Associated production of a SM Higgs boson with pair of top quarks ($t\bar{t}H$): Combination of CMS searches and perspectives for HL-LHC

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2nd workshop Red Española de LHC

ATLAS and CMS $t\bar{t}H$ results before April 10th (*What can we learn from a combination?*)

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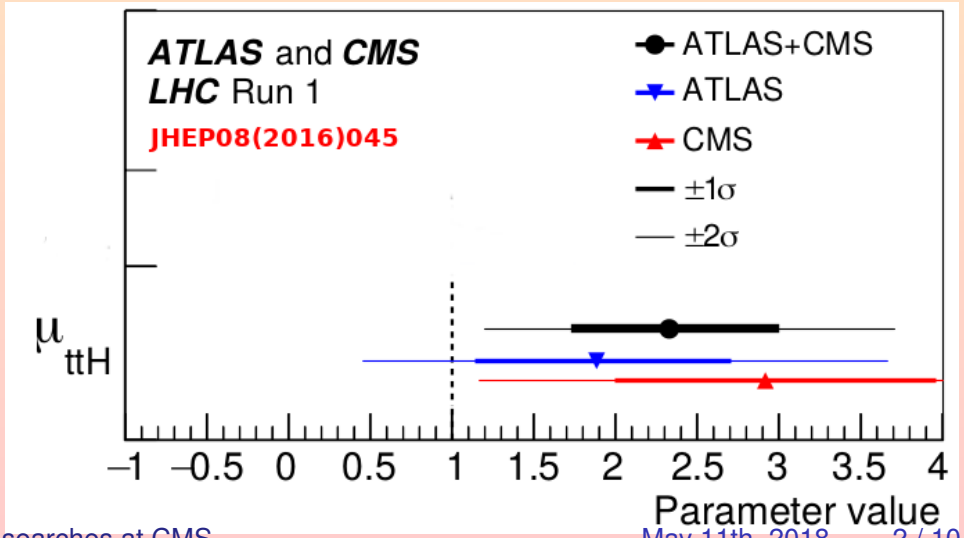
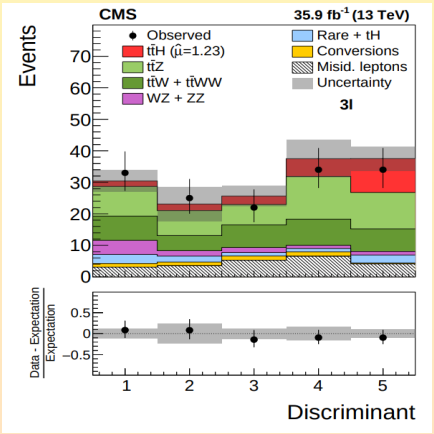
Run I (7+8 TeV) / Run II, 36 fb^{-1}	$\mu_{t\bar{t}H} = \sigma_{t\bar{t}H}/\sigma_{SM}$ ATLAS	$\mu_{t\bar{t}H} = \sigma_{t\bar{t}H}/\sigma_{SM}$ CMS	Significances obs (exp) ATLAS	Significances obs (exp) CMS
Run I comb.	$2.3^{+0.7}_{-0.6}$		4.4σ (2.0σ)	
bb	$0.8^{+0.6}_{-0.6}$	-0.2 ± 0.8	1.4σ (1.6σ)	
multilepton	$1.6^{+0.5}_{-0.4}$	1.2 ± 0.4	4.1σ (2.8σ)	3.2σ (2.8σ)
τ_h +X	(included in multilep comb.)	(included in multilep comb)	comb. in multilep	
$\gamma\gamma$	$0.6^{+0.7}_{-0.6}$	$2.2^{+0.9}_{-0.8}$		3.3σ (1.5σ)
ZZ	< 1.9 95% CL	$[0.0, +1.2]$ 68% CL with $\mu \geq 0$		
Combination	$1.2^{+0.3}_{-0.3}$		$4.2\sigma(3.8\sigma)$	

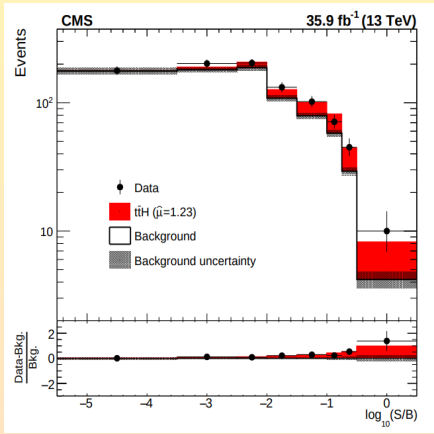
- $\mu_{t\bar{t}H} \neq 0$ is generally favoured: **evidence for $t\bar{t}H$ production!!!**
- **What should we do with the Run I result?**
- Pattern of the excesses can be used as probe for Type-I 2HDM models (http://arxiv.org/abs/1703.06834)



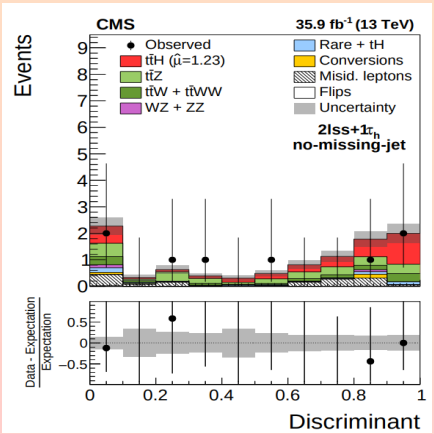
Production and decay (*leptons, sweet leptons*)

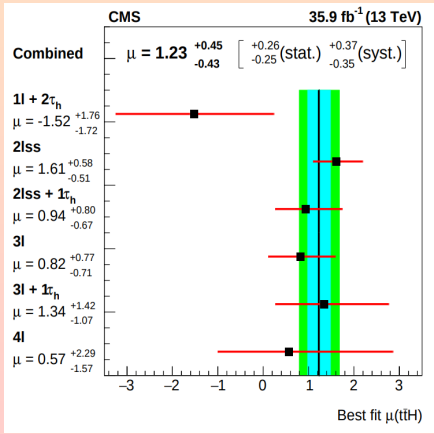
- Multi-leptonic (light) ($H \to ZZ*$, $H \to WW*$, $H \to \tau\tau$)
  - The low-background one with the highest rate

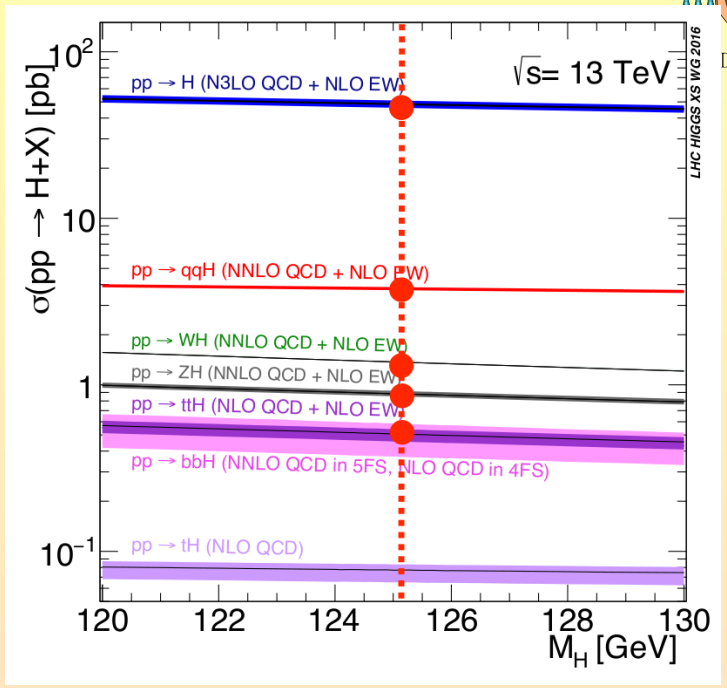


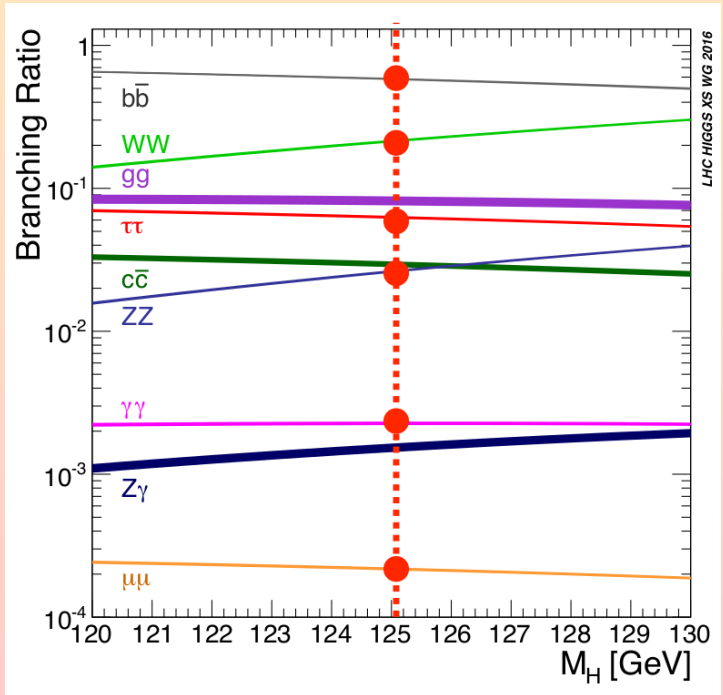


- Multi-leptonic w/ hadronically decaying taus (τ_h) ($H \to \tau\tau$, also $H \to ZZ*$, $H \to WW*$)
  - Significant jet$\to\tau_h$ *fake* background



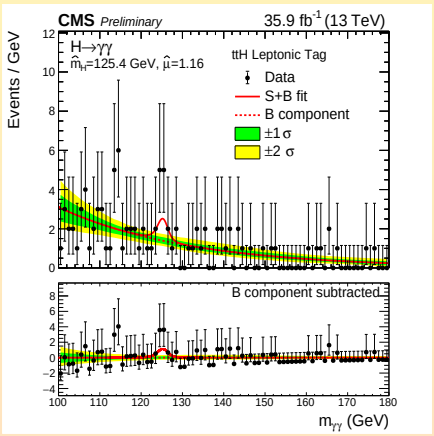


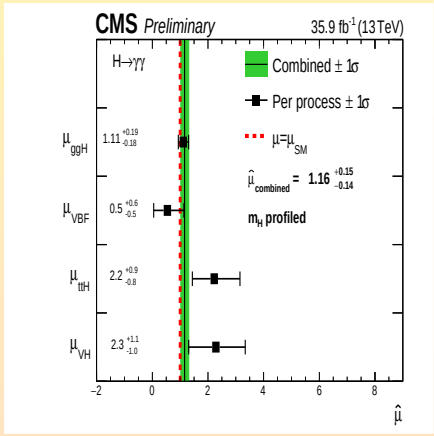




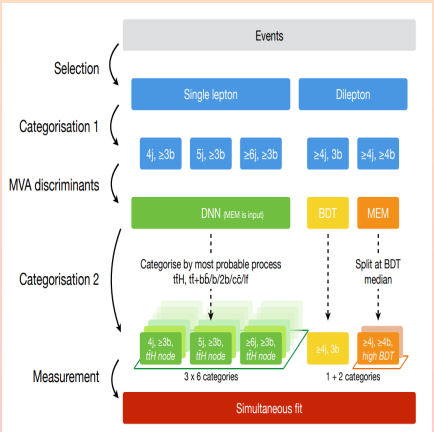
Production and decay (*down the calorimetric hole*)

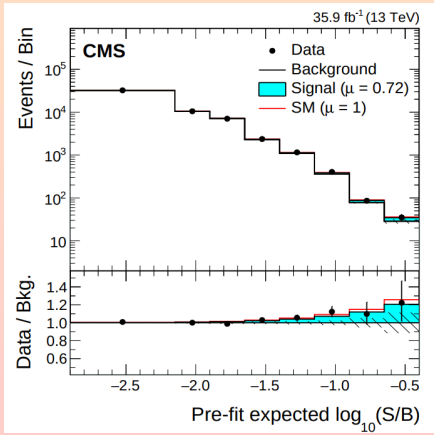
- $H \to \gamma\gamma$
  - Small $\mathcal{B}(H \to \gamma\gamma)$, but clean final state (low syst. uncertainties)
  - Excellent diphoton mass resolution

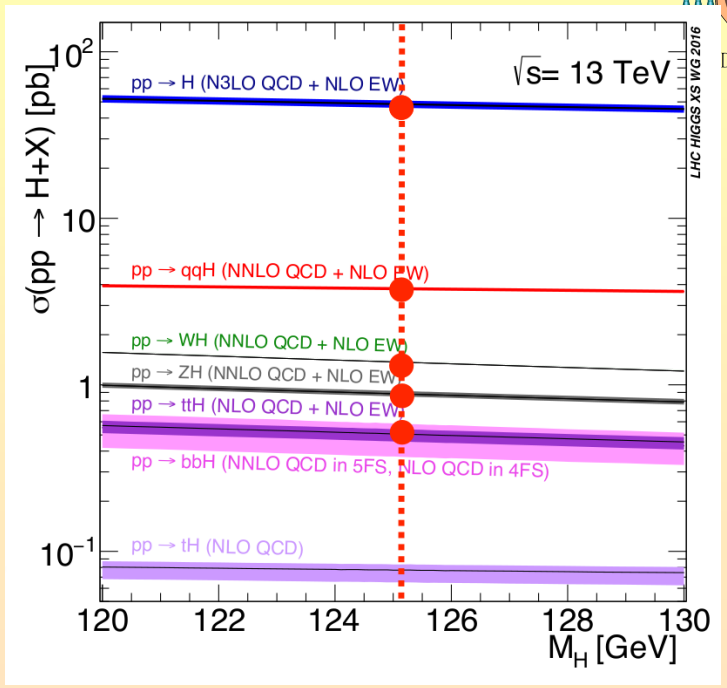


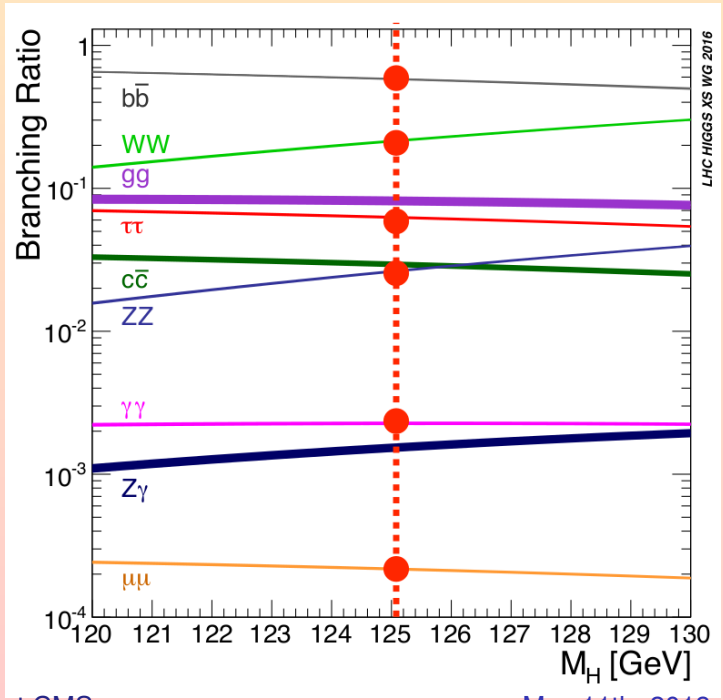


- $H \to b\bar{b}$
  - High branching ratio, but complex multi-jet final state





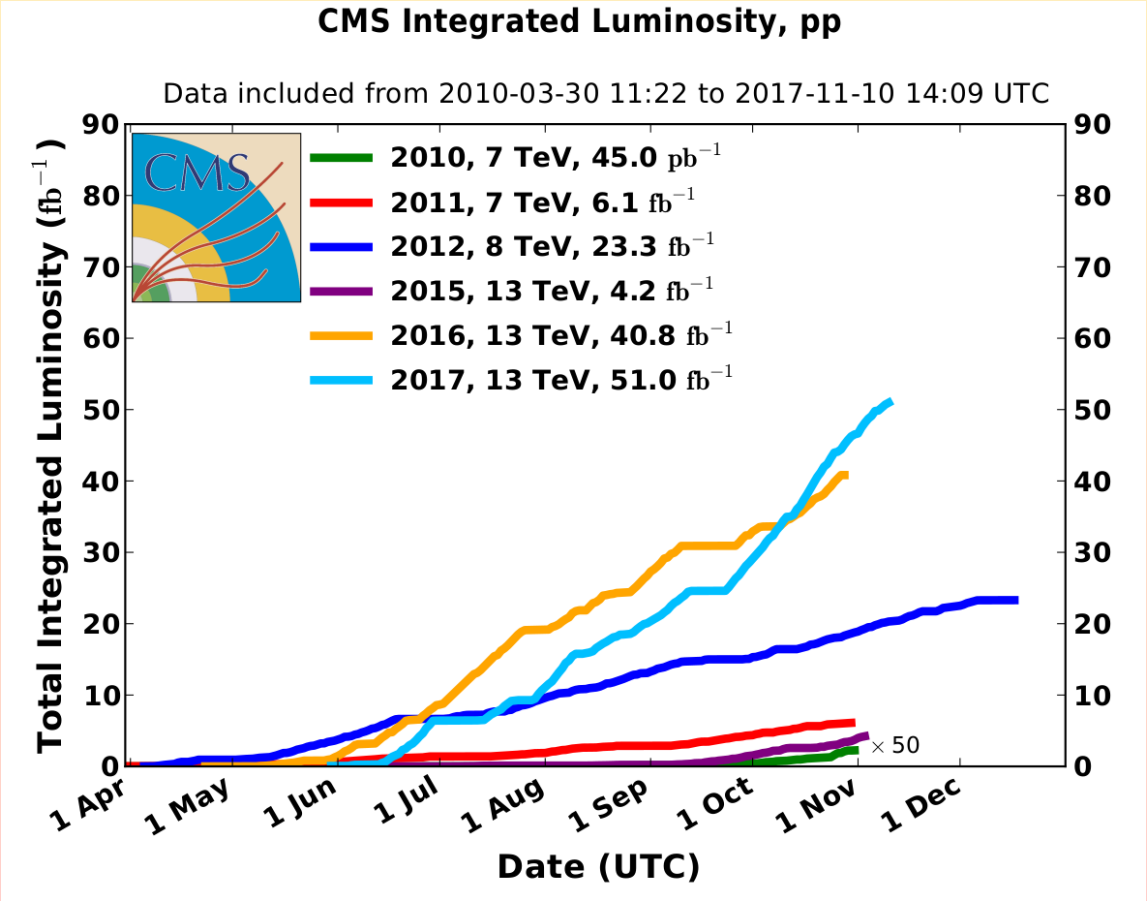




Contributing analyses (*how complicated is the statistical model?*)

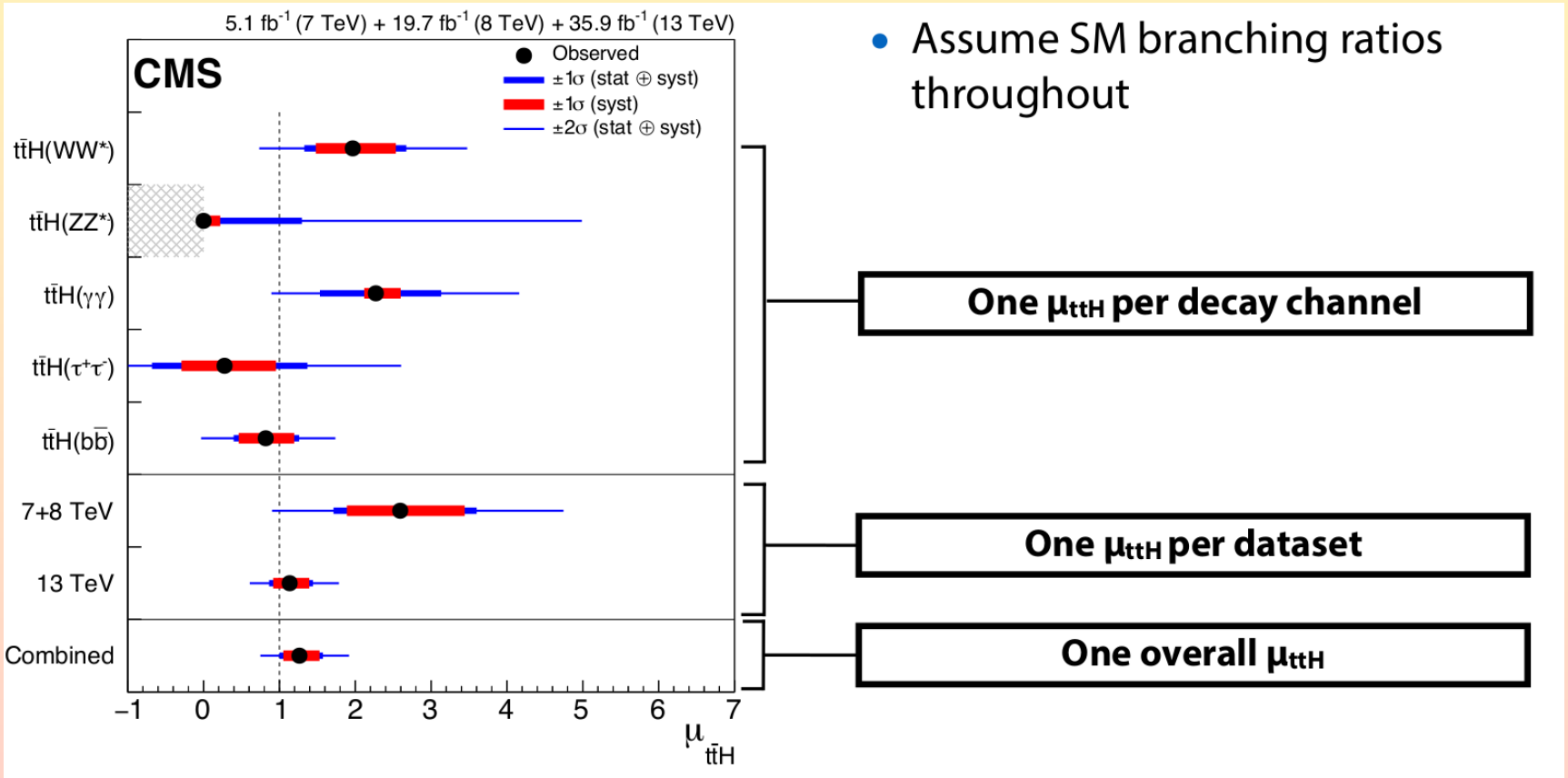
- 13 TeV (35.9 fb^{-1})
  - All of the dedicated $\text{t}\bar{\text{t}}\text{H}$ analyses and categories on the 2016 dataset
- 7+8 TeV (up to 5.1 fb^{-1} + 19.7 fb^{-1})
  - Dedicated analyses targeting the $\text{b}\bar{\text{b}}$ and multilepton final states
  - The $\text{t}\bar{\text{t}}\text{H}$ categories of the $\text{H} \rightarrow \gamma\gamma$ analysis
  - Mass updated to 125.09 GeV, signal normalisation and uncertainties updated to latest values from LHC Higgs XS WG (same calculations as used in Run 2 analyses)

- Correlations carefully assessed between Run-1 and Run-2
  - Inclusive signal theory and some background theory uncertainties correlated
  - Experimental uncertainties largely uncorrelated



The combination (*so, is it 1 or 2?*)

- Measure $t\bar{t}H$ signal strength in combined analysis for three parameterisations
- Expected contamination from other Higgs processes (e.g. ggH, tH) is small
  - Treated as backgrounds normalized to SM prediction, subject to standard theoretical uncertainties



The combination (*with all its uncertainty*)

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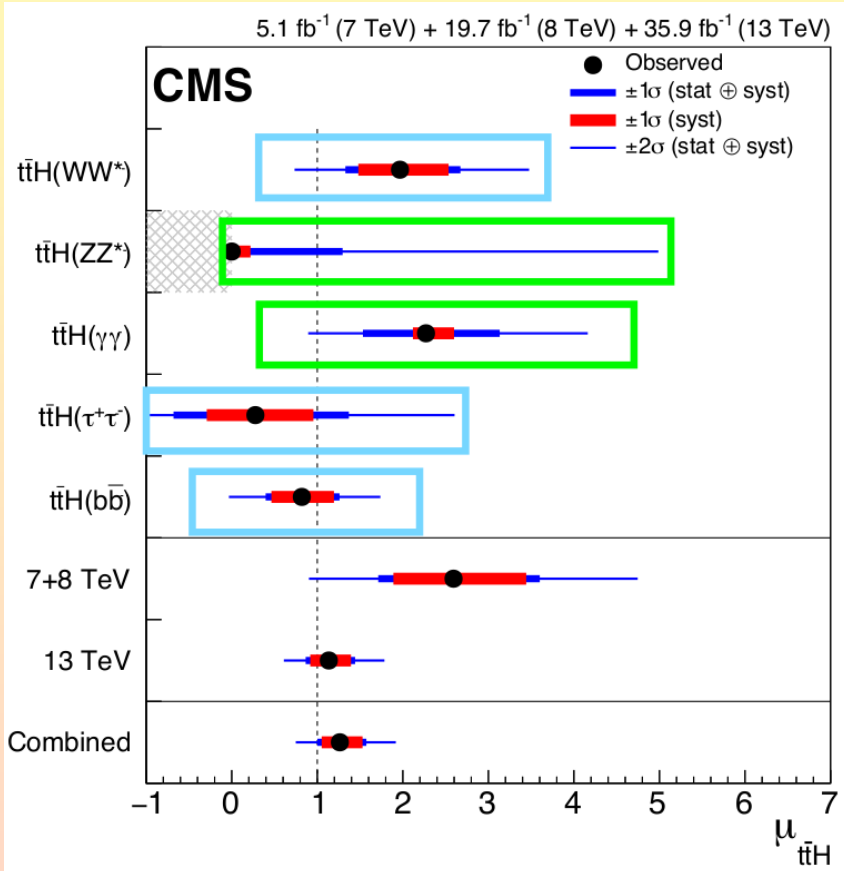
$$\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26} = 1.26^{+0.16}_{-0.16}(\text{stat})^{+0.17}_{-0.15}(\text{expt})^{+0.14}_{-0.13}(\text{bkg th})^{+0.15}_{-0.07}(\text{sig th})$$



Parameter	Best fit	Uncertainty: Stat	Expt	Thbgd	Thsig
$\mu_{t\bar{t}H}^{WW^*}$	$1.97^{+0.71}_{-0.64}$ $\left(^{+0.57}_{-0.54}\right)$	$^{+0.42}_{-0.41}$ $\left(^{+0.39}_{-0.38}\right)$	$^{+0.46}_{-0.42}$ $\left(^{+0.36}_{-0.34}\right)$	$^{+0.21}_{-0.21}$ $\left(^{+0.17}_{-0.17}\right)$	$^{+0.25}_{-0.12}$ $\left(^{+0.12}_{-0.03}\right)$
$\mu_{t\bar{t}H}^{ZZ^*}$	$0.00^{+1.30}_{-0.00}$ $\left(^{+2.89}_{-0.99}\right)$	$^{+1.28}_{-0.00}$ $\left(^{+2.82}_{-0.99}\right)$	$^{+0.20}_{-0.00}$ $\left(^{+0.51}_{-0.00}\right)$	$^{+0.04}_{-0.00}$ $\left(^{+0.15}_{-0.00}\right)$	$^{+0.09}_{-0.00}$ $\left(^{+0.27}_{-0.00}\right)$
$\mu_{t\bar{t}H}^{\gamma\gamma}$	$2.27^{+0.86}_{-0.74}$ $\left(^{+0.73}_{-0.64}\right)$	$^{+0.80}_{-0.72}$ $\left(^{+0.71}_{-0.64}\right)$	$^{+0.15}_{-0.09}$ $\left(^{+0.09}_{-0.04}\right)$	$^{+0.02}_{-0.01}$ $\left(^{+0.01}_{-0.00}\right)$	$^{+0.29}_{-0.13}$ $\left(^{+0.13}_{-0.05}\right)$
$\mu_{t\bar{t}H}^{\tau^+\tau^-}$	$0.28^{+1.09}_{-0.96}$ $\left(^{+1.00}_{-0.89}\right)$	$^{+0.86}_{-0.77}$ $\left(^{+0.83}_{-0.76}\right)$	$^{+0.64}_{-0.53}$ $\left(^{+0.54}_{-0.47}\right)$	$^{+0.10}_{-0.09}$ $\left(^{+0.09}_{-0.08}\right)$	$^{+0.20}_{-0.19}$ $\left(^{+0.14}_{-0.01}\right)$
$\mu_{t\bar{t}H}^{b\bar{b}}$	$0.82^{+0.44}_{-0.42}$ $\left(^{+0.44}_{-0.42}\right)$	$^{+0.23}_{-0.23}$ $\left(^{+0.23}_{-0.22}\right)$	$^{+0.24}_{-0.23}$ $\left(^{+0.24}_{-0.23}\right)$	$^{+0.27}_{-0.27}$ $\left(^{+0.26}_{-0.27}\right)$	$^{+0.11}_{-0.03}$ $\left(^{+0.11}_{-0.04}\right)$
$\mu_{t\bar{t}H}^{7+8\ \text{TeV}}$	$2.59^{+1.01}_{-0.88}$ $\left(^{+0.87}_{-0.79}\right)$	$^{+0.54}_{-0.53}$ $\left(^{+0.51}_{-0.49}\right)$	$^{+0.53}_{-0.49}$ $\left(^{+0.48}_{-0.44}\right)$	$^{+0.55}_{-0.49}$ $\left(^{+0.50}_{-0.44}\right)$	$^{+0.37}_{-0.13}$ $\left(^{+0.14}_{-0.02}\right)$
$\mu_{t\bar{t}H}^{13\ \text{TeV}}$	$1.14^{+0.31}_{-0.27}$ $\left(^{+0.29}_{-0.26}\right)$	$^{+0.17}_{-0.16}$ $\left(^{+0.16}_{-0.16}\right)$	$^{+0.17}_{-0.17}$ $\left(^{+0.17}_{-0.16}\right)$	$^{+0.13}_{-0.12}$ $\left(^{+0.13}_{-0.12}\right)$	$^{+0.14}_{-0.06}$ $\left(^{+0.11}_{-0.05}\right)$
$\mu_{t\bar{t}H}$	$1.26^{+0.31}_{-0.26}$ $\left(^{+0.28}_{-0.25}\right)$	$^{+0.16}_{-0.16}$ $\left(^{+0.15}_{-0.15}\right)$	$^{+0.17}_{-0.15}$ $\left(^{+0.16}_{-0.15}\right)$	$^{+0.14}_{-0.13}$ $\left(^{+0.13}_{-0.12}\right)$	$^{+0.15}_{-0.07}$ $\left(^{+0.11}_{-0.05}\right)$

- $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$ channels still limited by statistics
- $H \rightarrow$ leptons and $H \rightarrow b\bar{b}$ searches dominated by systematics

Breakdown of uncertainties (*where should I do better next time?*)

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- Each of the four uncertainty components of comparable magnitude
- Further breakdown reveals main components
- Signal theory
  - Mainly inclusive $t\bar{t}H$ prediction
- Background theory
  - Mainly $t\bar{t}$ +HF prediction in $t\bar{t}H$ (bb)
- Experimental
  - Lepton efficiencies
  - Lepton mis-id
  - b tagging
  - MC stats

Uncertainty source	$\Delta\mu$	
Signal theory	+0.15	−0.07
Inclusive ttH normalisation (cross section and BR)	+0.15	−0.07
ttH acceptance (scale, pdf, PS and UE)	+0.004	−0.004
Other Higgs boson production modes	+0.002	−0.003
Background theory	+0.14	−0.13
tt + bb/cc prediction	+0.13	−0.11
tt + V(V) prediction	+0.06	−0.06
Other background uncertainties	+0.03	−0.03
Experimental	+0.17	−0.15
Lepton (inc. τ_h) trigger, ID and iso. efficiency	+0.08	−0.06
Misidentified lepton prediction	+0.06	−0.06
b-Tagging efficiency	+0.05	−0.04
Jet and τ_h energy scale and resolution	+0.04	−0.04
Luminosity	+0.04	−0.03
Photon ID, scale and resolution	+0.01	−0.01
Other experimental uncertainties	+0.01	−0.01
Finite number of simulated events	+0.08	−0.07
Statistical	+0.16	−0.16
Total	+0.31	−0.26

Significance (*are you really sure?*)

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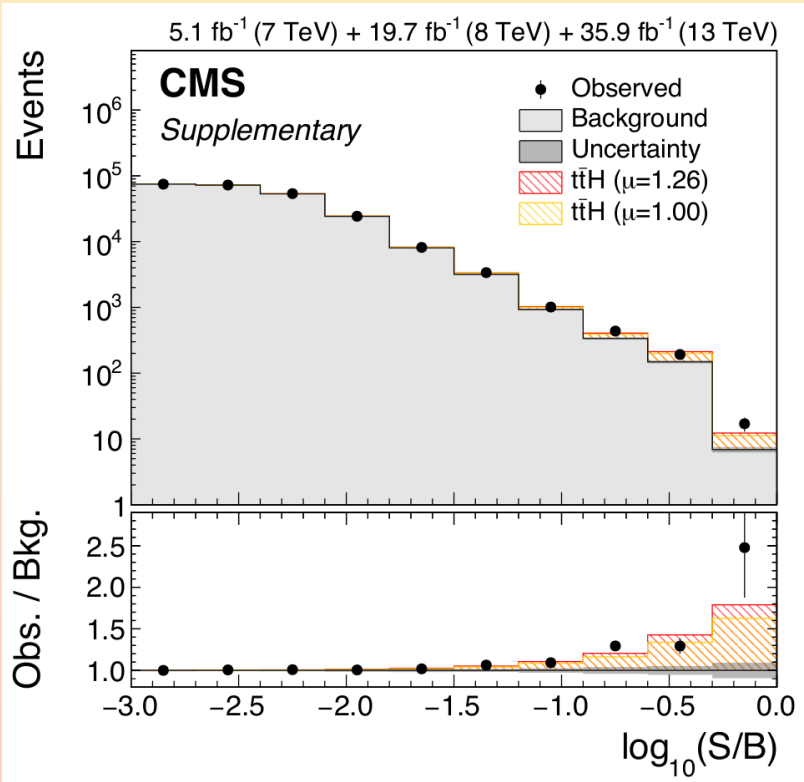
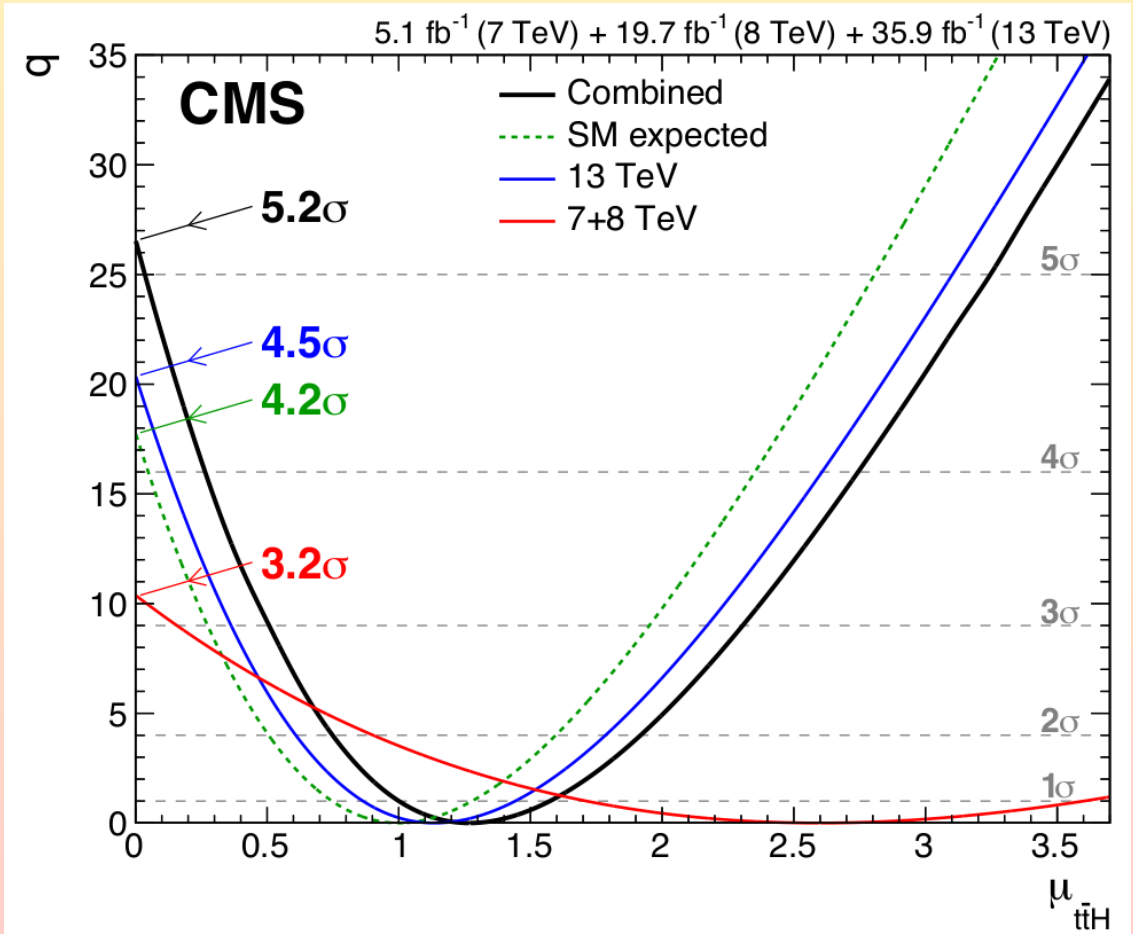
- A total of 88 event categories enter the combination
- Observed significance: 5.2σ (4.2σ exp.) with respect to the $\mu_{\mathrm{t}}\bar{\mathrm{t}}\mathrm{H} = 0$ hypothesis
- First observation of the $\mathrm{t}\bar{\mathrm{t}}\mathrm{H}$ production process:

arXiv:1804.02610: paper accepted by PRL!!!

- Clear excess in the most signal-sensitive bins

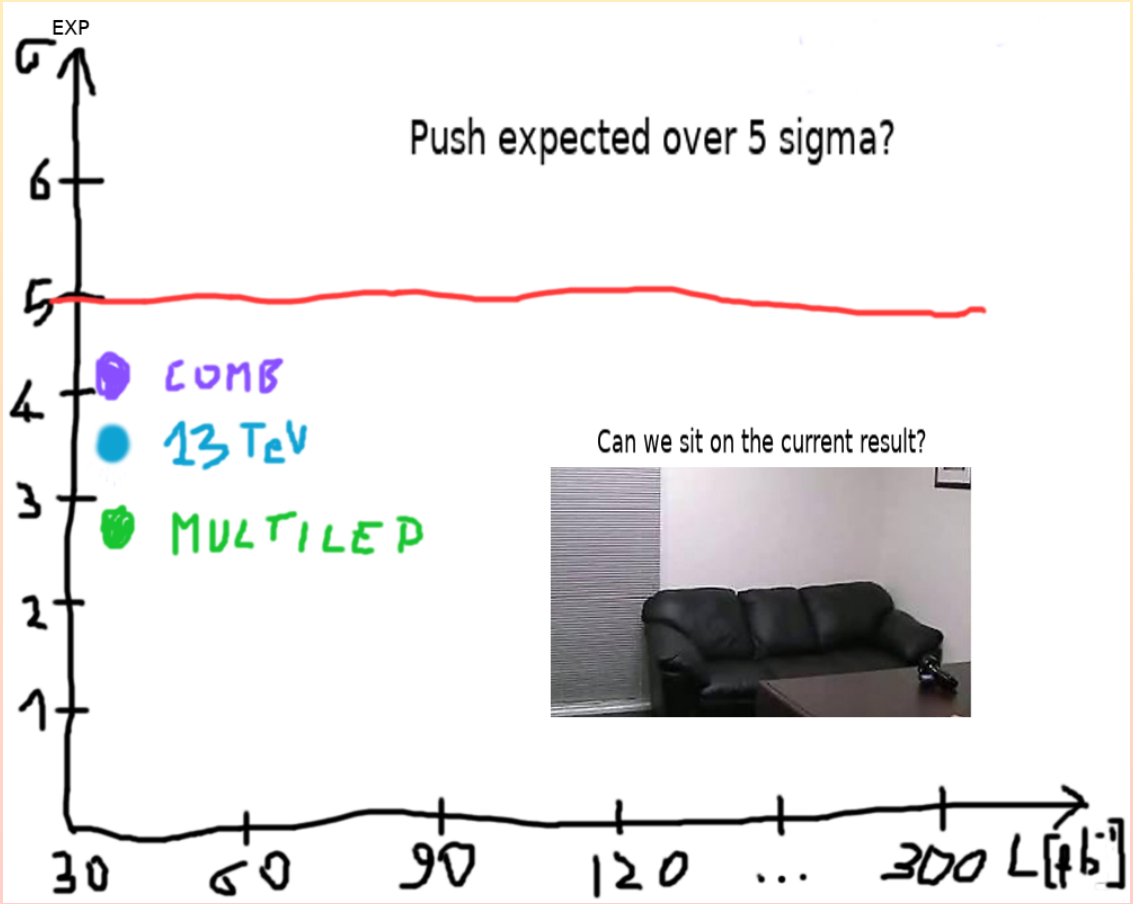




Perspectives (*how to employ the next few years*)

	$\mu_{t\bar{t}H} = \sigma_{t\bar{t}H}/\sigma_{SM}$		Significances obs (exp)	
	ATLAS 13 TeV	CMS 7,8,13 TeV	ATLAS	CMS
Combination	$1.2^{+0.3}_{-0.3}$	$1.26^{+0.31}_{-0.26}$	$4.2\sigma(3.8\sigma)$	$5.2\sigma(4.2\sigma)$

- 13 TeV excesses mostly compatible with SM $t\bar{t}H$
- 5.2σ CMS observation accepted by PRL
- Improve expected sensitivities to put final word
- Excellent perspectives for multilepton for legacy RunII and for RunIII
- Reduce uncertainties
  - Lepton ID, fakes (MVA)
  - Rethink and improve analyses methods (signal extraction...)
- Working on the next Yellow Report! (coming this year)



THANKS FOR THE ATTENTION!