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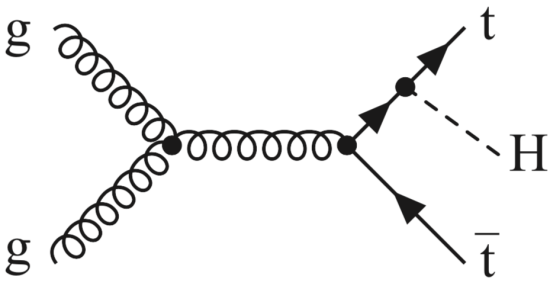
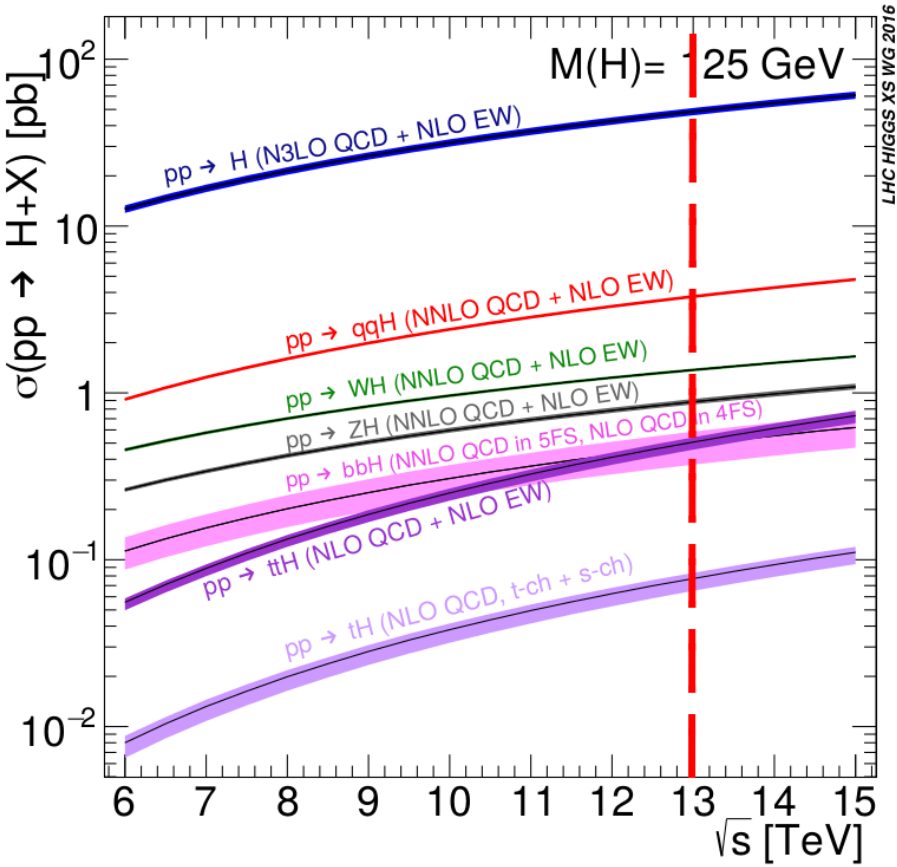
(for the CMS Collaboration)

DIS 2019 (Torino)

Measurement of ttH production at CMS

INTRODUCTION

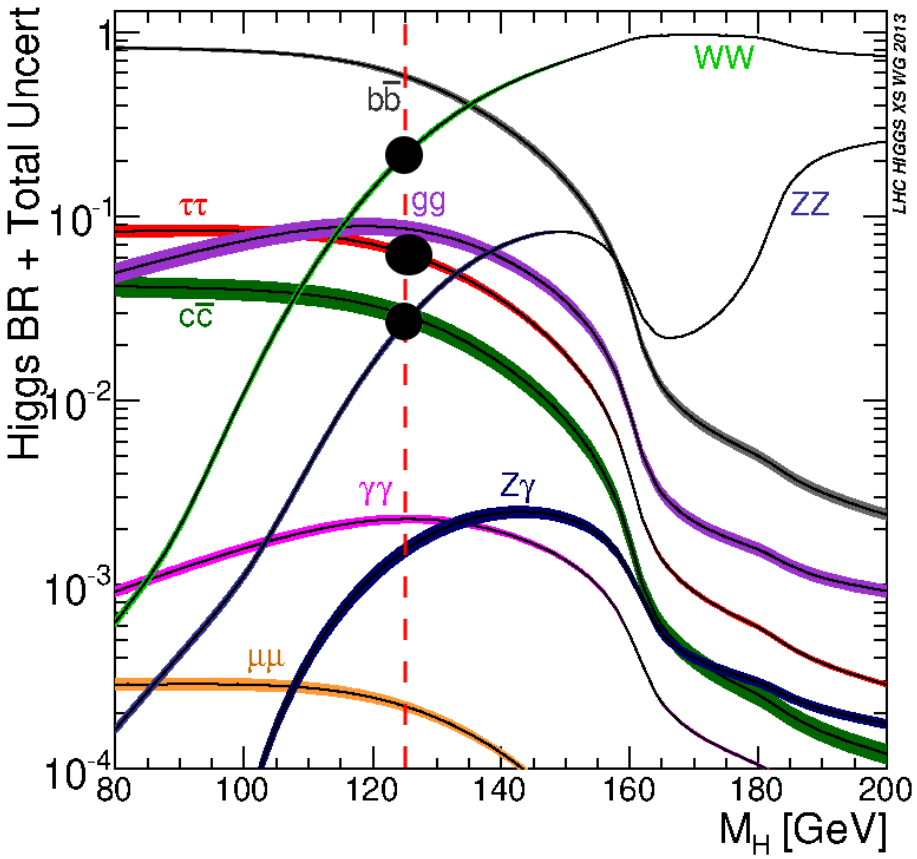




- ttH production provides a direct measurement of the Yukawa coupling of the top to the Higgs
- Other ways to probe the Yuwaka coupling. Some examples:
  - Four top production (**CMS-PAS-18-003**)
  - Differential $t\bar{t}$ production (**CMS-PAS-TOP-17-004**)
  - tHq production (**CMS-PAS-HIG-17-005**)⇒ also sensitive to the sign of the coupling
    - Very rich signatures due to the different decays of the Higgs
    - Also very challenging because of the low production cross-section

DECAYS TARGETED

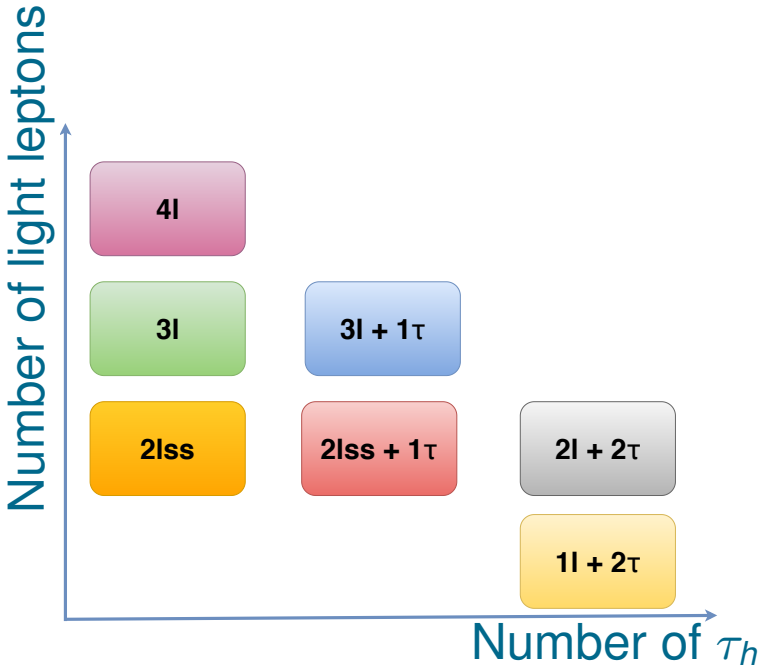
- Focusing in the latest results in multilepton channels (**HIG-18-019**)
- Sensitive to the ZZ, WW and $\tau\tau$ decays
- Reasonably large branching ratio
- Moderate amount of background

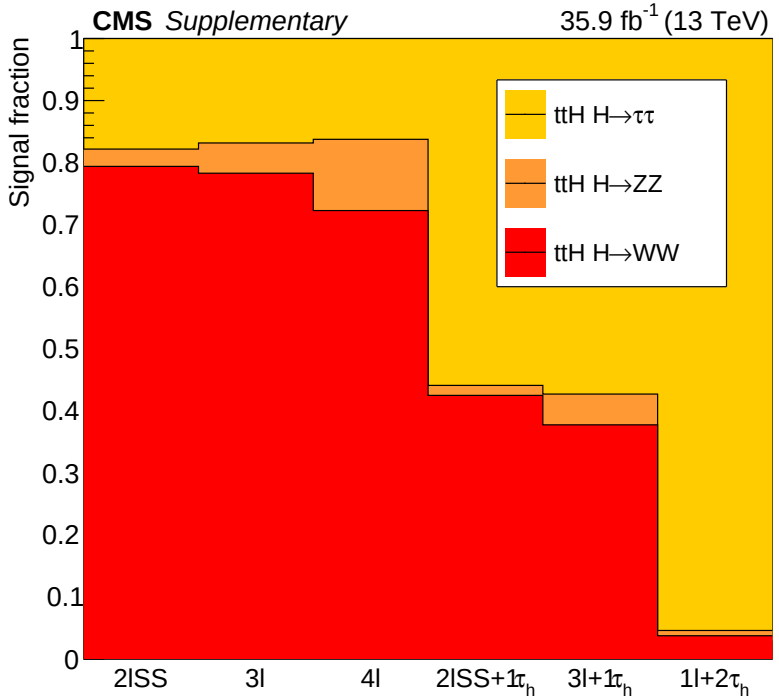


- This talk will focus on the analysis with 2017 data
  - Will also cover the combination with other datasets
- Searches exist focusing in the $b\bar{b}$ and $\gamma\gamma$ channels
- Search targetting $H \to ZZ \to 4\ell$ also not covered

EVENT SELECTION AND CATEGORIZATION

- Events are categorized based on the number of light leptons (e and μ) and hadronic τ
- Different jet and *b* jet multiplicity criteria are applied to each of the regions





- Further categorization is made according to
  - *b* jet multiplicity
  - lepton charge and flavor
  - dedicated MVA discriminants for each region

Background estimation

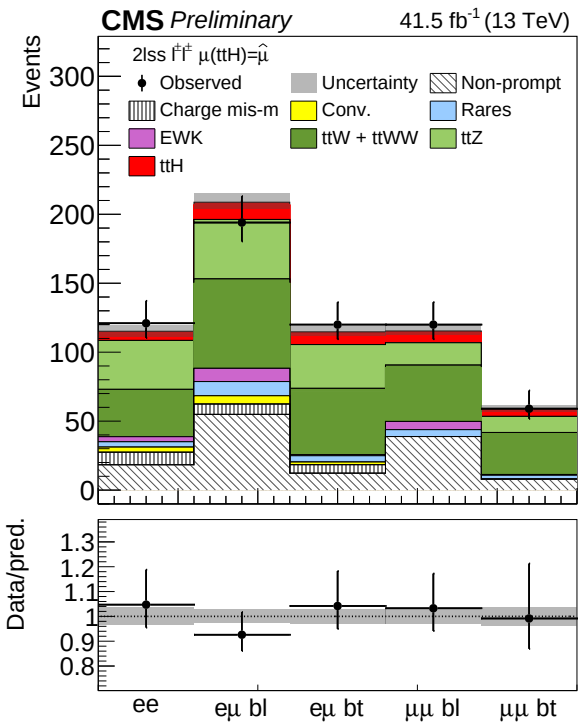
Main backgrounds

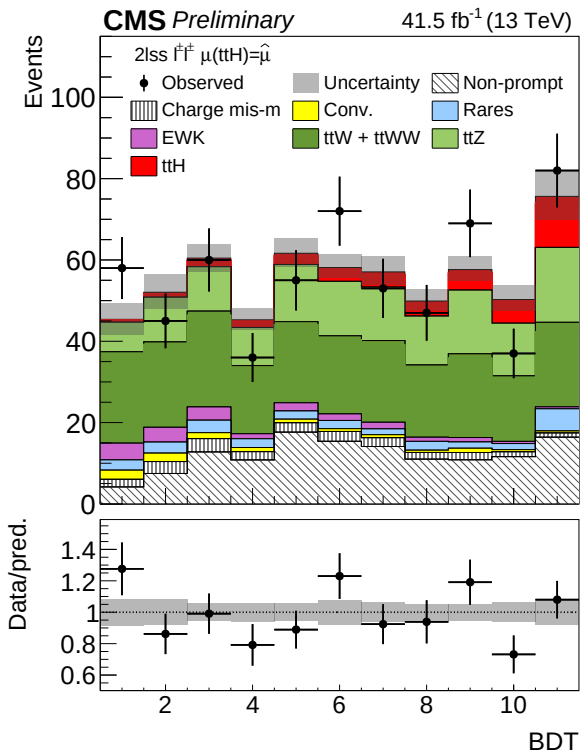
- Top quark pair production associated with a vector boson (ttW, ttZ)
  - Similar kinematics to the signal
  - Estimated with Monte Carlo simulations
  - Control regions are used in the fit to constrain these processes
  - ttZ and ttW are parameterized with signal strength modifiers in the signal extraction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

Category	$2\ell ss$	3ℓ	4ℓ
$t\bar{t}H$	43.0 ± 7.1	18.8 ± 4.8	0.7 ± 0.3
$t\bar{t}W + t\bar{t}WW$	218.5 ± 13.7	51.0 ± 5.3	0.13 ± 0.03
tH	2.4 ± 0.1	0.9 ± 0.1	< 0.05
$WZ + ZZ$	< 0.05	12.0 ± 1.7	0.15 ± 0.10
$t\bar{t}Z/\gamma^*$	138.2 ± 7.6	74.1 ± 6.3	3.9 ± 0.6
Misidentified	132.1 ± 10.0	26.8 ± 4.0	< 0.05
Conversions	11.6 ± 3.0	6.6 ± 1.3	< 0.05
Signal flip	22.8 ± 2.3	< 0.05	< 0.05
Other	26.7 ± 3.9	9.7 ± 2.2	< 0.05
SM expectation	595.3 ± 20.6	200.0 ± 10.8	5.0 ± 0.7
Observed data	614	195	6

2LSS REGION

- Requiring at least 4 jets and at least one tight* or two loose *b* tagged jets
- In the ee channel, a Z mass veto is applied and $L_D > 30$ GeV
- Events categorized in lepton flavor and charge, and *b* jet multiplicity
- Dedicated discriminants used to discriminate ttH from $t\bar{t}$ and ttZ and ttW





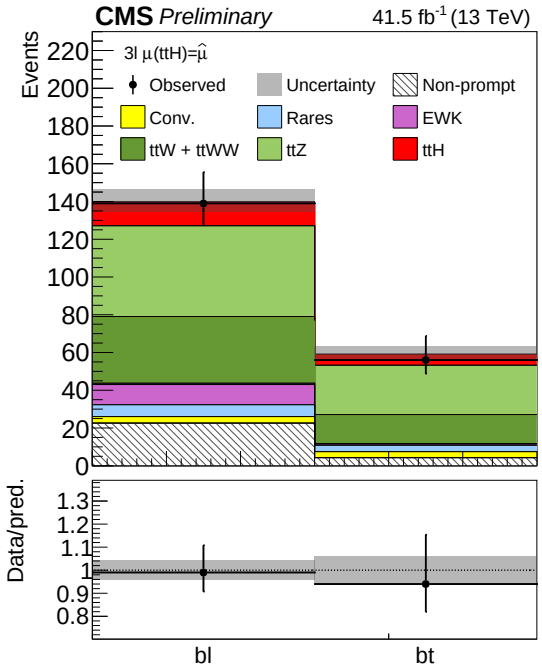
- Discriminants use kinematic variables, hadronic top tagger ($t\bar{t}$) and Higgs jet tagger (ttW, ttZ)
- Discriminants are merged into a single discriminant using clustering techniques

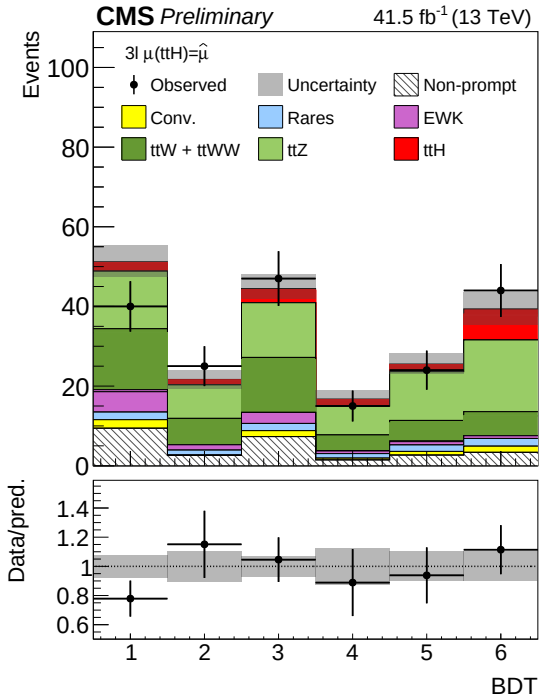
- ttW control region is defined relaxing the jet multiplicity cut

* Loose (tight) b tagged jet: 10% (1%) misidentification probability

3L REGION

- Events are required to have at least 2 jets and one tight or two loose b* tagged jets
- Events with an OSSF lepton pair compatible with a Z are vetoed
- L_D cut depending on jet multiplicity and lepton flavor
- Categories based on *b* jet multiplicity and charge

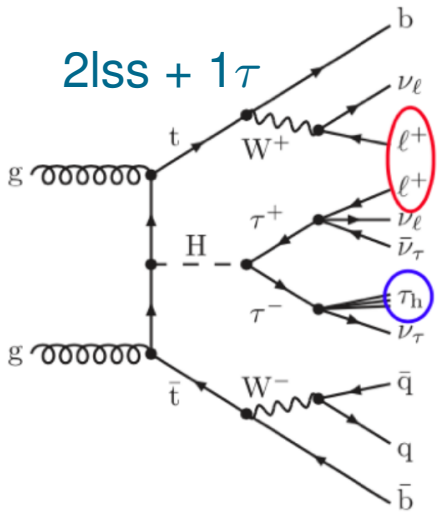




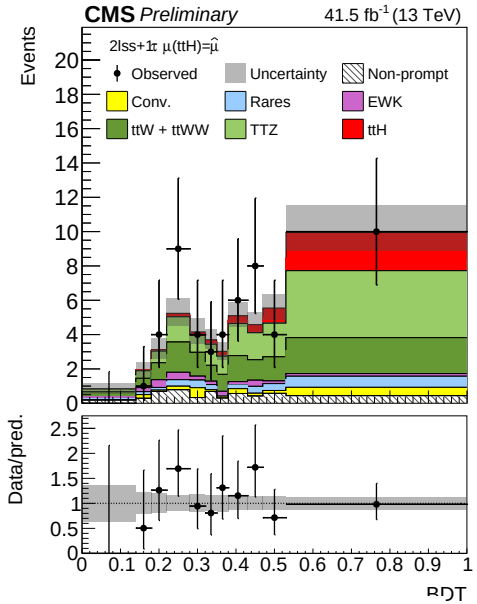
- Discriminants use kinematic variables
- Discriminants are merged into a single discriminant using clustering techniques

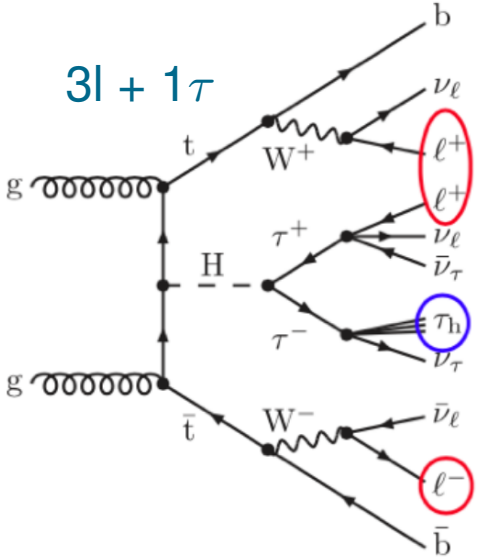
- ttZ control region is defined inverting the Z candidate veto
- WZ control region defined further inverting the *b* jet requirement
- 4l category requiring 4 leptons instead of three ⇒ no categorization

Categories with 1 τ

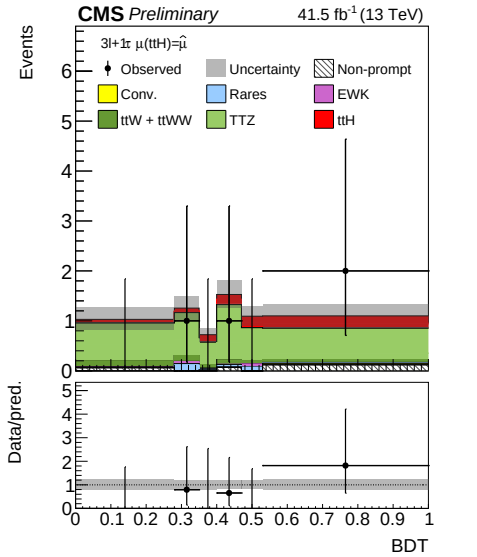


- Sum of lepton and τ charge equal to $\pm$ 1
- At least three jets
- At least one tight or two loose b jet
- L_D cut and Z mass veto in the ee channel



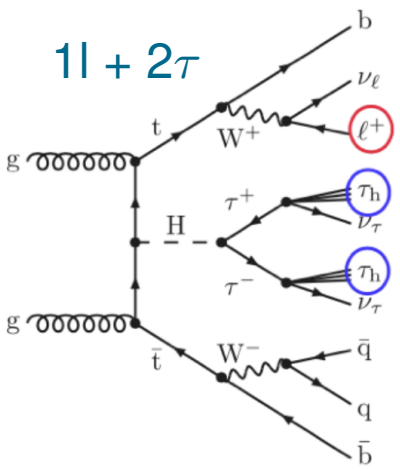


- Sum of charges equal to 0
- At least two jets
- At least one tight or two loose jets
- Events with an OSSF lepton pair compatible with a Z are vetoed

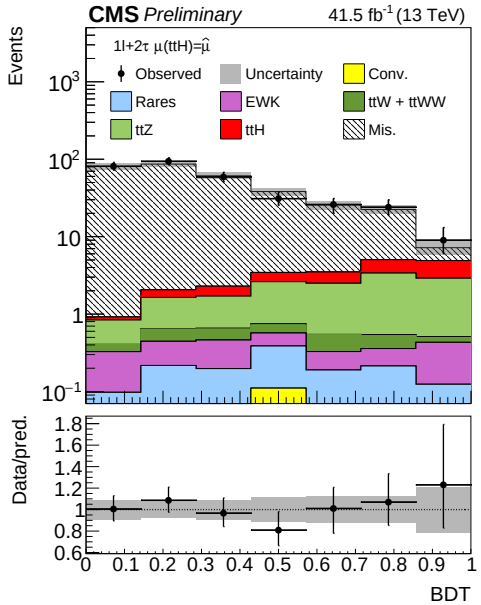


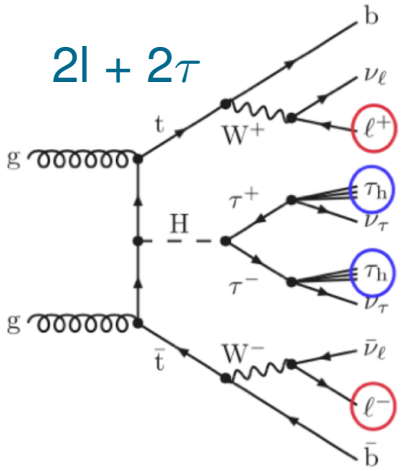
- BDTs trained against $t\bar{t}$, ttZ and ttW. Some categories use hadronic top reconstruction

CATEGORIES WITH 2 τ

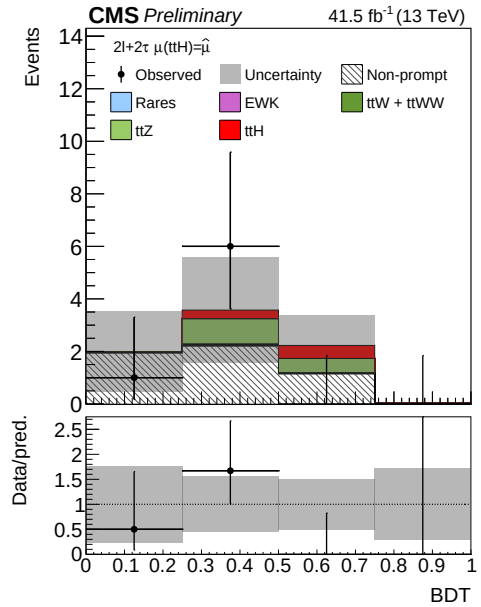


- At least 3 jets, at least one tight or 2 loose b tagged jets
- τ are required to have opposite charge



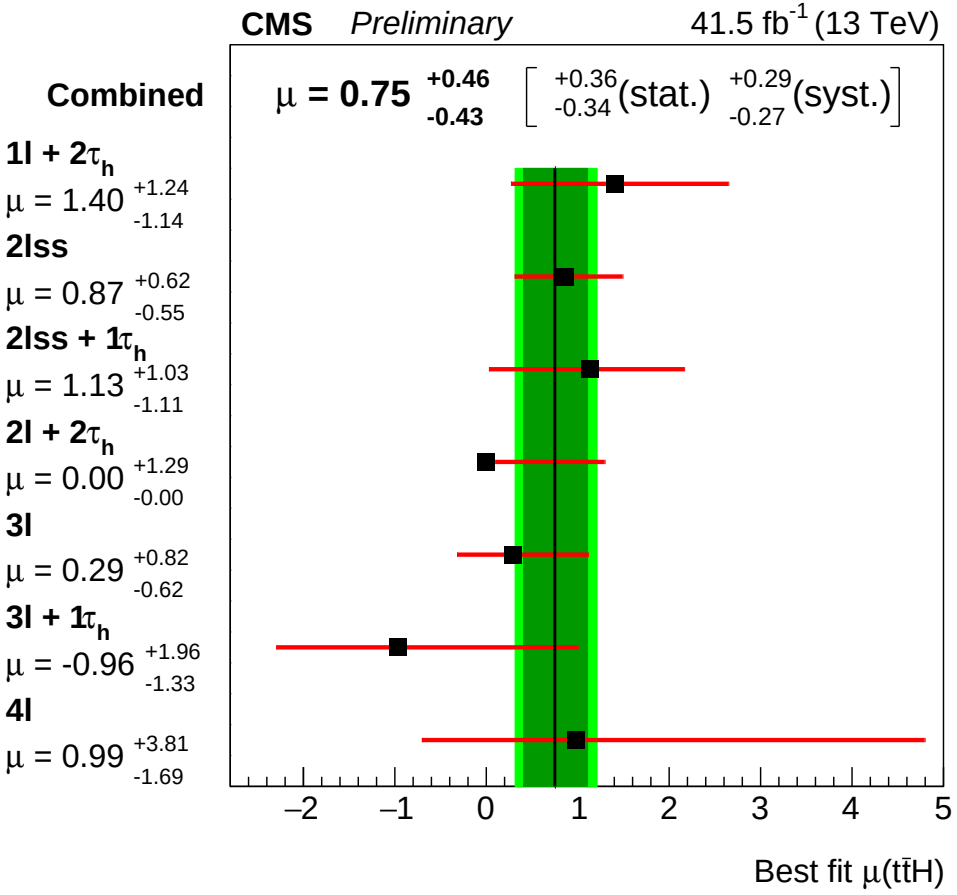


- Sum of the charges of leptons and taus must be 0
- At least 2 jets, at least one tight or 2 loose b jets
- L_D cut depending on jet multiplicity and lepton flavor



- BDTs trained against $t\bar{t}$, ttZ and ttW. Some categories use hadronic top reconstruction

RESULTS



Signal strength

- $\mu = 0.75^{+0.46}_{-0.43}$ (observed)
- $\mu = 1.00^{+0.39}_{-0.35}$ (expected)

Significance

- 2.7 σ observed and expected

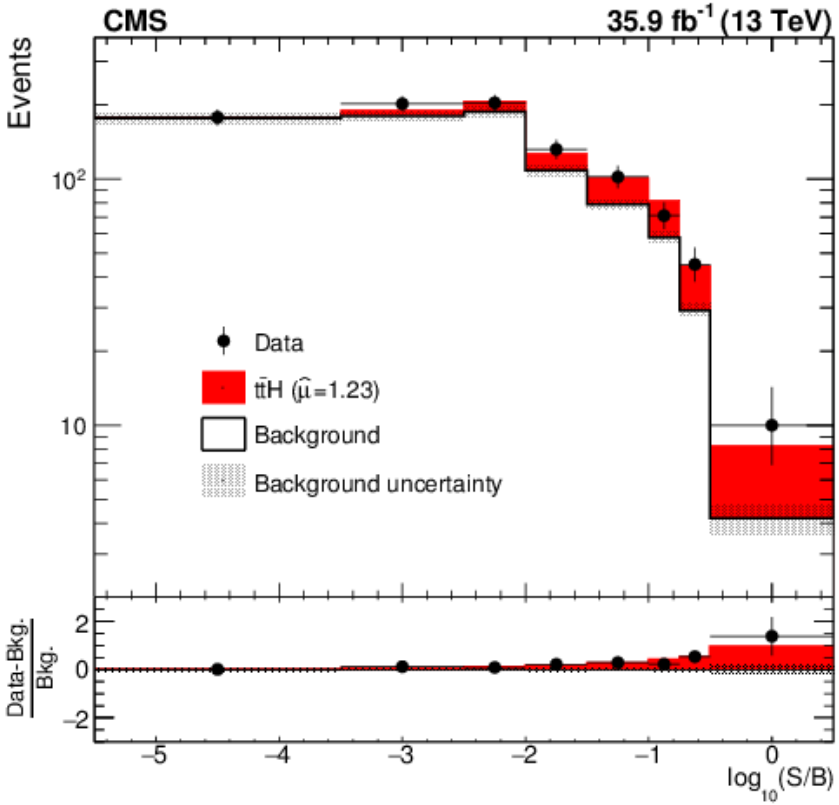
Best fit for ttZ and ttW

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

- Result consistent with the $\mu = 1$ hypothesis
- About 40% uncertainty with the 2017 only

Combination with 2016

- Result has been combined with the equivalent 2016 result (**JHEP 08 (2018) 066**)
- Signal strength
  - $\mu = 0.96^{+0.34}_{-0.31}$ (observed)
  - $\mu = 1.00^{+0.30}_{-0.27}$ (expected)
- Significance
  - 3.2 σ observed and 4.0 σ expected



- Uncertainty on signal strength largely reduced in the combination
- Uncertainty on μ dominated by ttH cross-section calculation uncertainty and fake lepton estimation

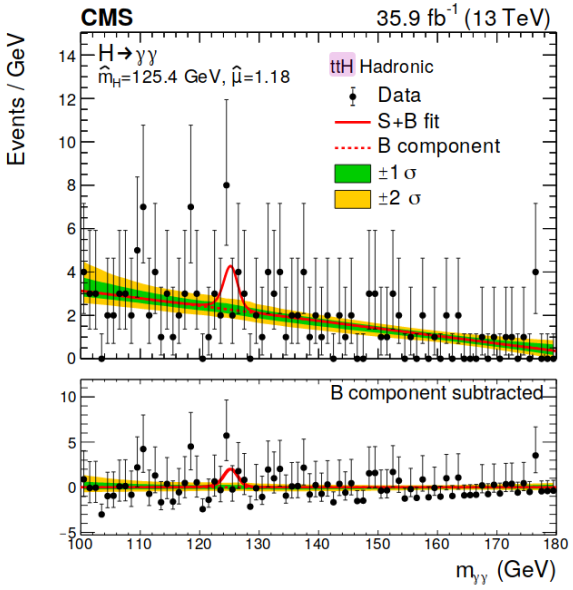
Source	Uncertainty [%]	$\Delta\mu/\mu$ [%] (2017)	$\Delta\mu/\mu$ [%] (Comb.)
Theoretical sources	≈ 8	8	9
e, μ selection efficiency	3–5	4	3
τ_h selection efficiency	5	3	5
τ_h energy calibration	1.2	1	2
b tagging efficiency	2–15 [48]	10	5
Jet energy calibration	2–15 [56]	3	3
Fake background yield	$\approx$ 30–50	17	9

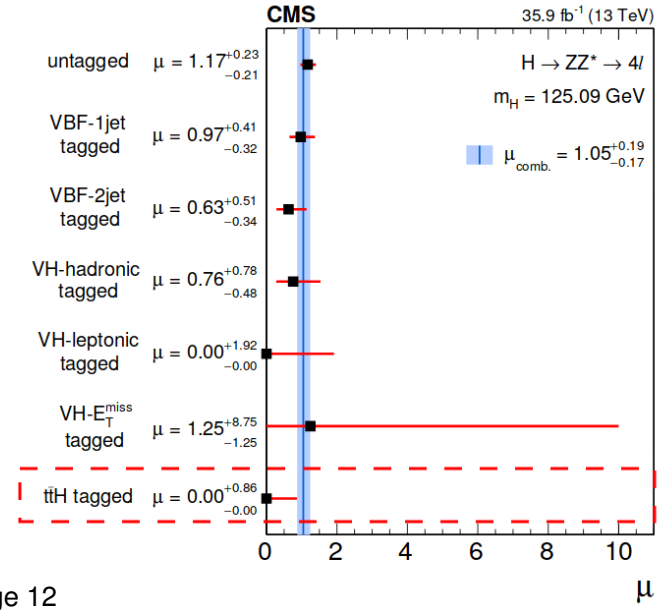
Combination with other channels

- Combination performed with other analyses targeting different signatures
- Only 2016 result used so far

$H \to \gamma\gamma$

- Clean final state and Higgs mass resolution
- Low statistics available
- Using semileptonic and fully hadronic channel
- JHEP 11 (2018) 185





$H \to ZZ \to 4\ell$

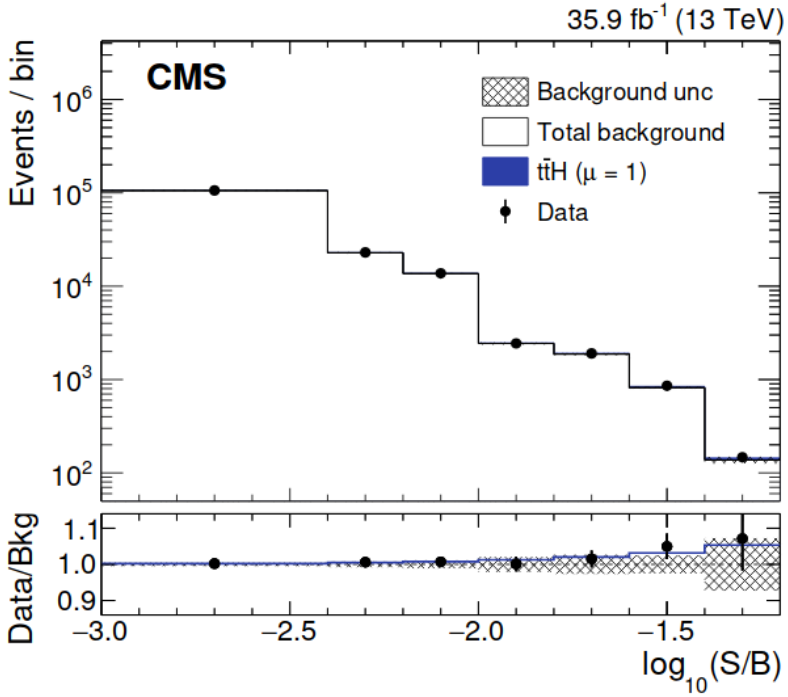
- Clean final state and Higgs mass resolution
- Using semileptonic and fully hadronic channel
- Very low branching ratio
- JHEP 11 (2017) 047

Combination with other channels

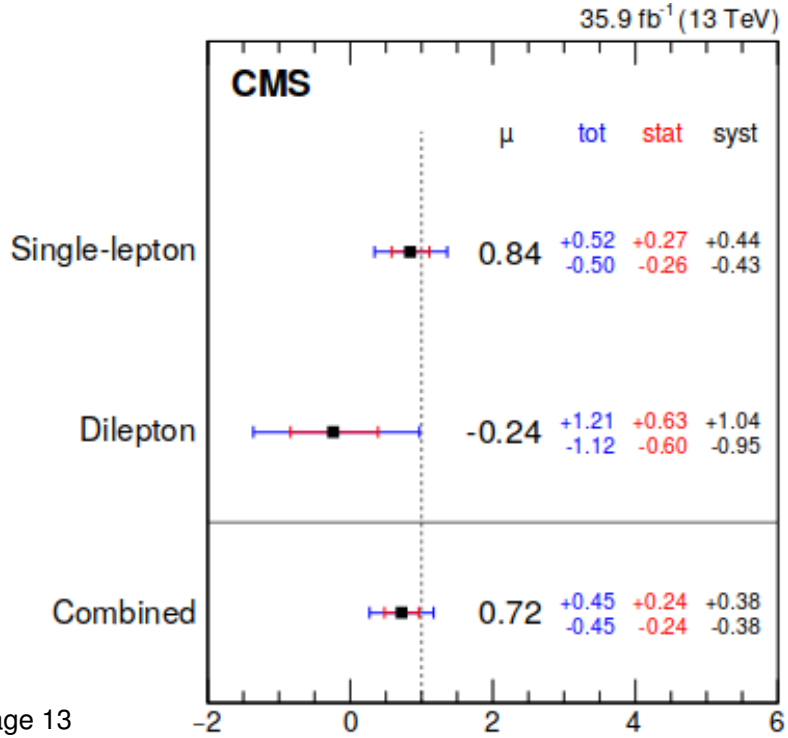
H → $b\bar{b}$ (fully hadronic)

- Overwhelming multijet background
- MEM discriminant used for the signal extraction

$$w_\Omega(\mathbf{y}) = \frac{1}{\sigma_\Omega}\sum_p \int d\mathbf{x} dx_a dx_b \frac{f_i(x_a,Q)f_j(x_b,Q)}{x_a x_b s}\delta^2(x_a P_a + x_b P_b - \sum p_k)|\mathcal{M}_\Omega(\mathbf{x})|^2 W(\mathbf{y}||\mathbf{x})$$



- JHEP06(2018)101

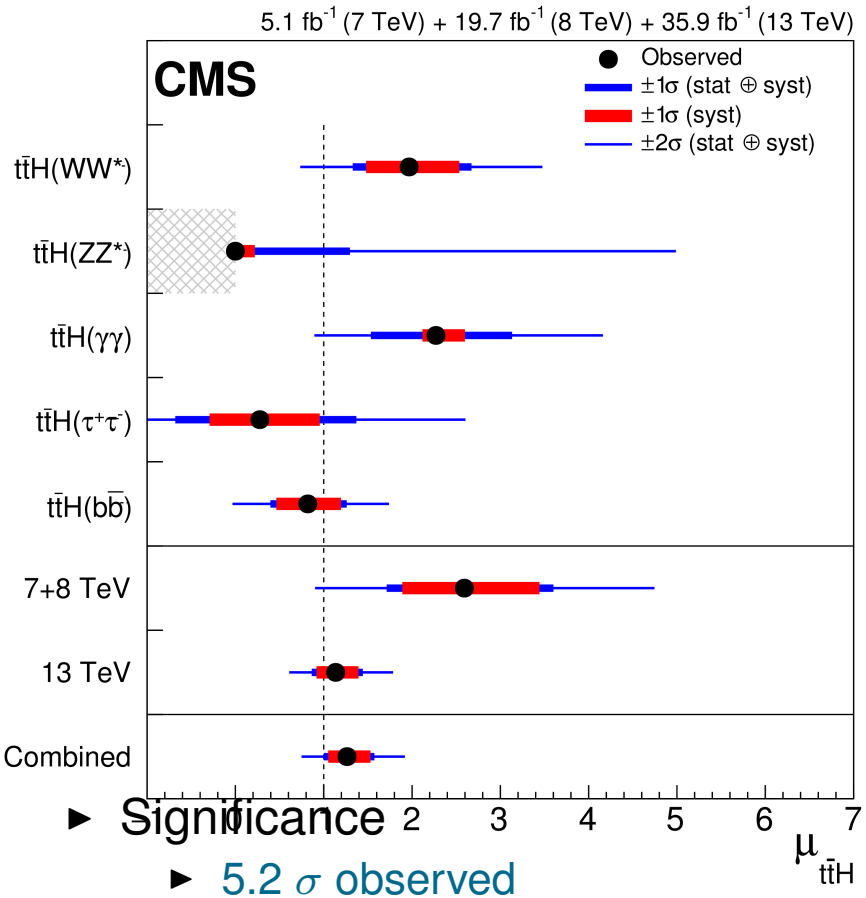


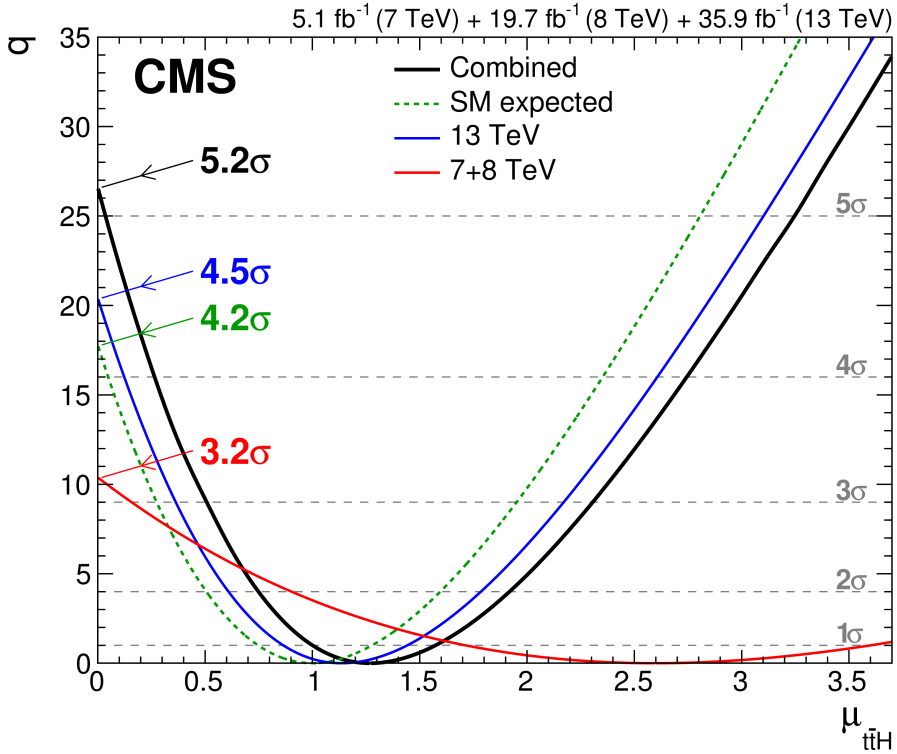
H → $b\bar{b}$ (single and double lepton)

- Challenging due to the irreducible $t\bar{t} + b\bar{b}$ background
- Elaborated analysis strategy using MEM and DNNs
- JHEP 03 (2019) 026

COMBINATION WITH OTHER CHANNELS

- Using data from Run I and 2016
- Signal strength fitted for each branching fraction and year, and combined
- Always consistent with unity





- Significance
  - 5.2 σ observed
  - 4.2 σ expected
- Best fit $\mu = 1.26^{+0.31}_{-0.26}$

CONCLUSIONS

- Reviewed the state-of-the-art of measurements of ttH in multileptonic channels
- CMS has provided evidence for ttH in this channel alone
  - Analysis provides 4 σ sensitivity to SM Higgs
- Observation of ttH when combining with other channels