Top Yukawa: $t\bar{t}H$ multilepton and $t\bar{t}$

Higgs 2020

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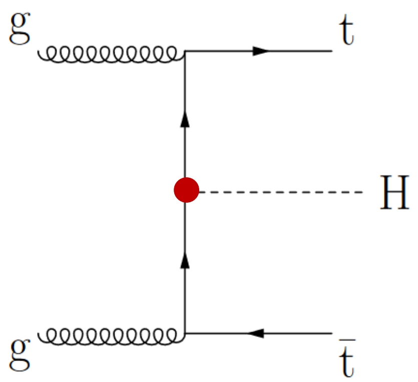
Introduction

Yukawa coupling is proportional to the mass of the interacting particles. Top Yukawa coupling is of special interest:

- Largest one: **close to unity**
- **BSM physics** could introduce **modified couplings** that alter top-Higgs interaction
- Experimentally accessible in multiple ways:

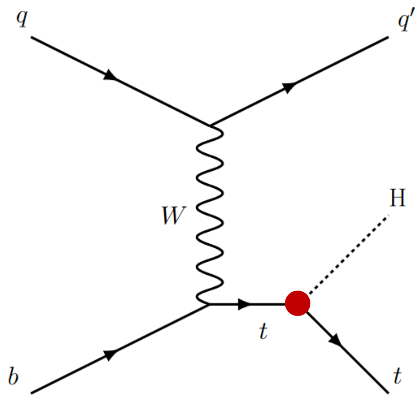
Direct measurements

$t\bar{t}$H



tH

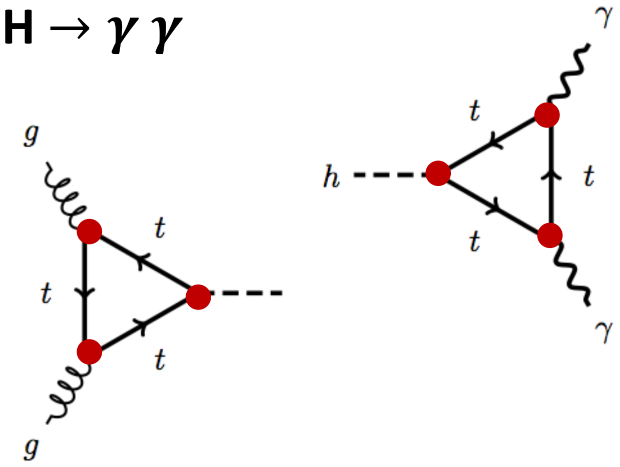
Sensitive to sign



Indirect measurements

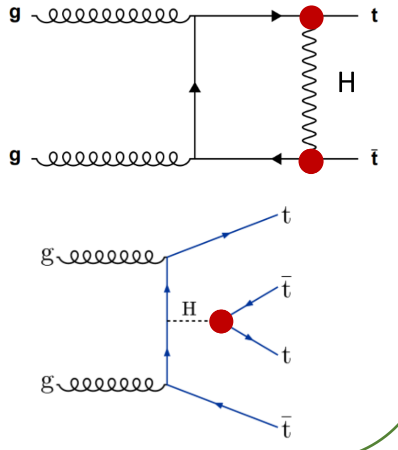
gg fusion Higgs production

H → $\gamma\gamma$



$t\bar{t}$

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



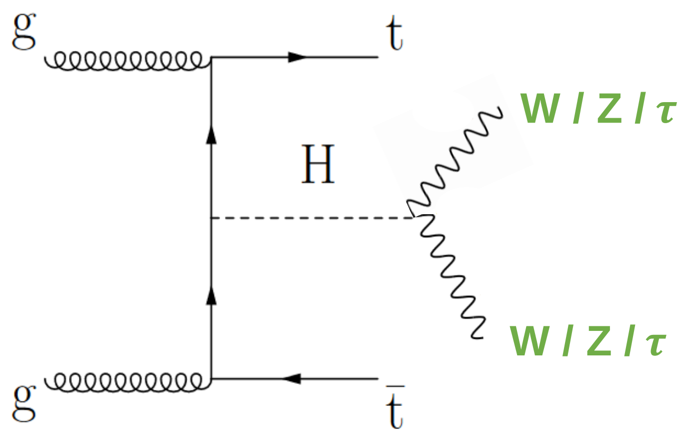
This talk will cover $t\bar{t}$H multilepton (CMS & ATLAS) and $t\bar{t}$ (CMS)

$t\bar{t}H$ multilepton

$t\bar{t}H$ Multilepton

Final state with multiple leptons (e,μ,τ_h) target:

- H $\rightarrow$ WW/ZZ/$\tau\tau$
- $t\bar{t} \rightarrow \ell + jets$, dilepton



Most recent analysis:

137 fb^{-1} **CMS-PAS-HIG-19-008**

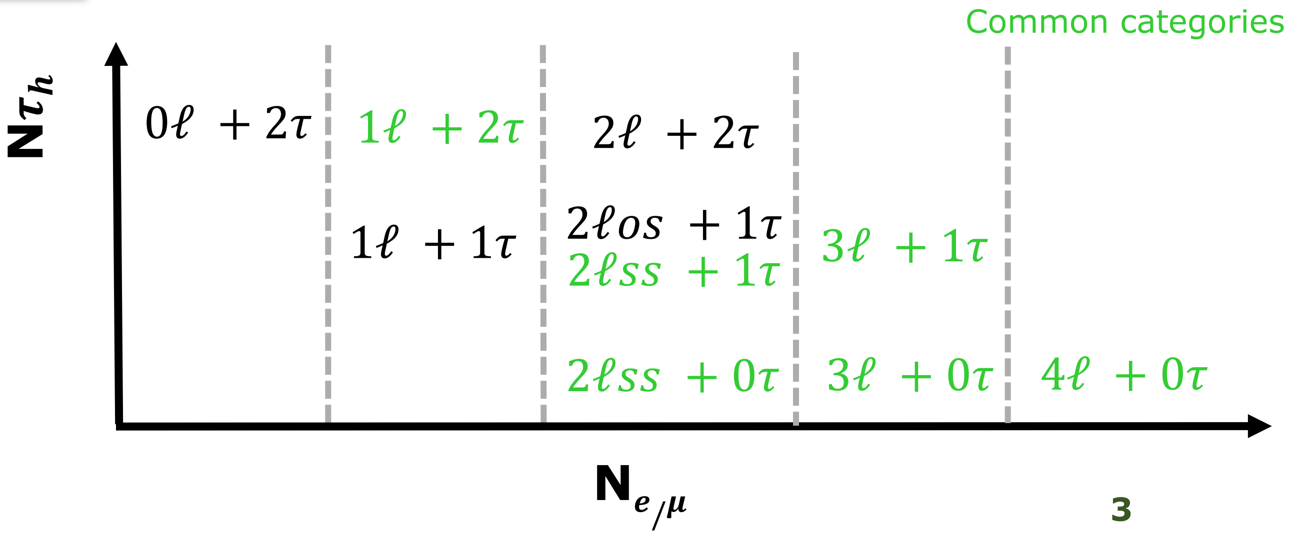
79.9 fb^{-1} **ATLAS-CONF-2019-045**

Analysis strategy:

In both CMS and ATLAS several stages:

First Step:

- Categories based on lepton multiplicity:
    - CMS: 10 categories
    - ATLAS: 6 categories



$t\bar{t}H$ Multilepton (II)

Second Step:

Dedicated selection on each category. Common item:

- **Jet and b tag multiplicity requirements**
    - **CMS**: Selection **consistent with $t\bar{t}H$** expected final state. In $2lss + 0\tau,\ 2lss + 1\tau, 3l + 0\tau$ event **selection** is **extended** to **target tH** events.
    - **ATLAS**: Baseline selction for all categories with low number of jets (LNJ): $\mathrm{N}_{Jets} \geq 2, N_{b\ tag} \geq 1$. Tightened to define SR (HNJ).

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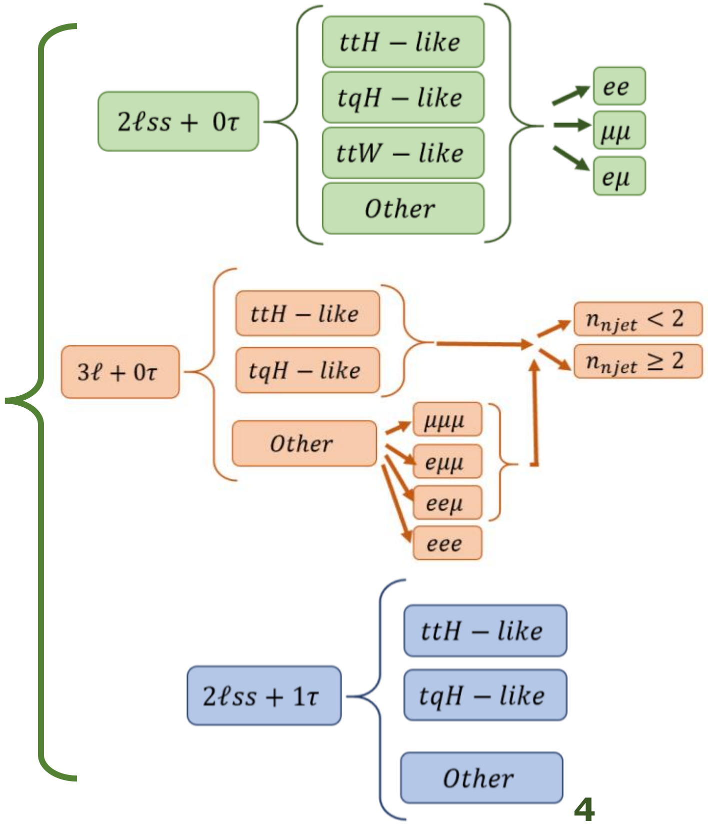
Third Step:

Categories based on MVA techniques:

- **CMS:**
  - **multiclass ANNs** used in categories sensitive to $t\bar{t}H$ and tH ⟶
    classification 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.



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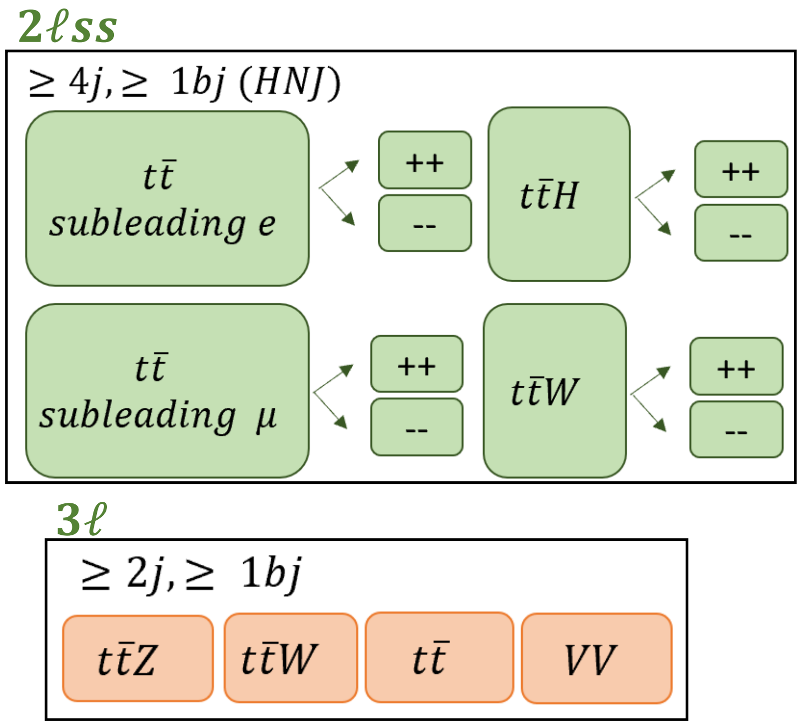
Third Step:

Categories based on MVA techniques:

- **ATLAS:**

  Combinations of BDTs. For the two most sensitive:
  - $\mathbf{2\ell ss+0\tau}$ $(SR, HNJ{:}\geq 4j,\geq\ 1bj)$: Combination of **2 BDTs (vs. $t\bar{t}$V, vs. $t\bar{t}$) in a 2D space** + categories in flavour and charge.
  - $\mathbf{3\ell\ +0\tau}$: $(SR{:}\ \geq 2j,\geq\ 1bj)$ **multi-class BDT** (vs. $t\bar{t}$W, vs. $t\bar{t}$, vs. $t\bar{t}$Z, vs. VV)

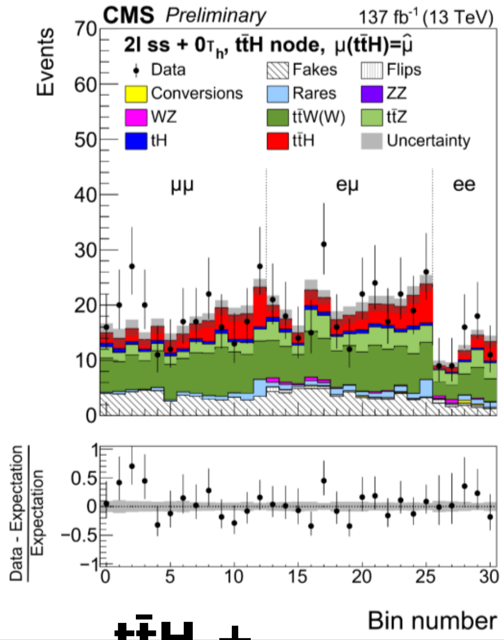


$t\bar{t}$H Multilepton: signal region (SR)

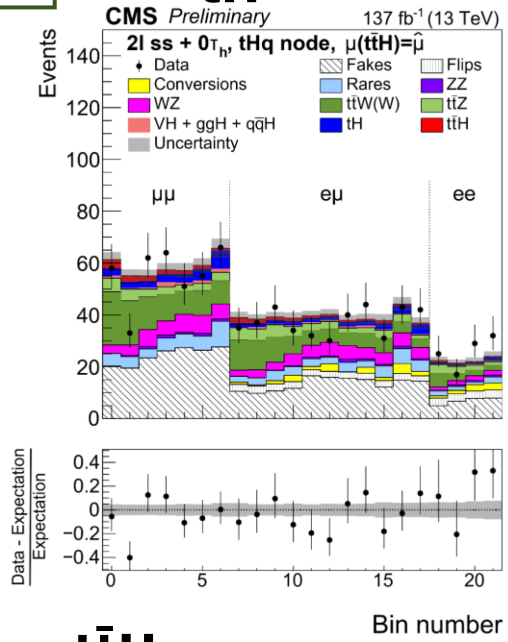
Signal regions

2lss

$t\bar{t}$H

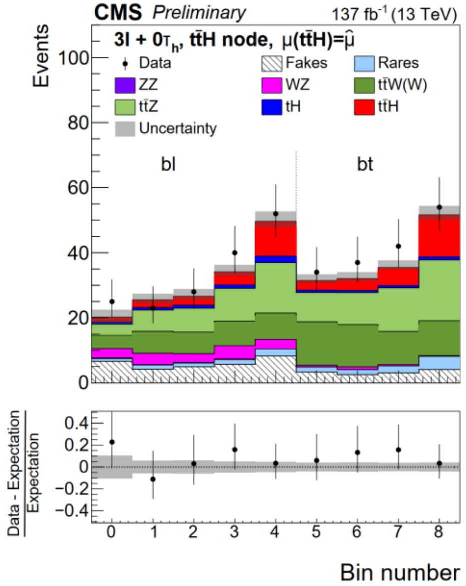


tH

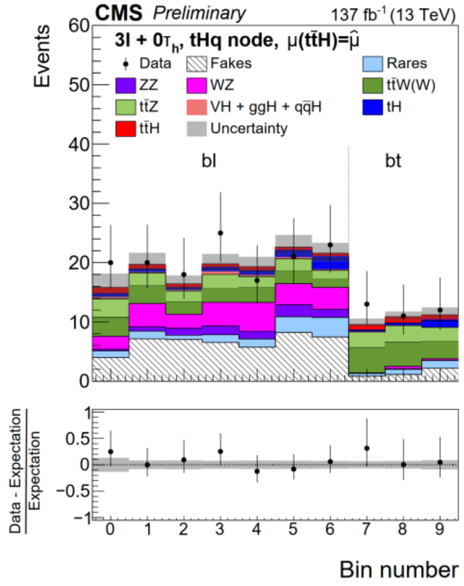


3l

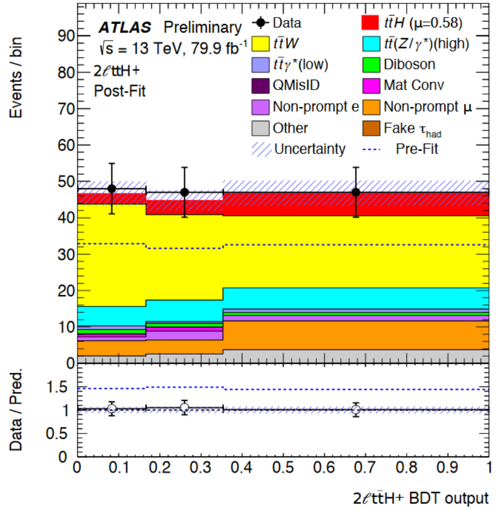
$t\bar{t}$H



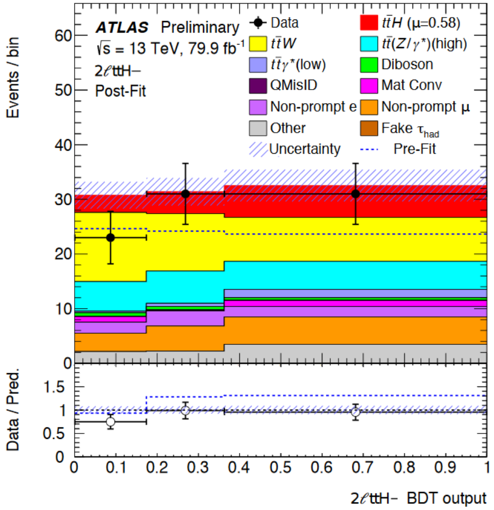
tH



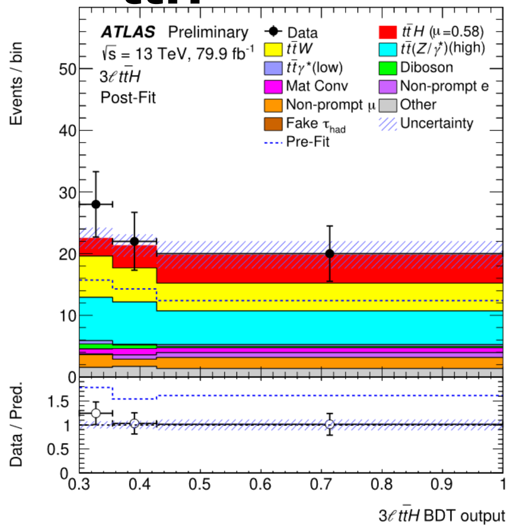
$t\bar{t}$H +



$t\bar{t}$H -



$t\bar{t}$H



ATLAS EXPERIMENT

$t\bar{t}H$ Multilepton: background

Background estimation is key in this analysis

Reducible backgrounds:

- ➢ Non prompt leptons and misidentified taus
- ➢ Electron charge flips
- ➢ Conversions

Irreducible backgrounds:

- ➢ $t\bar{t}Z$, $t\bar{t}W$
- ➢ Less importantly, dibosons

CMS:

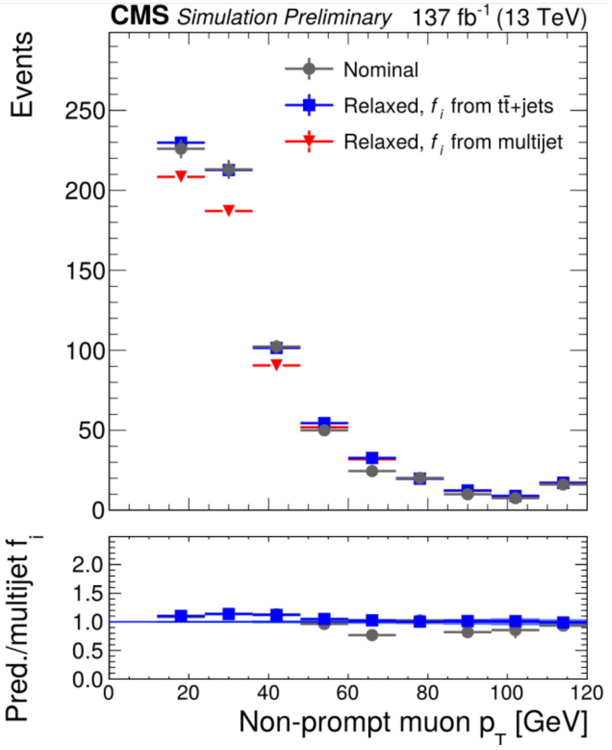
- Dedicated output node for **$t\bar{t}W$ in 2lss**.
- **Control regions** to constrain $t\bar{t}Z$ (3l & 4l)
  Normalization determined in the signal extraction fit

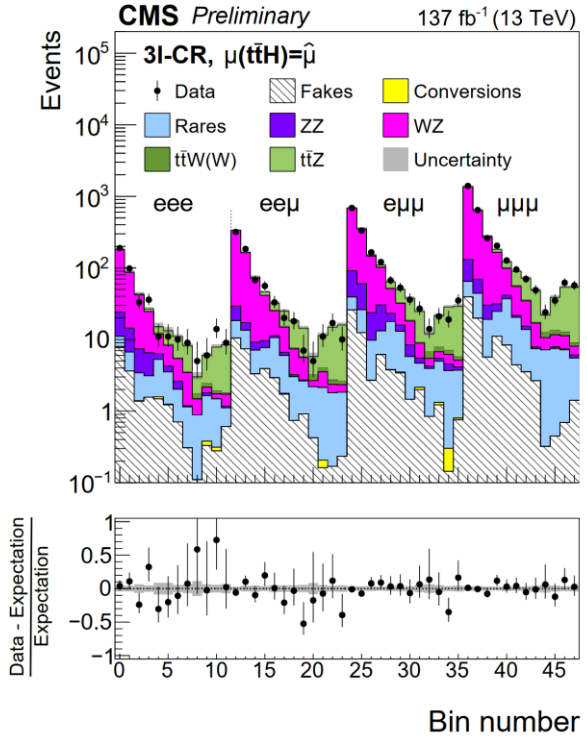
Non prompt background:

- Estimated with data-driven techniques (clousure for muons)

Photon conversions:

- Estimated with simulation





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ATLAS: ATLAS EXPERIMENT

- 13 dedicated control regions
- Norm. of non prompt, conversions and $t\bar{t}W$ measured simultaneously in the fit to data

$2\ell ss$

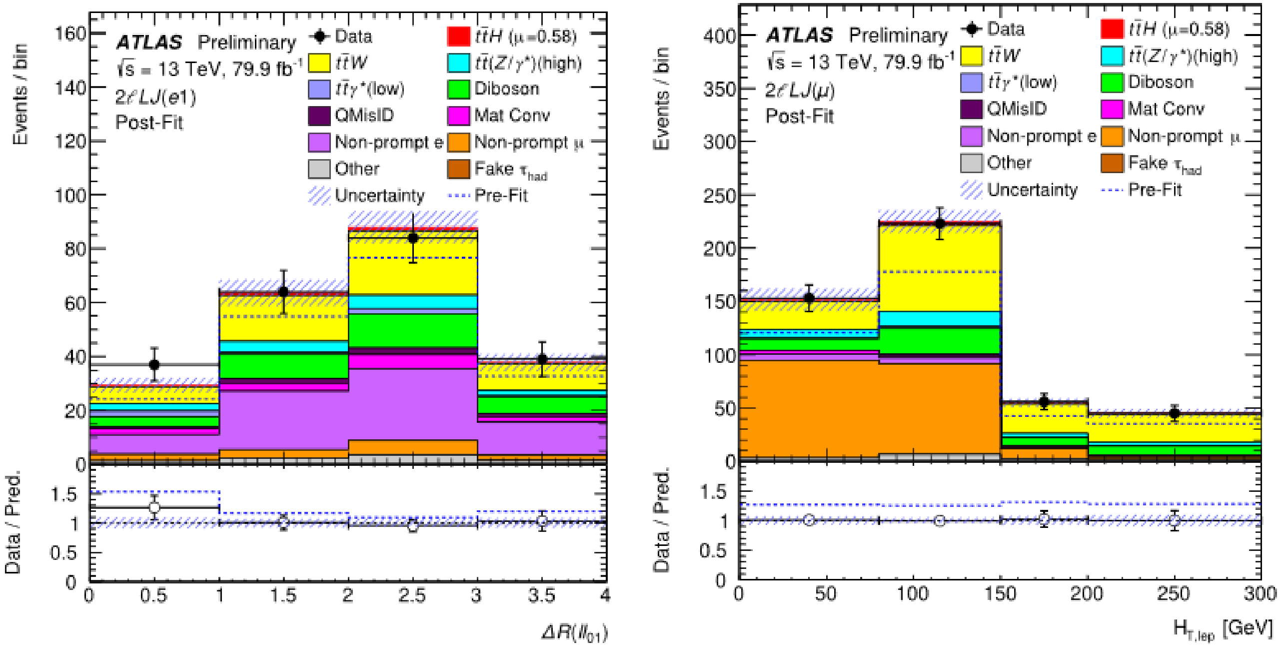
$(2-3)j, \geq 1bj$ (LNJ)

- Subleading e
  - 1B
  - 2B
- Subleading μ
- Int Conversion
- Material Conv.

3ℓ

$\geq 2j, \geq 1bj$

- Int Conversion
- Material Conv.



Material Conversion= Conversion can be resolved: displaced vertex is reconstructed

Internal Conversion = Conversion in hardprocess. Can't be resolved

$t\bar{t}H$ Multilepton: $t\bar{t}W$ background

Important background
Tension with SM seen both by CMS and ATLAS:

CMS	$\sigma_{t\bar{t}W} / \sigma_{t\bar{t}W}^{SM}$	ATLAS	$\sigma_{t\bar{t}W} / \sigma_{t\bar{t}W}^{SM}$
JHEP 08 (2018) 011 ($t\bar{t}W$ & $t\bar{t}Z$, 35.9 fb^{-1})	$1.23^{+0.30}_{-0.28}$	Phys. Rev. D 99 (2019) 072009 ($t\bar{t}W$ $t\bar{t}Z$, 36.1 fb^{-1})	1.44 ± 0.32
EPJC 80 (2020) 75 (4 tops, 137 fb^{-1})	1.3 ± 0.2	CERN-EP-2020-111 (4 top, 139 fb^{-1})	1.6 ± 0.3

Despite state-of-the-art simulation, modelling of QCD radiation is challenging

$t\bar{t}$H Multilepton: $t\bar{t}$W background

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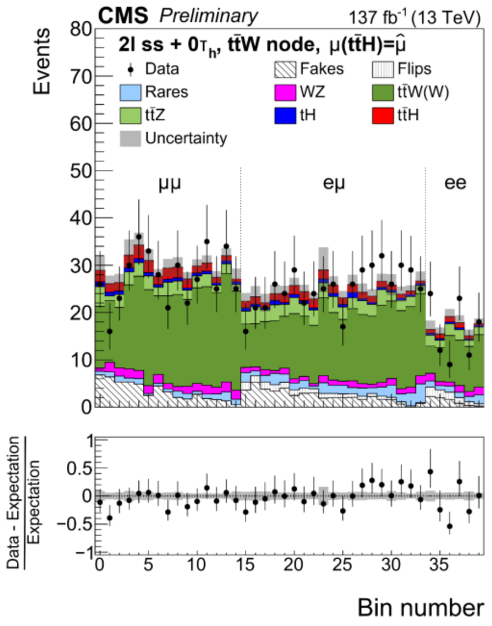
ttH multilep	$\mathbf{1.43 \pm 0.21}$	ttH multilep	2l LNJ	$1.56^{+0.30}_{-0.33}$
			2l HNJ	$1.26^{+0.19}_{-0.18}$
			3l	$1.68^{+0.30}_{-0.28}$
			Alternative fit	$\mathbf{1.39^{+0.17}_{-0.16}}$



- $t\bar{t}$W simulated with NLO QCD including α^3 and $\alpha^3\alpha_s$ terms
    - First LHC analysis to include these corrections at diff. level
- Normalization determined in the signal extraction fit
- Dedicated DNN node for $t\bar{t}$W

tt̄H Multilepton: tt̄W background

Important background
Tension with SM seen both by CMS and ATLAS:

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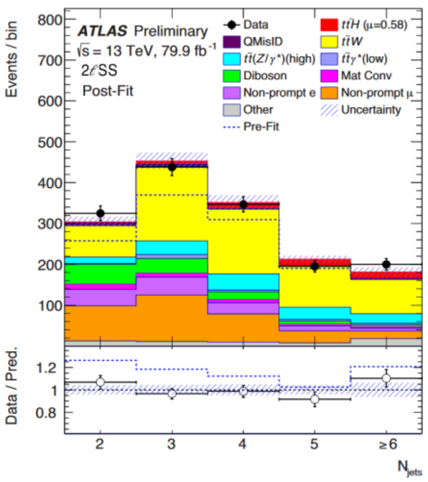

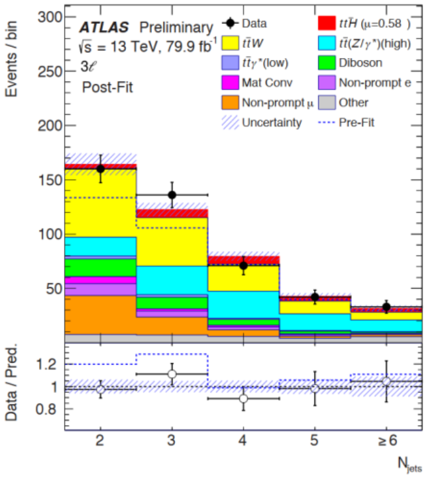

- Multiplicative factors to take into account QCD and EWK corrections on xsec
- 3 independent normalization factors obtained from the fit
- Additional uncertainties to cover for modelling of additional QCD radiation

$t\bar{t}H$ Multilepton: $t\bar{t}W$ background

Important background
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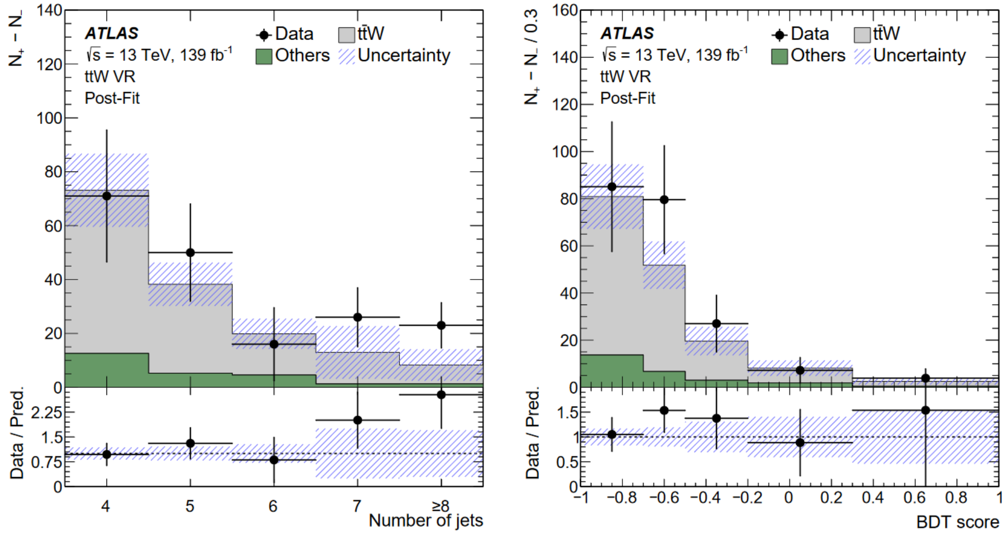


Dedicated ttW control region, normalization floated in the fit
Validation region:

$$N_{Jet} \geq 4, N_{b\,tag} \geq 2$$

$$\mathrm{N}_{+} - \mathrm{N}_{-} = \#\text{Events with } \left(\sum \ell_{\text{charge}}\right) > 0 - \#\text{Events with } \left(\sum \ell_{\text{charge}}\right) < 0$$

$t\bar{t}H$ Multilepton CMS results

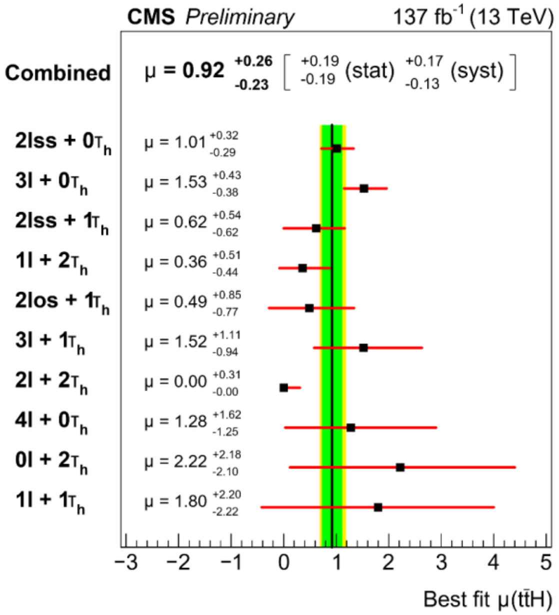
Results:

Signals are extracted fitting data in all categories:

- Lumi: 137 fb^{-1}
- Above **5σ sensitivity** for $t\bar{t}H$
- **4.7σ observed** significance for $t\bar{t}H$
- Observed tH significance: **1.4σ**

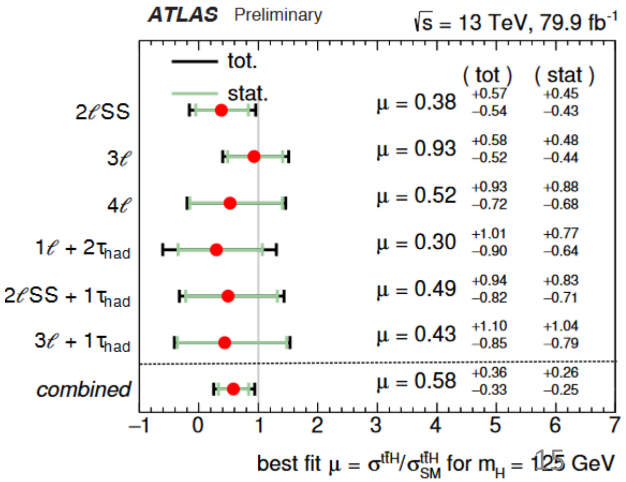
$$\mu_{ttH} = 0.92^{+0.26}_{-0.23}$$

$$\mu_{tH} = 5.67^{+4.1}_{-4.0}$$



- Lumi: 79.9 fb^{-1}
- **3.1σ expected** significance
- **1.8σ observed** significance

$$\mu_{ttH} = 0.58^{+0.36}_{-0.33}$$



$t\bar{t}H$ Multilepton CMS results (II)

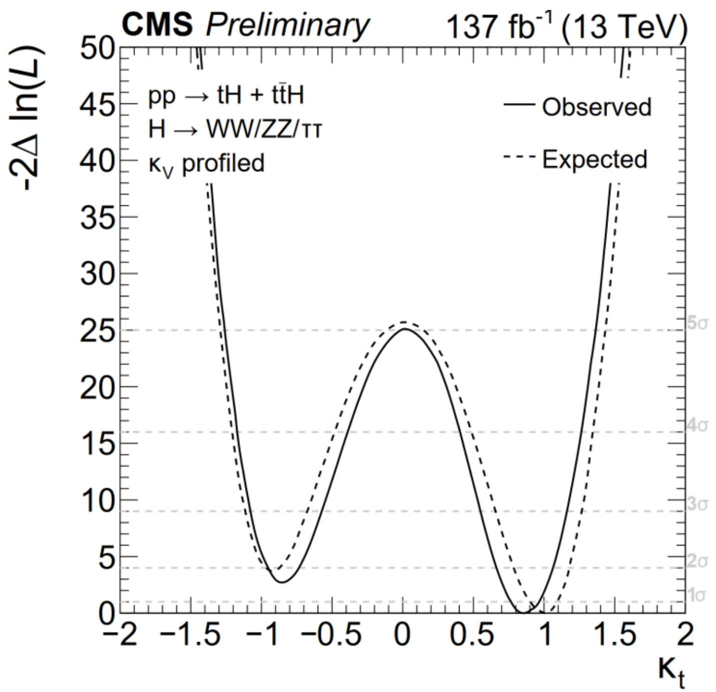
κ framework results:

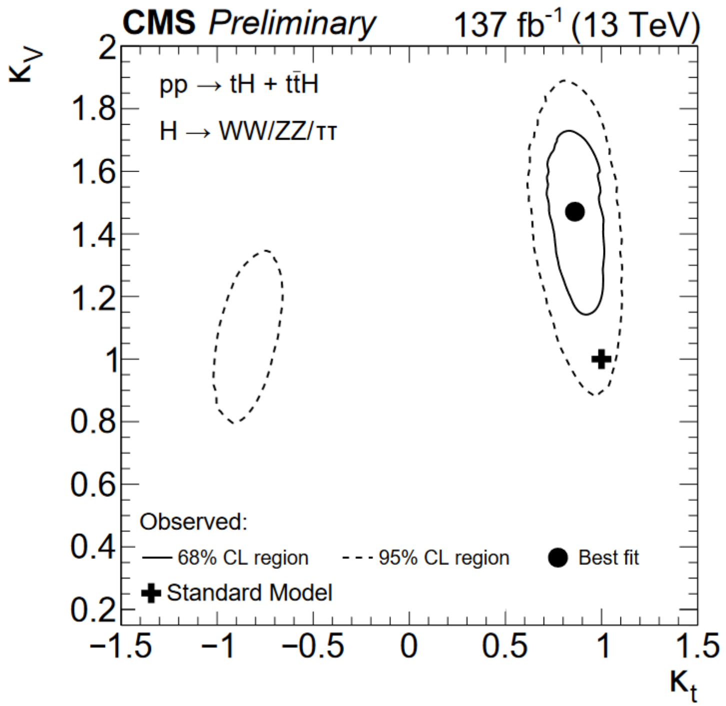
Interpretation of yields in terms of:

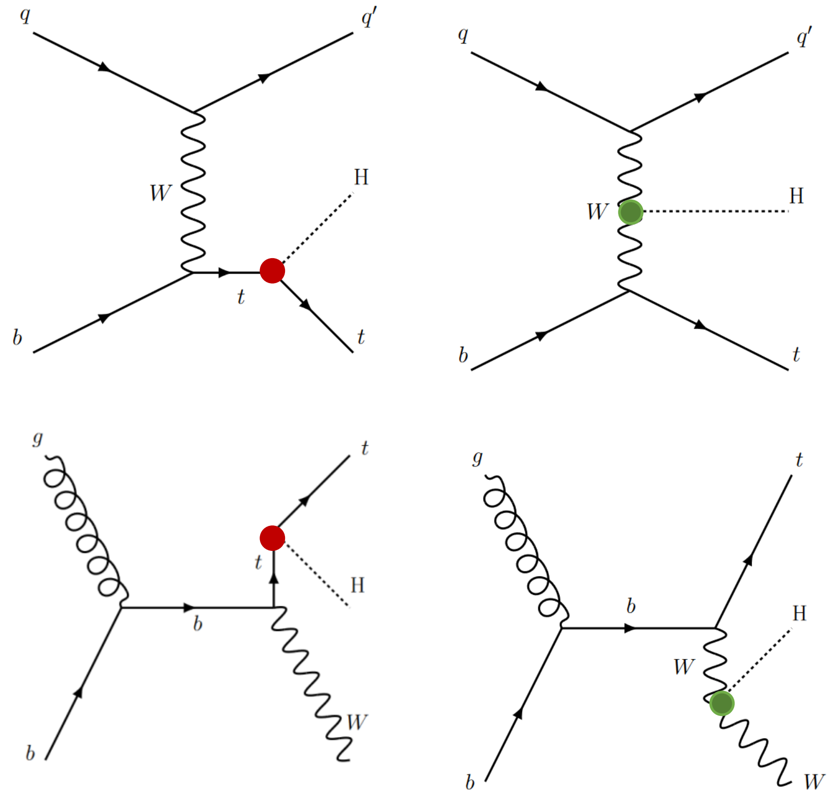
$$\kappa_t = \frac{y_t}{y_t^{SM}} \quad \kappa_V = \frac{g_{W/Z}}{g_{W/Z}^{SM}}$$

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

Likelihood scans as a function of κ_t κ_V:







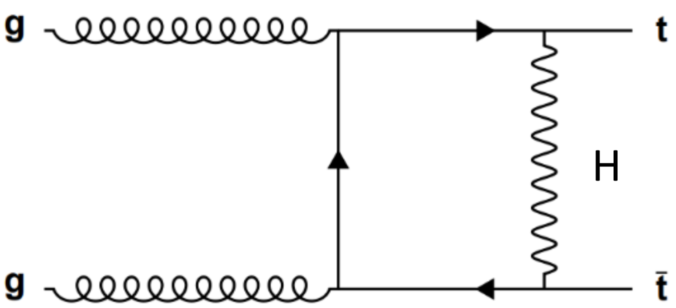
κ_t **constrained** to be within **-0.9 < κ_t <-0.7** and **0.7 < κ_t <1.1** at 95% CL

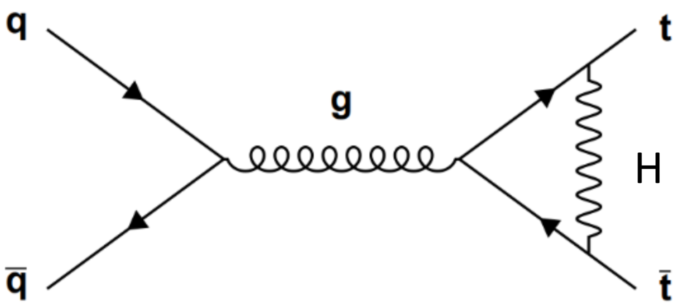
$t\bar{t}$ dilepton

$t\bar{t}$ dilepton CMS

CMS-PAS-TOP-19-008

In $t\bar{t}$ production, top-Higgs interaction via virtual Higgs exchange:





Ref:
arxiv:2009.07123
(submited to Physical Review D)

- EW diagrams enter **noticeably** into $t\bar{t}$ production at **order** $\alpha_s^2\alpha$
- Small effect on cross section, **noticeable shape effect** on differential distributions
- Effects are **bigger** if **Yukawa coupling is anomalously large**

Analysis strategy:

Data taken by the CMS experiment at 13 TeV during Run 2 (137 fb^{-1})

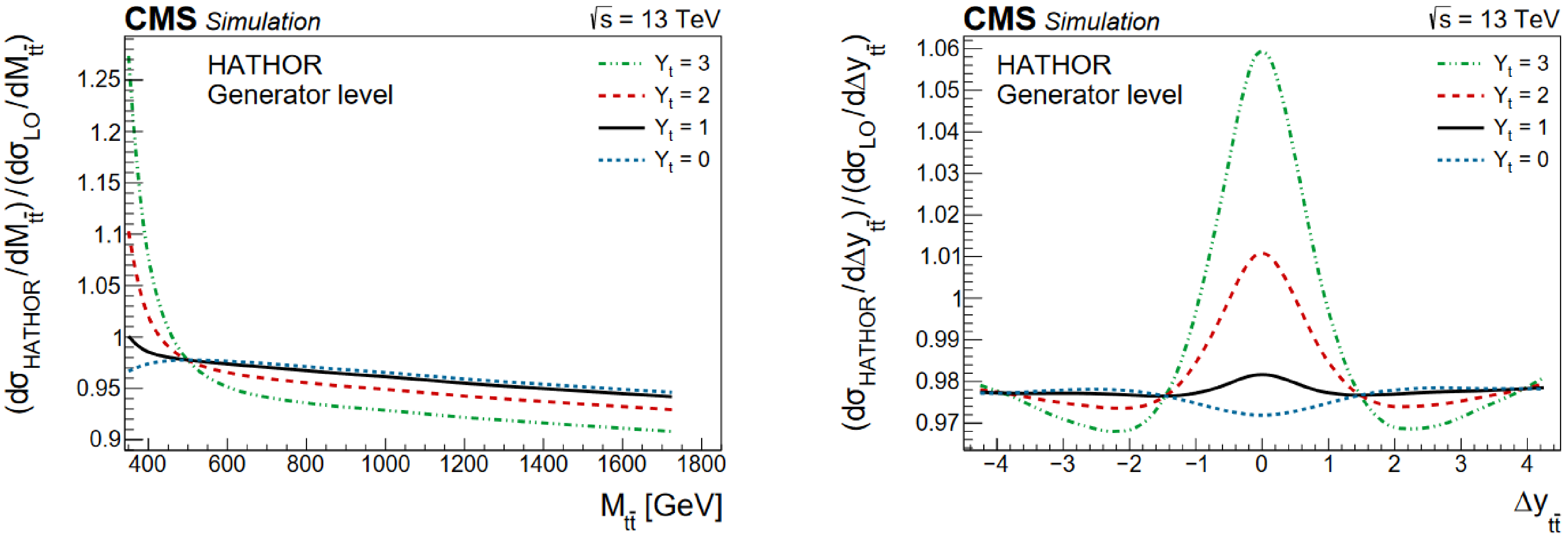
Events with two leptons are selected.
In ee and μμ channels $m_{\ell\ell}$ and p_T^{miss} requirements are added in order to reduce DY background.

$t\bar{t}$ dilepton CMS (II)

CMS-PAS-TOP-19-008

Electroweak corrections:

- **Invariant mass** $M_{t\bar{t}}$ and difference in **top quark rapidity** $\Delta y_{t\bar{t}}$ sensitive to $Y_t = \frac{y_t}{y_t^{SM}}$
- EWK corrections are added as weights, applying them at parton level to MC samples produced at NLO QCD → Calculated with HATHOR
- These multiplicative corrections $R_{EW}(M_{t\bar{t}}, \Delta y_{t\bar{t}})$ are generated as a function of $M_{t\bar{t}}, \Delta y_{t\bar{t}}$
- $R_{EW}(M_{t\bar{t}}, \Delta y_{t\bar{t}})$ is parametrized as function of Y_t and a profile likelihood scan on the Y_t is performed

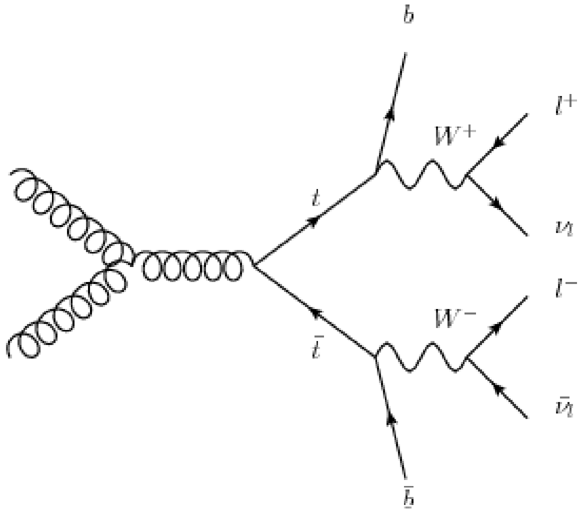


$t\bar{t}$ dilepton CMS (III)

CMS-PAS-TOP-19-008

Event reconstruction:

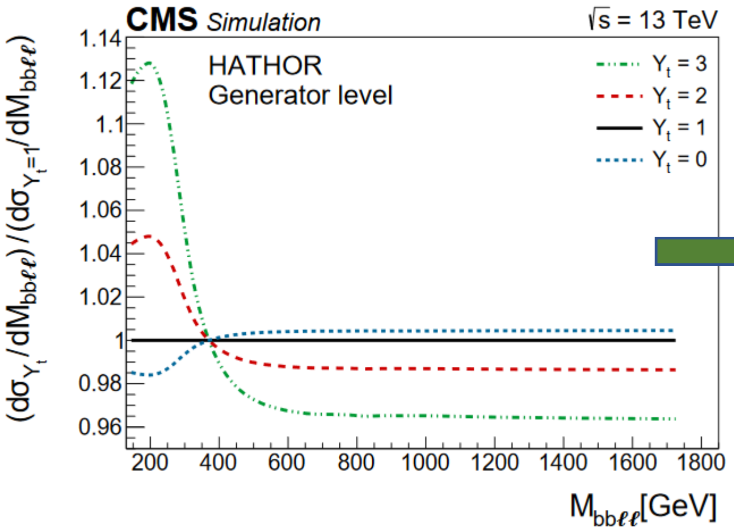
It is possible to reconstruct dilepton-channel top quark kinematics in good approximation, but it is very sensitive to MET measurement and deviation from on—shell

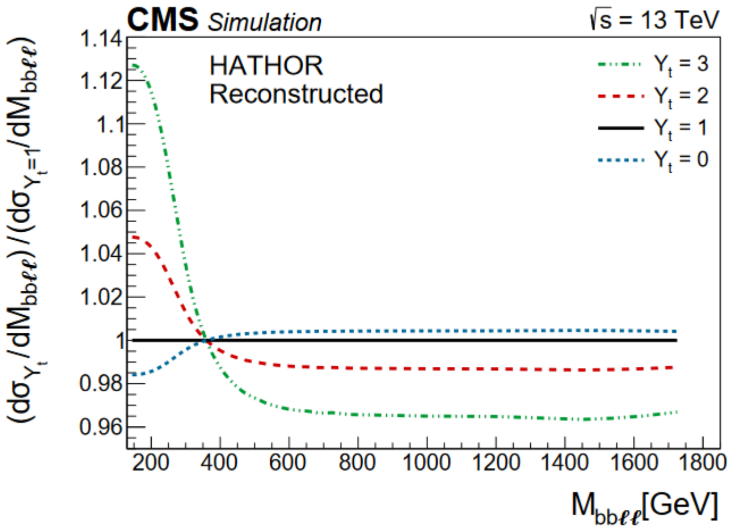


It is possible to use “proxy” kinematic variables:

$$M_{bbll} = M(b + \bar{b} + l + \bar{l})$$
$$|\Delta y_{blbl}| = |y(b + \bar{l}) - y(\bar{b} + l)|$$

Depends on the pairing of objects





Pairing in 3 steps:

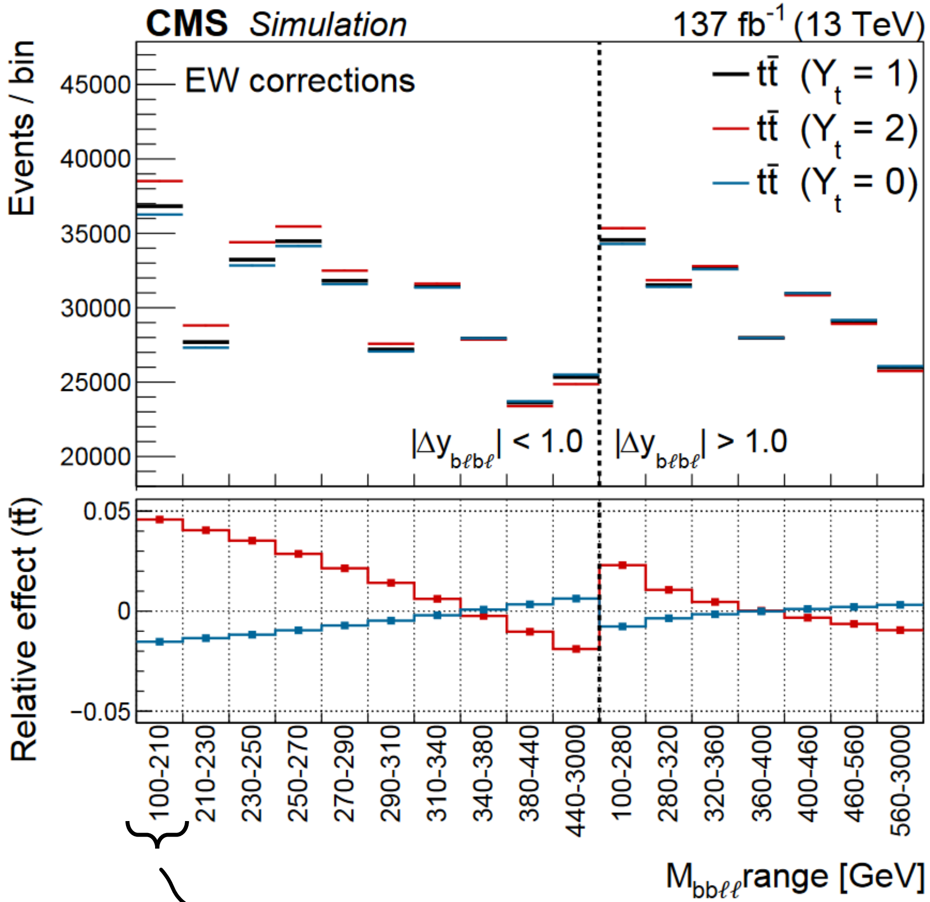
1) mass constrain
2) (if both pass 1) MET constrain
3) If no clear paring from ν kinematics → minimize geometrical distance between b quark and lepton

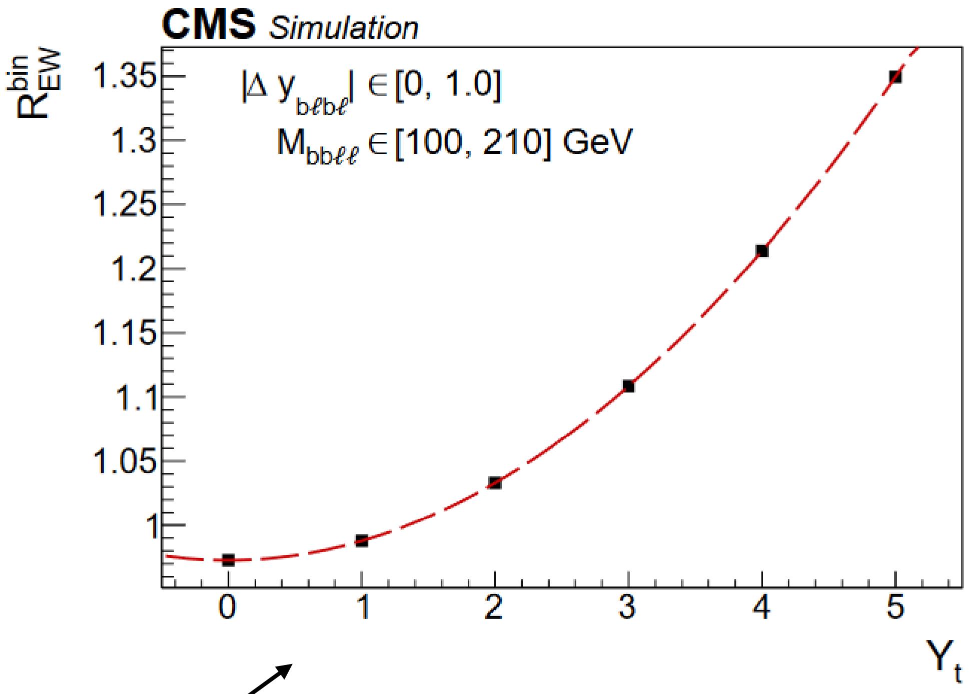
$t\bar{t}$ dilepton CMS (IV)

Effect of Yukawa on yields:

CMS-PAS-TOP-19-008

Events are categorized in bins of M_{bbll} and $|\Delta y_{blbl}|$. Each bin has a yield proportional to Y_t^2





$t\bar{t}$ dilepton CMS (V)

CMS-PAS-TOP-19-008

Results:

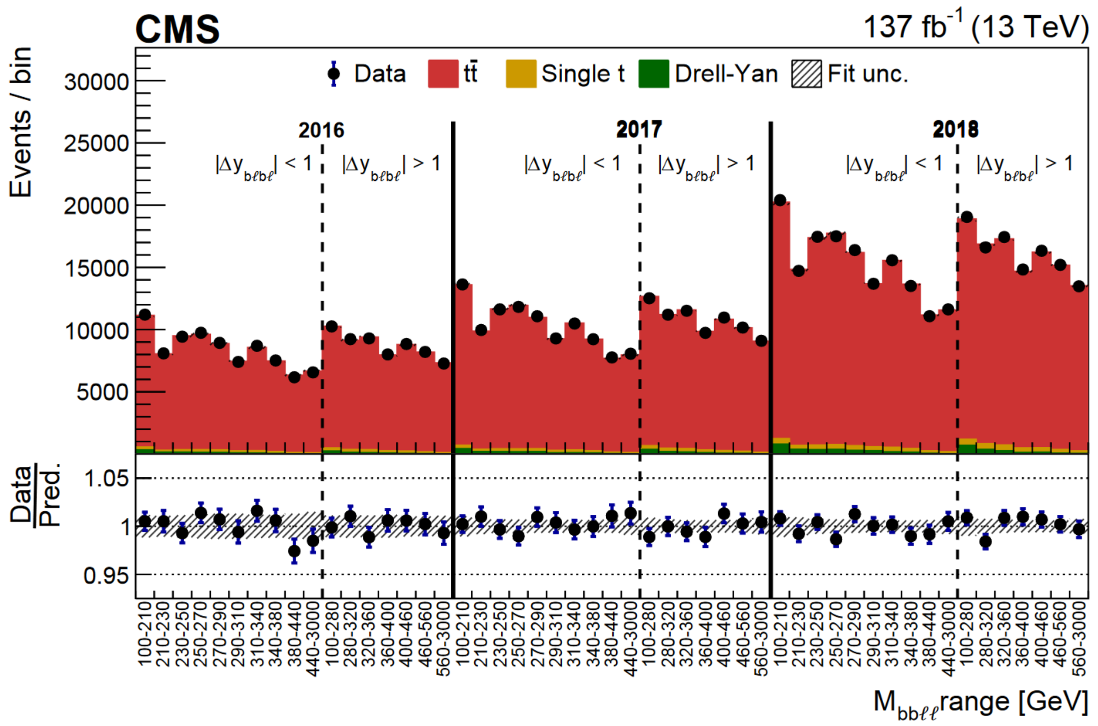
The profile likelihood scan yields

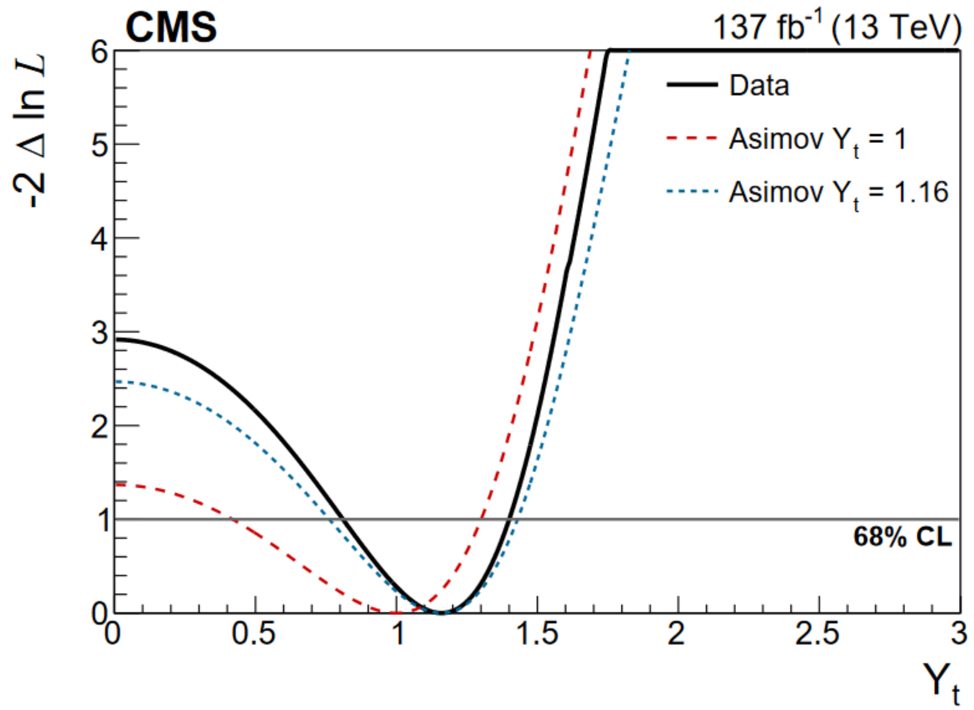
$$Y_t = 1.16^{+0.07}_{-0.08}(stat)^{+0.17}_{-0.27}(syst)$$

The coupling is **constrained to be Y_t< 1.54 at 95% CL**

Most important uncertainties:

- Modelling of ISR and FSR (~8% final measurement unc.)
- Weak corrections computation and application. They cover higher-order effects. (~7% final measurement unc.)

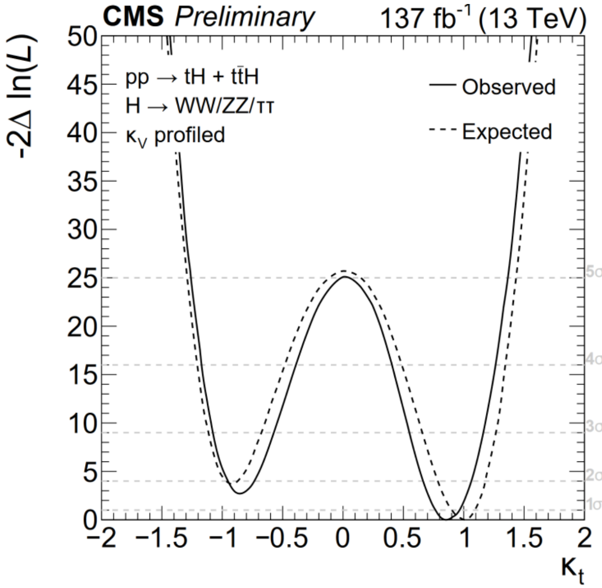




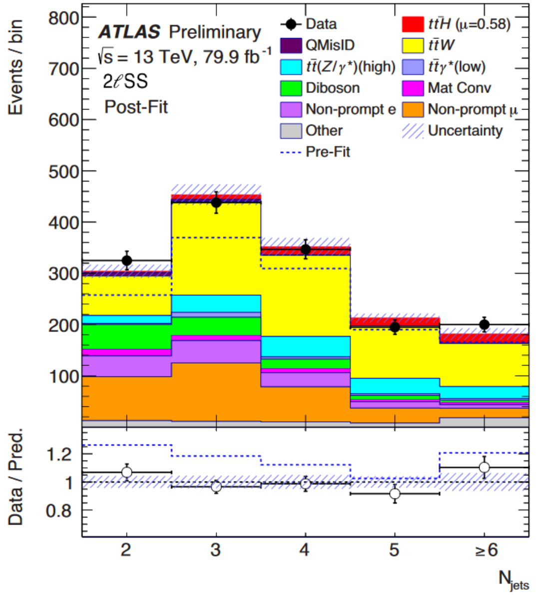
Summary

- Yukawa coupling measured with the full Run 2 dataset
- tt̄H+tH measurement is sensitive to negative values of Yukawa coupling and does not exclude inverted coupling scenario at 95% CL
- tt̄W modelling is key in tt̄H measurement
  - Both CMS and ATLAS working on this not only from tt̄H but from 4tops analysis:CERN-EP-2020-111
- tt̄ less sensitive than tt̄H measurement but do not depend on other parameters affected by the Yukawa coupling (BR)

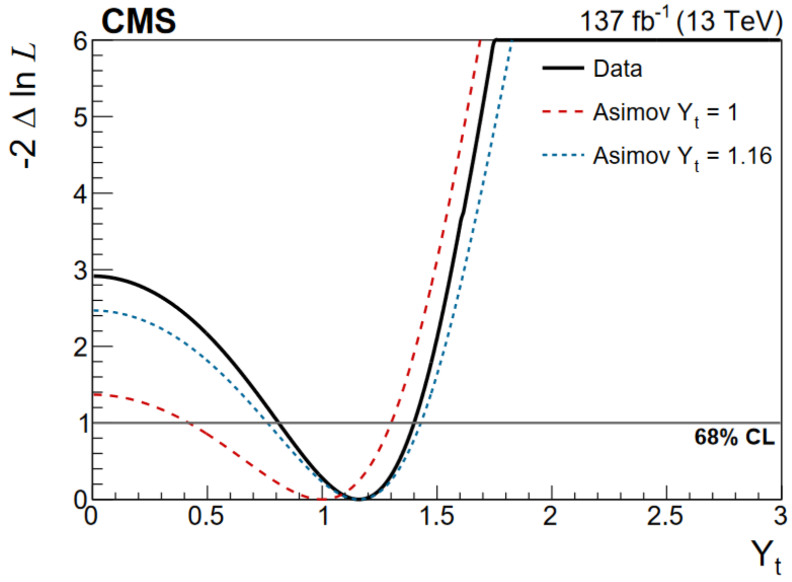
CMS-PAS-HIG-19-008



ATLAS-CONF-2019-045



CMS-PAS-TOP-19-008



Back up

$t\bar{t}H$ (CMS)

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

$t\bar{t}H$ (ATLAS)

Categories and selection

Channel	Selection criteria
Common	$N_{\text{jets}} \geq 2$ and $N_{b\text{-jets}} \geq 1$
2ℓSS	Two same-charge (SS) very tight (T*) leptons, $p_{\text{T}} > 20$ GeV No τ_{had} candidates $m(\ell^+\ell^-) > 12$ GeV for all SF pairs **13 categories**: enriched with $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}$, mat. conv, int. conv., split by lepton flavour, charge, jet and b-jet multiplicity
3ℓ	Three loose (L) leptons with $p_{\text{T}} > 10$ GeV; sum of light-lepton charges $= \pm 1$ Two SS very tight (T*) leptons, $p_{\text{T}} > 15$ GeV One OS (w.r.t the SS pair) loose-isolated (L*) lepton, $p_{\text{T}} > 10$ GeV No τ_{had} candidates $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2 \text{ GeV}\rvert > 10$ GeV for all SFOS pairs $\lvert m(3\ell) - 91.2 \text{ GeV}\rvert > 10$ GeV **7 categories**: enriched with $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$, VV, $t\bar{t}$, mat. conv, int. conv
4ℓ	Four loose-isolated (L*) leptons; sum of light lepton charges $= 0$ $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2 \text{ GeV}\rvert > 10$ GeV for all SFOS pairs $m(4\ell) < 115$ GeV or $m(4\ell) > 130$ GeV **2 categories**: Zenr (Z-enriched;1 or 2 SFOS pairs) or Zdep (Z-depleted; 0 SFOS pairs)
$1\ell 2\tau_{\text{had}}$	One tight (T) lepton, $p_{\text{T}} > 27$ GeV Two OS τ_{had} candidates At least one tight τ_{had} candidate $N_{\text{jets}} \geq 3$
$2\ell\text{SS}1\tau_{\text{had}}$	2ℓSS selection, except: One medium τ_{had} candidate $N_{\text{jets}} \geq 4$
$3\ell 1\tau_{\text{had}}$	3ℓ selection, except: One medium τ_{had} candidate, of opposite charge to the total charge of the light leptons Two SS tight (T) leptons

Uncertainties

Uncertainty source	$\Delta\hat{\mu}$	
Jet energy scale and resolution	+0.13	−0.13
$t\bar{t}(Z/\gamma^*)$ (high mass) modelling	+0.09	−0.09
$t\bar{t}W$ modelling (radiation, generator, PDF)	+0.08	−0.08
Fake τ_{had} background estimate	+0.07	−0.07
$t\bar{t}W$ modelling (extrapolation)	+0.05	−0.05
$t\bar{t}H$ cross section	+0.05	−0.05
Simulation sample size	+0.05	−0.05
$t\bar{t}H$ modelling	+0.04	−0.04
Other background modelling	+0.04	−0.04
Jet flavour tagging and τ_{had} identification	+0.04	−0.04
Other experimental uncertainties	+0.03	−0.03
Luminosity	+0.03	−0.03
Diboson modelling	+0.01	−0.01
$t\bar{t}\gamma^*$ (low mass) modelling	+0.01	−0.01
Charge misassignment	+0.01	−0.01
Template fit (non-prompt leptons)	+0.01	−0.01
Total systematic uncertainty	+0.25	−0.22
Intrinsic statistical uncertainty	+0.23	−0.22
$t\bar{t}W$ normalisation factors	+0.10	−0.10
Non-prompt leptons normalisation factors (HF, material conversions)	+0.05	−0.05
Total statistical uncertainty	+0.26	−0.25
Total uncertainty	+0.36	−0.33

$t\bar{t}W$ modelling

Subleading EWK corrections found to be significant.

- Primarily NLO_3 term driven by $t\bar{t}W$ + 1-jet diagram with a H in the t-channel

CMS $t\bar{t}H$:

- Samples with NLO QCD (up to 1 additional parton) + subleading EKW corrections (NLO_3)
- xsec with NLO_3 corrections
- Implemented at differential level

ATLAS $t\bar{t}H$:

- Samples with 1 additional parton at NLO and up to 2 partons at LO
- xsec reweighted by factor:
  - 1.11 to cover QCD corrections ($t\bar{t}W$+1-jet)
  - 1.09 to cover subleading EWK corrections

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

- Samples with 1 additional parton at NLO QCD
- xsec don not include EWK corrections

ATLAS $t\bar{t}t\bar{t}$:

- Samples with 1 additional parton at NLO and up to 2 partons at LO
- xsec with QCD + leading EWK corrections