Higgs boson production in association with top quark at CMS

Clara Ramón Álvarez*
(on behalf of the CMS Collaboration)

*Partially funded by
"Programa Severo Ochoa"

Grant PID2020-113341RB-100 funded by

PCTI ASTURIAS
EUROPEAN UNION
European Regional Development Fund

Gobierno del Principado de Asturias
Consejería de Ciencia, Innovación y Universidad

Gobierno de España
Ministerio de Ciencia e Innovación

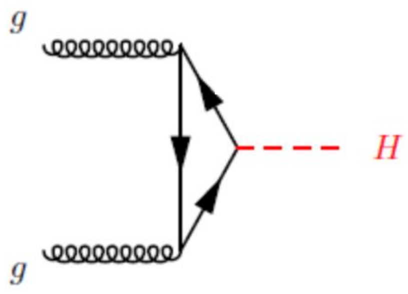
ICTEA
Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias

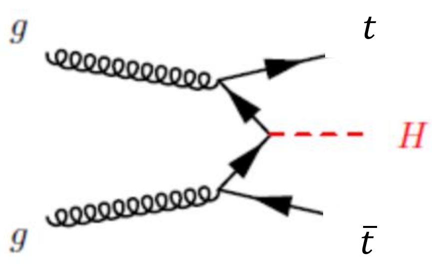
Universidad de Oviedo

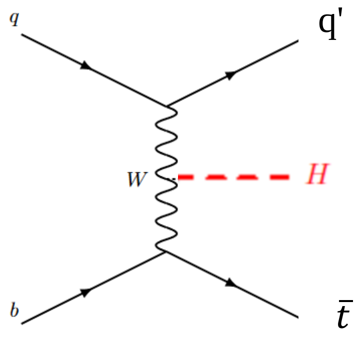
Higgs boson production

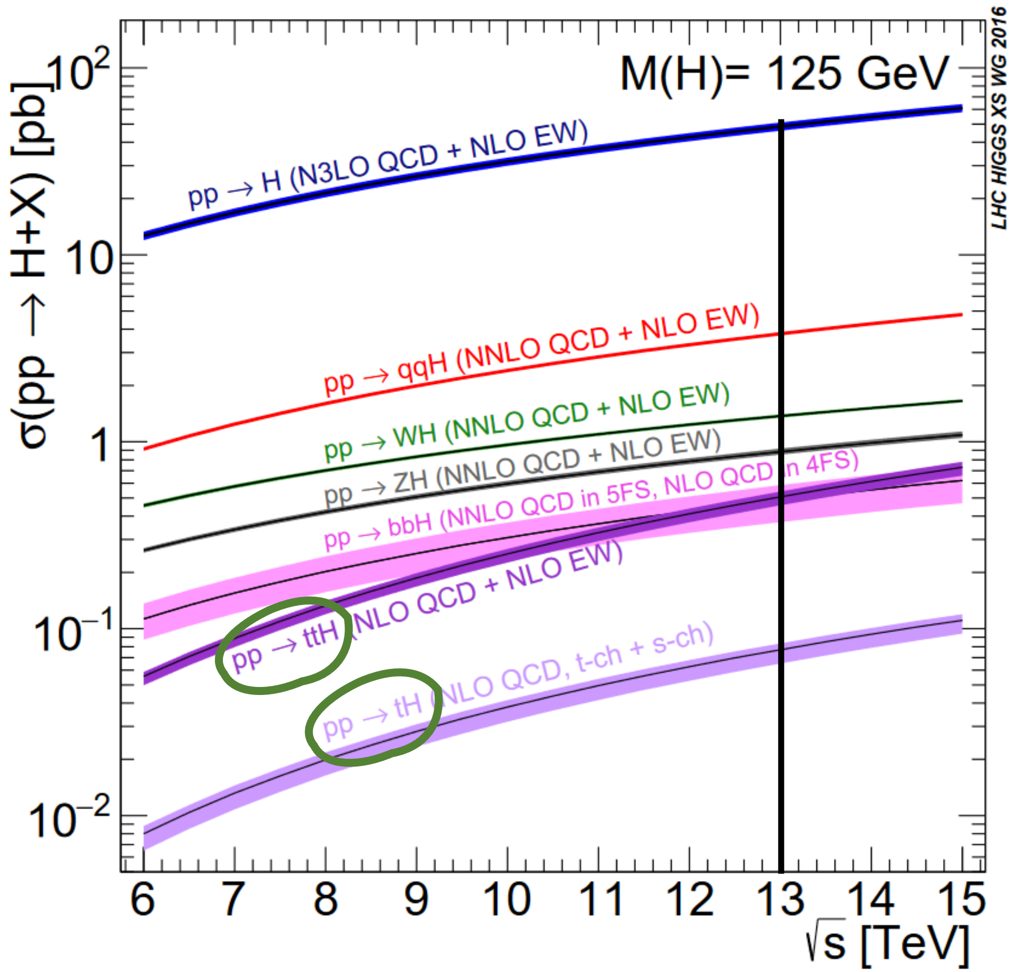
At LHC **gg fusion is the dominant** H production mode - $\sigma_{H,ggF}$ ~ 49 pb @ 13 TeV
Top asociated production, much lower rates:

- **$t\bar{t}H$ – $\sigma_{t\bar{t}H}$ ~ 0.5 pb @ 13 TeV**
- **tH - σ_{tH} ~ 0.07 pb @ 13 TeV**









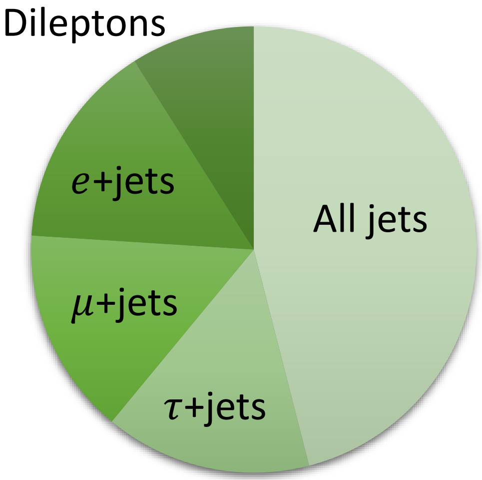
Challenging but interesting:

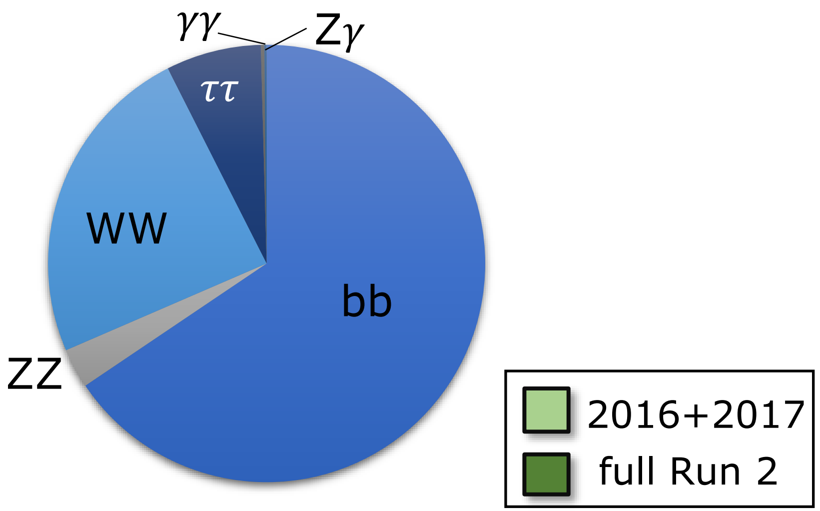
- **Direct probe** of top-Higgs Yukawa coupling
- y_t ~ 1 (largest in the SM)
- BSM y_t =-1→ constructive interference → σ_{tH} ~ 0.8 pb
- Probe EFT

Final states to study ttH+tH

$t\bar{t}$ **decays x Higgs decays**

t→ Wb





Branching ratio is not the end of the story…

H → bb

- Large number of events
- Large $t\bar{t}$+jets background contribution

HIG-18-030

H→ WW/ZZ/$\tau\tau$ multileptonic

- H and t leptonic decays
- Multiple leptons in the final state

EPJC 81, 378 (2021)

arXiv:2208.02686

accepted by JHEP

H→ $\gamma\gamma$ / 4ℓ

- Lower number of events
- Clear signature
- Resonant channels (peak)

Phys. Rev. Lett. 125, 061801

JHEP 07, 27 (2021)

Phys. Rev. D 104, 052004 (2021)

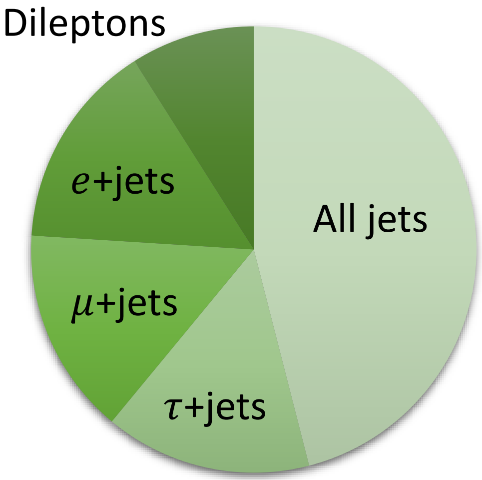
- $t\bar{t}H$ observed in 2018 (combining all channels) & observation in $\gamma\gamma$
- tH not yet observed
- $t\bar{t}H$ recent updates: CP measurements, STXS studies
- Higgs Couplings and non-resonant HH Combination

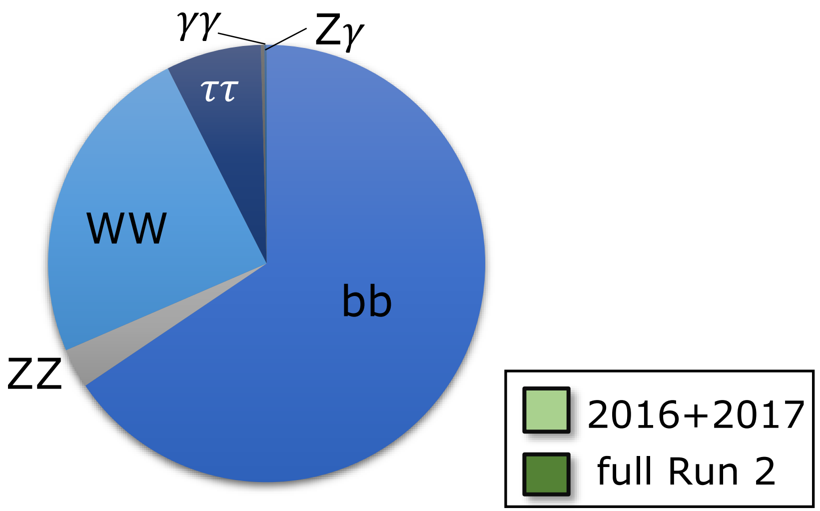
Nature 607, 60–68 (2022)

Final states to study ttH+tH

$t\bar{t}$ decays x Higgs decays

t→ Wb





Branching ratio is not the end of the story…

H → bb

- Large number of events
- Large $t\bar{t}$+jets background contribution

HIG-18-030

H→ WW/ZZ/$\tau\tau$ multileptonic

- H and t leptonic decays
- Multiple leptons in the final state

EPJC 81, 378 (2021)

arXiv:2208.02686 accepted by JHEP

H→ $\gamma\gamma$ /4ℓ

- Lower number of events
- Clear signature
- Resonant channels (peak)

Phys. Rev. Lett. 125, 061801

JHEP 07, 27 (2021)

Phys. Rev. D

Covered in this talk

- $t\bar{t}$H observed in 2018 (combining all channels) & observation in $\gamma\gamma$
- tH not yet observed
- $t\bar{t}$H recent updates: CP measurements, STXS studies
- Higgs Couplings and non-resonant HH Combination Nature 607, 60–68 (2022)

ttH→ $\gamma\gamma$

[Phys. Rev. Lett. 125, 061801]

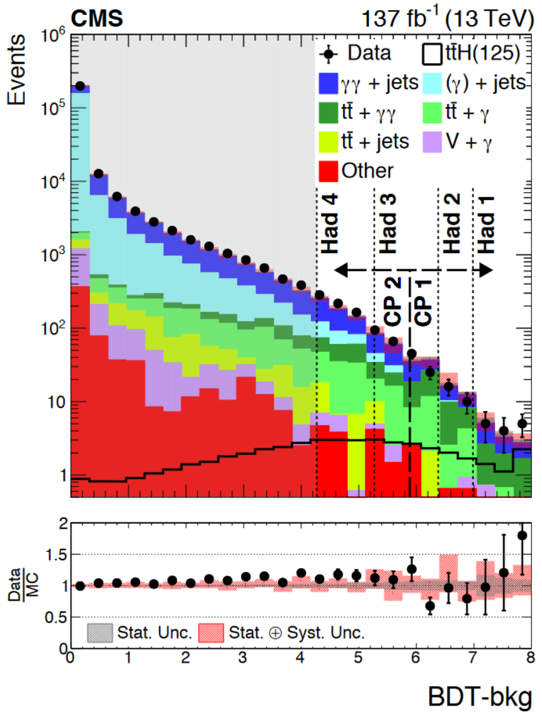
Selection:

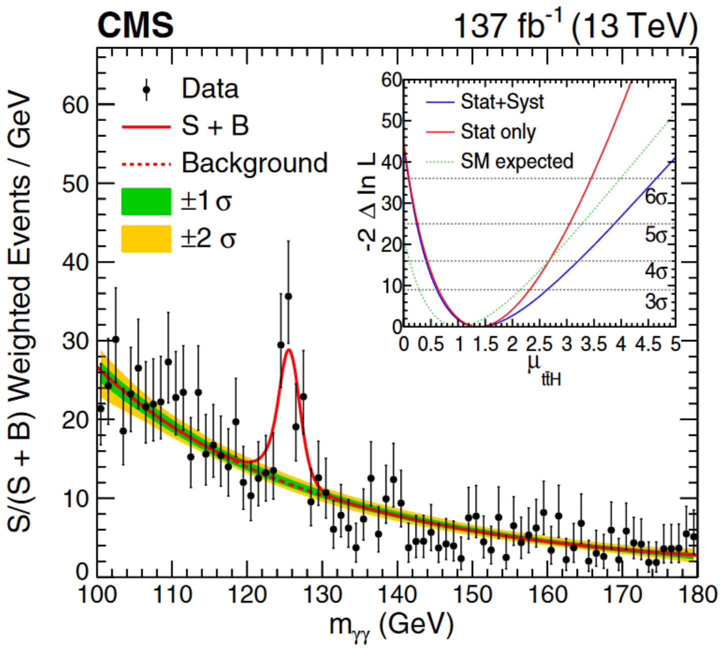
100 GeV < $m_{\gamma\gamma}$< 180 GeV

2 high pT γ+additional jets and leptons

Two categories depending on final state objects:

- Hadronic:
  0 Leptons & ≥ 3Jet & ≥ 1 btag
- Leptonic: ≥ 1 Lepton & ≥ 1Jet





- MVA (BDT-bkg) in each category to separate signal from background

- Simultaneous maximum likelihood (ML) fit performed using the $m_{\gamma\gamma}$

Results

First **observation** in a single H decay channel!
Observed significance of 6.6 s.d. (4.7 s.d.)

$$\sigma_{t\bar{t}H}\mathcal{B}_{\gamma\gamma} = 1.56^{+0.34}_{-0.32}\ \text{fb}$$

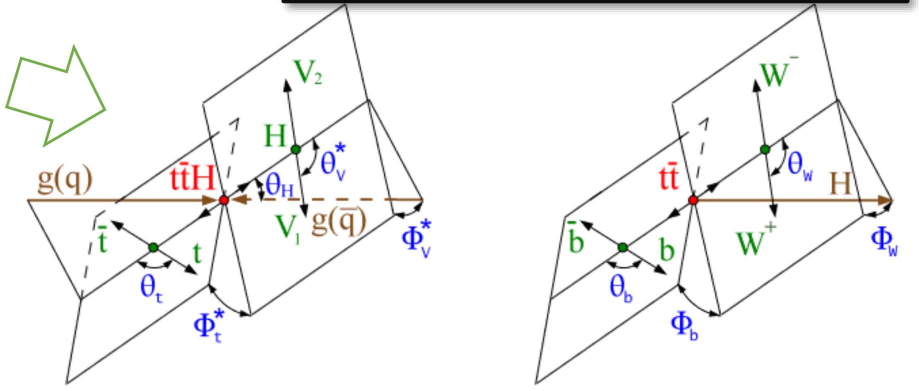
$$\mu_{t\bar{t}H} = 1.38^{+0.36}_{-0.29}$$

ttH→ $\gamma\gamma$: CP Interpretation

Phys. Rev. Lett. 125, 061801

Kinematic info in $t\bar{t}H$ production is very rich, angular variables and reconstructed $t\bar{t}H$ mass sensitive to modification in the Htt coupling

MVA to reconstruct D0- operator

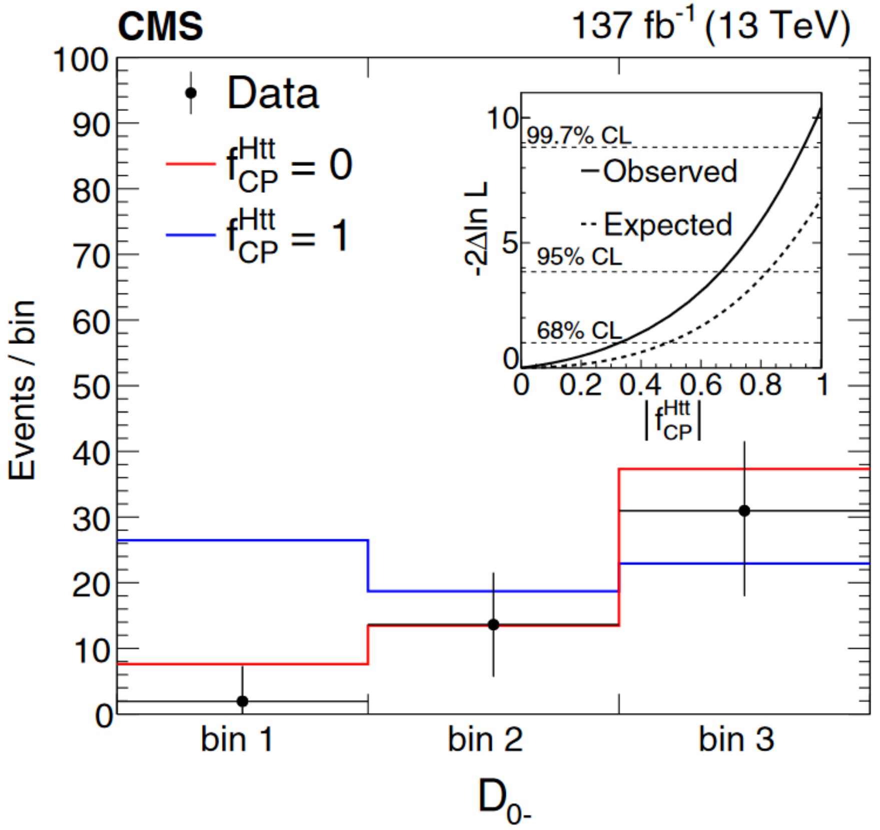


Fitting 12 categories: 2 (BDT-bkg) x 3 (D_{0-}) x 2 (final state)

- Yields parametrized using κ_t and $\tilde{\kappa}_t$ (ratio of the CP-even and CP-odd terms to SM expectation, respectively)

$$f_{CP} = \frac{|\tilde{\kappa}_t|^2}{|\tilde{\kappa}_t|^2 + |\kappa_t|^2}$$

$$f_{CP}^{Htt} = 0.00 \pm 0.33$$
$$|f_{CP}^{Htt}| < 0.67 @ \ 95\%\text{CL}$$



First CP measurement of Htt coupling

CP constrain dominated by statistical uncertainty

Pure Pseudo Scalar **CP odd coupling excluded at 3.2 s.d.**

ttH→ $\gamma\gamma$ STXS

JHEP 07, 27 (2021)

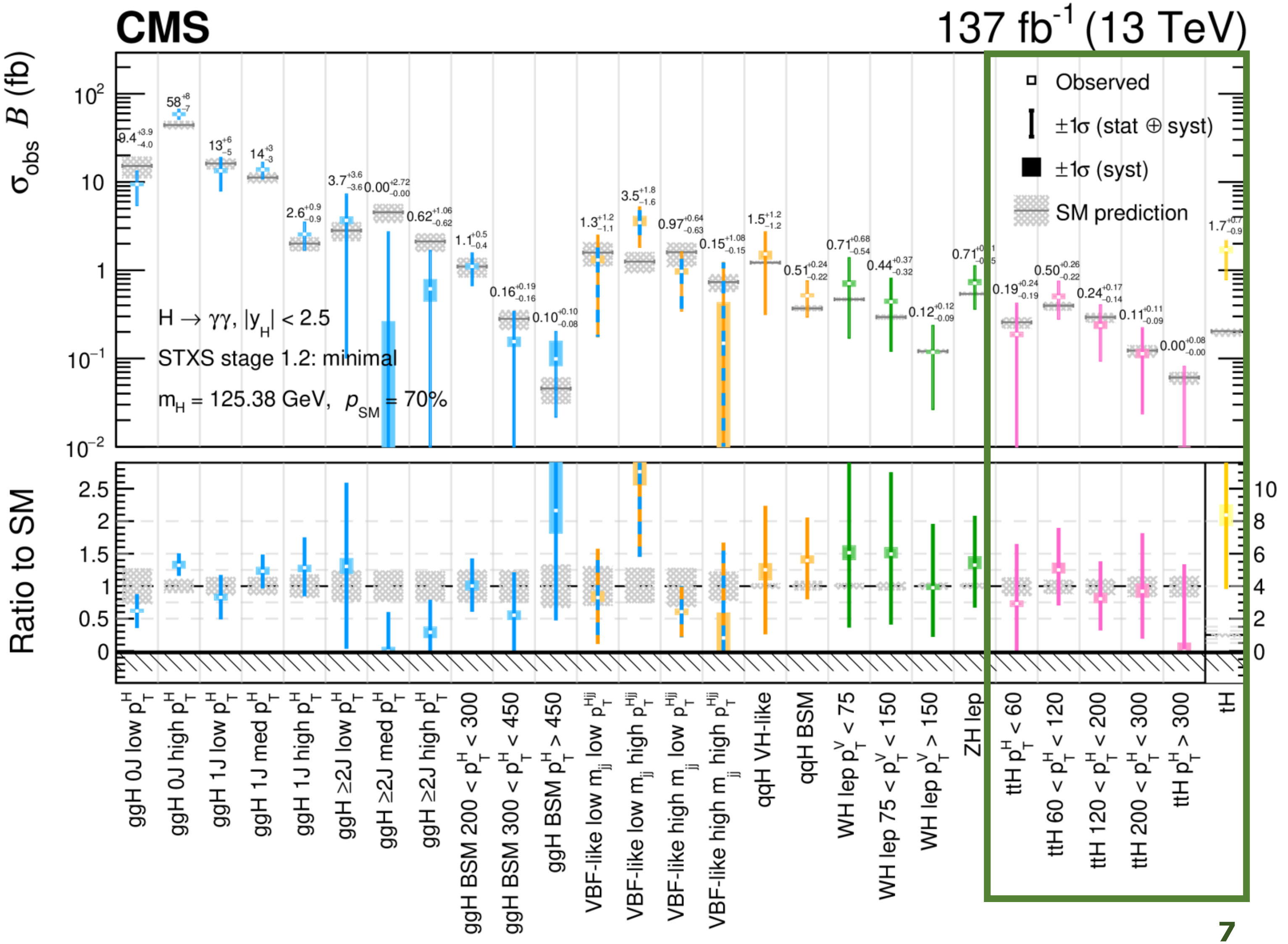
STXS (Simplified template cross section) **approach**. Categories targeting all H production modes, in particular $t\bar{t}H$ and tH

$t\bar{t}H$: 5 bins in p_T^H
tH: 1 categroy

Selection: the one in previous slide + NN to discriminate $t\bar{t}H$ vs tH

Results

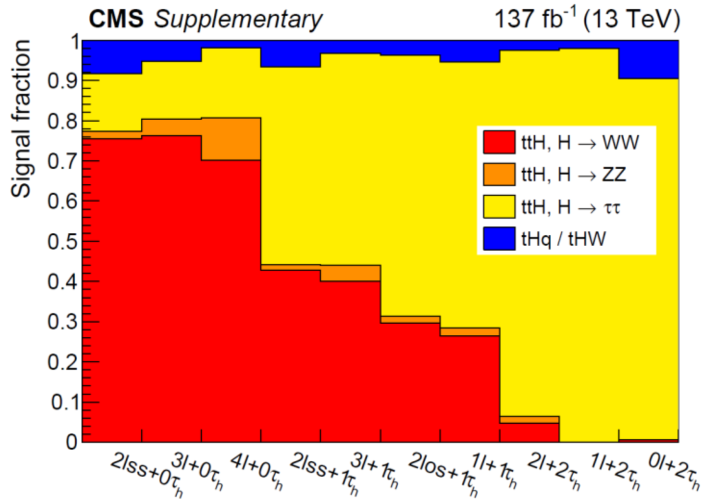
- First channel to perform $t\bar{t}H$ measurement differentially!
- Good agreement with SM
- Upper limit on the tH cross section is 14 (8 exp.) times the SM expectation



ttH→ multileptons

EPJC 81, 378 (2021)

Categorize events depending on the **lepton multiplicity**
Dedicated **MVA to select isolated leptons** from H, W and τ
Dedicated selection on each category. Using Jet and b-tagging multiplicities.



Backgrounds:

Reducible backgrounds:

- Non prompt leptons
- Electron charge miss ID.

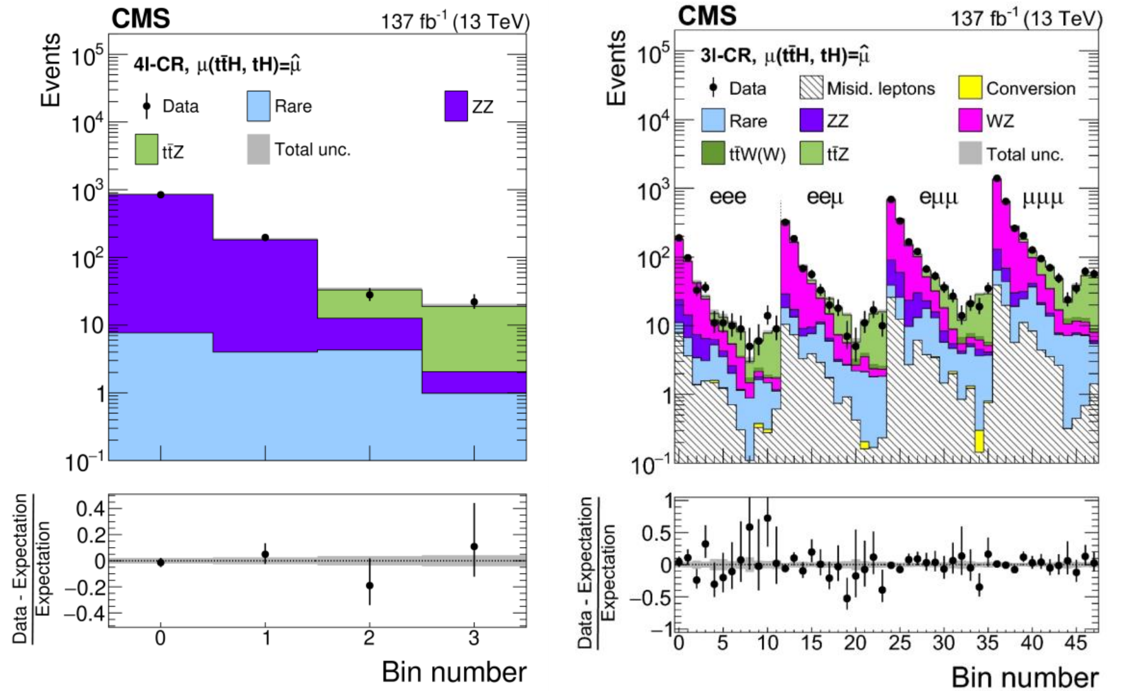
Estimated with data-driven techniques

- Photon Conversions

Irreducible backgrounds:

- $t\bar{t}Z$, $t\bar{t}W$
- Dibosons

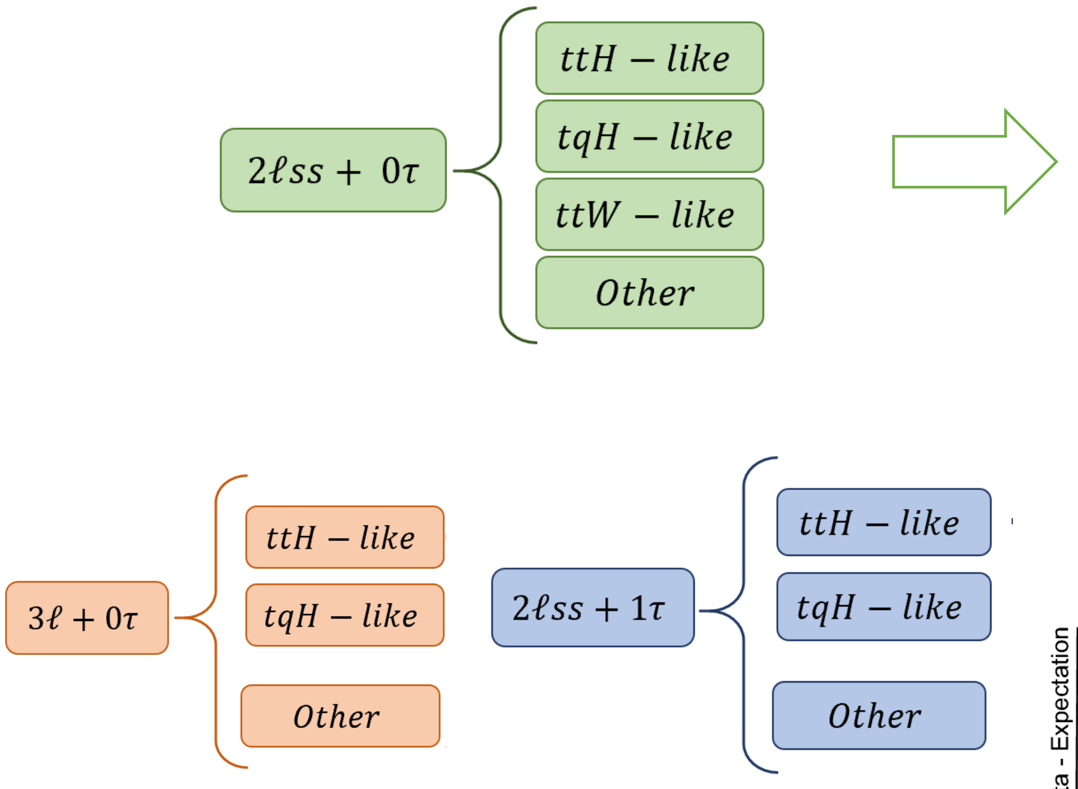
Control regions to constrain these backgrounds

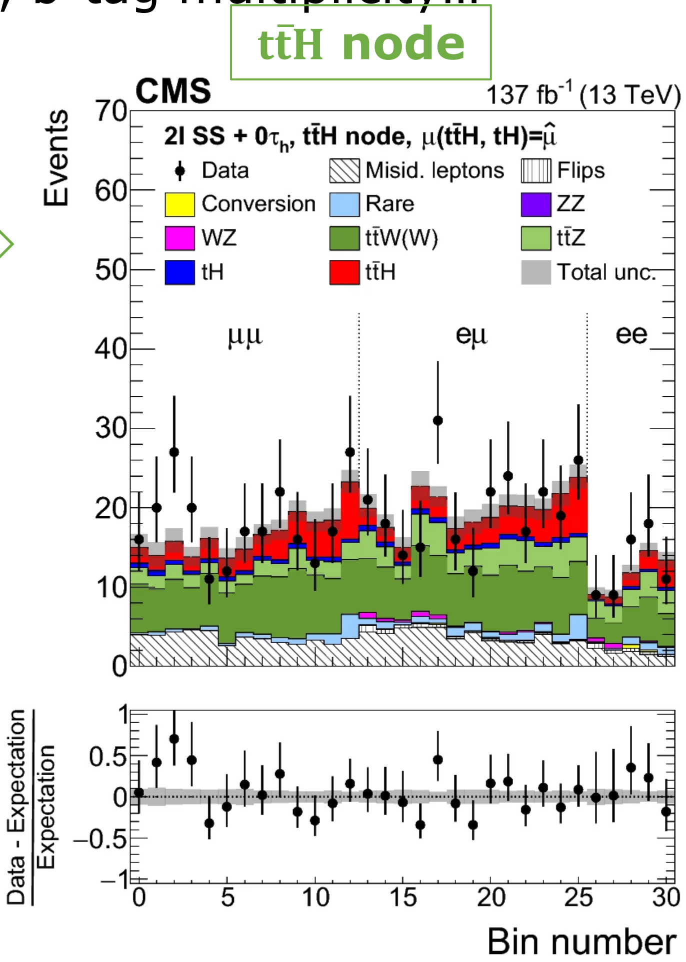


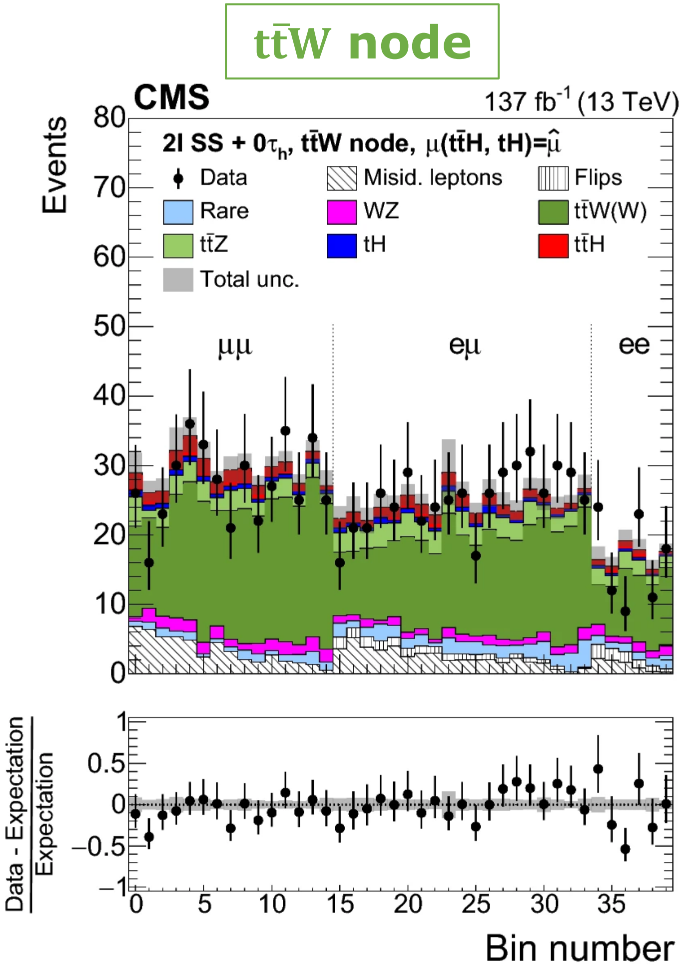
ttH → ml event classification

EPJC 81, 378 (2021)

- In each signal categories **Neural Network trained** to discriminate signal vs. background
- Dedicated **node to target** $t\bar{t}W$ in 2lss+0τ category
- Further classification depending on flavor, b-tag multiplicity…







Simultaneous **maximum likelihood fit** in the signal region categories as well as the control regions

- $t\bar{t}W$ and $t\bar{t}Z$ signal strengths (μ) freely floated in the fit

ttH → ml results

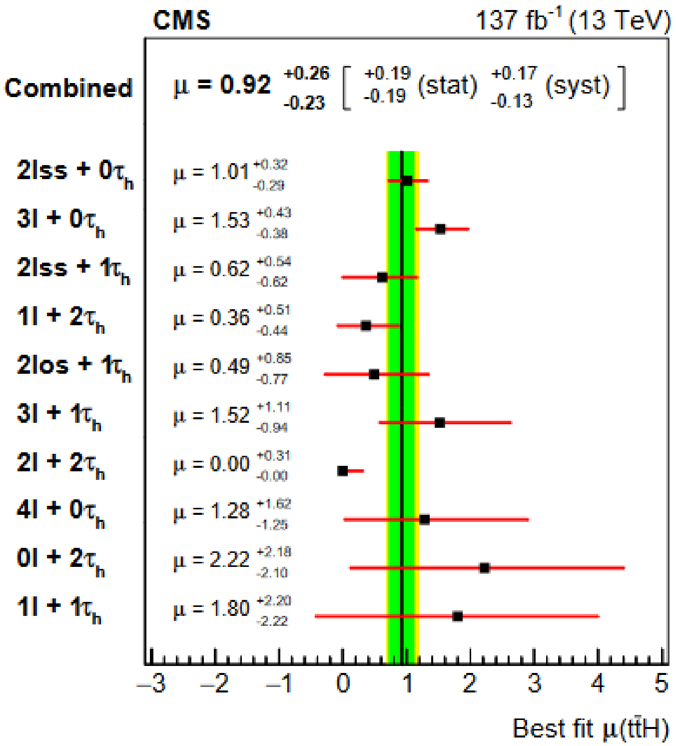
EPJC 81, 378 (2021)

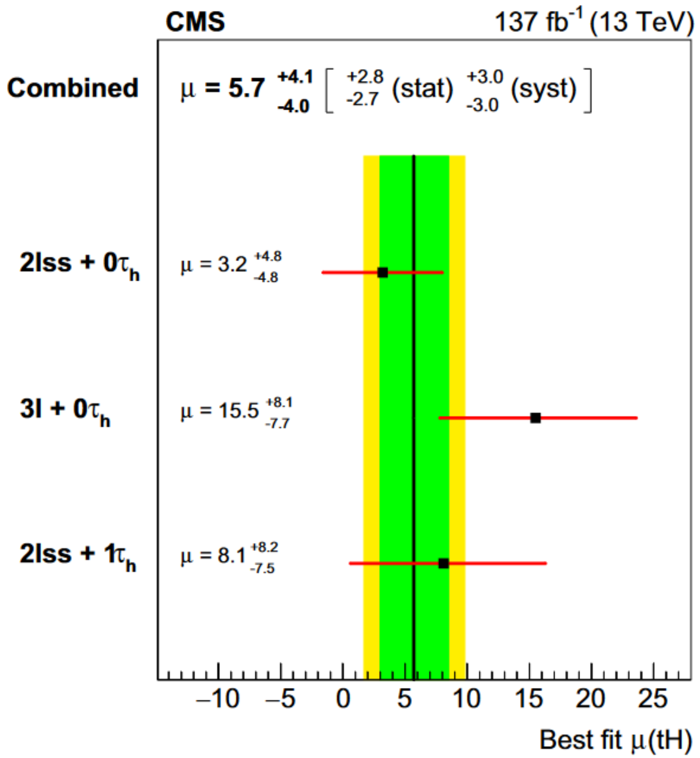
- Signal strengths in good agreement with SM

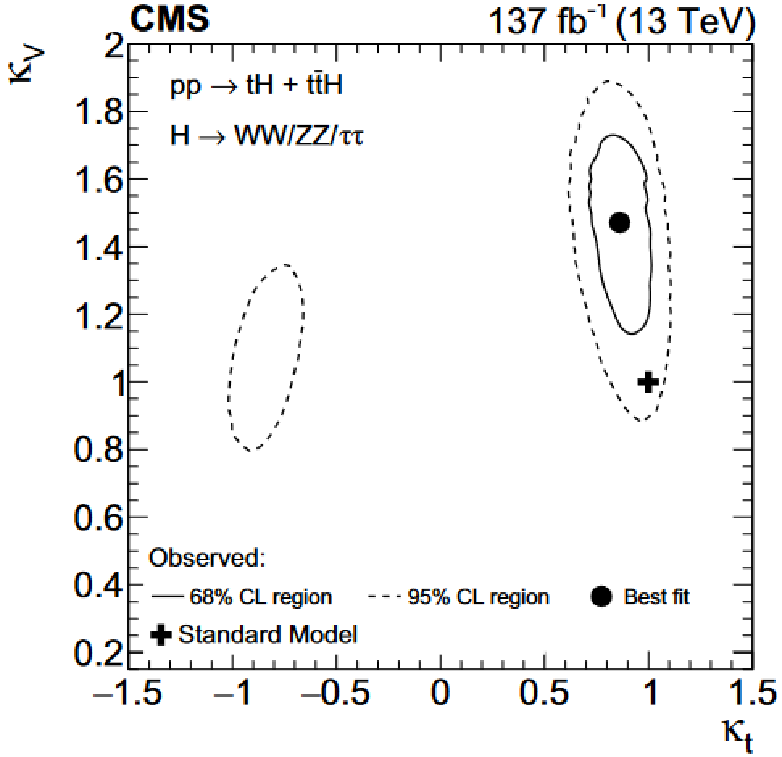
$$\mu_{t\bar{t}H} = 0.92^{+0.26}_{-0.23}$$ observed (expected) significance: 4.7 (5.2) s.d.

$$\mu_{tH} = 5.7^{+2.8}_{-2.7}(stat.)^{+3.0}_{-3.0}(syst)$$ observed (expected) significance: 1.4 (0.3) s.d.

- Study Top-Higgs (κ_t) and Higgs-W (κ_V) coupling:
  -0.9 < κ_t < -0.7 or 0.7 < κ_t < 1.1 at 95 % C.L.



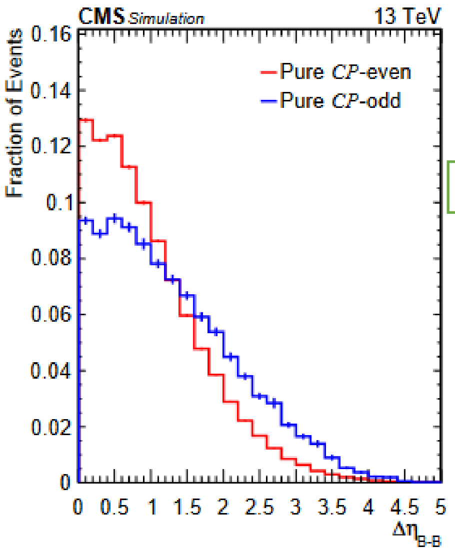




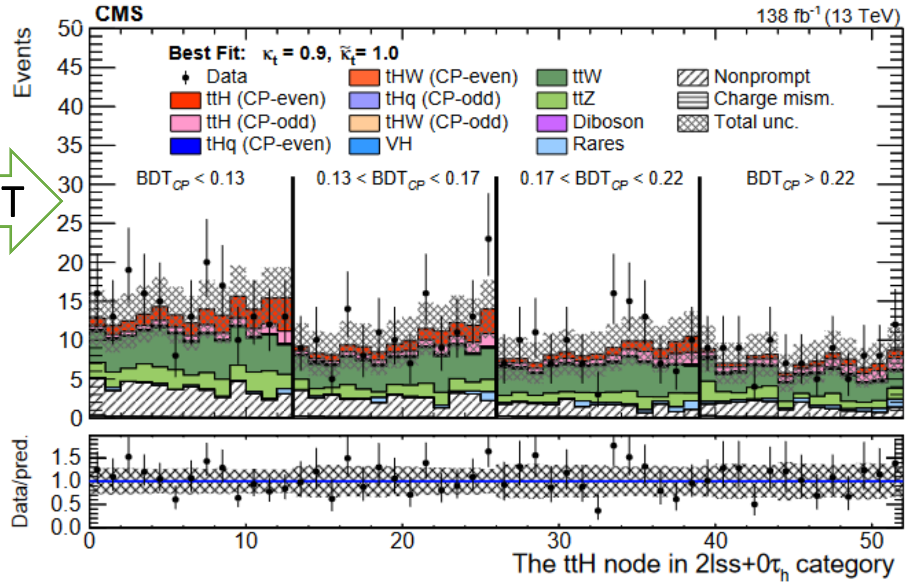
$t\bar{t}H \rightarrow$ ml: CP interpretation

arXiv:2208.02686

- kinematic differences between $t\bar{t}H$ CP-even and CP-odd components
- Dedicated BDT in each of the 3 most sensitive $t\bar{t}H$ enriched categories
- Yields parametrized using: κ_t and $\tilde{\kappa}_t$ (ratio of the CP-even and CP-odd terms to SM expectation, respectively)



BDT

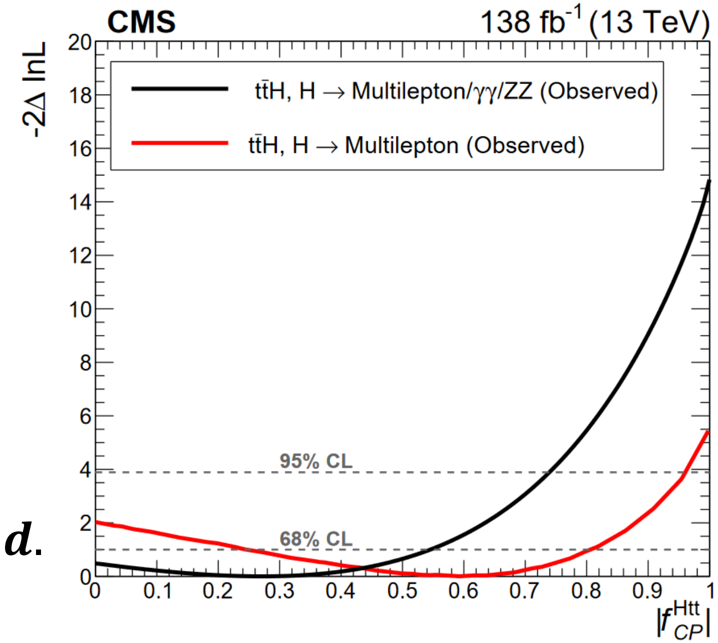


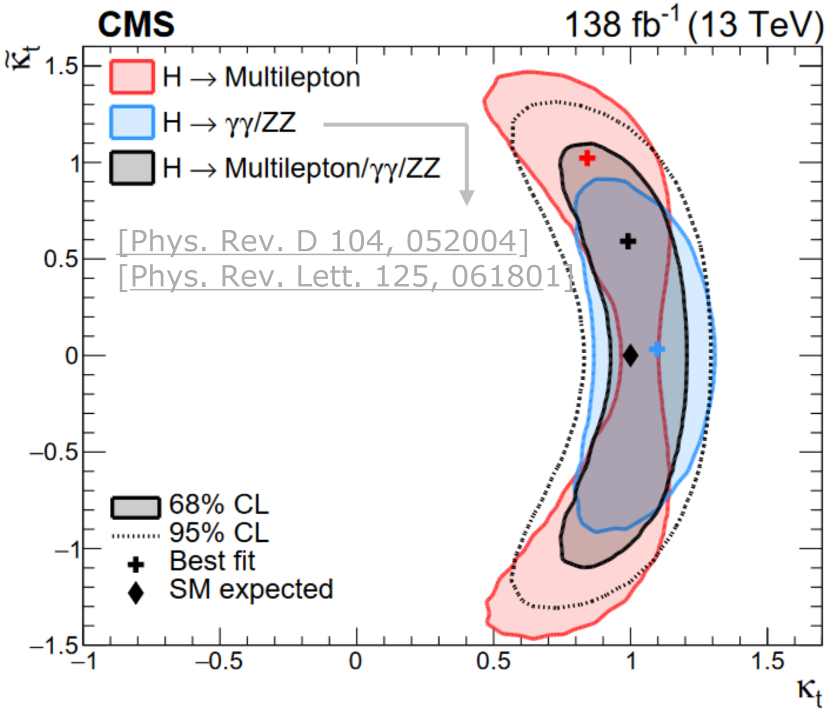
$$f_{CP} = \frac{|\tilde{\kappa}_t|^2}{|\tilde{\kappa}_t|^2 + |\kappa_t|^2}$$

ML fit profiling $\mu_{t\bar{t}H}$
Good agreement with SM

f_{CP}^{Htt} = **0.28** within (-0.55, 0.55) at 68% CL

$|f_{CP}^{Htt}| = 1$ **excluded with 3.7** $s.d.$

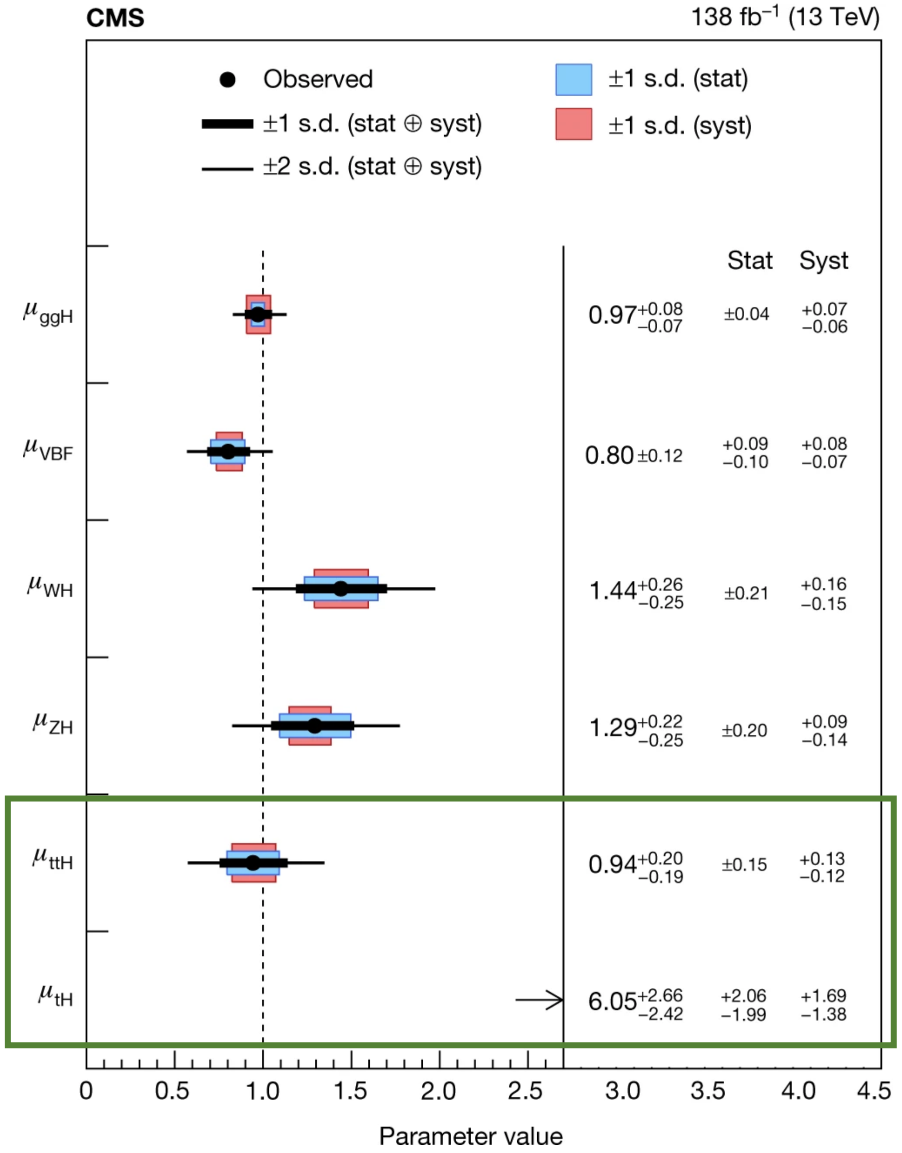


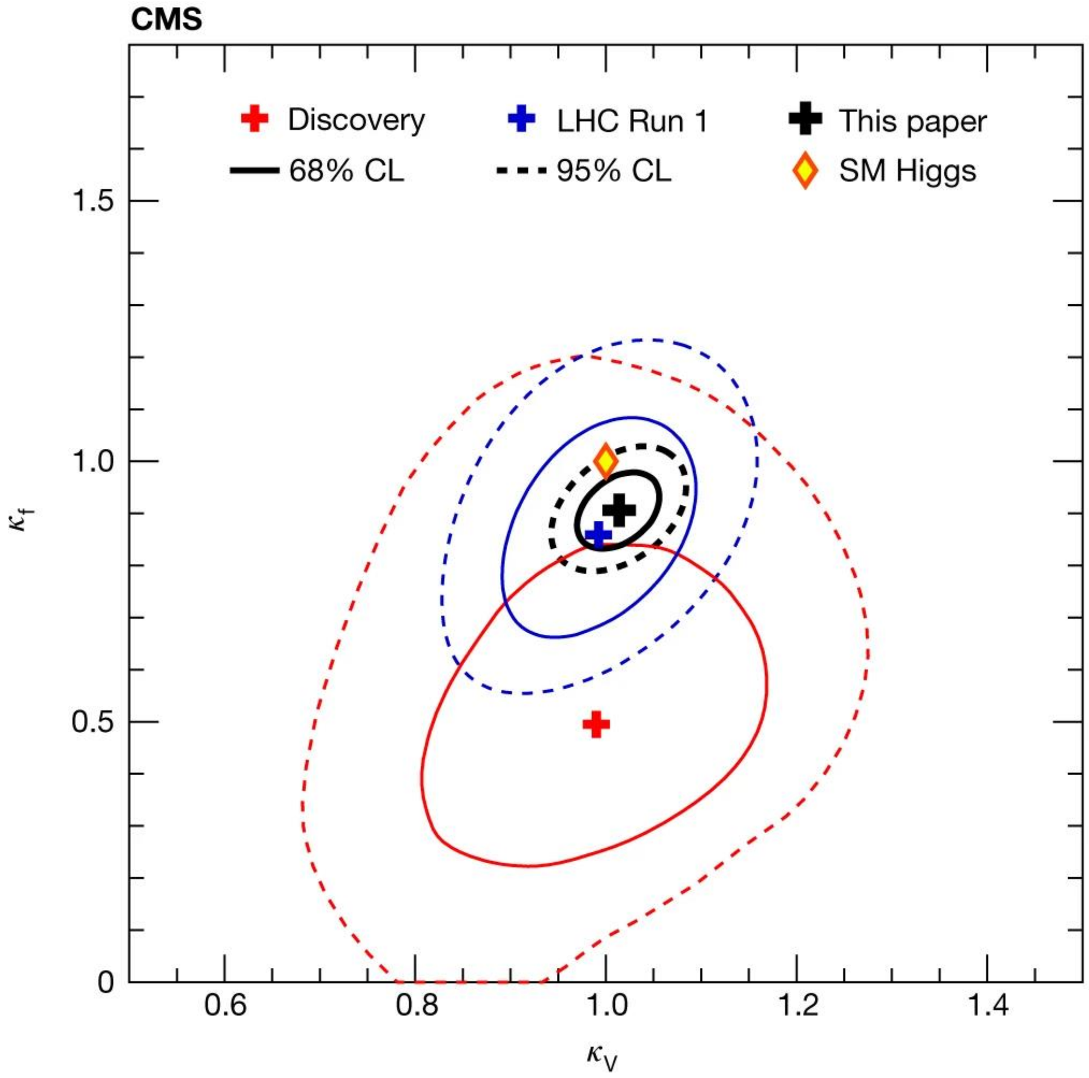


Nature combination

Nature 607, 60–68 (2022)

Using all published results. Including $b\bar{b}$, $\gamma\gamma$, 4l and multileptons final states





k modifier afects H decay but also production

k_V and k_f measured with < 10% unc.

Summary

Two of the most challenging H production modes had been studied during **Run 2**:

- $\mathbf{t\bar{t}H}$ **observation in 2018!** ★
- $t\bar{t}H$ observation in $\gamma\gamma$
- Have seen improvements on the control of backgrounds
- Differential measurements in some channels

The amount of data taken during Run 2 allowed us to study **Top-Higgs coupling**:

- Good agreement with SM
- CP interpretations

Still analyzing Run 2 dataset

Run 3 already started:

- **increase statistic a factor of ~3!**
- Work ongoing on how to **improve modelling** of $t\bar{t}W$ (H→ multilepton) and $t\bar{t}b\bar{b}$(H→ $b\bar{b}$).

Back-up

ttH $\rightarrow 4\ell$

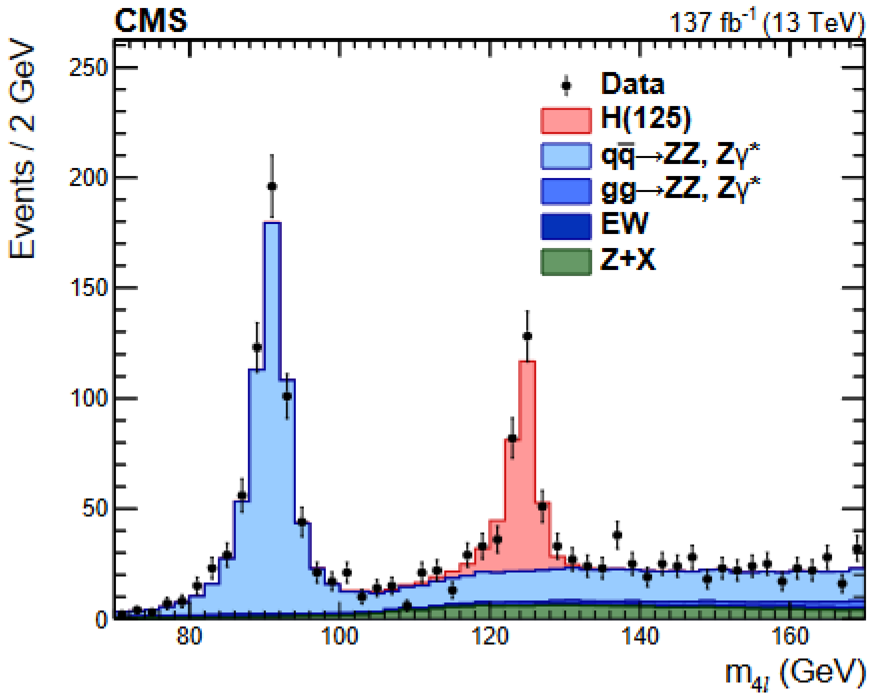
Use full Run 2 dataset
Selection: 4 isolated leptons that are opposite sign and same flavour -> used to reconstruct the ZZ pair

STXS approach. Categories targeting all H production modes, in particular ttH (little sensitivitiy to tH), binned in pTH

Two categories depending on top deacy:

- Hadronic: ≥ 4 Jets, ≥ 1 btag, 0 additional leptons
- Leptonic: ≥ 1 additional lepton

Two Dimesional fit to m4l and kinematic disceiminat sig. vs bkg



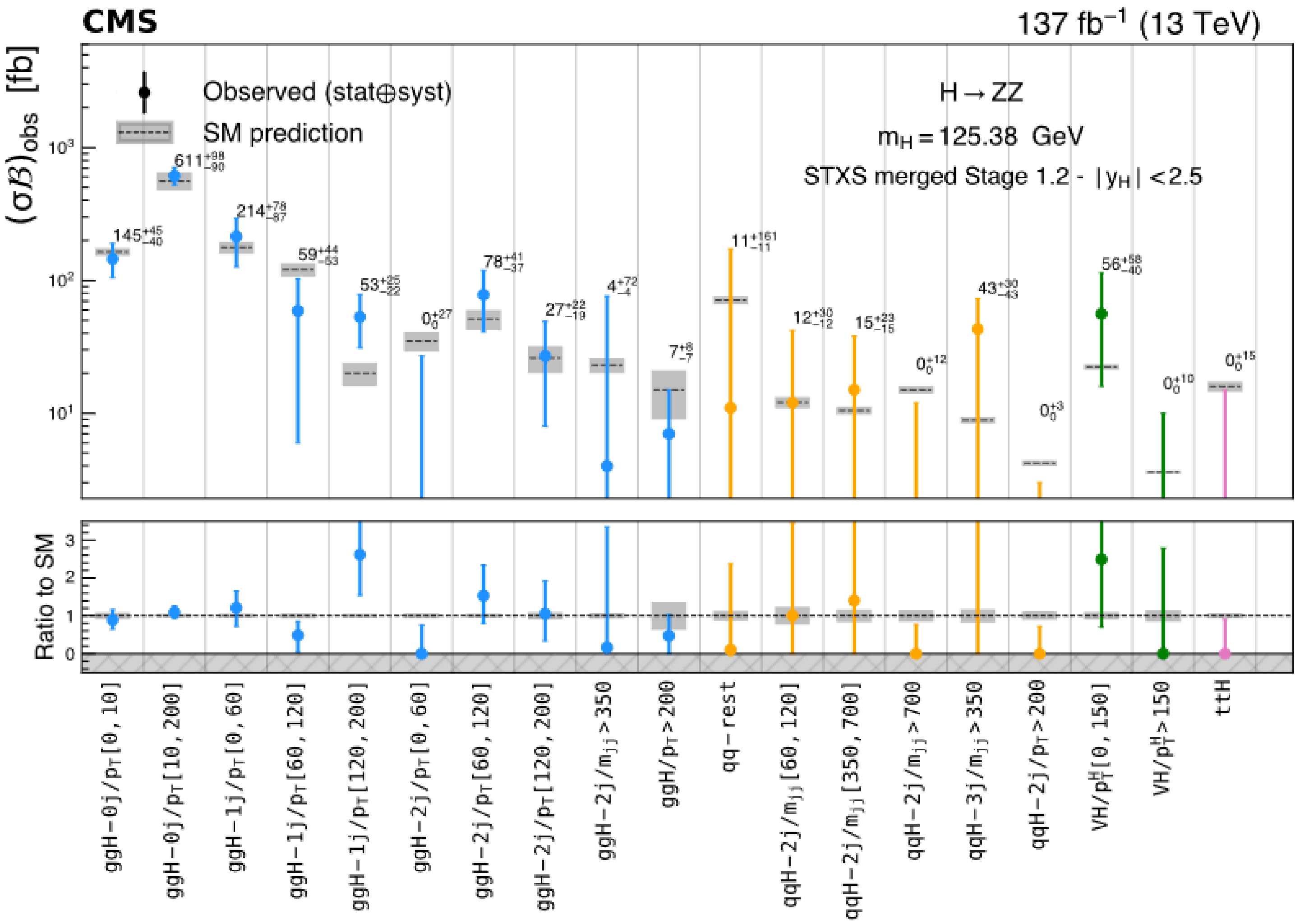
Results

	Expected	Observed
$\mu_{t\bar{t}H,tH}$	$1.00^{+1.23}_{-0.77}\,(\text{stat})^{+0.51}_{-0.06}\,(\text{syst})$	$0.17^{+0.88}_{-0.17}\,(\text{stat})^{+0.42}_{-0.00}\,(\text{syst})$

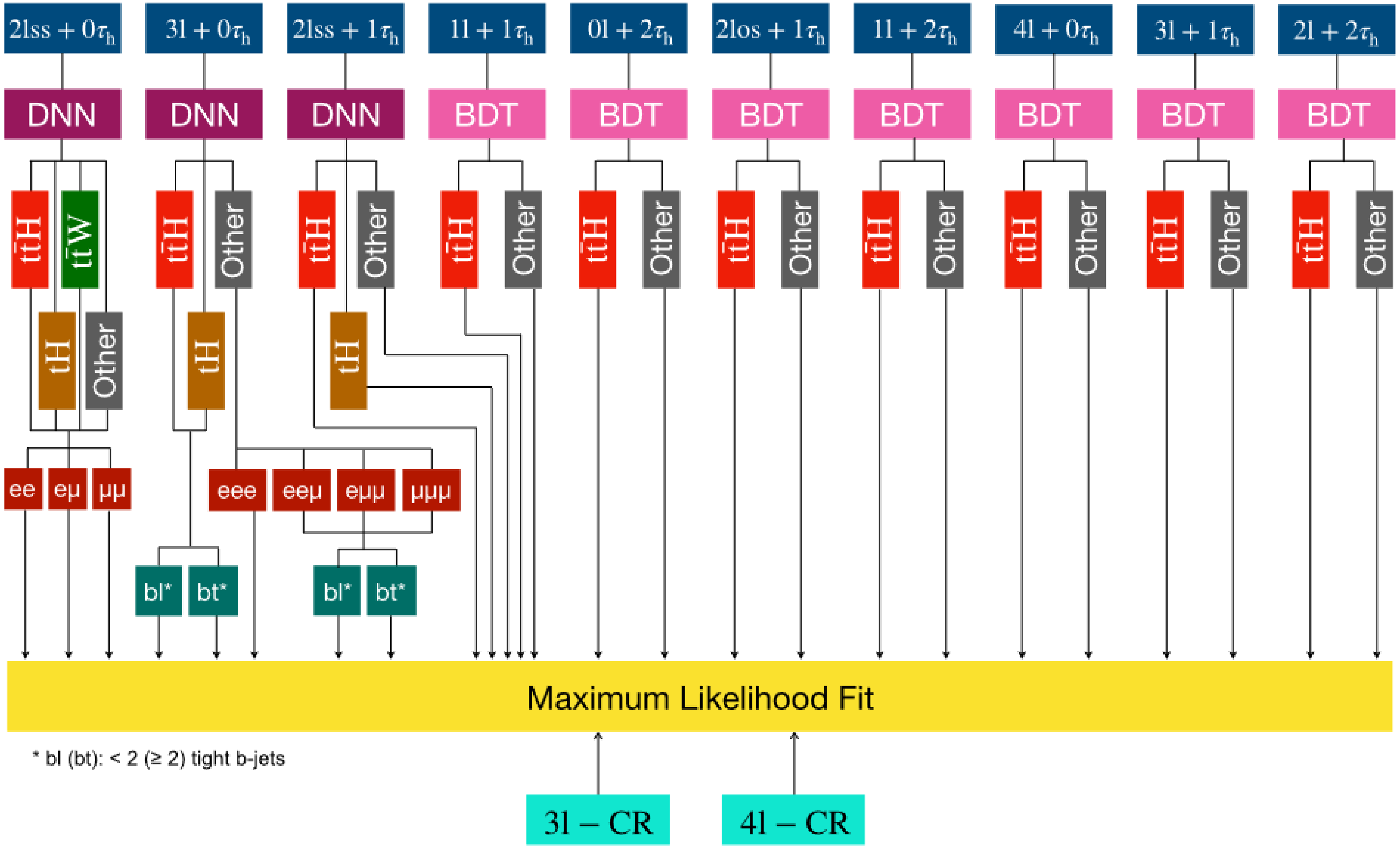
ttH $\to 4\ell$

	Expected	
$\mu_{t\bar{t}H,tH}$	$1.00^{+1.23}_{-0.77}$ (stat) $^{+0.51}_{-0.06}$ (syst)	0.17^{+0}_{-0}

Observed
$0.17^{+0.88}_{-0.17}$ (stat) $^{+0.42}_{-0.00}$ (syst)



ttH (ml) categories



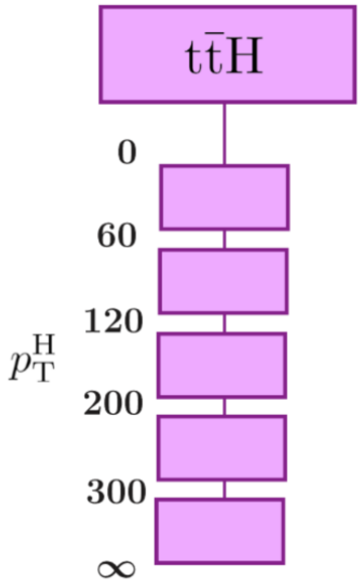
ttH (ml) syst

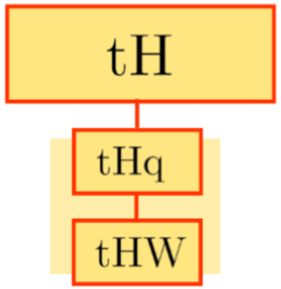
Source	$\Delta\mu_{t\bar{t}H}/\mu_{t\bar{t}H}$ [%]	$\Delta\mu_{tH}/\mu_{tH}$ [%]	$\Delta\mu_{t\bar{t}W}/\mu_{t\bar{t}W}$ [%]	$\Delta\mu_{t\bar{t}Z}/\mu_{t\bar{t}Z}$ [%]
Trigger efficiency	2.3	8.1	1.2	1.9
e, μ reconstruction and identification efficiency	2.9	7.1	1.7	3.2
τ_h identification efficiency	4.6	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 ($\gamma\gamma$) syst + STXS

Theoretical:
ttH normalization (QCD renormalization and factorisation scales)

Experimental:
b quark and photon identification
Jet energy scale and resolution
Integrated luminosity





CP interpretation

Lagrangian can be expressed as a superposition of CP-even and a CP-odd terms

$$\mathcal{L}_{t\bar{t}H} = \frac{-y_t}{2}\bar{\psi}_t(\kappa_t + i\gamma_5\tilde{\kappa}_t)\psi_t H$$

With:

- y_t the top-Higgs coupling
- κ_t ratio of the CP-even terms to SM expectation
- $\tilde{\kappa}_t$ ratio of the CP-odd terms to SM expectation

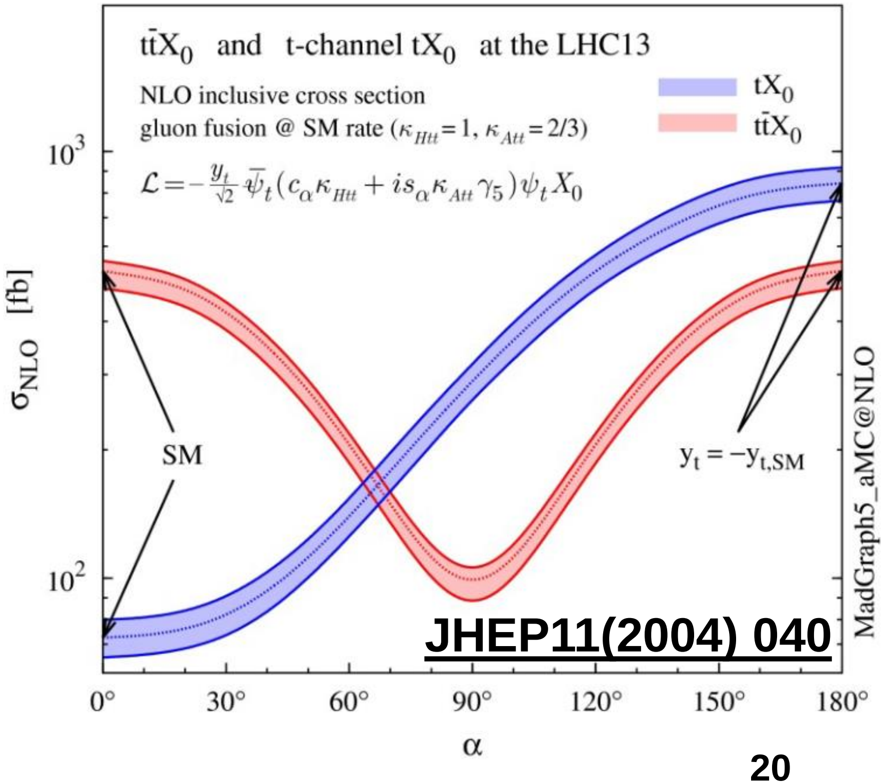
Defining α as the CP mixing angle:

- κ_t proportional to $\cos\alpha$
- $\tilde{\kappa}_t$ proportional to $\sin\alpha$

Kinematic differences as well as cross-section changes expected depending on the CP scenario

tH cross section sensitive to the inverted top coupling scenario (y_t = - y_t^{SM})

Scenario	α
Purely CP even	$\alpha = 0°$ or $180°$
Purely CP odd	$\alpha = 90°$
Mixed scenario	$\alpha \neq 0°, \neq 90°, \neq 180°$



JHEP11(2004) 040