University of Zurich[UZH]

Results on t(t)H and four-top-quark production, and the treatment of ttX (W/Z/bb) backgrounds

13th International Workshop on Top-Quark Physics (TOP2020)

15.09.20

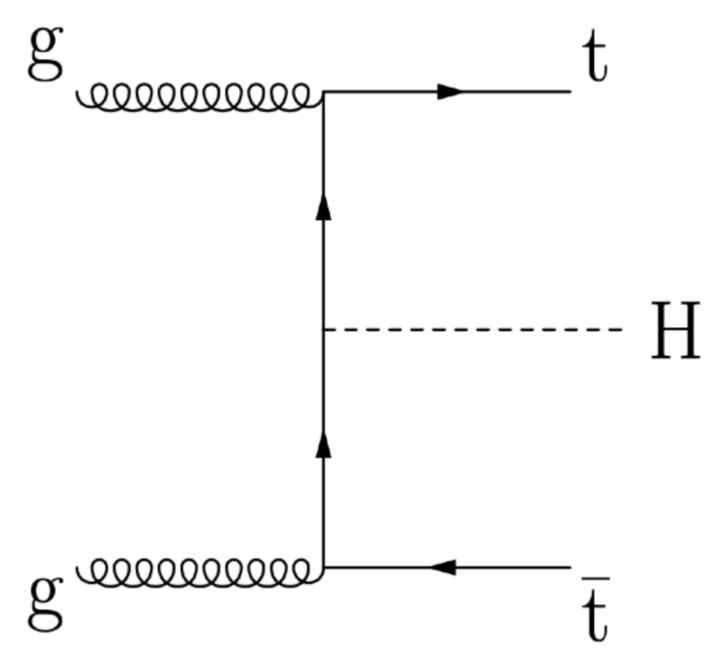
Korbinian Schweiger on behalf of the ATLAS and CMS Collaborations

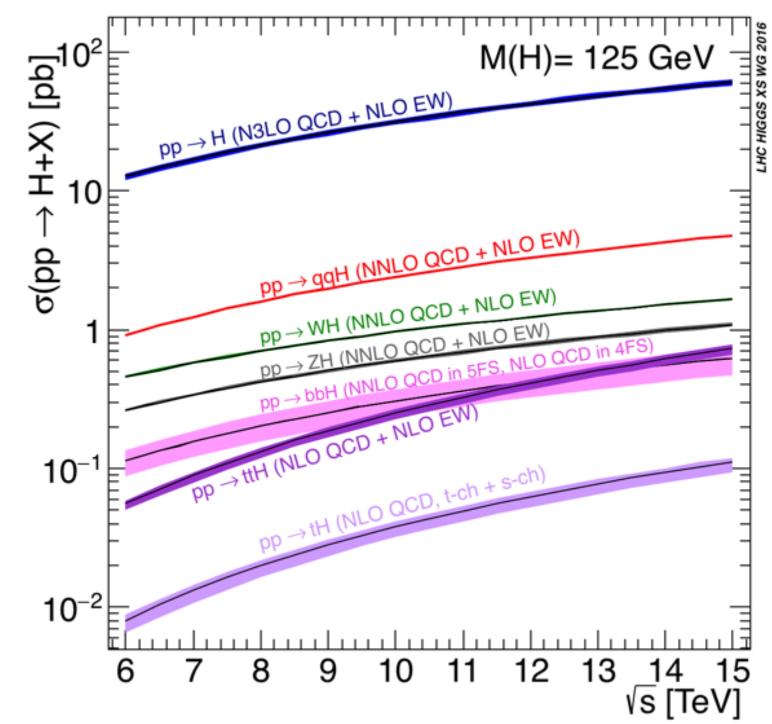
ATLAS EXPERIMENT

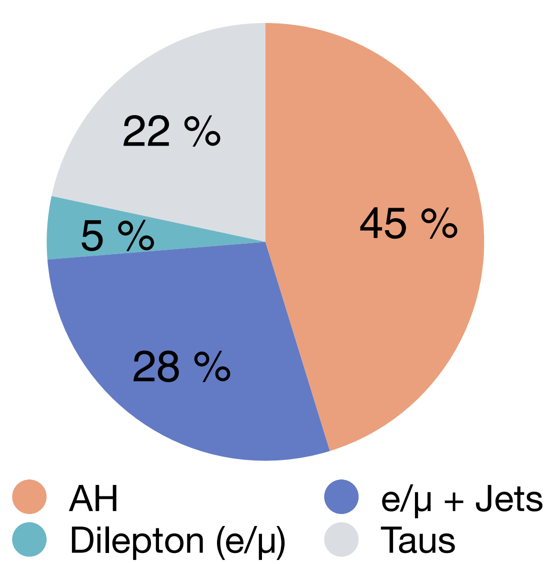
CMS Compact Muon Solenoid

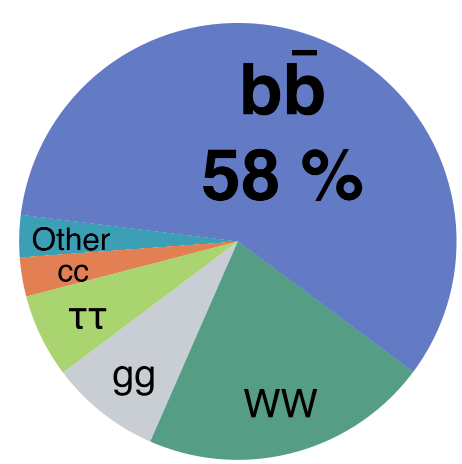
Why is ttH interesting?

- Production of $t\bar{t}H$ is rare → σ ~ 0.5 pb
- Direct measurement of Top-Yukawa coupling y_t at LHC only possible with $t\bar{t}H$ and tH
  - y_t expected to be largest Higgs-ferminon coupling in SM
  - Heavy particles from BSM physics would lead to significant deviation
- Searches/Measurements are targeting different combinations of **Top-quark pair** and **Higgs-boson decay modes**

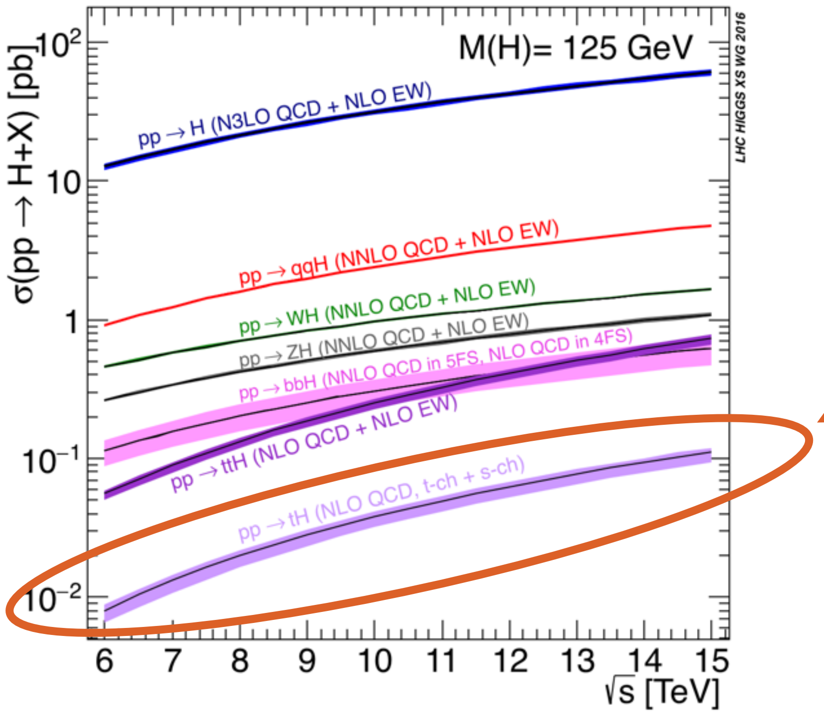








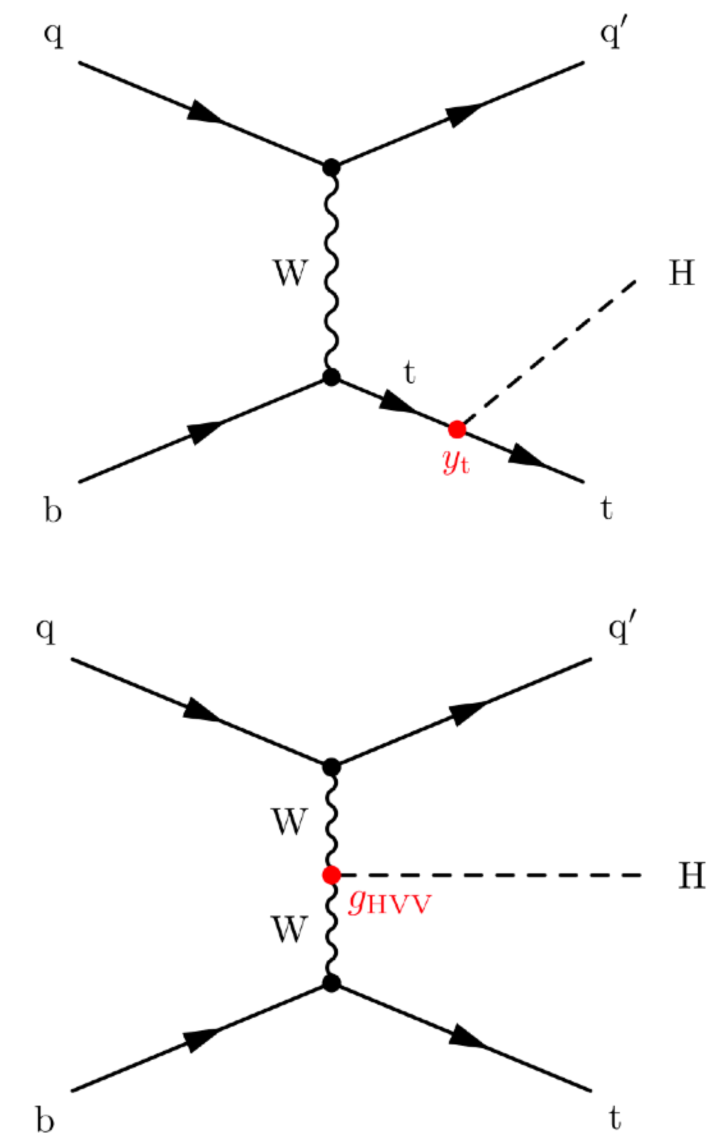
Why do we want to measure tH?



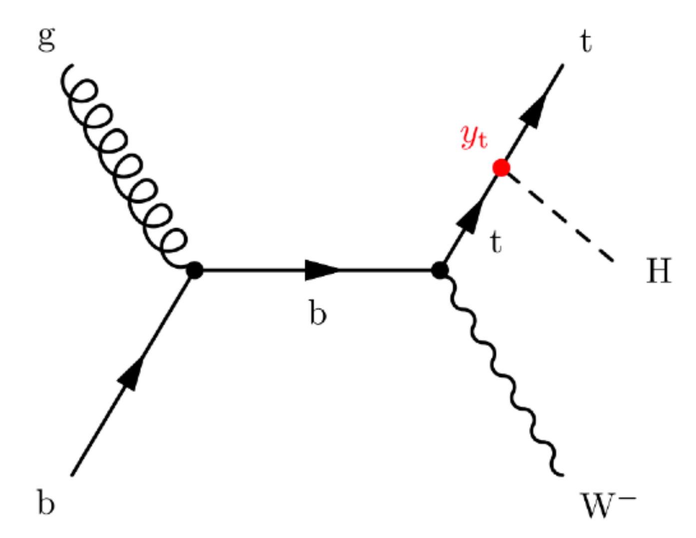
Even smaller production cross-section than $t\bar{t}H$!

- $t\bar{t}H$ can only determine magnitude of y_t
  - tH is sensitive to sign!
  - Depending on relative sign of g_W and y_t destructive (SS) or constructive (OS)
- tH can be measured simultaneously with ttH

tHq LO



tHW LO



Publication Overview - $t\bar{t}$H/tH

If not otherwise indicated on the slide, the first publication in the respective box is presented

- up to 2016 data taking period
- up to 2017 data taking period
- up to Full Run-2

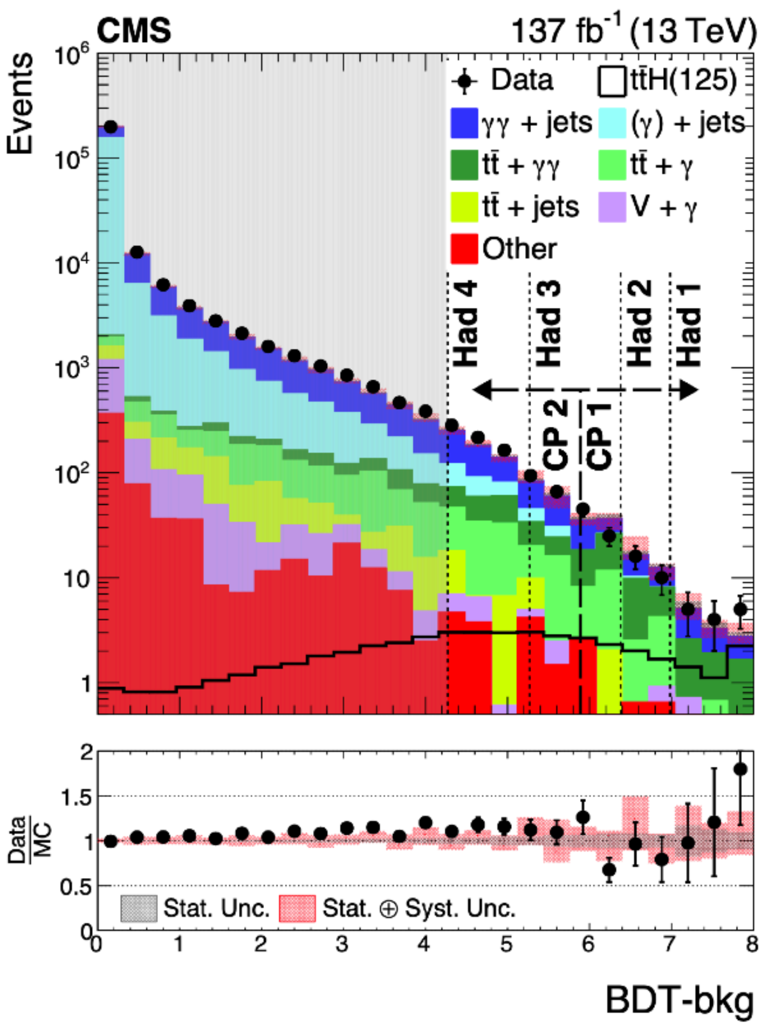
	ATLAS EXPERIMENT	CMS
H → γγ	Phys. Rev. Lett. 125 (2020) 061802 ATLAS-CONF-2020-026 *(H→γγ comb.)*	Phys.Rev.Lett. 125 (2020) 6, 061801 CMS-PAS-HIG-19-015 *(H → γγ comb., includes a.o. tH)*
H → Multilepton	ATLAS-CONF-2019-045	CMS-PAS-HIG-19-008
H → ZZ → 4l	2004.03447 *(H→ZZ→4l)*	CMS-PAS-HIG-19-001 *(H→ZZ→4l)* CMS-PAS-HIG-19-009 *(H→ZZ→4l anomalous couplings)*
H → bb	Phys. Rev. D. 97 (2018) 072016	CMS-PAS-HIG-18-030
Combinations	ATLAS-CONF-2020-027 *(Higgs Comb)* Phys. Lett. B 784 (2018) 173 *(ttH)*	Eur.Phys.J. C 79 (2019) 421 *(Higgs Comb)* Phys.Rev.Lett. 120 (2018) 231801 *(ttH)* Phys. Rev. D99 (2019) 092005 *(tH)*

$t\bar{t}H(\gamma\gamma)$ - Strategy

Full Run-2 results available by both experiments! + CP measurement

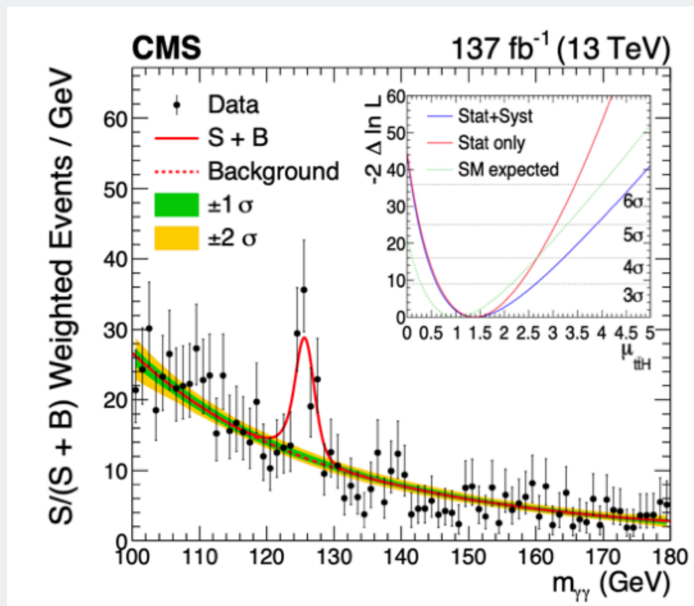
- Select events with two isolated photons in Higgs-boson mass range
  - $m_{\gamma\gamma} \in [105,160]$ (ATLAS) / $[100,180]$ (CMS)
- Categorization into leptonic and hadronic channels
  - Leptonic: ≥ 1 Jet (CMS) / ≥ 1 b-Jet (ATLAS) and ≥ 1 lepton (e/μ)
  - Hadronic: ≥ 3 Jets, ≥ 1 b-Jet and no leptons
- Main background $t\bar{t}$+γγ (both channels) and γγ+Jets (hadronic channel)
- Construct discriminant per channel BDT(**CMS**) / BDT+CP-BDT(**ATLAS**)

Had. Channels



$t\bar{t}H(\gamma\gamma)$ - Fit to $m_{\gamma\gamma}$

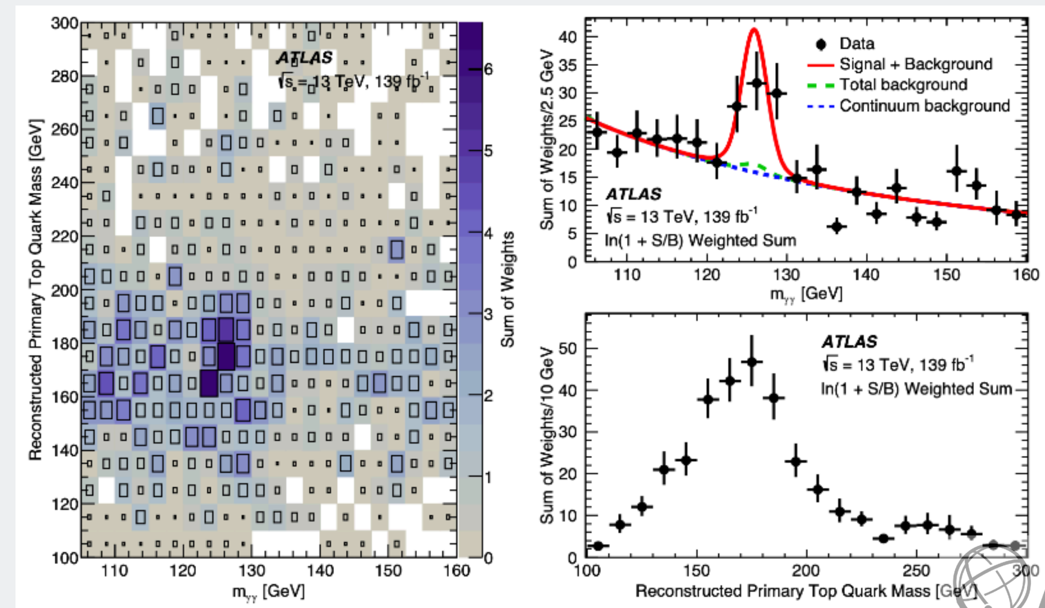
- $\sigma_{ttH} \cdot B_{\gamma\gamma} = 1.56^{+0.33}_{-0.30}$(stat)$^{+0.09}_{-0.08}$(sys) fb
  - $\mu_{ttH} = 1.38^{+0.36}_{-0.29}$(stat)$^{+0.21}_{-0.11}$(sys)



CMS-PAS-HIG-19-015

- From the H→ γγ combination:
  - Observed : $\sigma_{tH} \cdot B_{\gamma\gamma} = 0.8^{+0.8}_{-0.7}$ fb (UL of 12 times SM rate)

- $\sigma_{ttH} \cdot B_{\gamma\gamma} = 1.64^{+0.38}_{-0.36}$(stat)$^{+0.17}_{-0.14}$(sys) fb
  - $\mu_{ttH} = 1.43^{+0.33}_{-0.31}$(stat)$^{+0.21}_{-0.15}$(sys)



ATLAS-CONF-2020-026

- From the H→ γγ combination:
  - UL on tH production rate of 8 times SM prediction

Observation of the $t\bar{t}H$ process in a single Higgs-boson decay channel now available by ATLAS and CMS

$t\bar{t}H(\gamma\gamma)$ - CP structure measurement

- Measurements point to SM-like $J^{CP}=0^{++}$ Higgs boson

CMS

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

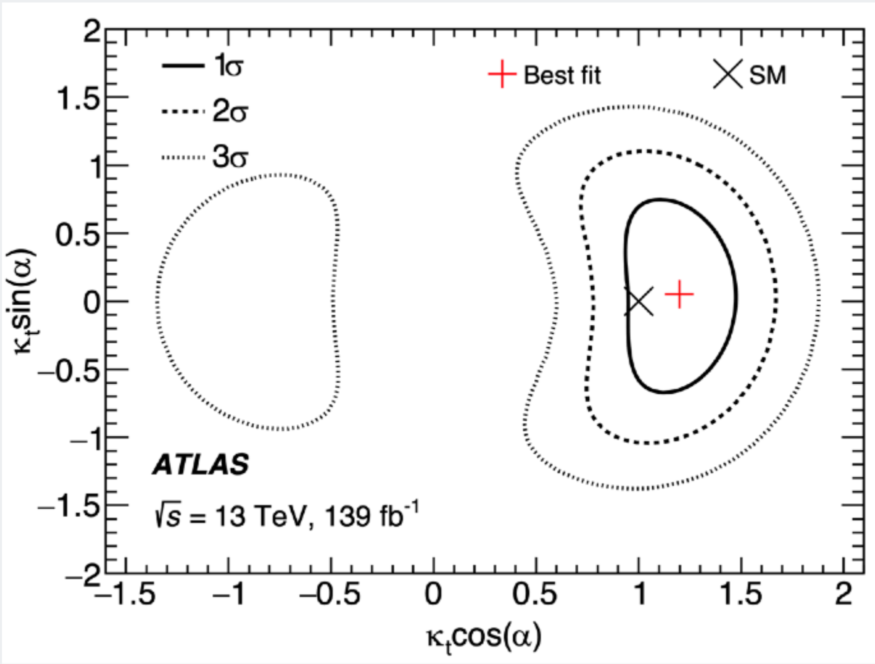
$$f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\mathrm{sign}(\tilde{\kappa}_t/\kappa_t).$$

- CP-even (SM): κ_t=1, $\tilde{\kappa}_t = 0$
- Pure CP-odd ($f_{CP}^{Htt} = 1$) excluded with 3.2σ
- Fractional CP-odd contribution is constrained to $f_{CP}^{Htt} = 0.00 \pm 0.33$ at 68% CL

ATLAS EXPERIMENT

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

- CP-even (SM): κ_t=1, $\alpha = 0°$
- Pure CP-odd ($\alpha = 90°$) excluded with 3.9σ
- $|\alpha| < 43°$ is excluded at 95% CL

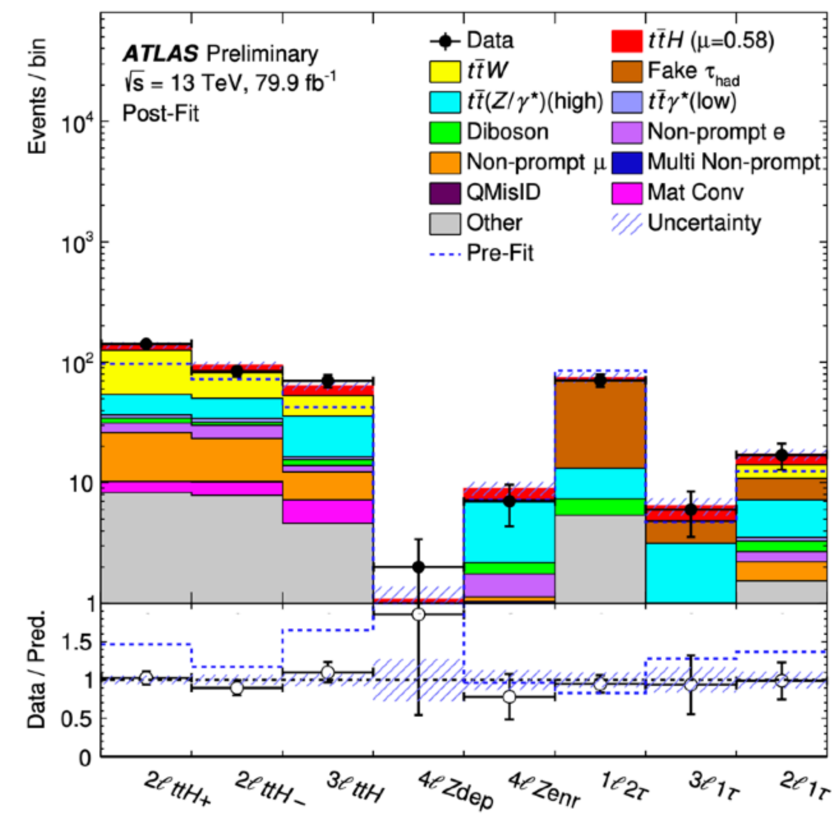


$t\bar{t}H$ Multilepton

$t\bar{t}H(ZZ \rightarrow 4l)$ is included in $H \rightarrow ZZ \rightarrow 4l$ measurement

- Measurement of $t\bar{t}H$ in final states with multiple
  - Electrons, Muons and
    - MVA-based removal of non-prompt leptons (from $t\bar{t}$+b)
  - hadronically decaying τ leptons
    - MVA methods using track and calo features
- Irreducible backgrounds: $t\bar{t}W$, $t\bar{t}(Z/\gamma^*)$ and VV
  - $t\bar{t}W$ and $t\bar{t}Z$ are taken from simulation but still challenging (e.g. modeling of QCD radiation in $t\bar{t}W$)
  - Normalization determined by fit
- Reducible backgrounds: From „non-prompt leptons“, charge misidentified electrons and misidentified τ_{Had}

ATLAS SRs



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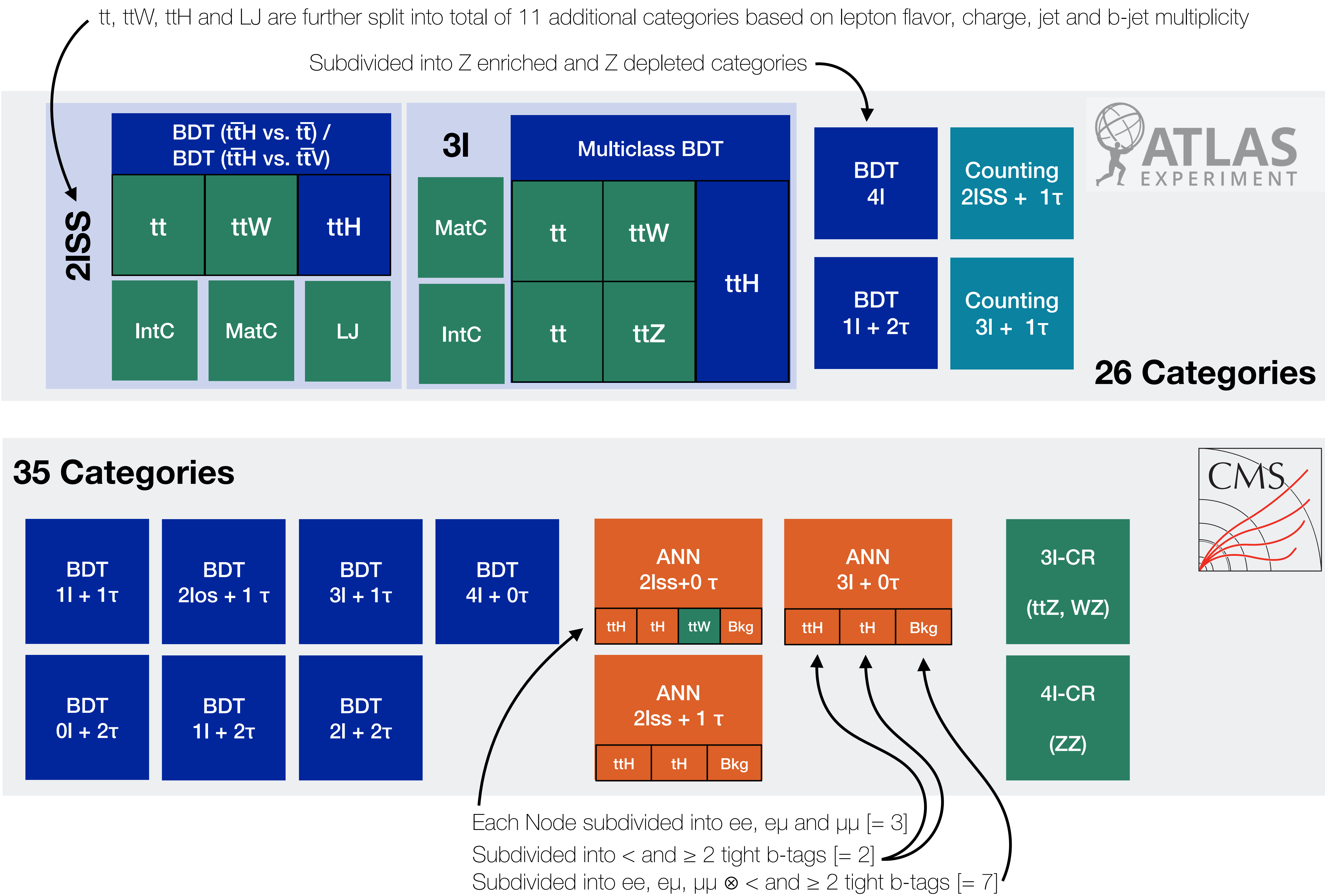
$t\bar{t}H$ Multilepton - Categorization

Control Regions

Signal Regions



$t\bar{t}H$ Multilepton - Result

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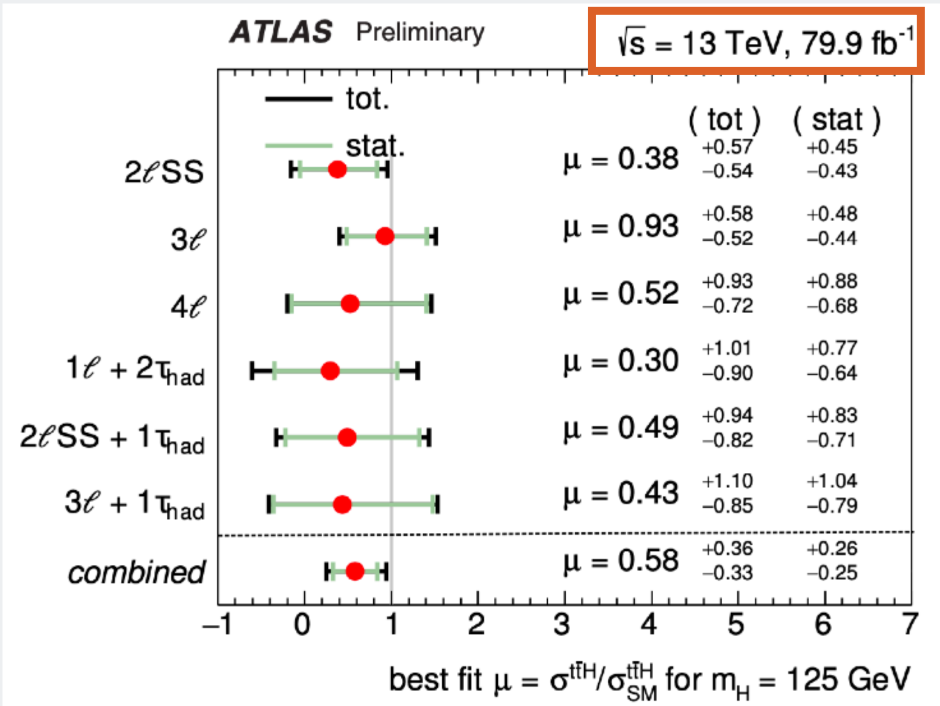
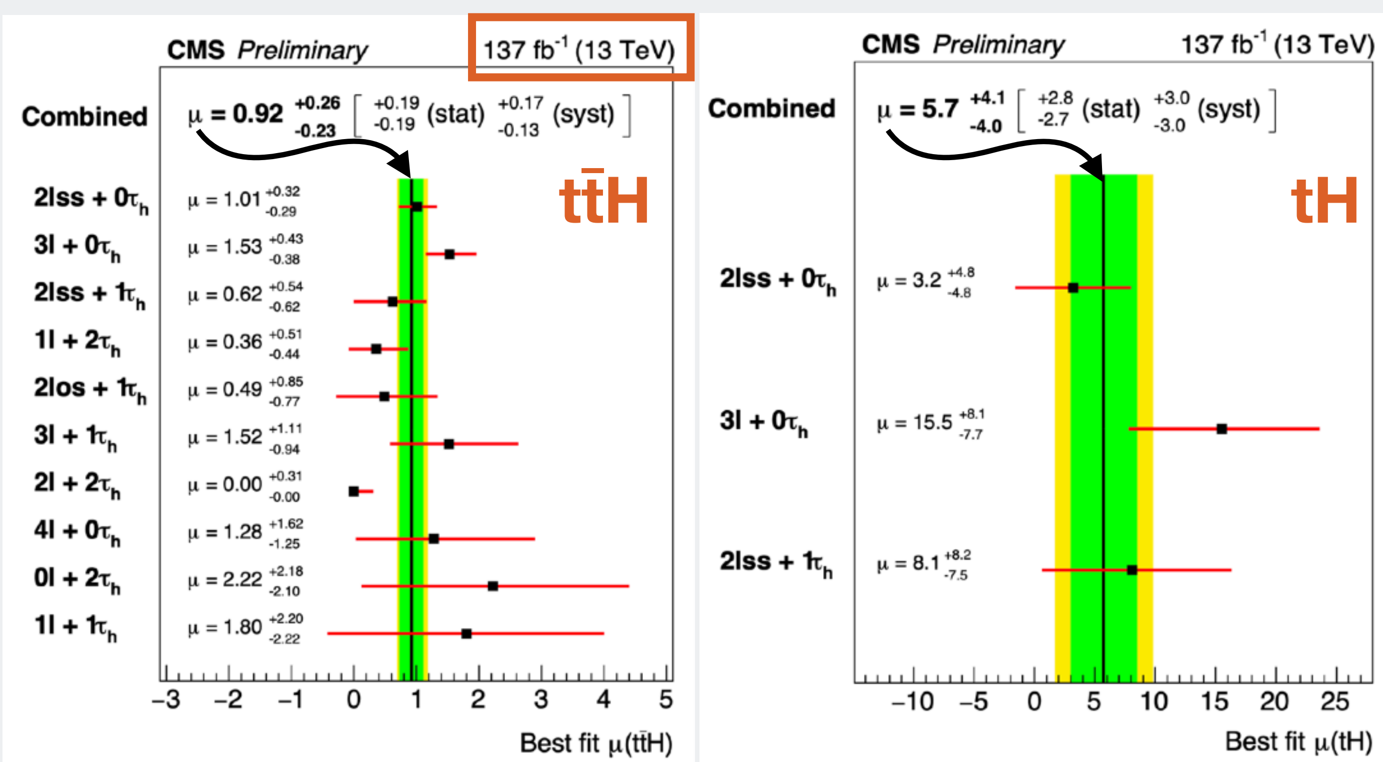


- Simultaneous fit in 25 distributions
- Obs. (exp.) significance 1.8 (3.1)

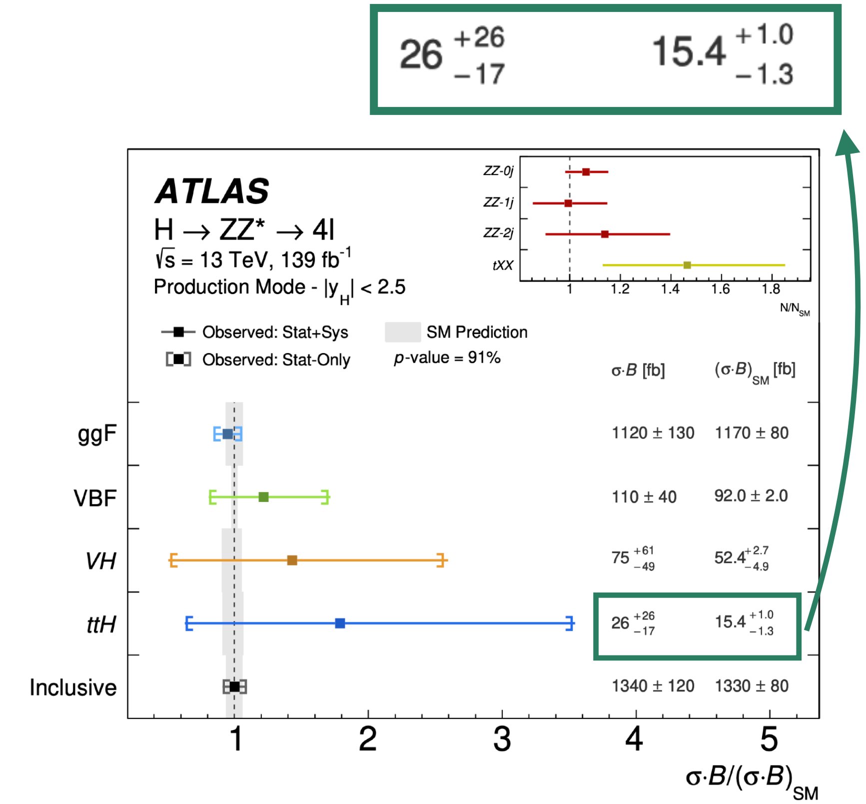


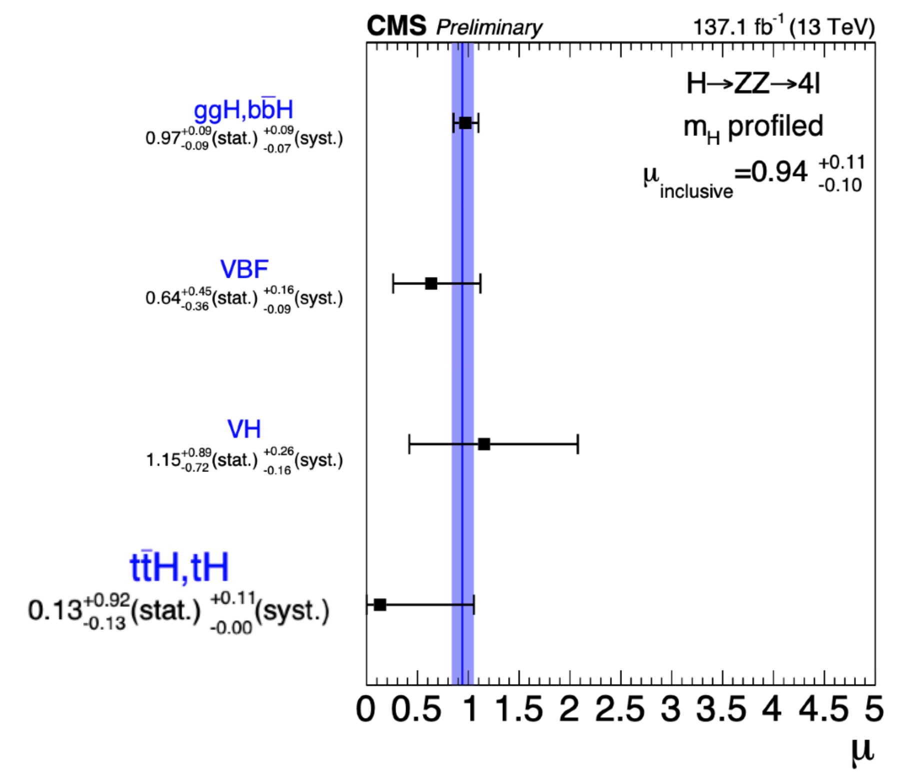
- Simultaneous fit on (35 x 3) distributions
- $t\bar{t}H$: Obs. (exp.) sig. 4.7σ (5.2σ)
  tH : Obs. (exp.) sig. 1.4σ (0.3σ)
- Constrained y_t: $-0.9 < y_t < -0.7$ or $0.7 < y_t < 1.1$ times SM expectation

$t\bar{t}H(ZZ \rightarrow 4l)$

†: Exact selection requirement differ between experiments but are not relevant for this overview

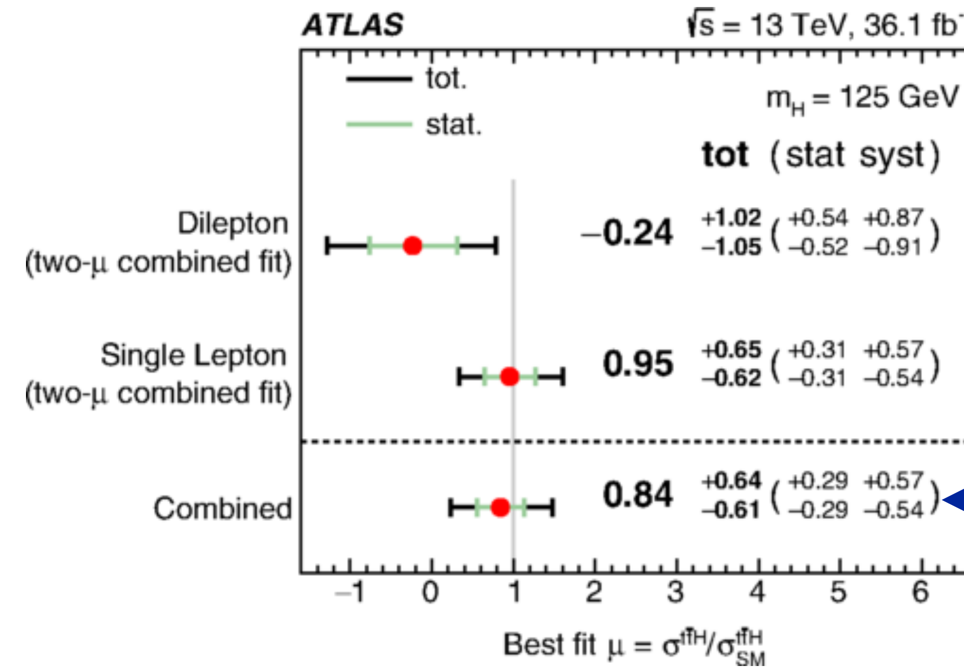
- Events with 2 SFOS lepton pairs passing kin. requirements to increase sensitivity are selected†
- Main irreducible background from ZZ via qq annihilation → $t\bar{t}$+X plays only minor role
- $t\bar{t}$H categories: High number of jets, b-tagged jets and 0 (hadronic channel) or 1 (leptonic channel) additional lepton†
- Signal extraction:
  - **CMS:** Fit to m_{4l} and kin. discriminant $D^{\text{kin}}_{\text{bkg}}$ in all categories
  - **ATLAS:** Fit to NN based discriminants or observed yield depending on category (ttH Had: NN / ttH Lep: yield)
- Various anomalous coupling measurements published (CMS-PAS-HIG-19-009) with full Run-2 dataset by CMS but are still limited by statistics.
  - E.g. anomalous Higgs-boson couplings to top quarks in the ttH process → $f_{CP}^{Htt} = -0.13^{+0.13}_{-0.24}$ observed

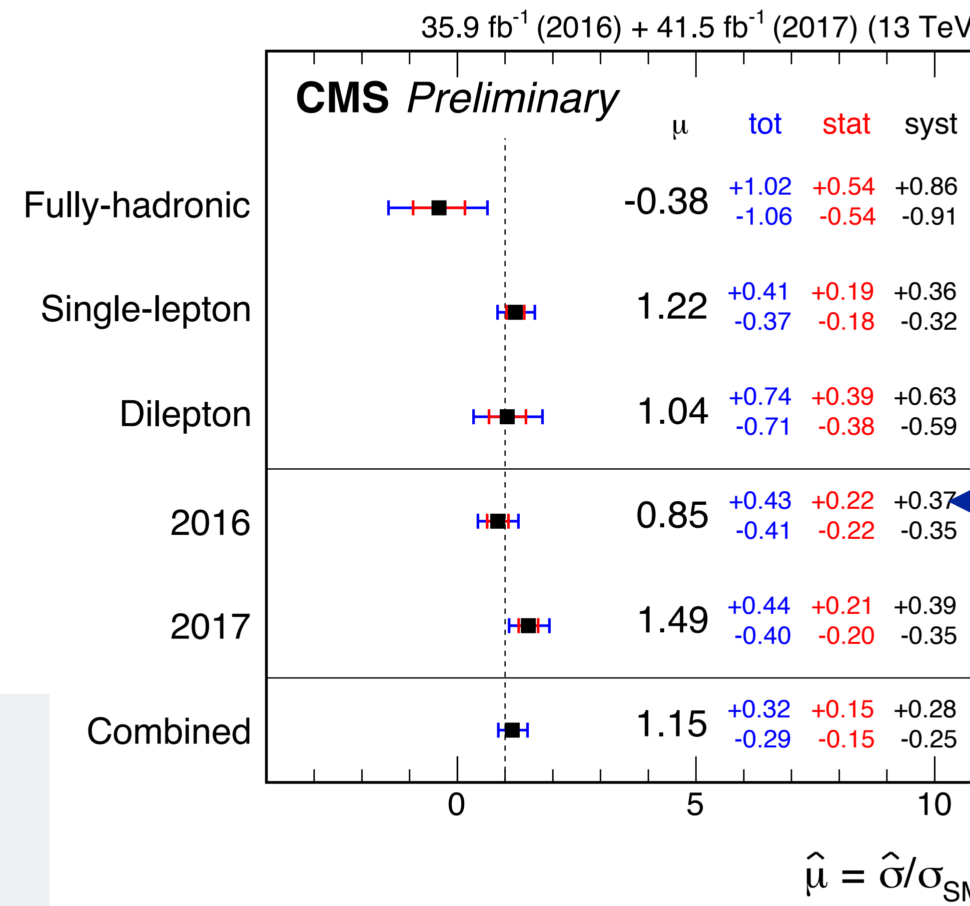




$t\bar{t}H(b\bar{b})$ - Results

- Targeting final states with at least 4 b-tagged jets in the dileptonic, semileptonic and fully-hadronic $t\bar{t}$ decay modes
- Dominated $t\bar{t}$+Jets background
  - Irreducible $t\bar{t}+b\bar{b}$ background
  - Large uncertainties on $t\bar{t}+b\bar{b}$ and $t\bar{t}$+cc normalization
- Measurement dominated by systematic uncertainties
  - b-tagging, $t\bar{t}+b\bar{b}$ modeling





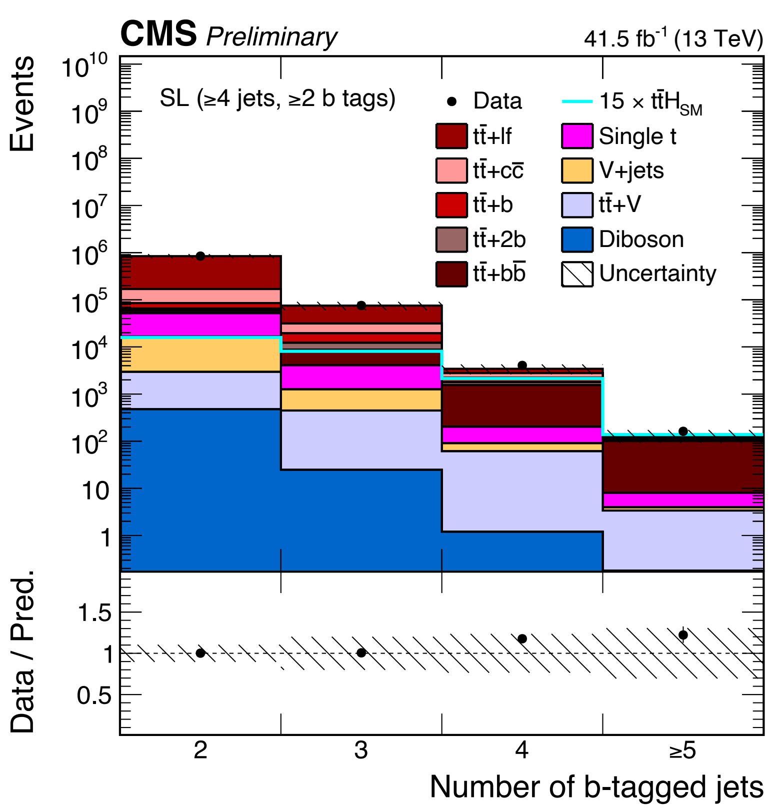
CMS tH combination:

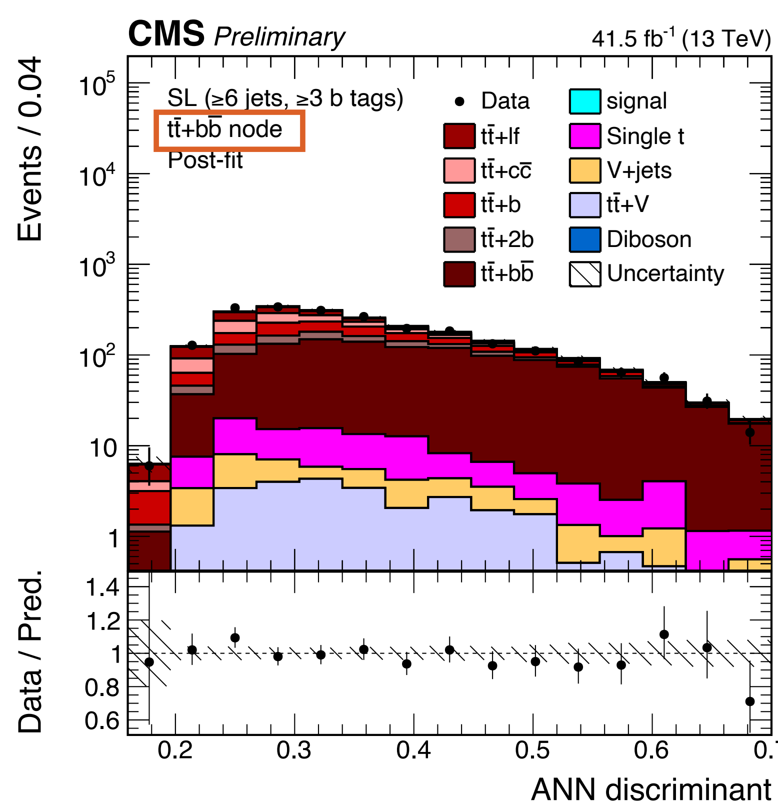
Phys. Rev. D99 (2019) 092005:

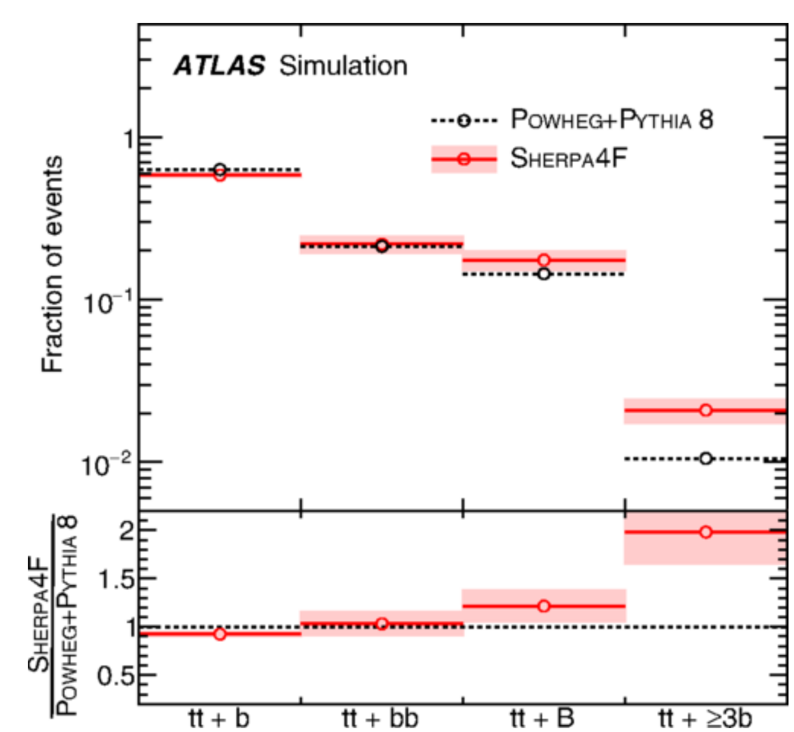
Observed (expected) UL on σ(tH($b\bar{b}$)) 6.88 ($3.19^{+1.46}_{-1.02}$) pb

$t\bar{t}H(b\bar{b})$ -Treatment of the $t\bar{t}+b\bar{b}$ background

- $t\bar{t} + b\bar{b}$ background is taken from 5FS `POWHEG+PYTHIA8` simulation
- A more precise prediction is needed!
  - Large discrepancies in N_{tag} spectrum obeserved
  - Large uncertainties on $t\bar{t}+b\bar{b}$
- Examples how this is tackled:
  - CRs introduced to fit to control $t\bar{t}+b\bar{b}$
  - **ATLAS:** Additional reweighting to improve modeling of additional bJets (4FS vs. 5FS)







Something left to say about $t\bar{t}H$?

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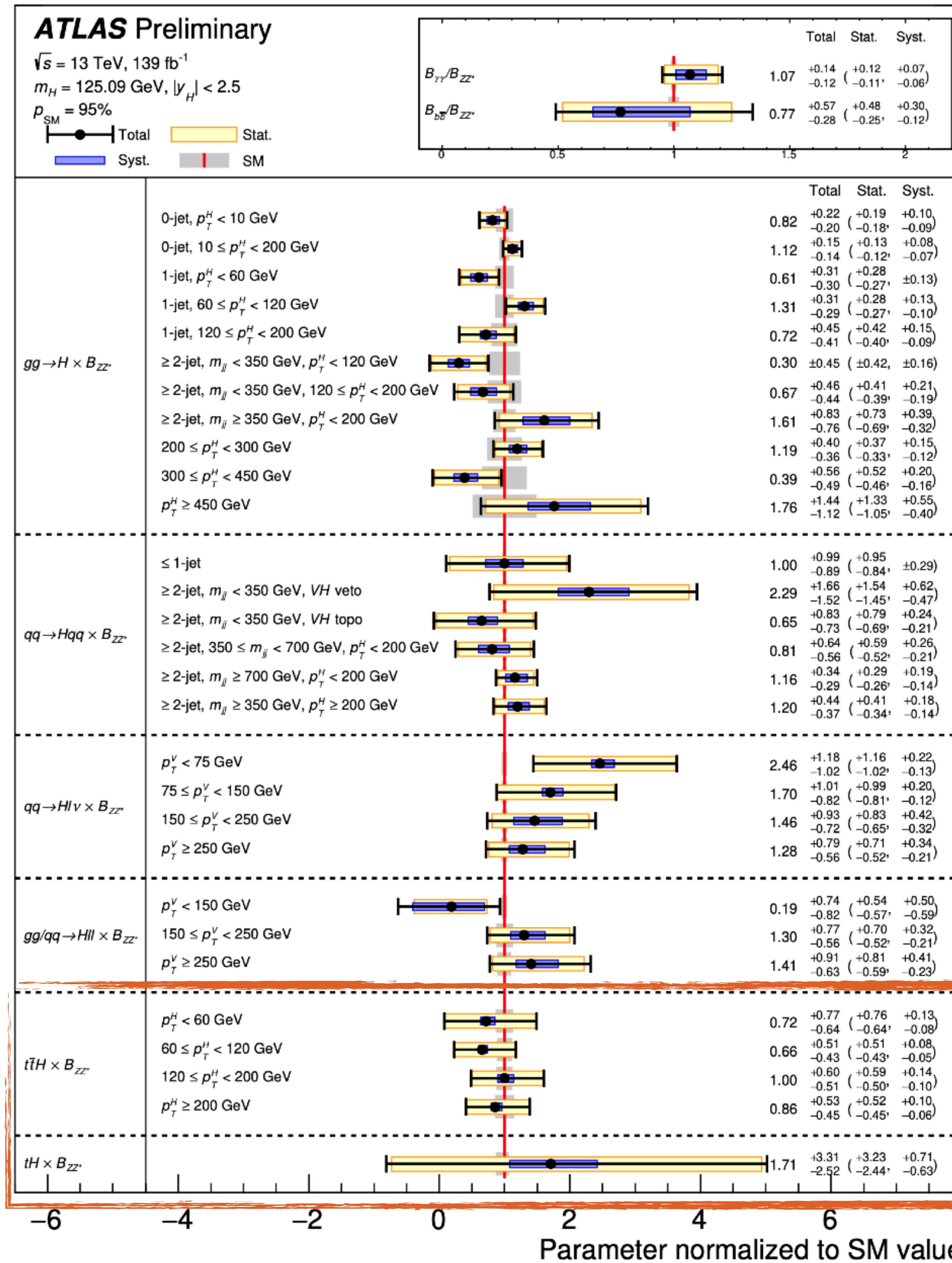
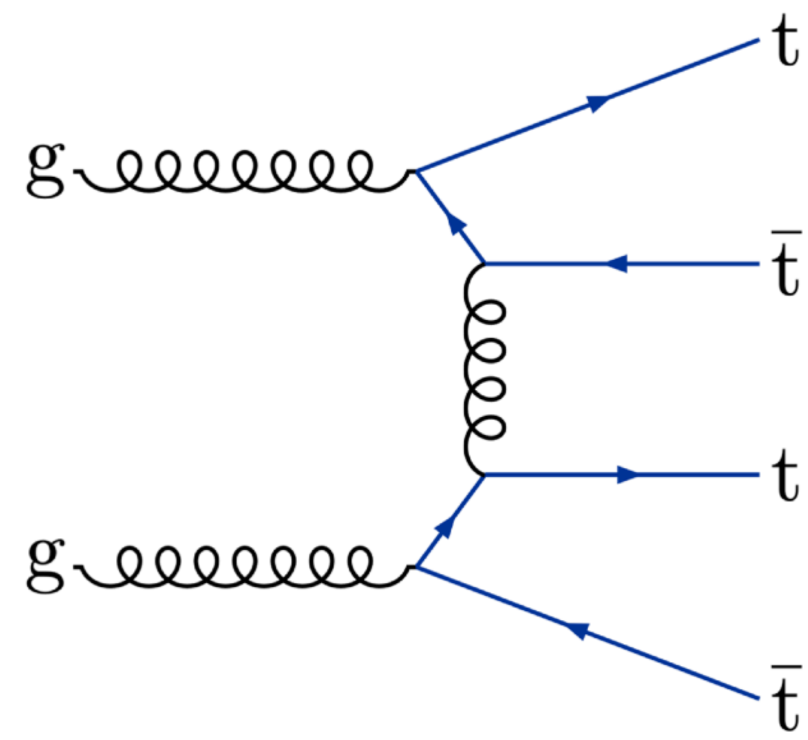
ATLAS-CONF-2020-027

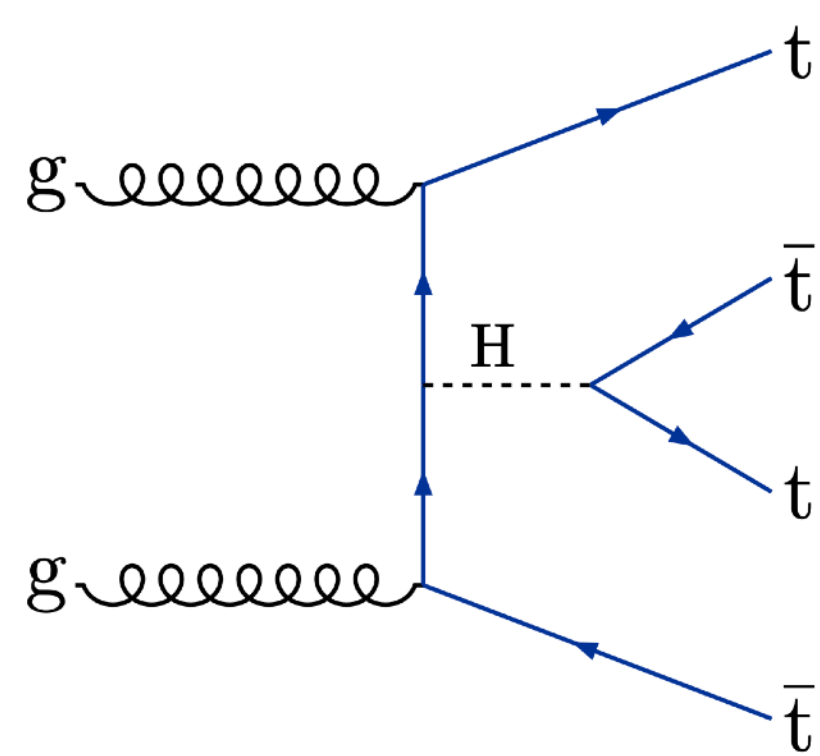
- Latest full Higgs combination published by ATLAS
  - Includes all previously discussed Run-2 results
  - Observed (expected) upper limit at 95% CL on the tH cross section is 8.4 (8.2) times the SM prediction.
  - neg. κ_t excluded with 2.9σ (2.7σ expected) in scenario with no BSM contribution to total Higgs width (Interpretation in κ-framework)



Four-top-quark production

- Production: $\sigma_{pp\rightarrow t\bar{t}t\bar{t},SM} = 12^{+2.2}_{-2.5}$fb
  - Very rare! $\sigma_{pp\rightarrow t\bar{t}H} \approx 500$fb !
  - $t\bar{t}H$ is a background
- All final states are very busy
  - 4 top quarks → 4 b quarks + 4 W bosons
- Can be used to constrain magnitude of y_t CP properties
- Production can be significantly enhanced by BSM particles and interactions





Publication Overview - $t\bar{t}t\bar{t}$

- up to 2016 data taking
- up to 2017 data taking
- Full Run-2

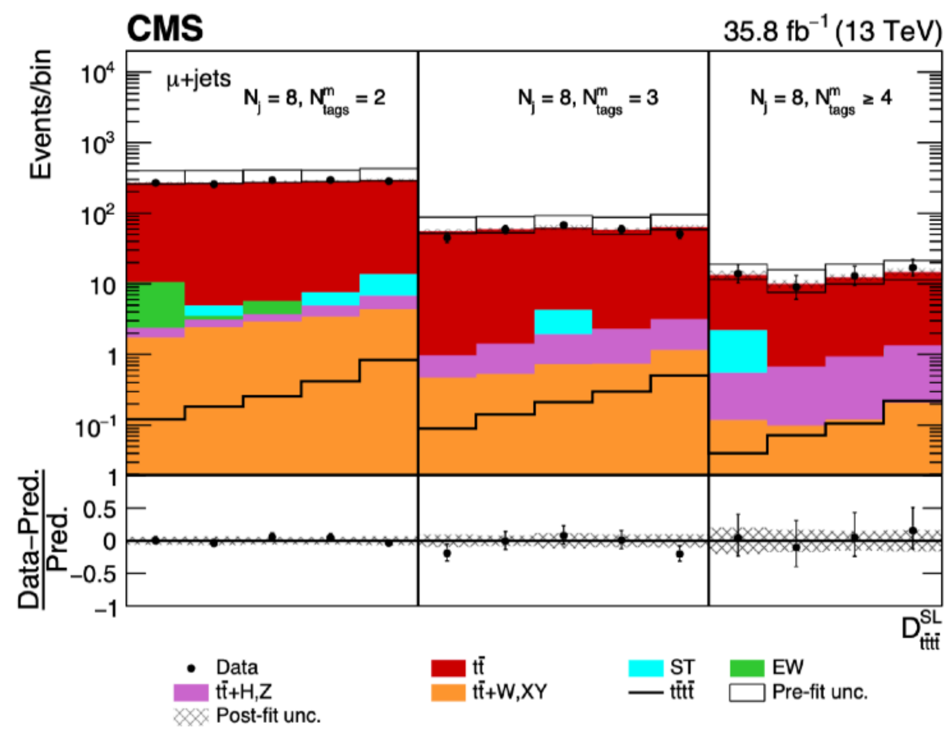
	ATLAS EXPERIMENT	CMS
SL, OS DL		JHEP 11 (2019) 082
SS, multilepton	2007.14858	*Eur.Phys.J.C* 80 (2020) 2, 75

Will not be covered in this Talk:
Detailed presentation
by E. Varnes on Friday at 14:30

$t\bar{t}t\bar{t}$ - SL and OS DL

† : OS, multilepton measurement using 35.8 fb^{-1}. Not the 137 fb^{-1} measurement presented next!

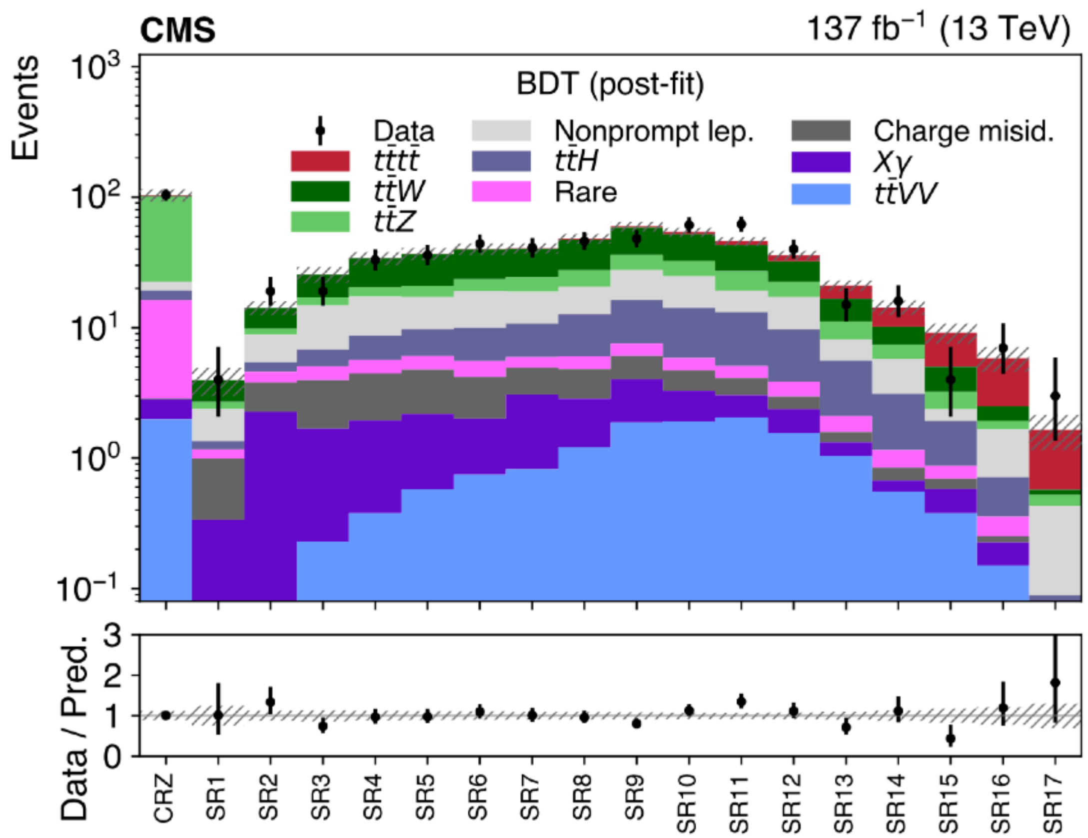
- Analysis done in two channels:
  - **Semileptonic (lj):** Exactly 1 μ(e), ≥ 7 (8) jets with 2 b-tags, HT ≥ 500
  - **Dileptonic(ll)**: Opposite sign lepton (e/μ) pair, ≥ 4 jets with 2 b-tags, HT ≥ 500
- Further categorization to increase sensitivity by jet- and b-tag multiplicity
- Final discriminant: BDT separating between signal and background trained per channel



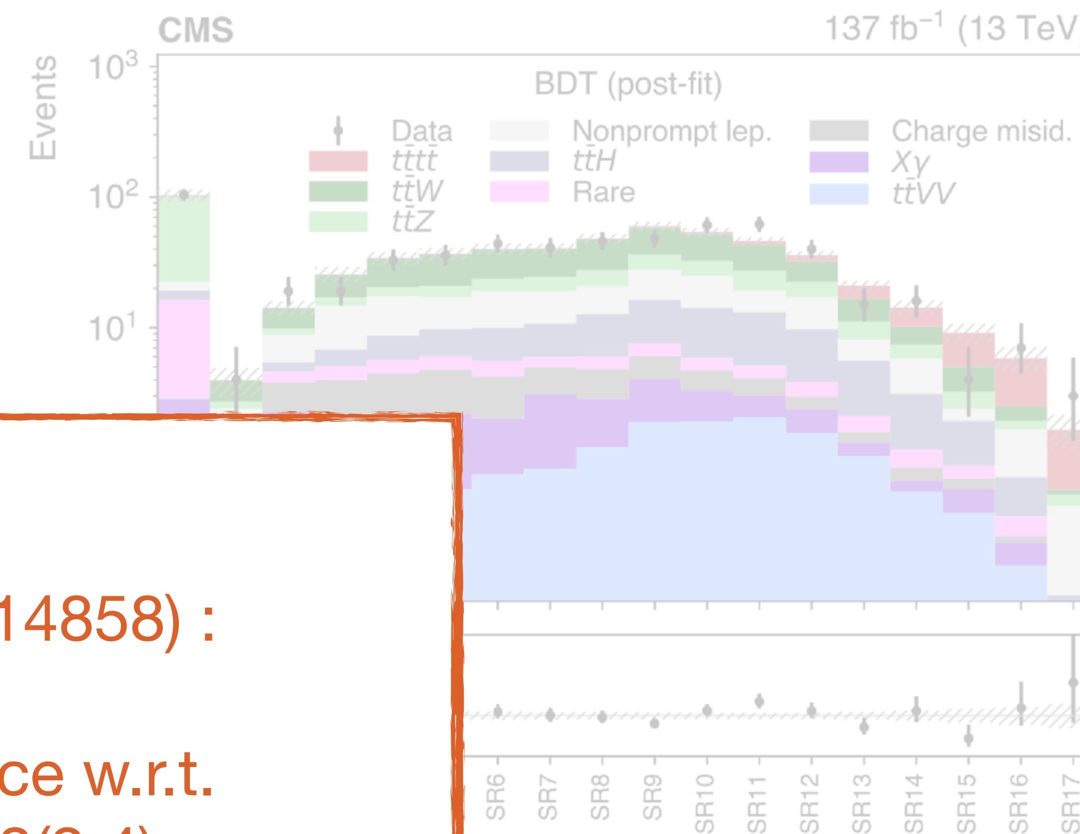
- Main background $t\bar{t}$ taken from simulation
  - Uncertainties for Top p_T reweighting, jet multiplicity modeling in $t\bar{t}$+jets, $t\bar{t}$+$b\bar{b}$ rate
- Only this analysis: Upper limit on σ($t\bar{t}t\bar{t}$) of 48 fb could be set
- Combination with previous CMS results†: σ($t\bar{t}t\bar{t}$) = 13^{+11}_{-9} fb and obs. significance of 1.4σ

$t\bar{t}t\bar{t}$ - SS, multilepton - Strategy and SM results

- Baseline selection: HT > 300, ≥ 2 Jets, ≥ 2 b-Jets, ≥ 2 Leptons
- „BDT-based“ categorization by discretizing the BDT ($t\bar{t}t\bar{t}$ vs. SM bkgs) output
- Main backgrounds
  - **ttW**, **ttZ**
    - CR for $t\bar{t}Z$
    - modeling is improved by applying a reweighing based on additional ISR/FSR jets
    - $t\bar{t}W$ and $t\bar{t}Z$ normalization can be constrained by the fit
  - **ttH** (mainly H→WW), $\mathbf{t\bar{t}}$ (misidentified prompt lepton / additional non-prompt lepton)
- In agreement with SM: $\sigma(t\bar{t}t\bar{t})$ = $12.6^{+5.8}_{-5.2}$fb and obs. (exp.) significance of 2.6σ (2.7σ)
- 95% confidence level (CL) limit of $|y_t/y_t^{SM}|$ < 1.7.



$t\bar{t}t\bar{t}$ - SS, multilepton - Strategy and SM results



- Baseline selection: HT > 300, ≥ 2 Jets, ≥ 2 b-Jets, ≥ 2 Leptons
- „BDT-based“ categorization by discretizing the BDT ($t\bar{t}t\bar{t}$ vs. SM bk
- Main backgrounds
  - **ttW, ttZ**
    - CR for $t\bar{t}Z$
    - modeling is i ... ditional ISR/FSR jets
    - $t\bar{t}W$ and $t\bar{t}Z$ r
  - **ttH** (mainly H→W ... non-prompt lepton)
- In agreement with SM: $\sigma(t\bar{t}t\bar{t}) = 12.6^{+5.8}_{-5.2}$ fb and obs. (exp.) significance of 2.6σ (2.7σ)
- 95% confidence level (CL) limit of $|y_t/y_t^{SM}| < 1.7$.

Spoiler alert:

ATLAS results (2007.14858) :

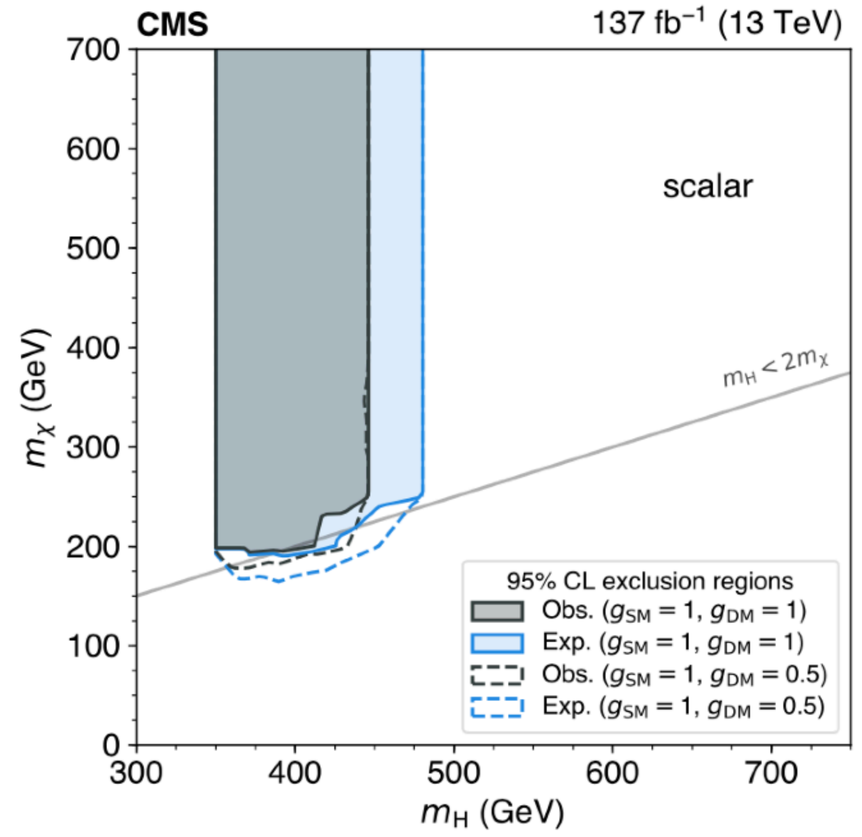
Obs. (exp.) significance w.r.t. backgorund-only: 4.3(2.4)σ

$\sigma(t\bar{t}t\bar{t}) = 24^{+7}_{-6}$ fb

See Talk by E. Varnes on Friday at 14:30

$t\bar{t}t\bar{t}$ - SS, multilepton - BSM Interpretations

- Analysis can also be interpreted to constrain BSM particles and couplings:
  - Higgs boson oblique parameter $\hat{H} < 0.12$ at 95% CL
  - Upper Limits ranging from 0.1 to 1.2 for new scalar (ϕ) or vector (Z′) particle with mass < $2m_t$
  - Upper limits, between 15 and 35 fb at 95% CL, for cross sections of new scalar (H) or pseudoscalar (A) particles with m > $2m_t$ (interpretation in context of Type-II two higgs-doublet model)



Conclusion

- Increasing number $t\bar{t}$H/tH measurement using the full Run-2 dataset are available
  - Further transition to precision measurement instead of pure searches
  - Sensitivity driven by precise modeling of backgrounds and multivariate techniques
  - Upper Limit on σ_{tH} : 8 times SM prediction
- All results are consistent with the SM but there is still room for BSM physics
- First four-top results using the full Run-2 dataset were published

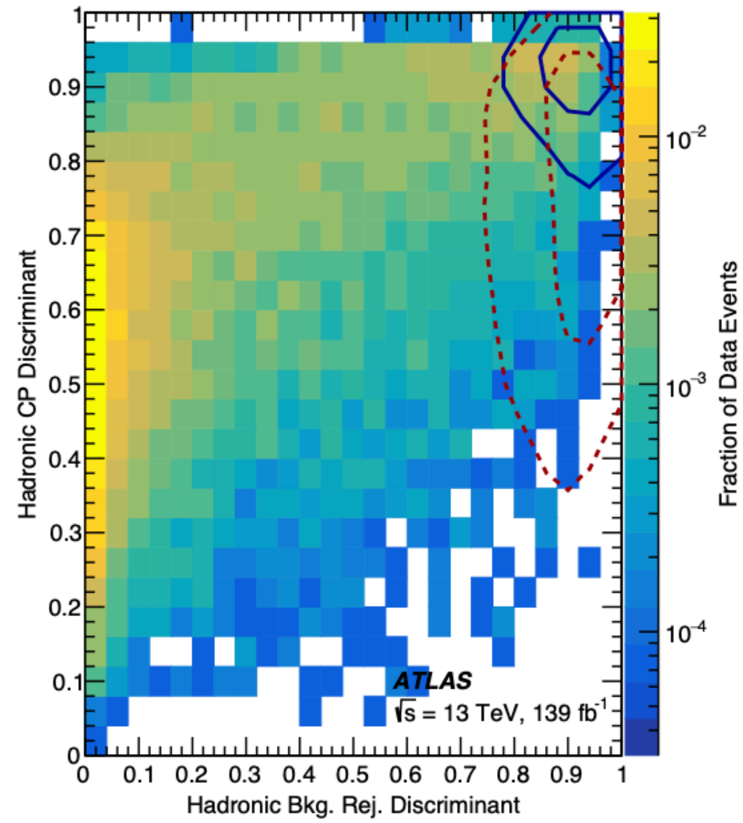
Thank you for your attention!

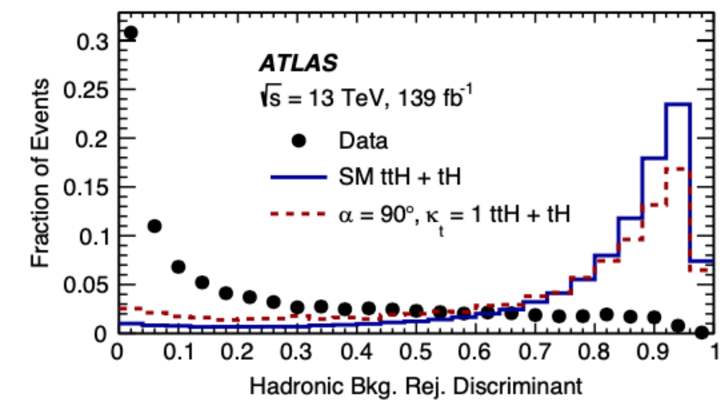
Additional Material

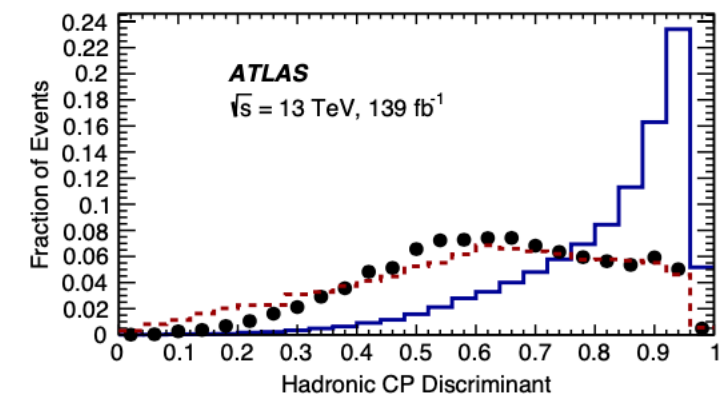
$t\bar{t}H(\gamma\gamma)$ — ATLAS

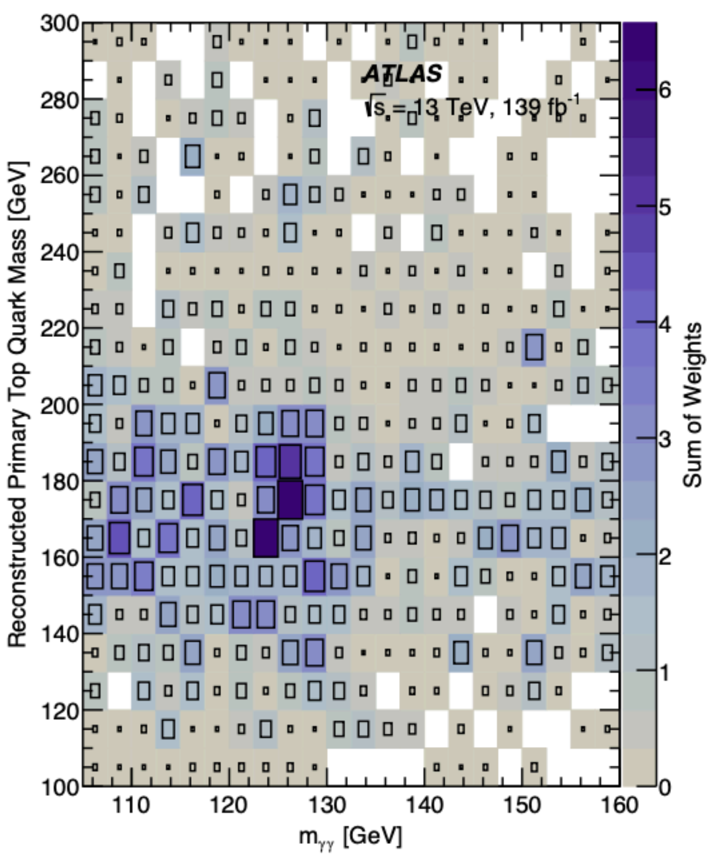
BDT trained to separate CP-odd and CP-even type events

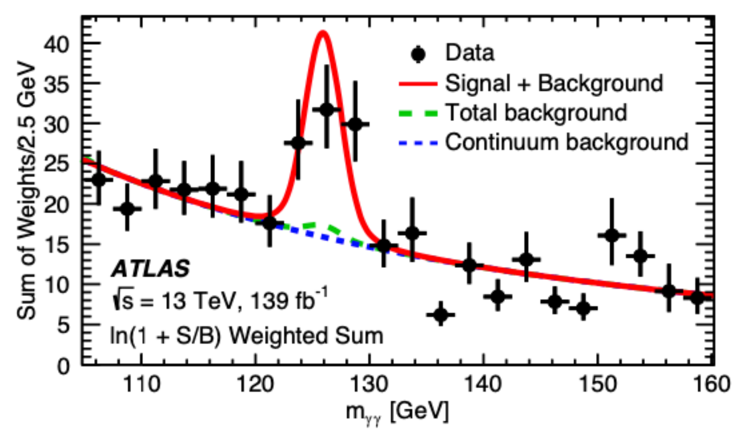
Hadronic channel

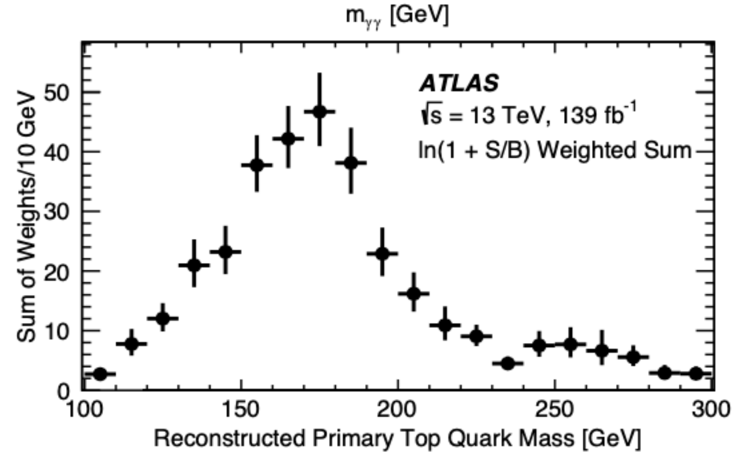






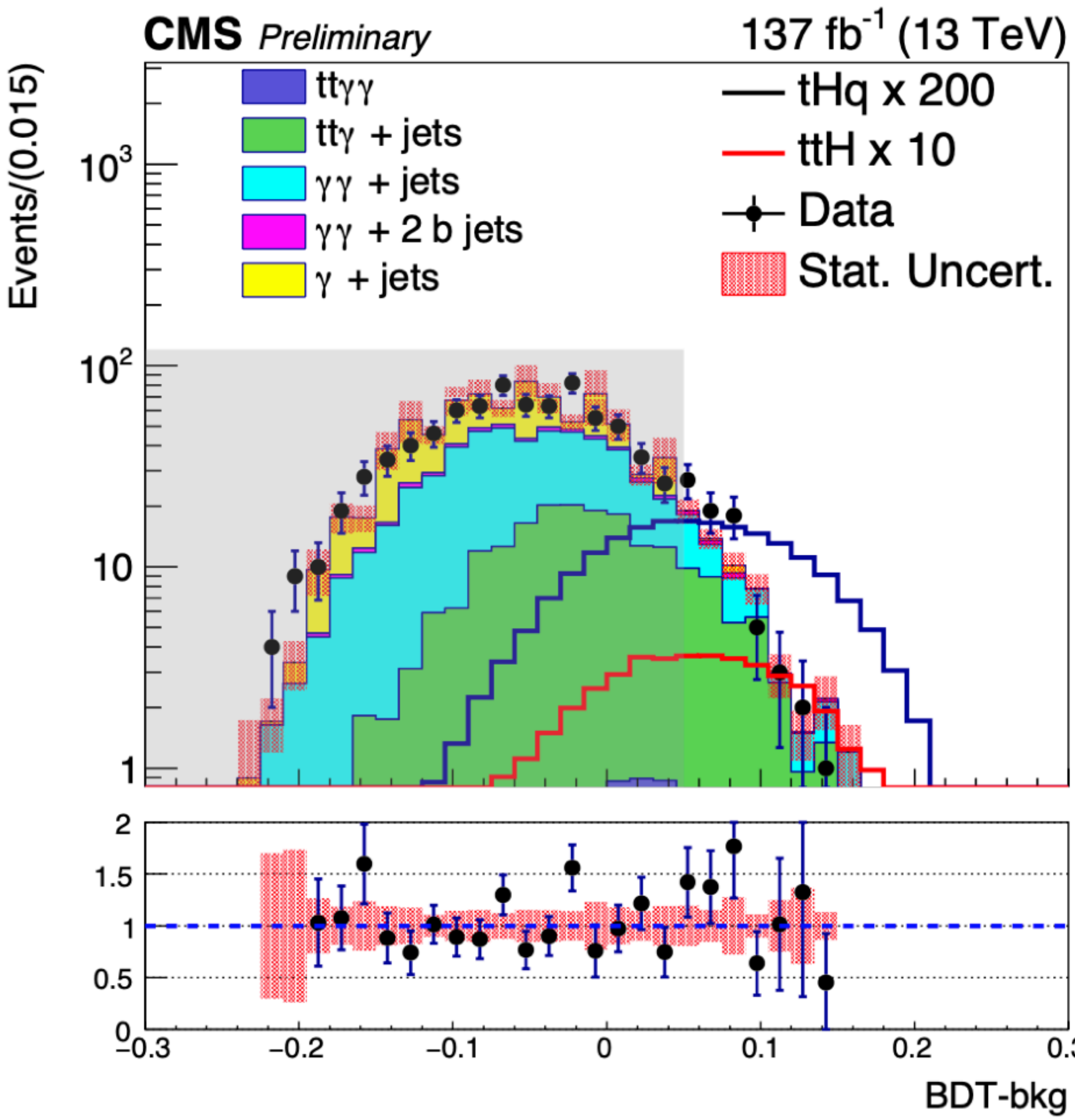


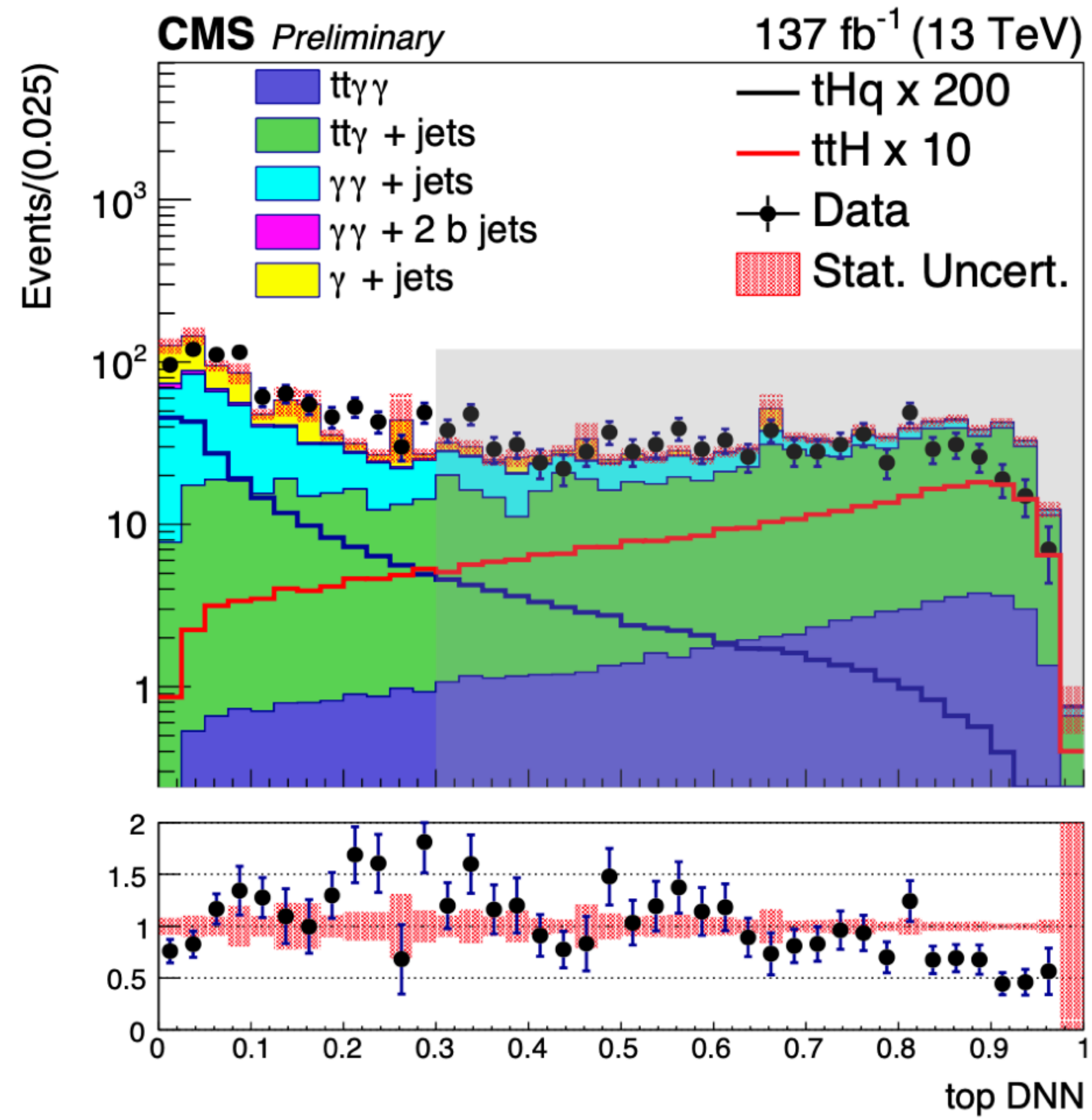




The events are weighted by $\ln 1 + S/B$ with S and B being the fitted signal and background yields in the smallest $m_{\gamma\gamma}$ interval containing 90% of the signal in each category

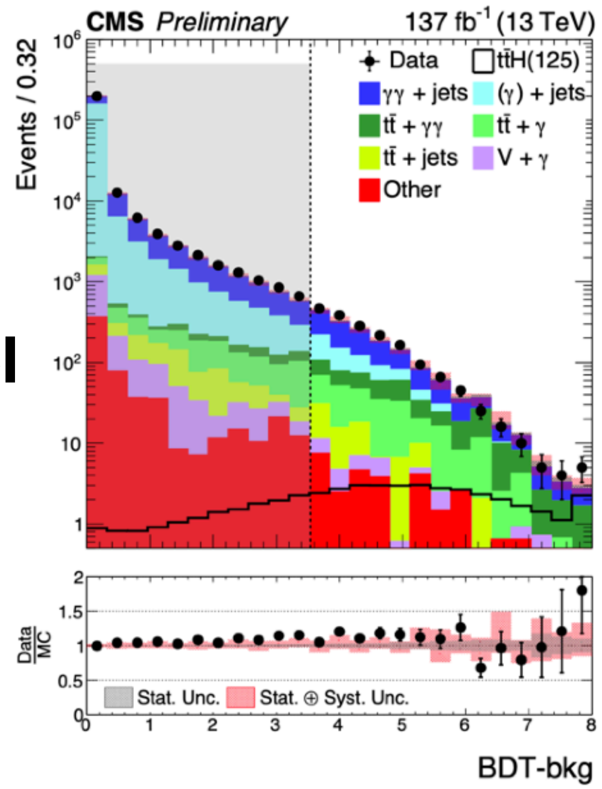
CMS-PAS-HIG-19-015 — tHq DNN



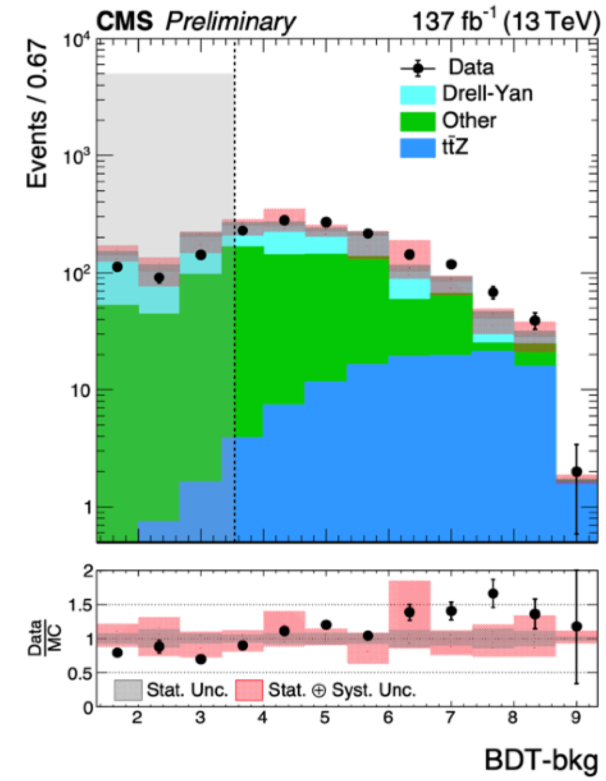


CMS-PAS-HIG-19-015 — Bkg-BDT SR and CR

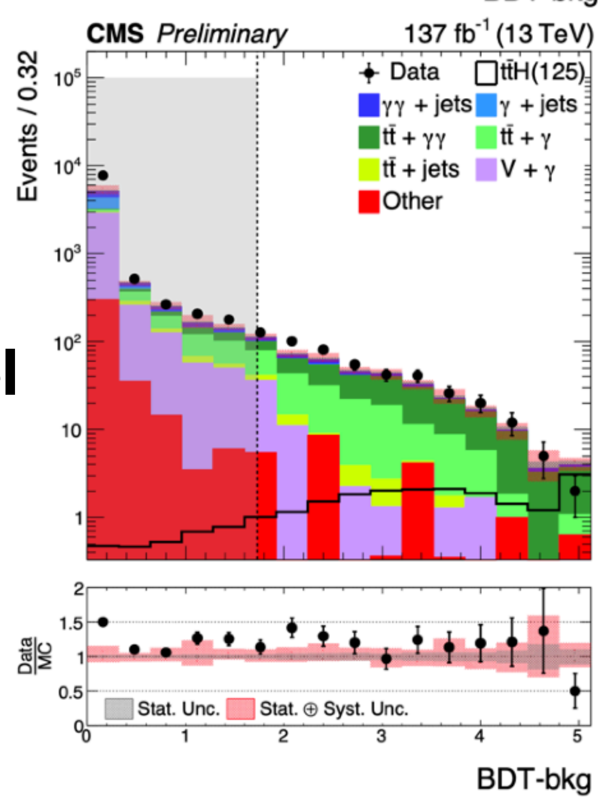
Hadronic Channel SR



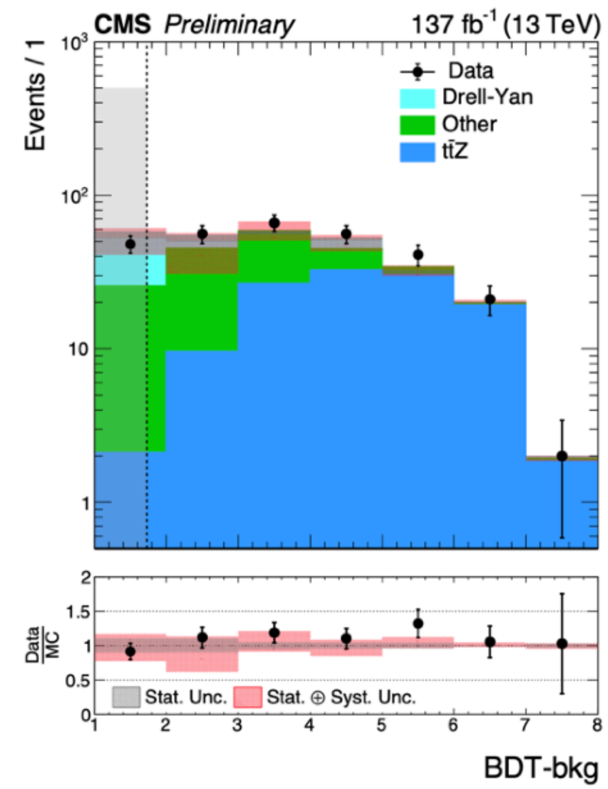
Hadronic Channel $t\bar{t}Z$ CR



Leptonic Channel SR

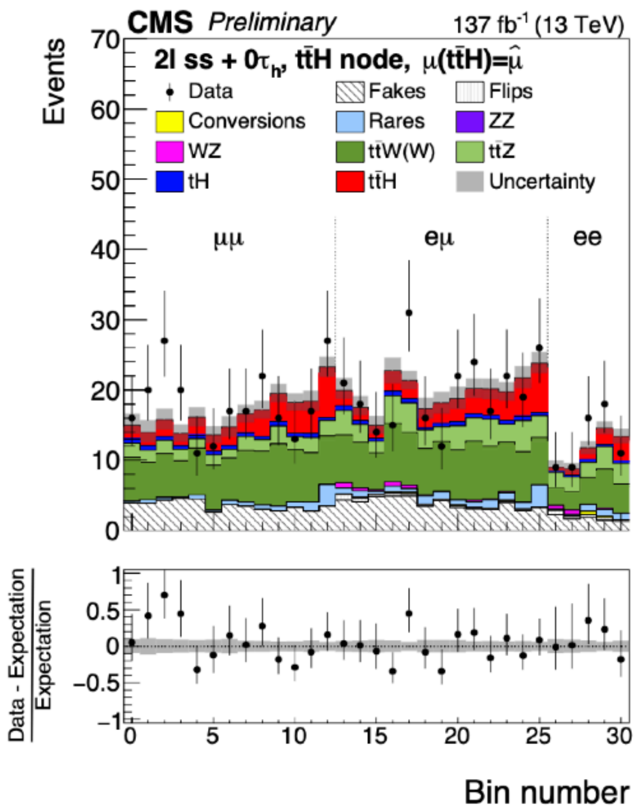


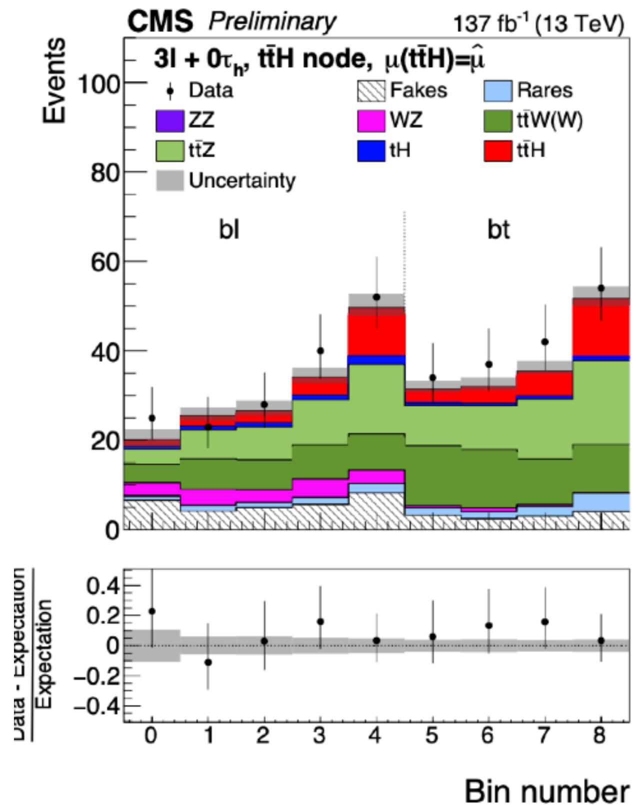
Leptonic Channel $t\bar{t}Z$ CR

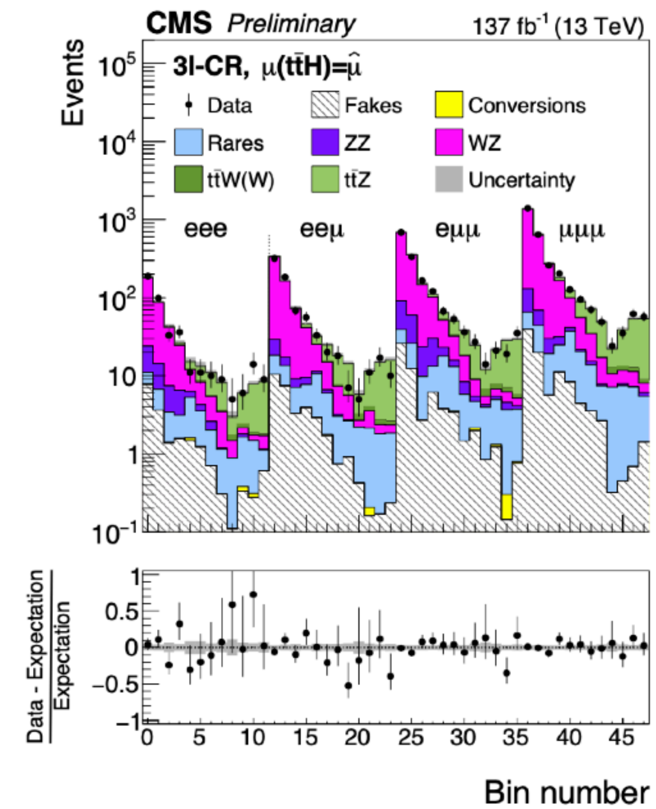


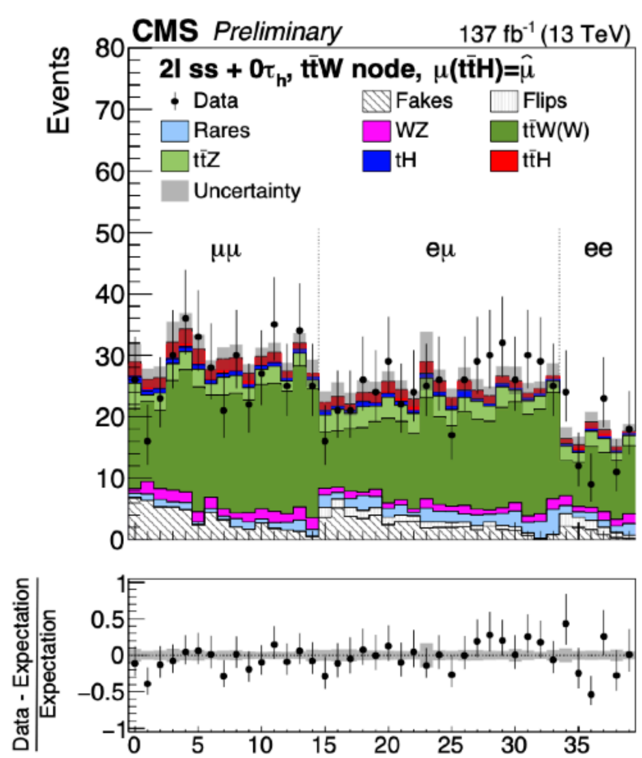
ttH Multilepton / CMS / Selection if Categories

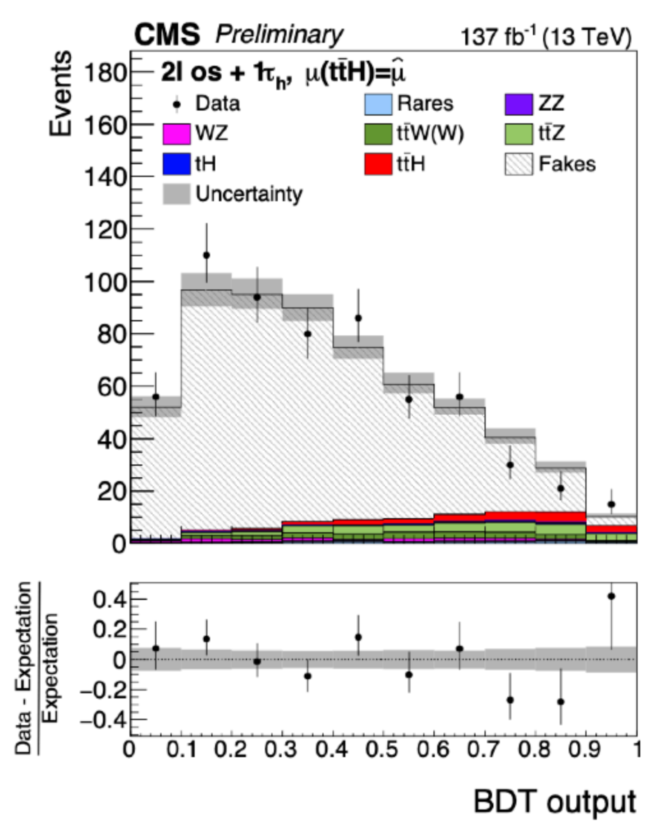
Used as CR

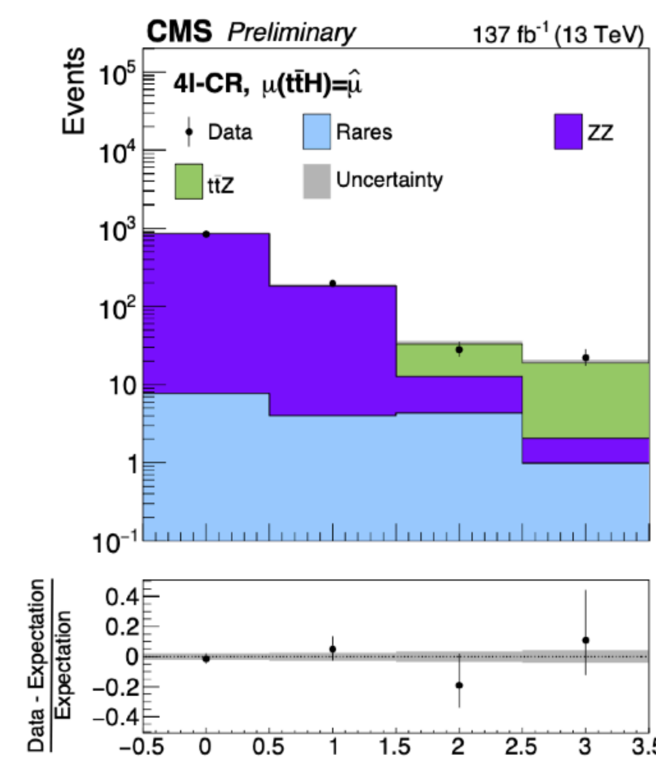












Used as CR

Used as CR

ttH Multilepton - CMS

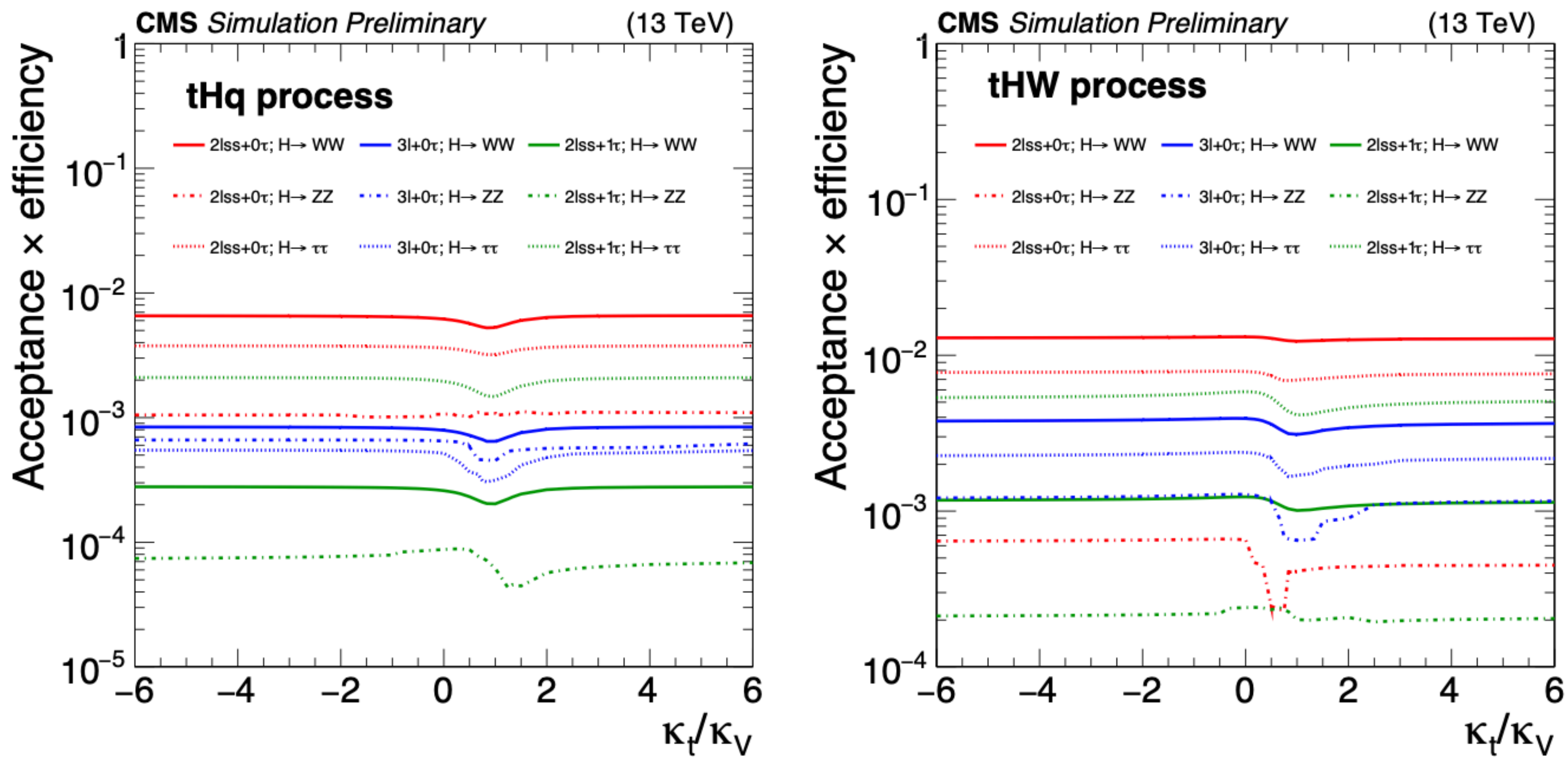


Figure 15: Probability for tH signal events produced by the tHq (left) and tHW (right) production process to pass the event selection criteria for the $2\ell ss + 0\tau_h$, $3\ell + 0\tau_h$, and $2\ell ss + 1\tau_h$ channels in each of the H boson decay modes as a function of the ratio κ_t/κ_V of the H boson couplings to the top quark and to the W boson.

- κ_t : Coupling modifier y_t / $y_{t,SM}$
- κ_V : Same as κ_t for for H-W coupling (H-Z is assumed to scale equal)

CMS-PAS-HIG-19-009 - Htt coupling

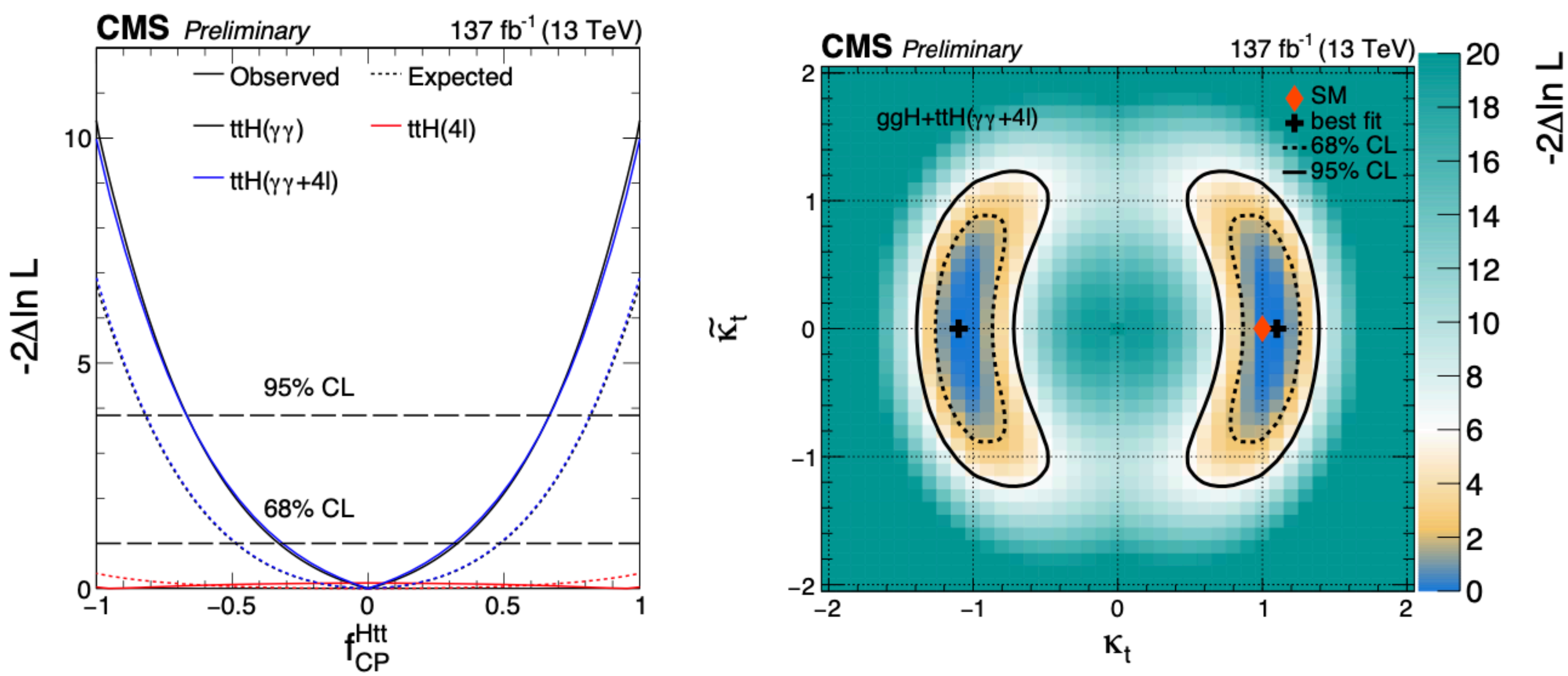
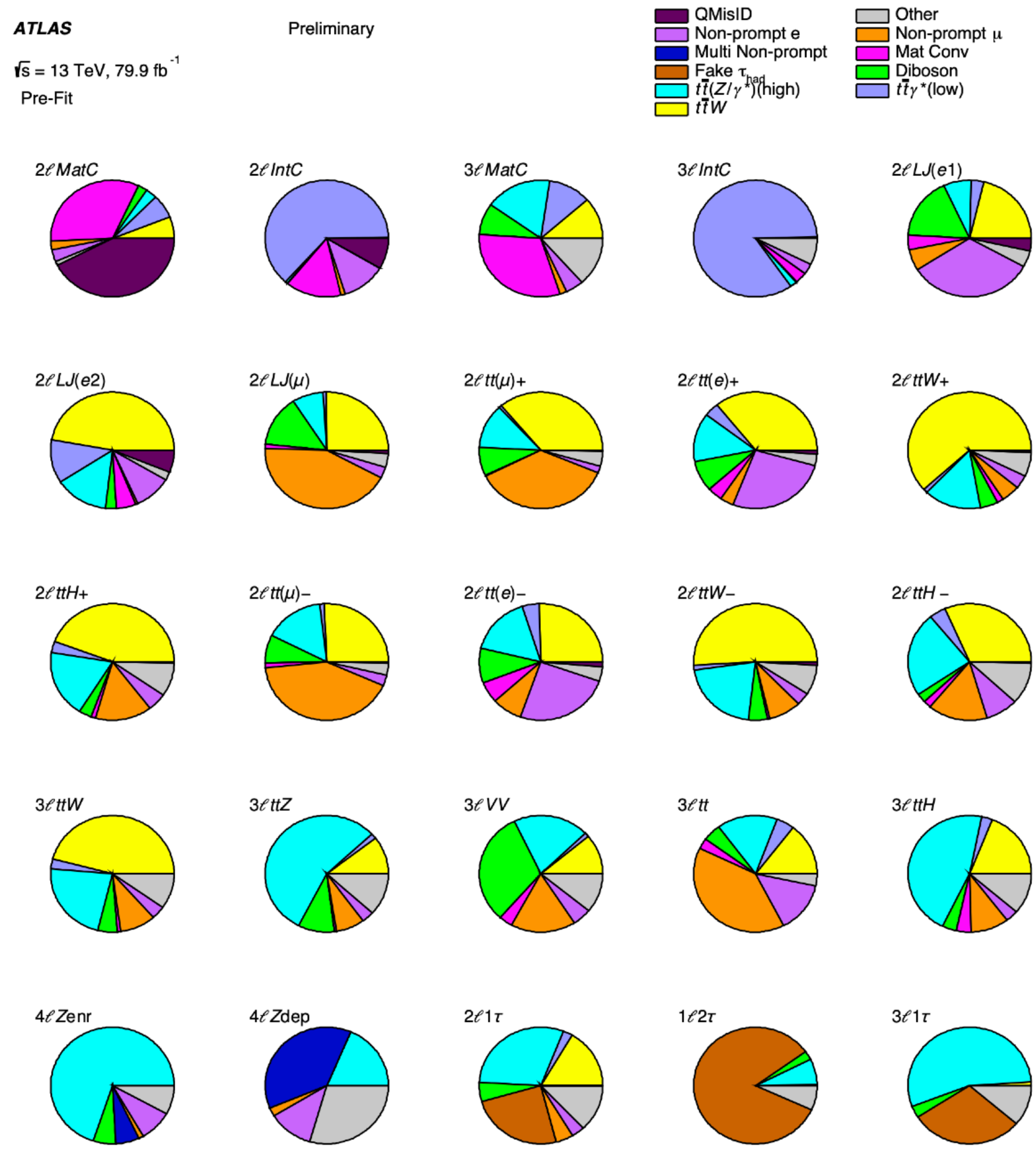


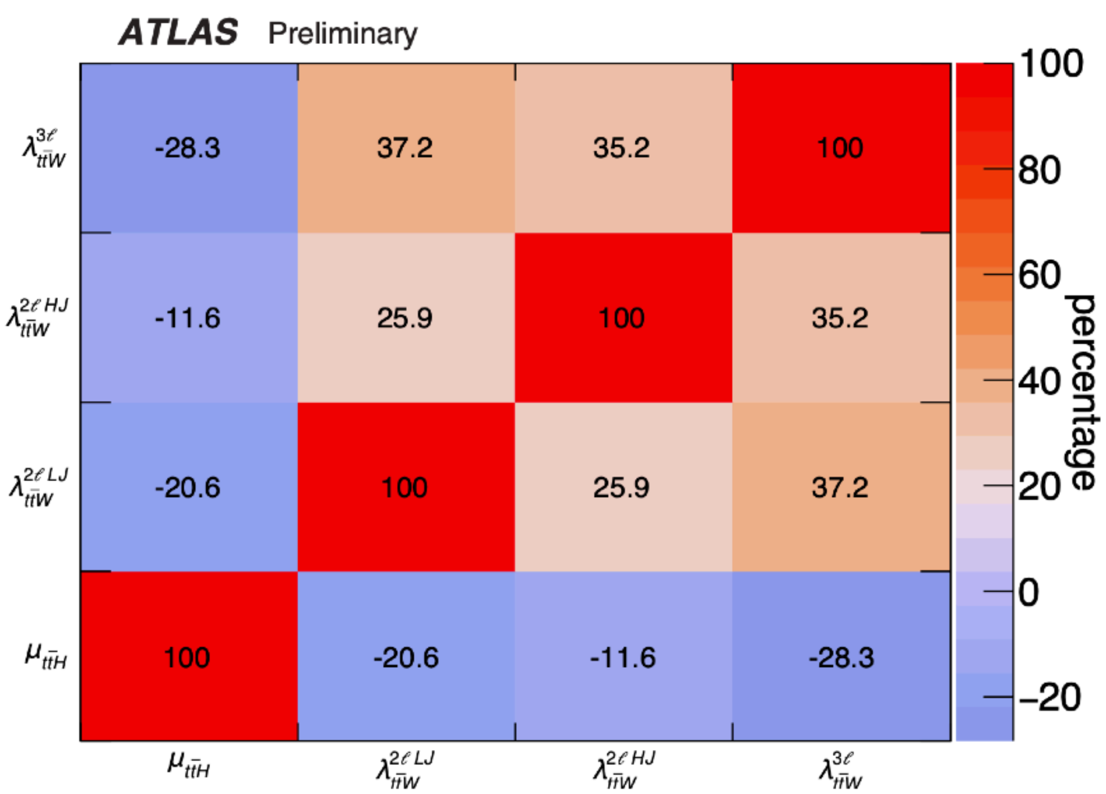
Figure 9: Constraints on the anomalous H boson couplings to top quarks in the $t\bar{t}H$ process using the $H \rightarrow 4\ell$ and $\gamma\gamma$ decays. Left: Observed (solid) and expected (dashed) likelihood scans of f_{CP}^{Htt} in the $t\bar{t}H$ process in the $H \rightarrow 4\ell$ (red), $\gamma\gamma$ (black), and combined (blue) channels, where the combination is done without relating the signal strengths in the two processes. The dashed horizontal lines show 68 and 95% CL. Right: Observed confidence level intervals on the κ_t and $\tilde{\kappa}_t$ couplings reinterpreted from the f_{CP}^{Htt} and $\mu_{t\bar{t}H}$ measurements in the combined fit of the $H \rightarrow 4\ell$ and $\gamma\gamma$ channels, with the signal strength $\mu_{t\bar{t}H}$ in the two channels related through the couplings as discussed in text. The dashed and solid lines show the 68 and 95% CL exclusion regions in two dimensions, respectively.

Parameter	Scenario	Observed	Expected
f_{CP}^{Htt}	$t\bar{t}H$ ($H \rightarrow 4\ell$)	$\pm 1 \mp 2$ $[-1, 1]$	0 ± 1 $[-1, 1]$
	$t\bar{t}H$ ($H \rightarrow \gamma\gamma$) [26]	0.00 ± 0.33 $[-0.67, 0.67]$	0.00 ± 0.49 $[-0.82, 0.82]$
	$t\bar{t}H$ ($H \rightarrow 4\ell$ & $\gamma\gamma$)	0.00 ± 0.31 $[-0.67, 0.67]$	0.00 ± 0.48 $[-0.82, 0.82]$
	ggH ($H \rightarrow 4\ell$)	$-0.32^{+0.31}_{-0.68}$ $[-1, 1]$	0 ± 1 $[-1, 1]$
	ggH & $t\bar{t}H$ ($H \rightarrow 4\ell$)	$-0.50^{+0.45}_{-0.50}$ $[-1, 1]$	0.00 ± 0.65 $[-1, 1]$
	ggH & $t\bar{t}H$ ($H \rightarrow 4\ell$ & $\gamma\gamma$)	$-0.13^{+0.13}_{-0.24}$ $[-0.61, 0.43]$	0.00 ± 0.29 $[-0.63, 0.63]$

ttH Multilepton / ATLAS / Selection if Categories



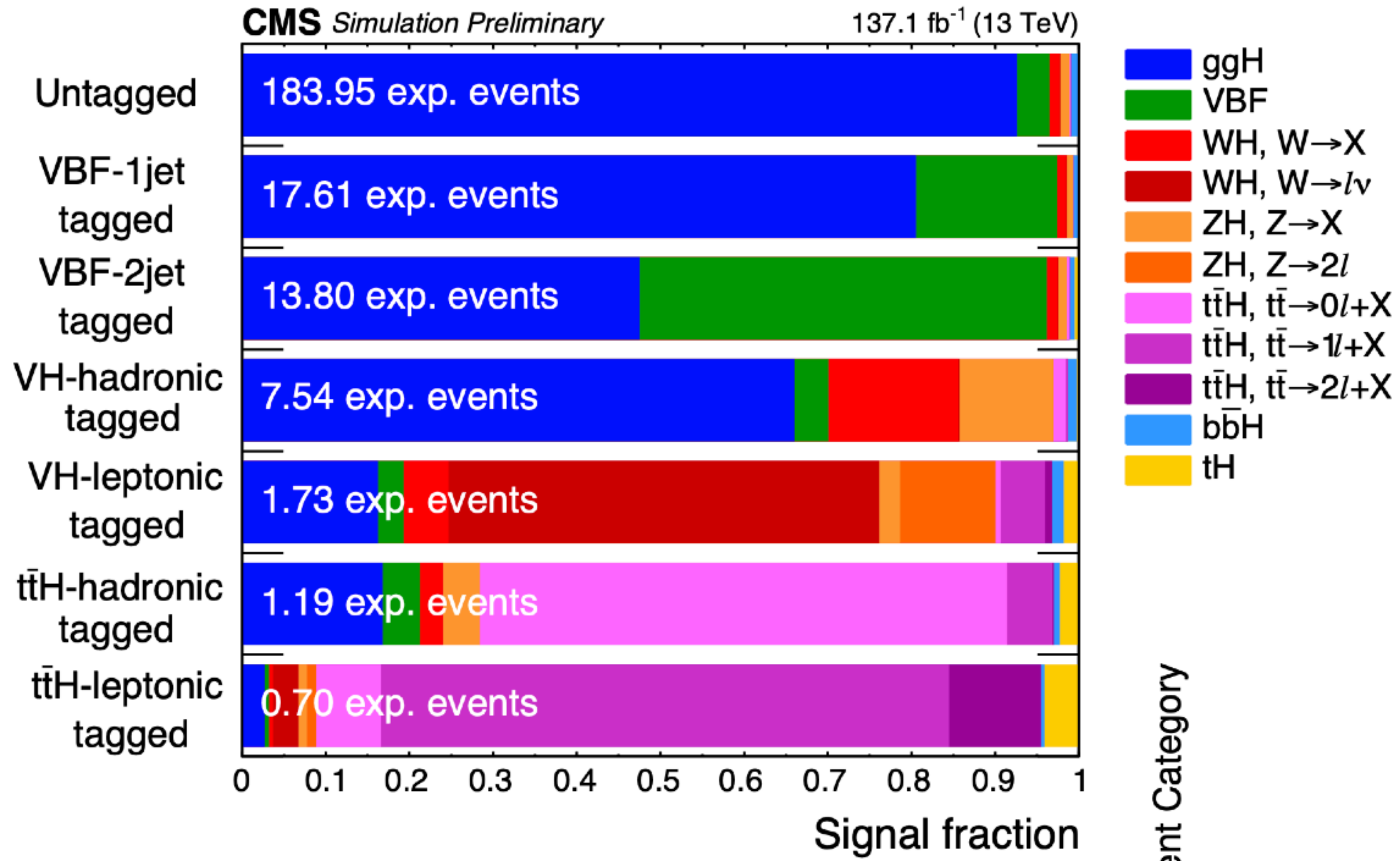
ttH Multilepton / ATLAS / ttW

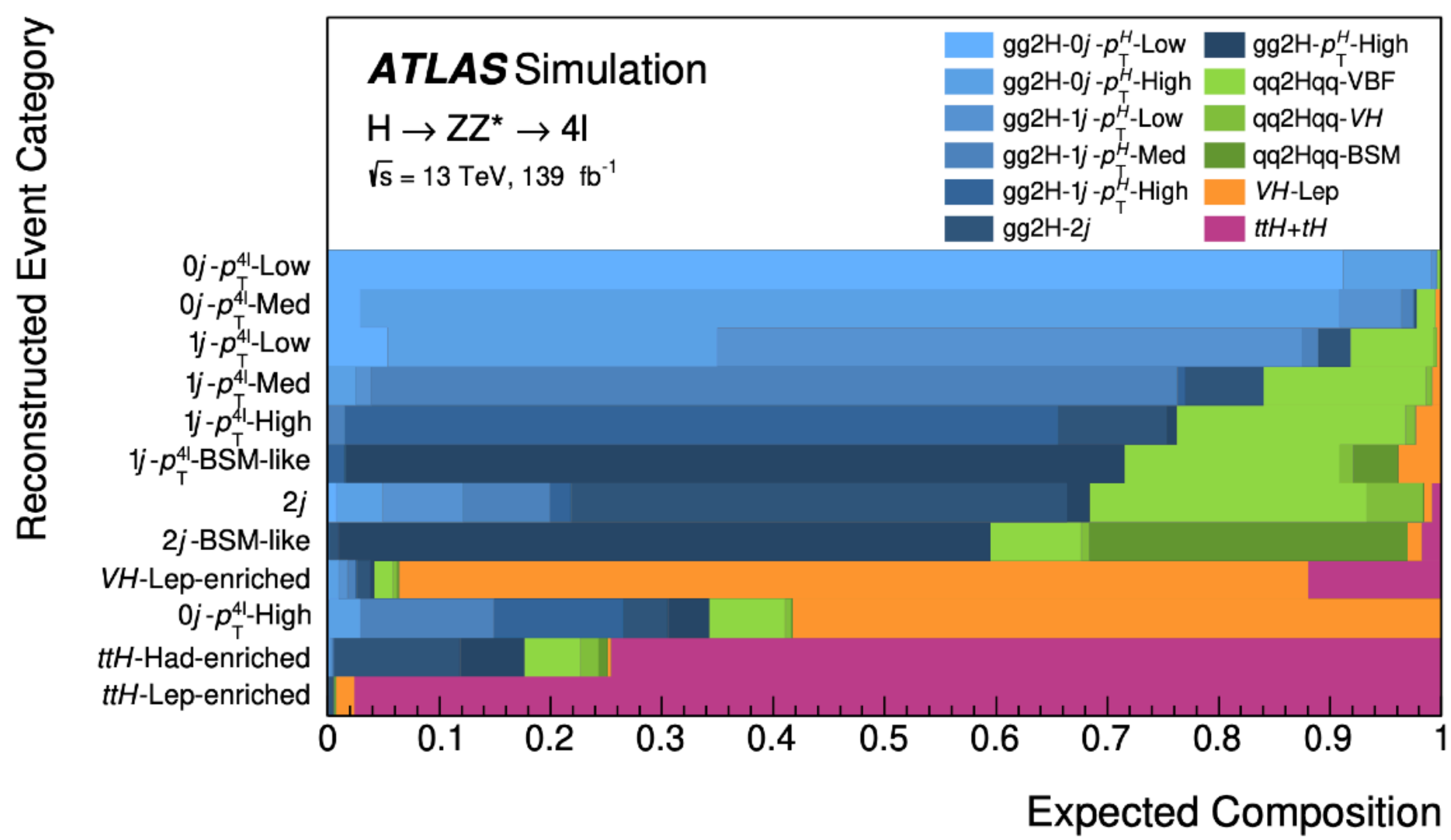


- To minimise the dependence of the $t\bar{t}H$ signal extraction on the $t\bar{t}W$ prediction
  - 3 ttW normalization factors in fit

$$\hat{\lambda}^{2\ell\mathrm{LJ}}_{t\bar{t}W} = 1.56^{+0.30}_{-0.28},\ \hat{\lambda}^{2\ell\mathrm{HJ}}_{t\bar{t}W} = 1.26^{+0.19}_{-0.18},\ \text{and}\ \hat{\lambda}^{3\ell}_{t\bar{t}W} = 1.68^{+0.30}_{-0.28}$$

H → ZZ → 4l — Signal fractions

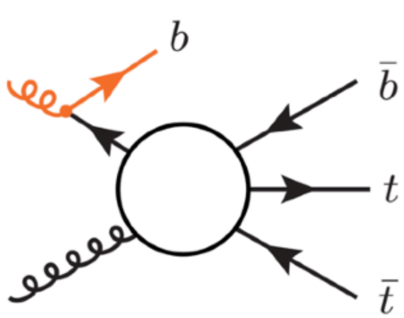




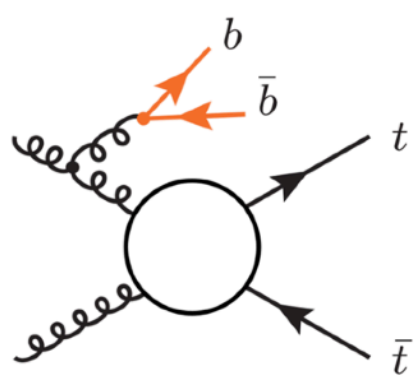
$t\bar{t}+b\bar{b}$ 5FS vs. 4FS

$t\bar{t}+b\bar{b}$ in 5FS

- $t\bar{t}+b\bar{b}$ described by $t\bar{t}$+jet ME and g → bb shower splittings
- Additional b-jets from PS
- Residual uncertainties difficult to quantify



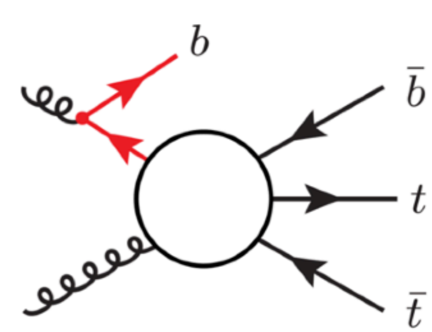
$t\bar{t}g$ + IS splittings

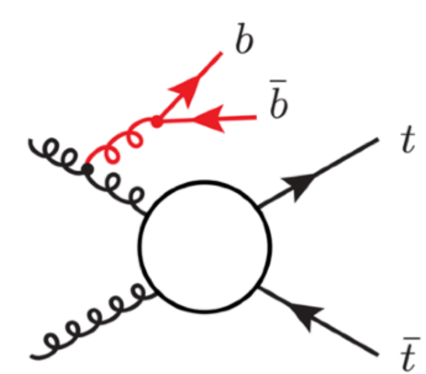


$t\bar{t}g$ + FS splittings

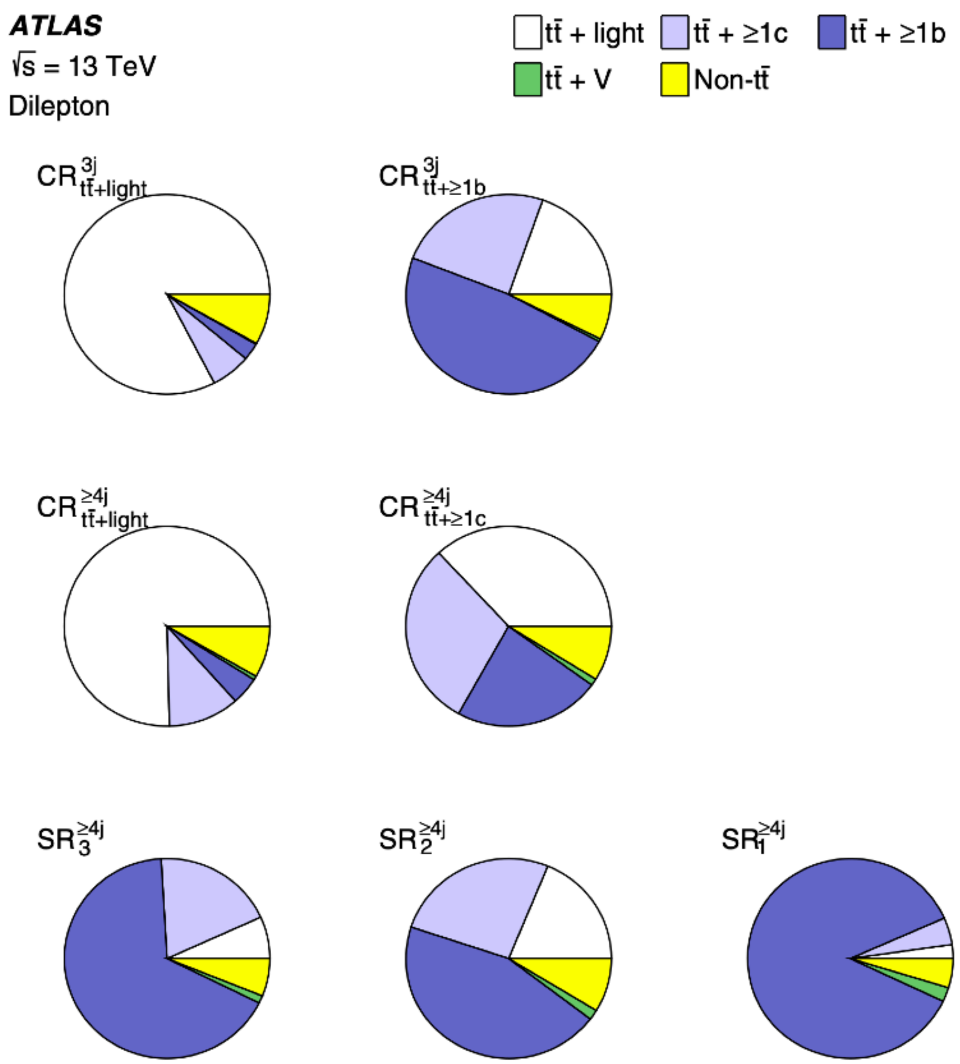
$t\bar{t}+b\bar{b}$ in 4FS

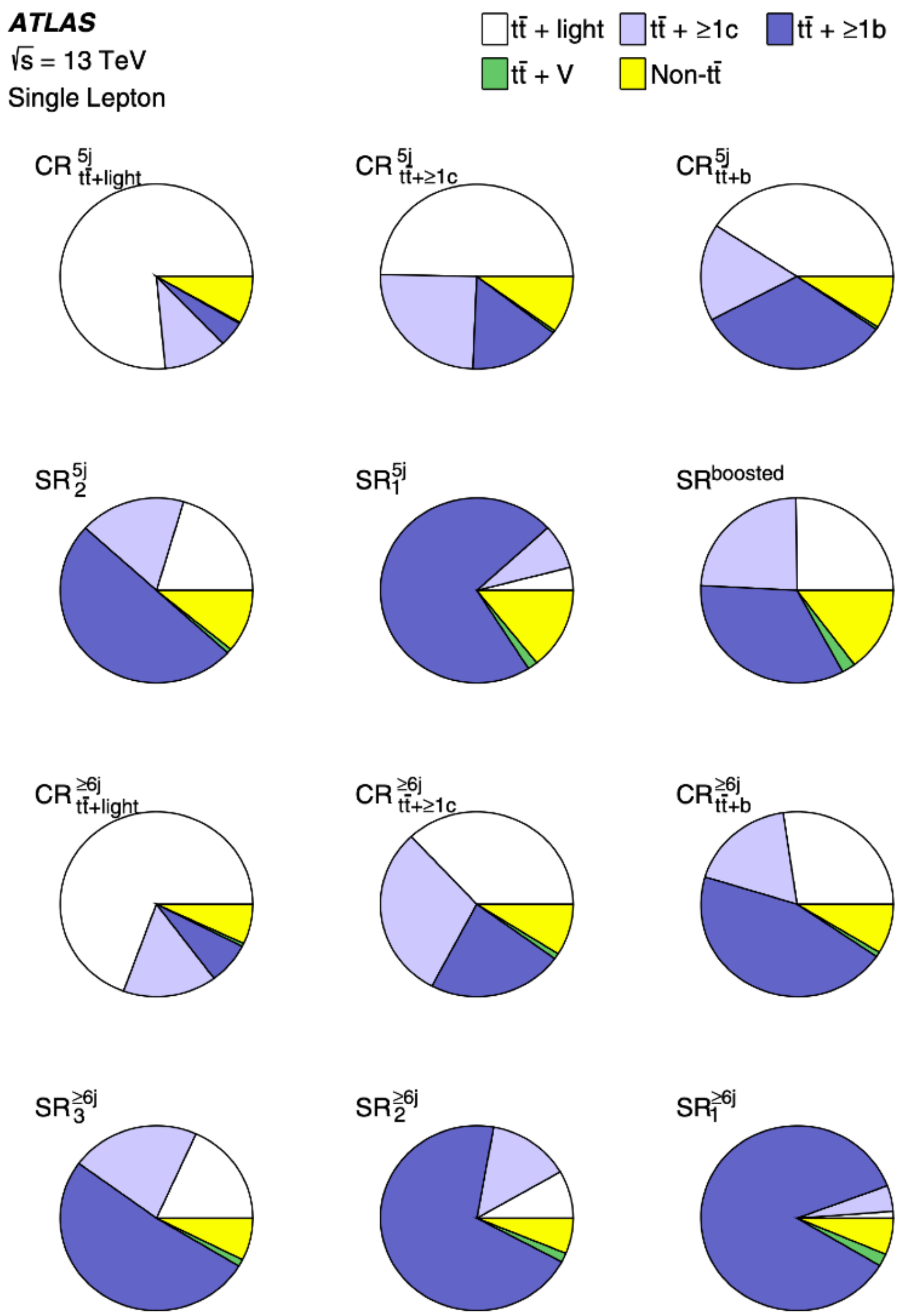
- $t\bar{t}+b\bar{b}$ described by $t\bar{t}+b\bar{b}$ ME (with mb > 0)
- Additional b-jets from ME
- Theoretically preferred option for tt+hf modeling



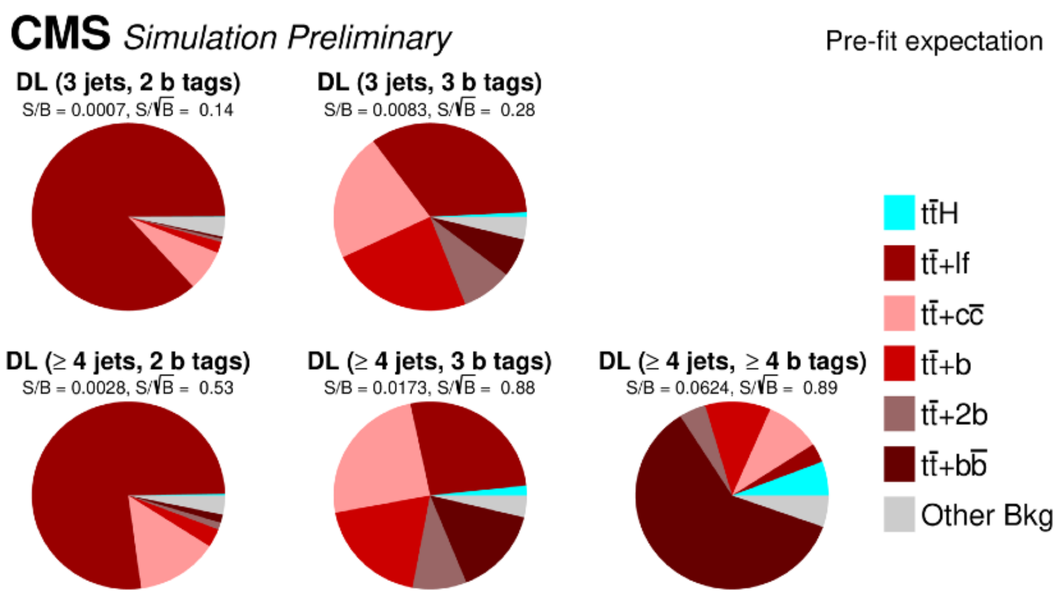


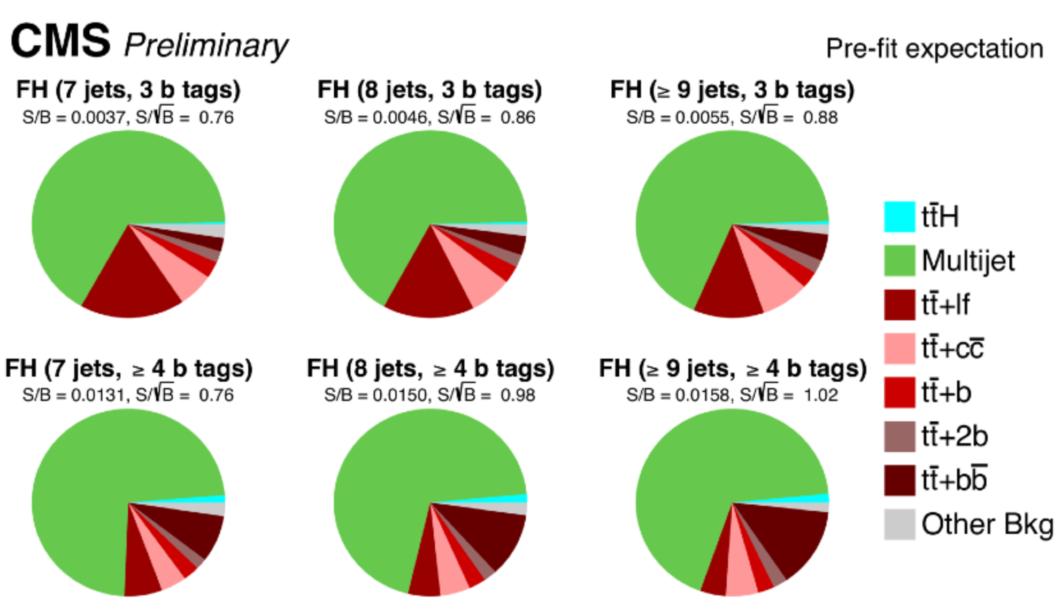
$t\bar{t}H(b\bar{b})$ — ATLAS — Categorization

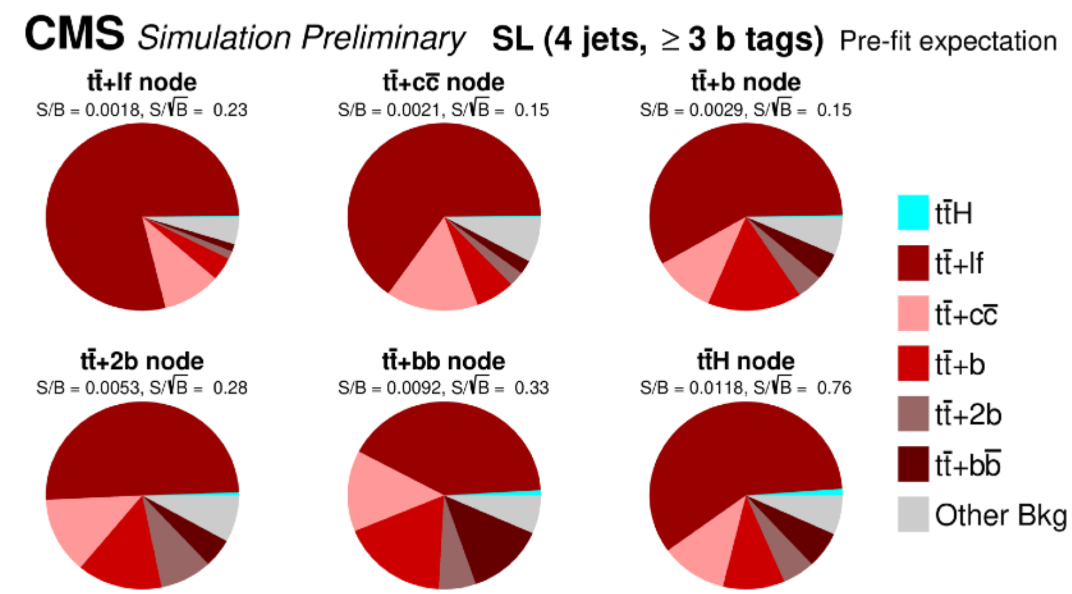


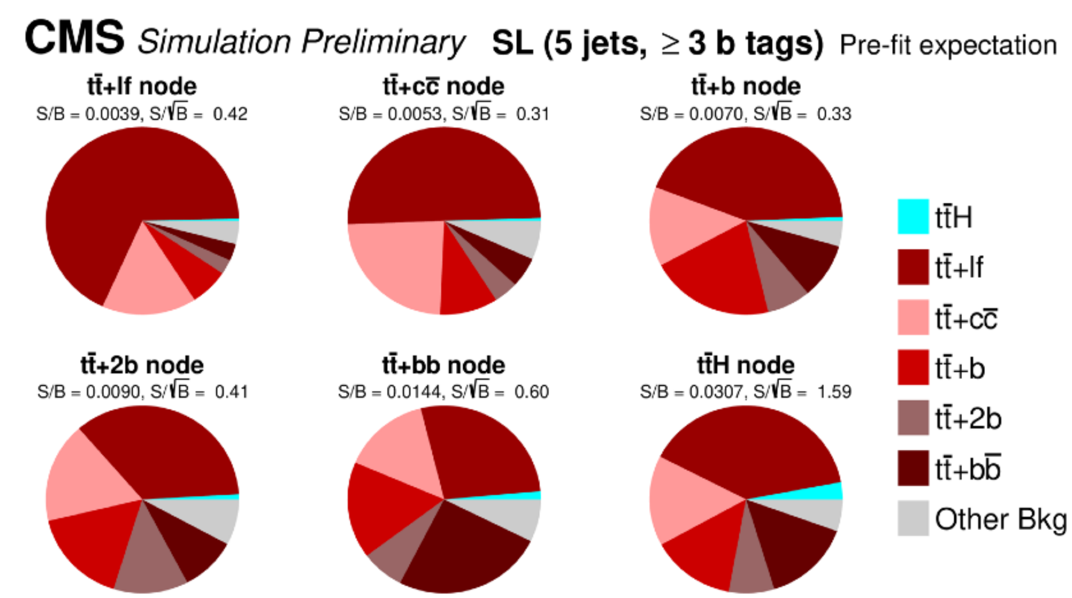


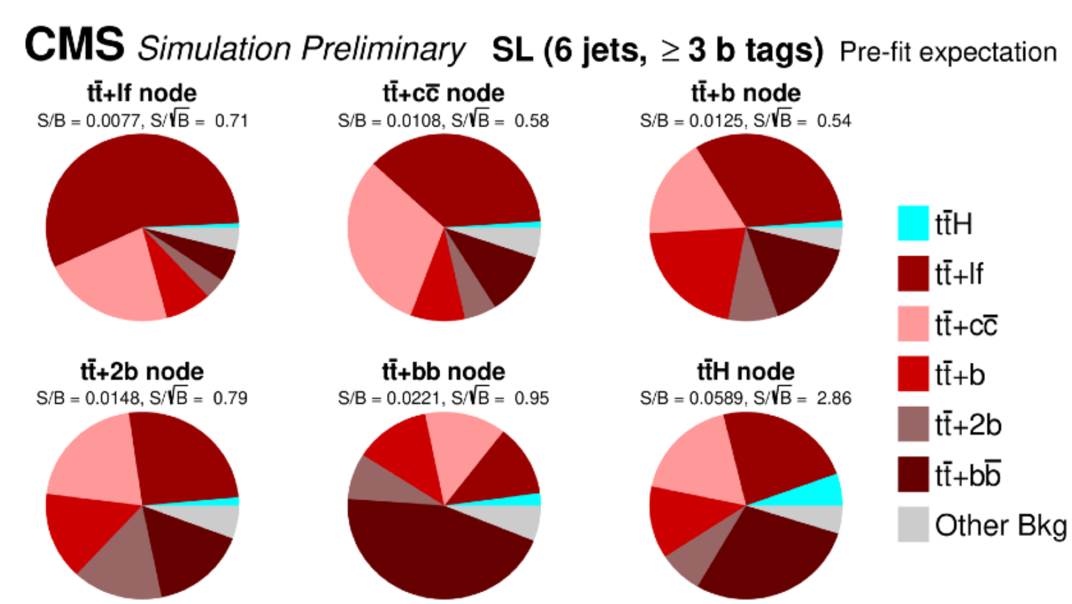
$t\bar{t}H(b\bar{b})$ — CMS — Categorization



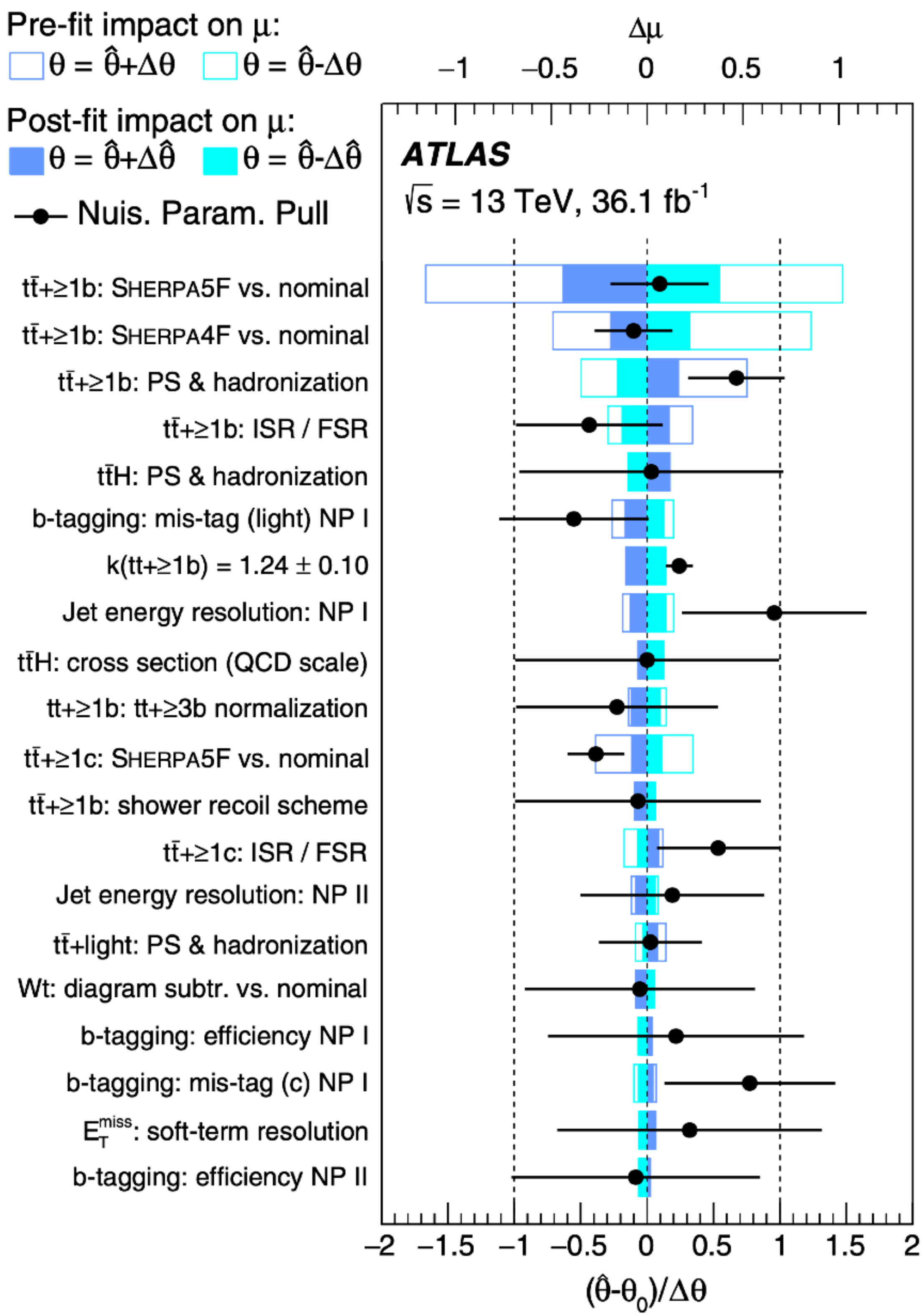


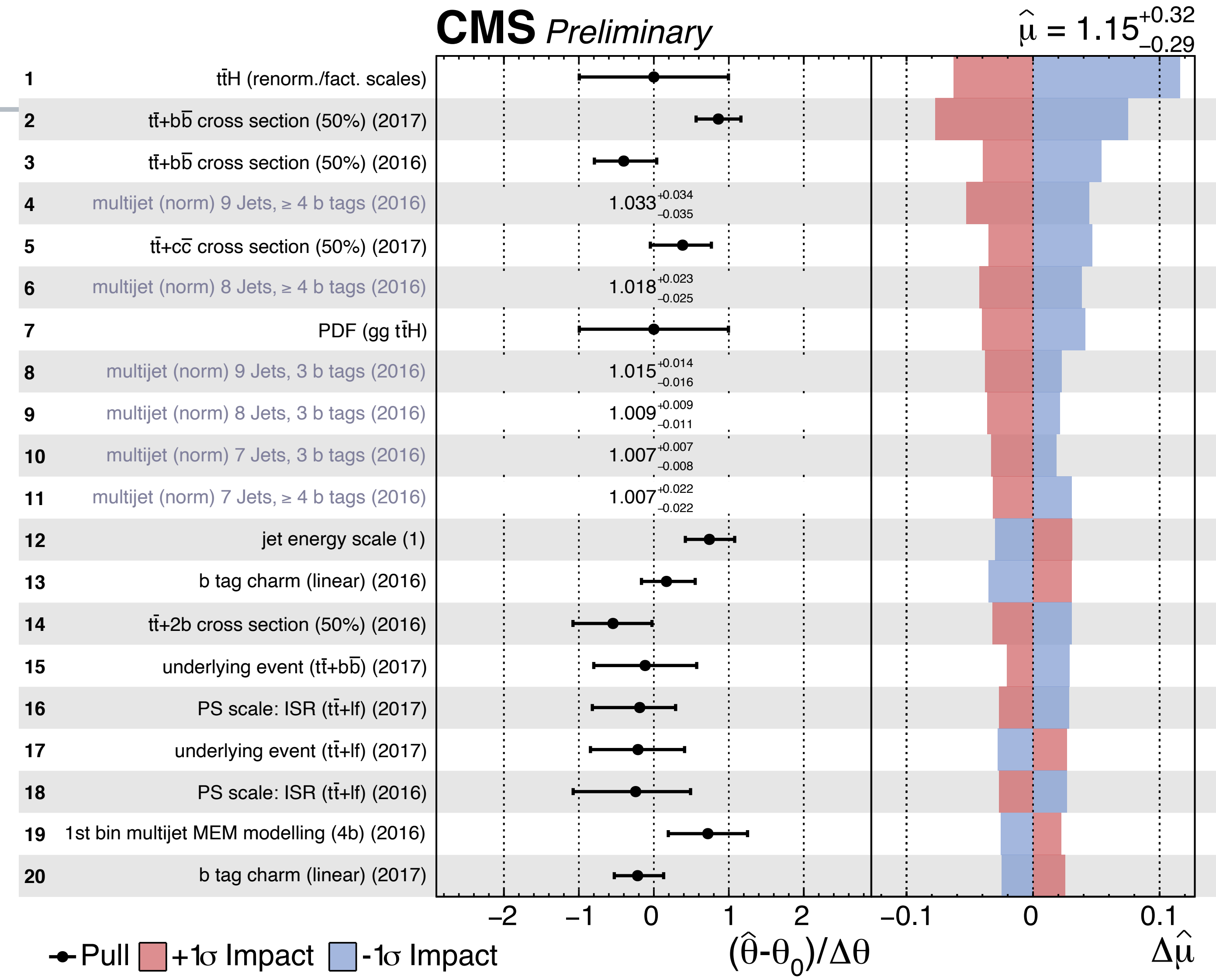






$t\bar{t}H(b\bar{b})$ — Impacts





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	$+0.32/-0.29$

$t\bar{t}t\bar{t}$ - SL and OS DL

Channel	Best fit μ	Best fit $\sigma_{t\bar{t}t\bar{t}}$ (fb)	Exp. significance s.d.	Obs. significance s.d.
Single-lepton	$1.6^{+4.6}_{-1.6}$	15^{+42}_{-15}	0.21	0.36
OS dilepton	$0.0^{+2.7}$	0^{+25}	0.36	0.0
Combined (this analysis)	$0.0^{+2.2}$	0^{+20}	0.40	0.0
SS dilepton + multilepton	$1.8^{+1.5}_{-1.2}$	17^{+14}_{-11}	1.0	1.6
Combined (this analysis + [21])	$1.4^{+1.2}_{-1.0}$	13^{+11}_{-9}	1.1	1.4

Channel	Expected limit, μ	Observed limit, μ	Expected limit (fb)	Observed limit (fb)
Single-lepton	$9.4^{+4.4}_{-2.9}$	10.6	86^{+40}_{-26}	97
OS dilepton	$7.3^{+4.5}_{-2.5}$	6.9	67^{+41}_{-23}	64
Combined (this analysis)	$5.7^{+2.9}_{-1.8}$	5.2	52^{+26}_{-17}	48
SS dilepton + multilepton	$2.5^{+1.4}_{-0.8}$	4.6	21^{+11}_{-7}	42
Combined (this analysis + [21])	$2.2^{+1.1}_{-0.7}$	3.6	20^{+10}_{-6}	33

$t\bar{t}t\bar{t}$ OS, multilepton — Uncertainties, Impact and Yield

Source	Uncertainty (%)	Impact on $\sigma(t\bar{t}t\bar{t})$ (%)
Integrated luminosity	2.3–2.5	2
Pileup	0–5	1
Trigger efficiency	2–7	2
Lepton selection	2–10	2
Jet energy scale	1–15	9
Jet energy resolution	1–10	6
b tagging	1–15	6
Size of simulated sample	1–25	<1
Scale and PDF variations †	10–15	2
ISR/FSR (signal) †	5–15	2
$t\bar{t}H$ (normalization) †	25	5
Rare, $X\gamma$, $t\bar{t}VV$ (norm.) †	11–20	<1
$t\bar{t}Z$, $t\bar{t}W$ (norm.) †	40	3–4
Charge misidentification †	20	<1
Nonprompt leptons †	30–60	3
$N_{\text{jets}}^{\text{ISR/FSR}}$	1–30	2
$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$ †	35	11

Postfit predicted backgrounds

	SM background	$t\bar{t}t\bar{t}$	Total	Observed
CRZ	102 ± 12	1.11 ± 0.43	103 ± 12	104
SR1	3.95 ± 0.96	< 0.01	3.96 ± 0.96	4
SR2	14.2 ± 1.8	0.01 ± 0.01	14.2 ± 1.8	19
SR3	25.5 ± 3.5	0.04 ± 0.03	25.6 ± 3.5	19
SR4	34.0 ± 4.0	0.08 ± 0.05	34.0 ± 4.0	33
SR5	36.7 ± 4.0	0.15 ± 0.07	36.8 ± 4.0	36
SR6	39.8 ± 4.2	0.23 ± 0.12	40.0 ± 4.2	44
SR7	40.3 ± 3.7	0.31 ± 0.16	40.6 ± 3.8	41
SR8	47.3 ± 4.3	0.72 ± 0.28	48.0 ± 4.3	46
SR9	58.5 ± 5.2	1.18 ± 0.46	59.7 ± 5.2	48
SR10	52.1 ± 4.3	1.91 ± 0.74	54.1 ± 4.2	61
SR11	43.0 ± 3.5	3.0 ± 1.2	46.0 ± 3.5	62
SR12	32.1 ± 3.0	3.7 ± 1.4	35.8 ± 2.9	40
SR13	16.7 ± 1.6	4.3 ± 1.6	21.0 ± 2.0	15
SR14	10.1 ± 1.2	4.2 ± 1.6	14.3 ± 1.8	16
SR15	5.03 ± 0.77	4.1 ± 1.5	9.1 ± 1.6	4
SR16	2.49 ± 0.61	3.4 ± 1.3	5.9 ± 1.3	7
SR17	0.57 ± 0.36	1.08 ± 0.42	1.65 ± 0.50	3

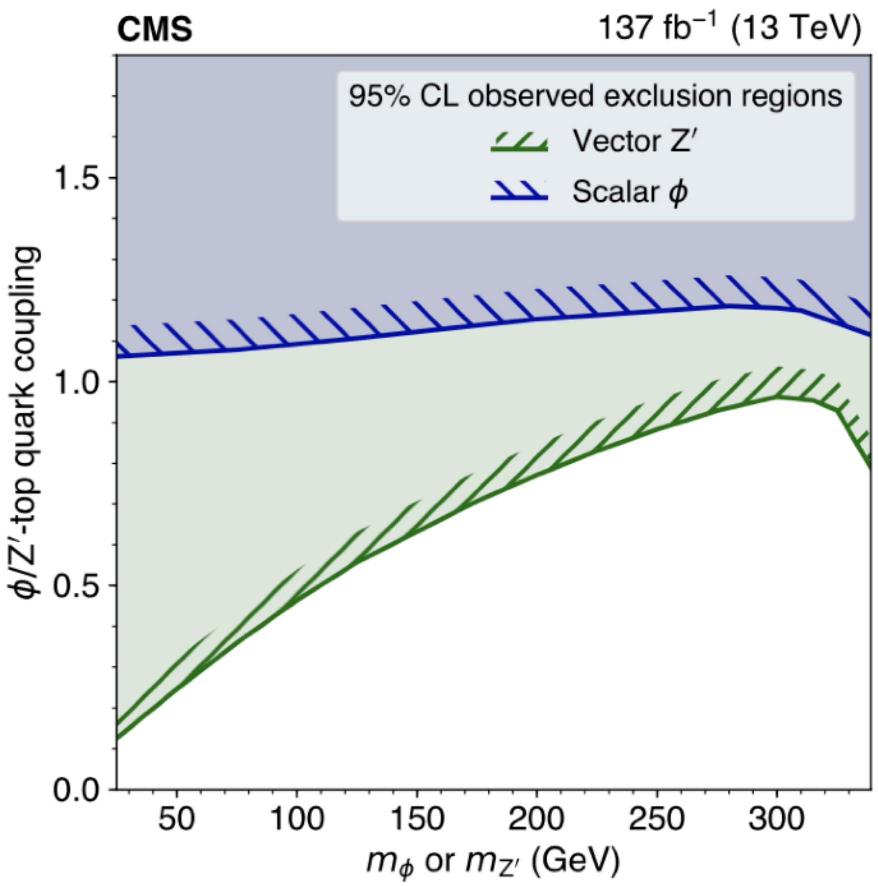
$t\bar{t}t\bar{t}$ SS, multilepton — Interpretation I

Eur.Phys.J.C 80 (2020) 2, 75

- „The measurement can be interpreted as a constraint on the Higgs boson oblique parameter $\hat{H}$, defined as the Wilson coefficient of the dimension-six BSM operator modifying the Higgs boson propagator“
- „Feynman diagrams where the virtual Higgs boson is replaced by a virtual BSM scalar (ϕ) or vector (Z′) particle with mass smaller than twice the top quark mass ($m < 2m_t$), are used to interpret the result as a constraint on the couplings of such new particles“
- „new particles with $m > 2m_t$, such as a heavy scalar (H) or pseudoscalar (A), can be produced on-shell in association with top quarks“ → New scalars can also decay to top-quark pairs

$t\bar{t}t\bar{t}$ SS, multilepton — Interpretation II

Exclude couplings larger than 1.2 for m_ϕ in the 25–340 GeV range and larger than 0.1 (0.9) for $m_{Z'}$ = 25 (300) GeV



„Comparing these limits with the Type-II 2HDM cross sections with tan β = 1 in the alignment limit, we exclude scalar (pseudoscalar) masses up to 470 (550) GeV, improving by more than 100 GeV with respect to the previous CMS limits“, Eur.Phys.J.C 80 (2020) 2, 75