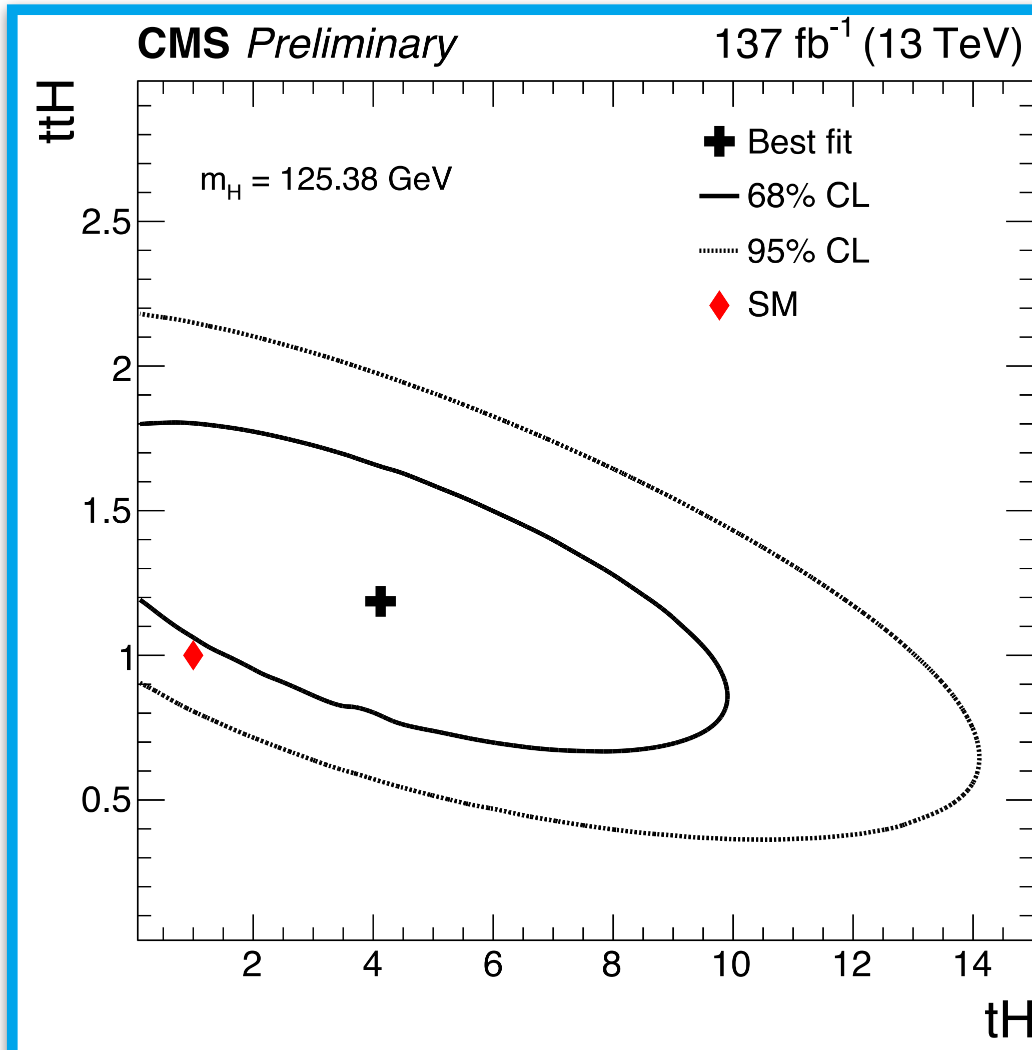
	Total	$t\bar{t}$H (%)	tH (%)	ggH (%)	VH (%)	VBF (%)	$b\bar{b}$H (%)
Had1	5.8	89.1	6.8	3.3	0.8	<0.1	0.1
Had2	4.2	82.9	6.8	8.7	1.4	0.2	0.1
Had3	11.6	78.6	7.2	10.3	3.5	0.3	0.1
Had4	13.6	65.4	7.7	19.3	6.9	0.7	0.1
Lep1	5.8	90.6	7.9	0.5	1.0	<0.1	<0.1
Lep2	4.9	90.0	6.7	0.4	2.9	<0.1	<0.1
Lep3	3.5	86.2	7.4	0.4	6.0	<0.1	<0.1
Lep4	5.7	78.1	8.2	1.1	12.7	<0.1	<0.1
Total	55.1	79.5	7.4	8.2	4.7	0.3	<0.1

CMS ttH+tH $\gamma\gamma$

CMS-PAS-HIG-19-015 **137 fb^{-1}**

University of Glasgow

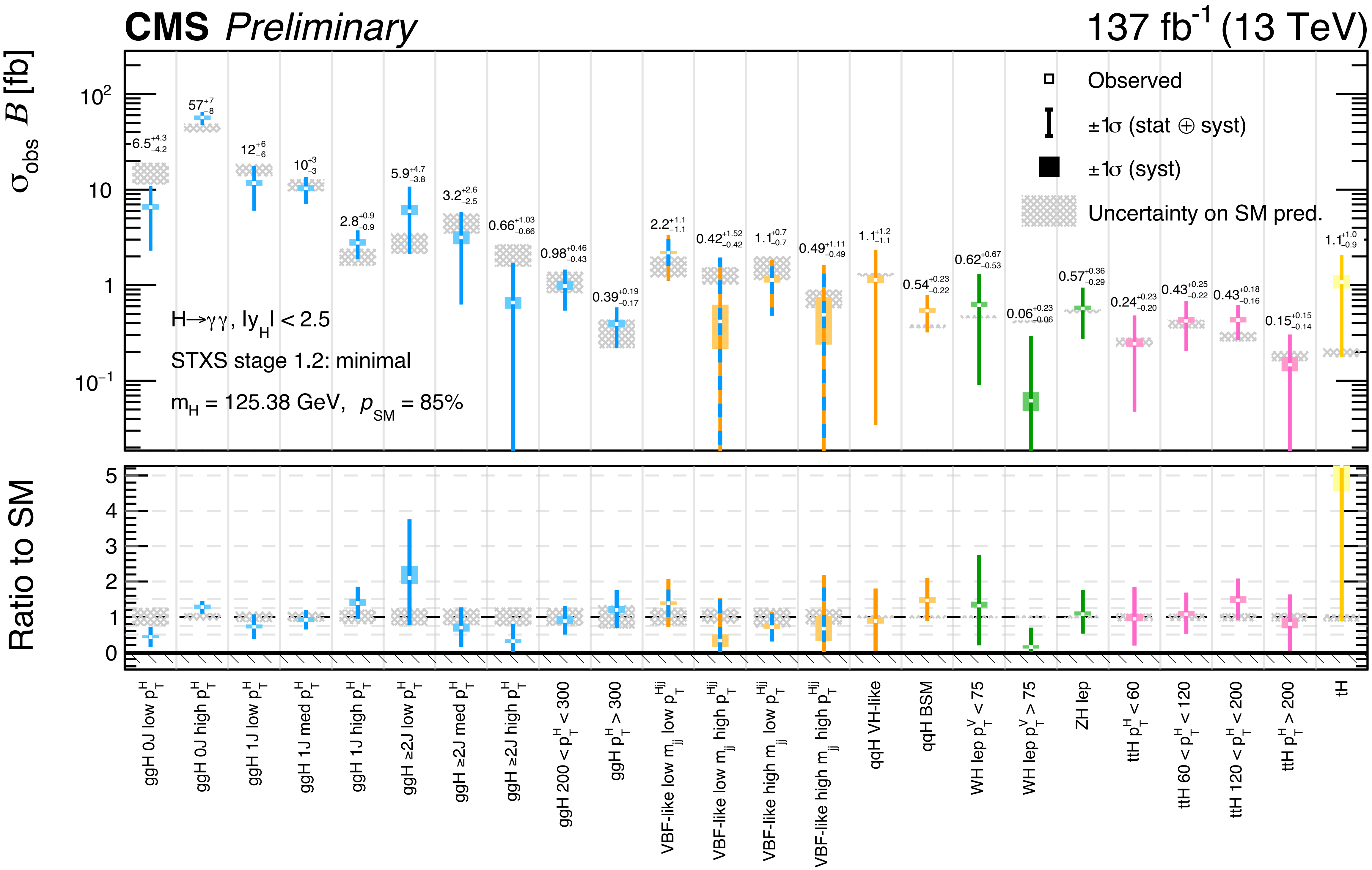
- Combined STXS measurement of all Higgs production modes has been performed
  - Minor changes are made to ttH analysis strategy with equivalent performance
  - ttH channel: 4 bins, tH channel: 1 bin
- The tH contribution is improved through using DNN to separate ttH and tHq
  - Combination improves precision on tH
  - Limit on tH (95%) : **12 x SM**



STXS stage 1.2: minimal merging scheme

Parameters	SM prediction (m_H = 125.38 GeV)	$\sigma\mathcal{B}$ [fb] Observed (Expected) Best fit	Stat unc.	Syst unc.	$\sigma\mathcal{B}/(\sigma\mathcal{B})_{SM}$ Observed (Expected) Best fit
ttH $p_T^H < 60$	$0.26^{+0.02}_{-0.03}$	$0.24^{+0.23}_{-0.20}\left(^{+0.23}_{-0.20}\right)$	$^{+0.23}_{-0.20}\left(^{+0.23}_{-0.19}\right)$	$^{+0.03}_{-0.02}\left(^{+0.03}_{-0.03}\right)$	$0.95^{+0.90}_{-0.76}\left(^{+0.90}_{-0.76}\right)$
ttH $60 < p_T^H < 120$	$0.40^{+0.04}_{-0.04}$	$0.43^{+0.25}_{-0.22}\left(^{+0.26}_{-0.23}\right)$	$^{+0.24}_{-0.22}\left(^{+0.26}_{-0.23}\right)$	$^{+0.03}_{-0.02}\left(^{+0.04}_{-0.04}\right)$	$1.07^{+0.62}_{-0.55}\left(^{+0.65}_{-0.57}\right)$
ttH $120 < p_T^H < 200$	$0.29^{+0.03}_{-0.04}$	$0.43^{+0.18}_{-0.16}\left(^{+0.18}_{-0.16}\right)$	$^{+0.18}_{-0.16}\left(^{+0.18}_{-0.16}\right)$	$^{+0.03}_{-0.02}\left(^{+0.02}_{-0.01}\right)$	$1.47^{+0.62}_{-0.55}\left(^{+0.60}_{-0.53}\right)$
ttH $p_T^H > 200$	$0.18^{+0.02}_{-0.02}$	$0.15^{+0.15}_{-0.14}\left(^{+0.12}_{-0.13}\right)$	$^{+0.15}_{-0.14}\left(^{+0.12}_{-0.13}\right)$	$^{+0.03}_{-0.02}\left(^{+0.02}_{-0.01}\right)$	$0.80^{+0.83}_{-0.78}\left(^{+0.65}_{-0.72}\right)$
tH	$0.20^{+0.01}_{-0.03}$	$1.08^{+1.03}_{-0.90}\left(^{+0.88}_{-0.20}\right)$	$^{+1.02}_{-0.88}\left(^{+0.88}_{-0.20}\right)$	$^{+0.19}_{-0.14}\left(^{+0.11}_{-0.11}\right)$	$5.27^{+5.07}_{-4.39}\left(^{+4.33}_{-1.00}\right)$

CMS ttH + tH



CMS Preliminary
137 fb^{-1} (13 TeV)
σ_{obs} $\mathcal{B}$ [fb]
Ratio to SM
Observed
±1σ (stat ⊕ syst)
±1σ (syst)
Uncertainty on SM pred.
H→γγ, |y$_H$| < 2.5
STXS stage 1.2: minimal
m$_H$ = 125.38 GeV, p_{SM} = 85%
$6.5^{+4.3}_{-4.2}$
57^{+7}_{-8}
12^{+6}_{-6}
10^{+3}_{-3}
$2.8^{+0.9}_{-0.9}$
$5.9^{+4.7}_{-3.8}$
$3.2^{+2.6}_{-2.5}$
$0.66^{+1.03}_{-0.66}$
$0.98^{+0.46}_{-0.43}$
$0.39^{+0.19}_{-0.17}$
$2.2^{+1.1}_{-1.1}$
$0.42^{+1.52}_{-0.42}$
$1.1^{+0.7}_{-0.7}$
$0.49^{+1.11}_{-0.49}$
$1.1^{+1.2}_{-1.1}$
$0.54^{+0.23}_{-0.22}$
$0.62^{+0.67}_{-0.53}$
$0.06^{+0.23}_{-0.06}$
$0.57^{+0.36}_{-0.29}$
$0.24^{+0.23}_{-0.20}$
$0.43^{+0.25}_{-0.22}$
$0.43^{+0.18}_{-0.16}$
$0.15^{+0.15}_{-0.14}$
$1.1^{+1.0}_{-0.9}$
ggH 0J low p_T^H
ggH 0J high p_T^H
ggH 1J low p_T^H
ggH 1J med p_T^H
ggH 1J high p_T^H
ggH ≥2J low p_T^H
ggH ≥2J med p_T^H
ggH ≥2J high p_T^H
ggH 200 < p_T^H < 300
ggH p_T^H > 300
VBF-like low m_{jj} low p_T^{Hjj}
VBF-like low m_{jj} high p_T^{Hjj}
VBF-like high m_{jj} low p_T^{Hjj}
VBF-like high m_{jj} high p_T^{Hjj}
qqH VH-like
qqH BSM
WH lep p_T^V < 75
WH lep p_T^V > 75
ZH lep
ttH p_T^H < 60
ttH 60 < p_T^H < 120
ttH 120 < p_T^H < 200
ttH p_T^H > 200
tH

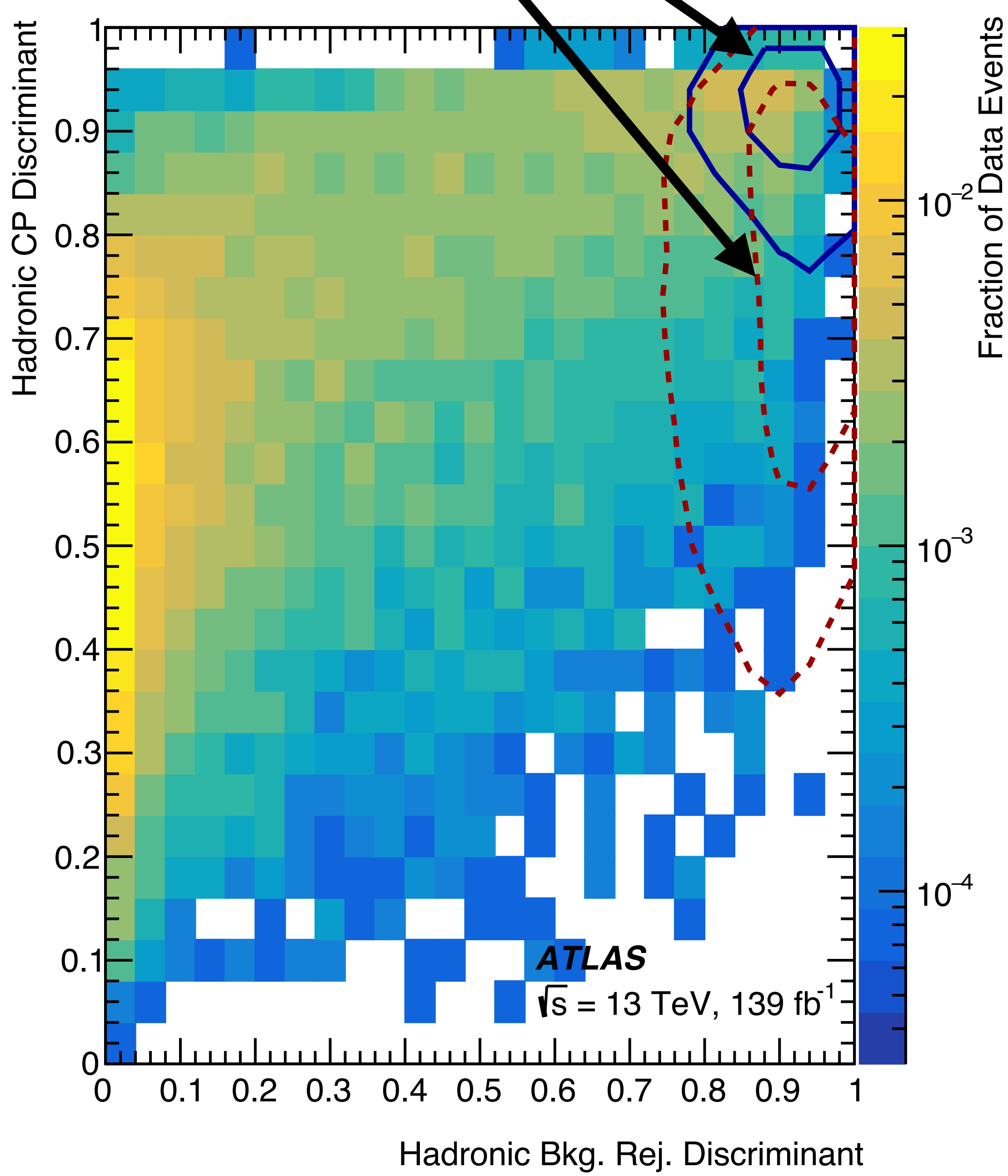
ATLAS tH+ttH $\gamma\gamma$

139 fb^{-1}

University of Glasgow

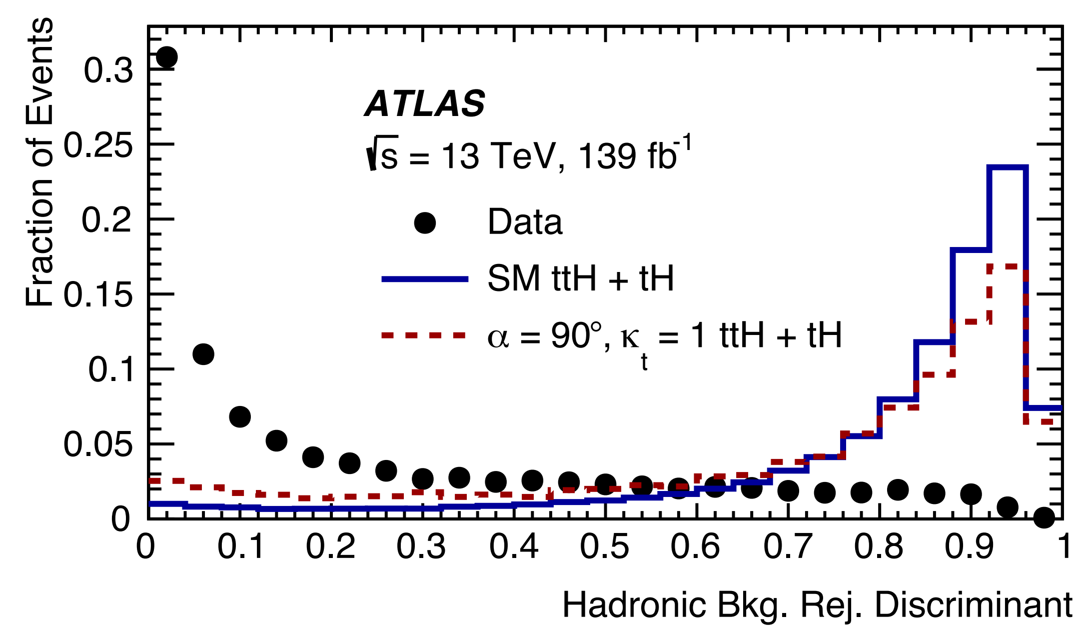
50% of signal

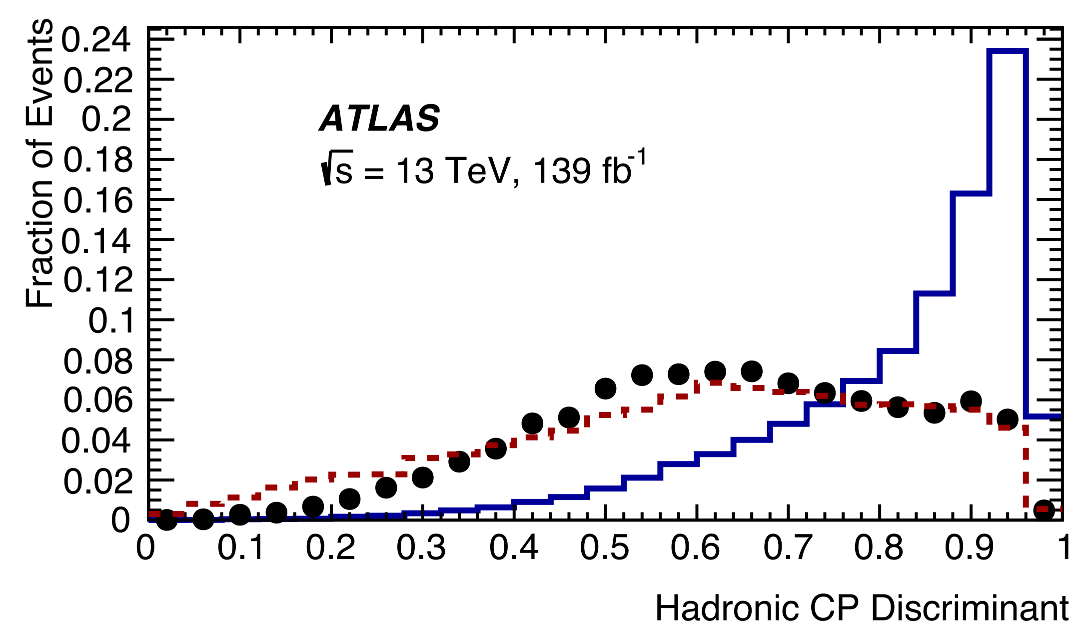
25% of signal



CP even tH + ttH

CP odd tH + ttH





Normalised to unit area