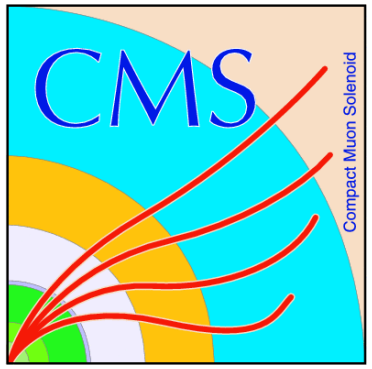
CMS: $t\bar{t}H$ multilepton

Red LHC 2020

3 November 2020



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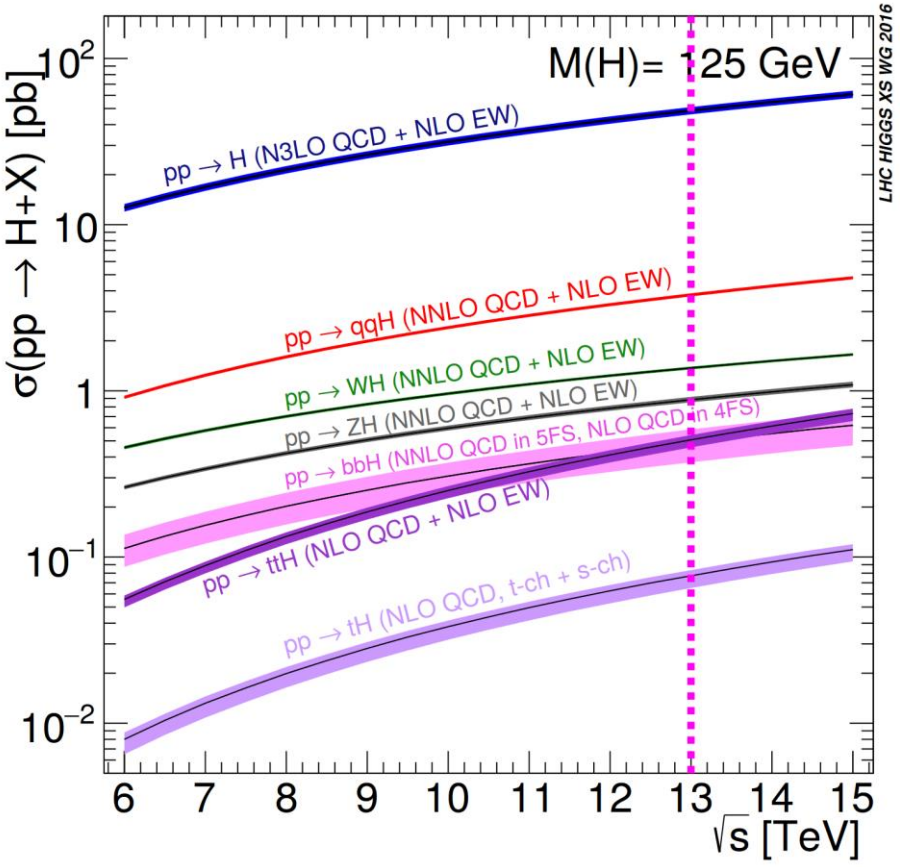
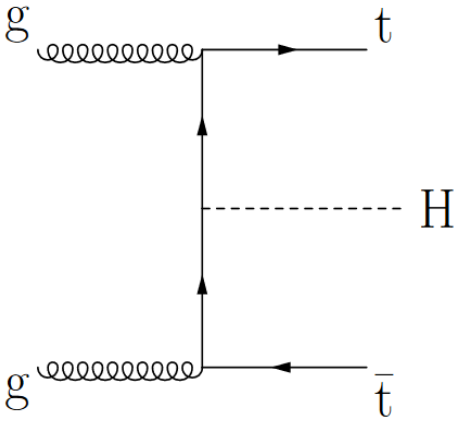
Introduction

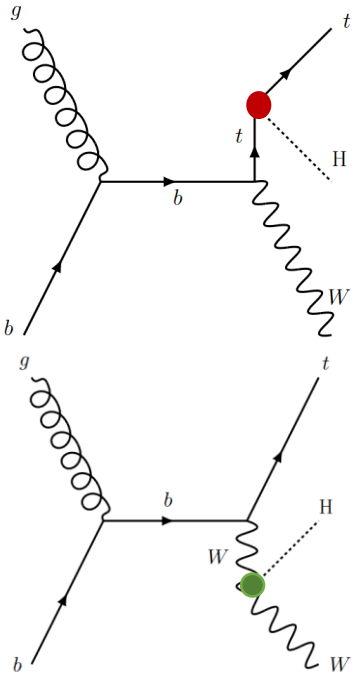
Study **Higgs boson properties** is very interesting
Run 3 allowed to study **top-Higgs interaction**
Top-Higgs coupling sensitive to **BSM physics**



$t\bar{t}H$:

- Best process to study this interaction at tree level
- **Sensitive to Yukawa coupling** (y_t) and CP violation
- Challenging to study: $\boldsymbol{\sigma \approx 0.5}$ **pb**





tH:

- Even more challenging to study: $\boldsymbol{\sigma \approx 74}$ **fb**
- Sensitive to y_t and g_w
- **Interference** between $\boldsymbol{y_t}$ **and** $\boldsymbol{g_w}$ diagrams → ITC (k_t / k_w = -1) enhance tH σ up to 10 times

Analaysis strategy

CMS-PAS-HIG-19-008

- **Several channels** to search for ttH and tH
- In this analysis **multilepton (e,μ,τ_h) final states** used targeting:
  H → WW/ZZ/$\tau\tau$
  $t\bar{t}$ → $\ell + jets$, dilepton

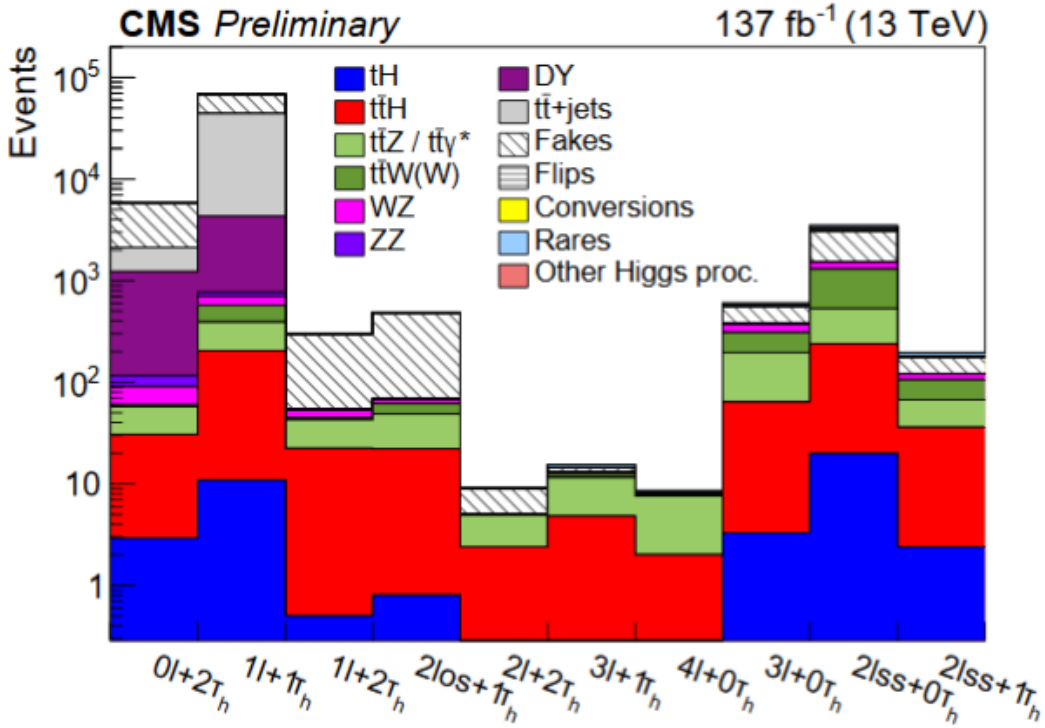
Data taken by the CMS experiment at 13 TeV (137 fb^{-1})

Signal Regions:

- 10 disjoint categories based on lepton (e,μ,τ_h) multiplicity
- Different background composition in each category
- Jet and b-tag multiplicity according to $t\bar{t}$H final state
  In $2lss + 0\tau$, $2lss + 1\tau, 3l + 0\tau$ event **selection** is **extended** to **target tH** events

Control Regions:

- With 3 and 4 leptons and a Z boson candidate to constrain $t\bar{t}$Z background

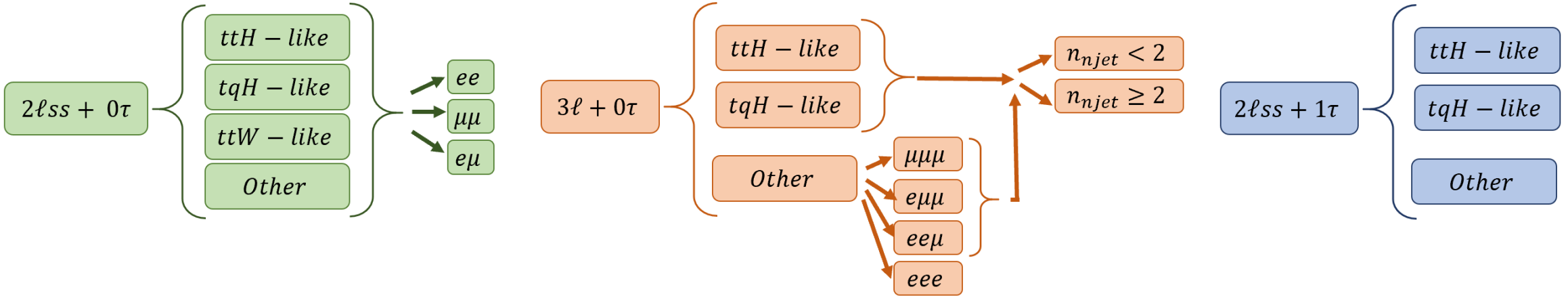


Background discrimination

CMS-PAS-HIG-19-008

MVA to enhance background to signal separation:

- **multiclass ANNs** used in categories sensitive to $t\bar{t}H$ and tH ($2\ell ss + 1\tau_h$, $2\ell ss + 0\tau_h$ and $3\ell + 0\ \tau_h$)



Further classification performed based on the score of the most probable process

- **BDTs** on categories not sensitive to tH: separate $t\bar{t}H$+tH against the backgrounds.

Inputs: 3-momenta (of leptons, τ_h and jets), angular variables, masses, object multiplicity…

Backgrounds I

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Background estimation is key in this analysis

Reducible backgrounds:

- **Non prompt leptons and misidentified tau**. Estimated with data-driven methods
- **Electron charge flips**. Estimated with data-driven methods
- **Photon conversions**. Estimated with simulation

Irreducible backgrounds, estimated with MC:

- **ttZ, ttW**
- Less importantly WZ, ZZ, rares (tZq, $t\bar{t}t\bar{t}$)
- $t\bar{t}$ and DY in $1l + 1\tau,\ 0l + 2\tau$ categories

Backgrounds II

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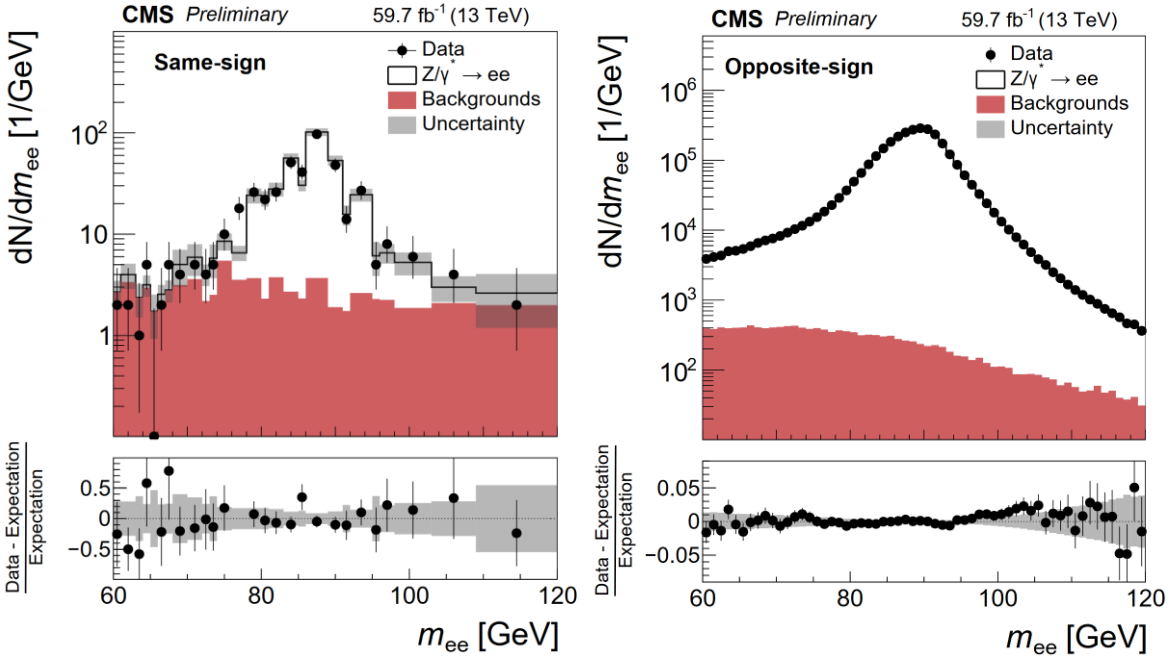
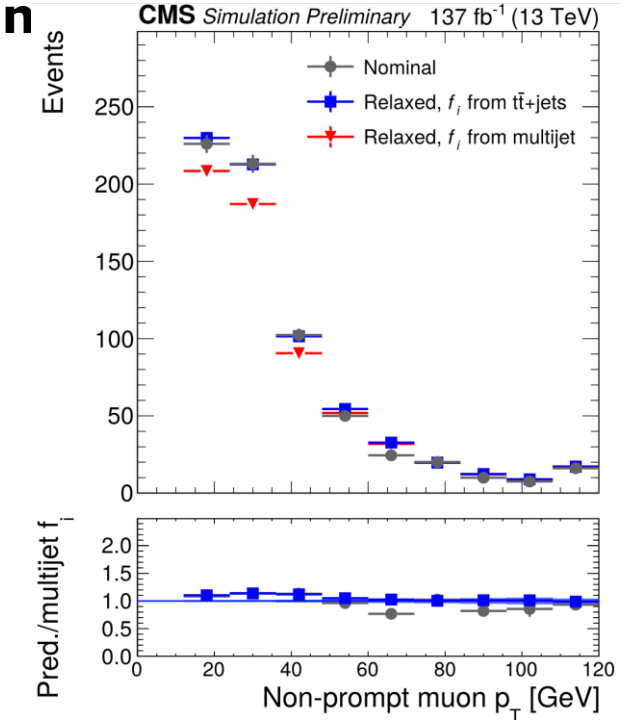
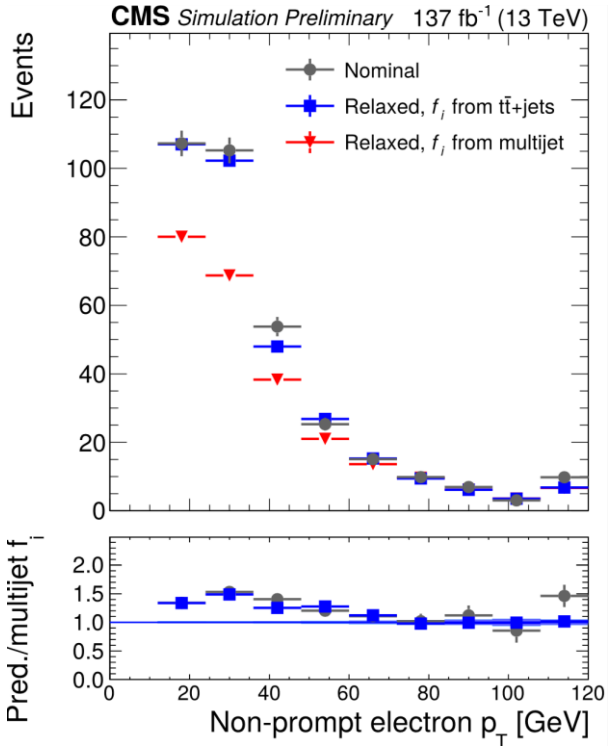
Non prompt leptons and misidentified tau

- **Suppressed** with **MVA** techniques in the **lepton identification**
- Estimated using the **tight-to-loose method**
- Fake rate measured in multijet events
- Check the method in $t\bar{t}$ simulations
- Similar procedure followed for misidentified τ_h







Electron charge flips

- Estimated from an opposite-sign side band

Backgrounds III

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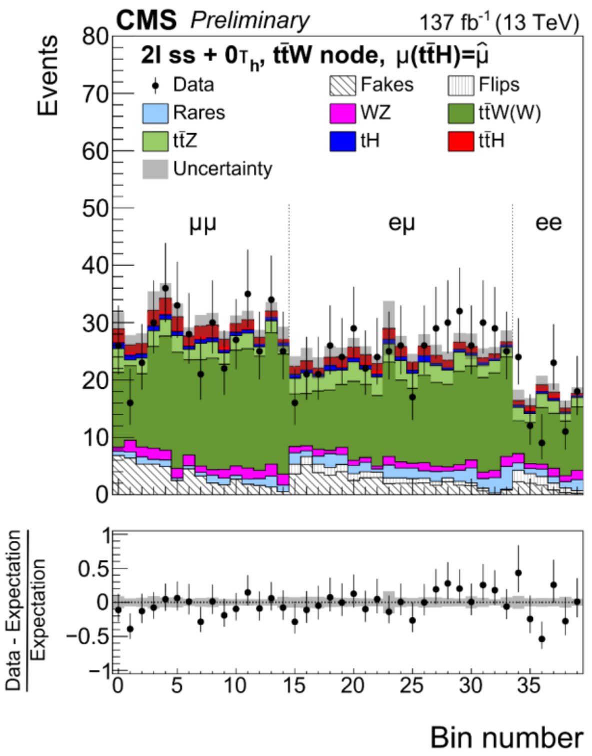
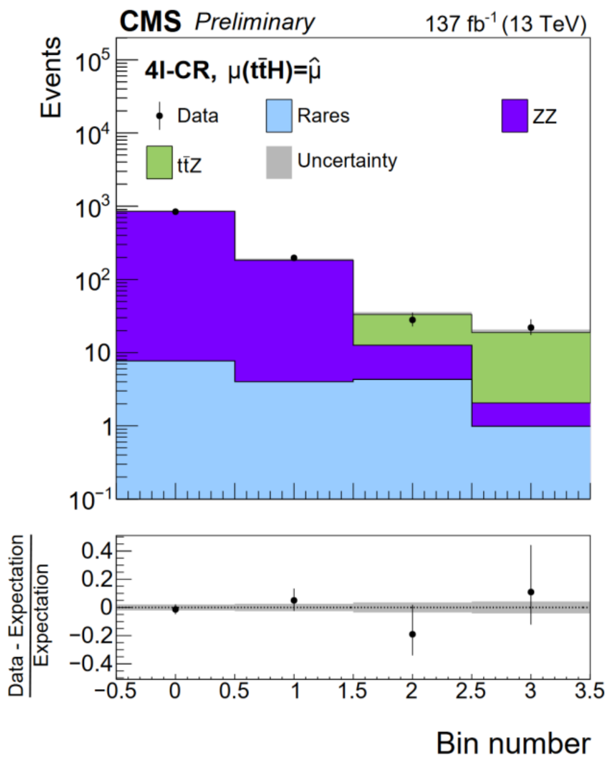
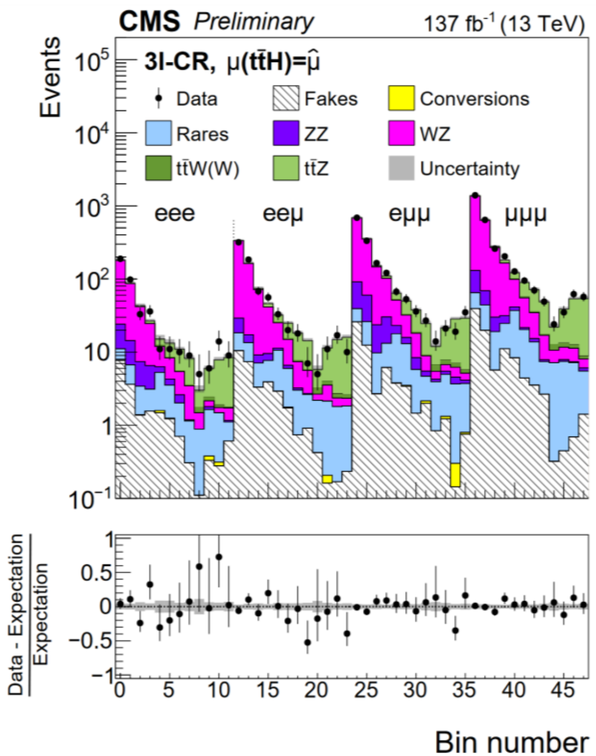
tt̄W and tt̄Z

- Dedicated **control regions** for tt̄Z (3 and 4 leptons with a Z boson candidate)
- Dedicated **ANN node** for tt̄W ($2\ell ss + 0\,\tau_h$)
- Normalization determined in the signal extraction fit
- **State of the art simulation**:
  - tt̄Z simulated with NLO QCD
  - tt̄W simulated with NLO QCD including α^3 and $\alpha^3\alpha_s$







Results

Signal regions in some categories

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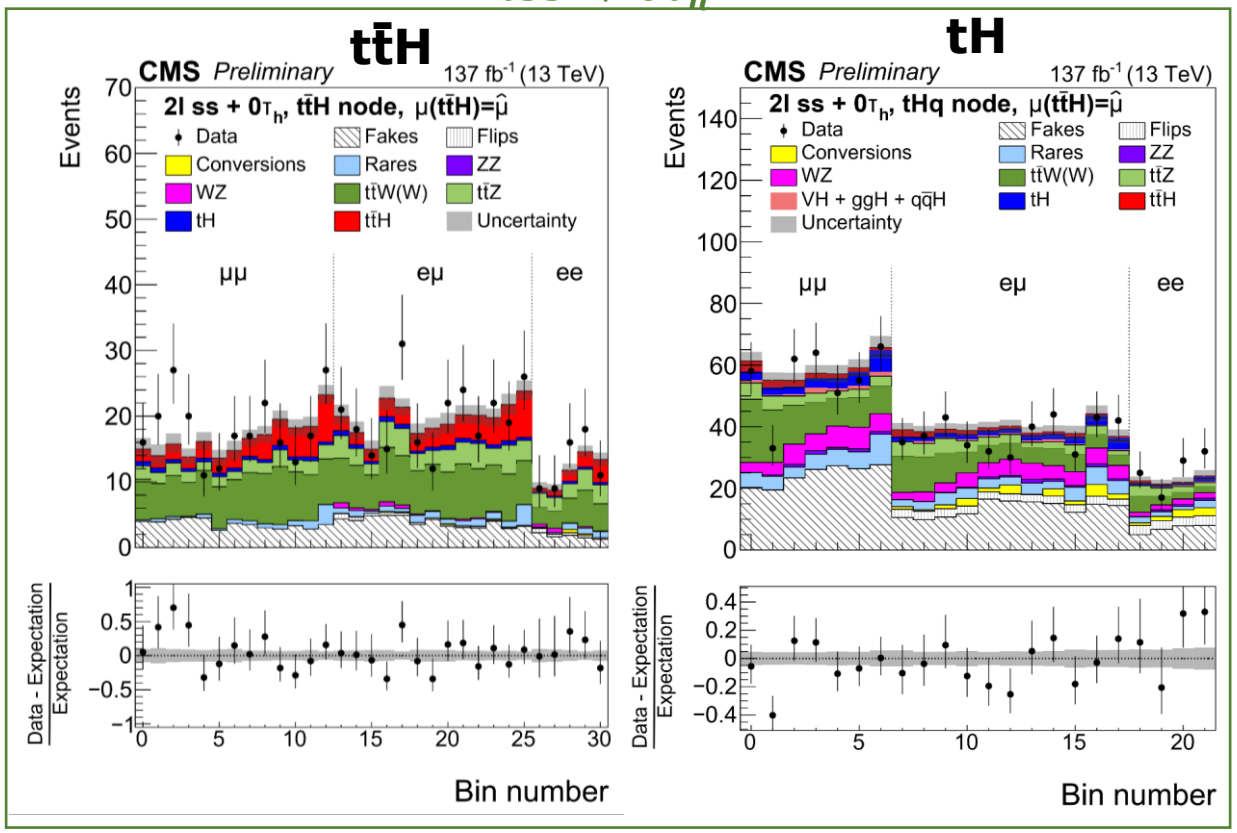
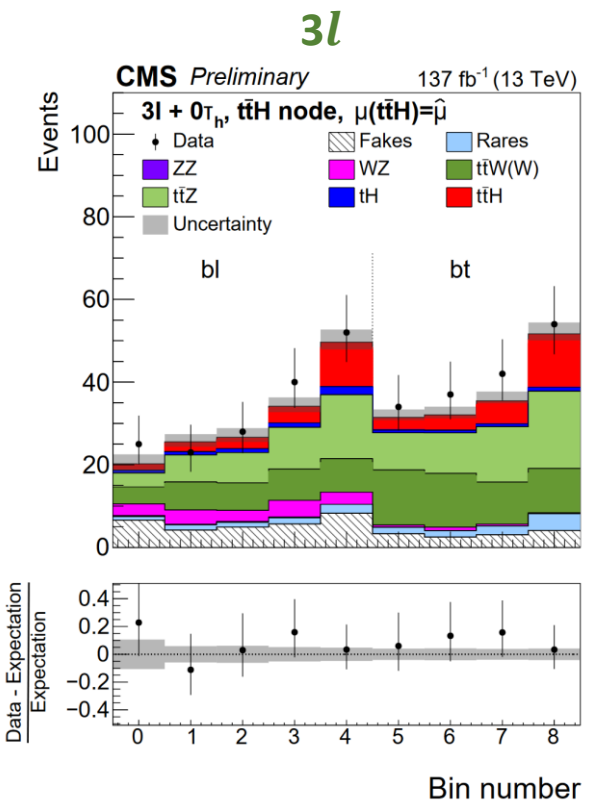
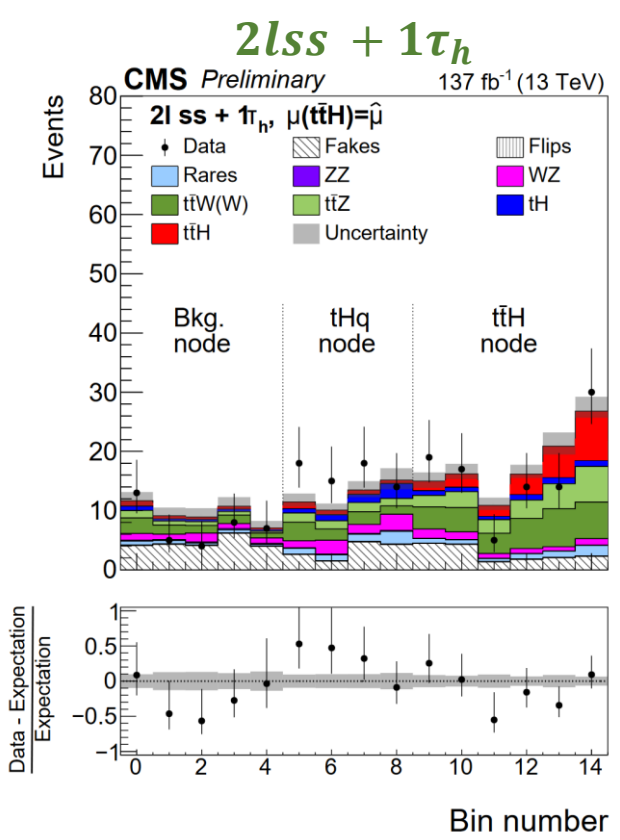
$2lss + 0\tau_h$



$3l$



$2lss + 1\tau_h$



- Good data MC agreement
- Clear presence of tt̄H signal in tt̄H targeting nodes

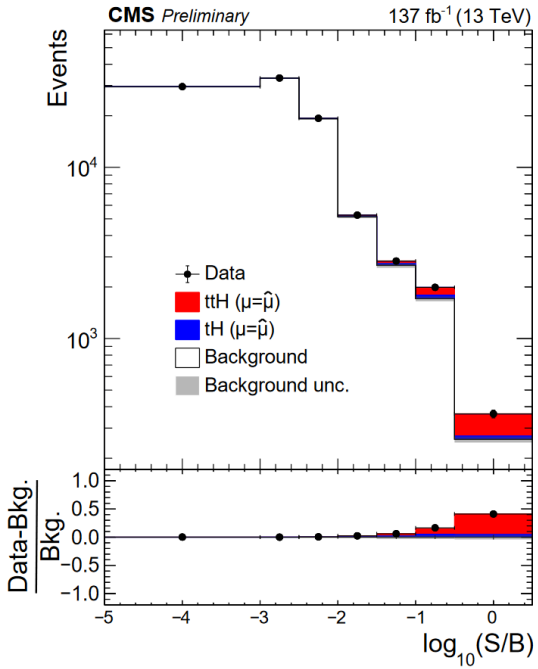
Signal extraction

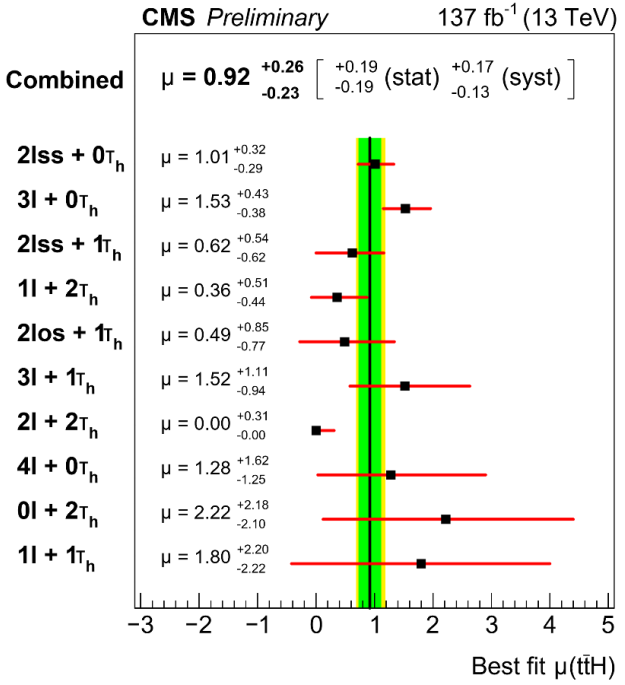
CMS-PAS-HIG-19-008

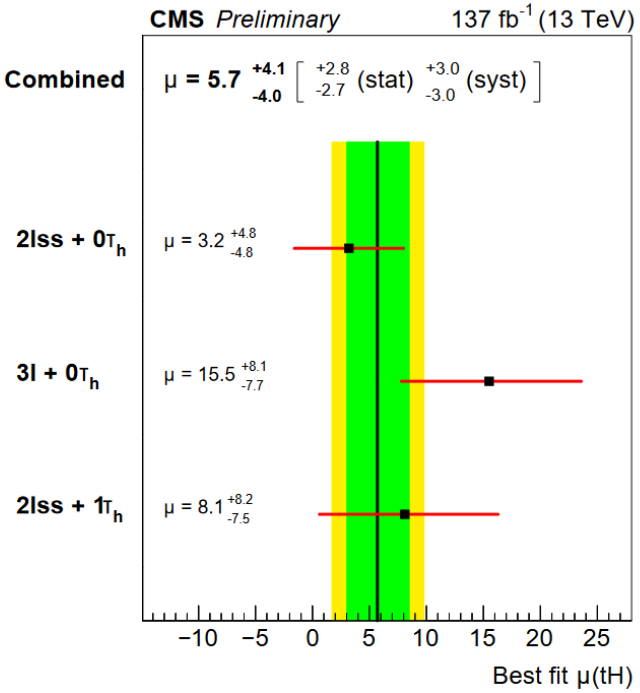
Signals are extracted fitting data in all categories:

- Above **5σ sensitivity for $t\bar{t}H$**
- **4.7σ observed** significance for $t\bar{t}H$
- Observed **tH** significance: **1.4σ**
- Results in good agreement with SM
- $\mu_{ttW} = 1.43 \pm 0.21 \rightarrow$ above expectation
- $t\bar{t}W$ measurement consistent with other CMS and ATLAS measurements

$$\mu_{ttH} = 0.92^{+0.26}_{-0.23} \qquad \mu_{tH} = 5.67^{+4.1}_{-4.0}$$







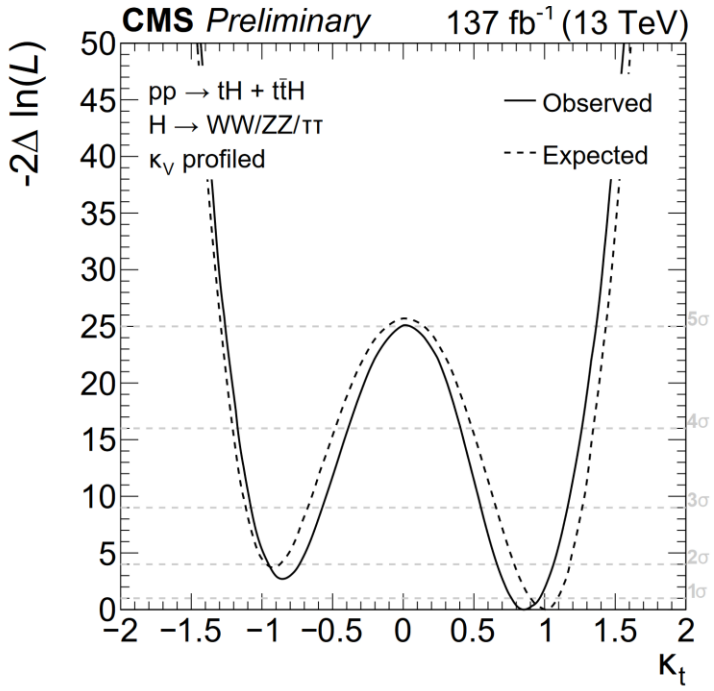
K framework results

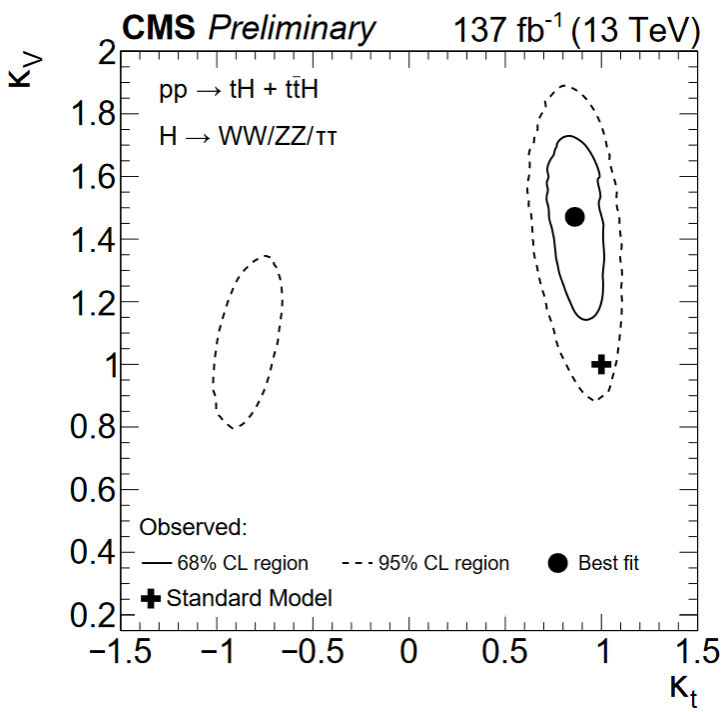
Interpretation of yields in terms of:

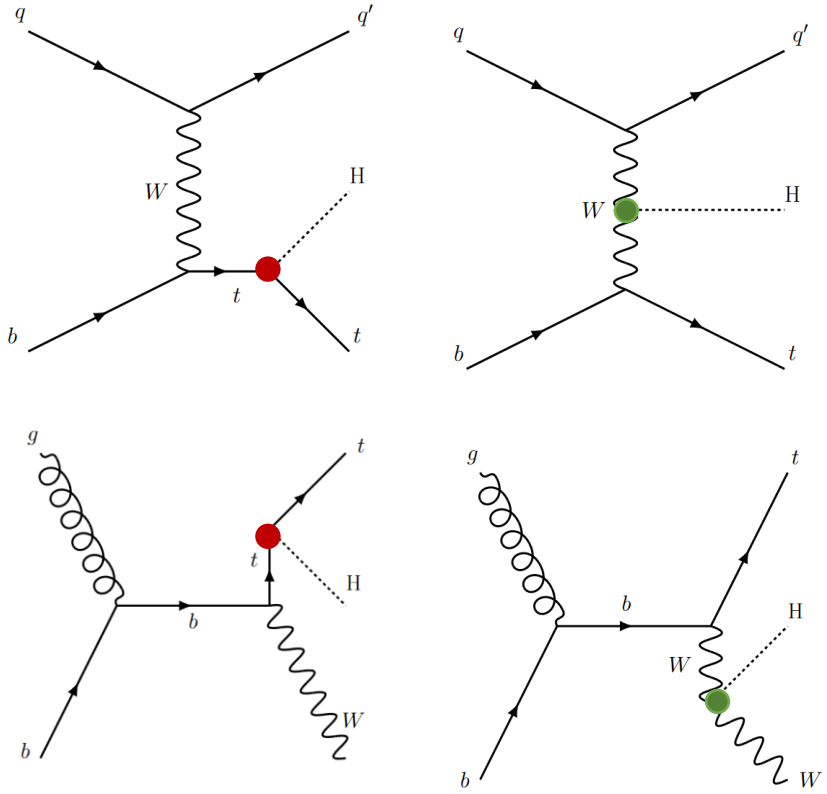
$$\kappa_t = \frac{y_t}{y_t^{SM}} \quad \kappa_V = \frac{g_{W/Z}}{g_{W/Z}^{SM}}$$

- Acceptance parametrized as function of κ_t / κ_V
- Modification of Higgs BR considered

Likelihood scans as a function of κ_t κ_V:





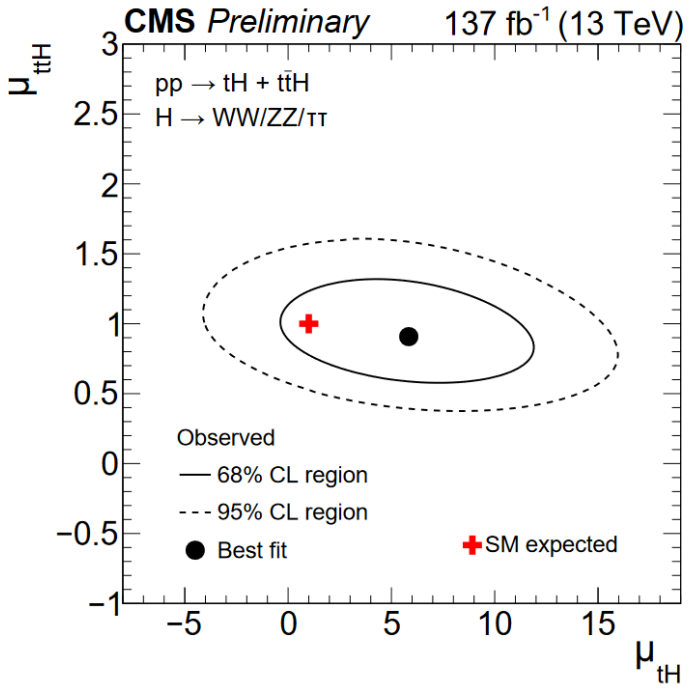


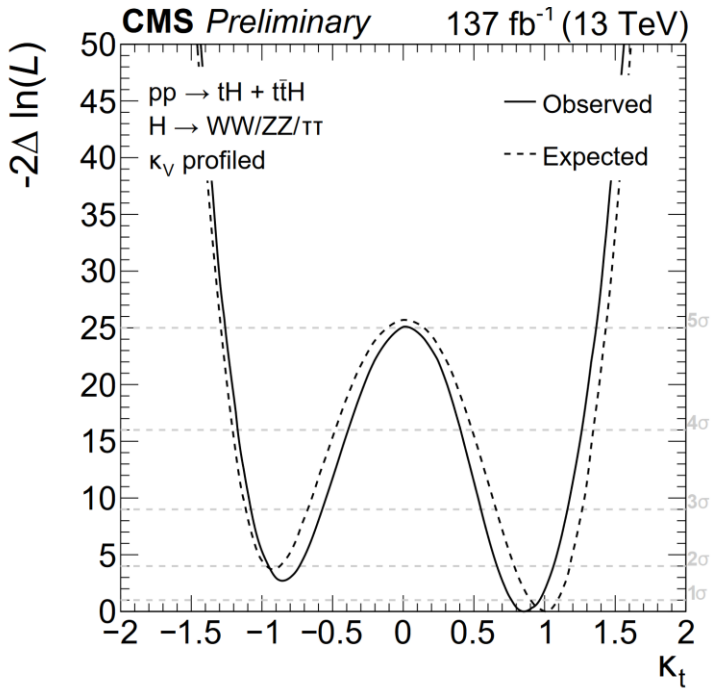
κ_t **constrained** to be within **-0.9 < κ_t <-0.7** and **0.7 < κ_t <1.1** at 95% CL

Summary

- $t\bar{t}H$ and tH measured in final state with multiple leptons using the complete run 2 dataset (137 fb^{-1})
- $t\bar{t}H$ sensitivity above 5σ
- Signal strengths obtained in good agreement with SM

- Results interpreted in terms if Higgs coupling modifiers
- Kt constrained to be within $-0.9 < \kappa_t < -0.7$ and $0.7 < \kappa_t < 1.1$ at 95% CL





Back up

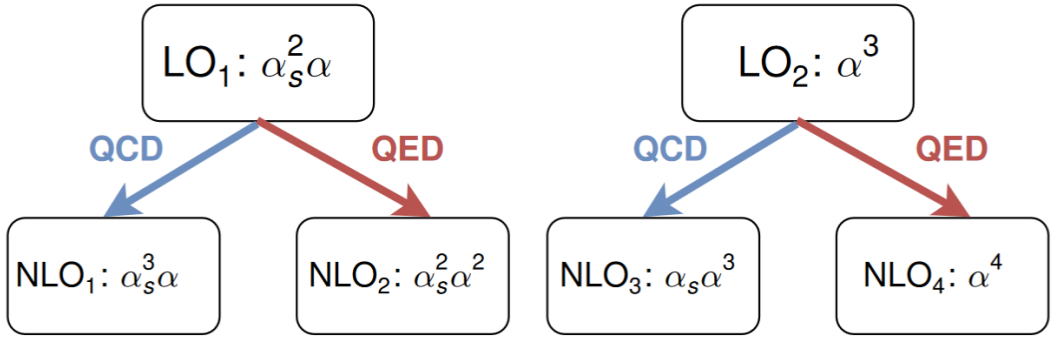
Uncertainties

Source	$\Delta\mu_{ttH}/\mu_{ttH}$ [%]	$\Delta\mu_{tH}/\mu_{tH}$ [%]	$\Delta\mu_{ttW}/\mu_{ttW}$ [%]	$\Delta\mu_{ttZ}/\mu_{ttZ}$ [%]
Trigger efficiency	2.3	8.1	1.2	1.9
e, μ reconstruction 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 and sideband statistical uncertainty	7.1	27.2	2.4	2.3
Theory-related sources	4.6	18.2	2.0	4.2
Normalization of MC-estimation processes	13.3	12.3	13.9	11.3
Luminosity	2.2	4.6	1.8	3.1
Statistical uncertainty	20.9	48.0	5.9	5.8

- Signals, ttZ and ttW normalization are freely floating
  - No assumption on total cross section
- Modeling of irreducible processes follows the most accurate calculations available

ttH and ttZ production
- Generated at NLO QCD with MADGRAPH5_aMC@NLO
- Normalized NLO QCD+EWK (arXiv:1610.07922)

tHq and tHW
- Generated at LO with MADGRAPH5aMC@NLO
- Normalized at NLO QCD (arXiv:1610.07922)



ttW production
- Generated at NLO QCD with MADGRAPH5aMC@NLOI
- Normalized to NLO QCD + EWK (arXiv:1610.07922)
- α^3 and $\alpha_s\alpha^3$ corrections are added on top (arXiv:2004.09552)

Selection step	$2\ell ss + 0\tau_h$	$2\ell ss + 1\tau_h$
Targeted $t\bar{t}H$ decay	$t \to b\ell\nu$, $t \to bqq'$ with $H \to WW \to \ell\nu qq'$	$t \to b\ell\nu$, $t \to bqq'$ with $H \to \tau\tau \to \ell\nu\nu\tau_h\nu$
Targeted tH decays	$t \to b\ell\nu$, $H \to WW \to \ell\nu qq$	$t \to b\ell\nu$, $H \to \tau\tau \to \ell\tau_h + \nu's$
Trigger	Single- and double-lepton triggers	
Lepton p_T	$p_T > 25$ / 15 GeV	$p_T > 25$ / 15 GeV (e) or 10 GeV (μ)
Lepton η	$\lvert\eta\rvert < 2.5$ (e) or 2.4 (μ)	
τ_h p_T	—	$p_T > 20$ GeV
τ_h η	—	$\lvert\eta\rvert < 2.3$
τ_h identification	—	very-loose
Charge requirements	2 same-sign leptons and charge quality requirements	2 same-sign leptons and charge quality requirements $\sum_{\ell,\tau_h} q = \pm 1$
Multiplicity of central jets	$\geq$3 jets	$\geq$3 jets
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	$L_D > 30$ GeV†	
Dilepton invariant mass	$\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV‡ and $m_{\ell\ell} > 12$ GeV	

Selection step	$3\ell + 0\tau_h$	$3\ell + 1\tau_h$
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu$, $t \to b\ell\nu$ with $H \to WW \to \ell\nu qq'$ $t \to b\ell\nu$, $t \to bqq'$ with $H \to WW \to \ell\nu\ell\nu$ $t \to b\ell\nu$, $t \to bqq'$ with $H \to ZZ \to \ell\ell qq'$ or $\ell\ell\nu\nu$	$t \to b\ell\nu$, $t \to b\ell\nu$ with $H \to \tau\tau \to \ell\nu\nu\tau_h\nu$
Targeted tH decays	$t \to b\ell\nu$, $H \to WW \to \ell\nu\ell\nu$	—
Trigger	Single-, double- and triple-lepton triggers	
Lepton p_T	$p_T > 25$ / 15 / 10 GeV	
Lepton η	$\lvert\eta\rvert < 2.5$ (e) or 2.4 (μ)	
τ_h p_T	—	$p_T > 20$ GeV
τ_h η	—	$\lvert\eta\rvert < 2.3$
τ_h identification	—	very-loose
Charge requirements	$\sum_\ell q = \pm 1$	$\sum_{\ell,\tau_h} q = 0$
Multiplicity of central jets	≥ 2 jets	
b tagging requirements	≥ 1 tight b-tagged jet or ≥ 2 loose b-tagged jets	
Missing transverse momentum	$L_D > 0$ / 30 / 45 GeV‡	
Dilepton invariant mass	$m_{\ell\ell} > 12$ GeV and $\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV§	
Four-lepton invariant mass	$m_{4\ell} > 140$ GeV¶	—

Selection step	$2\ell\text{os} + 1\tau_\text{h}$	$4\ell + 0\tau_\text{h}$
Targeted $\text{t}\bar{\text{t}}\text{H}$ decays	$\text{t} \to \text{b}\ell\nu$, $\text{t} \to \text{bqq}'$ with $\text{H} \to \tau^+\tau^- \to \ell\nu\nu\tau_\text{h}\nu$	$\text{t} \to \text{b}\ell\nu$, $\text{t} \to \text{b}\ell\nu$ with $\text{H} \to \text{WW} \to \ell\nu\ell\nu$ $\text{t} \to \text{b}\ell\nu$, $\text{t} \to \text{b}\ell\nu$ with $\text{H} \to \text{ZZ} \to \ell\ell\text{qq}'$ or $\ell\ell\nu\nu$
Trigger	Single- and double-lepton triggers	Single-, double- and triple-lepton triggers
Lepton p_T	$p_\text{T} > 25$ / 15 GeV (e) or 10 GeV (μ)	$p_\text{T} > 25$ / 15 / 15 / 10 GeV
Lepton η	$\lvert\eta\rvert < 2.5$ (e) or 2.4 (μ)	
τ_h p_T	$p_\text{T} > 20$ GeV	—
τ_h η	$\lvert\eta\rvert < 2.3$	—
τ_h identification	tight	—
Charge requirements	$\sum_\ell q = 0$ and $\sum_{\ell,\tau_\text{h}} q = \pm 1$	$\sum_\ell q = 0$
Multiplicity of central jets	$\geq$3 jets	$\geq$2 jets
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	$L_\text{D} > 30$ GeV†	$L_\text{D} > 0$ / 30 / 45 GeV‡
Dilepton invariant mass	$m_{\ell\ell} > 12$ GeV	$\lvert m_{\ell\ell} - m_\text{Z}\rvert > 10$ GeV§ and $m_{\ell\ell} > 12$ GeV
Four-lepton invariant mass	—	$m_{4\ell} > 140$ GeV¶

Selection step	$1\ell + 2\tau_h$	$2\ell + 2\tau_h$
Targeted $t\bar{t}H$ decays	$t \to b\ell\nu$, $t \to bqq'$ with $H \to \tau^+\tau^- \to \tau_h\nu\tau_h\nu$	$t \to b\ell\nu$, $t \to b\ell\nu$ with $H \to \tau^+\tau^- \to \tau_h\nu\tau_h\nu$
Trigger	Single-lepton and lepton+τ_h triggers	Single- and double-lepton triggers
Lepton p_T	$p_T > 30$ (e) or 25 GeV (μ)	$p_T > 25$ / 10 (15) GeV (e)
Lepton η	$\lvert\eta\rvert < 2.1$	$\lvert\eta\rvert < 2.5$ (e) or 2.4 (μ)
τ_h p_T	$p_T > 30$ / 20 GeV	$p_T > 20$ GeV
τ_h η	$\lvert\eta\rvert < 2.1$	$\lvert\eta\rvert < 2.3$
τ_h identification	medium	medium
Charge requirements	$\sum_{\ell,\tau_h} q = \pm 1$	$\sum_{\ell,\tau_h} q = 0$
Multiplicity of central jets	$\geq$3 jets	$\geq$2 jets
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Missing transverse momentum	—	$L_D > 0$ / 30 / 45 GeV†
Dilepton invariant mass	$m_{\ell\ell} > 12$ GeV	

Selection step	$0\ell + 2\tau_h$	$1\ell + 1\tau_h$
Targeted $t\bar{t}H$ decays	$t \to bqq'$, $t \to bqq'$ with $H \to \tau\tau \to \tau_h\nu\tau_h\nu$	$t \to bqq'$, $t \to bqq'$ with $H \to \tau\tau \to \ell\nu\nu\tau_h\nu$
Trigger	Double-τ_h trigger	Single-lepton and lepton+τ_h triggers
Lepton p_T	—	$p_T > 30$ (e) or 25 GeV (μ)
Lepton η	—	$\lvert\eta\rvert < 2.1$
τ_h p_T	$p_T > 40$ GeV	$p_T > 30$ GeV
τ_h η	$\lvert\eta\rvert < 2.1$	
τ_h identification	loose	medium
Charge requirements	$\sum_{\tau_h} q = 0$	$\sum_{\ell,\tau_h} q = 0$
Multiplicity of central jets	≥ 4 jets	
b tagging requirements	≥ 1 tight b-tagged jet or ≥ 2 loose b-tagged jets	
Dilepton invariant mass	$m_{\ell\ell} > 12$ GeV	