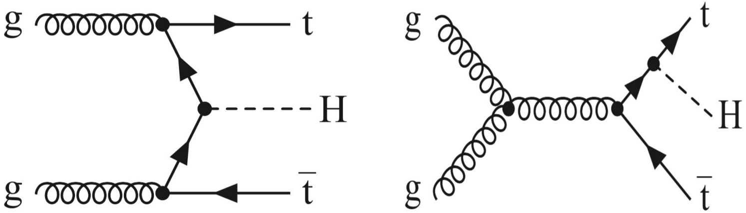
PPC 2024: XVII International Conference on Interconnections between Particle Physics and Cosmology, Hyderabad, India

14-18 October 2024, Hyderabad

Measurement of ttH and tH production cross-section in multi-lepton final states in pp collision at a center-of-mass energy of 13 TeV with the CMS detector



Mohammad Mobassir Ameen

IIT Madras (IN)

On behalf of the CMS collaboration

Outline

- Physics Motivation
- Analysis Strategy
- Event Selections
- Backgrounds Study
- Results
- Summary

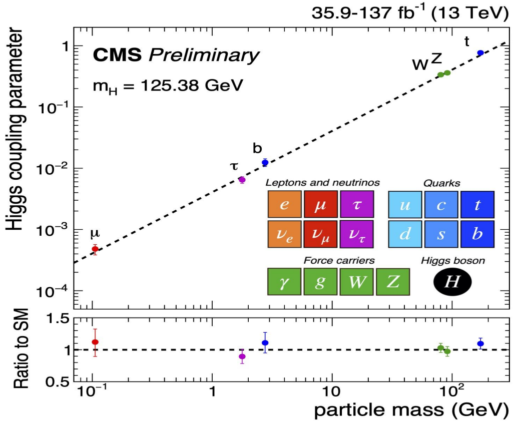
Physics Motivation

Why should we care about the Top Yukawa coupling? arXiv:1411.1923

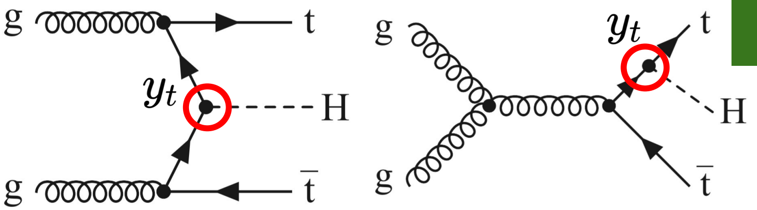
- The SM predicts Higgs boson coupling proportional to mass
- Largest in the SM, Top-Yukawa coupling $y_t = \sqrt{2}m_t/v \approx 1$

Why ttH production?

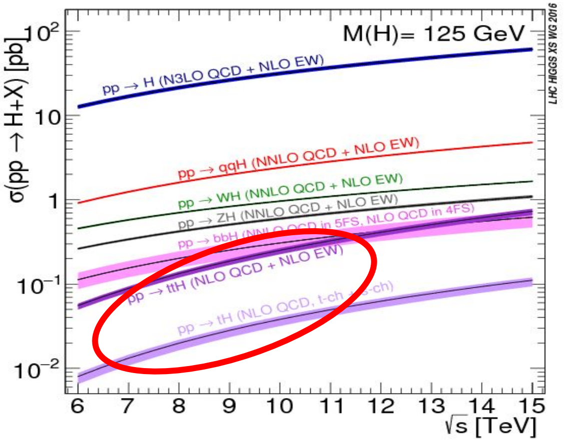
- Provides a direct probe to y_t
- Indirect measurement through ggF production and top-loop in $H \rightarrow \gamma\gamma$
- One can think but no access to decay H ⟶ tt (top is too heavy, even heavy as compare to Higgs)
- Deviation from SM ⟶ hint for new physics



Direct measurement



Sensitive to sigh



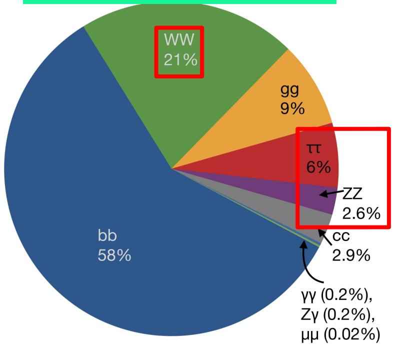
With the high luminosity available at the LHC: direct measurement of the top-Higgs coupling is accessible

Analysis strategy

- Data samples: Run-2 (2016 to 2018) ~ Luminosity 137 fb^{-1}
- 10 signal regions based on number of leptons and/or τ_{had} multiplicity

ℓ = e/μ
τ_h = hadronic tau
os/ss = Opposite/Same-sign

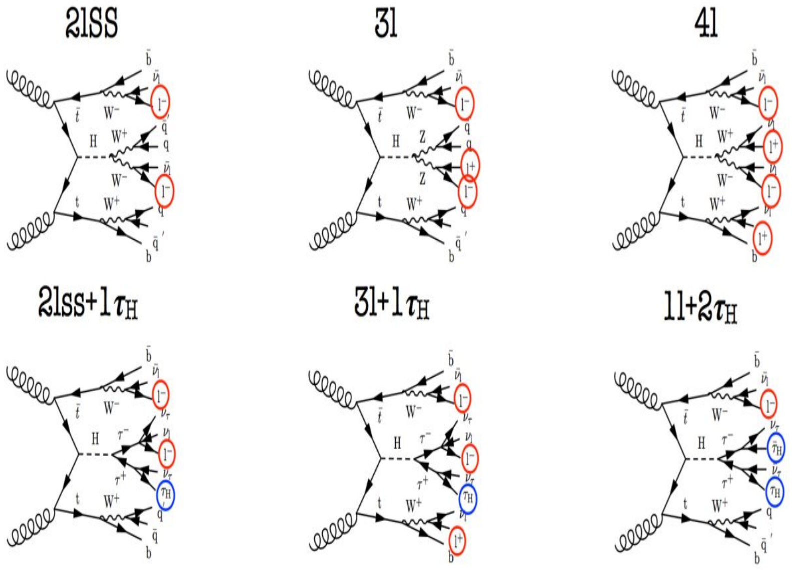
Higgs Branching Fractions



☐ Covered by ttH/tH multi-lepton analysis

ttH multilepton searches:

- Lower rate than H to bb, but clean final state and low background; better handle on irreducible background


2lSS

3l

4l

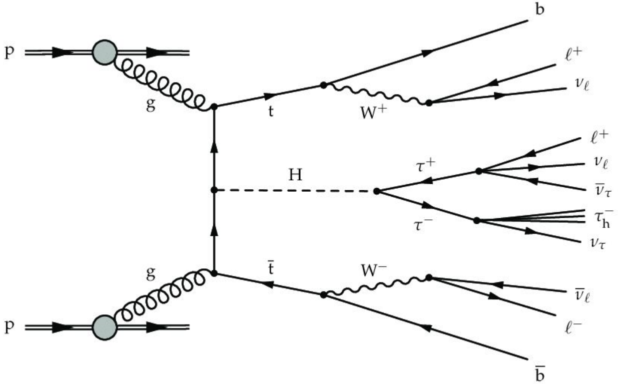
2lss+1τ_H

3l+1τ_H

1l+2τ_H

Event Selections

EPJC 81:378 (2021)



Dedication selection in each category:

- Lepton pT
- Jet and b-tag multiplicity requirements
  - At least 2 (3) jets in $2\ell ss+0\tau_h$ and $2\ell ss+1\tau_h$ ($3\ell+0\tau_h$)
  - ≥ 1 medium b-tagged Jet or ≥ 2 loose b-tagged Jet

} to **target ttH** events

  - 1 Light Jet (can be in the forward region) and b-tagged Jet (medium)

} to **target tH** events

- Missing transverse momentum requirements
- Z boson veto

Background discrimination

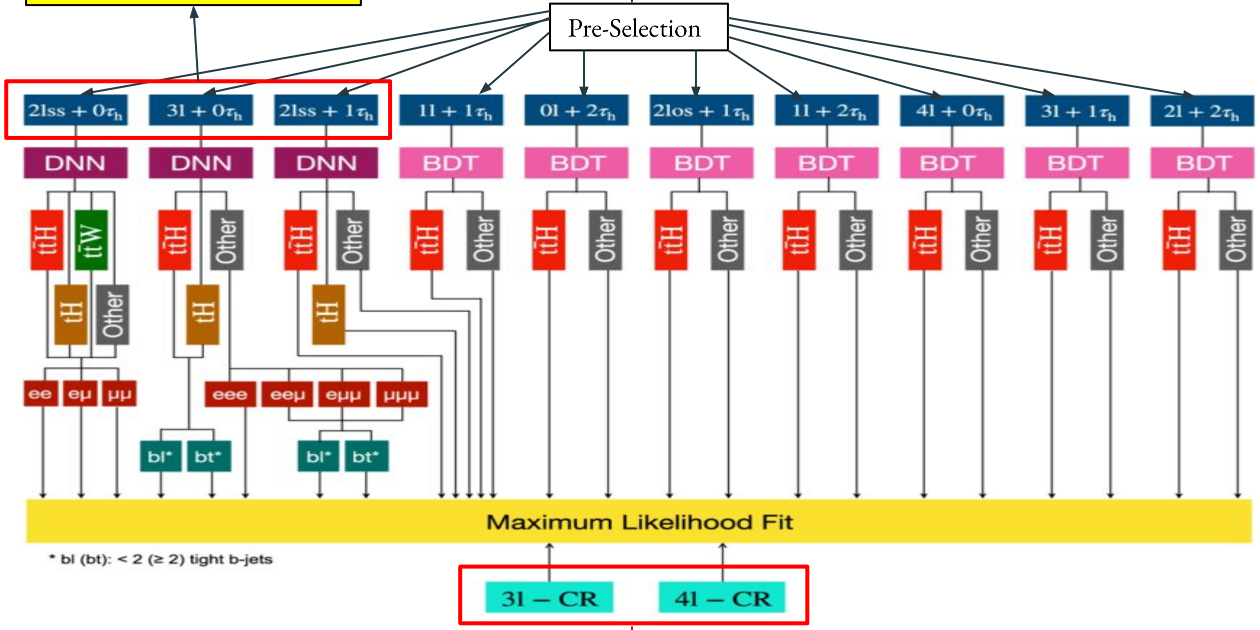
Events

Trigger

Mix of 1/2/3 Lepton, Lepton + τ_h Trigger used depending on the channel

tH signal acceptance enhanced by allowing events with 1 light (forward) Jet and 1 b-tagged Jet

Pre-Selection



Used to constrain ttZ background

EPJC 81:378 (2021)

Background - I

EPJC 81:378 (2021)

Background estimation is the key in the multi-leptons analysis

- **Irreducible backgrounds**:
  - ttZ and ttW processes are main background.
  - estimated with MC simulation.

- **Reducible background**: 3 main types -
  - **Non-prompts leptons and misidentification tau**: estimated with data-driven method
  - **Photon Conversions**: Electrons misidentified due to photon conversion estimated with simulation
  - **Electron Charge Flips**: Charge misidentification of leptons, particularly for electrons, estimated with simulation

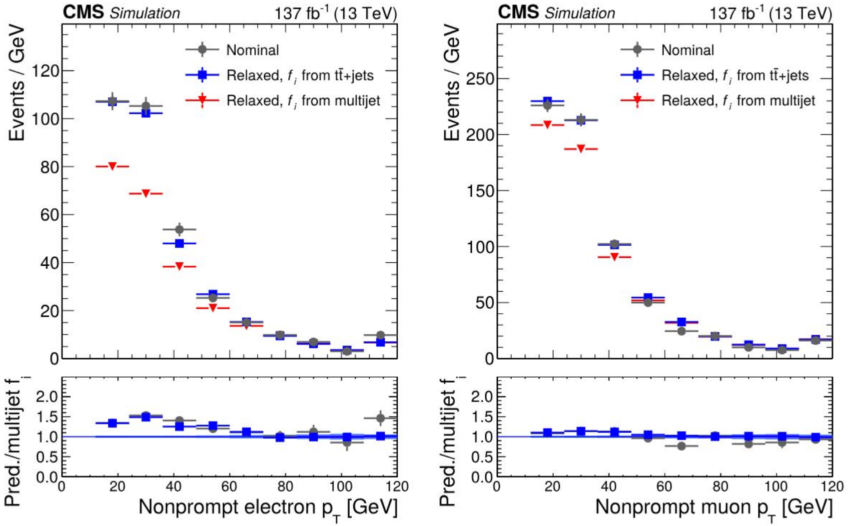
- Less importantly WZ, ZZ, rares (tZq, tttt)

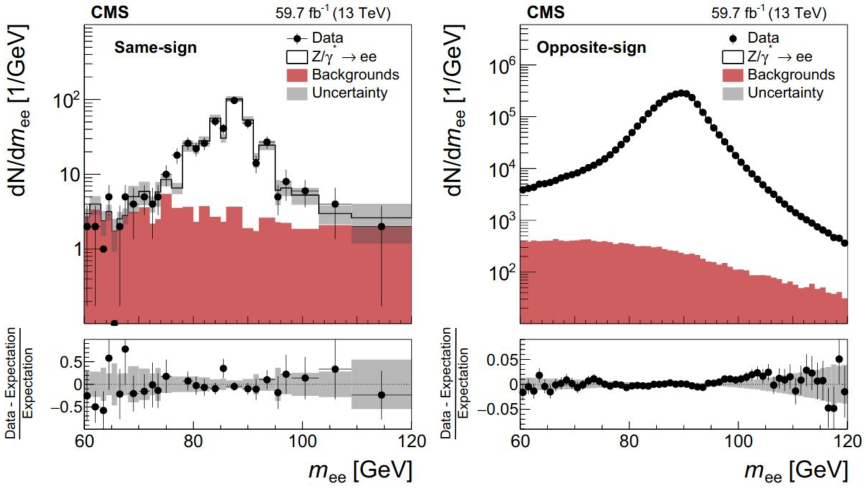
- ttbar and DY in few events category

Background - II

Non-prompts leptons and misidentification tau

- **Suppressed** with **MVA** technique in the lepton identification
- Estimate using the **tight-to-loose method**
- Fake rate measured in multijet events
- Similar method followed for the misidentification for τ_h





Electron Charge Flips:

- Estimated from an opposite-sign side band

EPJC 81:378 (2021)

Background - III

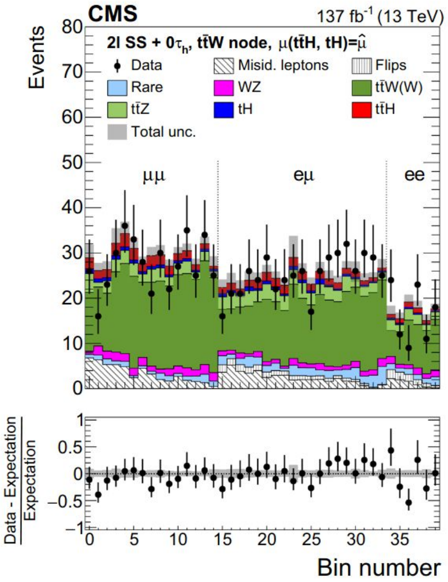
ttW(W) and ttZ: Major contribution in most signal regions (SRs)

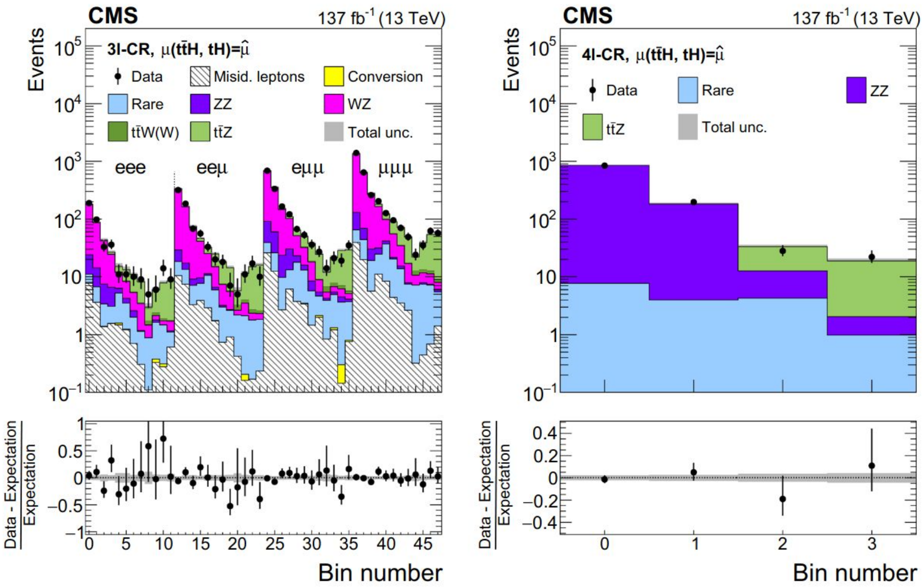
- Dedicated control regions for the ttZ (3 and 4 leptons with a Z boson candidate)
- Dedicated ANN node for ttW ($2\ell ss + 0\tau_h$)

EPJC 81:378 (2021)

State of the art of the simulations:

- ttZ simulated with NLO QCD
- ttW simulated with NLO QCD including α^3 and $\alpha^3\alpha_s$

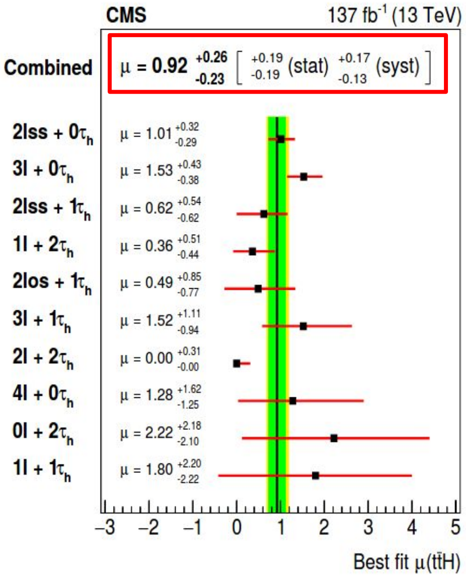


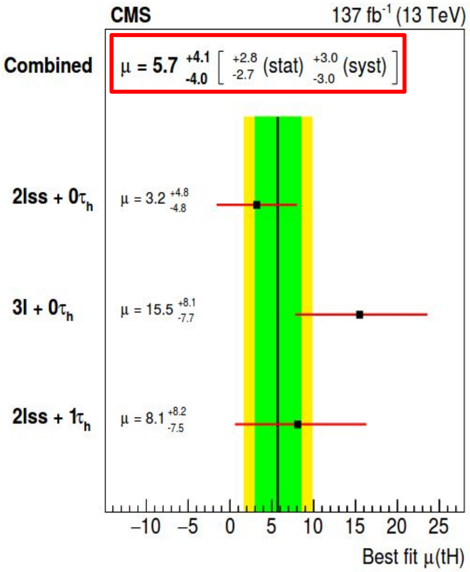


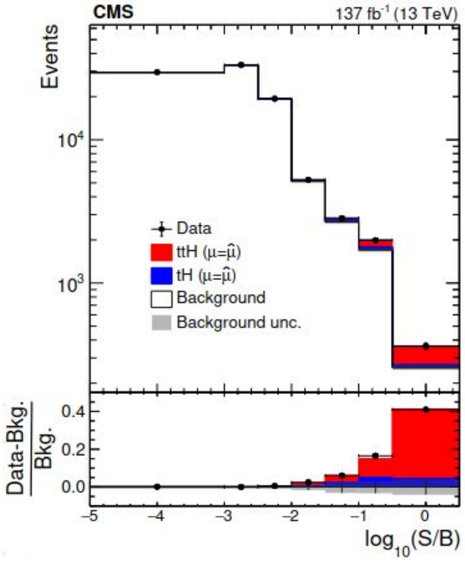
Results-I: Signal strength

$$\mu = \sigma_{meas}/\sigma_{SM}$$

EPJC 81:378 (2021)







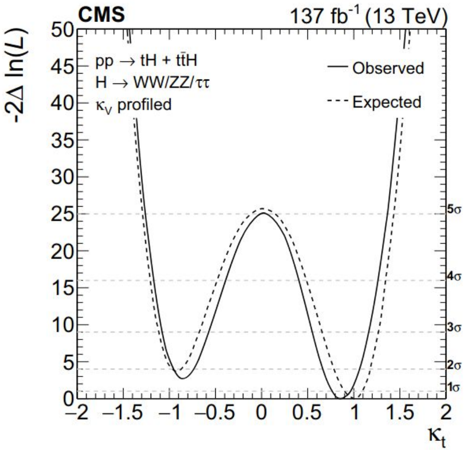
ttH Obs.(Exp.) Significance: 4.7σ(5.2σ)
tH Obs.(Exp.) Significance: 1.4σ(0.3σ)

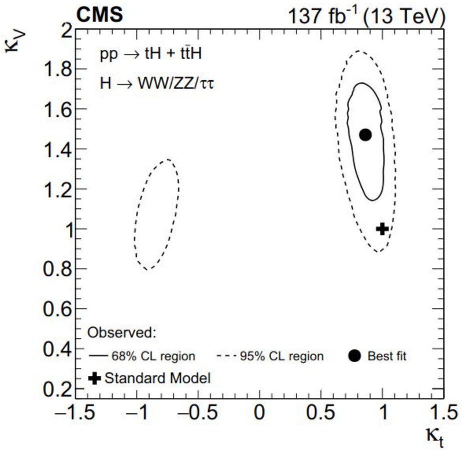
Post-Fit Events Yields & Systematics
In Backup
(slide- 17)

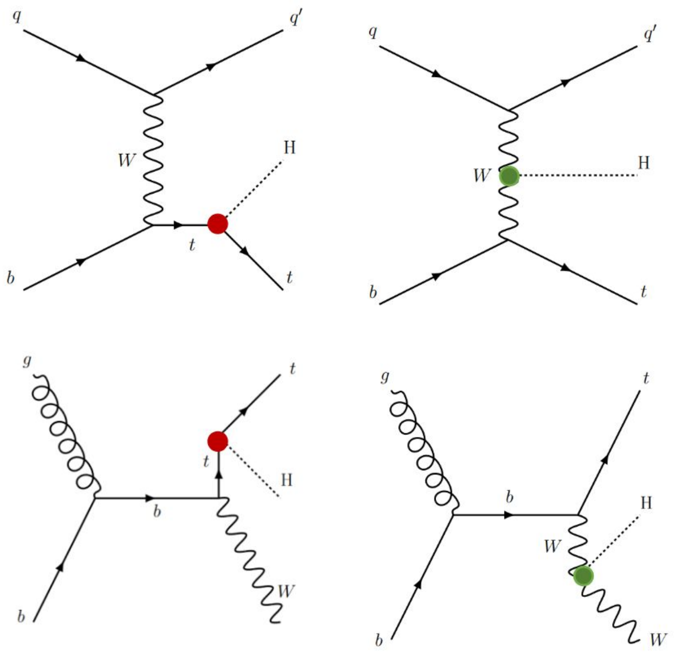
Results-II: Coupling modifier (κ)

EPJC 81:378 (2021)

- Interpretation in term of Yukawa Coupling modifier (κ framework): $\kappa_t = \frac{y_t}{y_t^{SM}}$ $\kappa_V = \frac{g_{W/Z}}{g_{W/Z}^{SM}}$
- Likelihood variation as a function of κ_t
- Modification of Higgs BR considered Likelihood scan as a function of κ_t and κ_v







κ_t constraints to be: - 0.9<κ_t<-0.7 or 0.7<κ_t<1.1 (@ 95% CL)

Summary

- Comprehensive overview of ttH and tH multi-lepton analysis using complete run-2 datasets (137 fb^{-1}) is presented.
- Measurement performed in 10 different categories.

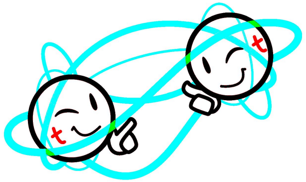
- Above 5σ sensitivity for ttH production
- ttH signal strength measured to be $0.92^{+0.26}_{-0.23}$
- Observed (expected) significance of 4.7σ (5.2 σ)

- tH signal strength measured to be $5.7^{+4.1}_{-4.0}$
- Observed significance of tH around 1.4σ (0.3σ)

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

- With 2022 and 2023 data taking ($\sqrt{s}$ = 13.6 TeV) recently concluded, looking forward to improve upon these results and to throw more light on the top-Higgs interaction in the future. (**Stay tuned for the Run-3 results**)

THANK YOU

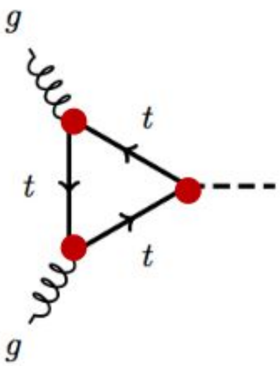


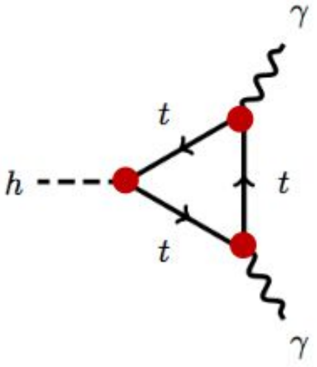

BACKUP

Indirect measurements

gg fusion Higgs production

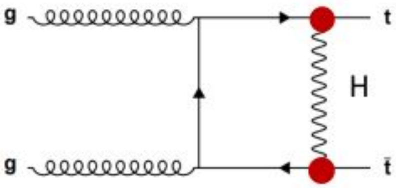
H → $\gamma\,\gamma$

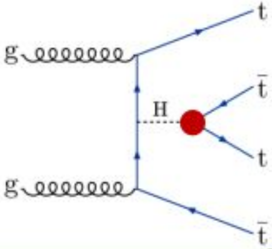




$t\bar{t}$

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





Analysis level objects

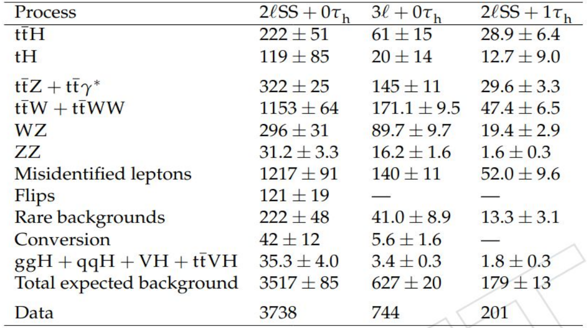
Involve all object:

- Particle Flow (PF) algorithm used to identify and reconstruction of all particle produced after the collision, with use of sub-detector information.

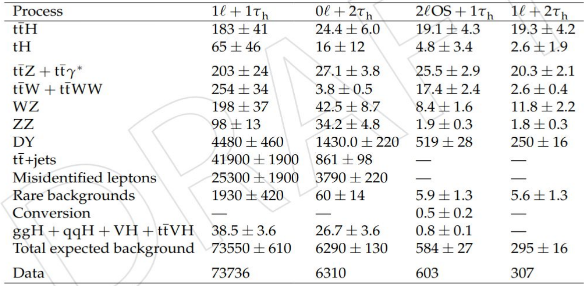
JINST 12 P10003 (2017)

- Jets reconstructed using anti-kT algorithm (R = 0.4) using as a input of two objects.
- b-jets identified by the DNN based algorithm, so called "Deep Flavour" or "Deep Jet" algorithm including ong lifetime of b hadrons, the high particle multiplicity and mass of b-jets compared to light quark and gluon jets. Most of the analysis use working point of this discriminator which gives 70% (10%) b-tagging efficiency (light jet mis-tag rate).
- Electrons identified by multivariate (BDT) based discriminator which include electron shower shape variables.
- Muons identified by PF based selections designed to reduce fakes muons from pions/kaons and punch through hadrons.
- Hadronic Taus identification use "hadrons plus strips" (HPS) algorithm, which reconstruct individual hadronic tau decay mode: 1 Prong + 0 pi0, 1 Prong + 1 pi0, 1 Prong + 2pi0 and 3 Prong + 0 pi0 using reconstruction of individually charge hadron, clustering photons by the PF algorithm and qualifying strict isolation criteria. Rejection of jets and leptons mimicking hadronic tau performed with DeepTau neural network- based identification: Tau-20-001
- Photons identified as ECAL energy cluster not linked to PG charged track. Dedicated shower shape based clustering and MVA regression is used to recover the full energy of both converted and unconverted photons inside the detector.

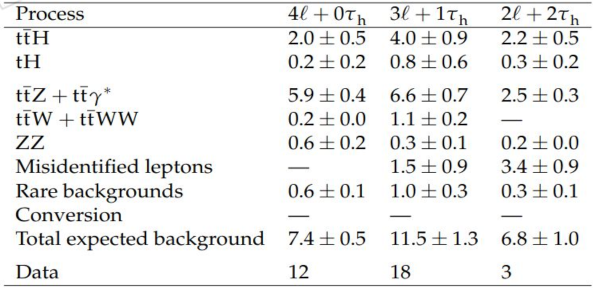
Post-Fit Events Yields and Systematic



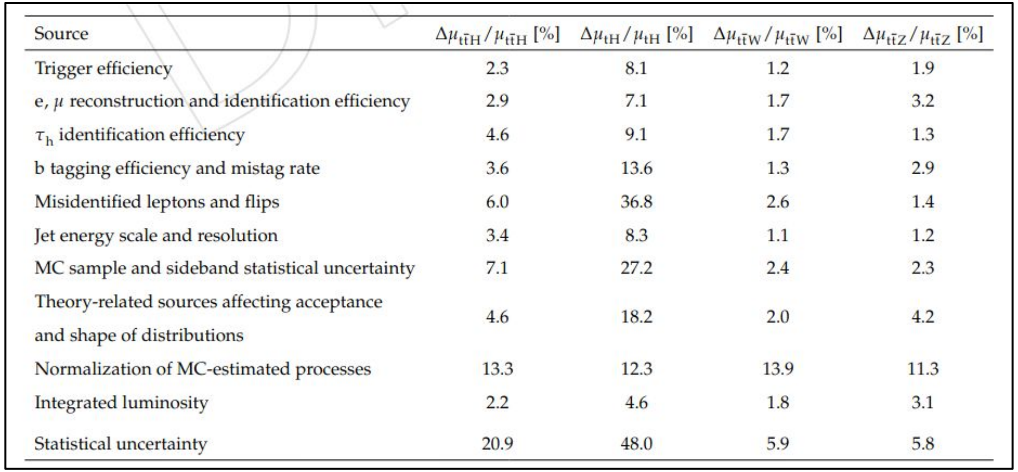
Process	$2\ell SS + 0\tau_h$	$3\ell + 0\tau_h$	$2\ell SS + 1\tau_h$
$t\bar{t}H$	222 ± 51	61 ± 15	28.9 ± 6.4
tH	119 ± 85	20 ± 14	12.7 ± 9.0
$t\bar{t}Z + t\bar{t}\gamma^*$	322 ± 25	145 ± 11	29.6 ± 3.3
$t\bar{t}W + t\bar{t}WW$	1153 ± 64	171.1 ± 9.5	47.4 ± 6.5
WZ	296 ± 31	89.7 ± 9.7	19.4 ± 2.9
ZZ	31.2 ± 3.3	16.2 ± 1.6	1.6 ± 0.3
Misidentified leptons	1217 ± 91	140 ± 11	52.0 ± 9.6
Flips	121 ± 19	—	—
Rare backgrounds	222 ± 48	41.0 ± 8.9	13.3 ± 3.1
Conversion	42 ± 12	5.6 ± 1.6	—
$ggH + qqH + VH + t\bar{t}VH$	35.3 ± 4.0	3.4 ± 0.3	1.8 ± 0.3
Total expected background	3517 ± 85	627 ± 20	179 ± 13
Data	3738	744	201



Process	$1\ell + 1\tau_h$	$0\ell + 2\tau_h$	$2\ell OS + 1\tau_h$	$1\ell + 2\tau_h$
$t\bar{t}H$	183 ± 41	24.4 ± 6.0	19.1 ± 4.3	19.3 ± 4.2
tH	65 ± 46	16 ± 12	4.8 ± 3.4	2.6 ± 1.9
$t\bar{t}Z + t\bar{t}\gamma^*$	203 ± 24	27.1 ± 3.8	25.5 ± 2.9	20.3 ± 2.1
$t\bar{t}W + t\bar{t}WW$	254 ± 34	3.8 ± 0.5	17.4 ± 2.4	2.6 ± 0.4
WZ	198 ± 37	42.5 ± 8.7	8.4 ± 1.6	11.8 ± 2.2
ZZ	98 ± 13	34.2 ± 4.8	1.9 ± 0.3	1.8 ± 0.3
DY	4480 ± 460	1430.0 ± 220	519 ± 28	250 ± 16
$t\bar{t}$+jets	41900 ± 1900	861 ± 98	—	—
Misidentified leptons	25300 ± 1900	3790 ± 220	—	—
Rare backgrounds	1930 ± 420	60 ± 14	5.9 ± 1.3	5.6 ± 1.3
Conversion	—	—	0.5 ± 0.2	—
$ggH + qqH + VH + t\bar{t}VH$	38.5 ± 3.6	26.7 ± 3.6	0.8 ± 0.1	—
Total expected background	73550 ± 610	6290 ± 130	584 ± 27	295 ± 16
Data	73736	6310	603	307



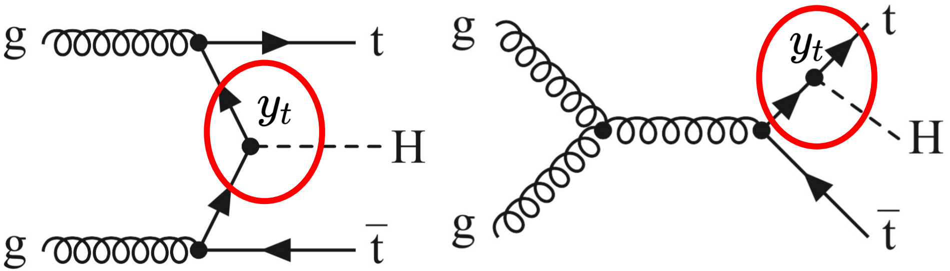
Process	$4\ell + 0\tau_h$	$3\ell + 1\tau_h$	$2\ell + 2\tau_h$
$t\bar{t}H$	2.0 ± 0.5	4.0 ± 0.9	2.2 ± 0.5
tH	0.2 ± 0.2	0.8 ± 0.6	0.3 ± 0.2
$t\bar{t}Z + t\bar{t}\gamma^*$	5.9 ± 0.4	6.6 ± 0.7	2.5 ± 0.3
$t\bar{t}W + t\bar{t}WW$	0.2 ± 0.0	1.1 ± 0.2	—
ZZ	0.6 ± 0.2	0.3 ± 0.1	0.2 ± 0.0
Misidentified leptons	—	1.5 ± 0.9	3.4 ± 0.9
Rare backgrounds	0.6 ± 0.1	1.0 ± 0.3	0.3 ± 0.1
Conversion	—	—	—
Total expected background	7.4 ± 0.5	11.5 ± 1.3	6.8 ± 1.0
Data	12	18	3



Source	$\Delta\mu_{t\bar{t}H}/\mu_{t\bar{t}H}$ [%]	$\Delta\mu_{tH}/\mu_{tH}$ [%]	$\Delta\mu_{t\bar{t}W}/\mu_{t\bar{t}W}$ [%]	$\Delta\mu_{t\bar{t}Z}/\mu_{t\bar{t}Z}$ [%]
Trigger efficiency	2.3	8.1	1.2	1.9
e, 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 sample and sideband statistical uncertainty	7.1	27.2	2.4	2.3
Theory-related sources affecting acceptance and shape of distributions	4.6	18.2	2.0	4.2
Normalization of MC-estimated processes	13.3	12.3	13.9	11.3
Integrated luminosity	2.2	4.6	1.8	3.1
Statistical uncertainty	20.9	48.0	5.9	5.8

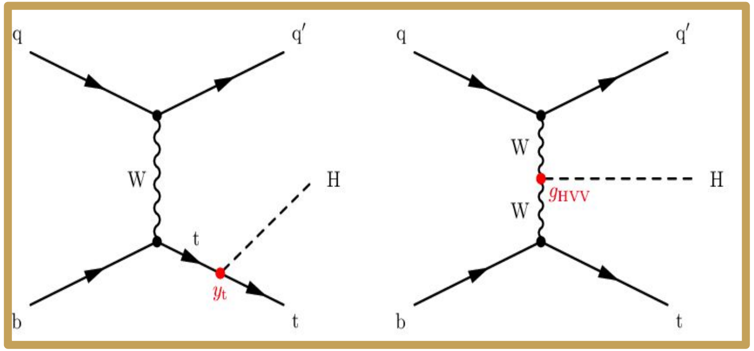
- ttH production provides <u>**direct**</u> **measurement of top Yukawa coupling**
- Largest in the SM: $y_t = \sqrt{2}m_t/v \approx 1$
    - ○ Relevant for the stability of the Higgs potential
    - ○ Sensitive to the presence of new physics

$$\boxed{\sigma_{ttH} \sim |y_t|^2}$$



- The measurement of ttH production is a corner stone for the characterisation of the Higgs boson

Most exciting results are not compatible with SM prediction. So finding with the agreement with the theory could be a signal of new discovery



- Not only ttH but also tH production is a powerful probe
    - ○ Sensitive to the sign of y_t
    - ○ Influence the interference between diagrams
        - ■ SM: y_t ~ 1, destructive interference
          σ_{tH} ~ 74 pb
        - ■ BSM: y_t ~ -1, constructive interference
          σ_{tH} ~ 850 pb
    - ○ Enhancement of the cross section by a factor ~11
- Both ATLAS and CMS are aiming at its measurement
- Evidence of tH production has not yet been achieved

All previous results

Many ttH measurements are done at ATLAS and CMS results at $\sqrt{s} = 13$ TeV

Large BR

ttH(bb)	ATLAS	Full Run-2 (139 fb^{-1})	ATLAS-CONF-2020-058
	CMS	41.5 + 36 fb^{-1}	CMS-PAS-HIG-18-030
ttH(WW, ZZ, ττ) multi-leptons	ATLAS	80 fb^{-1}	ATLAS-CONF-2019-045
	CMS	Full Run-2 (137 fb^{-1})	Eur. Phys. J. C 81 (2021)378 CMS-PAS-HIG-19-008
ttH(γγ)	ATLAS	Full Run-2 (139 fb^{-1})	Phys. Rev. Lett. 125, 061802 ATLAS-CONF-2020-026
	CMS	Full Run-2 (137 fb^{-1})	Phys. Rev. Lett. 125, 061801 CMS-PAS-HIG-19-015

Small BR

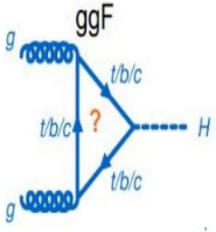
Why ttH is important ?

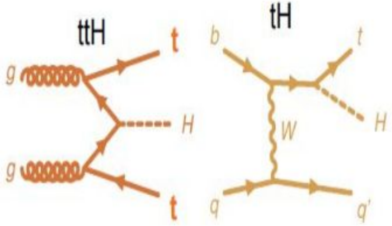
top-Higgs coupling largest in SM

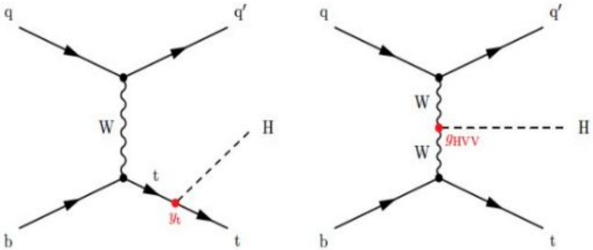
$y_t \sim m_t / v$

$$\boxed{\sigma_{ttH} \sim |y_t|^2}$$

Sign of y_t







pp@13 TeV

SM ($y_t \sim 1$):	44 pb	507 fb	74 fb

t-channel tHq production
SM: $y_t \sim 1$, constructive interference: σ_{tH} ~74 fb
BSM : $y_t \sim -1$, destructive interference σ_{tH}~850 fb

ttH+tH: direct probe of top-Higgs coupling

tH sensitive to sign of y_t