
Universidad de Oviedo
3rd Red LHC, May 6 - 8th, 2019
CMS
Compact Muon Solenoid
Associated Production of the Higgs boson with a Top quark pair in Multileptons
Red LHC España
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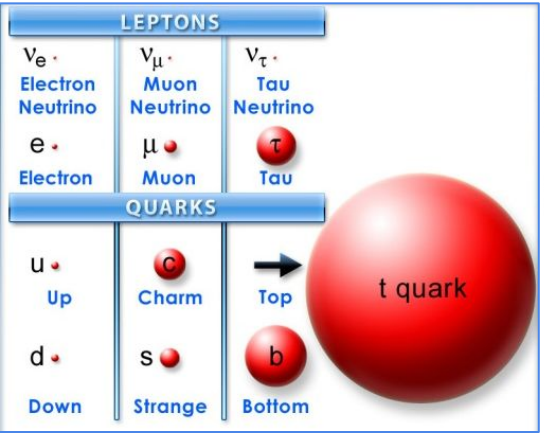
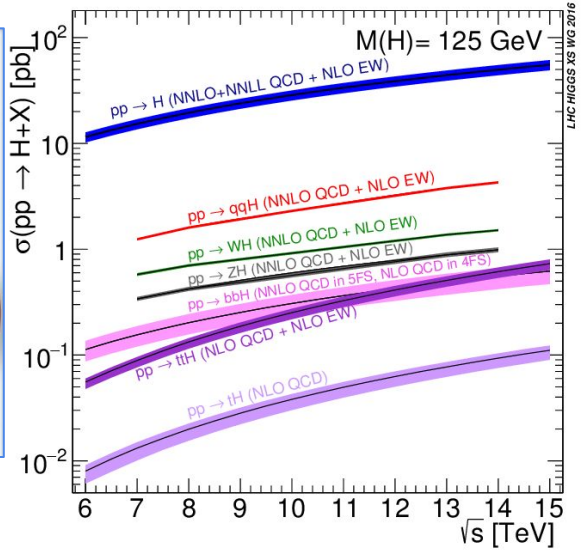
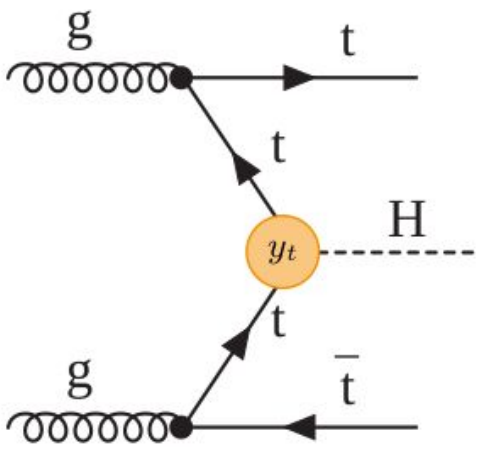
Introduction

ttH production provides a direct measurement of the **Yukawa coupling** of the **top** to the **Higgs**

- In the SM, the Higgs boson ***can couple to fermions*** with a coupling strength proportional to the fermion mass
- **Top quark:** heaviest elementary particle ➞ strongest coupling to SM Higgs
- Decay into top quarks is kinematically *impossible*
- Direct measurement of **top-Higgs coupling** at the LHC is done through the production of a Higgs boson and a top quark-antiquark pair or a single top







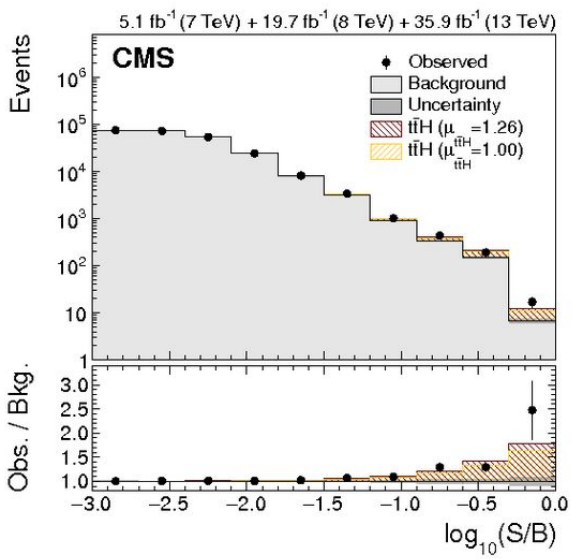
ttH and tH cross sections:

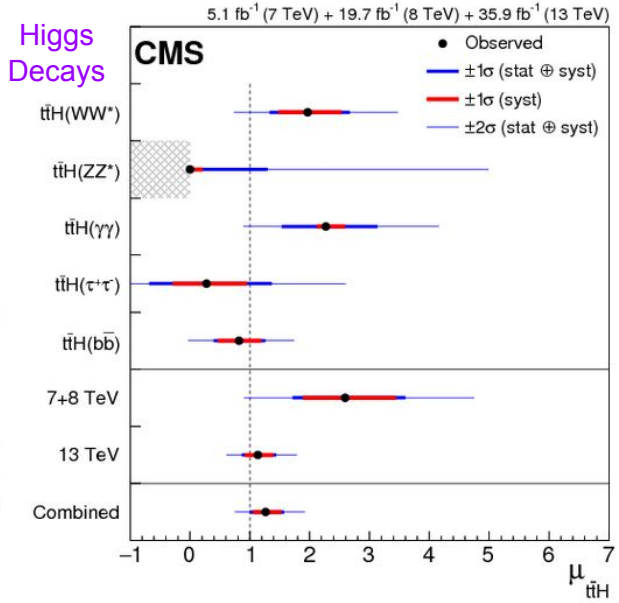
σ_{ttH} ~ 0.5 pb (13 TeV): best sensitivity to $|y_t|$

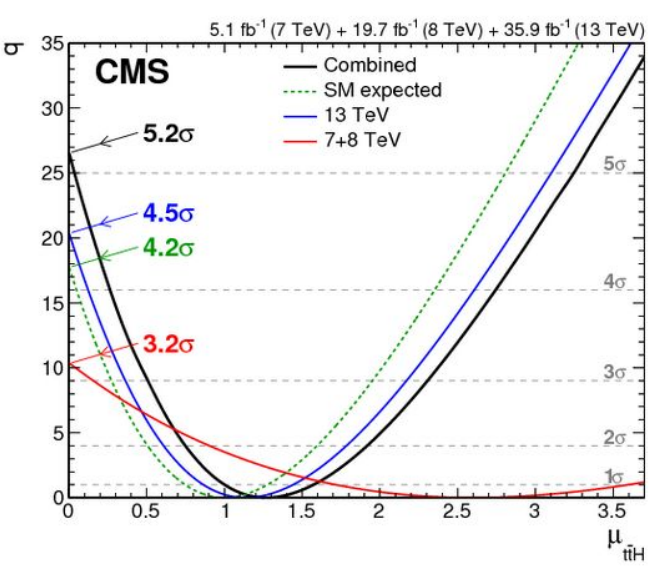
σ_{tH} ~ 0.1 pb (13 TeV): sensitive to sign of y_t

ttH Observation

- The observation of associated production of a Higgs boson with a top quark pair (ttH) has been reported by the **ATLAS and CMS** collaborations
- Analyses of final states from different Higgs boson decay modes have been combined
- **The observed ttH production rate is in agreement with the SM prediction**





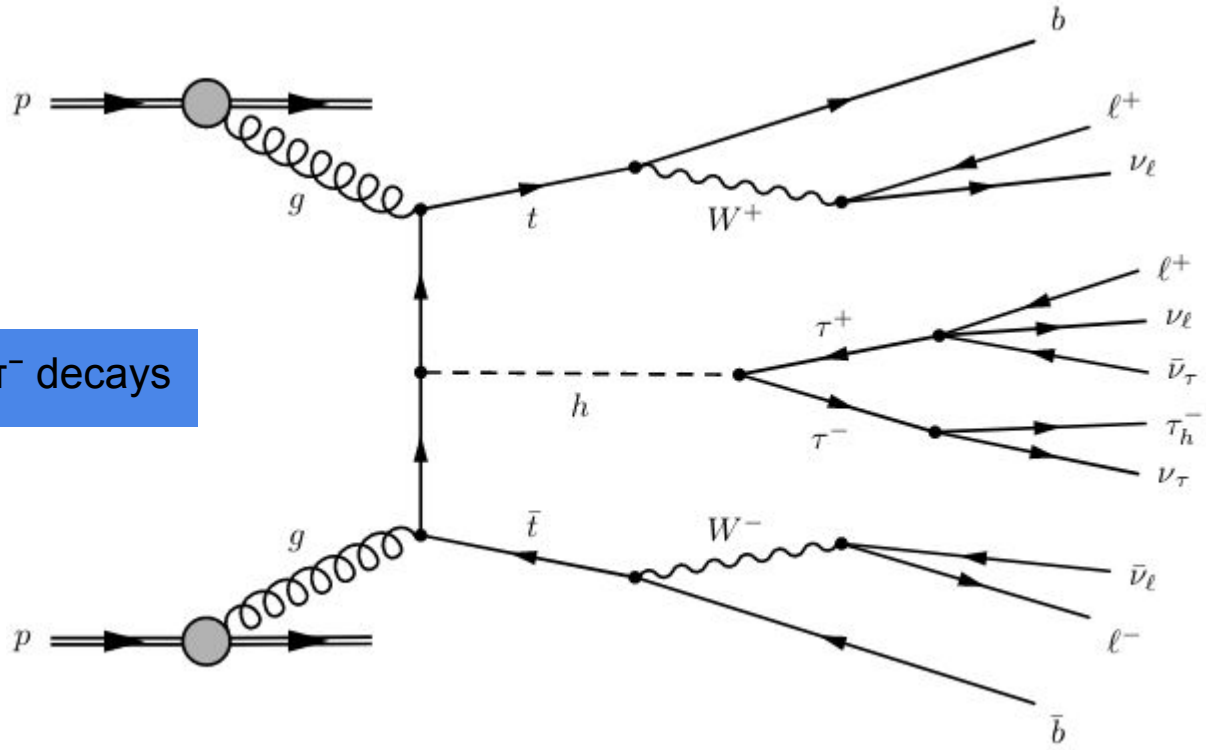


CMS: *HIG-17-035, Phys. Rev. Lett. 120 (2018) 231801*, **ATLAS**: *HIGG-2018-13, Phys. Lett. B 784 (2018) 173*

ttH Multileptons

Focusing on **Multileptons**

Targets: H → WW* , ZZ* , $\tau^+ \tau^-$ decays



Presenting results from HIG-18-019: http://cds.cern.ch/record/2649199/files/HIG-18-019-pas.pdf

The Oviedo group contributed in the **electron** and **muon** channels

Data Samples and Monte Carlo Simulation

- Dataset from **2017 @ 13 TeV,** corresponding to an integrated luminosity of **41.5 fb^{-1}**
  - Combination of single, double, and triple lepton triggers, complemented by triggers based on the presence of a lepton and a hadronic tau (τ_h)

- Signal and background samples are produced by **Monte Carlo (MC) simulation**, and are used to estimate event yields and to train algorithms for signal extraction

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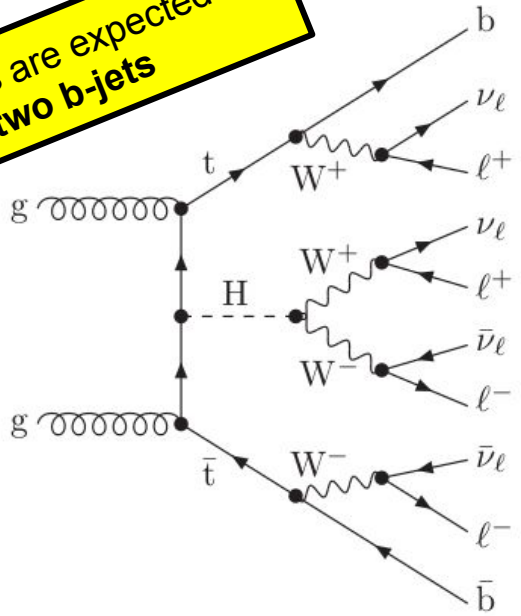
List of event generators used to produce samples for signal and background processes.

Generator	Processes
MADGRAPH5_aMC@NLO	$t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}+\gamma$+ jets, t + γ+ jets, $t\bar{t}WW$, WZ, WWW, WWZ, WZZ, ZZZ, Single top quark +Z, $tt\bar{t}\bar{t}$, $Z/\gamma^* \rightarrow \ell\ell$, W+jets
POWHEG	$t\bar{t}H$, WW, ZZ, $t\bar{t}$+jets, single top quark
PYTHIA	Minimum bias events

Event Selection

- Events grouped in **7 exclusive categories** based on the multiplicity of reconstructed candidates passing the *tight selection* criteria **based on lepton MVA (BDTs)**
- All events are required to contain at least **2 jets**: $p_T > 25$ *GeV and* $|\eta| < 2.4$
- At least 1 of these jets is required to be **b-tagged**

ttH signal events are expected to contain **two b-jets**



7 categories

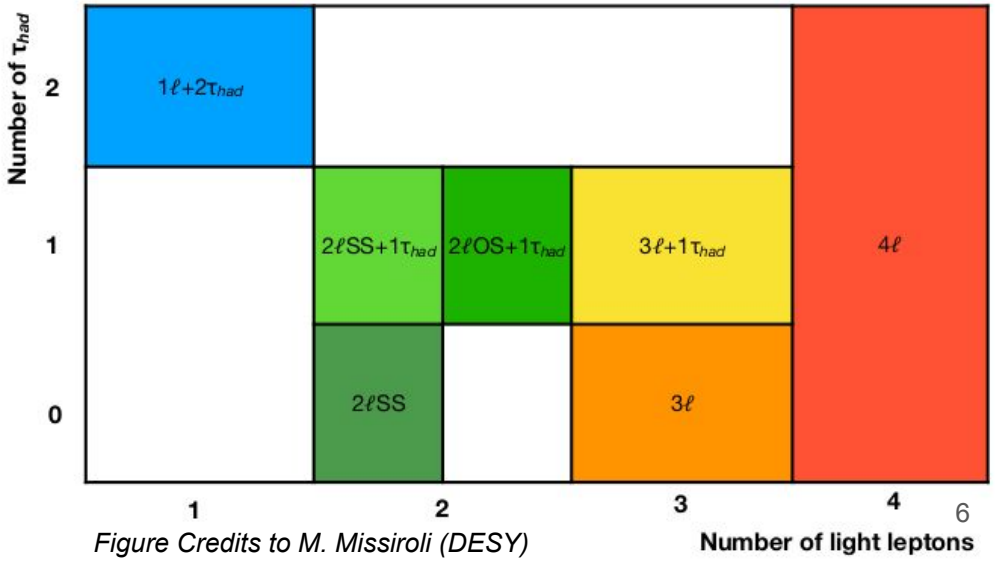


Figure Credits to M. Missiroli (DESY)

Background Estimation

Main background contributions : ttW/Z and fake/non-prompt leptons (tt + jets)

- **Top quark pair production associated with a vector boson (ttW, ttZ)**
  - Similar kinematics to the signal
  - Estimated with Monte Carlo simulations
  - **Control regions** are used in the **fit** to constrain these processes

Best fit for ttZ and ttW

- $\mu_{ttZ} = 1.69^{+0.39}_{-0.33}\ (1.00^{+0.24}_{-0.21})$
- $\mu_{ttW} = 1.42^{+0.34}_{-0.33}\ (1.0^{+0.27}_{-0.24})$

- **Processes with leptons not coming from W, Z or τ decays**
  - Dedicated MVA for the identification of prompt leptons
  - Data-driven estimation for this background

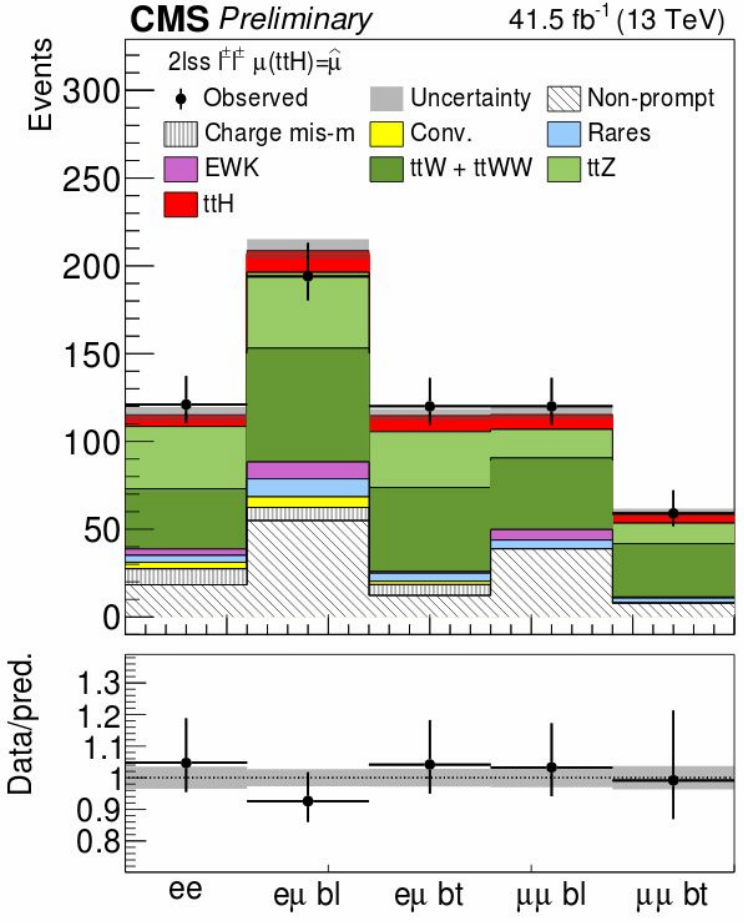
Event Yields

Observed data events in agreement with the SM expectation

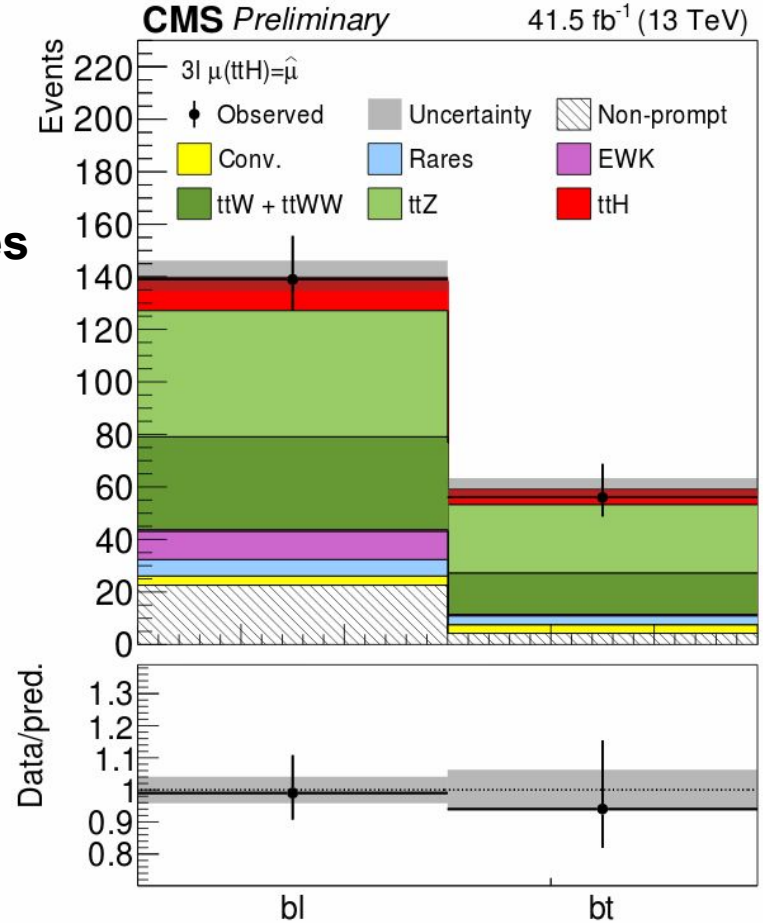
Category	$2\ell ss$	3ℓ	4ℓ	$1\ell + 2\tau_h$	$2\ell + 2\tau_h$	$3\ell + 1\tau_h$	$2\ell ss + 1\tau_h$
$t\bar{t}H$	43.0 ± 7.1	18.8 ± 4.8	0.7 ± 0.3	6.6 ± 3.6	0.9 ± 0.5	1.0 ± 0.4	5.1 ± 2.1
$t\bar{t}W + t\bar{t}WW$	218.5 ± 13.7	51.0 ± 5.3	0.13 ± 0.03	1.1 ± 0.3	< 0.05	0.5 ± 0.1	13.1 ± 2.4
tH	2.4 ± 0.1	0.9 ± 0.1	< 0.05	0.3 ± 0.1	< 0.05	< 0.05	0.5 ± 0.0
$WZ + ZZ$	< 0.05	12.0 ± 1.7	0.15 ± 0.10	1.5 ± 0.8	< 0.05	0.1 ± 0.0	2.8 ± 2.0
$t\bar{t}Z/\gamma^*$	138.2 ± 7.6	74.1 ± 6.3	3.9 ± 0.6	11.6 ± 2.6	1.6 ± 0.5	4.5 ± 0.7	15.4 ± 2.4
Misidentified	132.1 ± 10.0	26.8 ± 4.0	< 0.05	299.6 ± 19.1	5.3 ± 2.2	0.3 ± 0.3	5.3 ± 2.2
Conversions	11.6 ± 3.0	6.6 ± 1.3	< 0.05	0.3 ± 0.1	< 0.05	< 0.05	< 0.05
Signal flip	22.8 ± 2.3	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Other	26.7 ± 3.9	9.7 ± 2.2	< 0.05	1.2 ± 0.5	0.06 ± 0.04	0.3 ± 0.2	3.2 ± 1.1
SM expectation	595.3 ± 20.6	200.0 ± 10.8	5.0 ± 0.7	322.0 ± 19.6	7.9 ± 2.3	6.7 ± 0.9	45.3 ± 5.1
Observed data	614	195	6	324	7	4	53
S/B	0.08	0.10	0.16	0.05	0.13	0.18	0.13

- The **sensitivity** of the analysis is **driven** by the 2*l*ss, 3*l*, 1*l*+2τ_h and 2*l*ss+1τ_h categories
- The 2*l*+2τ_h, 3*l*+1τ_h, and 4*l* categories are **statistically limited**, may change using the **full Run2 dataset** (~150 fb^{-1})

Event Yields



Sub-categories



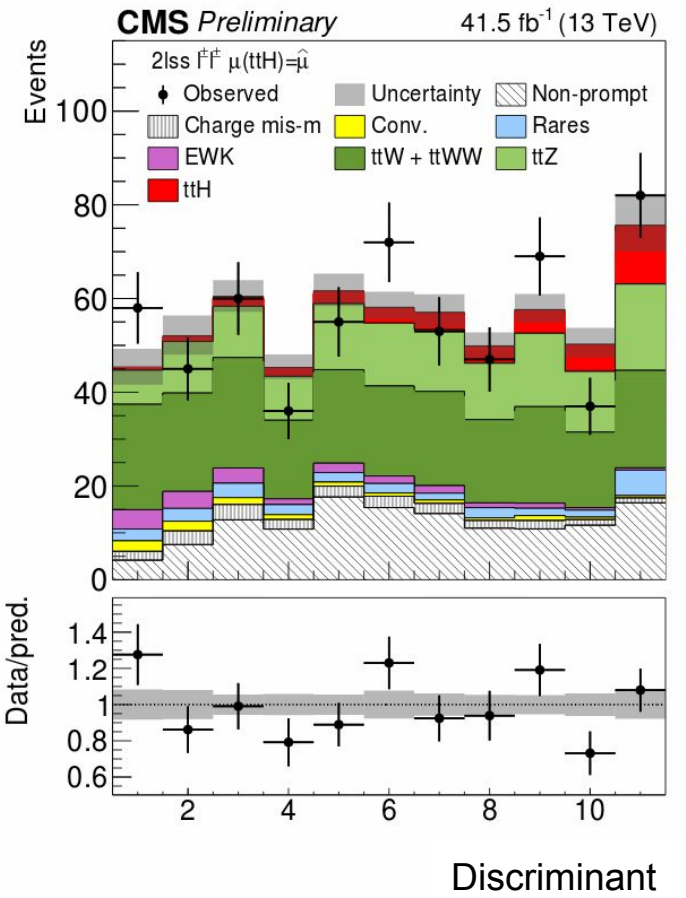
Signal Extraction and Dominant Uncertainties

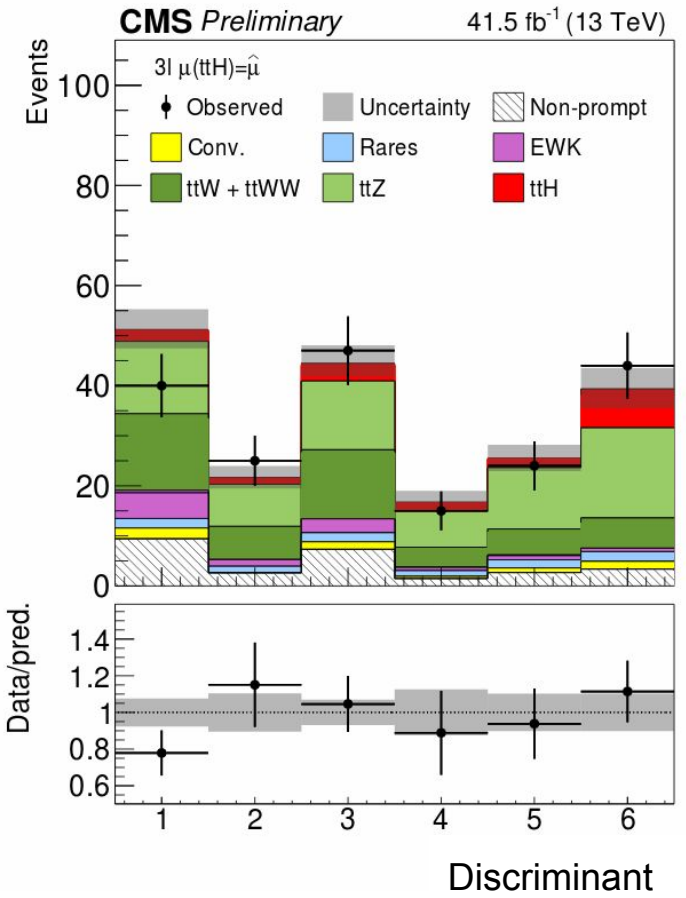
- **Signal Region** discriminants based on **Boosted Decision Trees** outputs
  - Optimize the separation between the **ttH** signal and the **main backgrounds** in *each category*
- *Binned maximum likelihood* fit to the distribution of a discriminant (optimized for each category) with the exception of the 4l where a event counting is performed
- The production rates of the **ttW(W), ttZ, and diboson** backgrounds are simultaneously fitted with the ttH signal, and constrained from dedicated **control regions**

Dominant systematic uncertainties and their impact on the fitted ttH rate

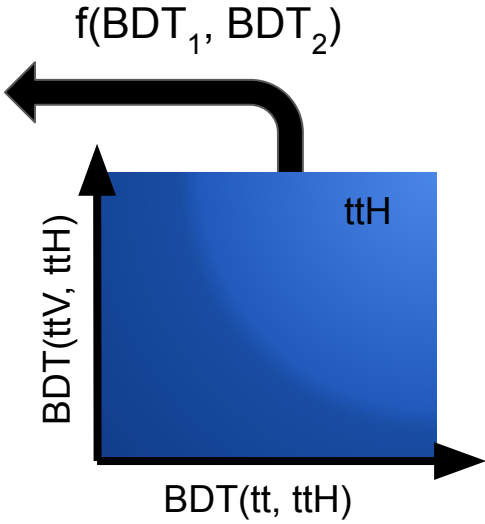
Source	Uncertainty [%]	$\Delta\mu/\mu$ [%] (2017)	$\Delta\mu/\mu$ [%] (Comb.)	Correlations
Theoretical sources	≈ 8	8	9	Correlated
e, μ selection efficiency	3–5	4	3	Correlated
τ_h selection efficiency	5	3	5	Correlated
τ_h energy calibration	1.2	1	2	Correlated
b tagging efficiency	2–15	10	5	Correlated
Jet energy calibration	2–15	3	3	Correlated
Fake background yield	$\approx$ 30–50	17	9	Un-correlated

Discriminants

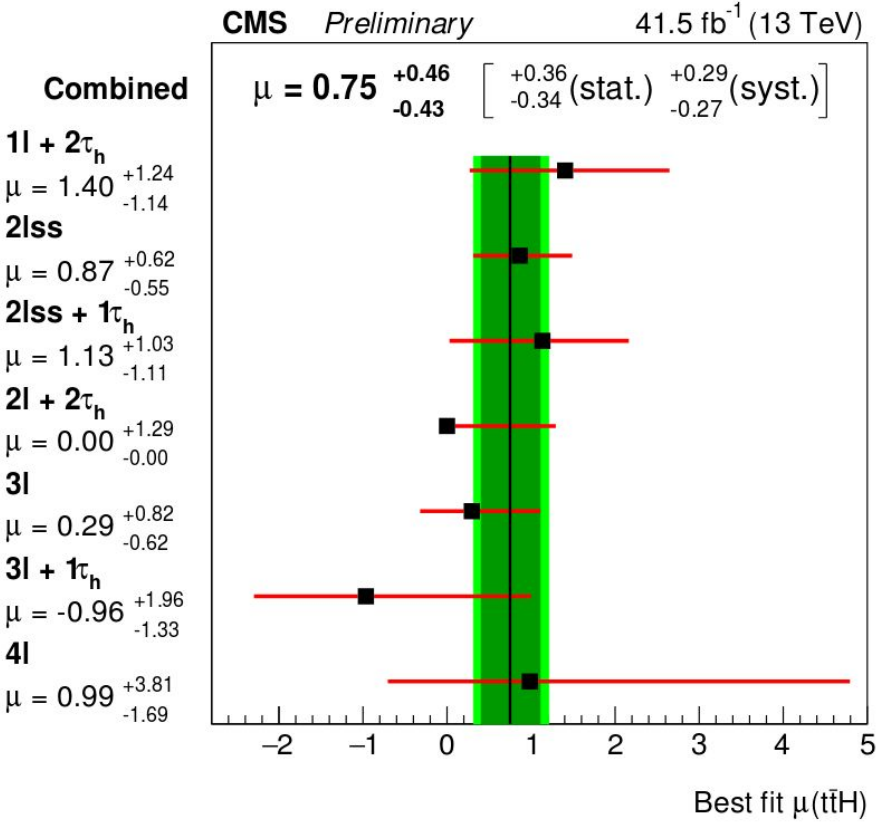




BDTs combined into 1D discriminant



Results



Category	Signal Strength ±1σ Measured	Expected
$1\ell + 2\tau_h$	$1.40^{+1.24}_{-1.14}$	$1.00^{+1.14}_{-0.93}$
$2\ell ss$	$0.87^{+0.62}_{-0.55}$	$1.00^{+0.53}_{-0.49}$
$2\ell ss + 1\tau_h$	$1.13^{+1.03}_{-1.11}$	$1.00^{+0.93}_{-0.80}$
$2\ell + 2\tau_h$	$0.00^{+1.29}_{-0.00}$*	$1.00^{+2.63}_{-1.56}$*
3ℓ	$0.29^{+0.82}_{-0.62}$	$1.00^{+0.59}_{-0.52}$
$3\ell + 1\tau_h$	$-0.96^{+1.96}_{-1.33}$	$1.00^{+1.91}_{-1.37}$
4ℓ	$0.99^{+3.31}_{-1.69}$	$1.00^{+2.41}_{-1.72}$
Combined	$0.75^{+0.46}_{-0.43}$	$1.00^{+0.39}_{-0.35}$
Combined with 2016 analysis	$0.96^{+0.34}_{-0.31}$	$1.00^{+0.30}_{-0.27}$

Observed (expected) significance of **3.2 σ (4.0 σ)**

Observed (expected) significance of **1.7 σ (2.9 σ)**

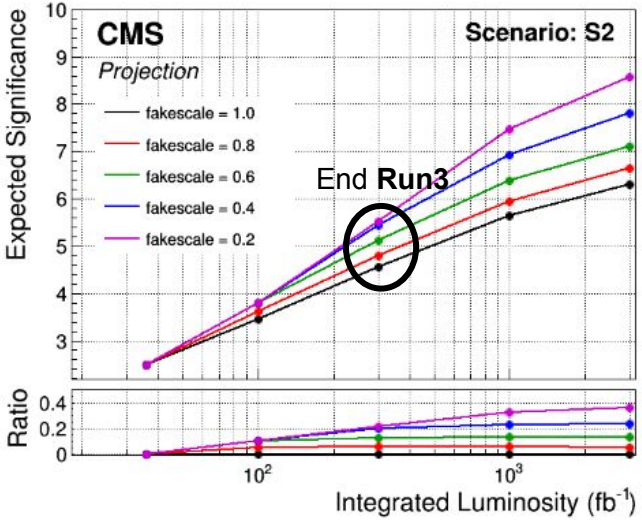
Evidence of **ttH** reached in **Multileptons**

Prospects

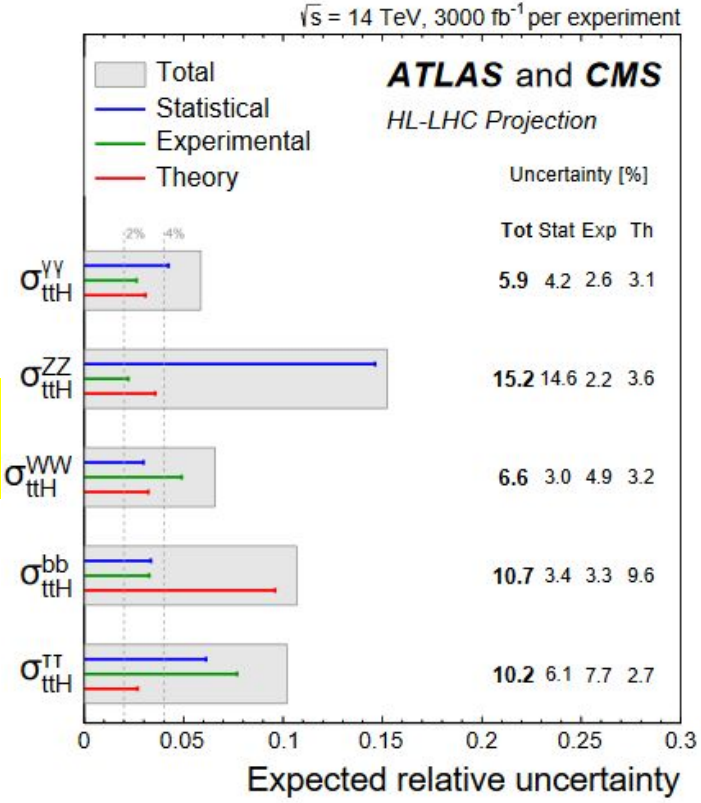
HL-LHC Projections: Higgs Physics at the HL-LHC and HE-LHC

- ATLAS and CMS projections for physics analyses at HL-LHC
- $\Delta\sigma_{ttH}$ = 4.3% (S2) projected for ATLAS+CMS at 3000 fb −1 per experim.
  - *S2: assumes lumi-scaling of some syst, and 1/2 theory uncertainties*

$\Delta\sigma_{ttH}$ = 4.3% = 1.3 (stat) + 1.8 (experimental) + 3.7 (theory) %



Results will be limited by the fakes uncertainty



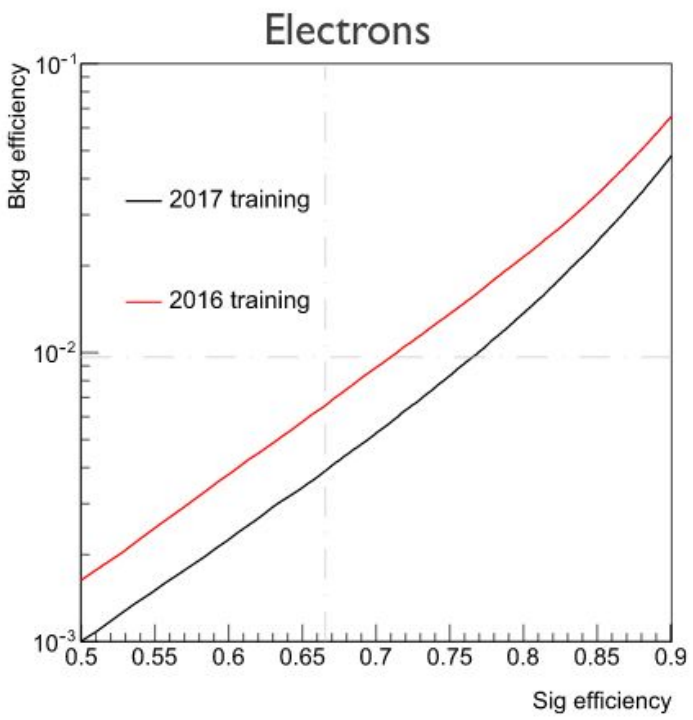
Summary

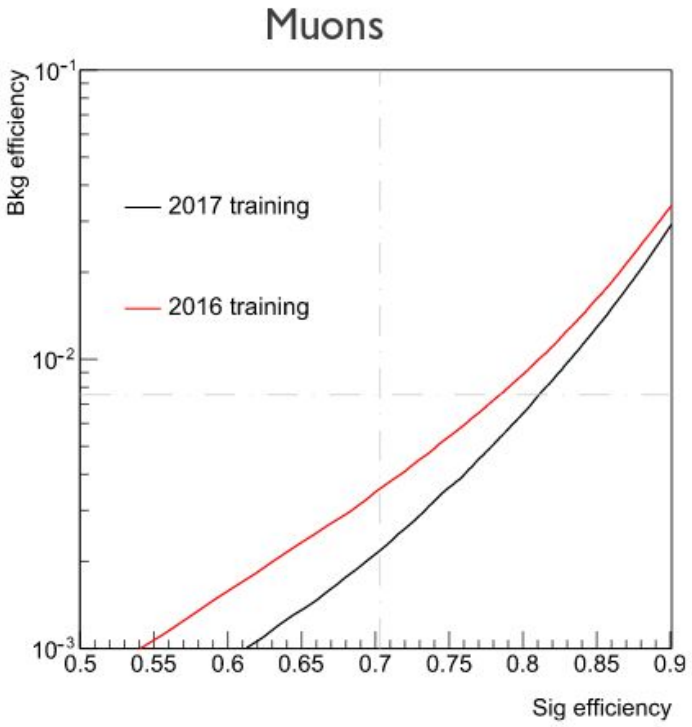
- The contributions of the **Oviedo group** to the CMS measurement of the production of a Higgs boson in association with a top quark pair in the **Multilepton channel** have been presented
- **All results are consistent with the SM expectation**, combining 2016 and 2017 the observed (expected) significance is 3.2 σ (4.0 σ)
- Big amount of work is on-going to get the final results of the full **Run2** dataset, **150 fb^{-1}**
- Many more to come with the **Run3** data...

STAY TUNED FOR NEW RESULTS!!


THANK YOU

Prompt Lepton MVAs





SYSTEMATIC UNCERTAINTIES

- **Experimental**
  - Trigger efficiency: 1-3%, shape uncertainty
  - Lepton ID efficiency: 2-5%
  - Tau ID efficiency: 5%
  - Jet and tau energy scale: shape uncertainty
  - B-tagging: shape uncertainty
  - Fake background estimation: 50%(30%) for normalization in categories where τ_h included (excluded) in FF method + shape uncertainty
  - Charge flip background: 30%
  - Luminosity: 2.3%
  - Pileup: < 1%
- **Theoretical**
  - ttH NNLO correction: +5.8%/-9.3%
  - ttH PDFs and α_s: 3.6%
  - ttV NNLO correction: 8-13%; PDFs and α_s: 3-4%
  - QCD renormalization and factorization scales: shape uncertainties
  - Di-boson, ttγ^*+rare SM backgrounds: 50%
  - Background due to fake τ_h in 2lss+1τ_h and 3l+1τ_h: 30%